An Advanced Superconducting ECR Ion Source SECRAL at IMP: First Results and Operation at 18 GHz


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OUTLINE

SECRAL: Superconducting ECR ion source with Advanced design in Lanzhou

- Goals for SECRAL
- SECRAL Structure and unique features
- Commissioning results and performance studies at 18GHz
- SECRAL operation for HIRFL accelerator
- Summary
• Achieve performance enhancement of HIRFL accelerator complex in order to satisfy the research requirements for super-heavy nuclei, RIB, and intense beam injection to the CSR.

• For cyclotron injector:
  - $\text{Ni}^{19+}$, $\text{Xe}^{31+}$, $\text{U}^{41+}$
  - CW Beam: 50-100 e$^-$ A
  - Pulsed Beam: 100-200 e$^-$ A
  - More intense beam is required for heavy ion linac injector

• Develop a compact fully superconducting ECRIS

HIRFL: Heavy Ion Research Facility in Lanzhou
Fully Superconducting ECR Ion Source

\[ n_e \sim I_{rf}^2, \quad I \sim I_{rf} \]
\[ B_{ecr} = \frac{m_e}{q} \cdot B_{inj} \cdot 2 B_{ecr} \]
\[ \text{High } B_{rf}, P_{rf} \]

Conventional Structure

Advantage:
- Higher sextuple field;
- Larger plasma chamber;
- Higher rf power up to 10 kW;
- Higher frequency >28GHz

Disadvantage:
- Very strong interaction forces;
- Much longer sextupole;
- Bigger source body;
- Hard to build

SERSE and VENUS are pioneers

SERSE in Catania (14.5-18 GHz)
VENUS in Berkeley (18-28 GHz)

MS-ECRIS, RIKEN SC-ECR, SuSi…
SECRAL Magnet Concept and Superconducting Coil Configuration

Iron Yoke and Shielding
Sextupole Coil

Iron Segments as Sextupole field Booster and coil Clamping, also reduce the stray field
Aluminum Clamping Ring

Iron pole

$\nabla$ VECTOR FIELDS

Completely new structure! Reverse conventional coil configuration

Inject. Solenoid
Middle Solenoid
Extract. Solenoid
The magnet was fabricated by ACCEL.
Unique Features for SECRAL

Axial solenoids are located inside of sextupole
- Reduced interaction force    → Easier to build and cost-effective
- Compact source body        → Efficient rf coupling and effective extraction
- Lower rf power and higher power density  → Good long-term stability

Cold iron structure with iron segments as field booster and coil clamping
- Increase sextupole field
- Reduce stray field, easy support and suspend the cold mass
- Very simple clamping scheme

Disadvantage:
- Plasma chamber and sextupole field are limited, not for >28GHz, chamber >130 mm
- But: 3.7 T injection field, 2.0 T sextupole field at the wall and 126 mm chamber, sufficient for 28 GHz, and higher power density!
SECRAL Milestone and Status

- 09. 2000  • Project approved.
- 04. 2002  • Fabrication contract with ACCEL.
- 04. 2005  • SECRAL magnet reached **100% fields at ACCEL.**
- 06. 2005  • SECRAL magnet installed at IMP in Lanzhou and reached **100% designed fields.**
- 10.08. 2005 • First Analyzed Beam at 18 GHz.
- 08. 2005-08. 2006 — Commissioning for intense highly charged beam production, some record beam intensities were produced.
- 08. 2006 — Moved to IMP cyclotron beam line.
- 05. 2007 — First beam provided to HIRFL continuously for one month.
Achieved axial field: 3.7, 2.2T
Sextupole at the wall: 2.0 T
RF frequency: 18-28 GHz
Plasma chamber: • 126
Extraction voltage: 20-30 kV
SECRAL and its components

Experiences from SERSE and VENUS are helpful for design of conventional Components.

Injection component with wave-guide, biased disk and oven
Cryogenics and Cold Mass

HTc Leads

One Stage Cryocooler at 30-50K

Magnet

Cold Mass
SECRAL Magnet Test and Measurements

- **5 Quenches to 100%**
- **13 Quenches to 100%**

**Quench History**

- **SECRAL Magnet Has Reached 100% Designed Fields.**
- **Stable and Reliable!**

**Achieved and measured fields:**
- 3.7 T, 0.8 T, 2.2 T
- 2.0 T sextupole field at the wall
SECRAL Beam Transport Line

Designed for 15-20 mA total beam transmission at 20-30 kV extraction

Main Design Issues:
1. High transmission efficiency
2. High mass resolution (1/100)
3. Match with the axial injection beam line

Analyzing magnet:
- Bending angle: 110 degree
- Bending radius: 600 mm
- Pole gap: 120 mm
SECRAL Commissioning Results and Performance Studies at 18GHz
Beams Obtained with two 18GHz RF Generators

O$^{7+}$: 810 eμA (2.5 kW, 23-25 kV)

B$_r$ 1.23 T, B$_{ inj}$ 2.2 T, B$_{ ext}$ 1.36 T, B$_{ min}$ 0.46 T

Ar$^{11+}$: 810 eμA (3.15 kW, 23-25 kV)

B$_r$ 1.18 T, B$_{ inj}$ 2.20 T, B$_{ ext}$ 1.20 T, B$_{ min}$ 0.455 T

Ar$^{14+}$: 270 eμA (3.2 kW, 23-25 kV)

B$_r$ 1.30 T, B$_{ inj}$ 2.48 T, B$_{ ext}$ 1.33 T, B$_{ min}$ 0.516 T

Ar$^{16+}$: 73 eμA (2.8 kW, 23-25 kV)

B$_r$ 1.49 T, B$_{ inj}$ 2.65 T, B$_{ ext}$ 1.53 T, B$_{ min}$ 0.55 T

Better results are expected for higher Q
Beams Obtained with Two 18 GHz RF Generators

$^{129}$Xe$^{20+}$: 505 eμA (2.75 kW, 23-25 kV)
$B_r$ 1.09 T, $B_{inj}$ 2.23 T, $B_{ext}$ 1.27 T, $B_{min}$ 0.47 T

$^{129}$Xe$^{27+}$: 306 eμA (2.85 kW, 23-25 kV)
$B_r$ 1.29 T, $B_{inj}$ 2.52 T, $B_{ext}$ 1.41 T, $B_{min}$ 0.529 T

$^{129}$Xe$^{30+}$: 101 eμA, $^{129}$Xe$^{34+}$: 21 eμA, $^{129}$Xe$^{38+}$: 2.4 eμA
(3.2 kW, 23-25 kV)
$B_r$ 1.29 T, $B_{inj}$ 2.52 T, $B_{ext}$ 1.41 T, $B_{min}$ 0.536 T

Better results are expected for higher Q
With maximum $P_{\text{rf}} = 1.6 \text{kW}$, some preliminary but very promising metallic ion beams were produced:

$287 \text{e} \cdot \text{A Ca}^{11+}$, $162 \text{e} \cdot \text{A Ca}^{14+}$, $75 \text{e} \cdot \text{A Ca}^{16+}$, $20 \text{e} \cdot \text{A Ca}^{18+}$, $2.3 \text{e} \cdot \text{A Ca}^{19+}$, $35 \text{e} \cdot \text{A }^{58}\text{Ni}^{17+}$, $10 \text{e} \cdot \text{A }^{58}\text{Ni}^{19+}$, $180 \text{e} \cdot \text{A Pb}^{25+}$, $173 \text{e} \cdot \text{A Pb}^{27+}$, $65 \text{e} \cdot \text{A Pb}^{31+}$

Results not so good, test time too short (10 days)

Better results of very high Q are coming for Ca, Ni, Pb, Bi and U next year, firstly modify injection part and also use Al chamber.
**SECRAL Commissioning Results at 18GHz and Beam Intensity (emA)**

**Comparison with other ECRIS**

<table>
<thead>
<tr>
<th>f (GHz)</th>
<th>SECRAL 18</th>
<th>VENUS 28 or 28+18</th>
<th>GTS 18</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>$^{6+}$</td>
<td>2300</td>
<td>2850</td>
</tr>
<tr>
<td></td>
<td>$^{7+}$</td>
<td>810</td>
<td>600</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>$^{11+}$</td>
<td>810</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>$^{12+}$</td>
<td>510</td>
<td>380</td>
</tr>
<tr>
<td></td>
<td>$^{14+}$</td>
<td>270</td>
<td>514</td>
</tr>
<tr>
<td></td>
<td>$^{16+}$</td>
<td>73</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td>$^{17+}$</td>
<td>8.5</td>
<td>14</td>
</tr>
<tr>
<td>$^{129}$Xe</td>
<td>$^{20+}$</td>
<td>505</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>$^{26+}$</td>
<td>410</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>$^{27+}$</td>
<td>306</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>$^{30+}$</td>
<td>101</td>
<td>116</td>
</tr>
<tr>
<td></td>
<td>$^{31+}$</td>
<td>68</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>$^{33+}$</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{34+}$</td>
<td>21</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>$^{35+}$</td>
<td>12</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>$^{37+}$</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>$^{38+}$</td>
<td>2.4</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table III. Comparison of key parameters between SECRAL and VENUS**

<table>
<thead>
<tr>
<th>Key parameters</th>
<th>SECRAL</th>
<th>VENUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed RF frequency (GHz)</td>
<td>18-28</td>
<td>18-28</td>
</tr>
<tr>
<td>Axial mirror magnetic fields (Tesla)</td>
<td>3.6, 2.2</td>
<td>4.0, 3.0</td>
</tr>
<tr>
<td>Sextupole field at the chamber wall (Tesla)</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Mirror to mirror space (mm)</td>
<td>420</td>
<td>500</td>
</tr>
<tr>
<td>Magnet length (mm)</td>
<td>1000</td>
<td>~ 1500</td>
</tr>
<tr>
<td>Plasma chamber diameters (mm)</td>
<td>• 126</td>
<td>• 140-150</td>
</tr>
<tr>
<td>Plasma chamber length (mm)</td>
<td>890</td>
<td>~ 1400</td>
</tr>
<tr>
<td>Material of the chamber in commissioning</td>
<td>St. St. Steel</td>
<td>Al</td>
</tr>
<tr>
<td>Volume of plasma chamber (liter)</td>
<td>~ 5</td>
<td>~ 9</td>
</tr>
<tr>
<td>RF frequency in commissioning (GHz)</td>
<td>18</td>
<td>18, 28+18</td>
</tr>
<tr>
<td>Maximum rf power coupled into chamber so far (kW)</td>
<td>3.2</td>
<td>6.0-9</td>
</tr>
<tr>
<td>Maximum rf power density achieved (kW/liter)</td>
<td>0.64</td>
<td>0.67-1.0</td>
</tr>
</tbody>
</table>

By Al chamber and 28 GHz/5kw / by 2-2.5
SECRAL Performance in Dependence of rf Power

To reach better results, SECRAL needs higher power up to limit 5 kW and 24-28 GHz rf frequency.

Obvious increment of Xe ion beam with the increase of $P_{rf}$.

**Typically 10% higher**

- Beam more stable and total reflected power much lower with two generators.

![Diagram showing SECRAL Performance in Dependence of rf Power]
Beam intensity
VS
Magnetic fields

- For optimum fields, good agreement with the scaling laws:
  - $B_{\text{inj}} \sim 4B_{\text{ECR}}$
  - $B_{\text{rad}} \sim 0.8B_{\text{ECR}}$
  - $B_{\text{rad}} \geq 2B_{\text{ECR}}$

- But for different rf power, the optimized fields are different.

- As expected, higher Q needs higher $B$

Table II. Typical beam intensities produced by SECRAL at the optimized magnetic field configuration and the coupled rf power.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Beam intensity (eµA)</th>
<th>Coupled RF power (kW)</th>
<th>$B_{\text{inj}}$ Tesla</th>
<th>$B_{\text{extr}}$ Tesla</th>
<th>$B_{\min}$ Tesla</th>
<th>$B_{\text{rad}}$ Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O^{7+}$</td>
<td>810</td>
<td>2.5</td>
<td>2.20</td>
<td>1.36</td>
<td>0.46</td>
<td>1.23</td>
</tr>
<tr>
<td>Ar$^{11+}$</td>
<td>810</td>
<td>3.15</td>
<td>2.20</td>
<td>1.20</td>
<td>0.46</td>
<td>1.18</td>
</tr>
<tr>
<td>Ar$^{16+}$</td>
<td>73</td>
<td>2.8</td>
<td>2.65</td>
<td>1.53</td>
<td>0.55</td>
<td>1.49</td>
</tr>
<tr>
<td>Xe$^{20+}$</td>
<td>505</td>
<td>2.85</td>
<td>2.23</td>
<td>1.27</td>
<td>0.47</td>
<td>1.09</td>
</tr>
<tr>
<td>Xe$^{27+}$</td>
<td>306</td>
<td>3.1</td>
<td>2.52</td>
<td>1.41</td>
<td>0.53</td>
<td>1.29</td>
</tr>
</tbody>
</table>

T. Nakagawa and D. Leitner did the similar experiments before at their sources.
Preliminary emittance measurement

IMP Allison-type emittance scanner. Located after the analyzing magnet

Use M. Stockli’s code to process data

At 15 kV, < 1kW, lower intensity
SECRAL at the Axial Injection Beam Line of IMP Cyclotron
The first beam: $^{129}\text{Xe}^{27+}$, extraction voltage: 22 kV, rf power 1.5-2.0 kW, Beam intensity: 130-160 eμA, Continuously operated for more than one month.

Dedicated to commissioning of IMP new project HIRFL-CSR.

SFC Xe beam increased by factor 10

SSC Xe beam increased by factor 50

CSRm accelerated Xe$^{27+}$ beam to 235 MeV/u, accumulated beam intensity up to 500 eμA (1×10$^8$ pps), the heaviest ion and the biggest beam intensity achieved for a heavy ion synchrotron with a cyclotron injector, impossible without SECRAL.

SFC : Xe$^{27+}$ 2.9 MeV/u, extracted intensity: 5-6 eμA
But SECRAL: 130-160 eμA
Low transmission efficiency.
One of reasons for low transmission: longitudinal space charge effect may reduce the buncher efficiency.
If at higher extraction voltage up to 60 kV, the buncher efficiency could be improved and may achieve a better transmission efficiency.

**Longitudinal acceptance of SFC**

\[(\Delta \phi = 10^\circ, \frac{\Delta W}{W} = 4\%)\]
1. A superconducting ECR ion source SECRAL with an innovative magnet structure has been successfully built. The unique features of SECRAL have resulted in some significant advantages, which may open a new way for developing a compact and high performance 18-28 GHz superconducting ECR ion source.

2. Commissioning results at 18 GHz are promising and some record beam intensities have been produced. Beam intensities are still increasing linearly with rf power and better results should be coming up with Aluminum chamber, higher rf power and higher rf frequency 24-28GHz.

3. SECRAL has been put into routine operation for HIRFL accelerator since May 2007. It has demonstrated SECRAL has a nice long-term stability, reliability with higher beam intensity for highly charged ions.
Acknowledgement

- Thank ACCEL for fabrication of the magnet.

- Many thanks go to the following colleagues for their kind help and fruitful discussions during design and commissioning of SECRAL:
  
  Dan Xie, Denis Hitz, Claude Lyneis, Daniela Leitner, Santo Gammino, Luigi Celona, T.Nakagawa, A. Efremov, Weijiang Zhao, A.Drentje....
Thank you for your attention!
Faraday-cup to measure beam current

- Good shielding to the ground.
- Water cooled down through BeO.
- Suppressor electrode -150 ~-200 V.
- Cone-shape cup prevents from electrons coming out.
Bremsstrahlung Measurements

- Increase $B_{\text{inj}}$, $B_{\text{min}}$; Reduce $B_{\text{extr}}$.
- Stronger X ray; Might be related to dB/dz.

**LHe consumption:**
- 90% Bmax (no plasma): <1.5 l/h;
- 1.0 kW, 18GHz: <1.5 l/h;
- 1.0-2.0 kW, 18GHz: 1.5-2.0 l/h;
- 2.0-3.0 kW, 18GHz: 2.0-2.5 l/h