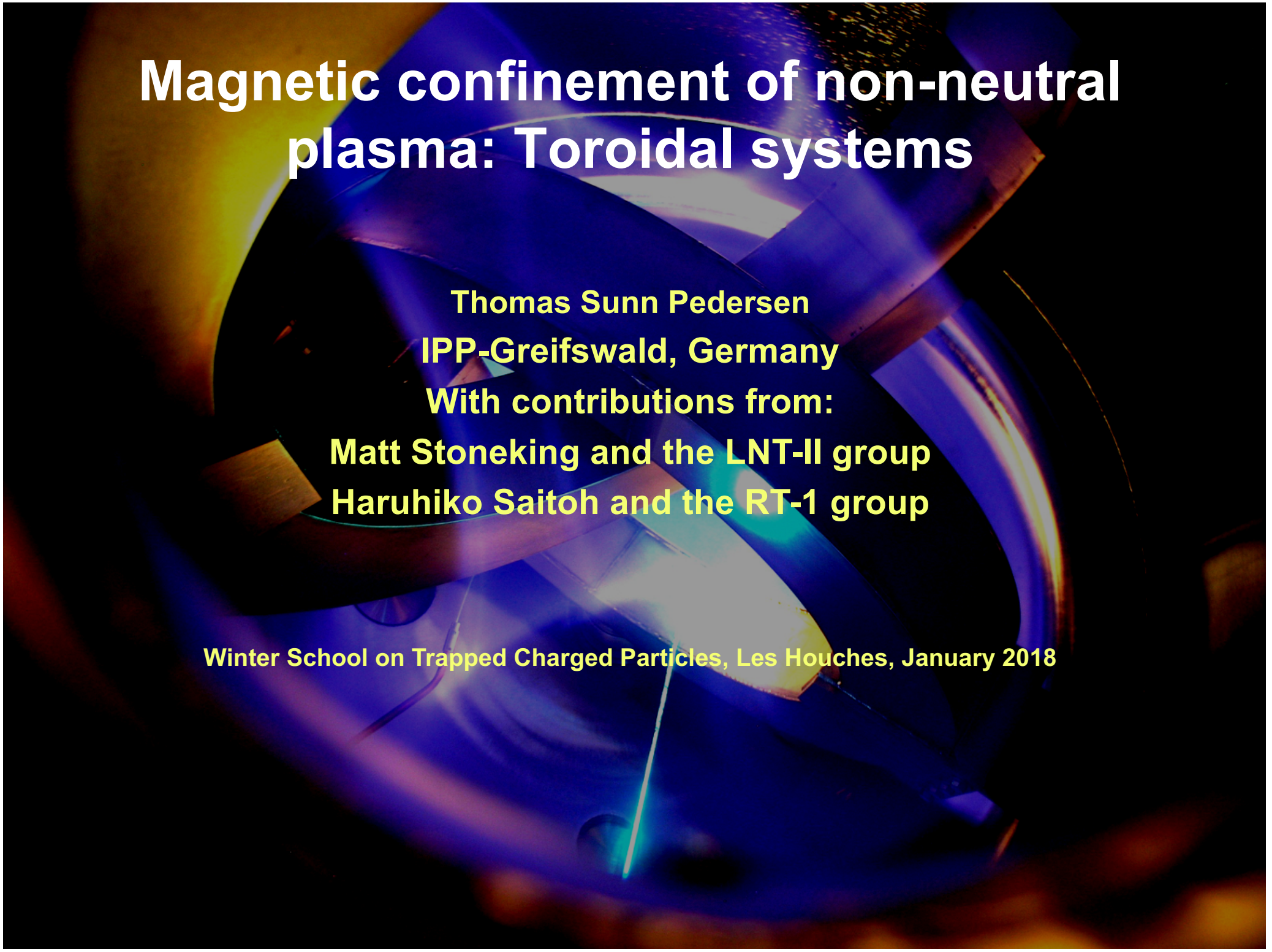

Magnetic confinement of non-neutral plasma: Toroidal systems

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IPP-Greifswald, Germany

With contributions from:

Matt Stoneking and the LNT-II group

Haruhiko Saitoh and the RT-1 group

Winter School on Trapped Charged Particles, Les Houches, January 2018

Overview

- Motivation for the study of toroidal configurations
- The pure toroidal field trap
  - Basic theory
  - History
  - Experimental results
- Dipole experiment(s)
- Stellarator experiments
- Partially neutralized plasmas in a stellarator
- Summary

Why study NNP in toroidal configurations?

- Penning traps can confine non-neutral plasmas infinitely long – what's there to improve?
- One can study different physics in toroidal configurations:
  - Partially neutralized plasmas (Penning traps confine only one sign of charge)
  - Electron-positron plasmas
  - 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:

$$\lambda_D = \sqrt{\frac{\epsilon_0 T}{ne^2}} \ll a \qquad (n\lambda_D^3 >> 1)$$

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

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

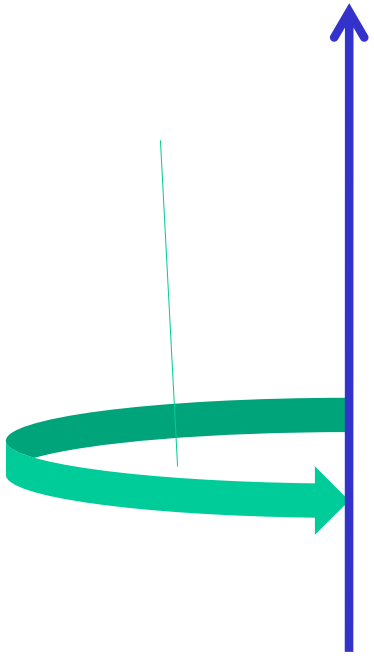
$$\Leftrightarrow \left|\frac{e\varphi}{T}\right| \approx \frac{e^2 n_e}{\varepsilon_0 T_e} a^2 = \frac{a^2}{\lambda_D^2} >> 1 \Leftrightarrow \left|\frac{e\varphi}{T}\right| >> 1$$

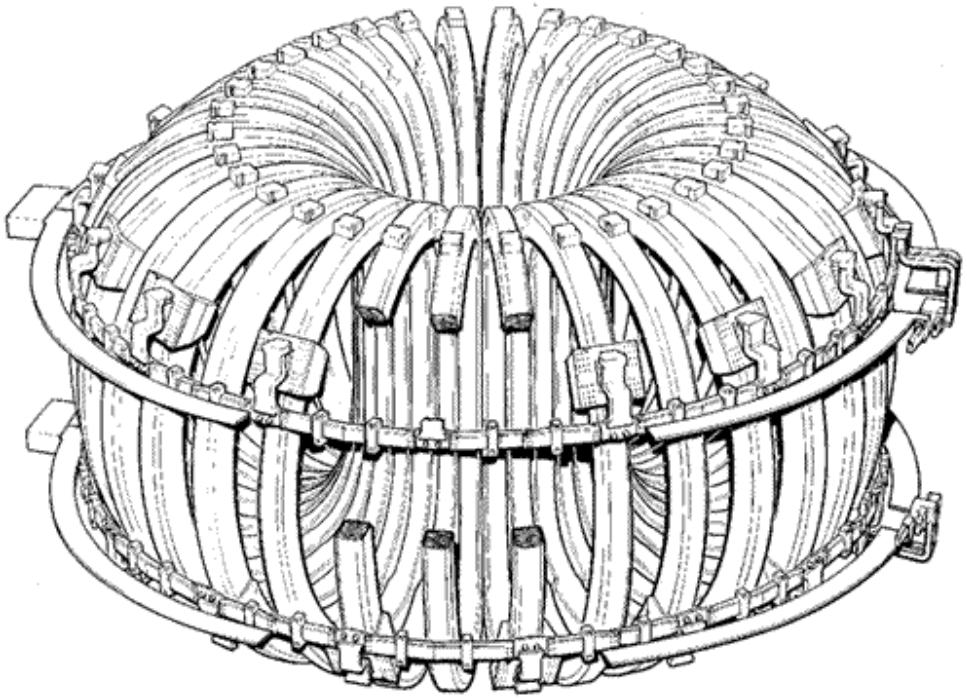
$$\left|\frac{v_{E\times B}}{v_{\nabla B}}\right| = \frac{|\nabla\varphi|/B}{T|\nabla B|/eB^2} \approx \left|\frac{e\varphi}{T}\right| >> 1$$

- 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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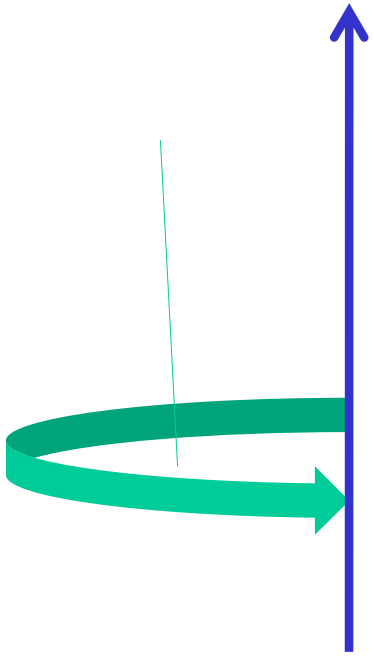


$$\vec{B} = B_\varphi \hat{\varphi} = \frac{\mu_0 I}{2\pi R}\hat{\varphi} \Rightarrow \nabla B = -\frac{\mu_0 I}{2\pi R^2}\hat{R}$$

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

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

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)

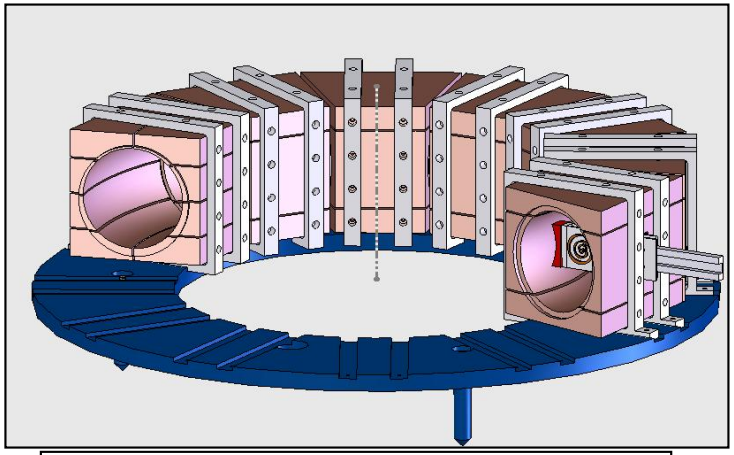
Brief history of pure toroidal field traps <2000

- 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

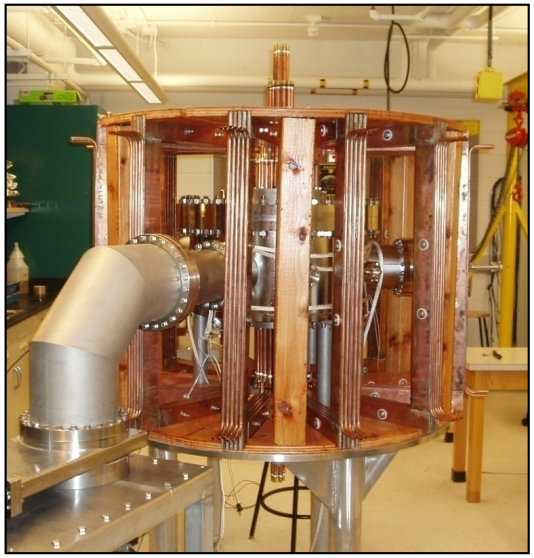
1. Daugherty, Eninger, Janes, Phys. Fluids 12, p.2677 (1969)
2. Mohri, Masuzaki, Tsuzuki, Ikuta, PRL 34 p. 574 (1975)
3. Zaveri, P. I. John, K. Avinash, P. K. Kaw, PRL 68, p. 3295, (1992)

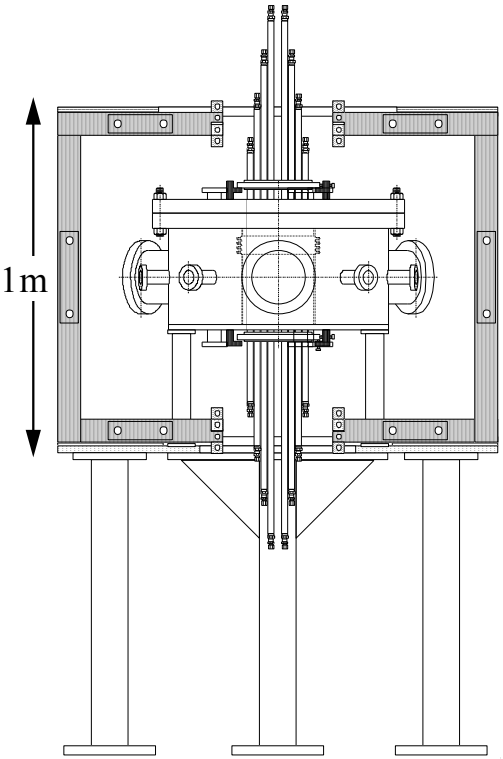
Pure electron plasmas in a pure toroidal magnetic field: Lawrence Non-neutral Torus II

- 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!

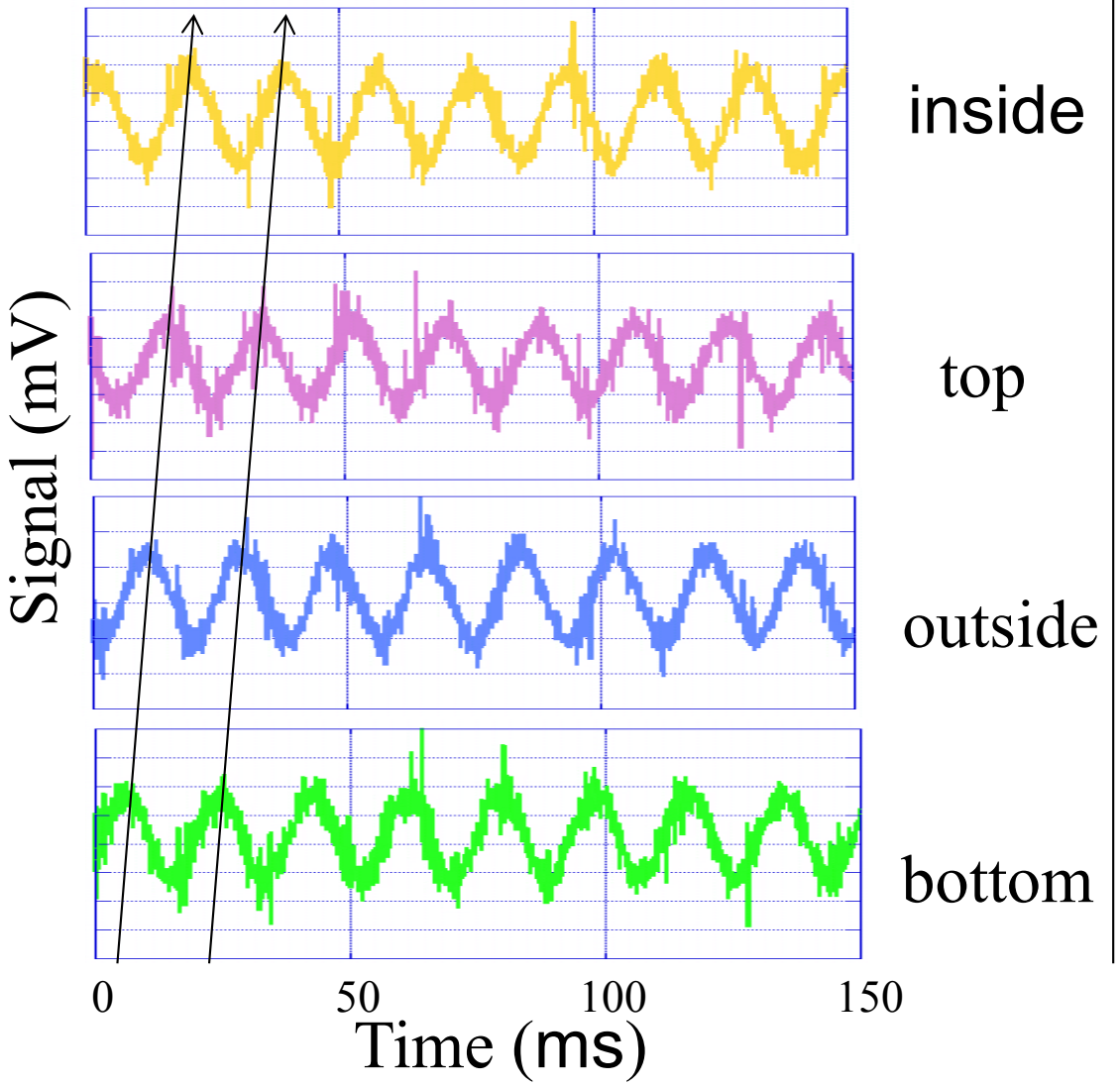


- Plasma major radius: 17.4 cm
- Plasma minor radius: ~1.3 cm
- Length: 82 cm (270 degrees)
  109 cm (360 degrees)





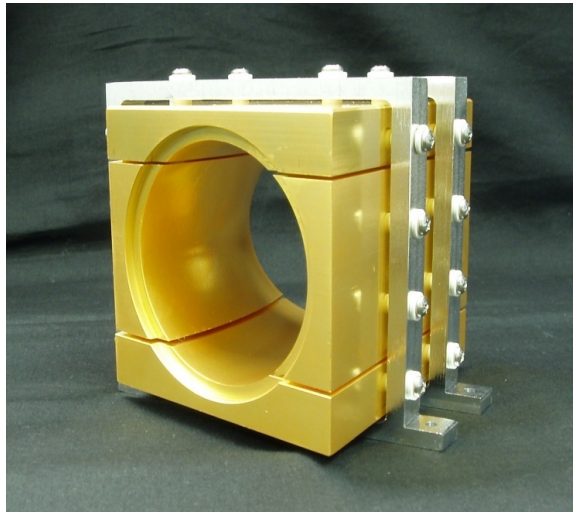
Observation of *m*=1 Diocotron Mode (ExB rotation of the entire plasma)



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

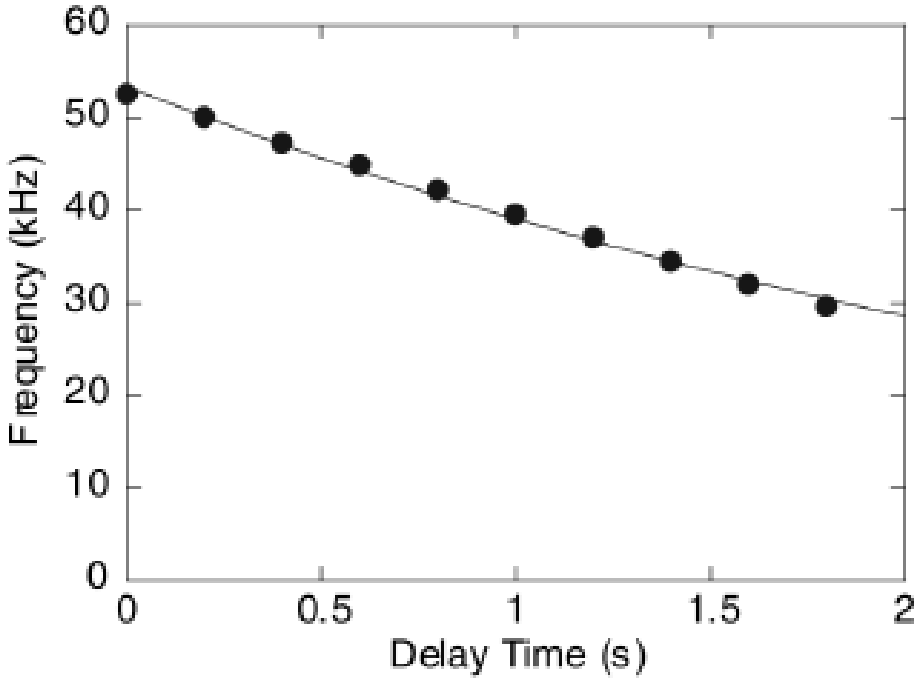
$$Q \approx 1.5\,\text{nC}$$

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

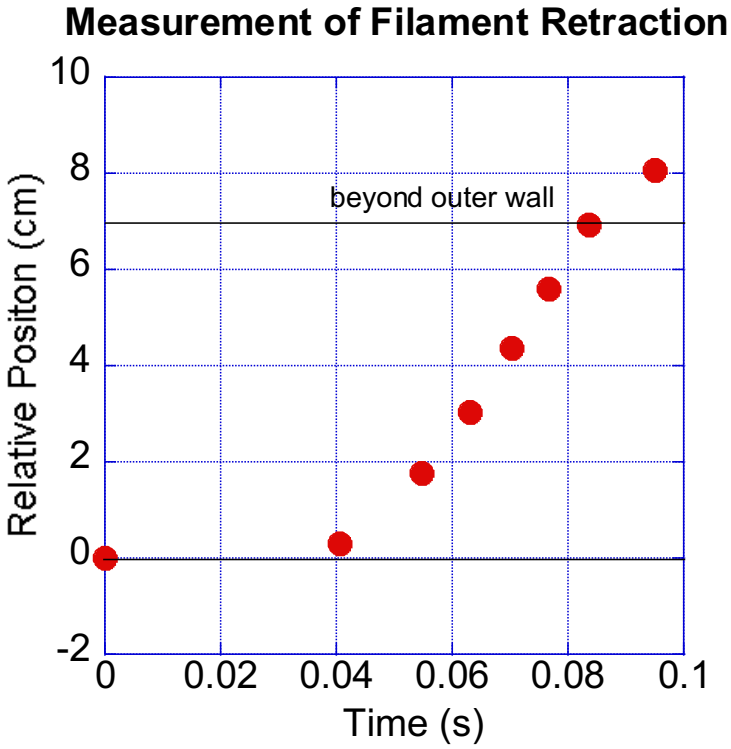


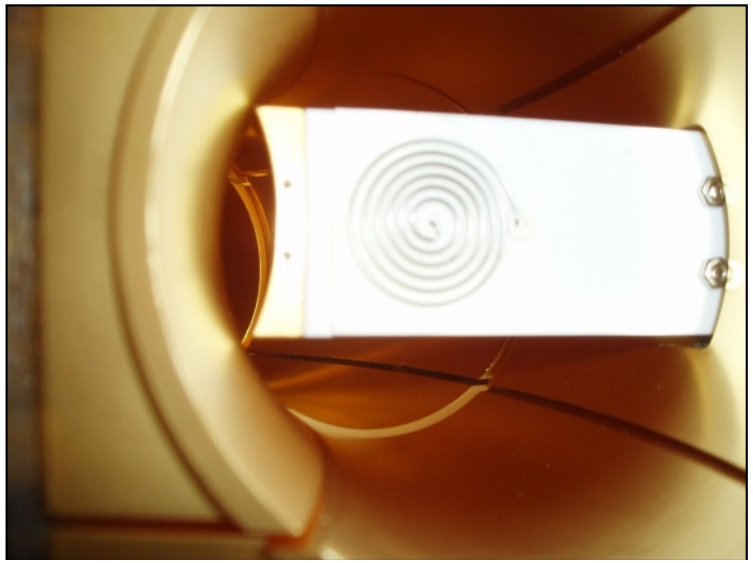
Confinement Time

- 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)

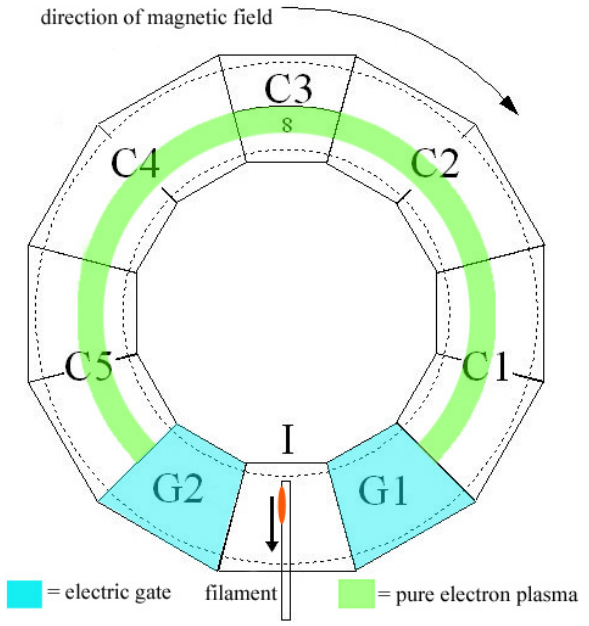


Removal of internal objects and electron sources

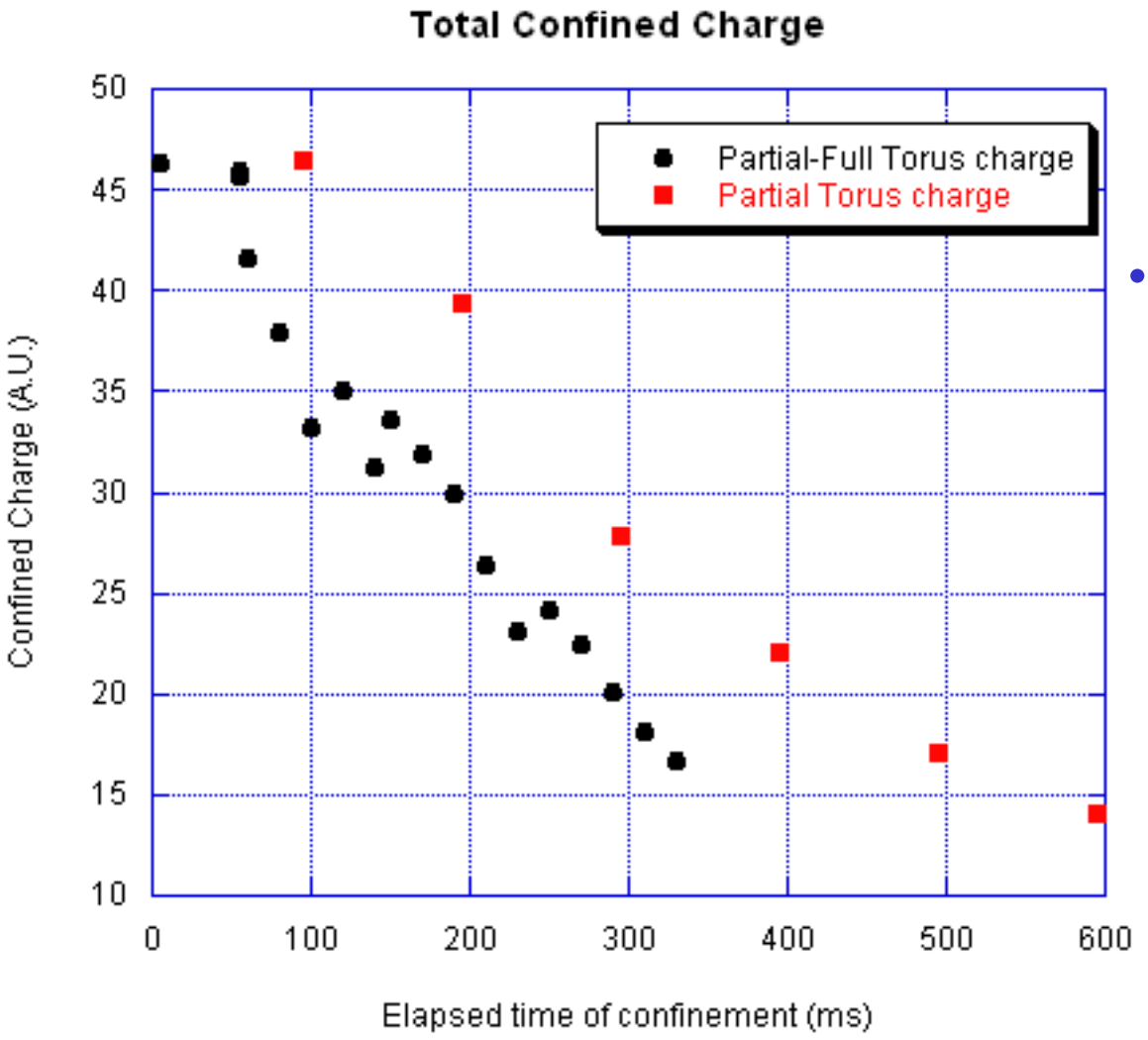




- Retract filament to study full toroid
- Retraction in about 50 ms
- Much faster than confinement time

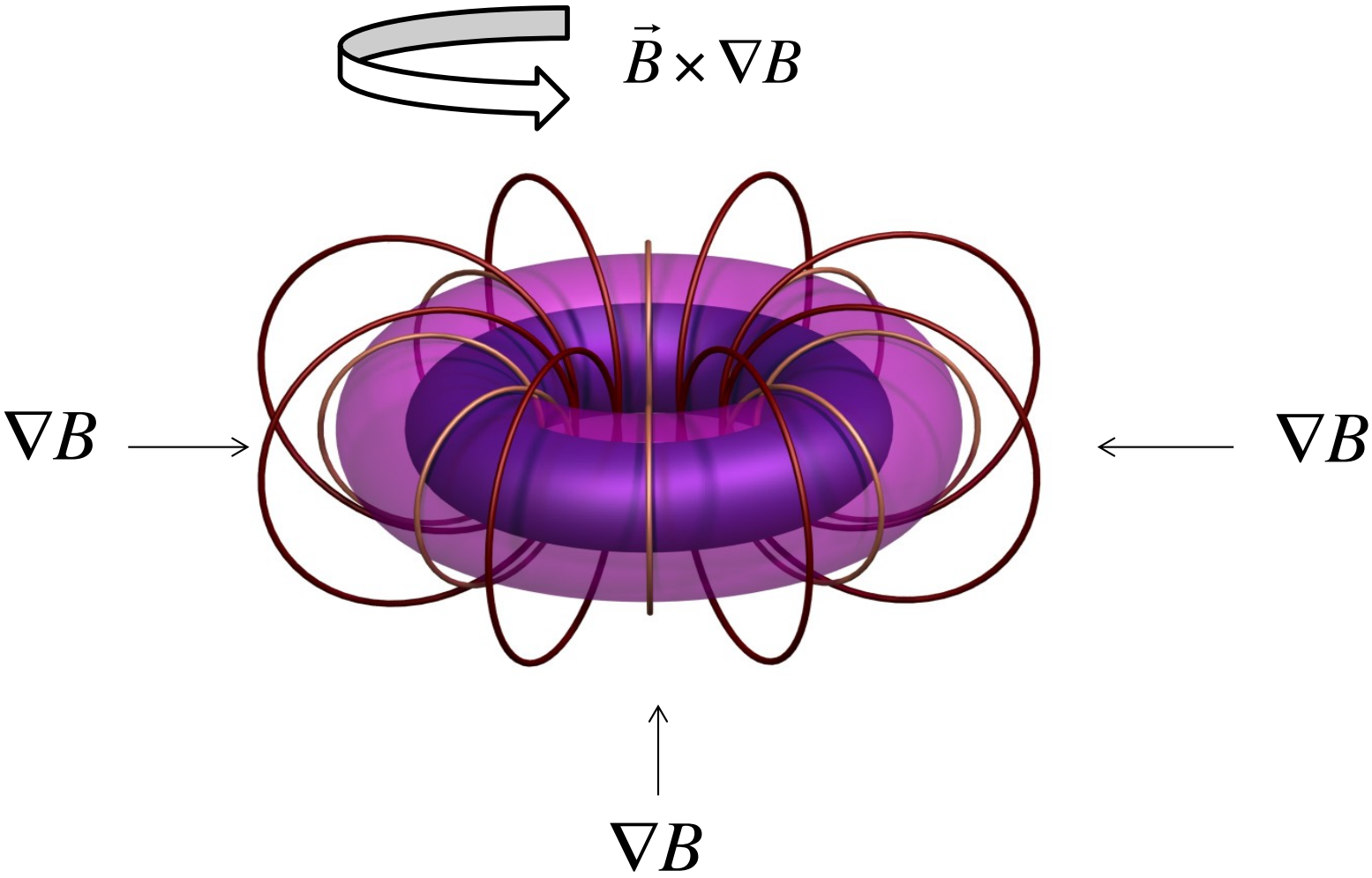


Confinement after removal poorer than expected



- 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
- Confinement time is particularly sensitive to neutral pressure – indicating that ion contamination is cause of the low confinement

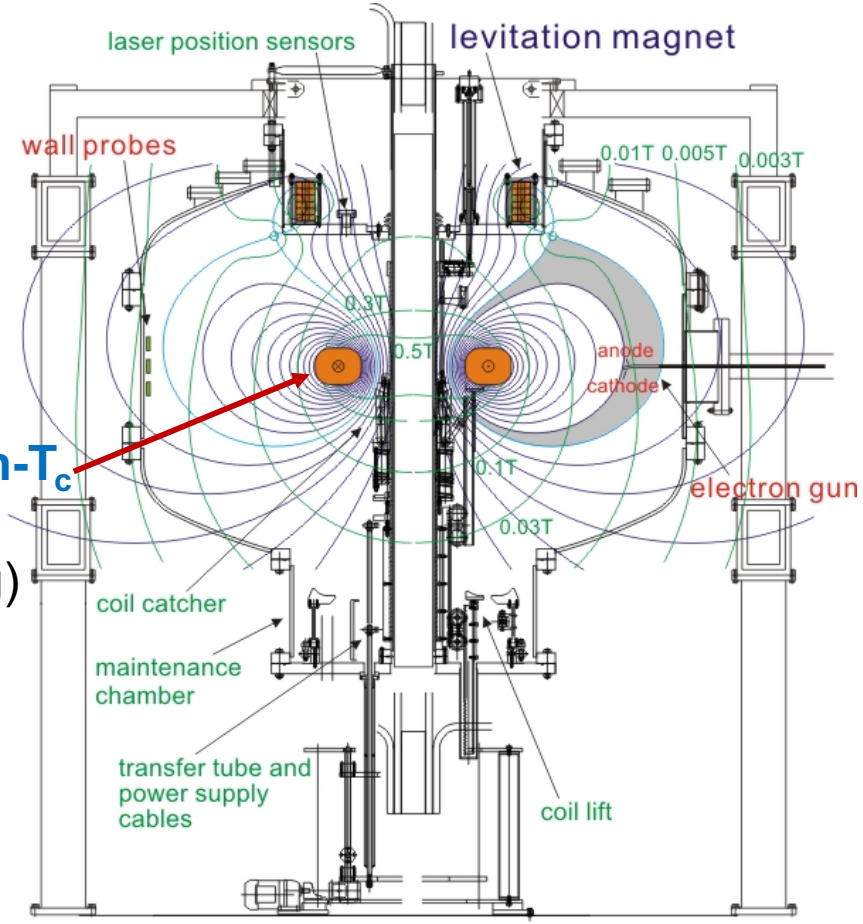
Single particles are confined in a levitated ring dipole

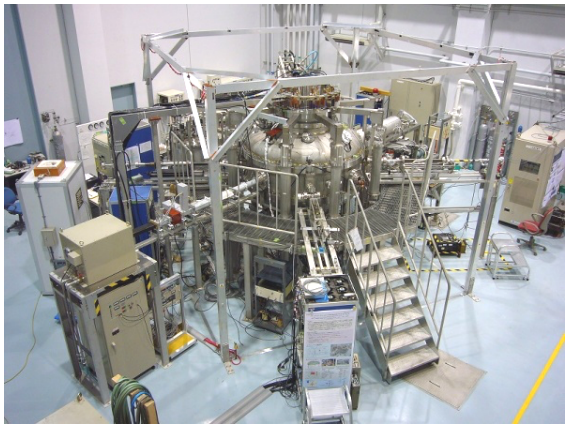


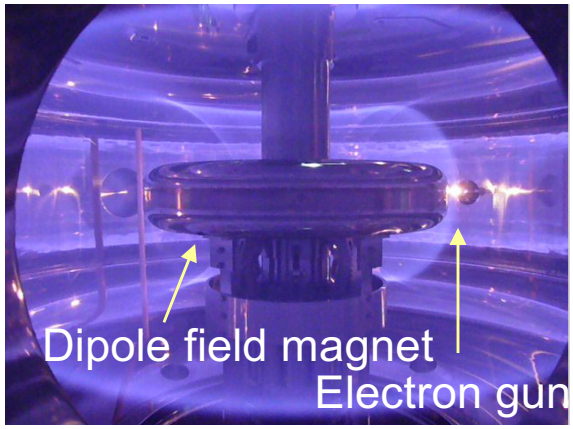
- Some particles are confined even in a supported dipole – due to mirror confinement
  - For a single species plasma, an appropriate electrostatic potential plugs the loss cone, and one can confine the whole Maxwellian

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)





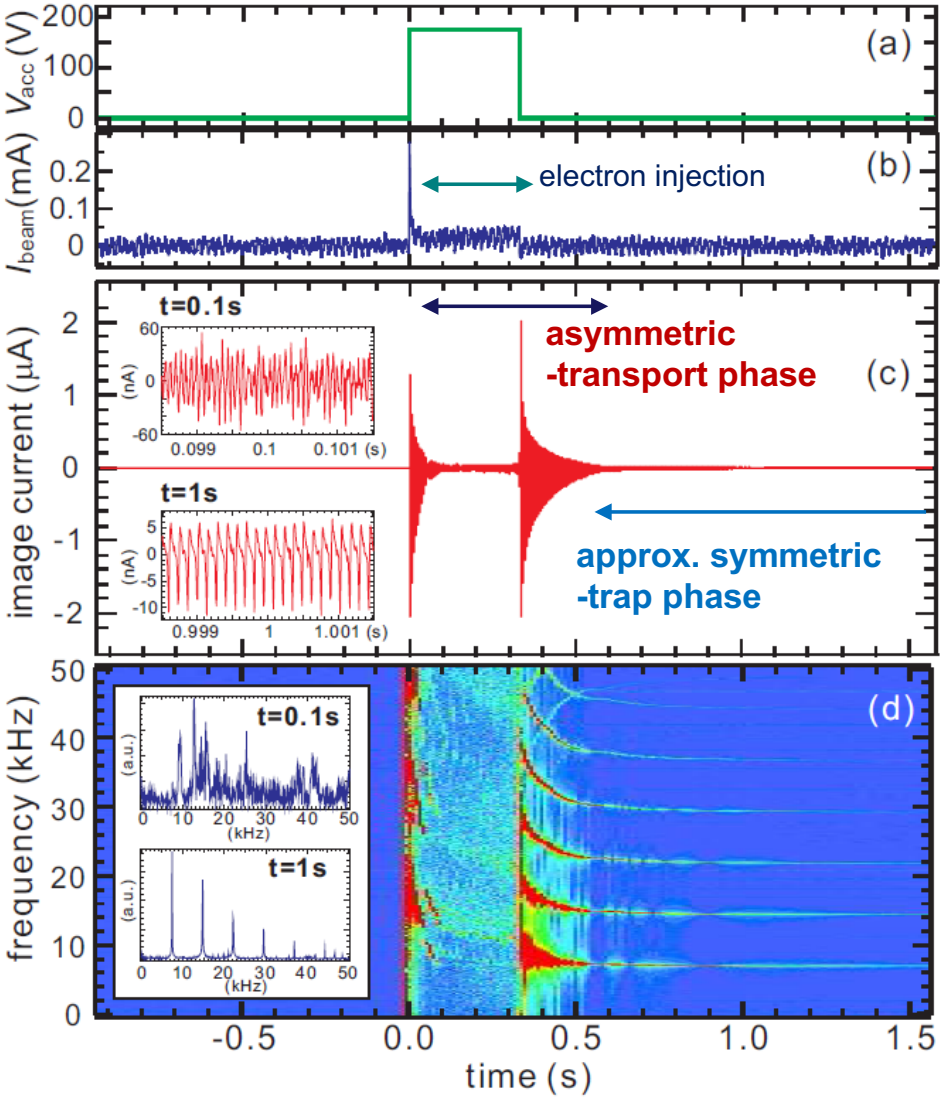


2009 Ogawa, Yoshida *et al.*, Plasma Fusion Res. 4, 020.

- **Toroidal non-neutral (pure electron) plasma**
  - **300s long confinement, rigid-rotating steady state, inward diffusion**

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

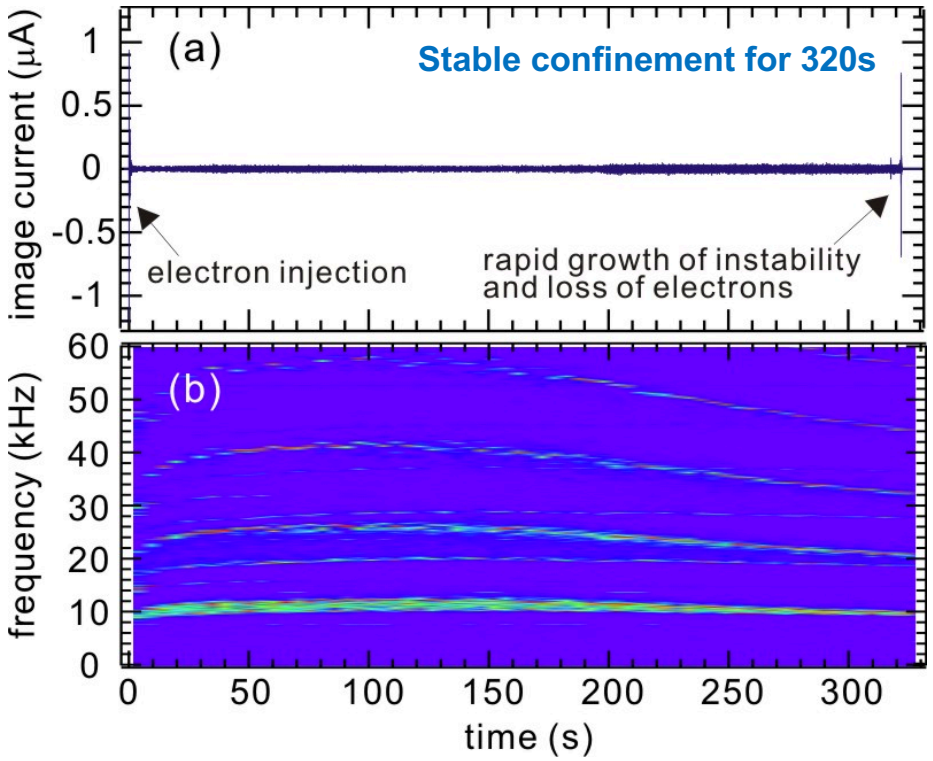


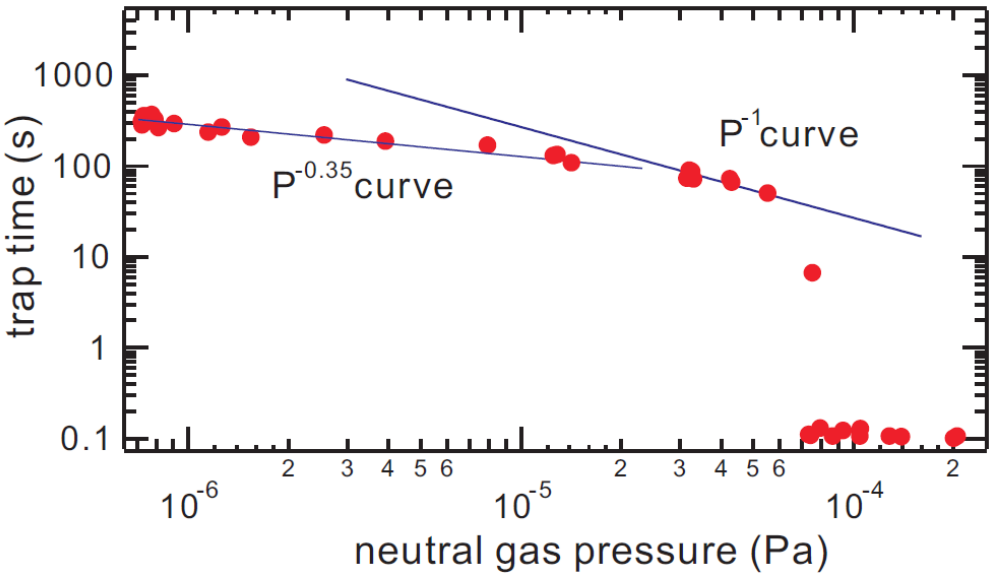
Formation and sustainment of toroidal PEP in RT-1.
(a) V_{acc}, (b) beam current, (c) electrostatic fluctuation, and (d) its frequency power spectrum.

- 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.

The magnetic topology of a stellarator

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

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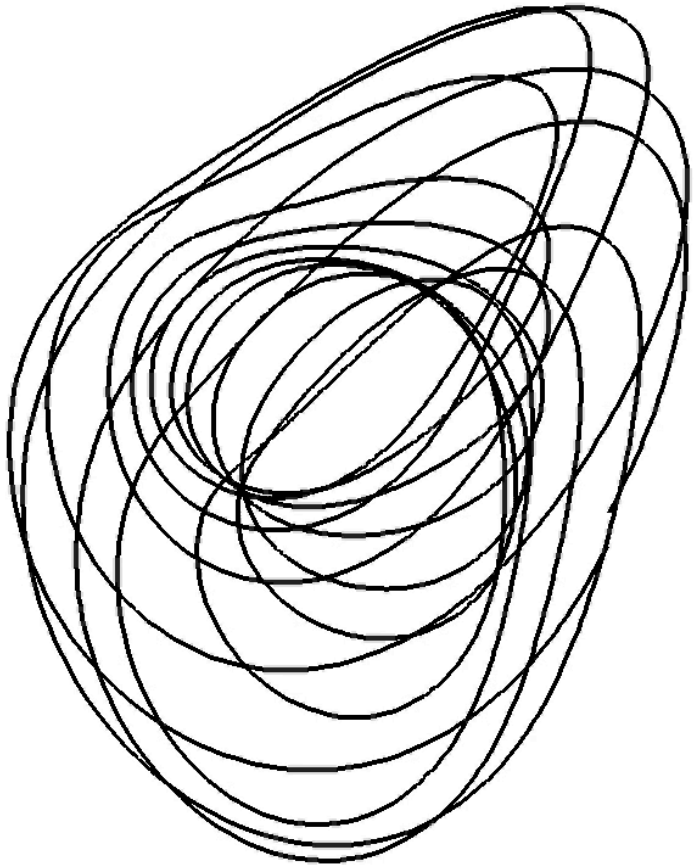
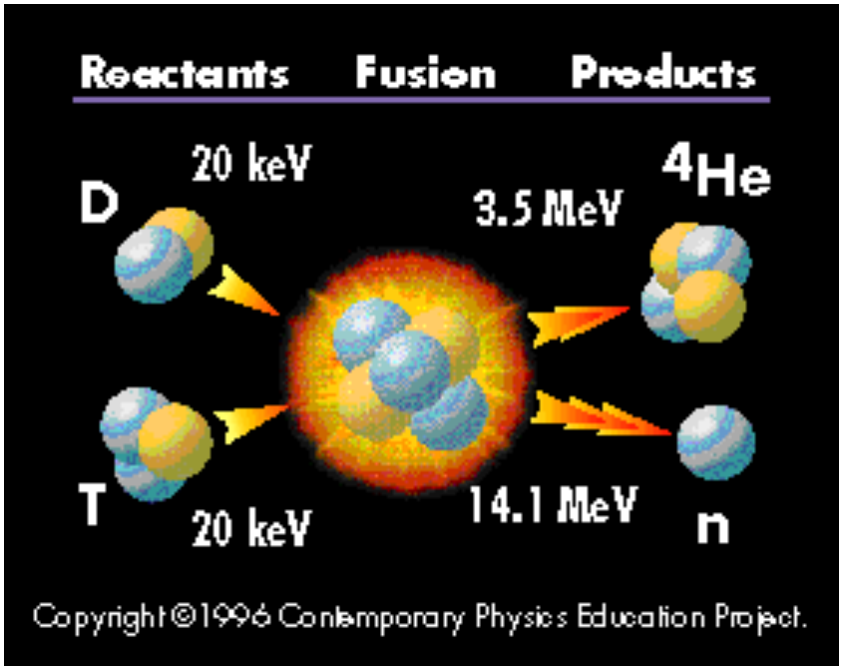


Stellarators in general

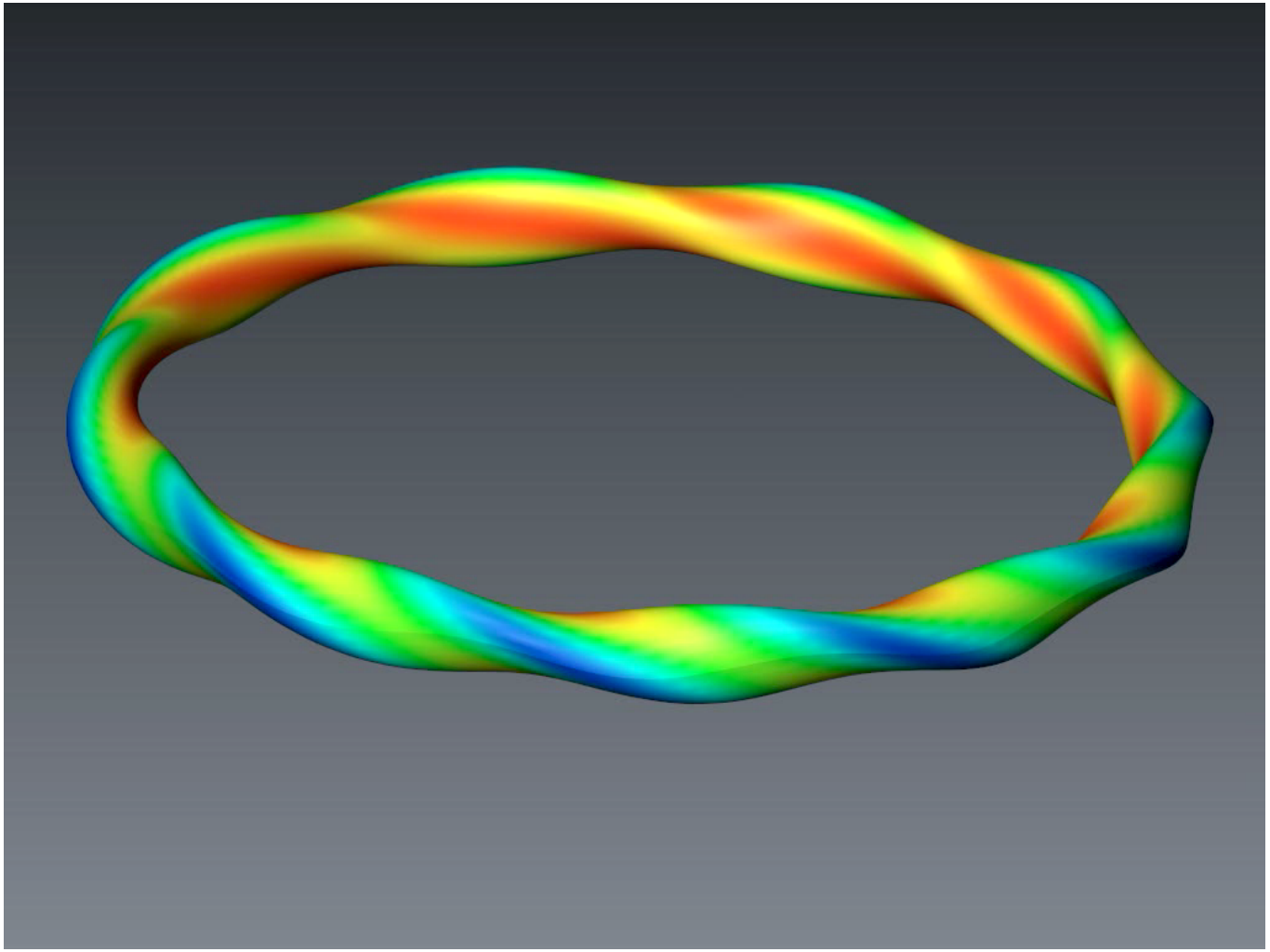
- The stellarator concept was developed for fusion 60 years ago
- Is still being pursued for fusion research today (short intro on the next few slides)
- Has advantages also as a toroidal non-neutral plasma trap

Fusion on Earth as an energy source?

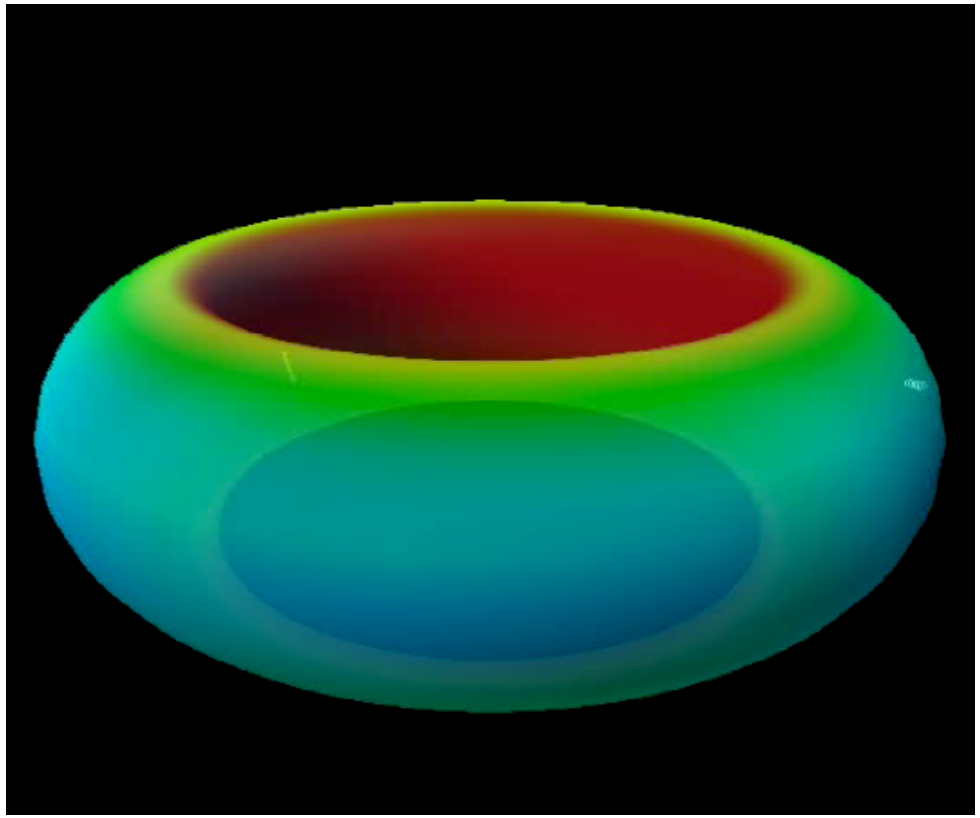


- D-T reaction has the highest cross section at low energies
- Still, Coulumb-collisions dominate over fusion-collisions by a factor of >100
- Fully thermalized hot plasma confined for many collision times
- 20 keV corresponds to appr. 200 million ^{o}C
- Magnetic confinement concepts:
  - Tokamak, **Stellarator,** Reversed Field Pinch, **Dipole** etc.

50 keV ion in a previous-generation stellarator

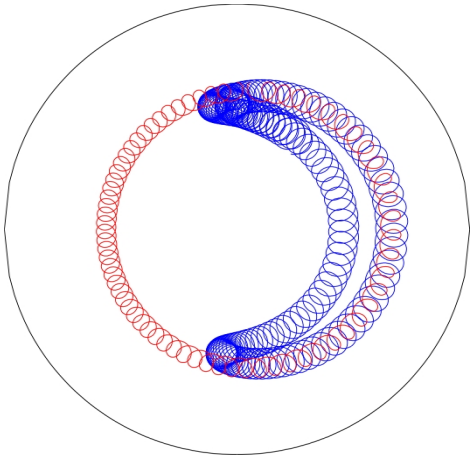


Tokamak confinement has historically been better than for any other confinement concept: Why are the tokamak orbits closed?



$$\vec{v}_{\nabla B} = \frac{mv_{\perp}^2}{2B}\frac{\vec{B}\times\nabla B}{qB^2}$$

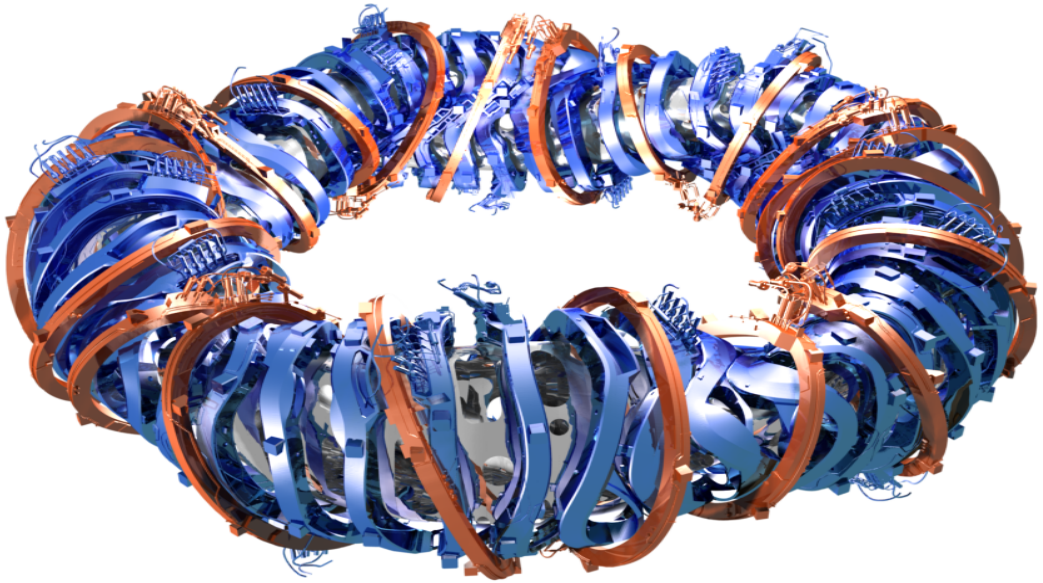
This drift is mostly vertical in a tokamak but it averages out due to symmetry



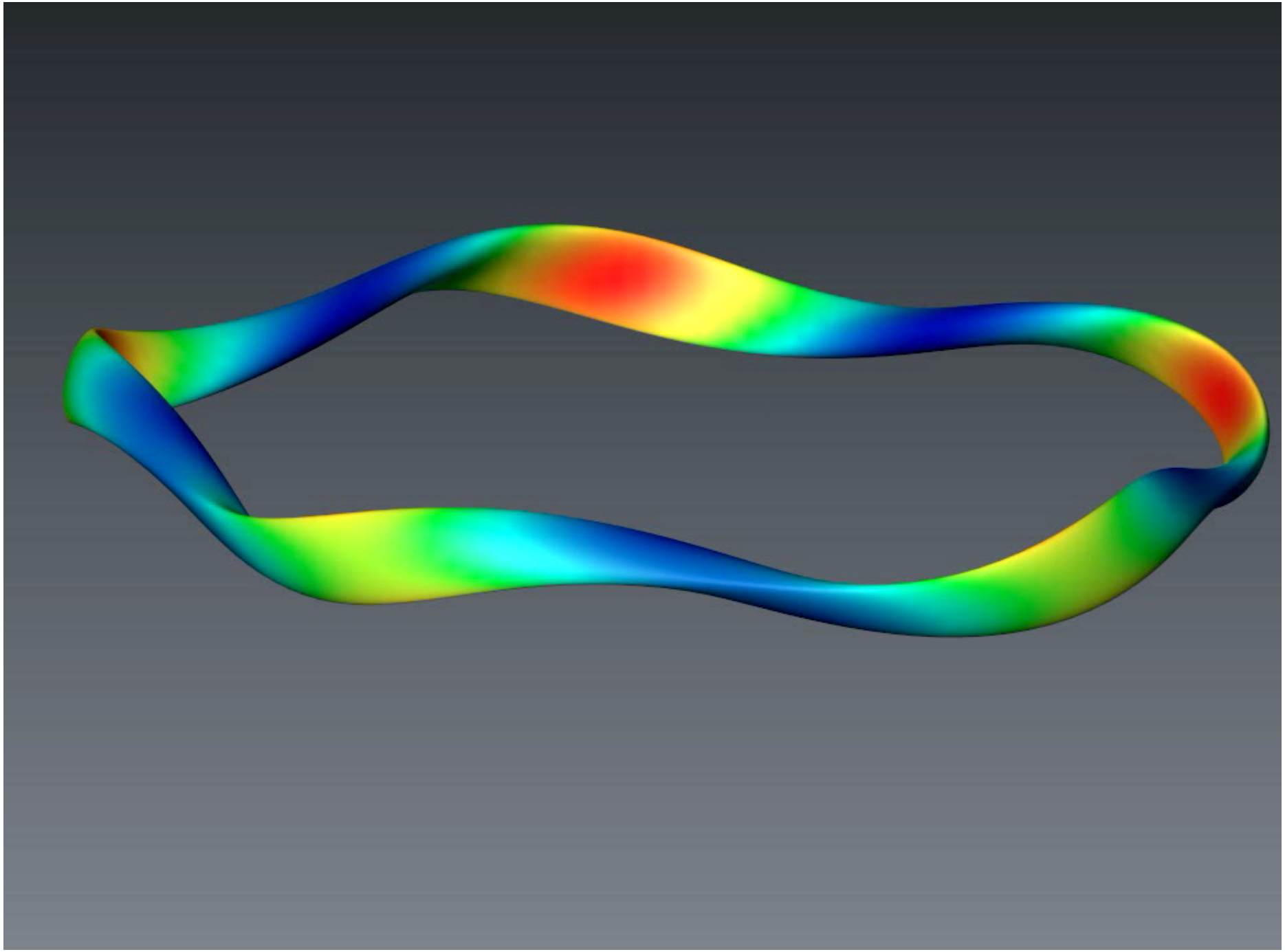
Poloidal projection: “banana orbit”

W7-X optimization attempts to fix drift problems by optimizing the shape of B

- Grad B drift lies on surfaces of constant B-field strength
- Can we make those surfaces close poloidally?
- Can we build in a symmetry (like in the tokamak) so that the magnetic drifts cancel out and the guiding center trajectories are closed?
- In the 80‘s theory was developed that said „yes we can!“ (to both, but separately)
- Once B is optimized, invert $\nabla \times \vec{B} = \mu_0 \vec{j}$
- Find coils:



Optimized stellarators can confine single particles very well

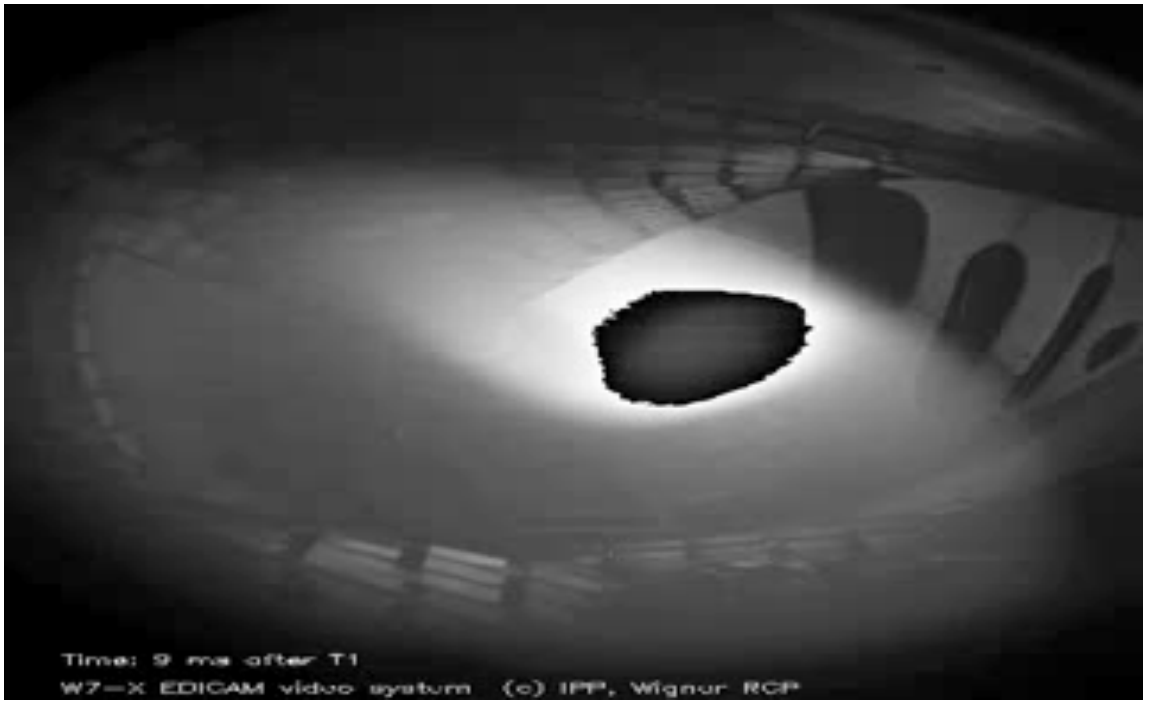


Time-lapse movie of W7-X construction

Yes, it confines hot plasma (>20 M°C)

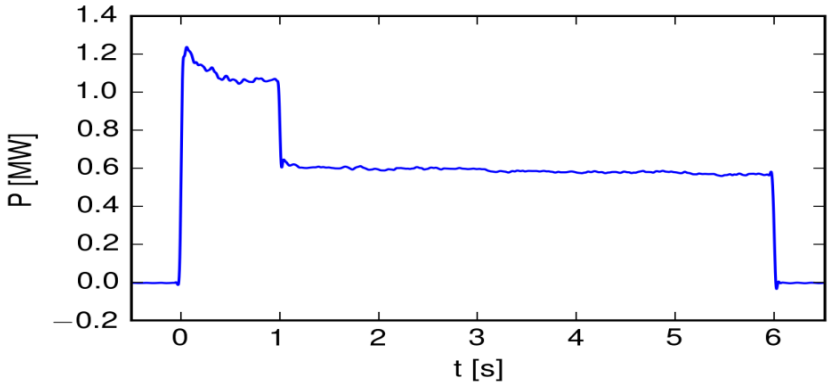
- 6 second discharge shown (1 s 1MW, then 5 s 0.6 MW):

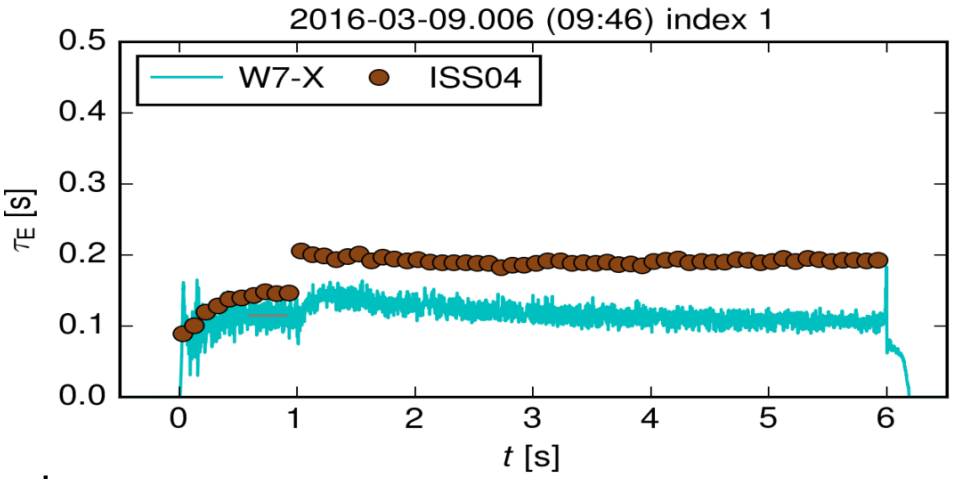
- Discharge terminates peacefully, as pre-programmed
- See next slides for analysis of such 6 second shots



T. Szepesi, G. Koczis

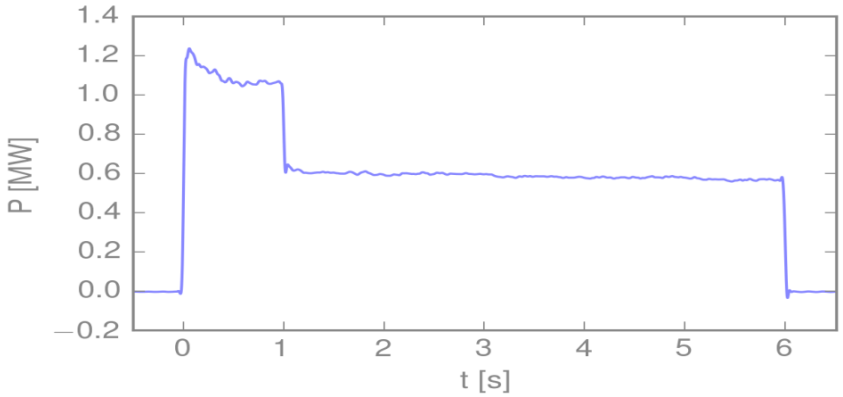
Confinement times of order 100-150 msec

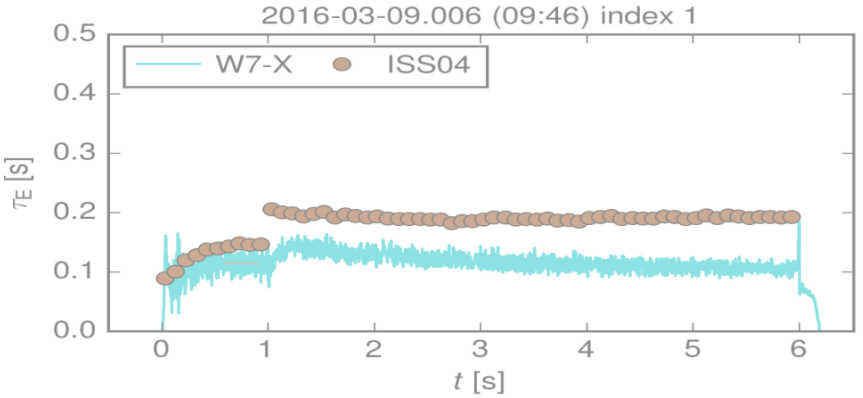


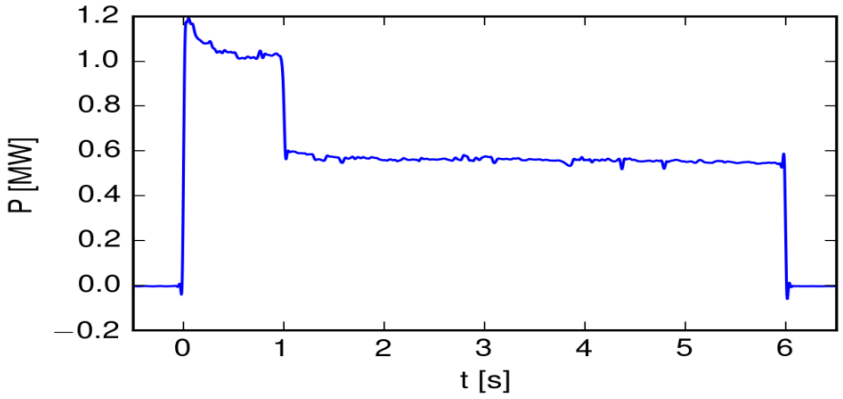


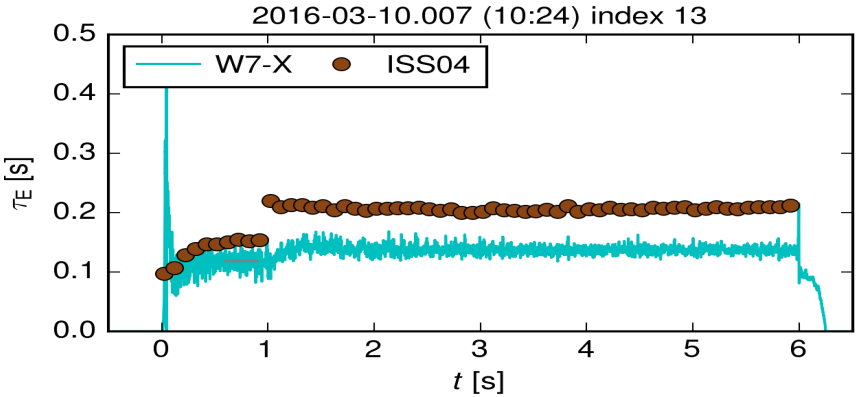
- Remarkably stable discharges over 6 seconds
- Can we prove the optimization of the guiding center drift orbits by comparing this to a somewhat de-optimized magnetic configuration in W7-X?

Confinement time with “de-optimized” configuration









Essentially no change in confinement…?

Why no change despite de-optimization?

1. Is it because turbulent transport already dominates and we need to further de-optimize to see an effect?
2. Is it because the orbits are “magically” well-confined even for de-optimized configurations?
3. Is it because the orbits were horrible and we couldn’t make them worse?

Answer is 2: The magic is in the radial electric field

Electric fields in stellarators

How large of a role does the bulk ExB drift play relative to the magnetic drifts?

$$\left|\frac{v_{ExB}}{v_{\nabla B}}\right| \approx \left|\frac{\nabla\phi / B}{(W_k \nabla B / eB^2)}\right| \approx \left|\frac{e\phi}{W_k}\right|$$

Pure-electron plasma: Dominant (factor of 10-1000)

Thermal particles in a quasineutral plasma: Depends.. (0.2-5)

Set by ambipolarity

For these W7-X plasmas, we had $T_e >> T_i$ which drives a relatively strong electric field

The orbit healing magic of a radial electric field cannot “fix” α-confinement in a future reactor:

Ratio is negligibly small: ~35 keV/3.5 MeV~0.01)

Stellarators for confinement of non-neutral plasmas

- Stellarators have some advantages over Penning and pure toroidal traps, and some disadvantages:
  - Fully toroidal – no end effects (advantage over Penning trap)
  - 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 but can be fixed with:
    - Computer optimization and complicated coils (W7-X)
    - Use of strong ExB drift (esp. for non-neutral plasmas)

Non-neutral plasmas in a stellarator: History

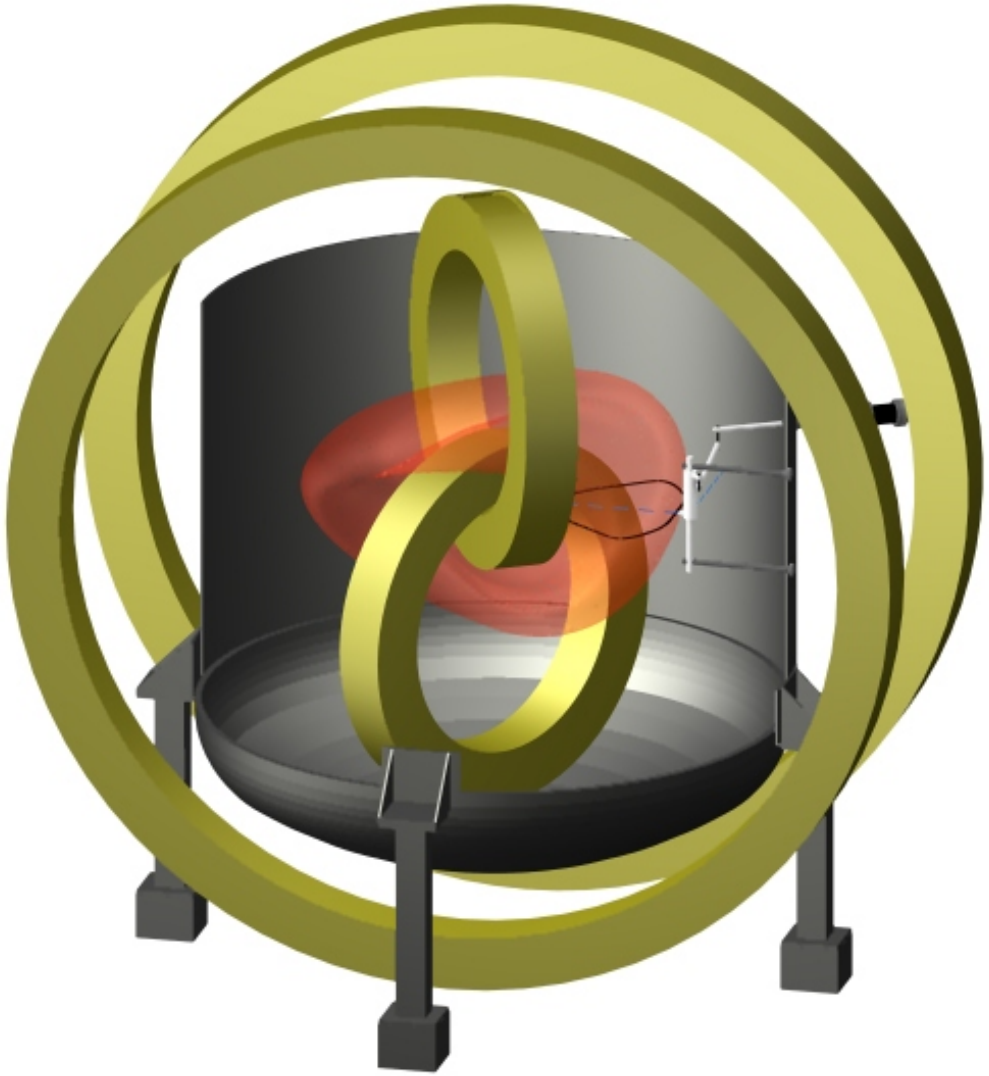
- The idea of confining a non-neutral plasma in a stellarator is about 10 years old[1]
  - Equilibrium equation derived
  - Unique capabilities recognized
- BUT! Non-neutral stellarator experiments were actually performed >20 years ago!
  - Auburn torsatron (USA, 1987)[2], and Uragan-2, Uragan-3 (USSR,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

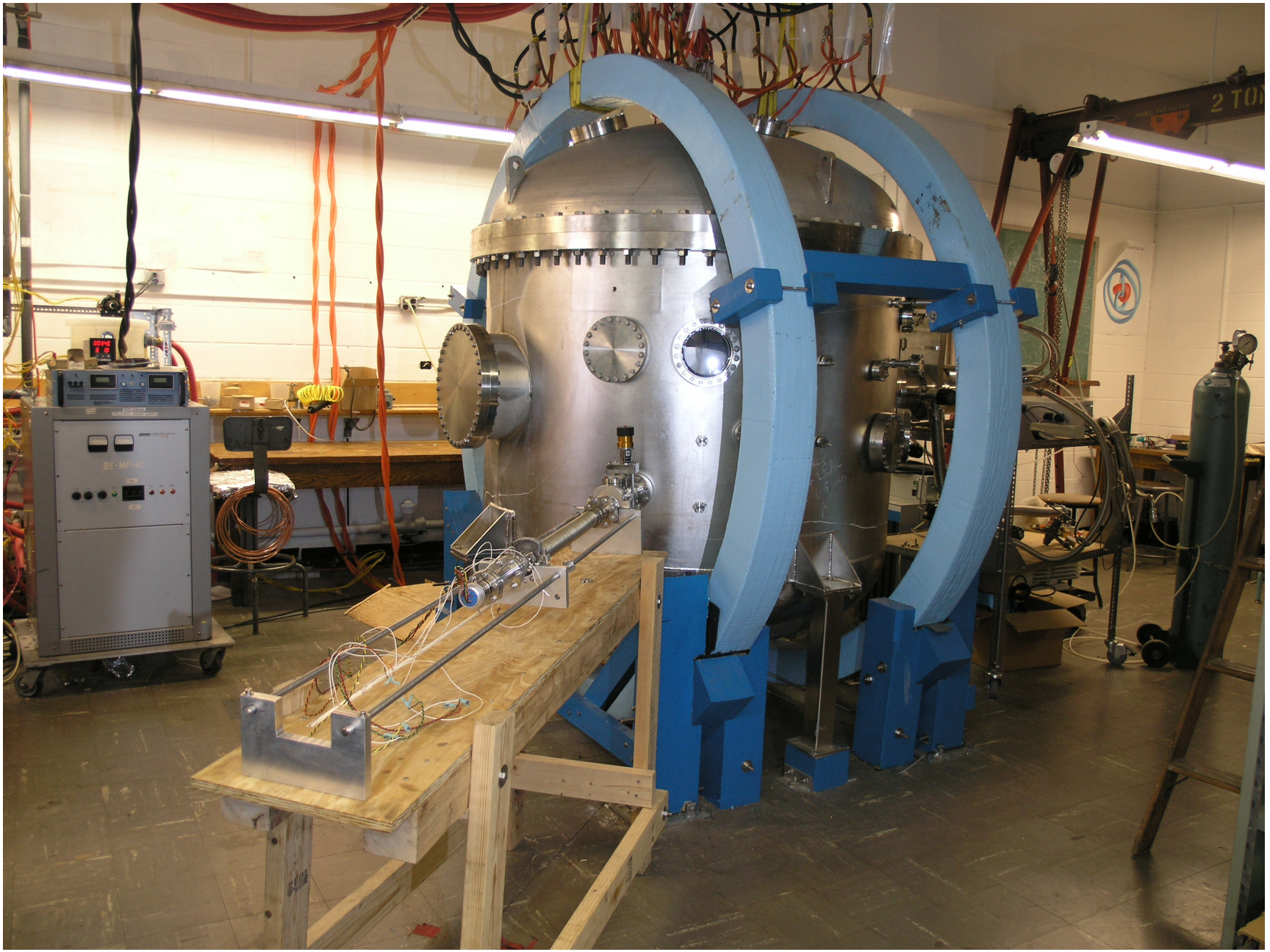
[3] A. G. Dikii, V. M. Zalkind, et al., Sov. J. Plasma Phys. **14** p. 160 (1988)

CNT 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)

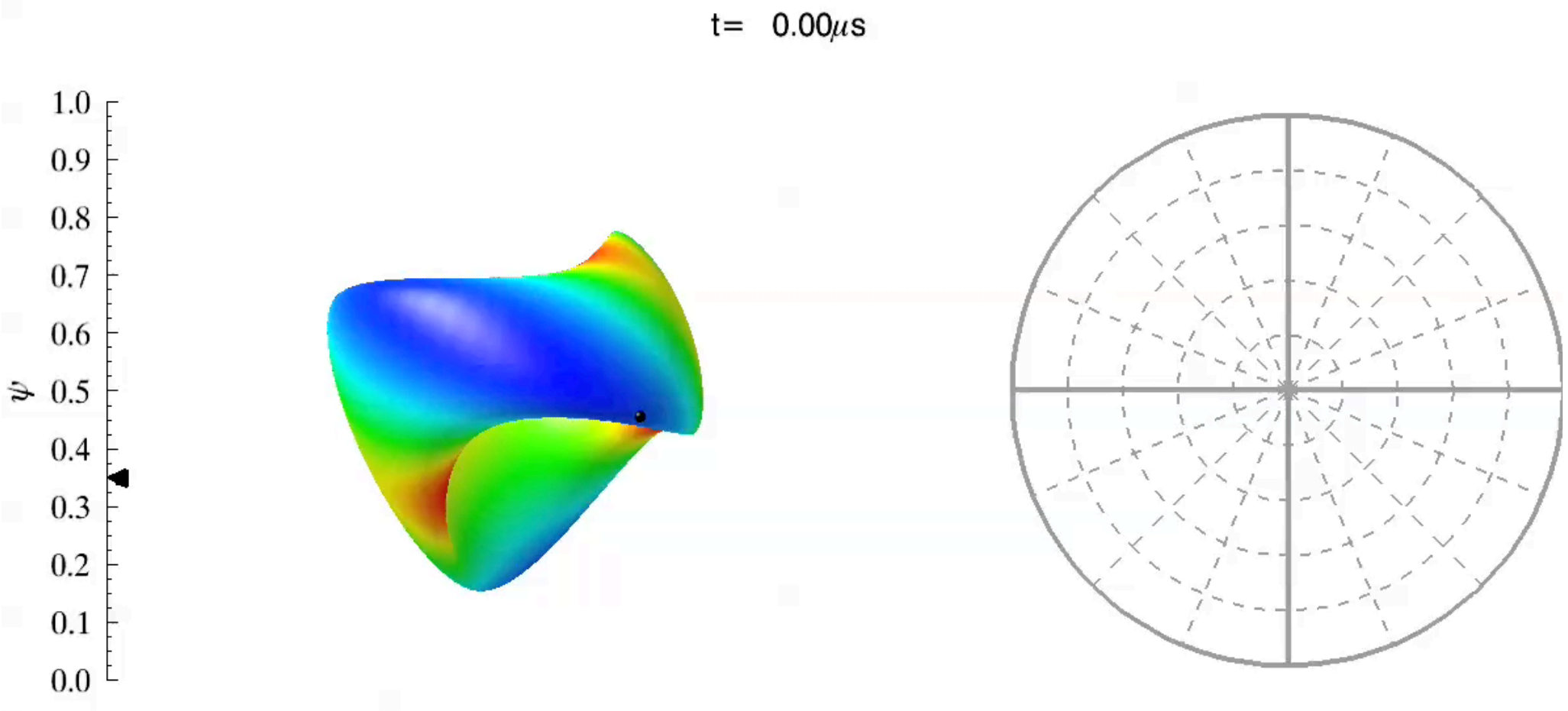
CNT ran as a non-neutral stellarator 2004-2011



Without E-field, CNT has “bad” orbits!

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

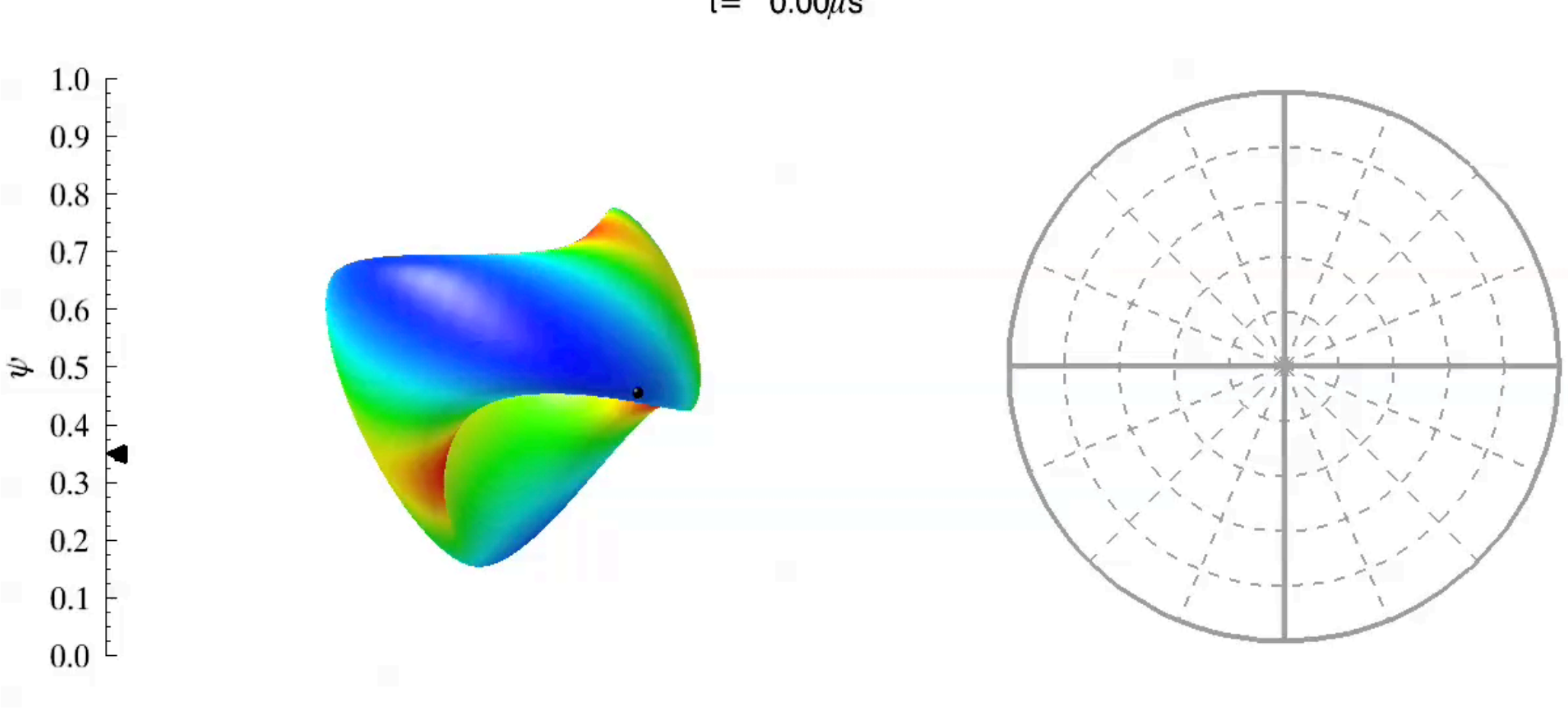
About 50% of particles are magnetically trapped (due to mirror force), don’t circulate toroidally, therefore don’t circulate poloidally, and consequently drift out of CNT. Example:



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



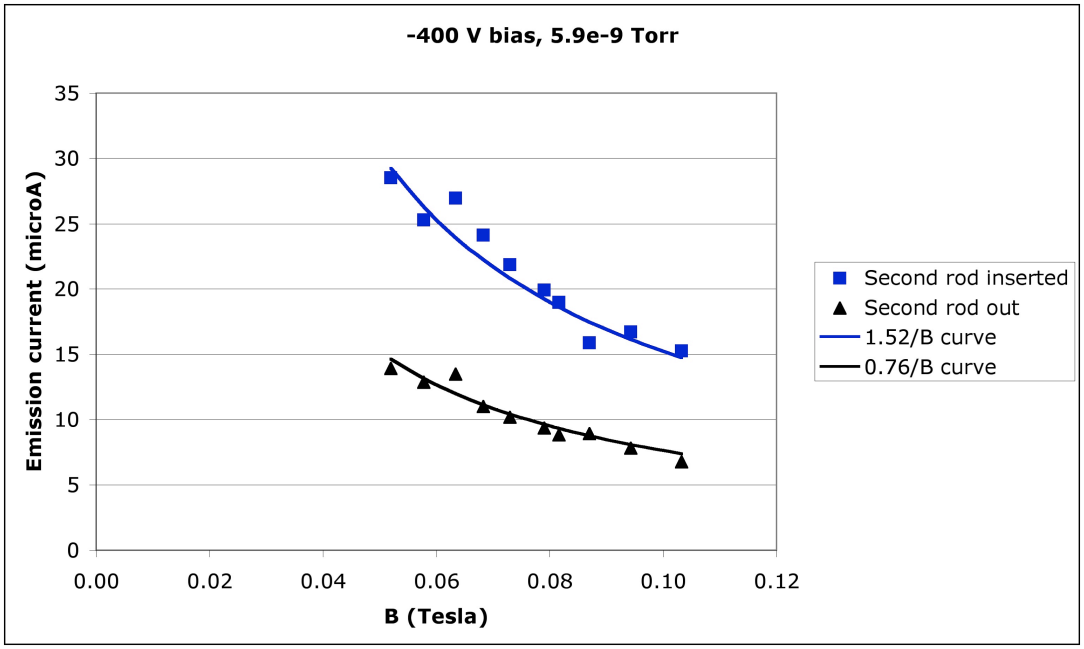
Expected particle confinement in CNT

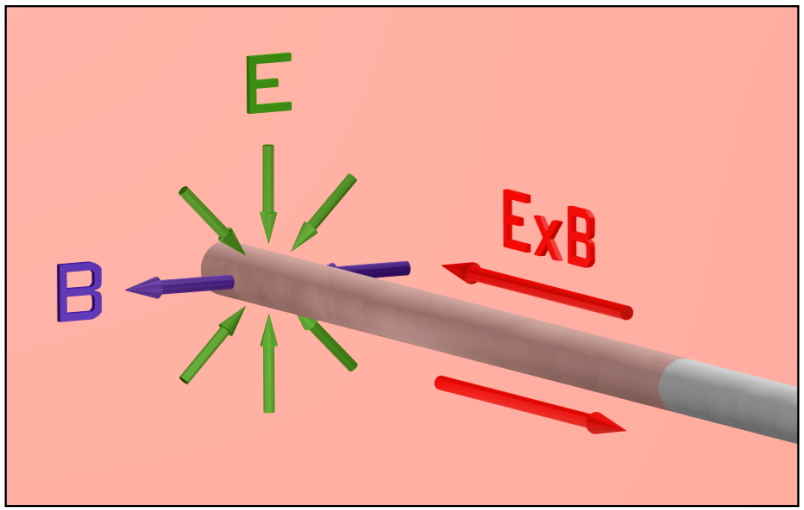
- CNT's pure electron plasmas have a strong electric field
  - $\Delta\phi$~200 V, T_e ~4 eV

$$\left|\frac{v_{ExB}}{v_{\nabla B}}\right| \approx \left|\frac{e\phi}{T_e}\right| \approx 50$$

- 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



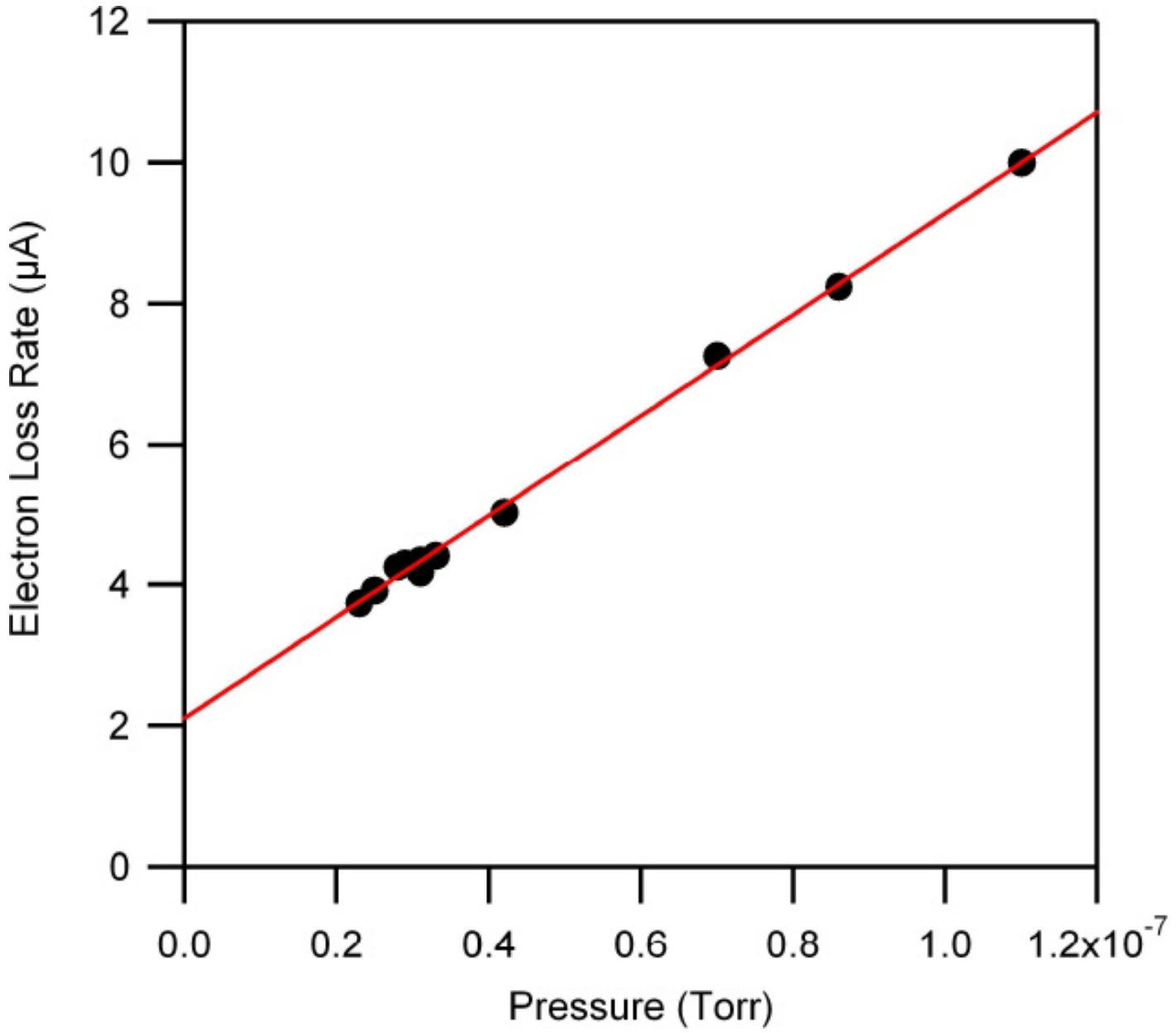


Insulated rods charge up negative relative to plasma to self-shield
Resulting ExB drift pattern convects particles along the rod all the way to the open field lines.

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

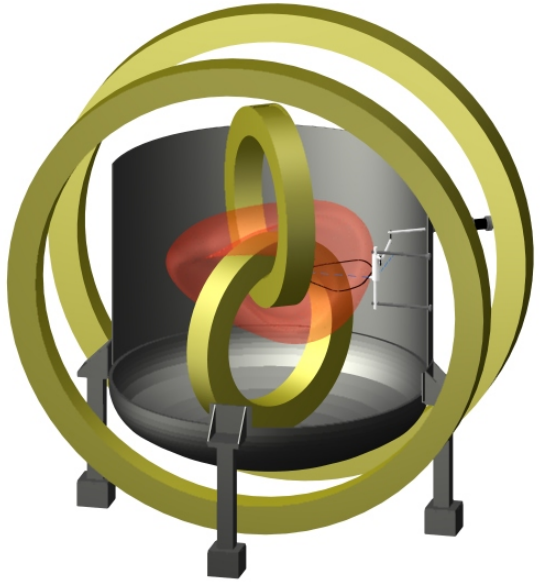
The loss rate due to neutral collisions is much larger than expected:

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:

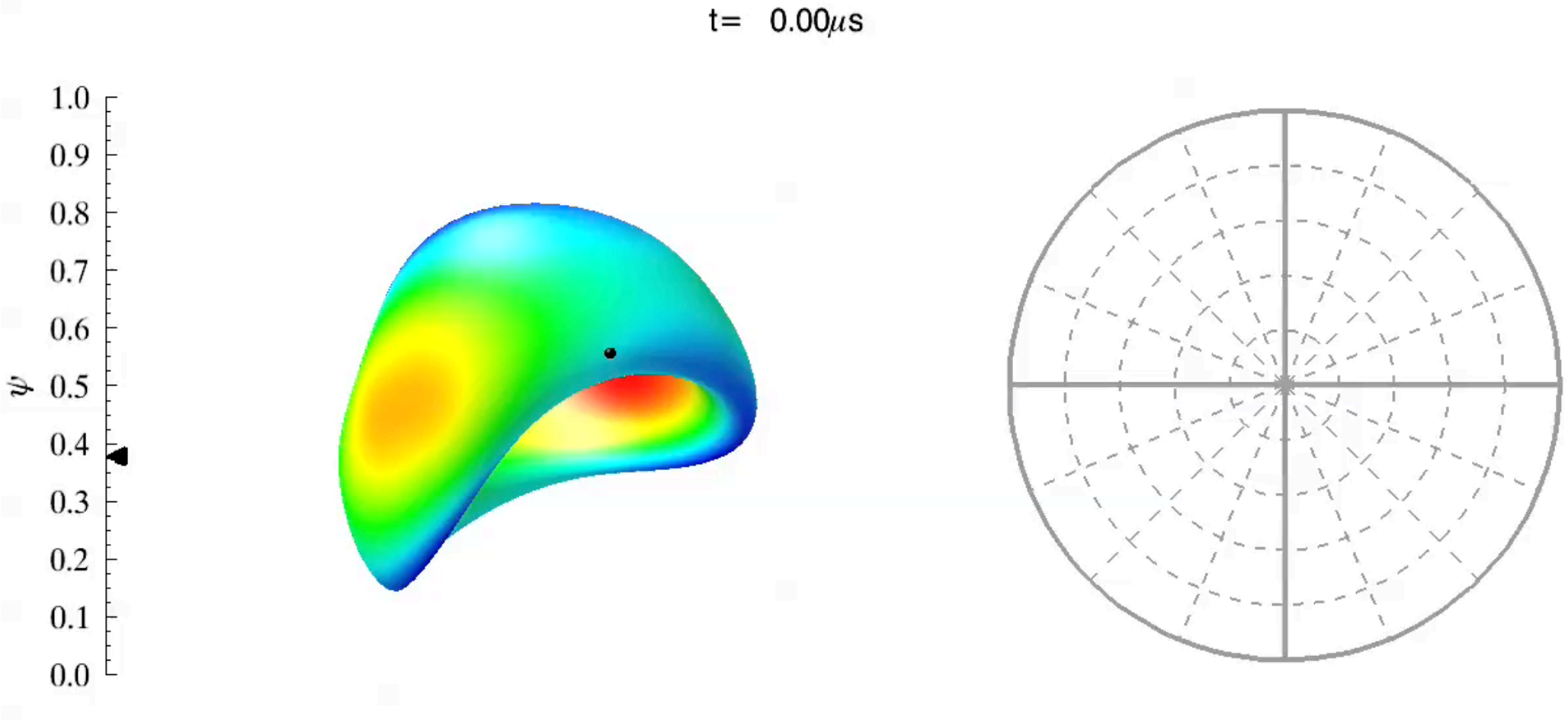
A numerical study was performed, adding the effects of the complex boundary condition in CNT



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)

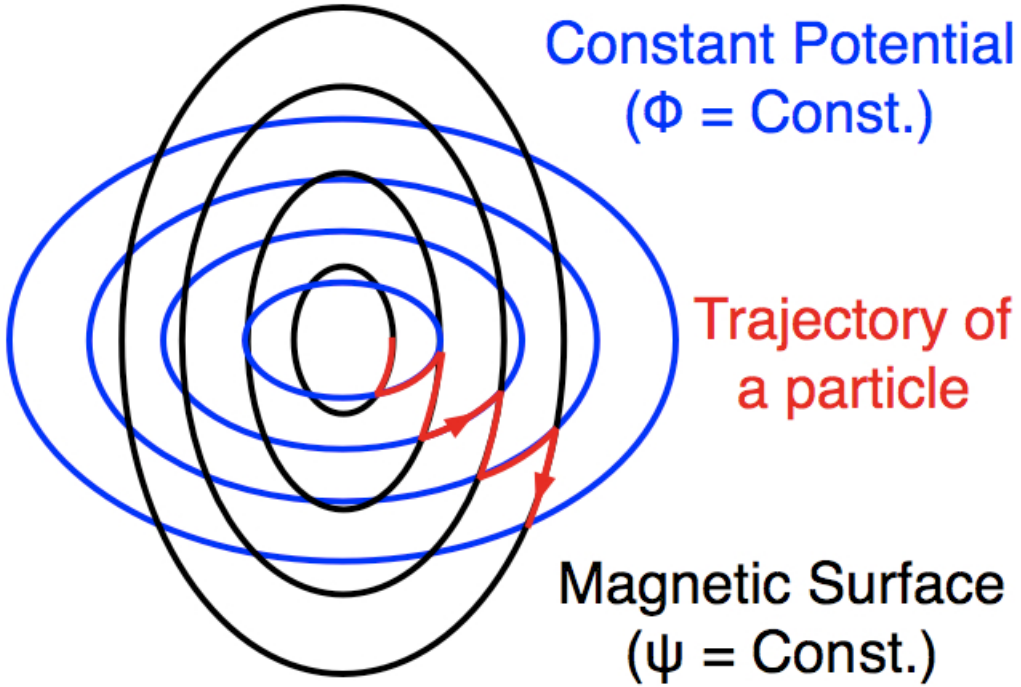
The effects of a non-conforming boundary condition

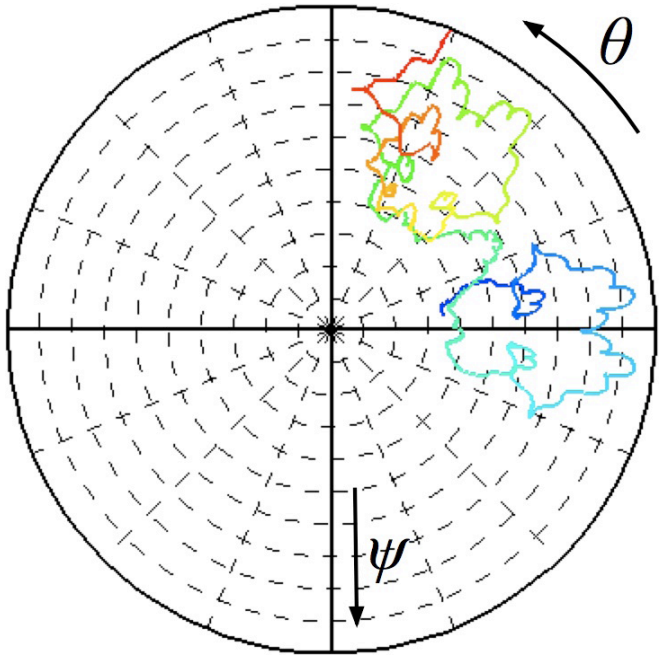
Until 2008, the internal coils and vacuum chamber set the electrostatic boundary condition **causing large electrostatic potential perturbations,** especially in the edge region



Intuitive picture of collisionless loss orbits with E

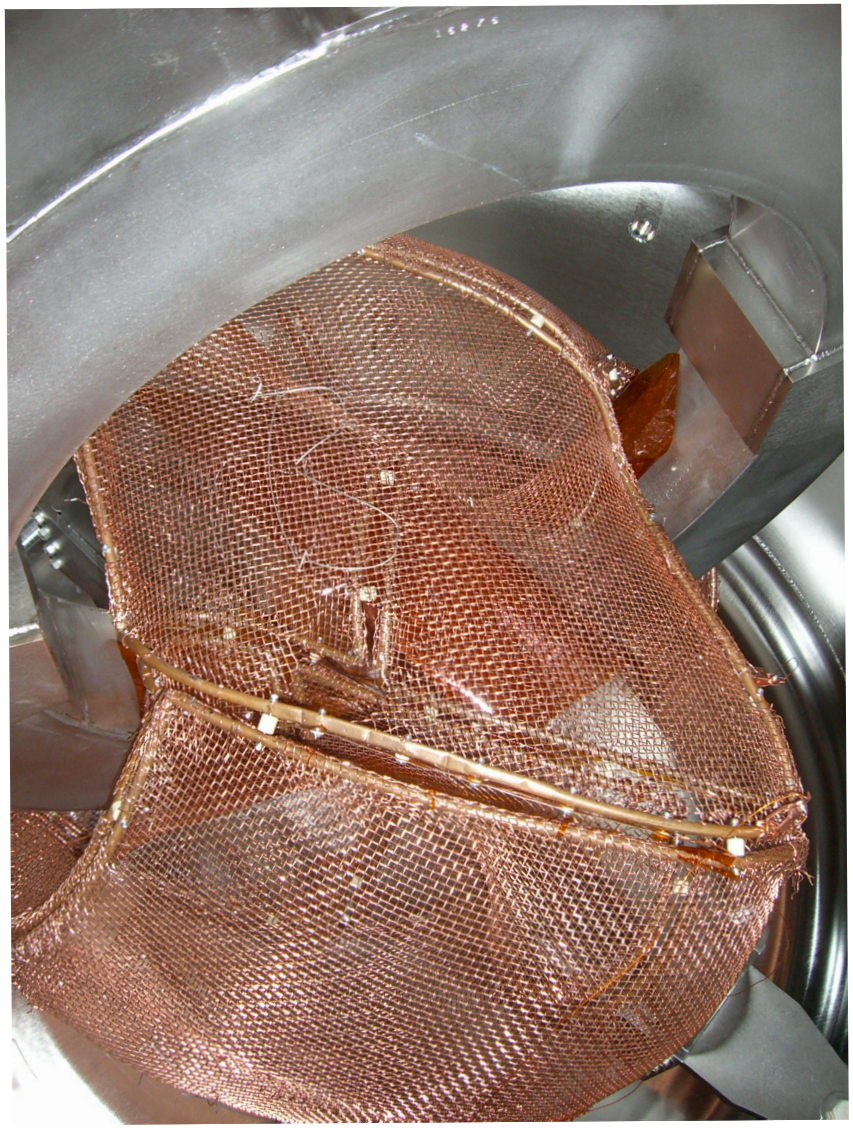
- ExB (perpendicular motion) takes electron along electrostatic potential contour
- Parallel motion of passing electrons (combined with rotational transform) takes electrons along the magnetic surface, moving them poloidally
- By switching between potential contours and magnetic surfaces, particles can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





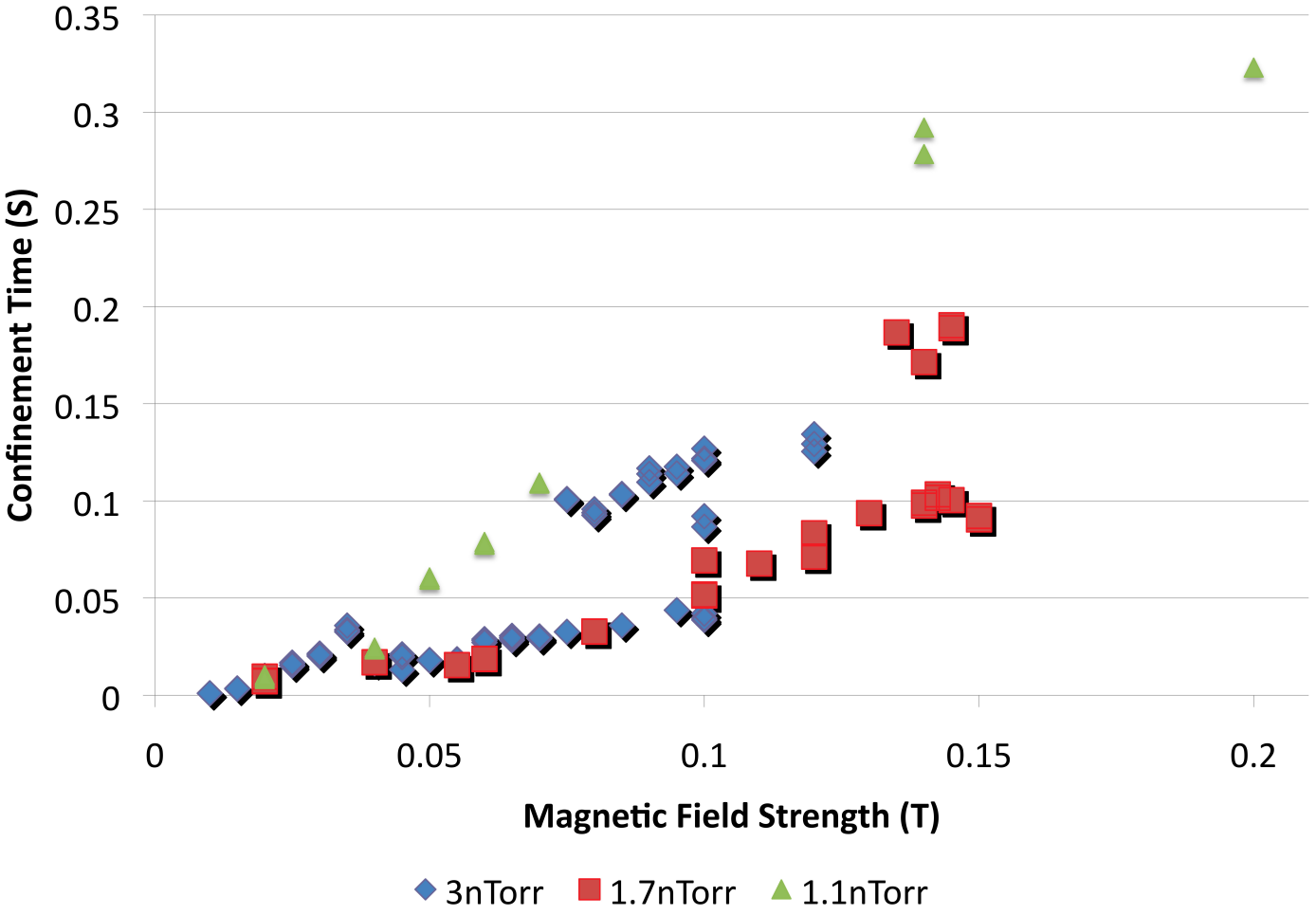
Flux surface conforming electrostatic boundary

- “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

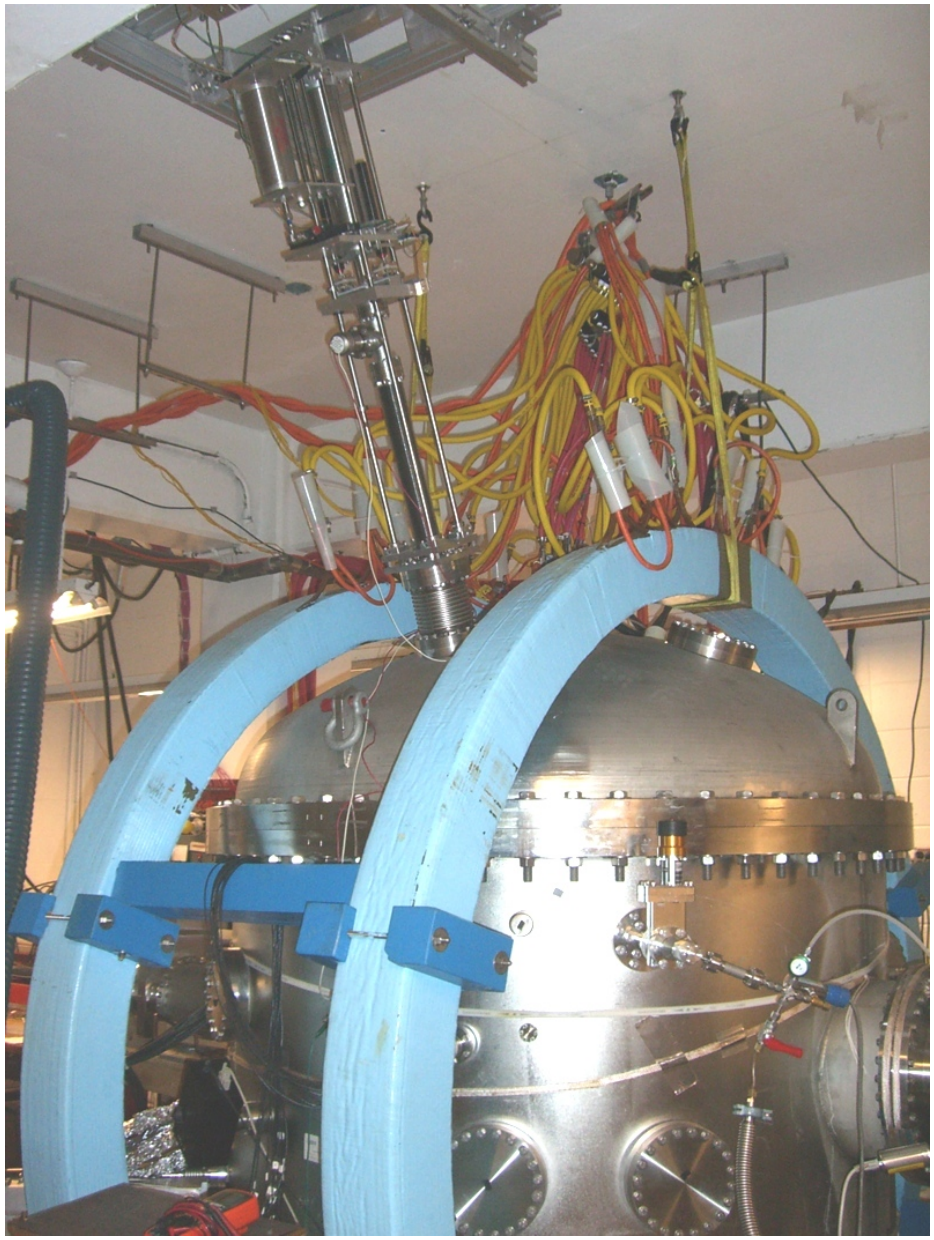
[1]P. W. Brenner et al., Contributions to Plasma Physics (2010)

Summary

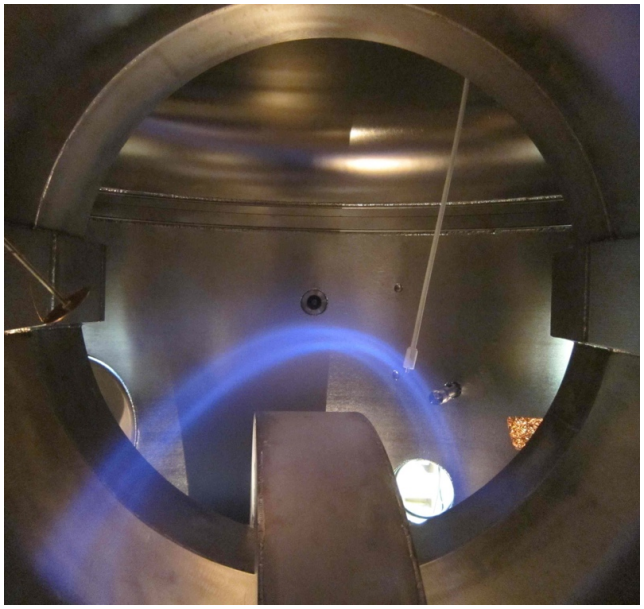
- Toroidal systems provide new interesting confinement and stability physics for non-neutral plasmas
  - Cannot compete with Penning trap in terms of confinement quality (can't beat infinity), but you can study other interesting phenomena
  - Due to the lack of a large sink for ions, ion accumulation in an initially pure electron toroidal plasma often limits confinement
- This was also seen in CNT once rods were eliminated (bonus slides)
- Low electron temperature and excellent vacuum important to keep ion contamination low
- One can also study partially neutralized plasmas in such traps (bonus slides)
- And possibly one day electron-positron plasmas…

Slides not shown due to lack of time

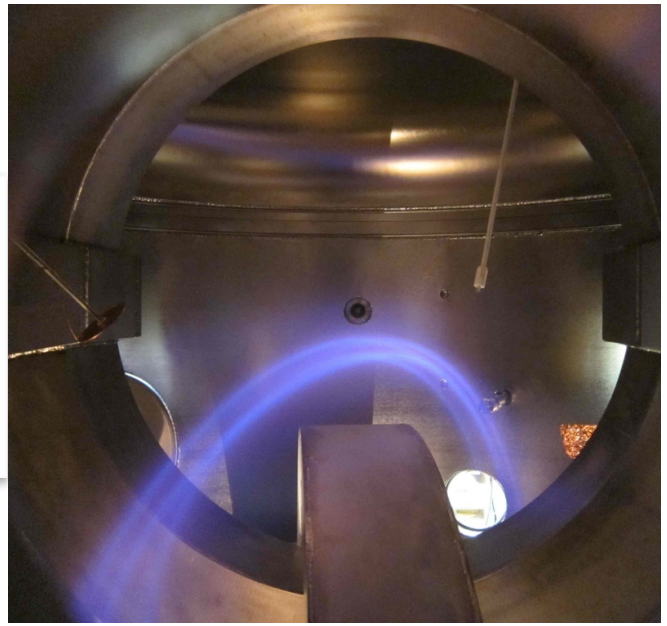
Emitter capable of retraction in 20 msec installed: There should be plasma left



In Surfaces



Retracted



Design: Berkery et al. RSI (78) 2007

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

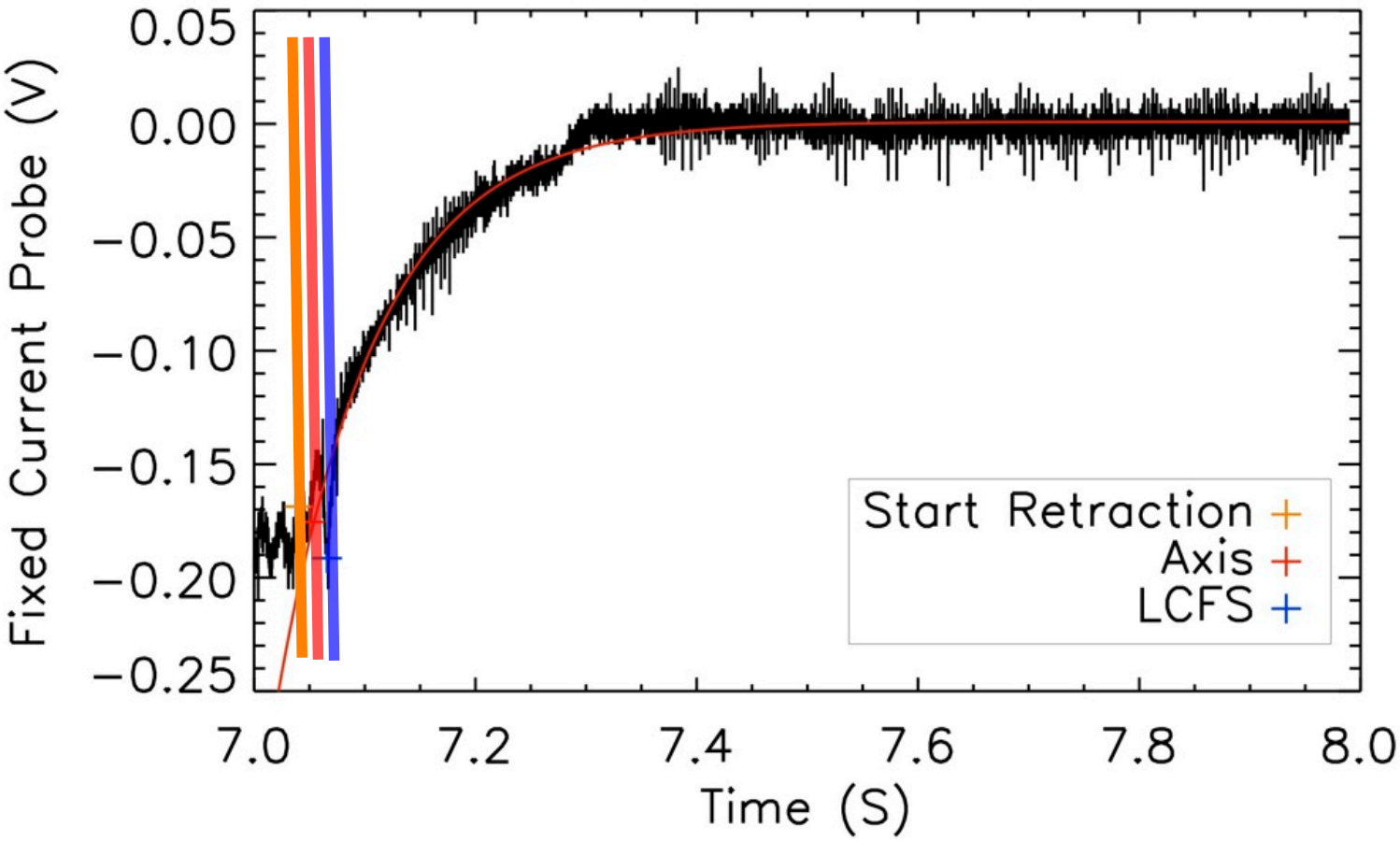
Were our previous confinement results somehow overestimated?

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:

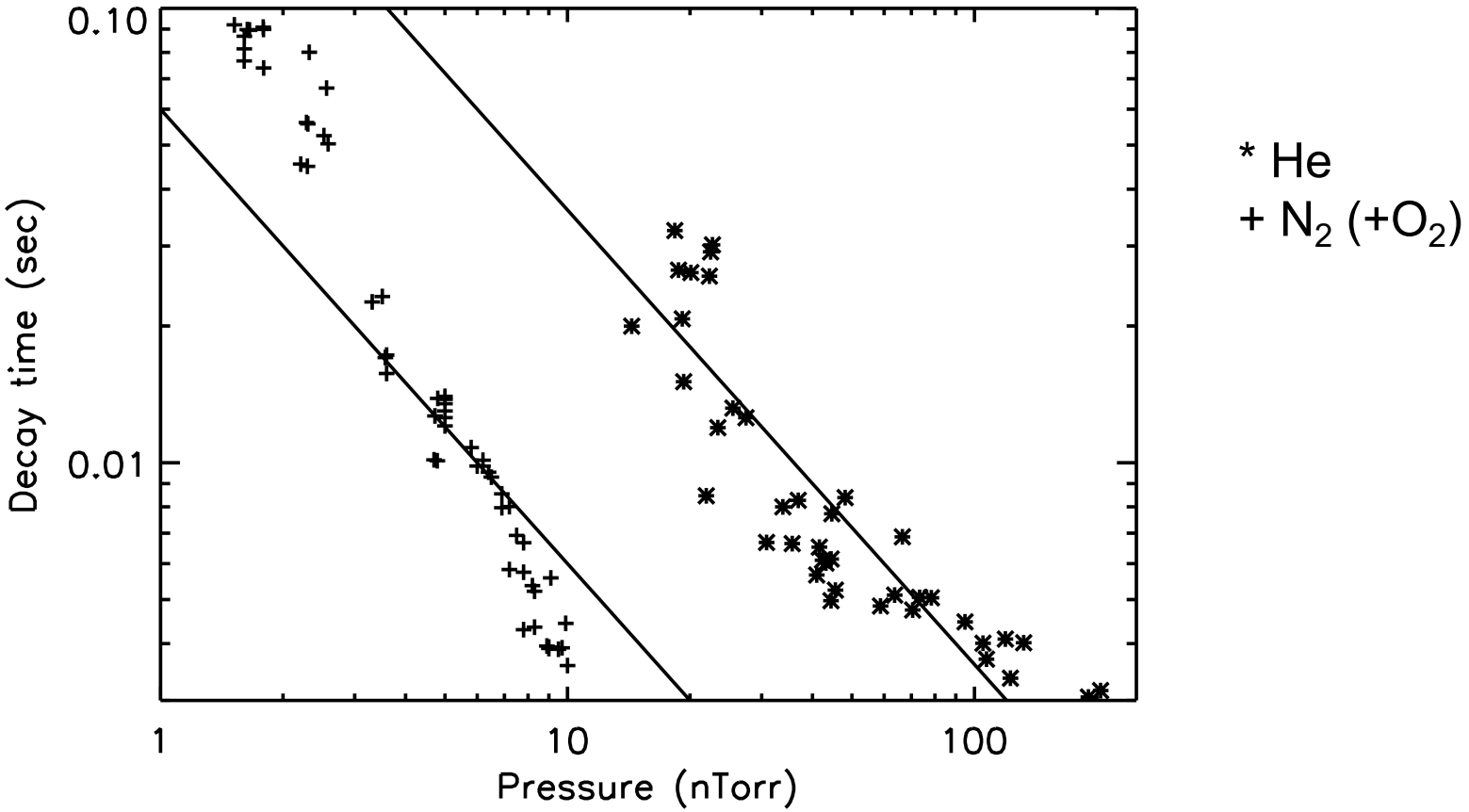
Confinement is much more sensitive to neutral pressure for retraction plasmas; confinement is much shorter for the neutral pressures that we can reach

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

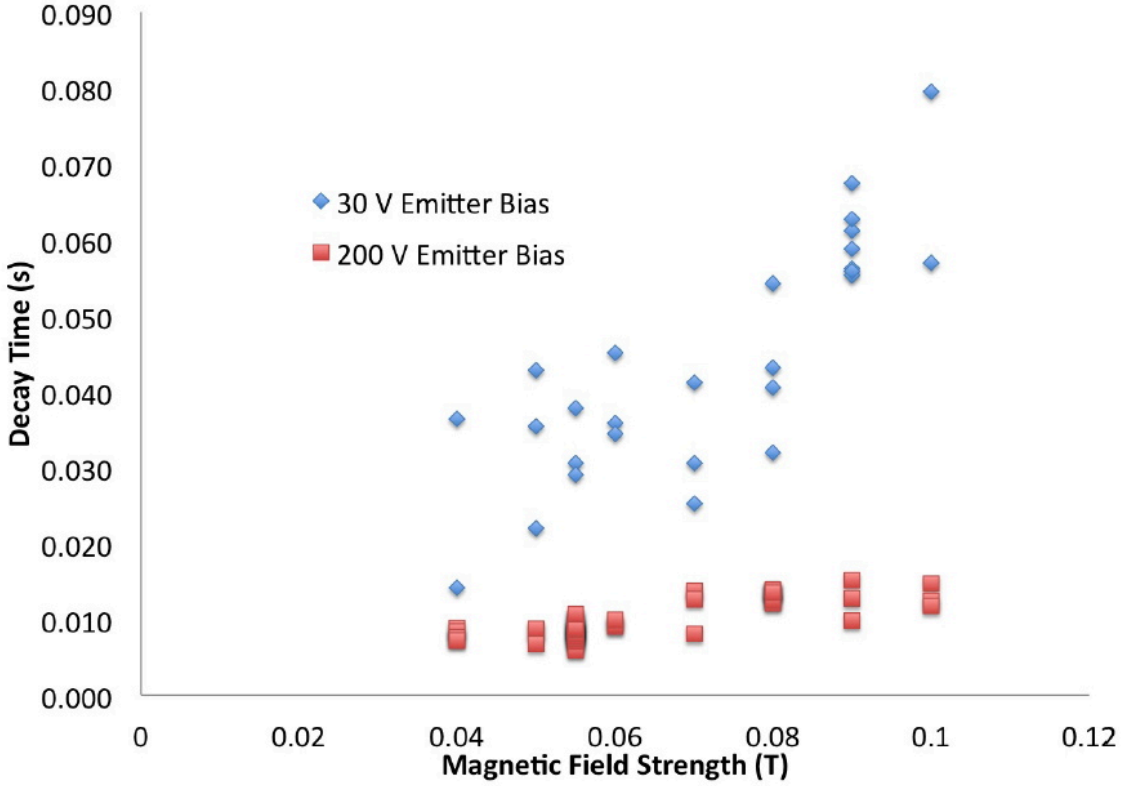
Plasma decay is determined by ion contamination



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 η=10^{-8} to 10^{-3}
•When you enter uncharted territory – begin charting!

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

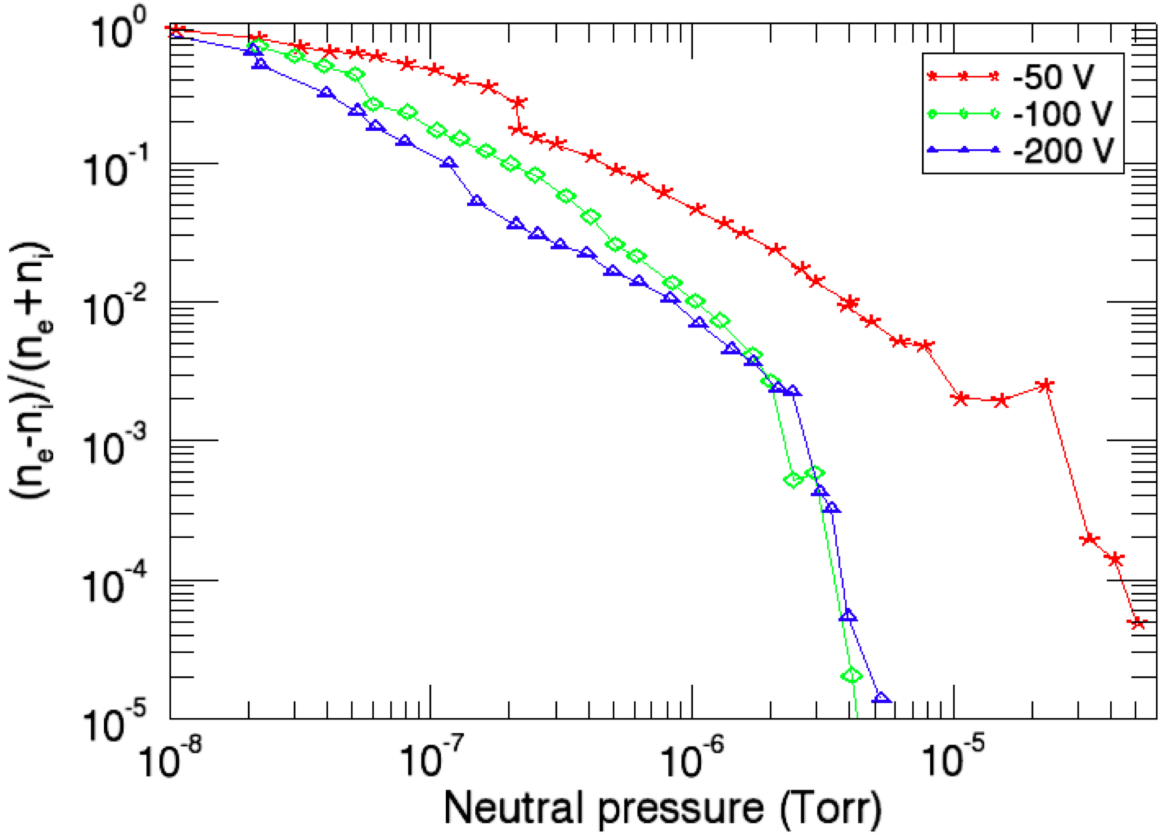
Charting the landscape from pure electron to quasi-neutral plasma

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

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

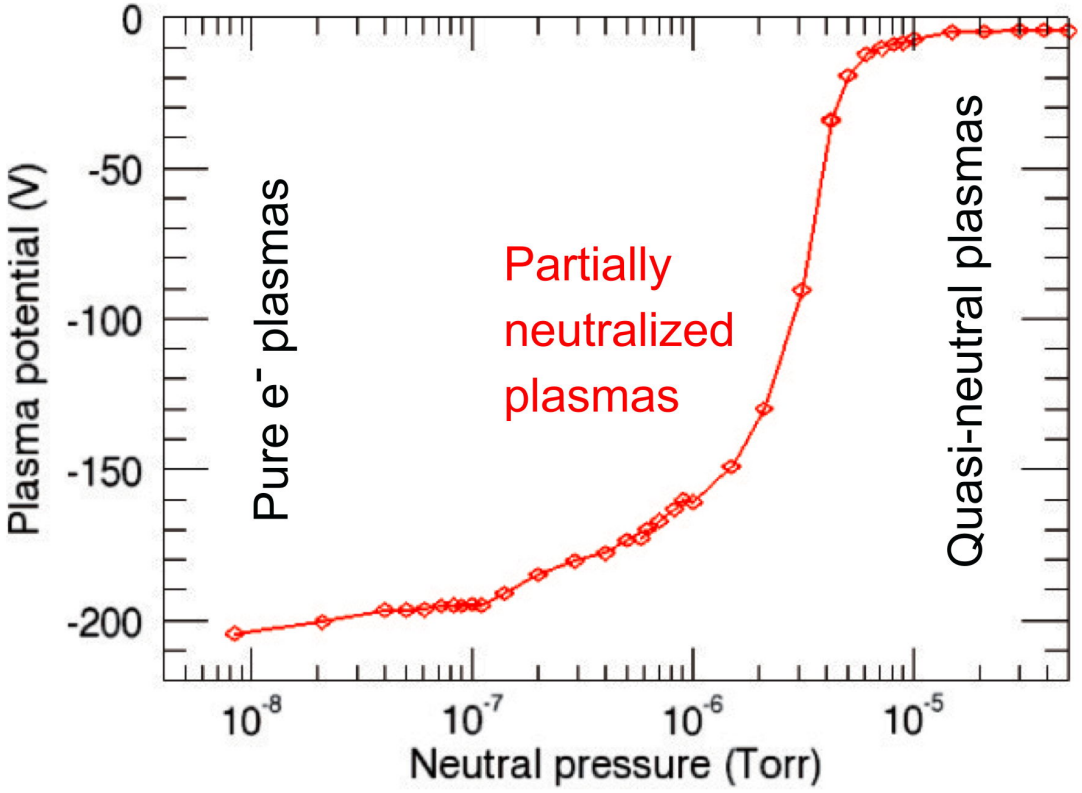
•A pure electron plasma has η=1

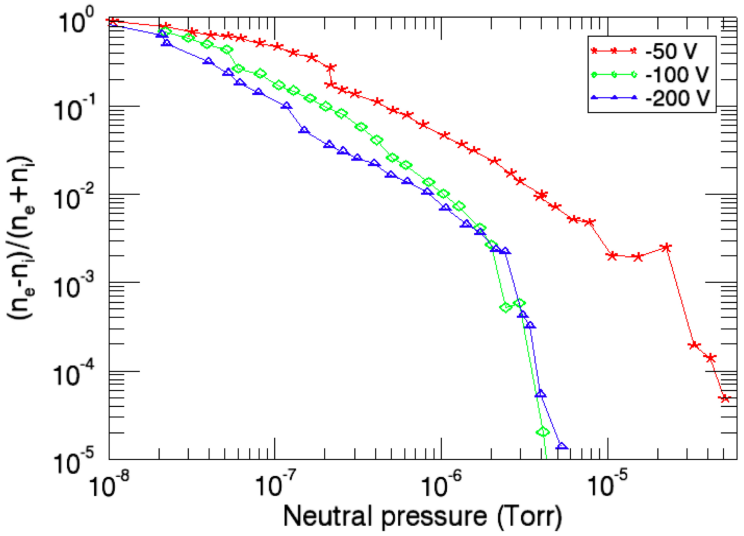
•Typical range for quasineutral laboratory plasmas is η=10^{-8} to 10^{-4}

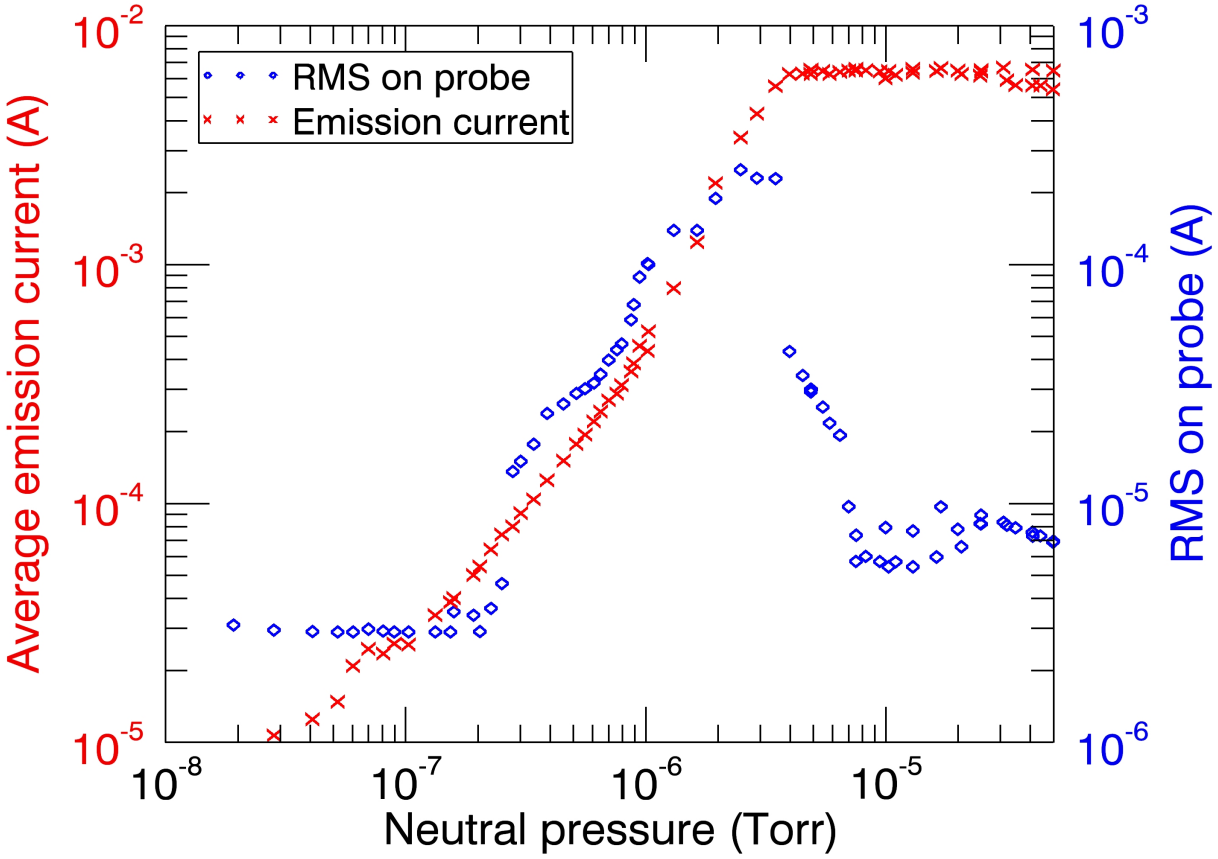
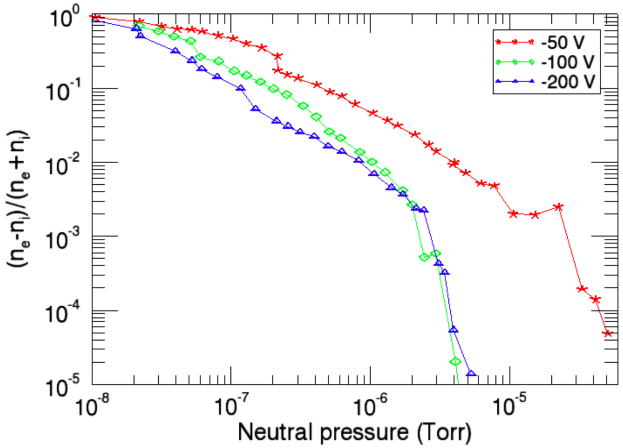
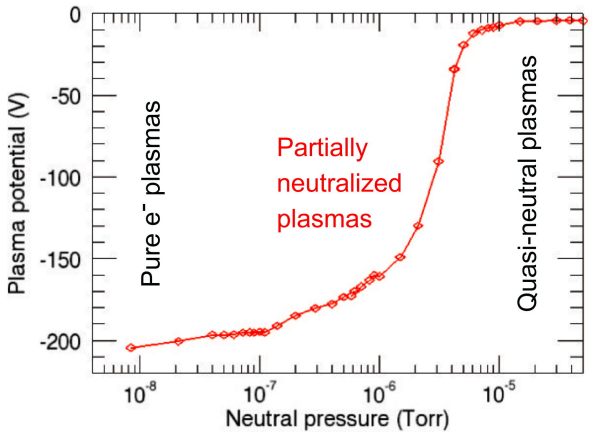


Charting the landscape from pure electron to quasi-neutral plasma

•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