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Sponsors

AIP | Review of Scientific Instruments

Lanzhou, China 1
## Committee

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<td>Hongwei Zhao (Chair)</td>
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<td>Jose Alonso</td>
<td>Friedhelm Ames</td>
<td>Chinwen CHEN</td>
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<td>Mainak Bandyopadhyay</td>
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<td>Evgeny D. Donets</td>
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<td>Dan Faircloth</td>
<td>Yong-Sub Cho</td>
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<td>Ursel Fantz</td>
<td>Baoqun Cui</td>
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<tr>
<td>Santo Gammino</td>
<td>Akiyoshi Hatayama</td>
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<tr>
<td>Ralph Hollinger</td>
<td>Chundong Hu</td>
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<td>Yong-Seok Hwang</td>
<td>Ivan Izotov</td>
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<td>Atsushi Kitagawa</td>
<td>Guillaume Machicoane</td>
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<td>Daniela Leitner</td>
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<td>Thomas Thuillier</td>
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<td>Richard Vondrasek</td>
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<td>Beatriz Schunke</td>
<td>Motoi Wada</td>
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<td>Martin Stockli</td>
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<td>Panagiotis Svarnas</td>
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<td>Katsuyoshi Tsumori</td>
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<td>Rick Vondrasek</td>
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<td>Daniel Z Xie</td>
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General and local information
18th International Conference on Ion Sources

Venue
The 18th International Conference on Ion Sources (ICIS’19) organized by the Institute of Modern Physics will take place at Crowne Plaza on the beautiful Yellow River shore.

Internet
Stay connected to the world with access to free Wi-Fi.
‘CrownPlaza’ - ‘I am visitor’ - ‘Agree’ - Enjoy it!
There will also be available an internet café on level 3 of the plenary. Computers and printing utilities will be available in the internet café.

Emergency Services
In any emergency, notify your event security provider immediately or dial 110 from the nearest internal phone.
For non-emergency security enquiries dial 18509316360 (Shan. Sha) from any internal phone or dial +86-18509316360 from any international roaming mobile phone.

First Aid
In any medical emergency notify your event security or first aid provider immediately. You can also report first aid/medical incidents to the emergency center by calling 120 from any internal phone.
For non-emergency treatment enquiries dial 18509316360 (Shan. Sha) from any internal phone or dial +86-18509316360 from any international roaming mobile phone.

Shopping center
Lanzhou Wanda Plaza, ~3 km from Crowne Plaza.
Lanzhou Center, ~8 km from Crowne Plaza.
## Conference Program

### Monday, September 2nd  
**Ballroom, Crown Plaza**

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<tr>
<th>Time</th>
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<th>Title</th>
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<tbody>
<tr>
<td>08:30-09:00</td>
<td>Registration</td>
<td>Registration</td>
</tr>
<tr>
<td>09:00-09:30</td>
<td>Opening Ceremony</td>
<td>High power accelerators for basic science research and applications and requirements to ion sources</td>
</tr>
<tr>
<td>09:30-10:00</td>
<td>MonI01</td>
<td>Wenlong Zhan: High power accelerators for basic science research and applications and requirements to ion sources</td>
</tr>
<tr>
<td>10:00-10:30</td>
<td>MonI02</td>
<td>Richard Pardo: Review of high intensity ion source development and operation for worldwide nuclear science facility</td>
</tr>
<tr>
<td>10:30-10:50</td>
<td></td>
<td>Conference Photo</td>
</tr>
<tr>
<td>10:50-11:20</td>
<td></td>
<td>Coffee Break</td>
</tr>
<tr>
<td>11:20-11:40</td>
<td>MonM01</td>
<td>Miha Marttinen: Estimating ion confinement times from beam current transients in conventional and charge breeder ECRIS</td>
</tr>
<tr>
<td>11:40-12:00</td>
<td>MonM02</td>
<td>Jibo Li: Effects of magnetic configuration on hot electrons in SECERAL-II plasma</td>
</tr>
<tr>
<td>12:00-12:20</td>
<td>MonM03</td>
<td>Takahiro Karino: Evaluation method of plasma instability in laser ion source using solenoid</td>
</tr>
<tr>
<td>12:20-14:00</td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>14:00-14:30</td>
<td>MonI03</td>
<td>Ivan Izotov: Measurements and simulations of the energy distribution of electrons lost from the minimum B-field</td>
</tr>
<tr>
<td>14:30-15:00</td>
<td>MonI04</td>
<td>Alessio Galatà: Self-consistent modeling of beam-plasma interaction in the charge breeding optimization process</td>
</tr>
<tr>
<td>15:00-15:20</td>
<td>MonA01</td>
<td>Luigi Celona: Multi-diagnostics setup as a tool to overcome the limits of compact ion sources</td>
</tr>
<tr>
<td>15:20-15:40</td>
<td>MonA02</td>
<td>Dong Wu: Particle-in-cell simulation of transport and energy deposition of intense proton beams in solid-density material</td>
</tr>
<tr>
<td>15:40-16:00</td>
<td>MonA03</td>
<td>Yushi Kato: Upper hybrid resonance heating experiments on Electron Cyclotron Resonance ion source</td>
</tr>
<tr>
<td>16:00-16:20</td>
<td>MonA04</td>
<td>Bryan Isherwood: Measurement of the energy distribution of electrons escaping confinement from an Electron Cyclotron Resonance ion source</td>
</tr>
<tr>
<td>16:20-18:00</td>
<td>MonP01-P43</td>
<td>Poster Session 1 (C01, C06, C10)</td>
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### Tuesday, September 3

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<th>Time</th>
<th>Session</th>
<th>Speaker</th>
<th>Topic</th>
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</thead>
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<tr>
<td>8:30-9:00</td>
<td>TueI01</td>
<td>Liangting Sun</td>
<td>Overview of High Intensity Ion Source Development in the Past 20 Years at IMP</td>
</tr>
<tr>
<td>9:00-9:30</td>
<td>TueI02</td>
<td>Edward Beebe</td>
<td>EBIS Development at RHIC for the BNL Heavy Ion Program and the EIC</td>
</tr>
<tr>
<td>9:30-9:50</td>
<td>TueM01</td>
<td>Takahide Nakagawa</td>
<td>Production of intense metal ion beam with RIKEN 28 GHz SC-ECRIS</td>
</tr>
<tr>
<td>9:50-10:10</td>
<td>TueM02</td>
<td>Wang Lu</td>
<td>Production of intense uranium beams with inductive heating oven at IMP</td>
</tr>
<tr>
<td>10:10-10:30</td>
<td>TueM03</td>
<td>Huanyu Zhao</td>
<td>Stable short-pulse ion beam production with the laser ion source at IMP</td>
</tr>
<tr>
<td>10:30-11:00</td>
<td></td>
<td></td>
<td>Coffee Break</td>
</tr>
<tr>
<td>11:00-11:30</td>
<td>TueI03</td>
<td>Laurent Maunoury</td>
<td>Charge breeding at Ganil: improvements, results and comparison with the other facilities</td>
</tr>
<tr>
<td>11:30-12:00</td>
<td>TueI04</td>
<td>Alain Lapierre</td>
<td>EBIS/T charge breeders for RIB facilities</td>
</tr>
<tr>
<td>12:00-12:20</td>
<td>TueM04</td>
<td>Arun Annaluru</td>
<td>The study of 1+ ion beam interaction in an ECR charge breeder ion source plasmas using Monte-Carlo Charge Breeding Code (MCBC)</td>
</tr>
<tr>
<td>12:20-14:00</td>
<td></td>
<td></td>
<td>Lunch</td>
</tr>
<tr>
<td>14:00-14:30</td>
<td>TueI05</td>
<td>Shixiang Peng</td>
<td>Selectable high intensity H+/H₂⁺/H₃⁺ beam with a 2.45 GHz ECR ion source</td>
</tr>
<tr>
<td>14:30-15:00</td>
<td>TueI06</td>
<td>Akira Ueno</td>
<td>J-PARC H⁻ source for 100 mA high energy and high duty factor H⁻ LINACs</td>
</tr>
<tr>
<td>15:00-15:20</td>
<td>TueA01</td>
<td>Tomoya Akagi</td>
<td>Commissioning of high current H⁺/D⁺ ion beams for the Linear IFMIF Prototype Accelerator</td>
</tr>
<tr>
<td>15:20-15:40</td>
<td>TueA02</td>
<td>Vadim Dudnikov</td>
<td>Small anode discharge ion source</td>
</tr>
<tr>
<td>15:40-16:00</td>
<td>TueA03</td>
<td>Weidong Chen</td>
<td>Commissioning of the RF H⁻ source in CSNS</td>
</tr>
<tr>
<td>16:00-16:20</td>
<td>TueA04</td>
<td>Martin Stockli</td>
<td>Upgrading the LANSCE accelerator complex with a SNS RF-driven H⁻ ion source</td>
</tr>
<tr>
<td>16:20-18:00</td>
<td>TueP01-P53</td>
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<td>Poster Session 2 (C02, C03, C04, C07)</td>
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<tr>
<td>Time</td>
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<td>Speaker</td>
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<tr>
<td>8:30-9:00</td>
<td>WedI01</td>
<td>Olli Tarvainen</td>
<td>Plasma diagnostic tools for ECR ion sources - what can we learn from these experiments for the next generation sources</td>
</tr>
<tr>
<td>9:00-9:30</td>
<td>WedI02</td>
<td>Risto Kronholm</td>
<td>ECRIS Plasma Spectroscopy with a High Resolution Spectrometer</td>
</tr>
<tr>
<td>9:30-9:50</td>
<td>WedM01</td>
<td>Yao Yang</td>
<td>Low energy highly charged ion beam production and the future opportunities for HCl physics at IMP</td>
</tr>
<tr>
<td>9:50-10:10</td>
<td>WedM02</td>
<td>Takashi Nagatomo</td>
<td>Well-controlled emittance of the metallic ion beam extracted from the 28-GHz Superconducting ECR ion source adapting the superconducting acceleration cavity for new super heavy elements research</td>
</tr>
<tr>
<td>10:10-10:30</td>
<td>WedM03</td>
<td>Kaori Nakamura</td>
<td>Feasibility study of a compact heavy ion source for investigation of laboratory magnetospheric plasma</td>
</tr>
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<td>10:30-11:00</td>
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<td>Coffee Break</td>
</tr>
<tr>
<td>11:00-11:30</td>
<td>WedI03</td>
<td>Yoshihide Higurashi</td>
<td>Status and perspectives for high intensity uranium beams from the RIKEN 28 GHz ECRIS</td>
</tr>
<tr>
<td>11:30-12:00</td>
<td>WedI04</td>
<td>Junwei Guo</td>
<td>A new microwave coupling scheme for high intensity highly charged ion beam production by high power 24-28 GHz SECRAL ion source</td>
</tr>
<tr>
<td>12:00-12:20</td>
<td>WedM04</td>
<td>Sergey Kondrashev</td>
<td>Development of a highly efficient NEG pumping system for EBIS</td>
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<td>12:20-14:00</td>
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<td></td>
<td>Lunch</td>
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<tr>
<td>14:00-14:30</td>
<td>WedI05</td>
<td>Gianluigi Serianni</td>
<td>First operation in SPIDER and the path to complete MITCA</td>
</tr>
<tr>
<td>14:30-14:50</td>
<td>WedA01</td>
<td>Katsunori Ikeda</td>
<td>Extension of high power deuterium operation of negative ion based neutral beam injector in LHD</td>
</tr>
<tr>
<td>14:50-15:10</td>
<td>WedA02</td>
<td>Dirk Wunderlich</td>
<td>Formation of large negative deuterium ion beams at ELISE</td>
</tr>
<tr>
<td>15:10-15:30</td>
<td>WedA03</td>
<td>Alessandro Mimo</td>
<td>Cavity ring-down spectroscopy system for the determination of negative hydrogen ion density at the ELISE test facility</td>
</tr>
<tr>
<td>15:30-15:50</td>
<td>WedA04</td>
<td>Marco Cavenago</td>
<td>Improvements of the NIO1 installation for negative ion sources</td>
</tr>
<tr>
<td>15:50-16:10</td>
<td>WedA05</td>
<td>Yahong Xie</td>
<td>R&amp;D progress of RF ion source for neutral beam injector at ASIPP</td>
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<tr>
<td>16:10-18:00</td>
<td>WedP01-P51</td>
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<tr>
<td>Time</td>
<td>Session</td>
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<tr>
<td>8:30-9:00 Thu</td>
<td>Th01</td>
<td>Kenichi Nagaoka</td>
<td>Optical Characteristics of Negative Ion Beam with Multi-Beam-Axes Produced by LHD-type Negative Ion Source</td>
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<td>9:00-9:20 Thu</td>
<td>Th01</td>
<td>Carlo Poggi</td>
<td>Design and development of an Allison type emittance scanner for the SPIDER ion source</td>
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<tr>
<td>9:20-9:40 Thu</td>
<td>Th02</td>
<td>Efim Oks</td>
<td>Generation of boron ion beam by different methods</td>
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<td>Brightness Award presentation</td>
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<td>10:00-10:30</td>
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<td>Brightness winner talk</td>
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<td>Coffee Break</td>
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<tr>
<td>11:00-11:20</td>
<td>Th03</td>
<td>Junichi Hirotsuka</td>
<td>Achievement of high power and long pulse negative ion beam acceleration for JT-60SA NBI</td>
</tr>
<tr>
<td>11:20-11:40</td>
<td>Th04</td>
<td>Robert Welton</td>
<td>Installation and commissioning of the ion source systems for the new SNS 2.5 MeV injector</td>
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<td>11:40-12:00</td>
<td>Th05</td>
<td>Mamiko Sasao</td>
<td>Prospect of Cs-free hydrogen negative ion sources using C12A7 plasma electrodes</td>
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<td>12:00-12:20</td>
<td>Th06</td>
<td>Scott Lawrie</td>
<td>A pre-injector upgrade for the ISIS pulsed spallation neutron facility, including a medium energy beam transport line and an RF-Driven, non-caesiated, external-antenna H– ion source</td>
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<td>Excursion</td>
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Note:
Excursion:
Route 1: Lanshan Scenic Area & Wuquan Park
Route 2: Gansu Provincial Museum

Banquet:
Gansu International Convention and exhibition Center

Lanzhou, China
### Friday, September 6

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<td>9:00-9:30</td>
<td>Fri01</td>
<td>Andrey Efremov</td>
<td>The role of ion sources in synthesis of the super-heavy elements</td>
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<tr>
<td>9:30-10:00</td>
<td>Fri02</td>
<td>Peter Klar</td>
<td>Ion thrusters and electrical propulsion developments</td>
</tr>
<tr>
<td>10:00-10:20</td>
<td>Fri01</td>
<td>Martin Becker</td>
<td>Capabilities of radio-frequency ion-sources in surface modification of materials</td>
</tr>
<tr>
<td>10:20-10:40</td>
<td>Fri02</td>
<td>Atsushi Kitagawa</td>
<td>Present status of ion sources at QST-NIRS and carbon-ion radiotherapy facilities</td>
</tr>
<tr>
<td>10:40-11:00</td>
<td>Fri03</td>
<td>Shunsuke Ikada</td>
<td>Neutron generator based on intense lithium beam driver</td>
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<td>11:00-11:20</td>
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<td>Coffee Break</td>
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<tr>
<td>11:20-11:40</td>
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<td>Young Scientist Award</td>
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<tr>
<td>11:40-12:10</td>
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<td>Conclusion Remarks</td>
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<td>12:10-12:30</td>
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<td>Conference Closing Ceremony</td>
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<td>12:30-13:30</td>
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<td>Lunch</td>
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<tr>
<td>14:00-16:30</td>
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<td>Lab Tour</td>
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<tr>
<td>16:30-18:00</td>
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<td>Free</td>
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- C01 Fundamental processes in ion source & plasma
- C02 Production of high intensity ion beams
- C03 Production of highly charged ion beams
- C04 Negative ion sources
- C05 Ion sources for fusion
- C06 Polarized ion sources
- C07 Radioactive ion beams sources and charge breeders
- C08 Beam formation, extraction, transport, and diagnostics
- C09 Key technologies for ion sources
- C10 Applications of ion sources
Monday, September 2
High power accelerators for basic science research and applications and requirements to ion sources

Wenlong Zhan
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
Corresponding Author: Wenlong Zhan, e-mail address: wlzhan@cashq.ac.cn
Review of high intensity ion source development and operation for worldwide nuclear science facility

Richard Pardo
Argonne National Laboratory
Corresponding Author: Richard Pardo, e-mail address: pardo@anl.gov

The Electron Cyclotron Ion Source (ECRIS) has transformed the nuclear physics research field over the last 40+ years. Today the performance of ECRIS sources are the first parameter that defines the design of new facilities and the performance of existing facilities. In this talk, I will review the current ‘state of the art’ performance capabilities for ECR ion sources and how those present capabilities form the primary design criteria for new facilities and set the limiting performance for existing facilities.
Estimating Ion Confinement Times from Beam Current Transients in Conventional and Charge Breeder ECRIS

M. Marttinen^1, J. Angot^3, A. Annaluru^2, P. Jardin^2, T. Kalvas^1, H. Koivisto^1, S. Kosonen^1, R. Kronholm^1, L. Maunoury^2, O. Tarvainen^1,4, V. Toivanen^1, P. Ujic^2

^1Department of Physics, University of Jyväskylä, PO Box 35, FI-40014 JYVÄSKYLÄ, Finland
^2Grand Accélérateur National d’Ions Lourds, BP 55027, 14076 CAEN CEDEX, France
^3Laboratoire de Physique Subatomique et de Cosmologie, Universite Grenoble Alpes, 38026 GRENOBLE CEDEX, France
^4STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX, UK

Corresponding Author: Miha Marttinen, e-mail address: misapema@student.jyu.fi

High-precision measurements [1] of the Doppler broadening of ion spectral lines have indicated, that ions in an ECRIS plasma may obtain much higher temperatures than is conventionally believed, i.e. on the order of 10 eV. The temperature is also observed to be charge state dependent. The anomalous temperatures could plausibly be explained by assuming the electrostatic confinement of ions in a potential well within the plasma potential, caused by accumulated hot electrons in the plasma core [2, 3]. In this confinement scheme, the ions would obtain long cumulative confinement times, which would allow them to be heated in collisions with the cold electron population. In the work presented herein, the ion confinement time is probed using a transient method similar to that employed in [4, 5]: Material injection into a buffer plasma is pulsed, and the extracted, decaying beam current transients are analyzed to obtain an estimate for the ion confinement time. The method is applied both in an ECR charge breeder source where material injection is realized by direct \( ^1+^2 \) injection of potassium, and in a conventional ECRIS using sputtering of copper into various buffer gases (O, He, Ar). The transient equation used for the data analysis is derived from the ion balance equation, and the validity of the assumptions made in its derivation are evaluated. The measurements from the two experimental campaigns analyzed for this work yielded mutually corroborative results: The confinement time is estimated to be on the order of tens of milliseconds for Cu and K ions at charge to mass ratios between 0.15 and 0.27, with higher charge states corresponding to longer confinement times. The long confinement times support the notion of electron-ion interaction as a source of the anomalous ion temperatures, and a qualitative model based on the electrostatic confinement and electron-drag heating is proposed to connect the ion temperatures to the confinement times. Understanding the confinement times of highly charged ions is important fundamentally, but also for the practical purpose of developing radioactive ion beams, which depend not only on fast and efficient ionization, but also on short ion confinement times, to prohibit the decay of the radioactive isotopes during the charge breeding process.

References and Acknowledgment

[1]: R. Kronholm et al. (accepted manuscript), Plasma Sources Science and Technology, 10.1088/1361-6595/ab27a1, (2019).
Effects of magnetic configuration on hot electrons in SECRAL-II plasma

J. B. Li¹, L. X. Li¹, ², J. W. Guo¹, L. B. Li¹, W. Lu¹, X. Z. Zhang¹, ², L. T. Sun¹, ², D. Hitz¹ and H. W. Zhao¹, ²

¹Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou 730000, China
²School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

To investigate the hot electrons population in highly charged electron cyclotron resonance ion source (ECRIS), the axial emitted bremsstrahlung spectra, along with microwave signal emitted from the ECRIS plasma are measured on SECRAL-II (Superconducting ECR ion source with Advanced design in Lanzhou No. II) ion source. The evolution of the hot electrons spectral temperature, Ts, is studied through the variation of magnetic configuration. The experimental results have shown that when the ratio of the minimum field to the resonance field (i.e. Bmin /Becr) is less than 0.75~0.80, there is a linear dependence of the spectral temperature on the ratio of Bmin /Becr, above this threshold Ts saturates and electron cyclotron instability appears simultaneously. This phenomenon may be due to the fact that the spectral temperature Ts provides an indication of the temperature of the hot electrons, significant losses of the hot and warm electrons caused by electron cyclotron instability will lead to a saturation of Ts. In addition, this investigation has also shown that Ts decreases with the increase of the gradient at the resonance zone at low mirror ratio and is insensitive to the gradient at high mirror ratio when Bmin is constant.
Evaluation method of plasma instability in laser ion source using solenoid

Takahiro Karino$^{1,2}$, Masahiro Okamura$^{2,3}$, Takeshi Kanesue$^3$, Shunsuke Ikeda$^3$ and Shigeo Kawata$^1$

$^1$Graduate School of Engineering, Utsunomiya University, Utsunomiya 321-8585, Japan
$^2$Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198 Japan
$^3$Collider-Accelerator Department, Brookhaven National Laboratory, NY 11973 USA

Corresponding Author: Takahiro Karino, e-mail address: dt167105@cc.utsunomiya-u.ac.jp

A laser ion source can provide stable intense heavy ion beams with relatively simple structure. Recently, solenoid confinement technique was developed and applied to the operating laser ion sources. By introducing solenoid, supplied ion beam current can be enhanced and adjusted for the applications. However, it is known that the expanding laser plasma confined by a solenoid field becomes unstable in a certain magnetic field region. To investigate the unstable condition further, it is essential to quantify the instability. In this study, we propose the most appropriate method to evaluate plasma instability. The validity was evaluated by comparing five methods, variation of maximum value, variation of integral value, variation of half width, variation of half value width divided by maximum value, integral value of difference from average waveform. The detailed comparison discussion will be given at the presentation.

References and Acknowledgment

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Measurements and Simulations of the Energy Distribution of Electrons Lost from the Minimum B-field

Ivan Izotov¹, Vadim Skalyga¹,², Dmitriy Mansfeld¹, Hannu Koivisto³, Risto Kronholm¹, Olli Tarvainen³, Ville Toivanen³, Egor Gospodchikov¹,², Alexander Shalashov¹,², Vladimir Mironov⁴

¹ Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603155, Russia
² Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603155, Russia
³ Department of Physics, University of Jyväskylä, Jyväskylä, 40500, Finland
⁴ Joint Institute of Nuclear Research, Dubna, 600000, Russia

Corresponding Author: Ivan Izotov, e-mail address: ivizot@ipfran.ru

Further progress in the development of ECR ion sources (ECRIS) requires a deeper understanding of underlying physics. One of the topics that remains little studied, though being crucial for the confinement of the plasma and performance of the ion source, is the electron energy distribution (EED). A well-developed technique of measuring the EED of electrons escaping axially from a magnetically confined plasma of an ECRIS is reported. The majority of the experimental data were recorded in pulsed and CW discharges with a room-temperature 14 GHz ECRIS at the JYFL accelerator laboratory. It was discovered that for 14 GHz source the EED is strongly non-Maxwellian in the range of 5–250 keV and exhibits several local maxima below 20 keV energy. It was observed that the most influential ion source operating parameter on the EED is the magnetic field strength, which affected the EED predominantly at energies less than 100 keV. The effects of the microwave power and frequency on the EED were found to be less significant. The latter measurements were focused on distinguishing between the EED in stable plasma and the one perturbed with kinetic instabilities. It was found that nonlinear phenomena alter the energy distribution of the lost electrons noticeably. It has been shown earlier that the two-frequency plasma heating mode, being widely used, boosts the ECRIS performance presumably thanks to suppression of kinetic instabilities. We report the observed changes in EED of the escaping electrons introduced by the secondary frequency in different regimes, including the one with the secondary frequency being below the cold ECR in the magnetic trap. Discussion on the suppression mechanism of kinetic instabilities by means of applying the secondary frequency heating and the role of RF pitch angle scattering is presented along with the comparison of experimentally obtained EED to the simulated one with the use of NAM-ECRIS PIC code.

References and Acknowledgment

The work was supported by the Russian Science Foundation, project #19-12-00377.
The slowing down and capture by a plasma of externally injected 1+ ions, as a consequence of very frequent elastic Coulomb collisions, is the main mechanism involved in the charge breeding process based on Electron Cyclotron Resonance Ion Sources. The INFN ion source group has been undertaking an intense activity on numerical simulations of the beam-plasma interaction, developing a code that has been proving to be very effective in reproducing several experimental results of charge breeding of light and heavy ions. This contribution will present the progress made in the development of the numerical code, focusing the attention on the latest simulations of charge breeding of Rb\textsuperscript{1+} ions employing a self-consistent plasma target model. The effect of the real plasmoid/halo structure on the capture process will be underlined, as well as the influence of different plasma excitation frequencies.
Multi-diagnostics setup as a tool to overcome the limits of compact ion sources

G. Castro\textsuperscript{1}, D. Mascali\textsuperscript{1}, G. Torrisi\textsuperscript{1}, M. Mazzaglia\textsuperscript{1}, E. Naselli\textsuperscript{1,2}, L. Celona\textsuperscript{1} and S. Gammino\textsuperscript{1}

\textsuperscript{1} INFN-LNS - Via S. Sofia 62, 95123, Catania, Italy; \textsuperscript{2} Università degli studi di Catania, dipartimento di fisica, Via S. Sofia 64, 95123, Catania, Italy; 
Corresponding Author: Giuseppe Castro, e-mail address: Castrog@lns.infn.it

The development of plasma diagnostics devoted to compact ion sources is being one of the main efforts of INFN-LNS ion source group. Indeed, the use of the brute force can lead to improvements in ion sources’ performances only if accompanied by a proper knowledge of plasma physics. The key goal of plasma diagnostics in compact ion sources is the volumetric knowledge of the electron energy distribution function (EEDF) and the on-line evaluation of the plasma composition. This information will allow tuning EEDF to maximize the generation of the desired ion. Moreover, development of time resolved diagnostics gives precious information about the strategy for decreasing the beam ripple and increasing the operability domain of ion sources. The paper will introduce the most relevant diagnostics developed in the last ten years at INFN-LNS (optical emission spectroscopy, volume and space resolved X-ray diagnostics, RF and Langmuir probe diagnostics, interfero-polarimetric diagnostics) together with the main experimental results they have permitted to attain. Particular relevance will be also given to the perspectives and next goals of plasma diagnostics in compact sources.
Particle-in-cell simulation of transport and energy deposition of intense proton beams in solid-density material

Dong Wu
Zhejiang University
Corresponding Author: Dong Wu, e-mail address: dwu.phys@zju.edu.cn

A complete particle-in-cell (PIC) simulation has, for the first time, been performed for the transport and energy deposition of an intense proton beam within a solid. In particular, for close interactions, we developed a novel Monte-Carlo binary collision model that takes into account all interactions between the incident protons and matter, e.g., proton-nuclei, proton-bound electron and proton-free electron. This includes especially also a Monte-Carlo model for the collisional ionization and electron-ion recombination as well as the depression of the ionization potential by surrounding charged particles. Moreover, we take into account collective electromagnetic effects by solving reduced Maxwell Equations. For intense proton beams, the collective electromagnetic effects ensure localized energy deposition by collimating proton beams, which would otherwise be deflected by the collisions with nucleus. This simulation model enables kinetic investigation of charged particle transport in high energy density plasmas.
We have been considered accessibility condition of electromagnetic and electrostatic waves propagating in ECR ion source (ECRIS) plasma, and then investigated their correspondence relationships with production of multicharged ions. It has been clarified that there exits efficient configuration of ECR zones for producing multicharged ion beams, and then has been suggested that new resonance, i.e. upper hybrid resonances (UHR), must have occurred.[1] We have been promoting new advanced experiments inducing actively these additional effects for enhanced furthermore multicharged ion beams with launching extra-ordinary (X) mode waves. Initially we had already conducted to applying 9GHz X-mode microwaves to 2.45GHz ECRIS, and it had been observed enhancements of higher energy tails of electron energy distributions function measured by the probe methods.[2] Next we have been trying similar experiments with 4-6GHz X-mode microwaves,[3] and we have succeeded in enhancing production of multicharged ions by launching these bands X-mode microwaves. Furthermore, at the same time we have observed sharp increases of electron energy distribution functions in ECRIS plasma by means of probe methods. It have been concluded that the UHR must have occurred by applying multiplex microwaves with their frequencies away from those for ECR in ECRIS. In this paper we will describe brief theoretical background and these new experimental results.

References and Acknowledgment

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Measurement of the Energy Distribution of Electrons Escaping Confinement from an Electron Cyclotron Resonance Ion Source

Bryan Isherwood1,2, Guillaume Machicoane1,2
1National Superconducting Cyclotron Laboratory, East Lansing, Michigan 48824, USA
2Michigan State University, East Lansing, Michigan, 48824, USA
Corresponding Author: Bryan Isherwood, e-mail address: isherwoo@nscl.msu.edu

The production of high charge state ions in electron cyclotron resonance ion sources (ECRIS) is dependent on the electron energy distribution (EED) within the source plasma. In order to better understand the EED a measurement of electrons escaping axially from an ECRIS device has taken place at the National Superconducting Cyclotron Laboratory (NSCL). Electrons were measured escaping from the Superconducting Source for Ions (SuSI), driven at 18 GHz. Dependencies of the observed EED on the confining magnetic field strength, injected microwave power, and neutral gas pressure were measured. Measurements of the axial bremsstrahlung spectrum were simultaneously measured to provide a direct comparison between both techniques. Results showed a large peak of electrons in the 600-1000 keV energy range. Calculations of the average electron energy and bremsstrahlung spectral temperature as a function of varying plasma parameters are also reported.
Pressure Effect on Planar Magnetron Discharge Plasma Electron Temperature and on Ion Composition

Alexey Vizir¹, Efim Oks², Maxim Shandrikov¹, George Yushkov¹
¹High Current Electronics Institute
²HCEI

Despite a magnetron discharge is generally used in thin film deposition processes, it can be also utilized for ion beam production. An ion source based on a planar magnetron discharge with 2-inch diameter target was realized and studied. It was shown that, at certain conditions, the discharge running in a high current pulsed mode effectively produces plasmas with a relatively high fraction of electrically conductive and even semiconductor [1] target material ions. The ion beam was extracted from the discharge plasma, and its composition was studied using a time of flight methodic. Plasma electron temperature was measured by a double probe. It was proven that the working pressure increase cools down electrons, which leads to the increase of the target material ion fraction due to their lower ionization potential compared to that of the working gas.

References and Acknowledgment
This work was supported by Russian Foundation for Basic Research under grant #19-58-53001.
The new version of the ion source based on plasma thruster’s technology is developed and tested. The ion source design uses a geometry of circular anode layer plasma thruster in which ion beam is extracted in radial direction from the full circumference. The device is simple in design and is suitable for use in the technological processes for the treatment of the inner wall surface of pipes and tubes. For effective operation of devices, it is important to know their usage parameters, therefore the electrical characteristics of the discharge in the ion sources operated in different modes were studied in the feed rate of operating gasses (argon, nitrogen and air) range up to 20 sccm. The current–voltage characteristic of the discharge as well as the temporal evolution of the pulse current–voltage relations have been acquired for a constant magnetic field. The open geometry of the discharge channel allows to observe the behavior of the anode layer and take the photo of it.

References and Acknowledgment

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A gas cluster ion beam system is set up to produce cluster ion beams by means of ultrasonic expansion of high-pressure gases. $\text{Ar}_{840}^+$ clusters with energy in the range of 3-20 keV are used to bombard surface of pressed Si nanopowder targets. High monotonous sputtering yield of the silicon nanopowder target is observed in the cluster energy range of 3-10 keV, which is considered as enhanced by the finite size effect of the target particles. Scanning electron microscopy reveals formation of debris on the target surface at cluster energy 10 keV and higher, which results in reducing the finite size effect and consequently the sputtering yield. Individual impacts of the argon clusters are observed as pocks of 8-14 nm in size on the silicon particle surface. Cluster bombardment results in ejection of silicon particles with mean size of 11.5 nm. Number of ejected particles is correlated with the sputtering yield in the energy range of 3-10 keV, hence, their formation associated with the sputtering enhanced by the finite size effect.
The results of a time resolved Ion Energy Distribution Function (IEDF) evolution study for a low density and temperature ECR hydrogen plasma are presented. Two magnetic field distributions have been used as case studies: one generated by four coaxial coils arranged in two pancakes and the other one created by an octupole multicusp permanent magnet arrangement. In the first case, a remarkable effect of plasma spatial distribution inside of the plasma chamber was observed where influence of ExB drift velocity strongly affects the IEDFs measurements and its interpretation. This hypothesis is supported by ultrahigh photography diagnostics that yields valuable information about free charge plasma spatial distribution that breaks plasma quasineutrality in at least two order of magnitudes higher than expected Debye length. The influence of the plasma collective effects and its influence on the ion velocities is demonstrated. Temperature time evolution is estimated for H$^+$, H$^{2+}$ and H$^{3+}$ ions.
The results of study of the formation, transportation, and separation of a boron ion beam formed by an arc ion source with a cathode spot erosion plasma, which uses lanthanum hexaboride as a cathode material are presented. The initiation of the cathode spot is carried out by a breakdown over the surface of a ceramic block with a diameter of about 2.5 mm, made of alumina ceramics, which is installed in the center of the working cathode. Due to such a design of the igniter, a sufficiently uniform erosion of the cathode is ensured, and due to the dimensions of the latter (1.4 cm in diameter and 1.4 cm in length), the long lifetime of the source is provided. The plasma source operates in a pulsed mode of the arc discharge with a pulse repetition rate of up to 10 ppm. With a discharge current of 150 A, a rectangular ion beam (4.5×0.6 cm$^2$) accelerated to 25 kV with a current amplitude about 100 mA was obtained. The beam separation was performed using a bending magnet.

**References and Acknowledgment**

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Investigation of Ion Acceleration Effect Influence on Formation of Ambipolar Potential Profile in the Expander Region

Ilya S. Abramov\textsuperscript{1}, Egor D. Gospodchikov\textsuperscript{1}, Roman A. Shaposhnikov\textsuperscript{1}, Alexander G. Shalashov\textsuperscript{1}

\textsuperscript{1}Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia

Corresponding Author: Roman A. Shaposhnikov, e-mail address: shaposhnikov-roma@mail.ru

Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia

This paper presents a study of plasma flux characteristics flowing out from the gasdynamic mirror trap along the magnetic field lines to a metal wall. The main feature of current work is that the effect of ion acceleration by ambipolar potential was considered not only in a thin Debye layer but in the whole expander region. The developed model also takes into account a possibility of transition from collisional expansion of electron flow in the vicinity the plug to kinetic nearly collisionless regime. The developed model allows to calculate the ambipolar potential profile and plasma characteristics in the expander region. The results are compared to experimental data.

References and Acknowledgment

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First measurements of the high energy electron distribution confined in a minimum-B ECRIS plasma

Vadim Skalyga1,2, Ivan Izotov1, Hannu Koivisto3, Risto Kronholm3, Olli Tarvainen3,4, Ville Toivanen3, Vladimir Mironov5
1 Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603155, Russia
2 Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603155, Russia
3 Department of Physics, University of Jyväskylä, Jyväskylä, 40500, Finland
4 STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX, UK
5 Joint Institute of Nuclear Research, Dubna, 600000, Russia
Corresponding Author: Vadim Skalyga, e-mail address: skalyga@ipfran.ru

Progress in minimum-B ECRIS development is currently hindered by significant technological difficulties in the construction of high-field magnetic structures meeting the scaling laws at desirable frequencies of the heating microwaves. At the same time, the most advanced experimental facilities face a problem of the plasma becoming unstable above a certain heating power level, which does not allow fully utilizing the available microwave power. These factors highlight the importance of fundamental studies of ECRIS plasmas to obtain a better understanding of the key processes affecting the ion source performances. The electron energy distribution (EED) seems to be one of the most crucial and complicated plasma properties defining its confinement and stability. A technique to analyse the electrons escaping through the extraction mirror of the ion source by detecting them with a secondary electron amplifier placed downstream from a dipole magnet serving as an electron spectrometer has been successfully applied first on SMIS 37 (IAP RAS, Nizhny Novgorod, Russia) and later on the 14 GHz ECRIS (JYFL, Jyväskylä, Finland). Nevertheless, the relation between the escaping and confined electron energy distributions has remained open so far. A method to evaluate the EED confined inside the ECRIS plasma is suggested in the present paper. It is based on pulsing the microwave power, first allowing the plasma to reach a steady-state, then switching off the heating pulse and measuring the time-resolved EED of the electrons escaping through the extraction mirror during the decay. In the absence of RF pitch angle scattering and kinetic afterglow instabilities, collisions are the main process scattering electrons into the loss cone. Assuming that the majority of the collisions are elastic, the integrated electron losses during the decay should represent the information on the EED prevailing inside the plasma at the moment of switching off the heating pulse. The effect of different electron loss channels on the experimental results is assessed. The results of the first attempt to apply the suggested technique with the 14 GHz ECRIS at JYFL are presented. The obtained data is compared to previous experiments and to the results of numerical simulations with NAM-ECRIS PIC code, showing a good agreement. Finally, the required steps to improve the technique are discussed.

References and Acknowledgment

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Optimization of laser-target parameters for the production of stable lithium beam

Antonino Cannavò1, Kazumasa Takahashi2, Masahiro Okamura3,4, Giovanni Ceccio1, Takeshi Kanesue3, Shunsuke Ikeda3

1Nuclear Physics Institute of CAS, Rez 25068, Prague, Czech Republic
2Department of Electrical Engineering, Nagoya University of Technology, Nisshin 940-2188, Japan
3Collider-Accelerator Department, Brookhaven National Laboratory, Upton, 11973, New York, USA
4Nishina Center for Accelerator-Based Science, RIKEN, Wako, Saitama 351-0198, Japan

Corresponding Author: Antonino Cannavò, e-mail address: cannavo@ujf.cas.cz

Demand for low energy, high-current stable lithium beam is getting more and more importance due to the increasing interest in many studies related to this material: such as the development of compact neutron source, Radioactive Ion Beam (RIBs) production or astrophysics applications. Laser ion source (LIS) coupled with a Radio-Frequency Quadrupole (RFQ) linac represents an innovative and efficient method for beam production and acceleration. With the aim to optimize the Li ions injection into the RFQ cavities, the laser-generated plasma from a different Li related material has been characterized using Faraday Cup (FC) and Electrostatic Ion Analyzer (EIA) in time of flight configuration. A wide range of laser power density has been investigated (10^10 – 10^12 W/cm^2) using two Nd:YAG lasers operating at different wavelength (1064, 532 nm), pulse duration (6, 17 ns) and maximum energy (1400, 210 mJ), respectively. The paper reports on how the current densities, the pulse durations, the ions energy and the charge states distributions are modified as the irradiation conditions are changed.

References and Acknowledgment

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Characteristics of miniature pulsed penning ion source: experiment and PIC simulation

N.V. Mamedov¹,², A.S. Rohmanenkov¹, V.I. Zverev¹,², S.P. Maslennikov¹,², A.A. Solodovnikov¹, A.A. Uzvolok¹, D.I. Yurkov¹,²

¹ Dukhov Automatics Research Institute (VNIIA), Federal State Unitary Enterprise 22, Suschevskaya Ul., Moscow 127055, Russia, vniia4@vniia.ru
² National Research Nuclear University MEPhI 31, Kashirskoye Sh., Moscow 115409, Russia

The results of the experimental and PIC simulation studies of the discharge combustion modes in a miniature penning ion source (PIS) under the pulse-periodic power supply conditions are presented. The amplitude-time characteristics of the discharge current (Id) and the extracted ion current (Iex) were measured in the gas pressure range P = 0.1 – 10 mtorr for the various values of the anode voltage amplitude (Ua) ranging from 1.5 to 3.0 kV. Ua pulses frequency (f) varied from 0.2 to 10 kHz, the pulse duration adjustment range was tvp = 30 – 200 µs. Accelerating voltage (Uex) was set to -20 kV. The influence of Ua, f and tvp on the amplitude-time and current-voltage characteristics of the PIS is studied. The discharge operation modes of PIS and the corresponding ranges of gas pressures, at which various penning discharge modes are realized, are revealed.

The obtained experimental data showed that:

a. the anode current in the pulsed mode of supply saturates at the value equivalent to the current in the continuous mode of supply at the same gas pressure;

b. the pressure range of the discharge ignition was 0.8 - 1 mtorr. However at pressures below 2 mtorr instability of the discharge can develop, leading to the triangular current pulse shape.

c. the operating pressures is in the range of 4 – 6 mtorr. In this range the discharge is stable, current pulses have regular rectangular shape. The discharge current and extracted current increase linearly with pressure (Id from about 200 to 500 µA; Iex from about 180 to 230 mA). Characteristic delay time of the current pulse (tdelay) is in the range of 10 - 5 µs, the current rise time (tfront) is from 2 to 1.3 µs. In all pressure ranges, the falling edge time does not exceed 1.3 µs. The accuracy of time measurements is ~0.3 µs;

d. an increase in the pressure above 7 mtorr leads to a sharp exponential increase in the discharge current to values above 1 mA.

The results of penning discharge numerical simulation in a 3D setting are also presented. The simulation is based on the electrostatic method of particles in cells (PIC) using structured rectangular grids and implemented in the VSim software package. The Monte Carlo collision method was used to simulate kinetic processes in gas-discharge plasma. A comparison of simulation results with experimental data is presented.
A model for real time, in-situ emissivity measurement of a vacuum immersed cesiated tungsten surface using infrared imaging

Pranjal Singh1, 2 and Mainak Bandyopadhyay1, 2
1 Institute of Plasma Research, Bhat, Gandhinagar 382428, Gujarat, India
2 Homi Bhabha National Institute (HBNI), Training School Complex, Anushakti Nagar, Mumbai 400094, India
Corresponding Author: pranjal.singh@ipr.res.in; mainak@ipr.res.in

The Langmuir theory of adsorption-desorption equilibrium and kinetics1 describes the behaviour of sub-monolayer coverage of cesium (Cs) atoms on a refractory metal, such as tungsten (W) surface. It is well known that quasi exponential behaviour of Cs coverage with time is obtained in a Cs/W system. The Cs deposition on the W surface alters its emissivity from pristine W emissivity value to a saturation value corresponding to complete Cs coverage. The change in emissivity therefore affects the infrared (IR) based temperature measurements using IR camera. The relationship between the emissivity and the surface temperature follows Hagen-Ruben (HR) relation2. In the present model Langmuir adsorption isotherm (LAI) and HR relation are coupled to study the emissivity variation with Cs deposition. Within 100°C temperature variation, the HR relationship can be approximated as linear. Therefore, we assume that the measured temperature and corresponding emissivity should follow a similar quasi exponential behaviour close to Langmuir adsorption isotherm (LAI) pattern. Following which independent equations for temperature and emissivity variation similar to that of LAI can be formulated. The temperature equation is then fitted with the experimentally measured time varying temperature assuming emissivity is constant. The temporal profile provides the fitting parameter (time constant) of the exponential behaviour. The time constant value then fitted in the emissivity equation for a constant tungsten temperature in order to obtain the emissivity profile. In the experiment tungsten temperature is maintained constant my monitoring filament heating current. The time is related to the Cs flux, measured separately by the surface ionization detector (SID). This model helps to estimate the emissivity of Cs/W system in vacuum. A simplified cathode-anode assembly is designed to test our model and measure the emissivity in correlation with Cs flux along with work function simultaneously, in vacuum conditions relevant to ion sources and surface conditions equivalent to plasma grid conditions.

Fig1. Thermal image of the filament (W) under constant filament heating current (~3A) by an IR camera: (a) (T~ 160 °C) before Cs deposition and (b) (T~ 100°C) after Cs deposition.

IR camera output shows (Fig.1 (a) and (b)) that the filament surface reduces its temperature by 60°C, (from 160 °C to 100 °C) when Cs is getting deposited on the filament surface while maintaining constant filament heating current (~3 amperes). IR camera assumes a constant emissivity value of tungsten (W) surface as an input while estimating the temperature as output. But actually temperature is maintained constant by supplying constant heating current under vacuum condition. The cooling effect due to conduction and convection routes are considered to be negligible compared to the radiation cooling due to thin nature of the filament dimension and vacuum level (~10^-6 mbar). Therefore, this virtual observed cooling effect is due to the change in emissivity value of the pristine W surface after Cs coating takes place on it. In this presentation we propose a model on a relationship between the emissivity change and the temporal variation of Cs coverage.

References and Acknowledgment

32 Lanzhou, China
Laser power density dependence on charge state distribution of heavy ion laser plasma

Masahiro Okamura\textsuperscript{1}, Shunsuke Ikeda\textsuperscript{1}, Takeshi Kanesue\textsuperscript{1}

\textsuperscript{1}Collider-Accelerator Department, Brookhaven National Laboratory, New York 11973 USA
Corresponding Author: Masahiro Okamura, e-mail address: okamura@bnl.gov

A conventional knob to control charge state of a beam provided from a laser ion source is laser power density which is commonly expressed with the unit of “W/cm\textsuperscript{2}.” Above around 10E8 W/cm\textsuperscript{2} of a laser power density, laser ablation plasma is emitted from surface of solid material. In general, a higher laser power density gives higher charge state distribution of the emitted expanding ablation plasma. For example, to provide singly charge state ion beams, the density is controlled not to exceed 10E9 W/cm\textsuperscript{2}. When the highest possible charge state is demanded, laser beam with the available maximum energy is irradiated with the most focused condition on the laser target surface, since this condition gives the highest laser power density. In this study, we explore the laser irradiation condition on heavy and medium mass target materials starting from the lowest laser power density. For most of accelerator applications, higher charge state beams are preferred, therefore we have not investigated intermediate charge state beams. In this study, we are trying to clarify the transition of charge state distribution depends laser power density. At the conference, the experimental results will be discussed.

Acknowledgment

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Spatial Distributions of Plasma Potential and Density in Electron Cyclotron Resonance Ion Source

Vladimir Mironov, Sergey Bogomolov, Andrey Bondarchenko, Andrey Efremov, Vladimir Loginov, Dmitrij Pugachev
Joint Institute for Nuclear Research, Dubna, Moscow region, Russia
Corresponding Author: Vladimir Mironov, e-mail address: vemironov@jinr.ru

The Numerical Advanced Model of Electron Cyclotron Resonance Ion Source (NAM-ECRIS) is applied for studies of the physical processes in the source. Solutions of separately operating electron and ion modules of NAM-ECRIS are matched in iterative way such as to obtain the spatial distributions of the plasma density and of the plasma potential. Results reveal the complicated profiles with the maximized plasma density close to the ECR surface and on the source axis. The ion-trapping potential dips are calculated to be on the level of ~0.01-0.05 V being located at the plasma density maxima. The highly charged ions are also localized close to the ECR surface. The biased electrode effect is due to an “electron string” along the source axis formed by reflection of electrons from the biased electrode and the extraction aperture. The string makes profiles of the highly charged ions more peaked on the source axis, thus increasing the extracted ion currents.
Numerical simulation has played a more important role in the development of electron cyclotron resonance ion source (ECRIS) as it can compensate for the limitations of experiment studies. However the complex process during the ECRIS operation also brings a lot of difficulties to simulations. One of the biggest problem is the compromise between accuracy and computational costs. From a computational viewpoint, models from single particle approaches to considering a plasma as a dielectric have been applied by numerous previous works. However single particle models lack the plasma collective feedback, while the plasma dielectric descriptions miss some important kinetic effects.

To simulate the non-linear evolution in ECRIS more accurately, Particle-in-cell (PIC) method is preferred here as it is in principle comprehensive, fully kinetic and self-consistent. However the computational cost will be comparatively high when applying PIC method, especially in 3D configuration space plus 3D velocity space which is exactly needed for an actual ECRIS simulation. A set of stability conditions must be satisfied, so time and space steps are restricted to very small scales. Even nowadays this PIC method is too expensive to use in ECRIS simulations. To satisfy the needs of simulation accuracy and speed, we have considered a hybrid simulative model MPM [1]. The electromagnetic fields are separated into a transverse and longitudinal parts which can be represented as a superposition of waveguide modes. For simplicity we assume that the system consists of a cylindrically symmetric waveguide with perfectly conducting boundaries and a constant wall radius. Therefore the coupling terms for the electromagnetic fields among the various modes are only due to the current sources of plasma charged particles. Theoretically there will be infinite modes (evanescent modes as well) excited by the current sources, and the field solution shows slow convergence with respect to mode number. A small number of modes truncated in the sum is clearly not enough to provide a convergent solution, while a large enough number makes it unpractical to solve all the evolution equations respectively. In this work, mode contributions to the global field have been analyzed and an analytical treatment on infinite evanescent modes is discussed.

References and Acknowledgment
[1] X. L. Jin et al. “The Hybrid Electromagnetic Simulation of Ionization Characteristics in ECR Ion Source”, presented at ICIS’17, Geneva, Switzerland Oct 2017, paper T3Mo45, unpublished. This work was supported by National Natural Science Foundation of China (Grant No. 61771105).
A 3D Numerical Simulation of Electron Confinement in ECRIS

Xiaolin Jin\textsuperscript{1}, Li Lei\textsuperscript{1}, Jibo Li\textsuperscript{2}, Tao Huang\textsuperscript{1}, Zhonghai Yang\textsuperscript{1} and Bin Li\textsuperscript{1}

\textsuperscript{1}Vacuum Electronics National Laboratory, University of Electronic Science and Technology of China, Chengdu 610054, China
\textsuperscript{2}Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Corresponding Author: Xiaolin Jin, e-mail address: jinxiaolin@uestc.edu.cn

Electron cyclotron resonance ion source (ECRIS) is one of the most effective tools in the world for highly charged ions (HCIs). In order to benefit the production of HCIs, electron confinement in ECRIS is supposed to be a key factor as it relates to higher electron energies and collision probabilities for ionization. Recently we have established a 3D electromagnetic Particle-in-cell (PIC) model of the electron dynamics in a practical minimum-B structure. Electrons were tracked to obtain the trajectories under the magnetic confinement. The single particle approach was applied to have a preliminary study on electron confinement in a minimum-B structure. During the ECRIS plasma start-up, the electron density and energy are quite low, so the electric field excited by the charged particle sources is negligible as compared to the incident electromagnetic wave. When the simulation time is short, the single particle approach is valid to describe the electron dynamics. The simulation area is set inside a vacuum cylindrical waveguide. An input microwave of a single TE\textsubscript{11} mode at 14.5 GHz (B_{cr} \sim 0.518 T) is loaded from the injection port. The external magnetic field used in the simulation is provided by the actual data of the ECRIS LAPECRI1U from IMP-Lanzhou [1]. It is a standard minimum-B structure providing both longitudinal and radial magnetic confinements. The initial electrons located randomly inside the ECR surface. Their velocities were assumed to have random directions and follow a Maxwell-Boltzmann distribution with an average energy $T_e = 100$ eV. After a simulation time of 100 ns, electron trajectories were prominently affected by the magnetic field. On either end of the waveguide a triangle-like distribution was observed which coincides with the experiment results. Besides electrons also hit on the waveguide wall following the magnetic field lines due to the transversal loss gaps of the hexapole field. After an input microwave was loaded, there is an enhancement on the electron confinement comparing to the case where the electrons move only in the presence of the external magnetic field. This is considered to be attributed to the greater transversal velocities of the heated electrons which expel them from the loss cone. Additionally, as the input power increases, the electron confinement gets enhanced and this enhancement slows down gradually till a saturation is reached.

References and Acknowledgment


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Measurement of time dependent beam profile of an RF-driven H⁻ ion source

M. Wada¹, K. Shinto², T. Shibata², M. Sasao³

¹School of Science and Engineering, Doshisha University, Kyotanabe, Kyoto 610-0321, Japan.
²J-PARC Center, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
³Organization for Research Initiatives and Development, Doshisha University, Kamigyoku, Kyoto 602-8580, Japan

Corresponding Author: Motoi Wada, e-mail address: mwada@mail.doshisha.ac.jp

There is the possibility that the negative hydrogen (H⁻) ion beam accompanies a small amplitude oscillation at the ion source driving frequency after the beam acceleration. Meanwhile, the results of optical diagnostics and numerical simulation studies reported that the density of an RF-driven ion source plasma oscillated at a frequency two times the driving RF. This density oscillation together with the change in local plasma potential induced by the RF field may directly affect the sheath structure around the extraction aperture to change the beam spatial and angular distributions during one cycle of the RF current. Thus, spatial distributions of H⁻ ion beams extracted from an ion source driven by a 2 MHz RF are investigated to study which factors are influential for the beam oscillation to appear. A Faraday cup detects the H⁻ ion current through a 0.1 mm wide 66.5 mm long slit. The cup travels in the direction both perpendicular to the beam axis and the slit length. As the signal measured at the beam center was compared to that measured near the beam edge, the observed H⁻ ion current showed a larger oscillation amplitude compared with the signal measured at the beam center. The observed fundamental frequency of the beam oscillation was twice the ion source driving RF. Possible mechanisms for observing the enhanced oscillation at the beam edge will be discussed.

References and Acknowledgment

Effects of Extending Length of Multipole Magnets and Improving Background Vacuum Conditions on Electron Cyclotron Resonance Ion Sources

Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Osaka Univ. 2-1 Yamada-oka, Suita-shi, Osaka 565-0871, Japan
Corresponding Author: Wataru Kubo, e-mail address: w.kubo@nf.eie.eng.osaka-u.ac.jp

The multicharged ion source on the basis of electron cyclotron resonance (ECR) plasma has been constructed for producing various ion beams in Osaka Univ.[1] ECR ion source (ECRIS) is used in various fields such as accelerator physics, engineering, cancer therapy, and ion engine in the satellite. The ECRIS consists of vacuum chamber, a pair of mirror and supplemental coils and multipole magnets.[2] Magnetic mirror field configuration with multipole magnets can be controlled to various shape of ECR zones. We are aiming to improve producing multicharged ions efficiently at the point of view from length of multipole magnets and vacuum conditions. Length of multipole magnets with the direction along to geometrical axis in the ECRIS is made longer than before one. Moreover, the diameter of connection pipe from main diffusion pump is made larger to improve vacuum conductance. The effects of these improving are investigated experimentally to measure pressure in the vacuum chamber, beam intensity and charge state distribution (CSD) of them. We confirm that purity of extracted beams and operating pressures are improved. These results are expected to have positive effects on the production of various species and synthesized ion beams, e.g. production of iron endohedral fullerenes, in the ECRIS.

References and Acknowledgment
Simulation studies of electron energy distribution in 2.45 GHz Microwave Ion Source Plasmas

Narender Kumar¹, G. Rodrigues², Y. Mathur², R. Ahuja², D. Kanjilal², A.C.Pandey³
¹Physics Department, University of Liverpool, Liverpool L697ZE, United Kingdom
²Inter University Accelerator Centre (IUAC), New Delhi 110067, India
Corresponding Author: G.Rodrigues, e-mail address: gerosro@gmail.com

A compact experimental facility based on a 2.45 GHz microwave ion source has been operational at the Inter University Accelerator Centre (IUAC), New Delhi since 2017 [1, 2]. This facility is used for generating intense ion beams in the energy range of a few keV to a few tens of keV. Various kinds of experiments have been carried out related to studies in materials sciences and plasma physics. Beam intensities extracted from the ion source strongly depends on the densities of the plasma. Studies on the electron energy distribution inside the plasma can give important information to further improve the densities. Particle-in-Cell (PIC) simulations were performed under the influence of the tunable magnetic field and microwave power under the assumption of collision-less plasma using CST particle solver. The result of the simulations along with X-ray measurements for various plasma parameters will be presented.

References
Coaxial Semi-Dipole Antenna Microwave Feeding on Electron Cyclotron 
Resonance Multicharged Ion Source

Wataru Kubo, Kota Hamada, Koji Onishi, Tatsuto Takeda, Kazuki Okumura, Takayuki Omori, 
Masaki Ishihra, Shuhei Harisaki, and Yushi Kato

Division of Electronic and Information Engineering, Graduate school of Engineering, Osaka Univ., 2-1 Yamada- 
oka, Suita-shi, Osaka 565-0871, Japan Corresponding Author: Wataru Kubo, e-mail 
address: w.kubo@nf.eie.eng.osaka-u.ac.jp

It has been investigated how to produce multicharged ions efficiently on an electron cyclotron resonance ion source (ECRIS) in Osaka Univ.[1] Particularly, in recent years we have 
focused on launching the second microwaves whose frequencies are much higher than ECR’s 
one’s and heating by upper hybrid resonance (UHR) superimposing to ECR plasma. And then it 
is required further optimization of ECR heating. Now in consideration of waves propagation, we 
installed coaxial semi-dipole antenna on the mirror end along to the geometrical axis of the 
vacuum chamber. Because we aim to enhance right-hand polarization (RHP) waves for efficient 
ECR. We measure plasma parameters using Langmuir-probes and charge state distributions of 
the extracted ion beams, and investigate their ranges at incident microwave powers from 20 to 
300 W and pressures from 0.1 to 1 mPa. In addition to we investigate their qualitative tendencies 
to incident microwave powers and pressures. In near future, we plan to conduct extraordinary (X) 
mode experiments for UHR heating based on the understanding of the plasma generated by these 
microwave launching system using coaxial semi-dipole antenna obtained in these experiments.[2]

References and Acknowledgment

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Proton generation from hydrocarbon polymer targets for laser ion source

Kazumasa Takahashi1, Yuki Matsumoto1, Masayuki Kuzumoto1, Toru Sasaki1, Takashi Kikuchi2
1Department of Electrical Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
2Department of Nuclear System Safety Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
Corresponding Author: Kazumasa Takahashi, e-mail address: kazumasa@vos.nagaokaut.ac.jp

A laser ion source can provide intense pulsed ion beams from a solid target. On the other hand, in order to obtain ions of gaseous elements at room temperature from a laser ion source, it is required that using a frozen target or a target made of compound that contains the element. Recently, proton beams generation from hydride targets were reported1,2. In this research, we demonstrated proton generation from three kinds of hydrocarbon polymer targets, which were polyethylene (C2H4)n, polypropylene (C3H6)n, polystyrene (C8H8)n to apply to laser ion sources. The used laser was a Nd:YAG laser (532 nm/17 ns) and the energy was 0.2 J. The ion current and the fraction of ion species were measured using a Faraday cup and an electrostatic ion analyzer. The results indicated that the peak currents of proton showed similar values for the different targets and the fraction of proton was smaller than that of carbon ions.

References
Control of current waveform of laser ion source using pulsed magnetic field

Kazumasa Takahashi¹, Masayuki Kuzumoto¹, Yuki Matsumoto¹, Toru Sasaki¹, Takashi Kikuchi²

¹Department of Electrical Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan
²Department of Nuclear System Safety Engineering, Nagaoka University of Technology, Nagaoka, Niigata 940-2188, Japan

Corresponding Author: Kazumasa Takahashi, e-mail address:kazumasa@vos.nagaokaut.ac.jp

A laser ion source supplies a pulsed ion beams with a shifted-Maxwellian like waveform. Due to the time evolution in density of the laser produced plasma, the meniscus of extraction surface between the plasma and ion beam changes in a pulse¹. As the result, the total emittance of ion beam in a pulse increases compared with the time resolved one. To reduce the emittance of laser ion sources, making ion current waveform with flattop has been considered to be effective. In this research, we examined to make the waveform with flattop by compensating the decrease of ion current using pulsed magnetic field. We employed a Nd:YAG laser (532 nm/17 ns) and the energy was 0.2 J. Pulsed magnetic fields generated with a solenoid coil were applied to laser produced plasmas at 0.3 m from the laser target. The adequate waveform of pulsed magnetic field for controlling ion current of laser ion source will be discussed.

References
Kinetic Analysis of Electron Transport in Hot-cathode Penning Ionization Gauge Sources

Jaeyoung Choi, June Young Kim, Kyoung-Jae Chung and Y. S. Hwang
Department of Nuclear Engineering, Seoul National University, Seoul 08826, Korea
Corresponding Author: Kyoung-Jae Chung, e-mail address: jkjlsh1@snu.ac.kr

Penning ionization gauge (PIG) plasma sources are still widely used in a variety of applications from semiconductor fabrications to particle accelerators due to their advantages such as structural simplicity and high-density plasma generation. In spite of its long history as a reliable ion source in industry, cross-field transport of electrons from the hot-cathode region where the plasma is generated by beam-plasma interaction to the extraction aperture is still not well understood. In this study, we have investigated the cross-field transport of electrons in two different types of commercial hot-cathode PIG sources (conventional indirectly heated cathode (IHC) and plasma transport enhanced IHC) using the measurements of electron energy probability functions (EEPFs) along radial direction perpendicular to the external magnetic field. In the conventional IHC source, it is found that the non-locality of electrons depending on their kinetic energy is responsible for the decrease in electron density and temperature along radial transport across the magnetic field. However, the plasma transport enhanced IHC source which is designed to utilize $E\times B$ drift inside plasma volume shows a clear improvement in the plasma density at the aperture region, indicating an enhancement in cross-field transport of electrons. From the observation of EEPFs depending on the operating conditions, we find that the electric field structure of the plasma transport enhanced IHC source combined with the external magnetic field is attributed to such enhancement of electron transport.
Interpreting the dynamic equilibrium during evaporation in a Caesium environment

M. Fadone1, a), M. Barbisan1, S. Cristofaro2, M. De Muri1, E. Sartori1, G. Serianni1
1Consorzio RFX, Associazione EURATOM-ENEA sulla fusione, c.so Stati Uniti 4, 35127, Padova, Italy
2Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
a)M. Fadone: michele.fadone@igi.cnr.it

Caesium oven prototypes for the prototype source of the ITER neutral beam injectors have been tested in CATS facility. Three types of diagnostics are available to determine the Cs vapour emission rate, the Cs density at various positions in the vacuum chamber and the density integrated over a line of sight. In this paper, we present a model to describe the dynamic equilibrium in the evaporation chamber of CATS during Cs evaporation. The model includes sticking and energy accommodation of the Cs atoms to the walls, calculates the flux density at the surfaces and provides the Cs atom density at the desired locations in the volume. By this model, we correlate the Cs emission with the equilibrium density, measured respectively by Langmuir-Taylor (LT) detector embedded in the Cs oven and by a movable LT detector and by Laser Absorption Spectroscopy (LAS). The experimental data, obtained in a background gas pressure of 10^{-7} mbar, are well matched with the simulations considering a sticking coefficient of 3%.

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Lanzhou, China
Movable electrical probes were used to diagnose the beam flux profile and potential of ion beams since the early 60s. Experimental measurements of beam plasmas can provide essential data related to the space charge neutralisation, but the current voltage characteristics obtained from such electrical probes is dominated by beam-ion impact and ion-induced secondary emission. In this work we present an analysis of the Langmuir characteristics obtained in a negative ion beam. We identify and discuss separately the contributions to the collected current given by secondary-plasma ions and electrons, by stripped electrons, beam ions and ion-induced secondary electron emission. We present the beam-plasma parameters obtained at different beam energies in NIO1.
Evaluation of Magnetic Field Error in ExtendedEBIS

Shunsuke Ikeda, Edward Beebe, Takeshi Kanesue, Sergey Kondrashhev, Masahiro Okamura

BNL

Corresponding Author: Shunsuke Ikeda, e-mail address: sikeda@bnl.gov

RhicEBIS has provided several types of ions from H to U with different charge states to RHIC and NSRL in BNL. A 5T-superconducting solenoid is used to propagate up to 10A and 500 A/cm² electron beam, which enables to produce $10^9$ of Au$^{32+}$ ions with 5 Hz. The upgrade of the EBIS, called ExtendedEBIS, is now in progress. Another 5T-superconducting solenoid will be added in series with 200 mm distance to the other solenoid. In the added solenoid, an injection device of pulsed gas and a 3He polarizer will be installed. The purposes of the development of ExtendedEBIS are increase of the ion trap capacity by a factor of 1.4 (1), improvement of efficiency to produce gas ions especially for H and He (2), and production of polarized 3He (3). In RhicEBIS, a gun solenoid, a superconducting solenoid, and a collector solenoid are used. It is not easy to perfectly align the solenoids and the magnetic field are adjusted by transverse coils. Some amount of field error is tolerated as long as electron beam is propagated. Meanwhile, in ExtendedEBIS, since another superconducting solenoid will be used, the field error is expected to be larger. In this research, the field error is estimated based on simulation and result of beam propagation test. The influence of the error on ions will be discussed.

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Cluster Ion Source for External Injection and High Capacity Filling of Light Elements into the RHIC EBIS

Sergey Kondrashev, Edward Beebe, and Masahiro Okamura
Brookhaven National Laboratory, Upton, NY 11973, USA
Corresponding Author: Sergey Kondrashev, e-mail address: skondrashev@bnl.gov

An advanced Electron Beam Ion Source (EBIS) is the primary ion source to supply highly charged ion beams of different elements to the Relativistic Heavy Ion Collider (RHIC) and to the NASA Space Radiation Laboratory (NSRL). Intense beams of highly charged ions of various elements of periodic table, ranging from helium to uranium have been demonstrated since EBIS became operational in 2010. EBIS routinely provides ion beams to RHIC and NSRL quasi-simultaneously with about one second switching time between different ion species. Such unique flexibility and rapid switching between ion species are based on external injection of singly charged ions into EBIS trap either in “fast” or “slow” injection modes. At present, a Laser Ion Source (LIS) provide most of ion species of solid materials using the “fast” injection mode into EBIS trap and a Hollow Cathode Ion Source (HCIS) provides most of ion species of gaseous elements using the “slow” injection mode into EBIS trap. Gas injection into EBIS trap is also possible, and has been used, but imposes some restrictions for simultaneous generation of highly charged ions such as Au$^{32+}$ ions for RHIC and ions of gaseous species for NSRL. Because light ions have relatively high velocity inside EBIS trap, efficient injection of hydrogen and helium ions and filling of the EBIS trap to high capacity is difficult from either LIS or HCIS. To overcome this restriction and enhance EBIS operational capability we suggest injecting beams of hydrogen and helium cluster ions into EBIS trap. Over the last 15 years significant progress has been made in the development of intense sources of cluster ions primarily for material applications. Thus, generation of argon cluster ions with average size of few thousand atoms per cluster and 1 μA total output current has been recently demonstrated. Such intensity will not only be sufficient to fill the EBIS ion trap in the “slow” injection mode (~ 10 ms), but may also be capable of filling the EBIS in “fast” mode (~ 100 μs). The ion accumulation in the fast injection mode would be extremely valuable for EBIS light ion production because the ion injection period would be a small fraction of the few millisecond confinement period. A cluster ion source of light elements with required high intensity is envisioned and will be designed, built, optimized and tested.

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Lanzhou, China
The study of electron extraction characteristics of DC-ICP source
Xianwen Luo and Feixiang Liu

Key Laboratory of pulse power, 596 S&T campus, IFP, CAEP, 610200, China
Corresponding Author: Xianwen Luo, e-mail address: 18681630592@163.com

In this poster, the working performance information of DC-ICP source is obtained by studying the relationship between the electron extraction characteristics and the experimental parameters such as RF power, gas flow rate and DC bias voltage. The research results show that the electron extraction characteristics of DC-ICP source are closely related to the experimental parameters such as RF power, gas flow rate and DC bias voltage. The conversion of E-H mode has a great influence on the electron extraction characteristics. The research results have important reference significance for the design and improvement of DC-ICP source.
Solutions to the ion beam injector for Jinping Underground Nuclear Astrophysics Facility (JUNA)

Q. Wu\textsuperscript{1}, J. L. Liu\textsuperscript{1}, Y. G. Liu\textsuperscript{1}, H. Y. Ma\textsuperscript{1}, Y. Yang\textsuperscript{1}, J. Q. Li\textsuperscript{1}, X. Z. Zhang\textsuperscript{1}, L. T. Sun\textsuperscript{1}, X. D. Tang\textsuperscript{1}, B. Guo\textsuperscript{2}, G. Lian\textsuperscript{2}, B. Q. Cui\textsuperscript{2}, W. P. Liu\textsuperscript{2} and H. W. Zhao\textsuperscript{1}

\textsuperscript{1} Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou 730000, PR China
\textsuperscript{2} China institute of Atomic Energy, Beijing 102413, PR China

Corresponding Author: Q. Wu, e-mail address: wuq@impcas.ac.cn

China Jinping Underground Laboratory (CJPL) is currently the deepest underground Lab in the world. By taking advantage of the ultralow background in Jinping underground lab, a 400 kV high voltage accelerator driven by an intense ECR ion source and highly sensitive detectors were developed to be used to study directly a number of important nuclear reactions. Such as (p, γ), (p, α), (α, p) and (α, γ) reactions. The beam requirements of the ion source for the accelerator are expected to produce 10 emA H\textsuperscript{+}, 10 emA 4 He\textsuperscript{+} and 2.0 emA 4 He\textsuperscript{2+} respectively. After series of investigation, it can conclude that there is no 4 He\textsuperscript{2+} ion produced with a 2.45 GHz ECR ion source. Therefore, to meet the requirements of physics experiments, we use an ECR ion source operated at the frequency of 14 GHz (LAPECRI-U) to produce low and medium charge state ions, such as 10 emA H\textsuperscript{+}, 2 emA 4 He\textsuperscript{2+}, and 10 emA He\textsuperscript{+}. The ion beams produced with LAPECRI-U is transported by the low energy beam transport line and injected into a 400 keV acceleration tube. The LAPECRI-U ion source and LEBT system have been commissioned on a 400 kV high voltage platform accelerator system in a ground level test laboratory at present. In this paper, the studies of this intense beam injection system, for instance, beam intensities, beam reliability, ion beam ratio and beam transmission efficiency in LEBT will be presented.
A $^{39}$Ar Enrichment System Based on Intense Ion Beam Spectrometer

Zehua Jia$^1$, Liangting Sun$^{1,2}$, Yuguo Liu$^{1,2}$, Jianli Liu$^1$, Qi Wu$^{1,2}$, Xing Fang$^1$, Weishun Yang$^1$, Yuhui Guo$^1$ and Qinwen Chen$^1$

$^1$ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
$^2$ School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding Author: Liangting Sun, e-mail address: sunlt@impcas.ac.cn

Water or glacier dating with $^{39}$Ar is a great way to research climate and geology change of the earth. The Atom Trap Trace Analysis (ATTA) method plays a very important role in this field for its small sample demand and high resolution. But $^{39}$Ar’s abundance limits ATTA’s dating efficiency. A $^{39}$Ar isotope enrichment system has been developed in IMP, which is designed to increase $^{39}$Ar’s abundance in the incident sample gas. With intense Ar$^+$ beam produced with a microwave source and a high mass resolution spectrometer dipole developed for this system, Ar isotopes are evidently separated at the target plane and selectively collected by the Al target. The separated Ar isotopes’ position has been observed in experiment, which is consistent with the simulation results. According to recent cross-checked results with ATTA, high enrichment factor of $^{39}$Ar has been successfully made and the ratio of $^{38}$Ar and $^{39}$Ar in the sample has been conserved has been validated with the ATTA’s analysis result. This paper will present the design and test results of the intense ion beam spectrometer system.
**C-PIMS based on a 2.45 GHz microwave ion source and a floating potential charge exchange cell**

Wenbin Wu, Shixiang Peng, Haitao Ren, Tenghao Ma, Yaoxiang Jiang, Jingfeng Zhang, Yuan Xu, Ailin Zhang, Tao Zhang, Jiamei Wen, Jiang Sun, Kai Li, Zhiyu Guo, and Jia'er Chen  
*State Key Laboratory of Nuclear Physics and Technology & Institute of Heavy Ion Physics*  
*School of Physics, Peking University, Beijing 100871, China*  
*Corresponding Author: Shixiang Peng, e-mail address: sxpeng@pku.edu.cn*

Carbon positive-ion mass spectrometry (C-PIMS) is a two stage mass spectrometer by producing high charge state carbon ions (C$^{2+}$/C$^{3+}$) directly in the ion source to eliminate molecular interferences and by converting the beam to negative ions in a charge exchange cell to eliminate $^{14}\text{N}$ interference. Results obtained by M. Hotchkis[1] based on 7 GHz ECR ion source has proved that PIMS is an effective method for the detection of radiocarbon at low levels. Now we propose a new conceptual design based on a 2.45 GHz microwave ion source and a floating potential charge exchange cell (CXC). Preliminary test results have proved that the 2.45 GHz microwave ion source can produce up to 40 μA@40 keV C$^{2+}$ beam. Very basic investigation of CXC design is also launched. Details will be presented.

**References and Acknowledgment**  
Intense carbon beams production with LAPECR3 ion source for heavy ion cancer treatment facility HIMM

J. Q. Li, Y. Cao, L. T. Sun, X. Fang, J. W. Guo, H. Wang, X. Z. Zhang, and H. W. Zhao

1Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou 730000, China
2School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding Author: J. Q. Li, e-mail address: lijiaqing@impcas.ac.cn

LAPECR3 (Lanzhou All Permanent magnet Electron cyclotron Resonance ion source No.3) had been developed as the ion injector of Heavy Ion Medical Machine (HIMM) accelerator facility since 2009 year. The first HIMM accelerator facility was built in Wuwei city in 2015, and LAPECR3 ion source has delivered C\textsuperscript{5+} ion beam to HIMM for more than 1000 days in the past three years. In order to improve the performance of LAPECR3 ion source for intense carbon beams production, continuous research and development work has been made. The recently developed LAPECR3 ion source together with the new LEBT can provide better performance in terms of both beam intensity and quality. This paper will generally review the LAPECR3 ion source operation status for HIMM, and the recent improvement will be presented, especially the stable beams production of C\textsuperscript{4+} and C\textsuperscript{5+}. 
Development of 1.2 GHz ECR Ion Source and Wien Filter for Inexpensive Ion Beam Processing System

Toyohisa Asaji¹, Hiroya Uyama¹, Takuro Umetsugu¹, Tsubasa Nakamura², Takeshi Hitobo³, and Yushi Kato⁴

¹National Institute of Technology, Toyama College, Toyama, Japan
²National Institute of Technology, Oshima College, Yamaguchi, Japan
³Tateyama Machine Co., Ltd, Toyama, Japan
⁴Graduate School of Engineering, Osaka University, Suita, Japan
Corresponding Author: Toyohisa Asaji, e-mail address: asaji@nc-toyama.ac.jp

A desktop-sized ion beam processing system with an inexpensive electron cyclotron resonance (ECR) ion source has been developed for industrial applications at NIT, Toyama College. A commercially available 1.2-1.3 GHz transceiver (10 W) is adopted as a microwave source to generate the ECR plasma. The minimum-B magnetic field composed of two ring and hexapole magnets is formed by arranging small rectangular permanent magnets. A Wien filter with orthogonal electric and magnetic fields is employed as a beam separator. The components contribute to the miniaturization of the system. At the end of the beam line, a process chamber with a substrate stage for ion beam applications such as ion implantation and microfabrication is installed. A radio frequency (RF) power source of 13.56 MHz is connected to the stage. The RF source produces capacitively coupled plasmas and creates a self-bias voltage. In the first experiment, Ar ion beams of about 50 µA were obtained at an extraction voltage of 4 kV. In addition, we demonstrated that Ar ions were separated with the Wien filter.
Feasibility Studies and Design Optimizations of 2nd Generation ECRIS for Accelerator Mass Spectrometry

Byoung Seob Lee¹, Jungbae Bahng², Eunhoon Lim², Jin Yong Park¹, Myoung Choul Choi¹, Mi-Sook Won³

¹Korea Basic Science Institute
²Korea University Sejong campus
³Dong-Eui University

Corresponding Author: Byoung Seob Lee, e-mail address: bslee@kbsi.re.kr

After development of 28GHz ECR ion source in Korea Basic Science Institute, ECR ion source researchers of Korea is started new topic about ECR ion source system for analytical instruments. Specially, we have interesting about supporting micro-dosing researches for biology and medicine. Feasibility studies has been performing for adoptable system design using ECR ion source of Korea University Sejong Campus. Because the targeting ions are carbon and boron isotope for mass spectrometry, we need information about effective generation of ions. From this studies, we obtained optimal design for modified 2nd generation ECRIS and information of relationship between electron density and generated ion. Also, we will introduce accelerator mass spectrometry system using 2nd generation ECRIS.
The development of a hydrogen-helium dual-beam ion implanter

Bing Tang, Baoqun Cui
China Institute of Atomic Energy, P.O. BOX275-3, Beijing 102413, China
Corresponding Author: Bing Tang, e-mail address: tangb364@126.com

Ion-beam irradiation will lead to the change of material microstructure. Multiple ion beam facilities are powerful tools to simulate the irradiation effects of neutrons on relevant nuclear materials. Since the hydrogen and helium are often generated in neutron irradiated materials as transmutation products and they play important roles in the defect evolution, it is high desirable to have triple ion beam (H, He and a beam of heavy ions that provides the majority of displacement damage) to bombard the target at the same time for more accurate simulation of neutron irradiation effects. The triple beam accelerator and TEM link in-situ facility instead of mono-beam or dual-beam facility is necessary to simulate the neutron irradiation. However, due to the limitation of both space and electro-magnetic field of the TEM pole-piece, it is very difficult to link three ion beams to TEM simultaneously. A hydrogen-helium dual-beam ion implanter has been developed for the triple ion beam in-situ facility at Xiamen University. A Penning ion source has been developed to produce and simultaneously. A special system consisted of two Wien-filters and an einzel lens has been proposed to eliminate the impurity ion of the dual-beam ion implanter. The detail of this hydrogen-helium dual-beam ion implanter will be introduced in detail.
Design of compact accelerator system for high flux Accelerator Based Neutron Source

Jungbae Bahng1, Byoung-Seob Lee2, Eun-San Kim1, Seong Hee Park1, Hyang-Kyu Park1

1Department of Accelerator Science, Korea University Sejong campus, Sejong 30015, South Korea
Corresponding Author: Jungbae Bahng, e-mail address: bahngjb@korea.ac.kr

Accelerator Based Neutron Sources (ABNS) has been studied for a material research as well as Boron Neutron Captured Therapy (BNCT). According to a significant effort on the (p,n) and (d,n) nuclear reaction, the specifications of the accelerator system have been determined. In this paper, we compared design results of two types on RFQ accelerators to provide proton and deuteron beams, respectively. Both systems consist of an Electron Cyclotron Resonance (ECR) ion source, a Low Energy Beam Transport (LEBT) system, an RFQ accelerator, a Medium Energy Beam Transport (MEBT) system, a Beryllium (Be) target and a Moderator system. In order to achieve a compact and a reasonable cost of an accelerator system, different requirements are applied to design RFQ accelerators. Proton RFQ has been designed with 352 MHz of the operation frequency, up to 4 MeV acceleration, 10 mA of beam intensity and CW operation mode to satisfy 0.84e9 n/s/cm² of neutron production. Whereas, deuteron RFQ has been studied with 200 MHz of the operation frequency, up to 2.5 MeV acceleration, 15 mA of beam intensity and CW operation mode to meet 1.02e9 n/s/cm² of neutron production. In this paper, we described on the two types of the RFQ accelerators and common system of the ECR ion source and Be target in detail.
Withdrawn
There are some needs of proton beam of several MeV in energy for some purpose; calibrating charged particle detectors and so on. For those purpose, electrostatic accelerators or Cyclotrons are usually appropriated, but those accelerators take much cost to provide proton beam. So a proton generating system which consists with $^3$He ion source and deuterated polyethylene target has been developed at the Research Center for Nuclear Physics (RCNP), Osaka University. The ion source provides 20 keV $^3$He beam. As a result of $^3$He+d fusion reaction, protons of 14.7 MeV have been obtained. New target base made of thin aluminum window also has been developed and protons in MeV region have been obtained through the windows, at the atmosphere side, successfully.
Positive and Negative Ion Reflections of Low-Energy Ion Beam from Materials Surface

Nozomi Tanaka¹, Fumiya Ikemoto², Ippei Yamada², Yuji Shimabukuro², Masashi Kisaki³, Wilson Agerico Dino⁴, Mamiko Sasao⁵, Motoi Wada⁵ and Hitoshi Yamaoka⁶

¹Institute of Laser Engineering, Osaka University, Suita, Osaka, 565-0871, Japan
²Graduate School of Science and Engineering, Doshisha University, Kyoto, 610-0231, Japan
³National Institute for Fusion Science, Gifu, 509-5292, Japan
⁴Department of Applied Physics, Osaka University, Suita, Osaka 565-0871, Japan
⁵Institute for R&D Promotion, Doshisha University, Kyoto, 602-8580, Japan
⁶RIKEN Spring-8 center, Hyogo 679-5148, Japan

Corresponding Author: Nozomi Tanaka, e-mail address: tanaka-n@ile.osaka-u.ac.jp

Understanding of the low-energy beam interaction with materials surface is important for the application of the ion beam technology application and also attracts much attention in the surface science field. We have studied positive and negative hydrogen ion reflections from surfaces under singly charged, low energy, and grazing incidence condition ion beam injections [1]. In this study, we prepared molybdenum and HOPG (highly oriented pyrolytic graphite) samples. Molybdenum is widely used for the plasma electrode, and HOPG is a cesium free negative ion sources candidate material [2]. Atomic and molecular hydrogen ions, H⁺, H₂⁺, and H₃⁺, were injected onto the sample surfaces. Energy-resolved spectra of both reflected positive and negative ions were measured by a magnetic momentum analyzer [3] for all combinations of incident ion beams and sample materials. The normalized intensity of both reflected positive and negative ions increased monotonically with increasing incident beam energy in all cases. Interestingly, only for the incident beams of the molecular ions of H₂⁺ and H₃⁺, the intensity ratio of the negative to positive ions increased drastically at the incident beam energy less than 500 eV/nucleon, achieving a maximum ratio of two at 200 eV/nucleon. This could be attributed to the difference in particles scattered from proton injection, as compared to particles scattered from molecular ion beam injection. Similar results have been reported for proton injections from 100 eV to keV energy range previously, showing a peak of negative ion fraction at several hundreds of eV [4]. However, the low-energy beam, including molecular beam, interaction with surface has not yet fully understood, especially in the negative ion source environment. The results will be discussed in terms of atomic and molecular ion – surface interaction.

References and Acknowledgment
Electron cyclotron resonance ion source (ECRIS) are widely used for practical purposes, such as heavy particle beam cancer therapy and ion engines mounted in an artificial satellite. In bio-nano materials research field, we are aiming at synthesizing iron endohedral fullerene by collision reaction in vapor phase in the ECRIS. Induction heating (IH) can heat solid material and generates pure iron vapor by means with pure iron surrounding IH coil (IH head). We had also succeeded in generating multicharged iron ions in the ECRIS by this IH method.[1] Insulated induction heating coil transformer circuit (IHCT)[2] that insulates between the iron source and the consumer IH power source, had examined, and improved characteristics of its performance. The input power is supplied from the IH power source to the IH head beyond the IHCT. In the IHCT, two parallel flat plate circular IH coils are inductively coupled with each other to insulate them from each other. The primary coil is connected to the IH power supply, and the secondary coil is connected to the IH head. By moving the primary coil against to the secondary one mutually and changing the distance between coil centers, and the coupling coefficient (k) changes. The IHCT can protect the IH power source from short and open circuits of the IH coil. We measured the primary and the secondary currents of the IHCT, heating temperatures, iron vapors, and pressures in the vacuum chamber.

In order to improve k and then heating efficiency, we exchange mica plate (3 mm thickness) to thin kapton polyimide sheet (0.15 mm thickness) as the insulator for the IHCT. We conducted experiments in the test chamber with the IH assembler similar to the case in the ECRIS. We plan to report the details of this experiment in this paper.

References and Acknowledgment
An electron cyclotron resonance ion source (ECRIS) are widely applied for plasma processing and ion beam applications.[1] In particular, we are focusing on producing multicharged Xe ion beams.[2] Xe ion are widely used for fuel of ion engines mounted in satellites.[3] Life time of satellites is typically required over 10-15 years. There are problems of accumulation damages by low energy Xe ion from the engine. And it is required to construct sputtering yield experimentally since there are not enough data of satellite component materials by ion beams in the low energy region from several hundred eV to 1keV. In our ECRIS, we aim to produce and extract various ion beams in the single device. We installed the extractor that consists of three electrodes (PE, E1, E2).[2,3] And we have constructed the ion beam irradiation system (IBIS) where we can decelerate and irradiate ion beams to the materials. The deceleration electrodes also consist of three electrodes (D1, D2, D3).[3] The ion beams are usually extracted from high voltage VPE about 10 kV and transported to the IBIS. Then ion beams are decelerated by the deceleration voltage VD3 in the IBIS. Therefore, it is necessary to improve not only the beam currents, but also the beam transport efficiency. We measure characteristics of ion beam currents on the E1 electrode voltage VE1, the transport efficiency, and decelerated ion beam currents. Then we obtained high transport efficiency, dependence of ion beam currents on the VE1 at various operating pressures. And we found the more ion beam currents than previous experiments. Now we plan to irradiate Xe ion beams to satellite materials and acquire sputtering yield in the low energy region.

References and Acknowledgment
A Miniaturized ECR plasma flood gun for wafer charge neutralization

Yaoxiang Jiang, Shixiang Peng, Wenbin Wu, Tenghao Ma, Jingfeng Zhang, Haitao Ren, Kai Li, Tao Zhang, Jiamei Wen, Yuan Xu, Ailin Zhang, Jiang Sun, Zhiyu Guo, Jia’er Chen
State Key Laboratory of Nuclear Physics and Technology & Institute of Heavy Ion Physics, Peking University, Beijing, 100871, People’s Republic of China
Corresponding Author: Shixiang Peng, e-mail address: sxpeng@pku.edu.cn

In a modern ion implanter, Plasma Flood Gun (PFG) is used to neutralize wafer charge during doping process, preventing the breakdown of floating wafers caused by the space charge accumulation. Typically, there are two kinds of PFGs, dc arc discharge with filament and RF discharge. As a PFG, the filament one has limited lifetime and can’t avoid metallic contamination because of the thermal emitting filament. As for RF discharge PFG, the metal contamination performance surpasses that of the filament PFG, but the gas flows required (several SCCM is needed) can result in high chamber pressures. ECR ion source is considered as an alternative way for those two PFGs, since it has the characteristics of high stability, long life, low gas consumption and no metallic contamination. At Peking University (PKU), a miniaturized 2.45 GHz permanent magnet electron cyclotron resonance Plasma Flood Gun (ECR-PFG) has been built and tested. It has realized the miniaturization of the ECR source volume and the associated microwave system. The plasma chamber dimension is φ30 mm×40 mm. In addition, the microwave system only consists of a microwave generator, a coaxial line and a coaxial waveguide converter. In continuous wave (CW) experiments, the electron extraction currents can be as high as 10 mA at input microwave power of 30 W. Details will be presented in the article.
A project on the development of a 2.45 GHz microwave ion source-based ion implanter facility has been taken up by Central University of Punjab, Bathinda (CUPB), India. This facility will have provision of in-situ plasma diagnosis using a Langmuir probe and Optical Emission Spectroscopy (OES) set-ups. The facility will provide ion energy in the range of 1 to 50 keV for research work related to ion implantation, etching, surface patterning and study of basic plasma physics. The electromagnetic design of ridge wave guide, microwave cavity, and extraction system have been optimized in such a way that experiments with plasma diagnostics and ion implantation can be accommodated in-situ easily. Details of the design will be presented.
Universal Control Architecture for Both Broad and Focused sub-10 nm 5 – 100 keV Ion Beam Systems

Jeroen A van Kan1,2, Gokul2, Rudy Pang1, Tanmoy Basu1,3, Sangita Chaki Roy1, Huei Ming Tan2

1Center for Ion Beam Applications, Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117542.
2Engineering Science Programme, Faculty of Engineering, NUS, EA-05-34, 9 Engineering Drive 1, Singapore 117575.
3Center for Advanced 2D Materials, Faculty of Science, NUS, Singapore 117546.
Corresponding Author: Jeroen van Kan, e-mail address: phyjavk@nus.edu.sg

We present critical parameters for advanced ion microscopy configurations for Nano Aperture Ion Source (NAIS) and Penning Source based broad beam ion implanters. These configurations feature accurate gas dosing control, accurate beam forming, and a compact ion microscopy system design. To reduce chromatic aberrations in ion beams, an electronic control system below 10 ppm accuracy is desirable, which in turn affects the design requirements for the electrical and mechanical assemblies in these systems.

However, commercial off the shelf Data Acquisition (DAQ) hardware for analog voltages is generally limited to <16 bits accuracy, which leads to larger chromatic aberration and larger beam spot sizes for charged particle beams in the NAIS. We present our development of an electronic control system featuring a 1 ppm 20-bit DAC, enabling greater levels of attainable precision, ease of miniaturization combined with the ruggedness, compatibility and scalability of an industrial system.

An additional development of the control system is the characterization of a computer controlled thermomechanical leak valve to achieve long term stable, accurate vacuum control to ~1%. Further investigation was also conducted to map the dynamic relationship between operating temperature, opening characteristics and long-term vacuum stability. These parameters can be tuned with the 1 ppm DAQ electronics and computer based PID control algorithm to fine tune chamber pressure and thus improve beam quality.
The ECR ion source and front-end test-bench for DERICA project

Sergey Bogomolov¹, Andrey Efremov¹, Timur Kulevoy², Gennadiy Kropachev², Alexey Sitnikov²

¹ Joint Institute for Nuclear Research, Dubna, Moscow region, Russia
² National Research Center “Kurchatov Institute”-ITEP, Moscow, Russia,
Corresponding Author: Timur Kulevoy, e-mail address: kulevoy@itep.ru

DERICA (Dubna Electron-Radioactive Ion Collider fAcility) project for the radioactive ions beam (RIB) research is under development in the Joint Institute for Nuclear Research [1]. The facility includes the driver LINAC-100 (energy up to 100 MeV/u) with operating mode close to CW, the fragment separator, the re-accelerator LINAC-30 (energy up to 30 MeV/u), the fast ramping ring (energy <300 AMeV), the collector ring and the electron storage ring. The 28 GHz ECR ion source has to provide the generation of ions with required charge state (up to U^{34+}) and intensity (at least 1 pA for uranium beam and 10 pA for boron one). One of the key problem is the 6D matching of high intensity ion beam generated by ECR with initial part of cw-linac (radio-frequency quadrupole – RFQ). The front-end test-bench for development of the proper matching channel and testing of the cw-RFQ is under construction in the JINR. The test-bench consist of the full permanent magnet ECR, LEBT with RF-buncher and initial sections of RFQ. The current status of the development of both the ECR ion source for the DERICA project and the front-end test-bench are presented and discussed.

References and Acknowledgment
Tuesday, September 3
Overview of High Intensity Ion Source Development in the Past 20 Years at IMP

Liangting Sun, Hongwei Zhao, Huanyu Zhao, Zhanwen Liu, Zimin Zhang, Xuezhen Zhang, Xiaohong Guo, Wang Lu, Junwei Guo, Yun Cao, Qi Wu
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
Corresponding Author: Liangting Sun, e-mail address: sunlt@impcas.ac.cn

In the past 20 years, obvious progress has been made with the IMP ion accelerator development in terms of high intensity, high energy and high power machines. We still foresee the facilities to be built in the near future, for instance HIAF (High Intensity heavy ion Accelerator Facility) and CiADS (China initiative ADS), and so on, which have strong demands of high intensity ion beams of H–U. High intensity ion source paves the way for the development of future ion accelerators. Therefore, continuous research and development work has been made at IMP to improve ion source performance by means of new machine developments and ion source physics investigations. For intense mono-charged ion beams, 2.45 GHz ion sources have been developed together with the low energy transmission lines. For intense CW/DC multiply charged ion beams production, high performance ECR ion sources have been developed with the operation frequencies of 14.5–45 GHz. As very high intensity pulsed ion beams could be used for synchrotron injection, especially of those of very refractory metals, laser ion source has also been introduced to IMP, and got remarkable progress in the past years with regards to ion beam intensities, charge states, and beam stabilities. This paper will give an overview of the high intensity ion source development at IMP, especially on the recent progresses and new results.
EBIS Development at RHIC for the BNL Heavy Ion Program and the EIC

Brookhaven National Laboratory, Upton, NY 11973, US
Corresponding Author: Edward Beebe, e-mail address: beebe@bnl.gov

The Extended EBIS will provide $2.1 \times 10^9$ Au$^{32+}$/pulse at the Booster ring entrance, a 40-50% intensity upgrade compared with the existing RhicEBIS at BNL. The axial magnetic field for an extended ion trap is achieved through the use of two closely coupled 5T superconducting solenoids, reinforced to withstand the axial forces between the modules. A 6A electron beam has been successfully propagated through the prototype of a novel “external” drift tube structure within one 5T superconducting solenoid. The second solenoid and corresponding drift tube structure has been added and testing is underway to establish 5-6A electron beam propagation through the extended two solenoid system. A highly efficient gas injection system has been designed, primarily for the injection of polarized $^3$He and other light gases. Beams of $^3$He$^{2+}$ with intensity up to $2.5 \times 10^{11}$ ions per pulse and 70% polarization will be produced for RHIC and the future Electron Ion collider. Results of the present tests and plans for the Extended EBIS development will be discussed.

References and Acknowledgment
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Production of intense metal ion beam with RIKEN 28 GHz SC-ECRIS

Takahide Nakagawa, Yoshihide Higurashi, Takashi Nagatomo and Jun-ichi Ohnishi
Nishina center for Accelerator based science, RIKEN, Hirosawa 2-1, Wako, Saitama 351-0198, Japan
Corresponding Author: T. Nakagawa, e-mail address: Nakagawa@riken.jp

To produce intense metal ion beams (e.g. Ti^{13+}, V^{12+}, U^{35+}) for super-heavy element search and RIBF experiments at RIKEN, we tried to optimize the RIKEN 28 GHz SC-ECRIS performance. We systematically measured the beam intensity of various heavy ions as a function of $B_{\text{inj}}$, $B_{r}$ and $B_{\text{ext}}$ with 14, 18 and 28 GHz microwaves for various heavy ions. In these experiments, we observed that (1) optimum $B_{\text{inj}} > 1.6 \sim 2 B_{\text{ext}}$, (2) optimum $B_{r} > 1.2 \sim 1.4 B_{\text{ext}}$ and (3) optimum $B_{\text{ext}}$ is dependent on the charge state. Using this systematics, we obtained ~400 e micro A of V^{13+} at low RF power of ~2kW and very low magnetic field ($B_{\text{ext}} \sim 1.4$ T with 28 GHz). For long term operation (one month), we successfully produced very stable beam of 100~200 e micro A of V^{13+} ion. Based on the systematics, we also produced ~225 e micro A of U^{33+} ion beam and ~200 e micro A of U^{35+} ion beam at only 2.2~2.6 kW of RF power. In this contribution, we discuss the mechanism to obtain these systematics using simple model calculation. And we report the experimental results and how to produce intense metal ion (Ti, V, and U ions) beams in detail.
Production of intense uranium beams with inductive heating oven at Institute of Modern Physics

W. Lu¹, L. T. Sun¹, C. Qian¹ ², L. B. Li¹, J. W. Guo¹, W. Huang¹ ², X. Z. Zhang¹, and H. W. Zhao¹

¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
²University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding Author: Wang Lu, e-mail address: luwang@impcas.ac.cn

HIAF (High Intensity heavy ion Accelerator Facility) is a new accelerator complex under construction at Institute of Modern Physics. As the main injector of this project, the high-charge-state ECR ion source needs to provide intense uranium beams, such as 700 euA of U³⁵⁺, and so on. This requires the performance of metal ovens to be further improved so that the crucible can operate at ultra-high temperature for a long time without damage in high magnetic field (>3 T). In order to meet these requirements, an inductive oven with special thermal shielding and support has been developed in past two years. The off-line test result has shown that this oven can reach up to 2000 degree C with ~1.2 kW of heating power. After ~5 days' continuous running on SECRAL-II platform, the tantalum crucible survived. In this contribution, we will discuss the structure of this inductive oven and analyze the test results as well.
Stable Short-pulse Ion Beam Production with the Laser Ion Source at IMP

Huanyu Zhao\textsuperscript{1,2}, Junjie Zhang\textsuperscript{1,2,3}, Xing Fang\textsuperscript{1}, Xuezhen Zhang\textsuperscript{1,2}, Liangting Sun\textsuperscript{1,2} and Hongwei Zhao\textsuperscript{1,2}

\textsuperscript{1} Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
\textsuperscript{2}School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{3}School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China

Corresponding Author: Huanyu Zhao, e-mail address: zhaohy@impcas.ac.cn

To extend the long-term operation capability of the laser ion source, a new manipulating system and the corresponding control system has been developed at the Institute of Modern Physics, into which a rotating axis was integrated besides the existing X, Y, and Z axes. With the new developed manipulating system, the laser ion source can be operated with cylindrical targets, which is meaningful for the practical application of the laser ion source because the surface area of a cylindrical target is much larger compared with a flat one. And with the help of the control system, the laser ion source can be operated in the continuous mode with the repetition rate below 5 Hz, which is limited by the laser and vacuum system. The pulse-to-pulse repeatability and thirty-hour stability of the carbon ion beam delivered by the laser ion source will be presented in this paper.
The 1+/n+ method, based on an ECRIS charge breeder originally developed at the LPSC laboratory, is now implemented at GANIL for the production of Radioactive Ion Beams (RIBs). Prior to its installation in the middle of the low energy beam line of the SPIRAL1 facility, the 1+/n+ system charge breeder has been modified based on the experiments performed on the CARIBU Facility at Argone National Laboratory. Later, it has been tested at the 1+/n+ LPSC test bench to validate its operation performances. Charge breeding efficiencies as well as charge breeding times have been measured for noble gases and alkali elements. The commissioning phase started at GANIL in the second semester of 2017. It has consisted of a stepwise process to test the upgrade of the SPIRAL1 facility from simple validation (operation of Charge Breeder (CB) as a stand-alone source) up to the production of the first 1+/n+ radioactive ion beam. Thus, this year, a $^{38}_{\text{K}}/^{38}_{\text{K}}$ radioactive ion beam has been successfully delivered to a physics experiment over a period of 1 week. The yields on the physics target were in the range of $\sim2-4.10^6$ pps at 9 MeV/u. The target ion source system (TISS) was made of a FEBIAD ion source connected to a hot graphite target. This is the first time a radioactive ion beam is accelerated with a cyclotron with the 1+/n+ method. Moreover, a production test with the FEBIAD TISS has confirmed the yields measured previously, which validates the extension of the GANIL/SPIRAL1 catalog for a number of isotopes.

In parallel R&D is being performed on new TISSs (e.g. a fast release one, using surface ionization source). Targets are also a subject of ongoing R&D for yield and release time optimization.

This contribution will present the new acceleration scheme of the SPIRAL1 facility, which largely extends the palette of RIBs available for nuclear physicists. It will be compared to the one used at similar ISOL facilities. This facility is more than a simple ISOL facility and an overview of the new potentials offered by the upgraded installation will be also discussed.
EBIS/T Charge Breeders at RIB Facilities

Alain Lapierre
National Superconducting Cyclotron Laboratory, Michigan State University, 640 S. Shaw Lane, East Lansing, MI, 48824, USA
Corresponding Author: Alain Lapierre, e-mail address: lapierre@nscl.msu.edu

At accelerator facilities, charge breeders convert ion beams of low charge states into multiply charged ion beams to increase (or boost) the energy of beams. A field of application that has grown over the past decades is charge breeding of rare-isotope beams (RIB). Several post-accelerators at RIB facilities currently in operation and under construction employ electron-beam ion sources and traps (EBIS/T's) as charge breeders. Compared with other charge breeding techniques, EBIS/T's have many advantages: high efficiency, fast and variable breeding times, small beam emittances, and high beam purity. This publication reviews the use of EBIS/T charge breeders of RIB with an emphasis on their use for post-acceleration.
The study of $^{+1}$ ion beam interaction in an ECR charge breeder ion source plasmas using Monte-Carlo Charge Breeding Code (MCBC)

Arun Annaluru, Maunoury Laurent, Delahaye Pierre, Zhao Liangji, Kim Jin-Soo, Mickael Dubois and Ujic Predrag

GANIL, bd H. Becquerel BP55027, F-14076 Caen cedex 05, France
FAR-Tech, Inc., 10350 Science Center Drive, San Diego, California 92121.
Corresponding Author: Arun Annaluru, e-mail address: arun.annaluru@ganil.fr

As a part of SPIRAL1 upgrade, experimental studies were carried out to understand the ion transport through the SP1 ECR charge breeder and to investigate the physical mechanisms involved in charge breeding process [1]. Numerical simulations were performed using SIMION 3D to reproduce the trends of low charge states ($^{+1}$ and $^{+2}$) experimental results (charge breeding efficiency versus $\Delta V$ curves) by transporting the $^{+1}$ ion beam through a potential map that reflects the presence of the ECR plasma (without collisions) [1]. The simulations results showed good agreement with the experiments and revealed the role of Coulomb collisions in the charge breeding process leading to a necessary detailed analysis using a full six-dimensional (6D) phase space Monte-Carlo Charge Breeding code (MCBC) [2, 3]. The simulation code models Coulomb collisions of the injected $^{+1}$ ion beam in an ECR plasma and atomic processes which includes ionization and charge exchange. The background ECR plasma has been modeled by implementing a simplified plasma model scheme, proposed in the previous charge breeding simulation studies [4, 5]. The charge breeding simulations were performed for three experimental cases (interaction of Na$^{+1}$ with a helium plasma, K$^{+1}$ with a helium plasma and K$^{+1}$ with an oxygen plasma). The model finally able to reproduce the low charge state ($^{+1}$ and $^{+2}$) experimental trends by varying each plasma parameter (plasma density, ion temperature and electron temperature) independently. Finally, the estimated plasma parameters obtained from each case are presented and the reasons for the difference in charge breeding efficiencies between Na and K species are discussed.

References and Acknowledgment
Selectable High Intensity H⁺/H₂⁺/H₃⁺ Beam with a 2.45 GHz ECR Ion Source

Peng Shixiang¹, Wu Wenbin¹, Ren Haitao¹, Xu Yuan¹, Zhang Jingfeng¹, Zhang Tao¹, Zhang Ailin¹, Ma Tenghao¹, Jiang Yaoxiang¹, Li Kai¹, Wen Jiamei¹, Xu Yuan¹, Zhang Ailin¹, Guo Zhiyu¹, Chen Jiaer

¹ State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China

Corresponding Author: Shixiang PENG, e-mail address: sxpeng@pku.edu.cn

At Peking University (PKU), experimental research as well as theoretical study on how to produce high intense H⁺, H₂⁺ or H₃⁺ domain ion beams with a compact permanent magnet 2.45 GHz ECR ion source (PMECRIS) have been continuously carried out in the past decades. With a so-called standard PKU PMECRIS, a 130 mA@50 keV pulsed (100 Hz/1 ms) H⁺ beam with H⁺ faction of 90% was obtained in 2016. A 50 mA@50 keV CW H⁺ beam with this PMECRIS has been run continuously for 300 hours without any beam-off, spark, beam drop. It proved that the availability and reliability of this standard PKU PMECRIS is nearly 100%. The root-mean-square (RMS) emittance of 50mA@50keV CW H⁺ is about 0.19 π.mm.mrad. Investigation on high intensity H₂⁺ and H₃⁺ ion domain beam generation has been also carried out since 10 years ago. In 2013, 40 mA H₂⁺ and 20 mA H₃⁺ beams were obtained with a source named as PKU PMECR II. The corresponding fractions of H₂⁺ ion and H₃⁺ ion within the total extracted beam are 47.7% and 43.2% respectively. Recently, more attentions were paid on the understanding of hydrogen plasma to improve the performance of 2.45 GHz ECR hydrogen ion sources. Some hydrogen plasma parameters were acquired with method of optical emission spectroscopy (OES) in a 2.45 GHz ECR ion source. Meanwhile, a numerical model based on the particle population balance equations was developed for quantitative comprehension of electron cyclotron heated (ECH) hydrogen plasma. On these basis, working parameters of the source, wall material of the discharge chamber, and other factors have been optimized according to the calculated results. With these improvements, more than 42 mA H₂⁺ ion beam with species fraction of 54% and 20 mA H₃⁺ ion beam with species fraction of 55% were obtained with PKU PMECR II [10]. Recently, a miniaturized ECR ion source was developed and a 52 mA hydrogen beam was extracted. Under the guidance of the model developed here on the ion species fraction selection, this miniaturized ECR ion source can easily produce either H⁺ or H₂⁺ or H₃⁺ domain beam. Measurement results with the miniaturized ECR ion source show that under different working parameters H⁺, H₂⁺ and H₃⁺ fraction can reach up to 88%, 80% and 82%, respectively.

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J-PARC H⁺ Ion Source and Space-Charge Neutralized LEBT for 100 mA High Energy and High Duty Factor LINACs

Akira Ueno
J-PARC Center, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
Corresponding Author: Akira Ueno, e-mail address: akira.ueno@j-parc.jp

The Japan Proton Accelerator Research Complex (J-PARC) cesiated RF-driven H⁺ ion source has successfully operated with a 57 mA & 50 keV beam for a 50 mA beam at the exit of the J-PARC 400 MeV LINAC for about one year from October 2018. It is also producing a 72 mA beam for the J-PARC LINAC 60 mA operation studies. The world’s highest class intensity beam with transverse emittances suitable for RFQs of high energy H⁺ ion LINACs is produced with several unique measures, such as, slight water molecules addition into the hydrogen plasma, the low temperature (about 70 °C) operation of the 45º-tapered plasma electrode with a 16-mm thickness, a 30-MHz CW plasma igniter, the macro-pulse chopping with a rapid rising time by the H⁺ ion energy modulation being below the RFQ longitudinal acceptance, and so on [1, 2]. Its stable 8 hours 100 mA beam operation was demonstrated in a test stand by increasing the terminal voltage from 50 kV to 62 kV [2]. In this paper, these measures essential for a 100 mA operation are reviewed and explained. The recent transverse emittance improvements with the shortest beam extractor are also presented. The horizontal/vertical 95 % beam normalized rms emittances of a 100 mA & 62 keV beam were improved by about 8 % form 0.262/0.3 π·mm·mrad to 0.242/0.273 π·mm·mrad with the thinnest extraction electrode (1.5 mm thinner) and the ground electrode 1.5 mm extended to upper stream. The emittances of a 66 mA & 50 keV beam and a 80 mA & 56 keV beam were also improved about 8 % with the shortest beam extractor. About 94 % of each beam with the intensity of 66, 80 or 100 mA is distributed in the transverse phase planes inside of the normalized 1.5 π·mm·mrad ellipse, the water bag distribution in which is commonly used to design RFQs of high energy LINACs.

References and Acknowledgment
Commissioning of High Current H⁺ /D⁺ ion beams for the Linear IFMIF Prototype Accelerator (LIPAc)

Tomoya Akagi¹, Luca Bellan², Benoît Bolzon³, Philippe Cara⁴, Yann Carin⁵, Nicolas Chauvin⁵, Michele Comunian², Hervé Dzitko⁵, Enrico Fagotti², Francis Harrault³, Atsushi Kasugai¹, Keitaro Kondo¹, Keishi Sakamoto¹, Masayoshi Sugimoto¹

¹ National Institutes for Quantum and Radiological Science and Technology (QST), Rokkasho-mura, Aomori, Japan
² Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, Legnaro, Italy
³ Commissariat à l’Energie Atomique et aux Energies Alternatives, Gif-sur-Yvette, France
⁴ IFMIF/EVEDA Project Team, Rokkasho-mura, Aomori, Japan
⁵ Fusion for Energy, Garching, Germany

Corresponding Author: Tomoya Akagi, e-mail address: akagi.tomoya@qst.go.jp

The Linear IFMIF (International Fusion Materials Irradiation Facility) Prototype Accelerator (LIPAc) is aiming at demonstration of the low energy section of 40 MeV/125 mA IFMIF deuteron accelerator up to 9 MeV with a full beam current in continuous wave (CW). For such high-power beam, the LIPAc injector is required to produce a 100 keV D⁺ beam with 140 mA. The injector is composed of the ECR ion source based on the CEA-Saclay SILHI source and a Low Energy Beam Transport (LEBT) line. The capability of the injector to produce 100 keV/140 mA D⁺ beam with emittance of 0.25 π mm mrad has already been demonstrated by 2017. The H⁺ beam with half energy and half current with respect to the nominal D⁺ beam is also used at the initial phase of the beam commissioning of the 175 MHz, 5 MeV Radio Frequency Quadrupole (RFQ). In 2019, the commissioning of the RFQ to demonstrate the D⁺ beam acceleration at low duty cycle (0.1%) is being implemented. This paper describes the latest results obtained through the efforts to characterize the pulsed D⁺ beam as well as H⁺ beam extracted from injector. The progress of demonstration of high current D⁺ beam acceleration will be also presented.
Ion source modification is proposed for efficient production of ion beam and extending of operating lifetime. Ionization efficiency of the Bernas type ion source has been improved by using a small anode-thin rod, oriented along the magnetic field. The transverse electric field of small anode transport plasma by drift in crossed field to the emission slit. Optimization of the cathode material recycling is used to increase the operating lifetime. Optimization of the wall potential is used for suppression of flakes formation. A three-electrode extraction system was optimized for low energy beam production and efficient space charge neutralization. An ion beam with emission current density up to 60 mA/cm² has been extracted from discharge in BF₃ gas. Ion beams of ¹¹B isotope with intensity up to 6 mA for 3 keV, up to 11 mA for 5 keV, 18 mA for 15 keV have been transported through the analyzer magnet.
Commissioning of the RF H\textsuperscript{+} source in CSNS

Weidong Chen\textsuperscript{1,2}, Hui Li\textsuperscript{2,3}, Renli Zhu\textsuperscript{2,3}, Xiuxia Cao\textsuperscript{1,2}, Yongjia Lü\textsuperscript{1,2}, Yongchuan Xiao\textsuperscript{1,2}, Shengjin Liu\textsuperscript{1,2}, Kangjia Xue\textsuperscript{1,2}, and Huafu Ouyang\textsuperscript{1,2}

\textsuperscript{1}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 730000, China
\textsuperscript{2}Dongguan Neutron Science Center, Dongguan 523803, China
\textsuperscript{3}University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding Author: Weidong Chen, e-mail address: chenwd@ihep.ac.cn

China Spallation Neutron Source has started to serve the users since March of 2018. To upgrade the beam power to 500 kW and improve the performance of ion source, an RF coupled H\textsuperscript{+} source is under development. The source has a Si3N4 ceramic plasma chamber surrounded by a 4.5-turn antenna. The plasma is ignited by a pulsed DC spark gap and then driven by a 2 MHz solid-state amplifier with a repetition rate of 25 Hz. The commissioning of the source started in the January of 2019. When un-cesiated, it produced more than 30 mA beam at an RF power of 32 kW and pulse width of 450 $\mu$s. Further improvements is still ongoing.
Upgrading the LANSCE Accelerator Complex with a SNS RF-driven H\textsuperscript{+} Ion Source

Martin P. Stockli\textsuperscript{1}, Ilija N. Draganic\textsuperscript{2}, Baoxi Han\textsuperscript{1}, Yuri K. Batygin\textsuperscript{2}, Mike Clemmer\textsuperscript{1}, Sarah M. Cousineau\textsuperscript{1}, Vadim Dudnikov\textsuperscript{3}, Robert W. Garnett\textsuperscript{2}, Alan Justice\textsuperscript{1}, Yoon W. Kang\textsuperscript{1}, David Kleinjan\textsuperscript{2}, Jacob L. Medina\textsuperscript{2}, Joel P. Montross\textsuperscript{2}, Syd N. Murray Jr.\textsuperscript{1}, Terry R. Pennisi\textsuperscript{1}, Chip Piller\textsuperscript{1}, Gary Rouleau\textsuperscript{2}, Chris M. Stinson\textsuperscript{1}, Robert F. Welton\textsuperscript{1}

\textsuperscript{1} Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA
\textsuperscript{2} Los Alamos Neutron Science Center, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
\textsuperscript{3} Muons, Inc, Batavia, Illinois, 60510, USA

Corresponding Author: Martin Stockli, e-mail address: stockli@ornl.gov

The LANSCE (Los Alamos Neutron Science CEnter) accelerator complex is currently driven by a filament-powered, biased converter-type H\textsuperscript{+} ion source that operates at a high plasma duty factor of 10\%. This is the world’s highest duty factor for pulsed high-current H\textsuperscript{+} accelerators using only $\sim 2.2$ sccm of H\textsubscript{2} (standard cubic centimeter per minute). The ion source needs to be replaced every 4 weeks with a $\sim 4$ day startup phase. The measured negative beam current of 16-18 mA falls below the desired 21 mA acceptance of the LANCSE accelerator especially since the beam contains several mA of electrons.

On the other hand the SNS (Spallation Neutron Source) RF-driven, H\textsuperscript{+} ion source injects $\sim 50$ mA of H\textsubscript{+} beam into the SNS accelerator at 60 Hz with a 6\% duty factor and an availability of $\sim 99.9\%$, but requiring $\sim 30$ sccm of H\textsubscript{2}. Up to 7 A·hrs of H have been produced during the up to 14-week long service cycles, which is an unprecedented lifetime for small emittance, high-current pulsed H\textsuperscript{+} sources. The SNS source also features unprecedented low Cs consumption and can be installed and started up in $\sim 10$ h.

LANSCE and SNS are considering the use of a SNS H\textsuperscript{+} ion source on the LANSCE accelerator because it should a) decrease the source replacement time by a factor of $\sim 8$, b) increase source lifetime by a factor of 2-3, and c) increase the accelerator power by up to $\sim 40\%$. However, this is a significant challenge as characteristics and normal operating regimes are drastically different. This talk will report on operating the SNS source with a 10\% duty factor and adapting the small-diameter, small-emittance SNS beam to the 2-solenoid magnetic LANSCE LEBT (low- energy beam transport).

Acknowledgment

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Development of A New High-temperature Oven for the Production of Intense Metallic Ion Beams with ECR Ion Sources

W. Huang\textsuperscript{1,2}, D. Z. Xie\textsuperscript{2} and L. Sun\textsuperscript{1}

\textsuperscript{1}Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
\textsuperscript{2}Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720, USA

Corresponding Author: Wei Huang, e-mail address: whuang8@lbl.gov

High-temperature oven (HTO) has been widely used to evaporate refractory materials in ECR ion sources to produce multiple and highly-charged ion beams. To meet the demand of milliamperes of multiply-charged uranium and other metallic heavy ion beams for the future accelerators, a new and low-cost HTO is under development at Lawrence Berkeley National Laboratory to achieve the needed long-term stability with high evaporation rates. As an HTO for ECR ion sources is immersed in very high magnetic fields, ANSYS simulations have been carried out to optimize the new HTO with as low heating current as possible to reduce the EM forces. Large loading volume is employed to mitigate the high material consumption. Off-line tests have shown that the unloaded new HTO operates very stable up to 1800-1900 $^\circ$C with low temperature gradients and good repeatability. This paper discusses the new HTO design features, off-line tests and future online developments.

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Lead Evaporation Instabilities and Failure Mechanisms of the Micro Oven at the GTS-LHC ECR Ion Source at CERN

Toke Kövenen1,2, Detlef Küchler1, Ville Toivanen3
1European Organization for Nuclear Research (CERN), Geneva, Switzerland
2University of Hamburg, 20146 Hamburg, Germany
3University of Jyväskylä, Department of Physics (JYFL), 40500 Jyväskylä, Finland

The GTS-LHC ECR ion source at CERN provides heavy ion beams for the chain of accelerators from Linac3 up to the LHC for high energy collision experiments and to the SPS for fixed target experiments. During the standard operation the oven technique is used to evaporate lead into the source plasma to produce multiply charged lead ion beams.

Intensity as well as stability are key parameters for the beam and the operational experience is that some of the source instabilities can be linked to the oven performance. Over long operation periods of several weeks the evaporation is not stable which makes the tuning of the oven unpredictable and non-reproducible. A dedicated test stand is used to study the oven performance and possible improvements independently of the source operation.

It was observed that the measured evaporation rate of the oven can vary spontaneously in a wide range even when stable operating conditions are applied to the oven controls. Data collected at the test stand hints that these fluctuations are caused by temperature instabilities of the oven itself. Several ways to improve the oven stability were tested, including insulation changes and modifications of the oven crucible. Some of the most promising results regarding the stability of the evaporation will be presented in this paper.
Powerful Pulsed “Point-Like” Neutron Source Based on the High-Current ECR Ion Source

Sergey V. Golubev\textsuperscript{1}, Vadim A. Skalyga\textsuperscript{1}, Ivan V. Izotov\textsuperscript{1}, Roman A. Shaposhnikov\textsuperscript{1}, Sergey V. Razin\textsuperscript{1}, Alexander V. Sidorov\textsuperscript{1}, Alexey F. Bokhanov\textsuperscript{1}, Mikhail Yu. Kazakov\textsuperscript{1}, Roman L. Lapin\textsuperscript{1}, Sergey S. Vybin\textsuperscript{1}

\textsuperscript{1}Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia
Corresponding Author: Roman A. Shaposhnikov, e-mail address: shaposhnikov-roma@mail.ru

Neutron tomography is one of perspective directions in modern physics, which is applied in medicine, archeology, engineering etc. Neutongraphy requires specialized neutron sources, such as nuclear reactors and large accelerators equipped with collimators for generating neutron fluxes with a small angular spread. However, these facilities are very expensive and complicated in operation, and that fact significantly hinders the spread of neutron tomography as a routine technique.

Evolution of tomography methods in general is connected with transition to point-like radiation sources to increase efficiency and reduce minimal necessary dose. This work is aimed at a "point-like" neutron source development based on a powerful D-D neutron generator. In frames of such approach the quality of the neutronographic image depends on the size of the neutron emitting region on the target, which is determined by the efficiency of ion beam focusing. Therefore, it is necessary to obtain the smallest possible transverse size of the beam. Previously it was demonstrated that gasdynamic ECR ion source could produce the deuterium beams of a high quality perspective for neutronographic application. In the present work the first neutronographic image of a test object collected at SMIS 37 facility will be shown. A plastic prism was chosen as the test object and its image was received by analysis of a radiochromic plate, accumulating defects from neutrons, which was located behind the prism. Another radiochromic plate was placed between the target and the prism on a purpose to control the neutron source size. The lead screen was located after the target in order to absorb x-rays.

In described experiments dense plasma of ECR discharge, which was sustained by a powerful gyrotron radiation, was confined in a simple mirror magnetic trap. A two-electrode extraction system was used on a purpose to extract ion beam, which then was focused by a magnetic lens. Experimental results demonstrated the possibility of ion beam focusing in the region with size of 1 mm. Ion current density on a target was 7.6 A/cm\textsuperscript{2}. Neutron flux measurements were conducted with dosimeter-radiometer and total yield values were at the level of 10\textsuperscript{18} s\textsuperscript{-1}, which correspond to neutron flux density 10\textsuperscript{12} cm\textsuperscript{-2} s\textsuperscript{-1} in the emitting region on the target. It is worth noting that presented results can be improved by using a combined electrostatic and magnetic focusing system. Numerical modelling demonstrates the perspective of such approach, which allows to focus ion beam in the region with size much less than 1 mm.

References and Acknowledgment
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Status of High Intensity Proton Injector for FAIR

Rustam Berezov, Olivier Delferriere, Jerome Fils, Yannick Gauthier, Ralph Hollinger, Klaus Knie, Carl Kleffner, Olivier Tuske

1GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
2Commissariat à l’Energie Atomique et aux Energies Alternatives, IRFU, F-91191-Gif-sur-Yvette, France

Corresponding Author: Rustam Berezov, e-mail address: r.berezov@gsi.de

The high intensity proton injector for the international accelerator Facility for Antiproton and Ion Research (FAIR) located at GSI (Darmstadt) in Germany consists of pulsed 2.45 GHz microwave ion source, a Low Energy Beam Transport (LEBT) and an electrostatic chopper matching the proton beam to the RFQ. The ion source is based on Electron Cyclotron Resonance (ECR) plasma production and it has to provide a proton beam at 95 keV energy and up to 100 mA current. The LEBT with two short solenoids system including two magnetic steerers will transport the proton beam into the compact proton linac that will accelerate proton beam to the energy of 68 MeV and serving as injector of the upgraded Heavy Ion Synchrotron (SIS18). This paper describes the commissioning of the proton injector including beam characterization measurements that have been done at CEA/Saclay in France and nowadays is on the final commissioning stage.
Status of the Gasdynamic Ion Source for Multipurpose Operation (GISMO) development at IAP RAS

Vadim Skalyga¹ ², Alexey Bokhanov¹, Sergey Golubev¹, Ivan Izotov¹, Mikhail Kazakov¹, Roman Lapin¹, Sergey Razin¹, Roman Shaposhnikov¹, Sergey Shlepnev¹, Sergey Vybin¹

¹Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, 603155, Russia
²Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603155, Russia

Corresponding Author: Vadim Skalyga, e-mail address: skalyga@ipfran.ru

A new experimental facility called GISMO (Gasdynamic Ion Source for Multipurpose Operation) was constructed for continuation of investigations in the field of gasdynamic ion sources at the IAP RAS. The source utilizes 28 GHz/10 kW gyrotron radiation for heating magnetically confined plasma. Magnetic field configuration provided by a fully permanent magnet system is much alike a simple mirror trap. GISMO source is aimed at the production of bright ion beams with hundreds of mA current. The facility has been tested for CW operation with 2 kW of heating power to check durability of a microwave injection system and the plasma chamber. A 4-electrode extraction system was designed for a formation of CW high current beam with up to 100 kV accelerating voltage. First results on ion beam production at GISMO will be presented together with the general progress status of the facility.

References and Acknowledgment

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Préliminary results of BETSI test bench upgrade at CEA-Saclay

Olivier Tuske, Olivier Delferriere, Francis Harrault, Yannick Gauthier
Commissariat à l’Energie Atomique et aux Energies Alternatives, IRFU, F-91191-Gif-sur-Yvette, France
Corresponding Author: Olivier Tuske, e-mail address: olivier.tuske@cea.fr

The BETSI test bench was built in 2009 for the Spiral2 project. Year after year upgrade were done on the low energy beam line side in order to have a complete injector equipped with 2 solenoids and vacuum chambers with multiple viewports for various kind of beam diagnostics. BETSI was designed for the 50kV of high voltage and all the sources that were installed on the platform were also designed for that voltage.

As the ALISES ions source family is getting larger, design were made for higher extraction, voltage. As the common extraction voltage is 100kV, BETSI test bech and platform were upgraded to this voltage value. The control-command was upgraded and at thoses voltage a great care on the electromagnetic protections were done in order to protect equipment when spark occurs.

This paper describes the choice of the upgrade, its installation and gives some performances already obtained with a permanent magnet ion source equipped with a large accelerating tube.
Encouraging results were obtained with ALISES II ECR ion source (Advanced Light Ion Source Extraction System) on BETSI test bench (Banc d’Etude et de Test des Sources d’Ions) in 2016 with a proton beam of 43 mA produced at 50 kV through a plasma extraction aperture of 6 mm diameter in CW mode. Based on the ALISES concept, improvements have been realized on the source geometry as well as on the ion source assembly. The new source ALISES III has been fabricated and assembled at the beginning of 2017. Unfortunately, implication of ion source team in different international projects and the need to upgrade the BETSI test bench from 50 kV to 100 kV have postponed source test to beginning of 2019. To be able to restart our R&D program on ECR compact ion sources, a new dedicated 50 kV test bench, TROPICS (Test, Research and Optimization for Production of Ions with Compact Sources), has been developed in 2018. This paper describes the ALISES III main characteristics, its installation on TROPICS and gives the performances already obtained.
A very compact permanent magnet 2.45 GHz ECR ion source has been designed and developed for various purposes. The RF power is introduced to the plasma chamber by the coaxial antenna instead of the waveguide, the magnetic field is produced by two NdFeB permanent magnet rings and the diameter of the source body is only 10 cm, therefore the volume of ion source system is reduced greatly. A 4 mA proton beam could be extracted from a 5 mm diameter extraction aperture in preliminary test, the extraction beam current is mainly limited by the maximum RF power that antenna could sustain and further optimization of the antenna is underway.
Formation of high-intensity axially symmetric and ribbon beams of low-energy metal ions

Alexander Ryabchikov, Denis Sivin, Aleksey Shevelev, Georgy Modebadze
Tomsk Polytechnic University
Corresponding Author: Alexander Ryabchikov, e-mail address: ralex@tpu.ru

Low-energy metal ion beams are of considerable interest for the development of a high-intensity implantation method providing modification of the elemental composition, microstructure and properties of various materials at depths many times exceeding the projective range of ions in a substance. This paper presents the results of experimental studies on plasma–immersion formation followed by a spherical and cylindrical ballistic focusing of aluminum, titanium, and chromium ion beams. The features of the formation, transport, and ballistic focusing of an ion beam are discussed, depending on the parameters of the vacuum-arc plasma, conditions of its preliminary injection into the drift space and beam focusing, amplitude, duration, frequency of the bias potential pulses, presence of dynamic compensation or decompensation of the space charge of the focused beam having significant gradient in the density of the ion current and, accordingly, the space charge. The optimal conditions for the formation of high-intensity beams of metal ions purified from the microdrop fraction from the vacuum-arc plasma with a current of more than 1 A and a current density of up to 1 A/cm² are determined.

References and Acknowledgment
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Ballistic formation of high-intensity low-energy gas ion beams

Alexander Ryabchikov¹, Denis Sivin¹, Aleksey Shevelev¹, Yurriy Akhmadeev², Olga Korneva¹, Anna Ivanova¹, Ilya Lopatin²

¹Tomsk Polytechnic University
²Institute of high current electronics

Corresponding Author: Alexander Ryabchikov, e-mail address: ralex@tpu.ru

The development of the method of high-intensity implantation of low-energy ions requires the development and study of efficient systems for generating high-intensity ion beams of various elements with a current density of tens and hundreds of milliamperes per square centimeter with ion energies not exceeding 1 keV. This paper considers the regularities of formation of high-intensity beams of nitrogen ions, argon and mixed beams of argon and hydrogen ions in spherical and cylindrical grid systems with ballistic focusing of the ion beam. The studies were carried out with the plasma-immersion formation of pulse-periodic ion beams with a duration from units to hundreds of microseconds, a pulse frequency of up to 105 pulses/s with negative bias potentials in the range from 0.6 to 3 kV. The report presents data on the influence of cell size of the grid ion extractor, its geometric dimensions and shape as part of a sphere or cylinder, plasma density, parameters of negative bias potential on the formation, transport and ballistic focusing of high-intensity ion beams of various gases. The possibility of stable formation of gas ion beams with a current of up to 3 A from the gas-discharge generator plasma with hot and hollow cathodes is demonstrated. The report presents data on the regularities of formation of high-intensity beams of gas ions with the ability to control ion energy in the range from 0.2 to 1 keV.

References and Acknowledgment

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The Simulation of Radio Frequency Inductively Coupled Plasma Ion Source Used in Electromagnetic Isotope Separator

Kun Xu, Xiuyan Ren, Ziqiang Zeng and Guobao Wang
Department of Nuclear and Technology Application, China Institute of Atomic Energy, Beijing 102413, China
Corresponding Author: Kun Xu, e-mail address: bjxunxu@163.com

Ion source is a key part of electromagnetic isotope separator (EMIS). It can influence the abundance and output of the separated isotope. Radio frequency inductively coupled plasma (RF-ICP) ion source has been applied widely in many domains because it has many advantages such as simple structure, high density plasma and long lifetime. In this paper, we proposed that RF-ICP ion source can be applied in EMIS. The finite element simulation model has been done for RF-ICP ion source based on COMSOL software. The factors such as gas flow rate in entrance, frequency and power of RF influenced on electron density and temperature have been studied. This work will provide reference for the manufacture of RF-ICP ion source used in EMIS.
Investigation of Low Charge State Ion Production by a Laser Ion Source

Keisuke Yamada$^1$ and Hirotsugu Kashiwagi$^1$

$^1$National Institutes for Quantum and Radiological Science and Technology, Gunma 370-1292, Japan

Corresponding Author: Keisuke Yamada, e-mail address: yamada.keisuke@qst.go.jp

The 400 kV Ion Implanter in TIARA [1] is required to provide ion beams of various ion species from hydrogen to bismuth for material science experiments. A Freeman type ion source which produces heavy ions from the vapor of solid material by using an oven could not produce sufficient ion beam current in the case of high melting point materials, and the ion source requires time for the switch of ion species. In order to provide various heavy ion beams, we are developing a laser ion source (LIS) as an ion source for the Ion Implanter [2]. The LIS is possible of producing pulsed ion beams from any solid material and fast switching of ion species. To conduct ion implantation experiments that require high ion dose using a LIS, it is necessary to irradiate a laser to a solid target material at a high repetition rate. Low charge state ions are suitable for operation at a high repetition rate because the production of the ions is less affected by changes in the solid target surface shape caused by laser irradiation. In this study, we investigated the laser power density to produce low charge state ions with a nanosecond laser. The laser power density was controlled with both the position of a focusing lens and the angle of a half-wave plate, which was placed at upstream of a polarizing beam splitter. We measured the charge state distribution of ions in the laser-produced plasma with an electrostatic ion analyzer by changing laser power density. The experimental results with a carbon target will be presented.

References and Acknowledgment

Investigation of time interval of generating laser plasma for high-repetition operation

Hirotugu Kashiwagi, Keisuke Yamada
National Institutes for Quantum and Radiological Science and Technology, 1233 Watanuki-machi, Takasaki, Gunma 370-1292, Japan
Corresponding Author: Hirotugu Kashiwagi, e-mail address: kashiwagi.hirotugu@qst.go.jp

Laser ion sources (LISs) generate high-intensity ion beams from almost any solid material by focusing a high-intensity pulsed laser beam on a target. Ion species can be changed by replacing target materials or mounting multiple targets on a target holder. In TIARA ion implanter, we are developing a LIS as an alternative source for the existing Freeman ion source equipped with the oven for vaporizing solid materials. The beam current from the high-melting-point material produced by the Freeman source is insufficient and decreases with time. Furthermore, conducting experiments using multiple kinds of ions is difficult, because it takes time to switch ion species due to the long heating time of the oven (2-3 hours). In order to apply LIS as an ion source of the implanter, high repetition operation is required to obtain a sufficient number of particles for the experiment. However, in the plasma generation with a short pulse interval, there is a concern that the generated plasma or gas may interact with the following laser, resulting in different characteristics and instability from those in the single plasma generation. In order to clarify the conditions for generating plasma at a high repetition rate using LIS, experiments of measuring the ion current of the produced plasma were carried out by irradiating the target with two laser beams of equal energy and pulse width at different time intervals. The results obtained from experiments using carbon plasma will be presented.
A new accelerator facility FAIR (Facility for Antiproton and Ion Research) is being built at GSI accelerator research center in Darmstadt, Germany. One of the key-elements for future FAIR experiments is uranium. It will be required to achieve 23 mA of $\text{U}^{4+}$ ions inside an emittance of $220\pi \text{mm}\cdot\text{mrad}$ in front of the RFQ (Radio Frequency Quadrupole) with beam pulse length of 100 µs. Recently achieved ion beam current from operation terminal North with VARIS ion source is 15 mA. Thus, in order to fulfill the FAIR requirements it will be necessary to increase the beam intensity and the beam brilliance for $\text{U}^{4+}$ ions in front of the RFQ. This could be achieved by reducing the beam losses in the post-acceleration system of operation terminal as well as in the LEBT (Low Energy Beam Transport line) between terminal and RFQ. Recently these losses are above 75%. For this purpose in the frame of the PRIDE-project (PRe-Injector DEdicated for uranium operation) a new ion source operation terminal (terminal West) with enhanced geometry of the post-acceleration system as well as a dedicated straight beam transport line (compact-LEBT) will be constructed at GSI. Besides, availability of dedicated uranium terminal will drastically reduce a risk of a cross-contamination of other ion sources and service areas with radioactive uranium, as the result, it will improve general radiation safety in this area. In this work the challenges of the project will be discussed and the recent status will be presented.
Electron gun System for the Anti-Proton Trap of the Gravitational Behavior of Anti-matter at Rest experiment

Eunhoon Lim¹, Eun-San Kim¹, Moses Chung², Kyoughun Yoo², Donghwan Won³
Gwanhyung Park³ and Sunkee Kim³

¹Department of Accelerator Science, Korea University, Sejong 30019, Rep. of Korea
²Department of Physics, Ulsan National Institute of Science and Technology, Ulsan 44919, Rep. of Korea
³Department of Physics & Astronomy, Seoul National University, Seoul 08826, Rep. of Korea
Corresponding Author: Eun-San Kim, e-mail address: eskim1@korea.ac.kr

The GBAR (The Gravitational Behavior of Anti-matter at Rest) experiment has been proposed to observe the behavior of anti-matter in gravity at CERN. The anti-hydrogen is a representative particle of anti-matter since it is relatively easily produced by collisions with positrons and anti-protons. An ion trap with extraction system into following beam transport line has been adopted system to increase the intensity of the anti-hydrogen. The trap system consists of a superconducting magnet for generating a uniform magnetic field, a multi-ring electrode (MRE) for an optima electric field configuration, a cold ultra-high vacuum (UHV) system for expanding lifetime of anti-proton, an e-gun and their related power system. The purpose of the e-gun is to provide electrons into the MRE zone to obtain quick cooling down of anti-protons to minimize the beam loss. The design goal of the e-gun is to generate an electron beam with 50 eV of the kinetic energy, a few hundred uA of the beam intensity and DC mode. In this paper, we described the simulation of electron beam generation by CST code and the measurement result.
HIISI: A New 18 GHz Room Temperature Electron Cyclotron Resonance Ion Source for Highly Charged Ion Beams

Hannu Koivisto1, Anssi Ikonen1, Taneli Kalvas1, Risto Kronholm1, Olli Tarvainen1,2, and Ville Toivanen1

1University of Jyväskylä, 40500 Jyväskylä, Finland
2STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX, UK

Corresponding Author: Hannu Koivisto, e-mail address: hannu.koivisto@phys.jyu.fi

An innovative 18 GHz HIISI (Heavy Ion Ion Source Injector) room temperature ECR ion source has been designed and constructed at the Department of Physics, University of Jyväskylä (JYFL) for the nuclear physics program of the JYFL Accelerator Laboratory. The primary objective of HIISI is to increase the intensities of medium charge states (m/q ≤ 5) by a factor of 10 in comparison to the JYFL 14 GHz ECRIS, and to increase the maximum usable xenon charge state from 35+ to 44+ to serve the space electronics irradiation testing program. HIISI is equipped with a refrigerated permanent magnet sextupole and a non-cylindrical plasma chamber to achieve very strong radial magnetic confinement with $B_{rad} = 1.42$ T. The commissioning of HIISI began in fall 2017 and in spring 2019 it has met the main objectives. As an example, the intensity of the Xe$^{27+}$ ion beam has improved from 20 µA to 230 µA. In addition, the beam intensity of the Xe$^{44+}$ ion beam clearly exceeds the beam intensity of Xe$^{35+}$ produced earlier by the JYFL 14 GHz ECR ion source. The performance of HIISI is outstanding being comparable to superconducting ECR ion sources with the same maximum microwave frequency of 18 GHz and total power of 3 kW. For example, Ar$^{16+}$ and Xe$^{30+}$ ion beam intensities of 130 µA and 106 µA, respectively, have been obtained at the total microwave power of 3 kW distributed between 18, 17.4, and 14.5 GHz frequencies. The ion beams have been extracted through an 8 mm plasma electrode aperture using 15 kV extraction voltage. The latest development work, extracted ion beam intensities, special features and future prospects of HIISI will be presented in this paper.
The Biased Disc of an Electron Cyclotron Resonance Ion Source as a Probe of Instability-Induced Electron and Ion Losses

Olli Tarvainen\textsuperscript{1,2}, Risto Kronholm\textsuperscript{1}, Taneli Kalvas\textsuperscript{1}, Hannu Koivisto\textsuperscript{1}, Ivan Izotov\textsuperscript{3}, Vadim Skalyga\textsuperscript{3}, Ville Toivanen\textsuperscript{1,4} and Laurent Maunoury\textsuperscript{4}

\textsuperscript{1}University of Jyväskylä, 40500 Jyväskylä, Finland
\textsuperscript{2}STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX UK
\textsuperscript{3}Institute of Applied Physics, RAS, 46 Ul’yanova st., 603950 Nizhny Novgorod, Russian Federation
\textsuperscript{4}Grand Accé lè rateur National d’Ions Lourds (GANIL), 14076 Caen Cedex 5, France

Corresponding Author: Olli Tarvainen, e-mail address: olli.tarvainen@stfc.ac.uk

Electron Cyclotron Resonance Ion Source (ECRIS) plasmas are prone to kinetic instabilities that often limit the parameter space available for optimizing the extracted currents of high charge state ions. Various diagnostics methods including the detection of plasma microwave emission, bremsstrahlung bursts and oscillation of the extracted beam current have been applied in the past to observe the transition between stable and unstable discharge regimes. The kinetic instabilities are associated with electron and ion losses that are notoriously difficult to quantify using the above diagnostics. We report the results of a measurement campaign with the JYFL 14 GHz ECRIS where the biased disc of the ion source was used as a direct probe for instability-induced electron and ion losses. It was observed that each instability event causes a burst of electrons to escape the magnetic confinement, which results in significant increase of the plasma potential followed by a burst of ions carrying an equal (but opposite) charge with the initial electron burst, all taking place in less than 10 µs. The data and its interpretation are supported by the measurement of the ion beam energy spread transient associated with the instability. The measurement of the electron and ion losses towards the biased disc are coupled with electron tracking simulations to estimate the range of the total charge expelled from the plasma in a single instability event. The application of the biased disc probe for further studies of the instability mechanism is discussed.
Upgrade of the superconducting ECR ion source SECRAL at Institute of Modern Physics

W. Lu¹, L. T. Sun¹, B. M. Wu¹, X. D. Wang¹, J. W. Guo¹, W. H. Zhang¹, S. J. Zhen¹, C. Li², Z. F. Ge², X. Z. Zhang¹, and H. W. Zhao¹

¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
²Xi'an Superconduting Magnets Technology Co. LTD, Xi'an 710018, China

Corresponding Author: Wang Lu, e-mail address: luwang@impcas.ac.cn

The superconducting Electron Cyclotron Resonance (ECR) ion source SECRAL, built in 2005, is currently under upgrade at Institute of Modern Physics. The magnetic body of upgraded source, SECRAL-I, will be comprised of the existing superconducting magnet and a completely new designed cryostat. The expected dynamic heat load with 100% exciting current but no plasma is 7~7.5 W with five 4.2 K@ 1.8 W G-M cryocoolers installed. As part of the upgrade, a larger warmbore will be applied to provide ~10 percent higher radial magnetic field on the plasma chamber wall. A three-electrode extraction system similar to SECRAL-II will also be used to improve the extraction beam transportation. In August 2019, after assembling and testing at XSMT (Xi'an Superconducting Magnet Technology), SECRAL-I will be installed on LEAF (Low Energy Accelerator Facility) platform, to provide highly charged heavy ion beams for the commissioning. Upgrade status and progress of SECRAL-I will be presented in this contribution.
A new room temperature LECR5 ion source for the SESRI project

Cheng Qian, Liangting Sun, Zehua Jia, Libin Li, Yingming Ma, Xing Fang, Hui Wang, Junwei Guo, Wang Lu, Xuezhen Zhang, Hongwei Zhao
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
Corresponding Author: Cheng Qian, e-mail address: qianc@impcas.ac.cn

Space Environment Simulation and Research Infrastructure (SESRI) project that uses various ion beams as irradiated materials and life science research, will be built in Harbin Institution of Technology (HIT). A new room temperature Electron Cyclotron Resonance (ECR) ion source (named LECR5-Lanzhou Electron Cyclotron Resonance ion source No. 5) has been designed and constructed as the intense highly charged heavy ion beam injector, which provides the ion beams from H to Bi, typically ~100 Bi$^{32+}$. LECR5 is designed to operate at the microwave of frequencies of 18 GHz. The typical magnetic parameters are designed based on the ones optimized for SECRAL working at 18 GHz. This paper will present LECR5 ion source and its test bench, and the first beam results as well.
Fourth generation ECR ion source 45 GHz FECR: Status and development
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
Corresponding Author: Hongwei Zhao, e-mail address: zhaohw@impcas.ac.cn

The Superconducting ECR ion source with higher magnetic fields and higher microwave frequency is the most straightforward path to achieve high beam intensity and high charge state. To meet the demands for higher beam intensities and higher charge states of heavy ion beams from HIAF (High Intensity heavy ion Accelerator Facility) accelerator facility being built by IMP, the world first fourth-generation ECR ion source, a 45 GHz superconducting ECR ion source FECR\(^1\) (a first Fourth generation ECR ion source) is being built at IMP. FECR will be a Nb\(_3\)Sn superconducting-magnet-based ECR ion source with 6.5 Tesla maximum axial mirror field, 3.5 Tesla maximum sextupole field on the plasma chamber inner wall and 20 kW@45 GHz microwave coupling system. The most challenging development for FECR is the Nb\(_3\)Sn superconducting magnet. A prototype of the Nb\(_3\)Sn superconducting magnet is being built to verify the feasibility of FECR magnet in both engineering design and key technologies. This paper will focus on FECR ion source status and its Nb\(_3\)Sn superconducting magnet development.

References and Acknowledgment

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Optical spectroscopy as a routine diagnostic tool for metal ion beam production with an ECRIS

Jan Mäder, Fabio Maimone, Ralf Lang, Patrick Tedit Patchakui, Klaus Tinschert and Ralph Hollinger

GSI Helmholtzzentrum fuer Schwerionenforschung, Planckstr. 1, 64291, Darmstadt Germany
Corresponding Author: Fabio Maimone, e-mail address: f.maimone@gsi.de

At GSI the CAPRICE ECRIS is used to provide heavy ion beams to the UNILAC accelerator. In order to satisfy the demand of metal ion beams a resistively heated oven is routinely used. This evaporation technique allows the ion beams production from natural and enriched solid elements or compounds with high efficiency and low material consumption. Often it is required to provide high charge state ion beams from rare or extremely rare isotopes as $^{48}$Ca used by the material research groups and for the production of super heavy elements. In order to maintain the ion beam stable for the entire scheduled beam time, the plasma inside the ion source must remain as stable as possible. When chemical reactive materials, like $^{48}$Ca, are deposited inside the plasma chamber at internal components the long-term stability can be compromised. The tuning of ion source parameters and oven power affecting the oven temperature and in turn the evaporation rate is necessary. A strong relationship between the microwave power and the oven heating was observed, thus affecting the power control, the plasma stability and the material consumption.

Therefore, it was investigated how an optical spectrometer can be used as a predictive diagnostic tool to detect ion source instabilities or oven overheating leading to high material deposition. Further the effect of parasitic oven heating by coupled microwaves was investigated. Optical emission spectroscopy was performed by analyzing the light from the plasma and from the oven through the extraction aperture. The measurements enabled to distinguish between resistive heating and microwave heating. The results of this investigation are presented here.
Low field experiment with 18GHz RF power of the RAON ECR ion source (II)

Yonghwan Kim, Taeksu Shin
Institute for Basic Science
Corresponding Author: Yonghwan Kim, e-mail address: yhkim1972@ibs.re.kr

As an early stage of the characterization test for a 28GHz fully superconducting ECRIS, performance tests using 18GHz RF power are underway. During the experiments, there was phenomena that beam current fluctuation suddenly appeared even though RF power and power density were relatively low. Then, we inspected the inside of the plasma chamber and modified some parts of the injection side. After the modification, the fluctuation did not appear. However, another undesirable phenomenon was observed that, when the RF power was increased, the beam current value suddenly decreased to a low value. Again, we modified the injection side and monitored the change by beam test. And the test result is reported in this paper.
Preliminary Test of ECR Ion Source for Swift Heavy Ion Beam Application

Jeong-jeung Dang, Won-hyeok Jung, Hyeok-jung Kwon, Seung-hyun Lee and Han-sung Kim
Korea Multi-purpose Accelerator Complex, Korea Atomic Energy Research Institute, Gyeongju, 38680, Korea
Corresponding Author: Jeong-jeung Dang, e-mail address: jjdang@kaeri.re.kr

The compact heavy ion beam accelerator has been developed in the KOrea Multi-purpose Accelerator Complex (KOMAC). Main application of this heavy ion beam is an implantation to make micro-pores on a membrane. This accelerator consists of an ECR ion source and a RFQ which can accelerate heavy ion whose A/q is 2.5 up to 1 MeV/nucleon. The ECR ion source is driven by less than 100 W of 10 GHz RF power with a permanent magnet. Einzel lens, magnetic steerers and a 90 degree dipole magnet were installed to control the beam and separate the ion beams according to the charge states. The individual components were tested before the ion beam extraction. The helium and krypton beam were generated by the ECR ion source system. The beam currents of the respective charge states of the helium and krypton beam were measured. In addition, their emittance were measured by the Allison type emittance scanner. Also, a long time operation stability of the ion source was examined.

References and Acknowledgment
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The primary test on multi-charge ions generation with a 2.45GHz microwave-driven ion source

Tenghao Ma, Shixiang Peng, Jingfeng Zhang, Wenbin Wu, Yaoxiang Jiang, Haitao Ren, Yuan Xu, Jiang Sun, Kai Li, Zhiyu Guo, Jiaer Chen
Peking University, Beijing 100871, China
Corresponding Author: Tenghao Ma, e-mail address: math1125@pku.edu.cn

A 2.45GHz microwave-driven ion source for the generation of multi-charged ions was designed and built at Peking University (PKU) recently. The magnetic field configuration of this ion source is a minimum-B type with a combination of a hexapole field and an axial mirror field. Argon was selected as the first tested beam generated by this ion source. A 63 eμA Ar$^{4+}$ ion beam at 35 kV extraction voltages was obtained in pulsed mode with frequency of 50 Hz and the pulse width of 500 μs. Without the hexapole magnetic field the highest charge state was only Ar$^{2+}$, no Ar$^{4+}$ ion can be found. Both the understanding and the experimental results will be given in this article.
Experimental characterization of the AISHA Ion Source


INFN-LNS- Via S. Sofia 62, 95123, Catania, Italy
Corresponding Author: Luigi Celona, e-mail address: Celona@lns.infn.it

The Advanced Ion Source for Hadrontherapy (AISHa) has been designed to generate high brightness multiply charged ion beams for hadrontherapy applications. Aisha is a compact ECRIS whose hybrid magnetic system consists of a permanent Halbach-type hexapole magnet and a set of independently energized superconducting coils. This has allowed to achieve high performances in a cost effective way. During the commissioning phase a few criticalities have been observed and fixed in 2018/19; the improvements will be briefly described and the results of the operations with a single 18 GHz generator will be presented. Particular relevance will be given to the production of high intensity beams of Oxygen and Argon and Carbon, the latter having huge importance for hadrotherapy.
A high intensity highly charged laser ion source has been being studied at the Institute of Modern Physics in the last years. In order to investigate the ablation and hydrodynamic expansion of laser produced plasma, the charge state and energy distributions of ions from pure Cu, Ag and Cu-Ag alloy, whose atomic number ratio between Cu and Ag is 2 to 3, generated by a 8J / 8ns Nd:YAG laser were measured with a 90° cylindrical electrostatic ion analyzer. It was shown that the yields of highly charged Cu ions are higher for the pure Cu target. On the contrary, higher yields of highly charged Ag ions were obtained from the Cu-Ag alloy target. Moreover, the ion energy distributions were derived from the time-of-flight spectra for the ions with different ion charge states and compared between the pure metal and alloy targets. These results will be presented and discussed in this contribution.
Record Availabilities of the Spallation Neutron Source H+ Injector

Martin P. Stockli, Baoxi Han, Syd N. Murray, Terry R. Pennisi, Chris M. Stinson, Johnny Y. Tang, Robert F. Welton

Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA
Corresponding Author: Martin P. Stockli, e-mail address: stockli@ornl.gov

Since about a year SNS (Spallation Neutron Source) is routinely operating at 1.4 MW with an availability of ~90%. The Cs-enhanced, RF-driven Hion source continues to feed ~50 mA into the RFQ, which provides large margins for operation.

Since 2017, when sputter-loss measurements showed that the ion source life time exceeds the SNS target lifetime, source replacements during neutron production runs became rare events. This is the main reason that the typical availability of the SNS ion source and LEBT (low-energy beam transport) improved from ~99.5% to ~99.9%.

However, it still occasionally happens that an ion source needs to be replaced during a neutron production run. It appears that the 99.9 % availability can be maintained with following recently introduced changes: a) tighter control of the Cs release, b) increased delay after the Cs release before activating high voltages and c) by limiting the 2 MHz source power to ~60% during the first ~20 hours. This presentation will discuss these and other availability enhancing efforts.

References and Acknowledgment

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Withdrawn
A Compact ECR Negative Hydrogen Ion Source for Evaluation of Plasma Grid Materials

Takayuki Eguchi1, Mamiko Sasao2, Yuji Shimabukuro1, Hernandez James1, Masashi Kisaki3, Haruhisa Nakano5, Motoi Wada1, Katsuyoshi Tsumori4
1Graduate School of Science and Engineering, Doshisha University
2Doshisha
3NIFS
4National Institute for Fusion Science
Corresponding Author: Takayuki Eguchi, e-mail address: ctwd0305@mail4.doshisha.ac.jp

Several materials are proposed suitable for plasma grid (PG) of a Cs-free negative hydrogen (H-) ion source. A small piece of C12A7 electride sample has produced H- ions in an exposure to a hydrogen plasma [1]. However the performance of this material as the PG has not been demonstrated yet in an actual beam extraction geometry. A compact ion source that produces hydrogen source plasma with an electron cyclotron resonance (ECR) configuration has been designed and built to study material performance as a PG.

The main part of the designed source is illustrated in Fig.1. A 2.45 GHz microwave excited and produces plasma in a region of 15 mm diameter and 18 mm long. A pair of permanent magnets is installed at the extraction electrode structure, where a sample piece of 34 mm diameter and 2 mm thick with a cone-shaped extraction hole of 6 mm diameter is held in position to work as a PG. The system has been assembled and tested with an aluminum sample producing 30 to 40 nA beam current against 7.5 mA extraction (mainly electron) current under 15 W discharge power. The operation result with the C12A7 electride sample will be reported.

References
Impedance Measurement of CSNS RF Ion Source

H. Li\textsuperscript{1,2}, X. Cao\textsuperscript{1,2}, W. Chen\textsuperscript{1,2}, S. Liu\textsuperscript{1,2}, Y. Lv\textsuperscript{1,2}, H. Ouyang\textsuperscript{1,2,}, Y. Xiao\textsuperscript{1,2}, K. Xue\textsuperscript{1,2} and R. Zhu\textsuperscript{1,2}

\textsuperscript{1} Institute of High Energy Physics, Chinese Academy of Sciences (CAS), Beijing 100049, China
\textsuperscript{2} Dongguan Institute of Neutron Science, Dongguan 523803, China

Corresponding Author: W. Chen, e-mail address: chenwd@ihep.ac.cn

The China Spallation Neutron Source (CSNS) aims to upgrade beam power to 500kW in the future, which requires a beam current of more than 50mA. To achieve the higher beam current, an RF H\textsuperscript{−} source is developed in CSNS, which starts to commission in the beginning of 2019. The ion source has a cylindric discharge chamber with an inner diameter of 67mm, length of 140mm, which is wound by an external 4.5-turns antenna. To minimize the reflection of the RF power, a matching network was developed. To study the feature of the plasma, the impedance was measured with the aid of the matching circuit. The influence of gas flow rate, frequency shift, RF power to the impedance was studied.
A comparison of SNS internal and external antenna sources operation with and without caesium

Tiago Sarmento¹, Sarah Cousineau¹, Dan Faircloth², Baoxi Han¹, Scott Lawrie², Syd Murray¹, Terry Pennisi¹, Tiago Sarmento³, Chris Stinson¹, Martin Stockli¹, Olli Tarvainen⁴, Robert Welton¹

¹Oak Ridge National Laboratory
²UKRI
³Isis Neutron and Muon Source
⁴STFC Rutherford Appleton Laboratory

Corresponding Author: Tiago Sarmento, e-mail address: tiago.sarmento@stfc.ac.uk

Experiments comparing the internal and external antenna H⁺ sources at the Spallation Neutron source (SNS) with and without caesium revealed key performance differences which provide insight to the source physics and will guide the development of an RF H⁺ source at ISIS Neutron source. RF power sweeps were taken for each of these cases, for which the total charge, electron to H⁺ ratio, and H⁺ extracted per kW, are all studied and plotted. At 40 kW and typical Hydrogen flow and cooling parameters, caesiated sources output ~35 mA square beam pulses where uncaesiated sources output ~15 mA. At these settings, the beam pulse for the internal source initially spikes while the external source rises slowly. This observation discussed with the difference in coupling between antenna and plasma in mind. Sweeps of RF pulse repetition rate and collar temperature only affected caesiated sources, which is attributed to surface processes affecting the H⁺ production only in the presence of caesium. Possible improvements by modifying the gas flow into the external source's plasma gun and by removal of the collar assembly in uncaesiated operation are discussed.
The standard 1X ISIS Negative Penning Surface Plasma Source (SPS) has reliably produced an H– beam for ISIS operations for 35 years. In order to meet the 60 mA, 2 ms, 50 Hz beam current and duty cycle required for the Front End Test Stand (FETS) [REF] a 2X scaled source has been developed [REF]. The 2X source has a plasma chamber twice the linear dimensions of the 1X source. This paper investigates the comparison between different emission areas (plasma electrode aperture dimensions) for both the 1X and 2X sources. Slit and circular extraction schemes are studied. Beam currents, current densities and emittances are compared along with perveance sweeps.

References and Acknowledgment
Extending the Pulse Length of the ISIS H⁻ Penning Ion Source

Olli Tarvainen¹, Rob Abel¹, Scott Lawrie¹, Dan Faircloth¹, Tiago Sarmento¹, John Macgregor¹, Chris Cahill¹, Mark Whitehead¹, Trevor Wood¹ and Nicolas Savard²

¹STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX UK
²D-Pace Inc., P.O. Box 201, Nelson, BC, Canada, V1L5P9

Corresponding Author: Olli Tarvainen, e-mail address: olli.tarvainen@stfc.ac.uk

The ISIS Penning ion source is a caesiated pulsed DC discharge surface plasma source routinely delivering 55 mA beam of negative hydrogen ions (H⁻) in 250 µs pulses for neutron and muon physics at 50 Hz pulse repetition rate at the Rutherford Appleton Laboratory (RAL). Meeting the 60 mA, 2 ms, 50 Hz specifications of the Front End Test Stand (FETS) [1] requires extending the ion source discharge pulse length to 2.2 ms and counteracting the droop of the beam current observed in long pulse operation of the standard source. One approach for this was to increase the size of the discharge volume and extraction aperture as demonstrated by the 2X scaled source [2]. This paper investigates an alternative method of combating the droop when running a standard 1X source at long duty cycles [3]. We summarize recent experiments that have identified the root cause of the ~200 µs discharge breakdown transient forcing to prolong the discharge pulse beyond the required beam current pulse. Engineering solutions applied to suppress the breakdown oscillations are described and their effect on predicted electrode erosion is discussed. Analysis of the erosion mechanisms suggests that eliminating the breakdown oscillations allows extending the beam pulse length without jeopardizing the ion source lifetime. We introduce a physical model attempting to explain the observed droop of the beam current in long pulse operation of the standard source and present the first results obtained with tailoring the temporal profile of the discharge current to achieve flat 55-60 mA H⁻ pulses longer than 1 ms. Finally, the development steps of the ion source and its ancillary equipment needed to demonstrate the FETS requirements including beam transport are outlined.

References and Acknowledgment

To investigate the chiral magnetic effect, $^{96}$Zr and $^{96}$Ru beams were accelerated at the relativistic heavy ion collider (RHIC) during Run 18 at Brookhaven National Laboratory (BNL). $^{96}$Zr and $^{96}$Ru beams were provided from the electron beam ion source (EBIS) injector and tandem Van de Graaff, respectively. At the conference, $^{96}$Zr beam production and acceleration will be reported. The EBIS injector consists of a laser on source, an EBIS high charge state ion breeder, a 300 keV/u RFQ and a 2 MeV/u IH-DTL. The natural abundance of $^{96}$Zr is only 2.8% with about 50% consisting of $^{90}$Zr. To obtain sufficient beam current, Zr material enriched to $^{96}$Zr ~50% was used. Unfortunately, the only available form of the enriched material is oxide powder which is not well suited for a laser ion source target. We have studied and established a sintering technique of ZrO$_2$ powder to make a solid sample which can be installed into the laser ion source. The singly charged Zr and oxygen were produced in a laser ablation plasma, extracted, and delivered to the EBIS to be ionized further to $^{96}$Zr$^{16+}$. We have optimized the laser irradiation condition, the EBIS confinement time, and transport through the RF linacs to maximize the performance of the injector. The detailed R&D works will be discussed.

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Analysis of the Cesium Distribution in the JT-60SA Negative Ion Sources for Steady Long-Pulse Operation

Masafumi Yoshida¹, Wataru Oohara¹, Masahiro Ichikawa², Junichi Hiratsuka², Glynnis Mae Q. Saquilayan², Naotaka Umeda², Atsushi Kojima², and Mieko Kashiwagi²

¹Department of Electrical, Electronic, and Information Engineering, Yamaguchi University, Ube 755-8611, Japan
²National Institutes for Quantum and Radiological Science and Technology, 801-1, Mukouyama, Naka 311-0193, Japan

Corresponding Author: Masafumi Yoshida, e-mail address: yoshidam@yamaguchi-u.ac.jp

To realize a stable negative ion beams for 100 s required in the neutral beam injector (NBI) of JT-60SA, a physics model to control cesium (Cs) distribution inside the negative ion source has been developed in order to maintain stably the negative ion production at the plasma grid (PG) surface with the Cs. In the initial model, time variations of the Cs on the wall and the PG for 100 s were analyzed, where time variations of the temperature at the wall and the PG were referred from the experimental ones, but temperature distributions were assumed to be uniform [2]. This model clarified that the Cs deposited on the chamber wall is excessively desorbed at more than 60 Celsius of the wall temperature and is piled up on the PG, and consequently, degrades the negative ion current. But, the Cs deposited on the PG extremely increased by a factor of ten. To develop more realistic model, a three-dimensional Cs transportation code is newly developed to consider the spatial Cs distribution taking the mechanical structure of the negative ion source into account, and the spatial temperature distribution of the wall are also introduced. As the result, the reasonable variation of Cs coverage during 100 s was obtained. Based on this model, the operational temperature to sustain stable negative ion current are proposed for JT-60SA.

References and Acknowledgment
Study of Gasdynamic ECR Plasma VUV Emission to Optimize Negative Hydrogen Ion Production Efficiency

R.L. Lapin¹, V.A. Skalyga¹,², I. Izotov¹, S.V. Golubev¹, S.V. Razin¹, R.A. Shaposhnikov¹, S.S. Vybin¹, A.F. Bokhanov¹, M.Yu. Kazakov¹ and O. Tarvainen³,⁴

¹Institute of Applied Physics, Russian Academy of Sciences, 603950 Nizhny Novgorod, Russia
²Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, 603155, Russia
³STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX
⁴University of Jyväskylä, Department of Physics, FI-40014 Jyväskylä, Finland

Corresponding Author: Roman L. Lapin, e-mail address: lapin@ipfran.ru

Negative hydrogen ion sources are widely used in high-energy physics studies as injectors into accelerators and as a part of neutral beam plasma heating systems in thermonuclear fusion experimental research. The majority of processes in low-temperature hydrogen plasma, such as dissociation via repulsive excited states and molecular de-excitation populating high vibrational levels of the ground state molecules, are accompanied by emission of electromagnetic radiation in vacuum ultraviolet (VUV) range. Studying of the VUV radiation is a well-known diagnostic tool providing plasma-chemical processes rates and plasma parameters to make it possible to optimize them to increase negative hydrogen ion current. We report experimental studies on negative hydrogen ion production in a high-density gasdynamic ECR discharge plasma, the results of VUV emission measurements and optimization of negative hydrogen beam current. Experiments were performed with a high density plasma sustained by a pulsed 37 GHz / 100 kW gyrotron radiation in a two-stage magnetic system, consisting of two identical simple mirror traps. The first trap was used for the plasma production under ECR condition. Dense hydrogen plasma flux from the first trap flows into the second one through a perforated plate, which prevents the propagation of microwaves into the last trap. The configuration presumably helps to separate plasma volumes with “hot” (50 - 100 eV) electrons confined in the first trap and “cold” (<1 eV) electrons confined in the second one. “Hot” electrons flow to the second trap and excite hydrogen molecules through singlet states B and C to high vibrational states, losing their energy as a result of interaction. These molecules participate in the H⁻ generation process as a result of dissociative “cold” electron attachment. Described approach has already demonstrated a possibility to reach up to 80 mA/cm² of negative ion current density.

Measurement of the absolute VUV-power provides information on the production rate of high vibrational levels of the hydrogen molecules that serve as precursors for the H⁻ production through dissociative electron attachment. We studied the ECR plasma emission in the ranges corresponding to the lines of atomic (122±10 nm - Lyman-alpha line) and molecular emission (160±10 nm - Lyman band, and 180±20 nm - molecular continuum) of hydrogen in both traps. The volumetric emission power was measured in a wide range of parameters with appropriate filters and calibrated diode. A 45 W/cm³ in the range of 110-200 nm was measured (under assumption of uniformly distributed over plasma volume isotropic source of emission) from the second trap under conditions corresponding to the maximum level of extracted negative ion current. Such a high value implies that the electron temperature in the second trap might be too high for the formation of negative ions. Thus, the negative ion production efficiency may be presumably enhanced by further lowering of the electron temperature in the second trap.

Moreover, a volumetric power of 240 W/cm³ was measured from the first trap under conditions of a high hydrogen pressure (close to 1 atm), which demonstrates that gasdynamic ECR discharge in a simple mirror trap can be used as effective highpower VUV emission source.

References and Acknowledgment

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The negative ion source producing 500 keV and 22 A (130 A/m$^2$) beams for 100 s has been developed for the neutral beam injector of JT-60SA. One of critical issues to realize this target is filament breaking by arcing: a localized abnormal discharge between the filament (cathode) and the plasma/the chamber wall (anode). The arcing has limited discharge power and pulse length, consequently, disturb to realize the ion current density of 130 A/m$^2$ for 100 s. As causes of the arcing, impurities like Oxygen [1] and filament positions [2] have been investigated. These could affect the arcing, but it was observed that the arcing remarkably increases if cesium (Cs) is seeded to the ion source to enhance the negative ion production. This indicates that the arcing is triggered by the Cs ion bombardment to the filament. The influence of Cs on the arcing was examined in the test using small KAMABOKO ion source and the three stageaccelerator, which simulate the JT-60SA negative ion source. The Cs is introduced by the Cs oven, and mainly deposits on the metal surfaces, such as the chamber wall and the plasma grid to extract the negative ions. Some of Cs are evaporated from these surfaces and becomes the Cs ions in the plasma. The variation of the Cs amount in the plasma was measured from the Cs light. In this test, the arcing has been started after the Cs seeding. The Cs light is initially increased with the seeded Cs amount, but finally saturated even if the Cs is additionally seeded. Since the Cs evaporated from the metal surfaces becomes constant, it is considered that the arcing cannot be suppressed due to the position and the shape of the filaments. To reduce damage on filaments due to the arcing, fast cutoff the arc power supply (P/S) is considered to be effective. In the original system, arcing detection was performed in the control room and the signal to cutoff the arc P/S was sent to the arc P/S. The total duration to the cutoff was 1 ms. The total energy to the filament was 10.6 J. To reduce this energy, FPGA (Field Programmable Gate Array) was installed at the P/S side on the 500 kV stage, which can detect arcing and send the cutoff signal of the arc P/S. The total duration is shorten to 0.1 ms. The total energy is reduced to 0.4 J. As the result, the filament lifetime is expanded to three times longer even if sufficient input power to produce 130 A/m$^2$ is injected. To operate this system stably at the 500 keV stage, the surge absorber consisting of registers and capacitors was introduced in the new system using FPGA. Finally, this system realizes the stable long pulse operation, and contributes to demonstrate 500 keV, 154 A/m$^2$ beam for 118 s, which fulfills the requirement.

References and Acknowledgment
Large scale negative ion sources are one of the key components for the Neutral Beam Injection (NBI) systems being presently applied at the Large Helical Device (LHD) and under development for ITER. In these sources, negative hydrogen ions are produced by surface conversion on caesiated surface of the Plasma Grid (PG, the first grid of the beam extraction system). The NBI system that is in routine operation at LHD is based on filament-driven negative ion sources. A Research and development Negative Ion Source (NIFS-RNIS) on test stand at NIFS (NIFS-NBTS) is used for further source performance improvement of the filament-driven LHD-NBI type source based on physics understanding. In contrast, the ITER NBI is based on RF driven negative ion sources. The test facility ELISE, in operation at IPP, uses a 1/2 ITER size RF-driven source. The ELISE contributes to the R&D program towards the sources for ITER NBI by demonstrating the size scalability from the 1/8 prototype source towards the full size source and the demonstration of the fulfillment of the required ITER parameters for pulses of up to 1 h. The test facility for the full-size ITER source (SPIDER, hosted at Consorzio RFX Padova, Italy) started operation in summer 2018, first caesiation is foreseen in 2020.

Understanding the H\(^-\) dynamics from their production on the PG, transport in the plasma and extraction is inevitably required for further improving these sources. Of particular interest is to identify and understand differences in these physical effects between filament-driven and RF-driven sources. In 2018, a Cavity Ring-Down Spectroscopy (CRDS) system for negative hydrogen/deuterium ion density measurement consisting of two lines of sight (LOS) was successfully installed at ELISE as part of the international collaboration between the NIFS and the IPP. The axial distance from the PG surface of the LOS used in ELISE is 2 cm; this distance is also accessible by the movable CRDS in the NIFS-RNIS [1]. This work will compare absolute values and the dependences of the negative ion density in the NIFS-RNIS on discharge parameters, such as discharge power, gas pressure, gas species (hydrogen and deuterium), bias voltage and beam extraction voltage, with those in the ELISE ion source for short pulses.

References and Acknowledgment


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A Study of the Optical Effect of Plasma Sheath in a Negative Ion Source Using IBSimu Code

Anand George\textsuperscript{1,3}, Taneli Kalvas\textsuperscript{2}, Stephane Melanson\textsuperscript{1}, Dave Potkins\textsuperscript{1}, Morgan Dehnel\textsuperscript{1} and Neil Broderick\textsuperscript{3}

\textsuperscript{1}D-Pace, P O Box 201, Nelson, BC, Canada
\textsuperscript{2}Department of Physics, University of Jyväskylä, Finland
\textsuperscript{3}Department of Physics, University of Auckland, New Zealand

Corresponding Author: Anand George, e-mail address: a.george@auckland.ac.nz

Plasma sheath inside an ion source has a strong focusing effect in the formation of an ion beam from the plasma. The most accessible experimental variable dependent on the plasma sheath is the beam emittance. Variation of beam emittance is a reflection of the properties of plasma sheath, with minimum emittance for the optimal shape of the plasma sheath. Location and shape of the plasma sheath is governed by complex physics and can be understood by simulations using plasma models in particle tracking codes like IBSimu\textsuperscript{[1]}. In the current study, a model of the plasma and extraction of D-Pace’s TRIUMF licensed filament powered volume-cusp negative ion source is made using IBSimu code by matching the beam emittance between experiments and simulations. Dependence of beam emittance optimum on the electron to ion ratio, gas pressure and electric field are determined experimentally and behaviour of the plasma sheath is determined using IBSimu simulations.

References and Acknowledgment

A negative oxygen ion source is under development to produce $\text{O}^-$ and $\text{O}_2^-$ beams used for secondary ion mass spectrometer at IMP, and both filament-driven and RF-driven schemes were tested. The filament driven ion source has a 10-pole multicusp plasma chamber, two sets of virtual magnetic filter and a 3-electrode extraction system. The RF ion source, which is improved by changing a RF back plate from the filament ion source, has an external planar spiral RF antenna behind an AlN window. The RF power system consists of a CW 13.56 MHz/2 kW power supply, a capacitive auto-matching network and a water-cooled flat RF antenna made from 6 mm copper tube. Oxygen and carbon dioxide gases were used for production of negative oxygen ion beams in both two plans, and more than 1 mA ion beam was extracted with energy 20 keV. However, filament ion source could not operate stably while the RF one could work with no maintenance for a long lifetime, and a direct comparison will be given on negative oxygen ion production with two different technologies using our ion source test facility.
Optical emission spectroscopy for CSNS negative ion source

Shengjin Liu, Huafu Ouyang, Hui Li, Yongchuan Xiao, Xiucia Cao, Yongjia Lv, Kangjia Xue, Weidong Chen
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 730000, China
Corresponding Author: shengjin Liu, e-mail address: liusj@ihep.ac.cn

The formation of negative ions in plasma sources by the surface process requires covering the discharge electrode surface with a material of low work function. Usually, this can be achieved by cesium evaporation. However, the increase of Cs amount will erode discharge electrodes drastically and short the lifetime of ion source. For CSNS negative ion source, the 40mA H- can be produced with 25Hz and 600us. The higher current intensity will be required for the CSNS II. To understand the dynamical mechanism of the plasma discharge and the Cs effect, the diagnostic tool of optical emission spectroscopy (OES) is thus applied to CSNS penning surface negative ion source. Suitable diagnostic lines including Cs lines and H Balmer lines are obtained. The DC and AC discharges procedures of CSNS ion source are diagnosed using OES. At pulse discharge, Cs lines and H lines are investigated by changing arc current, penning magnetic field and H2 flux. Furthermore, the ratio of Cs852 line and H lines are studied. These diagnostic results are discussed.
We have been developing a high current filament-driven direct current (DC) negative hydrogen ion source required for boron neutron capture therapy (BNCT) and radioisotope (RI) production. In order to perform the cesium (Cs) seeding efficiently compared with our conventional ion source, we carried out the following improvements. The position of the Cs injection port was changed from near the filaments to near the plasma electrode, in order to increase the probability of the presence of Cs near the plasma electrode. The material of the plasma chamber and the back plate was changed from copper to nonmagnetic stainless steel. That can maintain the surface temperature of the plasma chamber above the Cs freezing point, and the stainless is less expensive than copper and has good workability. Cooling water of the plasma chamber was flowed spirally from the plasma electrode side to the back plate side to make a temperature gradient in the chamber. The structure of the permanent magnet forming the multicusp magnetic field and the filter magnetic field was changed to a half split structure in order to facilitate the exchange of the magnet. The permanent magnet material was changed from the conventional samarium cobalt magnet to the neodymium magnet.

In this paper, we reported the results of the Cs-free operation of the newly developed ion source.

References and Acknowledgment
Spatial Distribution of Negative Ion Density near the Plasma Grid

Shingo Masaki¹, Haruhisa Nakano², Masashi Kisaki¹,², Kenichi Nagaoka³, Katsunori Ikeda², Masaki Osakabe¹,² and Katsuyoshi Tsumori¹,²

¹SOKENDAI (The Graduate University for Advanced Studies), Toki, Gifu 509-5292, Japan
²National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
³Graduate School of Science, Nagoya University, Nagoya, Aichi 464-8603, Japan

Corresponding Author: Shingo Masaki, e-mail address: Masaki.shingo@nifs.ac.jp

Neutral beam injection (NBI) for heating plasmas and current drive to torus fusion plasmas needs high power beams of either negative hydrogen (H⁻) ions or negative deuterium (D⁻) ions. For the negative ion sources, cesium (Cs) vapour is introduced to increase the negative ion current and to reduce the electron current co-extracted with the negative ions. In Cs-seeded plasma in negative ion sources, estimation using electron saturation current is not available because the density of electrons decreases much less than that of negative ions [1]. The density of negative ions, therefore, should be corrected with aid of other diagnostic methods such as the line-averaged density of negative ions obtained with Cavity Ring-Down (CRD) measurement [2][3].

In this study, spatial distribution of the negative ions was measured with the laser photodetachment method in R&D Negative Ion Source of National Institute for Fusion Science (NIFS-RNIS). A Nd:YAG laser was injected to the H ion source parallel to the plasma grid. An electrostatic probe detected photodetached electron current induced by the laser irradiation corresponding to the local negative ion density. The density of the negative ion has been measured within 230 mm of the distance parallel to the plasma grid. The spatial distribution of the photodetachment current was measured in the hydrogen plasma both with and without Cs seeding. At different distance from the plasma grid, the density of electron changes drastically near the grid, and it might provide the clue to understanding the complicate transport of charged particles in the vicinity of the grid. For this reason, we obtained the one-dimensional distribution of negative ions with different distance from the plasma grid. The distribution profile of the negative ion density can be affected by the magnetic structure combined with filter field and electron deflection filed penetrated inside the extraction region. Near the plasma grid, the distribution peaks at the center of the grid. On the other hand, the distribution becomes flatter at the distance where the strength of the electron deflection field is weaker. In this presentation, the relation between the magnetic structure and negative ion distribution parallel to the plasma grid is discussed.

References and Acknowledgment
The small medical cyclotron developed by the China Institute of Atomic Energy (CIAE) adopts an internal negative hydrogen ion source, which has the advantages of small size, compact structure and easy maintenance. An improved structure of the ion source is proposed and tested, faced with the phenomenon that the vacuum in the center of cyclotron is poor resulting ion sources ignite easily. The experimental results show that the improved ion source can restrain the gas discharge space, reduce the hydrogen injection flow rate and improve the vacuum in the central region. In addition, the relationships between beam intensity and vacuum, hydrogen injection flow rate, extraction voltage, arc power and axial magnetic field are also measured by the experiments.
Experimental Investigation Of The Cs Behavior In The Cesiated H⁻ Ion Source During High Power Long Beam Operation

Glynnis Mae Q. Saquilayan, Junichi Hiratsuka, Masahiro Ichikawa, Naotaka Umeda, Kazuhiro Watanabe, Hiroyuki Tobari and Mieko Kashiwagi
National Institutes for Quantum and Radiological Science and Engineering (QST), Naka 311-0193, Japan
Corresponding Author: Glynnis Mae Q. Saquilayan, e-mail address: mae.glynnis@qst.go.jp

The stable operation of high-power negative ion beams is required for neutral beam injector (NBI) systems of fusion reactors. In the MeV test facility (MTF) in QST, high current negative ion beams for NBI’s are being developed using cesium (Cs) to reduce the work function at the plasma grid (PG) surface to enhance the production of negative ions through electron transfer. In previous experiments, the optimal layer of the adsorbed Cs has been realized by controlling the temperature of the PG surface. However, it was observed in the test of the negative ion production up to 100 s that the negative ion current degraded when the Cs in the plasma volume excessively increases and influences to the condition of the PG surface [1]. Even with short pulses of 100 keV H⁻ beams [2], the backstream ions produced in the accelerator impinges on the chamber walls and liberating the adsorbed Cs in to the plasma as well. In addition, the increasing amount of Cs in the plasma will cause Cs leakage to the downstream region and affect the voltage holding in the extraction and accelerator grids. Although cesium is essential to the production of negative ions, this adds to the complexity in realizing the stable high energy and high current negative ion beam for the NBI systems. This study attempts to understand the behavior of Cs in the test which produces the H⁻ negative ion beams having energies of 0.5 MeV with the current density of 150 A/m² for 100 s.

In this test, the plasma chamber to produce the negative ions was installed on the top of the three-stage accelerator. The temperature on the chamber walls was kept below 60 °C by enhancement of the cooling capability for suppressing the evaporation of the deposited Cs on the wall surfaces and penetration to the plasma. The Cs D2 emission line in the plasma volume was monitored during the long duration of beam operation. In the test period of 30 days, the Cs was introduced around 0.1 g in a day. In one pulse during a few tens of seconds, the Cs D2 line intensity increased rapidly in the beginning of the discharge and saturated at around 10 seconds. The back streaming positive ions did not cause any significant changes in the Cs D2 line emission. This saturation level of the Cs D2 line slightly varied day by day, but did not corresponded to the total Cs amount introduced to the chamber. This result suggests that the Cs flux from the chamber walls during discharge is constant even when the total Cs amount and also including the Cs deposition on surfaces continuously increased. For the period of the campaign, the generated H⁻ negative ion beam exhibited a stable ion beam current. The experimental result shows that the performance of the negative ion source has stable operation when the amount of Cs neutrals in the plasma is properly controlled.

References and Acknowledgment
In order to better realize the pre-research and optimization of the key technologies of the RF negative ion source for CFETR (China Fusion Experimental Test Reactor), which is the next-generation nuclear fusion device of China, a prototype CFETR negative ion based neutral beam injection system is under design and will be developed at Institute of Plasma Physics, Chinese Academy of Science (ASIPP) in the next five years. Furthermore, it requires a neutral beam injector to provide a stable beam of high energy with large current, which means that the negative ion source operates at high power with large extraction dimension. The magnetic filter field in front of the extraction system plays an important role in transporting negative hydrogen ions to the extraction area and inhibiting co-extraction of electrons. High-speed electrons undergo a Larmor cyclotron effect as they pass through the filter field, with the collision loses energy, so the electron temperature is thus lowered. For the large source, the filter field is better to be generated by the current flowing through the plasma grid. However, the optimal design scheme for the filter field has not yet been determined. Therefore, an attempt was made to design a filter field by a mode in which the PG current and the iron core coil cooperate, the current in PG and coil can be adjusted at any time to change the magnetic field, thereby facilitating a more reasonable configuration. The final design provides a more uniform magnetic field in the region within 100 mm above the plasma grid, while the field strength is around 5 mT and the integral Bdl quantity is greater than 1.2 mTm. The field uniformity at the center in front of the extraction area and the gradient distribution in the perpendicular plasma grid direction are fully compared, which will provide a reference for future improvements in design.
Withdrawn
Development and Installation of a combined RFQ Cooler with axial Magnetic Field


1 INFN-Laboratori Nazionali di Legnaro, Legnaro 35020, Italy
2 Univ. Milano, Dip. Fisica and INFN-MI, Milano 20100, Italy

Corresponding Author: M. Cavenago, e-mail address: cavenago@lnl.infn.it

For the accurate mass spectrometry (with resolution goal 1:20000) of exotic ion beams it is necessary to cool ions both in energy spread (goal is about 0.5 eVrms or better) and in transverse oscillations. In the radiofrequency (rf) quadrupole cooler (RFQC) this is accomplished by collisions with a light gas, while ions are trapped and transported by rf and static voltages applied to RFQC electrodes. The actual performance depends on a fine balance between cooling and heating effects (due to collisions and rf field) and on the ion extraction process, which needs a complicate theoretical, numerical and experimental investigation. To this aim, a prototype RFQC was developed at INFN-LNL and INFN-MI with a ten-fold electrode longitudinal segmentation and an optional axial magnetic field to improve confinement at reduced rf voltage. The RFQC installation (in the Eltrap context) is almost complete. The test Cs⁺ ion source and a movable pepperpot emittance meter have been calibrated in a test bench assembly. The electrostatic transport line, the differential pumping system and the RFQC enclosure (which is needed to regulate and maintain a He gas pressure up to 4 Pa), the rf matching box have been built and the in-vacuum multiplexer (for the distribution of rf and static voltages to the electrodes) is in the assembly stage. Simulations including Cs⁺/He differential cross sections and electrode geometry are well in progress. Other important issues are related to the challenging accuracy (sub-eV) of the output energy measurement: stability of bias Vd between RFQC and source must be in the order of 0.1 V; Vd should be scanned to simulate effects of a hot ion source; finally, a device like a Retarding Field Energy Analyzer with similar accuracy [1] must be used and adapted, which also requires time consuming simulations. To this aim, another Faraday cup with retarding field and grids is under construction.

References
Charge State Breeding of Rare Isotopes with ECRIS and EBIS at TRIUMF

F. Ames¹, J. Adegun¹, R. Baartman¹, M. Blessenohl², M. Cavenaile¹, C. Charles¹, S. Dobrodey², J. R. Crespo López-Urrutia², L. Graham¹, K. Jayamanna¹, R. Kanungo³, O. Kester¹, M. Marchetto¹, S. Saminathan¹, B. Schultz¹

¹TRIUMF, Vancouver BC, Canada
²Max Planck Institute for Nuclear Physics, Heidelberg, Germany
³Saint Mary’s University, Halifax NS, Canada
⁴University of Victoria, Victoria BC, Canada

Corresponding Author: F. Ames, e-mail address: ames@triumf.ca

Charge state breeding is essential for the efficient acceleration of radioactive isotopes at ISOL facilities like ISAC at TRIUMF. The radioactive ion beams (RIB) are produced by bombarding solid targets with high energy particles. They diffuse out of the target into an ion source which produces mainly singly or low charged ions. At TRIUMF 480 MeV protons are presently used at the ISAC facility. A new target station using gamma rays from the Bremsstrahlung of a high intensity electron beam at 30 MeV is being constructed for the ARIEL facility. A 14.5 GHz ECRIS has been put into operation several years ago for the charge state breeding at ISAC. It has been used for isotopes up to 160Er with efficiencies up to several percent. Improvements, mainly to reduce background from stable components of the plasma have been implemented. At present 2 frequency heating is being investigated to increase the efficiency and stability. Mainly to reduce background and to improve efficiency a new system based on an EBIS is presently being commissioned. The EBIS has been designed and built at the Max Plank Institute for Nuclear Physics at Heidelberg and installed at TRIUMF. It uses a 6 T magnet and an electron beam current up to 1A. This will allow a breeding time of less than 10 ms to reach the desired charge states (A/Q≤7) for elements up to uranium and thus minimize losses due to the radioactive decay of the isotopes. The system will operate in a pulsed mode with a pulse repetition frequency of 100 Hz. Bunching of the ion beam in front of the EBIS is done by a gas filled radio frequency quadrupole. Operational experiences with the ECRIS and first commissioning results with the EBIS will be presented.
Development of Prototype RF system for RFQ Cooler Buncher of RISP

Seongjin Heo\textsuperscript{1,2}, Ramzi Boussaid\textsuperscript{1}, Taeksu Shin\textsuperscript{1,2}, Young-Ho Park\textsuperscript{1,2}, Hyock-Jun Son\textsuperscript{1}, Jun-Young Moon\textsuperscript{1}, Eun-San Kim\textsuperscript{2}, Jungbae Bahng\textsuperscript{2}

\textsuperscript{1}Rare Isotope Science Project, Institute for Basic Science, Daejeon 34000, Rep. of Korea
\textsuperscript{2}Department of Accelerator Science, Korea University, Sejong 30019, Rep. of Korea

Corresponding Author: Eun-San Kim, e-mail address: eskim1@korea.ac.kr

The radioactive ion beams produced from the Isotope Separation On-Line (ISOL) of RAON are to be delivered with a beam emittance around $3\pi\,\text{mm}\,\text{mrad}$, an energy spread $< 10\,\text{eV}$, and a short beam bunch width around 10 $\mu\text{sec}$ for the requirement of Electron Beam Ion Source (EBIS) charge breeder. A Radio Frequency Quadruple Cooler Buncher (RFQ-CB) will be used to meet the beam quality requirements mentioned above. In the RFQ-CB, the radial confinement force to the beam is produced by RF voltages of RFQ electrodes, and the axial force is by the DC voltages distributed along the segment electrodes. The trapped ions are cooled by collisions with the helium buffer gas. By the simulation using SIMION code, we were able to get various parameters such as the buffer gas pressures at the different sections, the required RF and DC voltages, and the resulting beam emittance and energy spread, etc. In order to obtain a bunching capacity of $10^8$ ions/bunch for various ion species, we tried to build a RF system with a maximum RF amplitude of $\sim 7\,\text{kV}$ and a frequency range of 1–10 MHz. The prototype RF system with a helical resonator, high voltage probes, and a 100-W high power RF amplifier was designed and tested. In this presentation, the test results of the prototype RF system will be described.

References and Acknowledgment

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Development of the reflection time of flight mass spectrometer for EBIS charge breeder

Liu Hao-lin\textsuperscript{1,2}, Hyock-Jun Son\textsuperscript{1}, Taeksu Shin\textsuperscript{1,2}, Young-Ho Park\textsuperscript{1,2}, Jongwon Kim\textsuperscript{1}, Eun-San Kim\textsuperscript{2}

\textsuperscript{1}Rare Isotope Science Project, Institute for Basic Science, Daejeon 34126, Rep. of Korea
\textsuperscript{2}Department of Accelerator Science, Korea University, Sejong 30019, Rep. of Korea

Corresponding Author: Eun-San Kim, e-mail address: eskim1@korea.ac.kr

A time-of-flight mass spectrometer (TOFMS) has been developed to analyze the mass to charge ratio of the generated ion beams by the EBIS (Electron Beam Ion Source) at the RAON. In order to achieve high transmission rate and mass resolution of 300 with a 20-keV Cs\textsuperscript{1+} ion beam, the TOFMS structure consisting of Bradbury-Nielson gate, steerer, mirror electrode, and MCP detector has been designed by using SIMION code. The double stages reflector was employed to obtain beam chromatic correction from the energy spread of the generated ion beam from the EBIS. Bradbury-Nielson gate is adopted to make a bunch beam with a 5-ns pulse width at the front end of the TOF system. The performance test has been conducted with the fabricated TOFMS system using the 20-keV Cs\textsuperscript{1+} ion beam. The detailed progress for the development of the TOFMS system will be presented in this presentation.
Initial component tests of the EBIS charge breeder system for the Rare Isotope Science Project

Hyock-Jun Son¹, Young-Ho Park¹,², Taeksu SHIN¹,², Seongjin Heo³, Liu Haolin², and Moses Chung³

¹ Rare Isotope Science Project, Institute for Basic Science, Daejeon 34126, Republic of Korea
² Department of Accelerator Science, Korea University, Sejong 30019, Republic of Korea
³ Department of Physics, Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea

Corresponding Author: Young-Ho Park, e-mail address: yhpark@ibs.re.kr

The RAON is a heavy ion accelerator facility, which is under construction in Korea for the Rare Isotope Science Project (RISP). This facility is designed to apply both In-flight Fragment (IF) and Isotope Separation On-Line (ISOL) techniques in order to produce various Rare Isotope (RI) beams for nuclear physics experiments. An Electron Beam Ion Source (EBIS) will be used for charge breeding of RI beams in the ISOL system. The mass-to-charge ratio (A/Q) of the RI beams after the charge breeding is in between 2 and 6. The RAON EBIS charge breeder system can be divided into 4 sections such as electron gun (e-gun), collector, ion trap, and ion transport section. The RAON EBIS will use a 3-A e-gun and a 6-T superconducting solenoid to increase electron beam current density for large trapping capacity, high breeding efficiency, and short breeding time. The ion trapping capacity of the RAON EBIS is expected to be 2.18 x 10¹¹ charges under the expected conditions of the electron beam and magnetic field configuration. The electron beam will be dumped into the collector which has been designed with a maximum power consumption up to 20 kW.

In our e-gun/collector test bench, an electron beam of 2.5 A has been extracted and collected. There are 10 drift tubes inside the trap chamber, and the ion trap length is about 800 mm. A strict vacuum level of 10⁻¹¹ torr range is required in this region. The pumping system consists of two TMPs, two cryo-pumps, and NEG ZAO modules. A vacuum test of the ion trap section has been performed with baking, and the vacuum level reached 2.1 x 10⁻¹¹ torr. For the ion transport line system, we have designed 5 sets of electrostatic ion beam optics to inject and extract the ion beams of different charge states. The manufacturing of the ion transport line system is nearly finished. Cs ions will be utilized for off-line commissioning of the RAON EBIS. The RAON EBIS requires five different high-voltage platforms and control hardware. Electrical and control systems were designed accordingly. In this paper, current development status and initial component test results of the RAON EBIS charge breeder will be presented in detail.

References and Acknowledgment

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Thermal-Electric Numerical Simulations of a Hot Plasma Ion Source for the Production of Radioactive Ion Beams

Maher Cheikh Mhamed, Ailin Zhang

Institut de Physique Nucléaire, CNRS-IN2P3, Université Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France
Corresponding Author: Maher Cheikh Mhamed, e-mail address: cheikh@ipno.in2p3.fr

Ion source and target system is the heart of every Isotope Separation On Line (ISOL) facility. For an efficient release of radioactive nuclei’s, targets are heated up to 2000°C – 2100°C. FEBIAD (Forced Electron Beam Induced Arc discharge) ion sources are widely used in such radioactive ion beam facilities (ISOL facilities) and operate at very high temperature level around 2000°C. A new FEBIAD type ion source IRENA3 was developed at ALTO facility based on a cylindrical thermionic cathode system for electron impact ionization. The study of the thermal behavior and the optimization of the thermal scheme of such ion source coupled to its thick target is a key point to assure a stable and efficient operating mode. A hybrid heating solution of the cathode system, using direct and indirect heating will be presented. Electrical, thermal and structural numerical model results will be presented and discussed.

Acknowledgment
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Self-Consistent Electromagnetic Analysis of the Microwave-coupling of an ECR-based Charge Breeder

C.S. Gallo\textsuperscript{1}, A. Galatà\textsuperscript{1}, G. Torrisi\textsuperscript{2}, D. Mascali\textsuperscript{2}  
\textsuperscript{1}INFN-Laboratori Nazionali di Legnaro, Legnaro, Padova, Italy  
\textsuperscript{2}INFN-Laboratori Nazionali del Sud, Catania, Italy  
Corresponding Author: A. Galatà, e-mail address: alessio.galata@lnl.infn.it

The Electron Cyclotron Resonance (ECR) Charge Breeding (CB) technique consists in transforming the charge state of an input beam from 1+ to n+, to allow post-acceleration. The optimization of an ECR-CB requires a deep investigation of ion dynamics and electrons heating, the latter being influenced by the microwave-to-plasma coupling mechanism. In this paper we report the electromagnetic analysis of the microwave-to-plasma coupling of the SPES charge breeder (SPES-CB) plasma chamber, taking into account the presence of the plasma through its dielectric tensor, performed using a self-consistent approach. In particular, the effect of two different frequencies on the plasma-wave interaction will be shown, in terms of electromagnetic properties like plasma-absorbed power, giving numerical evidence of the frequency tuning effect.
Wednesday, September 4
Plasma Diagnostic Tools for ECR Ion Sources – What Can We Learn from These Experiments for the Next Generation Sources

Olli Tarvainen¹,², Taneli Kalvas², Hannu Koivisto², Risto Kronholm², Miha Martinen², Muneer Sakildien¹,³, Ville Toivanen¹, Ivan Izotov⁴, Vadim Skalyga⁴ and Julien Angot⁵

¹STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX11 0QX UK
²University of Jyväskylä, 40500 Jyväskylä, Finland
³Accelerator Department, iThemba LABS (Laboratory for Accelerator Based Sciences), PO Box 722, Somerset West 7192, South Africa
⁴Institute of Applied Physics, RAS, 46 Ul’yanova st., 603950 Nizhny Novgorod, Russian Federation
⁵Université Grenoble-Alpes, CNRS-IN2P3, Grenoble Institute of Engineering (INP), LPSC, 38000 Grenoble, France

Corresponding Author: Olli Tarvainen, e-mail address: olli.tarvainen@stfc.ac.uk

The performance of Electron Cyclotron Resonance Ion Sources (ECRIS), producing high charge state ions from a great variety of elements, has improved dramatically over the past decades, thus enabling significant advances in accelerator-based nuclear physics. The order-of-magnitude performance leaps of ECR ion sources result from improvements to the magnetic plasma confinement, increases in the microwave heating frequency and techniques to stabilize the plasma at high densities. Parallel to the technical development of the ion sources themselves significant effort has been directed into development of their plasma diagnostic tools. We review recent results of ECRIS plasma diagnostics including e.g. wall and plasma bremsstrahlung, optical emission spectroscopy, measurement of the electron energy distribution as well as various time-resolved measurements on conventional and charge breeder ion sources yielding information on ion confinement and production times. Particular attention will be given to techniques used for studying plasma instabilities. The plasma diagnostics experiments and their results are compared to those obtained with fusion mirror machines, being direct ancestors of modern ECR ion sources. The data obtained mostly with the second-generation ECR ion sources operating at frequencies from 10 to 18 GHz are assessed to answer questions such as: “What can we learn from these experiments for the next generation sources?”, and “Which plasma diagnostics experiments should be carried out with the high-performance 3rd generation sources operating at frequencies higher than 20 GHz to pave the way for the next generation sources?”. Finally, we present a conceptual design of a permanent magnet ion source with quadrupole magnetic field topology and describe how this device could be used for validating certain trends emerging from the plasma diagnostics experiments with conventional minimum-B sources and how this information could open the door for source designs based on higher frequencies and stronger magnetic fields.
ECRIS Plasma Spectroscopy with a High Resolution Spectrometer

Risto Kronholm¹, Taneli Kalvas¹, Hannu Koivisto¹, Sami Kosonen¹, Miha Marttinen¹, Derek Neben², Muneer Sakildien³ and Ville Toivanen¹

¹University of Jyväskylä, 40500 Jyväskylä, Finland
²National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, USA
³iThemba LABS, P.O. Box 722, Somerset West, 7131, South Africa
⁴UK Research and Innovation, STFC Rutherford Appleton Laboratory, Chilton, OX11 0QX, United Kingdom

Corresponding Author: Risto Kronholm, e-mail address: risto.j.kronholm@jyu.fi

Electron cyclotron resonance ion source (ECRIS) plasmas contain high-energy electrons and highly charged ions. This kind of plasmas are very sensitive to outside disturbance, which means that only non-invasive methods are reliable in their characterization. One of the spearheads of the JYFL ion source group has been to utilize the spontaneous de-excitation of electronic states of atoms, ions and molecules for diagnostics. This enables studying multiple plasma parameters non-invasively through optical emission spectroscopy (OES) of weak emission lines characteristic to ECRIS plasmas. A high-resolution spectrometer (10 pm FWHM at 632 nm) coupled with a lock-in data acquisition setup has been developed at JYFL specifically for this purpose. Densities of ions, neutral atoms and the temperature of the cold electron population play a major role in determining the different reaction rates such as ionization of neutrals and low charge state ions, excitation to radiative and metastable states, and charge exchange. Methods to study these plasma parameters with high resolution OES and results from measurements with the JYFL 14 GHz ECRIS will be presented. The temperature of the cold electron population can be studied using a line-ratio method. For example, it has been observed that the cold electron temperature drops from 40 eV to 20 eV when the extraction voltage of the ion source is switched off, accompanied by almost two orders of magnitude decrease in Ar⁹⁺ optical emission intensity [1]. This suggests that diagnostics results of ECRIS plasmas obtained without the extraction voltage are not depicting the plasma conditions during normal ECRIS operation. The relative changes of both the plasma optical emission and the ion beam current have been measured in CW and amplitude modulation (AM) operation mode of microwave injection. It is concluded that in the normal CW operation mode the ion currents could be limited by diffusion transport and electrostatic confinement of the ions rather than beam formation in the extraction region and subsequent transport [2]. The study also revealed discrepancies between the parametric dependencies of high charge state ion densities in the core plasma and their extracted beam currents. The high resolution of the spectrometer also allows to study the ion temperature by measuring the Doppler broadening of the emission lines after subtracting the wavelength dependent instrumental broadening. The measured ion temperatures in the JYFL 14 GHz ECRIS are between 5–28 eV, depending on the plasma species and charge state [3]. These values are significantly higher than has been generally accepted for ECR plasmas. The effect of gas mixing on the measured ion temperature will be presented when oxygen is injected to pure argon plasma. It was found that 1+ ions reach temperatures on the order of 10 eV, which cannot be explained by ion heating via electron drag and therefore other possible heating mechanisms will be discussed. Finally, future plans to upgrade the spectroscopic setup to enable time-resolved measurements of the optical emission line broadening with millisecond resolution will be presented and the prospects of such experiments discussed

References and Acknowledgment

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Low energy highly charged ion beam production and the future opportunities for 
HCl physics at IMP

Yao Yang1, Liangting Sun1,2, Hongwei Zhao1,2
1Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
2University of Chinese Academy of Sciences, Beijing 100049, China
Corresponding Author: Yao Yang, e-mail address: yangyao@impcas.ac.cn

LEAF is a user facility, designed to produce and accelerate heavy ions, from H2 to U with M/Q between 2 and 7, to the energy of 0.5 MeV/u. The facility is mainly composed by a 45 GHz ECR ion source FECR, a 300 kV high voltage platform, a high intensity low energy beam transport line, a CW 81.25 MHz 4-vane radio frequency quadrupole (RFQ), and a medium energy beam transport line and several experimental terminals. This paper will report on the status of LEAF at IMP that will provide new opportunities for highly charged ion physics.
Well-controlled emittance of the metallic ion beam extracted from the 28-GHz Superconducting ECR ion source adapting the superconducting acceleration cavity for new super heavy elements research

Takashi Nagatomo, Yoshihide Higurashi, Jun-ichi Ohnishi, Akito UCHIYAMA, Masaki Fujimaki, Keiko Kumagai, Nobuhisa Fukunishi, Naruhiko Sakamoto, takahide Nakagawa, Osamu Kamigaito

Nishina center for Accelerator based science, RIKEN, Hirosawa 2-1, Wako, Saitama 351-0198, Japan

Corresponding Author: Takashi Nagatomo, e-mail address: nagatomo@riken.jp

To increase the intensity of heavy-ion beams such as V and Cr for synthesizing new super heavy elements (SHE) with $Z \geq 119$, we started to upgrade RIKEN Linear Accelerator (RILAC) as well as its electron-cyclotron resonance ion source (ECRIS) in 2017. The new ECRIS consists of a high temperature oven as a metal vaporizer and fully SC magnets, and is designed to produce the several hundred µA class metal-ion beams using 18-GHz and 28-GHz microwave heating.

We successfully extracted very stable V13+ beams of ~150 µA (more than 10 particle µA) with the 1-kW microwaves during 10-days commissioning period this June. RILAC is upgraded by adding superconducting (SC) rf cavities. Beam losses in the cold section, not only in the SC cavities but also in the beam pipes neighboring them, give serious contamination on the surface of the cavities. Then, it drastically decreases the acceleration voltage. Thus, the high-intensity beam with well-controlled emittance is required for this SHE project. To meet the requirement, we installed a slit triplet around a double focal point of the low energy beam transport (LEBT) to limit the transverse emittance of the ion beam with monitoring the emittance using several pepper-pot emittance meters. In addition, using the pepper-pot emittance meter, we can estimate the transverse 4-D phase-space distribution of the ion beam at the extraction of the ECRIS by the reversed beam tracking, and the 4-D distribution may give us information of the ionization process in the ECR plasma.

In this contribution, we report the recent results of the commissioning of the LEBT, and discuss the possibility to reduce the beam emittance according to ionization process estimated from the 4-D distribution by adjustment the mirror field, positions of the oven, the microwaves and the supporting gas inlets.
Feasibility study of a compact heavy ion source for investigation of laboratory magnetospheric plasma

Kaori Nakamura1, Masaki Nishiura1, Masahiro Okamura2, Takeshi Kanesue2, Shunsuke Ikeda2
1The University of Tokyo
2Brookhaven National Laboratory
Corresponding Author: Kaori Nakamura, e-mail address: nakamura.kaori17@ae.k.u-tokyo.ac.jp

We are developing a laser ion source to deliver a probe beam to investigate a plasma trapped by a dipole magnetic field. The Ring Trap 1 (RT-1) device at the University of Tokyo in which magnetically levitated superconducting coil produces dipole magnetic fields imitates magnetospheric plasmas in planets[1]. In the planetary magnetosphere, it has been reported that high energy particles and high beta plasma exist stably due to self-organization. By using the plasma created by RT-1, we can experimentally examine magnetospheric plasma. In the previous work on the RT-1, “Up-hill diffusion” was reported, where the plasma spontaneously gathered at high density points against the density gradient, and it was considered to contribute to self-organization[2]. In order to experimentally reveal the physical mechanism further in the magnetospheric plasma, we introduce a probe beam supplied by the laser ion source in the RT-1.

To deliver a good probe beam efficiently, the required characteristics, including selection of the species, charge state, incident direction and its velocity, need to be clarified. Also, mechanical constraint of the laser ion source to be accommodated by the RT-1 is being studied. Currently, we are testing noble gas-based ion beam as the probe particles. At the conference, preliminary design of the ion source system for the RT-1 device will be discussed.

References and Acknowledgment

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For RIKEN radioactive isotope beam factory (RIBF) project, the intense beam of highly charged uranium (U) ion beams was strongly required. Therefore, we tried to increase the beam intensity with 28 GHz RIKEN SC-ECRIS in last decade. For production of stable intense beam, it is obviously important to optimize both the ion source performance and U vapor production. For optimization of the ion source performance, we systematically studied the effect of the magnetic field distributions on the beam intensity of various heavy ions and applied it to produce the intense U beam. To produce U vapor, we chose two methods (sputtering and high temperature oven) and studied the effect of the various parameters (sputtering voltage, rod position, oven power etc) on the beam intensity. In this study, we also observed that the surface condition of the plasma chamber is important to produce intense beam with lower microwave power and lower consumption rate of the materials. Especially, the aluminum chamber plays important role to produce intense beam for long term operation.

Using these results, we produced ~200e\(\mu\)A of U\(^{35+}\), 225e\(\mu\)A of U\(^{33+}\), 300e\(\mu\)A of U\(^{29+}\) at the microwave power of ~2.5 kW (28 GHz + 18 GHz). For long term operation (longer than one month), intense beam of U\(^{35+}\) ions (120~140e\(\mu\)A) was produced for the experiments of RIKEN RIBF project.

To further increase the RI beam, the production of intense beam (more than 300e\(\mu\)A of U\(^{35+}\) ion beam) for long term is demanded. To meet the requirement, we have a plan to improve the oven system and ion source.

In this contribution, I will present the results of the systematic studies and operational experience for production of intense U ion beam with RIKEN 28 GHz SC-ECRIS. The future plan to increase the beam intensity will be also reported.
A New microwave coupling scheme for high intensity highly charged ion beam production by high power 24-28 GHz SECRAL ion source


¹ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
² School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
³ University of Electronic Science and Technology of China, Chengdu 610054, China

Corresponding Author: Junwei Guo, e-mail address: jwguo@impcas.ac.cn

The efficiency of the microwave-plasma coupling is a key issue to enhance the performance of electron cyclotron resonance ion sources (ECRISs) in terms of higher ion beam intensity yield. The coupling properties are affected by the microwave coupling scheme, especially for the high frequency and high power ECR ion sources. Based on the study of 24 GHz SECRAL ion source performances working at different launching systems, a new microwave coupling scheme is proposed in this paper, which can not only realize efficient power matching and feeding, but also effectively adjust the rf power distribution on the ECR surface. Here we describe these experiments and the results improve the understanding the microwave-plasma coupling properties on ECR ion source. Meanwhile, it will also provide a prototype for the development of the next generation ECRIS.
Ultra-high vacuum inside the ion trap volume is crucial for stable and reliable operation of an Electron Beam Ion Source (EBIS). We have developed and tested a compact linear pumping system based on ZAO NEG module with high pumping speed and enhanced sorption capacity for all active gases. Due to its minimal transverse dimensions, the system can be mounted adjacent to the ion trap inside superconducting solenoid bore and will provide pumping speed of the order of 1000 l/s for all active gases in that area. An externally supplied current (100 A DC) is used to heat ZAO NEG up to 650 °C for more than 1 hour, which is required for pump activation and/or reactivation cycles. The pumping system is being developed for use in the Extended EBIS Upgrade which is presently in progress at BNL. Design of the system and results of multiple tests will be presented and discussed in this presentation.

References and Acknowledgment
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First operation in SPIDER and the path to complete MITICA

G. Serianni¹, V. Toigo¹, D. Boilson², C. Rotti¹, T. Bonicelli¹, F. Paolucci¹, A. Chakraborty⁴, M. Kashiwagi⁵, U. Fantz⁶, the NBTF team and the contributing Staff of IO, F4E, IPR, QST, IPP and other laboratories

¹Consorzio RFX, Corso Stati Uniti 4, I-35127 Padova, Italy
²ITER Organization, Route de Vinon sur Verdon, CS 90 046, F-13067 St Paul-lez-Durance, France
³Fusion for Energy, C/ò Josep Pla 2, E-08019 Barcelona, Spain
⁴Institute for Plasma Research, Nr Indira Bridge, Bhat Village, Gandhinagar, Gujarat 382428, India
⁵National Institutes for Quantum and Radiological Science and Technology, 801-1 Mukoyama, Naka, Ibaraki-ken 311-0193, Japan
⁶IPP, Max-Planck-Institut fü r Plasmaphysik, Boltzmannstraße 2, D-85748, Garching bei München, Germany

Corresponding Author: Gianluigi Serianni, e-mail address: gianluigi.serianni@igi.cnr.it

To reach fusion conditions and to control the plasma configuration in ITER, the next step in thermonuclear fusion research, two heating and current-drive neutral beam injectors (NBIs) will supply 17MW each, by accelerating negative hydrogen or deuterium ions to 1MeV. The requirements of ITER NBIs (40A negative H or D ions for 1 hour) have never been simultaneously attained. So in the dedicated Neutral Beam Test Facility (NBTF) at Consorzio RFX (Italy) the performances of the ITER NBI (divergence <7mrad, aiming <2mrad) will be studied and optimised. The NBTF includes two experiments: MITICA, full-scale ITER NBI prototype, and SPIDER, full-scale prototype of the ITER NBI source with 100keV particle energy. SPIDER aim is to investigate source uniformity (over a 1m×2m area), negative ion current density and beam optics; MITICA will address the issues related with the accelerator, including high voltage holding in vacuum.

The present contribution will briefly outline the activities and the experiments carried out in the SPIDER beam source during its first year of operation with volume generation of negative ions. In order to extend the source pressure range and to provide a thorough investigation of the properties of the early SPIDER beams, a mask was installed in the accelerator, leaving only isolated beamlets (for a total number of ~100 beamlets out of 1280). The investigation of the efficiency of RF coupling to the plasma in different configurations of the RF circuits, is presented. During the first extraction of negative particles from the source, the features of the co-extracted electrons were studied and correlated with the plasma parameters. Particularly, the magnetic filter field effectiveness in reducing the co-extracted electron current was verified; correspondingly, the decrease of the plasma emissivity was studied as well as the influence on the negative ion current. Finally the first characterisation of the SPIDER beam, in terms of beamlet divergence and deflection, is proposed and compared with numerical models while varying the source parameters; the negative ion beam exhibits values of current density and optics similar to those expected in volume operation. As for MITICA, installation of the plants is well advanced. High voltage tests of the accelerator power supplies up to 1.2MV started in 2018, by subsequently adding the various components provided by different domestic agencies; these tests should be completed in autumn 2019. The integrated tests of the power supply system, at full power on dummy load, are planned for the first half of 2020. Afterwards, before installing the beam source and the beam line components, the power supplies and the vessel, together with an electrostatic mock-up, will be employed to gain experience on high voltage holding in vacuum, which is one of the main issues to be addressed in MITICA.
Extension of High Power Deuterium Operation of Negative Ion Based Neutral Beam Injector in LHD

Katsunori Ikeda1, Katsuyoshi Tsumori1,2, Kenichi Nagaoka1,3, Haruhisa Nakano1,2, Masashi Kisaki1,2, Yutaka Fujiwara1, Shuji Kamio1, Yasuaki Haba1, Shingo Masaki2 and Masaki Osakabe1,2

1 National Institute for Fusion Science (NIFS), Toki, 509-5292, Japan
2 SOKENDAI (Graduate School for Advanced Studies), Toki 509-5292, Japan
3 Graduate School of Science, Nagoya University, Nagoya 464-8603, Japan

Corresponding Author: Katsunori Ikeda, e-mail address: ikeda.katsunori@lhd.nifs.ac.jp

Deuterium operation of negative ion based neutral beam injector (N-NBI) was initiated in 2017 in the Large Helical Device (LHD). Negative ion sources and their accelerator were optimized for hydrogen operation. The specification of the H– current and the beam energy are 80 A and 180 keV, respectively. Total injection power was 16 MW for hydrogen operation by three beam lines. In the first deuterium beam operation, the D– current of 46.2 A was generated with the averaged current density of 190 A/m² for the electron ion current ratio of \( I_e / I_D^- = 0.39 \) by only changing operation gas using the same accelerator. In the second deuterium beam operation in 2018, the electron and ion current ratio decreases to \( I_e / I_D^- = 0.31 \) using the short extraction gap distance of 7 mm between the plasma grid and the extraction grid. Thermal load on the extraction grid for deuterium operation is as low as that for hydrogen operation. The volume of negative ion rich region between the plasma grid and EDM (electron deflection magnetic) field lobe is considered to be increasing in the vicinity of PG surface. The reduction of the electron current made it possible to operate a high power arc discharge and beam extraction. Then the deuterium negative ion current increases to 55.4 A and the averaged current density of 233 A/m². The injection beam power increases from 2.3 MW to 2.9 MW in one beam line, and the total beam injection power increases from 5.3 MW to 7 MW by three beam lines in the second deuterium campaign.

Lanzhou, China
Formation of Large Negative Deuterium Ion Beams at ELISE

D. Wünderlich, R. Riedl, A. Mimo, U. Fantz, B. Heinemann, W. Kraus, The NNBI-Team
Max-Planck-Institut für Plasmaphysik

Corresponding Author: D. Wünderlich, e-mail address: dirk.wuenderlich@ipp.mpg.de

Negative hydrogen or deuterium ion sources for neutral beam injection in fusion devices are based on the surface production process at caesiated low work function surfaces. The development of the ion source for ITER NBI follows a R&D roadmap defined by the European ITER domestic agency F4E and includes as intermediate step the test facility ELISE. The ion source of ELISE has the same width but only half the height of the ITER NBI source (0.9×1m²).

Aim of ELISE is to demonstrate the ITER requirements in terms of extracted negative hydrogen ion densities (329A/m² for hydrogen, 286A/m² for deuterium) for an pulse length of up to one hour in deuterium (1000s in hydrogen), using pulsed extraction and demonstrating an electron-ion ratio of less than one and deviations from an uniform beam of less than 10%. The experience gained during operation of ELISE is an important input for the commissioning and operation of the Neutral Beam Test Facility PRIMA in Padova and the ITER NBI system itself.

ELISE went into operation in 2013. Since then remarkable progress towards fulfilling the ITER requirements have been made. Recently, series of reproducible long pulses in hydrogen fulfilling the ITER requirement for the accelerated negative ion current have been demonstrated. Determined by IR calorimetry is an almost perfect global beam uniformity, which is degrading slightly (from 100% to 90%) over the length of the pulse. These pulses represent a milestone towards operation of the ITER NBI system during the initial operational phase in hydrogen (up to 2035).

The ongoing experiments at ELISE are mainly focussed on achieving the ITER requirements also in deuterium. The main challenge is to reduce a strong temporal increase of the co-extracted electrons. In parallel to this increase of the electrons, the extracted ions decrease slightly. The physical reasons behind these effects are not fully known up to now. They are much more pronounced in deuterium than in hydrogen and they can drastically restrict the achievable performance and/or the pulse length.

The contribution focusses on long deuterium pulses (up to one hour) at ELISE and on the stabilization of the co-extracted electrons. First step are dedicated experiments giving insight into the physics behind the strong isotope effect regarding the co-extracted electrons between hydrogen and deuterium. For deuterium plasmas, these experiments demonstrated a strongly increased release of caesium from reservoirs at inner source surfaces and thus stronger depletion of Cs in long pulses. Several measures for affecting the caesium dynamics and thus reducing and stabilizing the co-extracted electrons, namely modifications of the electrostatic potentials and the magnetic field topology in the ion source, are presented. Finally, the results obtained using these measures are presented and discussed.
Cavity Ring-Down Spectroscopy system for the determination of negative hydrogen ion density at the ELISE test facility

Alessandro Mimo\textsuperscript{1}, Haruhisa Nakano\textsuperscript{2,3}, Christian Wimmer\textsuperscript{1}, Dirk Wunderlich\textsuperscript{1}, Ursel Fantz\textsuperscript{1}, Katsuyoshi Tsumori\textsuperscript{2,3}

\textsuperscript{1}Max-Planck-Institut für Plasmaphysik
\textsuperscript{2}National Institute for Fusion Science
\textsuperscript{3}SOKENDAI (The Graduate University for Advanced Studies)

Corresponding Author: Alessandro Mimo, e-mail address: alessandro.mimo@ipp.mpg.de

The Neutral Beam Injection (NBI) system for ITER will rely on large and powerful RF sources of negative hydrogen (deuterium) ions, which are mostly produced by surface conversion of neutral hydrogen atoms on a converter surface (plasma grid). The ITER-NBI systems need to provide an accelerated ion current of 40 A in D\textsuperscript{−} for up to one hour, with a co-extracted electron current lower than the extracted negative ion current. The efficiency of negative ion surface production is enhanced by decreasing the work function of the plasma grid and this is achieved by evaporating Cs inside the negative ion source.

The large RF source at the ELISE test facility (half of the ITER-NBI source size) at IPP Garching has recently been equipped with a Cavity Ring-Down Spectroscopy (CRDS) system, in collaboration with the National Institute of Fusion Science (NIFS) in Toki, Japan. The aim is to measure the negative hydrogen ion density in front of the plasma grid. The system is based on the evaluation of the decay time of the intensity of a laser pulse (Nd:YAG at 1064 nm) inside a cavity formed by two high reflective mirror (R > 99.995 \%) inside a cavity formed by two high reflective mirror (R > 99.995 \%). The comparison between the decay time during the vacuum phase (no plasma) and in plasma, i.e. with the additional absorption of radiation due to photo-detachment of negative hydrogen/deuterium ions, allows for the determination of the line integrated density of negative ions. The high reflectivity of the mirrors is needed to achieve a high decay time (tens of microseconds) and therefore the required sensitivity for the detection of negative ions. The stability of the mirror reflectivity is also of importance for the reliability of the system: both temporary and permanent degradation of the mirror reflectivity can indeed take place in an ion source environment, as observed in the prototype source at the BATMAN test facility.

As the presence of the magnetic filter field in the horizontal direction causes a vertical plasma drift, two horizontal lines of sight at 2 cm distance from the plasma grid are dedicated to CRDS, in order to gain information on the vertical distribution of the negative ion density. This work will present the results of the first measurements, focusing on the investigations performed to ensure the reliability of the mirror reflectivity and on the dependence of negative ion density on the discharge parameters such as power, pressure and magnetic filter field intensity. Experiments performed both in volume production operation (no Cs evaporation) and in surface production operation (caesiated source) have shown that the system is reliable for long pulse duration (thousand seconds) and for high RF power. Typical value of the negative ion density measured at ELISE during surface production operation were in the range between $5 \times 10^{16}$ and $10^{17}$ m\textsuperscript{−3}, and only a limited vertical asymmetry (less than 50\% difference between the two lines of sight) was observed, in dependence with the magnetic filter field configuration and the bias voltage.
Improvements of the NIO1 Installation for Negative Ion Sources

M. Cavenago¹, R. Delogu², M. Barbisan², A. Pimazzoni¹, C. Poggi², M. Agostini², V. Antoni², C. Baltador¹, V. Cervaro², M. De Muri², D. Giora¹, P. Jain², B. Laterza², G. Maero¹, M. Maniero², D. Martini¹, A. Minarello¹, D. Ravarotto², M. Recchia², A. Rizzolo², M. Romé¹, E. Sartori², M. Sattin¹, G. Serianni², F. Taccogna¹, M. Ugoletti², V. Variale¹, and P. Veltri⁵.

¹ INFN-(Laboratori Nazionali di Legnaro, Bari and Milano groups), Legnaro 35020 PD, Italy
² Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA,) Padova, Italy
³ CNR-ISTP, (Milano,Padova,Bari), Italy
⁴ Dip. Fisica, Univ. Milano, Italy
⁵ ITER Organization, St. Paul Lès Durance, France

Corresponding Author: M. Cavenago, e-mail address: cavenago@lnl.infn.it

In view of the long term operation of neutral beam injectors (NBI) used for stellarator and tokamak heating and current drive, the negative ion source must be carefully optimized, especially because not only plasma but also surface wall conditions are involved in H- or D-production. The NIO1 (negative ion optimization phase 1) installation was developed and is operated since 2014 (in close collaboration between Consorzio RFX and INFN), as a convenient benchmark to study innovative solutions and to address physical questions. The comparatively smaller size of NIO1 (a relatively compact and modular 9 beamlet H- source) is of evident advantage for detailed modeling. The apparent plasma impedance is well in agreement with negligible rf reflection at plasma on, and reflections with plasma off (about 25 %) are well within limits tolerable by rf amplifier; transition between E and H modes of rf coupling can be controlled by increasing rf power or by decreasing gas pressure. The filter field intensity, Bₓ, has been extended to span the [-12, 5] mT range, and as a trend, source performances improve with |Bₓ|. Status and results of a first NIO1 cesium oven are reported. Installation of the Cavity Ring Down Spectrometer (CRDS) and recent years progress of beam diagnostics and of the quality of the volume-produced H- beam are briefly discussed, together with the status of the NIO1 full power "end calorimeter/beam imaging attenuator", to be placed at the end flange with auxiliary flanges for infrared observation. Conceptual tests of energy recovery system, perhaps using this full power calorimeter are also summarized.
R&D progress of RF ion source for neutral beam injector at ASIPP

Yahong Xie, Chundong Hu, Jianglong Wei, Yongjian Xu, Caichao Jiang, Yuming Gu, Yuanzhe Zhao, Qinglong Cui, Lizhen Liang, Shiyong Chen, Qi Wang
Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
Corresponding Author: Chundong Hu, e-mail address: cdhu@ipp.ac.cn

Neutral beam injection (NBI) is one of the most effective tools of four auxiliary plasma heating methods for fusion plasma heating and current driven. Now, a next generation fusion device, China Fusion Engineering Test Reactor (CFETR) is under design, and a giant negative neutral beam injector (NNBI) will be developed is foreseen. In order to demonstrate the key technology and performance of negative ion source, a negative RF ion source test facility has been developed since 2017 in the Institute of Plasma Physics, Chinese Academy of Science (ASIPP).

A prototype single driver ion source with dimension of 200mm was developed and tested on the test facility to pre research the key technology of RF plasma generator. The driver equipped with a water-cooled Faraday shield to protect the alumina cylinder from the plasma and the plasma expands into the rectangular expansion chamber. The RF power of 50 kW with frequency of 1MHz is transferred to the RF driver by a matching unit. The characteristics of plasma discharge were studied with classical diagnostic tools, such as Langmuir probe, optical emission spectroscopy (OES) and water-flow calorimetry (WFC). Based on the plasma performance tests, high power of 50 kW plasma discharge with long pulse of 1000s was achieved. In this paper, the detail design of ion source, characteristics of plasma and future research plan will be presented.

References and Acknowledgment
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Lanzhou, China
Beam Energy Recovery for Fusion: Collector design for the test on NIO1 source

V. Variale\textsuperscript{1}, V. Valentino\textsuperscript{1}, M. Cavenago\textsuperscript{2}, C. Baltador\textsuperscript{2}, E. Sartori\textsuperscript{3} and G. Serianni\textsuperscript{3}

\textsuperscript{1} INFN-Ba, Via Orabona 4, I-70126, Bari, Italy
\textsuperscript{2} INFN-LNL, Viale dell’università 2, I-35020, Legnaro(PD), Italy
\textsuperscript{3} Consorzio RFX, Corso Stati Uniti 4, I-35127 Padova, Italy

Corresponding Author: Vincenzo.Variale, e-mail address: Vincenzo.variale@ba.infn.it

The next fusion project DEMO which will be the evolution of the Experimental Fusion Reactor ITER, would require a high efficient energy production. As in ITER, DEMO will use fast Neutral Beam (NB) injectors to increase the plasma temperature needed for the fusion reaction ignition in the TOKAMAK. A way to recover the electric energy production efficiency in DEMO could be the beam energy recover in the NB production \cite{1}. The NB are produced by a Dbeam generated by e negative ion source which is neutralized by a gas cell with an efficiency of 60\%. Beam energy recovery system of the residual charged particles would improve that efficiency. A proposal of a very simple energy recovery device with an axisymmetric cylindrical ion collector which uses only decelerating electric fields combined with the beam space charge effect has been recently done \cite{2}. This energy recovery system will be tested on the beam of the NIO1 source. It is a compact ion source (scaled down from ITER size sources) which has been developed at INFN-LNL and Consorzio RFX (Padua), where effect of wall condition and source magnetic field changes on negative ion production can be easily studied \cite{3}. In this contribution the detailed collector design to be used in the test on one of the beamlet of the NIO1 source will be presented and discussed. Furthermore, a preliminary trajectory simulation for a beam with a rectangular geometry similar to the beam used in ITER to verify the beam recovery for a non-axial symmetric geometry will be also argued.

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To bridge the gap between ITER and fusion demonstration reactor (DEMO) and to realize the fusion power in China, a new fusion facility named the China Fusion Engineering Test Reactor (CFETR) is under conceptual design. Neutral beam injection (NBI) is one of the proposed auxiliary heating systems to bring the CFETR plasma to the ignition temperature. Two steady-state neutral beam with the total power ≥40 MW at ≥0.8 MeV is demanded for CFETR. As the most critical step towards the CFETR-NBI system, a research project of the CFETR neutral beam test facility (CFETR-NBTF) will be started in China over the next 5 years. The CFETR-NBTF will be equipped a negative ion source with multi RF drivers and a single stage accelerator of 400 keV. The objective of this study is to identify a single stage accelerator to produce 400 keV H- ion beam through the physics design based on beam optics, stripping loss of negative ions, and thermo-mechanical performance of the grids. In the beam optics study, a single-beamlet analysis is applied to evaluate the geometry of the grid apertures, the ratio of acceleration and extraction voltage, and the related beam divergence and clearance. Through a multi-beamlets analysis, magnetic configuration is designed to deflect electrons in the accelerator, and to minimize the effect of magnetic field on the beamlet. Besides, electrical field shaping plates (also named kerbs) are designed to compensate the repulsion between beamlets and to steer the beamlets to a focal point. Utilizing a 3D gas flow analysis to calculate the gas flow in the accelerator and to estimate the relevant the stripping loss of negative ions. The design of each grid segment is described in detail. The thermo-mechanical performance of the girds is evaluated by means of 3D fluid-thermal-structural models, in terms of cooling water velocity, pressure drop, grid temperature, stress, and deformation.
One of the most widespread methods of plasma heating in systems of controlled thermonuclear fusion is high-energy neutral beam injection. Neutral beam injectors production is a complex and multi-stage task, at the first step of which it is necessary to create a high-density wide-aperture plasma flux for the subsequent ion beam extraction. Plasma sources based on arc and RF-discharge are commonly used to solve this problem. In the IAP RAS the alternative approach based on ECR discharge sustained by powerful millimeter wavelength gyrotron radiation was proposed. This method allows to obtain 100% ionized plasma with low content of molecular ions (at a level of several percent). Additionally plasma heating with microwaves allows to use quasi-optical methods of its injection into a plasma and place a heating source at the ground potential reducing electric power consumption at a high-voltage platform of an ion source. This factor favorably distinguishes ECR discharge from other plasma production methods (including RF discharge). The principal difference of this work from the research previously conducted at IAP RAS is the use of a single solenoid field instead of a simple mirror trap. Such a simple magnetic configuration is convenient for scaling and looks technically and technologically attractive.

Results of experimental studies of discharge parameters and outgoing plasma flux are presented. Plasma density was determined from the broadening of emission spectral lines due to the Stark effect and it reached \( N_e \approx 10^{13} \text{ cm}^{-3} \), which is close to the critical value for the heating frequency 37.5 GHz used in experiments. Electron temperature measurements were carried out using Langmuir probe and temperature in the discharge was at the level of \( T_e \approx 30 \text{ eV} \). Probe measurements of the transverse plasma flux density profile demonstrated the possibility of obtaining a uniform distribution with maximum density \( j_{\text{max}}=750 \text{ mA/cm}^2 \). The total ion current from the source reached 5 A. Ways of significant improvement of the obtained results are discussed. The maximum plasma density value in this system increases in proportion to the square of the microwave radiation frequency which is used to sustain the discharge. Thus, application of modern gyrotrons with a frequency about 100 GHz could strongly increase system performance. Available high microwave power allows to use discharge chambers of larger diameter and increase the plasma flux aperture and the total ion flux.

**References and Acknowledgment**

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Update of Ion-Optical System of Neutral Beam of TCV Tokamak

A.V. Sorokin¹, T.D. Akhmetov¹, V.I. Davydenko¹, A.A. Ivanov¹, A.N. Karpushov², V.V. Mishagin¹, I.V. Shikhovtsev¹

¹Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
²Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

Corresponding Author: Alexey Sorokin, e-mail address: A.V.Sorokin@inp.nsk.su

The neutral beam for plasma heating in the TCV tokamak [1] was designed and delivered to Lausanne in 2016. The beam operating with deuterium achieved 1 MW neutral beam power, 30 keV beam energy, and pulse length up to 2 s. The TCV port for beam injection has dimensions of 220×170 mm, which set quite tight limitations on the beam size and its angular divergence. To meet the required beam parameters, a triode multislot ion-optical system with ballistic focusing was developed [2]. The neutral beam injector with the nominal power and pulse duration was put into operation, but the beam size appeared to be considerably larger than that expected and required [3]. Therefore, the beam losses in the duct exceeded design values, which led to overheating of the duct elements. As a result, pulse duration of the beam at the tokamak was limited to 0.7 seconds. Detailed inspection of the plasma grid slots revealed manufacturing defects in slot geometry. Numerical simulation accounting for these defects agreed reasonably well with the measured power density distributions. New version of the ion source grids less sensitive to machining defects were developed and tested. The updated version of the grids provided the beam with 45 A ion current, 27 keV energy, the effective focal distance of 376 cm and divergence of 24.4 mrad across the grid slots, and 398 cm, 10.3 mrad along the slots. The beam characteristics agree well with the simulation results and meet the requirements to the injection duct loads. The measured beam characteristics from the testbed are presented and discussed in the paper.

References and Acknowledgment

The use of solenoids in laser ion sources can suppress the spread of plasma, but it has been found that the plasma becomes unstable in a certain magnetic field region [1]. In previous research, it has been investigated for instability of the plasma after passing through the solenoid. In this study, we investigated how the plasma instability changes inside the solenoid. A Faraday cup is placed inside the solenoid, and the unstable region of the plasma is examined while changing the solenoid magnetic field. This experiment was conducted while moving the Faraday cup from the inlet to the outlet of the solenoid to investigate the change in the instability region inside the solenoid.

**References and Acknowledgment**


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Electrode bias technique has been widely used for controlling the ratio of negative ions to electrons in the extracted beam in negative ion sources for fusion. In our recent study, it was shown that the beam optics can be optimized by tuning the bias voltage in LHD-NNBI [1]. This result suggests that the electrode bias can affect the meniscus formation by modifying the plasma parameter in the vicinity of a plasma grid. However, a key plasma parameter to determine the meniscus shape was not clarified in the study due to the limited diagnostic tools for source plasmas.

In this study, the source plasma and the negative ion beam were simultaneously measured in NIFS-RNIS, in which diagnostic tools for source plasmas as well as the beam are fully equipped. The systematic scans of the discharge power were carried out at different bias voltages. It was found that the beam width changes along the same curve with respect to the negative ion density for different bias voltages while the negative ion-to-electron density ratio and the plasma potential significantly changed depending on the bias voltage. This implies that the most important parameter to determine the meniscus shape is the negative ion density.

References and Acknowledgment
In order to bridge the gap between ITER and fusion demonstration reactor (DEMO) and to realize the fusion power in China, a new fusion facility (China Fusion Engineering Test Reactor, CFETR) is put forward and some key technical tackles are being developed [1-3]. Neutral beam injection (NBI) is one of the most efficient means of four auxiliary plasma heating means and has been applied to drive current in nuclear fusion physics studies. For simpler mechanical structure, convenient maintenance and longer lifetime, RF driven ion sources are selected as the preferred ion source for CFETR heating neutral beam injector (NBI). According to the latest physics design of CFETR, two NBIs, which deliver a total of 40 MW not less than 3600s with 1MeV D0 , are demanded to support the current drive and the plasma rotation[4]. To minimize the risks and time to provide CFETR with reliable NBIs, a negative RF driven ion source test facility has been developed since 2017 at Institute of Plasma Physics, Chinese Academy of Science (ASIPP). Its mission is to understand the characteristics of the RF driven ion source and the negative ions generation and extraction and to improve the RF efficiency and the beam quality [5, 6]. In order to achieve this goal, a set of diagnostic tools will be developed on this test facility. For source diagnostics, optical emission spectroscopy (OES), Cavity Ring-Down spectroscopy (CRDS), laser absorption spectroscopy (LAS) and static prober are planned to perform. Beam emission spectroscopy (BES), 1D-CFC diagnostic calorimeter and beam dump with thermocouple and water-flow calorimetry (WFC) are used to assess the beam property. All of the diagnostic tools will be installed and tested within two years for R&D of negative ion source.

References and Acknowledgment

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Preliminary Result of CRDS System for Radio-frequency Negative Ion Source Test Facility at ASIPP

L. Z. Liang¹, C. D. Hu¹, J. Y. Yan¹,², Z. Z. Zhao¹ and Y. H. Xie¹

¹Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
²Graduate school, University of Science and Technology of China, Hefei 230026, China

Corresponding Author: C. D. Hu, e-mail address: cdhu@ipp.ac.cn

In order to support the development of the negative ion based neutral beam injection system for next generation fusion experimental reactor, a negative ion source test facility with radio frequency source is being built at Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP). Negative ion source is a core part of neutral beam injection system for magnetic confinement fusion devices. The density of produced hydrogen negative ions is a critical parameter of negative ion source. Cavity ring-down spectroscopy (CRDS) is an ultrasensitive absorption diagnostic technique for density measurement. Based on photo-detachment process, CRDS can measure integrated line-of-sight hydrogen negative ions density in high power ion source. CRDS diagnostic system has been applied to Hefei Utility Negative ion Test Equipment with RF source, which is now one of the references for China Fusion Engineering Test Reactor (CFETR) neutral beam injection system. The design and implementation of this diagnostic system is introduced in detail, especially the mode matching system, which has not been researched on other similar facilities. Typical ring-down signals are obtained to calculate the density of hydrogen negative ions. The time evolution of hydrogen negative ions density is successfully measured. Preliminary experiments show the accurate relationship between RF power and measured hydrogen negative ions density.

References and Acknowledgment

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The ITEP MEVVA Ion Source for Indium and Tin Ions Implantation into PCM Thin Films

Dmitry Seleznev\textsuperscript{1}, Alexander Kozlov\textsuperscript{1}, Timur Kulevoy\textsuperscript{1}, Alexey Sitnikov\textsuperscript{1}, Petr Lazarenko\textsuperscript{2}, Sergey Kozyukhin\textsuperscript{3}, Mikhail Smayev\textsuperscript{4}, Yuri Vorobyov\textsuperscript{5}, Alexey Sherchenkov\textsuperscript{2}

\textsuperscript{1} National Research Center "Kurchatov Institute"-ITEP, Moscow, Russia
\textsuperscript{2} National Research University of Electronic Technology, Zelenograd, Russia
\textsuperscript{3} Kurnakov Institute of General and Inorganic Chemistry of RAS, Moscow, Russia
\textsuperscript{4} Mendeleev University of Chemical Technology of Russia, Moscow, Russia
\textsuperscript{5} Ryazan state radio engineering university, Ryazan, Russia

Corresponding Author: Alexey Sitnikov, e-mail address: aleksey.sitnikov@itep.ru

One of the most perspective electrical and optical non-volatile memory type is phase change memory (PCM) based on the chalcogenide materials, particularly on Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} (GST\textsubscript{225}) \cite{1}. Introduction of dopants, like Tin (Sn) or Indium (In), is an effective method for purposeful change of the GST\textsubscript{225} film properties \cite{2}. The first Sn implantation into GST\textsubscript{225} was described in \cite{3}. The ion implantations were carried out on Multipurpose Test Bench (MTB) \cite{4} at NRC "Kurchatov Institute"-ITEP. For Sn and In ions implantation into GST\textsubscript{225} the following MTB elements were used: MEVVA type ion source, electrostatic focusing system, the system for the current and the beam profile measurements. The MTB parameters for Sn and In implantation are presented in this study. The exposure of the fabricated samples with femtosecond pulses was performed. It was shown that ion implantation leads to change in the threshold laser powers necessary for crystallization and re-amorphization. The results of the study can be useful for the optimization of the efficiency of the photonic PCM devices.

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Plan of experiments in support of the idea adiabatic photon neutralization in NBI system for large fusion devices

M.G. Atlukhanov¹, A.V. Burdakov¹,², A.A. Ivanov¹,³, S.S. Popov¹,³.
¹Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences, Novosibirsk, Russia
²Novosibirsk State Technical University, Novosibirsk, Russia
³Novosibirsk State University, Novosibirsk, Russia

Corresponding Author: M.G. Atlukhanov, e-mail address: atukhanov.m@gmail.com

Modern projects of energy sources based on fusion are of the great practical interest. One of the key points in such large devices is the injection of powerful neutral atoms to support the energy balance and excite a stationary toroidal plasma current. The energy efficiency of this an injector depends on the degree of neutralization of the initially negative beam.

At present, the necessity of replacement for gas neutralization by plasma or photon neutralizers is become increasingly recognized [1]. The photon neutralizer is capable of reaching 100% yield of neutral atoms, which is very important for future thermonuclear reactors. However, they require efficient accumulation of radiant energy in a limited space.

As a rule photon neutralizer projects are based on different variations of the Fabry-Perot resonator [2, 3, 4], but this approach contains a number sufficiently serious limitations on the quality of laser radiation, the stabilization of optical elements, and others. An alternative for resonant method is the accumulation of laser radiation in an adiabatic non-resonant trap [5], whose efficiency depends mainly on the reflection coefficient of the mirrors.

In work [6], the first successful results on the neutralization of beams of negative hydrogen and deuterium ions was presented, obtaining the maximum neutralization coefficient above 90% at an energy of 6–12 keV. The results obtained showed a high potential for the further development of the adiabatic photonic neutralizer.

In this paper, the optical scheme for large fusion devices is presented. The main technical problem is bombarding mirrors placed near from plasma volume and high energy particle beam. The lifetime of dielectric mirrors for large installations is estimated from experimental work [7] simulation in SRIM code and can achieve about 1 year or more for time operating fusion devices.

References

Novel comparative measurement of $\text{H}^-$ beam divergences at the BATMAN Upgrade test facility: single beamlet and a group of beamlets

C Wimmer$^1$, F Bonomo$^1$, A Hurlbatt$^1$, L Schiesko$^1$, U Fantz$^1$, B Heinemann$^1$, G Orozco$^1$, M Agostini$^2$, M Barbisan$^2$, M Brombin$^2$, R Delogu$^2$, A Pimazzoni$^2$, G Serianni$^2$, M Ugoletti$^2$, P Veltri$^3$

$^1$Max-Planck-Institut für Plasmaphysik (IPP), Boltzmannstr. 2, 85748 Garching, Germany
$^2$Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy
$^3$ITER Organization, Route de Vinon sur Verdon, CS 90 046, 13067 St. Paul-lez-Durance, France

Corresponding Author: Christian Wimmer$^1$, e-mail address: christian.wimmer@ipp.mpg.de

For the ITER fusion experiment, two neutral beam injectors (NBIs) are required for plasma heating and current drive. Each NBI supplies a power of about 17 MW, obtained from neutralization of 40 A (46 A), 1 MeV (0.87 MeV) negative deuterium (hydrogen) ions. Additionally ITER NBIs involve strict requirements regarding the beamlet divergence (< 7 mrad); the full beam is composed out of 1280 beamlets, formed in 16 beamlet groups. BATMAN Upgrade is a NBI test facility at IPP, which contributes to the R&D roadmap towards the ITER NBI. BATMAN Upgrade uses an ITER-like grid with one beamlet group, which consists of 70 apertures; beamlet calculations predict a minimum divergence in the range of 11–14 mrad at this setup. Beam Emission Spectroscopy (BES) is one of the main beam diagnostic tools used at the IPP NBI test facilities. BES measures an integrated signal along its line-of-sight covering the beam composed of the overlap of several beamlets. Spatially resolved CFC tile calorimeters are tools for the measurement of the footprint of individual beamlets. During a recent experimental campaign performed by IPP and Consorzio RFX to better assess the beam optics, the divergence of a single beamlet was compared to a group of beamlets. To this purpose, the top part of the BATMAN Upgrade grid system was selectively masked to leave just a single aperture open; the bottom part was left fully open for measurements of a group of beamlets. The single beamlet is measured by the CFC tile calorimeter and BES, whereas the divergence of the group of beamlets is measured with BES. Both diagnostics measure at a similar distance of 1.3–1.4 m from the last grid. These measurements showed for the first time two major results: first, the evaluation of the divergence from the two beam diagnostics showed an excellent agreement for the single beamlet. Second, the divergence of the single beamlet is in the range of the predicted minimum divergence and about a factor of two smaller than the estimation of the signal of the group of beamlets. These results initiate now further thorough investigations with performance scans in the experiment accompanied by modeling in order to get a deeper insight into the different behavior of the divergence of a single beamlet and the divergence obtained from the overlap of several beamlets.
Design and comparison of the Cs ovens for the test facilities ELISE and SPIDER

Sofia Cristofaro, Markus Fröschle, Alessandro Mimo, Andrea Rizzolo, Michela De Muri, Marco Barbisan and Ursel Fantz

1Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
2Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy

Corresponding Author: Sofia Cristofaro, e-mail address: sofiacristofaro@ipp.mpg.de

Negative ion sources for fusion rely on the surface formation of negative hydrogen (or deuterium) ions by conversion of atomic hydrogen and positive hydrogen ions at a low work function surface. In order to enhance the surface production of negative ions and achieve the current densities required by ITER, a low work function converter surface is required as plasma grid (the first grid of the extraction system). Cs is thus evaporated into the source in order to decrease the surface work function of the plasma grid. Consequently, Cs reservoirs are also formed at the source surfaces, and the interaction between the low temperature low pressure plasma and the Cs reservoirs leads to a removal and redistribution of Cs from the surfaces. To maintain a temporarily stable low work function of the converter surface during long and continuous plasma operation (up to one hour), a thick Cs layer is required (above few monolayers). Thus, maintaining a sufficient Cs flux towards the plasma grid thanks to the Cs redistributed from the source walls is necessary to achieve good performance during long operation. A reliable and continuous evaporation of caesium is then required, and this is performed by temperature controlled Cs ovens with evaporation rates of several mg/h. The Cs ovens applied at the ELISE test facility (IPP Garching) and foreseen at the SPIDER testbed (Consorzio RFX) are based on the evaporation of liquid Cs from a reservoir located at one end of the oven, and the evaporation of Cs is controlled by the reservoir temperature.

ELISE half ITER-size source is equipped with two ovens located at the side walls of the chamber. The typical reservoir temperature is around 100–130 °C, while the temperature of the oven body is kept to 280 °C in order to improve the Cs transport from the reservoir to the source. Cs is then injected into the source through a nozzle with an edge cut at 45° angle towards the backplate of the source. A valve allows to separate the source from the reservoir. The ovens allow to have evaporation rates from few to tens mg/h, and the typical total evaporation rate for good performance at ELISE is below 10 mg/h [1].

For the full size ITER-NBI source at the SPIDER teststand three ovens were recently manufactured and will be installed at the backplate. The ovens are based on a similar concept with respect to the IPP ovens, but a new design was required [2] since the entire oven will be placed in vacuum and remote operation must be assured. Additionally, the geometry of the nozzle is changed and it is a cylinder with 6 orifices on the lateral side.

In the present contribution, a description of the IPP and Consorzio RFX oven designs is briefly presented, focusing in particular on the modifications applied to the SPIDER ovens in view of their application in SPIDER. In order to study their reliability and performance, one of the newly manufactured SPIDER ovens is tested at the dedicated laboratory experiment CATS [3], and first results about the evaporation of Cs are here shown in terms of Cs density (measured by laser absorption spectroscopy) and Cs outflow (by means of surface ionization detector).

References and Acknowledgment
Optical Emission Spectroscopy (OES) on SPIDER Negative Ion Source [1] has been collecting data since beginning of operation in summer 2018. First months were devoted to complete the diagnostic commissioning and its integration with SPIDER Control and Data Acquisition System (CODAS) [2]. Consistent sets of spectroscopic data have been acquired under different experimental conditions, varying not only the plasma source filling pressure and injected power, but also changing the RF generators frequencies and the strength of the magnetic field acting as filter in front of the plasma grid. The main results of OES data analysis are presented in this work. Spider optical emission diagnostic comprises a set of 66 channels wavelength resolved, and 36 single line channels by means of interference filtered. Some of them collect the photons along line of sights (LOS) perpendicular to the grids through the 8 RF drivers, others along LOS parallel to and near the grids, both horizontally and vertically. Since the starting of extraction experiments, 22 channels have been dedicated to collect the extracted beam emission. The LOS layout allows tracing two 9-points vertical profiles of the source plasma in the expansion region at 35 and 5 millimeters from the Plasma Grid (PG), and four 4-points horizontal profiles spanning the 65 mm region before the PG. It is also possible to collect spectra from LOS looking in between the grids. Both Balmer series and Fulcher band between 600 nm and 640 nm were routinely collected. Their intensities are very sensitive to the plasma parameters, and when coupled to a collisional radiative model can give precious insights to electron density and gas dissociation. It has been found that Balmer emission and gas dissociation inside the drivers scale linearly with the RF power, the latter reaching value up to 20% at high power and low pressure. Rotational gas temperature has been also measured; it ranged between 900 K and 1400 K, where higher values were reached for higher pressures and RF powers.

References and Acknowledgment
High power high current neutral beam injector with tunable particle energy for plasma heating and stabilization

A. Brul¹, A. Abdраститов¹, A. Драничников¹, V. Давыденко¹, P. Дейчулі¹, N. Дейчули¹, A. Ivanov¹, V. Колмогоров¹, V. Капитонов¹, S. Korепанов², V. Mishagin², D. Осин², V. Raschenko¹, A. Sorokin¹, N. Stupishin¹, R. Vakhrushev¹

¹Budker Institute of nuclear physics, Novosibirsk, Russia
²TAE Technologies, CA, USA

Corresponding Author: Brul Aleksandr, e-mail address: A.V.Brul@inp.nsk.su

High-power neutral beams are widely used for plasma heating in fusion research [1]. A high value of the captured beam current (up to 1 kA) can support the formation of a stable plasma configuration in systems with a reversed field [2, 3]. Last progress of these researches lead to the requirement of the neutral beams injectors with tunable voltage, while maintaining the extracted beam current [4]. The operation of such type ion sources is not so difficult in case if the beam current changes synchronously with the voltage to preserve the perveance. The beam power is thus changes by tens of times during the pulse compared to the nominal one, which is not always acceptable in fusion experiments. The maintenance of the ion current with tuning the voltage is complicate problem due to the dramatically change of the beam formation condition. Such type of ion source has not been implemented before.

This report describes the high-current neutral beam injector, which started at 15 keV beam energy, and then the ion optical system (IOS) turned to the energy 40 keV according an arbitrary time scenario while maintaining the current near 140 A. To provide the formation of the beam at tunable voltage the four-grid IOS was used which operates at a first stage of the pulse as a triode. When it is necessary to increase energy the IOS operates as a tetrode in which the starting beam get additional acceleration up to given value. The neutral beam power increases from 1.6 MW to 3.4 MW. The total pulse duration is 30 ms, the type of particles H, D. The grids of the IOS have the multi-slit structure inside the Ø360 mm aperture. The grids surface has the spherical form with a radius ~3.5 m for the beam focusing. The plasma source based on 4 arc-discharge generators provides the extracted beam up to 180A. Titanium arc evaporators provide vacuum pumping with rate 400,000 l/s. Four tunable neutral injectors operate successfully at the C-2W machine [2].

References and Acknowledgment


Lanzhou, China
Simulation of the gas density distribution in the accelerator of the ELISE test facility

M. Siragusa\textsuperscript{1,2}, E. Sartori\textsuperscript{1,2}, F. Bonomo\textsuperscript{3}, B. Heinemann\textsuperscript{3}, G. Orozco\textsuperscript{1}, G. Serianni\textsuperscript{1}

\textsuperscript{1} Consorzio RFX, Corso Stat Uniti 4, 35127 Padova (PD), Italy
\textsuperscript{2} Università degli Studi di Padova, Via 8 Febbraio 2, I-35122 Padova (PD), Italy
\textsuperscript{3} Max-Planck-Institut für Plasmaphysik, Boltzmannstraße 2, 85748 Garching, Germany

Corresponding Author: G. Serianni, e-mail address: gianluigi.serianni@igi.cnr.it

In multi-aperture electrostatic accelerators, the plasma discharge is sustained by injecting gas in the plasma source, in a dynamic equilibrium with the gas flowing out through the accelerator. In this work we present a three-dimensional numerical simulation of the gas flow inside the extraction system of the large negative ion source ELISE at IPP Garching. In addition to the 640 apertures per electrode, in the case of ELISE the lateral gaps between the electrode support structures also contribute to the total gas conductance. Assuming molecular regime we estimated the gas conductance, the gas density profile along the path of the ion beams from upstream of the plasma grid to downstream of the ground grid, and the transverse non-uniformities in the accelerator. The simulation included the most relevant geometrical features, while the results are compared to analytical estimates.
Four-dimensional Emittance Study of the High Charged State High Intensity
Heavy Ion Beams Extracted from ECR Ion Source

Xing Fang
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
Corresponding Author: Xing Fang, e-mail address: fangxing@impcas.ac.cn

According to the research requirement of transverse coupling on the ion beams extracted from ECR ion source and the Afterglow beam transverse property, a Pepper Pot meter meeting ECR ion source extraction energy was firstly developed, the goal of the Pepper Pot meter was to measurement the ion beam four-dimensional (4D) emittance.
Experimental Study on Monitoring the Clinical Beam Purity in Multiple-Ion Beam Operation for Heavy-Ion Radiotherapy

Kota Mizushima, Yoshiyuki Iwata, Masayuki Muramatsu, Sung Hyun Lee, Toshiyuki Shirai
National Institutes for Quantum and Radiological Science and Technology
Corresponding Author: Kota Mizushima, e-mail address: mizushima.kota@qst.go.jp

National Institute of Radiological Sciences (NIRS) has performed carbon-ion radiotherapy since 1994 using the Heavy Ion Medical Accelerator in Chiba (HIMAC) [1], and the treatments with the carbon-ion beams have been successfully carried out there for more than 12000 patients. The NIRS has recently investigated multiple-ion therapy [2] using the beams of four ion species, helium, carbon, oxygen and neon ions, to improve the treatment results of refractory cancer. For this therapy, we have tested the method to quickly change the ion species of the irradiation beams. In this method, the beams of four ions, He$^{2+}$, C$^{2+}$, O$^{3+}$ and Ne$^{4+}$, are provided by only one ion source with fast gas-switching operation [3], and they are accelerated, after fully stripping electrons through a carbon foil, up to the energy of 430 MeV/u by the linear accelerators (linacs) and the synchrotron. However, when the fully-stripped ions, e.g. C$^{6+}$ and O$^{8+}$, are mixed with the He$^{2+}$ beam, they are also accelerated and irradiated together because of an equal mass-to-charge ratio (A/z). Although irradiation of the unwanted ions should be avoided, it is difficult to remove them with the same A/z in the transport line. Therefore, the contamination of the clinical beam must be reduced by the ion source [3], and it is desirable to verify the beam purity before irradiation. For this purpose, we have developed the measurement system to monitor the beam purity. This system can measure the averaged charge number of the beam particle by using an ionization chamber and a Faraday cup. We have performed the beam experiments to verify the validity of our beam-purity monitoring system at the HIMAC. An overview of our system features will be presented and discussed through the experimental results.

References and Acknowledgment
Simulation Based Optimization of the Slit Shape of an Internal Ion Source

Nagaaki Kamiguchi¹, Hiroshi Tsutsui²

¹ Technology Research Center, Sumitomo Heavy Industries, Ltd., Yokosuka 2378555, Japan
² Industrial Equipment Division, Sumitomo Heavy Industries, Ltd., Tokyo 94720, Japan
Corresponding Author: Nagaaki Kamiguchi, e-mail address: Nagaaki.Kamiguchi@shi-g.com

We Sumitomo Heavy Industries, Ltd. have been developing many type of cyclotrons and recently developing the new cyclotron for proton therapy. This cyclotron employs an internal ion source which is a kind of PIG ion sources with a hot cathode. It have been confirmed that this ion source is possible to generate over 40 µA H+ beam (1). In case of internal ion sources for cyclotrons, not all of particles extracted from the ion source is accelerated and some of them drop away from the acceleration phases and finally bump into the boundary of the vertical gap. Though high current beam gained from the ion source, in case with large emittance, the beam gets lost and its current decreases. Survive particles are extracted to outside of the cyclotron but dumped particles along the acceleration causes the radio activation so that low beam loss or small emittance beam is required. The emittance of beam extracted from the ion source is relation with rather the slit shape of its chamber than the extraction electrode shape called as the pierce angle. When the wall thickness where the slit exists becomes thick, the emittance becomes small but it is known that extracted beam current decreases. In this study, an optimization of slit shape and thickness were conducted by using IBSimu. Calculating absolute beam current is difficult in IBSimu Thus the prototype ion source is used as a bench mark and the proton density generated in an ion source is tuned to make the extracted beam density equal to other ion source model. Prototype one has 0.15 mm thickness and no pierce angle. In this situation, it was possible to extract large amount of beam but the extracted beam was spreading. When varying the thickness from 0.2 mm to 0.5 mm, the beam current and emittance decreased. When comparing the beam current in case that wall thickness 0.15 mm and 0.5 mm, it decreased to 40 %. The other hand, the emittance decreased to 36%. Next, when varying the pierce angle from 30 degrees to 60 degrees in case of 0.5 mm thickness, the beam current and emittance increased with the pierce angle. Concretely, 60 degrees pierce angle corresponded to 0.2 mm thickness without the pierce angle and 45 degrees corresponds to 0.3 mm. In considering the workability, 0.3 mm thickness without the pierce angle was balanced well.

References and Acknowledgment
\textbf{An innovative device of pepper pot for measuring emittance}

Renli Zhu\textsuperscript{1,2,3}, Weidong Chen\textsuperscript{1,3}, Hui Li\textsuperscript{1,2,3}, Huafu Ouyang\textsuperscript{1,3}, Shengjin Liu\textsuperscript{1,3}, Kangjia Xue\textsuperscript{1,3}, Xiuixia Cao\textsuperscript{1,3}, Yongchuan Xiao\textsuperscript{1,3}, Yongjia Lv\textsuperscript{1,3}

1 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Dongguan Institute of Neutron Science, Dongguan 523803, China

Corresponding Author: Weidong Chen, e-mail address: chenwd@ihep.ac.cn

China spallation neutron source (CSNS) Project Phase-II aims to upgrade to a beam power of 500KW. To meet this requirement, a RF driven negative hydrogen ion source is under development. To measure the intensity and the emittance of the beam extracted from the ion source, a pepper-pot method is used. The device has eight small Faraday cups. Each has a hole in the bottom with a diameter same as the other holes in the pepper-pot plate. Such design is used to normalize the beam intensity from each hole to the brightness of dots on the phosphor screen.
Development of CW High Voltage Negative Ion Beam Injector for Tandem Accelerator

Andrey Sanin, Yuri Belchenko, Aleksander Ivanov, Anatoly Gmyrya

Budker Institute of Nuclear Physics

Corresponding Author: Andrey Sanin, e-mail address: sanin@inp.nsk.su

A vacuum-insulated tandem accelerator, delivering 2 MeV protons with continuous current up to 8 mA for neutron production operates at the Budker Institute of Nuclear Physics since 2006. It uses the injection of negative ion beam with energy up to 25 keV. The new injector with improved negative ion source and transport section were developed. The injector scheme includes the surface-plasma negative ion source with Penning geometry and hollow cathodes, the transport section with ions bending and focusing by 900 magnet and the accelerating tube for negative ions pre-acceleration before the injection to tandem. Numerical modelling of the beam transport in the injector was carried out to calculate the optimal geometry and position of the injector elements.

The high-voltage beam production and transport were studied at the injector test stand, having the listed injector elements and equipped with a 1 m length beam transport chamber and beam diagnostics. Several optical diagnostics are installed to register the beam position and profile. A Faraday cup was used to measure the ion beam current at the transport chamber exit. The data on production and pre-acceleration of CW negative ion beam with current up to 13 mA will be presented.
Study of CW H- Beam Transport through the LEBT

Andrey Sanin, Sergei Popov, Yuri Belchenko, Aleksander Ivanov, Anatoly Gmyrya, Magomed Atlukhanov, S Abdrakhmanov

Budker Institute of Nuclear Physics

Corresponding Author: Andrey Sanin, e-mail address: sanin@inp.nsk.su

13 mA, 35 keV CW H- beam production and transport through the LEBT section were studied at the test stand. The Penning-type surface-plasma negative ion source with hollow cathode and cesium addition was used. H- beam was transported through the beam line, consisted of the 900 bending magnet and of 1 m long transport tube. Beam current was measured by a water-cooled Faraday cup, installed at the transport chamber exit. Beam sizes and profile were controlled by cameras, installed at the transport line axis and sides. The addition of hydrogen, argon and xenon to the transport tube and to the bending magnet chamber in the pressure range of $10^{-6} - 10^{-4}$ Tor were tested. The influence of gas added on the beam space charge compensation and beam transport was studied.
CRISP: a Compact RF Ion Source Prototype for emittance scanner testing

Carlo Poggi\textsuperscript{1}, Emanuele Sartori\textsuperscript{1,2}, Matteo Zuin\textsuperscript{1}, Matteo Brombin\textsuperscript{1}, Alessandro Fassina\textsuperscript{1}, Michele Fincato\textsuperscript{1}, Marco Siragusa\textsuperscript{1} and Gianluigi Serianni\textsuperscript{1}

\textsuperscript{1}Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete S.p.A.), C. Stati Uniti 4, 35127 Padova, Italy
\textsuperscript{2}Università degli Studi di Padova, Department of Management and Engineering, Padua, Italy

Corresponding Author: Carlo Poggi, e-mail address: carlo.poggi@igi.cnr.it

SPIDER is the prototype beam source of the ITER Heating Neutral Beam Injector, and it recently started beam acceleration, up to a voltage of 30 kV. A movable Allison type emittance scanner is being developed to characterize the phase-space distribution of its beamlets. To test the device, a Compact RF Ion Source Prototype (CRISP) has been set up at Consorzio RFX, capable to accelerate 0.5 mA of helium ions up to a voltage of 2 kV. A commercial 100 W RF generator creates a plasma inside a Pyrex tube, with a density between 10\textsuperscript{15} and 10\textsuperscript{16} m\textsuperscript{-3} and an electron temperature of a few eV. Three multi-aperture grids in accel-decel configuration extract and accelerate the ions, which impinge on a copper plate beam stopper, acting as a Faraday cup. We present in this paper the numerical simulations performed with SLACCAD and OPERA to dimension the grids and the calculation of the pressure profile inside the vessel made with the AVOCADO code. Measurements of beam current and profile are presented and compared with the simulations. Plasma density and temperature estimations obtained with a Langmuir probe are also reported.

Lanzhou, China

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Development of a Micro Duoplasmatron Type Ion Source

Tatsuya Kuzumi1, Motoi Wada2
1Graduate School of Science and Engineering, Doshisha University
2Doshisha University

Corresponding Author: Tatsuya Kuzumi, e-mail address: ctwd0332@mail4.doshisha.ac.jp

An ion source adaptive to commercially available vacuum ports with copper gasket flanges of ICF-34 standards are designed and built with a nickel alloy hollow cathode attached to a 1/4 inches stainless tube electrically insulated from the source body with an Al2O3 cylinder. The cathode is contained in a 10 mm diameter cylindrical volume of an iron made intermediate electrode. The intermediate electrode compresses the hollow cathode plasma down to 2 mm diameter in size toward the anode, while the magnetic field induced between the intermediate electrode and the iron made anode further constricts the size of the plasma column. The size of the aperture fixed on the anode is 0.5 mm. The ion beam is formed by an extraction electrode with the hole size of 1 mm across a 2 mm gap. The source is operated with hydrogen gas to see the proton ratio of the extracted beam. Species compositions in a low energy range less than 100 eV will be studied using a mass separation unit.
A large divergence of a low energy ion beam by space charge effect reduces signal intensity to make study on fundamental processes of a particle beam difficult in the energy range lower than 100 eV. A low energy beam transport system to study detector efficiency lower than 50 eV has been designed and is being tested the performance. The system is schematically shown in Fig.1. A 70 mm diameter and 90 mm long hot cathode ion source produces hydrogen ions to extract them through a 1 mm diameter aperture. The extracted hydrogen ions travel 40 mm to reach the region of the magnetic field of the mass separating bending magnet and the hydrogen ions are separated into H⁺, H₂⁺, H₃⁺ with a 100 mm Larmor radius. The beam travels another 130 mm before it reaches the slit of the Faraday cup for detecting the beam ion current. A typical result of the Extraction Voltage – Beam Current Characteristics is shown in Fig.2. The figure shows more than 2.4 nA at 50 eV energy for the H₂⁺ ion, while, the lowest beam energy for H₃⁺ ion at 2.5 eV is more than 100 pA
Development of a magnetic quadrupole lens for low energy heavy ion beam transport

Hiro Mikage, Motoi Wada, Michihiro Kitagawa
Graduate School of Science and Engineering, Doshisha University
Corresponding Author: Hiro Mikage, e-mail address: ctwd0342@mail4.doshisha.ac.jp

A beam of heavy ions in the energy range lower than 1 keV is necessary to study ion beam-solid surface interactions in several fields. For example, Xe⁺-carbon interaction in space thruster development and W⁺-W interaction in nuclear fusion research. A system capable of measuring spattering yields of Xe⁺ against carbon has beam designed and built for data collection with the beam energy less than 100 eV. The original design employed an electrostatic lens system, which showed a serious space-charge-effect to cause a large beam divergence. By replacing the electrostatic beam focusing system to a magnetic system, substantial improvement of beam intensity was obtained down to 100 eV Xe⁺ energy.

Modifications to improve the magnetic lens system is being carried out. These include precise tuning of the field intensity by coupling electromagnets and permanent magnets. Measurements of the magnetic field intensity distributions are also conducted to finely adjust the beam trajectory through the beam transport system down to the target. Figure 1 shows an example of the measurement indicating a linear distribution is realized up to 1.2 cm beam radius. The improvement of the entire system and the key factors governing the beam qualities are reported and discussed.
VUV to Visible Range Spectroscopy for Plasma Diagnostic Studies

Gajendra Singh1, A K Singh2, Narender Kumar3, Y. Mathur4, T. Nandi4 and G. Rodrigues4

1USICT, GGSIPU New Delhi, 110078, India
2Department of Applied Sciences, MSIT, USICT, GGSIPU New Delhi, 110058, India
3Physics Department, University of Liverpool, Liverpool L697ZE, United Kingdom
4Inter University Accelerator Center, New Delhi, 110067, India

Corresponding Author: Gajendra Singh, e-mail address: gpskmc@gmail.com

Spectroscopy is a standard diagnostic technique for astrophysical and laboratory plasmas; microwave ion sources are excellent tools to carry out such diagnostics. In the present work, our focus is on measurements of relative line intensities and line shifts for 2s2p \(^3\)P-2p \(^3\)P and 2s\(^2\)l\(^S\)-2s2p \(^2\)P transitions of impurity ions C III, O V, Ne VII etc. as a function of parameters such as input gas pressure, injected microwave power and tunable axial magnetic field [1] using the 2.45 GHz microwave ion source recently developed in our laboratory [2] to determine the ion temperature, electron temperature, ion number density (ni) and electron number density (ne). Theoretical computations for these atomic transitions will be presented using relativistic atomic structure GRASP2K code [3]. We have applied systematically enlarged Multiconfiguration Dirac-Fock wavefunctions with the inclusion of finite nuclear size effects, Breit interaction and quantum electrodynamic corrections to obtain accurate energy levels and transition rates. All the above computed data will help us in proper line identification during our plasma spectroscopic measurements using above microwave ion source. Present study is significant in the context of fusion device research as complete collision–radiative modelling of fusion plasma needs proper identification and measurements of the diagnostic lines of impurity ions.

References and Acknowledgment

Influence of Extraction Grid on Ion Beam Characteristics

Nikolai Alekseev\textsuperscript{1}, Alexander Balabaev\textsuperscript{1}, Igor Khrisanov\textsuperscript{1}, Timur Kulevoy\textsuperscript{1}, Anton Losev\textsuperscript{1}, Yuri Satov\textsuperscript{1,2}, Alexander Shumshurov\textsuperscript{1} and Andrey Vasilyev\textsuperscript{1}

\textsuperscript{1} NRC «Kurchatov Institute» - ITEP, Moscow 117218, Russia
\textsuperscript{2} National Research Center Kurchatov Institute, Moscow 123098, Russia

Corresponding Author: Timur Kulevoy, e-mail address: kulevoy@itep.ru

This work was performed as part of the development of a laser ion source for injectors of multiply charged ions. Experiment is devoted to investigation of the influence of metal grids on the characteristics of extracted ions. We compared energy spectra of ions in plasma expanding into drift tube with and without a grid. Plasma of different target materials was generated by pulses of a CO\textsubscript{2} laser at a radiation flux density of about 10\textsuperscript{11} W/cm\textsuperscript{2}. Measurements using an electrostatic TOF energy analyzer were carried out behind typical extraction grid. Significant influence of the grid on ion energy distribution was observed. This effect depends strongly on the ion mass. The probable explanation of this effect is that the “head” of the expanding plasma bunch induces an ablation of grid material and desorption of its surface. As a result, generated “cloud” of molecular gas prevents propagation of main part of plasma stream. The grid influence on laser plasma propagation depends strongly on plasma density and must be taken into account for design of laser ion source in the frame of setting of drift length, plasma density and, respectively, ion current density.
Measurement of Hydrogen Ion Beam Energy Spreads Generated by a Penning-Ionization-Gauge Type Ion Source with Electric Magnets for a MeV Compact Ion Microbeam System

Yasuyuki Ishii\(^1\), Takeru Ohkubo\(^1\), Hirotsugu Kashiwagi\(^1\), and Yoshinobu Miyake\(^2\)

\(^1\)National Institutes for Quantum and Radiological Science and Technology, Takasaki Advanced Radiation Research Institute, 1235 Watanuki-machi Takasaki 370-1292, Japan
\(^2\)Beam Seiko Instruments Inc., 1-20-3 Kamata Ohtaku, Tokyo 144-0052, Japan

Corresponding Author: Yasuyuki Ishii, e-mail address: ishii.yasuyuki@qst.go.jp

Beam energy spreads of hydrogen ion beams generated by a penning-ionization-gauge type ion source with electric magnets (EM-PIG) has been measured in this study. EM-PIG was designed and constructed to be installed in a MeV compact ion microbeam system (MeV-CMB) planned in QST. As a prototype of MeV-CMB, a 120 keV compact ion microbeam system with a dedicated electric focusing lens, namely three-stage acceleration lens, and a duoplasmatron type ion source with large electric power consumption (KeV-CMB) was developed to study the effectiveness of the lens [1]. An ion beam with low energy, high brightness, and small beam energy spread (Necessary Beam) is required to form ion microbeam by MeV-CMB and KeV-CMB. A 1.8 μm hydrogen ion beam has, so far, been formed using keV-CMB, which almost satisfied our goal of beam diameter [2]. In KeV-CMB, the large electric power of the duoplasmatron type ion source has been supplied using an electric power source with earth connection. However, the supply is difficult because the ion source was designed to be placed in a high voltage area in MeV-CMB. Therefore, a new ion source is required to meet small electric power consumption and a long maintenance interval as well as Necessary Beam. A general penning-ionization-gauge type ion source (PIG) is suitable to satisfy the small power consumption and the long maintenance interval. However, the generation of Necessary Beam was difficult using PIG due to not being designed to meet the generation. Therefore, EM-PIG was newly designed and constructed on the concept of the extraction of ion beam from a small and high-density plasma using strong magnetic field. A low energy hydrogen ion beam with high brightness was experimentally generated using EM-PIG in a preliminary study [3]. In this study, beam energy spreads of ion beams generated by EM-PIG were measured using a parallel-plat energy spread analyzer. The hydrogen ion beam energy spreads were measured on the basis of changing the parameters, such as extraction voltage, gas presser and so on, whose results will be reported in the conference. The beam energy spread has been almost satisfied to be installed in MeV-CMB.

References and Acknowledgment

Developments of real time emittance monitors at RCNP

Yasuyuki Morita, Mitsuhiro Fukuda, Tetsuhiko Yorita, Hiroki Kanda, Kichiji Hatanaka, Akira Nakao, Yuusuke Yasuda, Keita Kamakura, Hui Wen Koay, Shuhei Hara, keijiro Takeda, Takahumi Haru, Kyouhei Omoto
Research Center for Nuclear Physics, Osaka University, Osaka 5670047, Japan
Corresponding Author: Yasuyuki Morita, e-mail address: morita16@rcnp.osaka-u.ac.jp

The program of upgrade of AVF cyclotron is currently in progress at RCNP. As a part of that, an emittance monitor is being developed to improve the injection efficiency from ion sources to AVF cyclotron. As the efficiency of injection depends greatly on the optimization of ion sources and matching the ion beam emittance with the acceptance of AVF cyclotron. It is necessary to measure the beams extracted from ion sources quickly so that the quick and effective optimization. At this stage, we have already developed and operated the Pepper-Pot Emittance Monitor (PPEM)\[1,2\] at RCNP[3], which measures the emittance value at 2 Hz. As for this work, we developed an analysis method using LabVIEW, and measurement of particle density distribution in phase space and of emittance values at 4 Hz has been achieved. As a result, it has become possible to get a lot of information like 4-dim, Phase space, etc. visually in real time. We are also developing PPEM that can measure a wide range of emittance from a few π mm mrad to 200 π mm mrad by mechanically changing the pepper pot mask of PPEM.

References and Acknowledgment
EBIS Based Short Pulsed Proton Injector of 100 MeV Linac for a Pulsed Neutron Source at KOMAC

Seunghyun Lee, Jeong-Jeung Dang, Hyeok-Jung Kwon and Hang-Sung Kim
Korea Multipurpose Accelerator Complex, Korea Atomic Energy Research Institute, Gyeongju 38110, Korea
Corresponding Author: Seunghyun Lee, e-mail address: shl@kaeri.re.kr

The Korea Multipurpose Accelerator Complex (KOMAC) has been working on developing a new combined injector of a 100 MeV proton linac for long (> 1 ms) and short (< 1 μs) pulsed proton beams. The current operating injector is a microwave ion source which generates long proton pulses, and we plan to install an additional Electron Beam Ion Source (EBIS) based short pulsed proton injector. Using the combined injector, we intend to generate both long and short neutron pulses from a tungsten target at the end of the 100 MeV linac. To install and operate the EBIS based short pulsed proton injector along with the existing microwave ion source, we designed a new beamline which contains two quadrupole deflectors, a set of Einzel lens and an X-Y steerer. This makes compact and easy to operate two ion sources together. Here, we present extraction test results of short proton pulses from the standalone EBIS, implementation of a short pulsed proton injector with the beam transport system and its plans after the installation.

References and Acknowledgment

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Optical diagnostics of Negative Ion Beam transport

Sergey Popov¹, Sergey Abdakhmanov¹, Magomed Atlukhanov², Yuri Belchenko¹, Anatoly Gmyrya¹, Aleksander Ivanov¹, Andrey Sanin¹

¹Budker Institute of Nuclear Physics
²Novosibirsk State University

Corresponding Author: Sergey Popov, e-mail address: s.s.popov@inp.nsk.su

35 kV H⁻ beam transport with a CW current up to 13 mA through 1 m length LEBT of the negative ion injector [1] has been investigated by optic diagnostics consisting of two spectrometers with a resolution of 0.03 nm, 0.011 nm, and two sensitive cameras. The energy and angular spreads of the velocities of the ion beam were measured from the Doppler shift of the Hα lines. An influence on the width of the glow region excited by the beam has been investigated. Such adding leads to sufficient decreasing the width of beam. Using heavy gases allow effectively decrease at 40 % without significant losses due to neutralizing and positive ion creation. The small luminescence of various spectral lines of hydrogen, argon, and xenon excited by the collision of particles of a beam with atoms and molecules of gases introduced into the transport region has been measured. Additionally, photo cameras allow with time resolution about 50 ms to determine beam position, its incline, estimate a focusing. The possibilities of using the considered optical diagnostics for the on-line monitoring of the beam characteristics in the LEBT channel of a tandem accelerator with proton energy up to 2.5 MeV, developed in BINP for neutron therapy, are considered.

References and Acknowledgment
Assessment of the SPIDER beam features by diagnostic calorimetry and thermography

Antonio Pimazzoni\textsuperscript{1,2}, Matteo Brombin\textsuperscript{1}, Rita S. Delogu\textsuperscript{1}, Daniele Fasolo\textsuperscript{1}, Luca Franchin\textsuperscript{1}, Bruno Laterza\textsuperscript{1}, Roberto Pasqualotto\textsuperscript{1}, Gianluigi Serianni\textsuperscript{1}, Marco Tollin\textsuperscript{1}

\textsuperscript{1}Consorzio RFX, Corso Stati Uniti 4 – 35127, Padova (Italy)
\textsuperscript{2}INFN-LNL, Viale dell’Università 2, 1 – 35020, Legnaro (Italy)

Corresponding Author: Antonio Pimazzoni, e-mail address: antonio.pimazzoni@igi.cnr.it

The full-size ITER ion source prototype SPIDER has recently started beam operation; goal parameters: 100keV, 60A negative hydrogen-like ions for one hour. The source is presently operated in volume regime and the beam power is consequently limited. In such configuration, the high resolution calorimeter STRIKE, even though uncooled, may be used instead of the SPIDER beam dump without limiting the beam-on time. STRIKE is formed by unidirectional carbon fiber-carbon matrix (CFC) composite tiles which are exposed to the beam while their temperature is recorded by two infra-red cameras. This setup, thanks to the moderate broadening of the temperature profile guaranteed by the anisotropy of CFC, allows for the determination of detailed features of the beam current distribution (spatial resolution is about 2 mm). Furthermore, positively biasing the CFC tiles permits a direct electrical measurement of the negative ion beam current. Besides the total beam current and beam uniformity, which can be retrieved both by calorimetry and electrical measurement, beamlet divergence and deflection can be determined by infra-red thermography. This contribution describes the characterization of the SPIDER negative ion beam as a function of the source and accelerator parameters by means of the diagnostic calorimeter STRIKE in the volume regime.
Designing an Allison scanner for High Particle Energies

Martin P. Stockli\textsuperscript{1}, Baoxi Han\textsuperscript{1}, and Scott Lawrie\textsuperscript{2}

\textsuperscript{1} Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA
\textsuperscript{2} ISIS Neutron and Muon Source, Rutherford Appleton Laboratory, Didcot, Oxfordshire, OX11 0QX, UK

Corresponding Author: Martin P. Stockli, e-mail address: stockli@ornl.gov

Allison scanners have been introduced about 40 years ago and their advantages have been widely discussed. However, so far publications suggest that they are only used in low-energy beam transport sections where the typical proton energy does not exceed 100 keV. However, as particles are accelerated, their trajectory angles shrink, which reduces the required scanning range. For this reason Allison scanners can be used in medium-energy beam transport section, where the particle energies are typical in the order of 1 MeV. This presentation discusses the optimization of an Allison scanner for such an energy range.
Tomography Reconstruction of Beams Extracted From an Ion Source

S. Saminathan$^1$, F. Ames$^1$, R. Baartman$^1$, O. Lailey$^2$, A. Mahon$^3$, and M. Marchetto$^1$

$^1$TRIUMF, Vancouver, BC, Canada.
$^2$University of Waterloo, Waterloo, ON, Canada
$^3$McGill University, Montreal, QC, Canada

Corresponding Author: S. Saminathan, e-mail address: suresh@triumf.ca

Commissioning of the CANREB (CANadian Rare isotope facility with Electron Beam ion source) system and its associated beamlines has recently begun at TRIUMF. At the head of this beamline is an ion source used to produce stable alkaline ions with energy up to 60 keV for the CANREB system. Throughout commissioning it is essential to have a means of verifying beam quality and ensuring that the required beam parameters along the beamline are met. This is accomplished using tomography reconstruction, which consists of taking one-dimensional (1-D) scans at different projections and reconstructing an image of the beam in two-dimensions (2-D) using the MENT (Maximum ENTropy) algorithm. Tomography enables the visualization of the shape of the beam as well as the investigation into the possible presence of aberrations. Initially, tomography reconstruction is performed by using simulated beam profiles at the measurement locations, and is then performed by using measured beam profiles. Additionally, these measurements are bench-marked by fitting the initial beam parameters in our beam optics model, and the results are presented.
Modelization of fringe field of permanent magnet multipole applicable to numerical simulations

Thomas Thuillier, Thomas André, and José Antonio Mendez Giono
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble Alpes, CNRS-IN2P3, INP Grenoble, Grenoble 38026, France
Corresponding Author: Thomas Thuillier, e-mail address: thuillier@lpsc.in2p3.fr

Multipole magnets made with permanent magnets, as proposed by Halbach [1], are today widely used to focus particle beams in accelerators and to confine plasmas in ion sources. The multipole magnet structure conveniently produces very high magnetic field gradients and high magnetic field intensities. When the multipole of order \(2n\) with inner radius \(r\) and length \(L\) is sufficiently long, the inner magnetic field generated is usually approximated by a “hard edge” model with a pure transverse magnetic field whose components at point \(M(x,y,z)\) are defined as:

\[
B_x = B_0 \left(\frac{r}{R}\right)^{n-1} \cos(n\theta) \\
B_y = B_0 \left(\frac{r}{R}\right)^{n-1} \sin(n\theta) \\
B_z = 0
\]

where \(B_0\) is a constant (magnetic field at \(r=R\)), \(r^2=x^2+y^2\) and \(\theta=(x', y')\). The magnetic field is assumed to be null outside of the multipole. This model is commonly used in simulations as it is easy to implement and allows for fast calculation of a magnetic field value. Nevertheless, in many cases the magnetic field close to the multipole edge plays a non-negligible role in the process studied (for instance ion beam formation from an electron cyclotron resonance ion source) and it becomes important to consider the magnetic fringe field. Muratori found an analytical solution for a multipole’s fringe field applicable to numerical simulations,[2] but this solution is computationally expensive. In this contribution, the authors propose a complementary approach based on the analysis of permanent magnet multipole fringe fields properties. An empirical model based on the logistic function and its derivative is proposed to model simply and quite accurately the multipole field as a whole, including its fringe field. The model allows to simulate the magnetic field generated by a multipole in 3 dimensions with minimum effort and low added computation time. The model aims to replace the hard edge approximation in simulation programs and is applicable both for ion source and beam transport simulations. A practical chart proposing analytical formulas to model the fringe field as a function of the multipole parameters \(R\), \(L\) and \(n\) is included.

References and Acknowledgment


At the Inter University Accelerator Centre, New Delhi, the High Current Injector Programme, which mainly consists of an 18 GHz High Temperature Superconducting ECR Ion Source on a 200 kV high voltage platform followed by radiofrequency quadrupole and drift tube linear accelerators, will serve as an alternate injector to the Superconducting Linear accelerator. Understanding of the plasma potential of the ion source is an important parameter as it plays a role in contributing to the energy spread of the ion beams which in turn affects the longitudinal emittance. In our earlier studies [1], the plasma potential of HTS ECR ion source had been measured by utilizing the “decelerating” technique. In the present study, the plasma potentials of various ion beams have been measured using the “magnetic rigidity” method by utilizing the 90° analyzer magnet used for mass and charge analysis. The ion source was operated in the “gas mixing” mode and its effect on the plasma potential has been studied in detail. Longitudinal emittance measurements were carried out by utilizing the downstream Multi-harmonic buncher and a fast Faraday cup. The influence of the plasma potential of various multiply charged ions on the longitudinal emittance will be presented.

References
Development of the injection line for the CYCIAE-14

Xianlu Jia, Tianjue Zhang, Luyu Ji, Fengping Guan
China Institute of Atomic Energy, P.O. BOX275-3, Beijing 102413, China
Corresponding Author: Xianlu Jia, e-mail address: xljia@126.com

A 14MeV high intensity compact cyclotron, CYCIAE-14, was built at China Institute of Atomic Energy (CIAE) to generate neutrons for Boron neutron capture therapy (BNCT) research. The design evaluation of the CYCIAE-14 is about 1mA with 14.6MeV, however, which is only about 300uA now. To get to the designed goal, some measures will be taken, such as improving the accelerator vacuum with two cryopumps taking palace of the two diffusion pumps, decreasing the temperature of the spiral inflector by adding cooling water on it, increasing the beam injection efficiency by improving the injection line and decreasing the emittance of the high intensity ion source, etc. The paper will give the measures for the ion source and the injection line development.
Design of a high current Extraction structure for A H$_{2}^{+}$ Ion Source

He Zhang, Xianlu Jia, Jingfeng Wang, Tianjue Zhang, Xia Zheng, Pengzhan Li, Guang Yang

China Institute of Atomic Energy, P.O. BOX275-3, Beijing 102413, China
Corresponding Author: He Zhang, e-mail address: 576097154@qq.com

An electron cyclotron resonance ion source is building for H$_{2}^{+}$ ions production at China Institute of Atomic Energy (CIAE), while the geometric parameters of the extraction electrodes have an important influence on beam extraction from the ion source. After studying the working principle of the ion source, the basic parameters of the plasma are selected and the extraction structure of the ECR ion source is designed considering some necessary factors such as injection power, gas flow rate and beam current intensity. The simulation calculation has been finished with software IGUN, and a three-electrode extraction structure was gotten with high-brightness and high H$_{2}^{+}$ beam intensity extracted. The source is being installed on the test stand, and some results about plasma parameters, beam extraction, etc., will be gotten. Base on the results, the further optimize design of the ion source extraction structure will be done. This paper will give the theoretical design and simulation results of the H$_{2}^{+}$ ion source extraction structure.
The Transmission of Laser Ablation Plasma with Solenoid Field Confinement

G. C. Wang 1,2, H. Y. Zhao 1,2, Q. Y. Jin 1, J. J. Zhang 1, X. Z. Zhang 1,2, L. T. Sun 1,2, H. W. Zhao 1,2

1 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
2 School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China
Corresponding Author: H. Y. Zhao, e-mail address: zhaohy@impcas.ac.cn

A Laser Ion Source (LIS) can produce high charge state and high intensity ion beams (~emA), especially refractory metallic ion beams, which makes it a promising candidate as an ion source for heavy ion cancer therapy facilities and future accelerator complexes, where pulsed high intensity and high charged heavy ion beams are required. However, it is difficult for LIS to obtain a long pulse width while ensuring high current intensity, thus limiting the application of LIS. To solve the conflict, magnetic fields are proposed to confine the expansion of the laser produced plasma. With a solenoid along the normal direction to the target surface, the lateral adiabatic expansion of the laser ablation plasma is suppressed which extends the pulse width of the ion beam effectively. In the experiment, the full width at half maximum (FWHM), the total charge and the peak current of the ion pulse were measured by Faraday Cup (FC). It was observed that with the magnetic field increases, the pulse width of the C-beam increases by about 9 times. The total charge and peak current increase with the magnetic field and then become saturated. In addition, the experimental results show that the magnetic field of the solenoid changes the longitudinal and lateral distribution of the laser ablation plasma. And the repeatability test of carbon ion pulses showed that the introduction of magnetic confinement has no effect on the stability of LIS. The information on charge state distribution (CSD) within the laser ablation plasma was obtained with TOF method which varies as magnetic field. The transportation characteristics of laser ablation plasma with solenoid field confinement will be presented and discussed in this paper.
Development of a small electron gun to study electron transport in hydrogen negative ion source plasmas

Yoshikatsu Matsumoto¹, Masashi Kisakii²,³, Katsuhiro Shinto⁴, Haruhisa Nakano²,³, Mamiko Sasao⁵ and Motoi Wada⁵

¹Tokushima Bunri University, Nishihama, Tokushima 770-8514, Japan
²National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan
³SOKENDAI (The Graduate University for Advanced Studies), 322-6 Oroshi-cho, Toki, 509-5292 Japan
⁴Japan Atomic Energy Agency, J-PARC center, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
⁵Doshisha University, Kyotanabe, Kyoto 610-0394, Japan

Corresponding Author: Yoshikatsu Matsumoto, e-mail address: ymatsumoto@tokushima.bunri-u.ac.jp

Electron transports in negative hydrogen ion (H⁻) source plasmas play a key role to decide the performance of H⁻ sources. In order to study the electron transport mechanism, we introduce a novel idea utilizing an electron beam; a small electron gun is installed inside an ion source. It injects an electron beam into an ion source plasma which is already generated and is maintained by another electron source. Then, we expect to observe an enhancement of local electron density along the beam trajectory. The increment in electron density depending upon the distance from the electron gun yields useful information to study the electron transport in the plasma that can be compared with an analysis with Particle-In-Cell (PIC) simulation. In this presentation, we will report the development of the small electron gun.

The width and length of the electron gun are about 3 cm. In the gun, thermal electrons are emitted from a spring-shape tungsten filament. The gun confines these electrons around the filament with a Wehnelt electrode, and generates an electron beam with extraction and deceleration electrodes controlling beam energy and focusing. The extracted electron beam is measured by a movable Faraday cup which can scan the beam current density moving along the beam axis. According to the beam profile, we have confirmed in vacuum that the beam can travel at least 7 mm from the electron gun under the electrode voltage setting corresponding to 1 eV beam energy. We will also show an analysis of the beam profile with the PIC simulation.
The enhancement of output current density of intense pulsed ion beam diode system

Shijian Zhang$^{1,2,3}$, Xiao Yu$^{1,2,3,4}$, Nan Zhang$^{1,2,3}$, Haowen Zhong$^{1,2,3}$, Mofei Xu$^{1,2,3}$, Guoying Liang$^{1,2,3}$, Shicheng Kuang$^{1,2,3}$, Jianhui Ren$^{1,2,3}$, Sha Yan$^5$, Andery Stepanov$^6$, Gennady Efimovich Remnev$^6$, Xiaoyun Le$^{1,2,3}$

$^1$School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China
$^2$Beijing Advanced Innovation Center for Big Data-based Precision Medicine, Beihang University, Beijing 100191, China
$^3$Beijing Key Laboratory of Advanced Nuclear Energy Materials and Physics, Beihang University, Beijing 100191, China
$^4$School of Space and Environment, Beihang University, Beijing 100191, China
$^5$Institute of Heavy Ion Physics, Peking University, Beijing 100871, China
$^6$National Research Tomsk Polytechnic University, Tomsk 634050, Russia

Corresponding Author: Xiaoyun Le, e-mail address: xyle@buaa.edu.cn

Intense pulsed ion beam, as a flash high-power source, has been widely used in fields such as surface modification, film deposition, etc. It is of great significance to enhance the ion beam current density as it is the key parameter in increasing the surface heating effects. In this work, the effect of cone type beam collimator for increasing beam current density in a ballistic focusing pulsed ion beam diode was investigated with calorimetric diagnostics. Collimator of different materials, such as copper, stainless steel and polymer was tested and it is observed that with proper type of collimator, the maximum crosssectional beam energy density can be increased by a factor of over 2. However, a sacrifice in total beam energy and beam diameter may come as a result. Beam energy loss in the collimator was estimated and the applicability of this method in applications was discussed reasonably.
Study of a Ps-laser Generated Plasma as a Source of Singly-Charged Ions for External Injection into an EBIS

Sergey Kondrashev¹, Edward Beebe¹, Takeshi Kanesue¹, Masahiro Okamura¹, John Ritter¹, and Robert Scott²

¹ Brookhaven National Laboratory, Upton, NY 11973, USA
² Argonne National Laboratory, Argonne, IL 60439, USA

Corresponding Author: Sergey Kondrashev, e-mail address: skondrashev@bnl.gov

High rep-rate (~ 10 kHz) ps-lasers are becoming available on the market with reasonable cost and may offer several advantages compared to the ns-laser by generating quasi continuous beams of singly charged ions appropriate for the “slow” injection mode into Electron Beam Ion Source (EBIS). To evaluate these advantages, we will perform a study of a ps-laser generated plasma using a laser with pulse duration of 10 ps and energy up to 5 mJ per pulse. Vacuum chamber equipped with 3D target manipulator, focusing lens and a Faraday Cup (FC) has been designed and built for this study. Ion currents and ion pulse durations of different elements (from Al up to Ta) will be measured for different target irradiation conditions (focal spot size and laser pulse energy). The results obtained will allow us to specify all parameters and geometry of a laser ion source based on a ps-laser for external ion injection into RHIC EBIS.

References and Acknowledgment

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Experimental and simulation investigation of a calcium oven applied to electron cyclotron resonance ion sources

Alexandre Leduc1,2, Laurent Maunoury1, Thomas Thuillier2, Thomas André2, Olivier Bajeat1, Christophe Barué1, Jasua Jacob2, Frédéric Lemagnen1, Patrick Sole2

1GANIL, Bd Henri Becquerel, BP 55027, F-14076 Caen Cedex 05, France
2Laboratoire de Physique Subatomique et de Cosmologie - Université Grenoble Alpes - CNRS/IN2P3 - 53, rue des Martyrs, 38026, Grenoble Cedex, France

Corresponding Author: Alexandre LEDUC, e-mail address: alexandre.leduc@ganil.fr

A low temperature oven has been developed to produce calcium beam in electron cyclotron resonance ion source (ECRIS) plasma. The oven was successfully commissioned with the PHOENIX V3 ECRIS of the SPIRAL2 facility. Several particle microamperes of Ca16+ were produced with a consumption rate of 0.35 mg/h and 12% atom to ion conversion efficiency. In order to better understand the metal atom vapor dynamics in the oven and its ejection from the crucible, a simulation of the oven behavior has been developed. Experiments were carried in a dedicated vacuum chamber to investigate the calcium evaporation as a function of temperature along with the solid angle emission and the role of temperature on calcium evaporation using a quartz crystal microbalance. The simulation results are presented and compared with experimental measurements.
Heavy ion radiotherapy (HI-RT) has good advantages, i.e. the sharply localized dose distribution just on a tumor and the large relative biological effectiveness against radioresistant tumors due to its high linear energy transfer. The technology of HI-RT becomes established during over 40 years of experiences. The clinical results of HI-RT, obtained through scientific protocols and evaluations, have clearly demonstrated its advantages. At the same time the cost of treatment has gone down indebted to the optimization, downsizing, and hypofractionation. HI-RT awakens a worldwide interest. Several countries plan to construct a facility. The authors believe that HI-RT is one of important applications of a modern ion source.

At present, twelve facilities are under operation and six are under commissioning or construction worldwide. All of them mainly use carbon ions for the treatment. An electron cyclotron resonance ion source (ECRIS) is utilized for the production of carbon ions. On the other hand, some research programs have been proposed for a smaller facility or a better irradiation technique in future. It seems there is still room for further development to improve an ion source for HI-RT. We summarize the situation of HI-RT worldwide and consider its perspective.
In the previous work, we demonstrated to provide lithium ion beam production using laser ion source. We used metal lithium as a target material of the laser irradiation. Although intense lithium beam was demonstrated, some operational difficulties were observed. First, metal lithium is highly reactive to oxygen. To prepare the laser targets using metal lithium, all the work needed to be in noble gas environment and fabricated targets were required to be stored in a high vacuum condition. Second, metal lithium has a low melting temperature, 180 °C. When multiple laser irradiation was applied at a small area, the lithium target was easily evaporated. We could not apply several tens of laser shots on a single spot and also evaporated lithium vapor contaminated inside wall of the vacuum system. For accelerator application, more robust and reliable target material has been demanded. Currently we are testing lithium niobate, LiNbO3, and lithium hydroxide. These materials do not require special handling to avoid oxidation and show longer target life. The detailed performances of some lithium compound materials will be reported.

References and Acknowledgment

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A compact H+ ECR ion source is under development. For reduction of the gas load to vacuum evacuation systems, the gas injection into the plasma chamber is chopped by a fast piezoelectric gas valve. To achieve the enough short time constant of gas flow, a small plasma chamber with 50 cm² is adopted and the chamber is operated in 6 GHz TE111 mode. The magnetic field is generated by permanent magnet for reduction of the required volume. The ECR volume is maximized by a multi-mirror magnetic field in a limited plasma chamber volume.
The ITEP ECR light ion source for BELA project

Dmitry Seleznev, Alexander Zarubin, Timur Kulevoy, Viktor Kuzmichev

Corresponding Author: Dmitry Seleznev, e-mail address: selesnev@itep.ru

In the framework of the BELA (Based on ECR ion source Linear Accelerator) project, injection complex based on three ion sources is intended for different tasks. One of the tasks is triple beam irradiation for reactor materials radiation resistance analysis. Heavy (Fe) and light (H2/He) ion beams from ion sources will irradiate a target at the same chamber simultaneously. The paper includes description of ECR light ion source, preliminary results obtained with hydrogen gas.
Studies on the EM modes in a multi-mode ECR cavity

Hitesh Aggrawal¹, G. Rodrigues², P.S Lakshmy², Kedar Mal², Jyotsna Sharma¹, A.C.Pandey²
¹Department of Applied Physics, Amity School of Applied Sciences, Amity University, Haryana, Gurugram, 122413, India
²Inter University Accelerator Center, New Delhi, 110067, India
Corresponding Author: G.Rodrigues, e-mail address: gerosro@gmail.com

Studies on the possible EM modes in the ECR cavity of the 18 GHz High Temperature Superconducting (HTS) ECR ion source have been performed using the CST microwave studio solver and the results have been further verified using COMSOL Multiphysics. The coupling of the EM waves is from a transverse mode (TE_10) to a coaxial mode (TE_mnl/TM_mnl, ECR cavity). Various dominant modes have been identified. The possibility to improve the coupling by directly inserting the waveguide into the ECR cavity has been looked into. The possible effects on the “frequency tuning” technique and the results of the simulations and solutions to improve the coupling will be presented.

References

In the RIKEN Radioactive Isotope Beam Factory (RIBF) project, a superconducting RIKEN linear accelerator (SRILAC) has been implemented to enhance the beam energy necessary for promoting super-heavy element search experiments. A new 28-GHz electron cyclotron resonance ion source (ECRIS) has been installed for SRILAC and the beam commissioning is underway. The control system has been implemented by the programmable logic controller (PLC) with Experimental Physics and Industrial Control System (EPICS) because basically the same control system has been successfully operated for another ECRIS control system for RIBF. On the other hand, the new 28-GHz ECRIS control system is not just a dead copy, improves the reliability of the interlock compared with the conventional system.

From past experience, one of the key points for ECRIS control system needs rapid scalability. By connecting PLC stations utilizing star-topology field bus, the rapid scalability is realized for the sudden use of new devices, such as a power supply of oven system. Furthermore, a unique data acquisition system using a 920 MHz band radio has been developed for measurement of temperature and voltage in a high-voltage stage. This system is useful with rapid scalability, because we can easily install the equipment for data acquisition. In this conference, design of the new 28-GHz SCECRIS control system, the feature, and issues to be solved in the near future are reported in detail.
Numerical simulation of experimental tests performed on ZAO® Non-EvaporableGetter pump designed for NBI applications

M. Siragusa$^{1,3}$, E. Sartori$^{1,3}$, F. Siviero$^2$, M. Mura$^2$, G. Serianni$^1$

$^1$ Consorzio RFX, Corso Stati Uniti 4, 35127 Padova (PD), Italy
$^2$ SAES Getters S.p.A., Viale Italia 77, 20020 Lainate(MI), Italy
$^3$ Università degli Studi di Padova, Via 8 Febbraio 2, I-35122 Padova (PD), Italy
Corresponding Author: G. Serianni, e-mail address: gianluigi.serianni@igi.cnr.it

Vacuum systems of neutral beam injectors have very demanding requirements in terms of pumping speed, throughput and capacity. Due to its high affinity to hydrogenic species, porous sintered non-evaporable getters (NEG) are a possible candidate for the deployment in giant hydrogen ion sources and neutral beam injectors for fusion. This paper presents the numerical interpretation of experimental tests on a recently developed NEG cartridge, part of a modular pump under development for neutral beam injectors. The cartridge is composed by six stacks of ZAO® porous sintered NEG disks and a heater. It was tested under hydrogen loads relevant for neutral beam injectors, namely at constant pressure or constant flow, such that the hydrogen pressure was in the range 20 mPa / 40 mPa. The result of the sorption test was reproduced by a three dimensional flow simulation in molecular regime, to determine the actual pumping speed, the effective sticking coefficient, and the uniformity of the gas load on the various NEG disks. The regeneration procedure was analyzed to determine the desorption rate per unit area and to compare with the equilibrium isotherms. The procedure developed, and the results obtained, provide the basic understanding for interpreting the large-scale tests on the modular pump, consisting of 34 of these cartridges.
A Novel Design of Superconducting Magnet for ECR Ion Source

Enming Mei\textsuperscript{1,2}, Wei Wu\textsuperscript{1}, Liangting Sun\textsuperscript{1,2}, Yu Liang\textsuperscript{1}, Yuquan Chen\textsuperscript{1}, Li Zhu\textsuperscript{1}

\textsuperscript{1}Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding Author: Enming Mei, e-mail address: meiem@impcas.ac.cn

Since the powerful capability of producing high charge state ion for heavy ion and the long lifetime of ECR ion source, it is deemed to be one of the most robust ion source types. So far, the 3rd generation ECR which is built with NbTi superconductor has got a most wonderful performance with reference to ECR used by LBNL and IMPCAS for a long time. But this type of ECR has not got a well spread and further development either in accelerator systems or in other areas. The reason is its inefficiency of electromagnetic design and complexity of mechanical structure design and technical realization. Aim to conquer this embarrassed situation of the 3rd ECR magnet. This paper proposes a novel structure design which is a combination of graded layers of solenoids, Canted-Cosine-Theta and Discrete-Cosine-Theta coils that embedded in the machined grooves. Besides the high magnetic field generation efficiency, this structure can also reduce the accumulation of the coils’ Lorentz forces. The details of the electromagnetic design and the stress analysis of this new magnet structure will be described in this paper.
Thursday, September 5
Optical Characteristics of Negative Ion Beam with Multi-Beam-Axes Produced by LHD-type Negative Ion Source

Kenichi Nagaoka1,2, Yasuaki Haba2, Katsuyoshi Tsumori1,3, Masaki Kisaki1,3, Haruhisa Nakano1,3, Katsumori Ikeda1, Shingo Masaki1, Kenji Miyamoto4, Kazunori Takahashi5 and Masaki Osakabe1,3

1National Institute for Fusion Science, Natural Institutes of Natural Sciences, Toki 509-5292, Japan
2Graduate School of Science, Nagoya University, Nagoya 464-8602, Japan
3SOKENDAI (The Graduate University for Advanced Studies), Toki 509-5292, Japan
4Naruto University of Education, Naruto 772-8502, Japan
5Department of Electrical Engineering, Tohoku University, Sendai 980-8579, Japan

Corresponding Author: Kenichi Nagaoka, e-mail address: nagaoka@nifs.ac.jp

Optimization of negative-ion beam optics is a key issue for high-power negative-ion-based neutral beam injection (NBI) development for application to nuclear fusion research. The application of negative-ion-based NBI to the experiments of magnetically confined plasmas have been successfully demonstrated in Large Helical Device (LHD) and JT60-U, in which filament-arc negative ion sources have been developed. We developed an accelerator with slot-grounded grid for the NBI on LHD and it was simultaneously achieved both to increase beam power and to keep the beam divergence in the low level, typically, around 5 mrad [1]. On the other hand, the beam divergence angle of ITER-like RF negative ion source has not achieved the ITER requirement. Therefore, further understanding of beam optical property of negative ion beam is required to further improvement of beam divergence angle.

In this study, the experimental investigation of the phase space structure (emittance diagram) of negative ion beam produced with a Research & development Negative Ion Source at National Institute for Fusion Science (NIFS-RNIS) which is scaled a half volume to LHD sources was carried out, and three beam components were identified within a single beamlet in horizontal direction, in which the negative ion beam is bended by electron deflection magnetic field. The spatial profile of each beam component is available to be fit with Gaussian profile; i.e. the beamlet is separated into three Gaussian beams. The experimental investigation how the three Gaussian beams behave reveals that the focal condition for 1/e width of each Gaussian beam coincides the condition that three beam axes converges, which is considered as a reason why the divergence angle is so small in our filament-arc source. In the conference, the beam phase space structure in the vertical direction and the origin of three beam axes will also be discussed.

References and Acknowledgment


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Design and development of an Allison type emittance scanner for the SPIDER ion source

Carlo Poggi¹, Emanuele Sartori¹,², Marco Tollin¹, Matteo Brombin¹, Enrico Fagotti³ and Gianluigi Serianni¹

¹ Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete S.p.A.), C. Stati Uniti 4, 35127 Padova, Italy
² Università degli Studi di Padova, Department of Management and Engineering, Padua, Italy
³ INFN-LNL, viale dell’Università 2, 35020 Legnaro (PD) (Italy)

Corresponding Author: Carlo Poggi, e-mail address: carlo.poggi@igi.cnr.it

Low divergence negative ion beams are crucial for the development of ITER-like fusion reactors. SPIDER is the prototype beam source of the ITER Heating Neutral Beam Injector, and it recently started beam acceleration, up to a voltage of 30 kV. The main diagnostics used to measure beamlet divergence are a movable diagnostic calorimeter (STRIKE), which gives the thermal footprint of the beamlets, beam emission spectroscopy and visible imaging. These systems do not allow a direct measurement of single beamlet phase-space distribution, which is useful for the comparison with numerical simulations and to estimate accelerator performances. To this purpose, a movable Allison type emittance scanner for the SPIDER negative ion beam was developed and proposed for the installation on the STRIKE supporting structure. This paper describes the numerical analyses performed to dimension the mechanical and electrical components, such as the Faraday cup and the slits. An analytical approach based on the integration of an arbitrary phase-space distribution was adopted in order to simulate the device performances. The constraints due to the operation in a high heat load environment are discussed.
ThuM02 18th International Conference on Ion Sources

**Generation of boron ion beam by different methods**

Efim Oks¹, George Yushkov², Alexey Nikolaev², Alexey Vizir², Vasily Gushenets², Konstantin Savkin², Maxim Shandrikov²

¹Institute of High Current Electronics, Russian Academy of Sciences, Tomsk, 634055, Russia
²High Current Electronics Institute

Corresponding Author: Efim Oks, e-mail address: bull56@mail.ru

The report provides an overview of recent work on the generation of boron ions in the laboratory of Plasma Sources of the Institute of High-Current Electronics, Tomsk, Russia. To obtain boron ions, pulsed discharge systems of a vacuum arc discharge and a high-current magnetron discharge in self-sputtering mode were used. In both discharge systems, cathodes from pure boron and lanthanum hexaboride were used to generate boron-containing plasma. In the experiments, the main attention was paid to the study of the mass-charge composition of the ion beam and the search for conditions provided the achievement of the maximum fraction of boron ions in the ion beam.
Optically-pumped polarized H\(^-\) and \(^3\)He\(^{++}\) ion sources development at RHIC

Anatoli Zelenski
Brookhaven National Laboratory, Upton, NY 11973, USA
Corresponding Author: Anatoli Zelenski, e-mail address: zelenski@bnl.gov

The RHIC Optically-pumped Polarized H- Ion Source (OPPIS) upgrade with the atomic beam hydrogen injector and the He-ionizer cell was commissioned for operation in the Run-2013. The use of the high brightness primary proton source resulted in higher polarized beam intensity and polarization delivered for injection to Linac-Booster-AGS-RHIC accelerator complex. The proposed polarized \(^3\)He\(^{++}\) acceleration in RHIC and future electron- ion collider (eRHIC) will require about \(2 \times 10^{11}\) ions in the source pulse. A new technique had been proposed for production of high intensity polarized \(^3\)He\(^{++}\) ion beam. It is based on ionization and accumulation of the \(^3\)He gas (polarized by optical-pumping and metastability-exchange technique in the high magnetic field of a 5.0 T) in the Electron Beam Ion Source (EBIS). We present a status of the \(^3\)He\(^{++}\) ion source development.
Achievement of High Power and Long Pulse Negative Ion Beam Acceleration for JT-60SA NBI

Junichi Hiratsuka¹, Mieko Kashiwagi¹, Masahiro Ichikawa¹, Naotaka Umeda¹, Glynnis Mae Q. Saquilayan¹, Himyuki Tobari¹, Kazuhiro Watanabe¹, Atsushi Kojima¹, and Masafumi Yoshida²

¹National Institutes for Quantum and Radiological Science and Technology (QST), 801-1 Mukoyama, Naka 311-0193, Japan
²Yamaguchi University, Department of Electrical, Electronic, and Information Engineering, Ube 755-8611, Japan

Corresponding Author: Junichi Hiratsuka, e-mail address: hiratsuka.junichi@qst.go.jp

High power density of hydrogen negative ion beams with over 70 MW/m² at the energy of 500 keV has been demonstrated stably over 100 s by using a multi-aperture and three-stage accelerator. Such continuous negative ion beam accelerations over 100 s with high power density has never been achieved before in the world. This result fulfills the requirement of the negative ion source for the neutral beam injector (NBI) of JT-60SA (500 keV, 130 A/m² for 100 s) and also contributes to the 1 MeV negative ion accelerator for the ITER NBI.

In this negative ion source, Cesium (Cs) is seeded to enhance the negative ion production near the plasma grid. However, anomalous discharge, so-called arcing, which causes damage on filament, was observed when the Cs is seeded. This has limited the arc power and pulse length. In addition, negative ion current was gradually decreasing after 50 s because Cs evaporated from the chamber wall excessively deposits on the plasma grid when the chamber wall temperature is increased over 60 degree Celsius [1, 2]. For high energy beam acceleration, it has been concerned that the voltage holding capability is degraded when Cs leaks to the accelerator.

In this test, a small KAMABOKO ion source is attached on the top of the three-stage accelerator, whose aperture arrangement and the gap lengths are the same ones as the negative ion source of JT-60SA. To inject the necessary arc power with less filament damage, the input energy to the filament was successfully reduced from 10.6 J to 0.4 J by installing fast cutoff system of the arc power supply at 500 kV stage. To maintain the stable negative ion production, excess Cs from the chamber wall to the plasma grid could be suppressed by maintaining the wall temperature around 50 degree Celsius. As the result, 500 keV and 130 A/m² beams have been achieved. The power loads on each acceleration grid were lower than the allowable value of 5 % of the total beam power. Then, the pulse length was gradually extended. Even though the power loads on the grid was sufficiently low for the long pulse operation, the pulse length was limited up to 60 s initially due to breakdowns. This result indicates that cause of the breakdown is not only the thermal loads on the acceleration grids but also particle incident to these grids by beams. To extend the pulse length, the long pulse beam acceleration has been tried at slightly low energy of 400 keV. Consequently, the pulse length has been gradually extended over 60 s, and finally reached to 175 s. After that, pulse length of 500 keV beam was gradually extended, and reached over 100 s. Finally, acceleration of 500 keV, 154 A/m² beams for 118 s has been achieved. No degradation of voltage holding capability for extraction and acceleration was observed even after the total amount of Cs injection corresponded to the same level of JT-60U by extrapolation of the chamber size. These operational technique for long pulse operation can be directly applied to JT-60SA NBI, and contribute to the ITER accelerator.

References and Acknowledgment
Installation and Commissioning of the Ion Source Systems for the New SNS 2.5 MeV Injector

Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
Corresponding Author: R.F. Welton, e-mail address: welton@ornl.gov

The U.S. Spallation Neutron Source (SNS) is a state-of-the-art neutron scattering facility delivering the world’s most intense pulsed neutron beams to a wide array of instruments which are used to conduct investigations in many fields of engineering, physics, chemistry, material science and biology. Neutrons are produced by spallation of liquid Hg by bombardment of short (~1μs), intense (~40A) pulses of protons delivered at 60 Hz by a storage ring which is fed by a high-intensity, 1 GeV H- LINAC. This facility has operated nearly continuously since 2006 but has recently undergone a 4-month maintenance period which featured a complete replacement of the 2.5 MeV injector feeding the LINAC. The new injector was developed at ORNL in an off-line beam test facility and consists of an ion source, Low Energy Beam Transport (LEBT) and Radio Frequency Quadrupole (RFQ). This report first describes the installed configuration of the new injector detailing the ion source system. The first beam current, RFQ transmission, emittance and energy measurements from the injector installed on the SNS are reported which not only show a significant performance improvement for our existing facility but will now make accessible the higher beam current requirements for future SNS upgrade projects: the Proton Power Upgrade (PPU) and Second Target Station (STS).
A new inorganic material, C12A7 electride [1,2] has been experimentally studied as a candidate material for Cs-free hydrogen negative ion (H-) sources. A high production rate of H- was observed from a C12A7 electride surface immersed in hydrogen/deuterium low-pressure plasmas [3]. In our previous work using a compact ECR ion source [4], it was found that the H-current extracted from the source with an electride Plasma Electrode (PE) is higher than that with a clean molybdenum, by a factor of 80-100, as expected from the experimental results at Marseille [3]. However, the absolute values of beam intensity were too low for an actual use and the dependence of H-current on the microwave power, was not observed clearly.

In the present study, key issues to realize a compact H-source for the actual use in accelerator injectors are investigated. Firstly, the ECR ion source was modified so that a dense plasma from the ECR region could be injected directly towards the PE. Preliminary results showed a clear dependence on the microwave power and the H-current increased by more than a factor 10.

In H-production on the cesiated metal surface, the work function (WF) of the surface plays the essential role because the H-electron might transfer back to empty states of the conduction band during it is moving away from the surface. In case of C12A7 electrode, the connected cages form a new conduction band called “cage conduction band” (CCB). The WF from CCB is as low as 2.4 eV, but there is a wide gap to valence band maximum (~5.5 eV) from CCB. Moreover, it is reported that some of the encaged electron are replaced by the H- ions when the electride is exposed to hydrogen circumstance. Considering these aspects, the effect of the extraction hole shape, and the correlation to the surface work function of the electride PE will be studied, and prospects to a H-source for the actual use will be discussed.

References and Acknowledgment
A Pre-injector Upgrade for the ISIS Pulsed Spallation Neutron Facility, Including a Medium Energy Beam Transport Line and an RF-Driven, Non-Caesiated, External-Antenna H⁻ Ion Source

Scott R Lawrie, Rob E Abel, Chris A Cahill, Dan C Faircloth, John H Macgregor, Sunil Patel, Tiago CdM Sarmento, Jon Speed, Olli A Tarvainen, Mark O Whitehead, Trevor W Wood and Dan Zacek

UK Research and Innovation, ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Oxfordshire, UK

Corresponding Author: Scott Lawrie, e-mail address: scott.lawrie@stfc.ac.uk

The ISIS pulsed spallation facility at the Rutherford Appleton Laboratory has been delivering powerful beams of neutrons and muons for materials characterization studies since 1984. The negative hydrogen (H⁻) linac was upgraded in 2004 with the addition of a 'pre-injector' based around a 665 keV radio-frequency quadrupole (RFQ). A Penning-type caesium-enhanced surface-plasma ion source supplies the pre-injector with around 55 mA of H⁻ beam current. Limitations in beam transport efficiency from both the ion source and between the RFQ and drift-tube linac (DTL) mean over 50% of beam current is lost between the ion source and synchrotron. Moreover, the Penning source lifetime is limited by cathode material sputtering inside the plasma discharge chamber. As such, facility operations must be stopped every two to three weeks to replace the ion source.

To address these issues, a project is underway to upgrade the pre-injector with the addition of a medium-energy beam transport (MEBT) line. A fast electrostatic sweep chopper is included in the MEBT and will notch the linac bunch train at the synchrotron frequency. The MEBT and chopper will increase beam transport efficiency significantly, reducing the output H⁻ current requirements from the ion source. As such, a long-lifetime, non-caesiated, RF-driven, external-antenna H⁻ ion source based on the successful CERN Linac4 and SNS designs is being constructed which will improve facility up-time and reliability.

This paper will highlight latest developments on the MEBT before focusing on the RF ion source. The RF ion source must deliver 35 mA of H⁻ beam current in pulses 400 µs long at 50 Hz repetition rate, with a transverse normalised 4.RMS emittance less than 1.2 π mm mrad. The beam current and emittance are within reach of a non-caesiated H⁻ source, whereas operating at relatively high duty cycles presents challenges in terms of thermal management. In particular, serious consideration must be paid to safe removal of a high current co-extracted electron beam.

Other novel developments to be discussed include a low power electron source as a plasma igniter, a solid-state 2 MHz 100 kW RF amplifier, a 3D-printed cooling jacket, an adjustable permanent-magnet filter field and low energy beam transport (LEBT) beam tracking studies. The detailed ion source and LEBT designs are complete and first machined components are due at the end of 2019. Vacuum, high voltage and interlocks commissioning will start in Spring 2020, with first beam expected towards the end of 2020.
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The role of ion sources in synthesis of the super-heavy elements

Andrey Efremov, Sergey Bogomolov, Vladimir Mironov
Joint Institute for Nuclear Research, Dubna, Moscow region, Russia
Corresponding Author: Andrey Efremov, e-mail address: aefremov@jinr.ru

Since the early 70s, attempts to synthesize Super Heavy Elements (SHE) have been made in many laboratories around the world. One of the main requirements of these experiments is a sufficiently large dose of target irradiation, which should be increased with a decrease in the reaction cross section. In this regard, the capacities of ion sources play an important role for the successful synthesis of SHE.

At the FLNR JINR the discovery and investigation of the new region of super heavy nuclei were based on fusion reactions of $^{48}$Ca with $^{238,240}$U–$^{249}$Cf target nuclei. In these experiments, a technique for the production of metallic $^{48}$Ca was developed. The operation mode of the ECR ion source was set to optimize the intensity of $^{48}$Ca ions and attain maximum ionization efficiency.

Because of the heaviest target for experiments on synthesis of SHE in heavy ion reactions is $^{249}$Cf, so further progress in the synthesis of elements with $Z > 118$ requires the production of intense beams of accelerated neutron enriched isotopes, such as $^{50}$Ti, $^{58}$Fe, $^{64}$Ni, etc.
The transition from old space to new space along with increasing commercialization has a major impact on space flight in general and on electric propulsion by ion sources in particular. The requirements of space industry for electric propulsion systems, e.g., ion thrusters as well as their peripheral devices, change rapidly. We will discuss some of the major developments and corresponding research tasks arising. Commercialization implies mass production at a low price. This has at least two major impacts: (i) shorter product development cycles, i.e., new products should enter the market more rapidly, and (ii) resource efficiency become important. For example, shorter development times require that the qualification procedures for thruster systems need to be rethought. How much ground testing is necessary? How can modelling help to speed up qualification and to predict lifetimes and performance in space? Resource efficiency implies that scarce materials should be avoided, e.g. xenon is scarce and not enough xenon is available as propellant for electric propulsion as a mass product, at least, not at a compatible price. Alternatives need to be sought. Are there suitable molecular propellants and what is the right strategy finding them? Is reactive iodine a cheap alternative to xenon as propellant? Prices of electric propulsion systems may also be considerably lowered by employing commercially available electronic components as part of the electric propulsion system. These components may have to be used beyond their specifications under extreme conditions, e.g., in the radiation environment of the Van-Allen belt. How to find suitable radiation-hard electronics? Formation flights of cheap and small satellites are an essential part of a data network. What does miniaturization imply? To which extent are current electric propulsion systems miniaturizable? How can electromagnetic compatibility with the environment on the satellite be tested and guaranteed?
The capabilities of ion-beam techniques for thin-film processing, i.e., for materials deposition by ion-beam sputtering and surface treatment, are reviewed. The basic interaction mechanisms between ions and solids are summarized and related to materials processing by ion sources. The applicability of ion-beam techniques in the controlled modification of surfaces is discussed and critically compared with wet-chemical etching procedures. Masking areas of a sample surface and, thus, protecting the surface below the mask from ion bombardment, is the basis of structuring surfaces by ion-beam etching. On the microscale and nanoscale, masks as structured coatings are typically generated by lithographic methods such as photolithography and electron-beam lithography.

Examples will be given, how ion-beam technology can unfold its potential in modifying surface topography by means of broad-beam bombardment with positively charged ions. Herein, we will focus on the transfer of the extraction grid pattern into primary and secondary beam.
Present status of ion sources at QST-NIRS and carbon-ion radiotherapy facilities

Masayuki Muramatsu¹, Atsushi Kitagawa¹, Ken Katagiri¹, Satoru Hojo¹, Takashi Wakui¹, Noriyoshi Suya¹, Mitsuru Suda¹, Takahiro Ishikawa¹, Masakazu Oikawa¹, Tsuyoshi Hamano¹, Katsuyuki Takahashi², Taku Suzuki², Fumihisa Ouchi², Hiroshi Li², Tadahiro Shiraishi², Toshinobu Sasano²

¹National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology (NIRS-QST), 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan
²Accelerator Engineering Corporation, 3-8-5 Konakadai, Inage, Chiba 263-0043, Japan

Corresponding Author: Masayuki Muramatsu, e-mail address: muramatsu.masayuki@qst.go.jp

NIRS-QST carries out research and development (R&D) life sciences, including: the effects of radiation on the human body; protection from radiation, including diagnosis and treatment of radiation injuries; and medical applications of radiation. To fulfill its R&D aims, NIRS-QST maintains a number of accelerators, including: two tandem accelerators, one large heavy-ion accelerator complex consisting of two synchrotrons and four linacs for heavy-ion radiotherapy, and three cyclotrons. Various types of ion sources supply the ion species required by the accelerators, and are used across various ion beam applications. A duoplasmatron ion source is installed in the 1.7 MV tandem accelerator for experiments requiring a particle-induced x-ray emission (PIXE) and micro beam irradiation systems. A multi-cusp ion source is installed in the 2.0 MV tandem accelerator for studies requiring neutron exposure. An ECR ion source is installed in the K=110 cyclotron (NIRS-930) not only for nuclear medicine but also for biology, physics, and material science experiments. The Heavy Ion Medical Accelerator in Chiba (HIMAC) has been used to conduct heavy-ion radiotherapy and basic experiments since 1994. Three electron cyclotron resonance (ECR) ion sources and a Penning ionization gauge (PIG) ion source are installed in the injector system of HIMAC. PIG ion sources are also installed in the two commercial cyclotrons for nuclear medicine. In this paper, the status of ion sources and some results of development are described.

A compact ECR ion source, named Kei2, has been developed for carbon-ion radiotherapy at QST-NIRS. After the successful performance test, Kei-series, a commercial version of Kei2, are used at four Japanese facilities at present and another will be installed in the 7th facility in Japan. Additionally, two sources are under construction at Seoul and Taipei. These facilities are optimized for the production of only carbon ions in order to reduce the initial construction cost and efforts of operation. Since one Kei-series source is installed in each facility, the reliability of ion source is very important. All Kei-series have sustained daily treatment. The status of Kei series is also reported.
We are proposing a compact neutron generator based on Li beam driver. Nowadays, many proposals of small size neutron generator using Li (p, n) Be or Be (p, n) B reactions are seen, since availability of research nuclear reactor is getting difficult. These reactions are endothermic and undesired radiations could be reduced, because no nuclear reactions are expected below the threshold energies. Although, most of the proposals are planned to use proton beams provided by accelerators, we are proposing to use fully stripped Li ions as a driver beam. By using Li beam, we could eliminate unwanted radiation dramatically. 7Li is seven times heavier than proton and the gravity center of the nuclear reaction keeps on moving forward. As a result, neutron emissions are well directed to forward. This feature may enable us to build very clean neutron generator.

The proposed accelerator system comprises, laser ion source, RFQ, DTL and hydrogen gas target. We have developed very intense heavy ion beam using direct plasma injection scheme (DPIS) and plasma window. Those two key technologies are applied to realize a new compact neutron generator. At the conference feasibility of the system, especially focusing on the ion source part, will be discussed.

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Shanghai Kelin Technology Development Co. Ltd. was established in May 1999. It is the only one of China’s private companies to participate in the development of accelerator equipment for Proton Therapy. It is one of the members of the China Particle Accelerator Association. It is a high-tech enterprise in Shanghai, has undertaken several national major project projects and Shanghai major project projects, and has won the Shanghai science and technology achievement recognition certificate and Shanghai municipal new product award for many times. Main business for particle accelerator equipment research and development, manufacturing and assembly integration. The products involve the research and development of nuclear physics, particle accelerator, aerospace, nuclear medicine and other fields. The equipment supplied includes electromagnet, RFQ, IH-DTL, APE-DTL, IE-Buncher, Re-Buncher, High frequency vacuum chamber, Undulator and beam line experiments, etc. We owns more than ten invention and utility model patents.
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Contact: Huoyin Zhai+86-13909466094, E-mail: ruyiyan188@139.com
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天津盛科泰控科技有限公司（天源科能）: 电话: 022-24051321 传真: 022-24051320/1-8600
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Lanzhou, China 217
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