Status of High Current Ion Sources

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• Overview of available high current sources
• Requirements for underground accelerator
• Why ECR Ion Sources for NUSEL?
• Options for the NUSEL Accelerator
• Beam transport
• Areas for R&D
High current Ion sources
Brief Overview

- **MEVVA (Metal Vapor Vacuum Arc Ion Source) and Laser Evaporation Ion Sources**
  - Medium charge states
  - High currents >100 mA
  - no gases
  - Pulsed

- **Multicusp ion sources (Filament/ RF) and cathode based ion sources**
  - Single to low charge states
  - High currents >100 mA
  - Limited lifetime

- **Microwave Sources**
  - Singly Charged Ions
  - High currents >100 mA
  - High Reliability
  - Long Lifetime

- **High charge ECR Ion sources (Electron Cyclotron Resonance)**
  - Medium to high charge state ions
  - Medium currents (μA to mA)
  - High Reliability
  - Long Lifetime
What are the requirements for an underground injector system

- High Reliability
- Low Maintenance
- Easy Operation
- Flexibility
  - change charge state to change energy
  - beams from solid material and gases
- Low Power Consumption
  - high voltage Platform
- High Stability
Why are ECR Ion Sources the ideal ion source type for NUSEL?

- Runs 24 hours/day, 7 days/week with minimum intervention
- Minimum maintenance (typically not required for years)
- Excellent Beam Stability
- High Reliability
- High intensities
- High flexibility
- Can produce ion beams from every element
- Good beam quality

AECR-U Injector at the 88-Inch Cyclotron as an example
How do ECR ion sources work

\[ \omega_e = \frac{B}{q \cdot m} = \omega_{rf} \]

\[ I \propto \omega_{rf}^2 M^{-1} \]

\[ I \propto \log B^{1.5} \]
ECR Ion source have been developed mainly for two areas

- **High charge state ECR ion sources**
  - High charge states and low charge states
  - 10^{-7} to 10^{-6} mbar, total current \( \approx \) 1-5 emA
  - \( \text{Ar}^{8+} \) (2000 e\( \mu \)A)
  - \( \text{O}^{6+} \) (1500 e\( \mu \)A)
  - Several mA for light ions
  - Beam transport challenging
  - R&D area (RIA)

- **Single Charged ECR ion source (Chalk River)**
  - Single charge
  - 10^{-3} to 10^{-2} mbar total current up to 130 emA*
  - Beam transport challenging but demonstrated (LEDA)
  - R&D area for high quality beams

LEDAs has demonstrated > 100 mA H⁺ transported through CW RFQ

Low-energy demonstrator accelerator (LEDA)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam current (mA)</td>
<td>117</td>
</tr>
<tr>
<td>Proton fraction (%)</td>
<td>90</td>
</tr>
<tr>
<td>Beam energy (keV)</td>
<td>75</td>
</tr>
<tr>
<td>Discharge power (W) 2.45 GHZ</td>
<td>600 to 800</td>
</tr>
<tr>
<td>Beam noise (%)</td>
<td>±1</td>
</tr>
<tr>
<td>Ion source emittance (πmm-mrad)</td>
<td>0.13 (rms, normalized)</td>
</tr>
</tbody>
</table>

*J. Sherman, et. al. RSI, vol. 69, pp. 1003, 1998*
High Charge state ECR ion source development at LBNL

\[ n_e \propto \omega_{rf}^2 \]
\[ \tau_{ion} \propto B L_{mirror} \]
\[ I \propto \omega_{rf}^2 M^{-1} \]
\[ I \propto P_{rf}^{1/3} \]

**ECR (1983)**
0.4 T, 0.6 kW, 6.4 GHz

**AECR-U (1996)**
1.7 T, 2.6 kW, 10 + 14 GHz

**VENUS (2001)**
4.0 T, 14 kW, 18 + 28 GHz
The frequency scaling for the LBNL ECR ion sources

Argon Charge State

analyzed current [eμA]

10^3
10^2
10^1
10^0
10^-1
10^-2

AE CR-U  14 and 10 GHz

LBL-ECR 6.4 GHz
Most advanced ECR ion source is VENUS at LBNL

Evolution of the 88-Inch Cyclotron Performance for Heavy Ions at 1pnA

Energy in MeV/amu

Particle Mass in amu

0 5 10 15 20 25 30 35

AECR-U 1995
VENUS
ECR-1989
PIG-1984

Produce the world most intense high charge state heavy ion-beams for the 88-Inch Cyclotron

RIA R&D Ion Source
10 pμA U^{30+}

Provide highest current high-charge state beams for the next generation heavy ion accelerators.
VENUS Components

Superconducting Structure

Conventional Components

Beam Transport

RIA R&D Source
10 puA U^{30+}

1. Superconducting magnet structure forces a completely new ion source design, not an extension of an existing design.

2. VENUS serves as test bed to understand the transport of high current heavy ion beams.
Venus at 18 GHz outperforms AECR-U especially for heavy ions.
High performance fully permanent magnet ECR ion source (commercially available)

- High Frequency 14.5 GHz
- Fully permanent magnet
- Compact, but
  - Performance limited
  - Ovens difficult
  - Beam transport difficult
- Compact RF system (Traveling Wave Tube) Power limited (400 W)
- Especially suitable for high voltage platforms

> 2 mA of H+
150 eµA O^{6+}
350 eµA of Ar^{8+}
Very tight injection for oven inserts

Permanent magnets imply very narrow extraction (beam blow up due to space charge)

Ref.: C. Bieth, J. L. Bouly, J. C. Curdy, S. Kantas, P. Sortais, P. Sole, and J. L. Vieux-Rochaz
A conventional ECR Ion source offers more operational flexibility and higher intensities than fully permanent sources.
Comparison of highest performance conventional and fully permanent ECR ion sources

Data

- SNANOGAN (compact)
- AECR-U 14 GHz
- RIKEN 18 GHz

Graph showing current in euA vs. Argon Charge State.
Beam Transport
Multi Charged ECR Ion Beam Transport

- Space charge dominated beams
- Charge state distribution for each species present at extraction (each contribution must be taken into account correctly)
- Different focusing properties for each M/Q
- Emittance contribution due to the high solenoid field at the extraction
The ECR Ion Source Emittance dominated by the magnetic field at extraction

\[ \varepsilon_{xx' - \text{rms - norm}}^{\text{MAG}} = 0.032 \cdot r^2 \cdot B_0 \cdot \frac{1}{M/Q} \]

Magnetic Field Dominates Emittance for given M/Q above

- \( M/Q = 1 \), \( B_0 > 0.07 \text{ T} \)
- \( M/Q = 5 \), \( B_0 > 0.15 \text{ T} \)
- \( M/Q = 30 \), \( B_0 > 0.38 \text{ T} \)

Therefore the ion source emittance for every ECR ions is dominated by the magnetic field at extraction.

VENUS Low Energy Beam Transport

LEBT-Design

25 mA proton-equivalent current at 30 kV extraction voltage
Emittance Measurements combined with Ion Beam simulations are essential for understanding the ion beam transport for ECR ion source.

- Essential for providing very high quality beams as required for precision measurements
- RIA R&D will provide an essential data base for the beam transport
Experimental requirements are needed for the optimum design of the injector

- Injector system type
  (Power and Space available)
- Intensity needed
- Energy range
- Ion species
- Purity of Ions
- CW or pulsed
- Timing (chopping)
- Beam quality
  - Beam Noise
  - Stability
  - Spot size

High Intensity single charge Ion Source
Maybe required for some low cross section experiments

High charge state ECR
Conventional/permanent magnet
Charge state can vary to change energy
Charge state selection

Beam transport
Conclusion and areas for R&D

• **ECR sources are ideal sources for an underground accelerator**
  - Demonstrated performance record on accelerator
  - High Reliability and Flexibility
  - Have to decide which kind of ECR is best suited (depends mainly on intensity required)

• **R&D (simulations and experiments) for the ECR ion beam transport would be beneficial**
  - To assure very high quality beams
  - Build injector system to measure beam parameter
  - overlap with RIA R&D