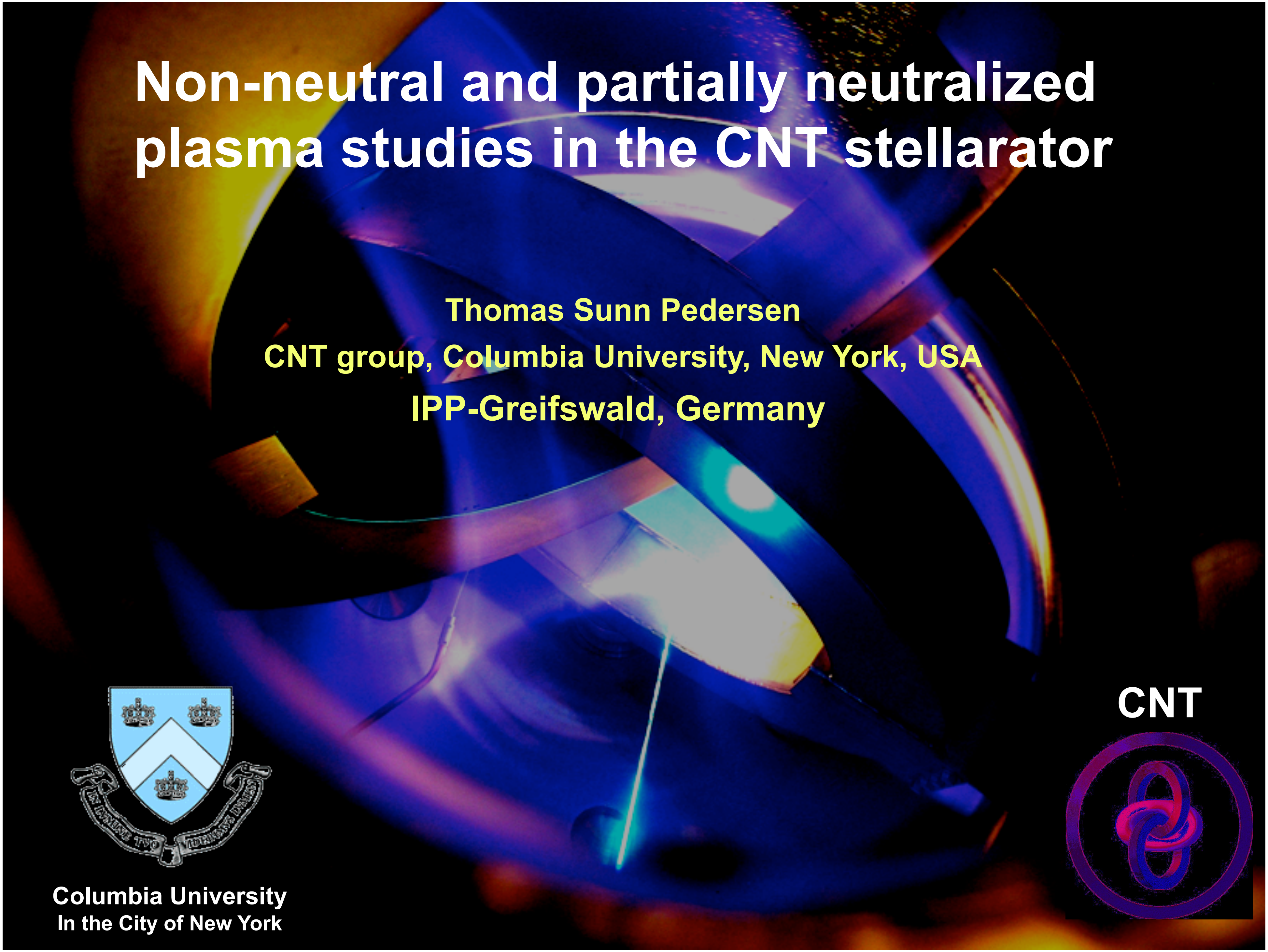

Non-neutral and partially neutralized plasma studies in the CNT stellarator

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CNT

Overview

- Introduction to the basic physics of non-neutral plasmas
- Physics of pure electron plasmas in stellarators
  - Motivation and history
  - Experimental investigation of confinement in CNT
  - Orbit simulations for CNT
  - Confinement improvement
  - Operation and diagnosis of plasmas without internal objects
- Physics of partially neutralized plasmas
  - More or less unexplored territory – will show initial “map”
- Plans for electron-positron plasmas
- Summary

Some basic characteristics of non-neutral plasmas

- 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:

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

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

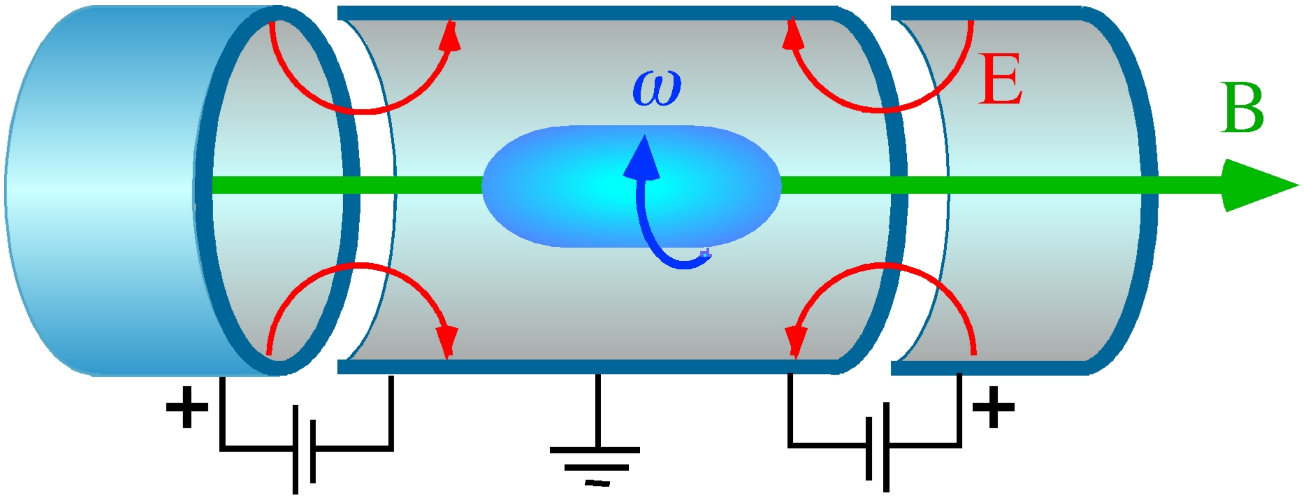
$$\left|\frac{v_{E\times B}}{v_{\nabla B}}\right| = \frac{|\nabla\varphi|/B}{T|\nabla B|/eB^2} \approx \left|\frac{e\varphi}{T}\right| >> 1$$

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

Why study non-neutral plasmas?

- **Small scale experiments with interesting and unique physics - excellent for University research**
- Global thermal equilibrium can be obtained (in some traps)
- Plasmas are highly reproducible, low noise (in some traps)
- Long time confinement of antimatter can lead to interesting physics:
  - Antihydrogen
- Long time confinement and cooling of just a few particles
  - (Precision spectroscopy, solid state physics, crystal formation)
- Can study phenomena of broad interest
  - Example 1: Neoclassical confinement in stellarators in the “ion root” regime
  - Example 2: Electron-positron plasmas
  - Example 3: High intensity beams

Penning Trap: Why it confines single component plasmas so well



Cylindrical symmetry, single species => long confinement time

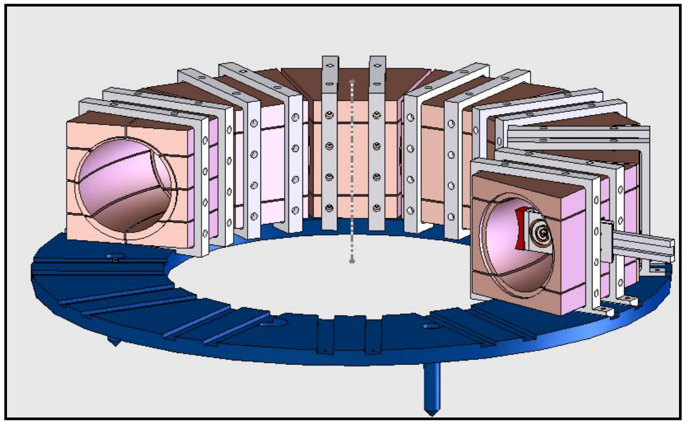
$$P_\theta = \sum_{i=1}^{N} [\cancel{m v_{\theta i} r_i} + \frac{eB}{2c} r_i^2] = const.$$

Note: For a neutral plasma, this conservation does not restrict the radial transport!
Confined thermal equilibrium: *T* uniform, ω uniform (rigid rotor)

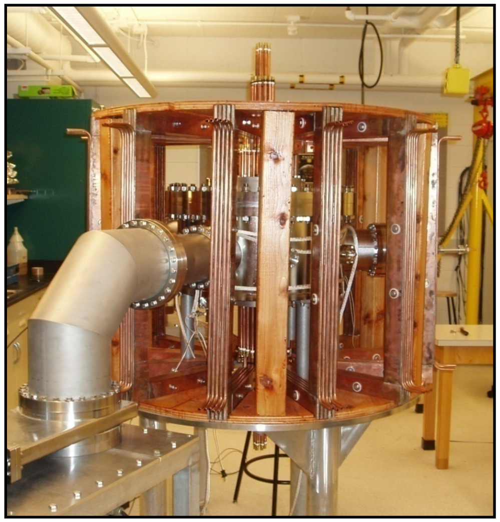
Davidson and Krall, Phys. Fluids 1970
Dubin and O'Neil, R.M.P. 1999

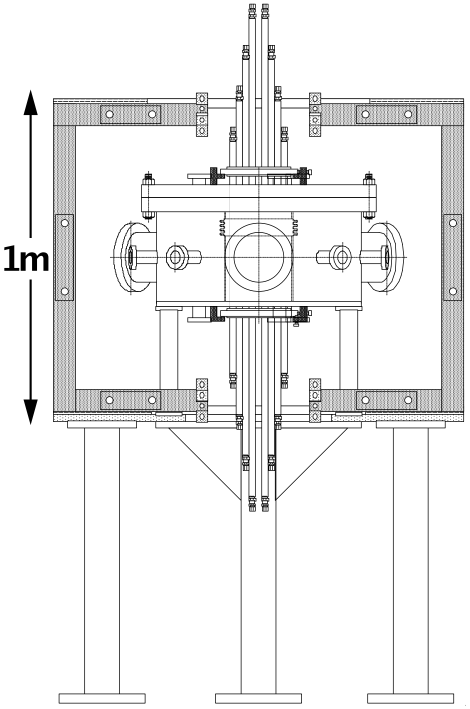
Pure electron plasmas in a pure toroidal magnetic field: Lawrence Non-neutral Torus II

- Experiment led by Matt Stoneking, Lawrence University, Wisconsin
- Pure toroidal field
- Predicted excellent particle confinement because the ExB drift provides an effective rotational transform (poloidal motion), and $v_{ExB} >> v_{\nabla B}$
- Results presented here are from a partial torus (“a bent Penning trap”)
  - Confinement is worse for a full torus by the way!

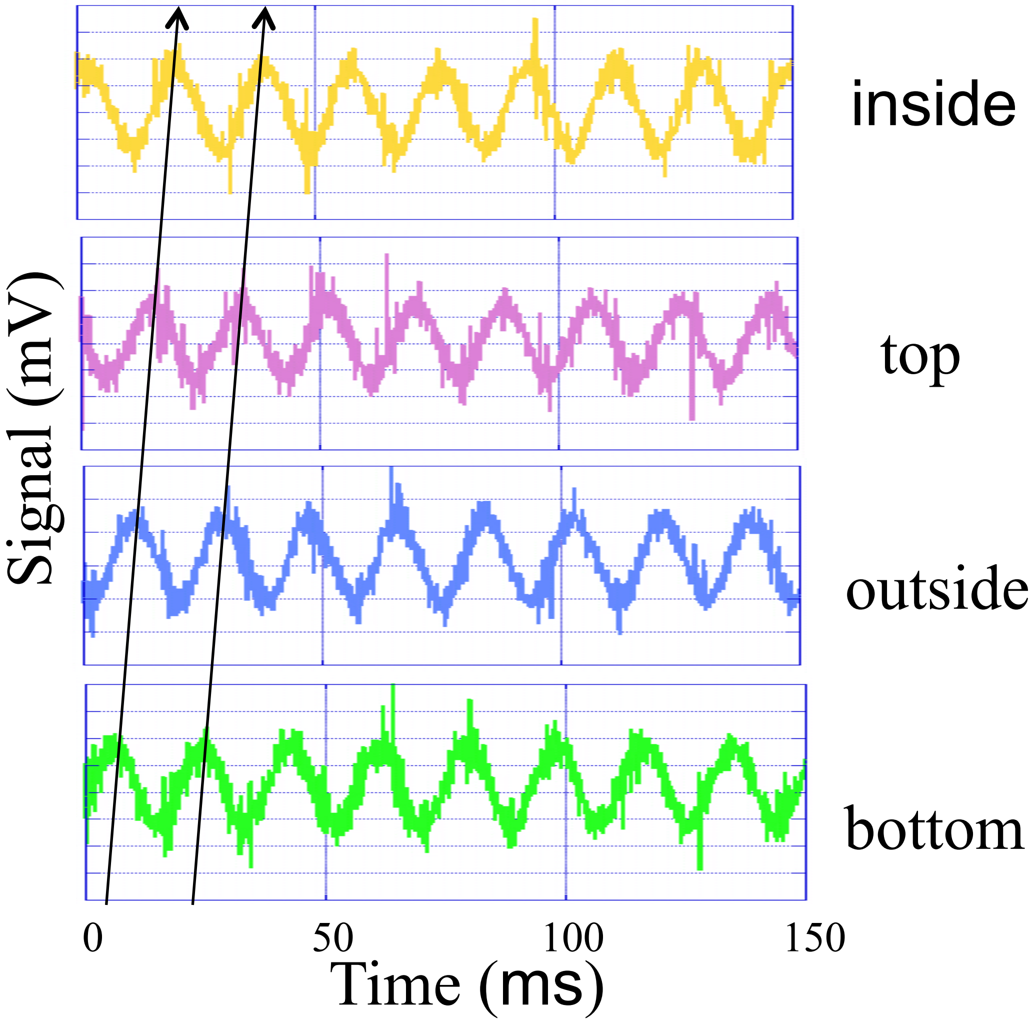


- Plasma major radius: 17.4 cm
- Plasma minor radius: ~1.3 cm
- Length: 82 cm (270 degrees)
  109 cm (360 degrees)





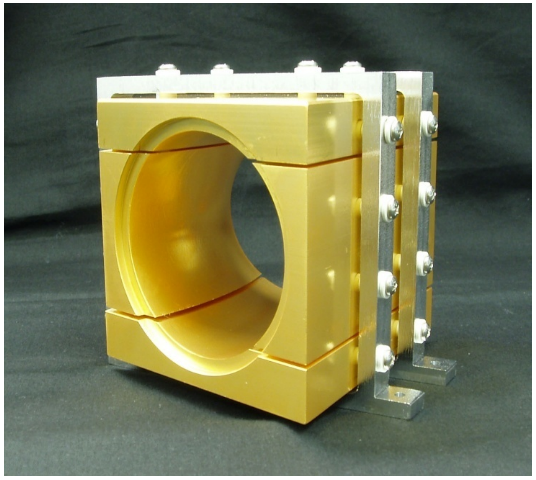
Observation of *m*=1 Diocotron Mode (ExB rotation of the entire plasma)



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

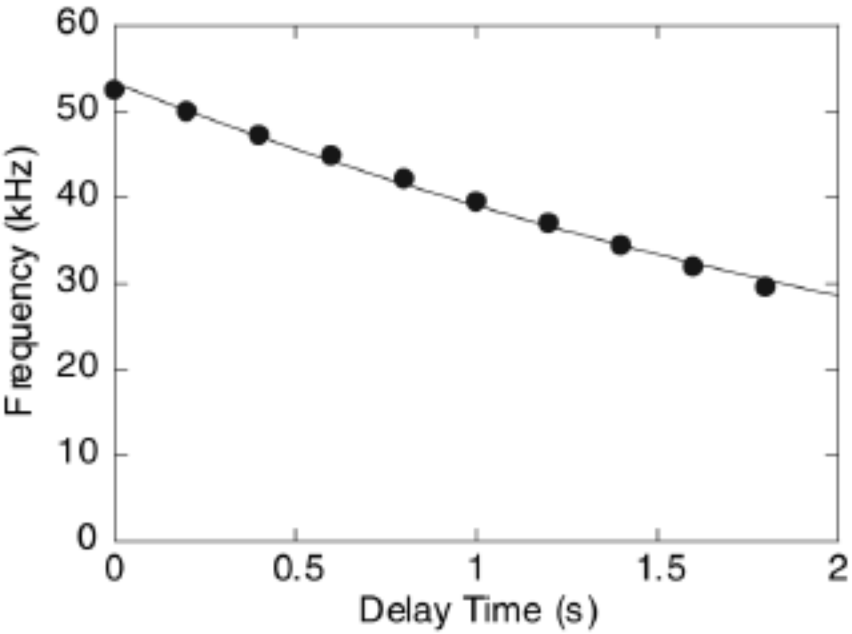
$$Q \approx 1.5\,\mathrm{nC}$$

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



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)

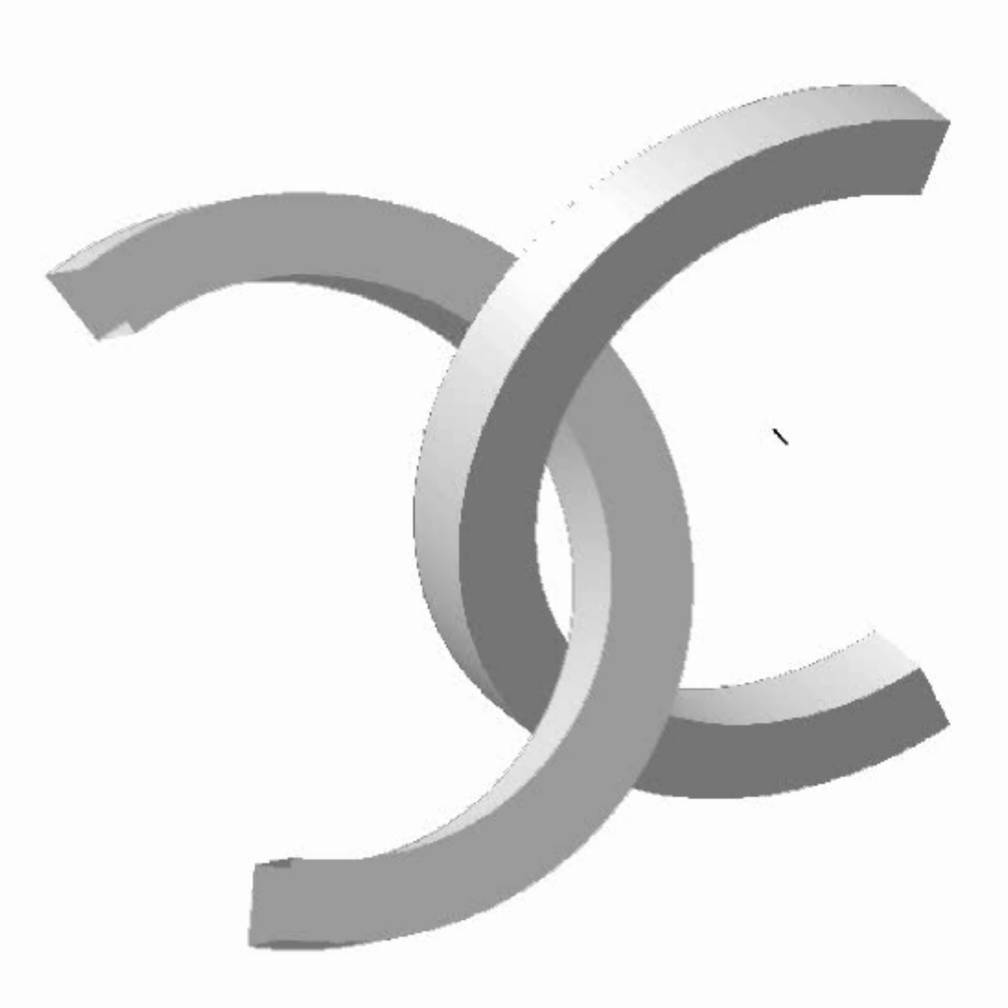


Non-neutral plasmas in a stellarator

- 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
    - Not true for Penning trap
    - 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

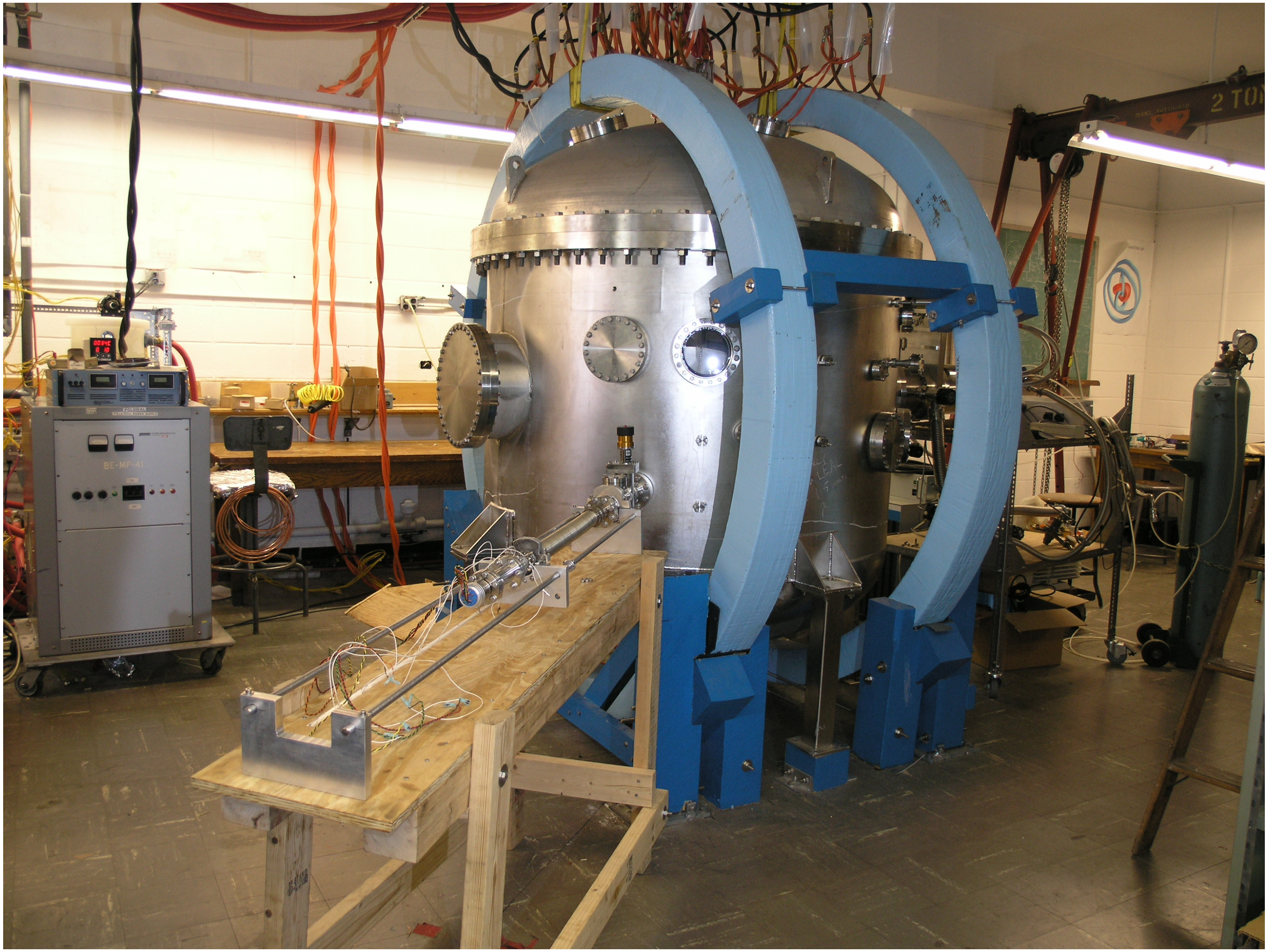
- A stellarator is a magnetic surface configuration: Each magnetic field line wraps around a toroidal surface, never leaving the surface.



Non-neutral plasmas in a stellarator

- The non-neutral stellarator idea is about 10 years old
  - (Sunn Pedersen and Boozer, PRL **88**, 2002)
  - Equilibrium equation derived
  - Unique capabilities recognized
- BUT! very similar experiments were actually performed >20 years ago!
  - Auburn torsatron (USA, 1987), and Uragan-2, Uragan-3 (USSR, 1988) “Stellarator diode” – a field line mapping technique
  - Drawbacks of this field line mapping technique and were likely caused by the creation of pure electron plasmas and the associated collective effects made the situation complicated!
- Now, several stellarators do non-neutral physics
  - CNT (this talk)
  - CHS, Japan (until recently)
- There are also NNP studies in dipoles now (RT-1, Saitoh et al. Japan)

CNT: A stellarator dedicated to NNP physics since 2004

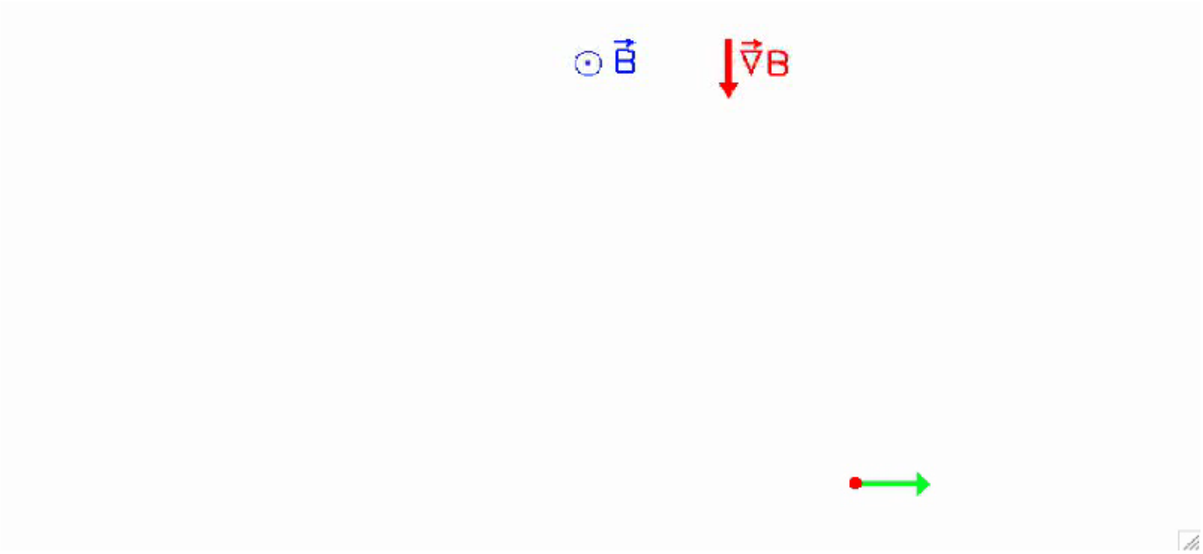


CNT is a simple and compact stellarator

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

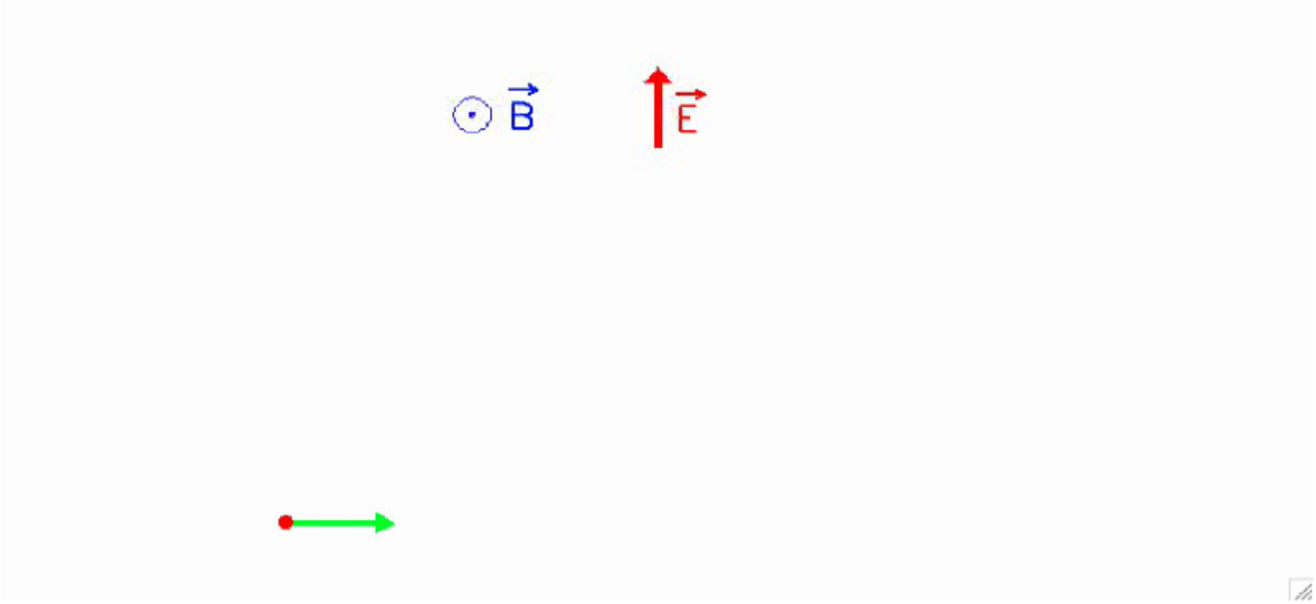
Neoclassical transport

- A charged particle performs a screw-like path if it is confined by a straight uniform magnetic field and it feels no other forces
- However, if the field is not that simple, or if electric fields are present, the particle drifts in addition – usually slowly compared to the parallel motion.
- Example: ∇B



Neoclassical transport and ExB drift

- Since the parallel free streaming leads to no transport from surface to surface, transport rates are usually determined by these drifts
- Example: E



First expectation of neoclassical confinement in CNT

•CNT’s pure electron plasmas are (paradoxically) in the extreme “ion root” of stellarator neoclassical transport

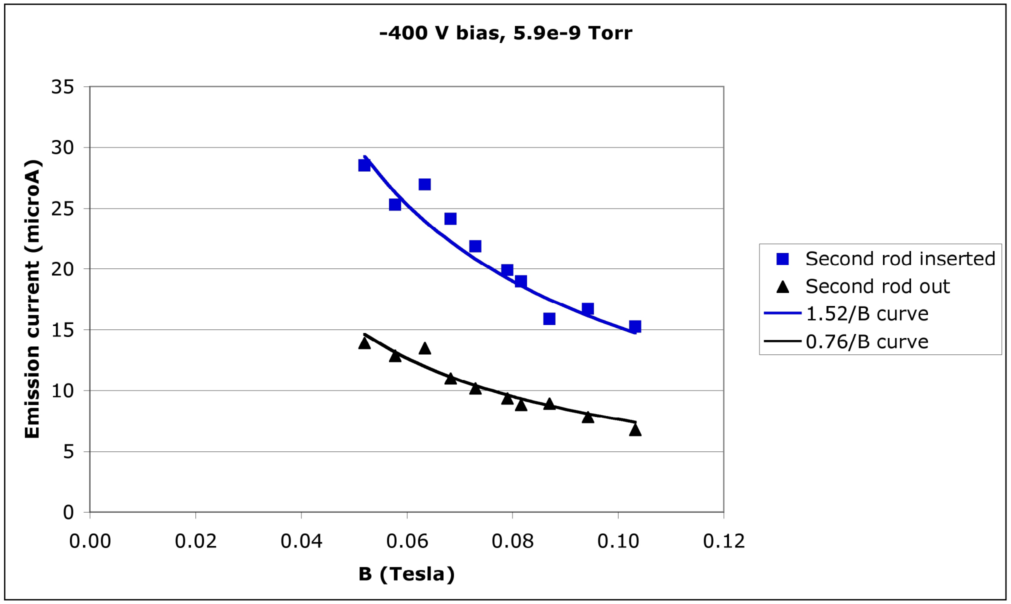
•CNT: $\Delta\phi$~200 V, T_e ~4 eV

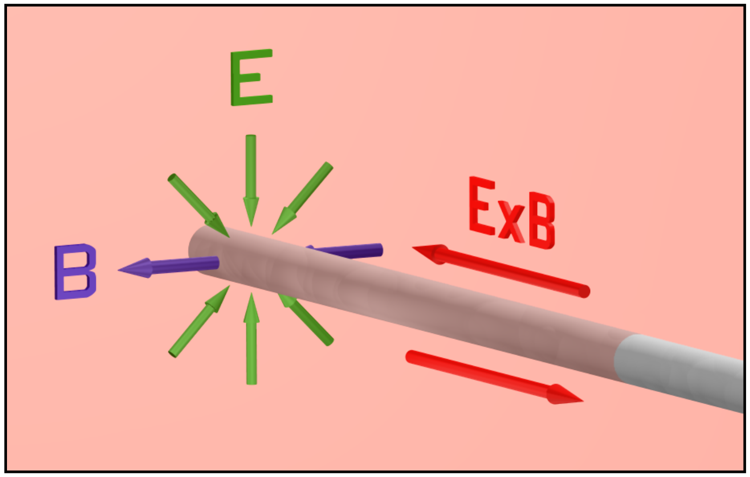
$$\left|\frac{v_{ExB}}{v_{\nabla B}}\right| \approx \left|\frac{e\phi}{T_e}\right| \approx 50$$

•Since ExB drift dominates over grad B and curvature drifts it should close otherwise bad orbits (just as it does in the pure toroidal field trap – LNT II)

•Much reduced neoclassical transport (squeezing of drift orbits and absence of bad orbits)

Experimental finding 1: Internal rods drive transport



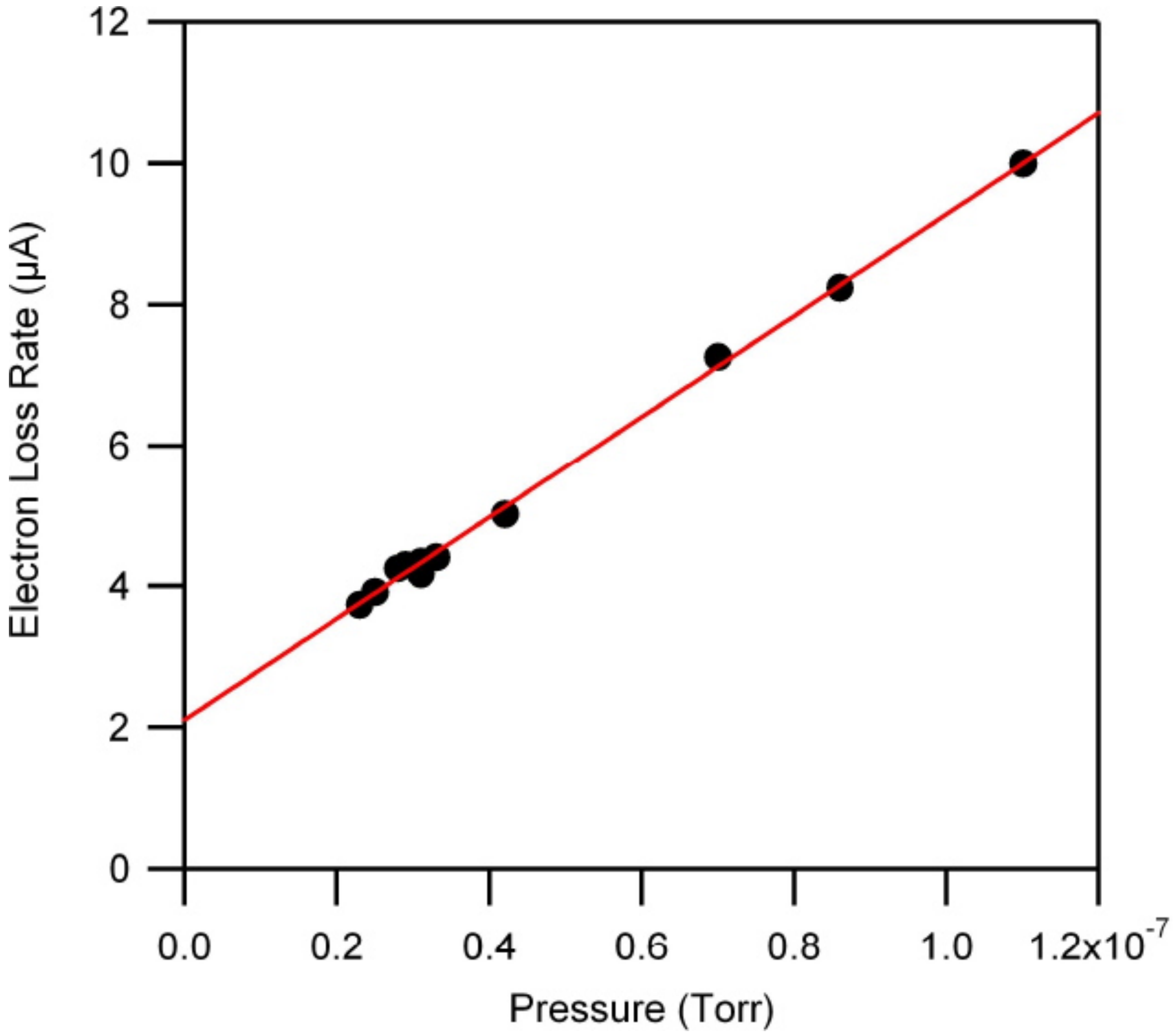


Insulated rods charge up negative relative to plasma to self-shield
Resulting ExB drift pattern convects particles along the rod all the way to the open field lines.

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:

Numerical study:

Confirmed good orbits when the electric potential does not vary on a magnetic surface

But when we use a realistic electrostatic potential (one that varies on magnetic surfaces as a result of the electrostatic boundary condition in CNT), we see poor orbits (next few slides)

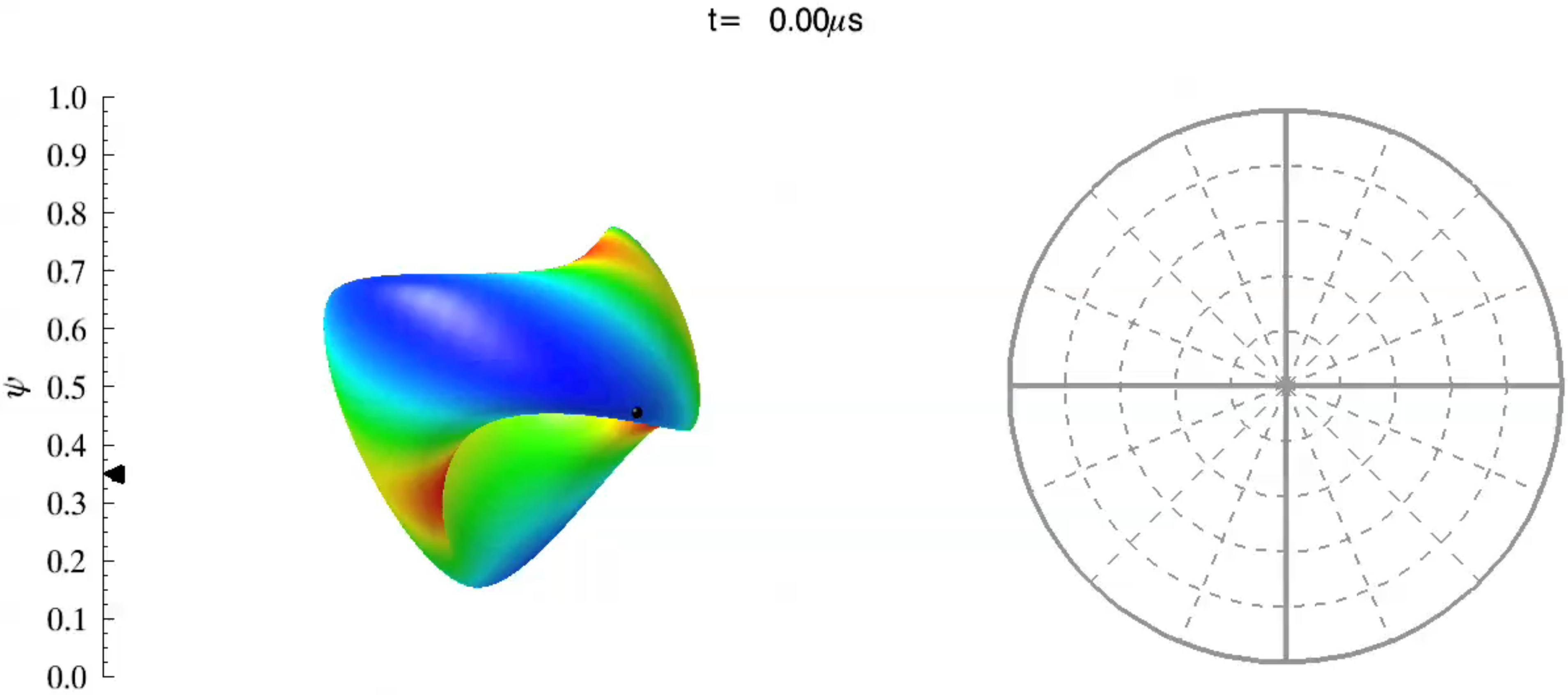
Details published in: “Numerical investigation of electron trajectories in the Columbia Non-neutral Torus”, B. Durand de Gevigney et al, Physics of Plasmas **16**, article 122502 (2009)

Simulation 1: No electric field

If the electric field is weak, the ExB drift is small, magnetic drifts important

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

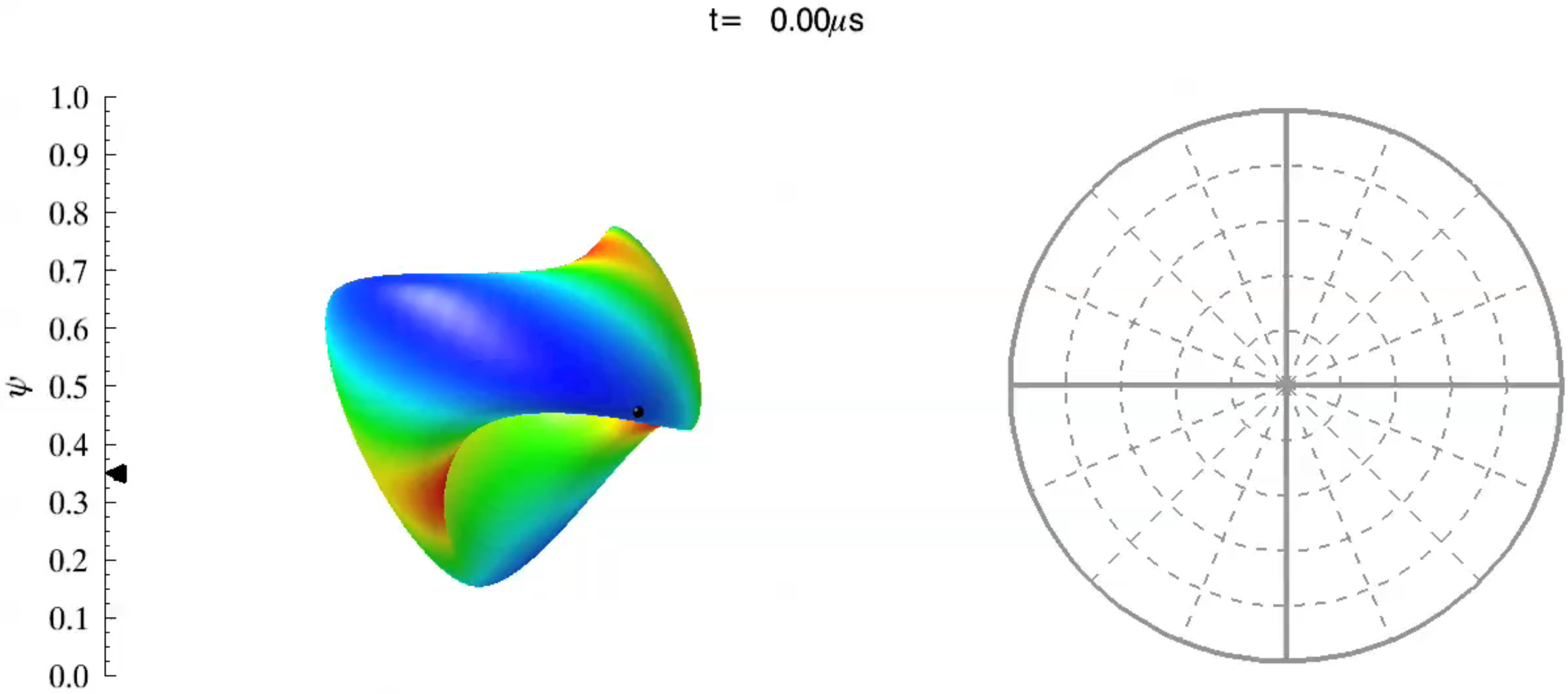
About 50% of particles are magnetically trapped and drift out of CNT.



Simulation 2: Idealized electric field

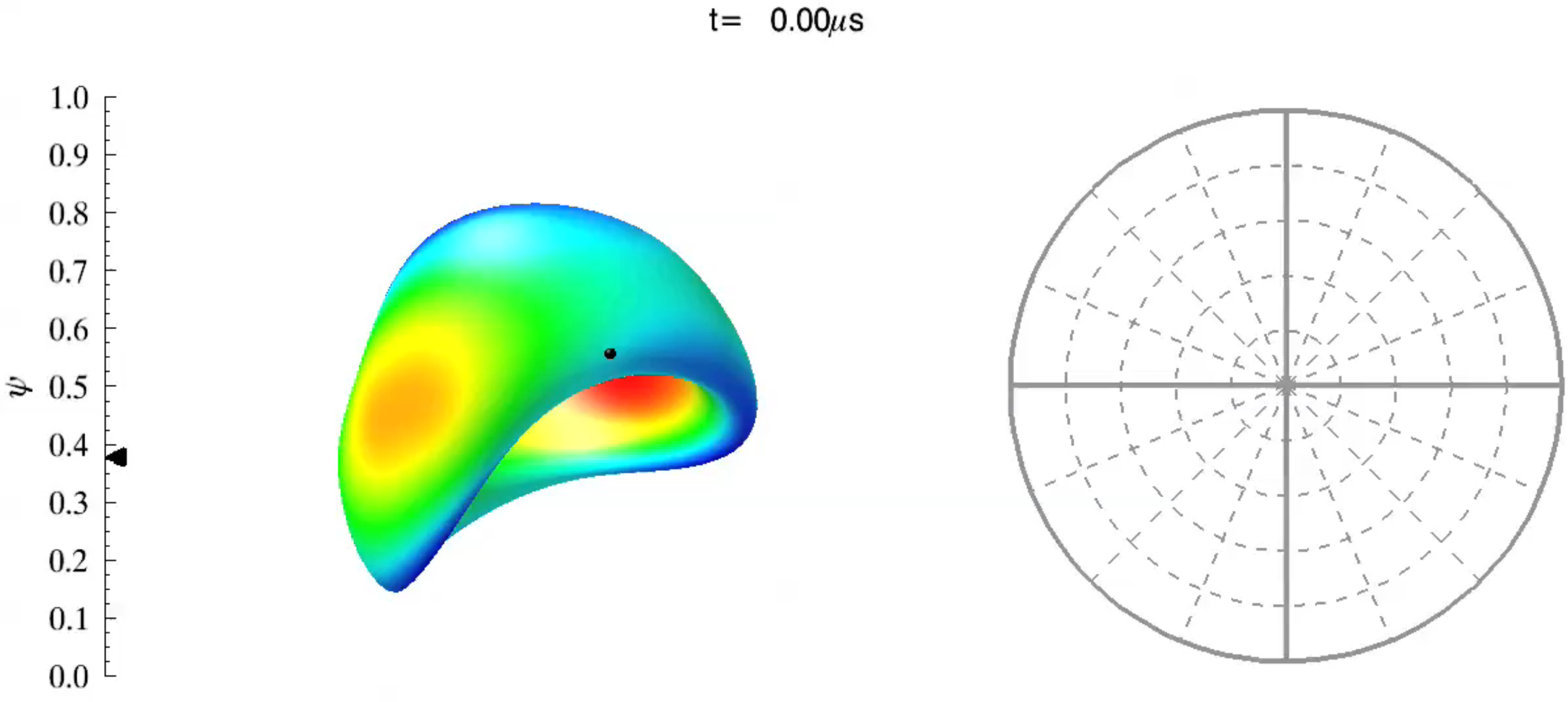
A strong space charge electric field – constant on a magnetic surface – is added to the simulation of the trapped particle

Now it is confined!



Simulation 3: 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

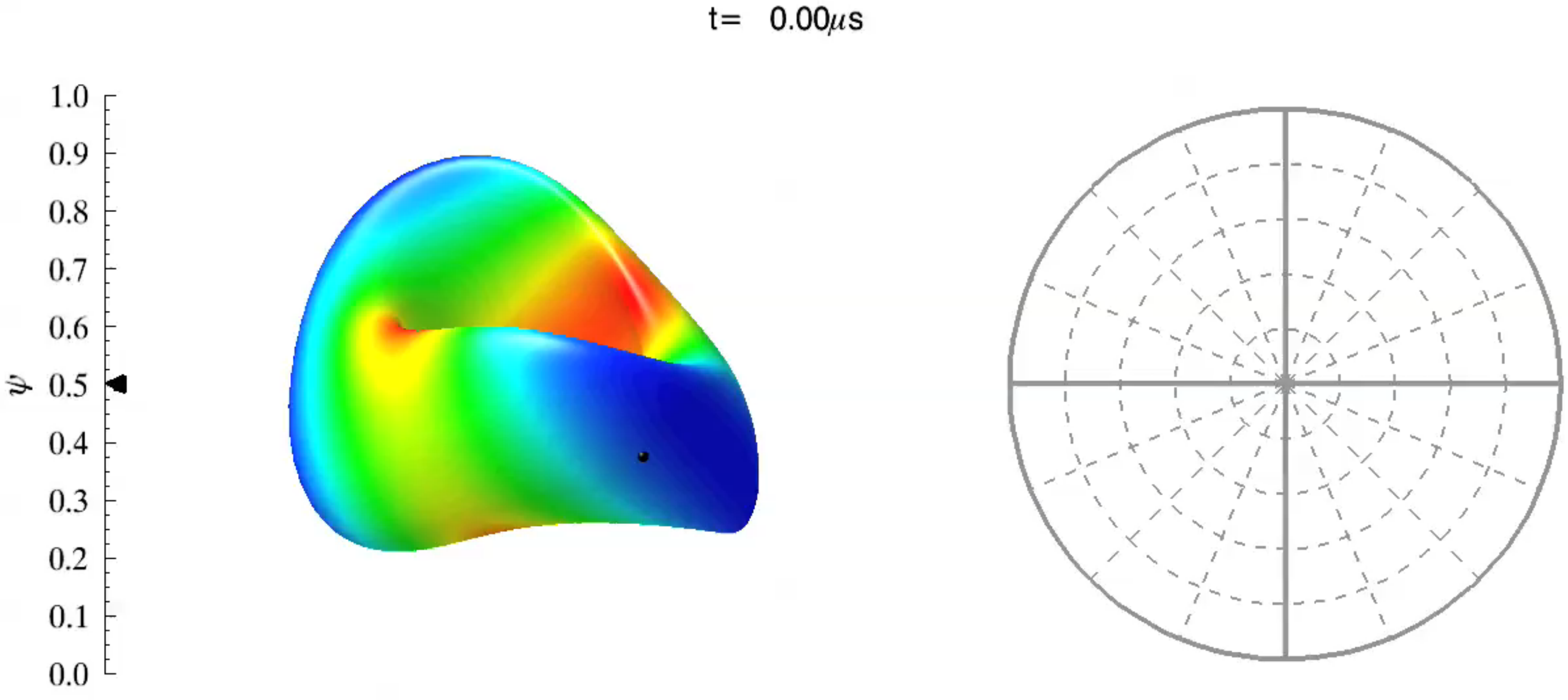


Simulation 4: Idealized electric field with resonance orbit

Orbits can make large excursions even with the idealized electric field

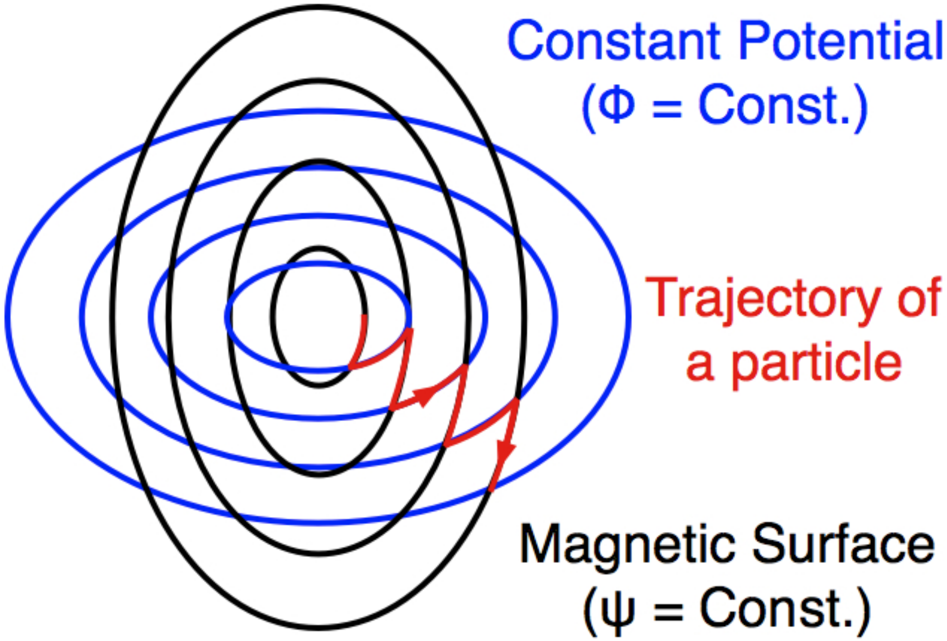
This is a resonance phenomenon – only a small fraction of particle orbits are affected: ExB cancels poloidal part of parallel motion for passing particles

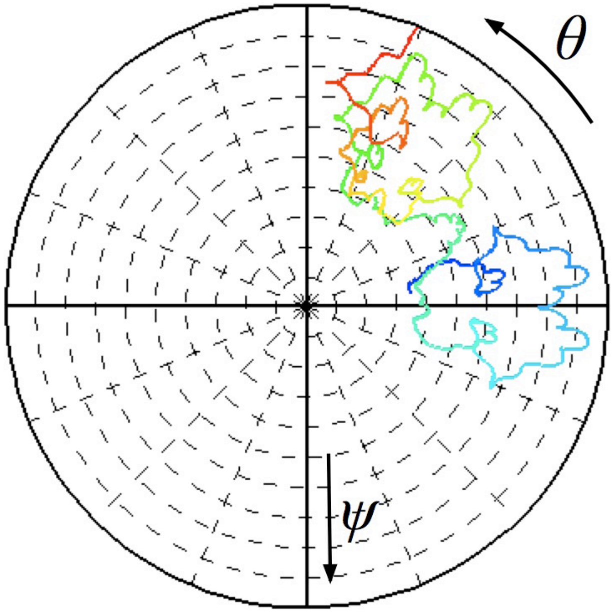
Similar apperance to tokamak “banana” orbits – but for passing particles (banana orbits in tokamaks are magnetically trapped)



Intuitive picture of collisionless loss orbits with E

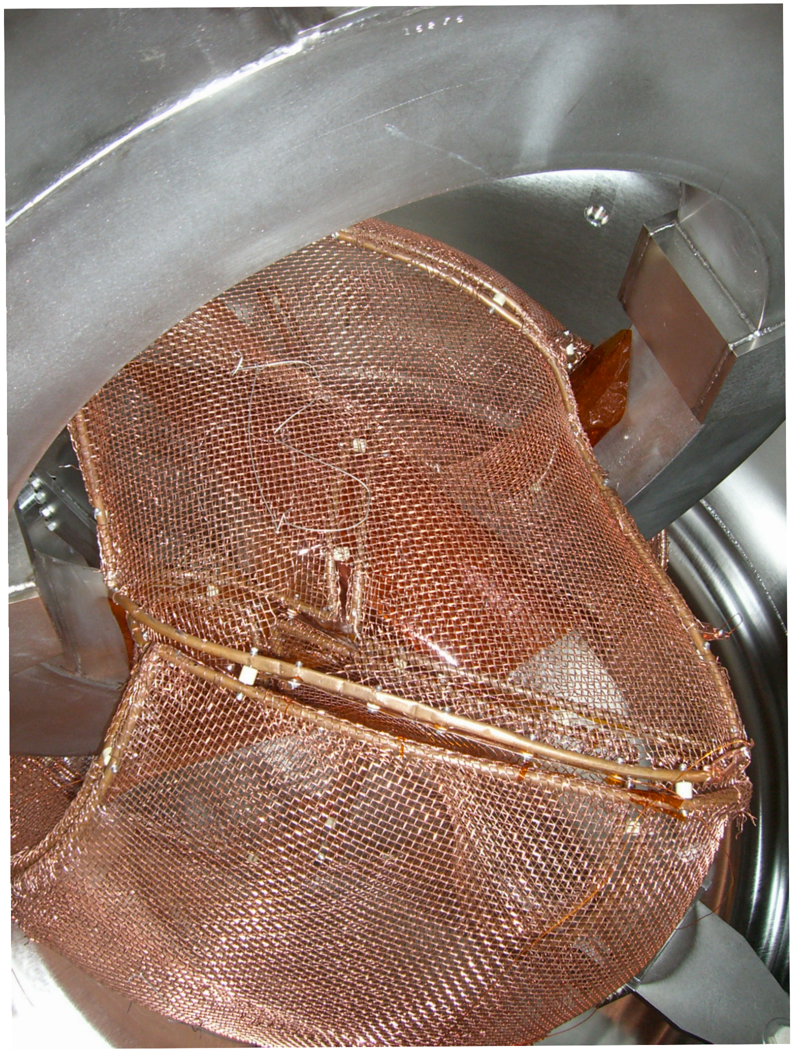
- ExB (perpendicular motion) takes electron along electrostatic potential contour
- Parallel motion of passing electrons (combined with rotational transform) takes electrons along the magnetic surface, moving them poloidally
- By switching between potential contours and magnetic surfaces, particles can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





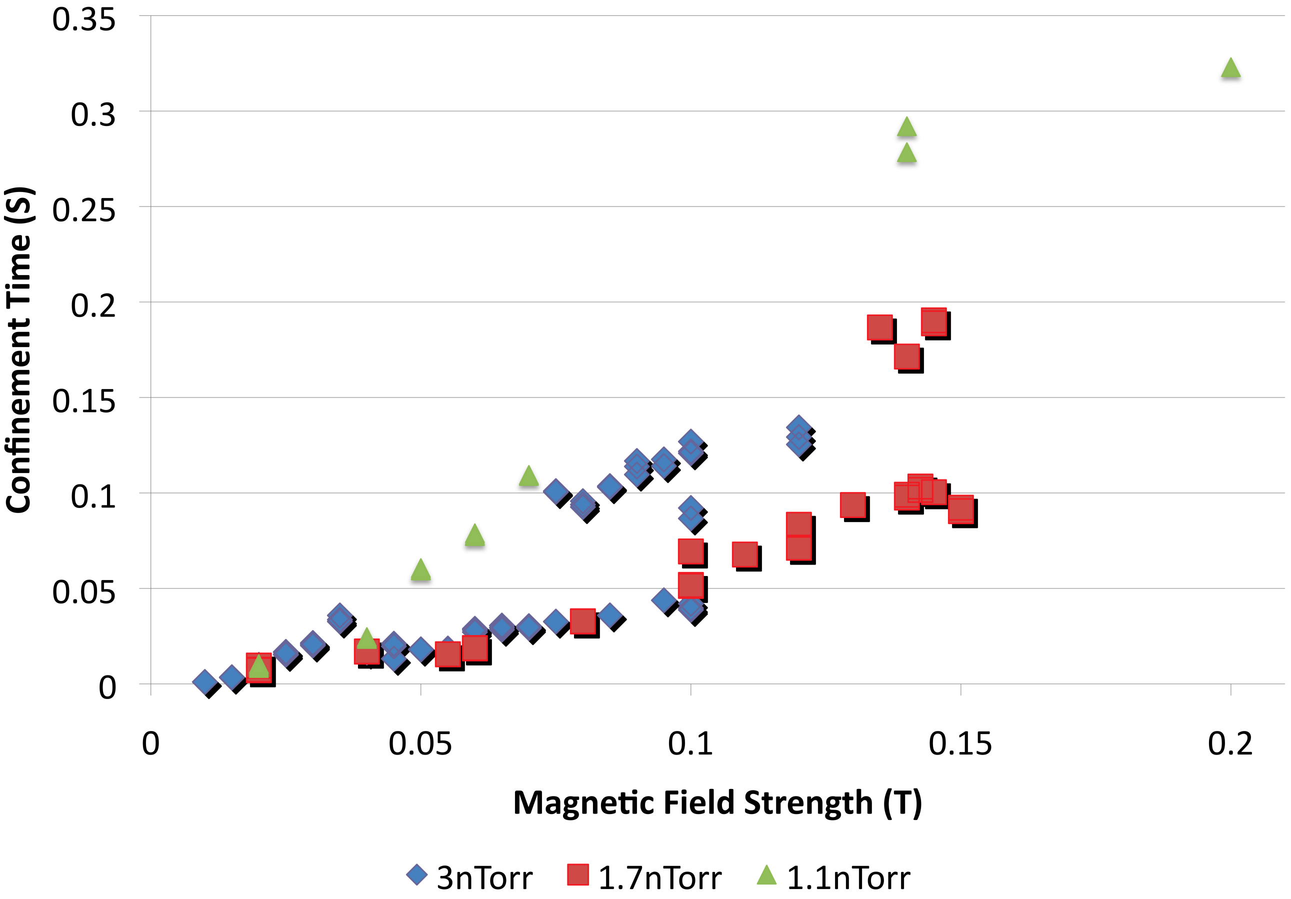
Flux surface conforming electrostatic boundary

- “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

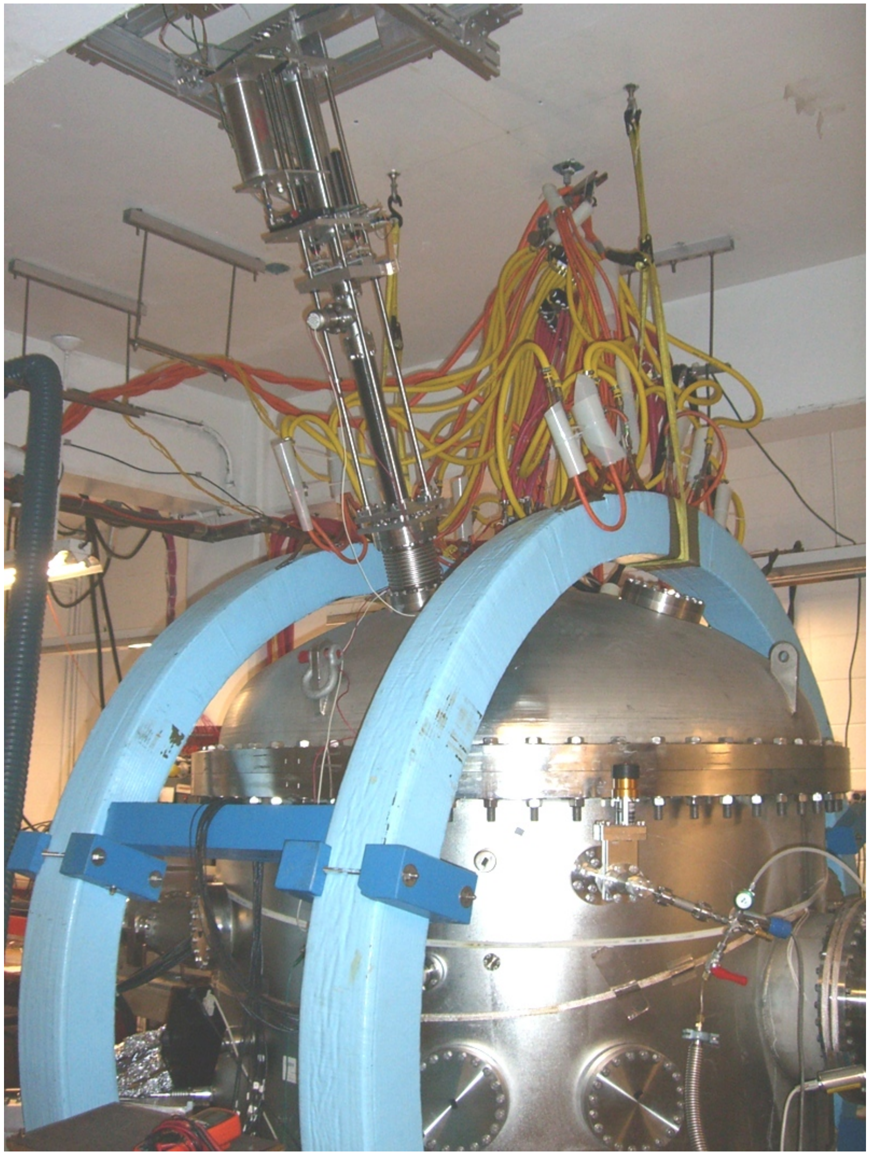


Confinement time increase is due mainly to better vacuum and a higher B-field but also due to smaller Debye length and improved orbit quality

Next step: Eliminate rods

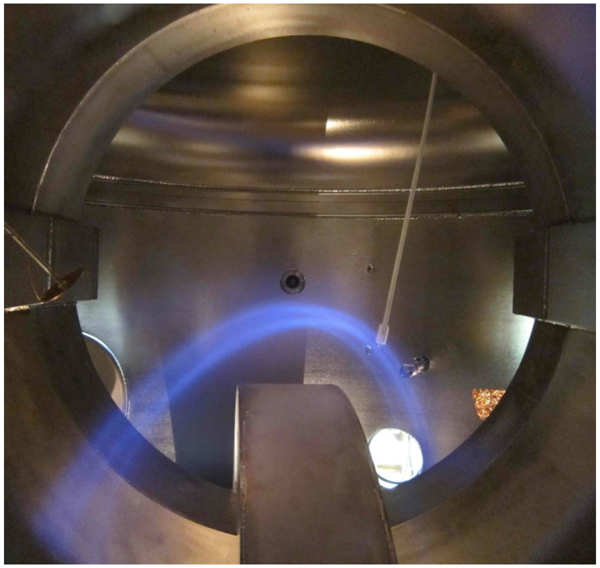
[1]P. W. Brenner et al., Contributions to Plasma Physics (2010)

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

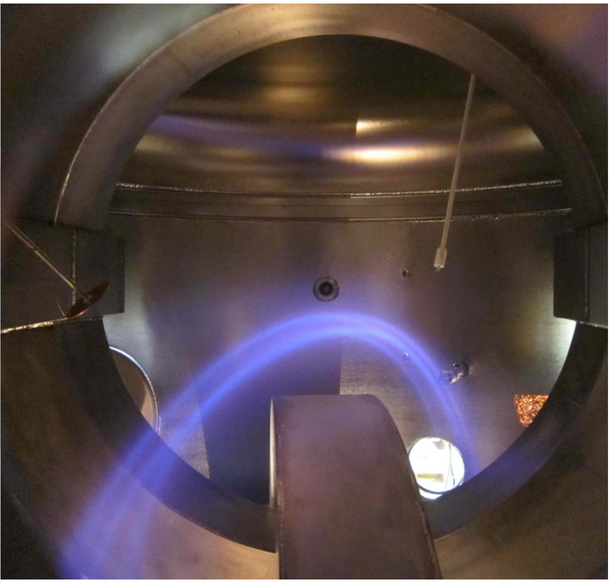


Design: Berkery et al. RSI (78) 2007

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

True even for conditions that should result 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

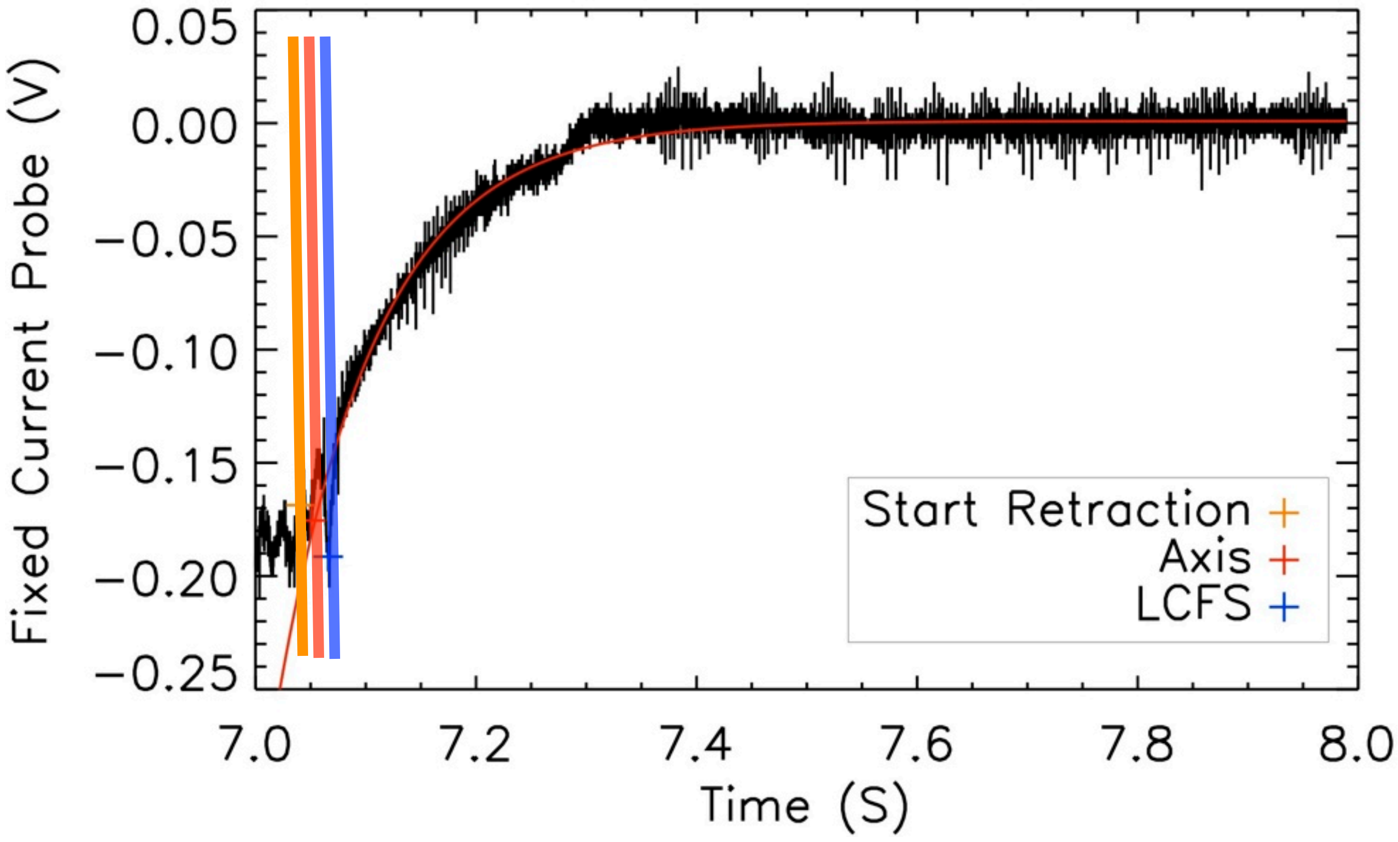
Were our previous confinement results somehow overestimated?

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

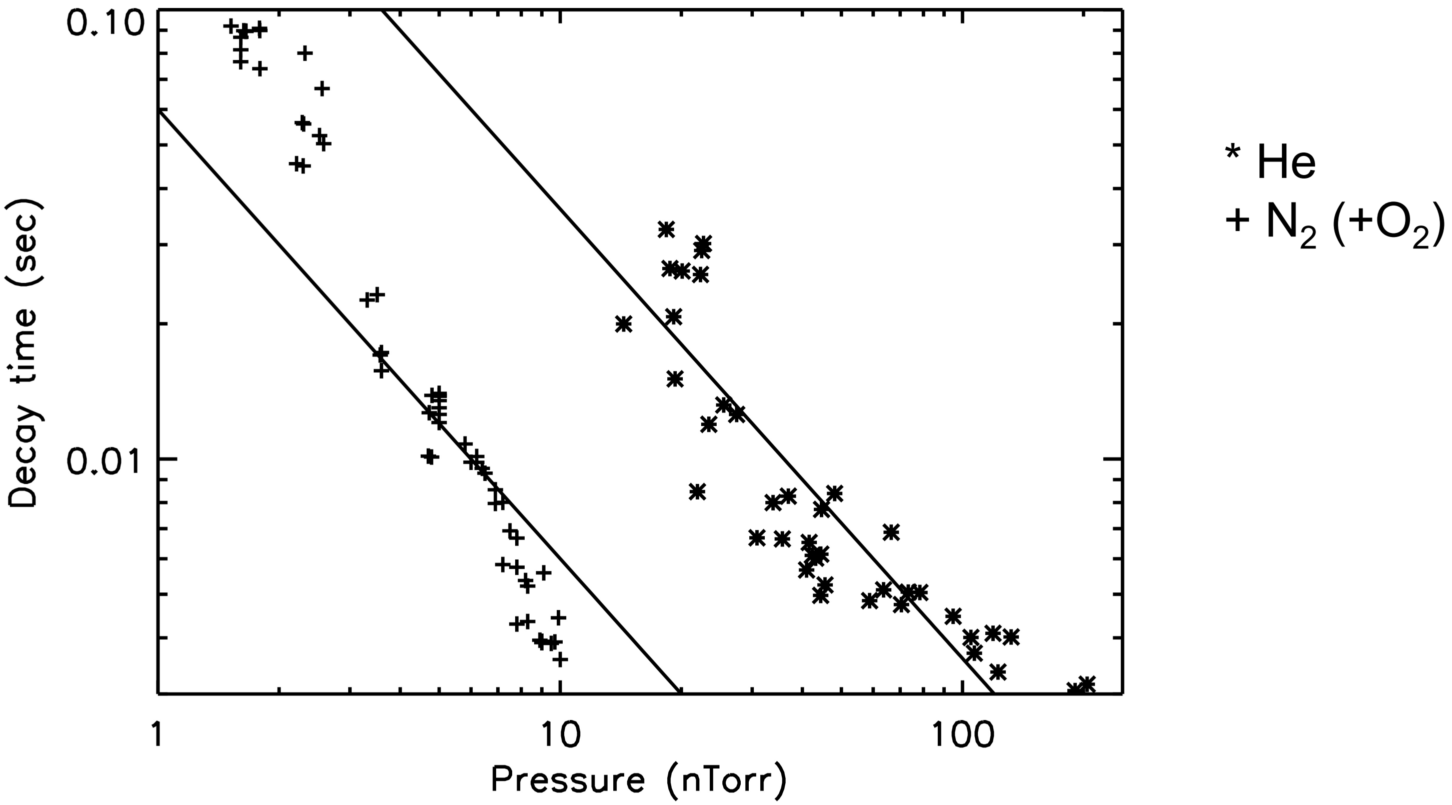


Plasma clearly remains after retraction:

~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

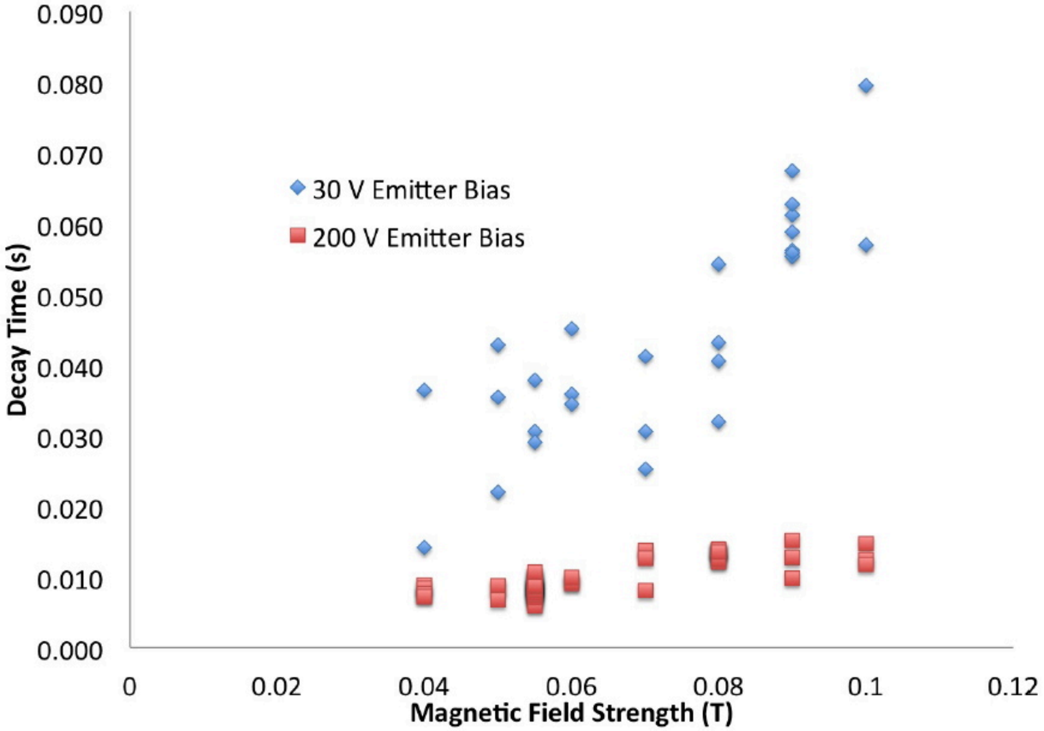


Confinement scales faster than linear with neutral pressure for nitrogen dominated discharges (+) and the decays are very fast. Confinement is much better and scales approximately linearly with neutral pressure for helium dominated discharges (*). Data at 0.055 T, φ=-200 V

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)



Summary for pure electron plasmas

- Steady state plasmas can be confined with confinement times up to 320 msec
- Plasmas without internal objects can be created – and last up to 92 msec
  - Ionization of background gas must be avoided
    - Avoid high electron plasma temperature
    - Avoid neutrals in general
    - Avoid easy to ionize neutrals in particular
  - If ionization is avoided, a higher B-field gives a higher confinement – appears to be a linear scaling

Partially neutralized plasmas

- It is normally said that a plasma must be quasineutral
- We learned from the Penning traps that completely non-neutral (pure electron) plasmas can also be created
- Can we create plasmas that are in between?
  - And at the same time have a small Debye length?
  - And at the same time are stably partially neutralized

- Must have the ability to confine both positive and negative particles simultaneously (rules out Penning trap)

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!

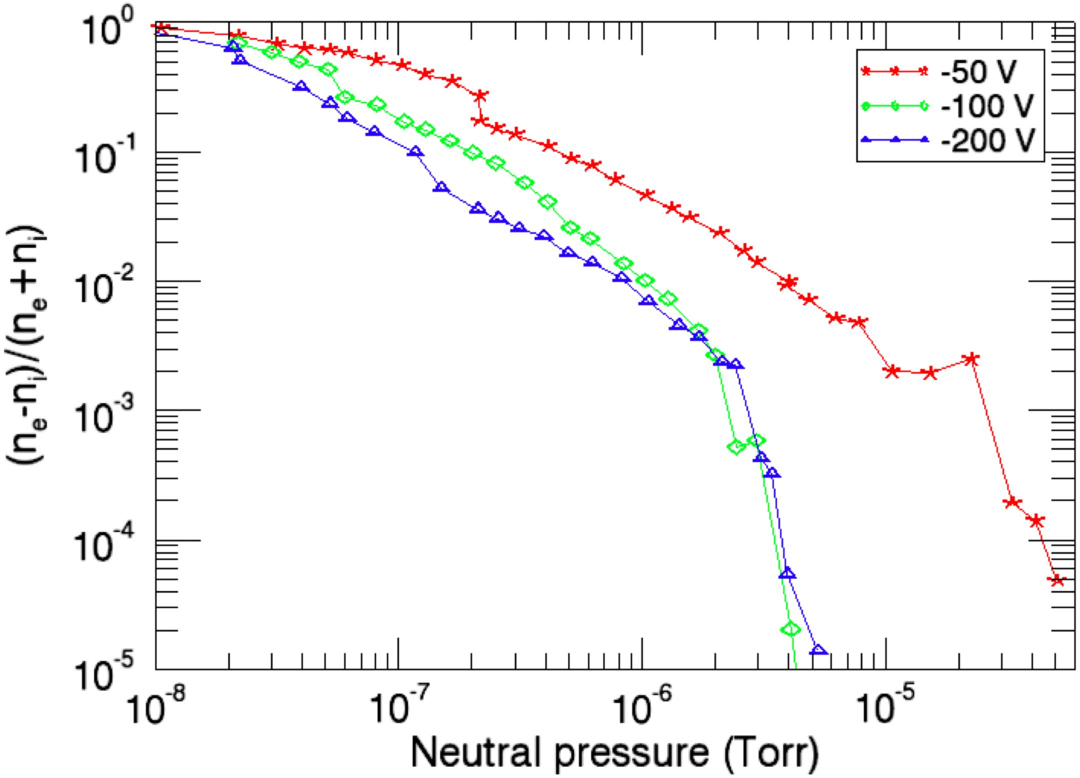
[1] X. Sarasola et al., Contributions to Plasma Physics (2010)

Charting the landscape from pure electron to quasi-neutral plasma

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

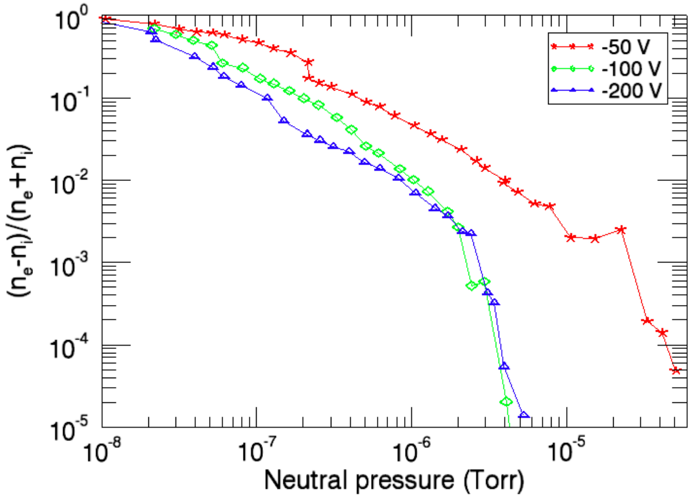
$$\eta = \left| \frac{Zn_i - n_e}{Zn_i + n_e} \right|$$

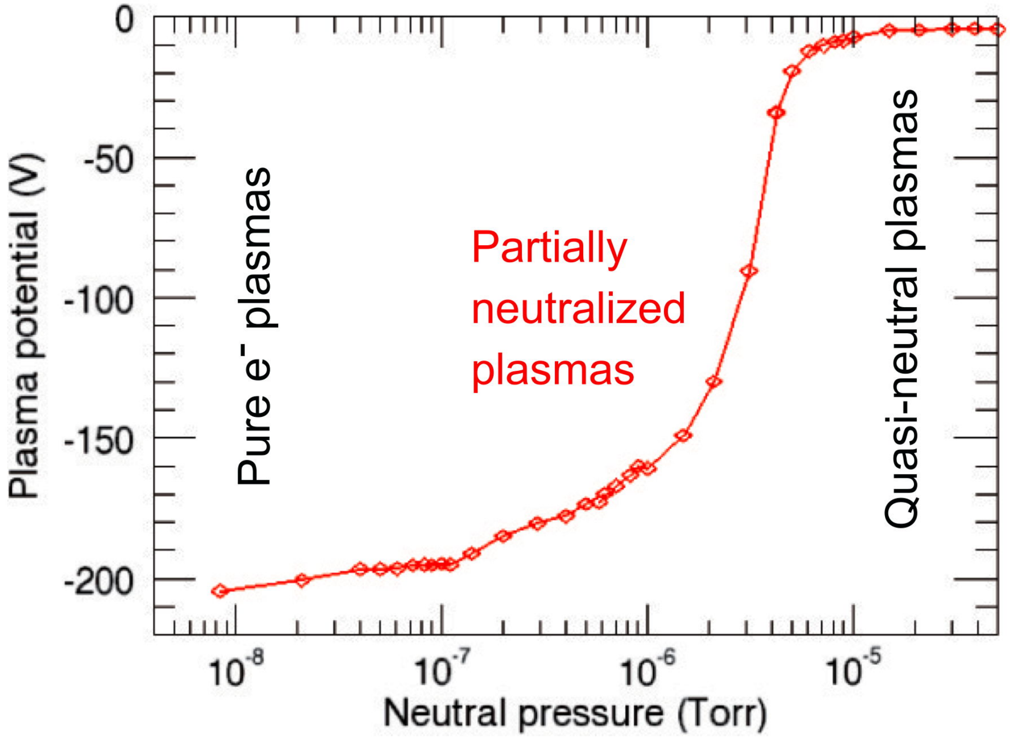
- A pure electron plasma has η=1
- Typical range for quasineutral laboratory plasmas is $\eta=10^{-8}$ to 10^{-4}



Charting the landscape from pure electron to quasi-neutral plasma

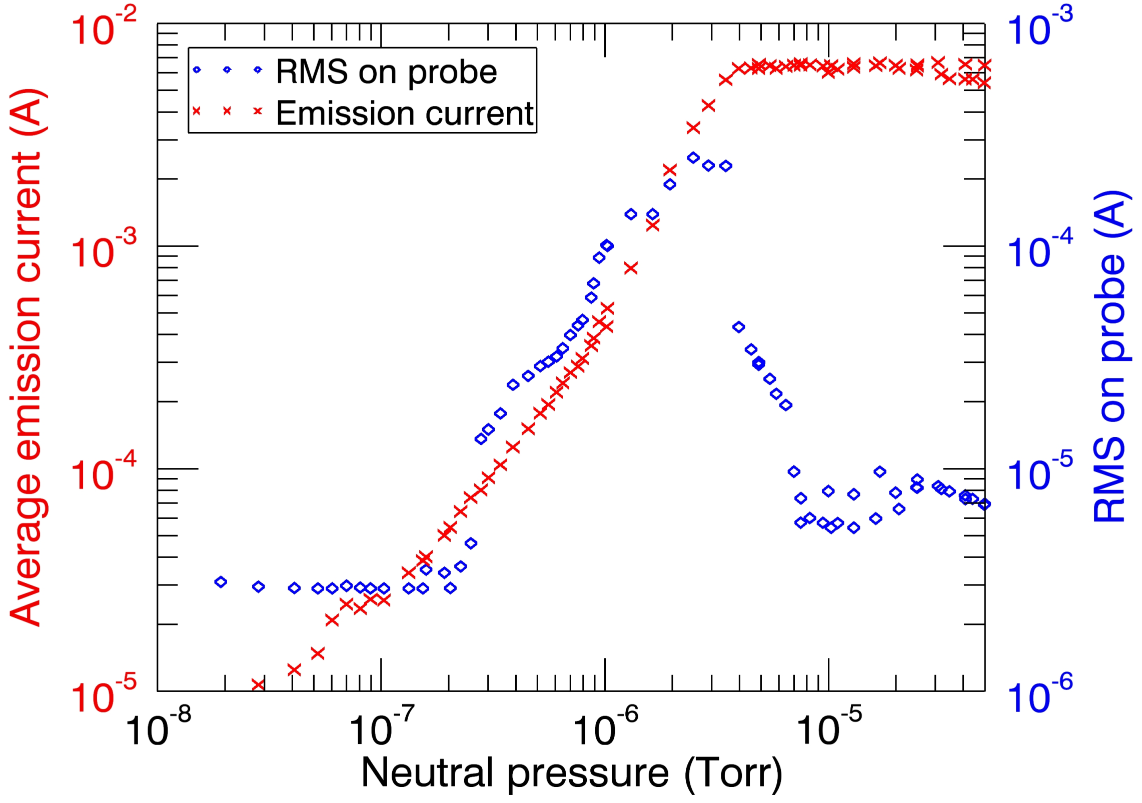
- Plasma potential decouples from filament bias as the plasma becomes quasineutral

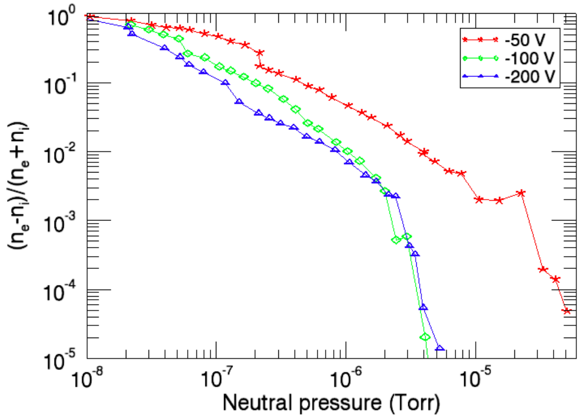


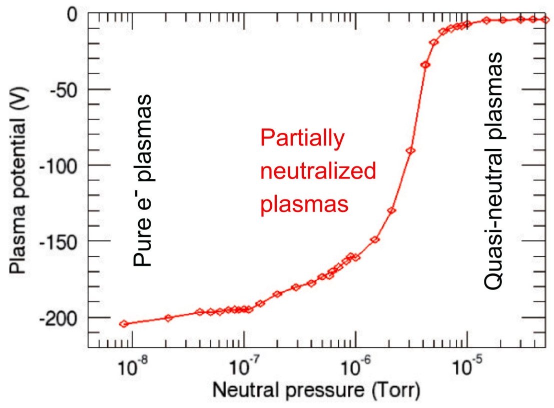


Charting the landscape from pure electron to quasi-neutral plasma

- Pure electron plasmas: Quiescent, well confined
- $\eta\sim0.5$: ~100 kHz single mode behavior (Marksteiner et al., PRL 2008)
- $\eta\sim0.01$: Broadband turbulence
- $\eta\sim0.0001$:4 kHz single mode behavior
- Charge confinement continually deteriorates







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)

Challenges

- How to create
- How to confine
- How to measure

Summary for pure electron plasmas (again)

Plasmas without internal objects can be created – and last up to 92 msec

- Ionization of background gas must be avoided
  - Avoid high electron plasma temperature
  - Avoid neutrals in general
  - Avoid easy to ionize neutrals in particular
- If ionization is avoided, a higher B-field gives a higher confinement – appears to be a linear scaling:

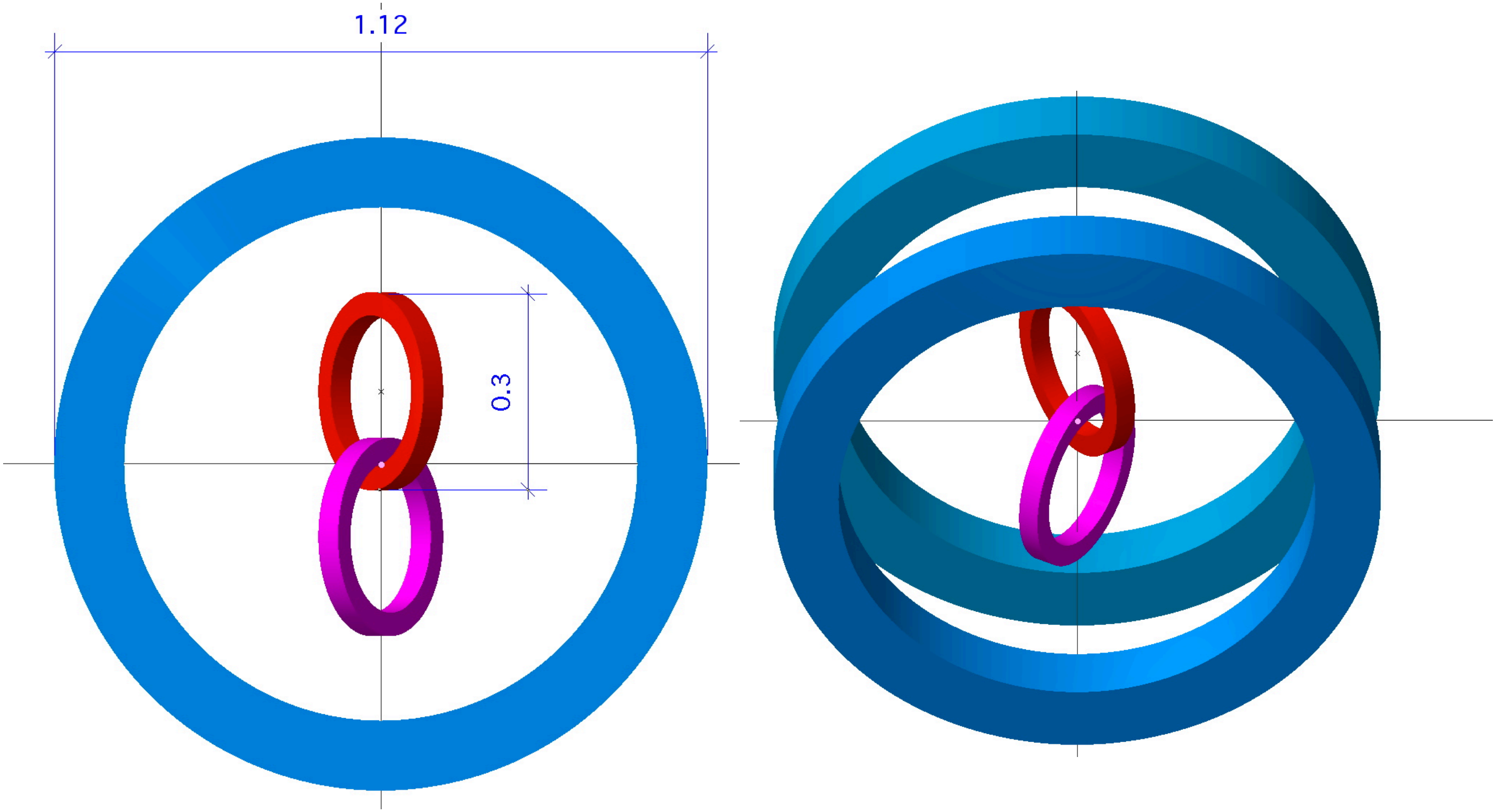
High B, low neutral pressure in APEX (A Positron Electron eXperiment)

High B is a double win: Better confinement, and cyclotron radiative cooling becomes more efficient

(also costs more..)

APEX design

- Design is being developed with engineering help from Felix Schauer, IPP
- Similar to CNT’s 64 degree configuration
- Size reduced factor of appr. 2.5 relative to CNT (factor 10 in volume)



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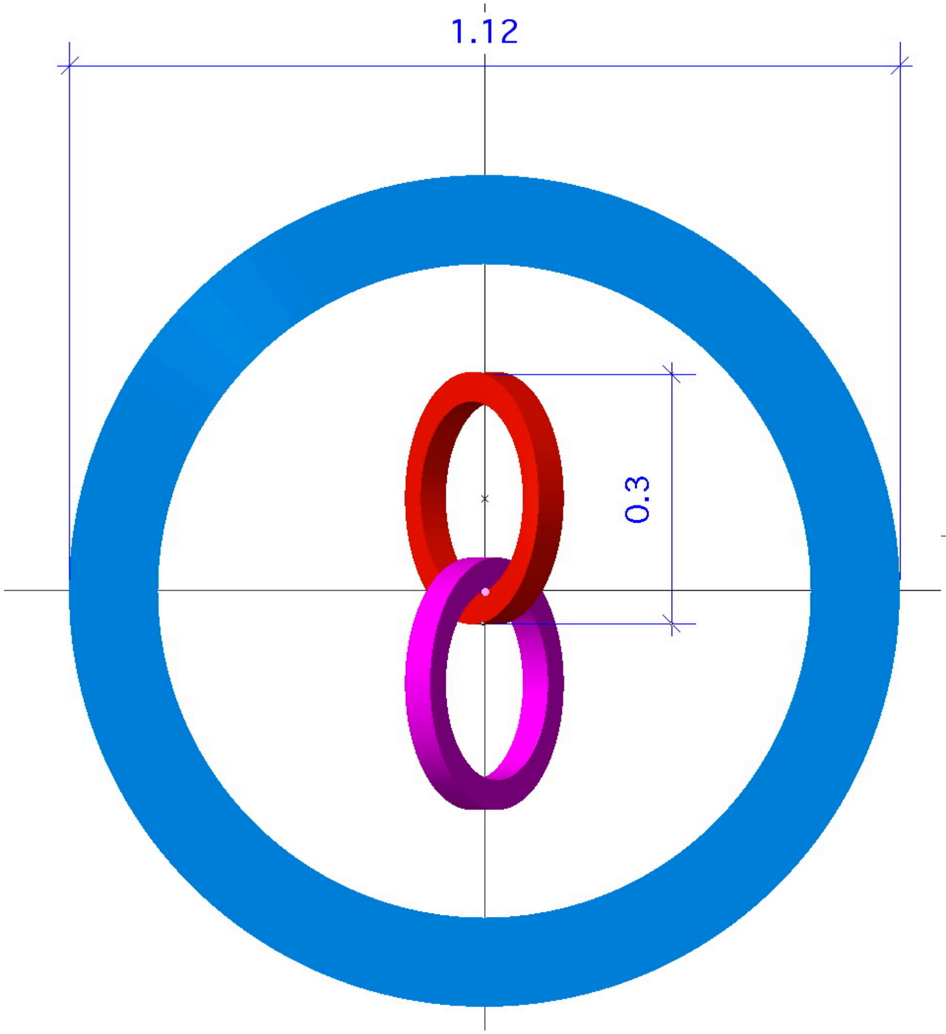
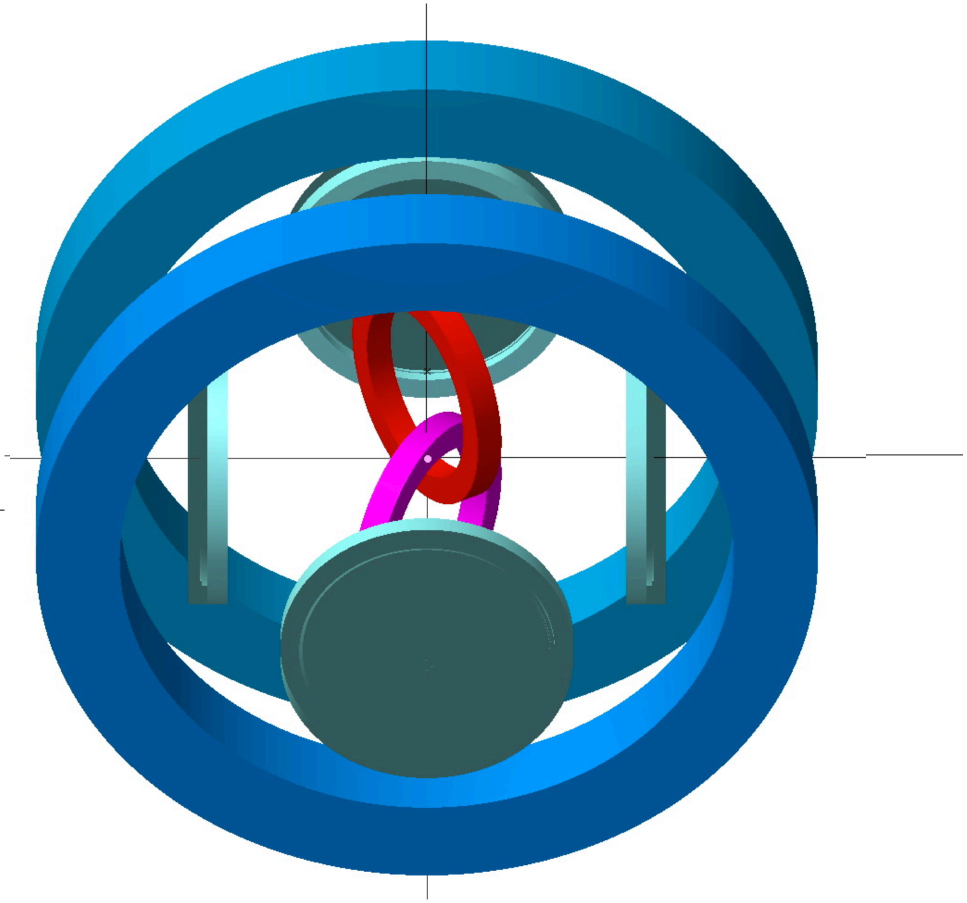
- Size reduced





PET design: Size isn’t everything

- Design is being developed with engineering help from Felix Schauer, IPP
- Similar to CNT’s 64 degree configuration
  - Most robust against coil alignment errors, largest confined volume
- Size reduced:
  - For the same pumping speed (money) get better vacuum
  - Coils are cheaper in smaller size
  - Not clear we need to optimize confinement time further
  - For the same number of positrons, get more Debye lengths by making experiment smaller:

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

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

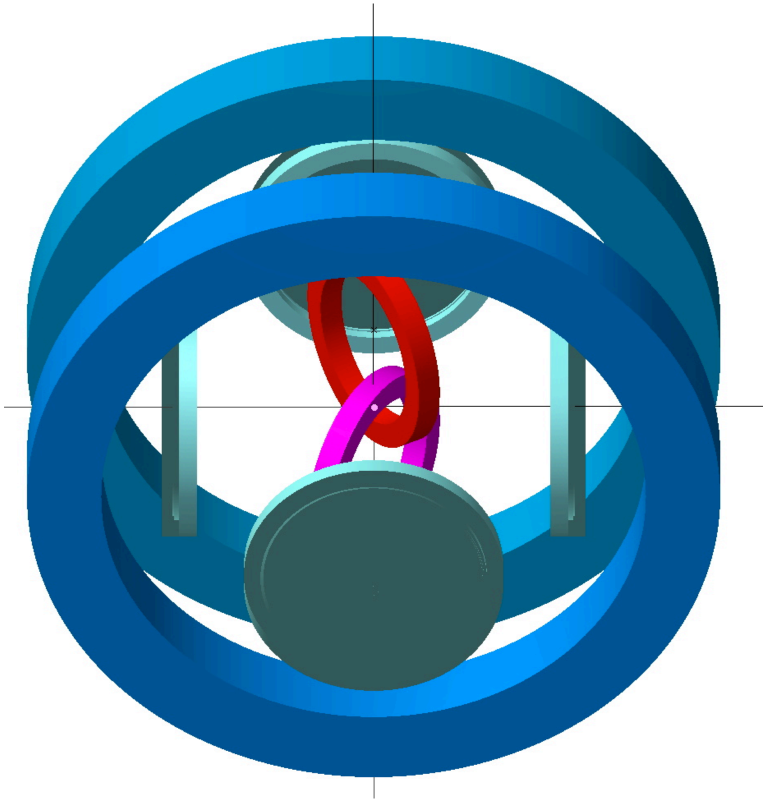
- Why not miniaturize?
  - We should use standard sizes for feedthroughs
  - Larger coils make water cooling in steady state easier (PF coils)
  - There should be room for diagnostics
  - Miniature plasma means miniature plasma physics – diagnostic challenge could be worse!

PET design: Better vacuum than in CNT

- CNT now creates plasmas without internal objects
  - Confinement very sensitive to neutrals
- Concern that a small ion content will fundamentally change the plasma physics – dominate over electron-positron plasmas
- Concern about annihilation (probably not a serious issue)

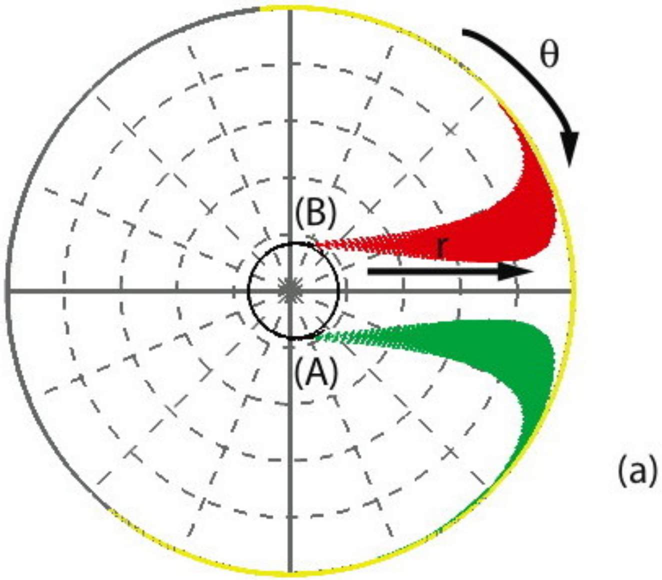
PET design: Higher B-field and steady state: SC coils

- Steady state B is requested by FRM-II facility in order to not disturb other experiments in the area where PET will be built
  - Stray DC fields much less perturbing than AC
- Steady state is very convenient when it comes to run time
- Steady state can be achieved with copper coils for the PF coils but the IL coils will need to be superconducting – also allows much larger fields



Injection scheme 1: Drift-injection

- Drift orbits connecting the edge and core region in a non-neutral stellarator can be created or removed using modest electrostatic perturbations
- Can be imposed from biased plates at the edge of the plasma
- Can be switched on and off in 10^{-5} seconds
  - Modest power required
  - No perturbation outside the vacuum chamber
- Has been demonstrated numerically (B. Durand de Gevigney and T. Sunn Pedersen, Phys. Plasmas 2011):



First 10 microseconds: Inward drift of positron due to electrostatic perturbation (plate is biased)

The positron remains on the black orbit if the perturbation is switched off in less than 10 microseconds

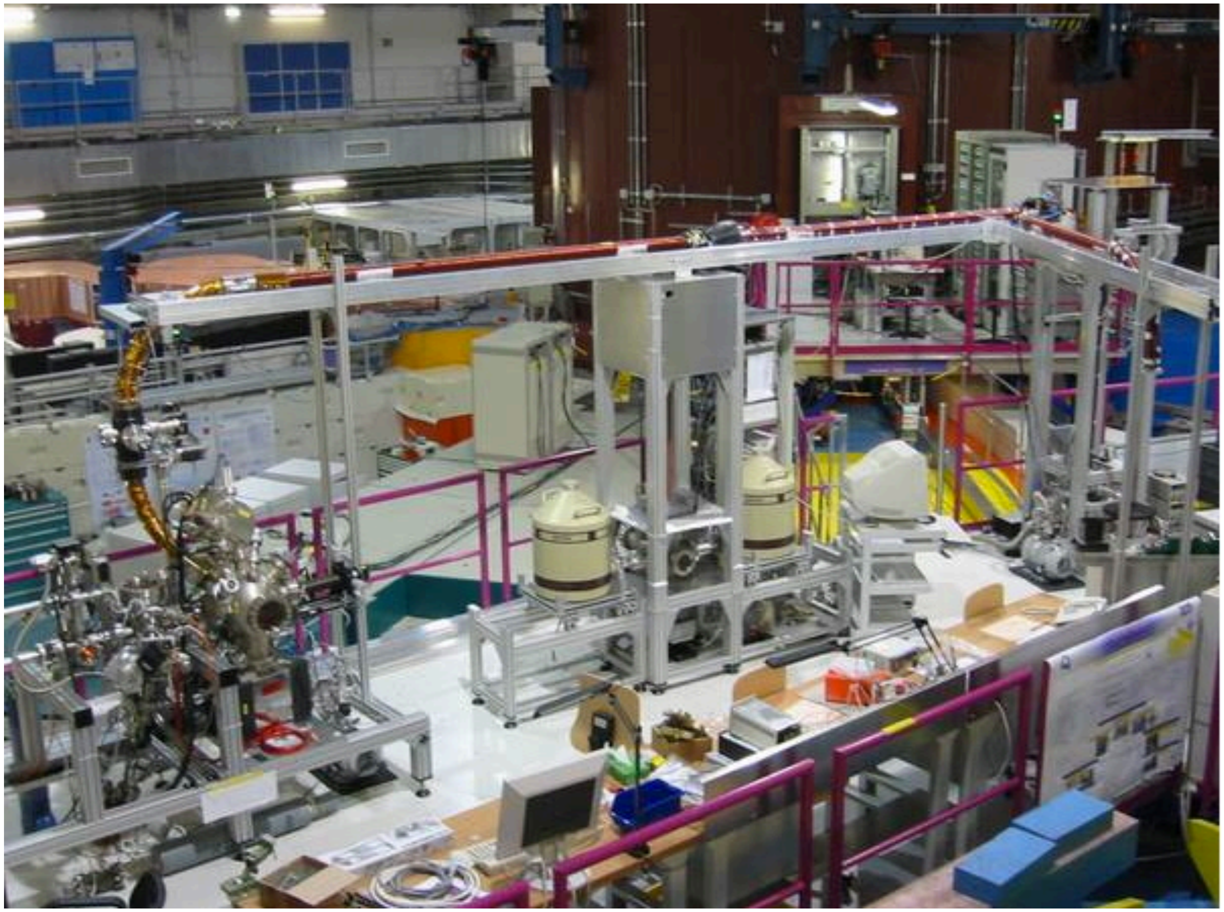
If the perturbation is not switched off, the positron will drift back out

Laser injection scheme

- Idea of Chr. Hugenschmidt, TUM
- Investigation in progress (E. Winkler et al., IPP-Greifswald in Germany, D. Cassidy, UC Davis, USA)
    - Positrons incident on heated metal surfaces have been observed to be converted into neutral positronium with better than 50% efficiency.
    - Si surfaces (when properly prepared) can get near 100% efficiency
    - The positronium would then be excited to n>1 by a laser near the metal surface and ionized by a second laser inside the magnetic surfaces.
- Would allow control of the e-p plasma temperature by tuning the ionization laser
    - Systematic study of warm plasma waves
    - Allows the creation of potentially very cold plasmas (<0.1 eV) which would have a small Debye length even at rather low densities

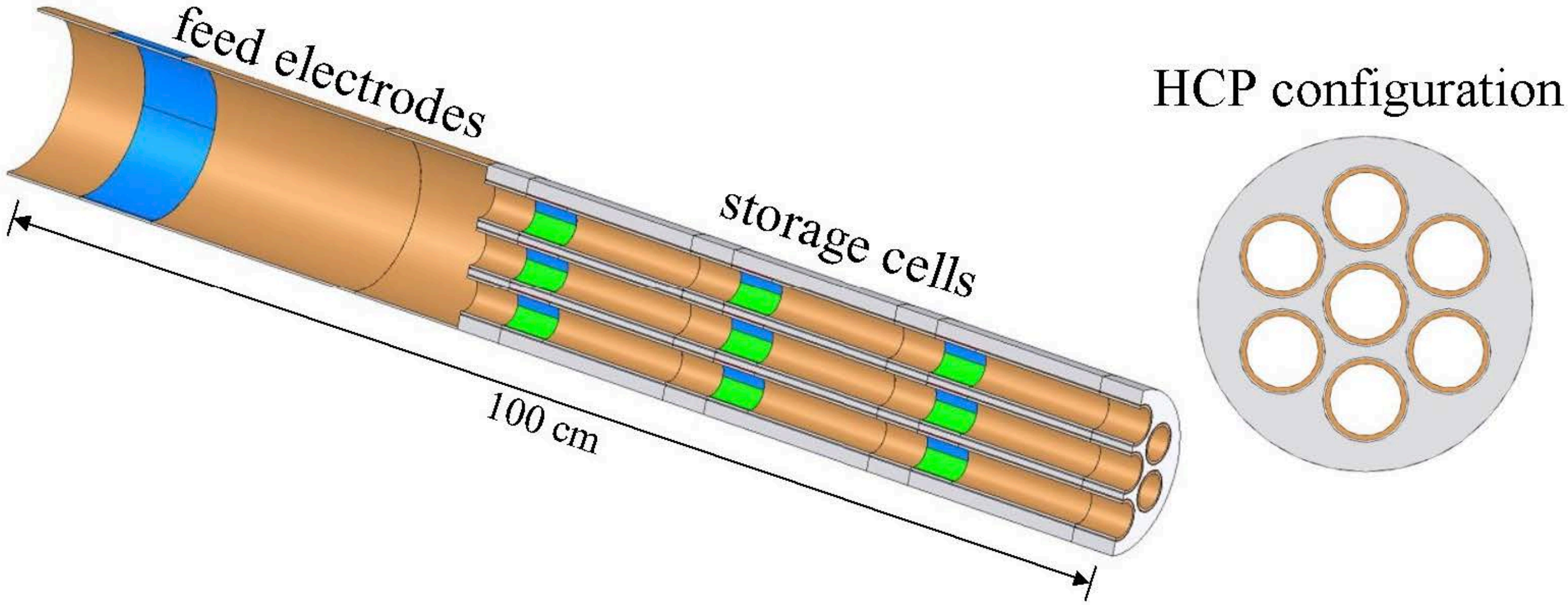
Positron accumulation experiment (PAX)

- 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



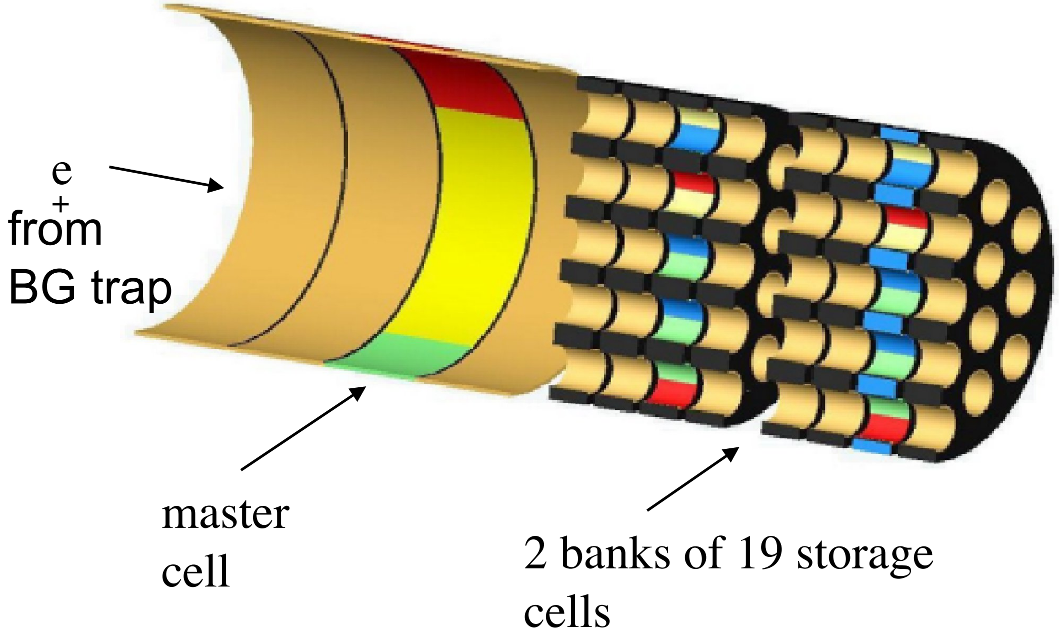
Positron Accumulation eXperiment (PAX)

- 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
  - Buffer gas trap fills multicell Penning trap array
  - PAX positrons are injected into APEX



Requirements for trapping

- Even the brightest sources today cannot supply more than 10^{11} positrons in less than 10^{-2} seconds (ie. 10^{13} positrons/second).
- NEPOMUC source in Munich has achieved $9*10^{8}$ positrons/second
- We will need a positron accumulation stage to do this:
    - See talks by Cliff Surko and James Danielson for how to do it
    - See talks by Lutz Schweikhard and Gerrit Marx on Penning traps in Greifswald



J. Danielson and C. Surko, UCSD (2006)

Summary

- One can make many basic plasma physics studies in a stellarator
- Stellarators can be made from very simple coil sets
  - Not fusion relevant ones (yet?)
- Non-neutral plasmas in a stellarator can be well confined
- Complicated drift orbits may be present and may limit confinement
  - Space charge electric field may be good or bad
  - Mostly good if the electrostatic potential is a flux function
  - But these bad orbits represent only a part of phase space – plenty of good orbits even in a simple stellarator
- 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
  - Experimental design in progress
  - Injection schemes being developed
  - Diagnostic schemes being developed