Perspectives in High Intensity Heavy Ion Sources for Future Heavy Ion Accelerators

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Preface

JLEIC/Jlab
(Proposal)

HIAF/IMP
(Funded)

FAIR/GSI
(under construction)

RIBF/RIKEN
(In operation)
Preface

Nuclear Physics
- Intense heavy ion beams
- High beam power

High Energy Density Physics
- High energy very heavy ion beams
- High power density

Electron Ion Collider
- High energy ion beams
- High Luminosity
Outline

- Accelerator Requirements
- High intensity HCI sources
- Future developments and perspectives
## Accelerator Requirements

### Typical requirements of high intensity heavy ions

<table>
<thead>
<tr>
<th>Facility</th>
<th>Typical Ion</th>
<th>Required Intensity*</th>
<th>Pulse Length</th>
<th>Physics Goal</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAIR/GSI</td>
<td>U^{28+}</td>
<td>2.75 \times 10^{12}</td>
<td>82 μs</td>
<td>Nuclear Physics HEDP, ENC</td>
<td>Construction</td>
</tr>
<tr>
<td>HIAF/IMP</td>
<td>U^{35+}</td>
<td>20 μA</td>
<td>CW</td>
<td>Nuclear Physics HEDP, ENC</td>
<td>Funded</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pulsed 1.25 \times 10^{11}</td>
<td>0.5 ms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRIB</td>
<td>U^{33+, 34+}</td>
<td>14 μA</td>
<td>CW</td>
<td>Nuclear Physics</td>
<td>Construction</td>
</tr>
<tr>
<td>RHIC</td>
<td>Au^{32+}</td>
<td>3.4 \times 10^9</td>
<td>10~40 μs</td>
<td>Nuclear Physics</td>
<td>Operation</td>
</tr>
<tr>
<td>JLEIC</td>
<td>Pb^{30+}</td>
<td>Pulsed \sim 2.6 \times 10^{10}</td>
<td>0.25 ms</td>
<td>EIC</td>
<td>Proposal</td>
</tr>
</tbody>
</table>

* Particles per pulse
Requirements of ion source for those high energy (GeV/u) high current heavy ion accelerators

- \( E \sim Q^2 \) for cyclotrons
- \( E \sim Q \) for linac

- Higher power
- Simpler injection mode

Developing intense highly charged ion source is both \textit{performance-effective} and \textit{cost-effective}. 
## Accelerator Requirements

<table>
<thead>
<tr>
<th></th>
<th>$^{238}$U$^{34+}$</th>
<th>$^{238}$U$^{46+}$</th>
<th>$^{238}$U$^{55+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection E (MeV/u)</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Output E (MeV/u)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Design $I_{\text{max}}$ (emA)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SC cavity</td>
<td>HWR009+HWR015+Spoke021</td>
<td>HWR009+HWR015+Spoke021</td>
<td>HWR009+HWR015+Spoke021</td>
</tr>
<tr>
<td>SC cavities</td>
<td>44+100+248=392</td>
<td>40+92+176=308</td>
<td>32+80+152=264</td>
</tr>
<tr>
<td>Solenoids</td>
<td>78</td>
<td>65</td>
<td>55</td>
</tr>
<tr>
<td>CRM Reduced</td>
<td>11</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Total length (m)</td>
<td>288</td>
<td>225</td>
<td>197</td>
</tr>
<tr>
<td>Budget reduced</td>
<td>&gt;70 M$$</td>
<td>&gt;100 M$$</td>
<td></td>
</tr>
</tbody>
</table>

(MP not included)

Courtesy of H. W. Zhao@ICIS’13 Talk
### Accelerator Requirements

<table>
<thead>
<tr>
<th></th>
<th>238U^{34+}</th>
<th>238U^{46+}</th>
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<tbody>
<tr>
<td><strong>Injection E (MeV/u)</strong></td>
<td>1.3</td>
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</tr>
<tr>
<td><strong>Output E (MeV/u)</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SC cavity</td>
<td>HWR009+HWR015+</td>
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</tr>
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<td>Budget reduced</td>
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<td>&gt;100 M$</td>
<td>(MP not included)</td>
</tr>
</tbody>
</table>

It is very much worthy of developing highly charged ion source aiming at very high charge state!!

Courtesy of H. W. Zhao@ICIS’13 Talk
High intensity HCI sources

**A**(n+1)+ ionization potential

- $6.8 \times 10^{-16}$
- $6.6 \times 10^{-19}$
- $3.474 \times 10^{-20}$
- $9.321 \times 10^{-22}$
- $1.02 \times 10^{-24}$

## It is hard to produce intense HCI beams

- **HCl production needs energetic electrons** $T_e$
- **HCl production cross sections is low**
  - Long enough confinement time $\tau_i$
  - High enough electron density $n_e$

<table>
<thead>
<tr>
<th>Charge State</th>
<th>I.P. (eV)</th>
<th>Cross Section (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+</td>
<td>6.8</td>
<td>$\sim 2.4 \times 10^{-16}$</td>
</tr>
<tr>
<td>22+</td>
<td>660</td>
<td>$\sim 4.9 \times 10^{-19}$</td>
</tr>
<tr>
<td>54+</td>
<td>3,474</td>
<td>$\sim 1.4 \times 10^{-20}$</td>
</tr>
<tr>
<td>72+</td>
<td>9,321</td>
<td>$\sim 7.8 \times 10^{-22}$</td>
</tr>
<tr>
<td>82+</td>
<td>102,000</td>
<td>$\sim 1.5 \times 10^{-24}$</td>
</tr>
</tbody>
</table>
High intensity HCI sources

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

• **LIS or Laser Ion Source**
  » Proposed by Dr. Bykovskii et al. and Peacock, Pease in 1969
  » Laser irradiation on solid target induced plasma, **pulsed beam**

• **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, **dc and pulsed beam**

• **Charge Stripping Scheme**
  » In operation for GSI since 1990s
  » HCI beams With high intensity low charge sate ion source + Linac + Stripper, **pulsed beam**
High intensity HCl sources: EBIS

- Total charge of ions extracted per pulse: \(~ (0.5 – 0.8) \times (N_e \text{ in the trap}) - K_1\)
- Ion output/pulse proportional to the trap length \(L\), electron current \(I_e\), Ion q fraction \(K_2\)
- Ion charge \(q\) increases with increasing confinement time
- Output current pulse almost independent of species or charge state

**Radial trapping of ions = space charge of the electron beam**

**Axial trapping = electrostatic potentials at ends of trap**

\[
N_q = \frac{I_e \times L}{q \times \sqrt{U_e}} \times K_1 \times K_2
\]
High intensity HCl sources: EBIS

RHIC-EBIS Source Assembly

Parameter | RHIC EBIS
---|---
Max. electron current | $I_{el} = 10 \text{ A}$
Electron energy | $E_{el} = 20 \text{ keV}$
Electron density in trap | $j_{el} = 575 \text{ A/cm}^2$
Length of ion trap | $l_{trap} = 1.5 \text{ m}$
Ion trap capacity | $Q_{el} = 1.1 \times 10^{12}$
Ion yield (charges) | $Q_{ion} = 5.5 \times 10^{11} (10 \text{ A})$
Yield of ions Au$^{32+}$ | $N_{Au}^{32+} = 3.4 \times 10^9$

- Very high charge state
- Variable extraction pulse length
- Pure ion beams

Courtesy of E. Beebe@ICIS’17 Talk
High intensity HCl sources: EBIS

D, $^3\text{He}^{2+}$, $^4\text{He}^{1+}$, $\text{Li}^{3+}$, $\text{C}^{5+}$, $\text{O}^{7+}$, $\text{Ne}^{5+}$, $\text{Al}^{15+}$, $\text{Si}^{11+}$, $\text{Ar}^{11+}$, $\text{Ca}^{14+}$, $\text{Ti}^{18+}$, $\text{Fe}^{20+}$, $\text{Cu}^{11+}$, $\text{Kr}^{18+}$, $\text{Zr}^{15+}$, $\text{Zr}^{16+}$, $\text{Nb}^{16+}$, $\text{Xe}^{27+}$, $\text{Ta}^{38+}$, $\text{W}^{31+}$, $\text{Au}^{32+}$, $\text{Pb}^{34+}$, $\text{Th}^{39+}$, $\text{U}^{39+}$

RHIC-EBIS in Operation

Total charge/pulse ($10^{11}$) vs. Electron Beam Current (A)

1.5 m Trap Max.

1.78 m Trap Max.

Courtesy of E. Beebe@ICIS’17 Talk
High intensity HCl sources: ECRIS

Electron Cyclotron Resonance Ion Source

\[ \omega_{ce} = \frac{e \cdot B_{ecr}}{m_e} \]

- \( I_i^q = \frac{1}{2} n_i^q q e V_{ex} \) \( \tau_i^q \) ion density for species \( i \) charge \( q \) confinement time for species \( i \) charge \( q \)
  \[ \sum_{i,q} n_i^q q_i = n_e \text{ (Plasma neutrality)} \]

- RF dispersion equation at resonance: \( (n_e T_e) \approx \left( \frac{m_e e_0 \omega^2}{e^2} \right) m_e c^2 \)
  \[ \alpha \omega_{ECR}^2 \]

- Plasma Stability condition: \( \beta = \frac{n_e k_b T_e}{B^2} < 1 \) As \( n_e \uparrow \) \( B \uparrow \)
High intensity HCl sources: ECRIS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>State of the Art ECRISs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{rf}$</td>
<td>GHz</td>
<td>24–28</td>
</tr>
<tr>
<td>$P_{rf}$</td>
<td>kW</td>
<td>10.0</td>
</tr>
<tr>
<td>$B_{mirror}$</td>
<td>T</td>
<td>3.7–4.0/2.2–2.8</td>
</tr>
<tr>
<td>$B_r$</td>
<td>T</td>
<td>1.8–2.0</td>
</tr>
<tr>
<td>Chamber ID</td>
<td>mm</td>
<td>$\varnothing$100–150</td>
</tr>
<tr>
<td>Mirror Length</td>
<td>mm</td>
<td>400–500</td>
</tr>
<tr>
<td>HV</td>
<td>kV</td>
<td>30</td>
</tr>
</tbody>
</table>

- Very high charge state
- ~ms pulse to dc beam
- High beam intensity
High intensity HCI sources: ECRIS

- ECRIS performances are keeping boosting in years
- ~emA order HCI beams available

<table>
<thead>
<tr>
<th>Ion beam</th>
<th>I (emA)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O^{6+}</td>
<td>6.7</td>
<td>28</td>
</tr>
<tr>
<td>Ar^{12+}</td>
<td>1.42</td>
<td>24</td>
</tr>
<tr>
<td>Ar^{14+}</td>
<td>1.04</td>
<td>28</td>
</tr>
<tr>
<td>Ar^{16+}</td>
<td>0.62</td>
<td>28</td>
</tr>
<tr>
<td>Ar^{18+}</td>
<td>0.015</td>
<td>28</td>
</tr>
<tr>
<td>Ca^{11+}</td>
<td>0.71</td>
<td>24</td>
</tr>
<tr>
<td>Kr^{18+}</td>
<td>1.02</td>
<td>28</td>
</tr>
<tr>
<td>Kr^{28+}</td>
<td>0.146</td>
<td>28</td>
</tr>
<tr>
<td>Xe^{26+}</td>
<td>1.1</td>
<td>24</td>
</tr>
<tr>
<td>Xe^{30+}</td>
<td>0.365</td>
<td>28</td>
</tr>
<tr>
<td>Xe^{38+}</td>
<td>0.053</td>
<td>28</td>
</tr>
<tr>
<td>Xe^{42+}</td>
<td>0.017</td>
<td>28</td>
</tr>
<tr>
<td>Ta^{30+}</td>
<td>0.375</td>
<td>28</td>
</tr>
<tr>
<td>Bi^{30+}</td>
<td>0.71</td>
<td>24</td>
</tr>
<tr>
<td>Bi^{50+}</td>
<td>0.01</td>
<td>24</td>
</tr>
</tbody>
</table>
High intensity HCl sources: LIS

Target Chamber

Laser pulse: ns

Target

P~10^{-6} Torr

Extraction

Courtesy of S. Kondrashev/BNL
High intensity HCl sources: LIS

Target Chamber

Laser pulse: ns

P~10^-6 Torr

Target

Extraction

Courtesy of S. Kondrashev/BNL
High intensity HCl sources: LIS

Target Chamber

Laser pulse: ns

P\sim 10^{-6} \text{ Torr}

Target

Extraction

Courtesy of S. Kondrashev/BNL
High intensity HCl sources: LIS

Target Chamber

Laser pulse: ns

Target

Extraction

P~10^{-6} Torr

Courtesy of S. Kondrashev/BNL
High intensity HCI sources: LIS

Target Chamber

Laser pulse: ns

P~10^{-6} Torr

Target

Extraction

Drift Length: L
Pulse Length $\tau$: 2-30 $\mu$s

- $\tau \propto L$
- $I \propto L^{-3}$

Courtesy of S. Kondrashev/BNL
High intensity HCl sources: LIS

Advantage:
• Simple structure: Laser, Vacuum, Target, Extraction
• Short pulse: μs
• High charge state
• High intensity, tens of emA, $10^{10}$~$10^{11}$ppp
• Ion beams of any solid materials

Drift Length: L
Pulse Length $\tau$: 2-30 μs

$\tau \propto L$
$I \propto L^{-3}$

From target to extraction point (cm)

Pulse width - Al 10+
Pulse width - Ta 1+
Current - Al 10+
Current - Ta 1+

Al - 3 J/30 ns Nd-glass 1062 nm laser ($10^{11}$ W/cm²)
Ta - 1 J/5 ns Nd-YAG 532 nm laser ($10^{9}$ W/cm²)

Courtesy of S. Kondrashev/BNL
CSD of a lead ion beam generated by a CO₂ laser at a power density $P \approx 3 \times 10^{13}$ W/cm²

- Max. 3.5 emA or $2.8 \times 10^{10}$ ppp Pb\(^{27+}\) with a pulse length of 3.6 μs
- 16% Pb\(^{27+}\) in the extracted beam

- CERN-ITEP-TRINITI collaboration on LIS
- Design study towards to LIS capable to meet LHC demand for Pb\(^{25+}\) ions
High intensity HCl sources: LIS

<table>
<thead>
<tr>
<th>Ion Species</th>
<th>Specs.</th>
<th>Total Charge</th>
<th>Peak Current</th>
<th>Pulse length (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Avg</td>
<td>$1.38 \times 10^{-7}$ C</td>
<td>46.5 emA</td>
<td>1.64 μs</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>3.5%</td>
<td>10%</td>
<td>6.7%</td>
</tr>
<tr>
<td>Ni</td>
<td>Avg</td>
<td>$0.98 \times 10^{-7}$ C</td>
<td>15.5 emA</td>
<td>2.24 μs</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>2.6%</td>
<td>5.9%</td>
<td>4.7%</td>
</tr>
<tr>
<td>Al</td>
<td>Avg</td>
<td>$1.21 \times 10^{-7}$ C</td>
<td>35.2 emA</td>
<td>2.22 μs</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>2.6%</td>
<td>7.6%</td>
<td>8.1%</td>
</tr>
</tbody>
</table>

- Pulse to pulse stability: better than 10%
- Low Emittance: ~0.1 π. μm (n.rms)
- Routine operation (with):
  - LION source for RHIC in BNL
  - LIS source for NICA in JINR
  - LIS source for ITEP-TWAC

Courtesy of H. Y. Zhao/IMP
Courtesy of M. Okamura/BNL
High intensity HCl sources: Charge Stripping

VARIS
U4+
PIG
RFQ
IH1
IH2
Gas Stripper
f_r = 36 MHz
2.2 keV/u β = 0.0022
120 keV/u β = 0.016
1.4 MeV/u β = 0.054

MUCIS

HLI: (ECR, RFQ, IH)

f_r = 108 MHz
Alvarez DTL

Gas Stripper

11.4 MeV/u β = 0.16

To SIS18

Foil Stripper

RFQ, IH1, IH2

Alvarez DTL

Single Gap Resonators

Transfer to Synchrotron

2.2 keV/u β = 0.0022
120 keV/u β = 0.016
11.4 MeV/u β = 0.16

10m

frf = 36 MHz
frf = 108 MHz

Constructed in the 70th, Upgraded in 1999, → Injector for FAIR ion operation
High intensity HCI sources: **Charge Stripping**

**Operational data of the ion source**

- **Ion fraction**
  - $U^{3+} = 16\%$, $U^{4+} = 67\%$
  - $U^{5+} = 14\%$, $U^{6+} = 3\%$

- **Arc current/arc power**
  - 600–700 A/up to 30 kW

- **Pulse length/rep. rate**
  - 0.6 ms/1 Hz

- **Flux densities solenoid I + II/III**
  - 40 mT/0–60 mT

- **Extraction system**
  - 13 x 3 mm, multi-aperture aspect ratio 0.5

- **Emission current density**
  - 170 mA/cm$^2$
  - (for standard operation) (150 mA/cm$^2$)

- **Full beam ion current, FC**
  - 156 mA @ 35 kV
  - (for standard operation) (140 mA @ 32 kV)

- **DC accelerated ion current**
  - 55 mA @ 131 kV

- **Analysed $U^{4+}$ current**
  - 25 mA

- **$U^{4+}$ current for RFO injection**
  - 15 mA

- $\varepsilon_{\text{effective}}$ (156 mA @ 35 kV) 890 $\mu$mm mrad
- $\varepsilon_{\text{rms}}$ (156 mA @ 35 kV) 440 $\mu$mm mrad
- $\varepsilon_{\text{rms}}$ (156 mA @ 35 kV) 470 $\mu$mm rad
- $\varepsilon_{\text{rms}}$ (55 mA @ 131 kV) 400 $\mu$mm rad
- $\varepsilon_{\text{rms},90\%}$ (after separation, 15 mA) 180 mm rad
- $\varepsilon_{\text{rms},90\%}$ (after separation, 15 mA) 140 $\mu$mm rad
- Noise full beam/after separation $<\pm4\%/\pm5\%$
- Pulse to pulse stability Better than 80%
- Voltage break downs 2 per day for standard operation
- Cathode life time 12 h @ 0.6\% duty cycle

High intensity HCl sources: Charge Stripping

- **Pulsed gas valve synchronized with beam pulse timing**
- **Gas back-pressure up to 12 MPa**

Charge distribution after stripping of U projectiles in a H₂ gas target for different target thickness in comparison with N₂ target:

- **7.5 MPa gas cell** → **11.1 emA U^{28+}**
- **12.0 MPa gas cell** → **11.5 emA U^{29+}**
- **From formerly 7.6 emA (50% of FAIR requirement) → 74%**

High intensity HCI sources: **impact**

The diagram shows a log-log plot correlating Electron Cyclotron Resonance Ion Sources (ECRIS), LIS, EBIS, and other sources like JLEIC, FRIB, HIAF-CW, RHIC, FAIR, HIAF-pulse, NICA, SPIRAL2 with their respective charge stripping processes. The x-axis represents pulse length in seconds, while the y-axis shows particles per pulse.
High intensity HCI sources: **impact**

**CW operation:**
- FRIB
- HIAF-CW
- SPIRAL2

**Multi-turn injection:**
- FAIR
- HIAF-pulse
- JLEIC

**Single-turn injection:**
- RHIC
- NICA

**ECHIS, Charge Stripping**

**EBIS, LIS**
Future developments and perspectives

- Next Generation ECRIS
- Tandem EBIS
- Gasdynamic ECRIS (G-ECRIS)+Stripping
Next Generation ECRIS

$I^q \propto \omega^2_{ECR} \cdot G_q \sim (28/18)^2 = 2.4$

45 GHz~ $G_q = 2.6$

$>1.0 \text{ emA } U^{34+}, \text{ dc}$

($>2.0 \text{ emA, pulsed}$)

<table>
<thead>
<tr>
<th>Specs.</th>
<th>Unit</th>
<th>45 GHz ECRIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GHz</td>
<td>45</td>
</tr>
<tr>
<td>Mirror Fields</td>
<td>T</td>
<td>$\geq 6.4/3.2$</td>
</tr>
<tr>
<td>$B_{rad}$</td>
<td>T</td>
<td>$\geq 3.2$</td>
</tr>
<tr>
<td>Mirror Length</td>
<td>mm</td>
<td>$\sim 500$</td>
</tr>
<tr>
<td>Magnet coils</td>
<td>/ Nb$_3$Sn</td>
<td></td>
</tr>
<tr>
<td>Conductor</td>
<td>$J_c &gt; 1500 \text{ A/mm}^2$ @ 12T</td>
<td></td>
</tr>
<tr>
<td>Cooling Capacity@4.2 K</td>
<td>W</td>
<td>$\geq 10.0$</td>
</tr>
</tbody>
</table>
Next Generation ECRIS

HCl currents with a 4th G. ECRIS:
- $A = 12 - 40$ 200 puA (dc)
- $A = 40 - 100$ 100 puA (dc)
- $A = 100 - 238$ 30 puA (dc), 50 puA (pulse)

45 GHz FECR@IMP (2017~2020)
45 GHz FECR@IMP (2017~2020)

HCl currents with a 4th G. ECRIS:
- $A=12\sim40$ 200 puA (dc)
- $A=40\sim100$ 100 puA (dc)
- $A=100\sim238$ 30 puA (dc), 50 puA (pulse)
Two Straightforward methods to increase EBIS charge:
1) Increase the Electron Current $I_e$
2) Increase the ion trap length $L$

$$N_q = \frac{I_e \times L}{q \times \sqrt{U_e}} \times K_1 \times K_2$$

Courtesy of E. Beebe@ICIS2017, Talk
Tandem EBIS

\[ N_q = \frac{I_e \times L}{q \times \sqrt{U_e}} \times K_1 \times K_2 \]

RHIC-EBIS: \( \text{Au}^{32+} \sim 3.4 \times 10^9 \text{ ions/pulse} \)

Technical Approach:
- Increase from 10 A to 20 A \( (x\sim2.0) \)
- Regain optimal distribution \( K_1 \times K_2 \) \( (x\sim1.5) \)
- Tandem EBIS configuration \( (x\sim2.0) \)

Tandem EBIS Output
- \( \text{Au}^{32+} \sim 2 \times 10^{10} \text{ ions/pulse} \)
- \( \text{U}^{39+} > 1 \times 10^{10} \text{ ions/pulse} \)

Extended EBIS superconducting solenoids@BNL

Courtesy of A. Zelenski@IPAC’18, TUYGBE4

Courtesy of E. Beebe@HCI Sources Symposium 2014 in Lanzhou
G-ECRIS + Stripping

**Features**

- High current density: $1\sim10 \text{ A/cm}^2$
- Low emittance: $\varepsilon_{\text{rms}} < 0.1 \pi\text{.um}$
- High ionization efficiency
- Simple scaling of performance

---

**Scaled performance at 100 GHz**

<table>
<thead>
<tr>
<th>Ion</th>
<th>Charge</th>
<th>Current Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>+4</td>
<td>10 A/cm$^2$</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>+5</td>
<td>10 A/cm$^2$</td>
</tr>
<tr>
<td>Oxygen</td>
<td>+6</td>
<td>10 A/cm$^2$</td>
</tr>
<tr>
<td>Argon</td>
<td>+11</td>
<td>6 A/cm$^2$</td>
</tr>
<tr>
<td>Xenon</td>
<td>+20</td>
<td>4 A/cm$^2$</td>
</tr>
</tbody>
</table>

Courtesy of Vadim Skalyga/IAP
Intense metal beam production

- SMIS37: \(<Z>_{Pt} = 4.5\) @37.5 GHz/100 kW
- SMIS75: \(<Z>_{Pt} = 7\) @75 GHz/200 kW

- Higher frequency: >100 GHz
- Better confinement: MHD stability

Advantages

- Efficient acceleration before stripper
- Low beam emittance
- No life span in principle
- Produce both gaseous and metal beams

Courtesy of Alexander Vodopyanov/IAP
Next G. HCI sources: possibilities
Next G. HCl sources: possibilities

- ECRIS
- Tandem EBIS
- G-ECRIS+Stripping

Flexibility in both single-turn or multi-turn injection for Synchrotron

Higher intensity linac
Conclusion

◆ Remarkable progresses in high intensity high charge state heavy ion sources development in recent years
◆ No all-purpose ion source available for exiting facilities and next generation heavy ion accelerators
◆ Next generation accelerators need more powerful HCI sources
◆ Next generation or future HCI sources provide more possibilities/flexibilities for next generation heavy ion facilities
Thanks for your attention!

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