Review of High Intensity Ion Source Development and Operation

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Outline

• Introduction and limitations of talk
  • Many of the sources and facilities used for comparison are nuclear/high energy research facilities. Some non-research facilities lead the fields in performance.

• Electron Cyclotron Resonance Ion Sources

• High Current Light Ion Sources

• High Current Low Charge-state Ion Sources
  • For research, direction mostly dominated by GSI, but many commercial applications
  • PIG but most importantly, versions of Vacuum Arc technology (MEVVA, VARIS)

• Future Developments
Importance of Ion Sources

• Ion Source Performance
  • Sets framework for operating existing facilities and those under development
  • Measures of performance:
    • Beam current
    • Ion Species
    • Emittance
    • Brightness
    • Operating modes (CW vs Pulsed)
  • Day to day operation rule of thumb
    • Generally based on 50% of best performance
      • Even this assumption is a maximum assumption
Types of Ion Source for Consideration

- Light Ions
  - Protons and isotopes of hydrogen
  - Helium (mass: 3 or 4)
  - Lithium

- Positive Ions
  - Penning Ion Gauge (PIG)
  - Vacuum Arc Sources (MEVVA, etc.)
  - Multicusp Ion Sources
  - Electron Cyclotron Resonance (ECR) ion sources
Electron Cyclotron Resonance Ion Sources: History

• Electron Cyclotron Resonance Ion Sources (ECR ion source or ECRIS)
• Invented and first developed by Richard Geller and his group.
  • Began in late 1960’s and evolved out of plasma physics research
  • First suggested as a source of ions by H. Postma in 1969.
  • First papers demonstrating ions – high charge state ions, in 1972 by Geller and co-workers, but also by Bernhardi and Weisemann.
  • Geller’s first production of ions was with the Supermafios source which consumed large amount of power (over ~3 MW), was very large and even so only made ‘modest’ amount of high charge-state ions.
Electron Cyclotron Resonance Ion Sources: MINIMAFIOS

• Most of the problems identified with Supermafiios were solved when Geller (and P. Jacout) developed the MINIMAFIOS source.
  • First reported in 1982.
  • Solved the size and power problems of Supermafiios.
  • Improved on the beam currents and charge states of SUPERMAFIOS.
  • Literally saved many cyclotron facilities by allowing them to enter the ‘heavy-ion’ research era in nuclear physics.
Electron Cyclotron Resonance Ion Sources: Rules for source performance

• ECR Ion Sources have now far exceeded those early performance standards reported in the 1970s and early 1980s.

• The underlying plasma physics understanding of these sources is sufficiently accurate to allow an improvement path to be well defined.
  • Beam current is proportional to the plasma density.
  • Plasma density, $n$, scales with microwave frequency square ($n \sim f^2$).
  • But to heat the electrons efficiently the ECR condition must apply so:
    • $B \sim f$
    • Thus to get to high beam current, go to higher frequency, and thus to higher magnetic fields.
    • Many additional ‘tricks’ can be employed but basic scaling relations remain.

• ECR sources operate in both pulsed and CW mode.
  • Pulses give higher peak current, but
  • average current is larger is CW mode.
Electron Cyclotron Resonance Ion Sources: Rules for source performance (2)

- These rules thus mean that higher beam currents come by going to high frequency and high magnetic fields with no obvious limits.

- Such a path pushes one into the realm of superconductivity for generating the high magnetic fields while maintaining a confining field configurations. Thus to complex coil designs which have very high forces on the conductor that must be stabilized.

- Some designs mix RT coils, permanent magnets and SC coils.

- In addition, there seems to be a requirement for fairly large plasma volumes to maximize performance and certainly to reduce the energy density and cooling requirements that come with this approach.
Electron Cyclotron Resonance Ion Sources: Superconducting Source designs (present – Gen III)

• Pursuing this path, two magnet designs are currently dominant for SC sources.

• Grossly, Hexapole coils inside the solenoid coils (VENUS) and Hexapole coils outside (SECRAL). Both have been shown to be good choices for at least 28 GHz operation:
Electron Cyclotron Resonance Ion Sources: Room Temperature (Lower Frequency ECRs)

• Higher Frequency, Superconducting ECR Sources are proven to work well
  • Emittance has not grown as might have been expected.
  • But costs of these sources still make them unaffordable except for the largest, highest performance projects.
• Many application needs are still within reach of lower frequency, room temperature sources.
  • Careful coil design has allowed some increase in RT coil ECR source performance.
    • Allowed some increase is RF frequency (up to 19GHz at this point).
  • New HIISI source in Jyvaskla is a good example of current RT coil ECR source design.
  • Also GTS (enhanced) at GANIL and others.
  • Many ‘tricks’ can be employed to maximize the performance of these more affordable room temperature ECR source designs.
    • Multiple frequency heating, careful magnet design, improved RF coupling to plasma, etc.
### Examples of ECR Heavy Ion Source Performance - Gases

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Source</th>
<th>Facility</th>
<th>Charge State</th>
<th>Extracted Beam Current (eµA)</th>
<th>Source Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{16}\text{O})</td>
<td>SECRAL-II (SC)</td>
<td>IMP</td>
<td>6+</td>
<td>6700</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>VENUS (SC)</td>
<td>LBL</td>
<td>6+</td>
<td>4750</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>HIISI (RT)</td>
<td>Jyvaskyla</td>
<td>6+</td>
<td>1080</td>
<td>14 &amp; 18 GHz</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>AISHa (Hyb)</td>
<td>Catania</td>
<td>6+</td>
<td>1250</td>
<td>18 to 21 GHz</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>SECRAL-II</td>
<td>IMP</td>
<td>7+</td>
<td>1750</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>VENUS</td>
<td>LBL</td>
<td>7+</td>
<td>1900</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>HIISI</td>
<td>Jyvaskyla</td>
<td>7+</td>
<td>560</td>
<td>14 &amp; 18 GHz</td>
</tr>
<tr>
<td>(^{78}\text{Kr})</td>
<td>SECRAL-II</td>
<td>IMP</td>
<td>18</td>
<td>1030</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(^{78}\text{Kr})</td>
<td>VENUS</td>
<td>LBL</td>
<td>18</td>
<td>770</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(^{84}\text{Kr})</td>
<td>GTS (RT)</td>
<td>GANIL</td>
<td>22</td>
<td>27</td>
<td>14.5 GHz</td>
</tr>
<tr>
<td>(^{129}\text{Xe})</td>
<td>VENUS</td>
<td>LBL</td>
<td>27</td>
<td>705</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(\text{Xe})</td>
<td>SECRAL-II</td>
<td>IMP</td>
<td>20</td>
<td>820</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>(\text{Xe})</td>
<td>HIISI</td>
<td>Jyvaskyla</td>
<td>29</td>
<td>27</td>
<td>14 &amp; 18 GHz</td>
</tr>
<tr>
<td>(^{129}\text{Xe})</td>
<td>GTS</td>
<td>GANIL</td>
<td>25</td>
<td>63</td>
<td>14.5 GHz</td>
</tr>
<tr>
<td>(^{129}\text{Xe})</td>
<td>GTS</td>
<td>GANIL</td>
<td>29</td>
<td>9</td>
<td>14.5 GHz</td>
</tr>
</tbody>
</table>
### Examples of ECR Heavy Ion Source Performance - Solids

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Source</th>
<th>Facility</th>
<th>Charge State</th>
<th>Extracted Beam Current (eµA)</th>
<th>Source Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{39}$K</td>
<td>VENUS (SC)</td>
<td>LBL</td>
<td>9</td>
<td>1000</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>$^{51}$V</td>
<td>RIKEN-28 (SC)</td>
<td>RIKEN</td>
<td>13</td>
<td>400</td>
<td>28 GHz</td>
</tr>
<tr>
<td>$^{58}$Fe</td>
<td>CAPRICE (RT)</td>
<td>GSI</td>
<td>9</td>
<td>50</td>
<td>14 GHz Pulsed</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>VENUS</td>
<td>LBL</td>
<td>51</td>
<td>5</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>GTS-LHC (RT)</td>
<td>CERN</td>
<td>29</td>
<td>210</td>
<td>14.5 GHz Pulsed</td>
</tr>
<tr>
<td>$^{209}$Bi</td>
<td>VENUS</td>
<td>LBL</td>
<td>30</td>
<td>310</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>$^{209}$Bi</td>
<td>VENUS</td>
<td>LBL</td>
<td>45</td>
<td>63</td>
<td>18 &amp; 28 GHz</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>RIKEN-28</td>
<td>RIKEN</td>
<td>33</td>
<td>225</td>
<td>28 GHz</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>RIKEN-28</td>
<td>RIKEN</td>
<td>35</td>
<td>200</td>
<td>28 GHz</td>
</tr>
</tbody>
</table>
Low Charge State High Current Sources

• GSI is the lead research institute using such sources.
• A very large development program results in very high current of low to moderate charge states.
• Sources can be classified into 3 groups: PIG, Vacuum Arc, Filament Driven Sources.
• PIG sources can operate in CW mode, but for GSI they are used at relatively high frequency and for lighter ions.
• Filament driven sources such as CHORDIS, operate with gaseous materials best and in pulsed mode.
• Vacuum Arc sources operate in pulsed mode but can be used with all solid materials.
• Labs that led in this development included LBL and Tomsk as well as GSI.
Low Charge State High Current Sources (2)

- All of these sources are capable of producing mA currents of (usually) low charge-state heavy-ions and also very light ions.
- Pulsed mode operation.

MUCIS Filament Source for gases

VARIS Vacuum Arc Source for Solids
Low Charge State High Current Sources (3)

• The Performance of these sources at GSI is summarized in the table below:

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Source</th>
<th>Charge State</th>
<th>Beam Current (emA)</th>
<th>Emittance (rms πmrad)</th>
<th>Beam Time Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>MUCIS</td>
<td>5+</td>
<td>6</td>
<td></td>
<td>2 Hz/ 1 ms</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>MEVVA</td>
<td>1+</td>
<td>3</td>
<td></td>
<td>1 Hz/ 1 ms</td>
</tr>
<tr>
<td>$^{84}$Kr</td>
<td>MUCIS</td>
<td>2+</td>
<td>8</td>
<td></td>
<td>5 Hz/1 ms</td>
</tr>
<tr>
<td>$^{181}$Ta</td>
<td>VARIS</td>
<td>3+</td>
<td>8</td>
<td></td>
<td>1 Hz/ 0.5 ms</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>VARIS</td>
<td>4+</td>
<td>16</td>
<td>175</td>
<td>1 Hz/ 0.5 ms</td>
</tr>
</tbody>
</table>
Low Charge-state High Current Sources (4)

- Vacuum Arc, low charge-state high current sources also have applications in commercial setting.
  - They can be scaled to very large sizes
  - Currents \(\sim\) scale with size

Tomsk “TITAN” Vacuum Arc Ion Source
High Current Light Ion Sources

• Production of light ions continues to be very important.
  • For this talk I call ‘light ions” masses up to lithium, but as you will see, they are mostly focused on isotopes of hydrogen.

• Light ions, especially H⁻, are mostly used for secondary beam production such as neutrons, muons, pions, etc. Thus the production cross section of these secondary beams requires high primary currents to reach the secondary beam intensity required.

• Most applications today require pulsed beams at low duty factor, but not all applications. Facilities that hope to measure very low energy cross sections (as needed for stellar modeling and other astrophysical settings) require CW operation and thus CW sources, such as specialized ECR sources, are appropriate.
High Current Light Ion Sources: Pulsed Beams

• Present facilities generating neutrons, muons, pions and other exotic beams require very high currents of pulsed primary light ions. The accelerator must operate at high efficiency, so many times these facilities demand negative ions – often H⁻.

• Facilities of this type include the Spallation Neutron Source at ORNL (SNS), ISIS, CERN, Japan Proton Accelerator Research Complex (J-PARC), and FermiLab. These are pulsed synchrotron facilities and so cannot make good use of the CW operation of ECR sources.

• Beam requirements for H⁻ systems range for 200 µA to tens of mA.
# High Current Light Ion Sources: Pulsed Beams

<table>
<thead>
<tr>
<th>Ion Species /Facility</th>
<th>Charge State</th>
<th>Extracted Beam Current (mA)</th>
<th>Source Type</th>
<th>Emittance (rms $\pi$mm$^*$/mrad)</th>
<th>Short-term future current goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^-$ / J-PARC</td>
<td>-1</td>
<td>&gt;70 max. ~45 typ.</td>
<td>Pulsed Cs-RF</td>
<td>~0.25</td>
<td></td>
</tr>
<tr>
<td>H$^-$ / SNS (ORNL)</td>
<td>-1</td>
<td>&gt;60</td>
<td>Cs-RF multicusp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$^-$ / CERN</td>
<td>-1</td>
<td>65 max. ~40 max oper.</td>
<td>Volume &amp; cessiated RF</td>
<td>&gt;45 mA Typical</td>
<td></td>
</tr>
<tr>
<td>H$^+$ / PSI</td>
<td>+1</td>
<td>10-12 mA</td>
<td>ECR</td>
<td>~.045</td>
<td></td>
</tr>
</tbody>
</table>

Photo and schematic of the SNS cessiated RF multicusp H$^-$ source
High Current Light Ion Sources: CW Operation

• Light ion beams operating in CW mode
  • Often require positive ions from the source
  • May need beams other than protons such as isotopes of hydrogen or helium
  • May have more requirements on target beam size and emittance

• Examples of such applications are
  • Cyclotron operation such as at the Paul Scherer Institute
  • Facilities that focus on nuclear physics measurements for astrophysics
    • Examples are the low background facilities existing and planned at Gran Sasso (Italy, Europe), Sanford Labs (in old Homestake Gold Mine in South Dakota, USA, and JUNA (Jinping Underground Nuclear Astrophysics lab)
High Current Light Ion Sources: CW Operation

• Laboratory for Underground Nuclear Astrophysics in the Gran Sasso facilities has now operated since 2000 using beam currents of 200 uA at very low energies. Designs include a 1 mA maximum beam current for protons, lesser values for light HI.

• New facilities at Sanford Labs in the USA and at JUNA (Jinping Underground Nuclear Astrophysics lab) in China will require up to 10 mA beams from $\text{H}^+$ to $^4\text{He}^+$ in CW mode.

• An ECR ion source is planned for each of these facilities. Operating frequencies of these sources are expected to be 2.45 GHz with some designs that will allow study at higher microwave frequency.
Future Developments

• The current and immediate future performance of ion sources is NOT at an end.
• New ideas and continued development of present ideas already show that improved performance is certain.
• ECRIS development continues to push to higher frequency
  • But also multiple frequency heating, tailored field shape, better cooling all will contribute to improved performance. F
• FECR source at IMP is now under construction. ➔
  • Uses Nb$_3$Sn wire for coils – 6.5T axial & 3.5T radial fields
  • 45 GHz RF.
• MARS is another path to higher fields and thus frequency.
  • Ioffe coils in NbTi SC material
  • 45 GHz RF
• 60 GHz design using Ioffe by Thuillier, et al also being studied.

MARS coil design. ➔
Future Developments

• Laser ablation ion sources are moving into the serious design and test stages.
• Direct injection into an RFQ linac is being explored by Toshiba and the Cancer Research Center of Japan, as suggested by Okamura.
• Multiple mA of $^{12}$C$^{6+}$ have been measured.
Future Developments: Gas Dynamic ECR

• A different approach for obtaining high plasma density.
• All permanent magnet design.
• Small plasma volume.
• Very high power and frequency RF (28 GHz, 10 kW).
Summary

• This review is intended to give you a ‘taste’ of the present capabilities of ion sources as measured in beam current.

• It is intended, at best, to be only a ‘snap-shot’ of the technology of ion sources.

• Many facilities with similar performance not mentioned.

• I must apologize to all of you whose work I have not mentioned but are achieving similar, or in some cases, even better results.

• I do want to thank all who have provided me with their current research and operating status.

• I do hope I have reasonably described these results, but you can be sure that they will be exceeded in coming years.