The Relationship Between the Diffusion of Hot Electrons, Plasma Stability, and ECR Ion Source Performance

Bryan Isherwood and Guillaume Machicoane

24th International Workshop on ECR Ion Sources

9/28/2020
Outline

- ECR Ion Source Performance and Plasma Stability
- Apparatus and Diagnostics
- Results
- Summary
Outline

- ECR Ion Source Performance and Plasma Stability
- Apparatus and Diagnostics
- Results
- Summary
The Facility for Rare Isotope Beams (FRIB) Seeks to Push the High Intensity Frontier

Facility for Rare Isotope Beams (FRIB)

FRIB’s systems want:

• High intensity beam currents
• Prolonged stable accelerator operation

Fast Fragmentation
Empirical Magnetic Field Scaling Laws:

\[ B_{\text{Hex}} = 2 \, B_{\text{RF}} \]
\[ B_{\text{Inj}} = 3 - 4 \, B_{\text{RF}} \]
\[ B_{\text{Ext}} \approx 1.8 \, B_{\text{RF}} \]
\[ B_{\text{Min}} \approx 0.4 \, B_{\text{Hex}} \approx 0.8 \, B_{\text{RF}} \]

\[ \beta = \frac{\text{Kinetic Pressure}}{\text{Magnetic Pressure}} \approx 0.01 \]

\[ B_{\text{max}}/B_{\text{RF}} \approx 2: \text{Macroscopic Stability Criteria} \]
ECR Ion Source Performance is Limited by Kinetic (Cyclotron Maser) Instabilities that Cause Beam Current Variations

Normalized Beam Current

\( B_{\text{min}} \approx 0.8 \, B_{\text{RF}} \)

Performance Limit

Beam Current From SuSI

\( \frac{\partial n_e}{\partial t} > 0 \)

\( \frac{\partial n_e}{\partial t} < 0 \)

\( T_{\perp} \gg T_{\parallel} \)

Electron Evacuation

Microwave Burst


Stability Maps Show Large Unstable Regions Across Multiple Unique Parameter Spaces

Pressure = 131 nTorr
B_{Hex, max} = 1.1 T
Argon 8+

Parameter Space 1
B_{Inj} > 4 B_{RF}/B_{Ext} > 2 B_{RF}

Parameter Space 2
B_{Inj} > 3 B_{RF}/B_{Ext} \approx 1.8 B_{RF}

Parameter Space 3
B_{Inj} > 3 B_{RF}/B_{Ext} > 1.8 B_{RF}

Parameter Space 4
B_{Inj} > 4 B_{RF}/B_{Ext} < 1.7 B_{RF}

Scaling Laws
B_{Rad} = 2 B_{RF}
B_{Inj} = 3 - 4 B_{RF}
B_{Ext} \approx 1.8 - 2 B_{RF}
Stability Maps Show Large Unstable Regions Across Multiple Unique Parameter Spaces

Pressure = 131 nTorr
\( B_{\text{Hex, max}} = 1.1 \, \text{T} \)
Argon 8+

Scaling Laws
\[ B_{\text{rad}} = 2 \, B_{\text{RF}} \]
\[ B_{\text{Inj}} = 3 - 4 \, B_{\text{RF}} \]
\[ B_{\text{Ext}} \approx 1.8 - 2 \, B_{\text{RF}} \]

Parameter Space 1
\( B_{\text{Inj}} > 4 \, B_{\text{RF}} \), \( B_{\text{Ext}} > 2 \, B_{\text{RF}} \)

Parameter Space 2
\( B_{\text{Inj}} > 3 \, B_{\text{RF}} \), \( B_{\text{Ext}} \approx 1.8 \, B_{\text{RF}} \)

Parameter Space 3
\( B_{\text{Inj}} > 3 \, B_{\text{RF}} \), \( B_{\text{Ext}} > 1.8 \, B_{\text{RF}} \)

Parameter Space 4
\( B_{\text{Inj}} > 4 \, B_{\text{RF}} \), \( B_{\text{Ext}} < 1.7 \, B_{\text{RF}} \)
Stability Maps Show Large Unstable Regions Across Multiple Unique Parameter Spaces

Pressure = 131 nTorr
\( B_{\text{Hex,max}} = 1.1 \) T
Argon 8+

1. How does the magnetic field topology affect the plasma’s stability?
2. How do the instabilities affect ion source performance at low field strengths?

Scaling Laws
\( B_{\text{Rad}} = 2 \, B_{\text{RF}} \)
\( B_{\text{Inj}} = 3 - 4 \, B_{\text{RF}} \)
\( B_{\text{Ext}} \approx 1.8 - 2 \, B_{\text{RF}} \)
Outline

- Performance Scaling and Performance Optimization
- Apparatus and Diagnostics
- Results
- Summary
Superconducting Source for Ions (SuSI)

Plasma

\[ B_{RF} = \frac{18 \text{ GHz}}{28 \text{ GHz}} \cdot T \approx 0.64 \text{ T} \]
Ion Source and Beamline Diagnostics

Microwave Diagnostic

Beam Diagnostic

X-ray Diagnostic

SuSI ECR Ion Source

Microwave Power Detector

Einzel Lens

Dipole/Analyzing Magnet

Pb and W collimators

Faraday Cups

4-Jaw

Focusing Solenoids

X-ray Detector

ORTEC
Extraction Voltage has a Large Effect on Extracted Ions, Negligible Effect on Hot Electrons

\[ B_{\text{min}} = 0.397 \, \text{T}, P = 350 \, \text{W}, \text{Pressure} = 212 \, \text{nTorr} \]

\[ B_{\text{min}} = 0.465 \, \text{T}, P = 350 \, \text{W}, \text{Pressure} = 212 \, \text{nTorr} \]

\[ \ associates \propto -\frac{\hbar \omega}{T_s} \]

\[ \text{ln} I \gamma \propto -\frac{\hbar \omega}{T_s} \]

Background peak from facility experiment
Outline

▪ Performance Scaling and Performance Optimization
▪ Apparatus and Diagnostics
▪ Results
▪ Summary
Confining Magnetic Field Topology Affects the Distribution of the Diffusing Electrons

**Varying Magnetic Minimum**
- Decreasing high energy peak intensity
- Increasing high energy peak energy

**Varying Extraction Side Maximum**
- Decreasing high energy peak intensity
- No effect on energy
Increasing the Magnetic Minimum Towards the Scaling Laws Limit Increase Stability and Average Extracted Current

\[ B_{\text{min}} = 0.34 \, \text{T} \]  \quad \quad  \[ B_{\text{min}} = 0.40 \, \text{T} \]  \\
\[ B_{\text{min}} = 0.44 \, \text{T} \]  \quad \quad  \[ B_{\text{min}} = 0.47 \, \text{T} \]  \\
\[ \frac{B_{\text{min}}}{B_{\text{RF}}} \approx 0.7 \]
Increasing Extraction Side Field Maximum can Affect Beam Current Transience, Decreases Electron Diffusion Rate
Regardless of Plasma Stability, Higher Bremsstrahlung Intensities Appear to Correlate with Higher Extracted Current

\[
\frac{\mathbf{B}_{\text{min}}}{\mathbf{B}_{\text{RF}}} \approx 0.7
\]

\[
\frac{\mathbf{B}_{\text{ext}}}{\mathbf{B}_{\text{RF}}} \approx 1.8
\]
Parameter Spaces with Lower Extraction Side Field Maximums were Less Stable, but Extracted More Current

<table>
<thead>
<tr>
<th>Parameter Space 1</th>
<th>Parameter Space 2</th>
<th>Parameter Space 3</th>
<th>Parameter Space 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{inj}} &gt; 4 B_{\text{RF}}/B_{\text{ext}} &gt; 2 B_{\text{RF}}$</td>
<td>$B_{\text{inj}} &gt; 3 B_{\text{RF}}/B_{\text{ext}} \approx 1.8 B_{\text{RF}}$</td>
<td>$B_{\text{inj}} &gt; 3 B_{\text{RF}}/B_{\text{ext}} &gt; 1.8 B_{\text{RF}}$</td>
<td>$B_{\text{inj}} &gt; 4 B_{\text{RF}}/B_{\text{ext}} &lt; 1.7 B_{\text{RF}}$</td>
</tr>
</tbody>
</table>

Pressure = 131 nTorr  
$B_{\text{Hex, max}} = 1.1$ T  
Argon 8+

Stable
Unstable

$B_{\text{min}}/B_{\text{RF}} \approx 0.55 - 0.85$
Scaling Laws
$B_{\text{Rad}} = 2 B_{\text{RF}}$
$B_{\text{inj}} = 3 - 4 B_{\text{RF}}$
$B_{\text{ext}} \approx 1.8 - 2 B_{\text{RF}}$

$I_{\text{Avg}} > 60 \mu A$

$I_{\text{Avg}} > 100 \mu A$

Pressure = 131 nTorr  
$B_{\text{Hex, max}} = 1.1$ T  
Argon 8+

Stable
Unstable

$B_{\text{min}}/B_{\text{RF}} \approx 0.55 - 0.85$
Scaling Laws
$B_{\text{Rad}} = 2 B_{\text{RF}}$
$B_{\text{inj}} = 3 - 4 B_{\text{RF}}$
$B_{\text{ext}} \approx 1.8 - 2 B_{\text{RF}}$
Outline

- Performance Scaling and Performance Optimization
- Apparatus and Diagnostics
- Results
- Summary
Summary

- The scaling laws are reliable methods for optimizing the performance of ECR ion sources, however, they are poorly understood.
  - Kinetic plasma instabilities may limit ion source performance in the high field regime.
  - Time resolved measurements of extracted ions and steady state measurements of diffusing electrons can provide greater insight into scaling laws and instabilities.

- The magnetic field topology can affect the distribution of diffusing electrons and the stability characteristics of the plasma (repetition frequency/current variation):
  - Increasing the magnetic minimum towards the scaling laws made a more stable plasma and increased extracted currents.
  - Increasing the extraction side field maximum does *not* stabilize the plasma but demonstrates decrease in electron diffusion beyond scaling law limit.

- Best parameter spaces may balance large stable regions against highest performing operating points.
  - Lower extraction field maxima appear to correlate with less stable plasma, but higher extracted currents.
Special Thanks

- Facility for Rare Isotope Beams (FRIB)
  - Kent Holland
  - Thomas Russo

- Institute of Applied Physics (IAP)
  - Ivan Izotov
  - Vadim Skalyga

- National Superconducting Cyclotron Laboratory (NSCL)
  - Andreas Stolz
  - Derek Neben
  - Dirk Weisshaar
  - Larry Tobos
  - Jeff Stetson
  - Jesse Fogleman

- University of Jyväskylä (JYFL)
  - Ollie Tarvainen
Thank You for Your Attention!

Questions?