Plans for a laboratory electron-positron plasma experiment

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Electron-positron plasmas: Unique physics

- Unique plasma physics due to the symmetry between the two species
  - Theory comparatively 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)
    - No Faraday rotation (L and R waves propagate at same phase velocity)
  - "The hydrogen atom of plasma physics"
- Are important in many astrophysical settings (this workshop)
- 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[2,3].

[1]Tsytovich and Wharton, Comments Plasma Phys. Contr. Fusion **4** 91 (1978)

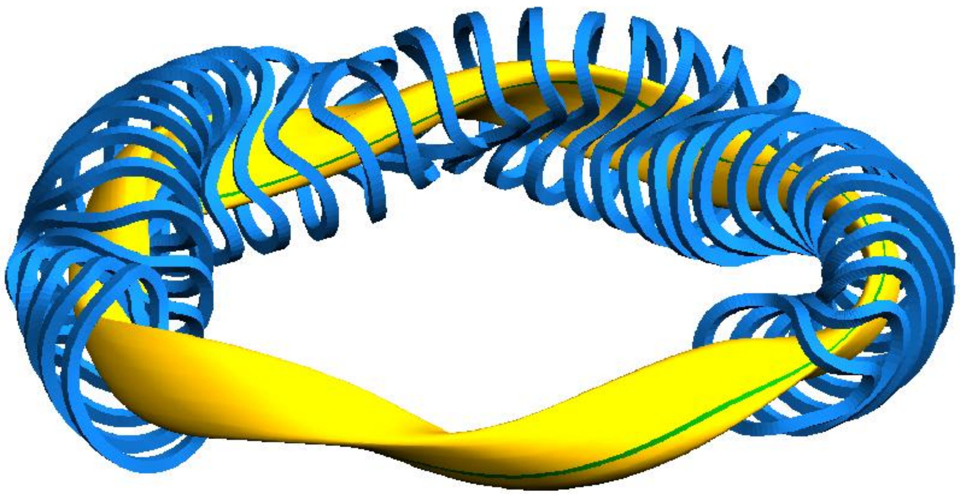
[2]T. Sunn Pedersen and A. H. Boozer, PRL **88** 205002 (2002)

[3]T. Sunn Pedersen et al., J. Phys. B **36** 1029 (2003)

What is a stellarator anyway?

- Magnetic confinement device:
  - Nested toroidal surfaces
- Developed for fusion energy (Spitzer, 1951)
- Different optimizations yield very different stellarators:

Fusion performance
Confinement of hot, dense
quasineutral plasmas



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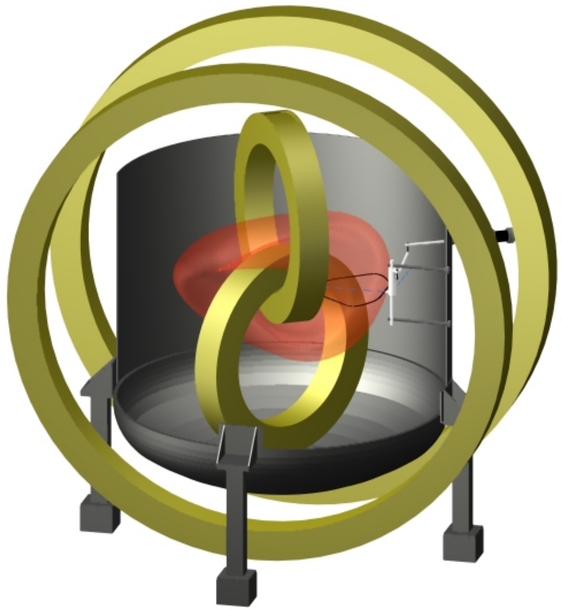
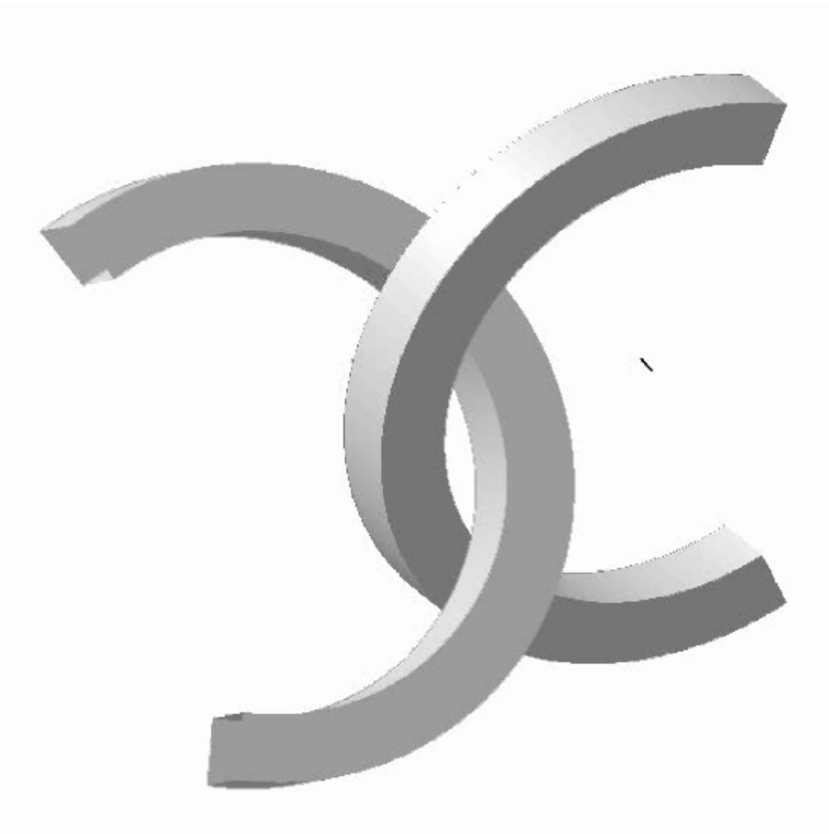
Compactness, and simplicity
Magnetic surface quality



Columbia Non-neutral Torus
Columbia University
New York, NY, USA

The 0th order principle of stellarator confinement

- Nested magnetic surfaces – follow a single field line and it will trace out a toroidal surface
- Particles circulate (approximately) on the magnetic surfaces
- Parallel equilibrium pertains not just to an isolated field line but to the entire magnetic surface
    - Provides macroscopic stability – plasma has to break parallel force balance to change its shape away from that of the magnetic surfaces



How many positrons are needed to make a pair plasma?

- Must get enough positrons to get 10 Debye lengths:

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 T_e}{n_e e^2}} << a \qquad \lambda_{D+} = \sqrt{\frac{\varepsilon_0 T_+}{n_+ e^2}} << a$$

- T=? Depends on how the pair plasma is made.
- Clearly colder is better
  - (up to a point; positronium formation, annihilation)
- Given a finite number of positrons, should we make the trap small (maximize n) or large (maximize a)?

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

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

Pedersen et al., New Journal of Physics **14** 035010 (2012)

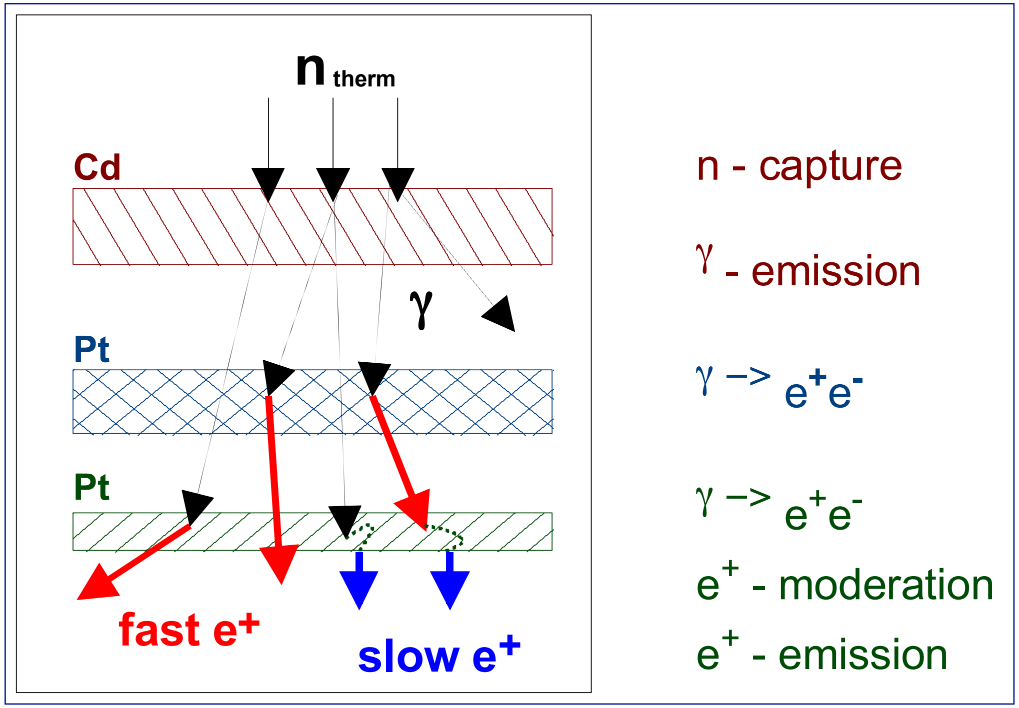
How many positrons are needed to make a pair plasma?

- Assume $T_e = T_+ = 5$ eV (NEPOMUC source – next slide)
- Assume a=5 cm, V=10 liter (APEX stellarator – later slide)
- Aim for 5 mm Debye length (<<a)

$$10\lambda_{De} = 10\sqrt{\frac{\varepsilon_0 T}{ne^2}} < a \Leftrightarrow 100\frac{\varepsilon_0 T}{ne^2} < a^2 \Leftrightarrow$$

$$n > 100\frac{\varepsilon_0 T}{a^2 e^2} \approx 1.1\times 10^{13}\ \mathrm{m}^{-3} \Rightarrow N = nV > 1.1\times 10^{11}$$

Positron source: NEPOMUC



•Thermal neutrons come from NEPOMUC source located at the FRM-II nuclear research reactor in Garching (by Munich)

•$9*10^8$ positrons/second with 5 eV energy spread achieved[1]

- Strongest source of moderated positrons in the world

•$3*10^9$ positrons/second predicted in the near future

•About 100 second minimum accumulation time

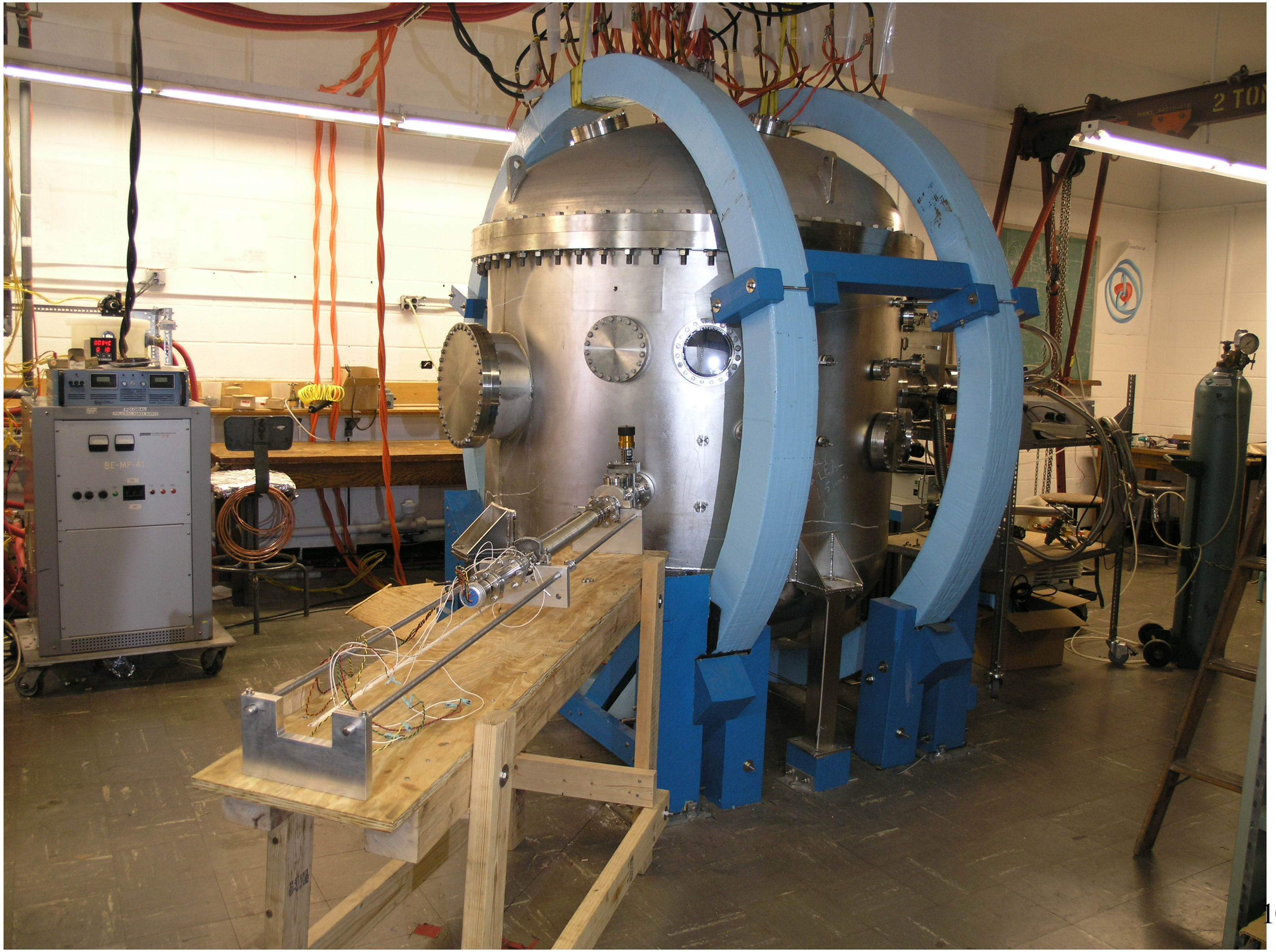
1. C. Hugenschmidt et al., 2008 Nucl. Instrum. Methods Phys. Res. A 593 616

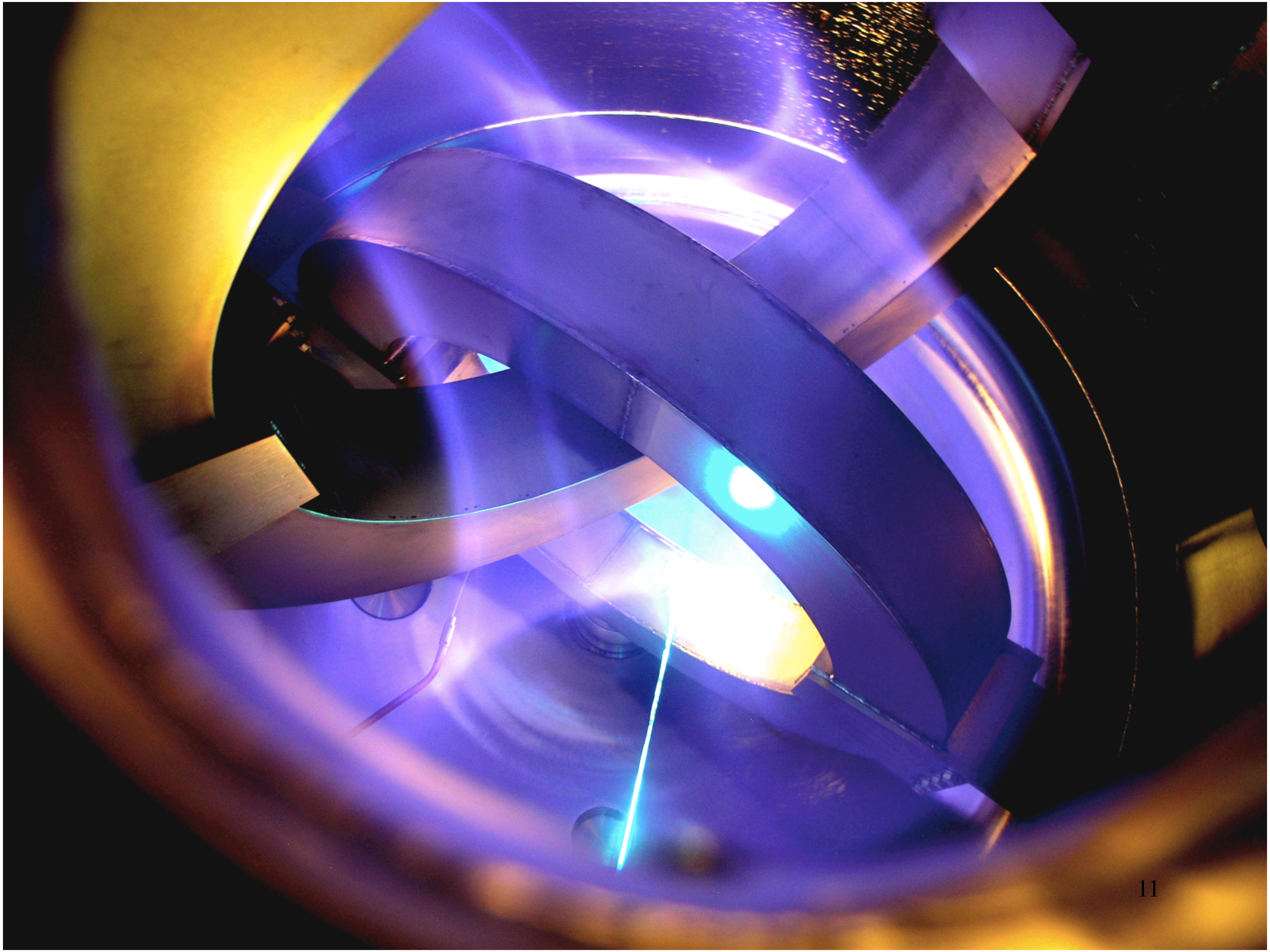
The CNT was built with electron-positron plasma physics in mind

- CNT=Columbia Non-neutral Torus – proposed in 2001
- Original plan[1,2]:
  - Design and build CNT stellarator
  - Create and study pure electron plasmas
  - Achieve 1000 second confinement for these plasmas without internal objects
  - Inject positrons during these 1000 seconds
  - Create more or less quasineutral electron-positron plasma
- Actual progress:
  - Built stellarator (2002-2004)[3,4]

1. T. Sunn Pedersen and A. H. Boozer, PRL **88** 205002 (2002)
2. T. Sunn Pedersen et al., Journal of Physics B p. 1018 (2003)
3. Sunn Pedersen et al. Phys. Plasmas **13** 012502 (2006)
4. Sunn Pedersen et al. Fusion Sci. Technol. **50** 372 (2006)

The Columbia Non-neutral Torus (CNT) 2005





The Columbia Non-neutral Torus

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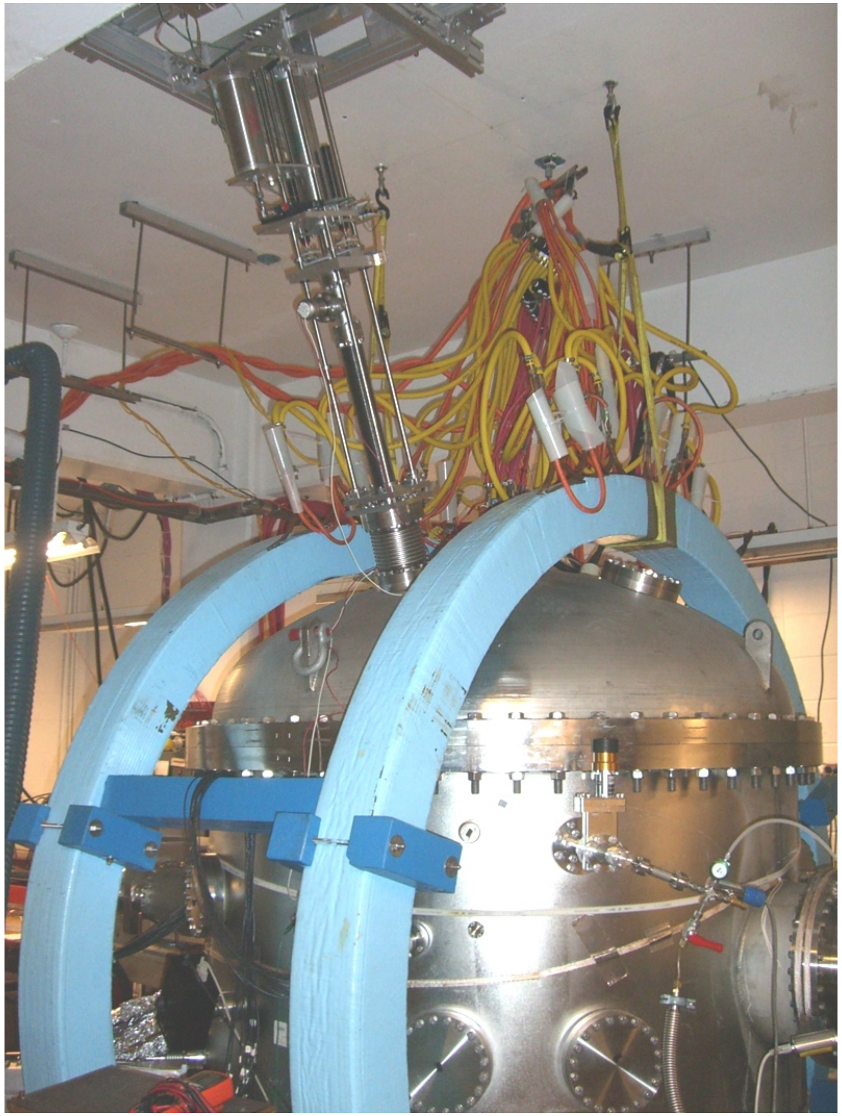
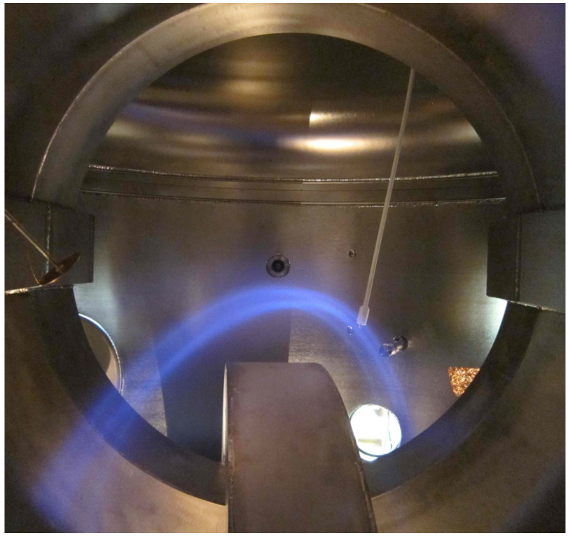
- What really happened:
  - Built stellarator (2002-2004)[3,4]
  - Created and studied pure electron plasmas with internal objects (2005-2011)
    - Initially: 20 msec confinement time[5]
    - Then: 300 msec confinement time[6]
  - Created pure electron plasmas without internal objects
    - Initially no plasma left after retraction (2007-10)[6]
    - Up to 90 msec confinement time (2011)[7]

1. T. Sunn Pedersen and A. H. Boozer, PRL **88** 205002 (2002)
2. T. Sunn Pedersen et al., Journal of Physics B p. 1018 (2003)
3. T. Sunn Pedersen et al. Phys. Plasmas **13** 012502 (2006)
4. T. Sunn Pedersen et al. Fusion Sci. Technol. **50** 372 (2006)
5. J. P. Kremer et al., PRL **97** 095003 (2006)
6. P. W. Brenner et al., Contrib. Plasma Phys. 50 678 (2010)
7. P. W. Brenner and T. Sunn Pedersen, submitted to Phys. Plasmas (2012)

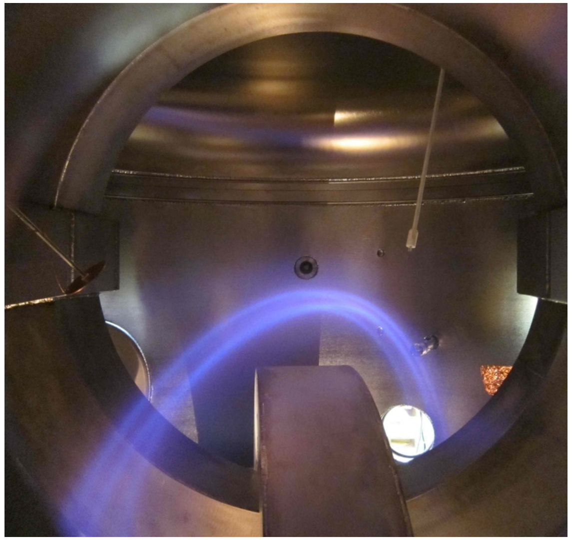
Electron emitter capable of 20 msec retraction





Inserted

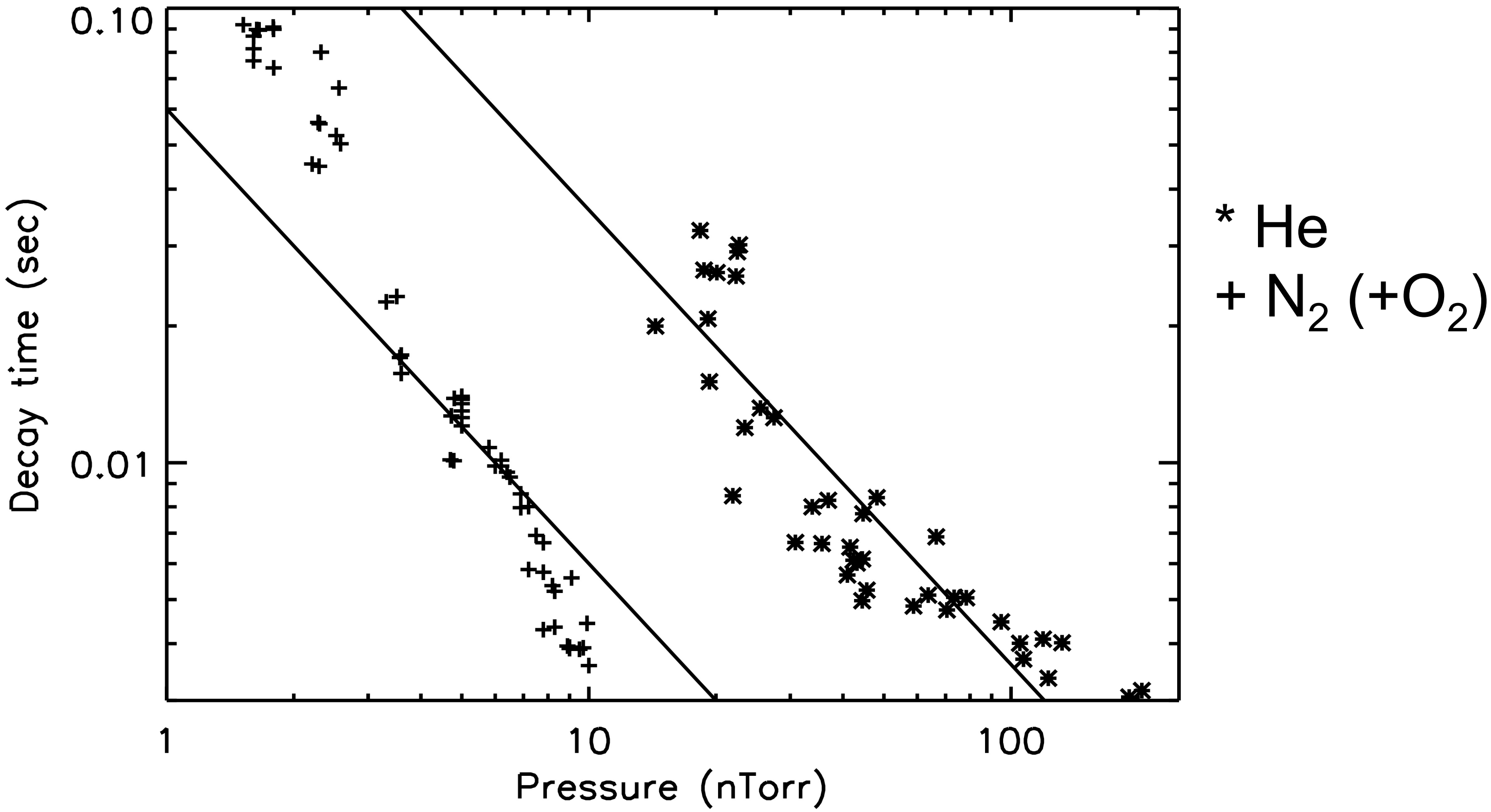
20 msec



Retracted

Design: Berkery et al. RSI (78) 2007

Ion accumulation limits confinement



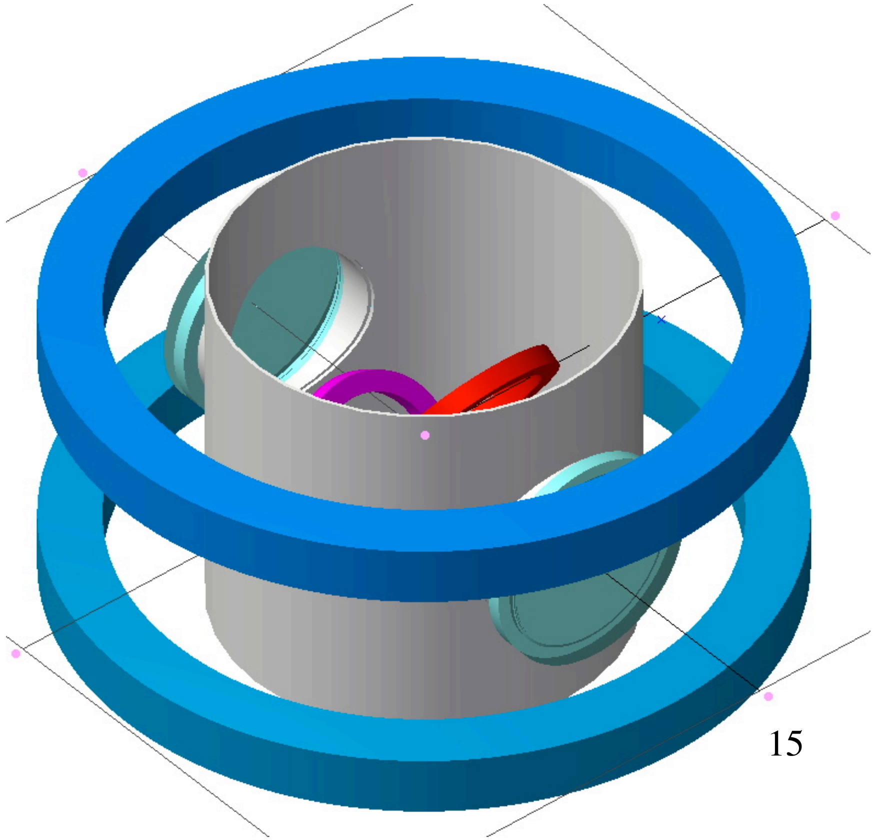
- Must avoid:
  - Neutrals in general and easily ionized ones in particular
  - High electron temperature
- High B-field will help confinement and give low temperature

Brenner and Pedersen, submitted to Physics of Plasmas (2012)

A Positron Electron eXperiment (APEX)

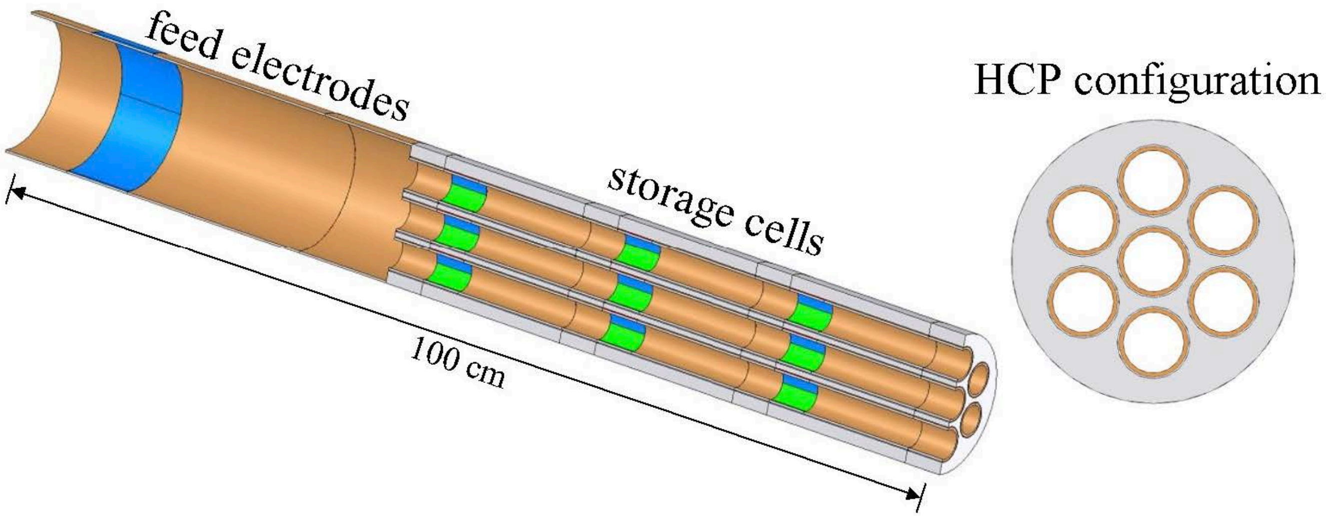
- Stellarator based on CNT but with:
  - 10 X higher B-field=2T (internal coils superconducting)
    - helps confinement
    - enables cyclotron cooling
  - Better vacuum $p_n < 10^{-10}$ Torr
    - Prevents ion related collapse
    - Ensures that electron-positron physics is dominant
  - Smaller size (as explained)

- Confinement time of CNT scales to above 1 second in APEX
- Recall: With NEPOMUC, need to accumulate for at least 100 s
- Not clear that 100 or 1000 seconds will be reached:
- Need for an additional Positron Accumulation eXperiment (PAX)



Two parallel developments

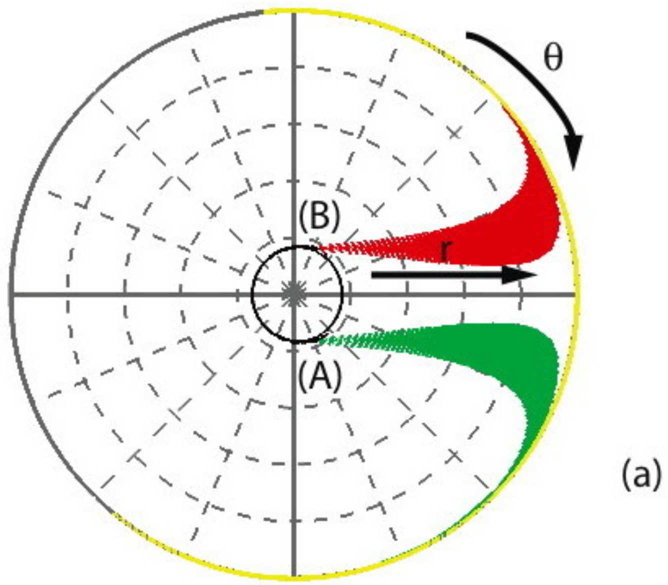
- The project consists of two parallel, largely independent sub-projects: APEX and PAX
  - APEX: A Positron Electron eXperiment
    - Being designed now
    - Will be built in Garching, by the NEPOMUC source
    - Initial studies of pure electron plasmas
  - PAX: Positron Accumulation eXperiment
    - Penning trap under construction in Greifswald
    - Will initially be used to study electron accumulation
    - Will then be transferred to Garching
    - Positron accumulation of 10^{11} up to 10^{12}
    - Based on Surko, Greaves, Danielson design:



Two potential injection schemes

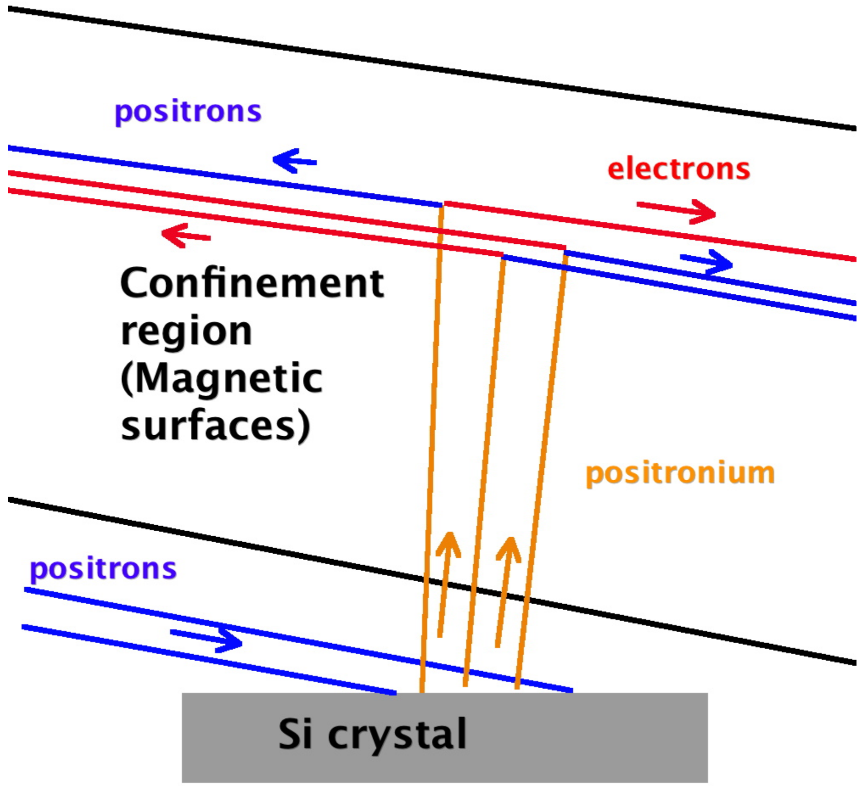
- The magnetic surface confinement makes it difficult for electrons and positrons to escape – but also difficult to inject them.
- We will pursue two completely different schemes:

Drift injection using external electrostatic potentials



B. Durand de Gevigney et al., Phys. Plasmas **18**, 013508 (2011)

Neutralization and re-ionization



D. Cassidy et al., PRL **106** 133401 (2011)
D. Cassidy et al., PRL **107** 033401 (2011)
D. Cassidy et al., PRL **108** 043401 (2012)

Diagnostics and physics issues

- The plasma will be diagnosed taking advantage of the annihilation gamma rays
    - Intensity -> density
    - Doppler shift -> temperature
    - See Xabi Sarasola's poster!
- Positrons are not expected to cause ionization collapse:
    - Gyrokinetic simulations show that plasma should be stable in relevant density regime[1]
    - Any instabilities will likely be interchange-like (driven by magnetic curvature) and very low frequency (100-500 Hz) and can be detected as coherent annihilations
- Any instabilities would indicate that codes are missing some important physics
- These plasmas are rather easy to simulate with gyrokinetic codes because of the equal masses
    - Often gyrokinetic simulations of electron-ion plasmas must use a more moderate mass ratio than 1:1836
- Transport of magnetized electron-positron plasma is important for the understanding of astrophysical observations (this workshop)

[1]T. Sunn Pedersen et al., J. Phys. B **36** 1029 (2003)

Summary

- The basic ingredients of an electron-positron plasma appear to be at hand
    - CNT stellarator performed initial physics study
    - APEX Stellarator will serve as confinement device
        - Basic studies performed in CNT in the last decade
        - APEX is being designed
    - PAX Penning trap array will serve as accumulation device
        - Basic studies performed at UCSD in the last two decades
        - PAX is under construction
    - NEPOMUC positron beam
        - In operation for more than five years
        - Currently in shutdown – restart operation in second half of 2012
- What can we do with astrophysical relevance? (This workshop)
- More information in this paper (published last week):

Pedersen et al., New Journal of Physics **14** 035010 (2012)