Measurement of the Energy Distribution of Electrons Escaping Confinement from an Electron Cyclotron Resonance Ion Source

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18th International Conference on Ion Sources, Lanzhou, Gansu, China
9/2/2019
Outline

- Electron Energy Distribution Function (EEDF) and the Production of High Charge State Ions
- Apparatus and Procedure for Measuring Escaping Electrons
- First Impression Results
- Future Work and Summary
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- Electron Energy Distribution Function (EEDF) and the Production of High Charge State Ions
- Apparatus and Procedure for Measuring Loss-Cone Electrons
- First Impression Results
- Future Work and Summary
Accelerator Facilities Use Electron Cyclotron Resonance Ion Source (ECRIS) to produce High Intensity, High Charge State Ion Beams

FRIB
Two ECRIS:
1. Room temperature 14 GHz ARTEMIS-B (Commissioning)
2. Superconducting 28 GHz VENUS based ECRIS (2020)

- Magnetic confinement and microwave heating are used to induce ionization
  - GHz range microwaves ignite source plasma
  - Solenoids and hexapole field confine the plasma

Charge State Distribution from ARTEMIS-B
Cyclotron Resonance of Electrons Creates an Electron Energy Distribution (EED) Capable of Making High Charge State Ions

\[ \frac{\partial n_i}{\partial t} \sim n_e n_{i-1} < \sigma_{i-1\rightarrow i}^{EI} v_e \]

- Microwaves heat electrons through the Electron Cyclotron Resonance (ECR) process
  - Magnetic field structure confines electrons and creates a resonance surface
    \[ \omega_{RF} = eB_{ECR}/\gamma m_e \]
  - Electron velocity distribution is highly anisotropic
    - ECR process principally heats electrons transversely
      \[ T_\perp \gg T_\parallel \]
    - EEDF can be controlled through ion source parameters
      - Magnetic field, microwave power, neutral gas pressure, etc.
Multiple Measurements Exist to Provide Information on the ECRIS Electron Energy Content

- **Langmuir probe**
  - Direct measurement of plasma
  - Invasive (perturbs plasma)

- **Bremsstrahlung**
  - Indirect, non-invasive measurement of the plasma (scattering electrons)
  - Difficult to separate plasma effects from scattering effects

- **Directly measuring electrons that escape confinement**
  - Indirect measurement of the plasma (Loss-cone distribution)
  - Can be affected by external factors (ambient/residual magnetic fields, beamline effects, etc.)
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Measurement of Electrons Escaping Confinement at NSCL: Superconducting Source for Ions (SuSI)

1. Vary power
2. Vary gas pressure
3. Varying radial field maximum
4. Vary $B_{\text{min}}/B_{\text{ECR}}$ with constant injection/extraction maxima
Measurement of Electrons Escaping Confinement at NSCL: Beamline and Diagnostics

Extraction, Puller, and Einzel lens electrodes are grounded.

- Argon Gas
- SuSI Ion Source
- Faraday Cup
- 4-Jaw Collimator
- Magnetic Field Probe
- EPICS System Archiver
- Dipole/Analyzing Magnet ($I = \pm 10A$)
- Pb and W collimators
- X-ray Detector (High Purity Germanium Detector)
Measurement of Electrons Escaping Confinement at NSCL: Electron Transport and Energy Selection

Minimum Reliable Electron Energy: ~ 30 keV
Measurement of Electrons Escaping Confinement at NSCL: Current Collector and Data Acquisition System

<table>
<thead>
<tr>
<th>Gap Area</th>
<th>Current Range</th>
<th>Current Var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5x38 mm²</td>
<td>~1 nA</td>
<td>0.2%</td>
</tr>
<tr>
<td>5x5 mm²</td>
<td>~100 pA</td>
<td>0.7%</td>
</tr>
</tbody>
</table>

Current Range vs Gap Area (HGxVG)

Front View

Side View

Horizontal Gap

Vertical Gap

Normalized Number of Electrons vs Gap Area [mm²]
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Grounding the Extraction Electrode Revealed Two Peak Electron Distribution with Limited Effects on Observed X-rays

<table>
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<tr>
<th>Microwave Power</th>
<th>Argon Pressure</th>
<th>Radial Field Max</th>
<th>$B_{\text{min}}/B_{\text{ECR}}$</th>
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</thead>
<tbody>
<tr>
<td>350 W</td>
<td>214 nTorr</td>
<td>1.22 T</td>
<td>0.621</td>
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</table>

**Measured Electron Distribution [nA]**

- **30 keV Threshold**

**Bremsstrahlung Distribution [Counts/s]**

- Differences in bremsstrahlung spectra limited to photon energies less than 125 keV

**Electron Energy [keV]**

**Bremsstrahlung Energy [keV]**

- **Extraction Voltage: 20 kV**
- **Extraction Voltage: Grounded**
An Increasing Microwave Power had a Small Effect on the Peak’s Central Energy, Large Effect on Measured Current

<table>
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<th>Varying Microwave Power</th>
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\[ \text{Normalized Temperature} \]

\[ \text{Electron Energy [keV]} \]

\[ \text{Bremsstrahlung Spectra [Counts/s]} \]

\[ \text{Bremsstrahlung Energy [keV]} \]

\[ \text{Microwave Power [W]} \]

\[ \ln(I_{\text{Brem}}) \propto -\frac{\hbar \omega}{T_s} \]

- EED Peak Temperature
- Spectral Temperature ($T_s$)

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An Increasing Neutral Pressure had a Small Effect on the Peak’s Central Energy, Small Effect on Measured Current

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**Graphs:**
- Microwave Power: Varying Argon Pressure
- Radial Field Max: $1.22 \text{ T}$
- $B_{\text{min}}/B_{\text{ECR}}$: 0.621

**Equation:**
$$\ln(I_{\text{Brem}}) \propto -\frac{\hbar \omega}{T_s}$$

- EED Peak Temperature
- Spectral Temperature ($T_s$)
An Increasing Radial Field had a Small Effect on the Peak’s Central Energy, Moderate Effect on Measured Current

Microwave Power | Argon Pressure | Varying Radial Field Max | $B_{\text{min}}/B_{\text{ECR}}$
---|---|---|---
350 W | 214 nTorr | | 0.621

$\text{EED Peak Temperature}$

$\text{Spectral Temperature (}$T_s$)$
Magnetic Minimum Controls the High Energy Peak’s Temperature and Amplitude, X-ray Distribution’s Temperature

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$$\ln(I_{\text{Brem}}) \propto - \frac{\hbar \omega}{T_s}$$

Microwave Power: 350 W, Argon Pressure: 214 nTorr, Radial Field Max: 1.22 T, Varying $\frac{B_{\text{min}}}{B_{\text{ECR}}}$
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Future Work

- Finalize analysis of the results from SuSI:
  - Corrections due to beamline transport:
    - Beamline transmission loss
    - Losses due to residual magnetic fields/optical corrections
    - Effect of the extracted ion currents on the escaping electrons
  - Possible effects from plasma instabilities (via microwave diagnostics)
- Repeat our measurement on ARTEMIS-B (14 GHz)
Summary

• ECR ion sources use microwaves to heat electrons in order to create an EED capable of creating high charge state ions.

• Measurements of the distribution of electrons escaping confinement were taken at the NSCL to better understand the EED.

• Electron measurements revealed:
  • A two-peak distribution consisting of a high energy peak (400 keV – 1.2 MeV) that follows $B_{\text{min}}/B_{\text{ECR}}$ and a lower energy peak (10 – 70 keV) that requires more complicated analyses to fully understand.
  • The peak energy of high energy electrons appears insensitive to changing microwave power, neutral gas pressure, and radial field maximum over the measured ranges.
  • Tandem bremsstrahlung measurements showed good qualitative agreement with variations in the high energy electron peak.
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?