Overview of High Intensity Ion Source Development in the Past 20 Years at IMP

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On behalf of the team members at IMP

Institute of Modern Physics, CAS, 730000, Lanzhou, China

ICIS’19, Sept. 1~6, 2019, Lanzhou, China
Outline

- The needs of high intensity ion beams at IMP
- Development of diverse high intensity ion sources at IMP
- Opportunities and Challenges
Needs

- Nuclear physics
- Atomic physics
- Nuclear chemistry
- Radiation chemistry
- Material science
- Hadron physics
- High Energy Density physics
- Accelerator physics

- Radiation biology
- Radiation medical science
- Radiation material
- Advanced nuclear energy
- Nuclear detecting technology

- Ion Accelerator
- Large scale experiment facilities
- Special experiment facilities

◆ >400 internal researchers
◆ >1000 ion beam users
Heavy Ion Research Facility in Lanzhou (HIRFL)

**SSC (K=450) - 1990s**
- 100 AMeV (H.I.), 110 MeV (p)

**SFC (K=69) - 1970s**
- 10 AMeV (H.I.), 17–35 MeV (p)

**CSR(Cooling Storage Ring)**
- CSRm 162 m - 2000s
  - 1000 AMeV (H.I.), ≤ 2.8 GeV (p)

**RIBLL1**
- RIBs at tens of AMeV

**RIBLL2**
- RIBs at hundreds of AMeV

**CSRé 128 m**

High intensity high charge state ion beams
 Needs

CiADS (2019-2025)

2.45 GHz ECR source

HIMM

14 GHz ECR source

HIAF (2018-2025)

HFRS

SECR

iLINAC

SESRI (2018-2022)

18 GHz ECR source
Development of Ion Sources: ECRIS

- Multi-purpose
- Medium charge state ions for HIRFL
- Heavy ions for HIRFL

Graph showing the relationship between maximum charge states and microwave frequency (GHz).
Highly Charged ECRIS

Electron Cyclotron Resonance Ion Source

\[ \omega_{ce} = \frac{e \cdot B_{ecr}}{m_e} \]

- \( I_i^q = \frac{1}{2} \frac{n_i^q q e V_{ex}}{\tau_i^q} \) ion density for species i charge q
- \( \tau_i^q \) Confinement time for species i charge q
- \( \sum_{i,q} n_i^q q_i = n_e \) (Plasma neutrality)

- RF dispersion equation at resonance: \( (n_e T_e) \approx \left( \frac{m_e e_0 \omega_{df}}{e^2} \right) m_e c^2 \)

- Plasma Stability condition: \( \beta = \frac{n_e k_b T_e}{B^2} < 1 \)
  As \( n_e \uparrow \) \( B \uparrow \)
Highly Charged ECRIS

Family of ECRISs

All permanent magnet ECRIS
- Nanogan series ion sources
- BIE series ion sources
- LAPECR1, LAPECR2, LAPECR3
- Kei1, Kei2
- SOPHIE
- Operated 2.45 ~ 14 GHz

Classical RM ECRIS
- GTS source
- AECR-U
- LECR2, LECR3, LECR4
- RIKEN 18 GHz
- ECR4, Caprice
- Operated 10 ~ 18 GHz

Hybrid SC-ECRIS
- RAMSE, SHIVA
- A-PHOENIX
- PKDELIS
- Dubna 18 GHz
- Operated 14 ~ 18 GHz

Fully SC-ECRIS
- SERSE 18 GHz
- VENUS 28GHz
- SECRAL 18~28 GHz
- SUSI 18~24 GHz
- RIKEN SCECRIS 28 GHz
- Operated 18 ~ 28 GHz

For intense low and medium charge state ion beams: O^{6+}, Ar^{8+}, Xe^{20+}...

For intense medium and high charge state ion beams: Ar^{14+}, Xe^{27+}, Bi^{30+}...

For intense high charge state ion beams: Ar^{16+}, Xe^{30+}, Bi^{36+}, U^{38+}...
Highly Charged ECRIS: Superconducting Sources

- $J_c \leq 11.0 \, \text{A/mm}^2$
- $B_r \leq 1.4 \, \text{T}$
- $\omega_{ecr} \geq 18 \, \text{GHz}$

<table>
<thead>
<tr>
<th>$\omega_{ecr}$ (GHz)</th>
<th>$B_{ecr}$ (T)</th>
<th>$B_{inj}$ (T)</th>
<th>$B_r$ (T)</th>
<th>PM</th>
<th>RM</th>
<th>SC</th>
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<tbody>
<tr>
<td>10</td>
<td>0.36</td>
<td>1.4</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td>0.52</td>
<td>2.0</td>
<td>1.0</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>18</td>
<td>0.64</td>
<td>2.6</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>1.0</td>
<td>4.0</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Superconducting technology to high performance ECRISs with $\omega_{ecr} \geq 18 \, \text{GHz}$
Highly Charged ECRIS: Superconducting Sources

- VENUS/LBNL
- SCECRIS/RIKEN
- SuSI/MSU
- SERSE/INFN-LNS
- ...

Conventional

Reversed Design

Min-B Confinement
Highly Charged ECRIS: Superconducting Sources

Operation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SECRLAL-II</th>
<th>SECRLAL*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{rf}$ (GHz)</td>
<td>18-28</td>
<td>18-24</td>
</tr>
<tr>
<td>Axial Field Peaks (T)</td>
<td>3.7 (Inj.), 2.2 (Ext.)</td>
<td>3.7 (Inj.), 2.2 (Ext.)</td>
</tr>
<tr>
<td>Mirror Length (mm)</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>No. of Axial SNs</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$B_z$ at Chamber Inner Wall (T)</td>
<td>2.0</td>
<td>1.7/1.83</td>
</tr>
<tr>
<td>Coldmass Length (mm)</td>
<td>~810</td>
<td>~810</td>
</tr>
<tr>
<td>SC-material</td>
<td>NbTi</td>
<td>NbTi</td>
</tr>
<tr>
<td>Magnet Cooling</td>
<td>LHe bathing</td>
<td>LHe bathing</td>
</tr>
<tr>
<td>Warm bore ID (mm)</td>
<td>142.0</td>
<td>140.0</td>
</tr>
<tr>
<td>Chamber ID (mm)</td>
<td>125.0</td>
<td>116.0/120.5</td>
</tr>
<tr>
<td>Dynamic cooling power (W)</td>
<td>~6</td>
<td>0</td>
</tr>
</tbody>
</table>

* Under upgrade, see W. Lu@TueP18
Highly Charged ECRIS: Superconducting Sources

Magnet Training Story:

- Lower and Lower risk of Training Quench after warm-up course
- Reach >100% design currents
- No quench happens during operation
Highly Charged ECRIS: Superconducting Sources

SECRLAL-II off-line test bench

28 GHz

Ø32 mm TE₀₁

<table>
<thead>
<tr>
<th>No.</th>
<th>Frequencies (GHz)</th>
<th>Used Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>18+28</td>
<td>12.4</td>
</tr>
<tr>
<td>3</td>
<td>28+45</td>
<td>7.4</td>
</tr>
<tr>
<td>4</td>
<td>18+28+45</td>
<td>7.3</td>
</tr>
<tr>
<td>5</td>
<td>45</td>
<td>4.0</td>
</tr>
</tbody>
</table>
## Highly Charged ECRIS: Superconducting Sources

<table>
<thead>
<tr>
<th>Ion</th>
<th>VENUS 28+18 GHz (~2018, 10 kW)</th>
<th>SECRAL 24+18 GHz (<del>2016, 7</del>8 kW)</th>
<th>SuSI 24+18 GHz (~2014, 5.5 kW)</th>
<th>SECRAL II 28+18 GHz (~2018, 10 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O^{6+}</td>
<td>4750</td>
<td>2300</td>
<td>2200</td>
<td>6700</td>
</tr>
<tr>
<td>O^{7+}</td>
<td>1900</td>
<td>810</td>
<td>1400</td>
<td>1750</td>
</tr>
<tr>
<td>Ar^{12+}</td>
<td>1060</td>
<td>1420</td>
<td>860</td>
<td>1190</td>
</tr>
<tr>
<td>Ar^{14+}</td>
<td>840</td>
<td>846</td>
<td>530</td>
<td>1040</td>
</tr>
<tr>
<td>Ar^{16+}</td>
<td>525</td>
<td>350</td>
<td>220</td>
<td>620</td>
</tr>
<tr>
<td>Ar^{17+}</td>
<td>120</td>
<td>50</td>
<td>--</td>
<td>130</td>
</tr>
<tr>
<td>Ar^{18+}</td>
<td>4.0</td>
<td>--</td>
<td>--</td>
<td>14.6</td>
</tr>
<tr>
<td>Kr^{18+}</td>
<td>770</td>
<td>--</td>
<td>--</td>
<td>1030</td>
</tr>
<tr>
<td>Kr^{23+}</td>
<td>420</td>
<td>--</td>
<td>--</td>
<td>436</td>
</tr>
<tr>
<td>Kr^{28+}</td>
<td>100</td>
<td>--</td>
<td>--</td>
<td>146</td>
</tr>
<tr>
<td>Kr^{30+}</td>
<td>17</td>
<td>--</td>
<td>--</td>
<td>20</td>
</tr>
<tr>
<td>Kr^{31+}</td>
<td>7.0</td>
<td>--</td>
<td>--</td>
<td>7</td>
</tr>
<tr>
<td>Kr^{32+}</td>
<td>7.0</td>
<td>--</td>
<td>--</td>
<td>0.5</td>
</tr>
<tr>
<td>Xe^{25+}</td>
<td>/</td>
<td>1100</td>
<td>920</td>
<td>/</td>
</tr>
<tr>
<td>Xe^{27+}</td>
<td>705</td>
<td>360</td>
<td>120</td>
<td>870</td>
</tr>
<tr>
<td>Xe^{30+}</td>
<td>330</td>
<td>120</td>
<td>22.6</td>
<td>365</td>
</tr>
<tr>
<td>Xe^{34+}</td>
<td>104</td>
<td>22.6</td>
<td>12</td>
<td>135</td>
</tr>
<tr>
<td>Xe^{38+}</td>
<td>26</td>
<td>12</td>
<td>--</td>
<td>56</td>
</tr>
<tr>
<td>Xe^{42+}</td>
<td>6</td>
<td>--</td>
<td>--</td>
<td>16.7</td>
</tr>
<tr>
<td>Xe^{44+}</td>
<td>2</td>
<td>1</td>
<td>--</td>
<td>3.9</td>
</tr>
<tr>
<td>Xe^{45+}</td>
<td>0.88</td>
<td>0.1</td>
<td>--</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Highly Charged ECRIS: Superconducting Sources

- High power microwave coupling via optimum WG opening
- Homogenous ECR surface microwave power radiation → better plasma stability

Efficient microwave coupling & ECRH

See Junwei Guo@WedI04
Highly Charged ECRIS: Superconducting Sources

Multi-frequency ECRH

- Manipulate HCl production with multi-frequency ECRH
- Interfere with HCl confinement
- Very effective for HCl beams

L. Sun@TuA5, ECRIS’18
**Highly Charged ECRIS: Superconducting Sources**

**ECR plasma investigation**

- $T_s$ increases approximately linearly with the increment of $B_{min}/B_{ecr}$ and saturates above a threshold (for 18GHz: $\sim$0.78, 24GHz: $\sim$0.76)
- Electron cyclotron instabilities have been detected simultaneously when $T_s$ is saturated

- $T_s$ decreases with the increase of the gradient at the resonance zone at low mirror ratio
- $T_s$ is not sensitive to the gradient at high mirror ratio when $B_{min}$ is constant

See Jibo Li @MonM02
Highly Charged ECRIS: Superconducting Sources

- Low RF power @18 GHz
- Dual RF feeding @24 GHz + 18 GHz
- Refined oven & new components @24 GHz + 18 GHz
- Dual RF feeding @24 GHz + 18 GHz + Cartridge oven
- Refined cooling to ECR area
- Improved metallic oven techniques
Highly Charged ECRIS: Superconducting Sources

Uranium beam production

A Refined Inductive Heating Oven

Φ18/24 mm
2 mm BN
1.0 mm BN
1.25 mm ZrO2
1 mm Ta
Coils

ID= 8 mm

Ø3 mm copper tube

IHO-2018

Crucible, Thermal Shield & Insulator

Off-line Test

Please See Wang Lu@TueM02

Max. 450 eμA
U^{33+} produced
Intense HCl beams studies

Beam quality and dynamics issues:
- Beam correlation (transverse coupling)
- Sources of high order aberration
- Beam quality improvement

See Yao Yang@WedM01

PEMiL
4-D emittance mapping for better beam quality evaluation

See Xing Fang@WedP16

Sextupole Magnet
2nd order aberration correction
Highly Charged ECRIS: Impact to HIRFL

SECRAL routine operation

- SECRAL served >31,000 hours beam time
  - >58% highly charged metallic ions
  - 26 ion species

SECRAL-II

Ion source drain current (eMA)

- Operation Time log (hrs)

>1,000 hours ~100 eμA Kr^{25+} with SECRAL-II
Highly Charged ECRIS: Room Temperature Sources

**LECR1**
10 GHz (1990)

- $\text{Ar}^{9+}$: 320 µA, $\text{Ar}^{11+}$: 80 µA
- $\text{Kr}^{15+}$: 100 µA, $\text{Kr}^{17+}$: 70 µA

**LECR2**
14.5 GHz (1997)

- $\text{O}^{7+}$: 140 µA, $\text{Ar}^{11+}$: 185 µA
- $\text{Kr}^{19+}$: 50 µA, $\text{Xe}^{26+}$: 50 µA
- $\text{Ca}^{11+}$: 130 µA, $\text{Fe}^{13+}$: 65 µA
- $\text{Zn}^{13+}$: 50 µA, $\text{Pb}^{30+}$: 8 µA

**LECR3**
14.5 GHz (2000)

- $\text{O}^{7+}$: 240 µA, $\text{Ar}^{11+}$: 325 µA
- $\text{Ar}^{8+}$: 1.0 nA, $\text{Xe}^{26+}$: 95 µA
- $\text{Fe}^{13+}$: 141 µA, $\text{Ar}^{17+}$: 0.4 nA
- $\text{Ar}^{18+}$, $\text{Pb}^{40+}$: 0.2 µA

**LECR4**
18 GHz (2013)

- $\text{O}^{7+}$: 560 µA, $\text{Ar}^{11+}$: 620 µA
- $\text{Ar}^{14+}$: 180 µA, $\text{Xe}^{27+}$: 135 µA
- $\text{Bi}^{31+}$: 92 µA, $\text{Bi}^{28+}$: 170 nA
- $\text{U}^{33+}$: 31 µA

**LECR5**
18 GHz (2019)

Commissioning
Highly Charged ECRIS: **Room Temperature Sources**

LECR4-prototype ion source with Evaporative cooling technology:
Based on the principle of **phase change heat transfer**, high insulating and room-temperature boiling point **organic coolant** is used to absorb the heat of electrical equipment.

**Typical source parameters**

<table>
<thead>
<tr>
<th></th>
<th>LECR4</th>
<th>LECR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Frequency (GHz)</td>
<td>18</td>
<td>14.5</td>
</tr>
<tr>
<td>Plasma Chamber (mm)</td>
<td>Ø76</td>
<td>Ø76</td>
</tr>
<tr>
<td>Axial Injection field (T)</td>
<td>&gt;2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Axial Extraction field (T)</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Max. Radial field (T)</td>
<td>1.0-1.1</td>
<td>1.0-1.1</td>
</tr>
<tr>
<td>Total Power (kW)</td>
<td>195</td>
<td>100</td>
</tr>
</tbody>
</table>
HCl beams favors:
- High fields
- Higher frequency

O^{7+} 560 μA, Ar^{11+} 620 μA
Ar^{14+} 180 μA, Xe^{27+} 135 μA
Bi^{31+} 92 μA, Bi^{28+} 170 eμA
U^{33+} 31 eμA.
Highly Charged ECRIS: Room Temperature Sources

LECR5 Typical Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LECR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{rf}$ (GHz)</td>
<td>18</td>
</tr>
<tr>
<td>$P_{rf}$ (kW)</td>
<td>2.5</td>
</tr>
<tr>
<td>$B_{\text{inj}}$ (T)</td>
<td>2.4</td>
</tr>
<tr>
<td>$B_{\text{min}}$ (T)</td>
<td>0.3 ~ 0.63</td>
</tr>
<tr>
<td>$B_{\text{ext}}$ (T)</td>
<td>1.4</td>
</tr>
<tr>
<td>$B_{\text{rad}}$ (T)</td>
<td>1.2</td>
</tr>
<tr>
<td>$L_{\text{mirror}}$ (mm)</td>
<td>340</td>
</tr>
<tr>
<td>Chamber ID (mm)</td>
<td>80</td>
</tr>
<tr>
<td>Extraction HV (kV)</td>
<td>30</td>
</tr>
</tbody>
</table>

An advanced room temperature for SESRI Project needs $>50 \, \mu\text{A} \, ^{209}\text{Bi}^{32+}$
Highly Charged ECRIS: **Room Temperature Sources**

See Cheng Qian@TueP19

**Preliminary Commissioning:**
- 1.35 emA O^{6+}
- 0.45 emA O^{7+}
- 0.26 emA Ar^{12+}
Highly Charged ECRIS: Impact to HIRFL

Contributed by Superconducting and Room Temperature ECR ion source

Beam intensities from SFC

Beam Energies from SFC

Beam Energies from CSRm
Highly Charged ECRIS: Impact to HIRFL

- Synthesis of 20 new nuclides
- Observation of super heavy nuclide $^{271}$Ds (Z=110)
- First mass measurement of 30 short-lived nuclides
- Post evaluation of CSR
Highly Charged ECRIS: Contribution to the Community

Records in solid marks made by IMP
Highly Charged ECRIS: Permanent Magnet Sources

LAPECR1
14.5 GHz (2002)

LAPECR2
14.5 GHz (2005)

LAPECR3
14.5 GHz (2012)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Intensity (eμA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He$^+$</td>
<td>5000</td>
</tr>
<tr>
<td>He$^{2+}$</td>
<td>2500</td>
</tr>
<tr>
<td>N$^{2+}$</td>
<td>&gt;1700</td>
</tr>
<tr>
<td>N$^{5+}$</td>
<td>160</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ion</th>
<th>Intensity (eμA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$^{6+}$</td>
<td>1000</td>
</tr>
<tr>
<td>Ar$^{8+}$</td>
<td>460</td>
</tr>
<tr>
<td>Ar$^{17+}$</td>
<td>2</td>
</tr>
<tr>
<td>Xe$^{20+}$</td>
<td>85</td>
</tr>
<tr>
<td>Ag$^{19+}$</td>
<td>84</td>
</tr>
<tr>
<td>U$^{31+}$</td>
<td>4</td>
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</table>

<table>
<thead>
<tr>
<th>Ion</th>
<th>Intensity (eμA)</th>
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</thead>
<tbody>
<tr>
<td>He$^{2+}$</td>
<td>&gt;6000</td>
</tr>
<tr>
<td>C$^{4+}$</td>
<td>&gt;600</td>
</tr>
<tr>
<td>C$^{5+}$</td>
<td>260</td>
</tr>
<tr>
<td>O$^{6+}$</td>
<td>360</td>
</tr>
<tr>
<td>Ar$^{9+}$</td>
<td>120</td>
</tr>
<tr>
<td>Ar$^{11+}$</td>
<td>50</td>
</tr>
</tbody>
</table>
Highly Charged ECRIS: Permanent Magnet Sources

Typical ion beams from 29 atoms:
- Gaseous ions: H, D, He, N, O, Ne, Ar, Xe, Kr, Cl, F
- Metal ions: U, Bi, Pb, Au, Ag, Eu, Fe, Ni, Ti, Mg, Cs, C, Li
- Ions from non-metal solids: C, Si, I, S, Br

Ion Beams Available:
- Ions: H⁺—U⁴³⁺
- Platform Voltage: 5 kV—320 kV
- Ion Energy: 5 keV—10 MeV
- Ion species: 200 /Year (i.e. Xe⁵⁺—Xe³⁰⁺, Ar¹⁺—Ar¹⁶⁺)

Total operation time: 85,000 hours
- Experiment time: 67,000 hours ----85%
- Down time: 4,300 hours --------7%
- Machine study: 4,700 hours -----7.7%
- Completed experiments: >670
Highly Charged ECRIS: Permanent Magnet Sources

LAPECR3 Test Bench

C⁴⁺ current

εₓ.n.rms = 0.06 πmm.mrad
εᵧ.n.rms = 0.10 πmm.mrad

See Jiaqing Li@MonP30
Laser Ion Source Development

- Production of high intensity heavy ion beams
- Reliable intense C^{6+} beam production
- Investigation on DPIS
- Investigation on laser produced plasma
Laser Ion Source Development

Production of high intensity heavy ion beams

- **Light to medium-mass elements:**
  - Currents--tens of emA
  - CSD--narrowed down around high charge states

- **Heavy elements:**
  - both currents and charge states much lower—needing of higher laser power

Time waveforms of the total ion beam pulses

Charge state distributions
Laser Ion Source Development

Reliable intense C\(^{6+}\) beam production

- Repeatability of laser focus condition on target
  - Stability of laser system
  - Precision of target movement

- Long-term capability of target
  - Cylindrical target with much larger surface compared with flat one

Repeatability of carbon ion pulses @0.33 Hz

Statistics for 2000 carbon ion pulses

<table>
<thead>
<tr>
<th>Pulse parameter</th>
<th>Mean value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current (emA)</td>
<td>46.5</td>
<td>3.1 (6.7%)</td>
</tr>
<tr>
<td>Total charge quantity (10(^{-7}) C)</td>
<td>1.38</td>
<td>0.048 (3.5%)</td>
</tr>
<tr>
<td>Pulse duration-FWHM (μs)</td>
<td>1.64</td>
<td>0.16 (10%)</td>
</tr>
</tbody>
</table>

See Huanyu Zhao@TueM03
Laser Ion Source Development

DPIS investigation

- With DPIS, C$_{6}^{+}$ was accelerated to 596 keV/u with the peak current of 13 emA


- A Hybrid Single Chamber-HSC (RFQ+DTL) PoP demonstrated

L. Lu, et al., PRAB 18, 111002 (2015)
2.45 GHz Proton Sources

1999
Neutron Source

2011
Neutron Source

2014
C-ADS

2016
JUNA

2017
39Ar Enrichment
2.45 GHz Proton Sources

Compact Pulsed Hadron Source (CPHS) at Tsinghua University

Ion Source Parameters

<table>
<thead>
<tr>
<th>Para.</th>
<th>Required</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (keV)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>H⁺ Current (mA)</td>
<td>≥ 60 emA</td>
<td>66</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>50 Hz</td>
<td>50</td>
</tr>
<tr>
<td>Pulse width (ms)</td>
<td>0.5 ms</td>
<td>0.5</td>
</tr>
<tr>
<td>Reliability</td>
<td>&gt;120 hrs</td>
<td>120</td>
</tr>
<tr>
<td>Operation time (hrs)</td>
<td>&gt;1000/yr</td>
<td></td>
</tr>
</tbody>
</table>

~10^{13} n/s epithermal-to-cold neutron yield for education, instrumentation development, and industrial applications

Courtesy of Q. Z. XING, et al from Tsinghua University

66 mA

LEBT output beam
### 2.45 GHz Proton Sources

#### ECR+ LEBT

#### C-ADS RFQ

#### C-ADS SRF Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>status</th>
<th>request</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle energy (keV)</td>
<td>35keV</td>
<td>35keV</td>
</tr>
<tr>
<td>Proton current (mA)</td>
<td>≥10mA/dc</td>
<td>10mA/dc</td>
</tr>
<tr>
<td>Beam tuning (uA)</td>
<td>~10</td>
<td>≤100</td>
</tr>
<tr>
<td>Reliability (hrs)</td>
<td>&gt;24</td>
<td>&gt;8</td>
</tr>
<tr>
<td>Fast Chopper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast protect</td>
<td>1 μs</td>
<td>≤5 μs</td>
</tr>
<tr>
<td>Leading edge</td>
<td>17 ns</td>
<td>20 ns</td>
</tr>
<tr>
<td>Trailing edge</td>
<td>17 ns</td>
<td>20 ns</td>
</tr>
<tr>
<td>frequency</td>
<td>1-10 kHz</td>
<td>1-20 Hz</td>
</tr>
</tbody>
</table>

- **Total operation time >4,000 hours**
- **Fully satisfy the high intensity SRF-linac commissioning**
  - **Pulsed: 26.1 MeV@12.6 mA**
  - **CW: 25 MeV@1 mA**
### 2.45 GHz Proton Sources

**Jinping Underground Laboratory for Nuclear Astrophysics (JUNA)**

Deep underground provides best natural background condition

- $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
- $^{13}\text{C}(\alpha, n)^{16}\text{O}$
- $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$
- $^{19}\text{F}(p, \alpha)^{16}\text{O}$

<table>
<thead>
<tr>
<th>Source type</th>
<th>JUNA Facility Design</th>
<th>Ion Source Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source type</td>
<td>ECR source</td>
<td>2.45 GHz +14GHz</td>
</tr>
<tr>
<td>Beam</td>
<td>H$^+$</td>
<td>10 mA</td>
</tr>
<tr>
<td></td>
<td>He$^+$</td>
<td>10 mA</td>
</tr>
<tr>
<td></td>
<td>He$^{2+}$</td>
<td>1~2.5 mA</td>
</tr>
<tr>
<td>Beam energy</td>
<td>70~800 keV</td>
<td>20~50 kV</td>
</tr>
</tbody>
</table>

See Qi Wu@MonP27
2.45 GHz Proton Sources

- \[^{39}\text{Ar}\] enrichment by a factor of \(>100\)
- \[^{39}\text{Ar}\] enrichment + ATTA = \[^{39}\text{Ar}\] dating

See Zehua Jia@MonP28
Opportunities and Challenges

**HIAF**

- **2018-2025**

  - **BRing:** Booster ring
    - C: 569 m
    - Bp: 34 Tm
    - E: 0.834 GeV/u
    - I: $1.0 \times 10^{11}$ ppp ($U^{35+}$)

  - **SRing:** Spectrometer ring
    - C: 278 m
    - Bp: 15 Tm

  - **iLinac:** Superconducting linac
    - L: 100 m
    - E: 17 MeV/u ($^{238}U^{35+}$)
    - I: 1 emA

  - **SECR**

**Phase-I (2025)**
- CW: 0.5 emA $U^{46+}$
- 1.0 emA $U^{35+}/0.3-5$ Hz@0.2-2 ms

**Phase-II (2030)**
- 10 emA $U^{46+}/20$ Hz@2 ms
Opportunities and Challenges

FEKR (First 4th generation ECR ion source)

Specs. of a 45 GHz ECRIS

<table>
<thead>
<tr>
<th>Specs</th>
<th>Unit</th>
<th>45 GHz ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>45</td>
</tr>
<tr>
<td>Mirror Fields</td>
<td>T</td>
<td>6.4/3.2</td>
</tr>
<tr>
<td>$B_{rad}$</td>
<td>T</td>
<td>3.2</td>
</tr>
<tr>
<td>Mirror Length</td>
<td>mm</td>
<td>~500</td>
</tr>
<tr>
<td>Magnet coils</td>
<td>/</td>
<td>Nb$_3$Sn</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td></td>
<td>$J&gt;1500$ A/mm$^2$@12T</td>
</tr>
<tr>
<td>Cooling Capacity@4.2 K</td>
<td>W</td>
<td>10.0</td>
</tr>
</tbody>
</table>

HCl currents with a 4th G. ECRIS:
- $A=12$~40, 200 puA (dc)
- $A=40$~100, 100 puA (dc)
- $A=100$~238, 30 puA (dc), 50 puA (pulse)

Obvious progress been made, see Poster TueP20 by H. W. Zhao
Opportunities and Challenges

- Long term stable operation for ECR with high beam intensity at the power of >5 kW (>10 MW/cm² heat sink)
  - Stability
  - Reliability

- Beam quality for high intensity ion beams
  - Emittance control
  - High efficiency transmission

![Plasma heat sink into plasma chamber](image)
Opportunities and Challenges

Frequency Campaign

- Higher B?
- Higher frequency?
- Higher Power?

14 GHz
28 GHz
45 GHz
60 GHz

Golovanivsky's Diagram

$14 \text{ GHz}$
$18 \text{ GHz}$
$28 \text{ GHz}$
$45 \text{ GHz}$
$60 \text{ GHz}$
Opportunities and Challenges

Solutions to 10 emA $^{46+}$?

- Intense medium charged ion source
- Solid charge stripper
- Intense beam heavy ion linac

Similar to UNILAC

- $\sim 10$ emA $^{46+}$
  - C Stripper
  - DTL 1.5 MeV/u
  - RFQ 0.2 MeV/u
  - Intense medium charge state ion source
  - ~20 emA $^{238}U^{15+}$

- $\sim X$ emA $^{46+}$
  - Ion Trap
  - Extraction
  - FECR source CW/pulsed
  - $\sim 0.5$ emA $^{238}U^{46+}$

> $2.7 \times 10^{13}$ particles

- Trapping efficiency
- Trap capacity
- Extraction efficiency

Private discussion with D. Xie
Summary

- Diverse and multi-purpose ion sources developed successfully at IMP over the last 20 years
- Breakthroughs in both techniques and physics realized
- Ion accelerator developments benefit from the R&D work
- Opportunities and big challenges...
  - Joint research
  - Postdocs
  - Long-term PIFI visitors
- Acknowledgement
  - Ion source team members
  - Accelerator Center and Linear Accelerator Center at IMP
  - Colleagues from LBNL, RIKEN, MSU, JINR/Dubna, CEA/Saclay, CEA/Grenoble, IAP/RAS, GSI, BNL, PKU, CIAE, IEE/CAS
Thanks for your Attention!!