The Columbia Non-neutral Torus: Status, Plans, and Opportunities for Theory Research

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With

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CNT

Columbia University
In the City of New York

CNT is a simple and compact stellarator

Magnetic surfaces are created from only four circular coils[1,2]

<R>=0.28 m, <a>=0.15 m

Ultrahigh vacuum

B=0.3 T for 15 s

Steady state at B≤0.06 T

1 Gourdon et al., Plas. Phys. Contrl. Nucl. Fus. Research p. 849 (1969)
2 Pedersen et al., Fusion Sci. Tech. 46 p 200 (2004)

Some of the questions we address in CNT

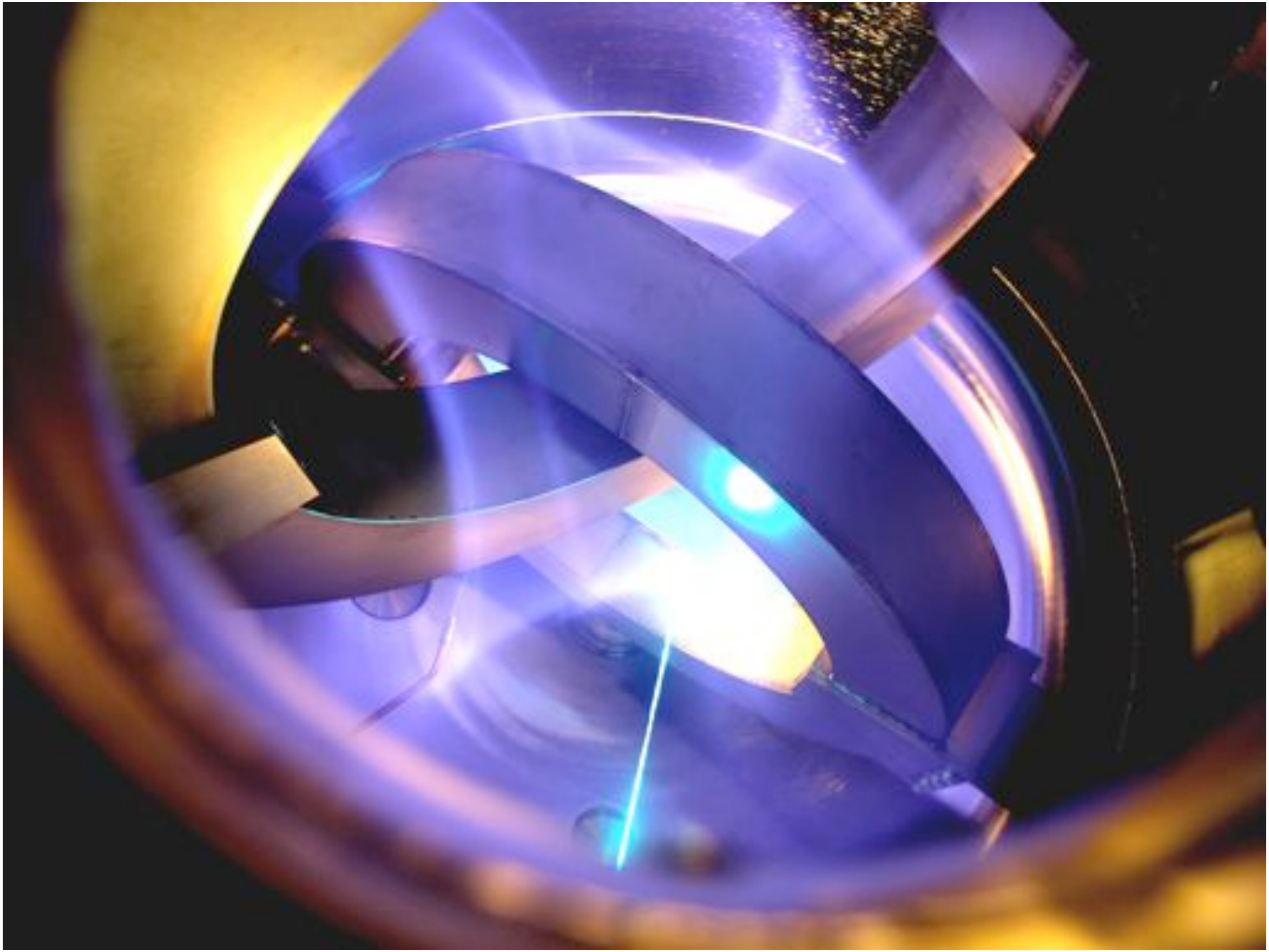
- Does a pure electron plasma have a stable equilibrium in a stellarator? (Theory: Yes[a,b]) What is the equilibrium like? [c]
- What are the principal transport mechanisms?
- Can confinement be excellent?
  - Neoclassical transport predicts excellent confinement in a non-neutral stellarator:
  - $\tau \sim 1/\upsilon\ (e\phi/T)^2$
  - Small Debye length pure electron plasma has $(e\phi/T)^2 \approx (a/\lambda_D)^4 >> 1$
  - So extremely long confinement is predicted, minutes or hours
- What are the properties of partially neutralized plasmas? (These can be created in a stellarator)
- Can electron-positron plasmas be created in a non-neutral stellarator[d]?

a Pedersen and Boozer, PRL 88, 205002 (2002)
b Boozer, Phys. Plasmas 11, p. 4709 (2004)
c Lefrancois et al, Phys. Plasmas 12, p. (2005)
d Pedersen et al., J. Phys. B 36, p. 1039 (2003)

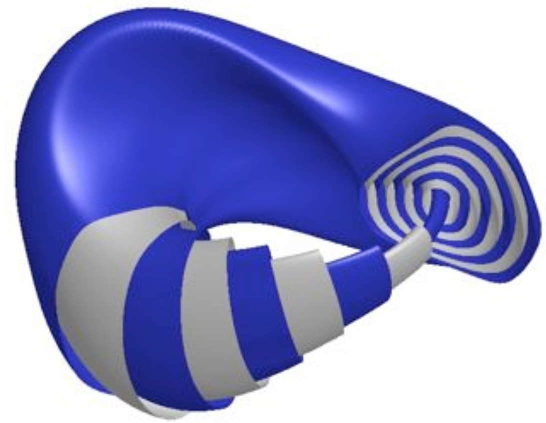
CNT fully operational since Nov 12 2004

CNT’s magnetic topology

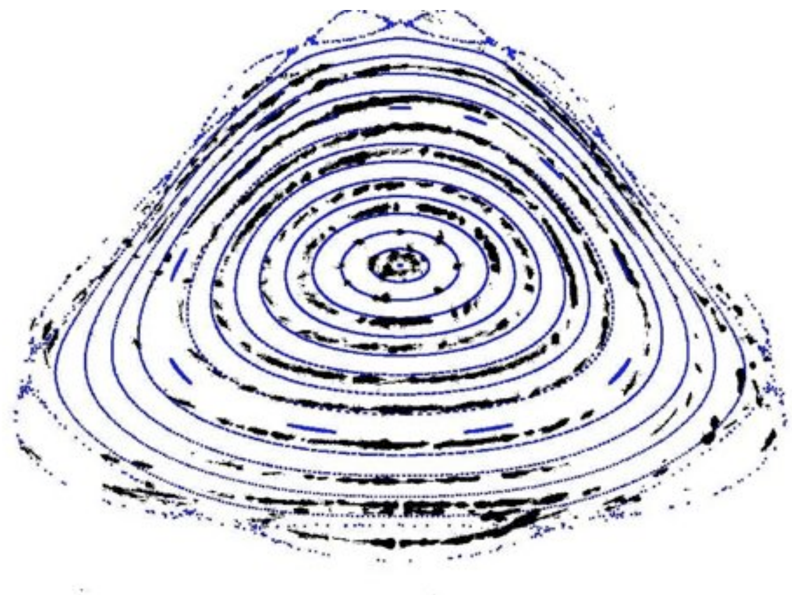
Two-period, ultralow aspect ratio (A<1.9) stellarator



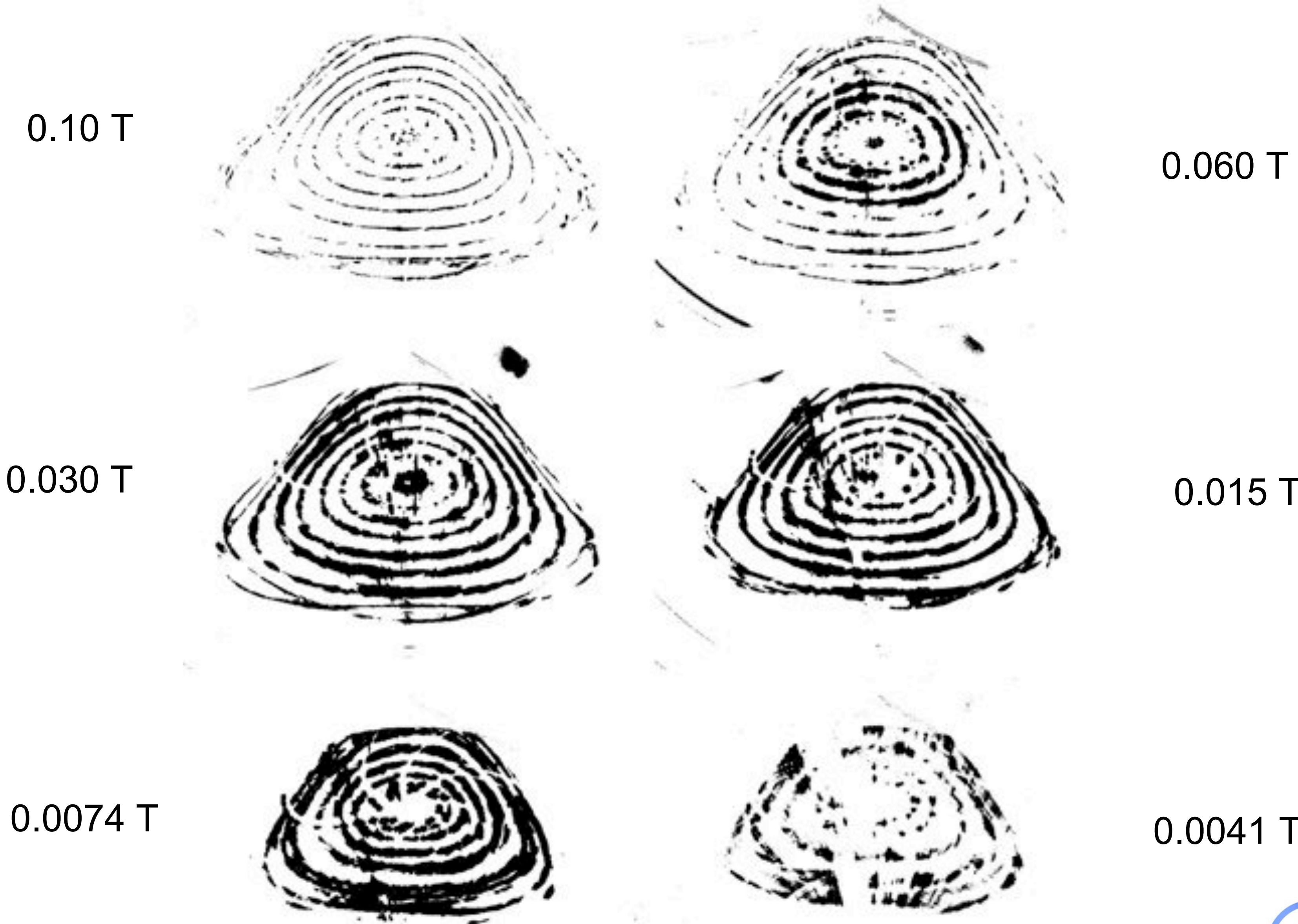
Field line mapping



Field line mapping - quantitative measurements

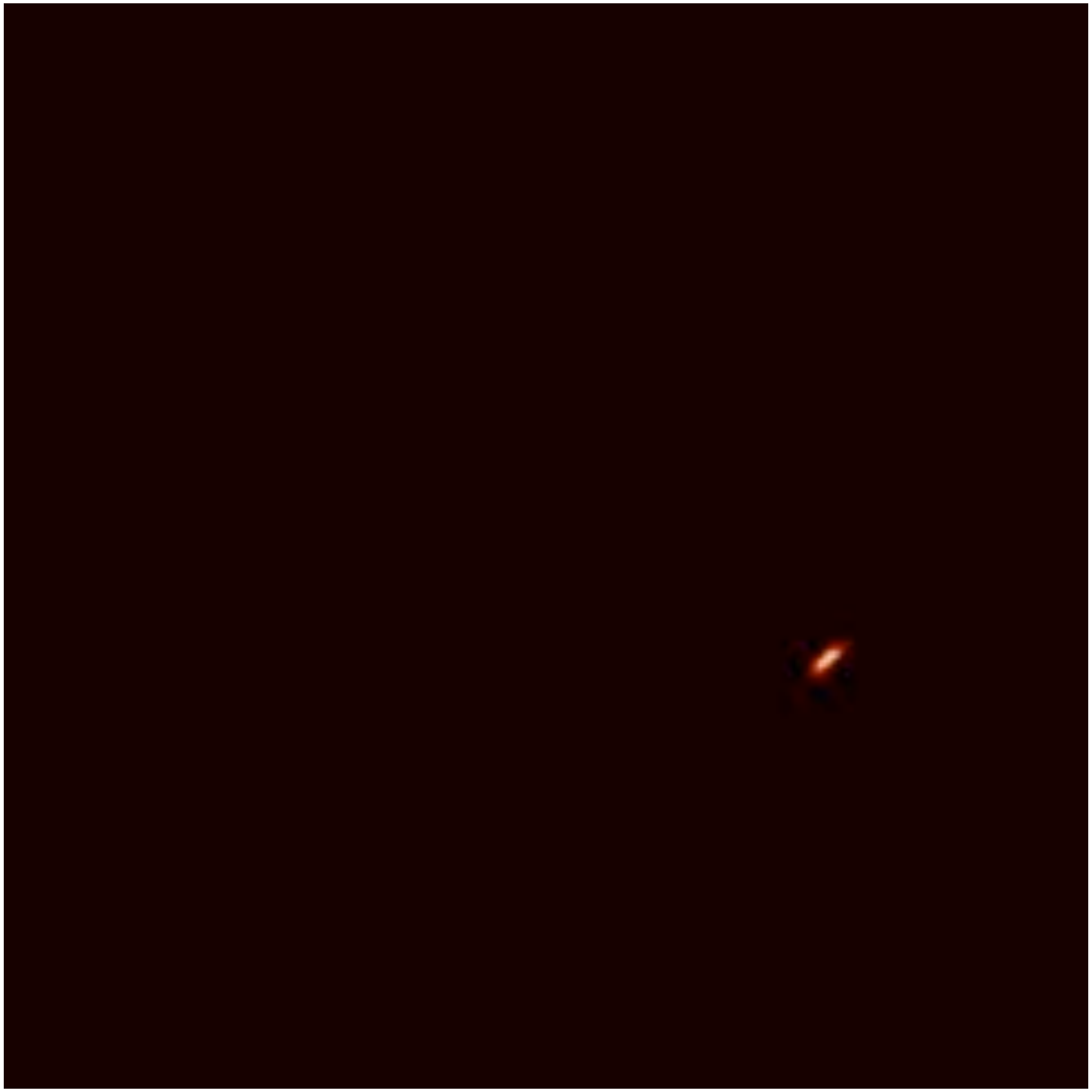


Excellent quality nested magnetic surfaces even at low B



Pedersen et al., Phys. Plasmas **13**, p. 012502 (2006)

Present scheme for creation of pure electron plasmas



Electron source:
Thermionic emission from heated tungsten filament

Placed on magnetic axis

Biased negatively

No anode (unlike e-gun)

Parallel transport fills field line on axis in ~ 1 μs

Perpendicular transport fills the rest of the surfaces

Reach steady state between emission and radial losses

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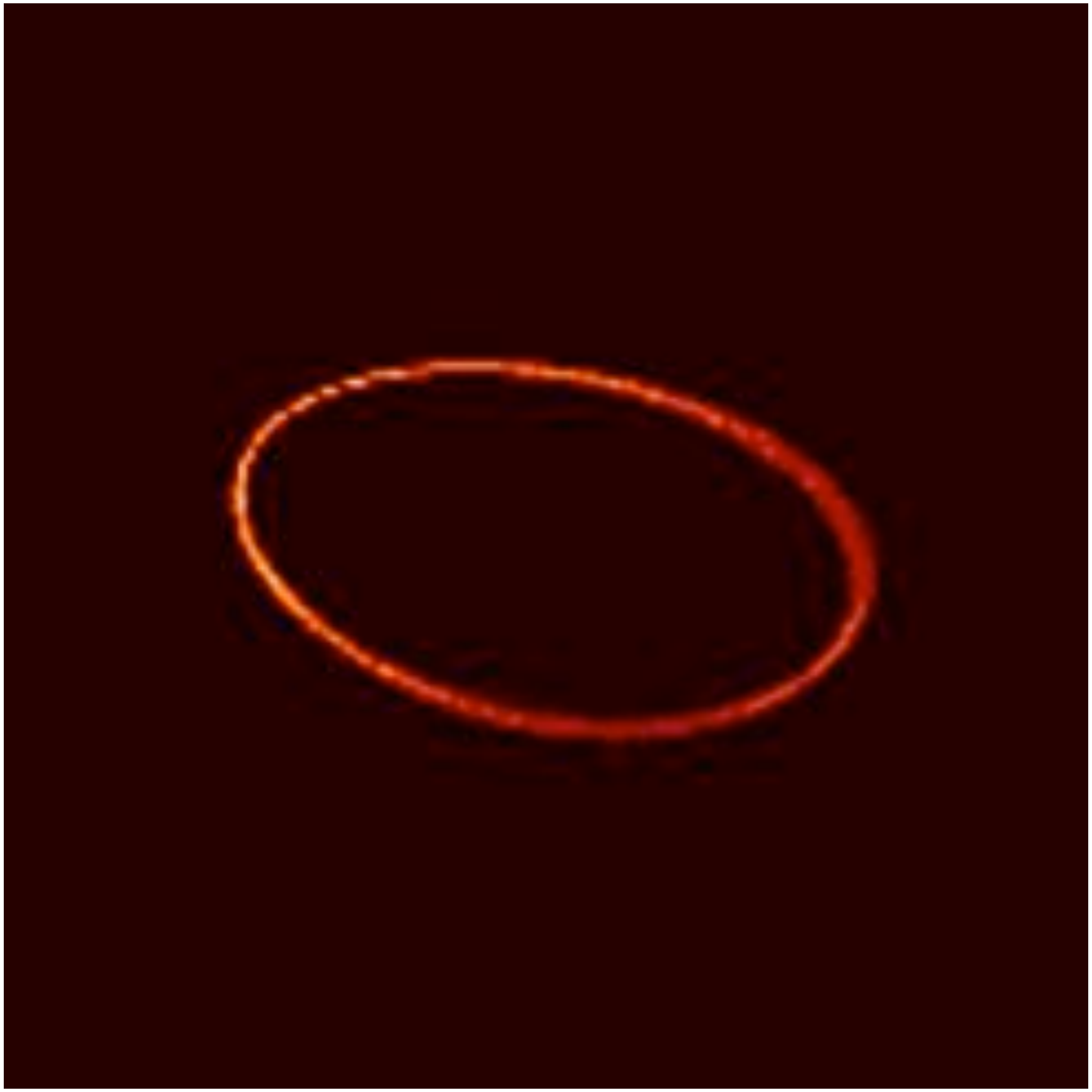

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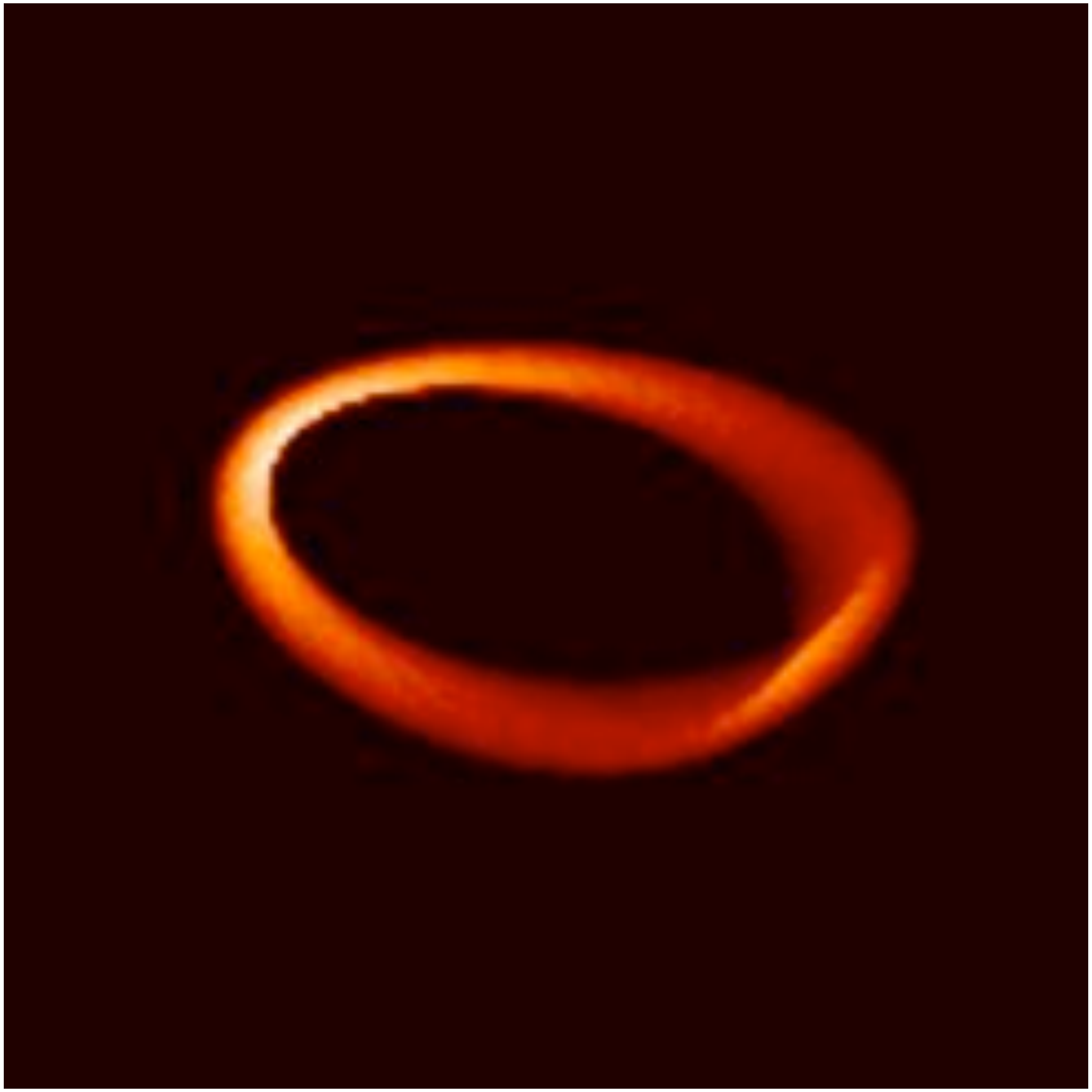

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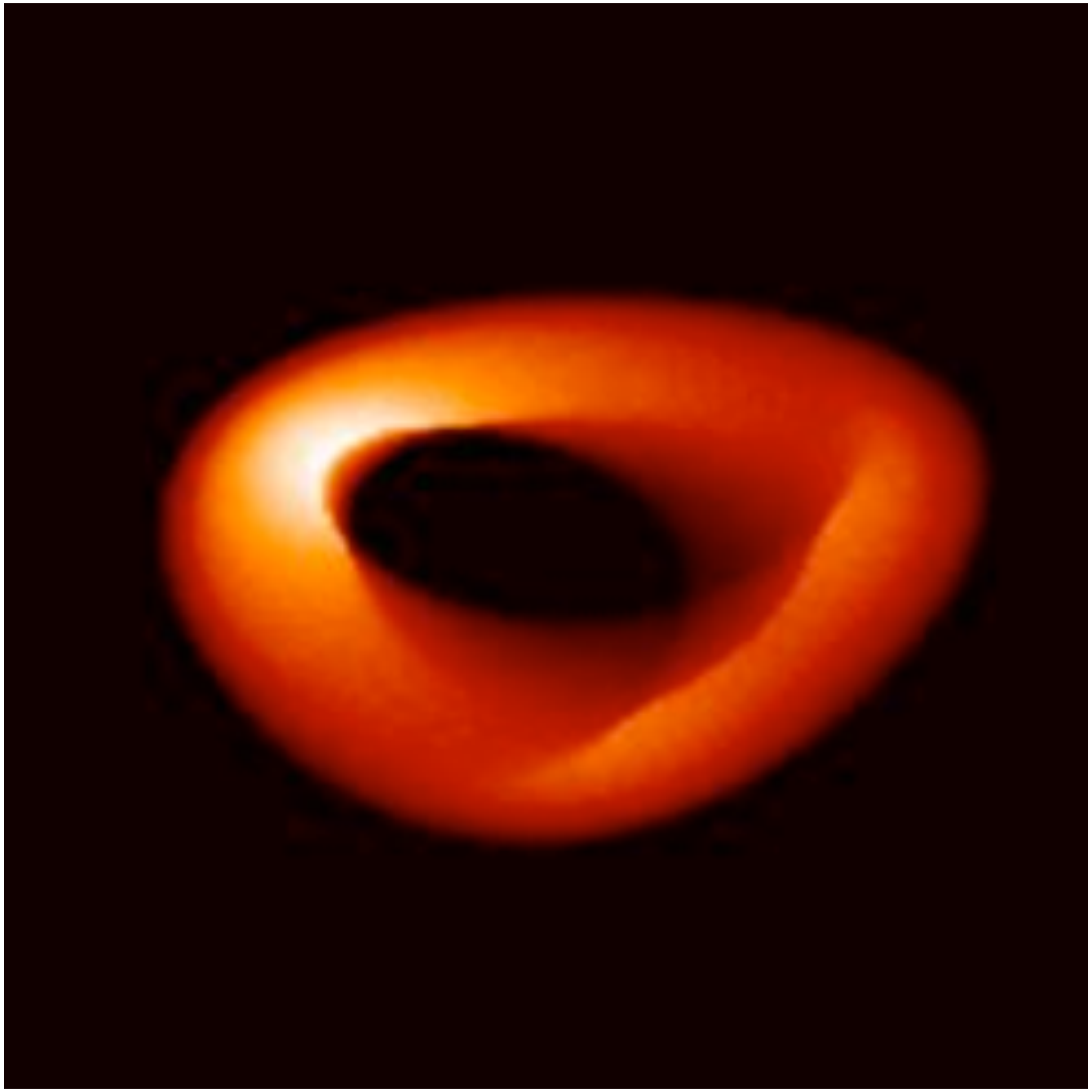

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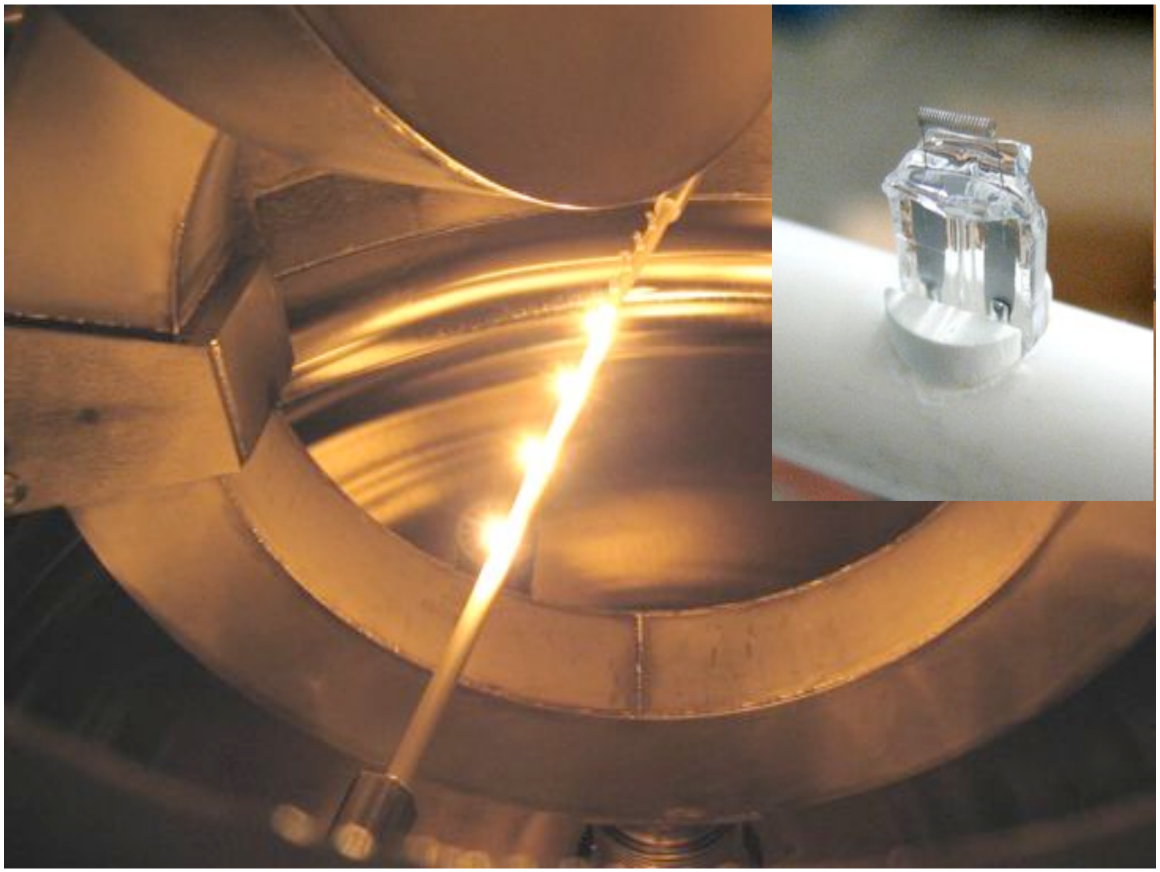
Emitting filaments serve multiple functions



2 ceramic rods with arrays of filaments

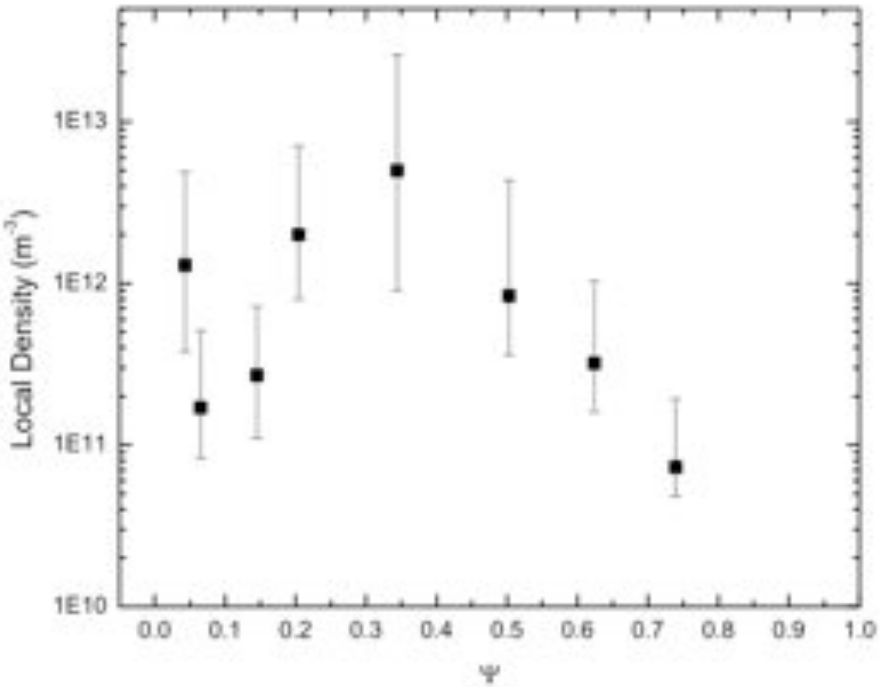
Filaments are halogen light bulbs (without the glass!)[2]

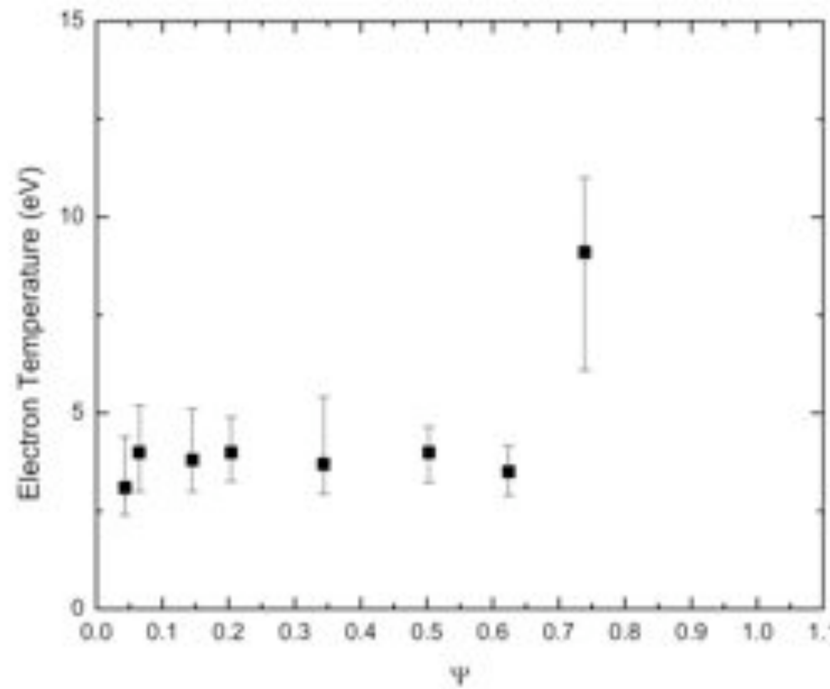
Each filament can serve multiple functions:

- Electron source
- Measure plasma potential
- Measure plasma temperature and density

[2] Inspired by M. Otte et al., IPP-Greifswald

Measured equilibrium density and temperature profiles





- Density measurements with probes in a pure electron plasma are challenging but possible (with large error bars)
- Interior temperature is flat at ~ 4eV
- Debye length ≈1.7 cm<<minor radius of CNT - plasma criterion satisfied!

CNT

Equilibrium equation for a pure electron plasma

- Low density force balance

$$\vec{\nabla}P - en_e\nabla\Phi = \vec{j}\times\vec{B}$$

- **Perpendicular** force balance is trivial - gives perpendicular flow velocity (the B field is unperturbed by the plasma - low density)
- **Parallel** force balance yields Boltzmann distribution of the electron density on each magnetic surface
- This must be consistent with Poisson's equation:

$$\nabla^2\Phi = \underbrace{\frac{e}{\varepsilon_0}N(\psi)\exp\left(\frac{e\Phi}{T_e(\psi)}\right)}_{\text{density}}$$

Ψ is constant on each surface (magnetic flux coordinate)

CNT

T. S. Pedersen and A. H. Boozer, Phys. Rev. Lett. **88**, 205002 (2002)

Equilibrium equation

$$\nabla^2\Phi = \underbrace{\frac{e}{\varepsilon_0} N(\psi)\exp\left(\frac{e\Phi}{T_e(\psi)}\right)}_{\textbf{density}}$$

- **Difficulty lies in non-linearity of problem**
- **Require two inputs to fully specify equilibrium:**

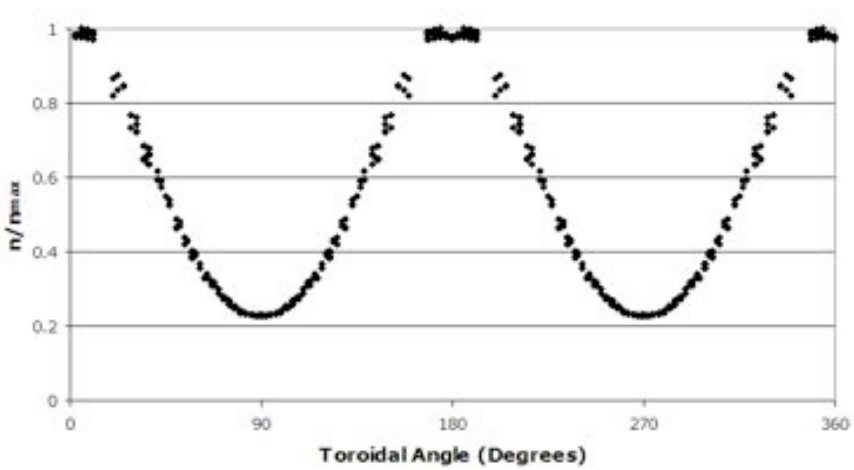
  1. N(ψ): provides freedom in density

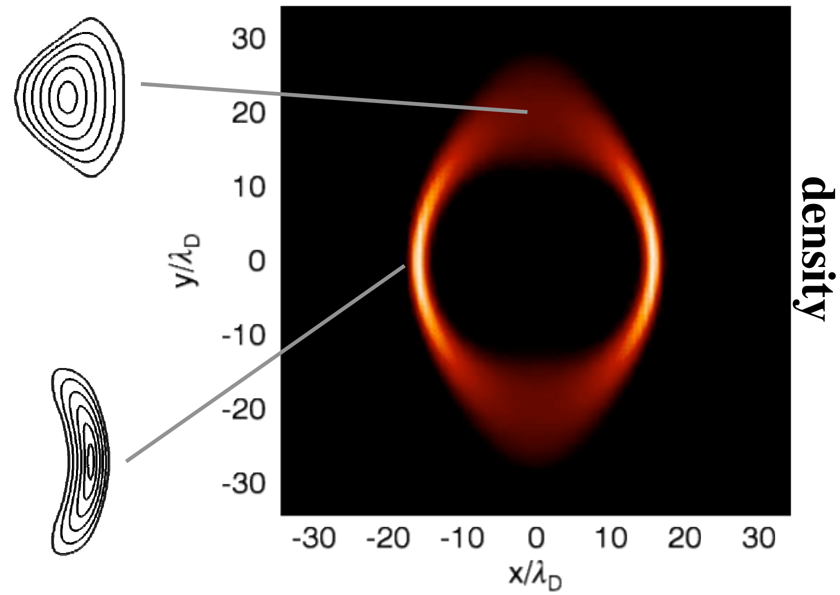
  2. $T_e(\psi)$: temperature is assumed to be a flux function due to rapid parallel thermal transport (but may vary from surface to surface)
- **A fully 3-D code has been developed to solve the equilibrium equation for arbitrary boundary conditions[1]**
- **Measured density and temperature profiles allow a complete CNT equilibrium reconstruction**

CNT

[1]R. Lefrancois *et al.*, Phys. Plasmas **12**, 072105 (2005)

Toroidal density variation ($\lambda_D \sim$ 1.6 cm)



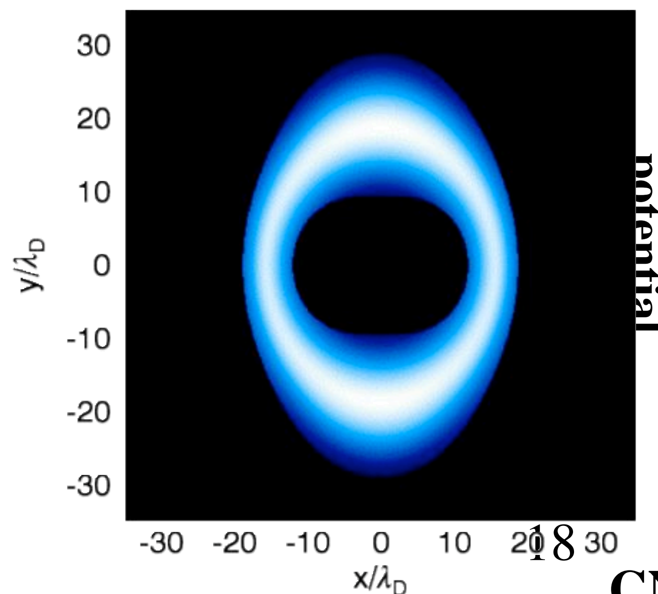


- **Large toroidal density variation due to changing cross-sectional area**

  - Potential is roughly constant along field lines (for $\lambda_D \sim$ 1.6 cm)

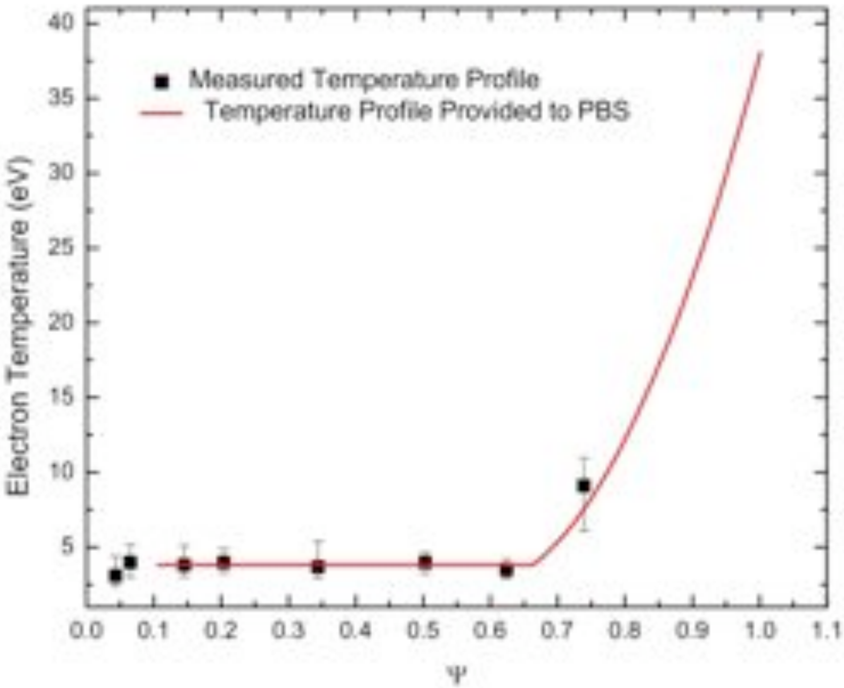
  - Density is higher at smaller cross-sections (like Penning-Malmberg / min B trap)

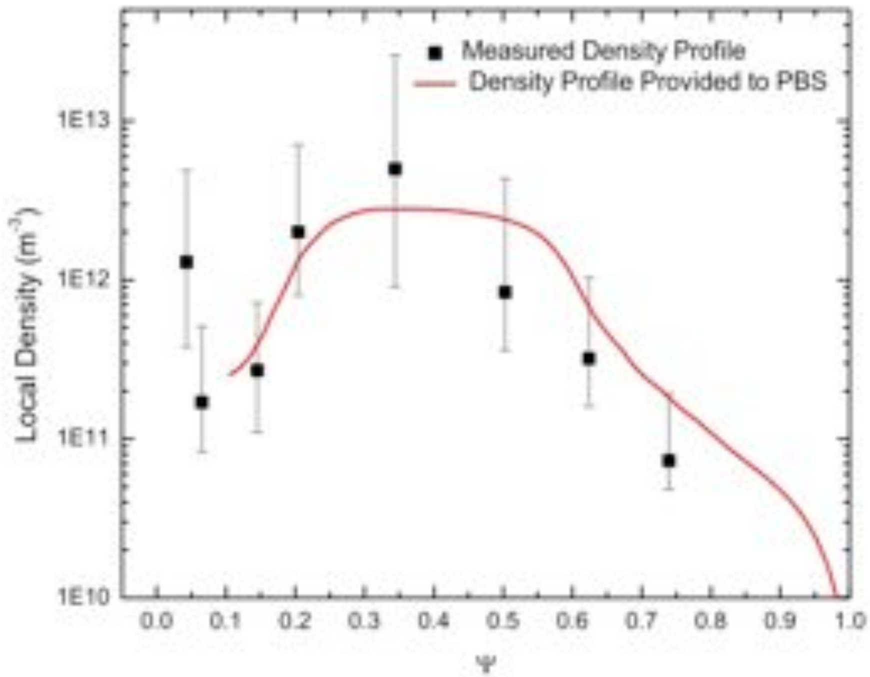
- **Calculation predicts a factor of ~ 4 variation of density on the magnetic axis**



[1]J. Fajans, Phys. Plasmas 10 p. 1209

T_e and n_e profiles for equilibrium reconstruction



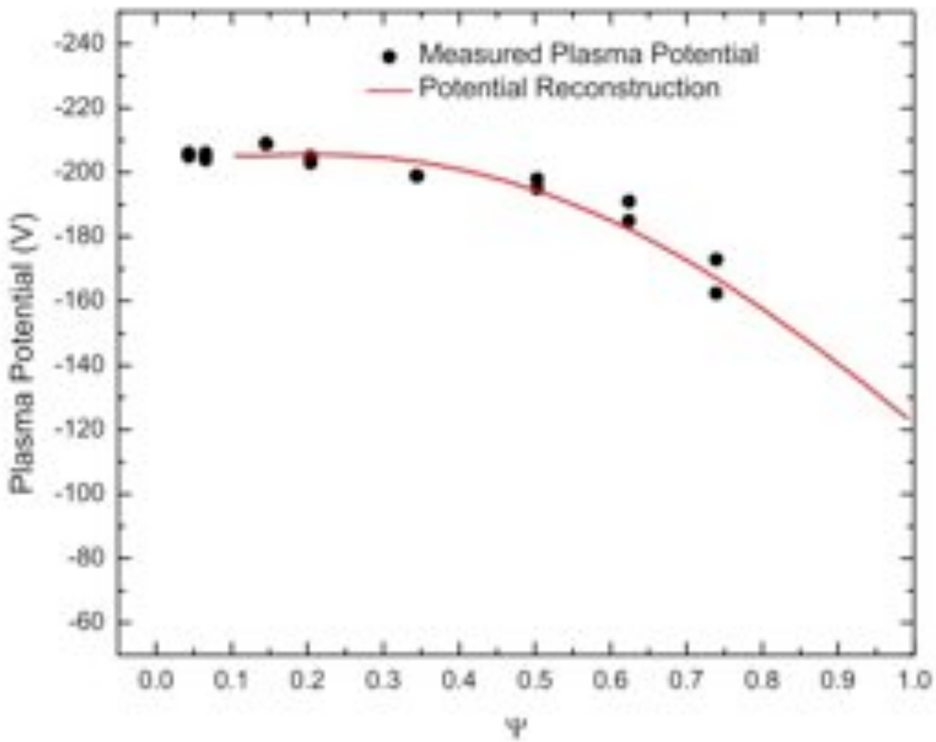


• Red graphs for density and temperature have been used to reconstruct CNT equilibrium, and calculate potential.

•Large temperature rise at edge is consistent with other measurements (not shown)

CNT

CNT equilibrium reconstruction



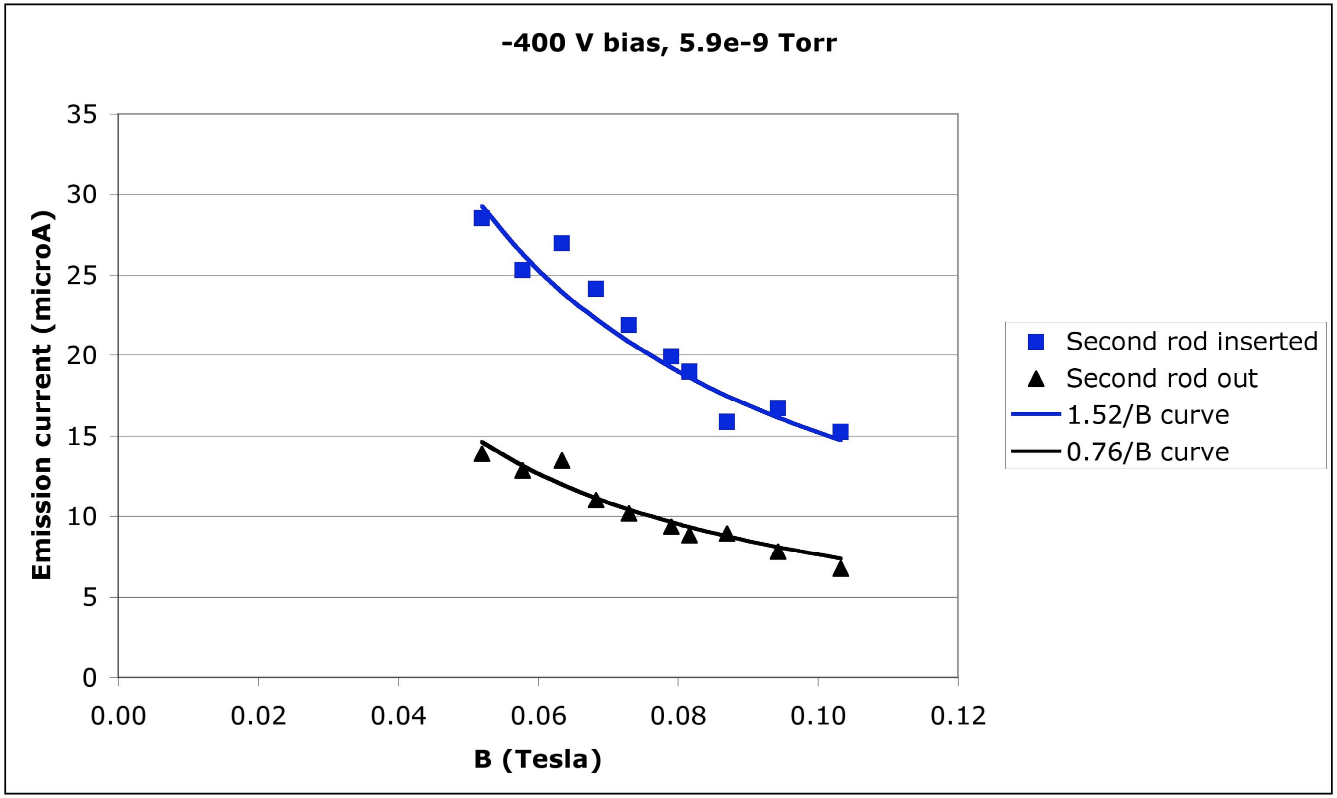
- Excellent agreement between calculated and measured potentials
- Equilibrium reconstruction also allows the electron inventory to be determined

CNT

Confinement time

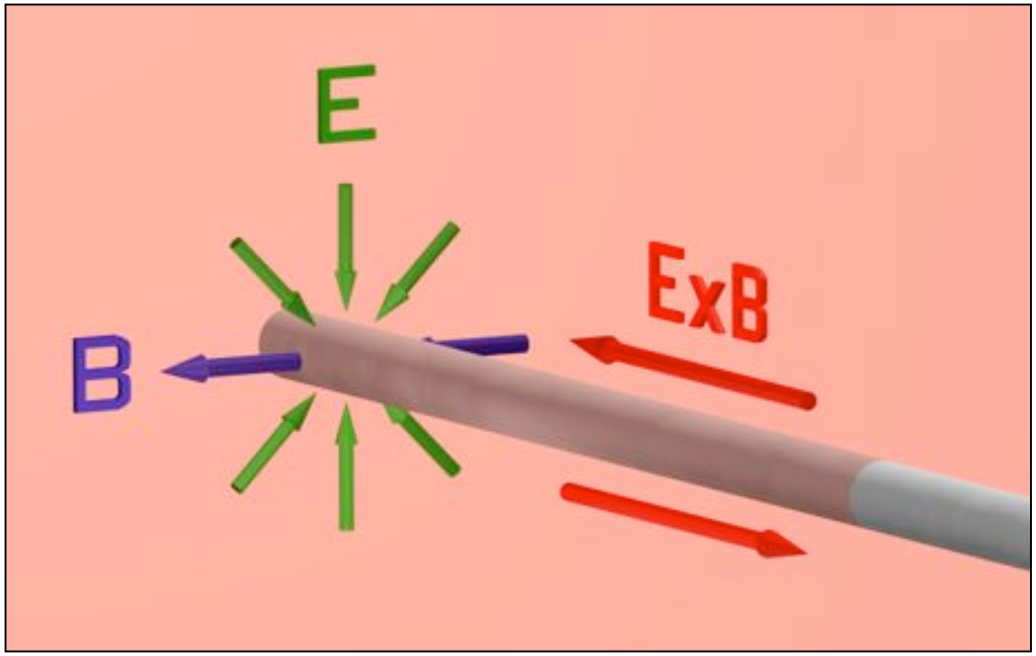
- Knowing the electron source rate, and the total electron inventory, the confinement time can be computed. It's up to **~20 ms**
  - Parallel force balance (within a magnetic surface) establishes itself in ~10 μs - electron fluid is in flux surface equilibrium
  - No large scale cross-surface ExB flows - these would lead to particle losses in ~10-100 μs
  - No significant direct "bad orbit" losses - direct ∇B drift out of the device would occur in ~300 μs
- **Conclusion: We have a macroscopically stable equilibrium**
- What limits the confinement? Why is it not many seconds?

Insulated rods limit confinement



- Two rods gives twice as much transport as one rod (for low neutral pressure and relatively large bias voltage)
- The rods are insulating, so they are not steady state sinks for electrons
- They are large electrostatic perturbations - drives ExB transport

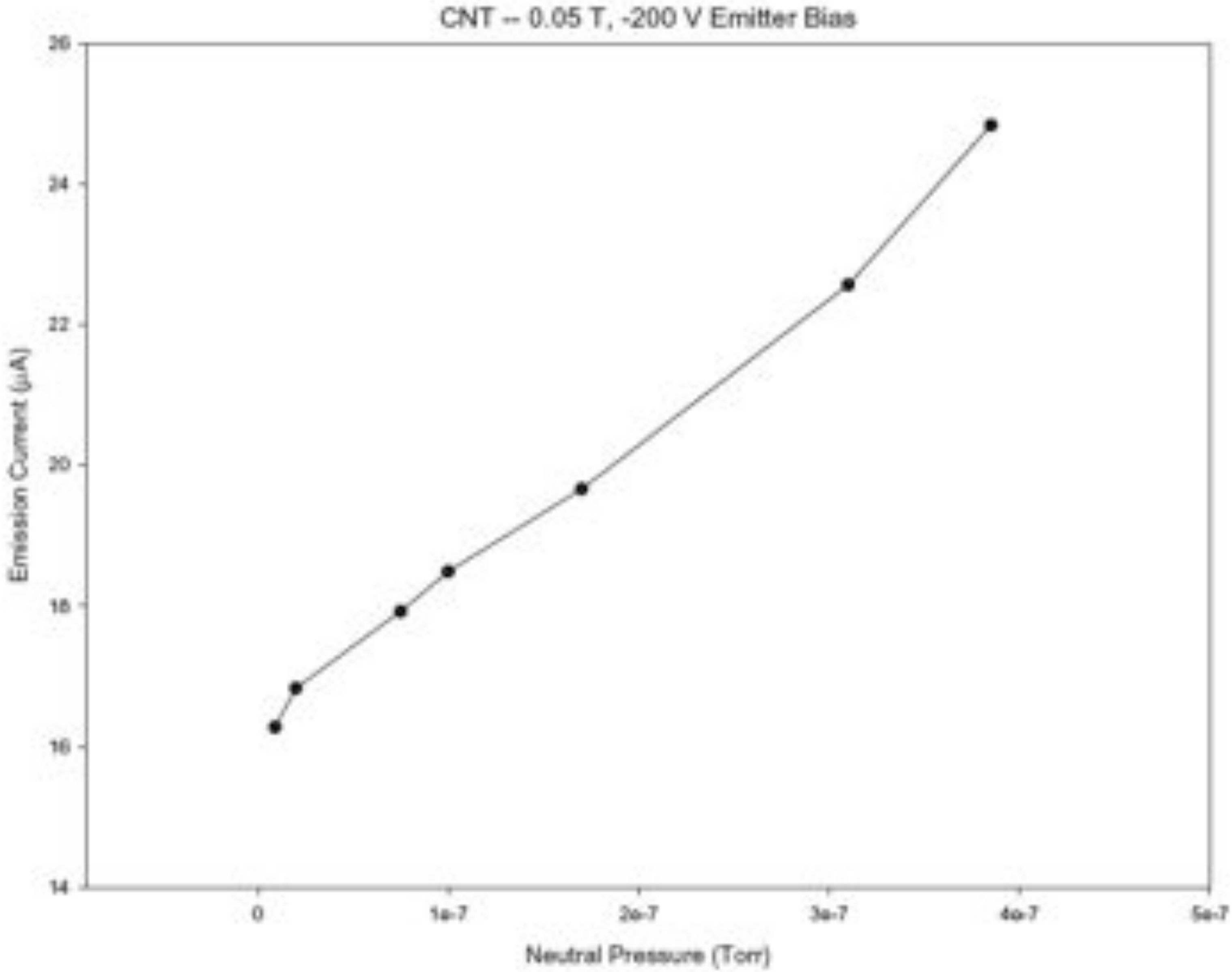
Insulated rods limit confinement



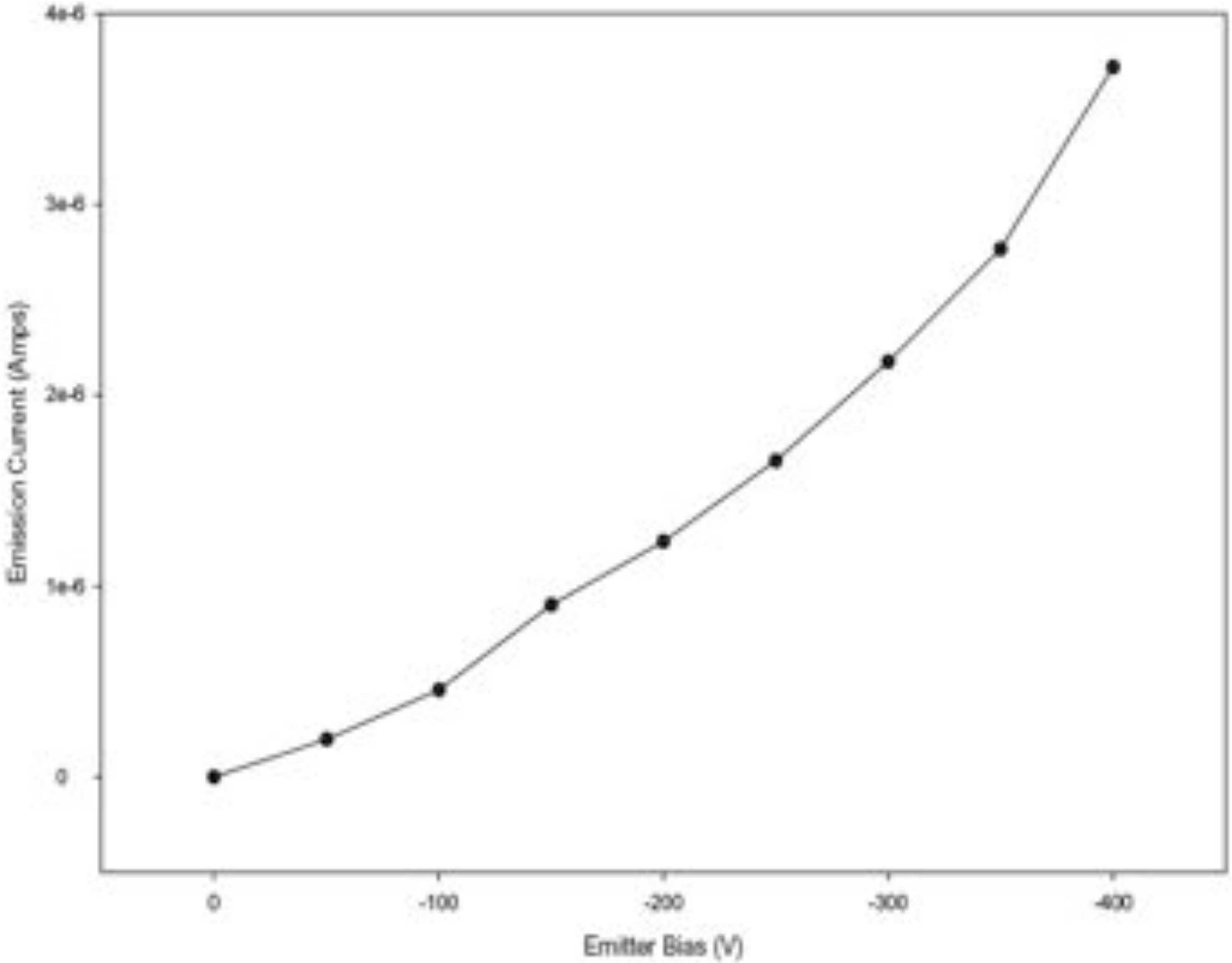
Insulated rods charge up negative relative to plasma
Resulting ExB drift pattern convects particles along the rod all the way to the open field lines

Observed order of magnitude and 1/B scaling of transport rate is consistent with this effect

Neutrals also degrade confinement



Bias voltage affects confinement



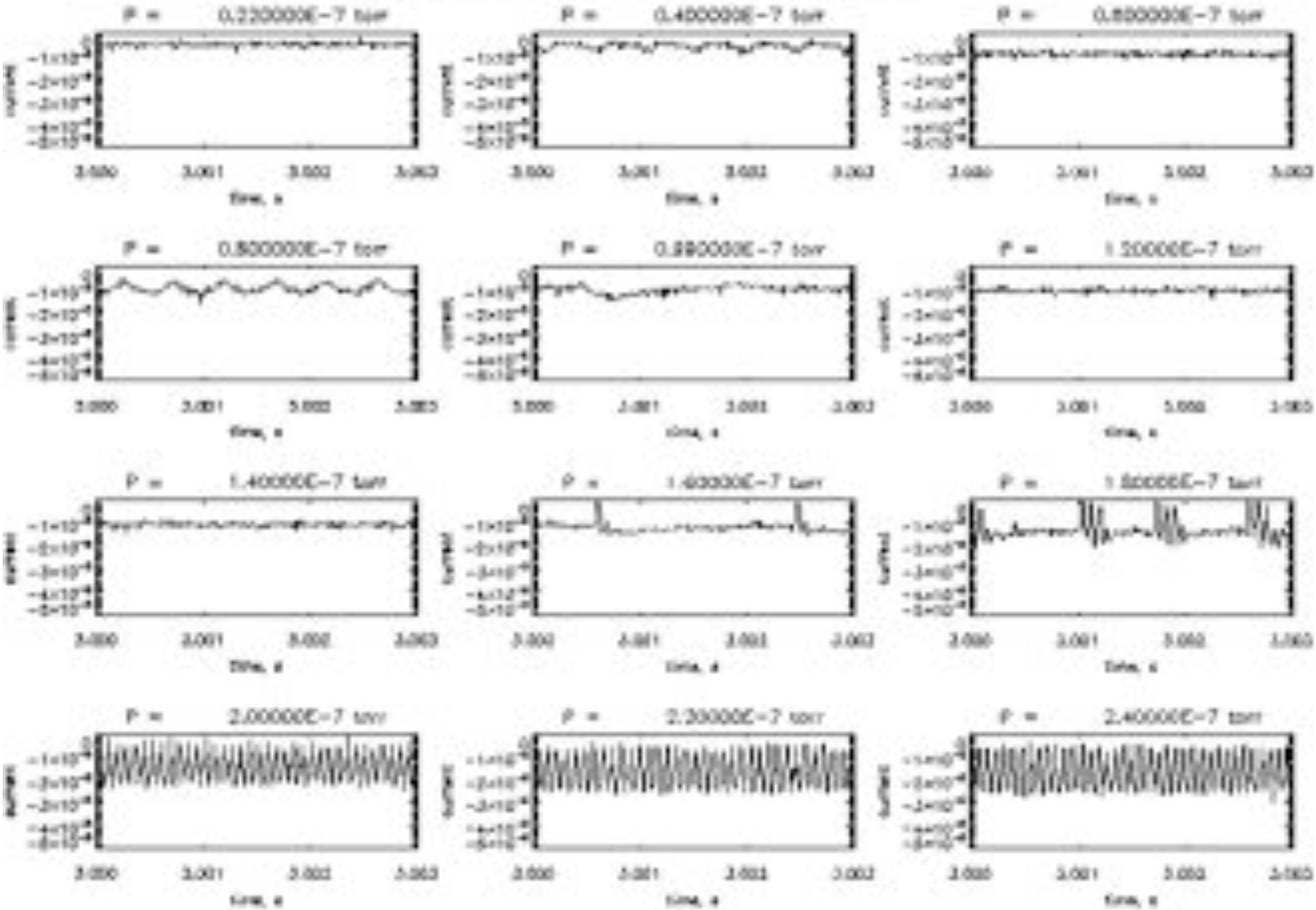
Retractable emitter - eliminate rod driven transport

Ions

- At neutral pressures of $5*10^{-9}$-$1*10^{-8}$ Torr the ion content is <1%
  - Essentially a pure electron plasma
  - Measured with large probe inserted specifically for this purpose
- If there were no sink then ions would continually accumulate - they don't
- Insulated (negatively charged) rods act as sinks for ions - allow a steady state ion density to establish itself
- At much higher neutral pressures (~$2*10^{-7}$ Torr) , CNT has 4-10% ions. At relatively low B-field strengths, this triggers an instability, similar to what has been seen in the CHS stellarator.[1]

1. H. Himura et al., to be published

Emission Current vs. Neutral Pressure, -200 V, .02 Tesla



Characteristic frequencies

- Observed oscillations are in the 10-50 kHz range
- For ϕ_{bias}=200 V, B=0.02 Tesla plasmas, assuming singly ionized nitrogen atoms:
  - ExB drift velocity ~ 20 kHz
  - Ion Larmor frequency ~ 20 kHz
  - Ion radial oscillation frequency (ignoring B) ~30 kHz
  - More work planned to understand these oscillations:
  - Use different ion species (change m_i)
  - Measure spatial structure (new probes and electronics)
  - Compare with theories and observations of ion-resonant instabilities in other confinement devices[1,2,3]

[1] R. H. Levy et al, Phys. Fluids 12. P 2616
[2] A.J. Peurrung et al., PRL 70 p. 295
[3] M. R. Stoneking et al. Phys. Plasmas 9 p. 766

Near term plans

- Measure confinement time and plasma behavior in the absence of rods
  - Will ions continually accumulate?
  - Will ion instability destroy plasma?
  - What will be the confinement time and confinement scalings?
- More spatially resolved equilibrium measurements
  - Full 2-D cross sectional measurements of n_e, T_e, plasma potential
  - Measurements at two principal toroidal cross sections

Near term plans

- Investigate physics of ion driven instability
    - Spatially resolved measurements
        - Determine mode structure (toroidal and poloidal)
        - Determine radial profile of instability amplitude
- Equilibrium:
    - Radial profile control
        - inject on multiple surfaces simultaneously
        - tailor potential profile - can we affect the temperature? Can we change the density profiles? Can we change confinement?

Not so near term plans

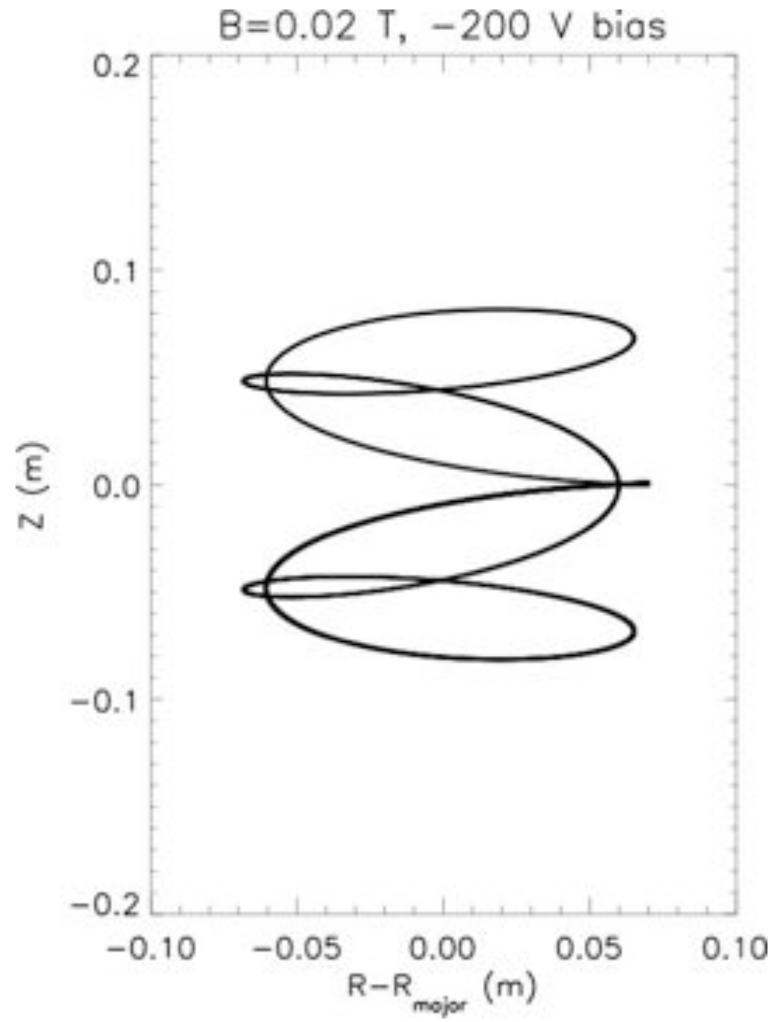
- Explore the two other tilt angles in CNT
    - 39° tilt angle: No shear, moderate iota
    - 44° tilt angle: Large iota, extreme shaping
- Electron-positron plasma research
    - Non-neutral stellarator may be ideal device for the creation and studies of electron-positron plasmas
    - Proposed injection scheme:
        - Create a well confined electron plasma
        - Open up stochastic edge region
        - Inject positrons on a stochastic (but long) field line

Theory opportunities: Overview

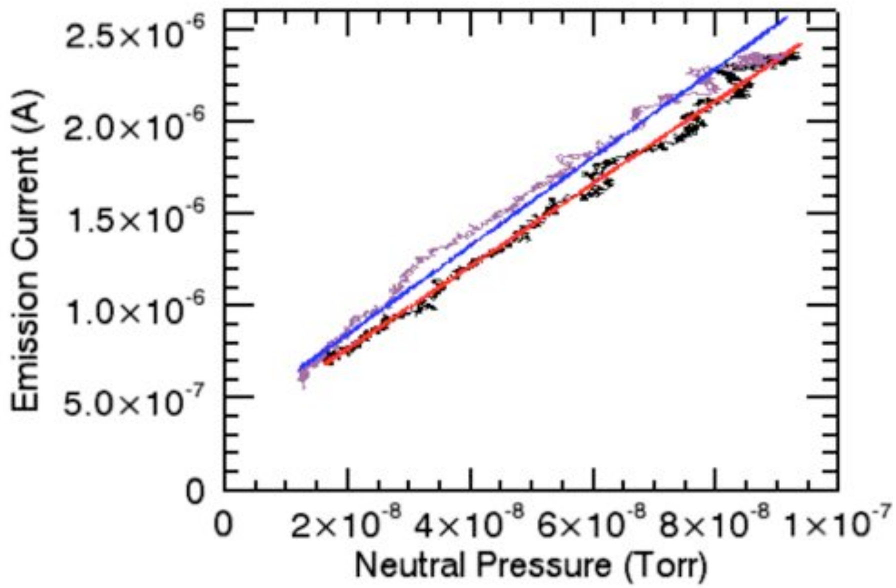
- What is the physics of the ion instability in CNT?
- Why is confinement so sensitive to neutral pressure in CNT?
- Why does the neutral driven transport scale as $B^{-1.5}$?
- Can we understand the profiles of density and temperature in CNT?
- Can a CNT-like configuration be fusion-relevant?

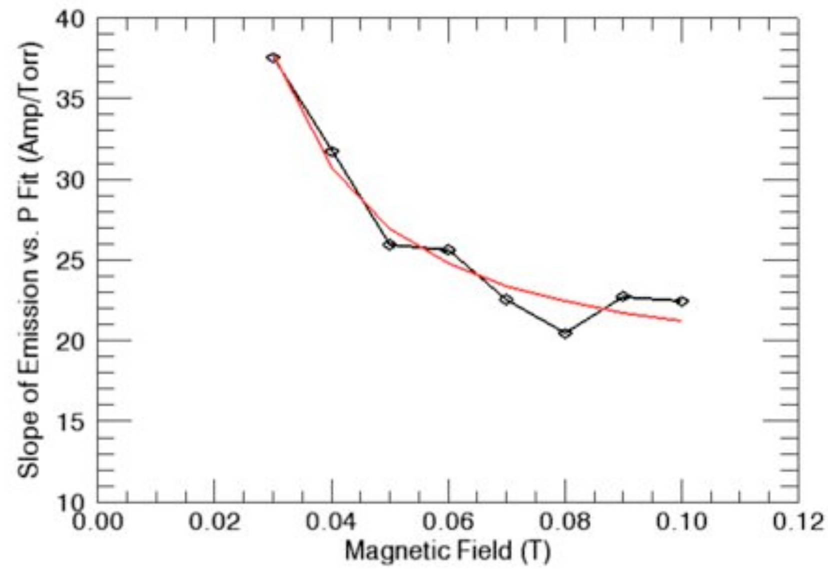
Theory opportunities: Ion instability

- Develop a theory for the ion instability in a magnetic surface device
  - Ion instability is well understood in Penning traps
  - Electron dynamics are fundamentally different in a stellarator - electron perturbation should damp out, except on rational surfaces
  - Ions need to be treated kinetically - particle orbits are on the order of the radial dimension



Transport due to neutrals





Confinement is determined by loss due to all sources (rods, classical, neo-classical…). The rods are a major source but other sources are significant:

- Emission scales linearly with p_n.
  - loss rates are much larger than neoclassical diffusion
- Slopes of Emission vs. Neutral pressure scale as $\sim B^{-1.5}$
  - Same scaling has been observed in Stoneking's pure toroidal field experiment
- Are there still direct loss orbits in CNT despite the large electric field?

Theory opportunities: Profile effects

- Understand measured n_e and T_e profiles
  - Why do we see a peak off axis in density even though we are injecting at the axis?
    - Implies a non-diffusive transport mechanism
    - Implies good local confinement in region of bump
  - Why is the electron temperature flat throughout most of the plasma? (electron - electron collision time is > confinement time)
  - One would expect “Joule heating” - electrons should pick up kinetic energy from the electrostatic potential as they diffuse out
  - Why does the temperature rise steeply near the edge?
    - Confinement is poor at the edge (we see low density) - so perhaps particles can Joule heat and not interact with the rest of the plasma?

Theory opportunities: Fusion relevance of CNT?

- CNT has several advantages as a fusion device, all of which have been verified experimentally:
  - Ultralow aspect ratio (compact device)
  - Extremely simple coils
  - Error field resilience
- But it is not a good candidate for fusion:
  - Far from any quasisymmetry - predicted very high neoclassical losses (H. Mynick, N. Pomphrey, PPPL, Seiwald, U. Graz)
- Can we optimize a CNT-like configuration for fusion, retaining the advantages of CNT?
  - Just started neoclassical optimization effort with B. Seiwald, Tech. Univ. of Graz, Austria

Summary

- CNT can explore unique non-neutral plasma physics
- Stable equilibria exist for pure electron plasmas in a stellarator
- Small Debye length has been achieved in CNT
- Confinement is decent - limited by presence of rods and neutrals
- Instabilities can be triggered by poor vacuum, large bias potential, or low magnetic field
- Plenty of phenomena to study!

More info: Contact me at tsp22@columbia.edu or look on our website: www.ap.columbia.edu/CNT