1. Introduction

2. Ion sources for pulsed beam production (physics and technology)
   2-1. Electron beam ion source
   2-2. Laser ion source

3. Ion sources for DC beam production (physics and technology)
   3-1. Electron cyclotron resonance ion source
Intense beam of highly charged heavy ions

$^{32+}$Au $\times 10^9$/pulse

$^{33+,34+}$U $8\mu$A

$^{12+}$Ar $1$mA

Heavy ion accelerator facilities in the world
Production rate of Radio isotope

C. Jiang et al, NIM A492(2002)57
Production rate of Radio isotope

In the case of $^{138}$Sn production by an in-flight uranium fission reaction, we obtain only ~5 times the production gain by increasing the energy from 200 MeV/u to 400 MeV/u.

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C. Jiang et al, NIM A492(2002)57
Production rate of Radio isotope

In the case of $^{138}\text{Sn}$ production by an in-flight uranium fission reaction, we obtain only ~5 times the production gain by increasing the energy from 200 MeV/u to 400 MeV/u.

Construction cost of a new ECRIS that can increase the beam intensity by a factor of five is significantly less than the construction cost of additional accelerators required to increase the energy.

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IPAC'13, May 12-17, 2013, Shanghai, China
In the case of $^{138}$Sn production by an in-flight uranium fission reaction, we obtain only ~5 times the production gain by increasing the energy from 200 MeV/u to 400 MeV/u.

Construction cost of a new ECRIS that can increase the beam intensity by a factor of five is significantly less than the construction cost of additional accelerators required to increase the energy.

In the past decade, the beam intensity of medium charge state of U ions, which is a suitable charge state for RIBF facility, has been increased by one order of magnitude.

C. Jiang et al, NIM A492(2002)57
Ion sources for Pulsed beam production

2.1 Electron beam ion sources (EBISs)

(I) Physics
(II) BNL-EBIS
(III) Beam instabilities
(IV) New developments

Tandem EBIS
The electron string ion source (ESIS)
The EBIS has very unique feature that the total extracted charge per pulse is almost independent of ion species or charge state. Additionally, the beam pulse width can be controlled by the extraction barrier voltage manipulation, and therefore the both short pulses (~10μs) of high current (several mA) are possible. It is suited for single turn synchrotron injection.
**EBIS for BNL RHIC**

### Requirements for pre-injector

<table>
<thead>
<tr>
<th>Ion species</th>
<th>He~U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam intensity</td>
<td>He^{2+} 5 \times 10^{10}/pulse</td>
</tr>
<tr>
<td></td>
<td>Fe^{20+} 4 \times 10^9</td>
</tr>
<tr>
<td></td>
<td>Au^{32+} 2.7 \times 10^9</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>5Hz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>10~40\mu s</td>
</tr>
<tr>
<td>Switching time</td>
<td>1 sec</td>
</tr>
<tr>
<td>Output energy</td>
<td>2MeV/amu</td>
</tr>
</tbody>
</table>

### Design parameters for EBIS

<table>
<thead>
<tr>
<th>Electron beam</th>
<th>10A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field (solenoid)</td>
<td>5.5T</td>
</tr>
<tr>
<td>Trap length</td>
<td>1.5m</td>
</tr>
<tr>
<td>Vacuum</td>
<td>&lt;10^{-10} Torr</td>
</tr>
<tr>
<td>Total extracted charge/pulse</td>
<td>5 \times 10^{11} (80nC)</td>
</tr>
<tr>
<td>Output energy</td>
<td>17keV/u</td>
</tr>
</tbody>
</table>

J. Alessi et al, RSI 81(2010)02A509

**IPAC’13, May 12-17, 2013, Shanghai, China**
The ion yield vs. electron beam current showed twice the output, compared to the BNL Test EBIS, since this EBIS has twice the trap length of the Test EBIS. Total charge/pulse of $\sim 9 \times 10^{11}$ was achieved at the electron current of $\sim 9A$.

A TOF spectrum of the extracted ion beam with and without Au external ion injection.

<table>
<thead>
<tr>
<th>Element</th>
<th>Ions per pulse</th>
<th>Charges per pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>He 1+</td>
<td>$67 \times 10^9$</td>
<td>$6.7 \times 10^{10}$</td>
</tr>
<tr>
<td>Ne 5+</td>
<td>$5.5 \times 10^9$</td>
<td>$2.7 \times 10^{10}$</td>
</tr>
<tr>
<td>Fe 20+</td>
<td>$1.7 \times 10^9$</td>
<td>$3.4 \times 10^{10}$</td>
</tr>
<tr>
<td>Au 32+</td>
<td>$0.92 \times 10^9$</td>
<td>$2.9 \times 10^{10}$</td>
</tr>
</tbody>
</table>

E. Beebe et al, HIAT2012

A. Pikin et al, Proc. of INT. SYMP. ON ELECTRON BEAM ION SOURCES AND TRAPS

RHIC-EBIS II

IPAC’13, May 12-17, 2013, Shanghai, China
RHIC EBIS performance

Figure 1: Schematic of the EBIS-based heavy ion preinjector
RHIC EBIS performance

Table 1: Preinjector Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He – U</th>
<th>Q / m</th>
<th>Current</th>
<th>Pulse length</th>
<th>Rep rate</th>
<th>EBIS output energy</th>
<th>RFQ output energy</th>
<th>Linac output energy</th>
<th>Time to switch species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions</td>
<td>He – U</td>
<td></td>
<td></td>
<td>≥1/6</td>
<td></td>
<td>17 keV/u</td>
<td>300 keV/u</td>
<td>2 MeV/u</td>
<td>1 second</td>
</tr>
<tr>
<td>Q / m</td>
<td></td>
<td>1/6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>&gt; 1.5 cmA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse length</td>
<td>10–40μs (for few-turn injection)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rep rate</td>
<td>5 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Parameters for helium, gold and iron ions demonstrated for CD-4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He$^{1+}$</th>
<th>Au$^{3+}$</th>
<th>Fe$^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>q/m</td>
<td>0.25</td>
<td>0.162</td>
<td>0.357</td>
</tr>
<tr>
<td>Platform Voltage (kV)</td>
<td>68</td>
<td>104</td>
<td>47.6</td>
</tr>
<tr>
<td>RFQ Power (kW)</td>
<td>40</td>
<td>95</td>
<td>20</td>
</tr>
<tr>
<td>Linac Power (kW)</td>
<td>75</td>
<td>180</td>
<td>37</td>
</tr>
<tr>
<td>Dipole Current (A)</td>
<td>1415</td>
<td>2270</td>
<td>1030</td>
</tr>
<tr>
<td>Pulse Length (μs)</td>
<td>20</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>Rep. Rate (Hz)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Intensity (10$^5$) ions/pulse</td>
<td>1250</td>
<td>3.7</td>
<td>4.75</td>
</tr>
<tr>
<td>Energy (MeV/u)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Transmission</td>
<td>75</td>
<td>90*</td>
<td>60*</td>
</tr>
<tr>
<td>RFQ input to middle of bend</td>
<td>(*=inferred, due to multiple charge states)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1: Schematic of the EBIS-based heavy ion preinjector

J. Alessi et al, PAC’11

IPAC’13, May 12-17, 2013, Shanghai, China
Despite the success using an EBIS in the application, it has reported that it has some **limitation of the behaviour**.

In 1990’s, Donets reported the **anomalous behaviour** that might limit EBIS performance.

One of the explanations is the existence of **plasma instabilities**. The instabilities associated with the beam current, electron beam and trapped ions were intensively studied. It was observed that the effective ionization rate was reduced and radial ion current was increased with the instabilities. It should affect the stability of the beam.

To further improve the performance. It is important to study the instabilities experimentally, theoretically with using the simulation code.

M. Levine et al, NIM A237(1985)429

It can make to **double** the EBIS intensity using the existing units: electron gun, electron collector, extraction/injection ion optics, and ion injection system.

A. Pikin et al, HIAT2012, p101
Next step I (Tandem EBIS)

Additional SC-solenoid coil

It can make to **double** the EBIS intensity using the existing units: electron gun, electron collector, extraction/injection ion optics, and ion injection system.

The longitudinal energy spread and transverse emittance growth resulting from a fast ion extraction should be minimizing to match the RHIC requirements.

A. Pikin et al, HIAT2012, p101
Donets proposed so-called reflex mode of EBIS.

This ion source has specially designed electron gun and electron reflector which allows the multiple use of the electron beam.

The electron string ion source (ESIS) is based on a specially designed electron gun and an electron reflector that allows multiple uses of beam electrons. At some conditions the electron can be reflected hundred times.

D. Donets et al, EPAC08
Donets proposed so-called reflex mode of EBIS.

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The electron string ion source (ESIS) is based on a specially designed electron gun and an electron reflector that allows multiple uses of beam electrons.

At some conditions the electron can be reflected hundred times.

Ar\(^{16+}\) 200 e\(\mu\)A  
Fe\(^{24+}\) 150 e\(\mu\)A  
Beam pulse: 8 \(\mu\)s  
Injected into JINR synchrotron

D. Donets et al, EPAC08
Ion sources for Pulsed beam production

2.2 Laser ion source (LIS)

(I) Physics

(II) CERN LIS

(III) DPIS
The main energy transfer from the laser to the plasma is inverse bremsstrahlung for the laser power density up to $10^{13}$ W/cm$^2$.

Inverse bremsstrahlung absorption coefficient

$$K_{ab} = \frac{\nu(n_{cr})L_h}{c}$$

$$\nu(n_{cr}) = 4\sqrt{2\pi}Ze^4\Lambda_{ei}n_{cr}/3m_e(kT_e)^{2/3}$$

Based on it, for laser ion source design, the laser which has the power density of $10^{10}$~several $10^{13}$W/cm$^2$, wave length $>1000$nm and pulse with of 1~100ns was used in many laboratories. In that case, the experimental results and theoretical calculation show the absorption efficiency is from 70 to 90%. 

**Absorption efficiency**

![Absorption efficiency graph](image)
The main energy transfer from the laser to the plasma is inverse bremsstrahlung for the laser power density up to $10^{13}$ W/cm².

Inverse bremsstrahlung absorption coefficient

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Electron temperature strongly dependent on the laser power density

$$T_e \propto \left(\frac{l^2m_i}{n_{cr}Z}\right)^{1/3}$$

For this reason, average charge state is also depend on the power
(higher power highly charged heavy ions)
The pulse width ($t$) and beam intensity ($I$) are defined as, $t \propto L, I \propto L^{-3}$, where $L$ is the distance from the target to the extraction system.

It is easy to increase the pulse width with increasing the drift distance.

Injected current to the RFQ becomes small, because the intensity is proportional to $L^{-3}$ as shown in the formula described above.

$$\tau_{1/2} = 2 \times 10^6 P^{-0.43} L$$
Thus to maximize the highly charged ion beam, $R_{3B}$ should be minimized.

High temperature and low-density plasma is desirable.

\[ R_{3B} \approx 10^{-26} Z^3 \frac{N_e}{T^{4.5}} \]

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\[ \tau_{1/2} = 2 \times 10^6 P^{-0.43} L \]
Parameters of CERN LIS for LHC

TABLE I. Specification parameters of the laser ion source (laser system scheme: master-oscillator/power amplifier).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total laser energy</td>
<td>( \geq 100 ) J</td>
</tr>
<tr>
<td>Useful laser energy</td>
<td>( \geq 80 ) J</td>
</tr>
<tr>
<td>Laser pulse duration</td>
<td>30–50 ns</td>
</tr>
<tr>
<td>Diameter of the focal spot</td>
<td>170–250 ( \mu )m</td>
</tr>
<tr>
<td>Laser power density</td>
<td>((0.8–1.2) \times 10^{13}) \text{ W/cm}^2</td>
</tr>
<tr>
<td>Laser beam diameter</td>
<td>160 mm</td>
</tr>
<tr>
<td>Focal length of the focusing mirror</td>
<td>200–300 cm</td>
</tr>
<tr>
<td>Incident angle at the target</td>
<td>(&lt; 5^\circ )</td>
</tr>
<tr>
<td>Plasma expansion length</td>
<td>200–260 cm</td>
</tr>
<tr>
<td>Total extraction current density</td>
<td>8.8 mA/cm(^2)</td>
</tr>
<tr>
<td>Diameter of the extraction hole</td>
<td>34 mm</td>
</tr>
<tr>
<td>Number of Pb(^{208}) particles with ( Z = 25^+ )</td>
<td>( 1.4 \times 10^{10} )</td>
</tr>
<tr>
<td>Ion pulse length</td>
<td>( 1.5; 3; 6 ) ( \mu )s</td>
</tr>
<tr>
<td>Emittance of extracted Pb(^{208}) ion beam ( \epsilon )</td>
<td>( 44 ) ( \text{mm mrad} )</td>
</tr>
<tr>
<td>(4 ( \text{rms at 9.6 keV/u} ))</td>
<td></td>
</tr>
<tr>
<td>Extraction potential</td>
<td>80 kV</td>
</tr>
<tr>
<td>Source repetition rate</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Energy spread ( dE/E )</td>
<td>(&lt; \pm 2.5% )</td>
</tr>
<tr>
<td>Number of LIS operation cycles between interventions</td>
<td>( 2 \times 10^5 )</td>
</tr>
</tbody>
</table>

S. Kondrashev et al, EPAC04
A 100 J/1 Hz CO2-laser system has been built for the CERN LIS. Stable operation has been demonstrated during a few hours.

Pb\textsuperscript{27+} ion beams (16% of total ion flux) was obtained for laser power density of $3 \cdot 10^{13}$ W/cm\textsuperscript{2}.

The ion beam has been extracted at 105 kV in 1 Hz rep-rate without vacuum problems or extraction system breakdowns.
The laser ablation plasma has very high density and has initial expanding velocity. We can transport the intense ion beam under the plasma condition (neutralization) into the first stage accelerator. The direct plasma injection scheme (DPIS) was proposed.
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Direct plasma injection scheme (DPIS)
Developments of DPIS

The obtained peak current was already more than 9 mA from a carbon graphite target using a 4 J CO₂ laser in the early stage of the test experiment.

After the test experiments, a new RFQ linac was fabricated to accelerate high intensity heavy ion beam (~100mA).

400 mJ Nd-YAG laser was tested to produce fully stripped carbon beam and the measured result showed that accelerated peak current reached up to 17 mA.

In 2005, Intense C beams (>60mA) were accelerated, when using 4J CO₂ laser. They also obtained 70mA of Al ions with 2.3J commercial Nd-YAG laser.

M. Okamura et al, PAC2005
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M. Okamura et al, PAC2005
The pulse width ($t$) and beam intensity ($I$) are defined as, $t \propto L, I \propto L^{-3}$. For this reason, it is easy to increase the pulse width with increasing the drift distance between ion source and RFQ. However the injected current to the RFQ becomes very small, because the intensity is proportional to $L^{-3}$.

Recently, to minimize the reduction of the current, a solenoid magnet was successfully used for focusing the beam.

M. Okamura et al, IPAC2010
Beam test of DPIS is carried out for the first time in China.

The $C^{6+}$ beam ($>6\text{ mA}$) is accelerated.

The RF power of about 195 kW is required to produce the peak beam current.

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Charge state distribution

- Number of particles as a function of charge state

Beam intensity as a function of RF power

- Current as a function of RF power (kW)

Z. Zhang et al, IPAC2011 MOPC028
Ion sources for DC beam production

3.1 **Electron cyclotron resonance ion source (ECRIS)**

(I) Physics

(II) SC-ECRISs (VENUS, SECRAL, RIKEN)

(III) What is the limitation of the beam intensity

(RF power, magnetic field, .......)
Time evolution of the beam intensity (ECRIS)
Time evolution of the beam intensity (ECRIS)

- \( \text{Ar}^{8+} \sim 80 \mu\text{A} \rightarrow 2\text{mA} \)
Time evolution of the beam intensity (ECRIS)

Ar$^{8+}$ $\sim$ 80e$\mu$A $\rightarrow$ 2mA

Beam intensity(e$\mu$A)

- Ar$^{8+}$
- Xe$^{20+}$
- Bi$^{31+}$
- Xe$^{30+}$

Year
- 1980
- 1990
- 2000
- 2010

Instruments:
- Caprice 10GHz Mini-mafios type
- Caprice 14GHz A-ECR(LBL)
- RIKEN 18GHz
- RIKEN 28GHz
- VENUS(28GHz)
- SECRAL(Lanzhou)
- SERSE(Catania)
Time evolution of the beam intensity (ECRIS)

- Ar$^{8+}$ ~ 80eμA → 2mA
- Caprice 10GHz
- Mini-mafios type
- Caprice 14GHz
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- RIKEN 18GHz
- RIKEN 28GHz
- VENUS(28GHz)
- SECRAL(Lanzhou)
- SERSE(Catania)

Graph showing the beam intensity evolution over years with markers indicating different ions and facilities.
Time evolution of the beam intensity (ECRIS)

- Ar$^{8+}$: ~80eμA to 2mA
- Xe$^{30+}$: ~100eμA to ~200eμA
- Bi$^{31+}$

Graphs showing the beam intensity from 1980 to 2010 with different sources:
- Caprice 10GHz Mini-mafios type
- Caprice 14GHz A-ECR(LBL)
- RIKEN 18GHz
- VENUS(28GHz)
- SECRAL(Lanzhou)
- SERSE(Catania)

**RIKEN 28GHz**

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Time evolution of the beam intensity (ECRIS)

- Ar\(^{8+}\) \(\sim 80\) e\(\mu\)A \(\rightarrow 2\) mA

**Questions**
- WHY?
- How?

**Beam intensity (e\(\mu\)A)**

- Caprice 10GHz Mini-mafios type
- RIKEN 18GHz
- RIKEN 28GHz
- VENUS(28GHz)
- SECRAL(Lanzhou)
- SERSE(Catania)
High B mode operation (\(B_{\text{inj}} > 3\sim4B_{\text{ecr}}, Br \sim 2B_{\text{ecr}}, B_{\text{ext}} < Br, B_{\text{min}} \sim 0.6\sim0.8B_{\text{ecr}}\))

Plasma confinement

\[ \frac{B_{\text{inj}}}{B_{\text{min}}} \text{ (Mirror ratio)} \]
High B mode operation ($B_{\text{inj}} > 3-4B_{\text{ecr}}$, $B_r \sim 2B_{\text{ecr}}$, $B_{\text{ext}} < B_r$, $B_{\text{min}} \sim 0.6-0.8B_{\text{ecr}}$)

Plasma confinement

We need high mirror ratio to produce highly charged heavy ions (good plasma confinement). However the beam intensity is saturated $B_{\text{inj}} > 3-4B_{\text{ecr}}$

Simulation (Fokker-Planck eq.)

Experimental

S. Gammino, RSI., Vol. 70, 1999,3577
Microwave absorption (ECR zone effect)

- $B_{\text{min}}$ affects ECR zone size and field gradient
- Energy transfer from microwave to electron at ECR zone


$$W_{\text{power}} = \left( \frac{\pi n e^2 E^2}{m \omega (dB/dz)} \right) S_{\text{ecr}}$$

Graph showing magnetic field variation with position.
Microwave absorption (ECR zone effect)

B\textsubscript{min} affects ECR zone size and field gradient

Energy transfer from microwave to electron at ECR zone


\[ W\text{\textit{power}} = \left( \frac{\pi n e^2 E^2}{m \omega (dB/dz)} \right) S\text{ecr} \]

Magnetic field gradient

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{magnetic_field_plot}
\caption{Magnetic field gradient with varying ECR zone sizes and RF power.}
\end{figure}
**Magnetic field effect - ECR zone**

**B\textsubscript{min}** affects ECR zone size and field gradient

Energy transfer from microwave to electron at ECR zone

Microwave absorption (ECR zone effect)

\[ W_{\text{power}} = \left( \frac{\pi ne^2 E^2}{m \omega \left( \frac{dB}{dz} \right)} \right) S_{\text{ecr}} \]


Beam intensity increases with decreasing the magnetic field gradient and/or increasing the ECR zone size
Frequency effect

SERSE
RF power 1.8kW
$B_{\text{inj}} \sim 3.5B_{\text{ecr}}$, $B_{\text{min}} \sim 0.8B_{\text{ecr}}$, $B_{\text{ext}} \sim 2B_{\text{ecr}}$
$B_r \sim 2B_{\text{ecr}}$

S. Gammino, RSI., Vol. 70, 1999, 3577
Frequency effect

SERSE
RF power 1.8kW
$B_{\text{inj}} \sim 3.5B_{\text{ecr}}, B_{\text{min}} \sim 0.8B_{\text{ecr}}, B_{\text{ext}} \sim 2B_{\text{ecr}}$
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SECRAL
$B_{\text{inj}} \sim 3.5B_{\text{ecr}}, B_{\text{min}} \sim 0.8B_{\text{ecr}}, B_{\text{ext}} \sim 2B_{\text{ecr}}$
$B_r \sim 2B_{\text{ecr}}$

S. Gammino, RSI., Vol. 70, 1999, 3577


IPAC’13, May 12-17, 2013, Shanghai, China
Frequency effect

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RF power 1.8kW
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S. Gammino, RSI., Vol. 70, 1999, 3577

SECRAL
$B_{\text{inj}} \sim 3.5B_{\text{ecr}}, B_{\text{min}} \sim 0.8B_{\text{ecr}}, B_{\text{ext}} \sim 2B_{\text{ecr}}$
$B_r \sim 2B_{\text{ecr}}$


18GHz
- 14.5
- 18
- 18×14.5

28GHz

18GHz 2.1 0.4 1.18 1.2T (18/28)
28GHz 3.15 0.62 1.83 1.86T

IPAC'13, May 12-17, 2013, Shanghai, China
Frequency effect (theoretical calculation)

\[ \frac{df_e}{dt} = C(f_e) + Q(f_e) + S(f_e) \]

\[ Q = \frac{1}{\sqrt{2}} \frac{\partial}{\partial v} \left( v^2 D_{vv} \frac{\partial f_e}{\partial v} \right) + \frac{1}{\sqrt{2}} \frac{\partial}{\partial \mu} \left( (1 - \mu^2) D_{\mu \mu} \frac{\partial f_e}{\partial \mu} \right) \]

\[ D_{vv} = D = \frac{4}{3} \pi \left( \frac{eE}{2m_e} \right)^2 \frac{d}{L\phi}, \quad D_{\mu \mu} = D \left( \frac{v}{v_{ph}} \right)^2. \]

- Strength of electric field (RF power)
- Magnetic field gradient (\(B_{\text{min}}\) effect)
- Smaller diffusion coefficient of pitch angle
- Higher critical density (higher frequency)
- Higher phase velocity


IPAC'13, May 12-17, 2013, Shanghai, China
Frequency effect (theoretical calculation)

Fokker-Planck equation

\[
\frac{df_e}{dt} = C(f_e) + Q(f_e) + S(f_e)
\]

\[
Q = \frac{1}{\sqrt{2}} \frac{\partial}{\partial \nu} \left( \nu^2 D_{\nu\nu} \frac{\partial f_e}{\partial \nu} \right) + \frac{1}{\sqrt{2}} \frac{\partial}{\partial \mu} \left( (1 - \mu^2) D_{\mu\mu} \frac{\partial f_e}{\partial \mu} \right)
\]

\[
D_{\nu\nu} = D = \frac{4}{3} \pi \left( \frac{eE}{2m_e} \right)^2 \frac{d}{L_0}
\]

\[
D_{\mu\mu} = D \left( \frac{V}{V_{ph}} \right)^2.
\]

- Strength of electric field (RF power)
- Magnetic field gradient (\(B_{\text{min}}\) effect)
- Higher critical density (higher frequency)
- Higher phase velocity
- Smaller diffusion coefficient of pitch angle

\(V_{ph} \propto n_{cr}\)

Power absorption


IPAC’13, May 12-17, 2013, Shanghai, China
VENUS was the first high magnetic field SC-ECR ion source developed for operating at 28 GHz. A number of modifications were carried out during its development, for example, the special cramping technique of the hexapole magnet to increase the radial magnetic field. The modifications of the VENUS were then incorporated into the design of new SC-ECR ion sources.
High performance SC-ECRIS I –VENUS 28GHz–

<table>
<thead>
<tr>
<th>Tuning Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>28 +18 Ghz</td>
<td>5-6 kW</td>
</tr>
<tr>
<td>Bmin</td>
<td>.56 T</td>
</tr>
<tr>
<td>Bmin 18 GHz</td>
<td>87.5%</td>
</tr>
<tr>
<td>Bmin 28 GHz</td>
<td>56 %</td>
</tr>
<tr>
<td>Heat load into the cryostat</td>
<td>1.7 W</td>
</tr>
</tbody>
</table>

Re-commissioning VENUS (18+28GHz)2010

<table>
<thead>
<tr>
<th>Ion</th>
<th>Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe26+</td>
<td>480</td>
</tr>
<tr>
<td>Xe27+</td>
<td>411</td>
</tr>
<tr>
<td>Xe30+</td>
<td>211</td>
</tr>
<tr>
<td>Xe32+</td>
<td>108</td>
</tr>
<tr>
<td>Xe35+</td>
<td>38</td>
</tr>
</tbody>
</table>

U^{33+} ~440eμA @8kW(18+28GHz)
(required beam intensity-FRIB,RISP)

VENUS was the first high magnetic field SC-ECR ion source developed for operating at 28 GHz. A number of modifications were carried out during its development, for example, the special cramping technique of the hexapole magnet to increase the radial magnetic field. The modifications of the VENUS were then incorporated into the design of new SC-ECR ion sources.

SECRAL is a compact SC-ECR ion source designed to operate at microwave frequencies of 18–28 GHz. The unique feature of the SECRAL source is its unconventional magnetic structure, in which superconducting solenoid coils are placed inside the superconducting sextupole. One of the advantages of this structure is that the magnet assembly can be compact in size as compared to similar high magnetic field ECR sources with conventional magnetic structures.


<table>
<thead>
<tr>
<th>SECRAL (18(+14.5)GHz)</th>
<th>RF power (kW)</th>
<th>&lt;3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{129}$Xe$^{20+}$</td>
<td>505 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{27+}$</td>
<td>306 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{30+}$</td>
<td>101 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{31+}$</td>
<td>68 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{35+}$</td>
<td>16 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{38+}$</td>
<td>6.6 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{42+}$</td>
<td>1.5 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{43+}$</td>
<td>1 $\mu$A</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECRAL (24GHz)</th>
<th>RF power (kW)</th>
<th>3–5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{129}$Xe$^{27+}$</td>
<td>455 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{30+}$</td>
<td>152 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{31+}$</td>
<td>85 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{35+}$</td>
<td>60 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{38+}$</td>
<td>17 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{42+}$</td>
<td>3 $\mu$A</td>
<td></td>
</tr>
<tr>
<td>$^{129}$Xe$^{43+}$</td>
<td>3 $\mu$A</td>
<td></td>
</tr>
</tbody>
</table>
SECRAL is a compact SC-ECR ion source designed to operate at microwave frequencies of 18–28 GHz. The unique feature of the SECRAL source is its unconventional magnetic structure, in which superconducting solenoid coils are placed inside the superconducting sextupole. One of the advantages of this structure is that the magnet assembly can be compact in size as compared to similar high magnetic field ECR sources with conventional magnetic structures.
The RIKEN SC-ECRIS can be operated at flexible axial field distributions with six solenoid coils.

It is possible to change the gradient of the magnetic field strength and the surface size of the ECR zone.

The RIKEN 28GHz SC ECRIS produced \(\sim 180\mu\text{A} \text{ of } \text{U}^{35+}, \sim 225\mu\text{A} \text{ of } \text{U}^{33+}\) with the sputtering method at the injected RF power of \(\sim 4\text{kW (28GHz)}\).


“Flat B\(_{\text{min}}\)” G. D. Alton and D. N. Smithe, Rev. Sci. Instrum. 65 (1994) 775
The RIKEN SC-ECRIS can be operated at flexible axial field distributions with six solenoid coils.

It is possible to change the gradient of the magnetic field strength and the surface size of the ECR zone.

The RIKEN 28GHz SC ECRIS produced ~180eμA of U^{35+}, ~225 eμA of U^{33+} with the sputtering method at the injected RF power of ~4kW (28GHz).


“Flat B_{min}” G. D. Alton and D. N. Smithe, Rev. Sci. Instrum. 65 (1994) 775
**Magnetic field effect**

\[ \varepsilon_{xx'}^{\text{norm}} = 0.032 B_0 \frac{q}{M} \]

Bo: axial magnetic field
q: charge state
M: mass

Cal: same q/M same emittance
: higher Bo larger emittance

Bo 18GHz ~1.2T
28GHz ~1.8T
**Magnetic field effect**

\[ \varepsilon_{\text{magnet}}^{xx'} = \text{norm} = 0.032B_0 \frac{q}{M} \]

- Bo: axial magnetic field
- q: charge state
- M: mass

Cal: same q/M = same emittance
: higher Bo = larger emittance

Bo
- 18GHz \(\sim 1.2T\)
- 28GHz \(\sim 1.8T\)

---

**Emittance**

18GHz

[Graph showing normalized emittance vs. M/q for different elements (\(\text{^{16}O}\), \(\text{^{124}Xe}\), \(\text{^{238}U}\)) at 18GHz with different markers for SS chamber, 28GHz SS, and 28GHz Al.]

28GHz

[Graph showing normalized RMS x-emittance vs. M/q for different elements (O ion, U ion) at 28GHz.]
Limitation of the beam intensity increase I

RF power vs. gas pressure (Fokker-Planck eq.)

B. Cluggish et al, NIM A 631(2011)111

IPAC’13, May 12-17, 2013, Shanghai, China
Limitation of the beam intensity increase I

RF power vs. gas pressure (Fokker-Planck eq.)

O⁶⁺

increase
decrease

Gas pressure

B. Cluggish et al, NIM A 631(2011)111
The effect of RF power on the plasma parameters (electron density, temperature and current) and high RF-power instability were demonstrated using FAR-TECH’s generalized ECRIS model (GEM)].

These showed that the threshold of the RF power for the instability increased with an increase in the gas pressure. The origin of the instability was the pitch-angle scattering of the electrons by the ECR heating process.

B. Cluggish et al, NIM A 631(2011)111
Experimental results (RF power dependence)

CAPRICE 14GHz

D. Hitz et al, RSI 71(2000)839

CAPRICE ~0.5L

Limitation >1~2kW/L
Experimental results (RF power dependence)

CAPRICE 14GHz

D. Hitz et al, RSI 71(2000)839

VENUS 28GHz

D. Leitner et al, HEP&NP 31(2007)1

Despite this important information, we have few experimental results for beam intensity saturation at present. The beam intensity of high-performance SC-ECR ion sources that have a larger plasma chamber volume increases linearly and is not saturated at high power. To clarify this phenomenon, we need to carry out further investigation under various conditions.
Effect of magnetic field

Beam intensity decreases with decreasing the magnetic field gradient
Beam intensity becomes unstable
To clarify this phenomenon, we need to carry out further investigation under various conditions
The beam intensity was strongly oscillated regularly.
The frequency was several 10 kHz~few 100kHz
The peaks were shifted by changing the RF power and gas pressure.
The amplitude increases with decreasing the gas pressure or increasing the RF power (plasma instabilities?)
Beam stability is very important factor for accelerator

**Spectrum analyzer**

<table>
<thead>
<tr>
<th>Gas pressure</th>
<th>Microwave Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>7x10^-7 Torr</td>
<td>400W</td>
</tr>
<tr>
<td>2.1x10^-6 Torr</td>
<td>100W</td>
</tr>
</tbody>
</table>
36GHz ECRIS

Required magnetic field strength

\[ B_{\text{inj}} \approx 5T \]
\[ B_r \approx 2.7T \]
\[ B_{\text{ext}} \approx 2.7T \]
\[ B_{\text{min}} \approx 0.8\text{~}1.2T \]

Example of RIKEN 28GHz ECRIS
28GHz $\rightarrow$ 36GHz
36GHz ECRIS

Required magnetic field strength

- $B_{\text{inj}} \sim 5T$
- $B_r \sim 2.7T$
- $B_{\text{ext}} \sim 2.7T$
- $B_{\text{min}} 0.8\sim1.2T$

Example of RIKEN 28GHz ECRIS

Solution

1) Use of NbTi wire at low temperature (<4.2K)
2) Use of other super-conducting wires (Nb$_3$Sn)
3) New structure SC-ECRIS

Exceed the critical current of NbTi wire at 4.2K
**36GHz ECRIS**

**Required magnetic field strength**

- $B_{\text{inj}} \approx 5 \text{T}$
- $B_r \approx 2.7 \text{T}$
- $B_{\text{ext}} \approx 2.7 \text{T}$
- $B_{\text{min}} \approx 0.8 \text{~}1.2 \text{T}$

**Example of RIKEN 28GHz ECRIS**

28GHz → 36GHz

**Solution**

1) Use of NbTi wire at low temperature ($<4.2 \text{K}$)
2) Use of other super-conducting wires (Nb$_3$Sn)
3) New structure SC-ECRIS

---

To produce intense highly charged heavy ions, we need higher $B_{\text{min}}$ and lower gas pressure.

In this case, heat load of X-ray becomes very high as shown in these figures:

Ex. $B_{\text{min}} \approx 0.8B_{\text{ecr}}$ RF power $\approx 6\text{kW}$

We will obtain 6W of X-ray heat load.

Solutions:
1) Use of large refrigerator (GM-JT) to obtain higher cooling power ($\approx 10\text{W}$)
2) To find new method to minimizing the X-ray heat load while keeping the beam intensity.
Lager zone size and steeper field gradient gives lower X-ray heat load using Al-chamber is lower than that using SS-chamber.

**Graphs:**
- **Graph a:** Ar$^{1+}$ RF power 1000W
- **Graph b:** Heat load (X-ray) vs. RF power (kW)

**Text:**
- Lager zone size and steeper field gradient gives lower X-ray heat load.