Toroidal systems

Thomas Sunn Pedersen
IPP-Greifswald, Germany

With contributions from:

Matt Stoneking and the LNT-II group

Haruhiko Saitoh and the RT-1 group

The CNT group

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CNT

Overview

- Motivation for the study of toroidal configurations
- The pure toroidal field trap
  - Basic theory
  - History
  - Experimental results
- Dipole experiment(s)
- Physics of pure electron plasmas in stellarators
  - Motivation and history
  - Experimental results
- Partially neutralized plasmas
  - First results
- Plans for electron-positron plasmas
- Summary

Why study NNP in toroidal configurations?

- Penning traps can confine non-neutral plasmas indefinitely – what's there to improve?
- One can study different physics in toroidal configurations:
  - Partially neutralized plasmas (Penning traps confine only one sign of charge)
  - Elimination of end effects
  - Toroidicity introduces new physics
- Toroidal magnetic traps are used in quasineutral plasma physics, especially in fusion energy research
  - Possibility for synergy with the large effort on confinement of plasma in stellarators and tokamaks
  - Is it the device (toroidicity) or the plasma (non-neutrality) that "dominates" the physics?
  - That is, which results from fusion are applicable to non-neutral plasmas in toroidal configurations, and which results from Penning traps are applicable in toroidally confined non-neutral plasmas?

A basic observation about non-neutral plasmas In toroidal configurations

- Non-neutral plasmas are defined similarly to quasineutral plasmas and therefore display collective behavior:

$$\lambda_D << a \qquad (n\lambda_D^3 >> 1)$$

- For a single component (eg. pure electron) plasma this implies that the electric field effects dominating over temperature related effects:

$$\varepsilon_0 \nabla^2 \varphi = en_e \Leftrightarrow \varepsilon_0 |\varphi| / a^2 \approx en_e \Leftrightarrow |\varphi| \approx en_e a^2 / \varepsilon_0$$

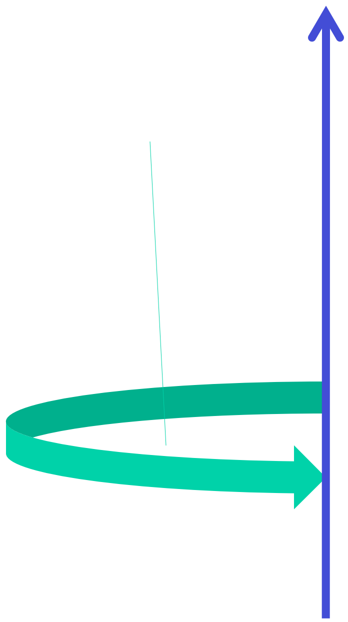
$$\Leftrightarrow \left|\frac{e\varphi}{T}\right| \approx \frac{e^2 n_e}{\varepsilon_0 T_e} a^2 = \frac{a^2}{\lambda_D^2} >> 1 \Leftrightarrow \left|\frac{e\varphi}{T}\right| >> 1$$

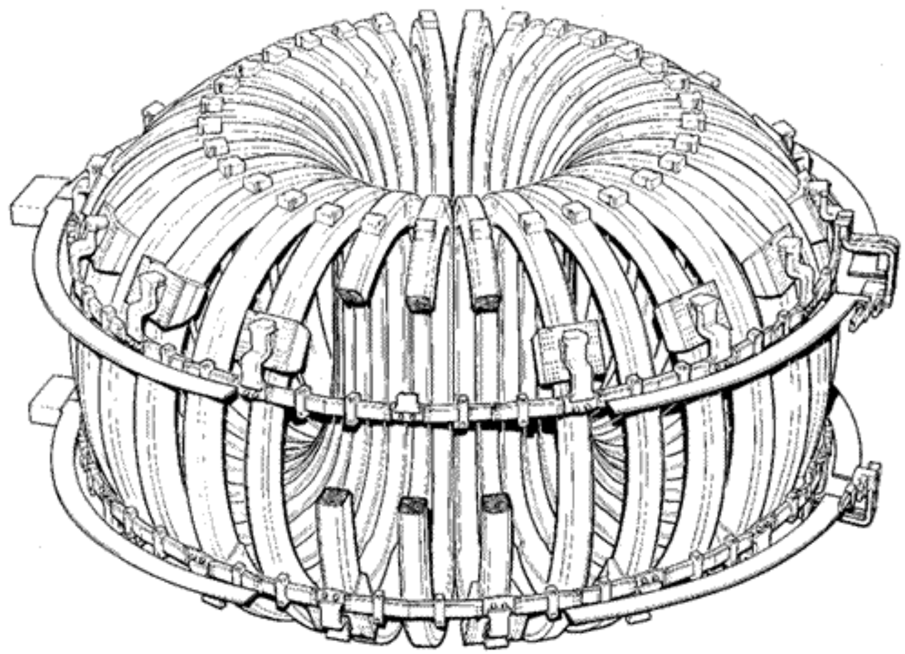
$$\left|\frac{v_{E\times B}}{v_{\nabla B}}\right| = \frac{|\nabla\varphi|/B}{T|\nabla B|/eB^2} \approx \left|\frac{e\varphi}{T}\right| >> 1$$

- For a quasineutral plasma, $\left|\frac{e\varphi}{T}\right| \sim 1$

The most basic toroidal trap: Pure toroidal field

- A pure toroidal field results from either a very large symmetrically arranged set of toroidal field coils, or (as an idealization) from an infinitely long straight current carrying wire:





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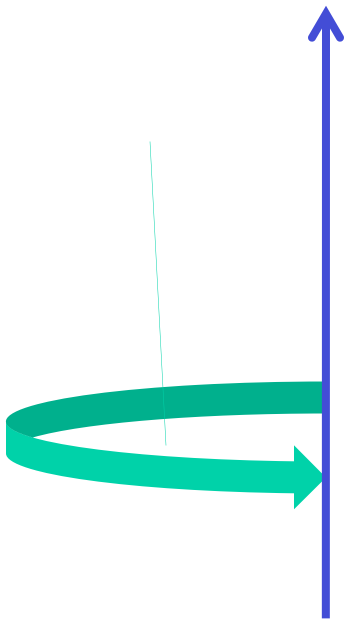


$$\vec{B} = B_\varphi \hat{\varphi} = \frac{\mu_0 I}{2\pi R}\hat{\varphi} \Rightarrow \nabla B = -\frac{\mu_0 I}{2\pi R^2}\hat{R}$$

- Thus, we have an inhomogeneous B-field and therefore particle drifts (vertical):

$$\vec{v}_{\nabla B + R_C} = \frac{2mv_\parallel^2 + mv_\perp^2}{2B}\frac{\vec{B}\times\nabla B}{qB^2} \longrightarrow \frac{T_\parallel + T_\perp}{qRB}\hat{z}$$

Theory: ExB comes to the rescue

- A lone electron will drift vertically out of the trap
- But if one manages to nucleate a pure electron plasma by overwhelming initial losses, the electrons can have very good confinement:

Recall $$\left|\frac{v_{E\times B}}{v_{\nabla B}}\right| = \frac{|\nabla\varphi|/B}{T|\nabla B|/eB^2} \approx \left|\frac{e\varphi}{T}\right| >> 1$$

- This means that the poloidal ExB drift is much faster than the vertical drift. Particle will move poloidally – and then the vertical drift cancels (radially inward, then radially outward)
- Electrostatic hoop force is balanced by image charges
- Equilibrium is predicted to exist[1], and is a maximum energy state and stable in the absence of dissipation[2] (like Penning trap equilibrium)
- Confinement is predicted to be limited by magnetic pumping/collisions[3]

1. Daugherty and Levy, Phys. Fluids **10**, 155 (1967)
2. O'Neil and Smith, Phys. Plasmas **1**, 8 (1994)
3. Crooks and O'Neil, Phys. Plasmas 3, p. 2533 (1996)

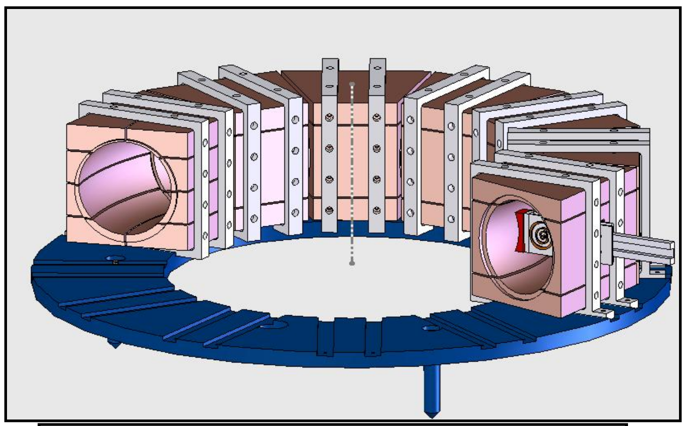
Brief history of pure toroidal field traps <2000

- First pure toroidal field non-neutral experiments were performed >40 years ago (USA, Avco Everett) [1]
  - 400 kV potential well, 60 μs confinement time
  - Significant ion content
  - Ionization limits confinement
  - High temperatures/beam population (less than one Debye length)
- Relativistic electron beam in 1970's [2]
  - 20 μs confinement time
  - Also limited by ion buildup, also less than one Debye length
- Low aspect ratio experiment in 1990's (IPR, India) [3]
  - Inward shift of column observed
  - 2-3 msec confinement time (much shorter than magnetic pumping time scale but significantly higher than vertical drift time)
  - T=20 eV – about one Debye length in the plasma

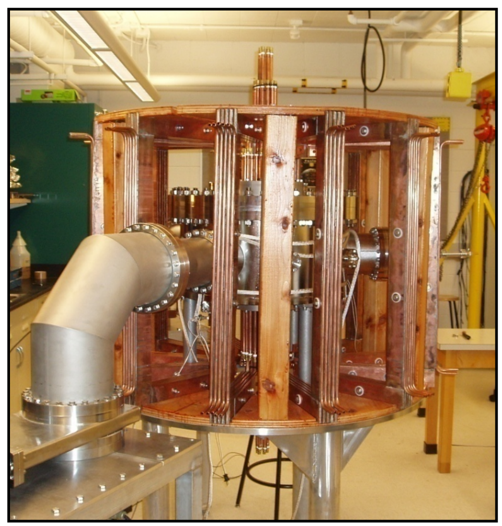
1. Daugherty, Eninger, Janes, Phys. Fluids 12, p.2677 (1969)
2. Mohri, Masuzaki, Tsuzuki, Ikuta, PRL 34 p. 574 (1975)
3. Zaveri, P. I. John, K. Avinash, P. K. Kaw, PRL 68, p. 3295, (1992)

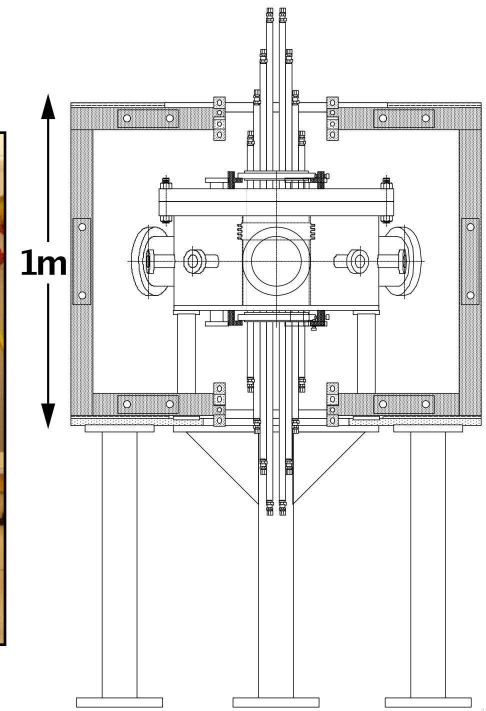
Pure electron plasmas in a pure toroidal magnetic field: Lawrence Non-neutral Torus II

- Experiment led by Matt Stoneking, Lawrence University, Wisconsin
- Pure toroidal field – good vacuum
- Small Debye length
- Results presented here are from a partial torus (“a bent Penning trap”)
    - Confinement is worse for a full torus by the way!

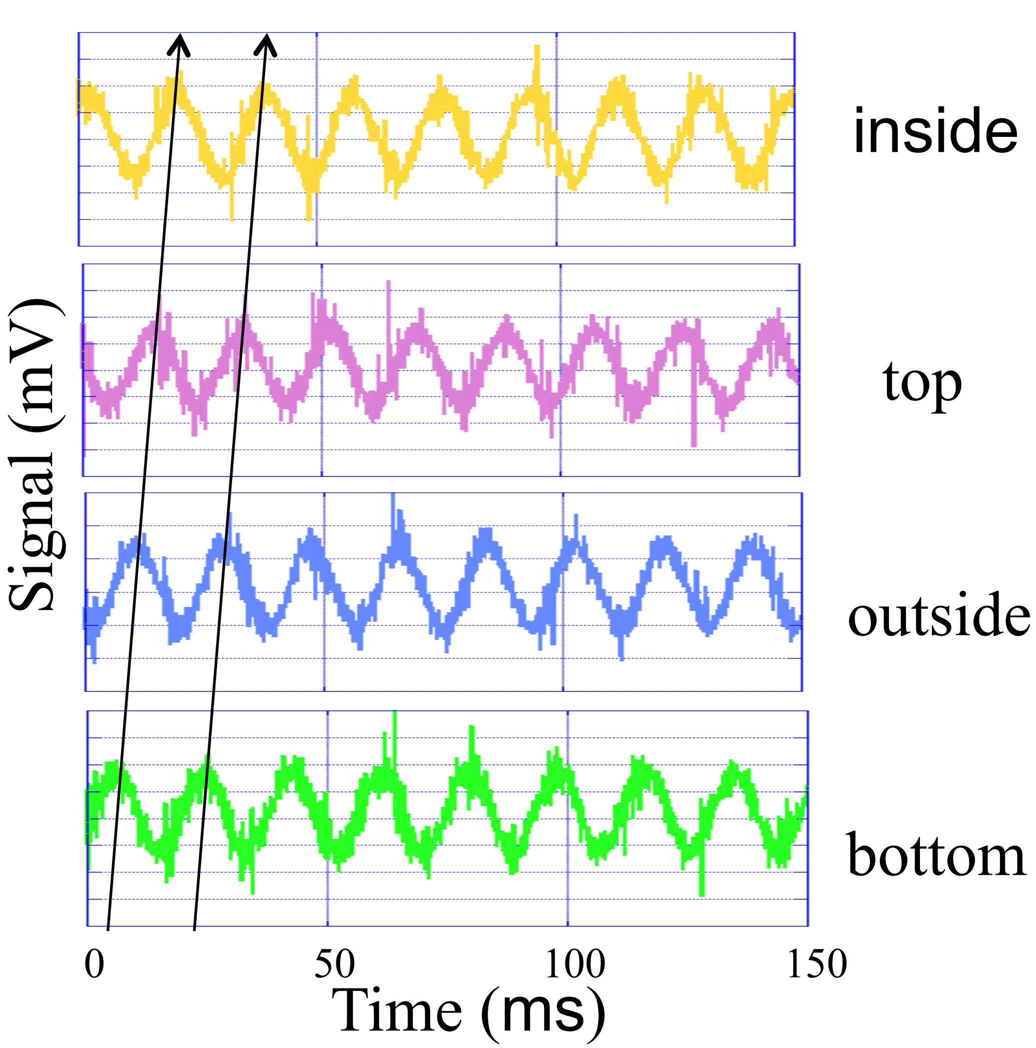


- Plasma major radius: 17.4 cm
- Plasma minor radius: ~1.3 cm
- Length: 82 cm (270 degrees)
  109 cm (360 degrees)





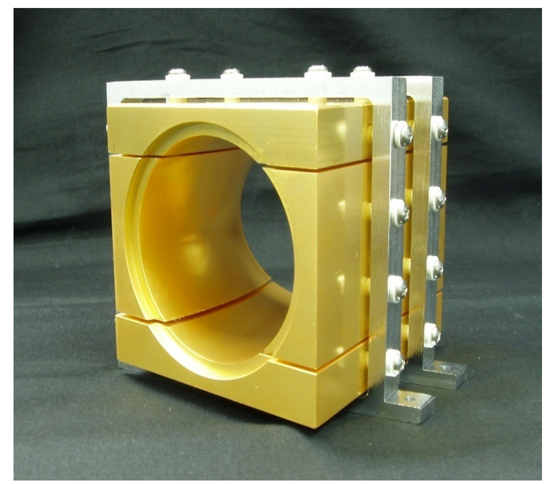
Observation of *m*=1 Diocotron Mode (ExB rotation of the entire plasma)



$$f_1 = \frac{Q}{4\pi^2 \varepsilon_o L b^2}\left(\frac{1}{B}\right) \approx 50\,\mathrm{kHz}$$

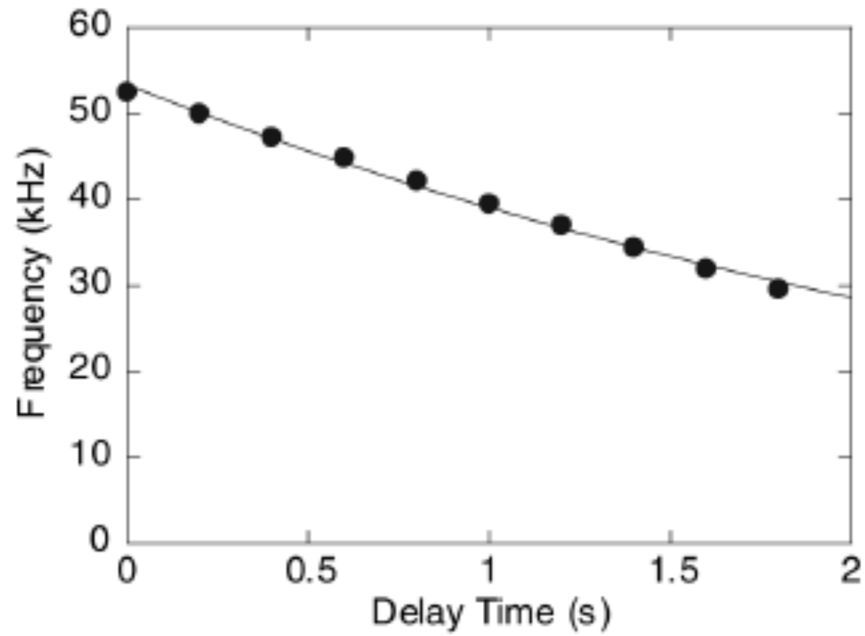
$$Q \approx 1.5\,\mathrm{nC}$$

$$\mathrm{N} \approx 10^{10}\ \text{electrons}$$

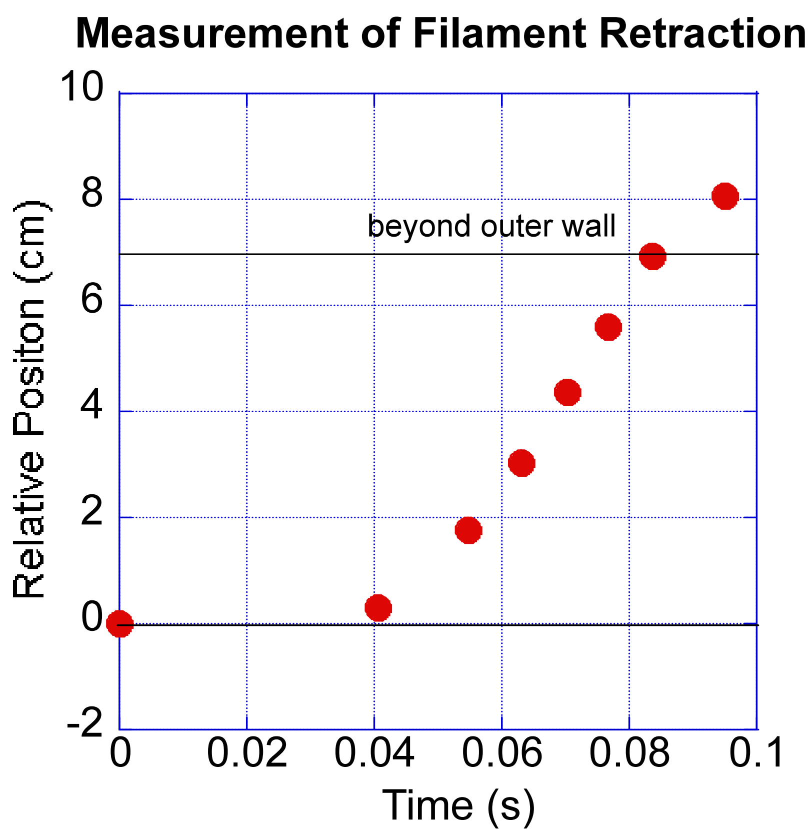


Confinement Time

- Frequency decays on ~3 s timescale → charge confinement time.
- ~100X improvement over previous non-neutral pure toroidal field experiments.
- Approaches theoretical predictions (infinite confinement is not expected here)

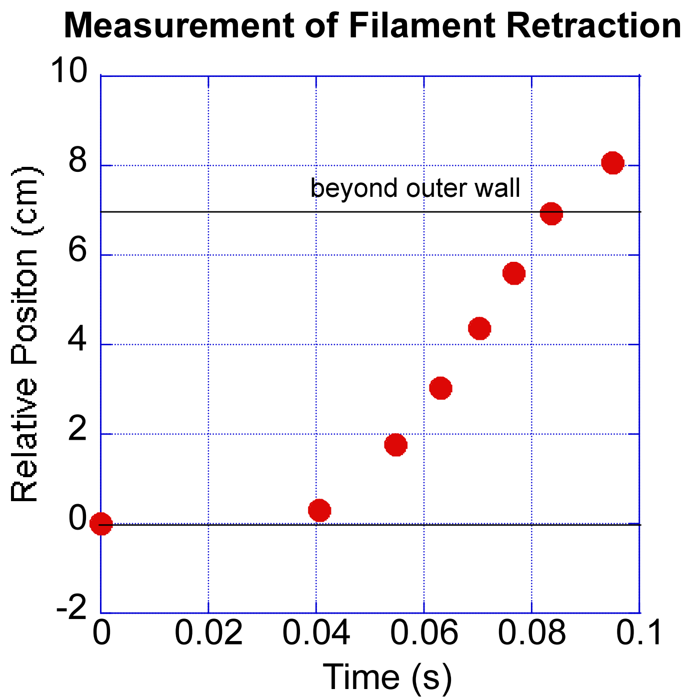


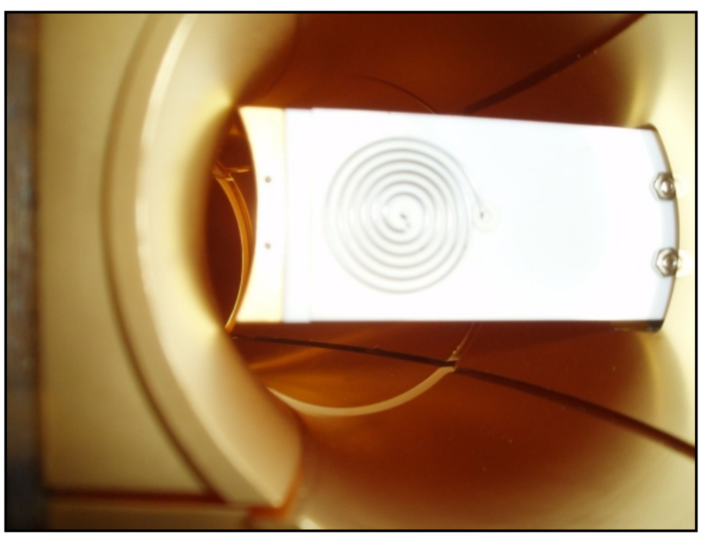
Removal of internal objects and electron sources



- Retract filament to study full toroid
- Retraction in about 50 ms
- Much faster than confinement time

Removal of internal objects and electron sources





- Retract filament to study full toroid
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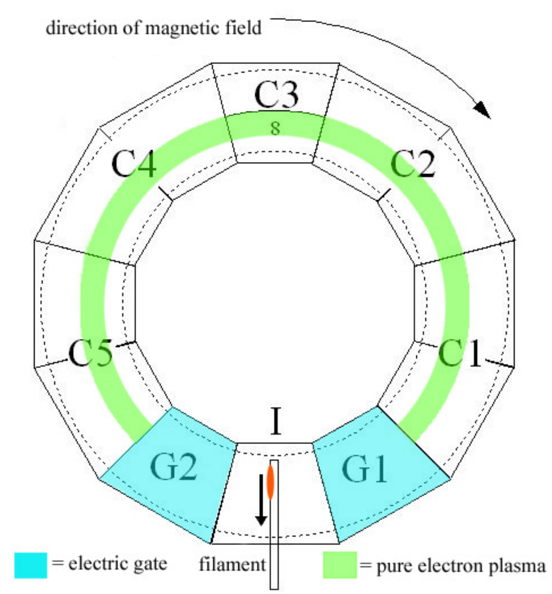
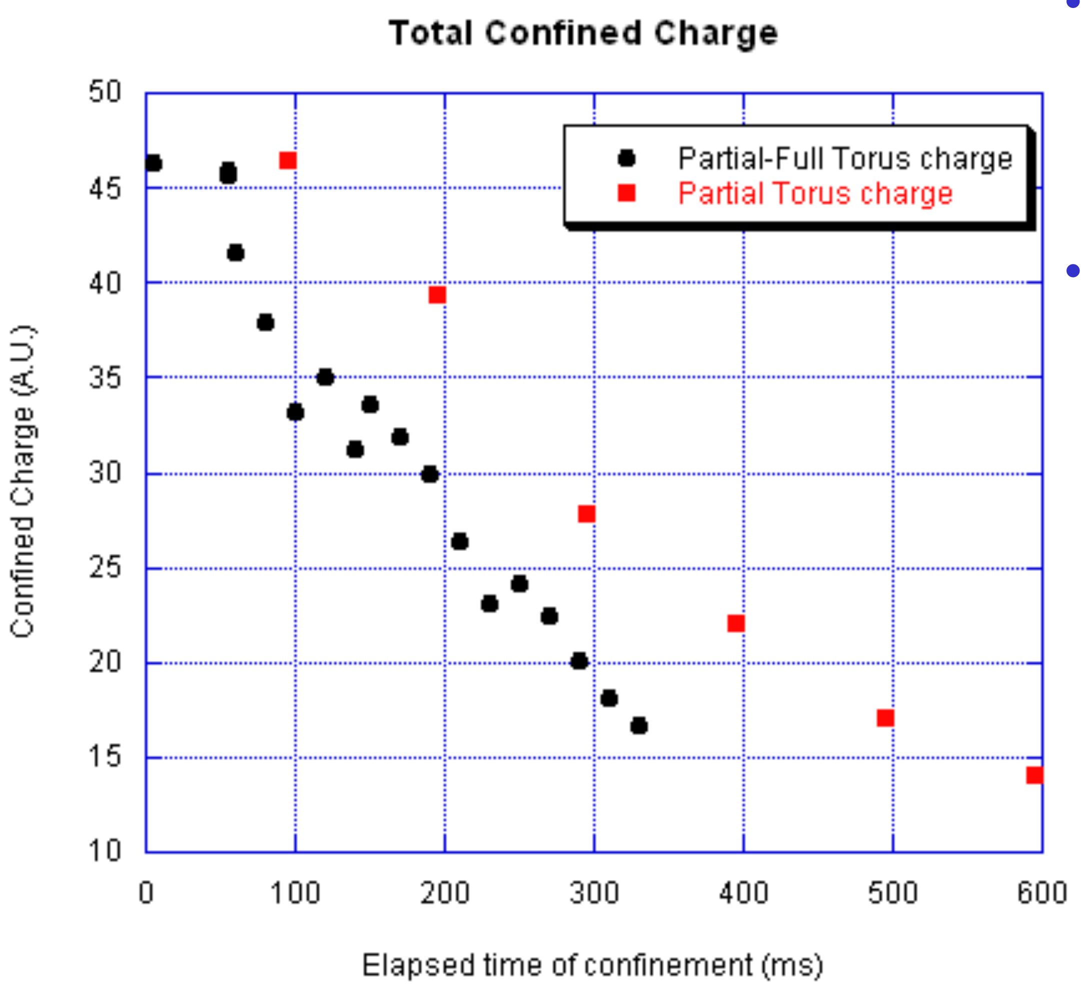


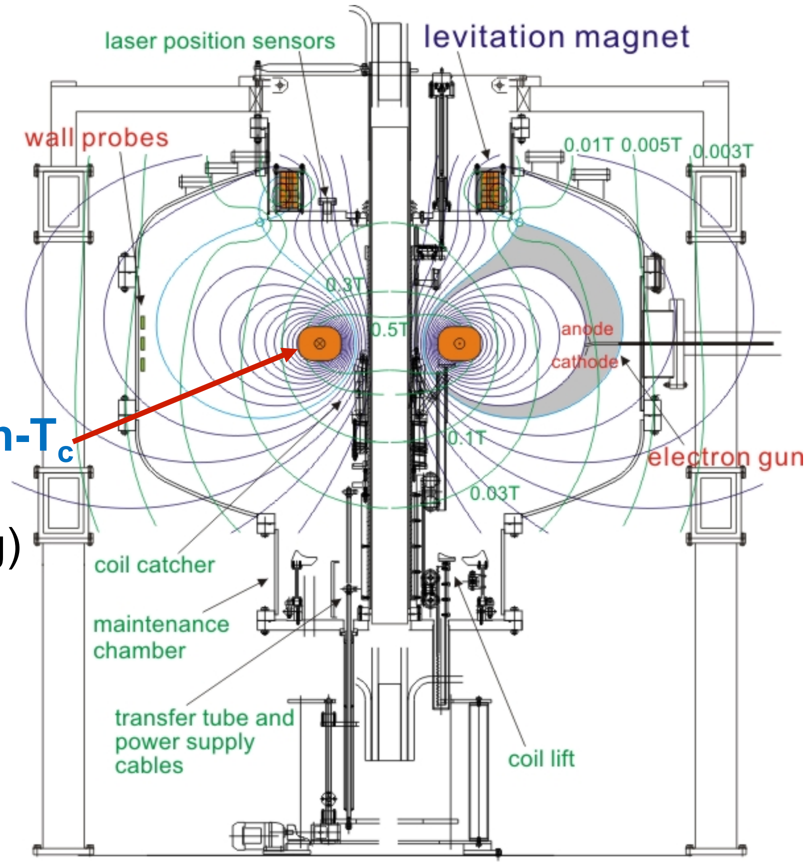
Confinement after removal poorer than expected

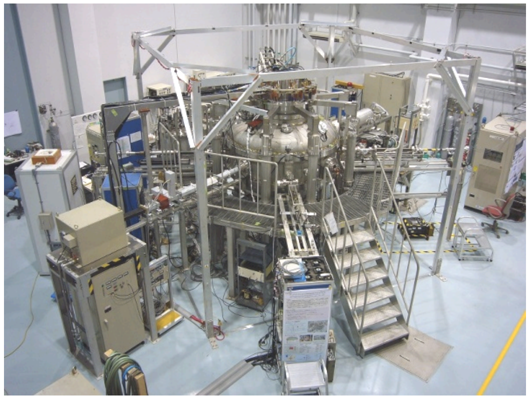


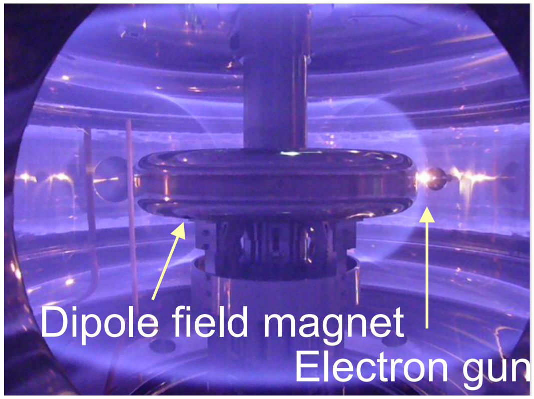
- Retract filament to study full toroid
- Retraction in about 50 ms
- Confinement time on the order of 100 msec or so – linear charge decay rate in this case
- Unclear why the confinement is worse

RT-1, a magnetosheric configuration generated by a levitated dipole field magnet, stably confines toroidal non-neutral (electron) plasma

Levitated High-T_c SC Magnet
(0.25MA,112kg)





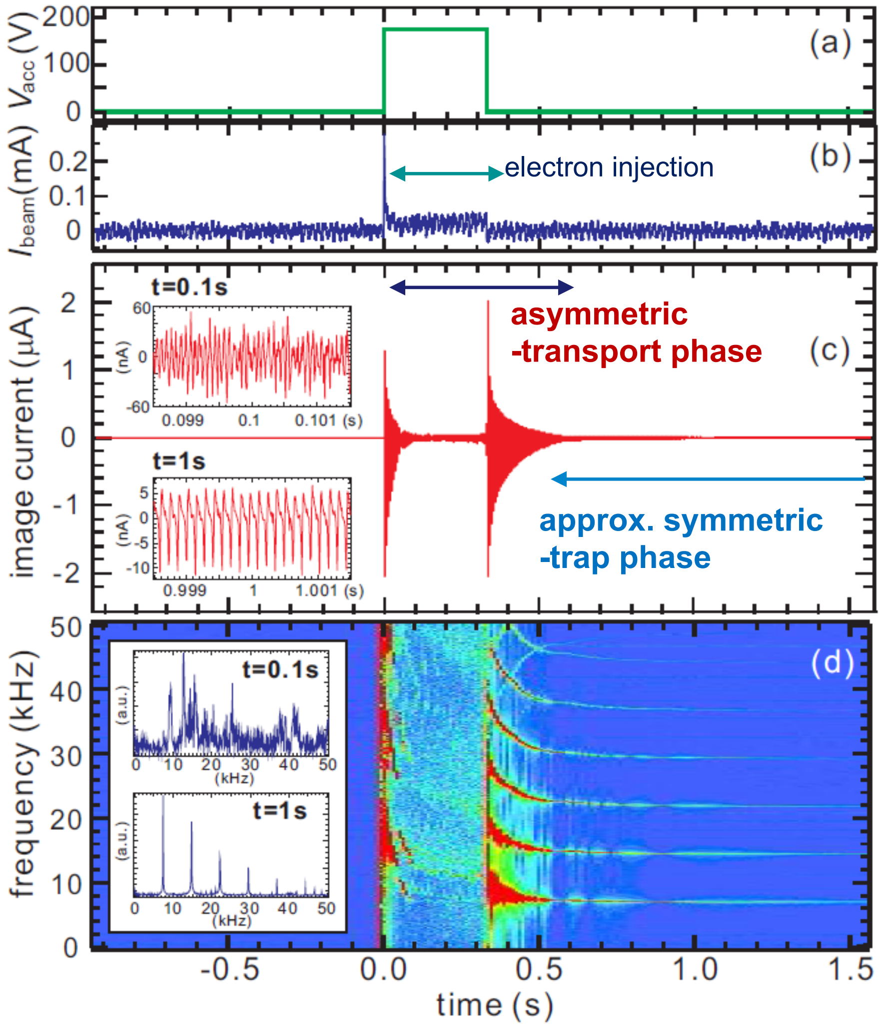


2009 Ogawa, Yoshida *et al.*, Plasma Fusion Res. 4, 020.

- **Toroidal non-neutral (pure electron) plasma**
  300s long confinement, rigid-rotating steady state, inward diffusion
- **High-β ECH plasma for advanced fusion: another research subject of RT-1**
  70% local β, confinement time ~0.5s, peaked density profiles

2011 Saitoh, Yoshida *et al.*, Nuclear Fusion 51, 063034.

Pure electron plasma (PEP) formation process in RT-1: Electron beam injection and stabilization of fluctuations

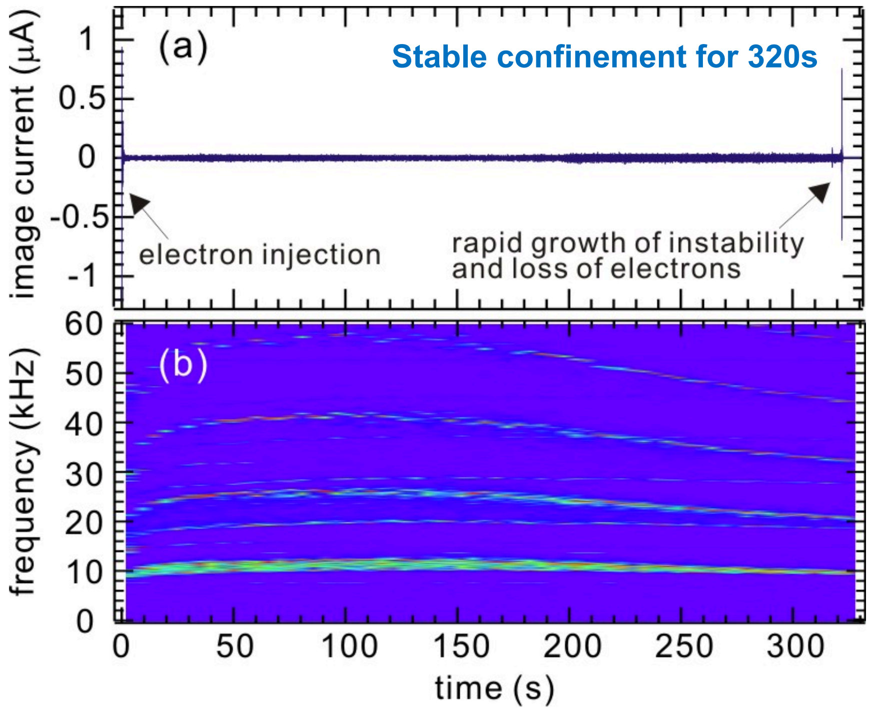


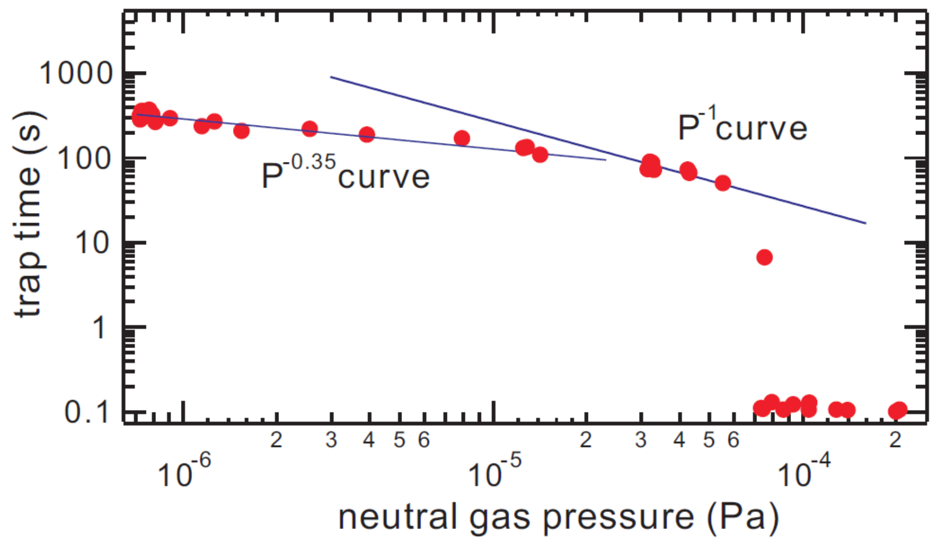
Formation and sustainment of toroidal PEP in RT-1.
(a) V_{acc}, (b) beam current, (c) electrostatic fluctuation, and (d) its frequency power spectrum.

- Electrons are injected with a gun located at edge confinement region.
- Soon after the start of beam injection, a charged cloud is created, which repels the beam and diminished the beam current to about 10^{-5}A.
- When the beam current is stopped, plasma becomes turbulent, and then relaxes into a quiescent state.
- Periodic oscillations (single mode with higher order harmonics) in this phase
- f~10kHz is comparable to the toroidal ExB rotation frequency.

2010 Yoshida *et al*., PRL 104, 235004.

Stable confinement of PEP for more than 300s is realized, trap time comparable to the diffusion time due to neutral collisions



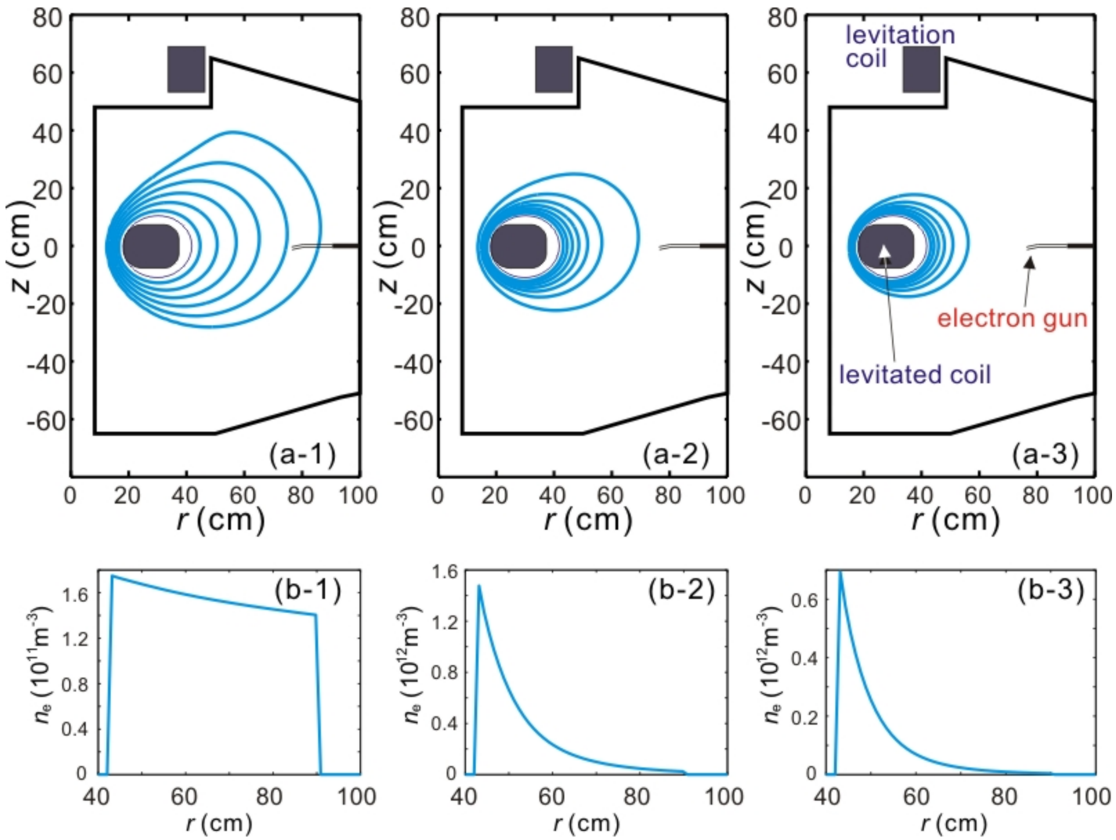


Temporal evolutions of electrostatic fluctuation and stable trap time in variation of neutral gas pressure

- The stable confinement time τ^* strongly depends on the neutral gas pressure P_n.
- The nonlinear relation ($\tau^* P_n \neq$ const.) indicates that electron-neutral collisions do not simply decide the trap time of PEP.
- Confinement ends with onset of instability, possibly due to ion resonance effects.

2010 Yoshida *et al.*, PRL 104, 235004.

Inward particle diffusion and formation of stable peaked profiles: Plasma diffuses inward to strong field region



Estimated density profiles of PEP
(a) during electron beam injection,
(b) just after beam injection ended,
(c) just before confinement ended.

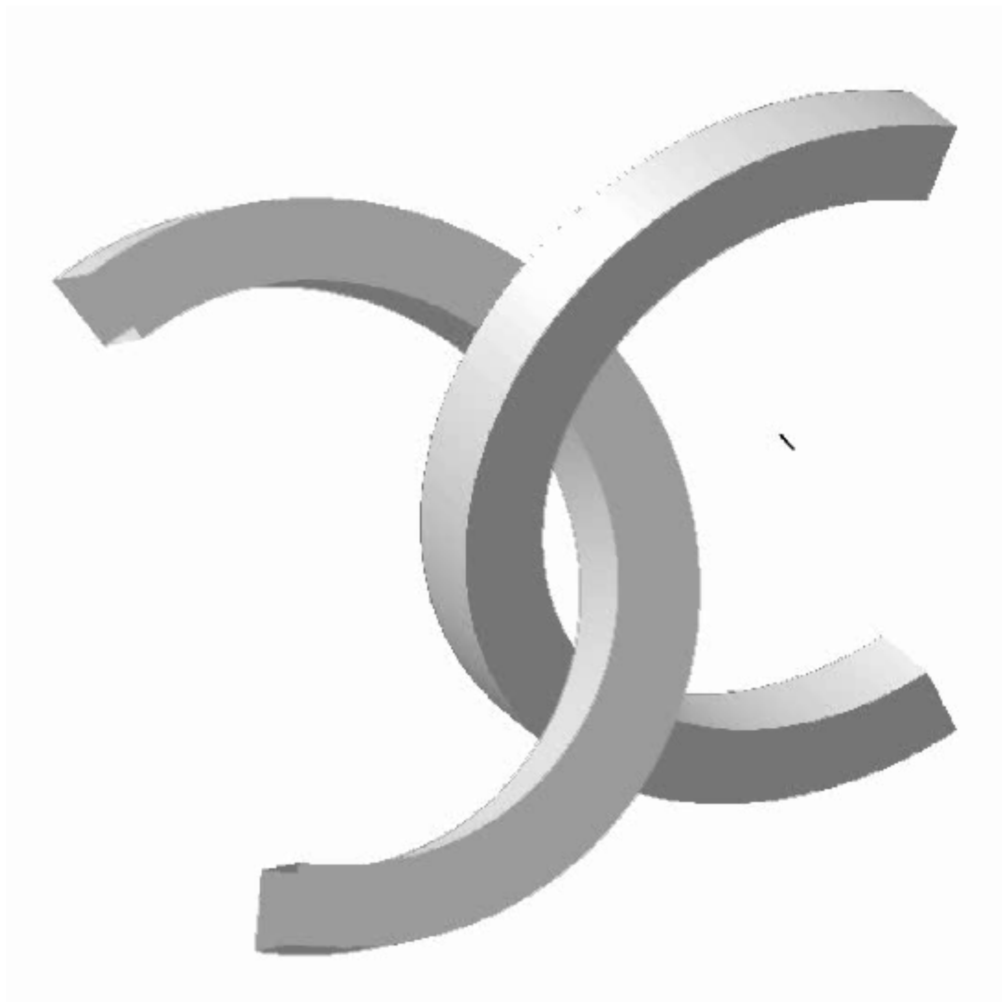
- The confinement region shifts inward to the strong field region.
- Peaked density profiles are stably sustained in the stable confinement phase.
- The observation of inward diffusion is consistent with theoretical prediction of the self-organization of *homogeneous density per flux tube* states

2011 Saitoh, Yoshida *et al*., PoP 18, 056102.

Non-neutral plasmas in a stellarator

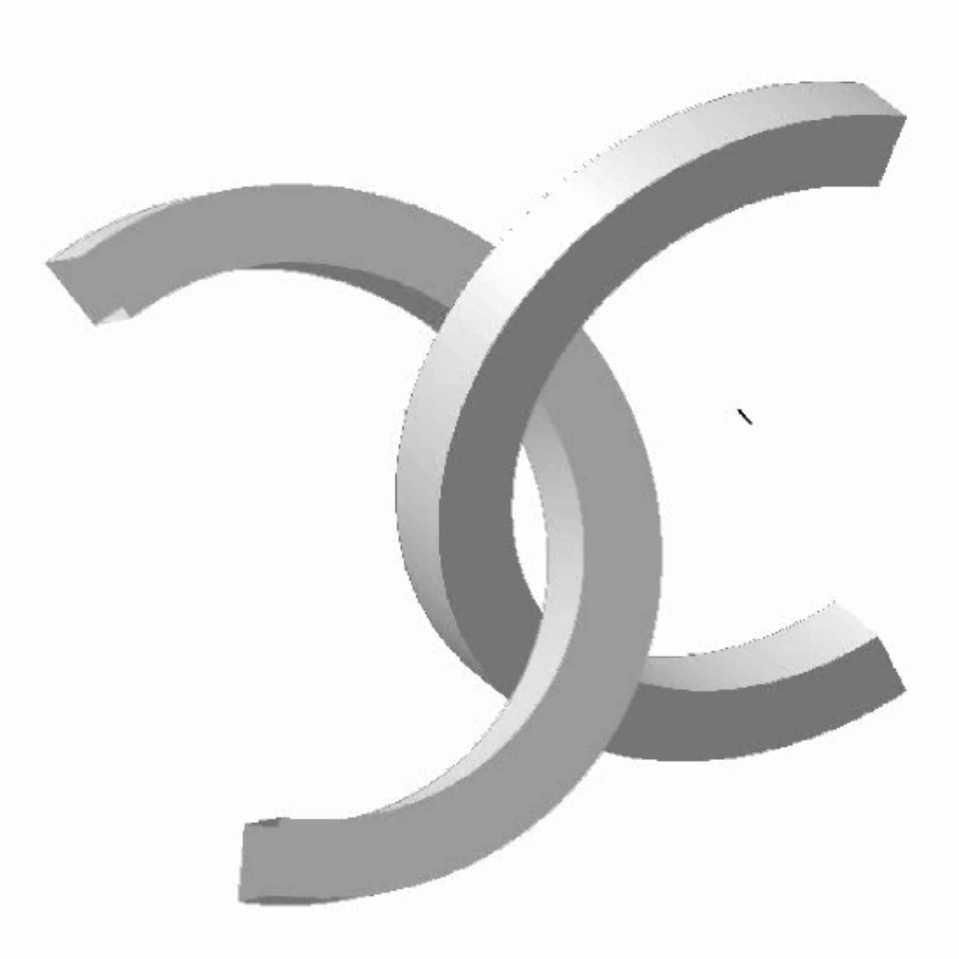
Non-neutral plasmas in a stellarator

- A stellarator is a magnetic surface configuration: Each magnetic field line wraps around a toroidal surface, never leaving the surface.



Non-neutral plasmas in a stellarator

- The twist of the magnetic field lines make the particles rotate poloidally as well as toroidally, averaging out the magnetic drifts even without any ExB drift.



Non-neutral plasmas in a stellarator

- The stellarator concept was developed for fusion 60 years ago
- Stellarators have some advantages over Penning and pure toroidal traps, and some disadvantages:
  - Fully toroidal – no end effects
  - Can confine plasma well even in the absence of significant space charge:
    - Not true for pure toroidal trap
  - Can confine both signs of charge simultaneously
    - Allows studies of partly neutralized plasmas, and arbitrarily low density non-neutral plasmas
    - Can confine electron-positron plasmas
  - Because of the lack of symmetry, confinement may be bad
    - Should be rather good by stellarator standards

Non-neutral plasmas in a stellarator: History

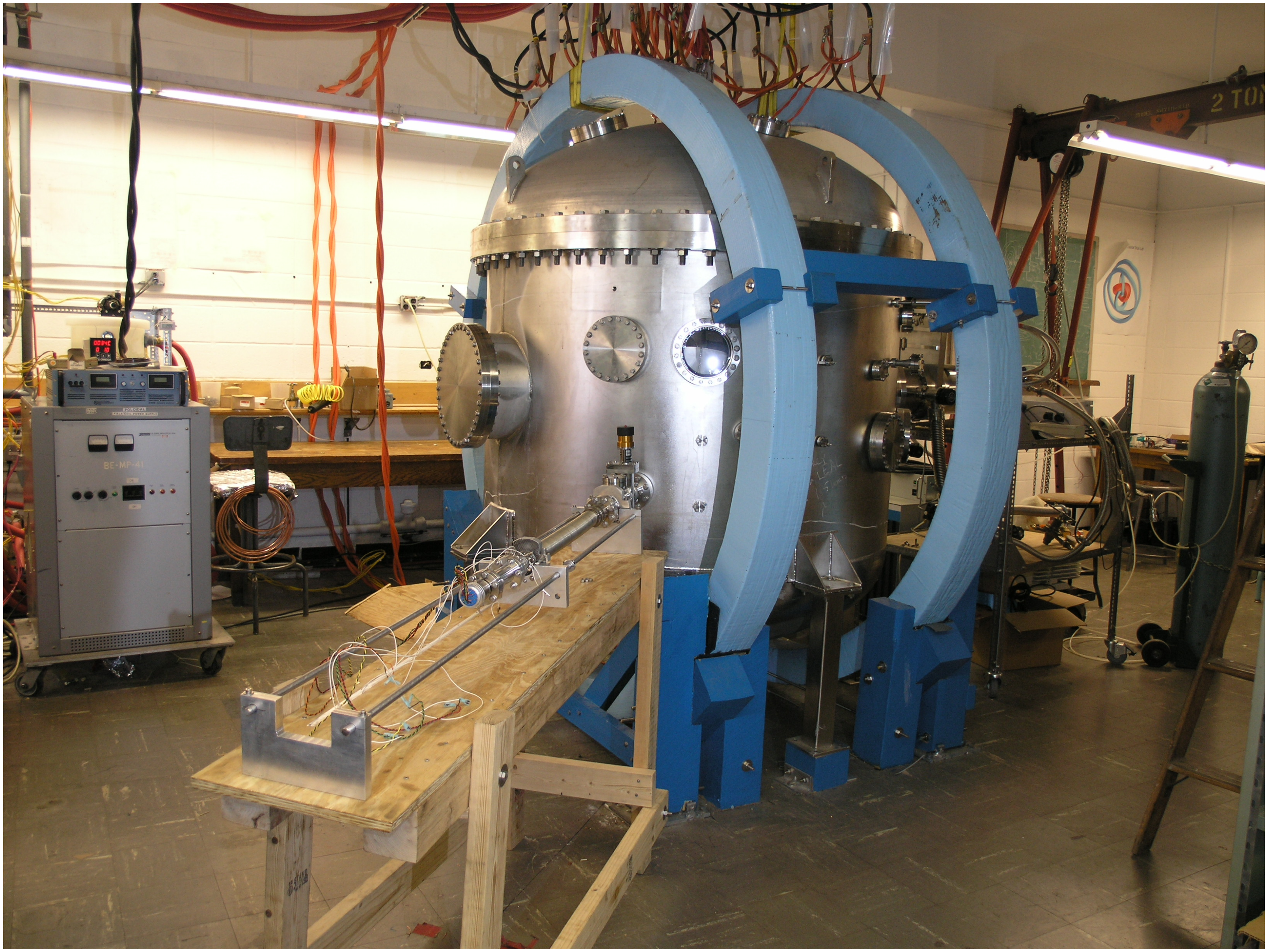
- The idea of confining a non-neutral plasma in a stellarator is about 10 years old[1]
  - Equilibrium equation derived
  - Unique capabilities recognized
- BUT! Non-neutral stellarator experiments were actually performed >20 years ago!
  - Auburn torsatron (USA, 1987)[2], and Uragan-2, Uragan-3 (USSR, 1988)[3] "Stellarator diode" – a field line mapping technique

[1] T. Sunn Pedersen and A. H. Boozer, PRL **88**, 2002

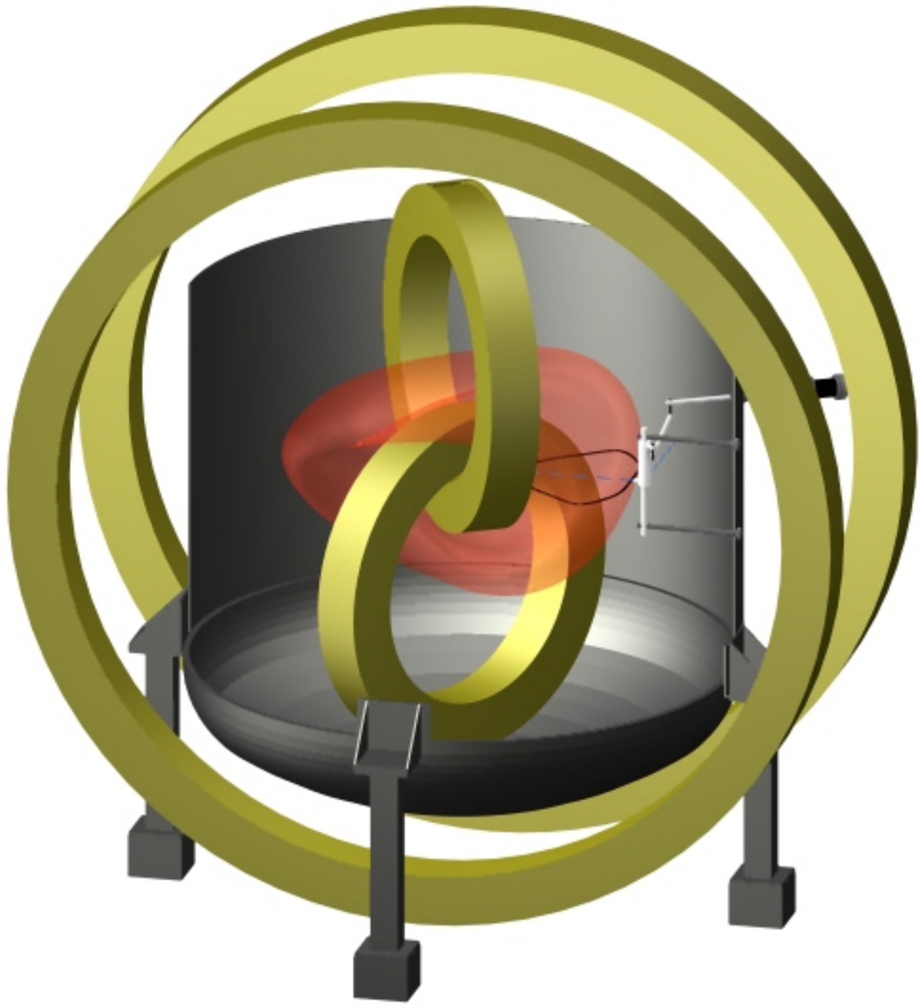
[2] R. F. Gandy, M. A. Henderson, et al., Rev. Sci. Instrum. **58** p. 509 (1987)

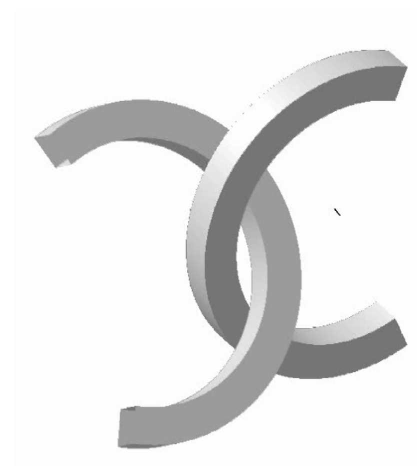
[3] A. G. Dikii, V. M. Zalkind, et al., Sov. J. Plasma Phys. **14** p. 160 (1988)

CNT: A stellarator dedicated to NNP physics since 2004



CNT is a simple and compact stellarator



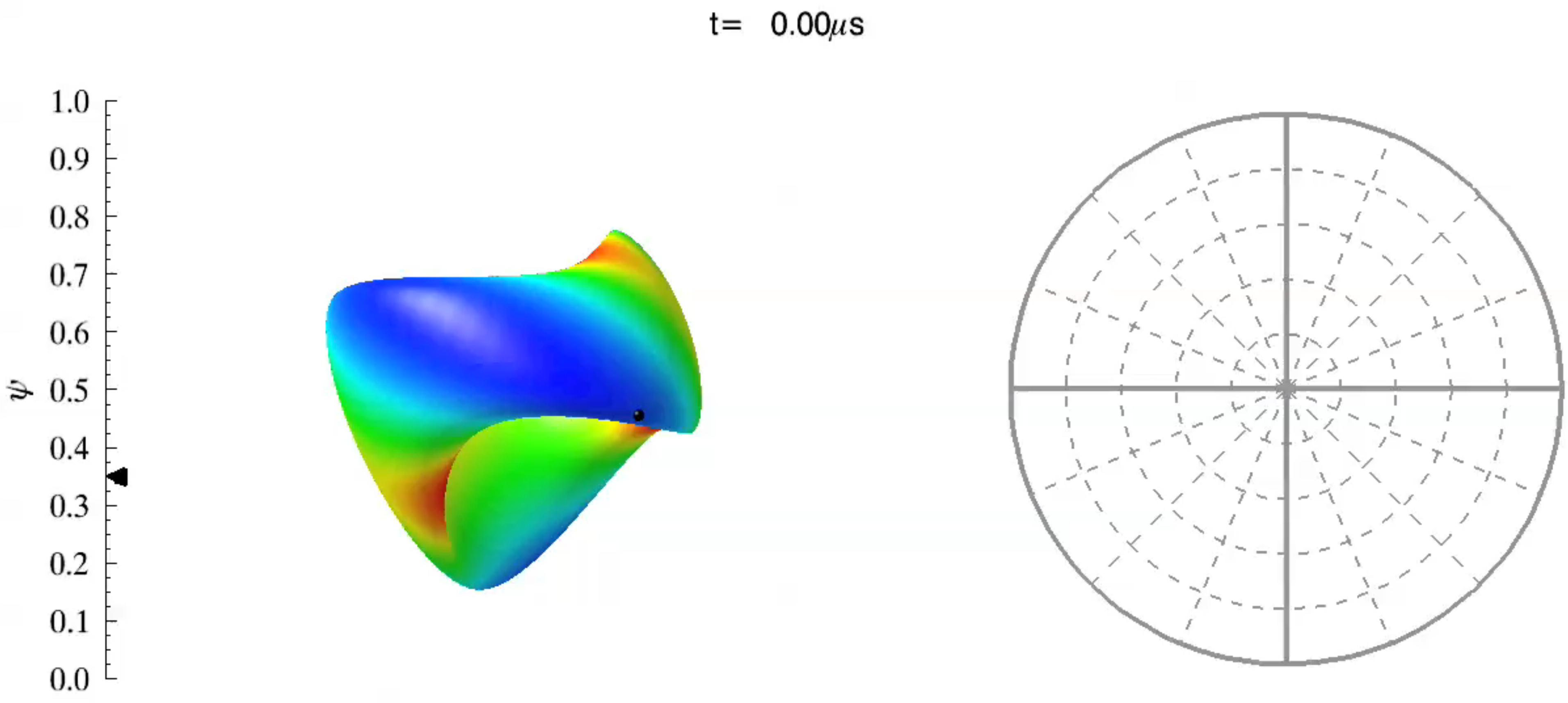


1 Gourdon et al., Plas. Phys. Contrl. Nucl. Fus. Research p. 849 (1969)
2 Pedersen et al., Fusion Sci. Tech. 46 p 200 (2004)

However, there are some “bad” orbits!

CNT is a “classical stellarator” – will not work well for fusion:

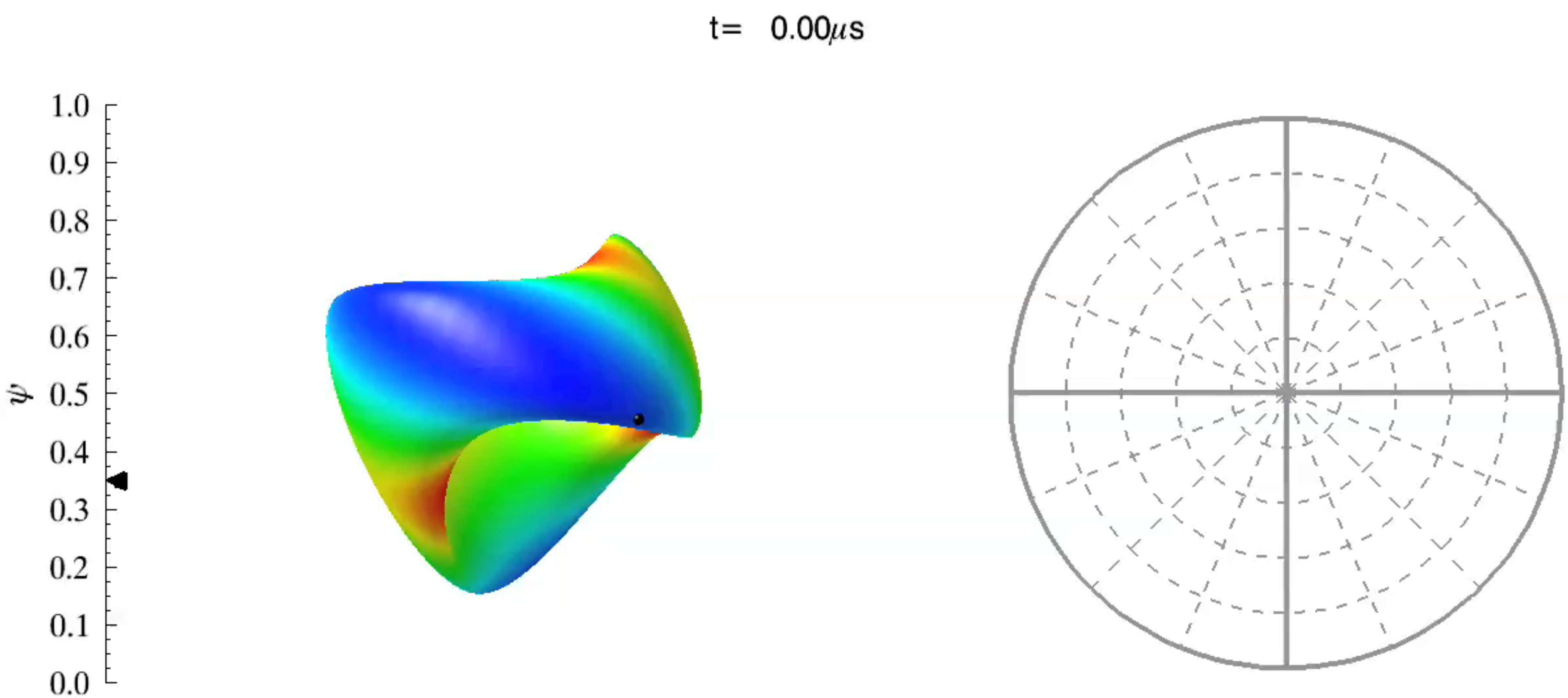
About 50% of particles are magnetically trapped (due to mirror force), don’t circulate toroidally, therefore don’t circulate poloidally, and consequently drift out of CNT. Example:



ExB comes to the rescue (again)

A strong space charge electric field – constant on a magnetic surface – is added to the simulation of the trapped particle

Now it is confined! For much the same reasons as in the pure toroidal field trap



Stellarators vs pure toroidal field traps

In a pure toroidal field trap, all particles in a Maxwellian distribution function are on “bad orbits”– unless ExB is strong

If ExB is strong (if plasma is non-neutral and the Debye length is small) then all particles have “good orbits”

A significant fraction of the particles in a Maxwellian is on “bad orbits” in a classical, unoptimized stellarator

If ExB is strong, then all particles may be on “good orbits”

An optimized stellarator (eg. quasi-symmetric or quasi-omnigenous) has almost all orbits (99%) of a Maxwellian confined.

Modest ExB can help even in this case – not just with single particle orbits but also to suppress unwanted collective phenomena (turbulence)

(but that is another topic)

Expected particle confinement in CNT

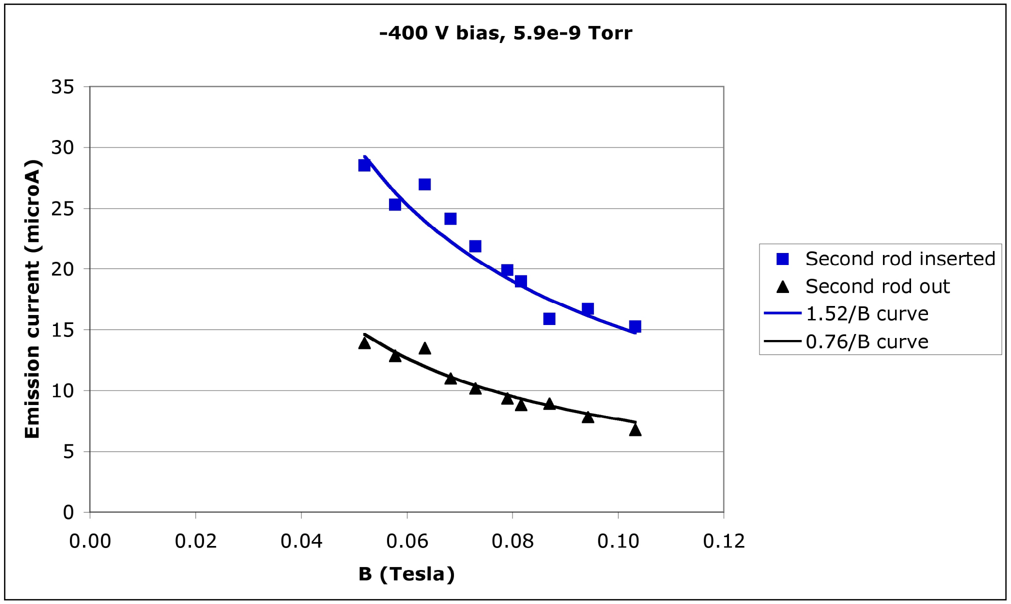
•CNT's pure electron plasmas have a strong electric field

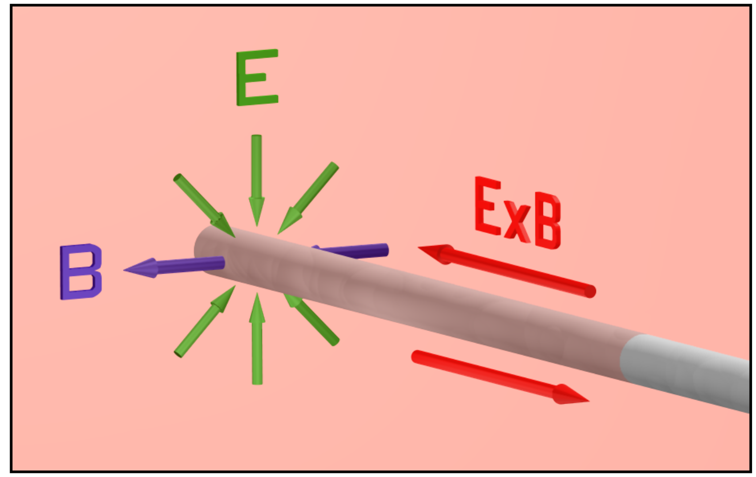
•$\Delta\phi$~200 V, T_e ~4 eV $\left|\frac{v_{ExB}}{v_{\nabla B}}\right| \approx \left|\frac{e\phi}{T_e}\right| \approx 50$

•Since ExB drift dominates over grad B and curvature drifts it should close otherwise bad orbits

•We expected confinement times well above 1 second

Experimental finding 1: Internal rods drive transport



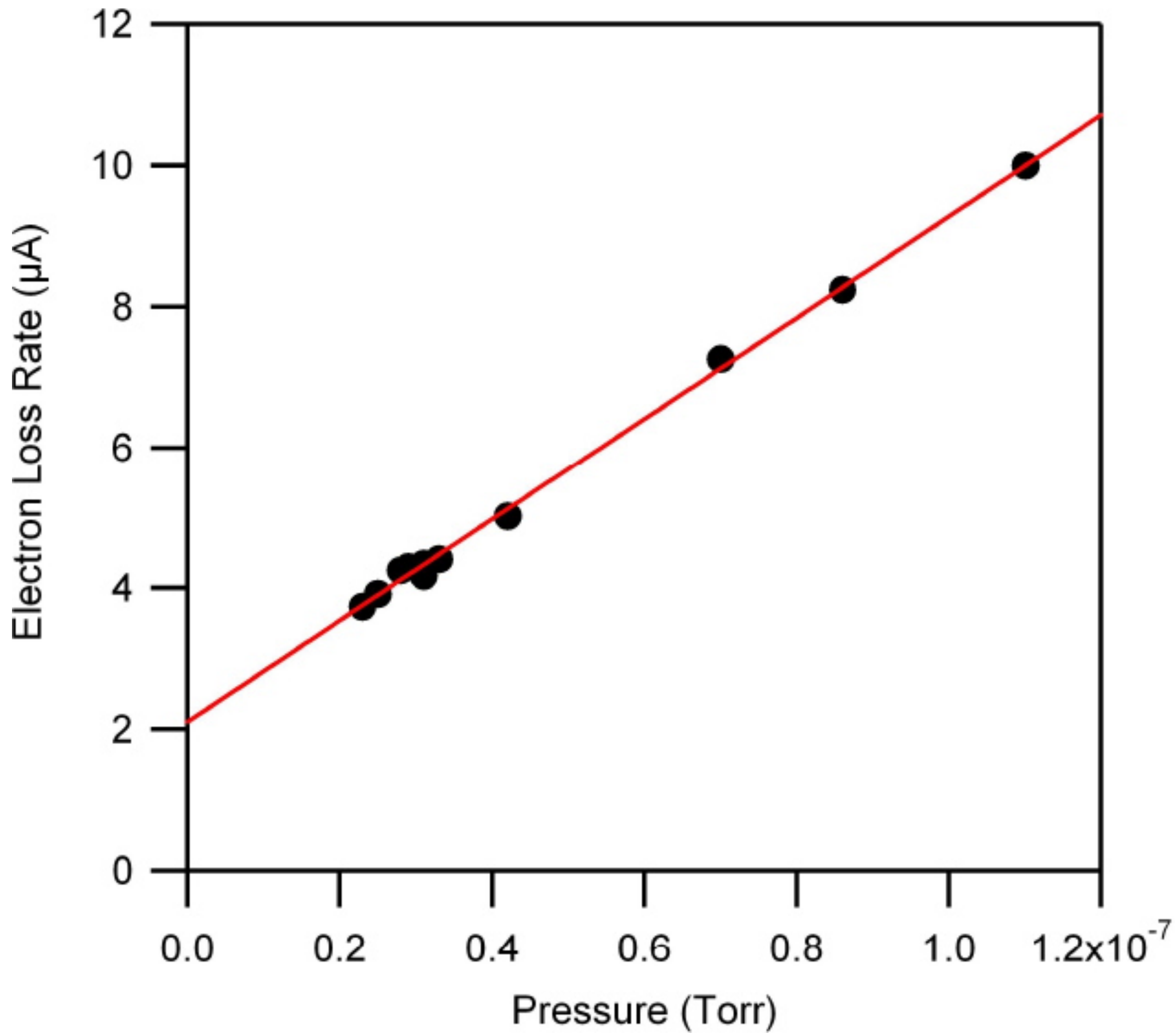


Insulated rods charge up negative relative to plasma to self-shield
Resulting ExB drift pattern convects particles along the rod all the way to the open field lines.

J. P. Kremer et al., PRL **97** (2006)

J. W. Berkery et al., Phys. Plasmas **14** 062503 (2007)

Exp. Finding 2: Neutrals also degrade confinement



Exp. Finding 2.1: Neutrals degrade confinement a lot

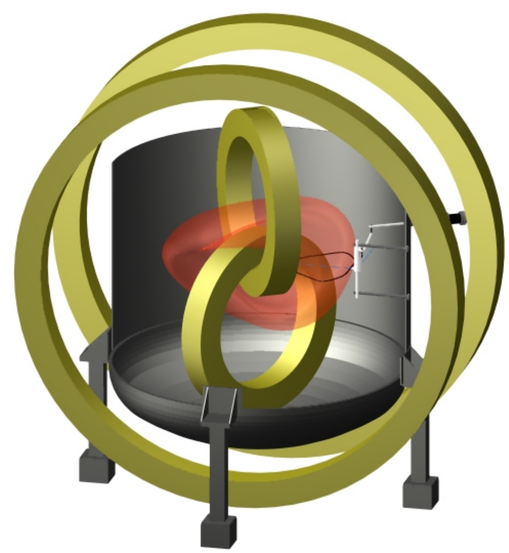
The loss rate due to neutral collisions is much larger than expected:

We would lose an electron after order unity electron-neutral collisions!

This is suggestive of poor particle orbit quality despite the large ExB drift

More detailed understanding of orbits in CNT needed:

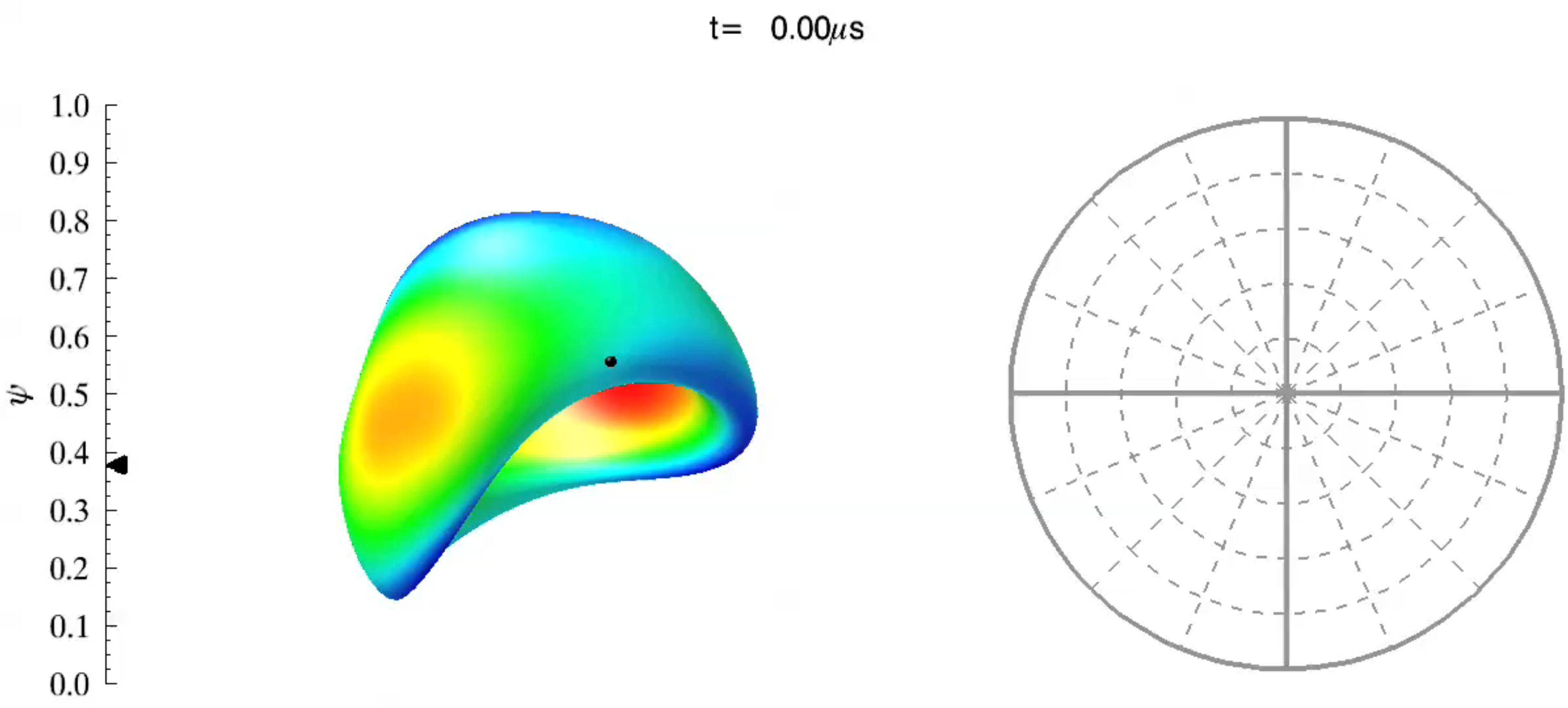
A numerical study was performed, adding the effects of the complex boundary condition in CNT



Details published in: “Numerical investigation of electron trajectories in the Columbia Non-neutral Torus”, B. Durand de Gevigney et al, Physics of Plasmas **16**, article 122502 (2009)

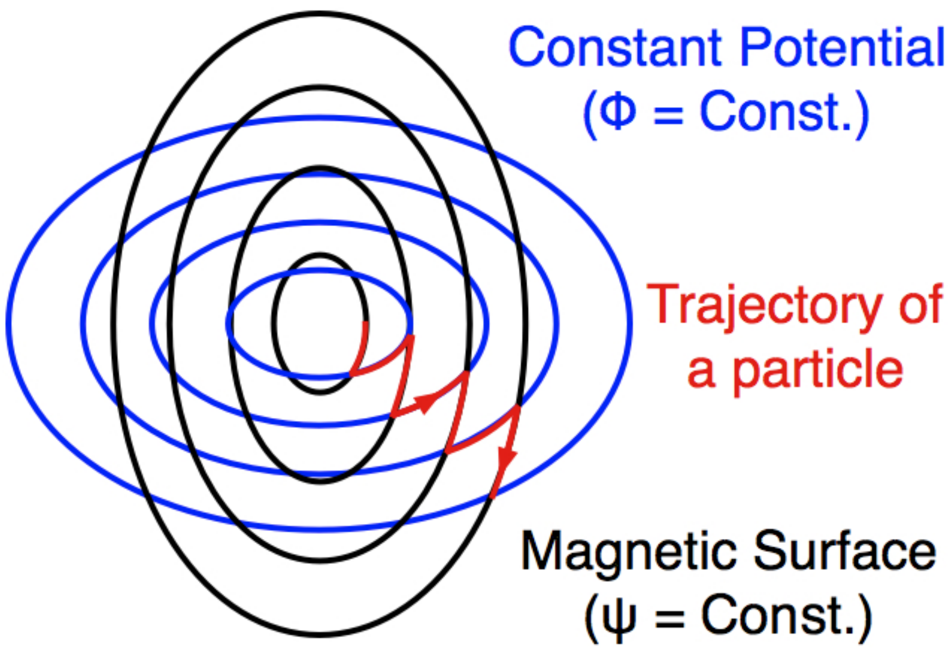
The effects of a non-conforming boundary condition

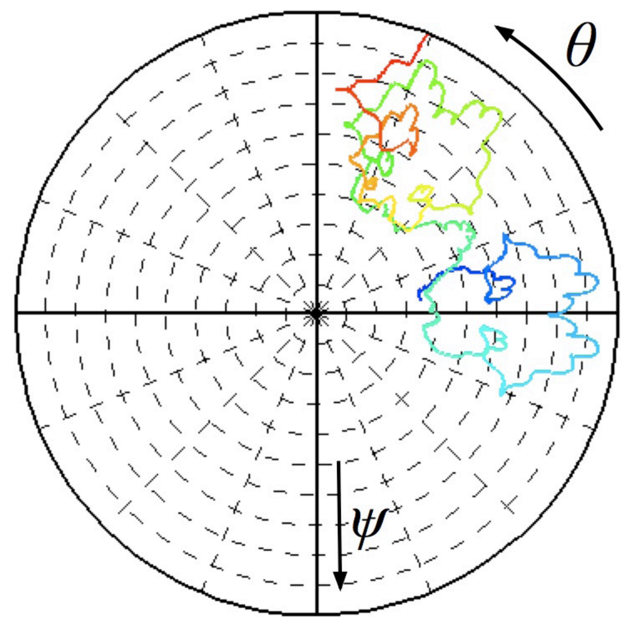
Until 2008, the internal coils and vacuum chamber set the electrostatic boundary condition **causing large electrostatic potential perturbations,** especially in the edge region



Intuitive picture of collisionless loss orbits with E

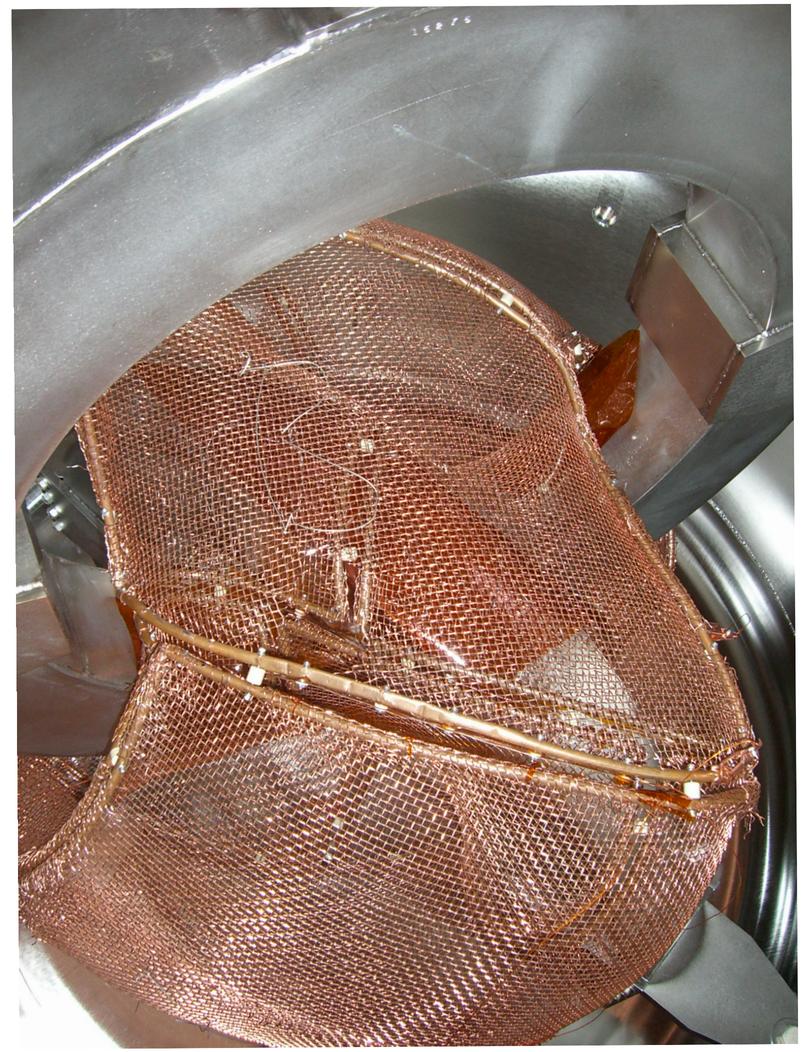
- ExB (perpendicular motion) takes electron along electrostatic potential contour
- Parallel motion of passing electrons (combined with rotational transform) takes electrons along the magnetic surface, moving them poloidally
- By switching between potential contours and magnetic surfaces, particles can make enormous radial excursions





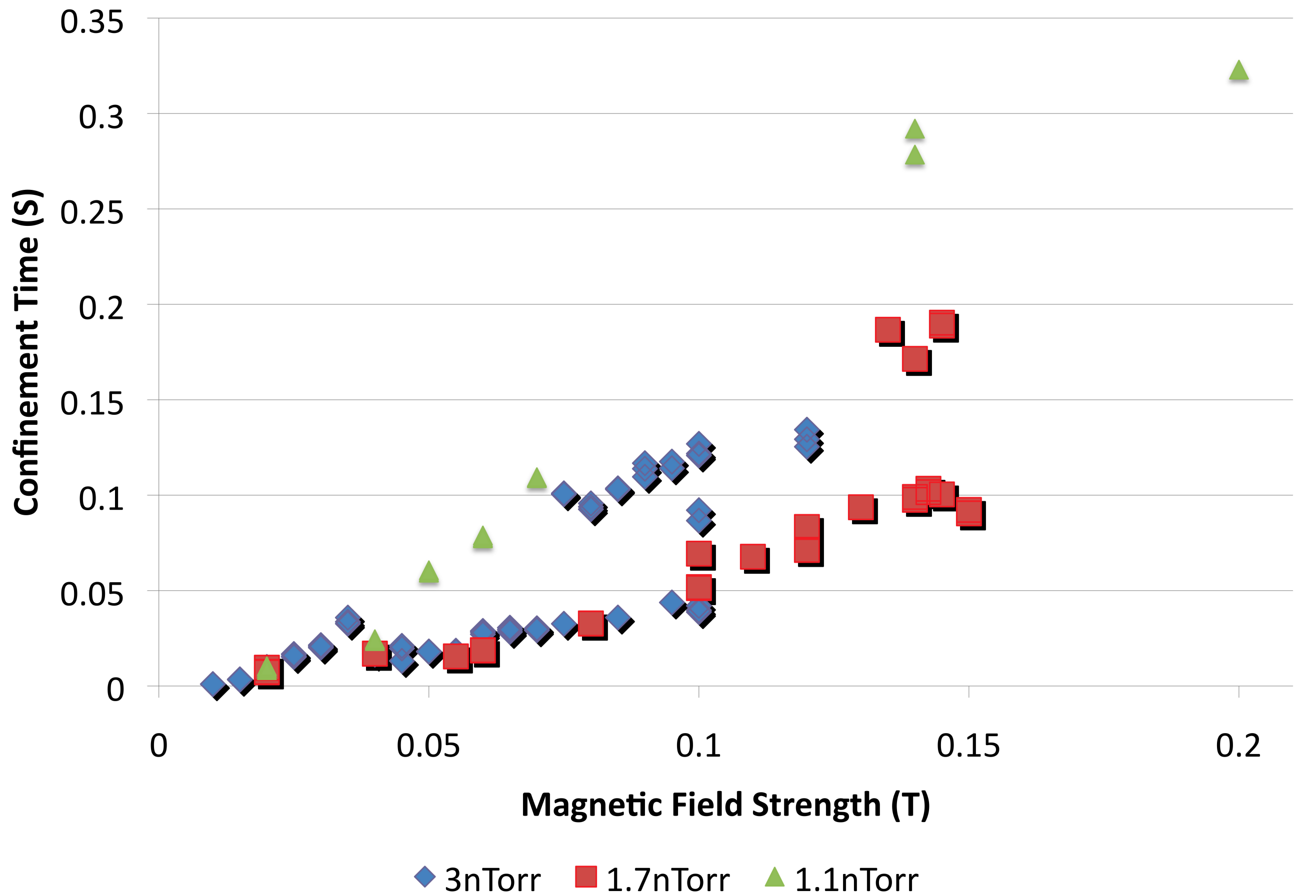
Flux surface conforming electrostatic boundary

- "Faraday cage" should bring us close to the ideal electric field (case 2)
- Was installed 2007-2010
- Was never perfectly aligned to the magnetic surfaces
- The mesh improved confinement significantly despite its flaws – but confinement improvements were not exactly as expected



P. W. Brenner et al., accepted in Contributions to Plasma Physics

Record confinement (for a stellarator): 0.32 seconds



Confinement time increase is due mainly to better vacuum and a higher B-field but also due to smaller Debye length but only a modestly improved orbit quality

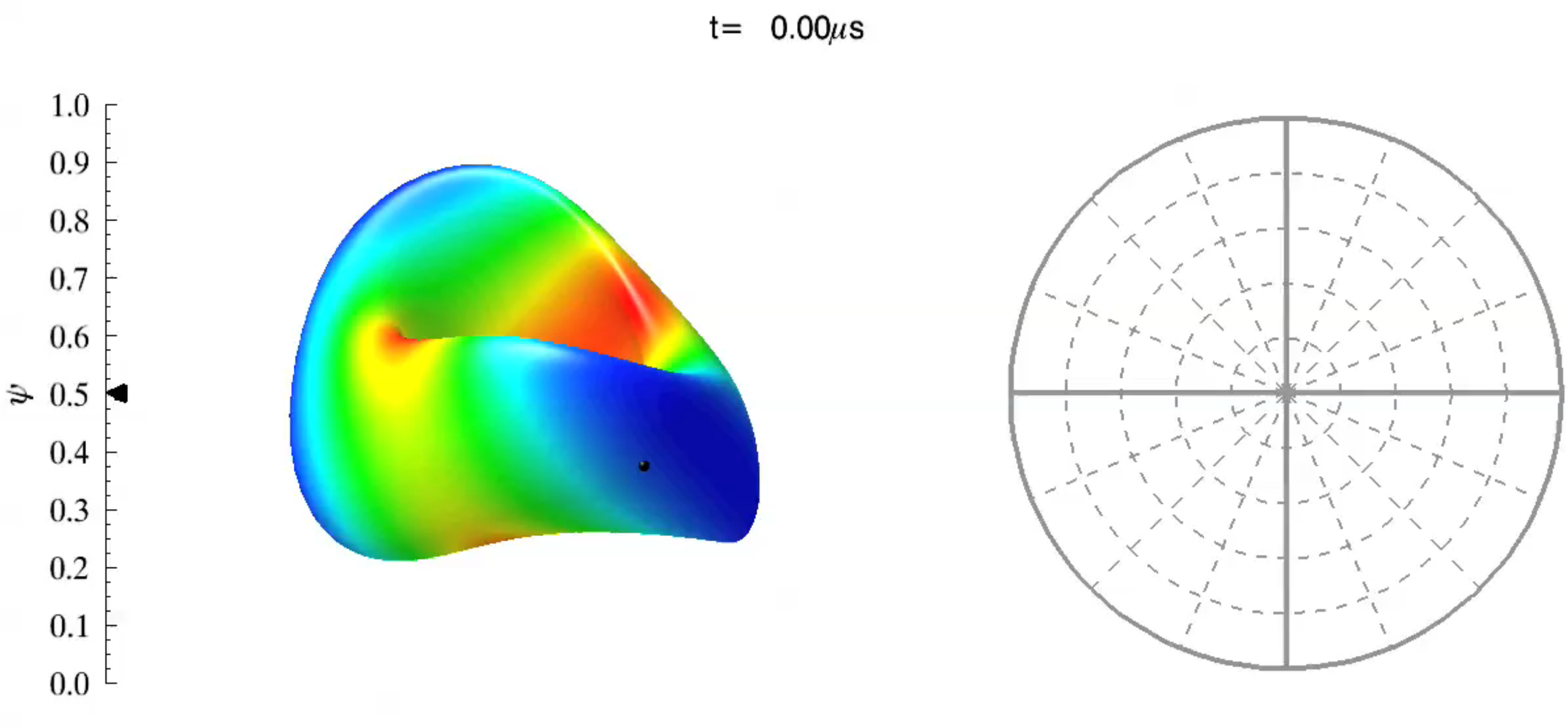
[1]P. W. Brenner et al., Contributions to Plasma Physics (2010)

Idealized electric field with resonance orbit

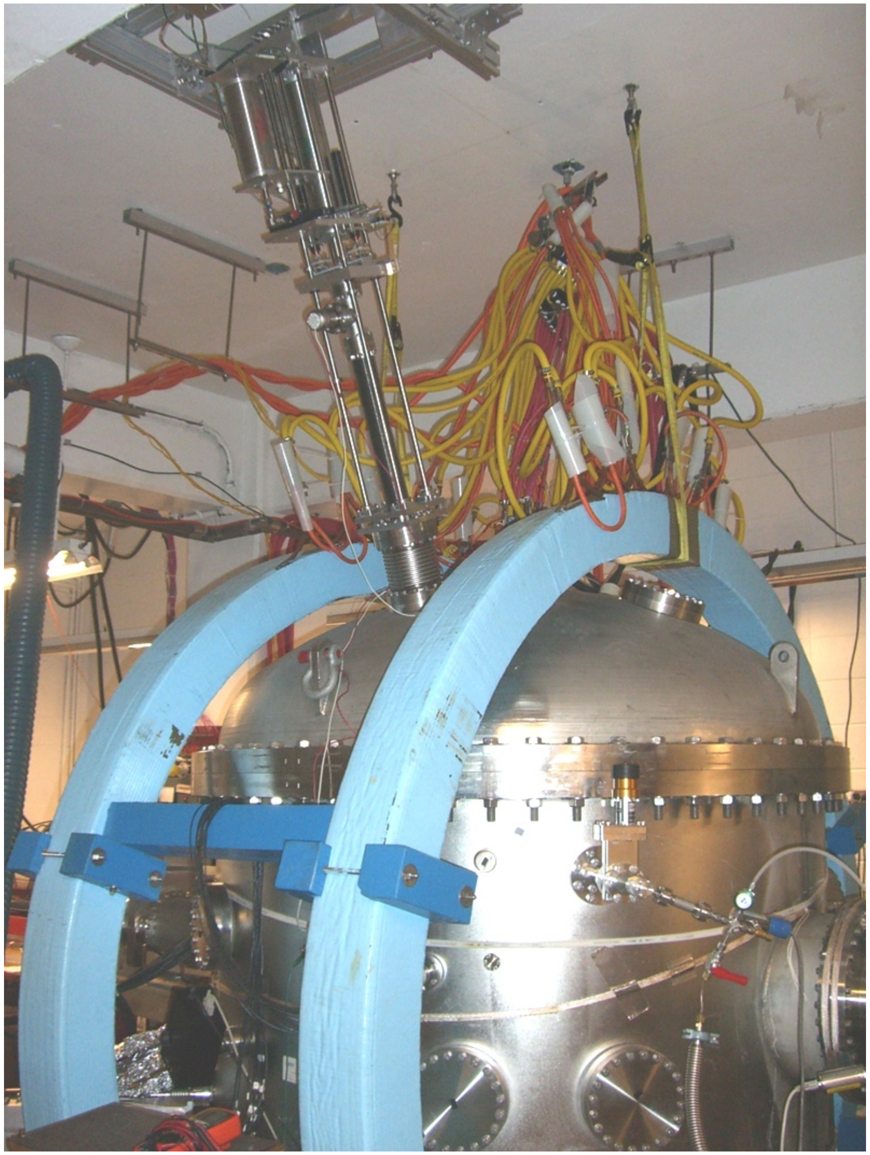
Orbits can make large excursions even with the idealized electric field

This is a resonance phenomenon – only a small fraction of particle orbits are affected: ExB cancels poloidal part of parallel motion for passing particles

Similar appearance to tokamak “banana” orbits – but for passing particles (banana orbits in tokamaks are magnetically trapped)

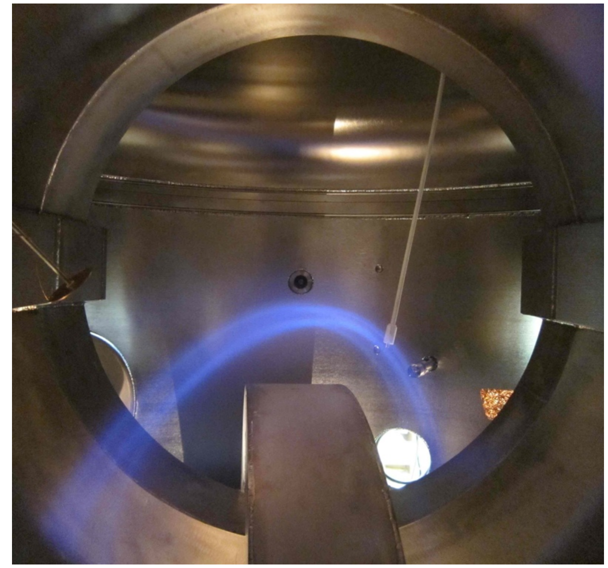


Emitter capable of retraction in 20 msec installed: There should be plasma left

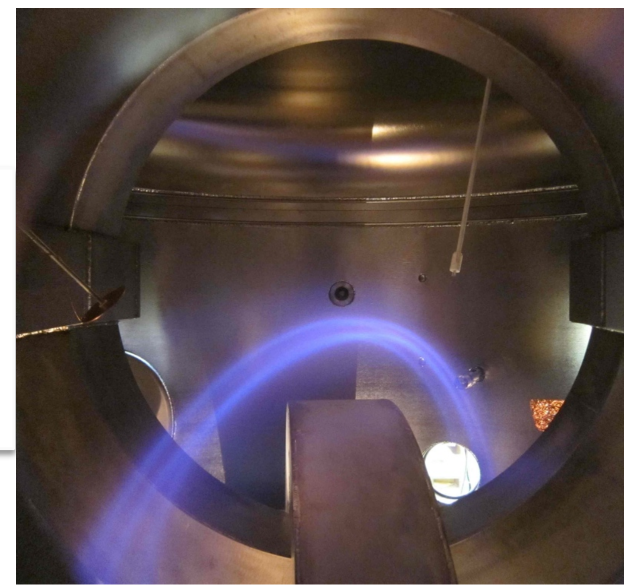


Design: Berkery et al. RSI (78) 2007

In Surfaces



Retracted



First results from retraction experiments were disappointing

Even though retraction in 20 msec was achieved, there appeared to be no plasma left after retraction

This was true even for conditions that for steady state injection resulted in at least 100 msec confinement

Were our previous confinement results somehow overestimated?

First results from retraction experiments were disappointing

Even though retraction in 20 msec was achieved, there appeared to be no plasma left after retraction

True even for conditions that should result in at least 100 msec confinement

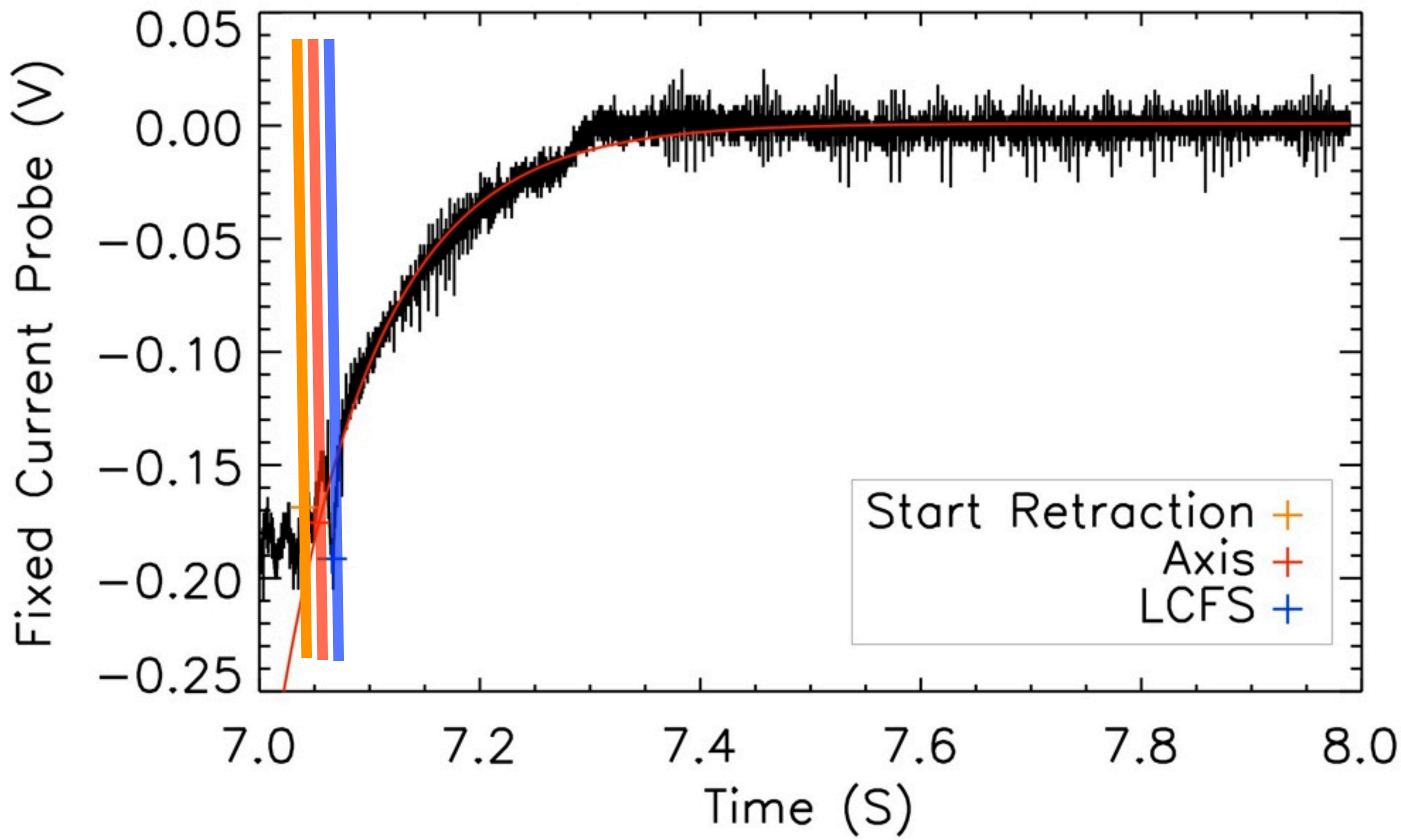
Were our previous confinement results somehow overestimated?

Diagnostic methods that were capable of measuring fast plasma decays (a few milliseconds) fully external to the plasma needed to be developed

With a reliable and non-perturbative diagnostic we found:

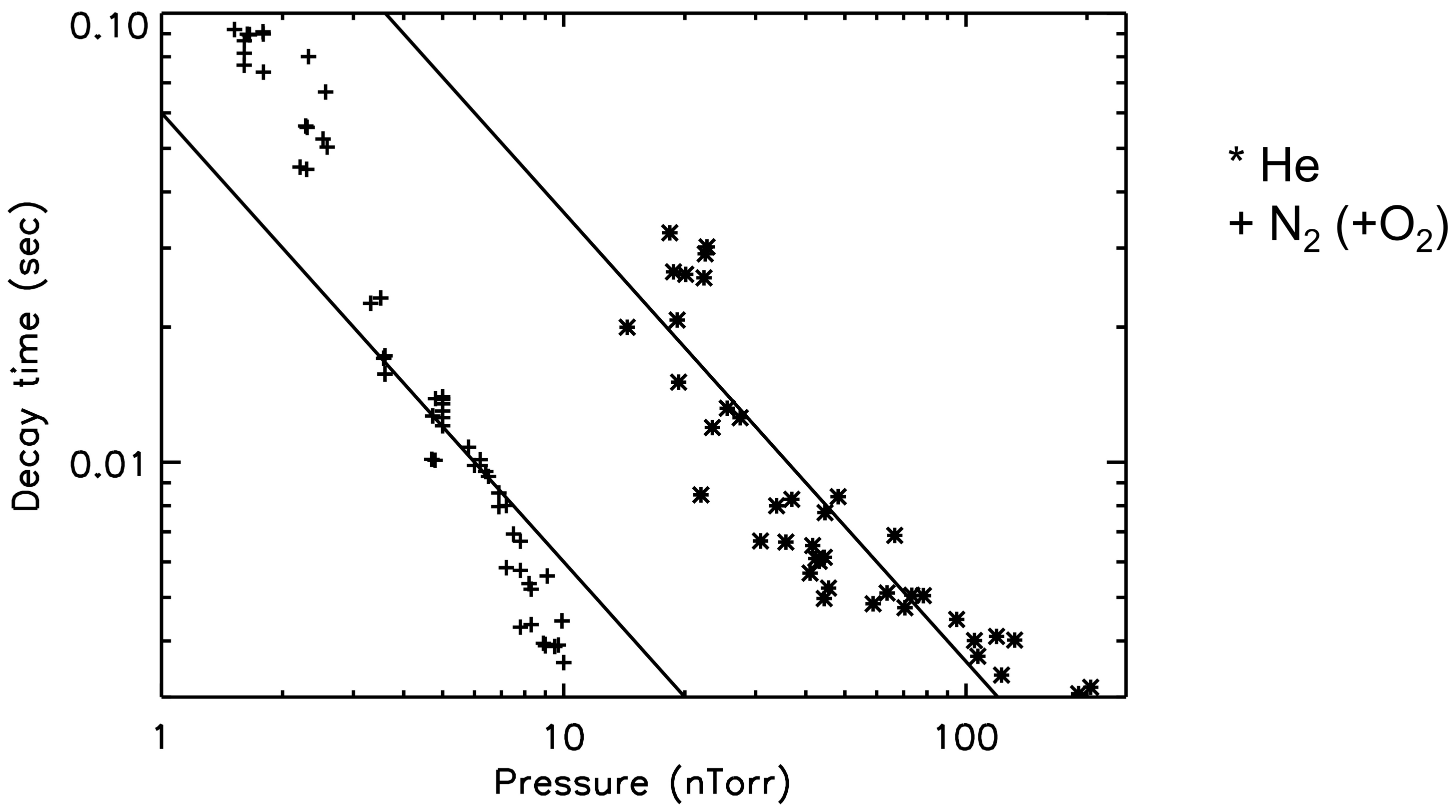
Confinement is much more sensitive to neutral pressure for retraction plasmas; confinement is much shorter for the neutral pressures that we can reach

Success: A plasma remains after retraction



Plasma clearly remains after retraction:
~90 msec exponential decay time (B=0.055T, p_n=1.8*10^{-9} Torr):
Plasma disappears quickly because of ion contamination

Plasma decay is determined by ion contamination

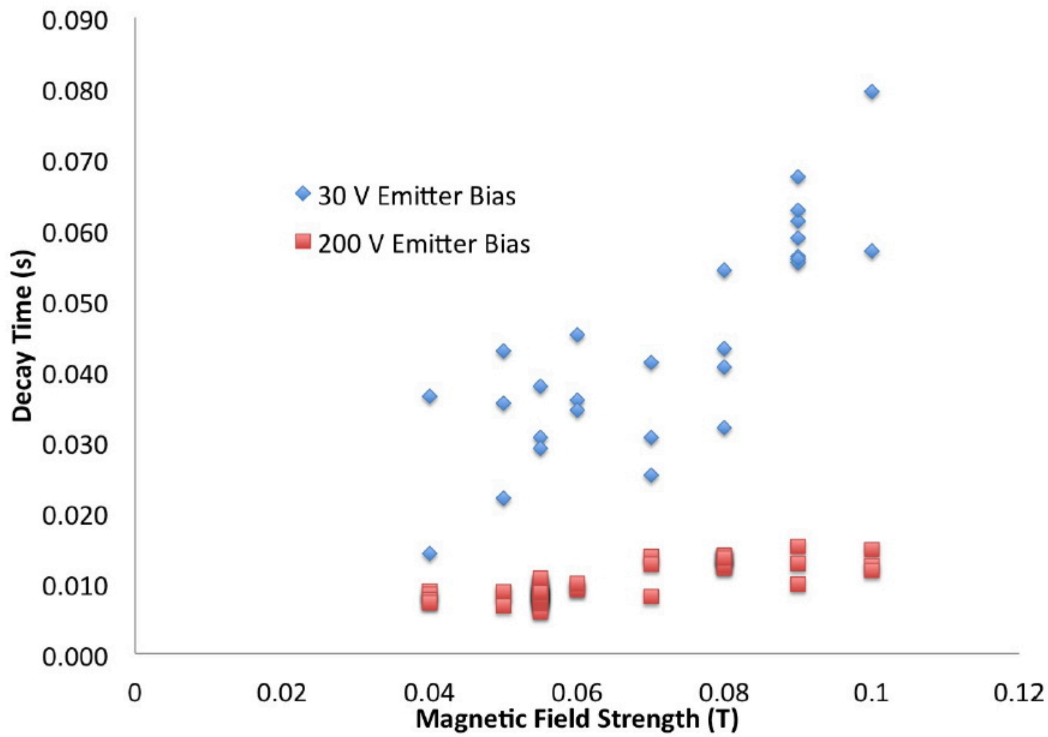


Confinement scales faster than linear with neutral pressure for nitrogen dominated discharges (+) and the decays are very fast. Confinement is much better and scales approximately linearly with neutral pressure for helium dominated discharges (*). Data at 0.055 T, φ=-200 V

First ionization energy: He 24.6 eV, N 14.5 eV

Comparison between low T and high T plasmas also consistent

- •We know from from previous experiments that T increases with the plasma potential so can operate below ionization threshold for thin plasmas
- •When we avoid the fast crash due to ionization, the confinement time τ is linearly improved by the B-field strength (as one would expect)



Partially neutralized plasmas

Partially neutralized plasmas

- Due to the longitudinal electrostatic confinement concept in the Penning trap, it can only confine single species plasmas (actually: plasmas with the same sign for the charge)
- Pure toroidal field traps rely on the non-neutrality of the plasma for confinement
- Stellarators, however, provide at least some confinement of particles regardless of the degree of neutralization
- Can we create and study plasmas at any degree of neutralization?
  - And at the same time have a small Debye length?
  - Can we operate stably for extended periods of time at any degree of neutralization?

Charting the landscape from pure electron to quasi-neutral plasma

- By increasing the neutral pressure we can vary the degree of neutralization (by adding ions)
- We parameterize the degree of non-neutralization this way:

$$\eta = \left| \frac{Zn_i - n_e}{Zn_i + n_e} \right|$$

- A pure electron plasma has η=1
- Typical range for quasineutral laboratory plasmas is $\eta=10^{-8}$ to 10^{-3}
- When you enter uncharted territory – begin charting!

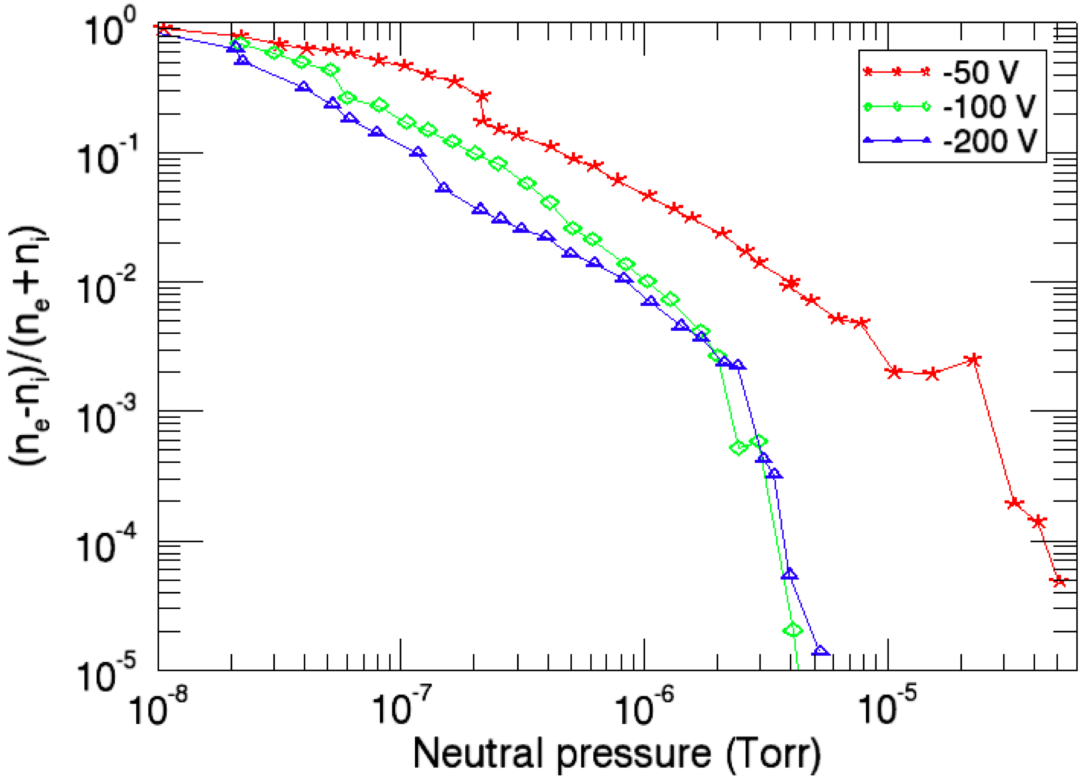
[1]X. Sarasola et al., Contributions to Plasma Physics (2010)

Charting the landscape from pure electron to quasi-neutral plasma

- We parameterize the degree of non-neutralization this way:

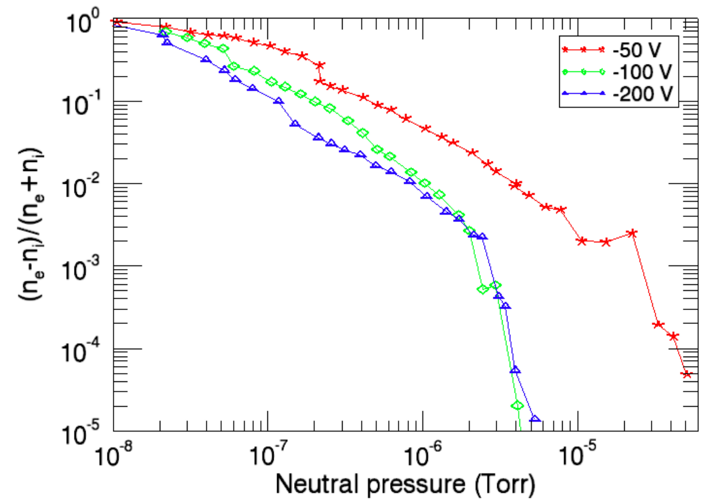
$$\eta = \left| \frac{Zn_i - n_e}{Zn_i + n_e} \right|$$

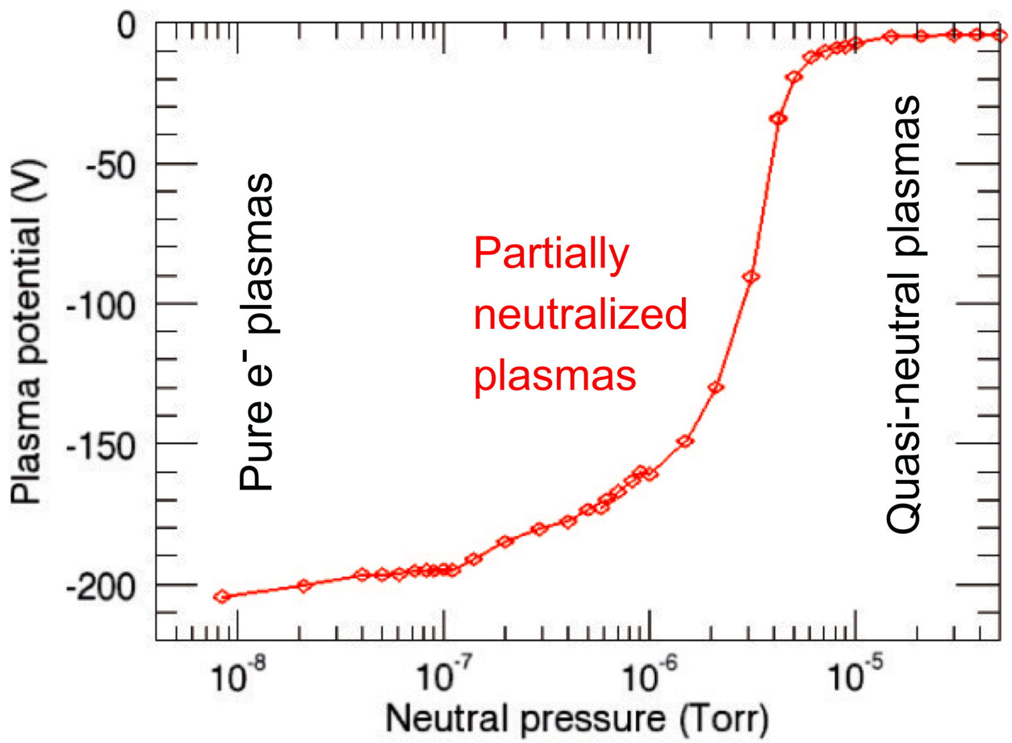
- A pure electron plasma has η=1
- Typical range for quasineutral laboratory plasmas is $\eta=10^{-8}$ to 10^{-4}



Charting the landscape from pure electron to quasi-neutral plasma

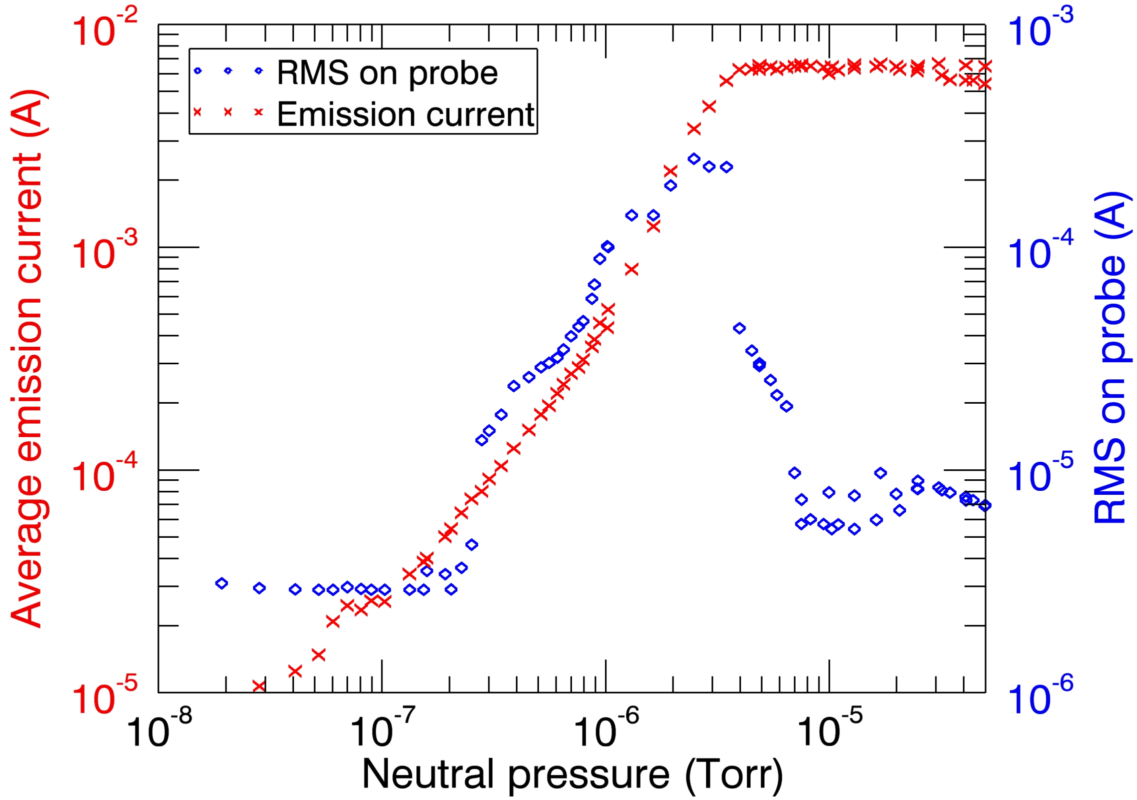
•Plasma potential decouples from filament bias as the plasma becomes quasineutral

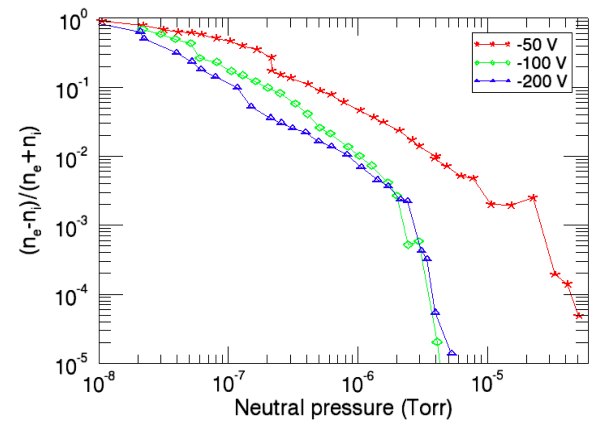


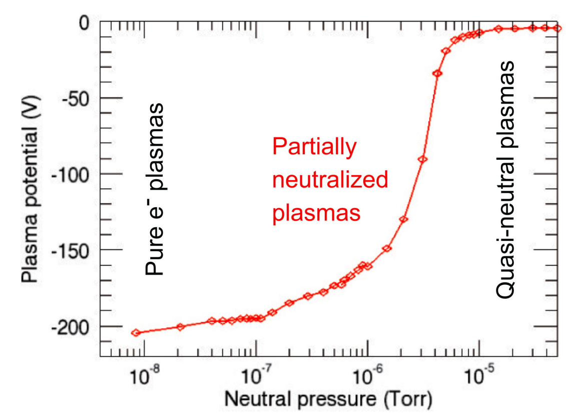


Charting the landscape from pure electron to quasi-neutral plasma

- Pure electron plasmas: Quiescent, well confined
- η~0.5: ~100 kHz single mode behavior (Marksteiner et al., PRL 2008)
- η~0.01: Broadband turbulence
- η~0.0001:4 kHz single mode behavior
- Charge confinement continually deteriorates







Future plans: Electron-positron plasmas

Future plans: Electron-positron plasmas

- Unique plasma physics due to the symmetry between the two species
  - Theory relatively easy
  - Numerical simulations relatively easy
  - Some interesting differences to electron-ion plasmas[1]:
    - Ion acoustic waves do not propagate (if $T_e = T_p$)
    - No difference between low frequency waves (eg. MHD) and high frequency waves (L, R, O, X)
  - "The hydrogen atom of plasma physics"
- Are important for the dynamics around black holes, neutron stars and other high energy density astrophysical objects
- Have not been created in a laboratory yet
  - Need bright source of moderated positrons
  - Need a confinement device that confines both electrons and positrons, at low density and possibly large energy
  - Stellarator may be the answer[2].

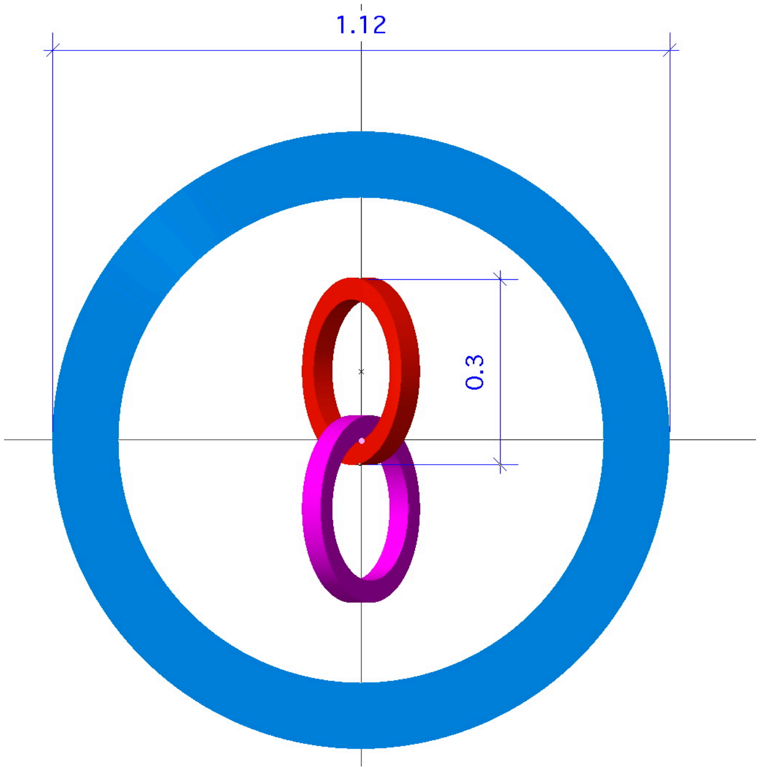
[1] Tsytovich and Wharton, Comments Plasma Phys. Contr. Fusion (1978)

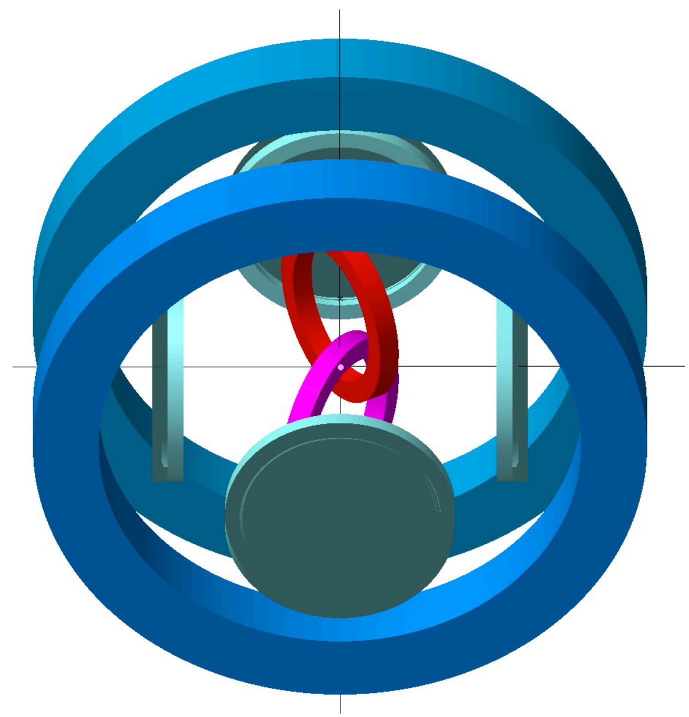
[2] T. Sunn Pedersen et al., J. Phys. B (2003)

A Positron Electron eXperiment (APEX)

- A stellarator based on CNT's design and results
- Volume reduced by factor of 10
- B-field increased by a factor of 10: 2 Tesla instead of 0.2 Tesla
- Vacuum will hopefully be $1*10^{-10}$ Torr during operation – also a factor of >10 better than CNT

- APEX is now in the design phase with the hope that it will be constructed this year





APEX volume 10 times smaller than CNT's

- For the same pumping speed (money) get better vacuum
- Coils are cheaper in smaller size
- We don't know how size affects confinement…but will take the chance
- For the same number of positrons, get more Debye lengths by making experiment smaller:

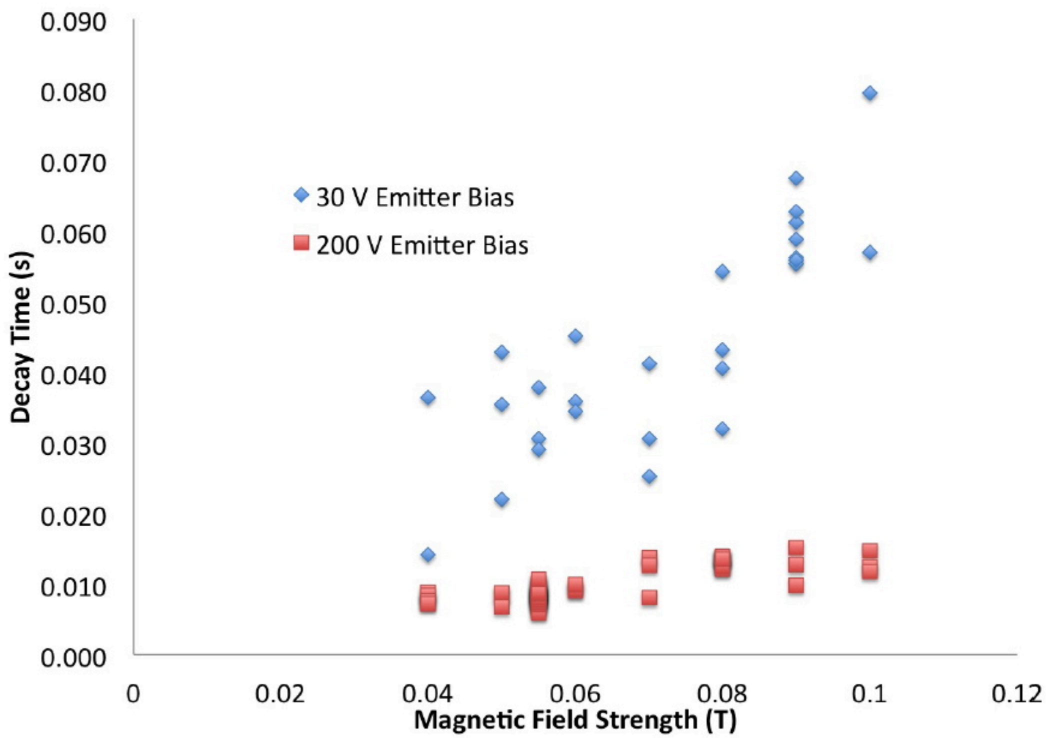
$$n = N/V = N * const * a^{-3}$$

$$\frac{a}{\lambda_D} = \frac{a}{\sqrt{\frac{\varepsilon_0 T_e}{ne^2}}} = \frac{a\sqrt{n}}{\sqrt{\frac{\varepsilon_0 T_e}{e^2}}} = \frac{a * k * \sqrt{N} * a^{-1.5}}{\sqrt{\frac{\varepsilon_0 T_e}{e^2}}} \sim a^{-0.5}$$

APEX B-field 10 times larger than CNT's

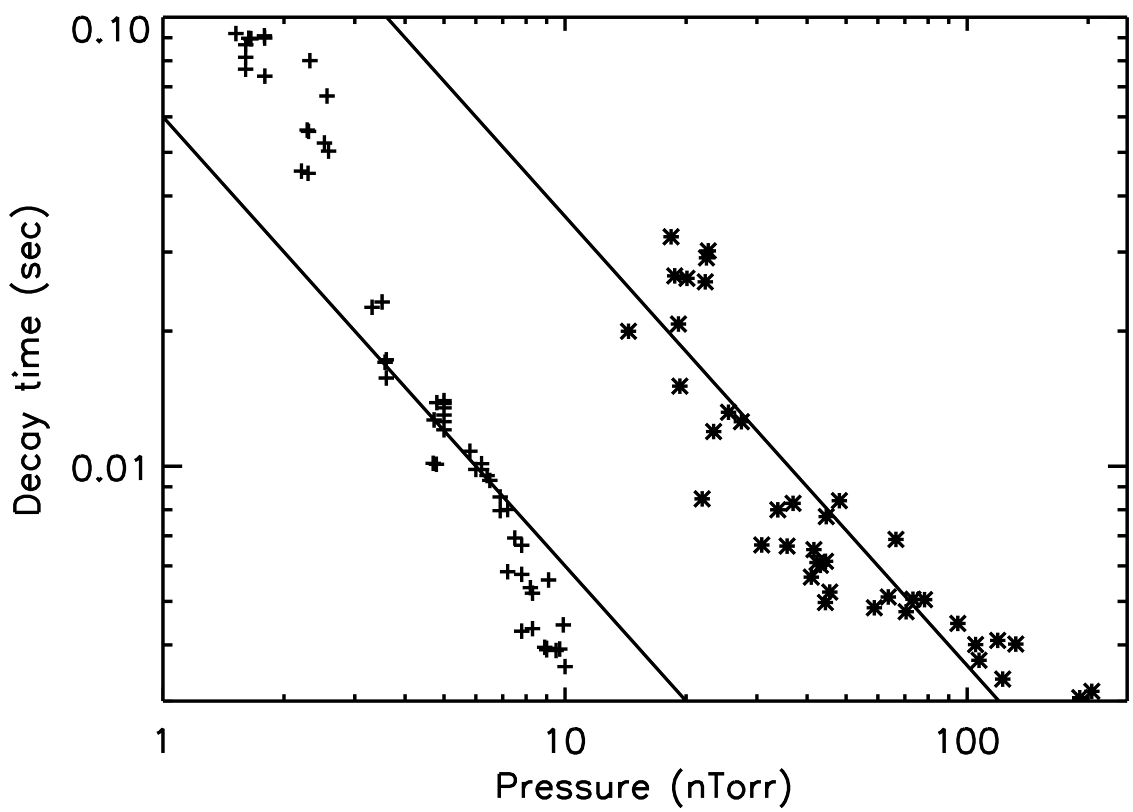
- When we avoid ionization collapse, confinement gets better with B
    - CNT data project to a confinement time above 1 second at B=2 T
- Cyclotron cooling becomes important at 2 Tesla and 1 second confinement time:

$$\tau_{\text{cooling}} \approx \frac{B^2}{4} \ (\text{in s/T}^2) \approx 1 \text{ sec for B} = 2 \text{ T}$$



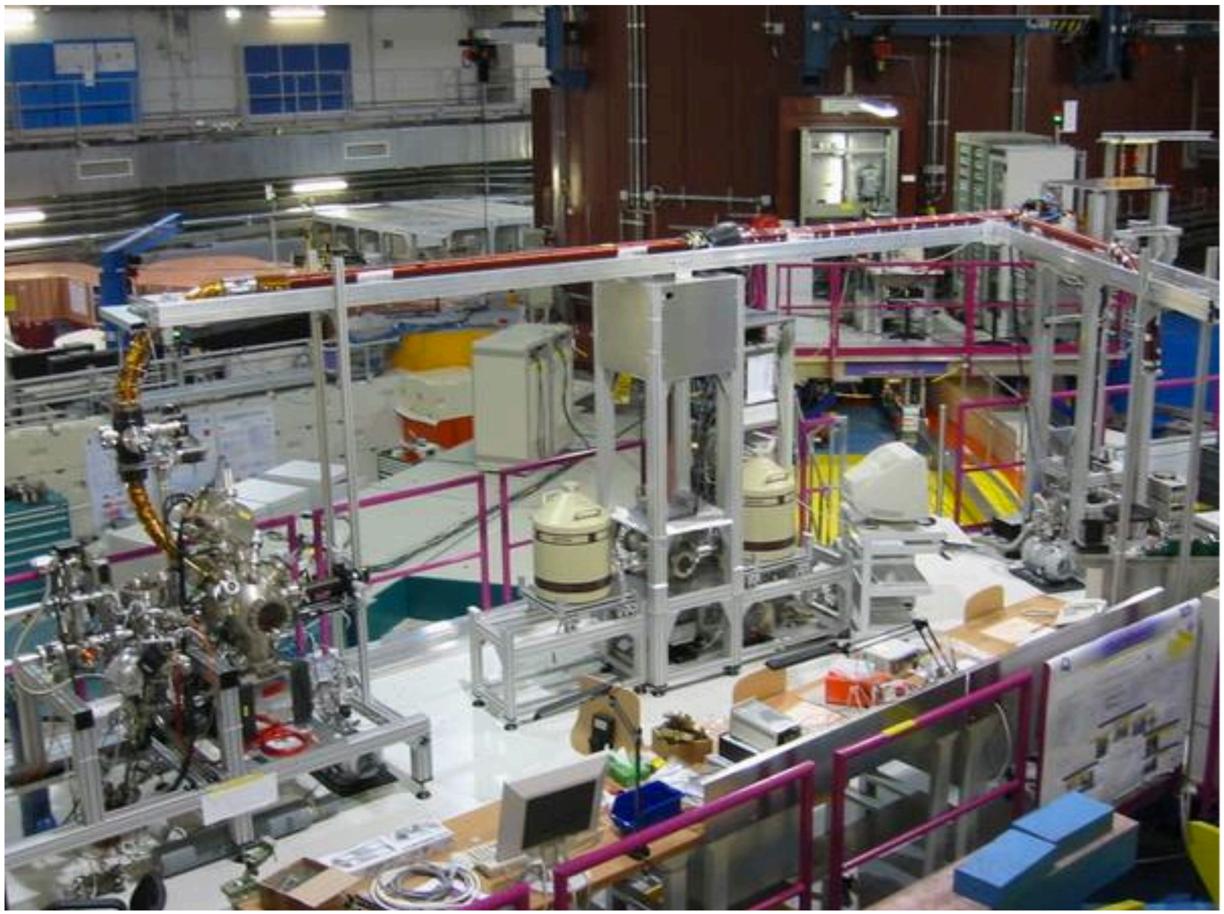
APEX vacuum 10 times better than CNT's

- Avoid ionization collapse
- Avoid ion contamination (electron-positron-ion plasma is interesting in its own right but we primarily want to study electron-positron plasmas)
- Avoid annihilation on neutrals (not a critical concern)



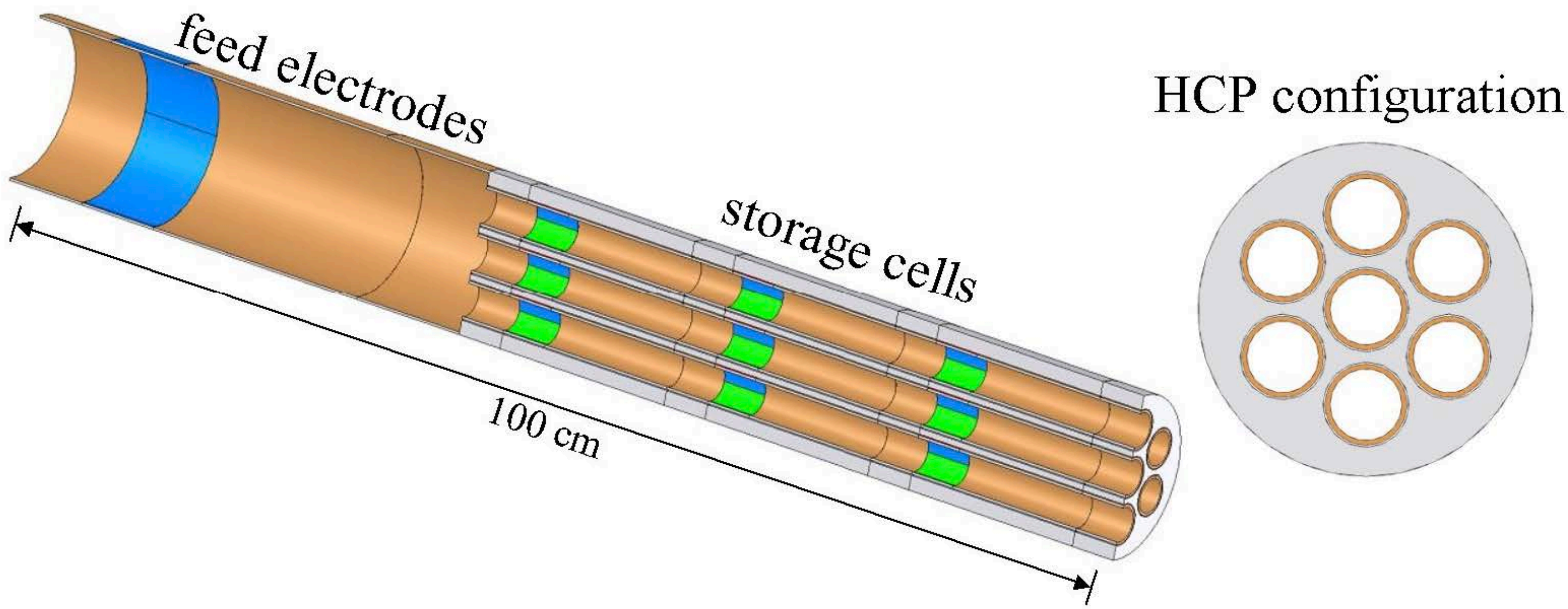
Positron accumulation experiment (PAX)

- Even the brightest sources today cannot supply 10^{11} positrons in $<10^{-2}$ seconds (ie. 10^{13} positrons/second).
- NEPOMUC source in Munich has achieved $9*10^{8}$ positrons/second
- Upgrade to new cadmium source may allow $3*10^{9}$ ps/sec this year



Positron Accumulation eXperiment (PAX)

- Even the brightest sources today cannot supply more than 10^{11} positrons in less than 10^{-2} seconds (ie. 10^{13} positrons/second).
  - (NEPOMUC $9*10^8$ moderated positrons/second, world leader)
- We will need a positron accumulation stage:
  - Collaboration with Cliff Surko and James Danielson UCSD
  - Buffer gas trap fills multicell Penning trap array
  - PAX positrons are injected into APEX



Summary

- Toroidal systems provide new interesting confinement and stability physics for non-neutral plasmas
    - Cannot compete with Penning trap in terms of confinement quality (can’t beat infinity), but perhaps in terms of interesting physics
- Due to the lack of a large sink for ions, ion accumulation in a pure electron toroidal plasma often limits confinement
- Low electron temperature and excellent vacuum (also) important
- Latest generation of toroidal experiments have much better confinement
    - Dipole with >300 second confinement time
- In stellarators, complicated drift orbits may be present and may limit confinement
    - Space charge electric field may be good or bad
    - Rods limit confinement but also limit ion build up
    - Partially neutralized plasmas can be studied
    - It appears feasible to make an electron-positron plasma in a stellarator