An ECR Ion Source and Accelerator for Nuclear Astrophysics Studies

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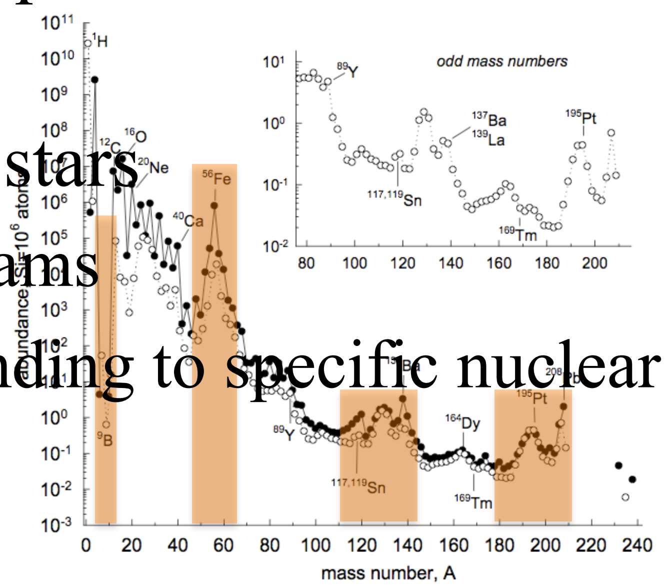
Work in this presentation supported by Grant #DE-FG02-01ER41041 and DE-FG02-97ER41033
USDOE Office of High Energy and Nuclear Physics

Outline

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

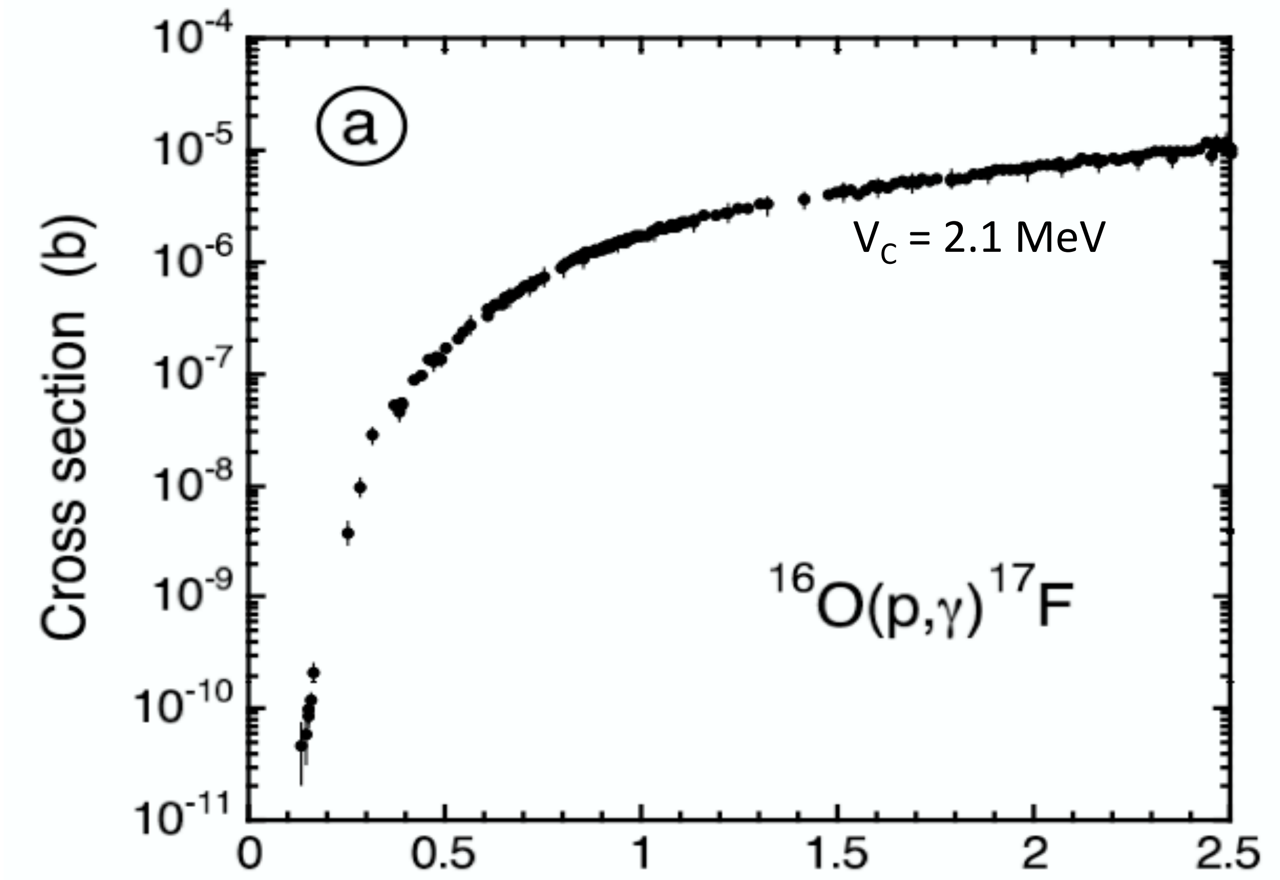
Astrophysical Motivation

- 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



K. Lodders, *Principles and Perspectives in Cosmochemistry*. (2010)

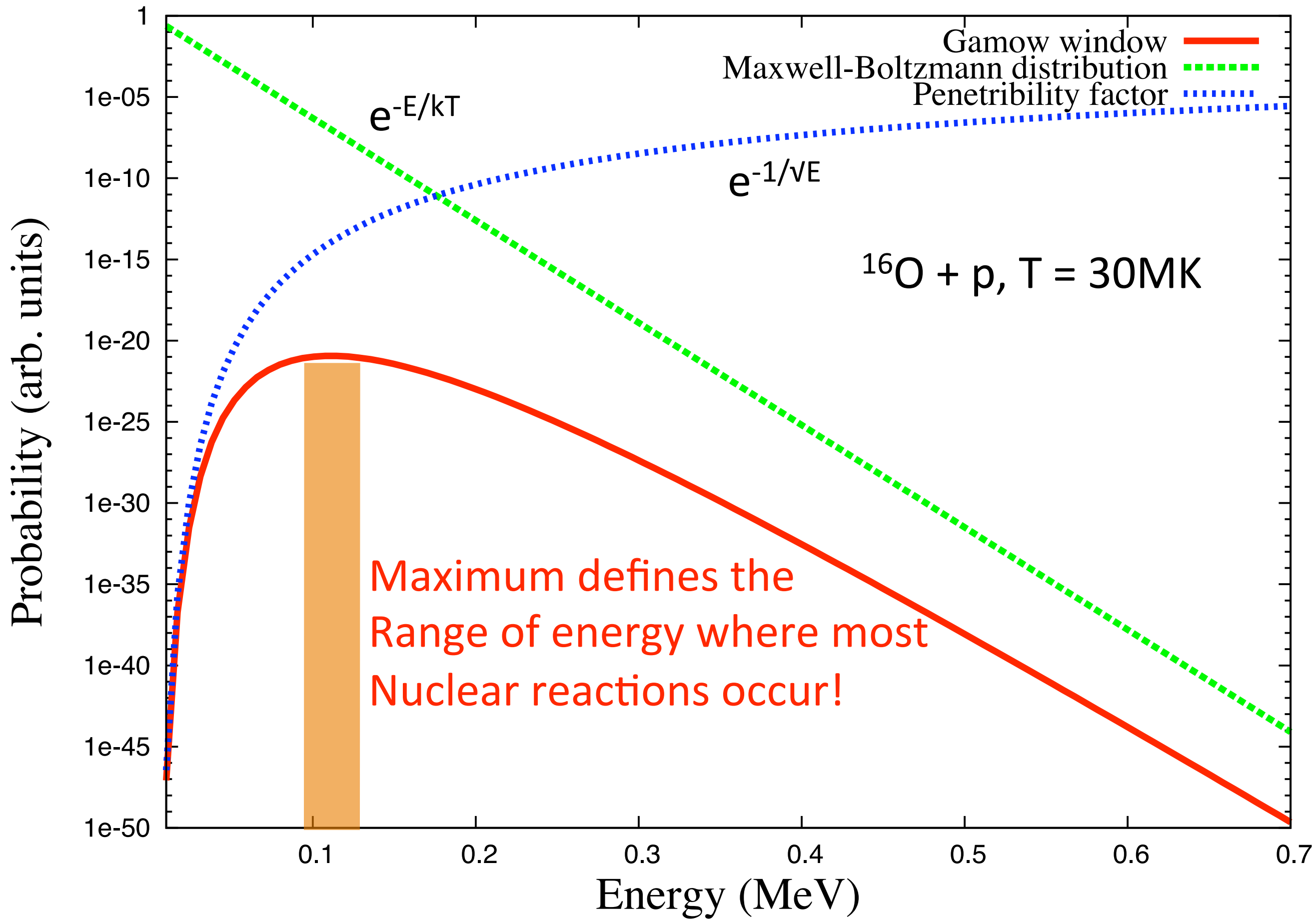
Stellar Cross Sections are Small!



Energy (MeV)

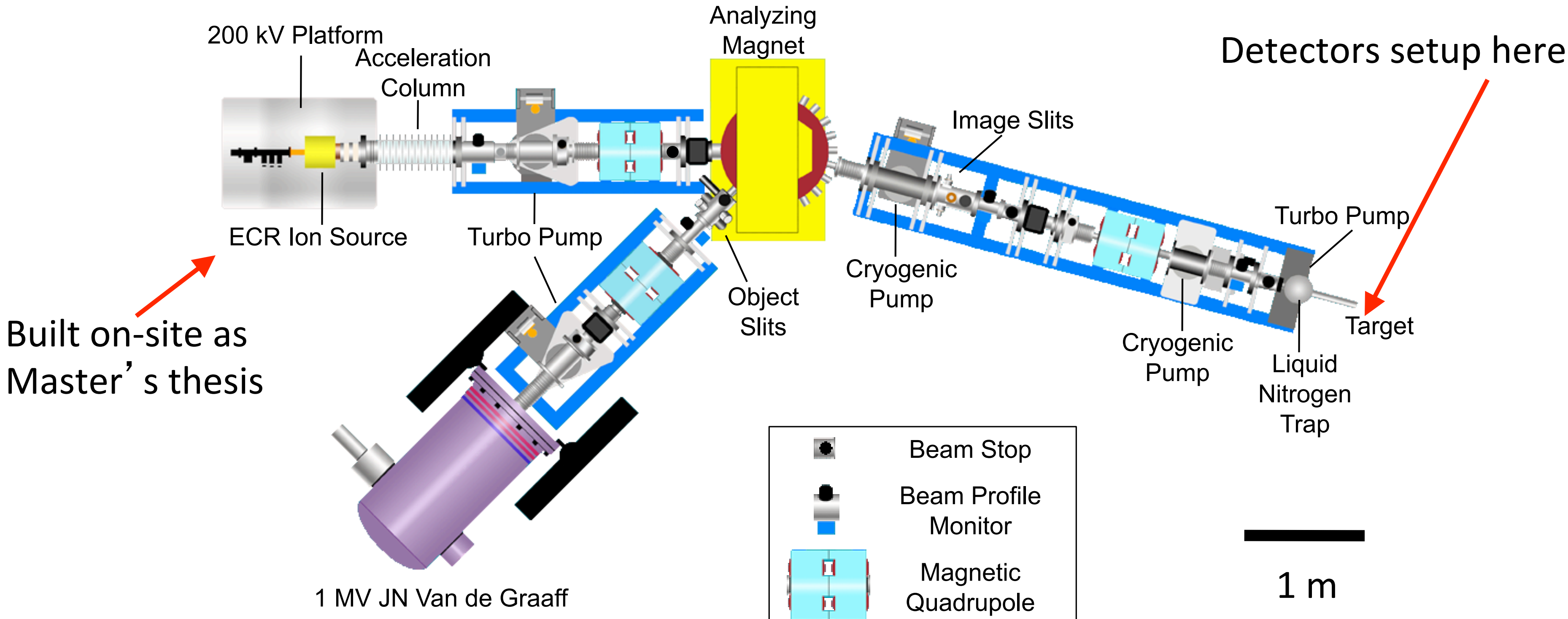
Cross sections for fusion reactions are exceedingly small at low energies!
Signal rates rival those of environmental background!

Effective Energy Region



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

Laboratory for Experimental Nuclear Astrophysics



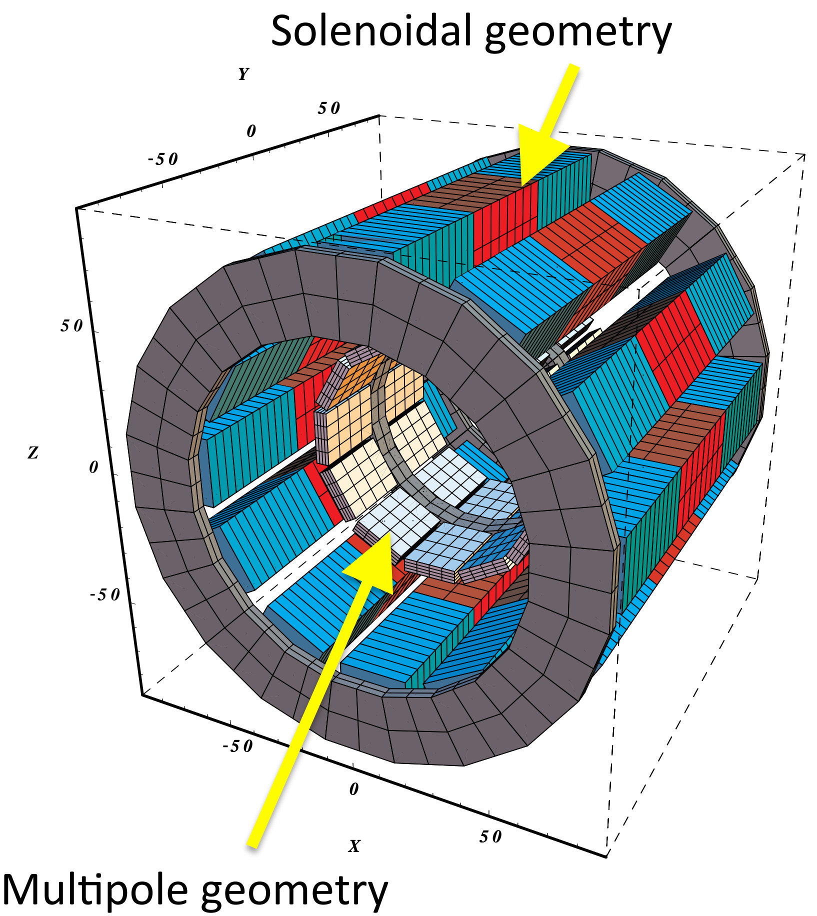
Low-energy facility solely devoted to making measurements of astrophysical importance
Student operated and maintained

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

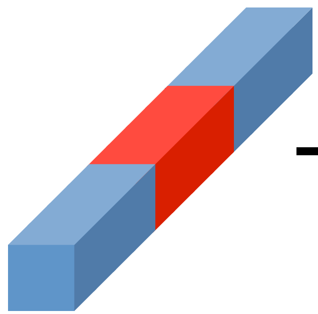
- Magnetic modeling in Radia [+] (Mathematica)
- Produce ~900 G solenoidal, magnetic-mirror field on axis
  - 12 bars, 25x25x150 mm
  - NdFeB and Fe
- Multipole geometry
  - 2 x 12 rings of 20x30x5 mm magnets
  - Alternate orientation wrt rings
- Source designed around permanent magnet geometry



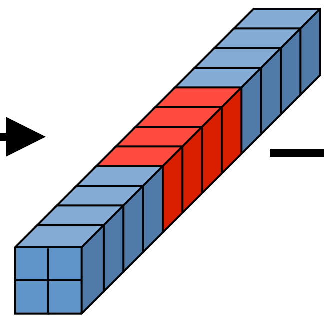
[+]ESRF - http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia

Radia Computation

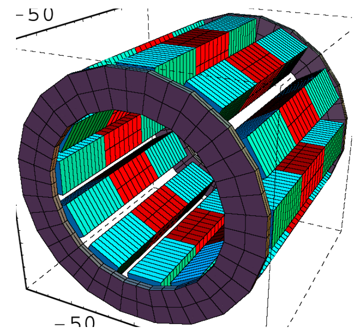
User specified volume element



Apply segmentation



Complete geometry

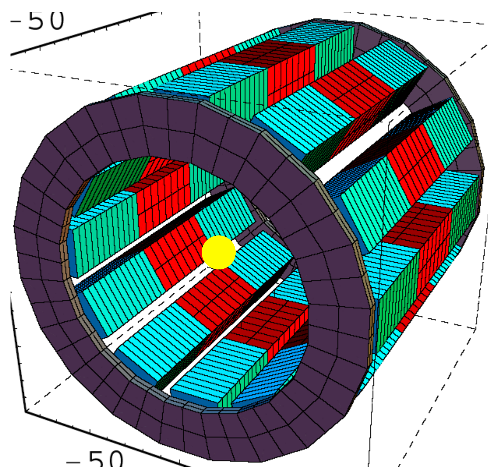


Interaction matrix

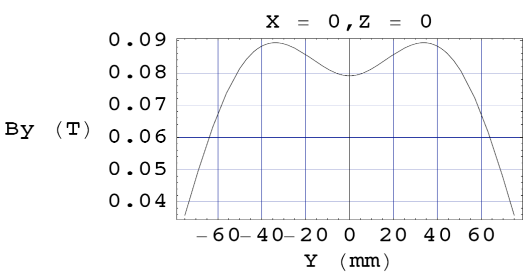
$$\begin{bmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \ddots & \vdots \\ \alpha_{n1} & \cdots & \alpha_{nn} \end{bmatrix}$$

$$\begin{bmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \ddots & \vdots \\ \alpha_{n1} & \cdots & \alpha_{nn} \end{bmatrix} \begin{bmatrix} M_{c1} \\ \vdots \\ M_{cn} \end{bmatrix}$$

Iterative multiplications with instant magnetization vectors

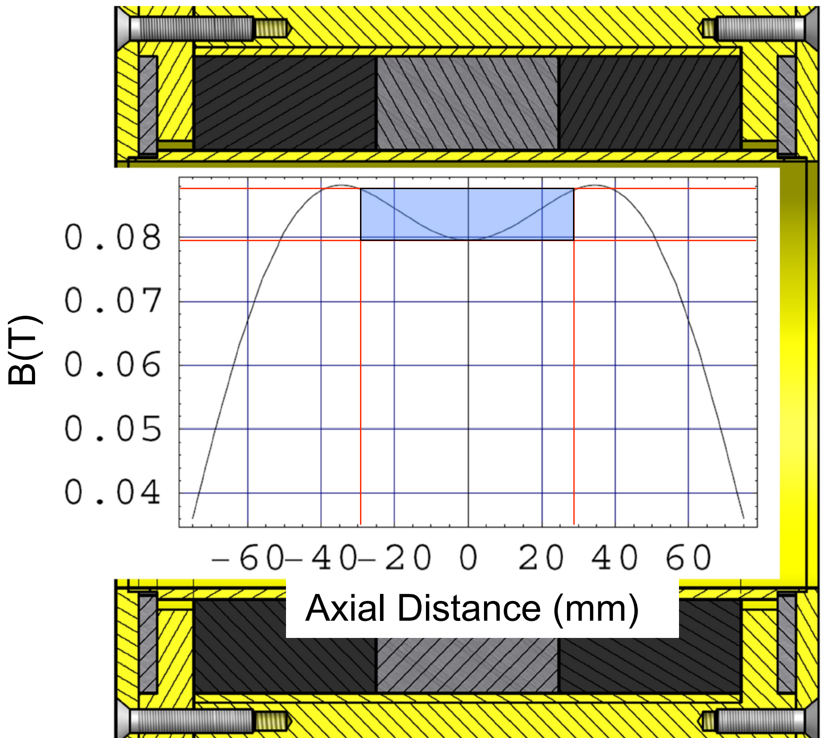


Output



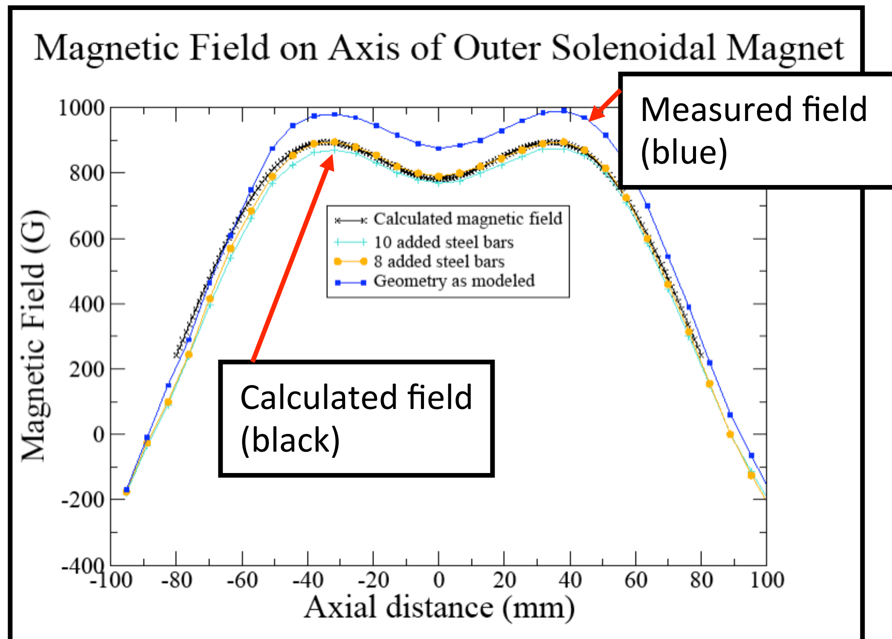
Simple Mirror: Axial Field

Calculated axial field

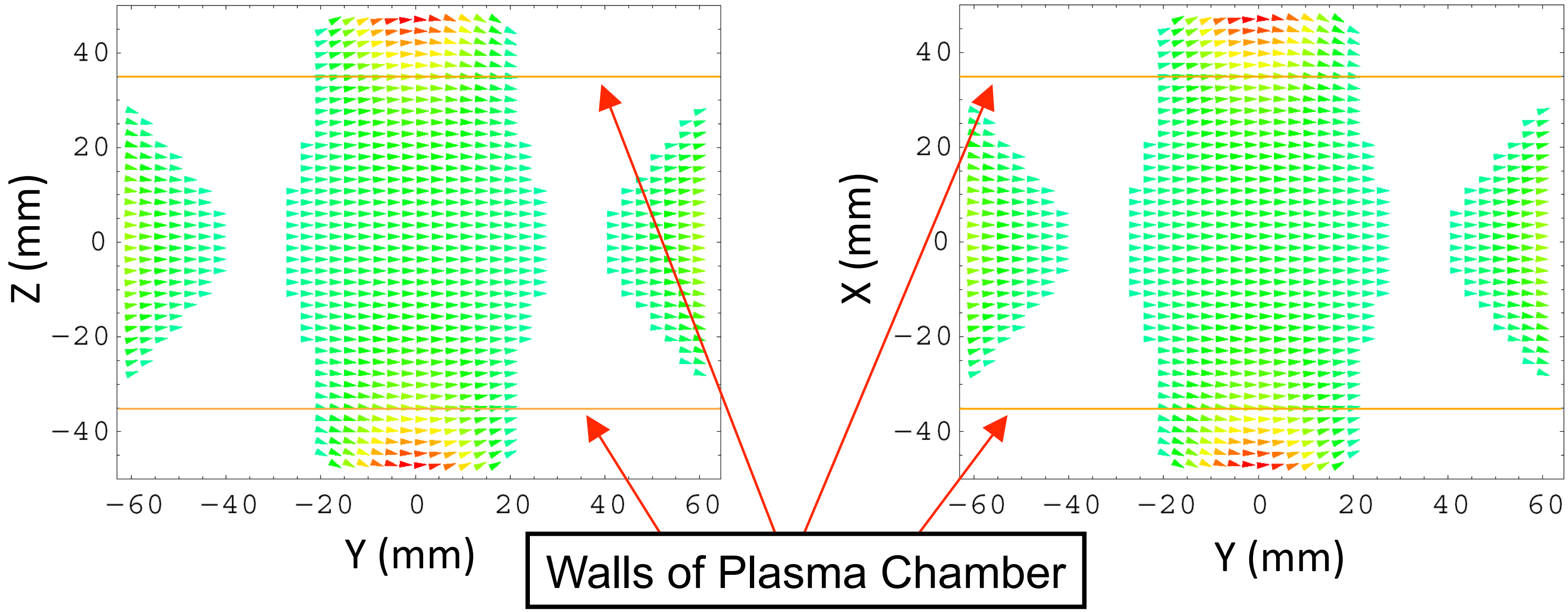


B_{max} = 89.0 mT Ratio B_{max}/B_{min} = 1.14
B_{min} = 79.0 mT ECR mirror zone ~ 2.2”

- 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

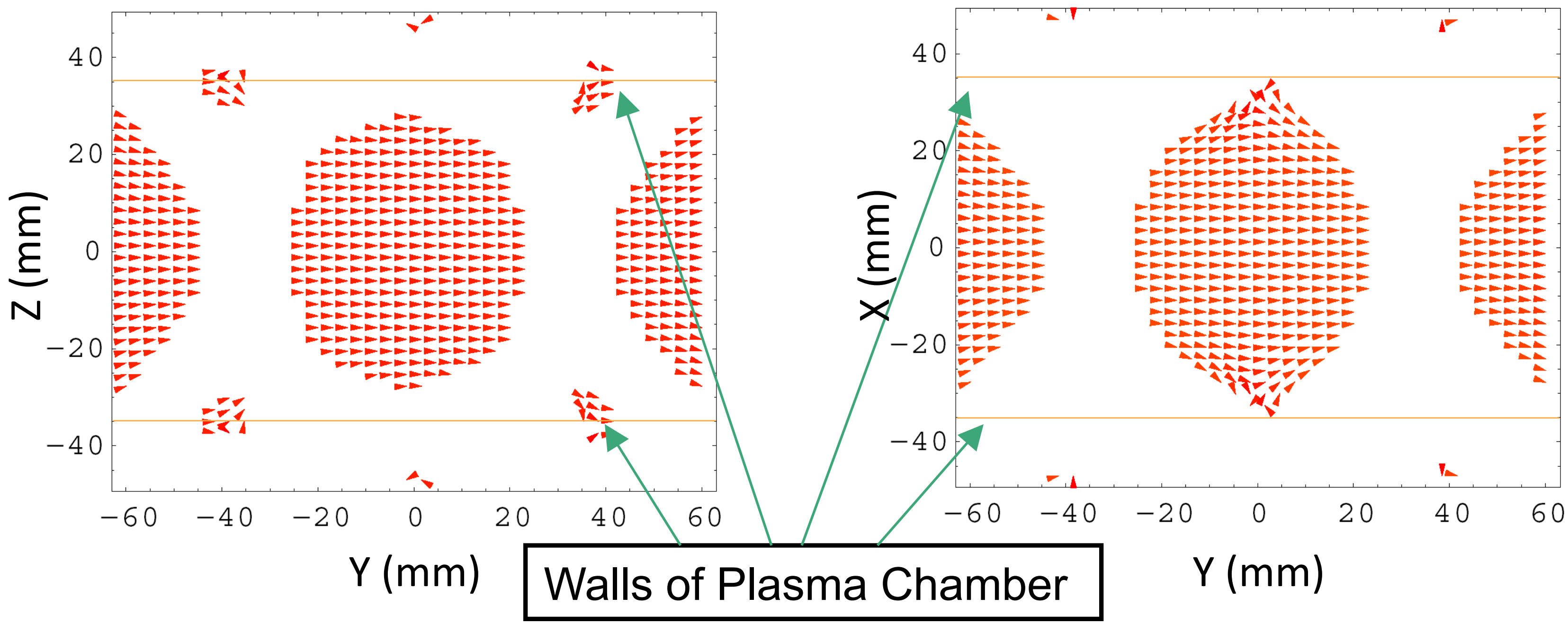


Simple Mirror: Radial Vector Fields



- Regions of $B \leq 87.5$ mT (B_{res}) are shown by as vector field.
- 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

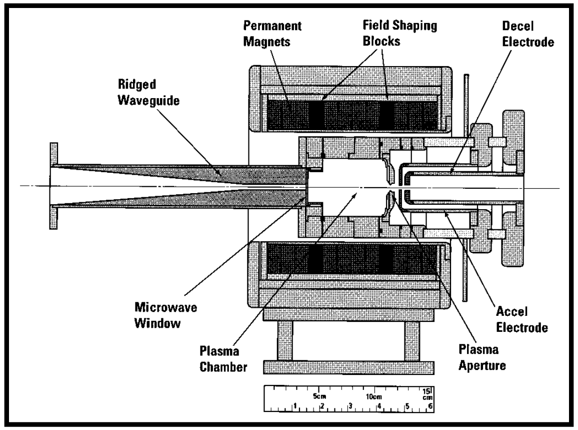
Simple Mirror Plus Min-B: Radial Vector Fields

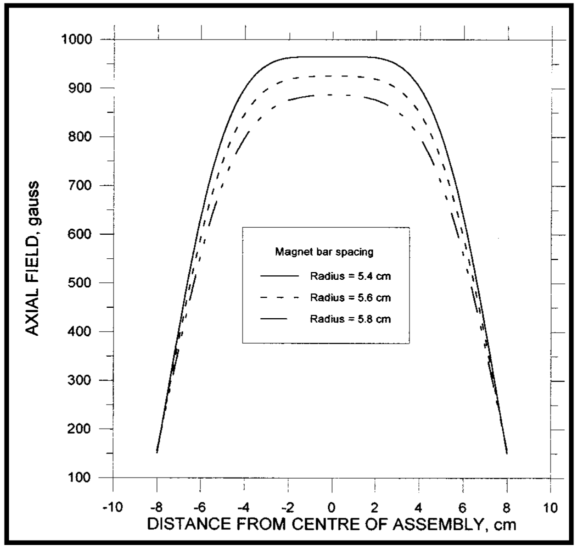


- Regions of B ≤ 87.5 mT are shown as vector fields.
- Notice the 'egg' -shaped low field region
  - Electrons are energized by crossing ECR surface, global heating
  - Multipole field keeps plasma of chamber walls
  - Much better confinement of plasma

Chalk River Source

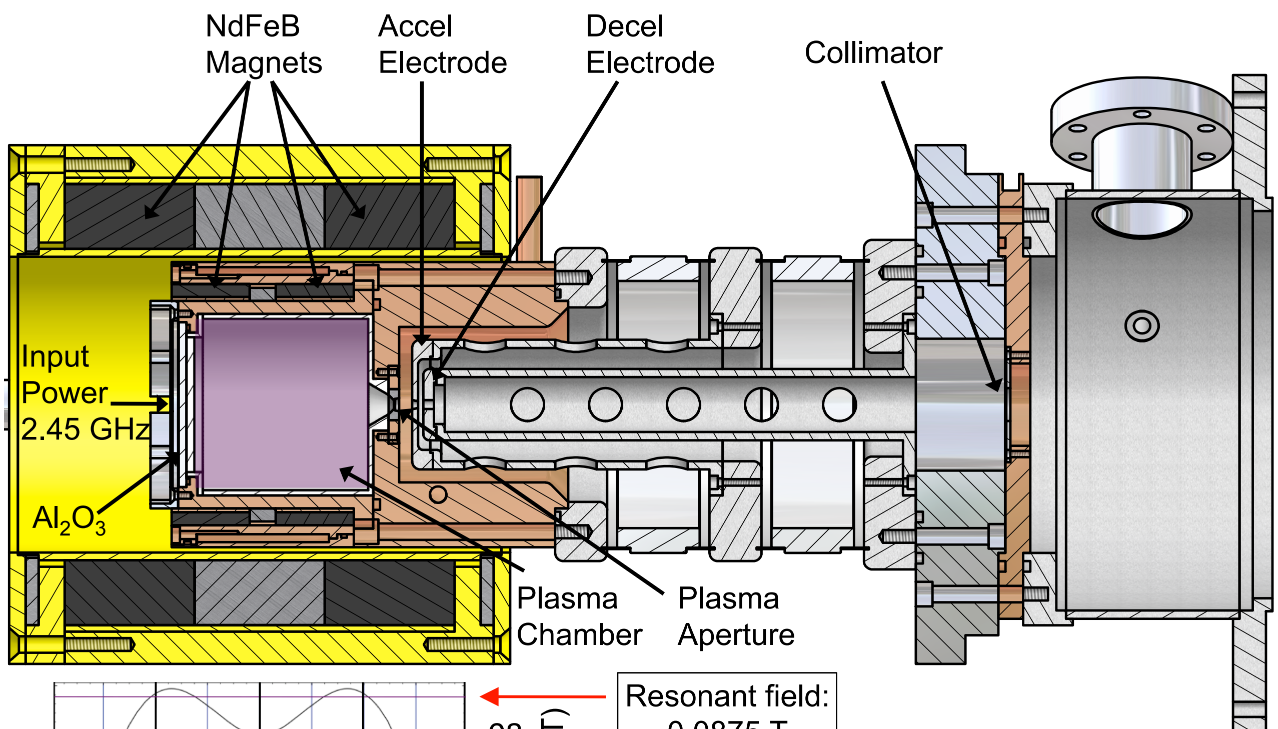
- Magnetic field generated by twelve NdFeB magnetic bars
- Field constant over ECR region
- Output:
  - I = 60 mA H^+ at extraction
  - 80% H^+ mass fraction

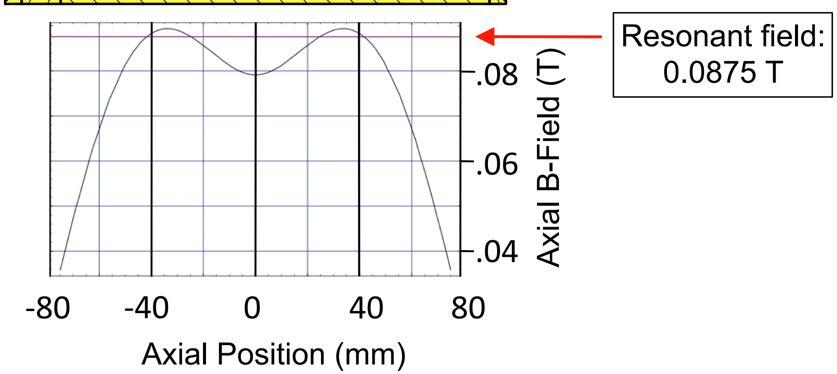




J.S.C. Wills, et al., Rev. Sci. Instr. **69**, 65 (1998).

LENA ECR Ion Source Layout

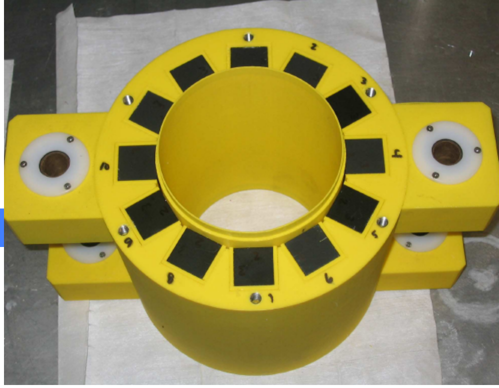




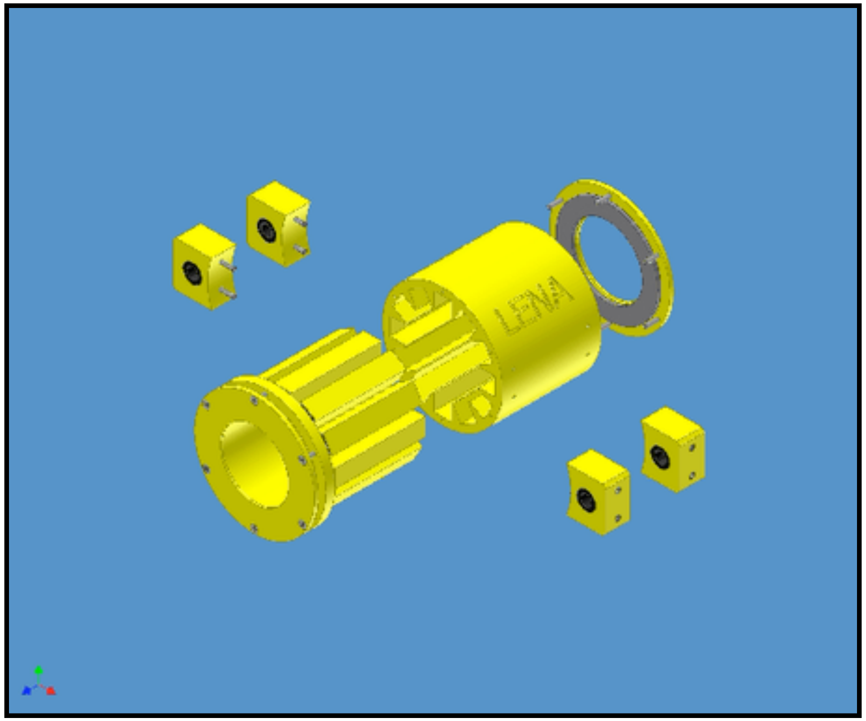
Extraction Parameters

Plasma Aperture:	10 to 15 kV
Accel Electrode:	-0.3 to -2.5 kV
Decel Electrode:	0V

Solenoidal Magnet

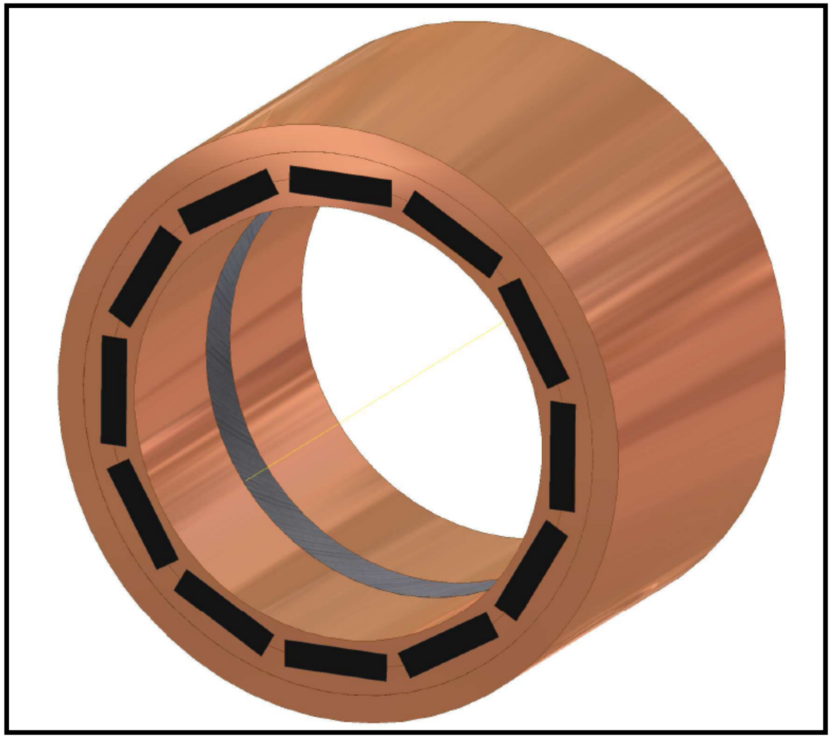


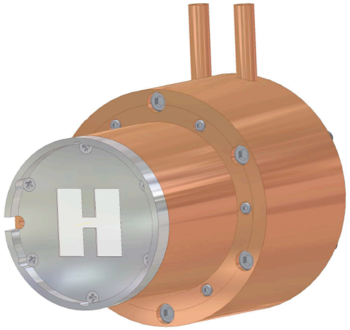
- Magnet Design
  - Made of ABS plastic
  - Printed using 3-D printer in UNC Shop
  - Magnetic bars contained in plastic sleeve
  - Field clamps held by magnetic field
  - Internal parts fully encase in plastic to isolate from high voltage and look cosmetically appealing!



Multipole Magnet for Min-B

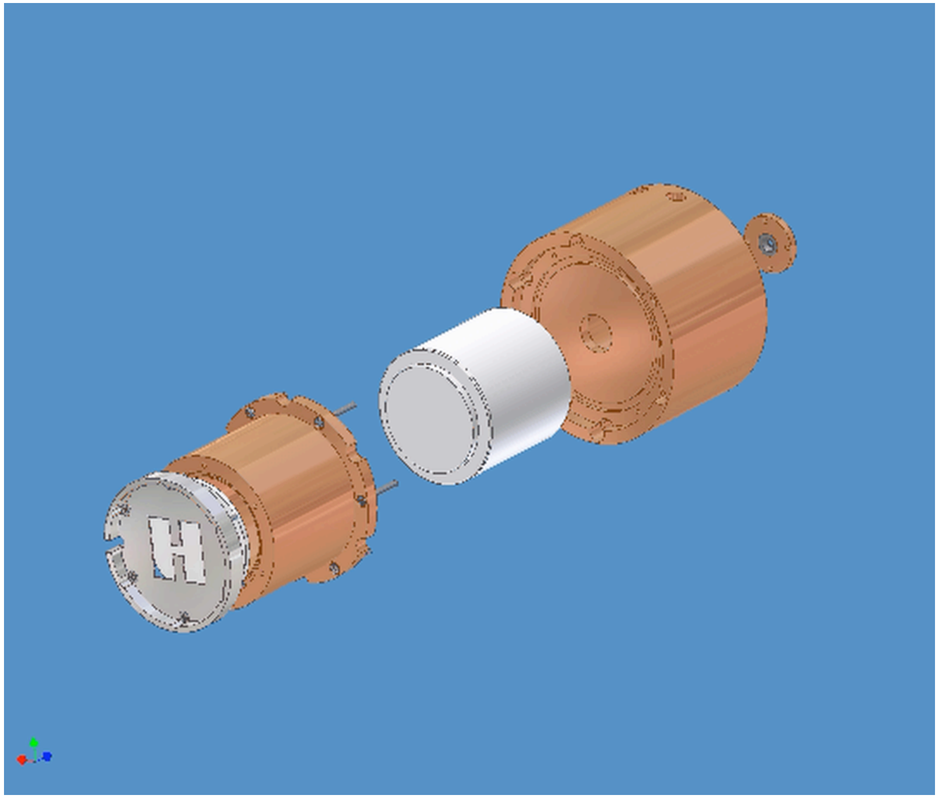
- Multipole magnet
  - Enclosed in copper
  - Parts machined by wire EDM
    - High current through copper wire, cuts through material
  - Copper is water cooled to protect magnets from heat.





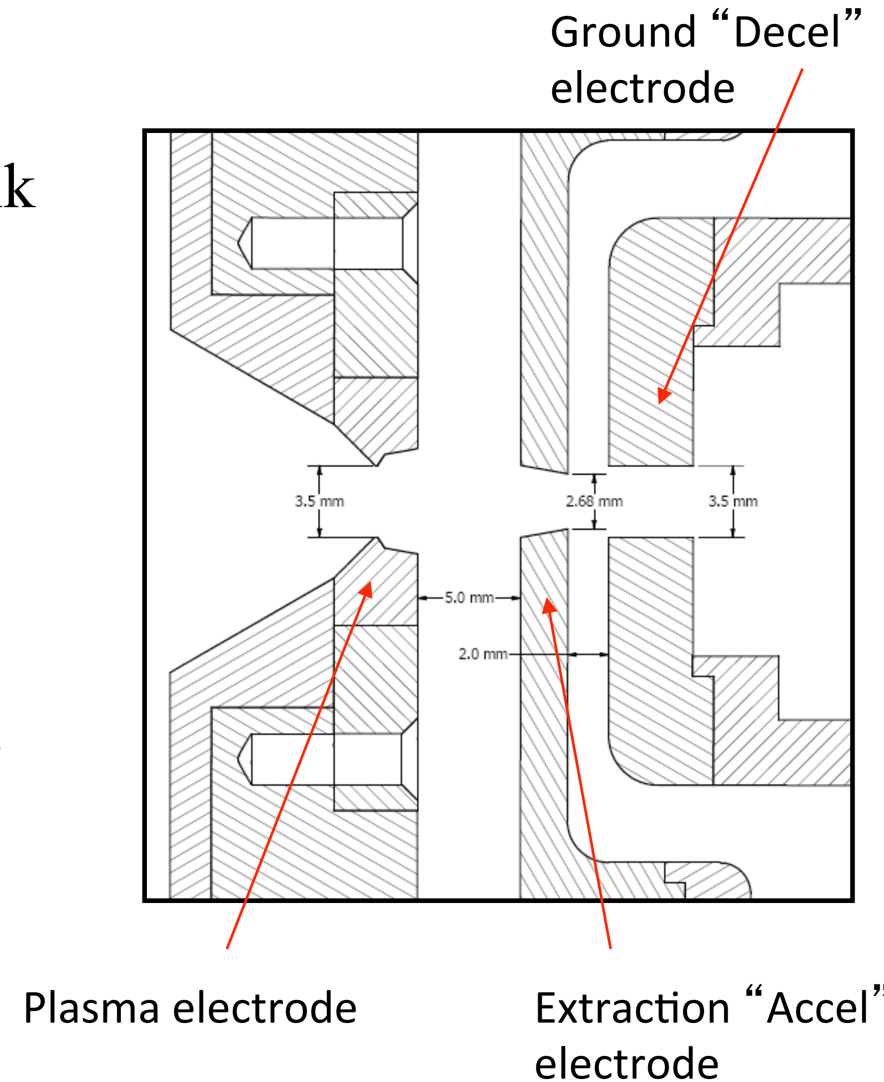
Design – Plasma Chamber

- 70 x 70 mm cylindrical copper chamber
- Lined with 2 mm thick boron nitride
  - BN increases mass fraction of H^+
  - Decreases loss of e^- to chamber walls
- RF entrance
  - 2.5" x 1/8" Al_2O_3 window
  - 1/8" thick boron nitride

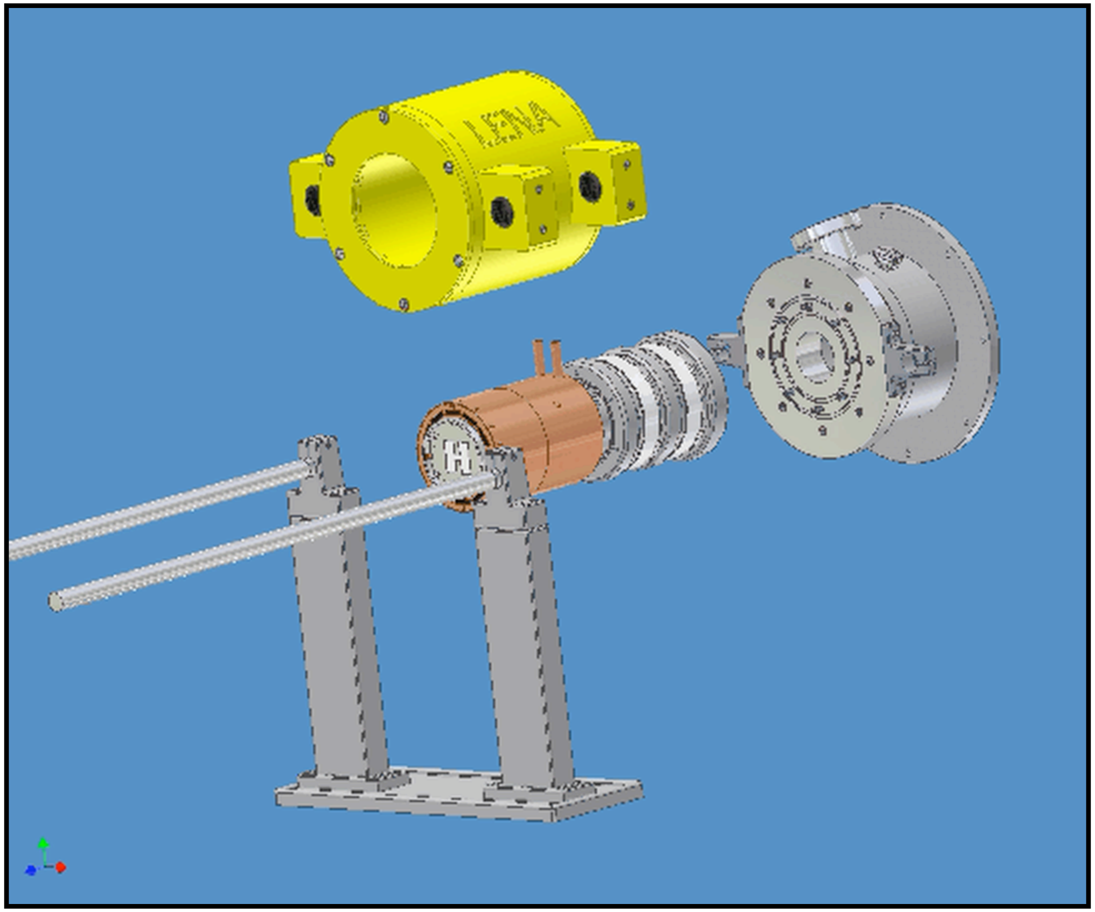


Extraction System

- 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

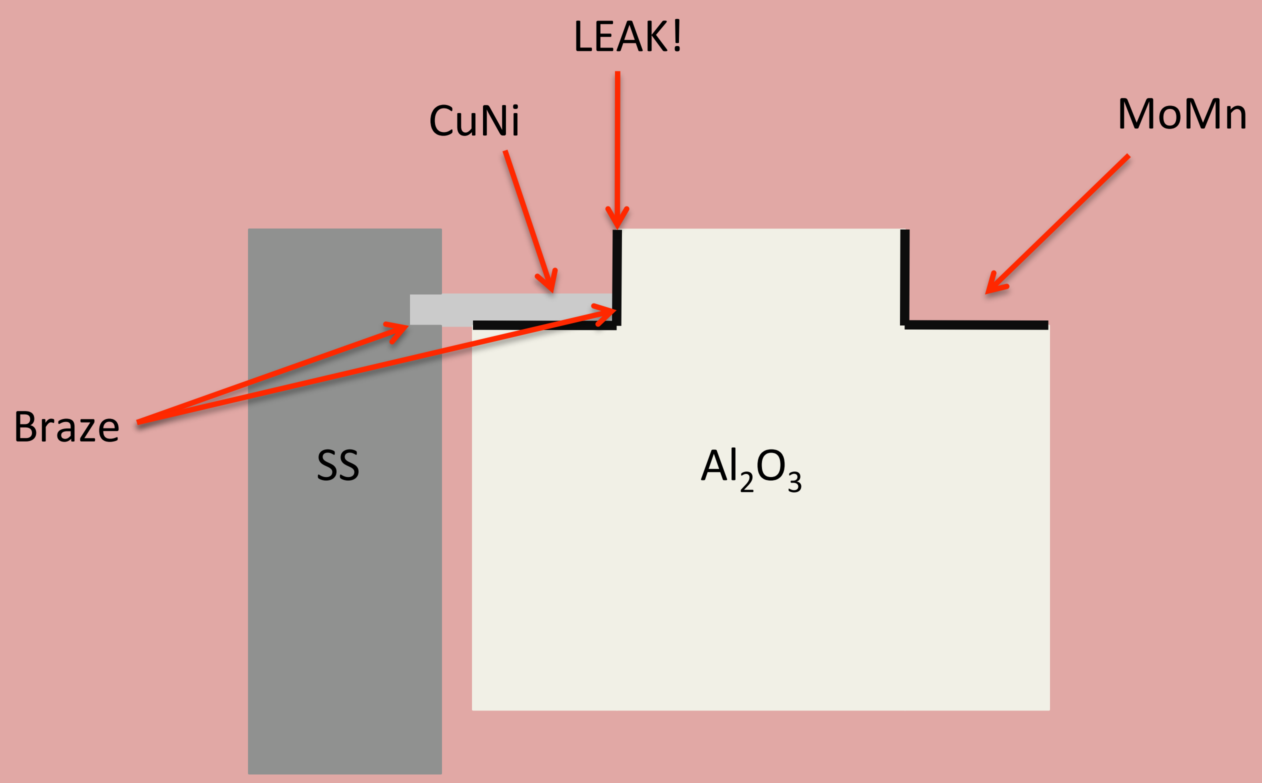


Control System

Bumps along the way…

- Brazed extraction column build to eliminate need for orings
- Brazed extraction column leaky
- Poor quality assurance

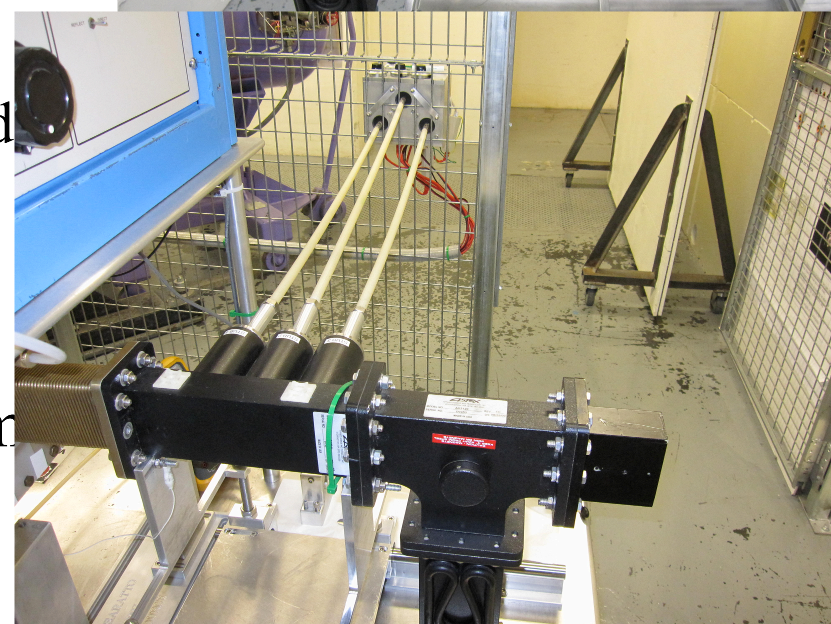
Column Leak




15 12:05PM

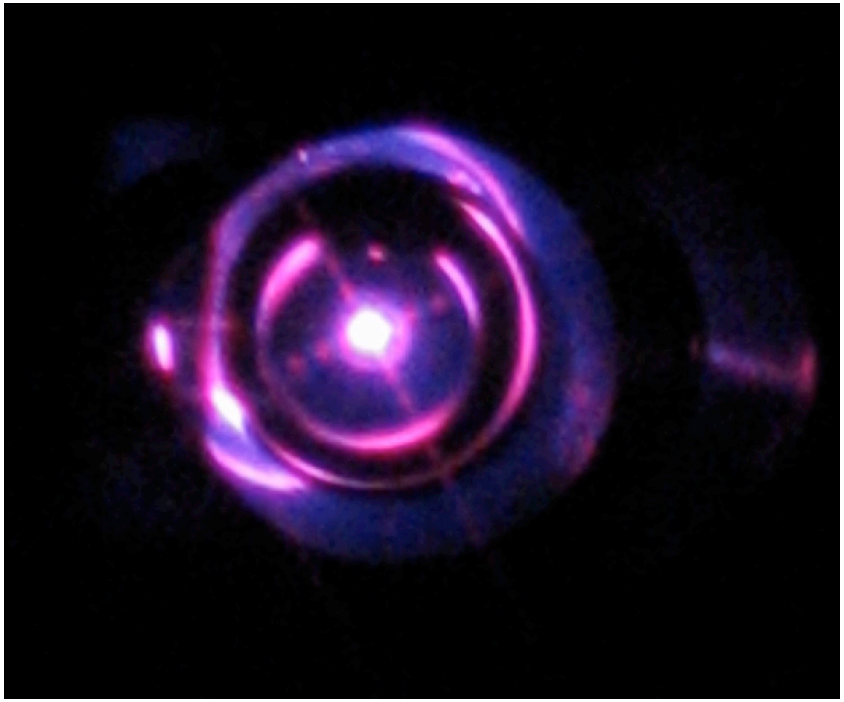
Microwave Power

- 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



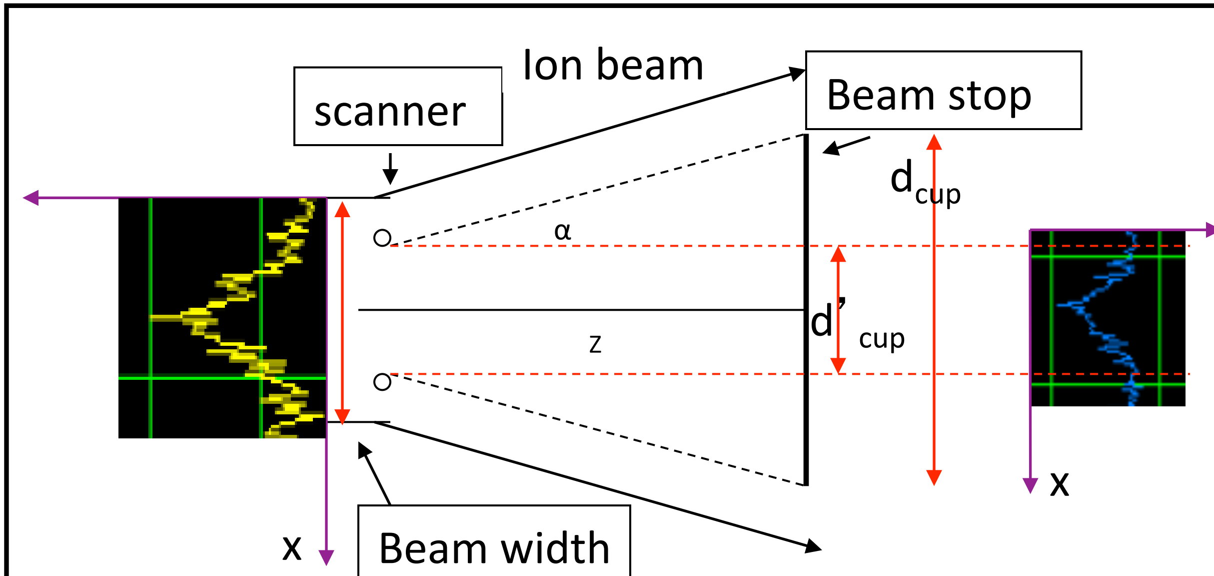
Initial beam tests

- 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?

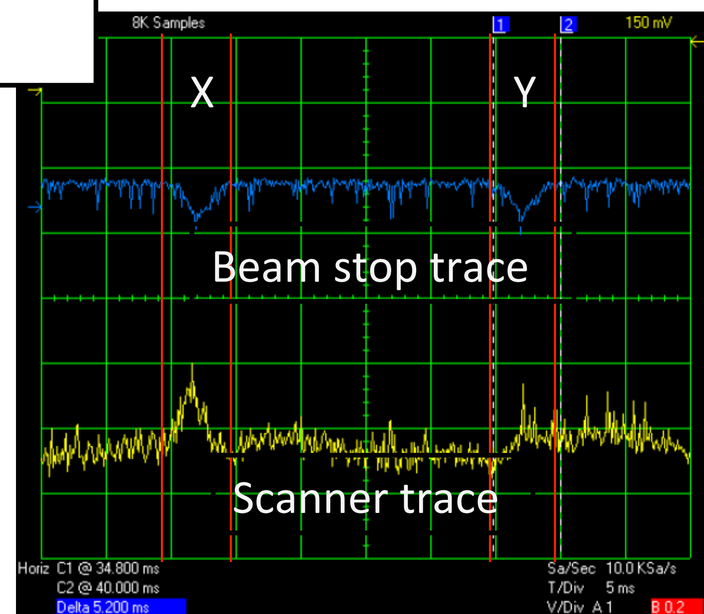


H^+ discharge

Emittance



- Beam scanner used to profile beam
- Beam stop determined beam spot size at scanner
- Emittance: $\varepsilon/\pi = xx' = x\alpha$
  - x - radius of beam spot
  - α - divergence of beam



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

*R. Geller. *Electron Cyclotron Resonance Ion Sources and ECR Plasmas*, 1996.

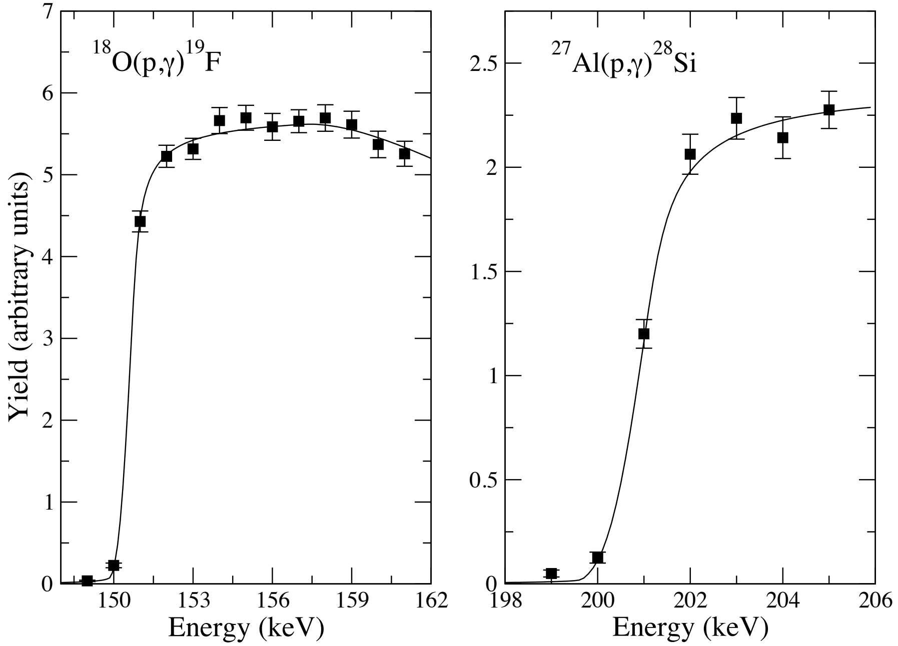
Acceleration System

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

Cesaratto et al. Nucl. Instum. Meth. A, **623**, 888 (2010)

Energy Calibration and Resolution

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

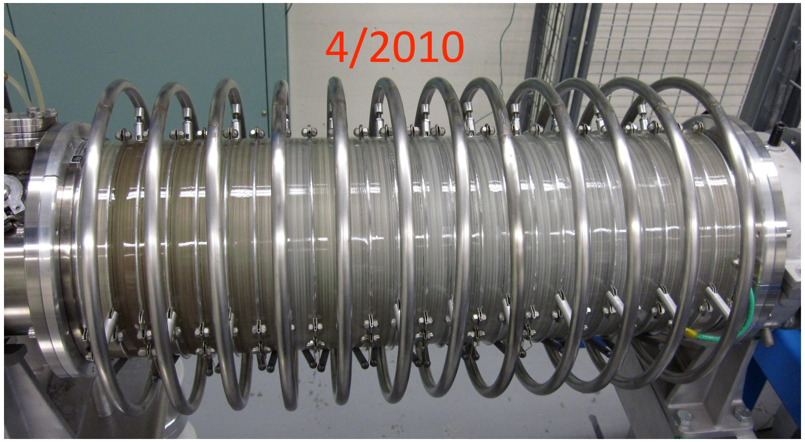


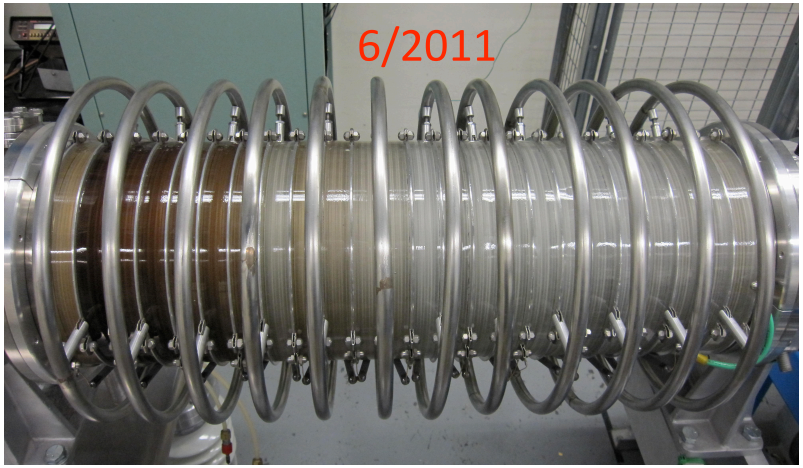
High X-ray Flux

- 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

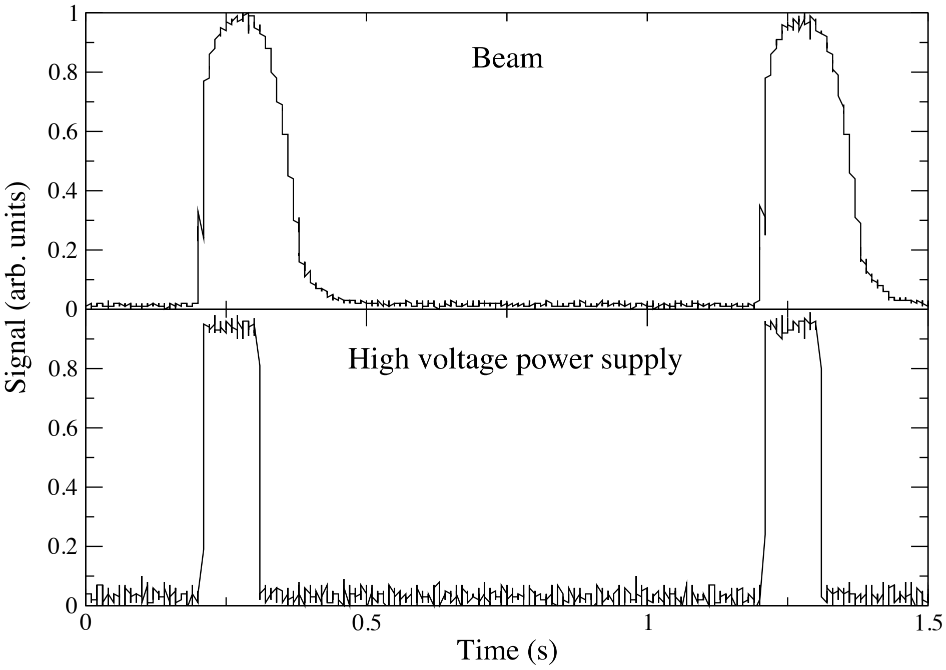
- Tube suffers from radiation damage
- On going effort to model beam transport
  - Optic-II B 36.0
  - PBO Lab Trace 3-D
- Suppression





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

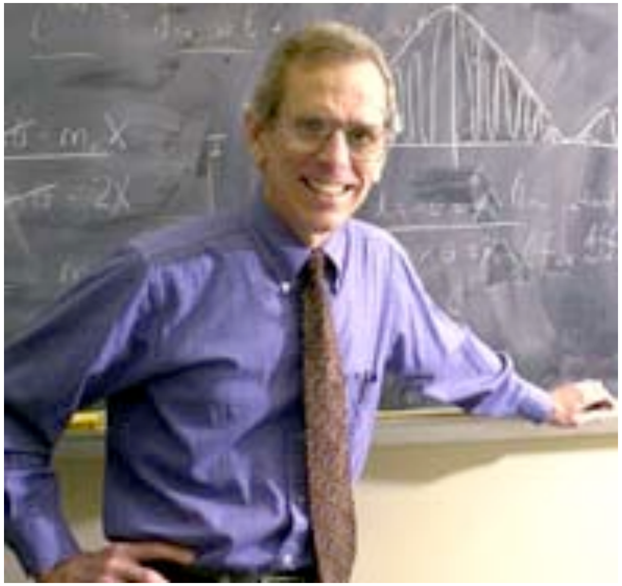
- New 1 kW magnetron and power supply
  - Well regulated
  - Pulsing capability
- Further magnet field modeling in extraction region
  - New materials for extraction electrodes?
  - Minimize B-field
- Plasma chamber dielectric materials
  - BN retains water vapor
  - Macor? Al_2O_3?
- Shorten extraction region
  - Reduce drift length
  - Increase extraction diameters

Summary

- A new ECR ion source and accelerator has been build 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

Acknowledgements

Art Champagne



Tom Clegg

- UNC machine shop
- TUNL technical staff
- Bill Hooke
- John Wills

- Alex Ratti
- You!