An ECR Ion Source and Accelerator for Nuclear Astrophysics Studies

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Outline

- Motivation for a high-intensity, low-energy accelerator
- Ion source requirements
- Design
  - NdFeB permanent magnet geometry
  - Source components
- Performance
- Future improvements
Astrophysical Motivation

• Stars shine by nuclear reactions
• The elements we see everyday are a result of nuclear burning
• Strive to understand reaction sequences and networks happening in stars
• Recreate reactions occurring in stars
  – Use accelerators to produce beams
  – Measure observables corresponding to specific nuclear processes
Stellar Cross Sections are Small!

Cross sections for fusion reactions are exceedingly small at low energies! Signal rates rival those of environmental background!
Effective Energy Region

To boost signal rates, need high-intensity, low-energy accelerator!

$^{16}\text{O} + p$, $T = 30\text{MK}$

$e^{-E/kT}$

$e^{-1/\sqrt{E}}$

Maximum defines the Range of energy where most Nuclear reactions occur!
Laboratory for Experimental Nuclear Astrophysics

Built on-site as Master’s thesis

1 MV JN Van de Graaff

Low-energy facility solely devoted to making measurements of astrophysical importance
Student operated and maintained
Instrumentation: ECR Ion Source and Accelerator

• Required
  – Compact, permanent magnet driven
    • For 2.45 GHz wave, need 875 G field
  – Produce 1 mA protons on target
  – Electrostatic, $E = 50 – 200$ keV

• Desired
  – 1 mA pulsed beam, @ 1 Hz
  – 10% duty cycle
ECR PM Design

• Magnetic modeling in Radia + (Mathematica)
  • Produce ~900 G solenoidal, magnetic-mirror field on axis
    – 12 bars, 25x25x150 mm
    – NdFeB and Fe

• Multipole geometry
  – 2 x 12 rings of 20x30x5 mm magnets
  – Alternate orientation wrt rings

• Source designed around permanent magnet geometry

Radia Computation

User specified volume element → Apply segmentation → Complete geometry → Interaction matrix

\[
\begin{bmatrix}
\alpha_{11} & \cdots & \alpha_{1n} \\
\vdots & \ddots & \vdots \\
\alpha_{n1} & \cdots & \alpha_{nn}
\end{bmatrix}
\]

Iterative multiplications with instant magnetization vectors

Output

By (T)

\[
\begin{bmatrix}
\alpha_{11} & \cdots & \alpha_{1n} \\
\vdots & \ddots & \vdots \\
\alpha_{n1} & \cdots & \alpha_{nn}
\end{bmatrix} \begin{bmatrix} M_{c1} \\ \vdots \\ M_{cn} \end{bmatrix}
\]
Simple Mirror: Axial Field

- Axial magnetic field on axis
- Actual field greater by ~10% of calculated field
- Field on axis can be decreased uniformly by adding steel bars axial along the outer diameter

\[
B_{\text{max}} = 89.0 \text{ mT} \quad \text{Ratio } \frac{B_{\text{max}}}{B_{\text{min}}} = 1.14 \\
B_{\text{min}} = 79.0 \text{ mT} \quad \text{ECR mirror zone } \sim 2.2''
\]
Simple Mirror: Radial Vector Fields

- Regions of $B \leq 87.5$ mT ($B_{\text{res}}$) are shown as vector fields.
- With simple mirror configuration, low field intersects walls of plasma chamber
  - Electrons are lost to walls
  - Poor confinement promotes electron/ion recombination at walls of chamber
  - Line walls with dielectric
Regions of $B \leq 87.5$ mT are shown as vector fields.

- Notice the ‘egg’-shaped low field region
  - Electrons are energized by crossing ECR surface, global heating
  - Multipole field keeps plasma of chamber walls
  - Much better confinement of plasma
Chalk River Source

- Magnetic field generated by twelve NdFeB magnetic bars
- Field constant over ECR region
- Output:
  - \( I = 60 \text{ mA} \ H^+ \) at extraction
  - 80% \( H^+ \) mass fraction

LENA ECR Ion Source Layout

- NdFeB Magnets
- Accel Electrode
- Decel Electrode
- Collimator
- Input Power: 2.45 GHz
- \( \text{Al}_2\text{O}_3 \)
- Plasma Chamber
- Plasma Aperture
- Resonant field: 0.0875 T

Extraction Parameters:
- Plasma Aperture: 10 to 15 kV
- Accel Electrode: -0.3 to -2.5 kV
- Decel Electrode: 0V
Solenoidal Magnet

- Magnet Design
  - Made of ABS plastic
  - Printed using 3-D printer in UNC Shop
  - Magnetic bars contained in plastic sleeve
  - Field clamps held by magnetic field
  - Internal parts fully encase in plastic to isolate from high voltage and look cosmetically appealing!
Multipole Magnet for Min-B

- Multipole magnet
  - Enclosed in copper
  - Parts machined by wire EDM
    - High current through copper wire, cuts through material
  - Copper is water cooled to protect magnets from heat.
Design – Plasma Chamber

- 70 x 70 mm cylindrical copper chamber
- Lined with 2 mm thick boron nitride
  - BN increases mass fraction of $\text{H}^+$
  - Decreases loss of $\text{e}^-$ to chamber walls
- RF entrance
  - 2.5” x 1/8” $\text{Al}_2\text{O}_3$ window
  - 1/8” thick boron nitride
Extraction System

- Based of extraction calculations made by Chalk River
- Triode extraction system
  - Plasma electrode
  - Extraction (Accel) electrode
  - Ground (Decel) electrode
- Removable, adjustable for increase/decrease in beam current
Assembly
Control System
Bumps along the way…

• Brazed extraction column build to eliminate need for orings
• Brazed extraction column leaky
• Poor quality assurance
Column Leak

Braze

SS

Al$_2$O$_3$

CuNi

LEAK!

MoMn
Bumps along the way

• $6k extraction column Leaked.  Badly.  If you don’t believe me, then watch…

• 200 kV damaged in shipment.  Twice.

8/4/11
Microwave Power

- 500 W, 2.45 GHz magnetron
- Power from magnetron transported via coax to launcher
- Port 1 of 3 port circulator
  - Port 2: to 3 stub tuner
  - Port 3: to dummy load, reflected power monitored
- Flexible waveguide
- 2.8” tapered waveguide
- Electrical break to isolate from high voltage
Initial beam tests

• Up to 7 mA extracted
  – Measured 0.3 m from source
  – +15 kV
  – 3.5 mm aperture
• Multipole magnet geometry
  – 4x less beam extracted
  – Not enough electron loss?
Emittance

- Extraction at high field is unavoidable!
- $\varepsilon_{n,\text{meas}} = 0.19 \, \pi\text{-mm-mrad}$
- For $5 < V_{\text{extr}} < 25 \, \text{kV}$, $\varepsilon_n = 0.5 \, \pi\text{-mm-mrad}$ typical*

Acceleration System

- 200 kV, 8kW power supplies
- Accel. column – 22 gaps, 10 MΩ/gap
- $E_p = 50 - 210$ keV
- $I_p = 1500$ uA on target
- $I_p / I_{tot} \geq 0.85$

Energy Calibration and Resolution

- Use low-energy resonances to test energy accuracy of beams
- Literature values:
  - $^{18}\text{O}(p,\gamma) \ E_r = 150.82(9) \text{ keV}$
  - $^{27}\text{Al}(p,\gamma) \ E_r = 202.8(9) \text{ keV}$
- Measured values:
  - $E_r = 150.6(2) \text{ keV}$
  - $E_r = 200.9(2) \text{ keV}$
- $\Delta E(151 \text{ keV}) = 0.84(7) \text{ keV}$
High X-ray Flux

• Initial measurements showed high levels of X-rays during acceleration
• 2 m from source:
  – @ 60 keV, 5 mr/hr
  – @100 keV, 500 mr/hr
• Caused by back streaming electrons
  – Beam scraping
  – Ionization in tube
• Lab shielding necessary
  – Concrete
  – Pb
• Suppression biasing of tube seems to help reduce X-ray flux
New Acceleration Column

• Tube suffers from radiation damage
• On going effort to model beam transport
  – Optic-II B 36.0
  – PBO Lab Trace 3-D
• Suppression
Beam Pulsing

- Reduce environmental backgrounds
  - 10x the beam in 1/10th the time, reduction of 90%!
- 10% duty cycle, at 1 Hz
  - 1s period, 100 ms beam on
- Still under development
  - Extraction voltage
  - RF power
Further Improvements: Ver. 2.0

• New 1 kW magnetron and power supply
  – Well regulated
  – Pulsing capability

• Further magnet field modeling in extraction region
  – New materials for extraction electrodes?
  – Minimize B-field

• Plasma chamber dielectric materials
  – BN retains water vapor
  – Macor? Al$_2$O$_3$?

• Shorten extraction region
  – Reduce drift length
  – Increase extraction diameters
Summary

• A new ECR ion source and accelerator has been built for studies in nuclear astrophysics.
• For labs that make these measurements, beam currents at LENA are unmatched.
• Provides ability to measure lower in energy with less time burden, necessary for astrophysics!
• Ver. 2.0 upgrades and improvements currently being pursued.
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