Intense High Charge State Heavy Ion Beam Production for the Advanced Accelerators

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Outline

• Introduction
• Physics of HCl
• Introduction to the State-of-the art HCl sources
  • ECRIS
  • EBIS
  • LIS
• Next generation HCl sources
Introduction: Global Needs of HCI Sources

RHIC (BNL), USA: EBIS (1.7emA Au^{32+} / 10\mu s)

FAIR (GSI), Germany: ECRIS (1emA U^{28+})

FRIB (MSU), USA: ECRIS (270euA U^{33+} & U^{34+})

U^+ \times 34 \text{ MV} = U^{34+} \times 1 \text{ MV}
Principle of HCl Production

- Electron impact ionization is the main mechanism to produce ions:
  \[ \nu (\text{collision frequency}) = n_e \sigma v_e \]
- Electron energy \( E_e \) must be enough to remove the outer electron of the atom to produce HCl

- Single impact ionization: \( A + e^- \rightarrow A^{z+} + (z+1)e^- \)
- Successive impact ionization: \( A^{z+} + e^- \rightarrow A^{(z+1)+} + 2e^- \)
- For mono-charge state and very low charge state, single impact ionization may dominate
- For HCl ion production, especially HCl of heavy elements, successive impact ionization dominates
Principle of HCl Production

For desired charge state $z$, optimum $T_e$ is needed, and the higher $z$, the higher $T_e$;
- Even works with optimum $T_e$, the ionization rate drops sharply
- $T_e^{\text{opt}} \approx 3\sim 5 \, \text{W}_j$

Golovanivsky’s diagram of the $(n_e \tau_i)T_e$ criteria
- $\xi n_e \tau_i \geq 3\sim 5 \times 10^4 \, (T_e^{\text{opt}})^{3/2}$, $\xi$ is the total number of electrons in the outer shell
High Charge State Ion Sources

• EBIS or Electron Beam Ion Source
  • Invented by Dr. Donets in 1965
  • Control precisely and independently $n_e$, $T_e$ and $\tau_i$

• LIS or Laser Ion Source
  • Proposed by Dr. Bykovskii et al. and Peacock, Pease in 1969
  • Least control of the three key factors

• ECRIS or Electron Cyclotron Resonance Ion Source
  • proposed by Prof. Geller in late 1960s
  • Reasonable control of the $n_e$, $T_e$ and $\tau_i$ factors but not independently, and they are coupled
EBIS Principles

Radial trapping of ions by the space charge of the electron beam. Axial trapping by applied electrostatic potentials at ends of trap.

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

- The total charge of ions extracted per pulse is \( \sim (0.5 - 0.8) \times (\text{# electrons in the trap}) \)
- Ion output per pulse is proportional to the trap length and electron current.
- Ion charge state increases with increasing confinement time.
- Output current pulse is \( \sim \) independent of species or charge state!
Pros and Cons

• Pros:
  • Easily produces high intensity short pulse HCl beams
  • Very high charge state ions (from EBITs):
    » SuperEBIT (LLNL) \(\rightarrow \sim 100 U^{90+} \) ions/s
    » Tokyo EBIT \(\rightarrow Bi^{81+} \)
  • Narrow charge state distribution, peaked on interested charge state
  • Produces beams of any species and intensity is independent of species
  • Pulse width can be precisely controlled
  • Fast beam species switching (~1 second)

• Cons:
  • Possibility of instability issues at high electron beam currents
  • High energy spread of fast-extracted ions
  • High technical challenges: ultrahigh vacuum, very well collimated superconducting solenoid field …
### Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. electron current $I_{el}$</td>
<td>10 A (up to 12 A)</td>
</tr>
<tr>
<td>Electron energy $E_{el}$</td>
<td>20 keV</td>
</tr>
<tr>
<td>Electron density in trap $j_{el}$</td>
<td>575 A/cm²</td>
</tr>
<tr>
<td>Length of ion trap $l_{trap}$</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Ion trap capacity $Q_{el}$</td>
<td>$1.1 \times 10^{12}$</td>
</tr>
<tr>
<td>Ion yield (charges) $Q_{ion}$</td>
<td>$8.1 \times 10^{11}$ (9.6 A)</td>
</tr>
<tr>
<td>Yield of ions Au$^{32+}$ $N_{Au}$</td>
<td>$3.4 \times 10^9$</td>
</tr>
</tbody>
</table>

### Superconducting solenoid specs

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum magnet field</td>
<td>5.0 T</td>
</tr>
<tr>
<td>“Warm” ID</td>
<td>204 mm</td>
</tr>
<tr>
<td>Length of solenoid</td>
<td>1900 mm</td>
</tr>
<tr>
<td>He refilling period</td>
<td>30 days</td>
</tr>
</tbody>
</table>
RHIC EBIS Performance

Beam intensity measured at Booster ring input:

<table>
<thead>
<tr>
<th>EBIS $I_e$ (A)</th>
<th>Ion</th>
<th>Booster Input (ions)</th>
<th>EBIS All Ch States (Charges)</th>
<th>Charge Fraction EBIS to Booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3</td>
<td>$^{63}\text{Cu}^{11+}$</td>
<td>$6.1 \times 10^9$</td>
<td>$6.9 \times 10^9$</td>
<td>9.7%</td>
</tr>
<tr>
<td>9.5</td>
<td>$^{197}\text{Au}^{32+}$</td>
<td>$1.5 \times 10^9$</td>
<td>$9.4 \times 10^9$</td>
<td>5.0%</td>
</tr>
<tr>
<td>9.6</td>
<td>$^{238}\text{U}^{39+}$</td>
<td>$1.1 \times 10^9$</td>
<td>$8.1 \times 10^9$</td>
<td>5.2%</td>
</tr>
</tbody>
</table>

Transmission to Booster input is $\sim 56\%$ of what is expected, and there are additional shortfalls in the Booster/AGS rings. We believe that the early losses are due to a broadening of the EBIS charge state distribution with high neutralization coupled with a 30% decrease in the RFQ/Linac transmission efficiency due to mismatch and/or emittance growth due to misalignment.
LIS Definition

 Ion source for selective ionization of isotopes
  - Multi-photon ionization of atoms

 Ion source using extremely high power density (> $10^{18}$W/cm$^2$) of fs-lasers
  - Irradiation of thin foil
  - Ionization by extremely strong electric field caused by separation of hot electrons and cold ions in space

 Ion source using moderate laser power densities (< $10^{15}$W/cm$^2$)
  - Irradiation of thick target
  - Ionization by electron impact into laser produced plasma
LIS Principles

Target Chamber

NaCl Window

P~10^-6 Torr

Target

Laser pulse: ns

Drift Length: L

Pulse Length: 2-10 μs

Advantage:

• Short pulse
• High charge state, high intensity
• Ion beams any solid material

\[ \tau \propto L \]

\[ J \propto L^{-3} \]

\( \tau \): Beam Pulse length;

\( J \): Beam intensity

Al - 3 J/30 ns Nd-glass 1062 nm laser (10^{11} \text{ W/cm}^2)

Ta - 1 J/5 ns Nd-YAG 532 nm laser (10^9 \text{ W/cm}^2)
Pros and Cons

• Pros:
  • Simple system setup
  • Very high beam current of HCl
  • Short pulses → LIS + RFQ is the best combination

• Cons:
  • Low reliability and stability
  • Short continuous operation time (very picky on target surface conditions)
  • Pulse to pulse beam current fluctuations
  • Target erosion, coating of optics by evaporated target material
  • Beam species limited to solid target (cryogenic target is costly)
  • Large beam emittance and energy spread

- Statistical fluctuations in pulse amplitude and pulse width from shot to shot were less than $\pm 15\%$. 1 Hz pulse trains lasting more than 60-70 minutes.
- $1-2 \times 10^{10}$ Pb$^{27+}$ in a pulse of 3-4 $\mu$s.

**CERN LIS:**
- CO$_2$ laser
- $\lambda = 10.6 \mu m$, 100 J, 1 Hz
- Laser pulse 15-30 ns
- Power density $10^{13}$ W/cm$^2$
- Ion pulse 1-10 $\mu$s
BNL LIS Performances

Nd: YAG Laser, f:100mm, 30cm from target, aperture:Ø6mm

Courtesy of M. Okamura, BNL
Traditional Injection Scheme for RFQ

Main Components:
- Laser
- Target illumination unit
- Plasma expansion region
- Extraction system
- LEBT

Disadvantages
- Strong space charge effect: Due to the low energy and highly charged states.
- Matching to the RFQ: Time variation of the beam emittance from the pulsed source.
- Multiple charged states: Effects from un-wanted charged state particles.
Direct Plasma Injection Scheme (DPIS)

Advantages

• OVERCOME SPACE CHARGE EFFECT
• NO NEED TO BUILD A HV STAGE
• NO NEED ANY FOCUSING OR EXTRACTION SYSTEM
• EXTREMELY SIMPLE
Next Generation LIS?

- Plasma cutoff density: \( n_{cr} \propto f^2 \)

- Empirically: \( J \sim d_f^2 * P \sim E_l \)
  - \( E_l \) of 10 - 200 J

- \( T_e \) & \( Q \propto P \ [W/cm^2] \)

- Special techniques
  - DPIS or LEBT injection to RFQ?
  - Plasma transverse confinement
  - Beam pulse length expansion without density decrease
  - \( P=10^{10}-10^{12} \text{W/cm}^2 \) for very intense LCS ion beams
  - \( P=10^{14}-10^{16} \text{W/cm}^2 \) for intense HCl ion beams

- Issues:
  - Stable operational time
  - Reliability and stability
  - Energy spread
Principles of ECRIS

Multicharged Ion production in a minimum-$|B|$.

- **Resonant Heating of electron by RF power (Stochastic process)**
  - $\text{RF}$
  - $\text{Vacuum}$
  - $\text{Ions}$
  - $\text{Hexapole}$
  - $\text{Solenoids}$

- $B_{\text{inj}}, B_{\text{ext}}, B_{\text{med}}$
- $\Omega_{\text{ce}} = qB/m_e = \Omega_{\text{HF}}$

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# Family Tree of ECRISs

<table>
<thead>
<tr>
<th>All permanent magnet ECRIS</th>
<th>Classical RM ECRIS</th>
<th>Hybrid SC-ECRIS</th>
<th>Fully SC-ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanogan series ion sources</td>
<td>GTS source</td>
<td>RAMSE, SHIVA</td>
<td>SERSE 18 GHz</td>
</tr>
<tr>
<td>BIE series ion sources</td>
<td>AECR-U</td>
<td>A-PHOENIX</td>
<td>VENUS 28GHz</td>
</tr>
<tr>
<td>LAPECR1, LAPECR2</td>
<td>LECR2, LECR3</td>
<td>PKDELIS</td>
<td>SECRAL 18~28 GHz</td>
</tr>
<tr>
<td>Kei1, Kei2</td>
<td>RIKEN 18 GHz</td>
<td>Dubna 18 GHz</td>
<td>SUSI 18~24 GHz</td>
</tr>
<tr>
<td>SOPHIE</td>
<td>ECR4, Caprice</td>
<td>Operated 14 ~ 28 GHz</td>
<td>RIKEN SCECRIS 28 GHz</td>
</tr>
<tr>
<td>Operated 2.45 ~ 14 GHz</td>
<td>Operated 10 ~ 18 GHz</td>
<td></td>
<td>Operated 18 ~ 28 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPERMAFIOS</td>
<td>CAPRICE (CEA)</td>
<td>VENUS* (LBNL)</td>
<td>G3</td>
</tr>
<tr>
<td>MINIMAFIOS</td>
<td>ECR4 (GANIL)</td>
<td>SECRAL* (IMP/CAS)</td>
<td></td>
</tr>
<tr>
<td>ECREVIS*</td>
<td>A-ECR (LBL)</td>
<td>SuSI* (MSU)</td>
<td></td>
</tr>
<tr>
<td>LBL ECR</td>
<td>RIKEN 18 GHz</td>
<td>RIKEN SCECRIS*</td>
<td></td>
</tr>
<tr>
<td>MSU ECR</td>
<td>PHOENIX (LPSC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ORNL ECR</td>
<td>SERSE* (LNS/CEA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OCTOPUS ISIS</td>
<td>GTS (CEA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>Cost: 1-4 M€</td>
<td>G4</td>
</tr>
</tbody>
</table>

*Superconducting ECRIS

Cost: 500 k€  

Cost: ?  

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Why Superconducting?

- \( I_i^q = \frac{1}{2} \frac{n_i^q q e V_{\text{ex}}}{\tau_i^q} \) 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)

- From RF dispersion equation at resonance: \((n_e T_e) \approx \left( \frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2} \right) m_e c^2 \)

Plasma Stability condition: \( \beta = \frac{n_e k_b T_e}{B^2 \left( \frac{2 \mu_0}{\omega_{rf}} \right)} < 1 \)

- \( B_{\text{inj}} \sim 3 - 4 \ B_{\text{ecr}} \) on axis
- \( B_{\text{ext}} \sim 2.2 \ B_{\text{ecr}} \) on axis (T)
- \( B_{\text{rad}} \sim 2B_{\text{ecr}} \) on plasma chamber wall
- Last closed Bmod inside chamber is \( \sim 2 \ B_{\text{ecr}} \)

Semi-empirical rules

<table>
<thead>
<tr>
<th>( f_{\text{ECR}} )</th>
<th>( B_{\text{ECR}} )</th>
<th>( B_{\text{inj}} )</th>
<th>( B_{\text{rad}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 GHz 0.5 T</td>
<td>2 T</td>
<td>1 T</td>
<td></td>
</tr>
<tr>
<td>28 GHz 1 T</td>
<td>4 T</td>
<td>2 T</td>
<td></td>
</tr>
</tbody>
</table>
Performance of the 3rd Generation ECRISs

![Graph showing ion beam intensity vs charge state Q for various ECRIS systems. The x-axis represents charge state Q, ranging from 8 to 18, and the y-axis represents ion beam intensity in euA. The graph includes data for SuSI_18GHz, VENUS_28GHz, SECRAL_24GHz, GTS_18GHz, and SPIRAL2, with SPIRAL2 aiming for a 1emA goal.]
Performance of the 3rd Generation ECRISs

- SECRAL-24GHz
- SuSI_18GHz
- VENUS_28GHz
- GTS-18GHz

Ne-like Xe ion
Breakthrough of U Beam

Liangting Sun, Guillaume Machicoane, Janilee Benitez and Claude Lyneis

Redesigned Re Oven

88 Inch Lab, LBNL, USA

VENUS: 6.5kW 28GHz + 1.7kW 18GHz, HV: 22kV

<table>
<thead>
<tr>
<th>Uranium ion</th>
<th>Beam current in µA</th>
</tr>
</thead>
<tbody>
<tr>
<td>28+</td>
<td>295</td>
</tr>
<tr>
<td>29+</td>
<td>361</td>
</tr>
<tr>
<td>31+</td>
<td>460</td>
</tr>
<tr>
<td>32+</td>
<td>453</td>
</tr>
<tr>
<td>33+</td>
<td>443</td>
</tr>
<tr>
<td>34+</td>
<td>400</td>
</tr>
<tr>
<td>35+</td>
<td>311</td>
</tr>
</tbody>
</table>

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Next Generation ECRISs

Geller’s Scaling Laws:

\[ I(q) \propto B_{ecr}^2 \sim \omega_{rf}^2 \]
\[ Q_{opt} \sim \log \omega_{rf}^3 \]

450euA U^{33+} @28GHz

~1.8emA U^{33+} @56GHz

Typical beam intensity enhancement in the last 10-30 years

<table>
<thead>
<tr>
<th>Ions</th>
<th>Year Intensity By ECRIS</th>
<th>Year Intensity By ECRIS</th>
<th>By factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>O^{6+}</td>
<td>1974, 15 eμA Supermafios</td>
<td>2011, ~2-3 eμA LBL VENUS IMP SECRL</td>
<td>~37 ys ~200</td>
</tr>
<tr>
<td>Xe^{30+}</td>
<td>1997-1998, 10-15 eμA RIKEN 18 GHz, LBL AECR-U</td>
<td>2011, ~236 eμA IMP SECRL</td>
<td>~14 ys &gt;15</td>
</tr>
<tr>
<td>Xe^{35+}</td>
<td>1997, 1.5 eμA LBL AECR-U</td>
<td>2011, ~64 eμA IMP SECRL</td>
<td>~14 ys &gt;40</td>
</tr>
<tr>
<td>U^{34+}</td>
<td>1997, 20 eμA LBL AECR-U</td>
<td>2011, ~400 eμA LBL VENUS</td>
<td>~14 ys &gt;20</td>
</tr>
</tbody>
</table>

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Choice of SC-magnet?

• Pros and Cons from Conventional and Non-conventional Structure?

Yes!!

• Does ECR Plasma care about the structure?

No!!

• So long as the magnetic field strengths are high enough!
Available Magnet Choices?

- VENUS Structure
- SECRAL Structure
- MK-I Structure
Comparison

Next Generation ECRIS’ Field

<table>
<thead>
<tr>
<th></th>
<th>24 GHz</th>
<th>28 GHz</th>
<th>18GHz</th>
<th>56GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{inj} (T)</td>
<td>3.4</td>
<td>4.0</td>
<td>2.6</td>
<td>8.0</td>
</tr>
<tr>
<td>B_{ext} (T)</td>
<td>1.8</td>
<td>2.2</td>
<td>1.4</td>
<td>4.4</td>
</tr>
<tr>
<td>B_{min} (T)</td>
<td>0.7</td>
<td>0.8</td>
<td>0.5</td>
<td>1.6</td>
</tr>
<tr>
<td>B_{rad} (T)</td>
<td>1.7</td>
<td>2.0</td>
<td>1.3</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Cons of the different options

<table>
<thead>
<tr>
<th>VENUS</th>
<th>SECRAL</th>
<th>MK-I</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Complicated forces at hexapole ends</td>
<td>• Lower radial field</td>
<td>• Complexity of the sextupole windings</td>
</tr>
<tr>
<td>• Bulky magnet body</td>
<td>• Smaller plasma chamber</td>
<td>• Coil clamping method is very challengeable</td>
</tr>
<tr>
<td>• Much higher stored energy</td>
<td>• Nn_{3}Sn wire problems</td>
<td>• Stepped cryostat and partial hexagonal warm bore and plasma chamber</td>
</tr>
<tr>
<td>• Nb_{3}Sn wire problems</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Other Challenges

- Effective coupling to the plasma of 10-20 kW/50-60GHz microwave power
- Strong ECR plasma bremsstrahlung radiation problems
  - Heat sink in cryostat
  - HV insulator degradation
- Intense high charge state ion beam (20-40emA) extraction and transmission and beam quality;
- Ion beam quality and stability from the ion source working at 10-20 kW/50-60GHz is unknown
- Intense metallic beam production, especially ion beams of refractory materials
Acknowledgement

Thanks for the fruitful discussion and data!!

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G. Machicoane MSU/USA
M. Okamura BNL/USA
T. Thuillier LPSC/France
D. Xie     IMP/China

Thank you for your attentions!!
Backup slides
Solid material feeding is still a challenge for intense beam production

- Frequency scaling is still applying well to ECRISs