Intense Beam Production of HCIs by the SC-ECRIS SECRAL for heavy ion Linacs

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Outline

- High Charge State Ion Sources
- Intense HCl Beams Production with SECRAL
  - \( \sim \text{emA} \) HCl beams
  - Metallic ion beams
  - Beam quality
- SECRAL II
- Scope of 4\textsuperscript{th} G. ECRIS
Heavy ion Linac inquires ion sources of highly charged ions and intense beams

- Developing intense highly charged ion source is both performance-effective and cost-effective.
**HCI Sources**

**Electron Beam Ion Source**

\[ C^+ = 3.36 \times 10^{11} I_e L_e \]

- Easily produces high intensity low duty factor HCI beams
- Very high charge state ions (from EBITs):
  - SuperEBIT (LLNL) \( \rightarrow \) \(~100\ U^{90+}\) ions/s
  - Tokyo EBIT \( \rightarrow \) Bi^{81+}
- Narrow charge state distribution, peaked on interested charge state
- Beam production of any species and intensity independent of species
- Low background contamination (charge breeder)
- Fast beam species switching (\(~1\) second)

**Electron Cyclotron Resonance Ion Source**

\[
I_i^q = \frac{1}{2} \frac{n_i^q q e V_{ex}}{\tau_i^q} \propto \omega_{ecr}^2
\]

- Irreplaceable machine for CW and high duty factor highly charged ion beams
- Long term stability reliability
- No life span issue
- Technology and physics advancing
ECRIS: as HCl beam injectors

World wide ECRISs and Applications
ECRIS: State of the Art

Cyclotrons | NC Linacs | SRF Linacs

10 eμA — 100 eμA — 1 eμA

Beam Intensity (eμA)

Ion Source Generation

6.4~18 GHz 18~28 GHz 40~60 GHz
ECRIS: as HCl beam injectors

MSU FRIB $^{233+} + ^{234+}$ 13 $\mu$A/ CW

RIKEN RIBF $^{235+}$ 15 $\mu$A/ CW

GSI FAIR: intense HCl uranium beam

1.0 emA $q/A=1/3$ and intense heavy ion beams of $q/A=1/6\sim1/7$ (optional)

Worldwide needs…
HCI Beam Production: HIRFL Introduction

- **SSC (K=450)**
- **CSR (K=69)**
- **SFC (K=69)**
- **ECR Area**
- **Existing HIRFL**

- **SSC-Linac**
  - ~1 MeV/u \( U^{37+} \)

- **CSR-Linac**
  - 7 MeV/u \( U^{37+} \)

- **RIBLL1**
- **RIBLL2**

- **CSRm**
  - 1000 AMeV (H.I.), \( \leq 2.8 \text{ GeV} \) (p)
ECRIS:
- Intense heavy ion beams
  - \( A > 40 \)
- High charge states
  - \( \text{Ni}^{19+}, \text{Bi}^{36+}, \text{U}^{37+} \ldots \)

Main parameters of SSC-Linac

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed ion</td>
<td>( \text{U}^{34+} )</td>
</tr>
<tr>
<td>Preferred ion</td>
<td>( \text{U}^{37+} )</td>
</tr>
<tr>
<td>RFQ</td>
<td>4-rod</td>
</tr>
<tr>
<td>Frequency</td>
<td>53.667 MHz</td>
</tr>
<tr>
<td>Input energy</td>
<td>3.728 keV/u</td>
</tr>
<tr>
<td>Output energy</td>
<td>143 keV/u</td>
</tr>
<tr>
<td>Inter-electrode voltage</td>
<td>70 kV</td>
</tr>
<tr>
<td>RF power</td>
<td>35 kW</td>
</tr>
<tr>
<td>Max. current</td>
<td>0.5 emA</td>
</tr>
<tr>
<td>IH-DTL</td>
<td>KONUS</td>
</tr>
<tr>
<td>Frequency</td>
<td>53.667 MHz</td>
</tr>
<tr>
<td>Input energy</td>
<td>0.143 MeV/u</td>
</tr>
<tr>
<td>Output energy</td>
<td>1.025 MeV/u</td>
</tr>
</tbody>
</table>
HCI Beam Production: HCI ECRISs at IMP

HCI ECRIS Family @ IMP

LECR1 1990-1995

LECR2 1996-1999

LECR3 1999-2002

LAPECR2 2003-2006

LAPECR3 2009-2012

LECR4 2010-2014

SECERAL 2002-2005

- Room temperature ECRIS
- Permanent magnet ECRIS
- Evaporative cooling ECRIS
- SC-ECRIS
**HCI Beam Production: SECRAL Design**

**SECRAL magnet**
Unique Design with Reversed structure

**Advantages**
- Lower/simpler interaction forces
- Compact magnet size and cryostat
- Simpler fabrication and lower cost
- Low stray field

**SECRAL Structure**
- Sextupole Coil
- Extract. Solenoid
- Middle Solenoid
- Inject. Solenoid

**Conventional Structure**
- Sextupole Coil
- Injection Solenoid
- Middle Solenoid
- Inject. Solenoid
## HCI Beam Production: SECRAL Specs.

### SECRAL ion source (since 2005)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SECRAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{rf}$ (GHz)</td>
<td>18-24</td>
</tr>
<tr>
<td>Microwave power (kW)</td>
<td>3 kW-18 GHz, 7 kW-24 GHz</td>
</tr>
<tr>
<td>Axial Field Peaks (T)</td>
<td>3.7 (Inj.), 2.2 (Ext.)</td>
</tr>
<tr>
<td>Mirror Length (mm)</td>
<td>420</td>
</tr>
<tr>
<td>No. of Axial SNs</td>
<td>3</td>
</tr>
<tr>
<td>$B_r$ at Chamber Inner Wall (T)</td>
<td>1.7/ 1.83</td>
</tr>
<tr>
<td>Coldmass Length (mm)</td>
<td>~810</td>
</tr>
<tr>
<td>SC-material</td>
<td>NbTi</td>
</tr>
<tr>
<td>Magnet Cooling</td>
<td>LHe bathing</td>
</tr>
<tr>
<td>Warm bore ID (mm)</td>
<td>140.0</td>
</tr>
<tr>
<td>Chamber ID (mm)</td>
<td>116.0/120.5</td>
</tr>
<tr>
<td>4.2 K cooling power with external recondenser (W)</td>
<td>~1.5</td>
</tr>
</tbody>
</table>
HCI Beam Production: SECRAL Status

- Averagely 7,000 hours beam time from all ECRISs
- Total beam time of SECRAL up to 25,000 hours as of summer 2016
# HCI Beam Production: SECERAL Status

## Beam List for HIRFL

**Beams Delivered for HIRFL**

**Beams Available**

- *Lanthanide series*
  - La
  - Ce
  - Pr
  - Nd
  - Pm
  - Sm
  - Eu
  - Gd
  - Tb
  - Dy
  - Ho
  - Er
  - Tm
  - Yb

- *Actinide series*
  - Ac
  - Th
  - Pa
  - U
  - Np
  - Pu
  - Am
  - Cm
  - Bk
  - Cf
  - Es
  - Fm
  - Md
  - No

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L. Sun, LINAC’16, East Lansing 14
HCl Beam Production: SECRAL Status

High Charge State Ar Beams with SECRAL

- 18 GHz test
- Dual WG of 18 GHz with $P = 3.2$ kW
- Sufficient magnetic confinement
HCI Beam Production: SECRAL Status

High Charge State Ar Beams with SECRAL

- 24 GHz + 18 GHz
- Frequency effect
- $P_{\text{max}} = 5$ kW

Charge State

Argon Beam Intensity (euA)
HCI Beam Production: SECRAL Status

High Charge State Ar Beams with SECRAL

- New microwave coupling mode
- Better cooling
- $P_{\text{max}} = 7 \text{ kW}$
Better microwave coupling efficiency
Higher ECRH efficiency in terms of HCI production
Recent test of tapered waveguide Ø20 mm with VENUS/LBNL gave very promising performance improvement, see D. Xie, THAO01, ECRIS’16

*Based on Ø20 mm TE$_{01}$

L. Sun, R.S.I. 87, 02A707 (2016)
HCl Beam Production: Metallic ion beams

- **Resister oven**
  - (500°C - 1500°C)
  - Matured technique
  - Low loading capacity
  - ~100 euA metal ion beams

- **Cartridge Heater oven**
  - (100°C - 700°C)
  - Allows precise control
  - High loading capacity
  - Good for emA metal ion beams

- **High Temp. oven**
  - (500°C - 1900°C)
  - For ion beams of very refractory metals, i.e. U
  - High loading capacity
  - Limited operation life span
  - Under R&D phase
HCl Beam Production: Metallic ion beams

**Ca**
- $\text{Ca}^{11+}$: 710 euA, 2.4 kW@24 GHz
- $\text{Ca}^{11+}$: 2.4 kW@24 GHz

**Bi**
- $\text{Bi}^{31+}$: 680 euA, 5 kW@24 GHz
- $\text{Bi}^{31+}$: 5 kW@24 GHz

**Table**

<table>
<thead>
<tr>
<th>Q</th>
<th>I (euA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>710</td>
</tr>
<tr>
<td>31</td>
<td>680</td>
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<tr>
<td>32</td>
<td>610</td>
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<td>33</td>
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<td>41</td>
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<td>45</td>
<td>49</td>
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<td>48</td>
<td>16.6</td>
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<td>50</td>
<td>10.7</td>
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<td>54</td>
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<td>11</td>
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<td>12</td>
<td>670</td>
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<td>13</td>
<td>480</td>
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<tr>
<td>14</td>
<td>270</td>
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L. Sun, R.S.I. 87, 02A707 (2016)
HCI Beam Production: *Refractory metallic ion beams*

For more reliable intense U ion beams:
- Resister HTO oven
- Inductive heating oven
- Electron beam heating oven
- Laser ablation tech.

Sputtering method for intense U beams

![Image of U target]
HCL Beam Production: **Metallic ion beams**

- **Gaseous beams:**
  - Fairly reasonable stabilities

- **Metal beams:**
  - Source conditioning
  - Oven stability
  - Material dissipation
  - On-call tuning

**Typically:** 50~150 eμA

Bi$^{31+}$ stability $<\pm 3\%$
HCl Beam Production: Intense HCl beam quality

**Figure:** Emittance vs. beam intensity

- **Bi^{31+}**
  - Normalized rms ~0.2 π.mm.mrad

**Graph:**
- X-axis: Bi^{31+} intensity (eA)
- Y-axis: Normalized RMS Emittance (π.mm)
- Data points for 100 eμA Bi^{31+} and 600 eμA Bi^{31+}

**Observations:**
- Increasing emittance with intensity
- Peak emittance at ~500 eμA
Conclusions:

- Ion beams from high charge state ECRIS are transversely coupled.
- High order aberration mostly comes from sextupole component of ion source.
- High order aberration can be compensated.
## SECRAL II: Magnet Design

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<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>~5</td>
<td>0</td>
</tr>
</tbody>
</table>
SECRAL II: Test Bench Layout

28 GHz

Ø32 mm $\text{TE}_{01}$

2013-2015
Beam Commissioning: Oxygen & Xenon

<table>
<thead>
<tr>
<th>Ion</th>
<th>$P_{28\text{ GHz}}$ (kW)</th>
<th>$I_{\text{drain}}$ (emA)</th>
<th>$I_q$ (emA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O^{6+}$</td>
<td>4.5</td>
<td>20.0</td>
<td>5.4</td>
</tr>
<tr>
<td>$O^{7+}$</td>
<td>3.5</td>
<td>13.0</td>
<td>1.57</td>
</tr>
<tr>
<td>$Xe^{27+}$</td>
<td>3.5</td>
<td>8.0</td>
<td>0.51</td>
</tr>
</tbody>
</table>

- Total beam transmission efficiency is 84% for 1.8 emA $O^{6+}$/8.0 emA drain current, and 86% for 450 euA $Xe^{27+}$/7.0 emA drain current
- ~10 days conditioning to produce 510 euA $Xe^{27+}$
Scope: Future development

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration
E=0.8 GeV/u,
I= $1.5 \times 10^{11}$ ppp ($^{238}$U$^{35+}$)

SRing: Spectrometer ring
Circumference: 290 m
Rigidity: 13 Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

MRing: Figure “8” ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length: 100 m
Energy: 17 MeV/u ($^{238}$U$^{35+}$)
Intensity: 30 pμA

SURF: 45 GHz ECRIS
Energy: 14 keV/u ($^{238}$U$^{35+}$)
Intensity: 20 pμA CW/50 pμA pulsed

HIAF
2017-2023
Scope: Future development

Challenges: (2015—2019)
- Nb$_3$Sn sextupole magnet
- 45 GHz microwave coupling
- >20 emA beam extraction and transmission
- Cryogenic solution

H. W. Zhao, MOBO01, ECRIS’16
Summary

- State of the art ECRISs can produce HCl beams of emA currents
- High performance SC-ECR ion sources are reproduceable
- Challenges lie in the production of high current, high quality reliable metallic ion beams
- 4th generation ECRIS is under development for next generation heavy ion Linacs
Thanks for your attention
谢谢！