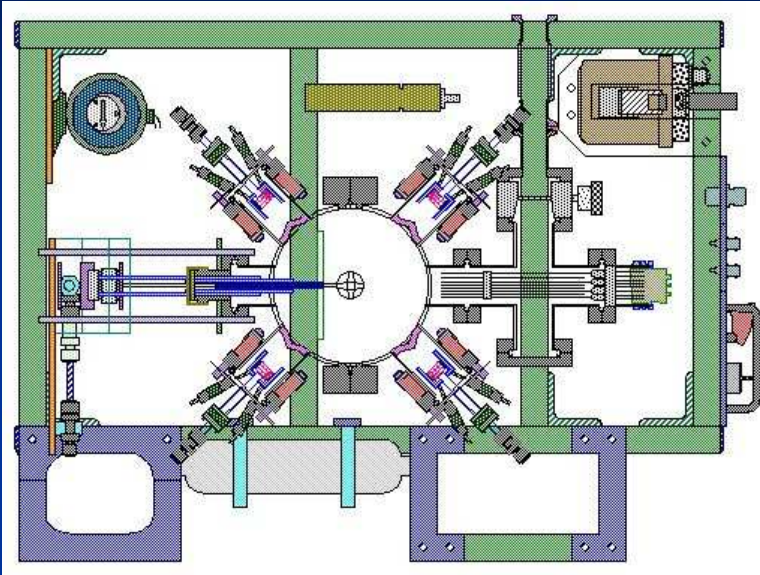


Ion Injector Design

Andrew Seltzman

IEC Fusion Neutron Source



Construction in progress:

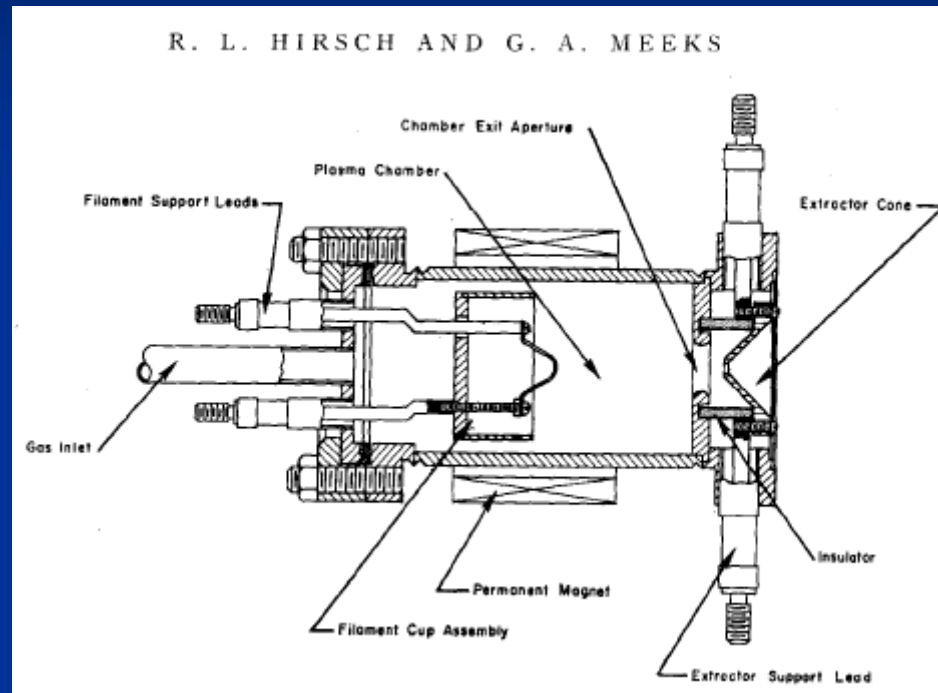
- Will fuse deuterium for 2.45MeV fast neutron production
- **Requires 4 ion injectors** positioned around reactor core for deuterium beam injection.



ION Injector Types

- Filament (Thermionic emission)
- RF Ionization
 - ICP / Ohmic Heating
 - ECRF / ICRF

Filament Ionization

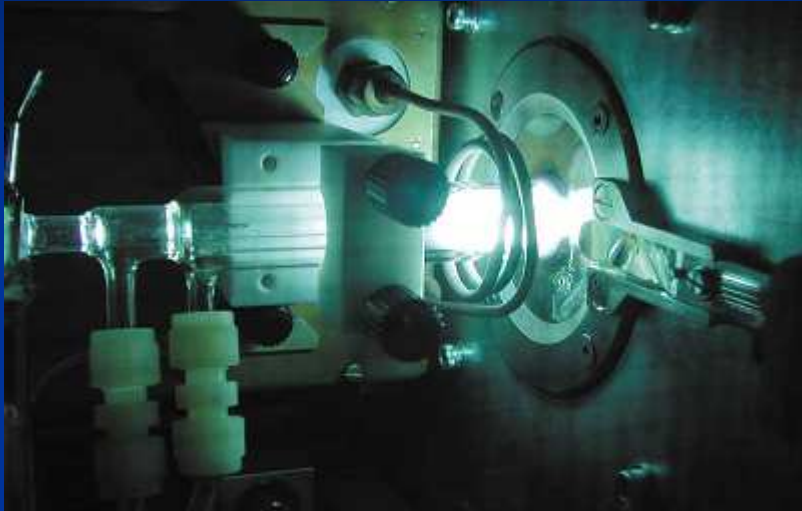


Hirsch Meeks ion injector

- Maximum beam current of 10mA at 12keV

- Benefits
 - Simplicity
 - Size
 - Low Cost
- Limitations
 - Filament life
 - Filament Sputtering
 - Filament Evaporation

RF Ionization: ICP



University of Tokyo ICP ion source

Inductive coupling to plasma

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

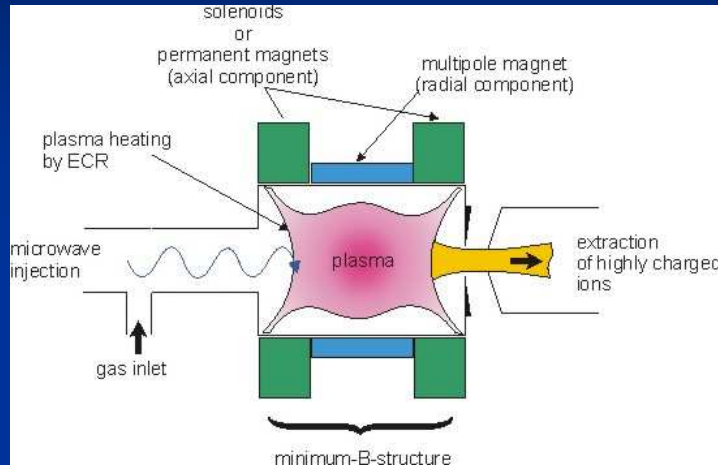
Eddy currents resistively heat plasma

$$R = \frac{e_i e \sqrt{m_e} \ln(\Lambda)}{6\pi \sqrt{3} \epsilon_0^2 (kT)^{3/2}} \quad \ln(\Lambda) = \ln \left(12\pi \left[\frac{(\epsilon_0 kT)^3}{n_2 e_2^4 e_1^2} \right]^{1/2} \right)$$

Resistance decreases with increasing temperature

- Upper limit on ICP plasma temperature
- Capacitive coupling of ICP coil in contact with plasma

RF Ionization ECR/ICR

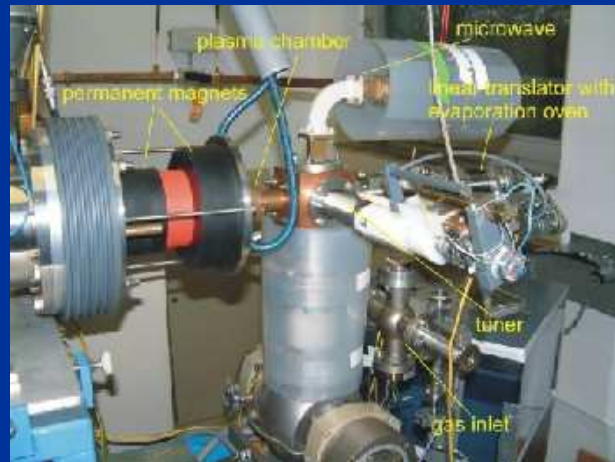
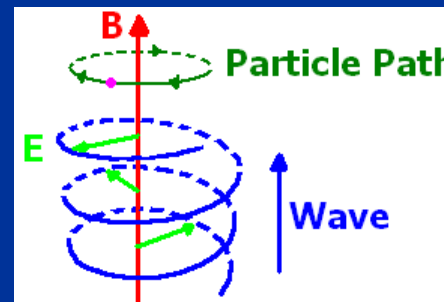


- RF excitation of electrons/ions at their fundamental gyro frequency

$$\Omega_{\sigma} = \frac{eB}{m_{\sigma}}$$

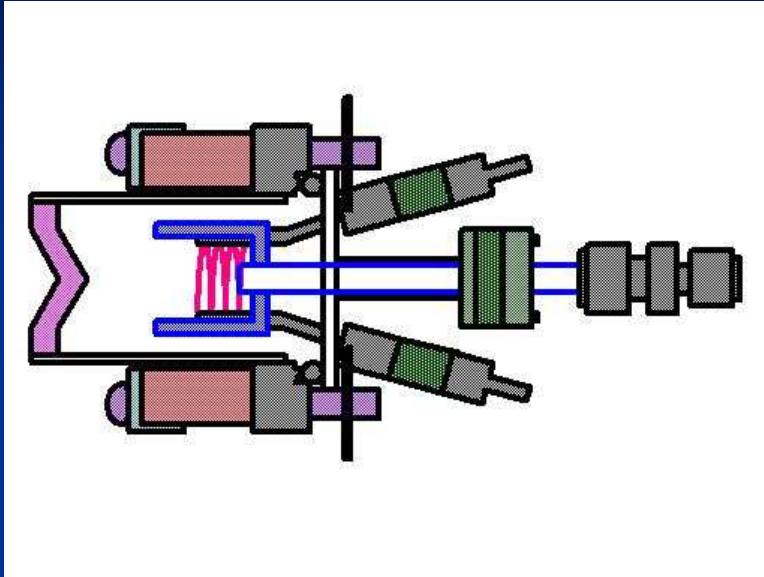
- X-mode resonance for CP or LP wave

$$c^2 k_z^2 - \omega^2 + \sum_{\sigma} \frac{\omega_p^2 \omega}{(\omega \pm \Omega_{\sigma})} = 0 \quad \omega_p^2 = \frac{1}{\epsilon_0} \left(\sum_{\sigma} \frac{n_{\sigma} e_{\sigma}^2}{m_{\sigma}} \right)$$



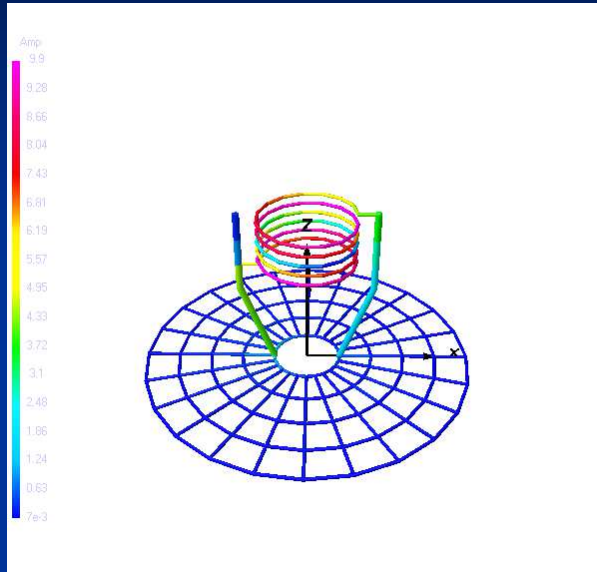
Institut für Atom- und Molekülphysik
ECR ion source

Injector Design Overview



- RF ionization
 - Resonant RF coil
- Minimum B trapping
 - External magnet yoke
- Electrostatic Extraction
 - Extractor cone
 - DC biased RF coil
- Expected performance:
 - 5-20mA @ 15keV

RF Coil Design



Modeled in NEC2

ECRF / ICP Frequency: 900MHz (33cm wavelength)

Coil Dimensions:

- 5.5 turns
- 1cm Diameter
- 0.9cm height

Coil Impedance: $41.2 + j166$ Ohms @ 900MHz

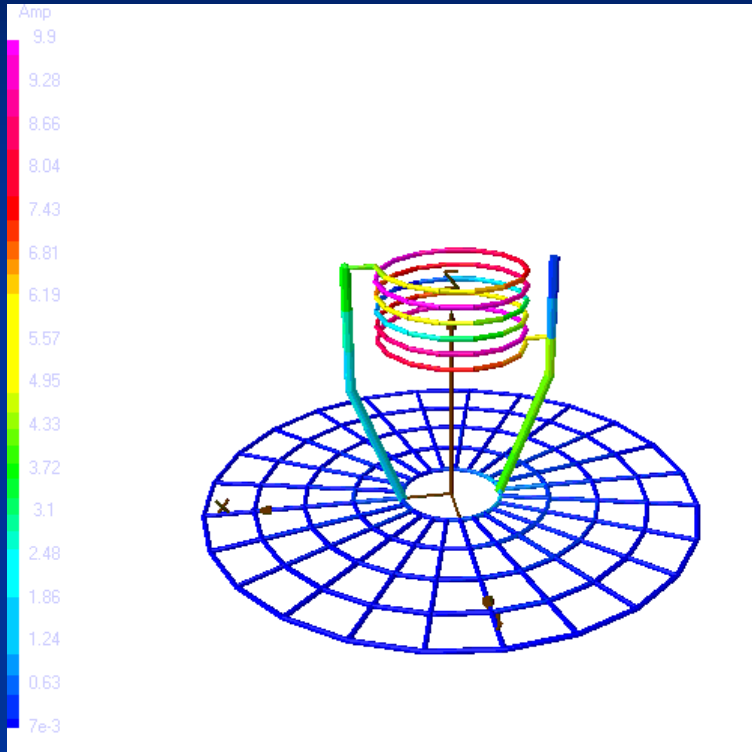
Pi low pass matching network

Molybdenum RF coil:

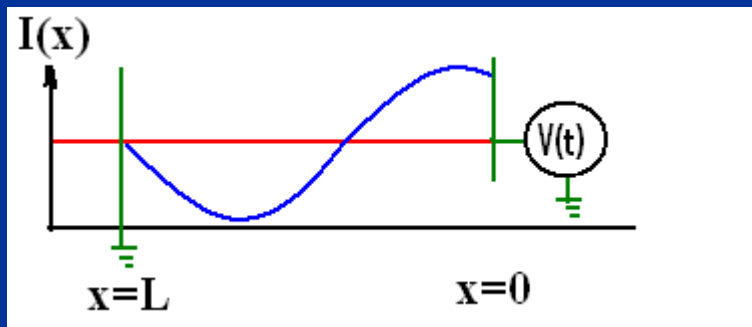
- Lower sputtering coefficient (As compared to stainless steel)
- Higher conductivity
- Higher melting temperature



RF Coil Currents



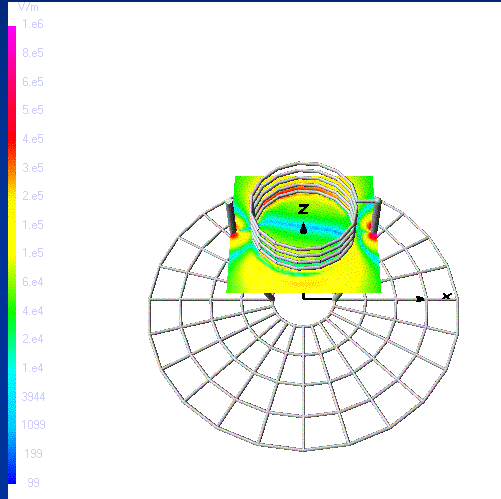
Coil of approximately 1 wavelength



Boundary conditions fixed by grounding non-driven end:

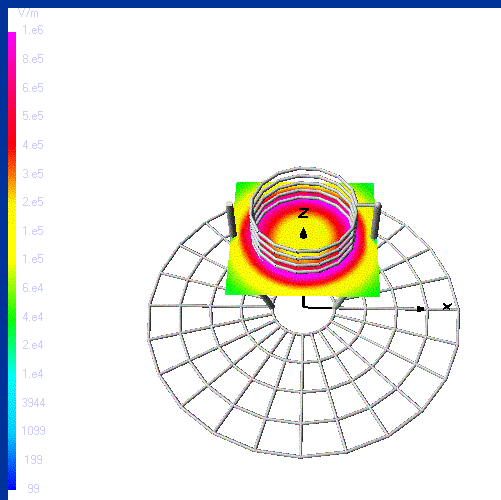
- Resulting standing wave generates EM field to drive plasma at resonance.

RF Coil Fields



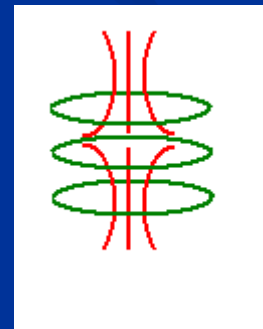
Ey RF Field

- Field tangential to B is greatest at coil center
- For electron gyro radii much smaller than coil diameter, electron sees well behaved linear field

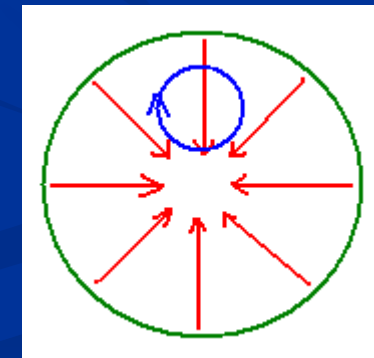


Ez RF Field

RF field vectors

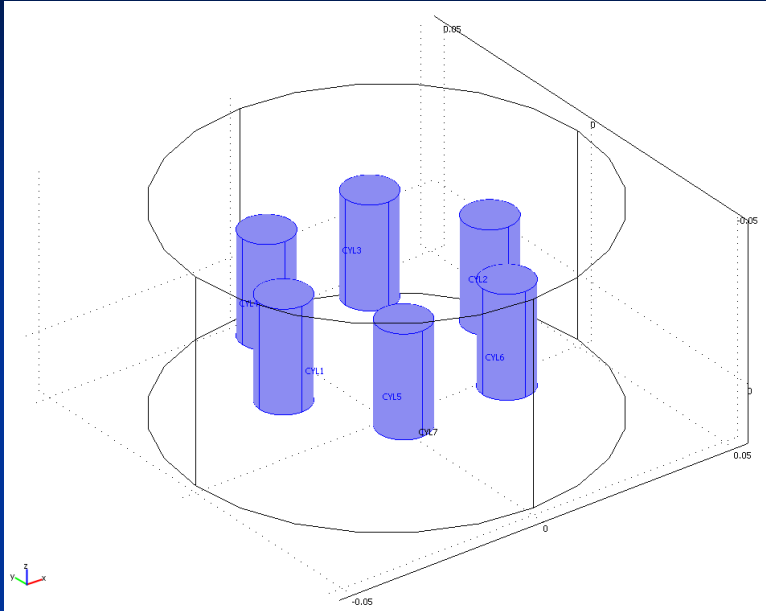


Electron Gyro radii



Magnetic Yoke

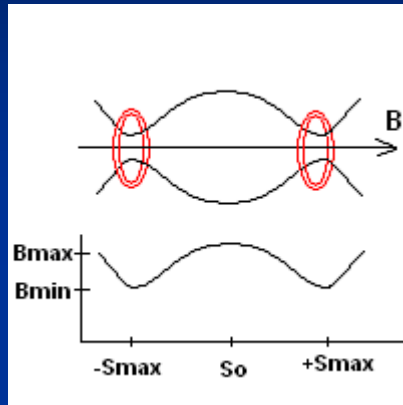
Provides Magnetic trapping of heated electrons



6 Cylindrical grade N48 rare earth magnets

- Centers positioned 27mm from injector axis
- 25.4mm length 12.7mm diameter

Simple Mirror Equation



Conservation of energy

$$\frac{1}{2} m [v_{\perp}^2(s) + v_{\parallel}^2(s)] = KE = const$$

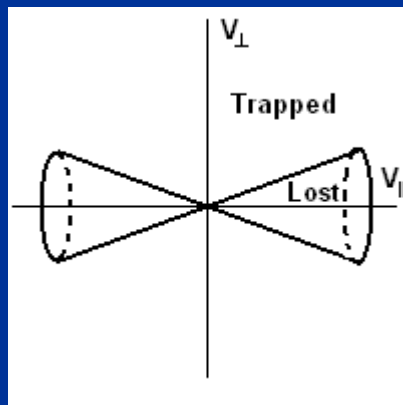
Conservation of angular momentum

$$p_{\theta} = m r_{\perp} v_{\perp} = \frac{m v_{\perp}^2(s)}{B(s)} = const$$

$$\mu \equiv \frac{1}{2} \frac{m v_{\perp}^2(s)}{B(s)} = const$$

Mirror Equation

$$\frac{1}{2} m v_{\parallel}^2(s) = KE - \mu B(s)$$



Boundary velocity

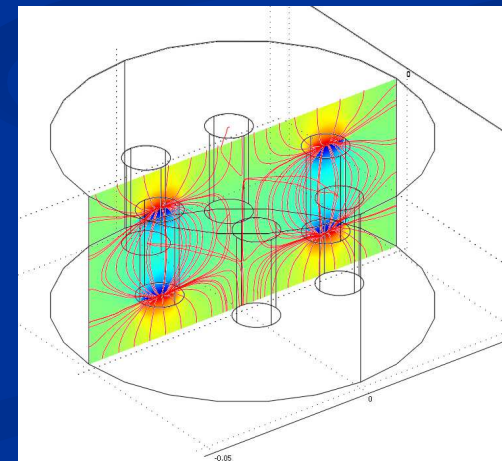
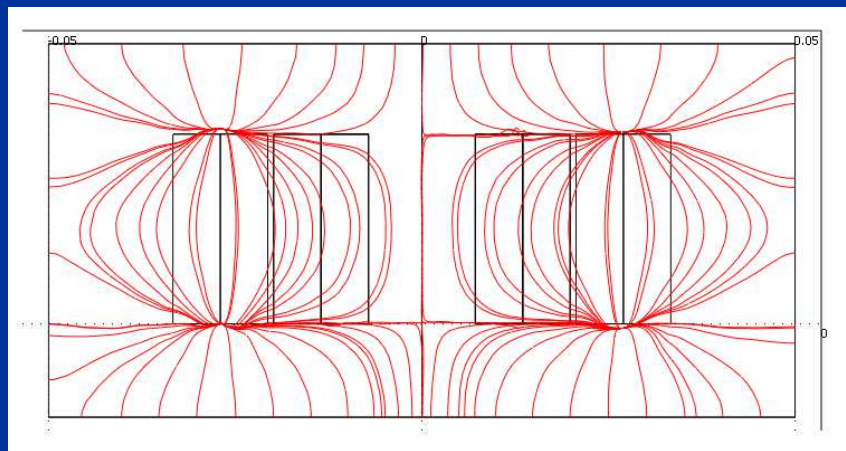
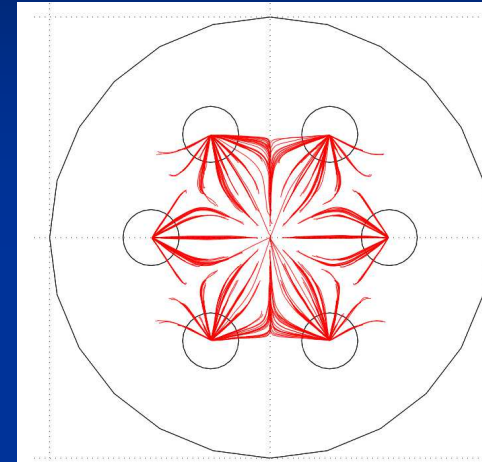
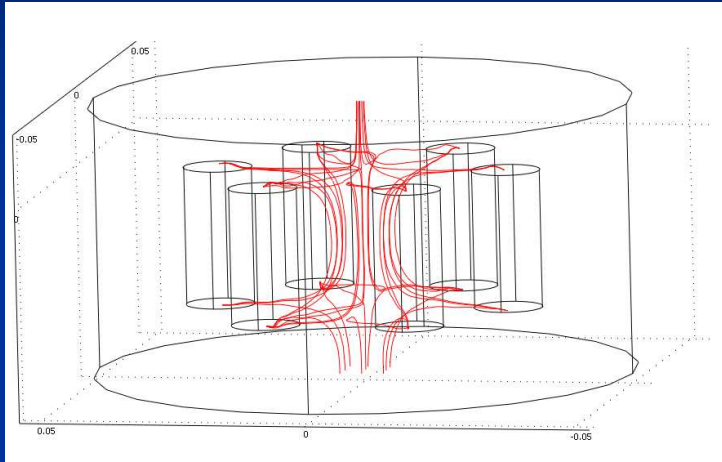
$$v_{\parallel}(s_0) = \pm \left(\frac{B_{max}}{B_{min}} - 1 \right)^{1/2} v_{\perp}(s_0)$$

Confinement time

$$\tau_p = (\tau_{p0})_{\perp} \log_{10} \left(\frac{B_{max}}{B_{min}} \right)$$

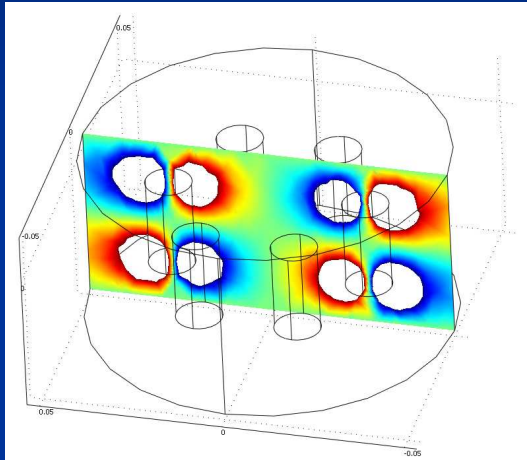
Bmax, Bmin to be measured at surface of ionization cup

Field Vectors

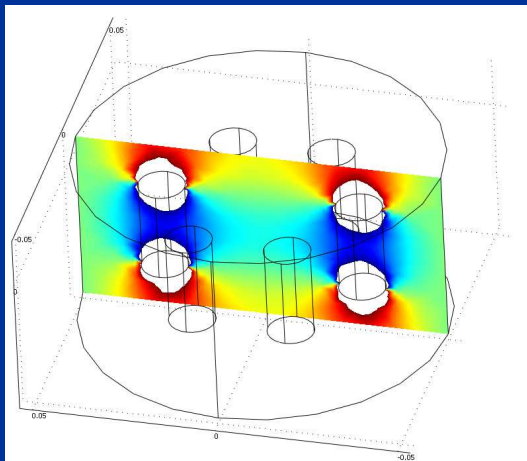


Field Magnitudes

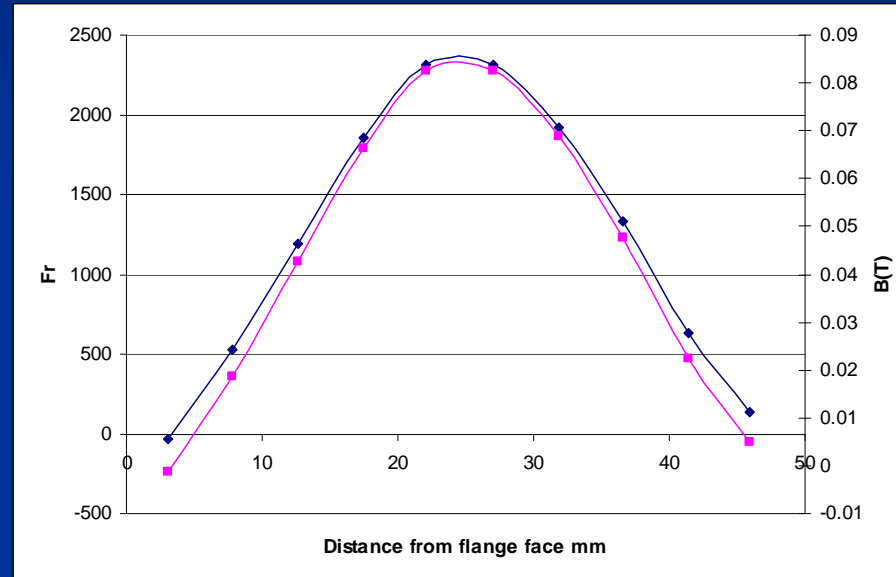
X-field



Z-field



Z-field magnitude measured on axis



- Field will be reduced to bring 900MHZ ECRF resonance to center of RF coil
- Mu-metal shielding

Extractor Field

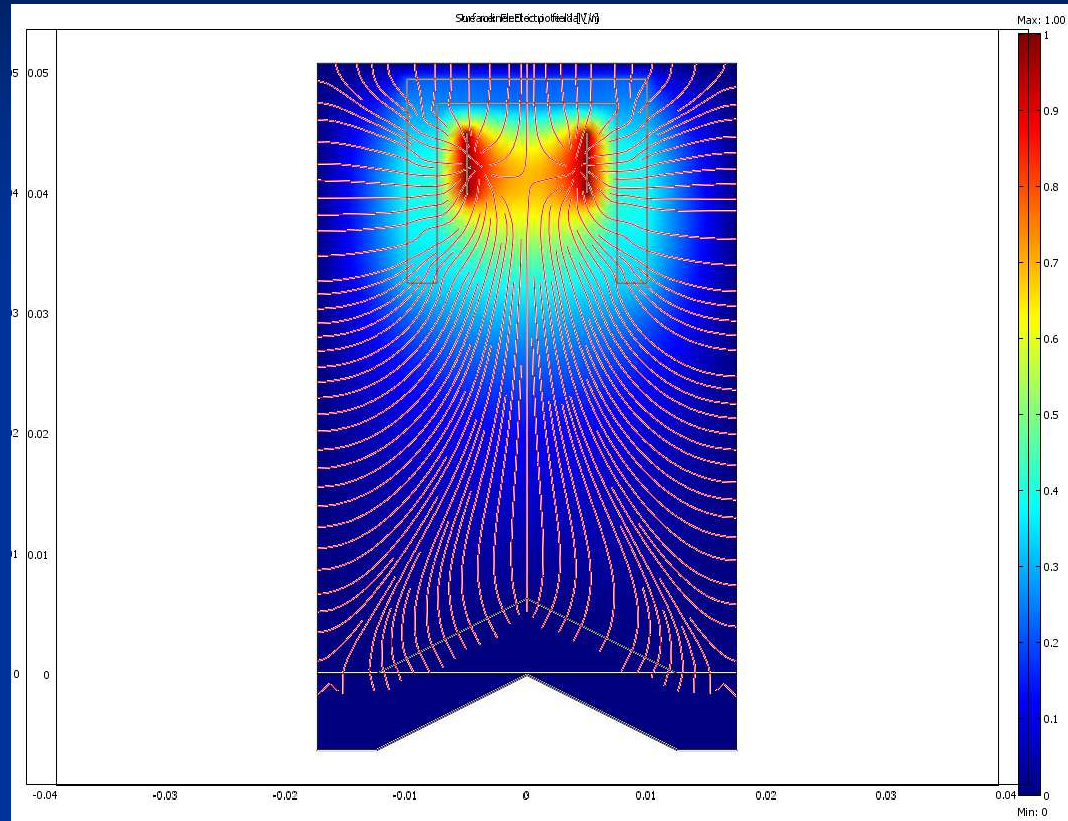


- Ionization Cup prevents current flow from biased antenna coil to sidewalls or rear of injector.
- Antenna coil bias: 0-15kV



- Extractor cone concentrates electric field on axis and assists in ion focusing.
- Extractor cone fabricated from 304L SS
- $\frac{1}{4}$ " height 1" base diameter
- 0.1" aperture

Extractor Field

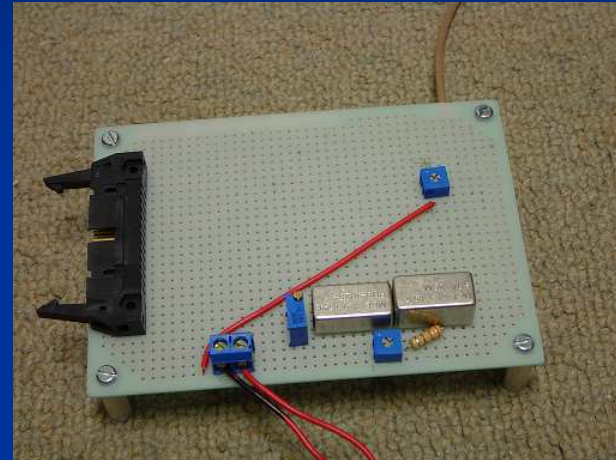


External Components

Main ECRF Amplifier 240W @900MHz



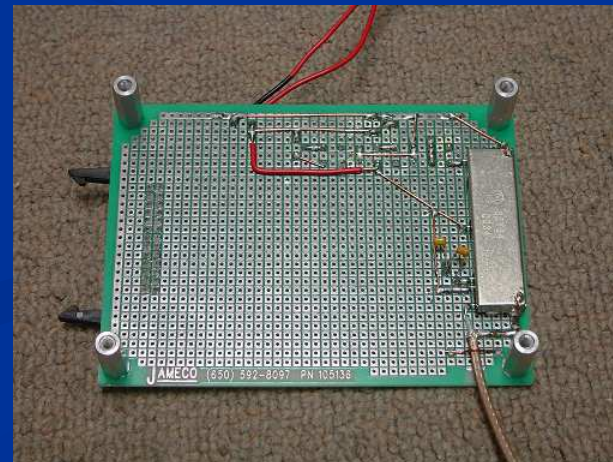
Oscillator and mixer



Bidirectional couplers /
active detectors



Preamplifier



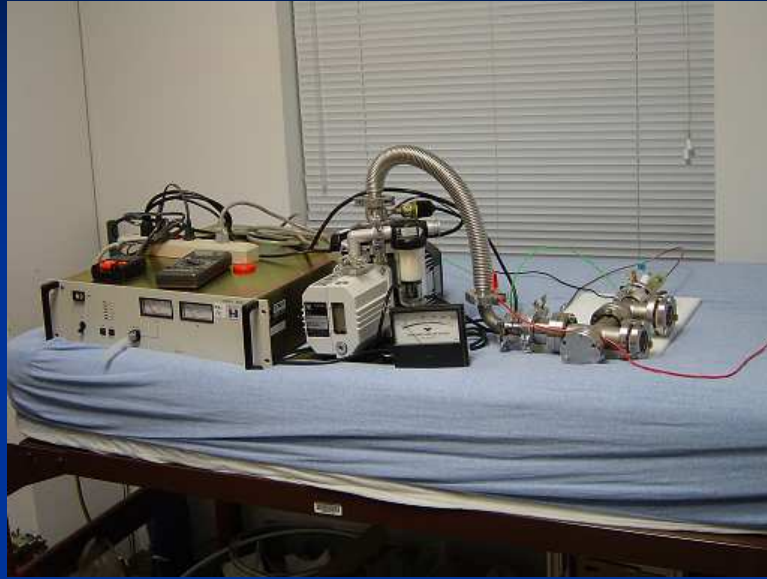
Injector Testing



Ion Injector Test bed

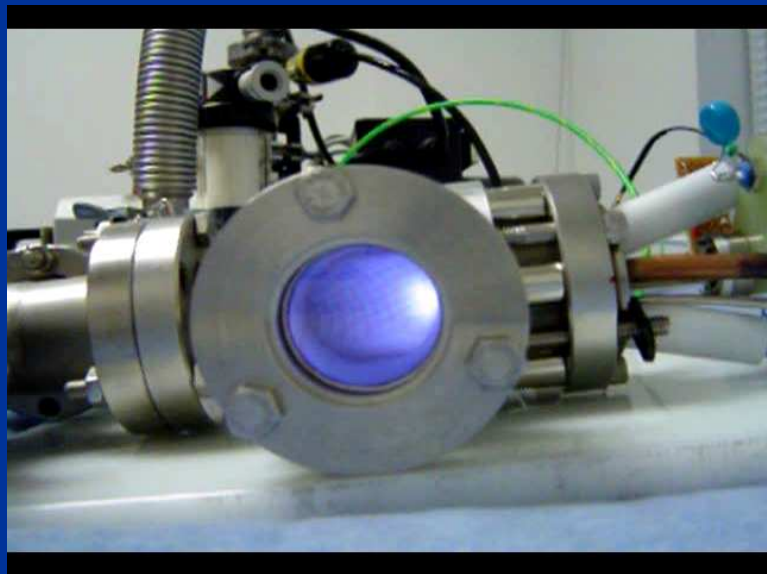
- Paschen discharge from biased standoffs
- High voltage feedthrough open air breakdown
- ICP excitation at 150MHz

Paschen discharge



Injector test bed was evacuated with a rotary vane vacuum pump.

Injector was connected to Hitek 3000 power supply: 0-35kV @ 75mA

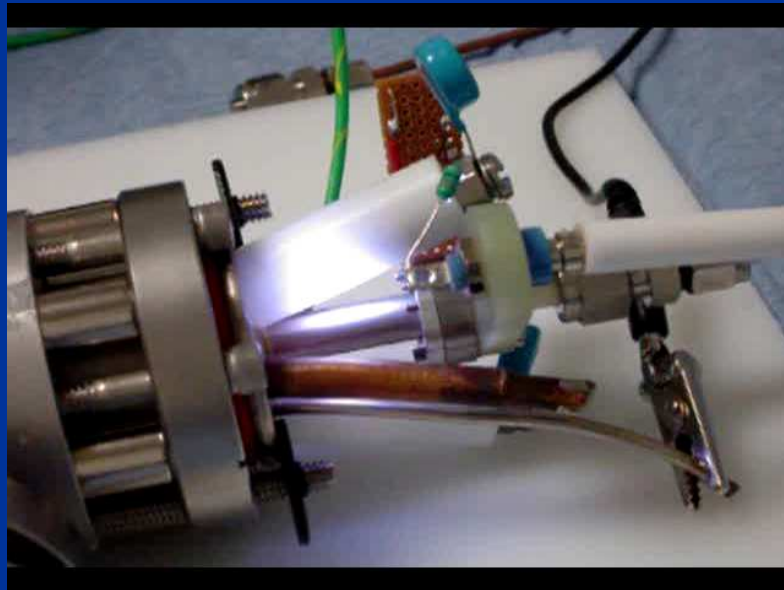


Discharge occurred at 8kV @ 30mTorr

High voltage breakdown



- High voltage feedthrough breaks down at 17kV
- Final design will be de rated to 15kV and feedthroughs will be potted in silicone.



ICP Excitation



- Matching network modified for 150MHz operation.



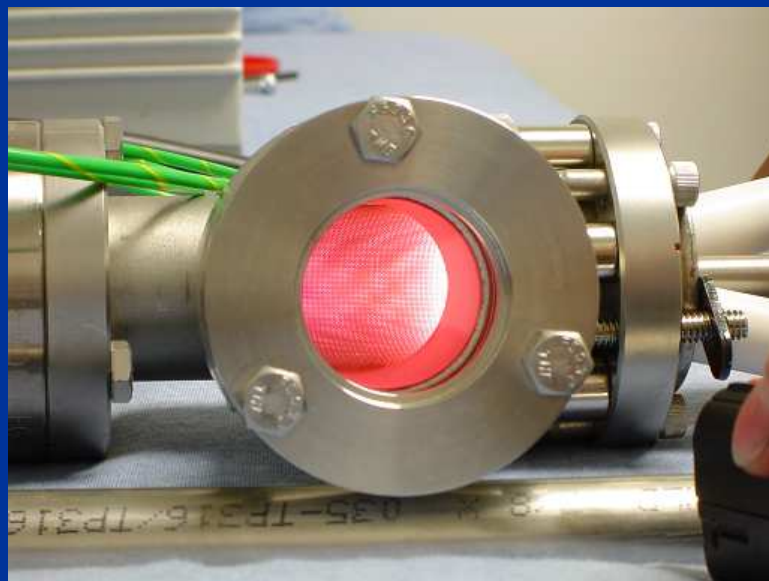
- Components
 - FT-50R transceiver
 - 150MHZ 45W RF Amplifier
 - -40dB bidirectional coupler
 - Celwave active detector 1/40 (V/W)

ICP Excitation



Successful ICP excitation at 150MHz

- 20W drive
- 5W reflected (PI match designed for 900MHz)



Future Modifications

- Switch PI low pass matching network for Pi high pass network for better protection of RF amplifier.
- Modification of magnetic field configuration for ECRF resonance at 900MHz.
- Assembly of 4.5W RF driver boards to feed main ECRF amplifier.
- Testing of extractor cone design.
- Measurement of deuterium beam current.

Questions?

