Intense Beam Ion Sources Development at IMP

L Sun
Institute of Modern Physics, CAS
Outline

- Needs for high intensity ion beams at IMP
- Heavy ion ECR sources
  - Room temperature ECRISs
  - Permanent magnet ECRISs
  - SC-ECRIS
- Intense proton beam sources
- Ion sources for next generation heavy ion accelerator
  - Next generation ECRIS
  - Laser ion source
Needs of intense ion beams

- HIRFL
- HIMMM
- CIADS
- HIAF

- ECR-35:
  - 3.0 GeV/u (e)
  - 7.5 x 10^13
  - 0.8 GeV/u (U) (1-3) x 10^9
  - 2.5 GeV/u (U) (0.2-1) x 10^9
  - 9.5 GeV/u (p)
  - 1.0 x 10^{12}

- ICR-35:
  - Electron injector
  - Electron-ion collision

- ABR-35:
  - 0.8 GeV/u (U)
  - (1-3) x 10^9
  - 2.5 GeV/u (U)
  - (0.2-1) x 10^9

- High Purity RIBs Station

- SC-LINAC

- RIBs line

- LIS

- ECR

- ECR+LEBT RFQ MEBT Cryomodule6 Cryomodule6
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RT-ECRIS

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

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

O$^7+$ 240µA, Ar$^{11+}$ 325µA Ar$^{8+}$ 1.0 mA, Xe$^{26+}$ 95 µA Fe$^{13+}$ 141 µA, Ar$^{17+}$ 0.4 uA Ar$^{18+}$ .. Pb$^{40+}$ 0.2 µA,

IMP 10 GHz LECR1
Bz 1.0T, Br 0.7T
1990-1995-1996

IMP 14 GHz
LECR2
Bz 1.5T, Br 1.0T
1997-1999

Preliminarily:
1.3emA O $^6+$ , 210eµA
Other beams:
F, Ne, S, Ar, Xe, Ca, Fe, Ni, Pb etc.

2005-2006

Updated to LECR2M
PM-ECRIS

LAPECRI1

>30keV/q

For HIRFL low charge state ion beam injection

Ar$^{1+\text{-}8+}$, Xe $^{1+\text{-}10+}$ and other low charge state ion beams

LAPECRI2

320kV HV platform

For multiple research activities

Ar$^{4+\text{-}16+}$, Xe $^{10\text{-}30+}$ and metallic ion beams

LAPECRI3

22 keV/q C$^{5+}$ for Hadron Cancer Therapy (HIMM)

> 100 euA C$^{5+}$ beam for the facility
LAPECR2 with 320 kV HV Platform

Side view of the experimental terminals
LAPECR2 with 320 kV HV Platform

- **Ion Species:**
  - Gaseous Elements (11): H, He, C, N, O, Ne, Ar, Xe, Kr, Cl, F
  - Solid Elements (11): Pb, Bi, Fe, Eu, Mg, Cs, Ni, Ti, I, S, Si
- **Typical delivered HCl beams:**
  - Bi^{33+}=15\,\mu A  Bi^{36+}=3\,\mu A
  - Eu^{30+}=10\,\mu A  Eu^{33+}=5\,\mu A
  - Fe^{13+}=25\,\mu A  Fe^{15+}=20\,\mu A
  - Cs^{23+}=20\,\mu A  Cs^{16+}=40\,\mu A  I^{25+}=35\,\mu A
  - Ar^{16+}=2\,\mu A  Xe^{30+}=11\,\mu A  Kr^{23+}=15\,\mu A
  - Mg^{7+}=35\,\mu A  Ni^{17+}=12\,\mu A  Ti^{11+}=20\,\mu A  Si^{9+}=12\,\mu A
- **Total operation time (2007—now):**
  - Experiment beam time: 31,300 hours
  - Service time: 3,000 hours
  - New beam study: 3,000 hours

> 37,000 hours’ operation time till now
**LAPECR3**

**Ion Source Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Field (T)</td>
<td>1.8-0.40-0.85</td>
</tr>
<tr>
<td>Field on Inner Chamber Wall $-B_r$(T)</td>
<td>1.0</td>
</tr>
<tr>
<td>Mirror Length (mm)</td>
<td>172</td>
</tr>
<tr>
<td>ECR Length (mm)</td>
<td>~70</td>
</tr>
<tr>
<td>Operation Frequency (GHz)</td>
<td>13.75-14.5</td>
</tr>
<tr>
<td>Chamber ID (mm)</td>
<td>47.5</td>
</tr>
<tr>
<td>Effective Chamber Volume (L)</td>
<td>0.30</td>
</tr>
<tr>
<td>RF Feeding</td>
<td>WR62 Rectangular</td>
</tr>
<tr>
<td>Plasma chamber cooling</td>
<td>Water Cooled</td>
</tr>
<tr>
<td>Max. Designed Operation HV (kV)</td>
<td>25</td>
</tr>
<tr>
<td>Max. Designed μW Power (kW)</td>
<td>0.70</td>
</tr>
<tr>
<td>External Dimension (mm)</td>
<td>Ø455 × 382</td>
</tr>
<tr>
<td>NdFeB Weight (kg)</td>
<td>157</td>
</tr>
<tr>
<td>NdFeB Type</td>
<td>N50M &amp; N42SH</td>
</tr>
</tbody>
</table>

**100 euA C\(^{5+}\) production**

<table>
<thead>
<tr>
<th>Ion Type</th>
<th>Current (eA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(^{+})</td>
<td>400</td>
</tr>
<tr>
<td>H(_2)^{+}</td>
<td>300</td>
</tr>
<tr>
<td>C(^{4+})</td>
<td>200</td>
</tr>
<tr>
<td>C(^{5+})</td>
<td>100</td>
</tr>
<tr>
<td>C(^{3+})</td>
<td>50</td>
</tr>
</tbody>
</table>

**Arbitrary Unit**
Fully superconducting magnet
Axial field: 3.6, 2.2T
Sextupole at the wall: 2.0 T
RF frequency: 18-28 GHz
Plasma chamber: Ø126 mm
Warm bore: Ø140 mm
Extraction voltage: 25 kV
Fabrication: 2002-2005
**SECERAL**

**Fully superconducting magnet**
- Axial field: 3.6, 2.2T
- Sextupole at the wall: 2.0 T
- RF frequency: 18-28 GHz
- Plasma chamber: $\varnothing$126 mm
- Warm bore: $\varnothing$140 mm
- Extraction voltage: 25 kV
- Fabrication: 2002-2005

> 100 euA Bi$^{31+}$, Xe$^{27+}$, …
Unique Design of SECRAL

Examples:
SERSE (INFN/Catania)
VENUS (LBNL)
SuSI (MSU)
SC-ECRIS (RIKEN)

Examples:
SECRAL (IMP/Lanzhou)
SECRAL II (IMP/Lanzhou)
Unique Design of SECRAL

Examples:
- SERSE (INFN/Catania)
- VENUS (LBNL)
- SuSI (MSU)
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Pros:
- Higher Sextupole Field
- Larger plasma chamber

Examples:
- SECRAL (IMP/Lanzhou)
- SECRAL II (IMP/Lanzhou)
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Pros:
- Higher Sextupole Field
- Larger plasma chamber

Examples:
- SECRAL (IMP/Lanzhou)
- SECRAL II (IMP/Lanzhou)

Pros:
- More compact magnet body
- Easier handling of magnet clamping
- Lower source cost
SECRAL Performance

Typical specifications for source test

<table>
<thead>
<tr>
<th>Frequency</th>
<th>18 GHz/24 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. RF Power</td>
<td>3.2 kW/5.0 kW</td>
</tr>
<tr>
<td>Plasma Chamber</td>
<td>SS/Al</td>
</tr>
<tr>
<td>Max. HV</td>
<td>26 kV</td>
</tr>
</tbody>
</table>

Typical performance from source test

<table>
<thead>
<tr>
<th></th>
<th>SECRAL</th>
<th>VENUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe^{27+}</td>
<td>455</td>
<td>411</td>
</tr>
<tr>
<td>Xe^{30+}</td>
<td>236</td>
<td>211</td>
</tr>
<tr>
<td>Xe^{35+}</td>
<td>64</td>
<td>38</td>
</tr>
<tr>
<td>Xe^{42+}</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bi^{31+}</td>
<td>395</td>
<td>310</td>
</tr>
<tr>
<td>Bi^{50+}</td>
<td>4.3</td>
<td>5.3</td>
</tr>
<tr>
<td>U^{33+}</td>
<td>202/SP</td>
<td>450/HiTO</td>
</tr>
</tbody>
</table>
**SECRAL Operation Status**

- Operation frequency 24 GHz/18 GHz
- Up to now the total beam time from SECRAL since May 2007: >13,000 hours
- Mostly for high charge state, very heavy ion beams, such as Xe^{27+}, Sn^{27+}, Bi^{36+}, U^{32+}

**SECRAL Beam Time Summary**

Up to 30\textsuperscript{th} April, 2013
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• Intense proton beam sources

• Ion sources for next generation heavy ion accelerator
  - Next generation ECRIS
  - Laser ion source
LIPS-1 for CHPS

Required Parameters

<table>
<thead>
<tr>
<th>E</th>
<th>50 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>≥ 60 emA</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>500 μs</td>
</tr>
<tr>
<td>Rise time</td>
<td>80 μs</td>
</tr>
<tr>
<td>Fall time</td>
<td>40 μs</td>
</tr>
<tr>
<td>Reliability</td>
<td>&gt; 120 hrs</td>
</tr>
</tbody>
</table>

Courtesy of X. L. Guan, et al from Tsinghua University

RFQ output beam bunch (from ACCT)

44 emA
LIPS-1 for C-ADS

- Ion type: proton
- Energy: 35 keV
- Beam current: 10 mA
- Operation mode: CW
- $\Delta E/E < 0.1\%$
- Beam stability: $< \pm 1\%$
- $\alpha$: 2.41
- $\beta$: 7.72 (cm/rad)
- $\varepsilon$ (n.rms): $< 0.2 (\pi \text{ mm.mrad})$

Beam transmission in LEBT
LIPS-1 on Test Bench

RFQ Entrance, CW: 25 emA @35 keV
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   Next generation ECRIS
   Laser ion source
HIAF Linac Injector

- Pulsed beam with repetition rate of 2 Hz and pulse width of 500 μs ~ 1 ms
- ECR ion source is the baseline design
- LIS is under intense R&D to meet the final requirement

```
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• ECR ion source is the baseline design
• LIS is under intense R&D to meet the final requirement

14 keV/u
```

Future upgrade

L Sun, IPAC’13, Shanghai, 15-May-13, Slide 18
Next G. ECRIS

\[ \omega_{rf} = \frac{eB}{m_e} \quad n_e \sim \omega_{rf}^2 \]

\[ \sum n_q = n_e \]

\[ I_q \propto n_q \cdot V_{\text{plasma}} \]

> 1 emA U^{34+}

<table>
<thead>
<tr>
<th></th>
<th>18GHz</th>
<th>24 GHz</th>
<th>28 GHz</th>
<th>42 GHz</th>
<th>56GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_{\text{inj}}) (T)</td>
<td>2.6</td>
<td>3.4</td>
<td>4</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>(B_{\text{ext}}) (T)</td>
<td>1.4</td>
<td>1.8</td>
<td>2.2</td>
<td>3.3</td>
<td>4.4</td>
</tr>
<tr>
<td>(B_{\text{min}}) (T)</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>(B_{\text{rad}}) (T)</td>
<td>1.3</td>
<td>1.7</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

High magnetic field with reasonably sized plasma chamber

Conventional Structure

Reversed Structure

Mixed structure

Fully Nb\(_3\)Sn

Fully Nb\(_3\)Sn

NbTi + Nb\(_3\)Sn

L Sun, IPAC’13, Shanghai, 15-May-13, Slide 19
Powerful LIS

CARBON TARGET

TRIGGER

H^+
C^1+
C^2+
C^3+
C^4+
C^5+
C^6+

E = 1.32J
Slit_1 = 0.5mm
Slit_2 = 19mm
V_{FC} = 0.565V
Powerful LIS

CARBON TARGET

H^+  C^1+  C^2+  C^3+  C^4+  C^5+  C^6+

TRIGGER

E = 1.32J
Slit_1 = 0.5mm
Slit_2 = 19mm
V_{FC} = 0.565V

~6 emA U^{34+} with pulse length of 500 us??

L Sun, IPAC'13, Shanghai, 15-May-13, Slide 20
Challenges

• Choice of high pulsed energy Laser machine for the ion source
  ✚ CO₂
  ✚ Nd: glass
  ✚ Nd: YAG
  ✚ ...

• Production of highly charged ion beams from very heavy metal materials

• Matching the extracted beam to downstream RFQ
  ✚ DPIS
  ✚ LEBT

• Beam quality control
  ✚ Beam emittance
  ✚ Stable operation time
  ✚ Reliability and stability
  ✚ Energy spread
Summary

• Series of reliable intense beam high charge state ion sources have been successfully built and put into application at IMP.

• Proton beam sources are under development to meet the needs of C-ADS project.

• To have the beam intensities for future advanced heavy ion accelerators, Mission impossible? →very challengeable!!
Thanks !!