The Equilibria of Electron Plasmas in Columbia Non-neutral Torus (CNT) Stellarator: First Results

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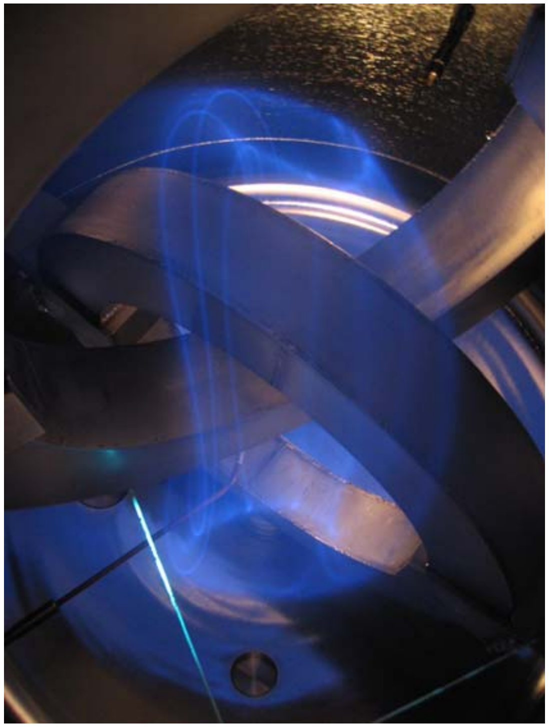
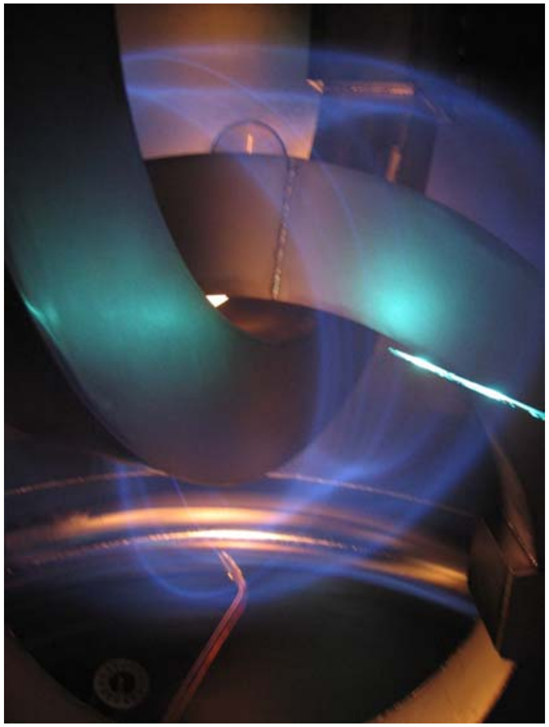


CNT



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Overview

- Introduce CNT
- Motivate the study of non-neutral plasmas in stellarators
- Outline the theory of non-neutral plasmas on magnetic surfaces

The first plasma experiments in CNT:

- What are the immediate goals?
- Describe how plasmas are made and diagnosed
- Highlight some of the results so far

The Columbia Non-neutral Torus (CNT)

- Only 4 circular, planar coils (Gourdon 1969)
  - Two internal interlocking (IL) coils inside vacuum chamber
  - Two poloidal field (PF) coils
- Simplest and lowest (<1.9) aspect ratio stellarator ever built.
- **The design is not *optimized* like a modern stellarator.**
  - **Will large electric fields improve confinement?**

B ~ 0.01-0.3 T
P ≥ 2×10^{-10} Torr
Aspect Ratio ~ 1.9
Volume ~ 0.2 m^3
ι = 0.13 – 0.21
<a> = 0.15 m
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Why study non-neutral plasmas in a stellarator?

- Non-neutral plasmas behave differently than quasi-neutral ones do: $e\phi >> T \rightarrow$ electric field effects dominate.
  - The resulting ExB flow may close bad particle orbits.
    - Confinement time may improve from < 1 ms to minutes.
  - The expected shear in the ExB flow may suppress turbulent transport.

- Physics is fundamentally different from previously studied non-neutral plasma traps (Penning and pure toroidal).
  - Equilibria, stability, and transport are all different (and relatively unstudied).

- May allow systematic studies of ‘exotic’ plasmas (partly neutralized and electron-positron plasmas)
  - A stellarator confines plasma of arbitrary neutralization at arbitrarily low density.

Electron Plasma Equilibrium on Magnetic Surfaces

Low density: $n_e << n_B \equiv \frac{1}{2} \varepsilon_o B^2 / m_e$

Rapid thermalization along **B**: $T_e = T_e(\psi)$

The density: $n_e = N(\psi)\exp\left(\frac{e\phi}{T_e(\psi)}\right)$

$$\nabla^2 \phi = \frac{e}{\varepsilon_0} N(\psi)\exp\left(\frac{e\phi}{T_e(\psi)}\right)$$

Pedersen, Boozer PRL 2002

- A 3-D code has been developed to study this equation. (Lefrancois PoP 2005)
- Equilibria described are stable to "reasonable" perturbations – Long confinement times (seconds, minutes?) are expected. (Boozer PoP 2004)
- Nonlinear in ϕ.
- Characterized by ϕ, n_e, and T_e

Electron Plasma Experiments in CNT

The Goals of the First Experiments in CNT

$$\lambda_D^2 = \frac{\varepsilon_0 T_e}{e n_e}$$

- **Learn to make small Debye length plasmas**
  - Plasma definition: $\lambda_D / a << 1$
  - The regime we want to study: $\frac{e\phi}{T_e} \sim \left(\frac{a}{\lambda_D}\right)^2$
  - Confinement time: $\tau_c \sim \left(\frac{a}{\lambda_D}\right)^4 \tau_e$

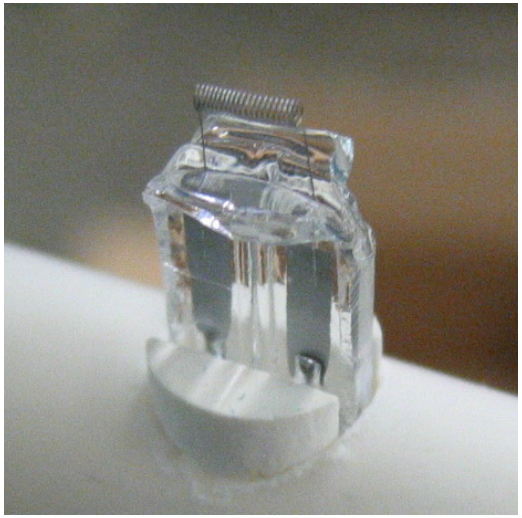
(Pedersen, Boozer PRL 2002)

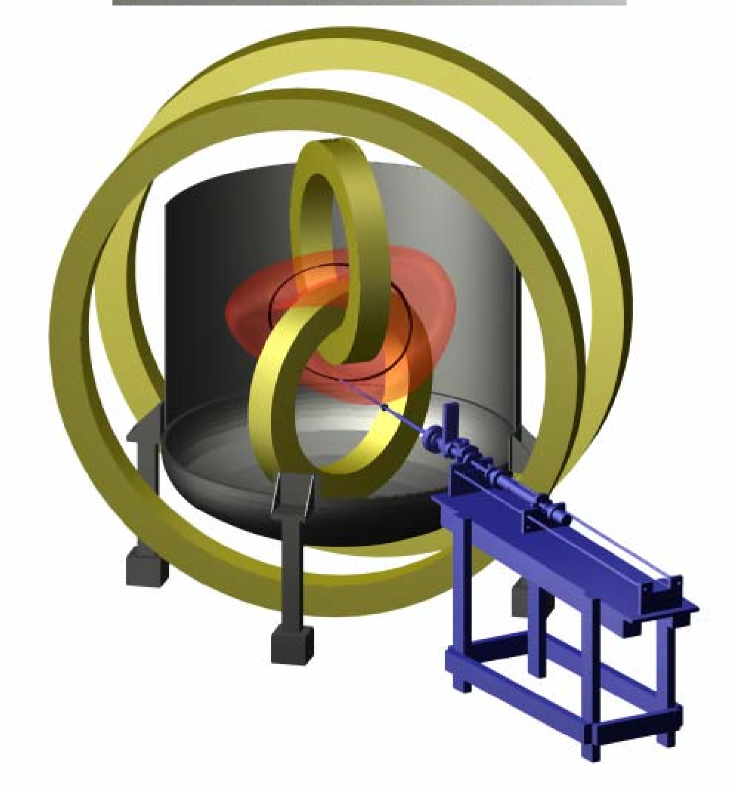
- **Learn to measure plasma potential, temperature and density**
  - Probe theory in non-neutral plasmas has not been well studied.
  - Plasma densities, temperatures and cross field transport are low.

- **Begin to characterize equilibrium**
  - How do confinement time, density, and temperature scale with experimental parameters (B, p_n, emitter bias, etc.)
  - How well do the 3D equilibrium predictions match with experimental results?

$$\nabla^2 \phi = \frac{e}{\varepsilon_0} N(\psi) \exp\left(\frac{e\phi}{T_e(\psi)}\right)$$?

The Electron Source





- Electrons are emitted from a heated, negatively biased tungsten filament placed in the confining region.
  - Electrons quickly fill up surface that the emitter sits on (~μs).
  - Other surfaces are populated by cross field transport (~ms).
  - Confining region fills up → emission is space charge limited.
  - **Steady state**
    - Emission current = loss rate
    - Our first diagnostic
- The emitter is mounted near the end of a long alumina-oxide rod; the rod is inserted such that the emitter is placed near the magnetic axis.

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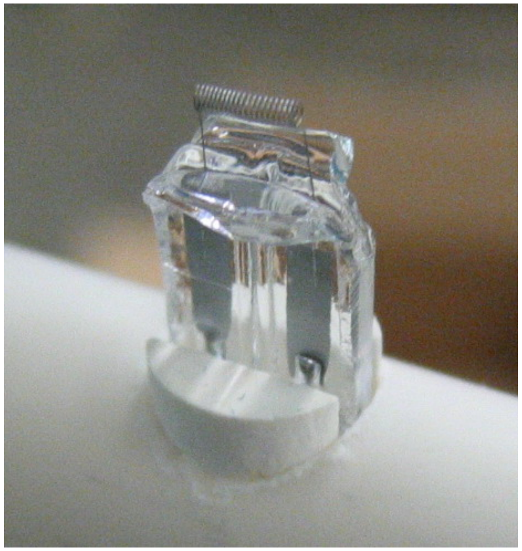

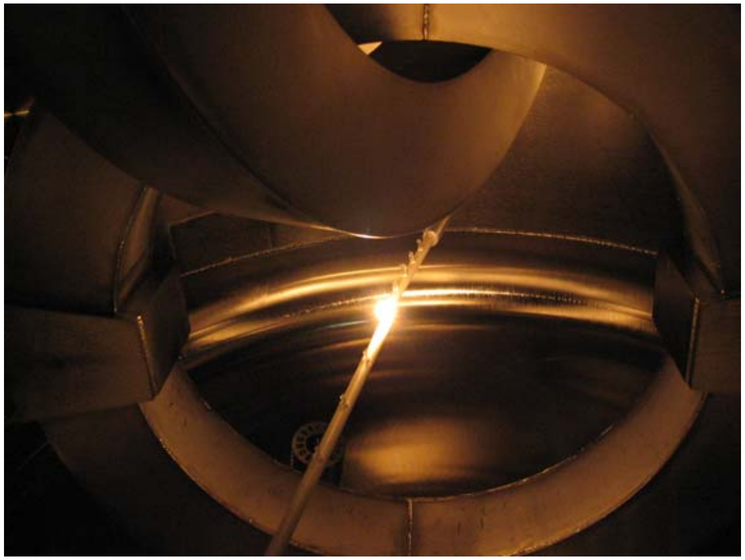

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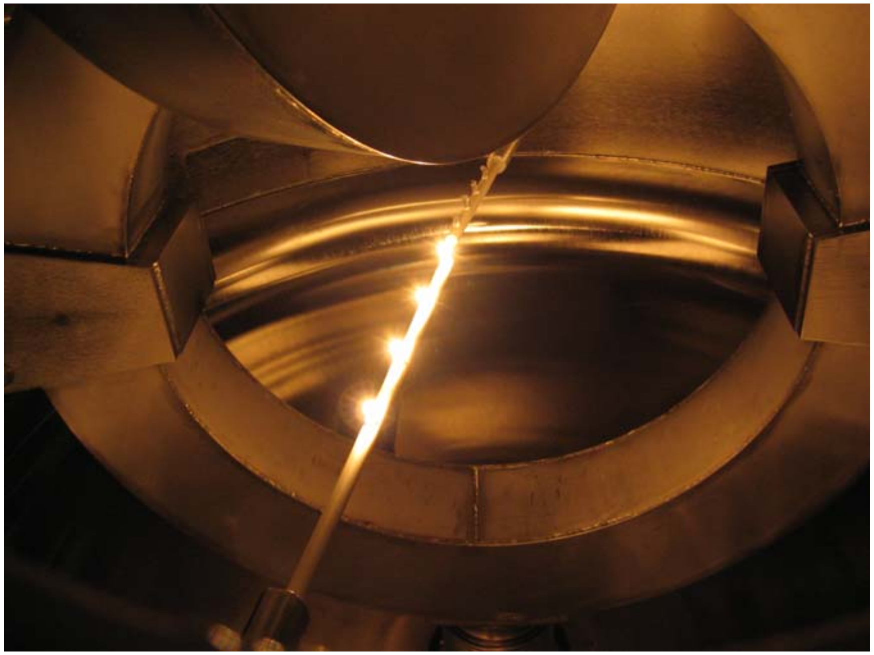
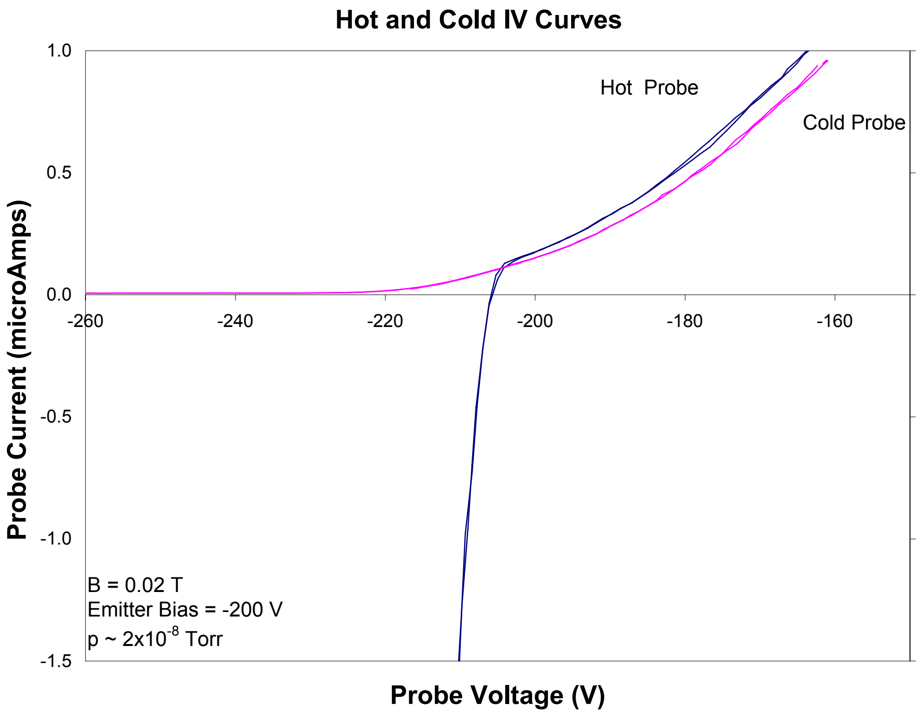
The Probes



- Same type of filament as emitter
  - A cold filament is a Langmuir probe (can only collect).
  - A hot filament is a emitting probe (can emit and collect).
  - Use these probes to measure ϕ, n, T.

- Three emitting probes are on alumina rod with the emitter; an additional eight are on a separate rod.
  - These are inserted radially into plasma so that radial profiles can be measured.

Using the Probes



The local plasma potential --

- The 'deviation potential' is where the cold and hot IV curves deviate.
  - This is the potential at which a hot filament starts emitting = ϕ_{plasma}.
  - The measurement error is from the finite filament heating voltage.

Local density and temperature—

- Measure the current-voltage characteristic of a cold filament (Langmuir)
- Electrons in a Boltzman distribution:

$$I(V_{probe}) = I_0(n_\infty, \sqrt{T_e})e^{\frac{e(V_{probe}-V_{plasma})}{T_e}}$$

- Temperature and density are found by fitting the exponential region of the resulting characteristic.

Some Results:

Total Electron Inventory and Density

Total electron inventory from the radial potential drop across the plasma:

$$\nabla^2\Phi = \frac{e}{\varepsilon_0} n \longrightarrow N \approx \frac{8\pi^2 \varepsilon_0 R(\nabla\Phi)}{e}$$

For a -150V emitter bias at B=0.05 T, $\nabla\Phi \approx 80$ V $\longrightarrow$ N ≈ 10^{11} electrons

$\longrightarrow$ $n_e = N / V \approx 10^{12}\ m^{-3}$

Local density measurements:

$n_e \approx 10^{12}\ m^{-3}$

The CNT 3D equilibrium code predicts (from measured ϕ and T_e) :

$n_e \approx 10^{12}\ m^{-3}$

∴ All three methods give the same estimate n_e.

Temperature and Debye Length

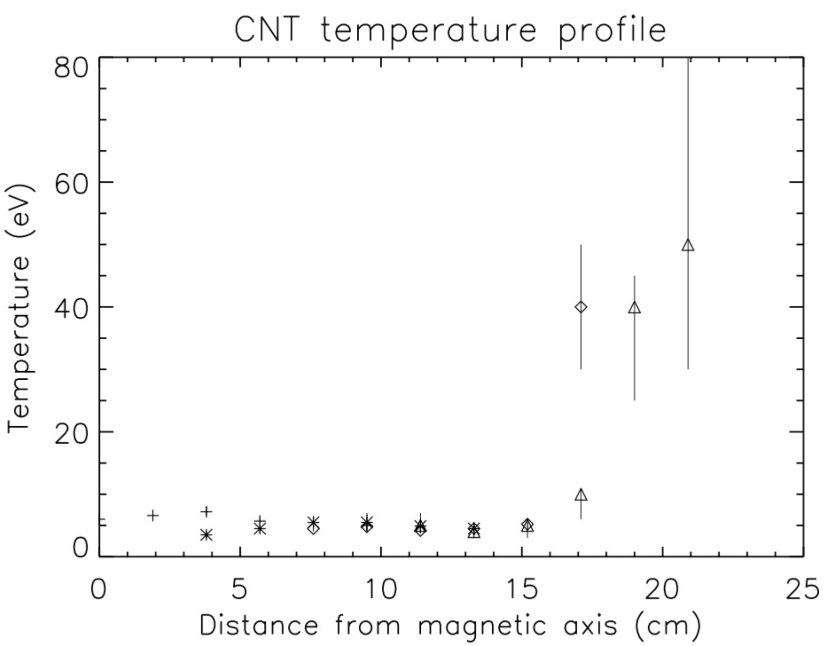
For –200 V emitter bias, B = 0.02 T and P_n = 5x10^{-9} Torr:

- Measured T_e as 3~6 eV
- The T_e profile was flat through most of the confining region.
- Using $n_e \sim 10^{12} m^{-3}$:

$\rightarrow \lambda_D \sim 2$ cm

$\therefore \lambda_D/a << 1$:

We have a plasma!



Emitter bias optimization:

- n_e has linear dependence on emitter bias.
- T_e seems to have minimum.

$\rightarrow$ Optimized emitter bias seems to be around -100V.

- What sets T_e?

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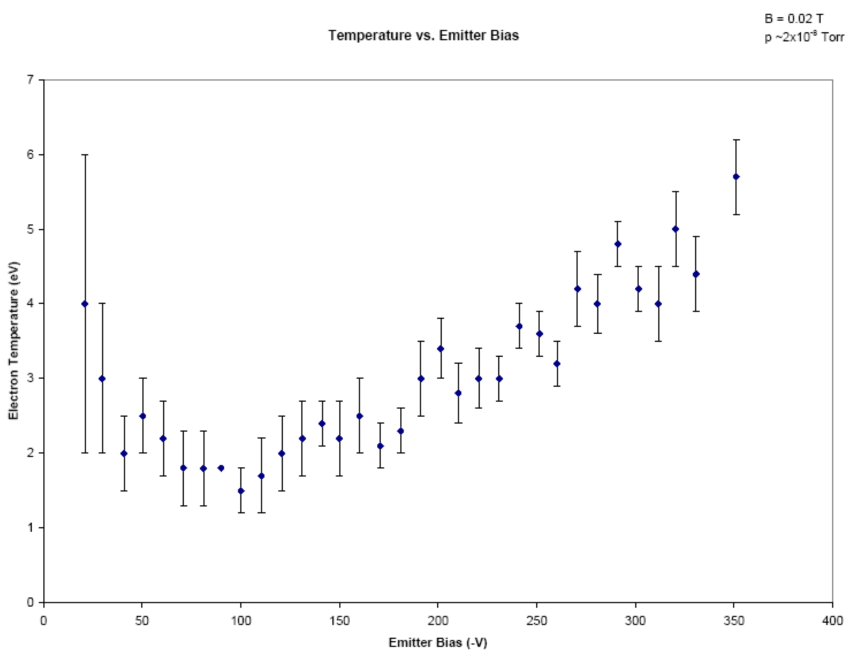

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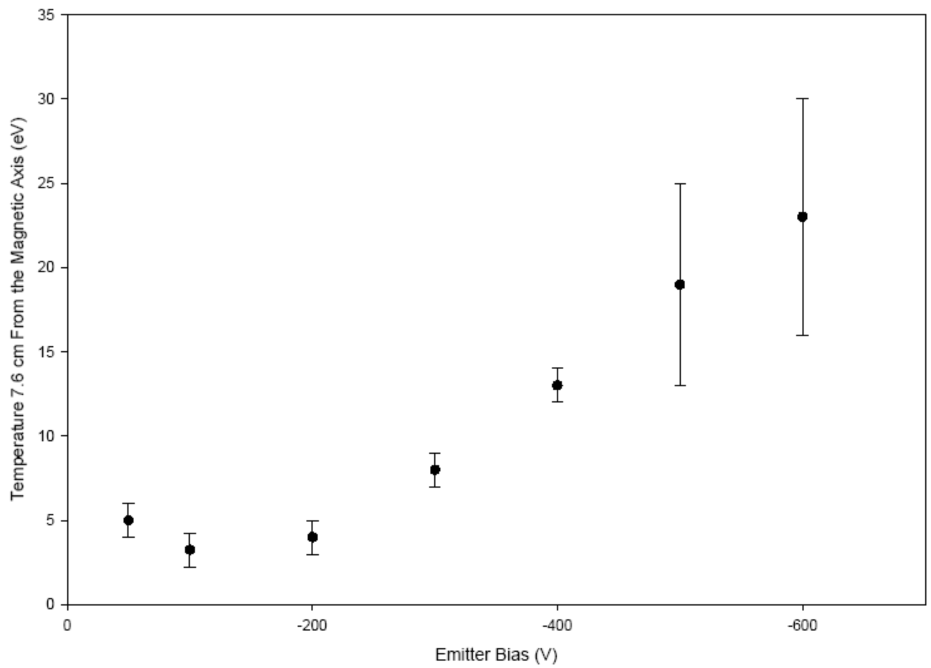

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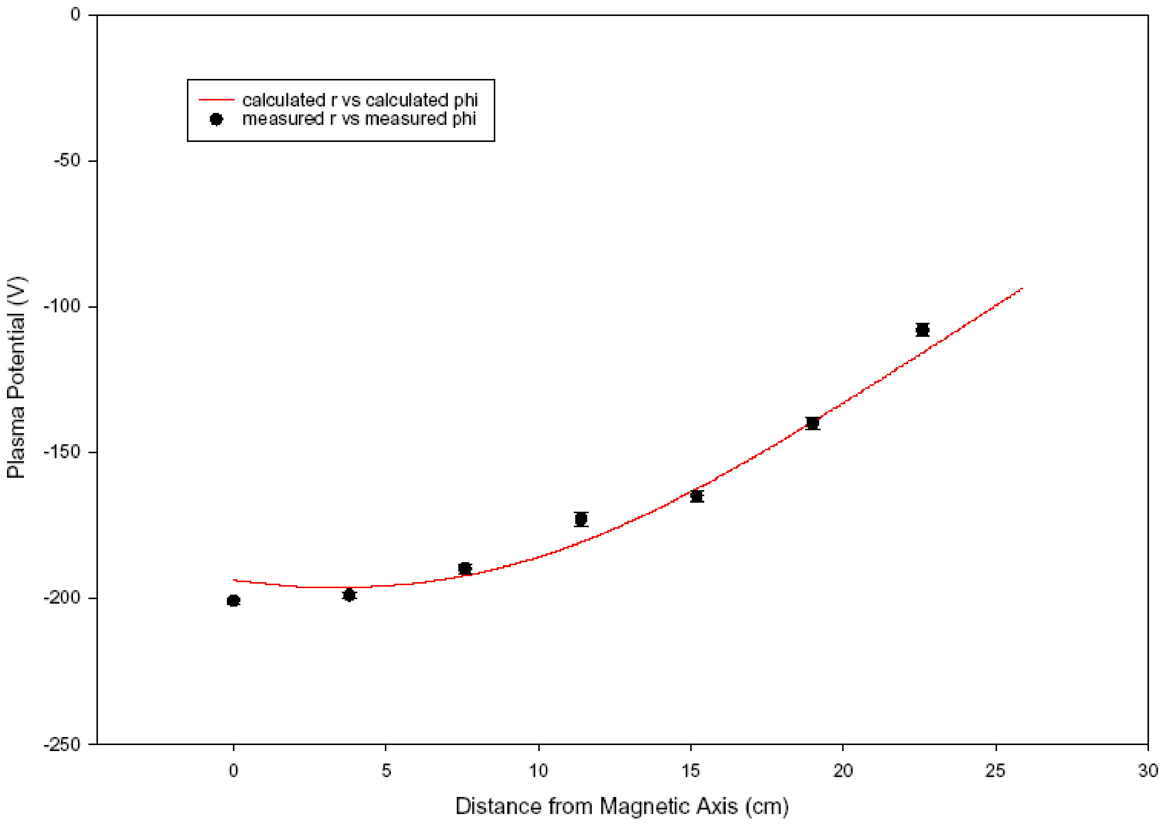
A Profile Measurement

- The 3-D equilibrium code was used to perform a fit on the potential profile.
  - Use measured temperature (flat profile at 5 eV).
  - Assume parabolic N(Ψ) profile.
  - Adjust N until best fit with measured potential profile.



This is consistent with:

$$\nabla^2 \phi = \frac{e}{\varepsilon_0} N(\psi) \exp\left(\frac{e\phi}{T_e(\psi)}\right)$$

Measurements are ongoing…

Electron Confinement Time

Measurement of the confinement time, τ_c:

- The source rate of electrons emitted from the filament is S = I/e.
- The loss rate of electrons from the confining region is L = N/τ_c.
- In steady-state, S = L.
  - τ_c = eN/I

We have measured τ_c ~ 20 ms.

A comparison of τ_c to other relevant time scales:

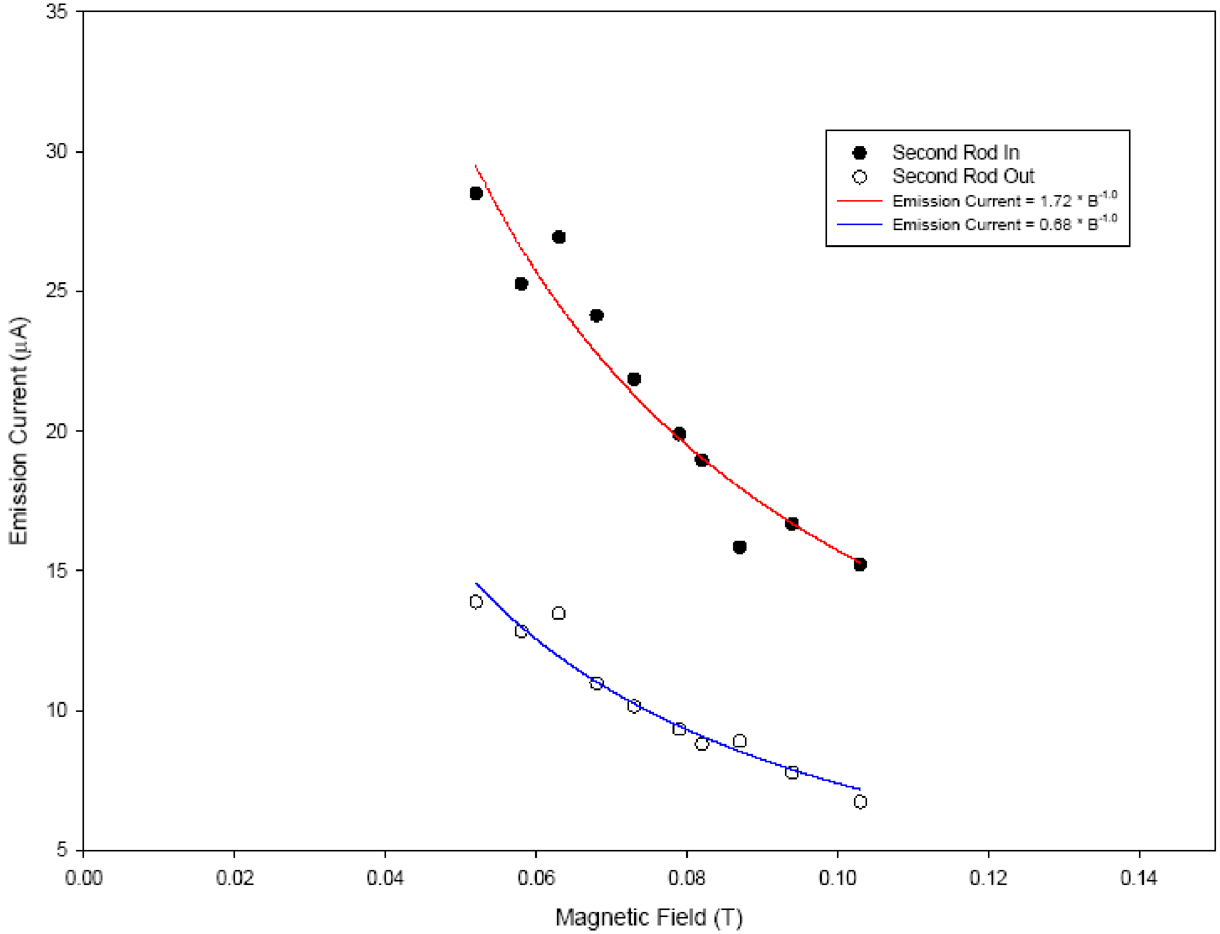
- Parallel force balance ~ 10 μs
- Time for an electron to escape at ExB velocity ~ 20 μs
- Time for an electron to ∇B drift out ~ 300 μs

$\therefore$Macroscopically stable equilibrium has been observed but…

- Expected confinement time scaling: $(a/\lambda_D)^4\,\tau_e$ ~ 600 s

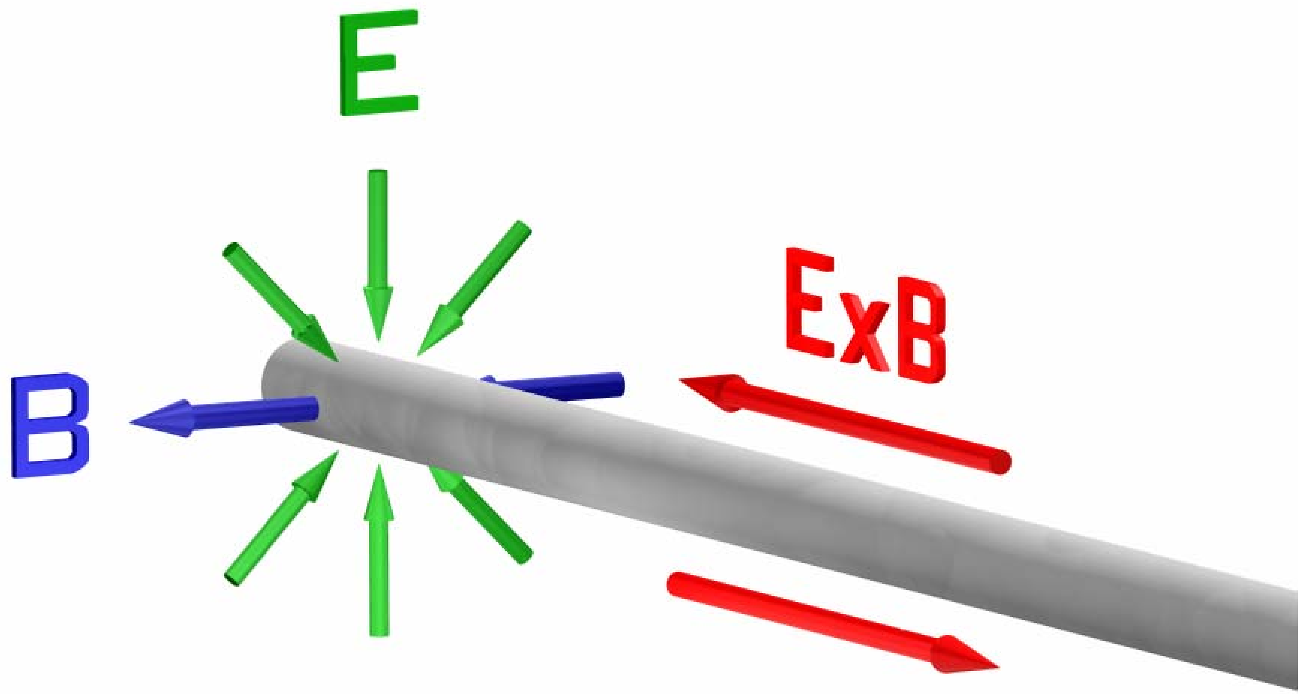
…confinement times are not as long as expected.

Measurement of Effect of Rods on Confinement



- Shorter confinement time (higher emission current) with the extra rod in.
- Emission scales as 1/B ($V_{ExB} \sim E/B$)
  - (Bohm scaling?).
- A retracting emitter is now under construction...

Bulk ExB Flows Along Rod?



- The insulating rod is a significant drive for radial particle transport.
  - The rod charges up negatively (electric field radial from rod).
  - The resulting local electric field crossed with the magnetic field drives inward and outward flows.
  - The net flow is outward.

Summary

- CNT is a university scale experiment designed to non-neutral and partially neutralized plasmas on magnetic surfaces.
  - The first CNT experiments are with pure electron plasmas.
- $\lambda_D/a << 1$ has been achieved.
- Profile measurements are consistent with theoretical equilibrium predictions.
- ~20 ms confinement times have been measured.
  - Confinement time is presently limited by rods.
- Future experiments will utilize less perturbative emitters and diagnostics.