Plans for the creation of the first matter-antimatter (electron-positron) plasmas on Earth

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Electron-positron plasmas: A new frontier in basic plasma physics

- We aim to produce the first symmetric (equal mass) matter-antimatter plasmas on Earth
- They will serve as a first experimental proxy for the plasma dynamics that dominated the very early Universe which presumably consisted of equal amounts of symmetric matter-antimatter plasma
- They are predicted to have unique properties due to the symmetry
    - Vastly reduced complexity of modes and instabilities
    - Generic coupling between density and potential perturbations disappears
    - Strong magnetization kills off the remaining instabilities

[1]Tsytovich and Wharton, Comments Plasma Phys. Contr. Fusion **4** 91 (1978)
[2]T. Sunn Pedersen et al., J. Phys. B **36** 1029 (2003)
[3]T. Sunn Pedersen et al. New Journal of Physics, **14**(3):035010, (2012)
[4]P. Helander, PRL (2014)
[5]T. Sunn Pedersen and A. H. Boozer, PRL **88** 205002 (2002)

Electron-positron plasmas: are we there yet?

•Despite the obvious loss mechanism (annihilation) such plasmas can be long-lived if a suitable confinement scheme is used
•Several such confinement schemes have been proposed
•Over 1000 theory papers on the topic (INSPEC search 2013)
•Why then, has no experiment been built yet?
•Positrons are hard to come by, especially cold ones

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

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

T. Sunn Pedersen et al. New Journal of Physics, **14**(3):035010, (2012)

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)?

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

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

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 (for simplicity, seems realistic goal)
- An extreme smallness of the plasma makes diagnostics and coil design difficult: Aim for tabletop size:
- Assume a=5 cm, V=10 liter (small toroidal device)
- Aim for 5 mm Debye length ($a/\lambda_D = 10 >> 1$)

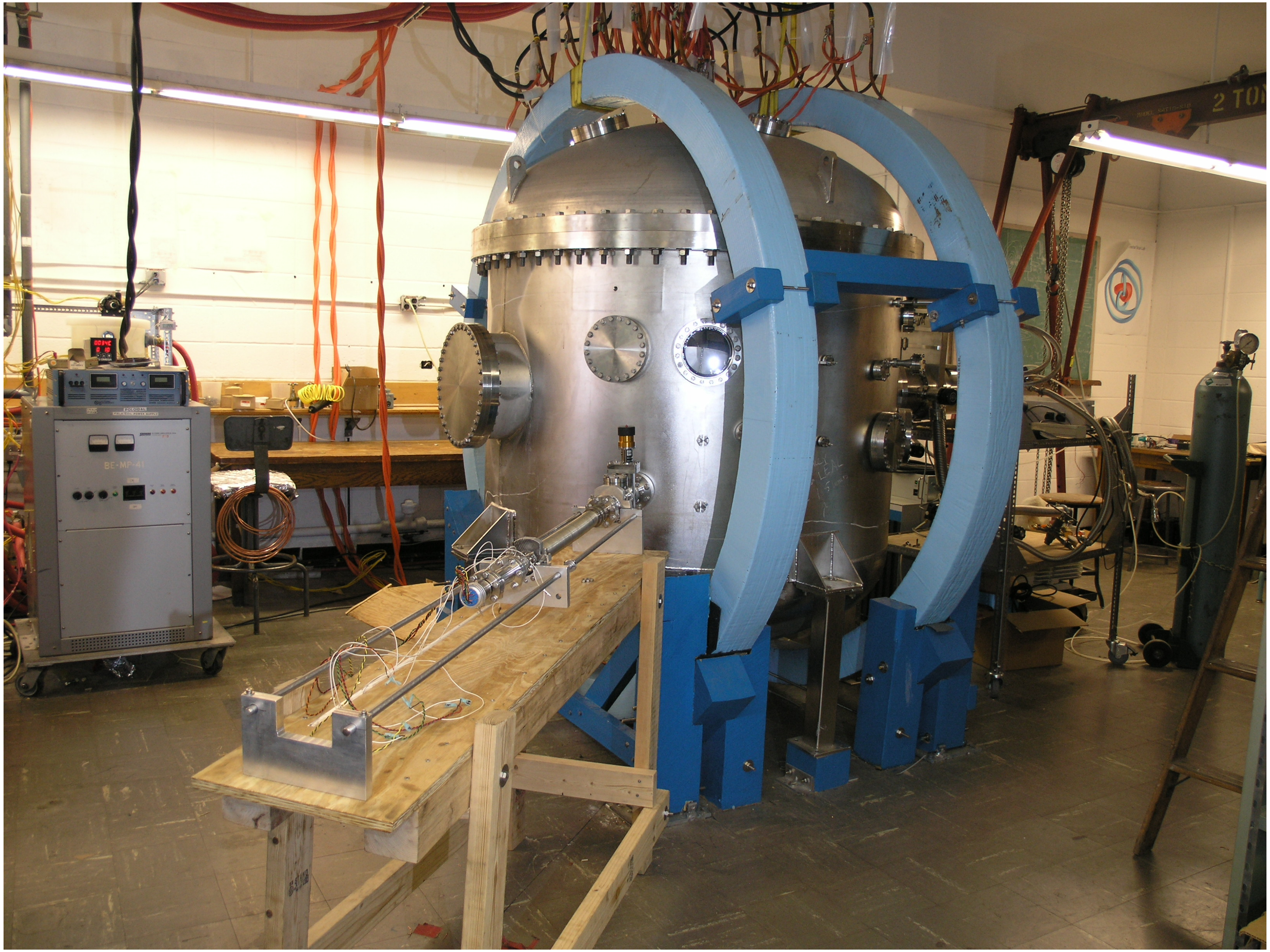
$$10\lambda_{De} = 10\sqrt{\frac{\varepsilon_0 T}{ne^2}} < a \Leftrightarrow 100\frac{\varepsilon_0 T}{ne^2} < a^2 \Leftrightarrow$$

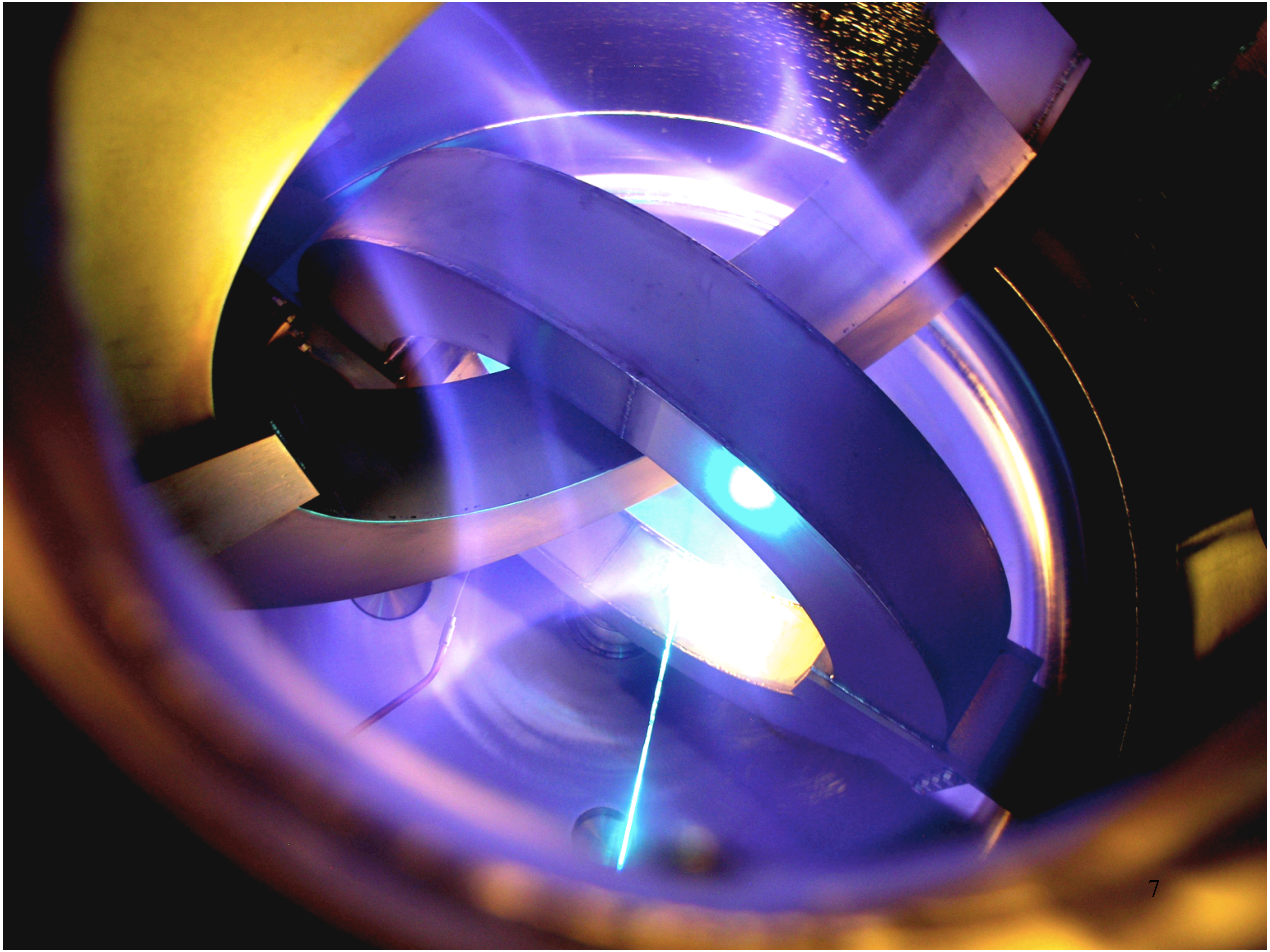
$$n > 100\frac{\varepsilon_0 T}{a^2 e^2} \approx 1.1\times 10^{13}\ \mathrm{m}^{-3} \Rightarrow N = nV > 1.1\times 10^{11}$$

$$N = 10^9 s^{-1} \cdot \tau_c \geq 10^{11} \Rightarrow \tau_c \geq 100 s$$

- Confinement device for e-p plasma would need better than 100 sec confinement time
- Should be possible in a dipole – but appears unlikely in a simple stellarator (as explained in the next slides)
- Plan A: Use Penning trap to accumulate – then inject into e-p plasma confinement device

Columbia Non-neutral Torus (CNT) results

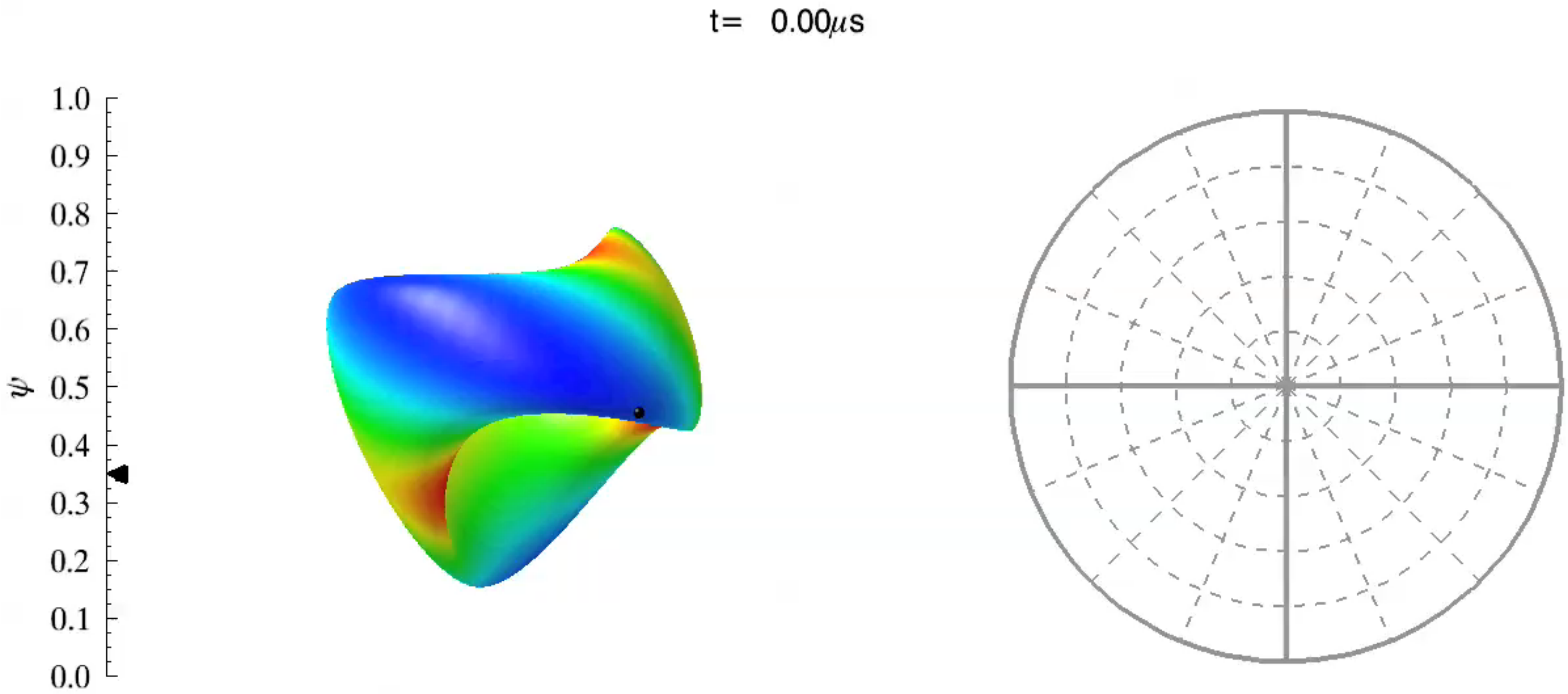




However, there are some “bad” orbits!

CNT is a “classical stellarator” – no complicated optimization:

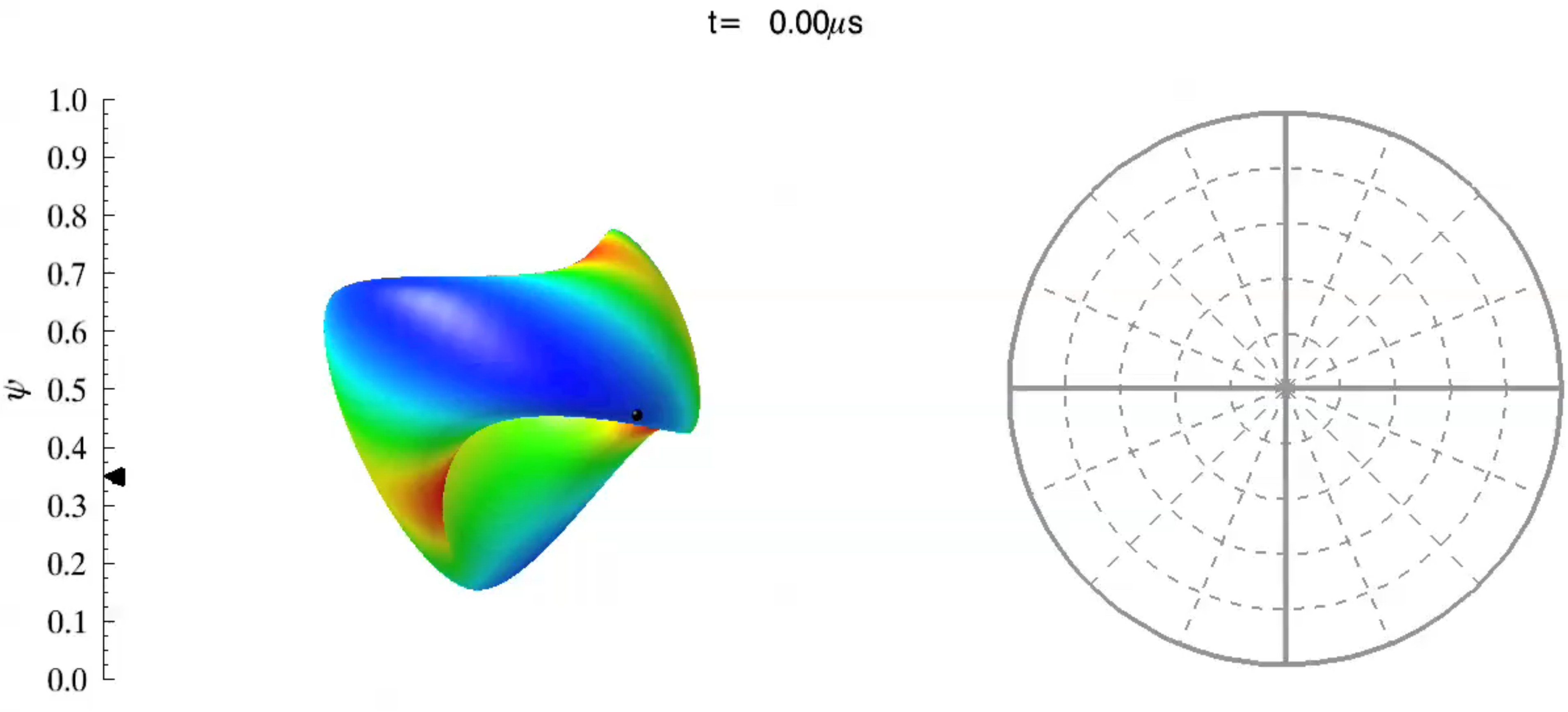
About 50% of particles in a Maxwellian are magnetically trapped due to mirror force and are not confined.
(Blue: low B, Red: High B)



ExB comes to the rescue (again)

Play the “pure toroidal trap” trick:

$a \gg \lambda_D$ guarantees v_{ExB} dominates over magnetic drifts



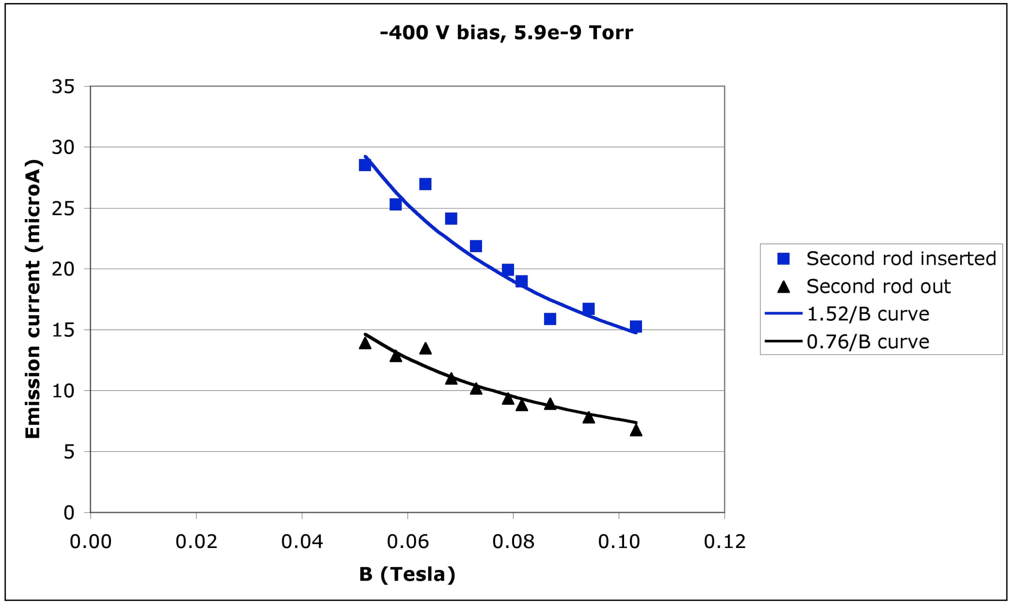
The Columbia Non-neutral Torus: Overview

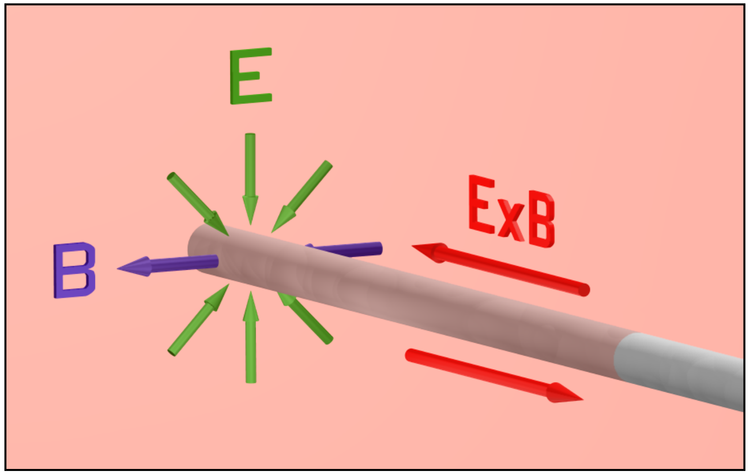
- Original plan[1,2]:
  - Design and build stellarator
  - Create and study pure electron plasmas
  - Achieve 1000 second confinement for these plasmas without internal objects
  - Inject positrons during these 1000 seconds
  - Create more or less quasineutral electron-positron plasma

- 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
    - 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, Letter in Phys. Plasmas (2012)

Experimental finding 1: ExB is sometimes bad





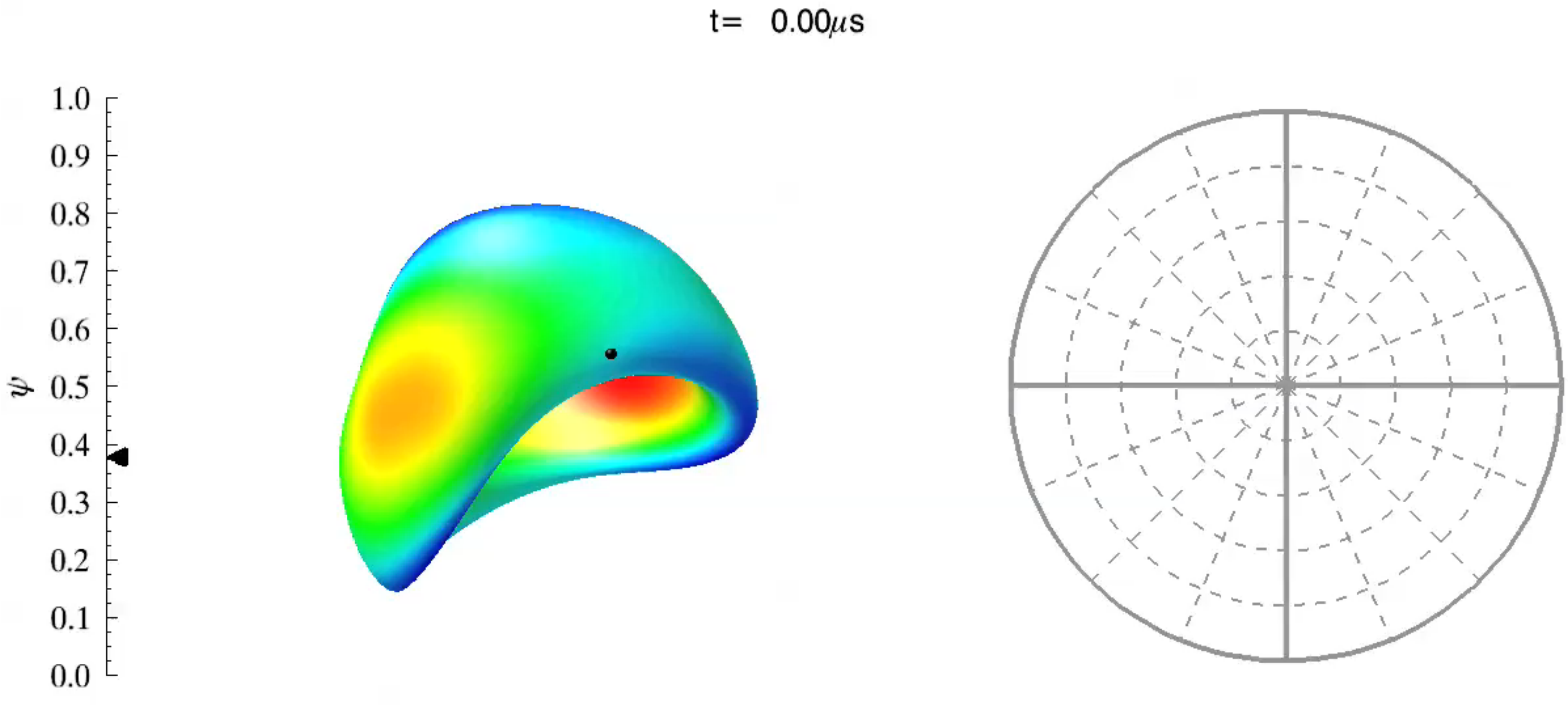
Insulated rods charge up negative relative to plasma to self-shield
Resulting ExB drift pattern convects particles along the rod all the way to the open field lines.

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

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

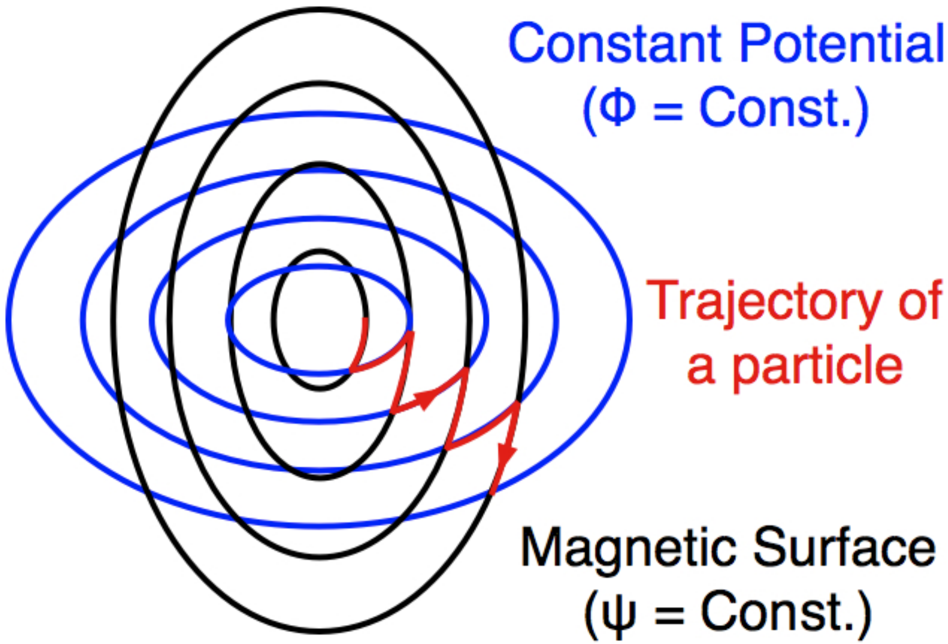
Numerical and experimental finding 2: ExB again

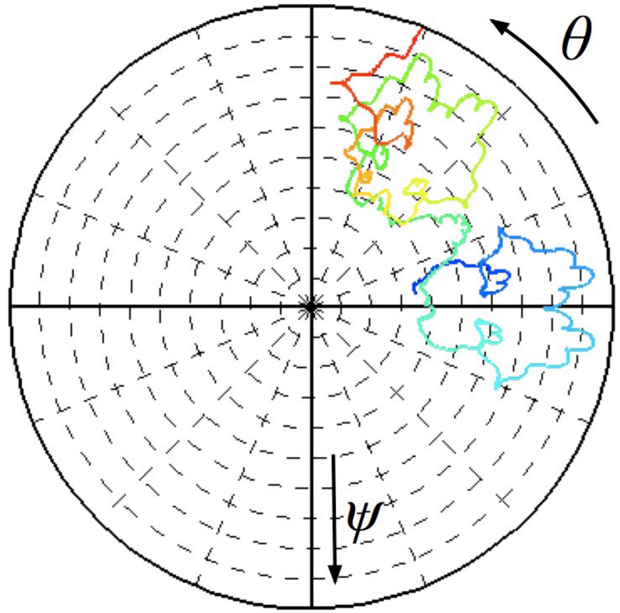
Orbits poorly confined due to ExB



Why is ExB bad? Intuitive picture

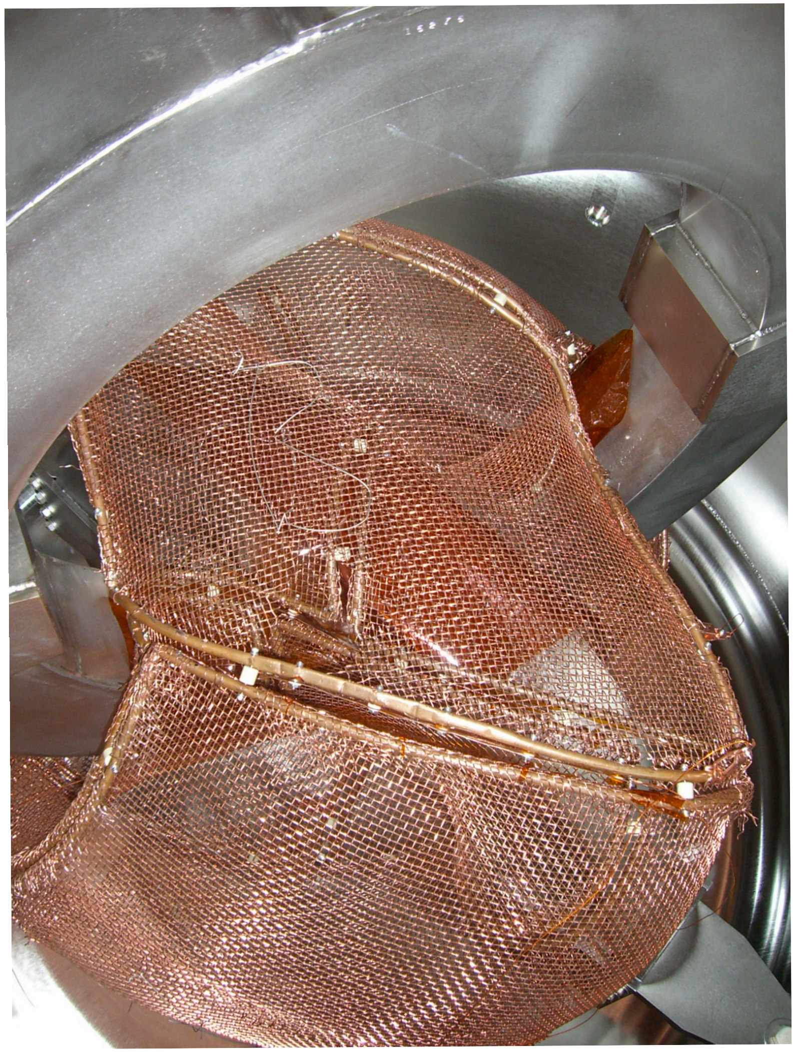
- ExB (perpendicular motion) takes electron along electrostatic potential contour
- Parallel motion of passing electrons (combined with rotational transform) takes electrons along the magnetic surface, moving them poloidally
- By switching between potential contours and magnetic surfaces, particles can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



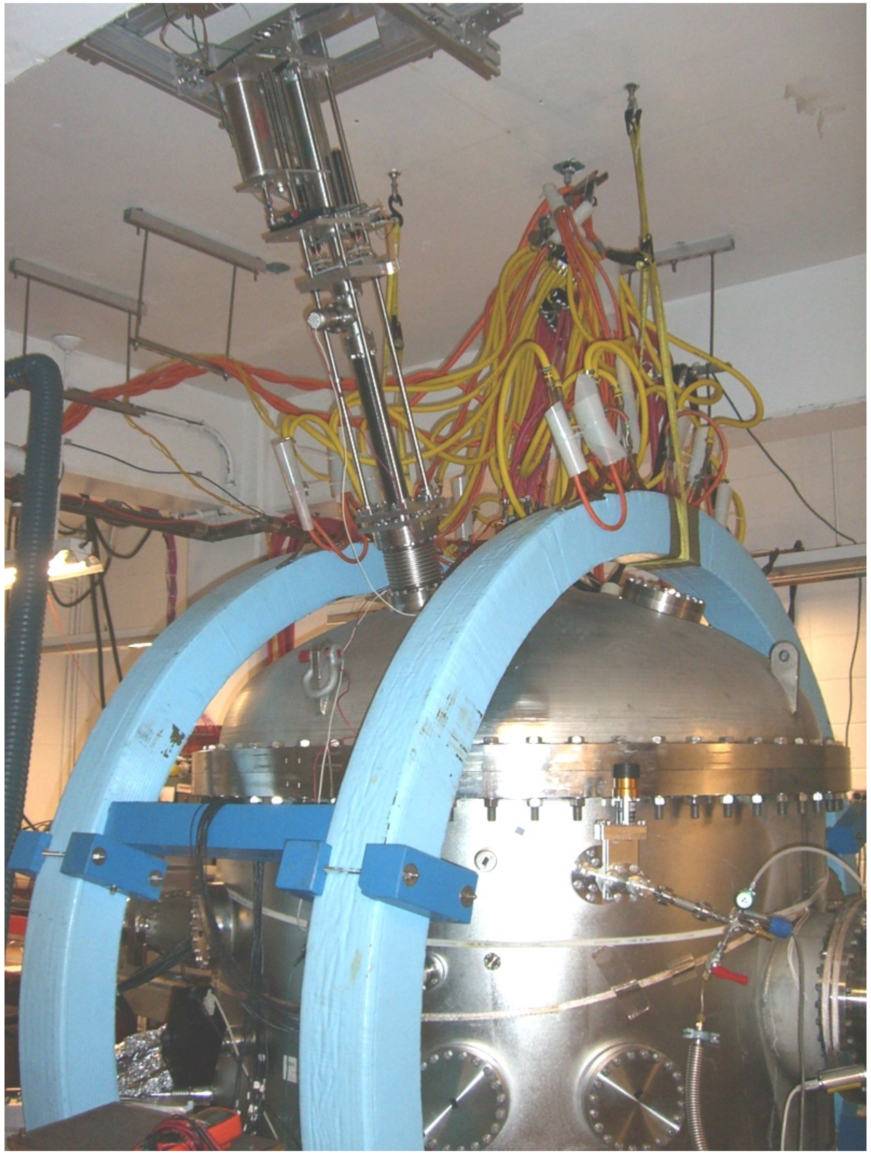


Fixing ExB part 1: Install “Faraday cage”

- This led to some improvement in particle confinement
- For details, see P. W. Brenner et al. Contributions to Plasma Physics (201)
- Next step: Remove internal rods

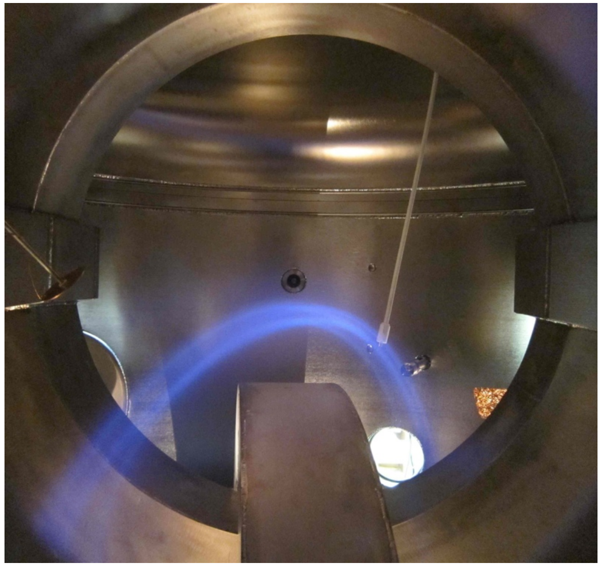


Fixing ExB part 2: Retract rods (20 msec)

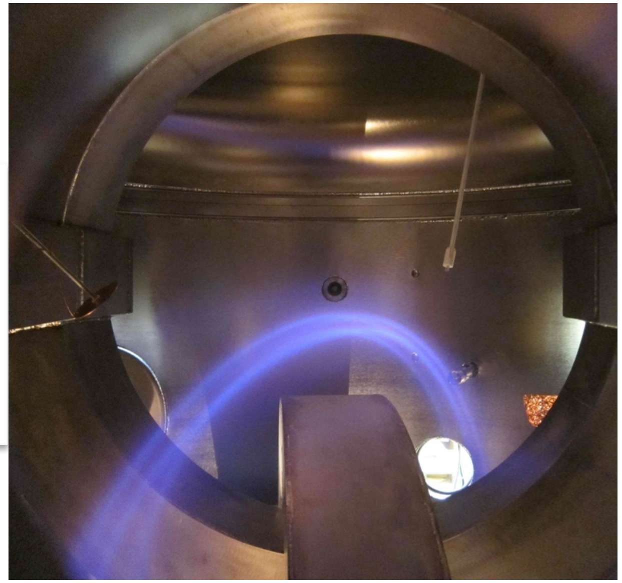


Design: Berkery et al. RSI (78) 2007

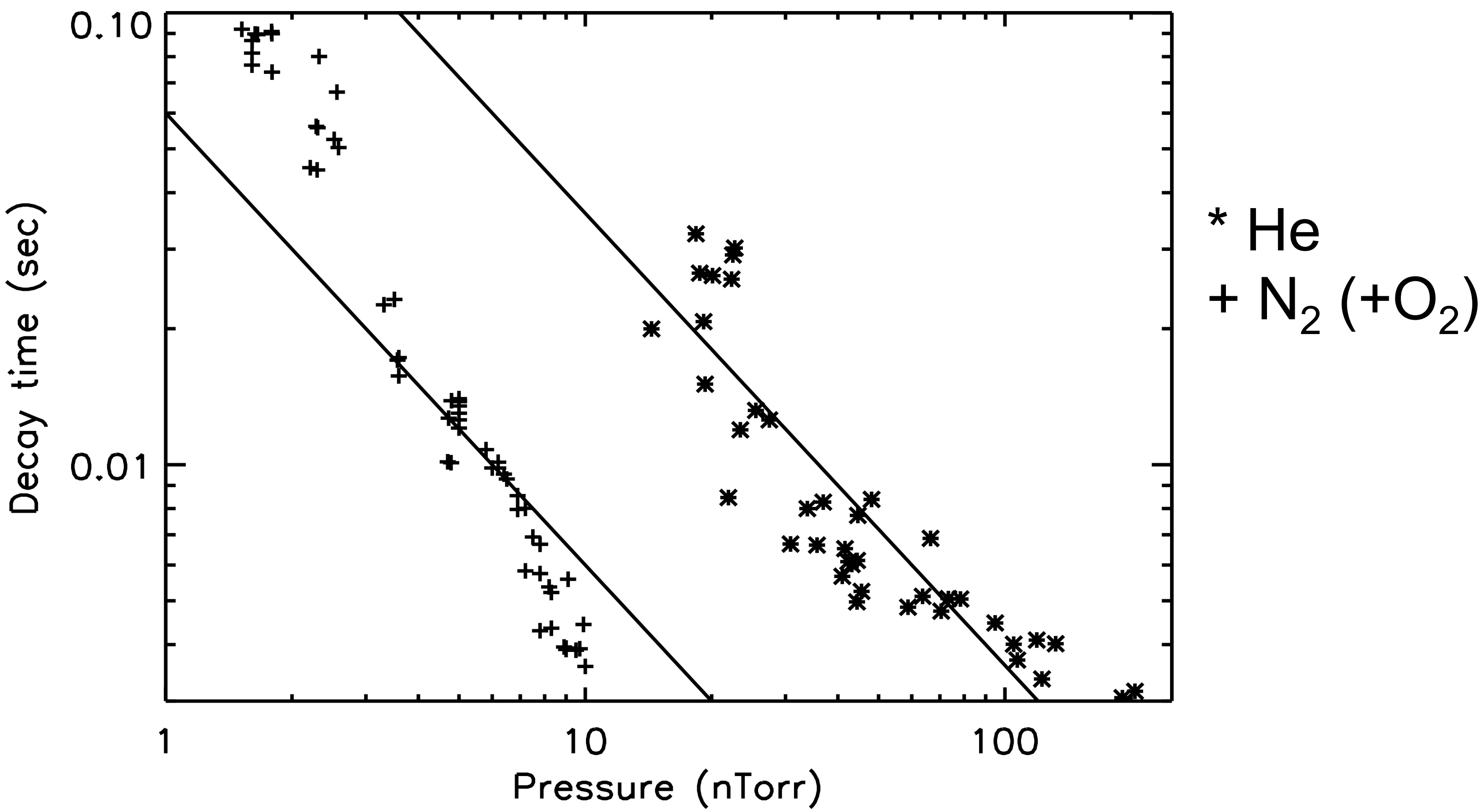
In Surfaces



Retracted



Then: ion accumulation limits confinement

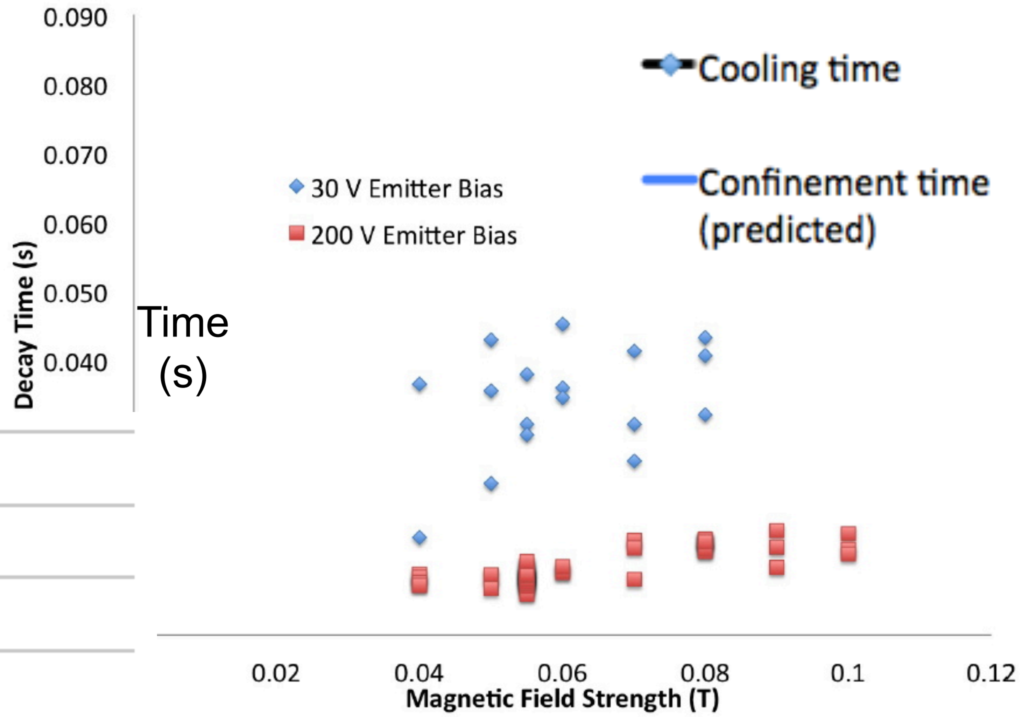


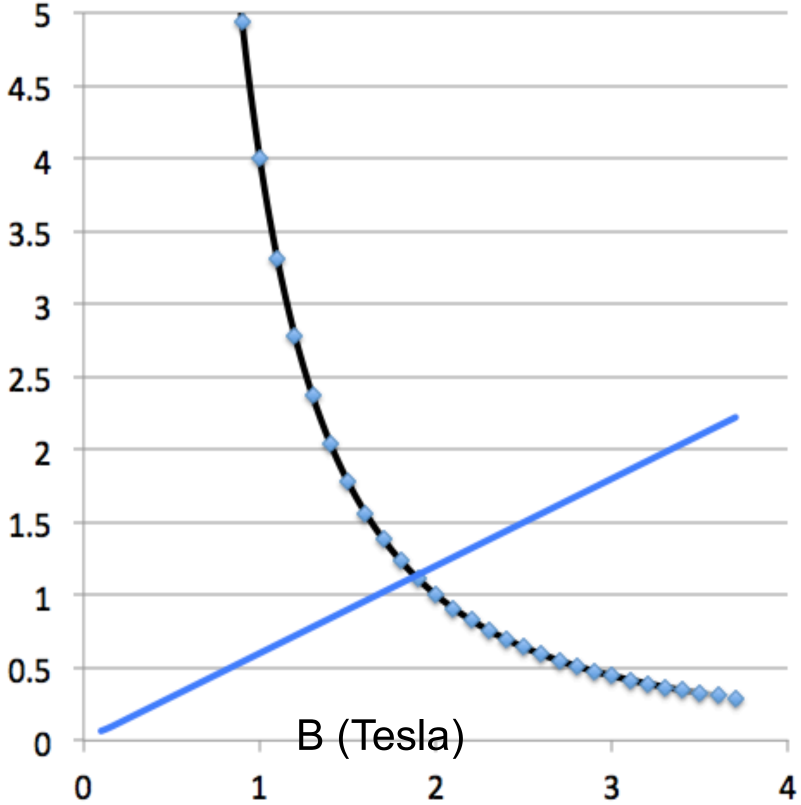
- Ion contamination must be avoided:
  - Lower plasma temperature
  - Lower neutral pressure

Brenner and Pedersen, Letter in Physics of Plasmas (2012)

Next step stellarator for e-p plasmas: >1 second confinement

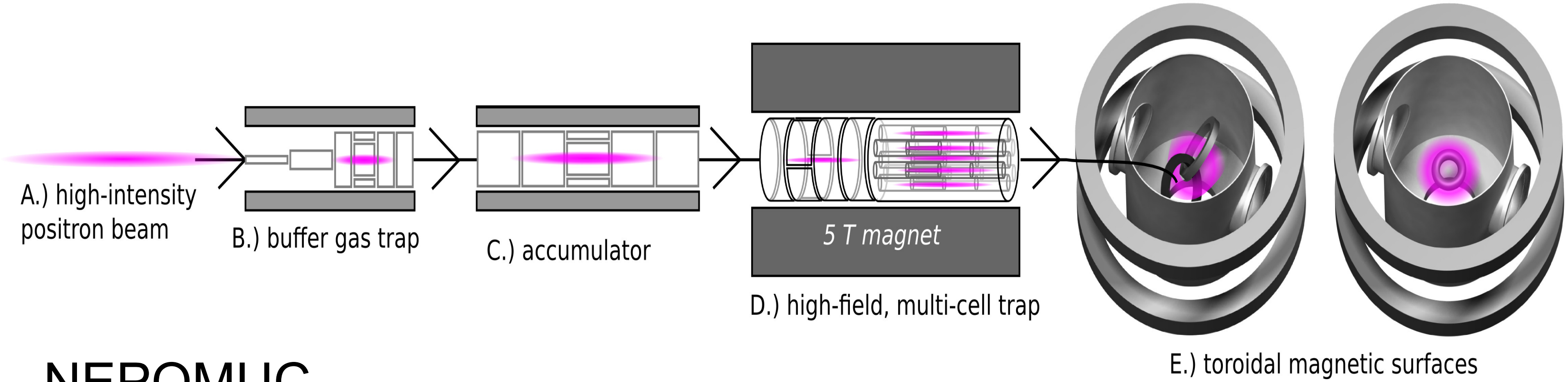
•Ionization crash avoided: Linear scaling with B





•B>2T should work so that plasma cools off at a faster rate than it decays

The grand scheme (plan A)



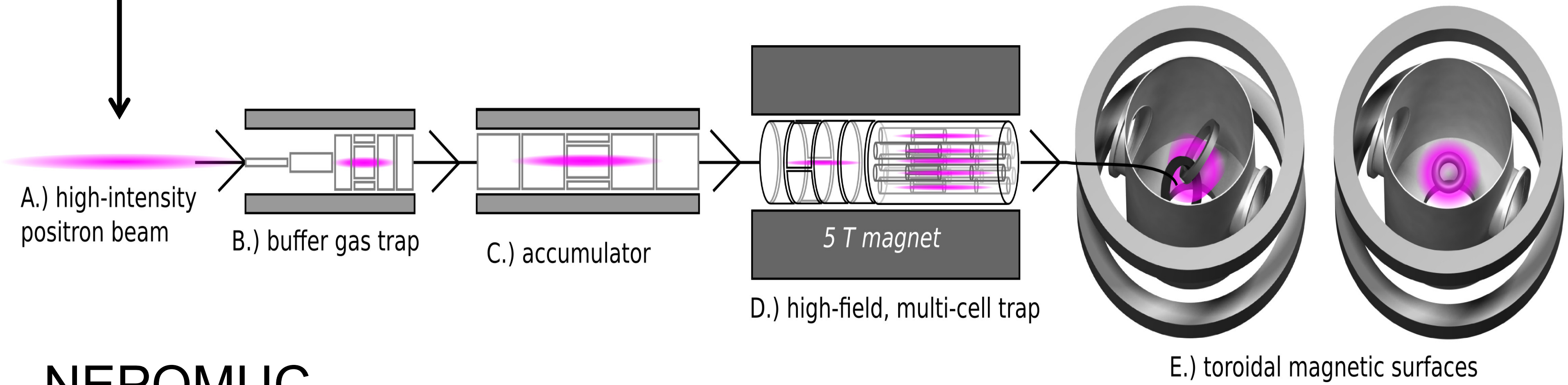
NEPOMUC

PAX

APEX

APEX-2

The grand scheme (plan A)



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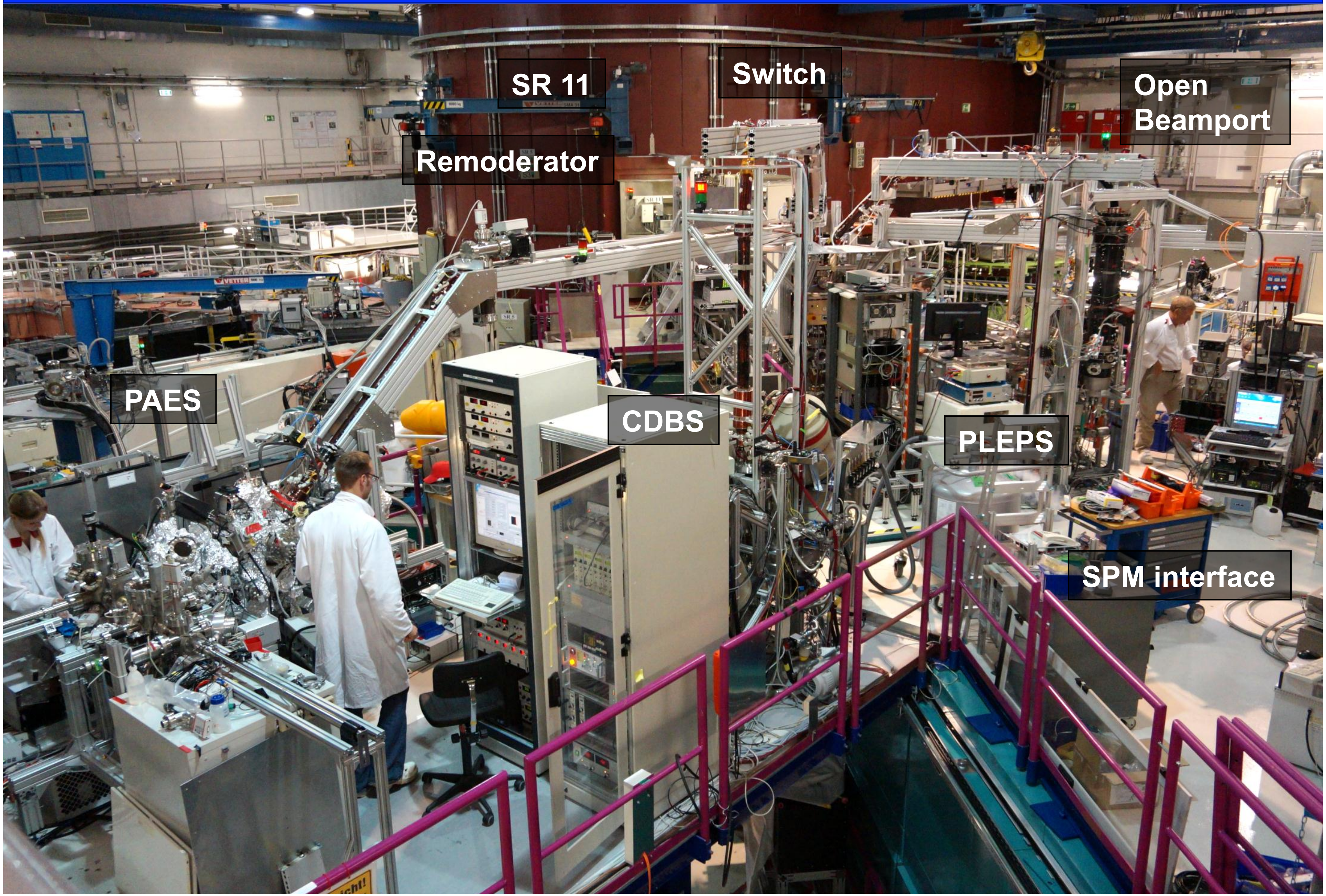
APEX-2

Positron Beam Facility at NEPOMUC



Beam Characteristics

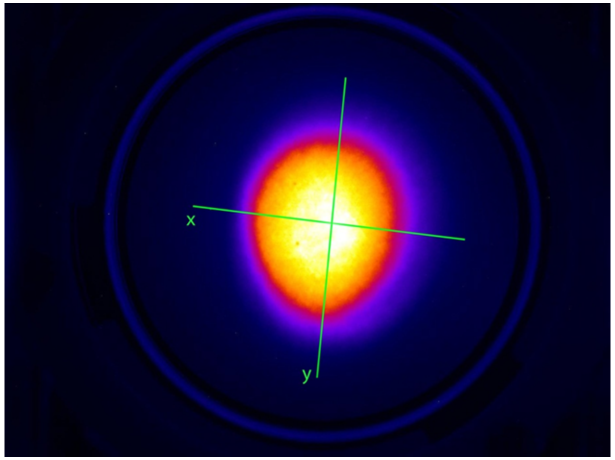
- Positrons created from gamma rays created in neutron capture. Neutrons come from the FRM-II reactor
- Beam parameters:

  $E = \mathbf{1\ keV}$

  $d_{FWHM} = 9$ mm guide field $B = 5$ mT

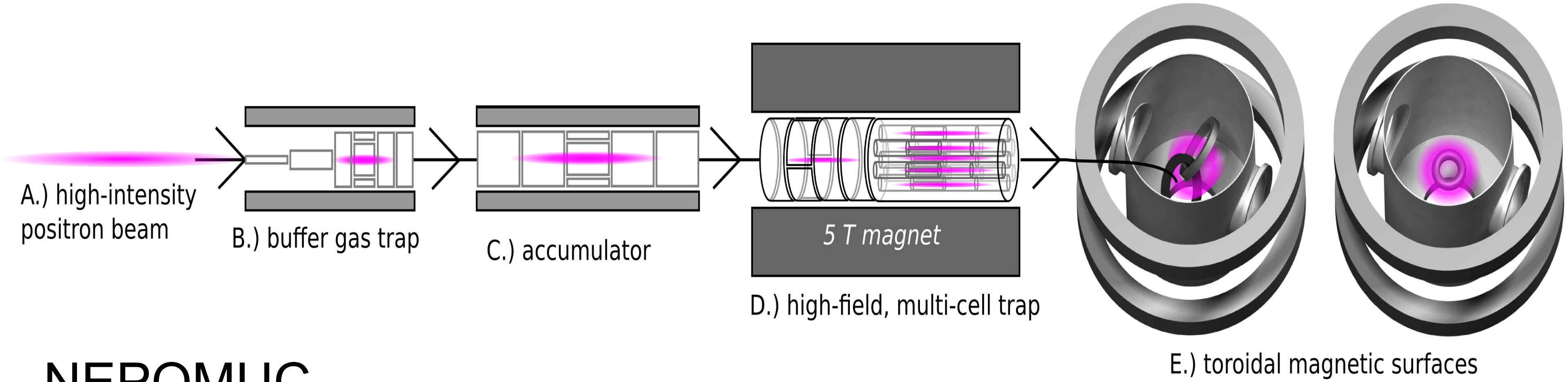
  $\mathbf{I_{beam} = 1.1 \cdot 10^9\ e^+/s}$
- **Energy spread:**
  - **F**or old beam at 5 mT: 1 eV
  - For new beam at 5 mT:

    First measurements will be attempted this week. Expectation: 1-10 eV



Cooperation with Christoph Hugenschmidt , TUM

The grand scheme



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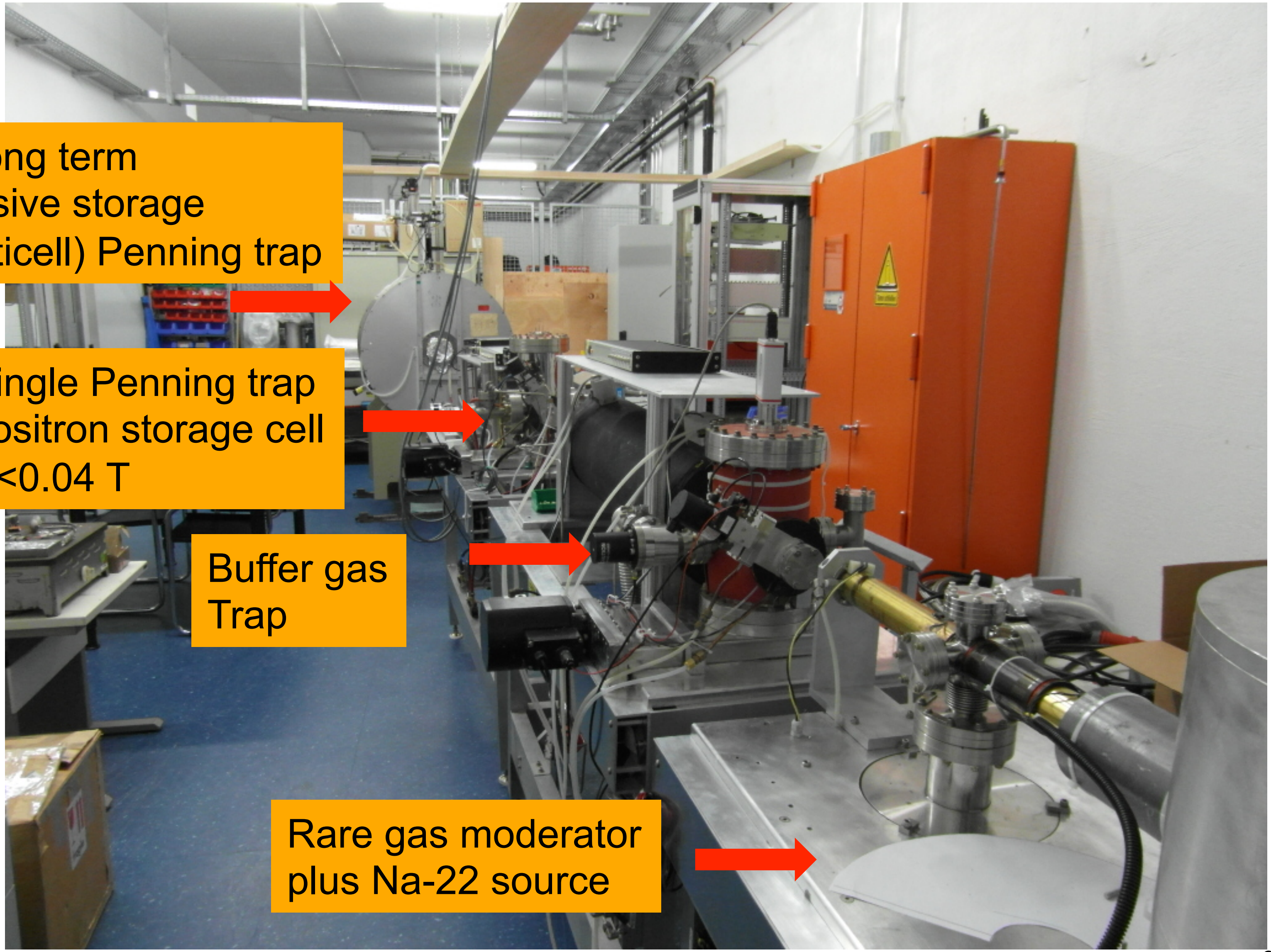
PAX

APEX

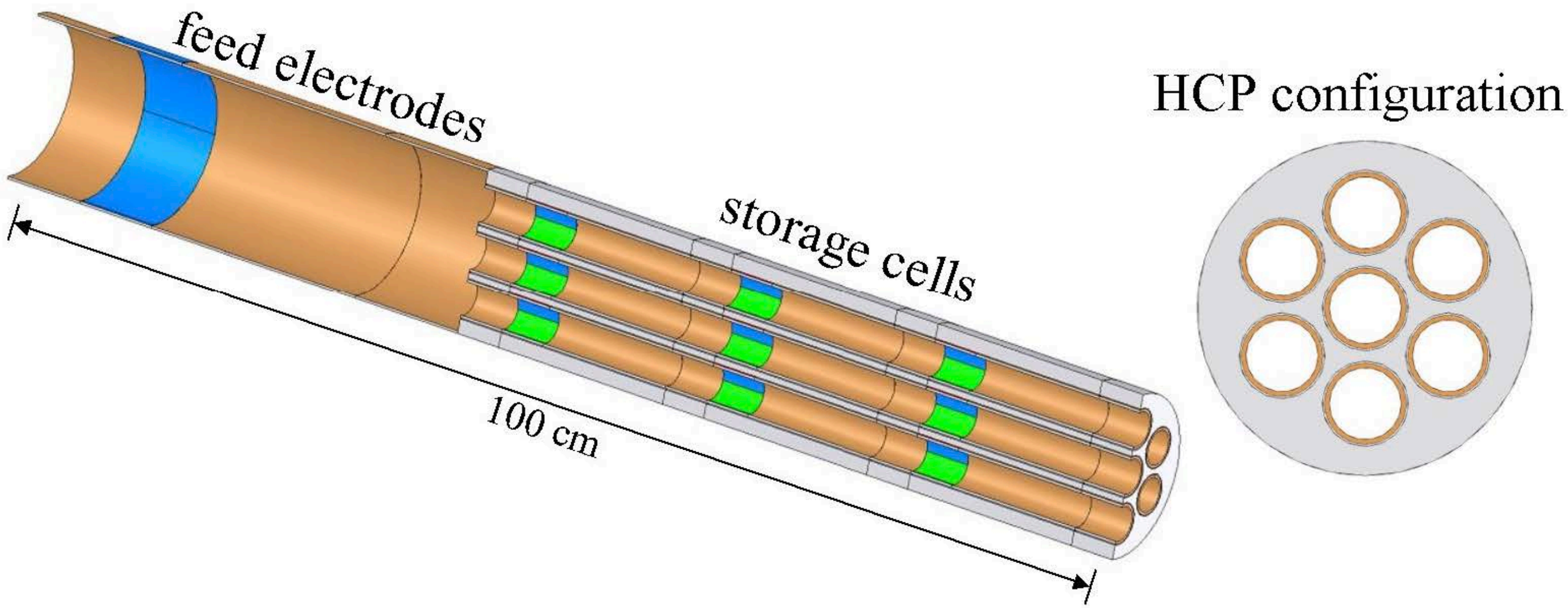
APEX-2

PAX components already in operation in Greifswald

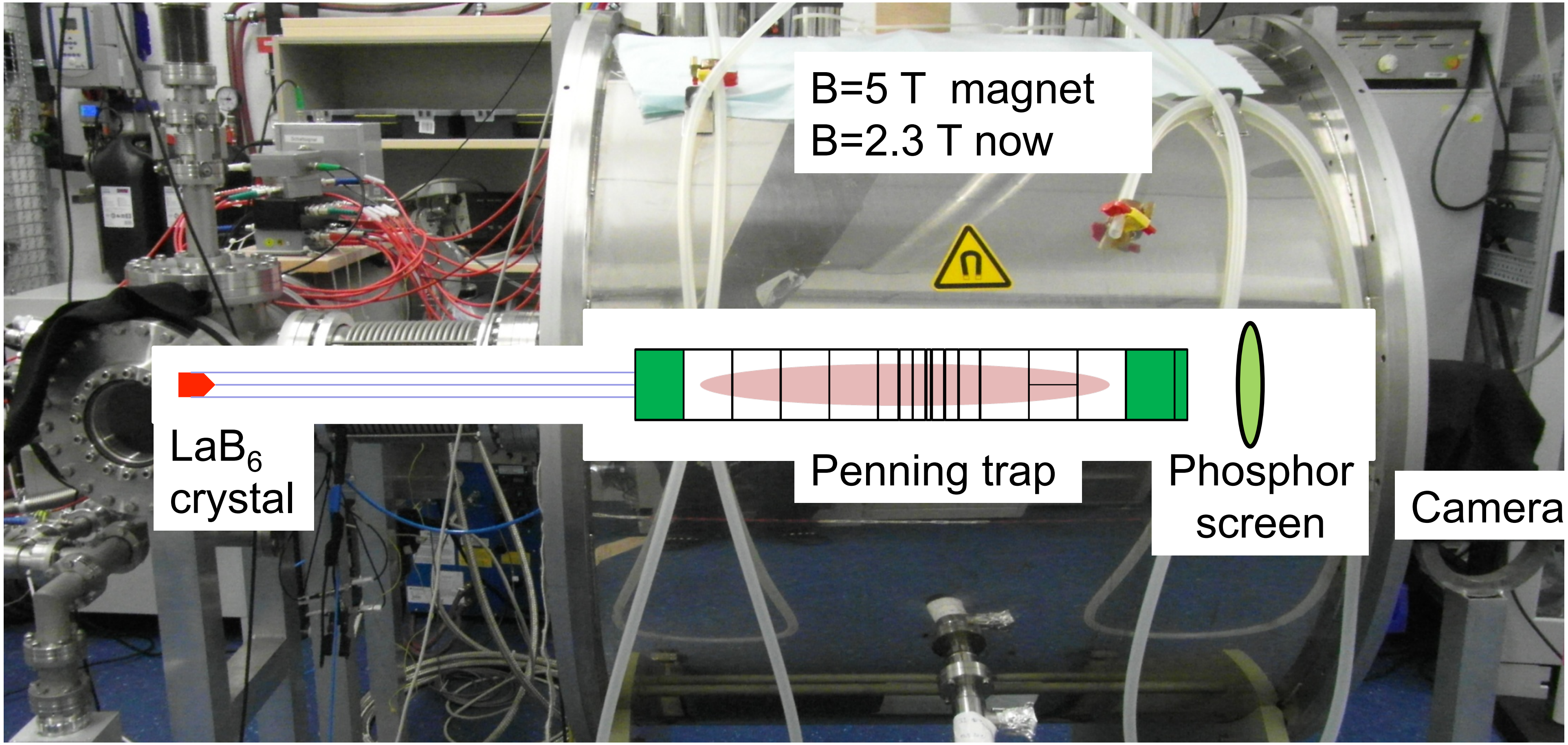


Positron Accumulation eXperiment (PAX)

- We will possibly/likely need a positron accumulation stage
- The stored number of positrons (10^{11}-10^{12}) will be larger by two orders of magnitude than earlier achieved
  - Collaboration with Cliff Surko and James Danielson, UCSD
  - Buffer gas trap fills multicell Penning trap array
  - PAX positrons are injected into APEX

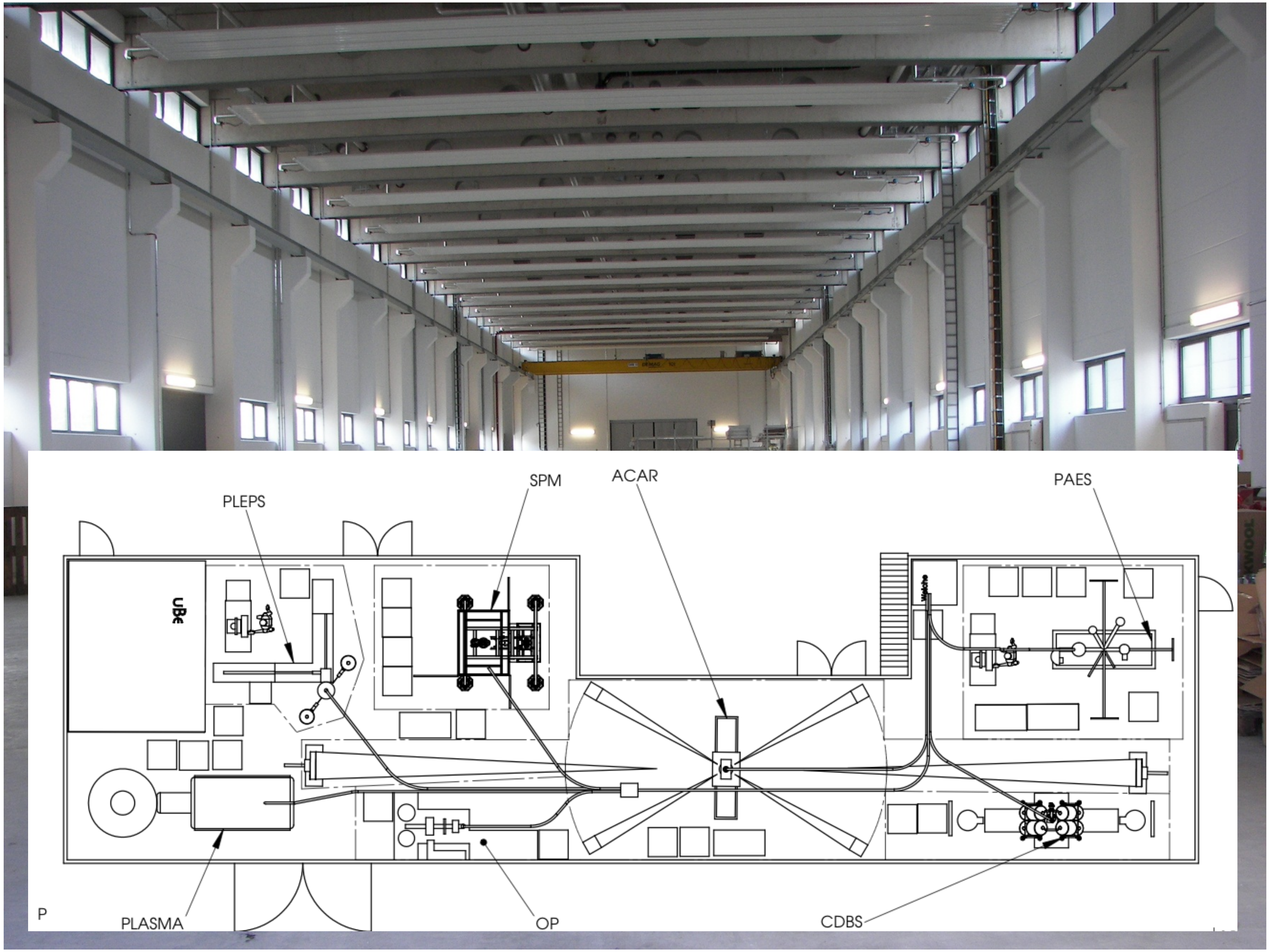


First experiments with electrons in storage trap

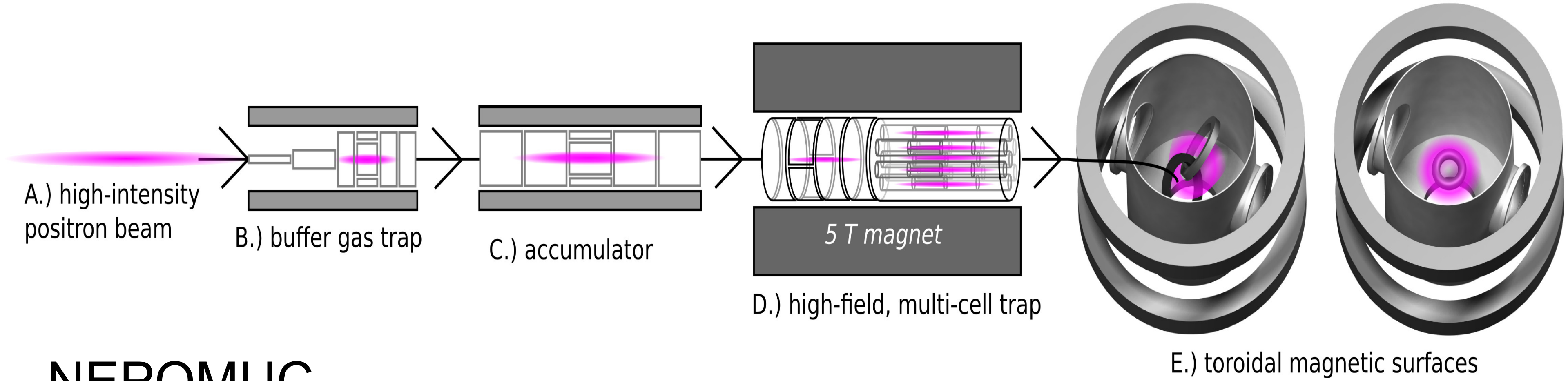


Up to 10 minutes of confinement achieved for $2*10^8$ electrons in a single Penning trap: 10 times below space-charge limit set by end-cap voltages.

PAX in Experimental Hall East in ~~2015~~ 2018



The grand scheme can only be implemented in 2018



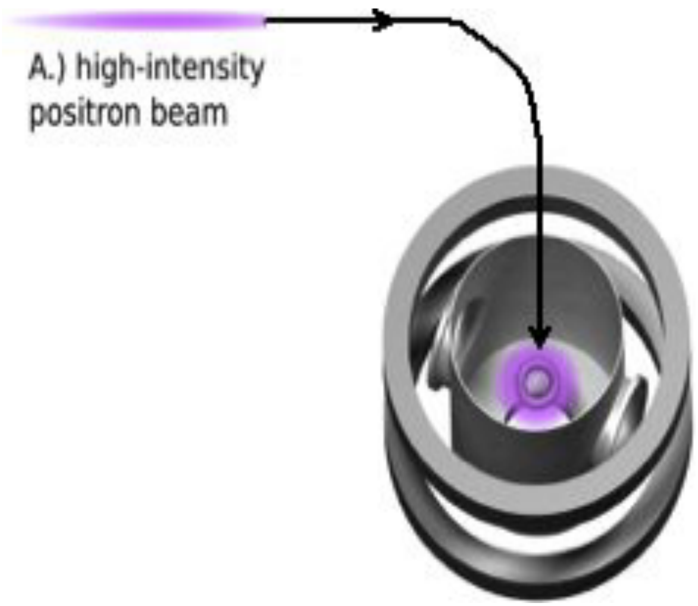
NEPOMUC

PAX

APEX-S APEX-D

The fast-track scheme (plan B)

NEPOMUC

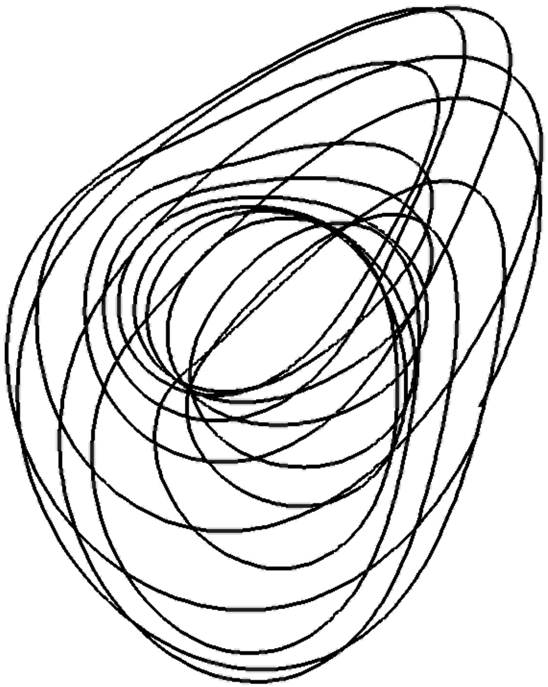


APEX-D

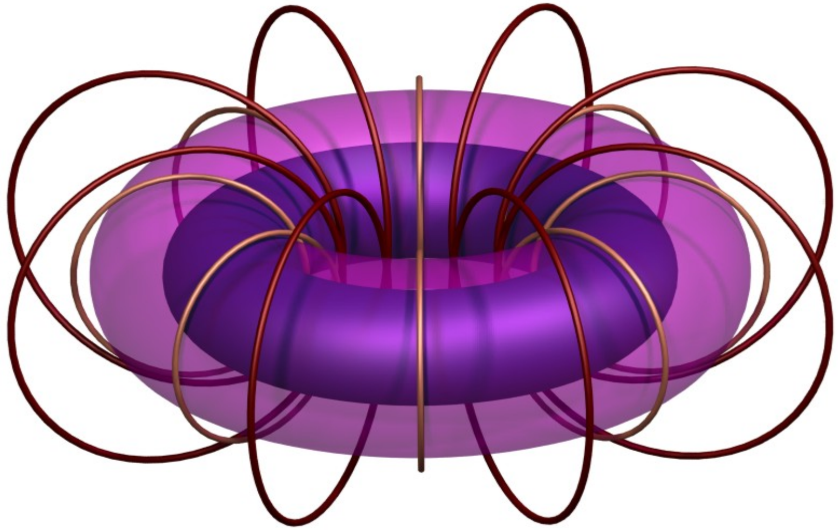
- Direct injection of 10^9 positrons/sec
- Hopefully >100 sec confinement time:
- 10^{11} stored positrons and electrons in a 10 liter volume: $n \sim 10^{13}$ m^{-3}
- Factor of at least 10 safety margin for injection efficiency:
- At $n=10^{12}$ m^{-3} and T=1 eV, λ_D=7 mm
- Fits into existing space in reactor hall at FRM-II

Give up stellarator? Different confinement and stability

Stellarator



Dipole

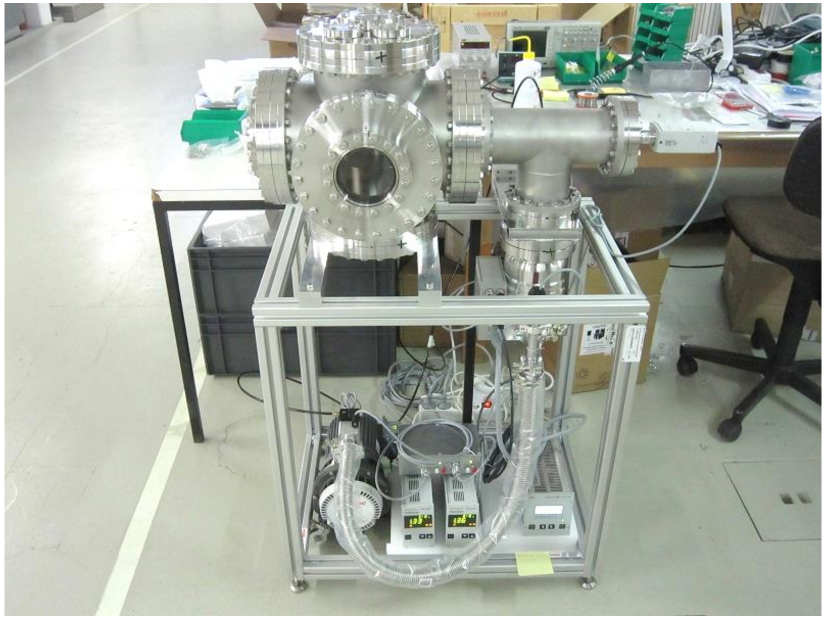


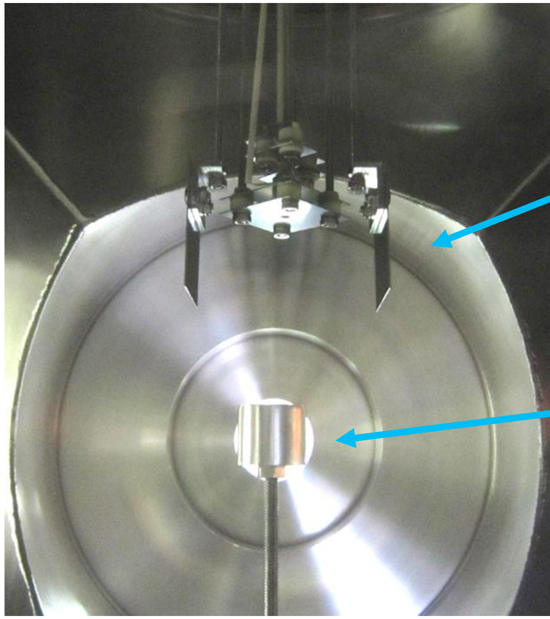
Both have closed field lines: How to inject?

Two potential injection/creation schemes

- We will pursue two completely different schemes:
- Scheme 1: ExB drift injection (next slides)
  - Use ExB drift plates to inject electrons and positrons into confined region
- Scheme 2: Positronium (ask if you are interested)
  - Create positronium from positrons
  - Drift positronium into confinement region
  - Laser- or field ionize into e-p plasma

First injection experiments in a dipole are running (this week!)



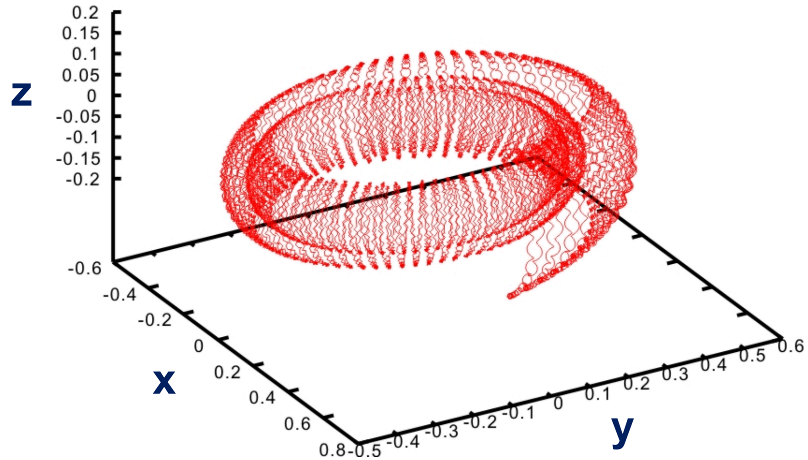


ExB electron injector

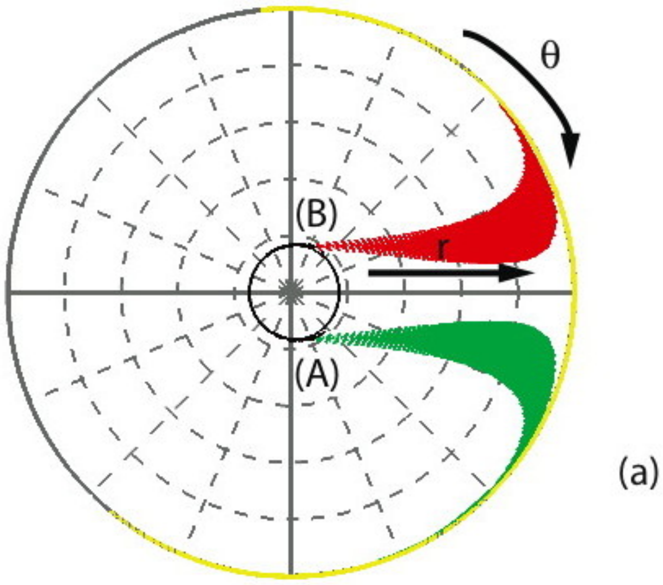
Neodymium magnet

- Neodymium magnet, B (at surface) ~ 0.4 T
- Injection onto closed field lines with ExB drift plates
- Electrode (magnet case) bias to get positron confinement
- Injection and trapping with electrons was already quite successful in this device

ExB injection deep into dipole or stellarator



• Local azimuthal electric fields just outside the confinement region are effective in dipole
H. Saitoh, et al., to be published

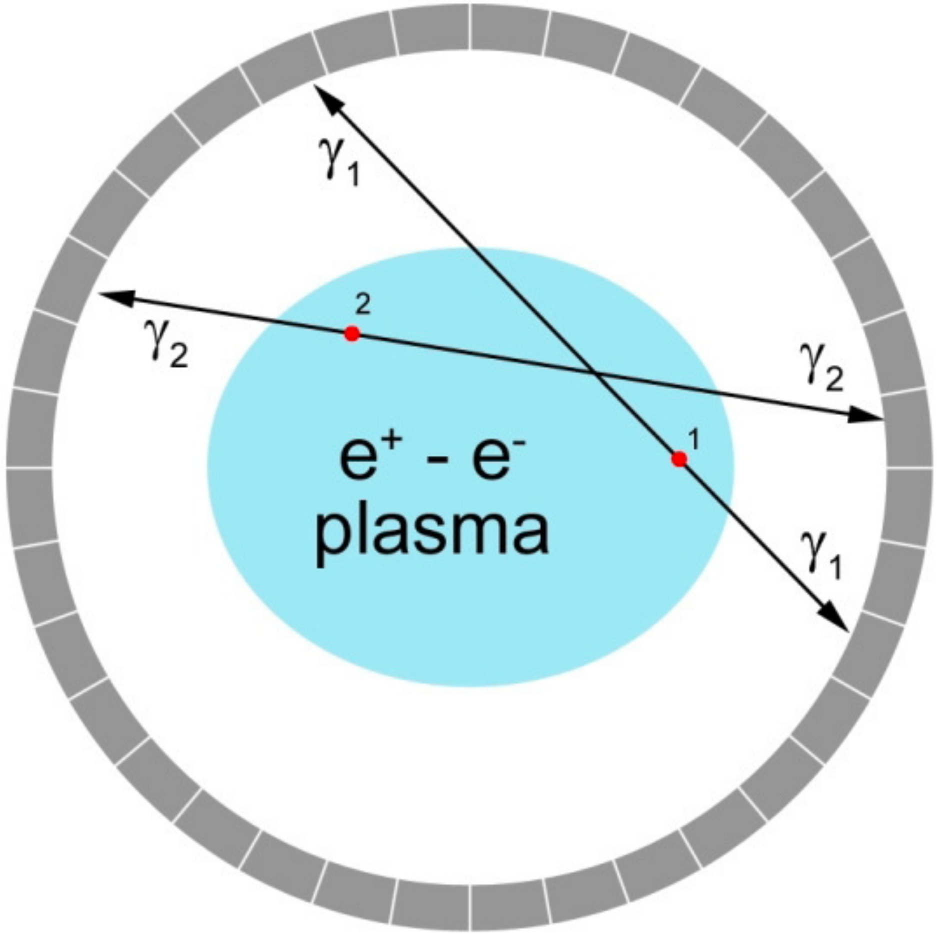


Drift injection using external electrostatic potentials also effective in a stellarator

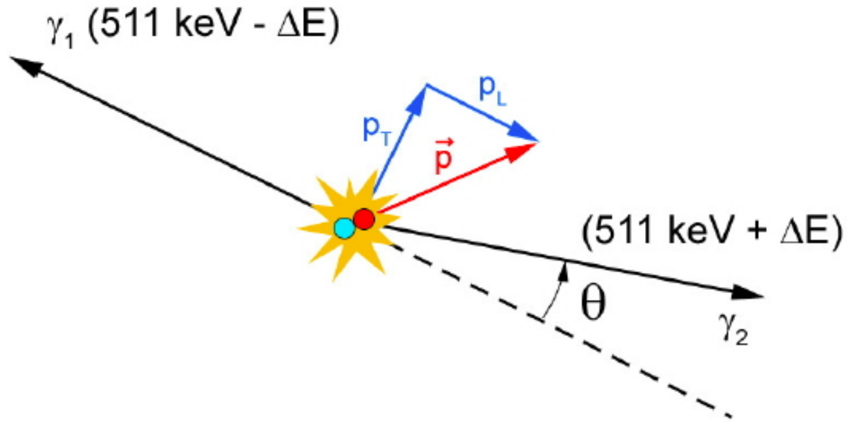
B. Durand de Gevigney et al., Phys. Plasmas **18**, 013508 (2011)

Diagnostics/annihilation

- Internal probes will lead to massive annihilation
- For a “good” e-p plasma (T=1 eV, n=10^{14} $m^{-3,}$ V=10 liter, N=10^{12}):
  - 10^8 annihilations/sec
  - 10^4 sec plasma decay time due to annihilation
  - Coincidence gamma ray detection



Annihilation can also measure temperature

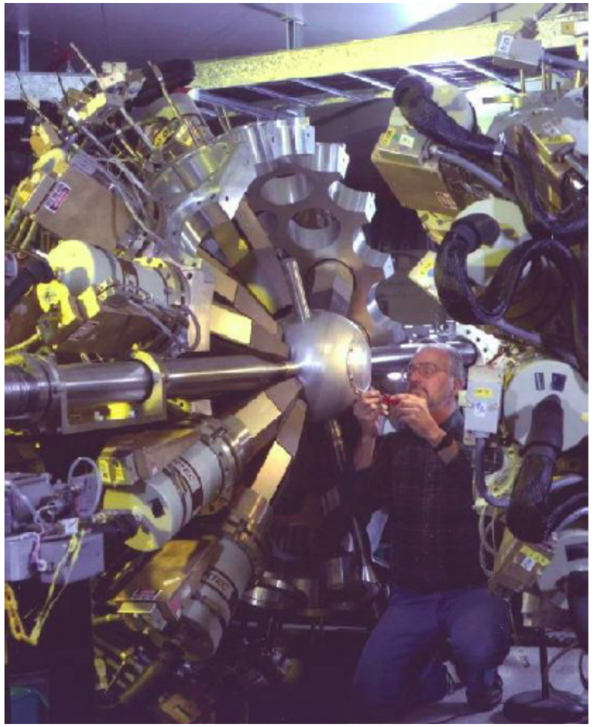


- Coincidence gamma ray detection also using Doppler effect:

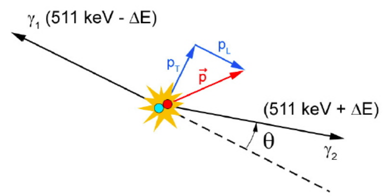
$$\Delta E \approx \frac{1}{2} p_L c$$

$$\text{for } T_e = T_p = 1 \text{ eV: } \Delta E \approx 0.6 \text{ keV}, \ \theta \approx 0.1^\circ$$

- High purity Germanium detectors (LN-cooled):
- ΔE~1.2 KeV, T~3 eV and above
- Detector set available (as a loan) from FRM-II/NEPOMUC group
- Shown for illustration:
  108 detectors “Gammasphere”
  Argonne Nat’l Lab, USA



Annihilation micropellets: localized measurements



- Shoot in r=0.1 mm micropellets
- Can be injected from foil or gel by laser blow-off (S Zoletnik, private comm.)
- Annihilation on pellet dominates over volume annihilation allowing radially resolved local measurement of "I_{sat}":

$$r = A\sqrt{T/m}\,n \approx 2\pi\cdot 10^{-8}\,\mathrm{m}^2\cdot 4\cdot 10^5\,\mathrm{m/s}\cdot 10^{13}\,\mathrm{m}^{-3} \approx 2.5\cdot 10^{11}\,\mathrm{s}^{-1} >> 10^8\,\mathrm{s}^{-1}$$

$$\tau = 2a_{plasma} / v_{\mathrm{pellet}} = 0.1\ \mathrm{m} / 100\ \mathrm{m/s} = 10^{-3}\ \mathrm{s}$$

$$\Delta\mathrm{N}{=}\mathrm{r}\tau = 2.5\cdot 10^8 << N = 10^{11}$$

Local measurement – almost non-perturbative

Summary

- A plan has been developed to create the world's first electron-positron plasmas
- Theoretical and numerical work is underway to detail the unique features of these plasmas confined in magnetic traps
- Positron source, manipulation techniques and accumulation techniques are being developed and integrated (first experiments done)
- Traps for matter-antimatter plasmas are being built
  - Prototype traps used for pure electron plasmas
  - First experiments with positrons running
- Injection schemes have been identified (POP stage)
- Diagnostic concepts have been identified (conceptual stage)