MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

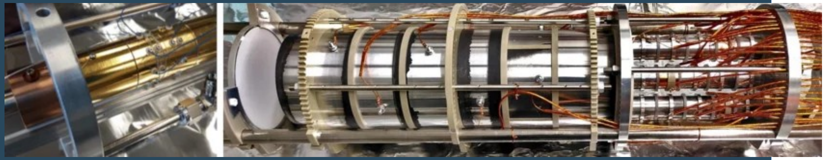
APEX

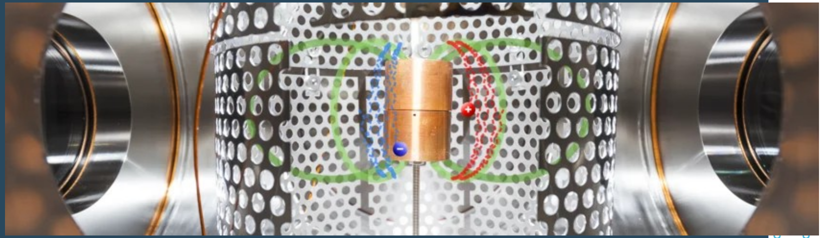
A Positron-Electron eXperiment's progress & future developments

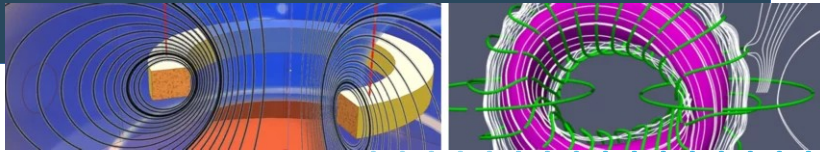
on the path to confined matter-antimatter plasmas

E. V. Stenson,
for the APEX Collaboration

MIPSE Seminar ○ 12 April 2023
University of Michigan ○ Ann Arbor







HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DFG Deutsche Forschungsgemeinschaft

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UCSD Foundation,
U.S. D.O.E.

A Positron Electron eXperiment (APEX) collaboration

Max Planck Institute for Plasma Physics
E. V. Stenson
A. Deller[2]
A. Card
J. von der Linden[3]
J. Smoniewski
S. Nißl[4]
Martin Singer[1]
P. Steinbrunner[1]
P. Huslage[5]
P. Gil[5]
C. W. Rogge[4]
P. Helander[1]
A. Mishchenko
M. Drevlak
P. Costello

University of Greifswald
L. Schweikhard

Lawrence University
M. R. Stoneking

The University of Tokyo
H. Saitoh

Technische Universität München
C. Hugenschmidt
F. Guatieri
S. Vohburger

University of California San Diego
C. M. Surko
J. R. Danielson

Culham Centre for Fusion Energy
Daniel Kennedy

Type One Energy
T. Sunn Pedersen

+ a growing contingent of alumni
(Markus Singer, U. Hergenhahn, S. König, J. Horn-Stanja, M. Dickmann, H. Niemann, X. Sarasola, et al.)

1 Univ. Greifswald, 2 UCSD, 3 Humboldt Fellow, 4 TUM, 5 LMU

Outline

I. Introduction

- the compelling goal of laboratory pair plasmas
- approaches to making them

II. The APEX Grand Scheme

- sufficient positrons
- suitable traps
- the parts in between

III. Recent progress

- key questions answered in prototype set-ups
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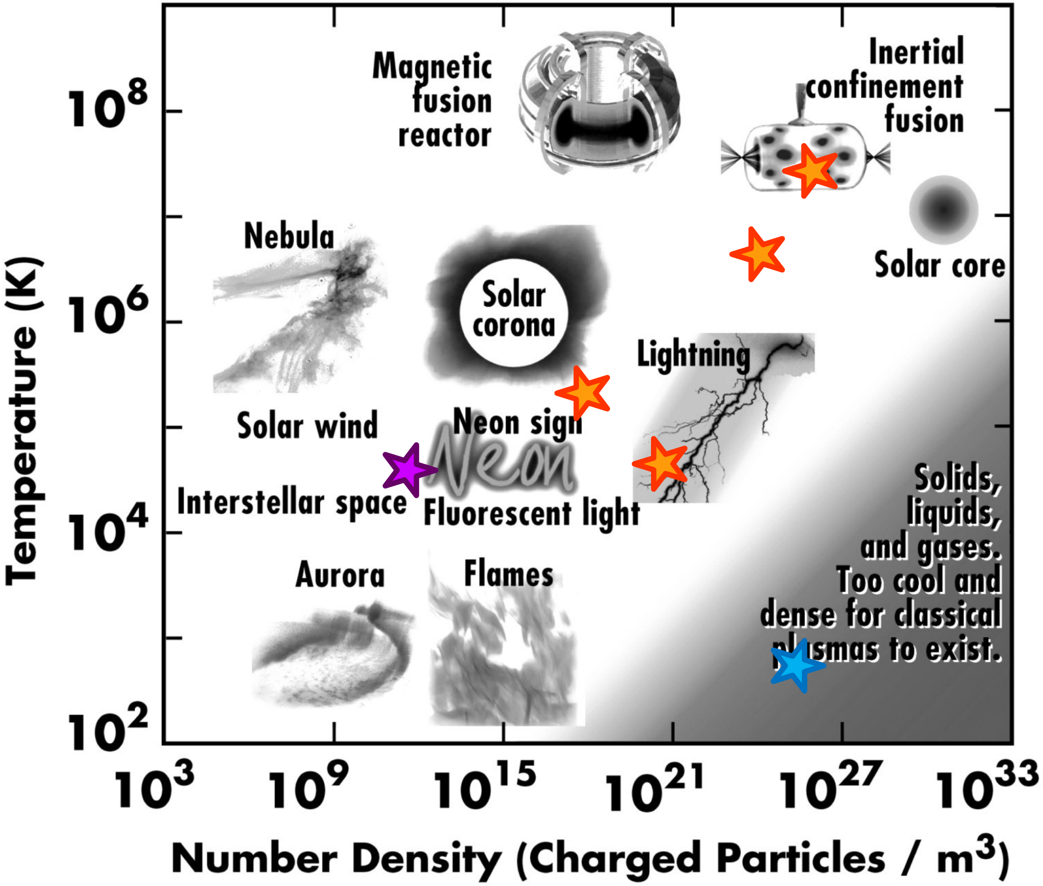
- moving into higher fields and collective behavior

IV. Coming attractions

Our place in the plasma universe

Goal:
to combine positrons and electrons to make an unusual --- but likely very interesting --- plasma out of half matter and half antimatter



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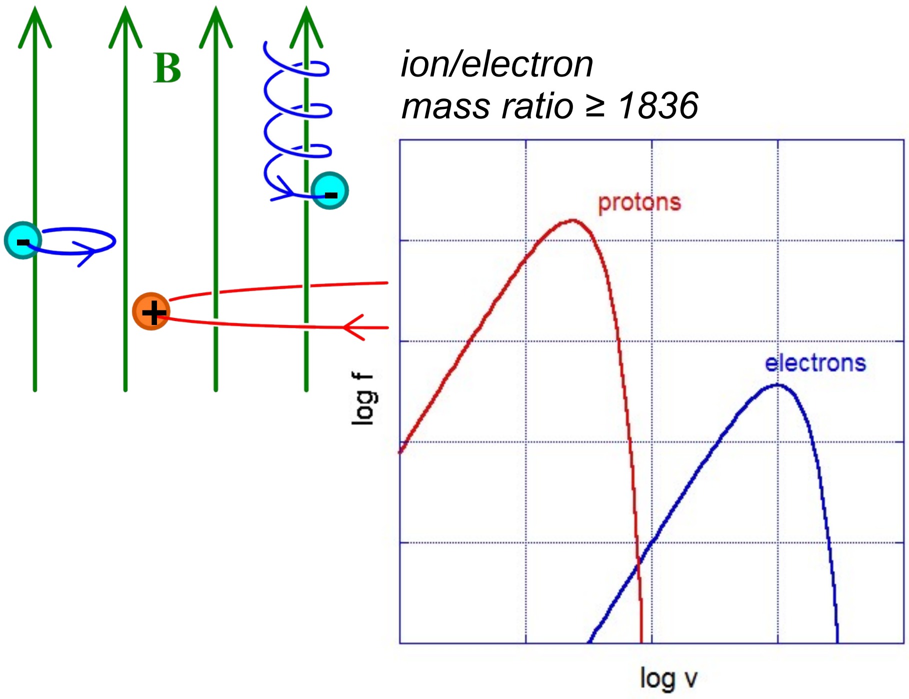
- standard temperature & pressure
- typical examples of "lab astrophysics"
- our target for lab e+e- plasmas

Pair plasmas: an exciting frontier

Mass asymmetry is a cornerstone of the physics of quasi-neutral plasmas . . .



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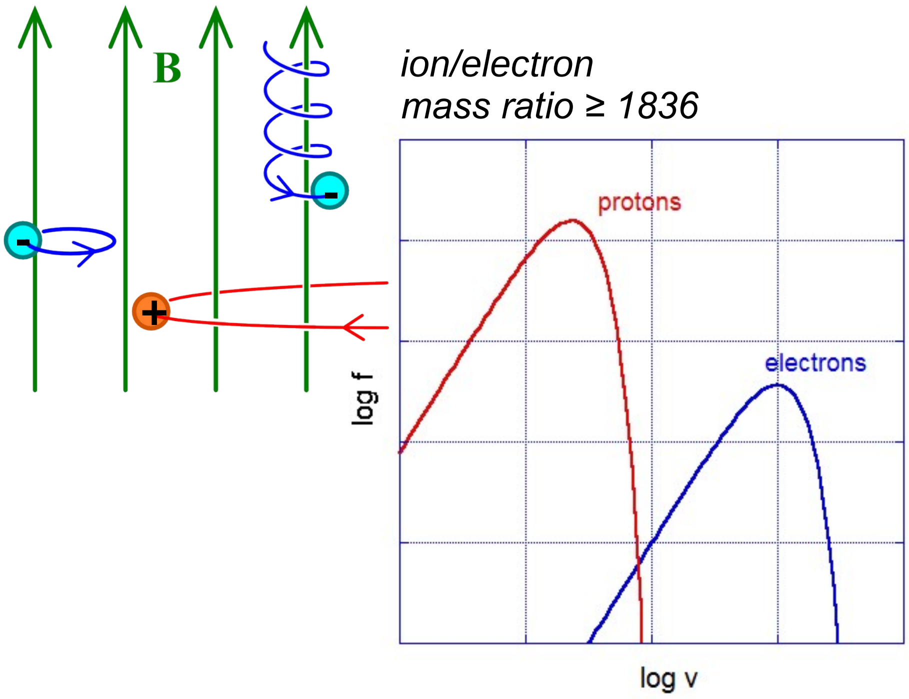
. . . but what if the mass ratio were unity?

➡ ~1000 papers on “pair plasmas”

(but experimental side still in its nascence)



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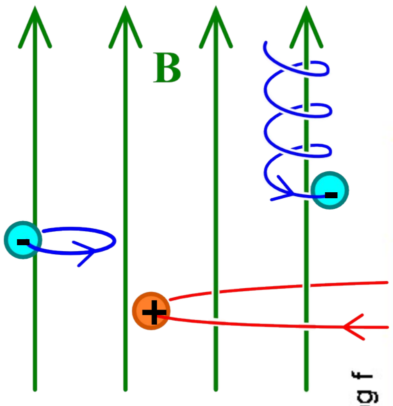

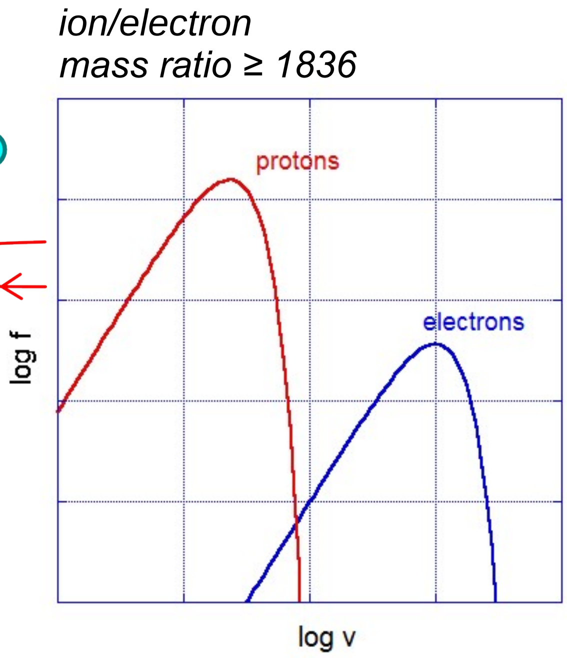

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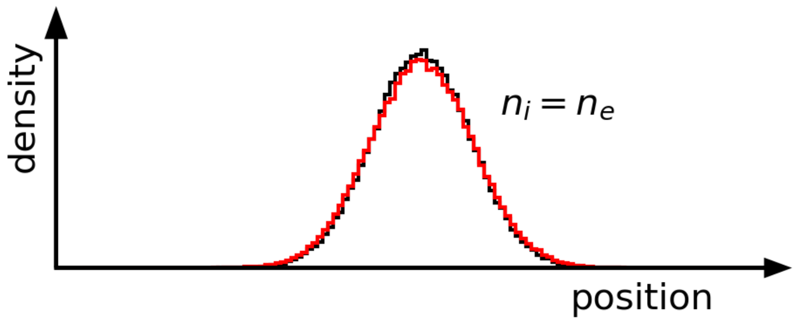
In comparison to electron/ion plasmas, certain dramatic changes to plasma properties are predicted:

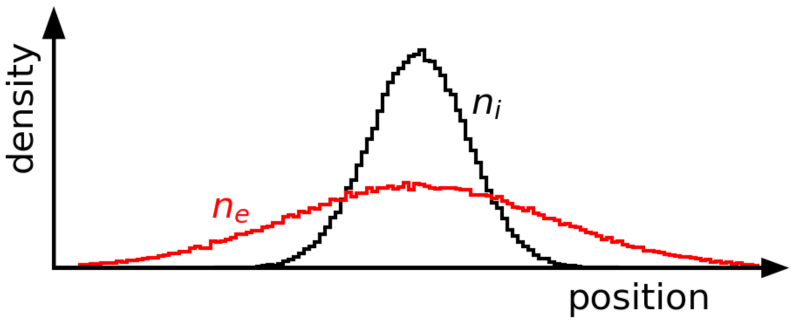
- disappearance of some phenomena (sheaths, Faraday rotation, whistler waves, lower hybrid waves . . .)
- changes in characteristic properties with regard to others (reconnection, turbulence, soliton solutions . . .)
- "remarkable stability properties" in certain geometries and parameter regimes → turbulence-free (!)

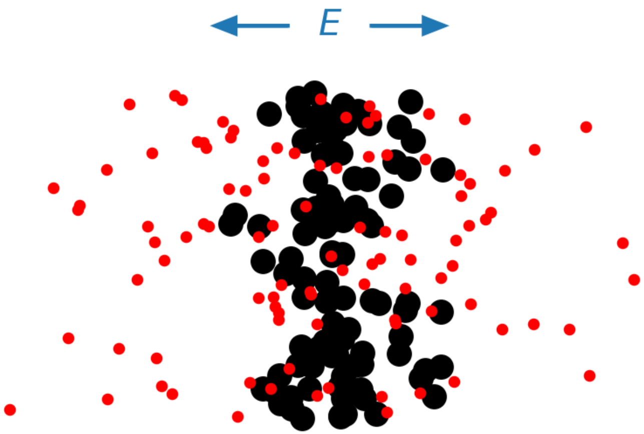
References:

Tsytovich & Wharton (*CPPCF* 1978)
Sarri et. al. (*JPP* 2015)
Helander (*PRL* 2014)
and many more . . .

Mass asymmetry → coupling between p and E





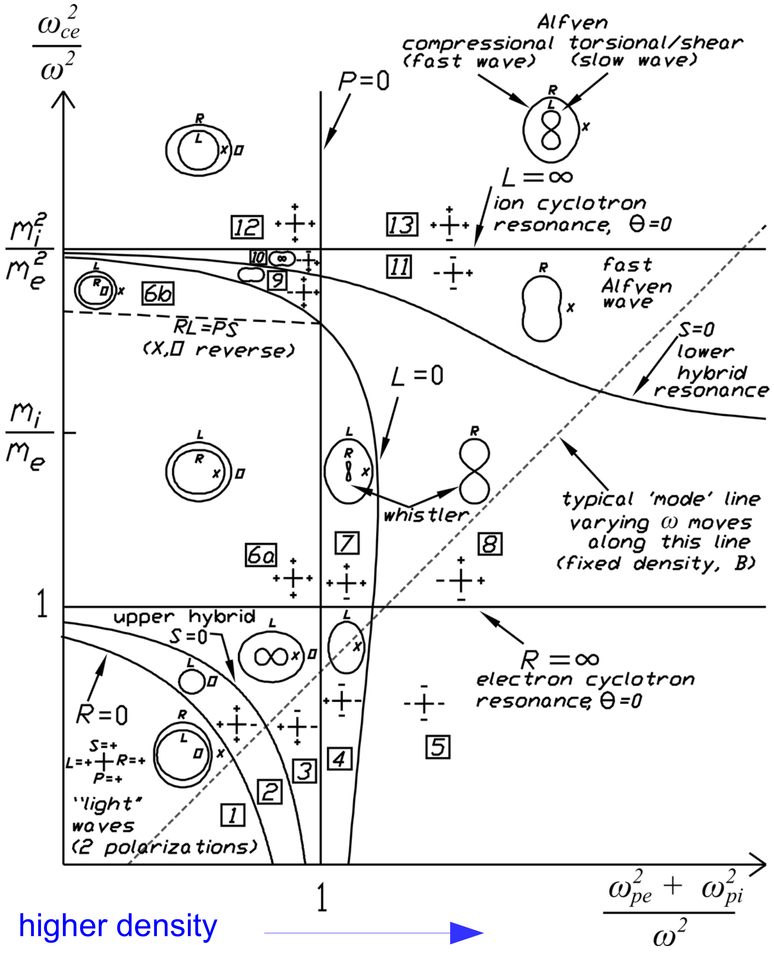


A. Deller (figure) & S. Nißl (simulations)

e-p+ movie
vs.
e-e+ movie

*M.R. Stoneking et al., **JPP** 86, 155860601 (2020).*

The landscape of basic plasma waves

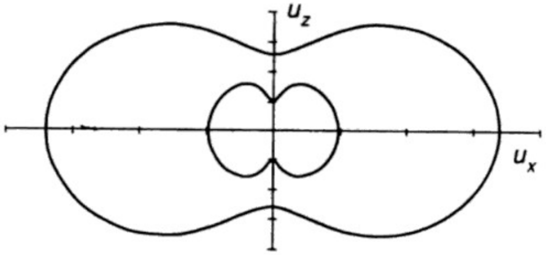


higher density

standard CMA diagram *(Bellan)*

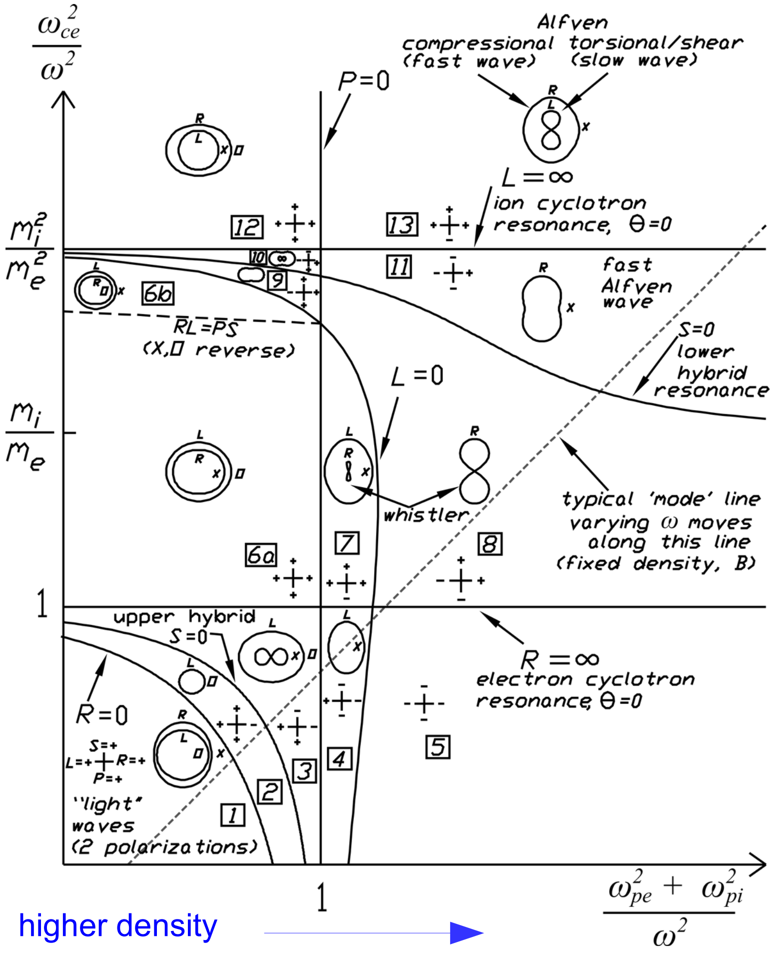
larger magnetic field

- “look-up” table (wave frequency, magnetic field, density)
- plasma is homogeneous, infinite, magnetized (z)
- two frictionless fluids with T=0
- linear modes
- up to 2 solutions to dispersion relation
- boundaries: cut-offs, resonances
- wave normal surface: locus of the normalized phase velocity vector



$= \omega/(k_x c)$

The landscape of basic plasma waves



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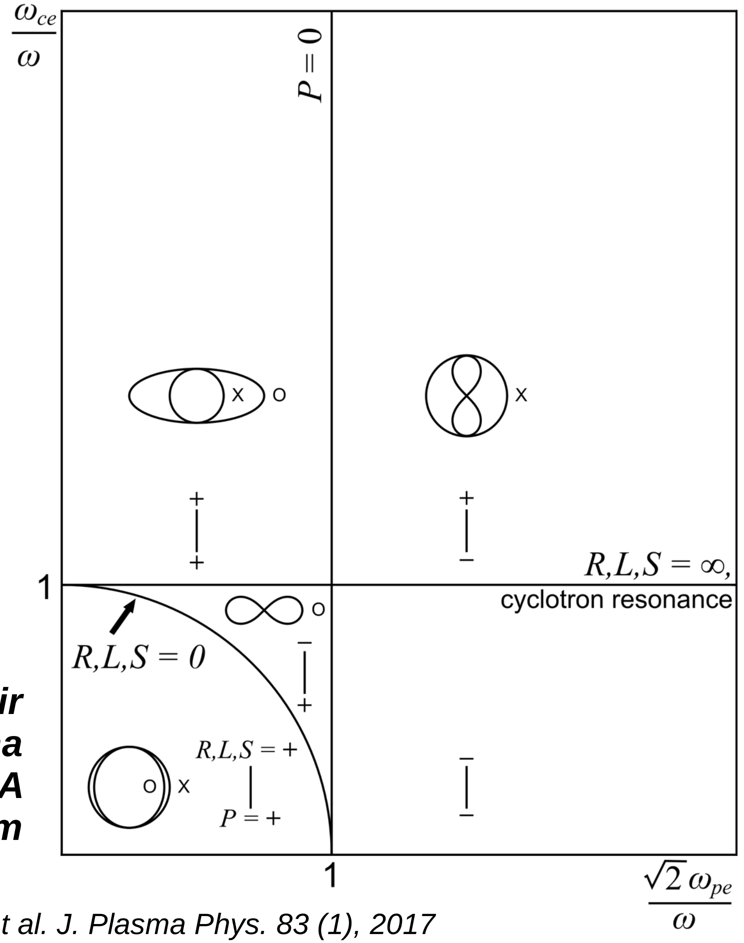


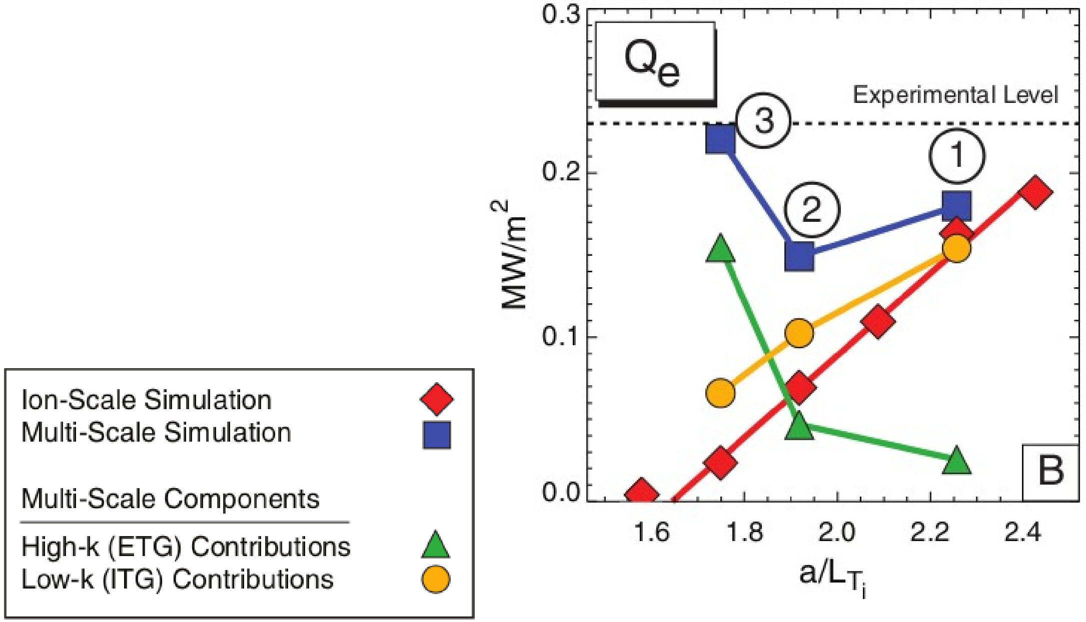
pair plasma CMA diagram

Stenson et al. J. Plasma Phys. 83 (1), 2017

Varying the mass ratio provides novel insights

- an established tool in simulations
- helps tease out what effects are or aren't important, such as the role of:
    - e- scales in turbulent transport

Tokamak turbulent transport: *requires multi-scale simulations at full mass ratio to reproduce experimental transport levels, due to strong interactions between ion-scale and electron-scale turbulence.*

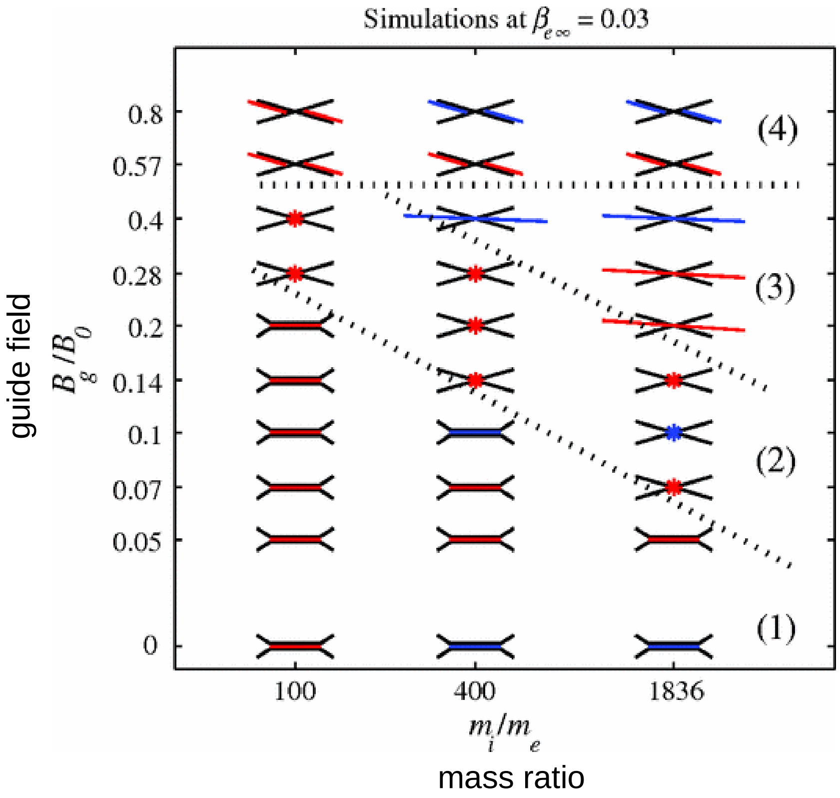


N. Howard, et al. ***Nuclear Fusion*** *(2016)*

Varying the mass ratio provides novel insights

- an established tool in simulations
- helps tease out what effects are or aren't important, such as the role of:
    - e- scales in turbulent transport
    - Whistler waves in reconnection

Magnetic reconnection: *Mass ratio has little effect on the total reconnection rate but does change other things, like the electron current structure (below).*



A. Le, et al. ***Phys. Rev. Lett.*** *(2013)*

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In physics, it's important to understand the limits.
("H atom of plasma physics")

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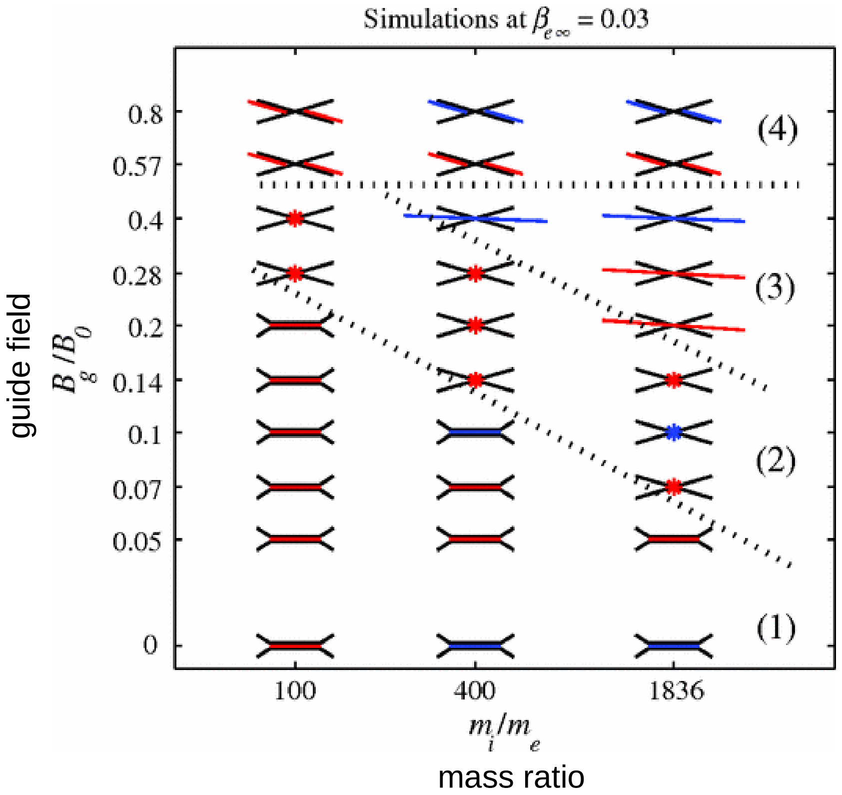


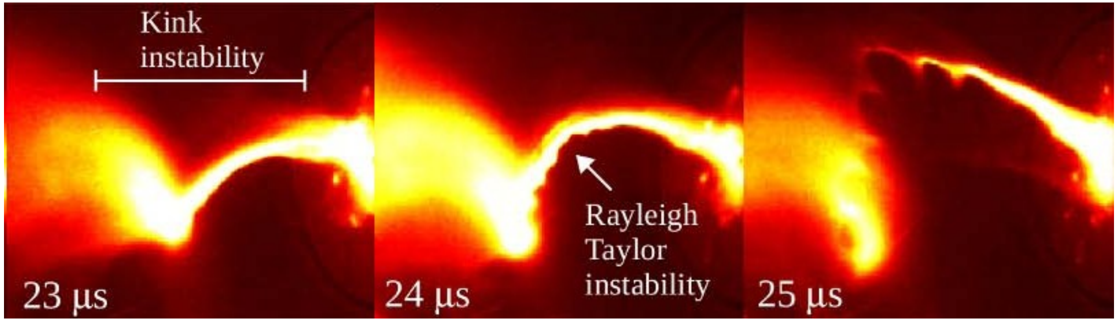
A. Le, et al. **Phys. Rev. Lett.** (2013)

Why “do the experiment”?

- Sometimes terms expected to be important turn out not to be (and vice versa).
- Sometimes the experiment works better (or worse) than anticipated.
- Sometimes, a system may start in one regime and evolve to cross a boundary into another.

> “ **Experiment can simulate computation:** Resolves all scales, includes all correlations, includes all MHD and kinetic effects, ‘CPU time’ < 1 second ”
>
> *~Stewart Prager*

e.g., a transition from ideal MHD to magnetic reconnection

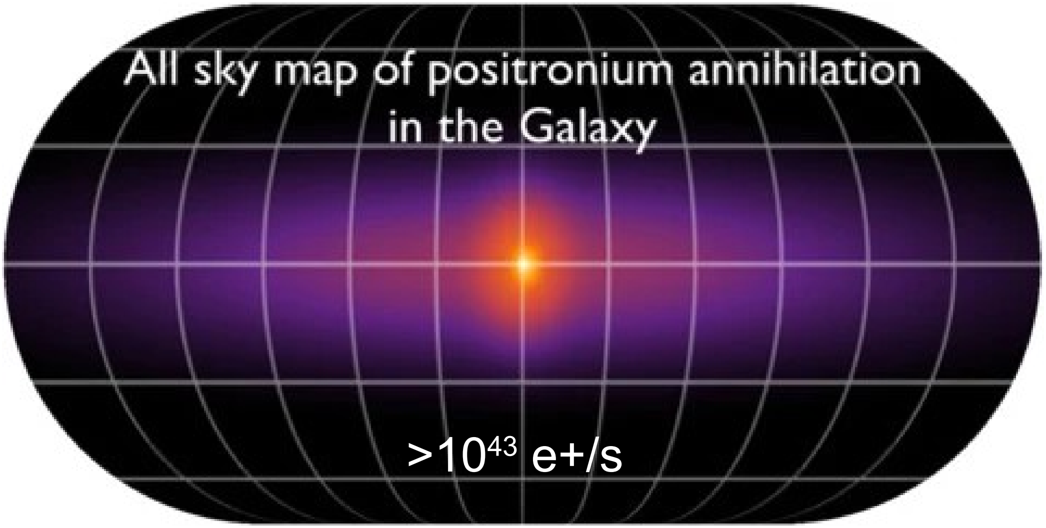


A. L. Moser & P. M. Bellan. Nature 482, 379–381 (2012)

Why pursue pair plasma experiments?

Laboratory tests of predictions for pair plasma behavior represent exciting new territory with the potential to test and advance:

- **Our understanding of fundamental aspects of plasmas.**
- **Our understanding of our universe.**
    - Lepton Epoch = 1-10 s post-Big-Bang
    - more recent phenomena involving e+e- plasmas: gamma ray bursts, pulsar winds, jets from active galactic nuclei
    - $>10^{43}$ e+/s annihilate in our galaxy (Ps formation with ISM)



matter:antimatter = 10^9:1

Ellis & Bland-Hawthorne, "Astrophysical signatures of leptonium". Eur. Phys. J. D(2018) 72: 18.

Siegert et al. "Gamma-ray spectroscopy of positron annihilation in the Milky Way". A&A 586, A84 (2016)

https://home.cern/science/physics/matter-antimatter-asymmetry-problem

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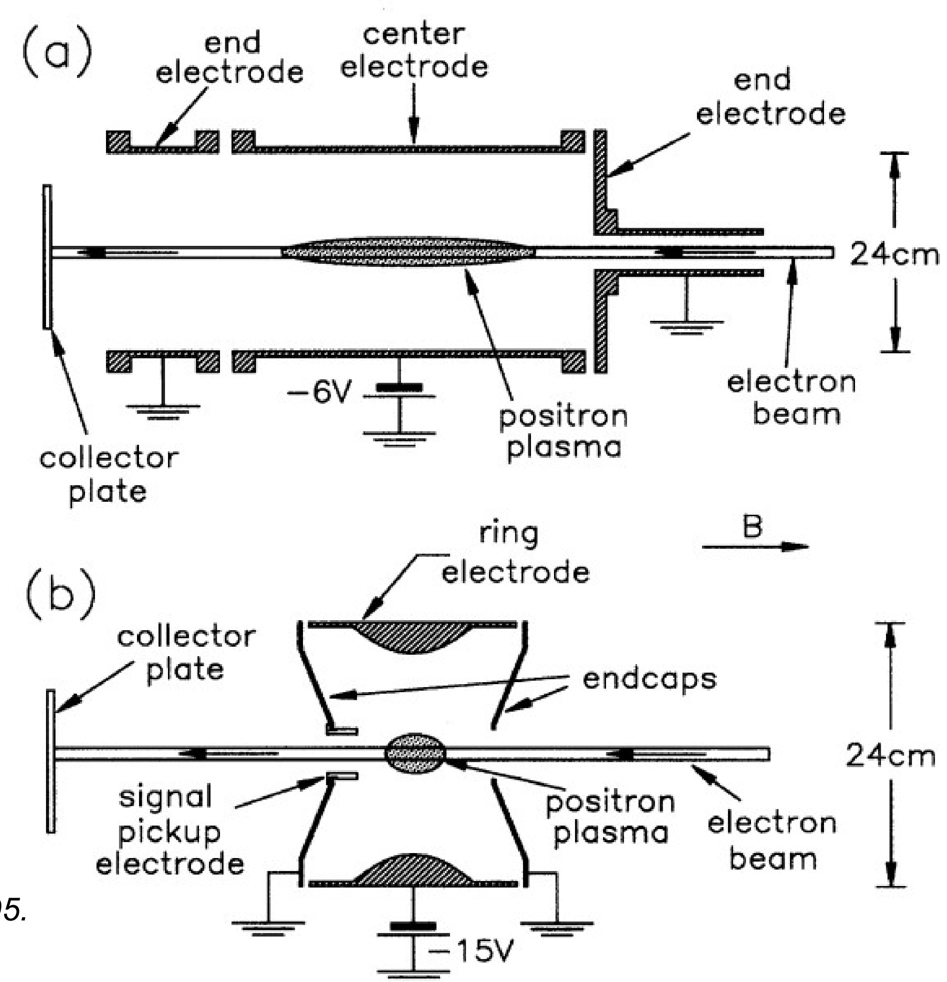
How to make a pair plasma

Pure positron plasma + electron beam:

- charge-neutral system
- two-stream instability observed
- electron Debye length > beam diameter



Greaves, R. G. & Surko, C. M. ***Phys. Rev. Lett.****, 75:3846, 1995.*

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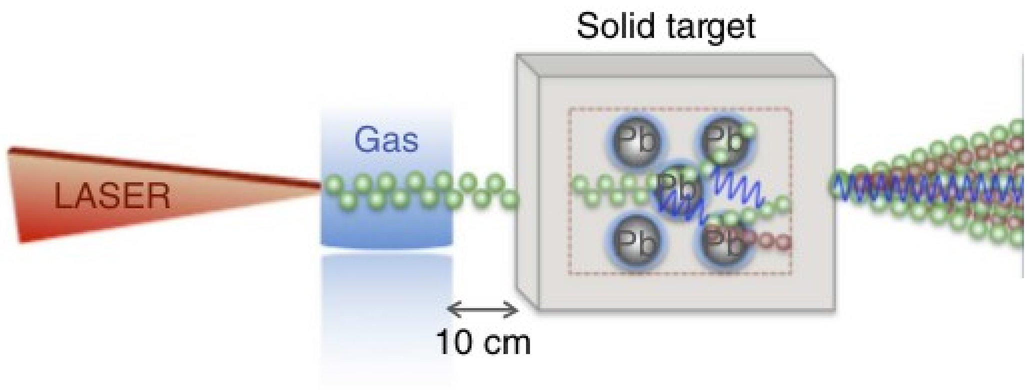
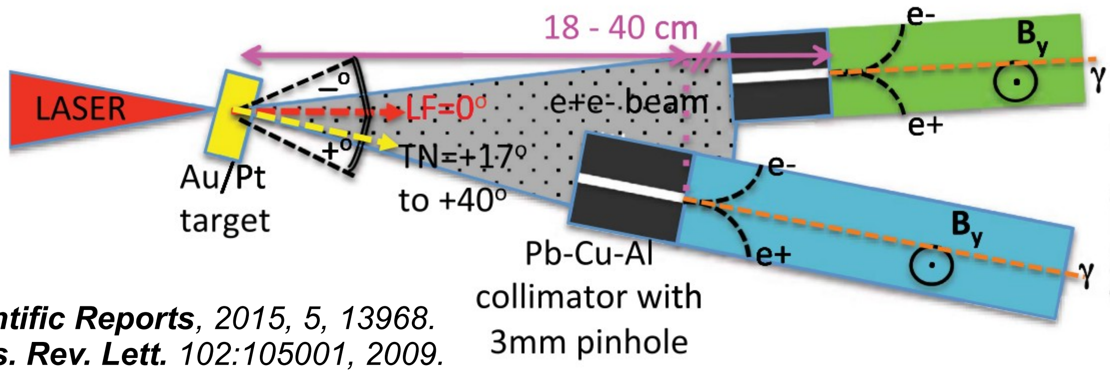
Laser-driven, relativistic e+e- beams:
- skin depth ~ beam size < Debye length
- charge neutrality approached asymptotically (but getting very close)
- simulations of collective behavior



Sarri, G. et al. ***Nat. Comm*** *6:6747, 2015.*



Liang, E. et al. ***Scientific Reports****, 2015, 5, 13968.*
Chen, H., et al. ***Phys. Rev. Lett.*** *102:105001, 2009.*

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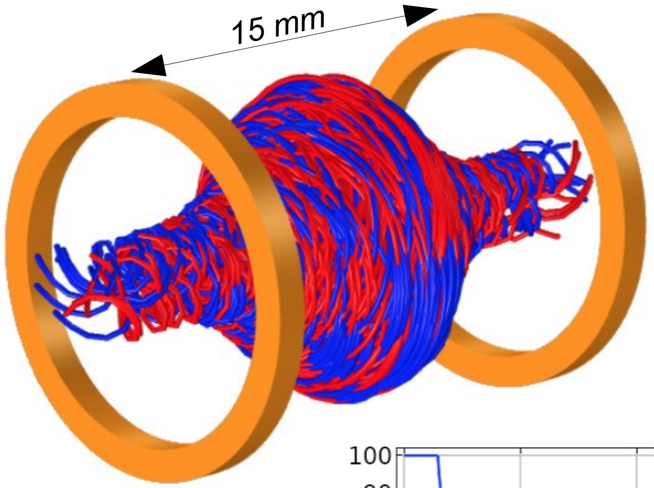

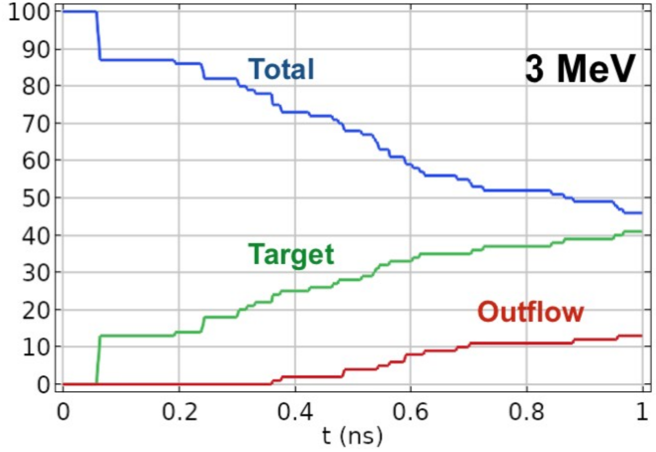

work by J. von der Linden, H. Chen, et al, as described in M. R. Stoneking, et al. (JPP 2020)

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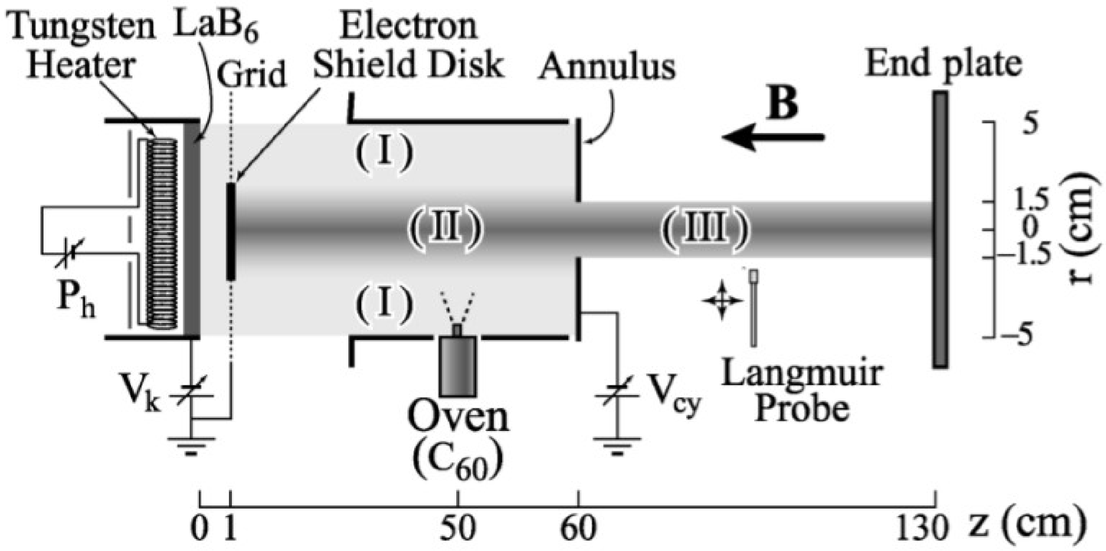
Fullerene pair plasmas
- Many Debye lengths achieved.
- Electrostatic modes investigated.
- electron contamination → 3 components
- gyroradius ≈ plasma radius



Oohara, W. & Hatakeyama, R. ***Phys. Rev. Lett.****, 91:205005, 2003.*
Oohara, W.; Date, D. & Hatakeyama, R. ***Phys. Rev. Lett.,*** *95, 175003, 2005.*

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Our goal:

**many Debye lengths,
both species magnetically confined**

Debye length: $$\lambda_D = \sqrt{\frac{\epsilon_0 \kappa T_e}{2 n_e e^2}}$$ (pair plasma, Maxwellian)

Larmor radius: $$r_L = \frac{\sqrt{m \kappa T}}{eB}$$

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➡ **Low-temperature e-e+ plasmas in toroidal traps**

(Another option: magnetic mirror trap)

Higaki, H., et al. ***New Journal of Physics****, 2017, 19, 023016*

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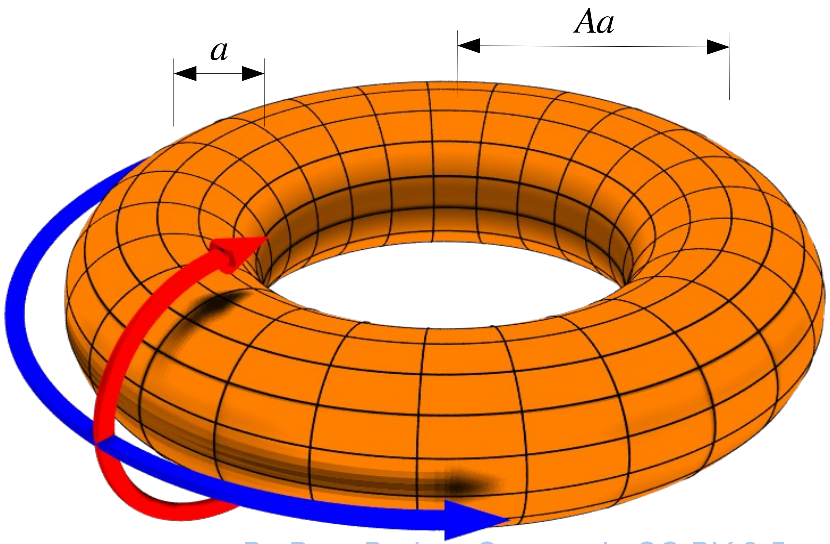
Getting to plasma densities with finite positrons

number of Debye lengths in a toroidal device:

$$\frac{a}{\lambda_D} = a\sqrt{\frac{ne^2}{\epsilon_0 T}} = \sqrt{\frac{Ne^2}{\epsilon_0 T 2\pi^2}} \times \frac{1}{\sqrt{aA}}$$

a	minor radius
A	aspect ratio
N	# of positrons
T	temperature



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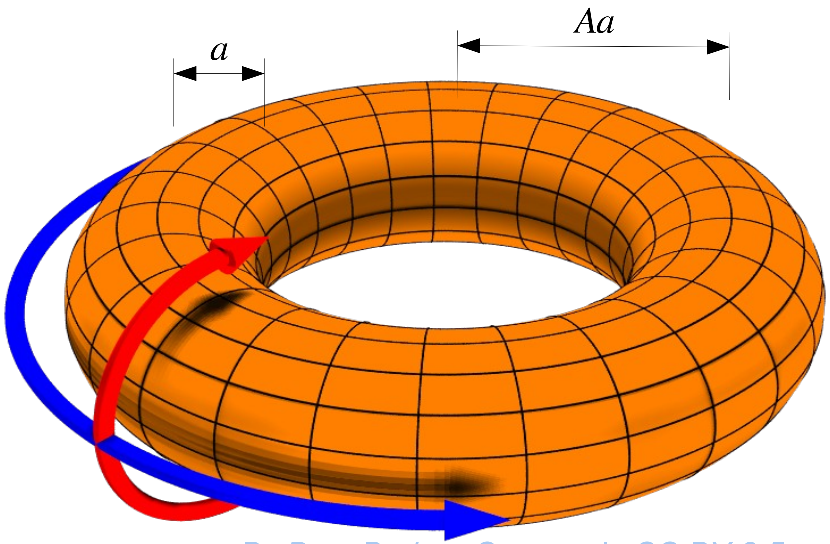

By DaveBurke - Own work, CC BY 2.5

Some scaling notes:

smaller linear dimension vs. smaller aspect ratio?
→ *equally helpful at increasing a/λ_D (all else equal)*

linear dimension ~ $V^{1/3}$ →
V within a factor of ~10
\+ *A within a factor of 3 (because e+ are hard to come by)*
= *length scale determined within a factor of 2-3*

T Sunn Pedersen et al, NJP 2012

Target properties/parameters

- **"tabletop-sized"**
  (balance between positron & funding availability and challenges of building & diagnosing a miniature experiment)

volume:	10 – 50 L
major radius:	15 – 30 cm
minor radius:	5 – 10 cm
aspect ratio:	2 – 5

Target properties/parameters

- **"tabletop-sized"**
  (balance between positron & funding availability and challenges of building & diagnosing a miniature experiment)
- **steady-state high magnetic field**
  (to get cyclotron cooling → superconducting coils)

volume:	10 – 50 L
major radius:	15 – 30 cm
minor radius:	5 – 10 cm
aspect ratio:	2 – 5
B-field:	1 – 2 T
temperature:	0.1 – 5 eV

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- **"tabletop-sized"**
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- **very low plasma densities**
  (because antimatter is hard to come by)

volume:	10 – 50 L
major radius:	15 – 30 cm
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B-field:	1 – 2 T
temperature:	0.1 – 5 eV
density:	10^{11} – 10^{13} m^{-3}

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- **low plasma temperatures**, in order to
  - have collective effects ($\lambda_D < r_{minor}/10$)
  - avoid creating ions from residual neutrals
  - avoid a dominant e+ loss channel
    (Ps formation on residual neutrals)

volume:	10 – 50 L
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B-field:	1 – 2 T
temperature:	0.1 – 5 eV
density:	10^{11} – 10^{13} m^{-3}
gyroradius:	O(µm)
Debye length:	O(mm – cm)
plasma skin depth:	O(m)
plasma β:	~10^{-11} %

What will limit pair plasma lifetimes?

- **not** annihilation, if we successfully keep temperatures low (at most a few eV)
- In Proto-APEX (low B, moderate vacuum), $\tau > 1$ s was limited by elastic scattering off residual neutrals.
- (quasi-)symmetry of the trap?

How long an e-e+ pair plasma would live, if limited via each of the following mechanisms:

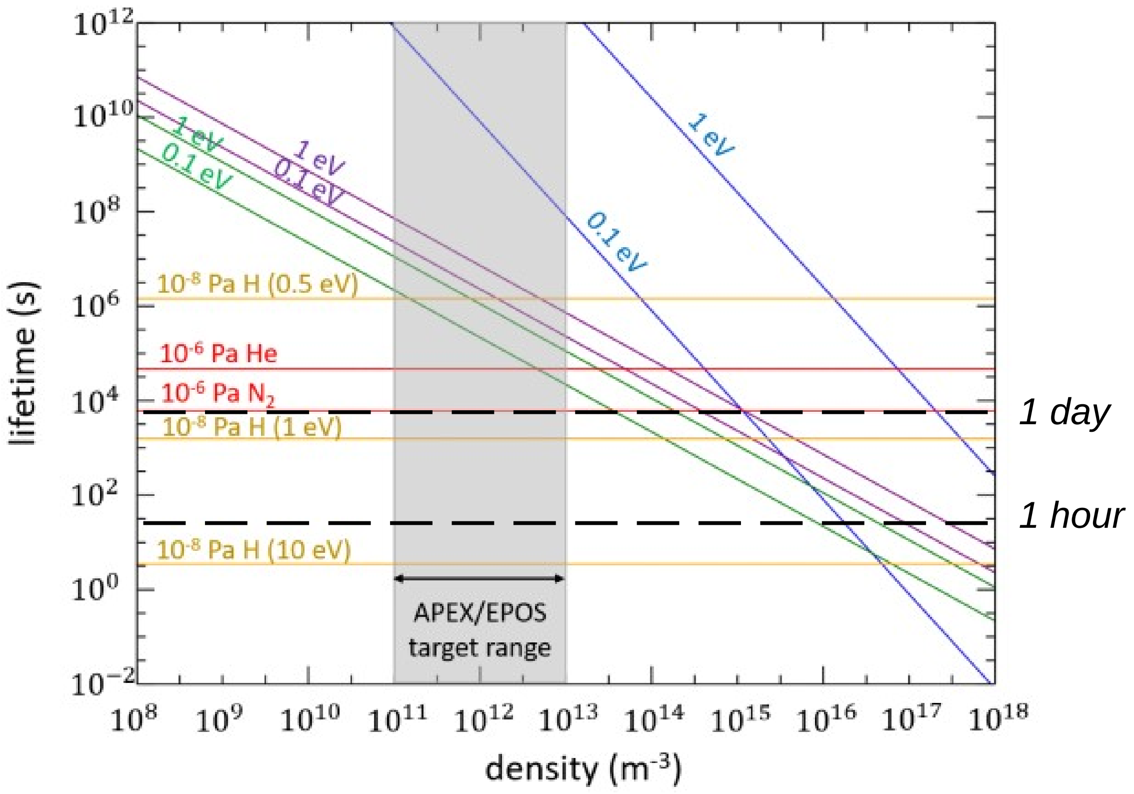
purple: direct annihilation with plasma electrons

green: Ps formation via radiative recombination

blue: Ps formation via three-body recombination

red: direct annihilation on atomic/molecular electrons

yellow: Ps formation via charge exchange on atomic hydrogen at various plasma temperatures



Stoneking et al. JPP 86, Issue 6, 155860601 (2020).

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gyroradius:	O(μm)
Debye length:	O(mm – cm)
plasma skin depth:	O(m)
plasma β:	~10^{-11} %

r_L << λ_D << device size << plasma skin depth

(strongly magnetized, weakly coupled regime)

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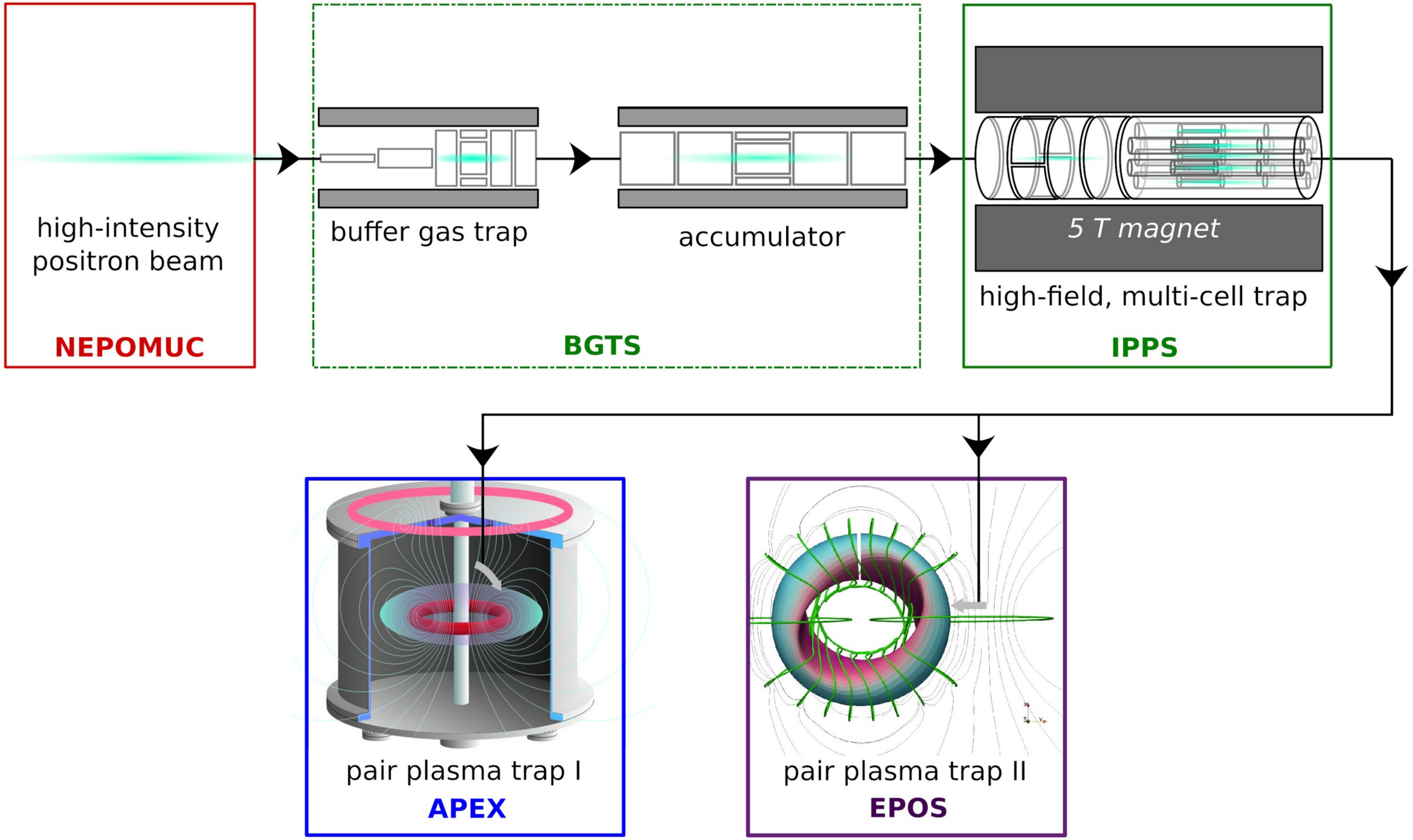
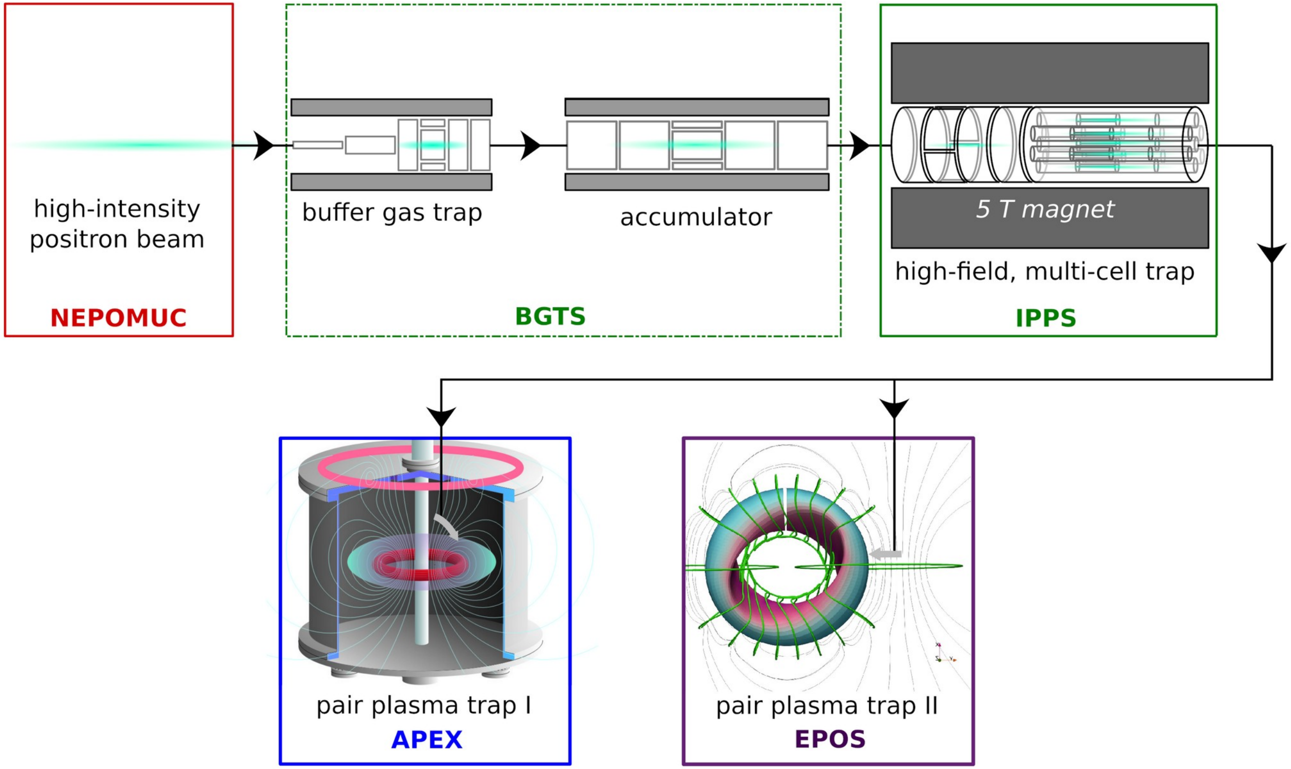
The APEX grand scheme

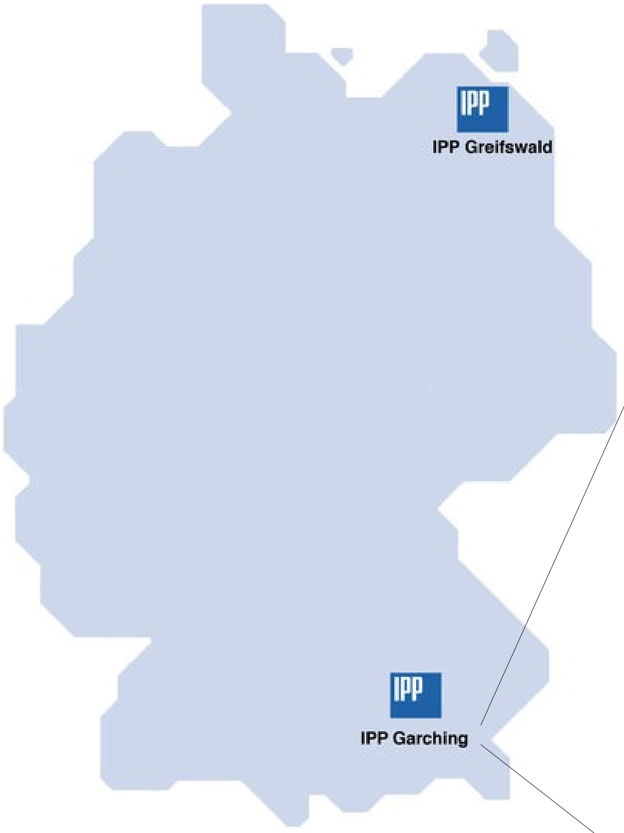


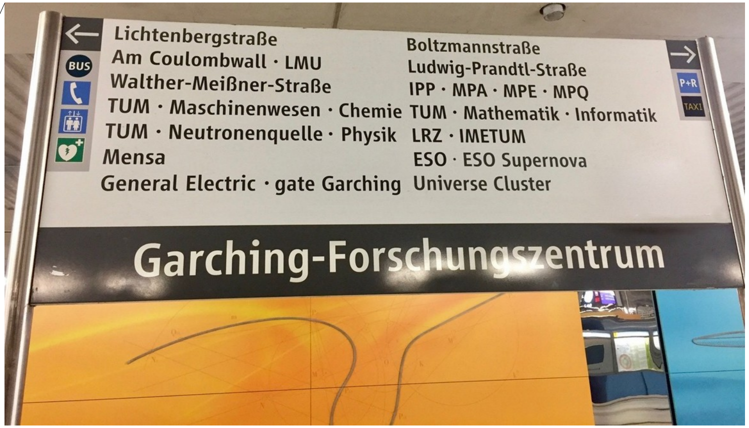
The APEX grand scheme

Step 1:
Obtain positrons from world-class source (up to 10^9/s)



Garching: one of IPP's two locations, and . . .





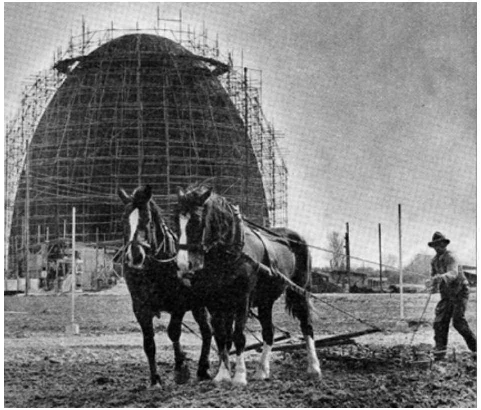
Garching: home of a world-class e+ source

APEX lab space @ IPP

APEX offices @ IPP

FRM-II:
Forschungs-
Neutronenquelle
Heinz Maier-Leibnitz

(started operation in
2004)



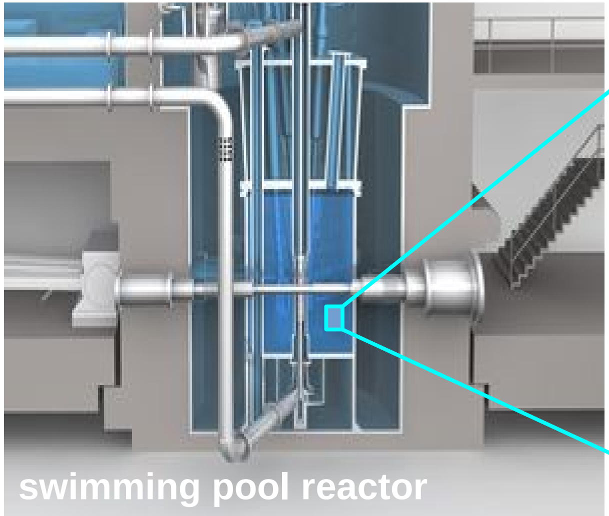
Forschungsreactor München (FRM) in 1957

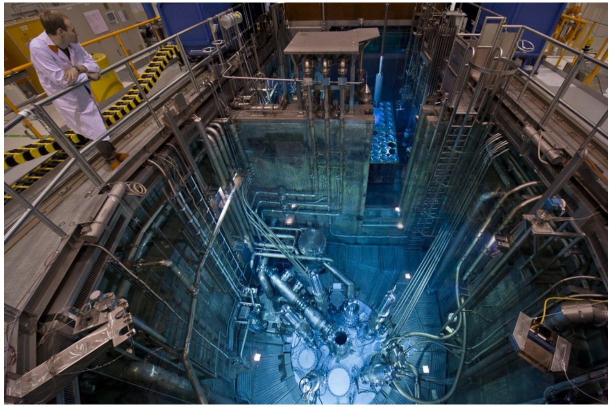
(operated 1957-2000)

coat of arms for the city of Garching

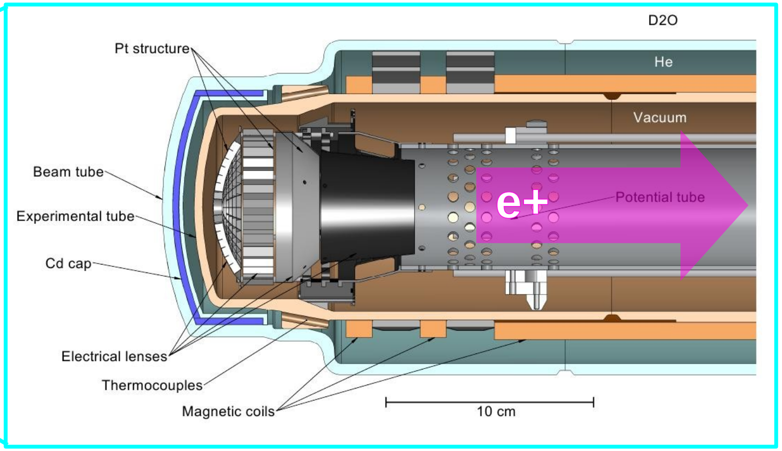
https://mlz-garching.de/aktuelles-und-presse/from-behind-the-sciences/als-vor-dem-atom-ei-noch-geackert-wurde.html

NEutron-induced POsitron source MUniCh





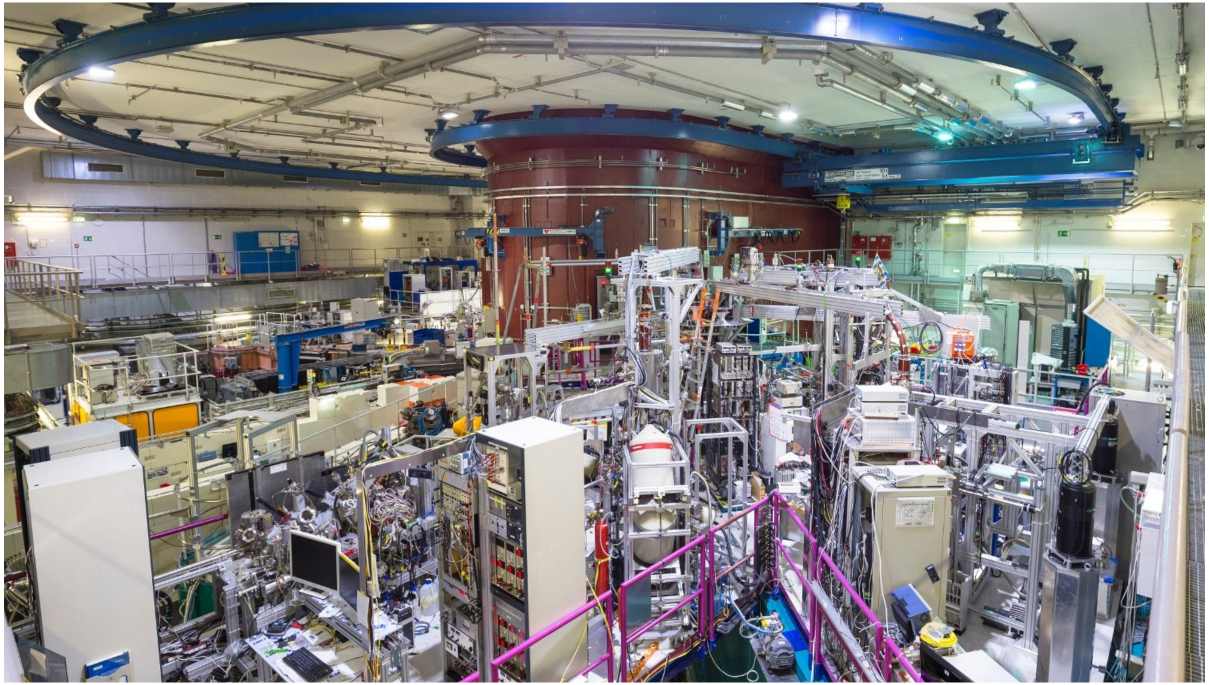
NEutron-induced POsitron source MUniCh (NEPOMUC) at the FRM-II neutron source

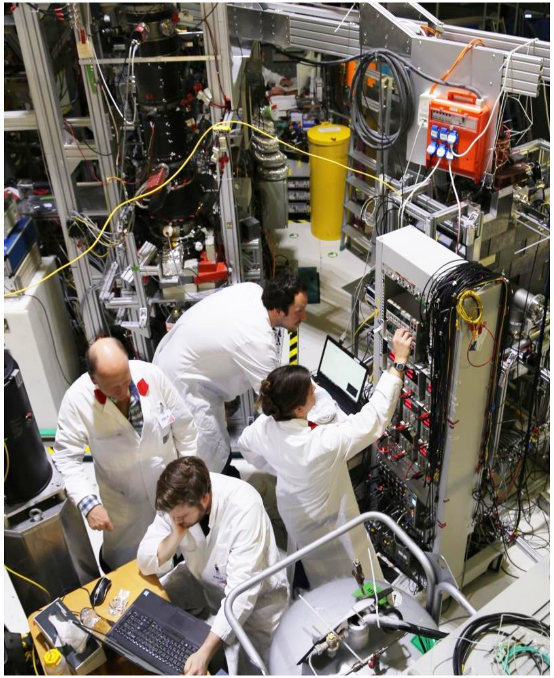


→ **primary beam** (10^9 e+/s @ 1 keV)

→ **remoderated beam** ($5x10^7$ e+/s @ 20 eV)

NEutron-induced POsitron source MUniCh





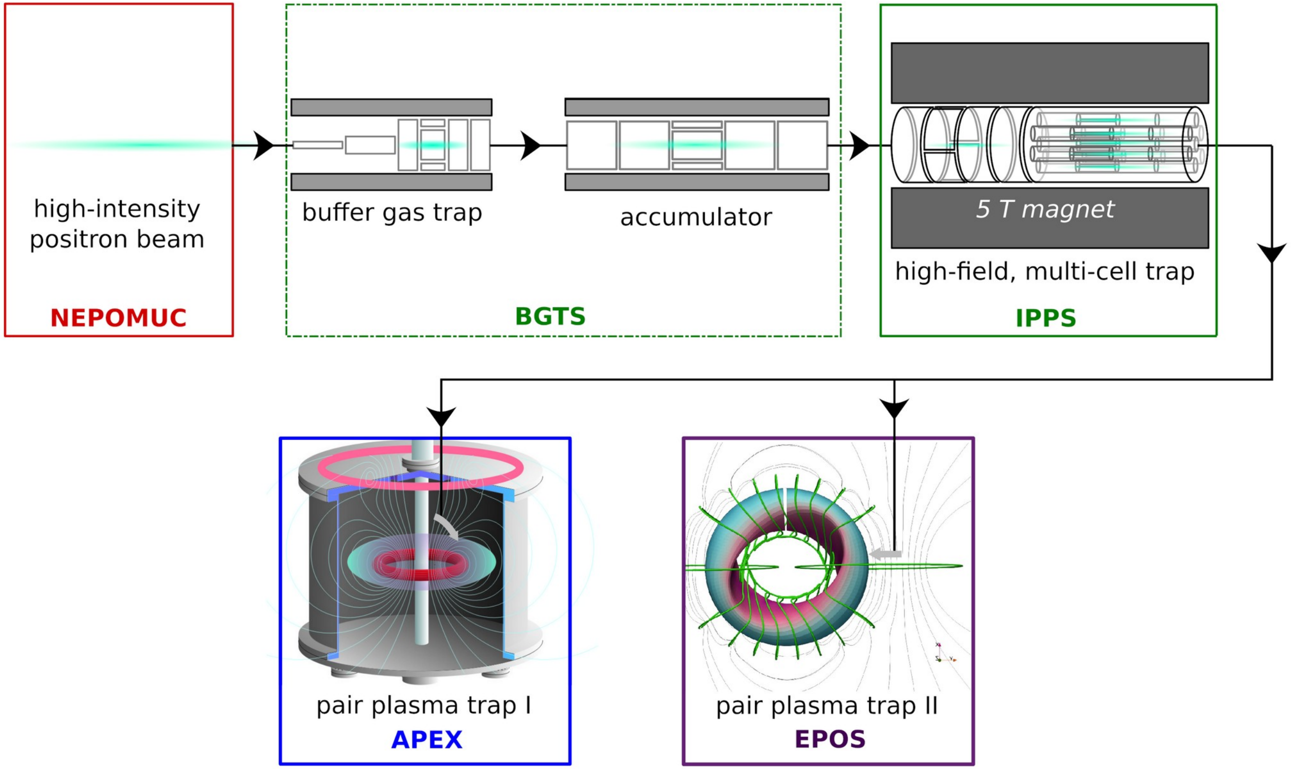
- five-way switch → different experiment stations
- myriad applications in materials & surface science, AMO & antimatter physics, among other areas

2-5 weeks/year of APEX e+ time at the open beam port

2014-2016: beam characterization/development
2015-2020: dipole injection & confinement

The APEX grand scheme

Step 1:
Obtain positrons from world-class source (up to 10^9/s)



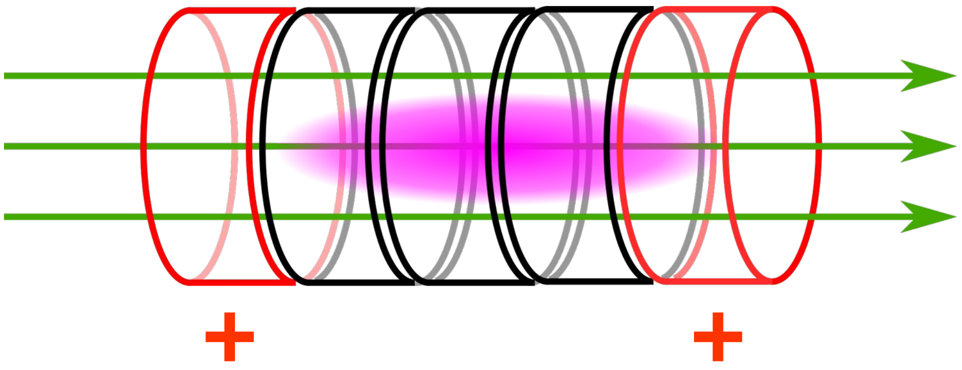
Step 2:
Use a series of non-neutral plasma traps to collect positrons, until we have enough to make a plasma.

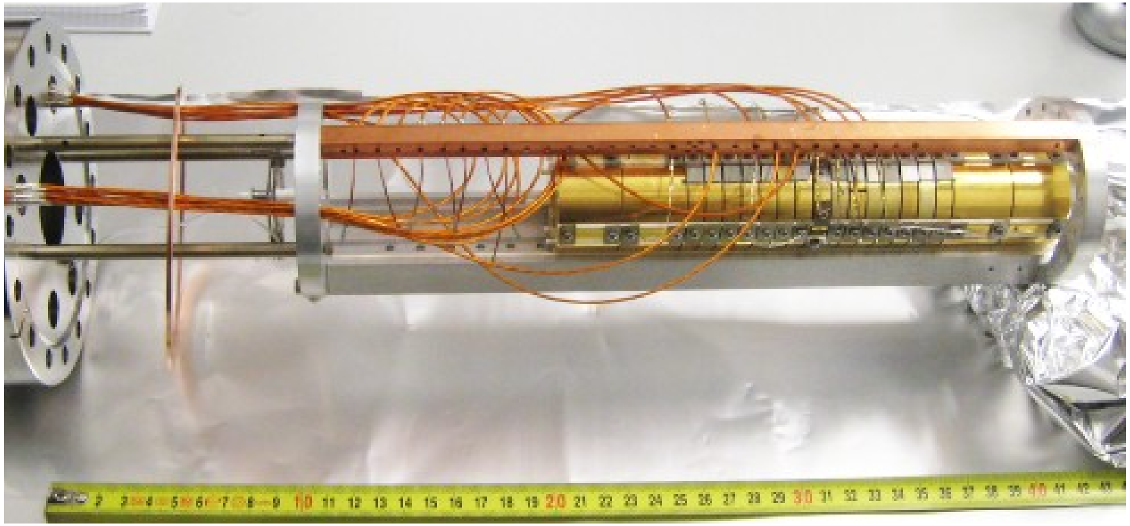
Highly effective traps for a single sign of charge

uniform B
+
axial potential well
+
UHV

=

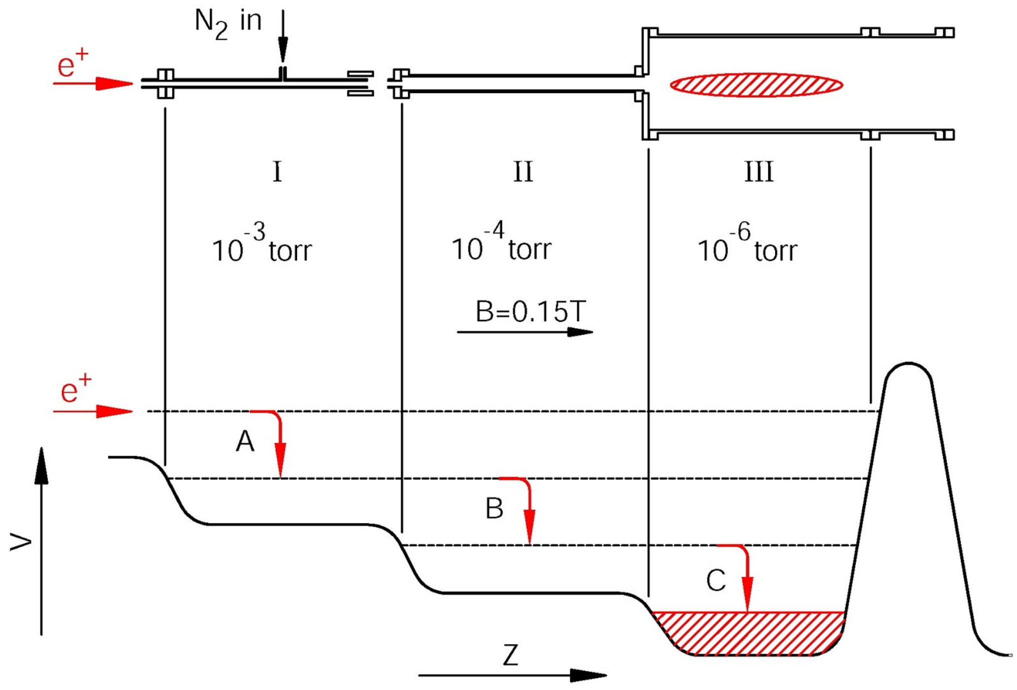
non-neutral
plasma trap





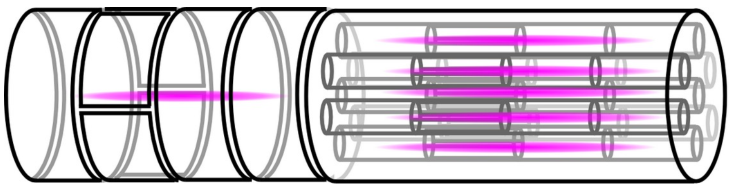
Variations on the basic non-neutral plasma trap

buffer-gas trap:



(uses stepped potentials and pressures to capture e+ from a low-density steady-steam beam)

multi-cell trap:



(array of traps to increase the total number of e+ you can stuff into the available volume)

Surko PRL '88; Murphy, PRL '92;
Surko Varenna I (2010); Danielson RMP '15

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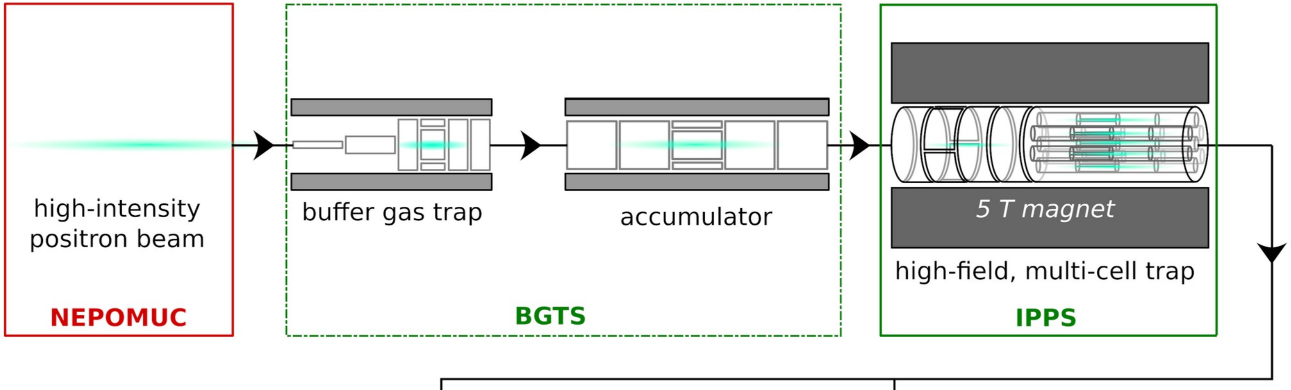
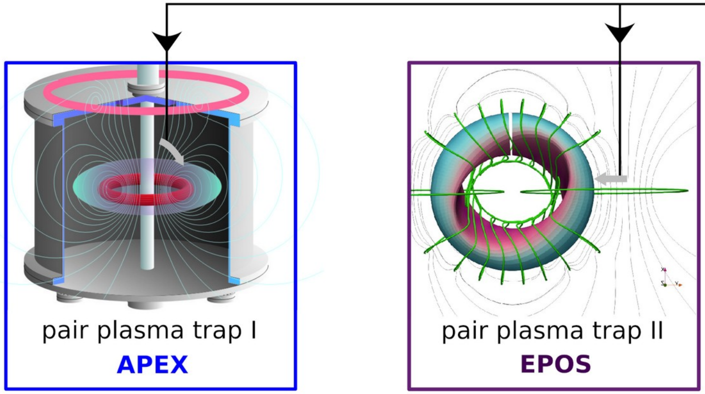


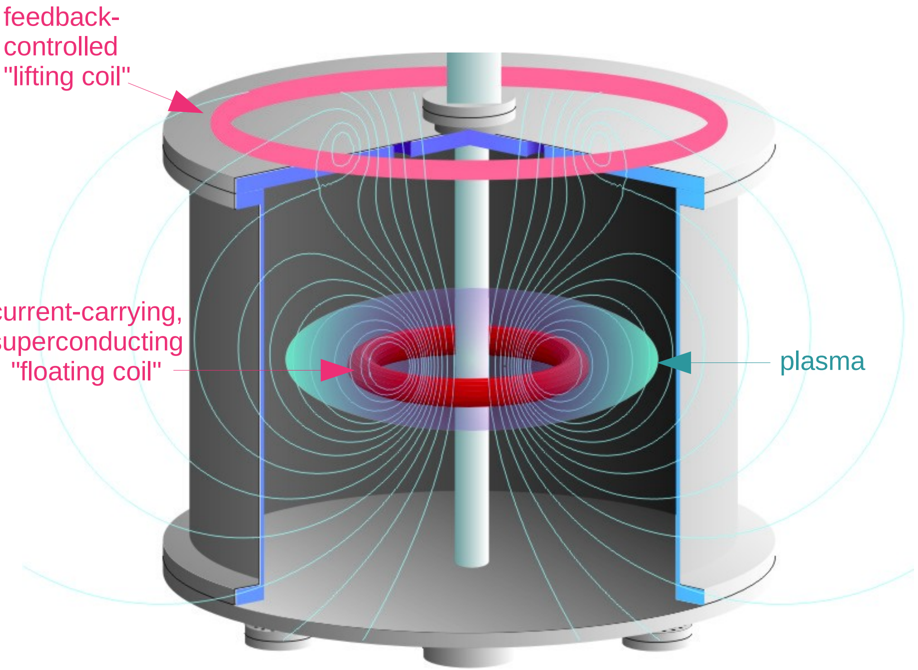
Step 2:
Use a series of non-neutral plasma traps to collect positrons, until we have enough to make a plasma.

Step 3 (version A):
Combine positrons with electrons in a levitated dipole trap.

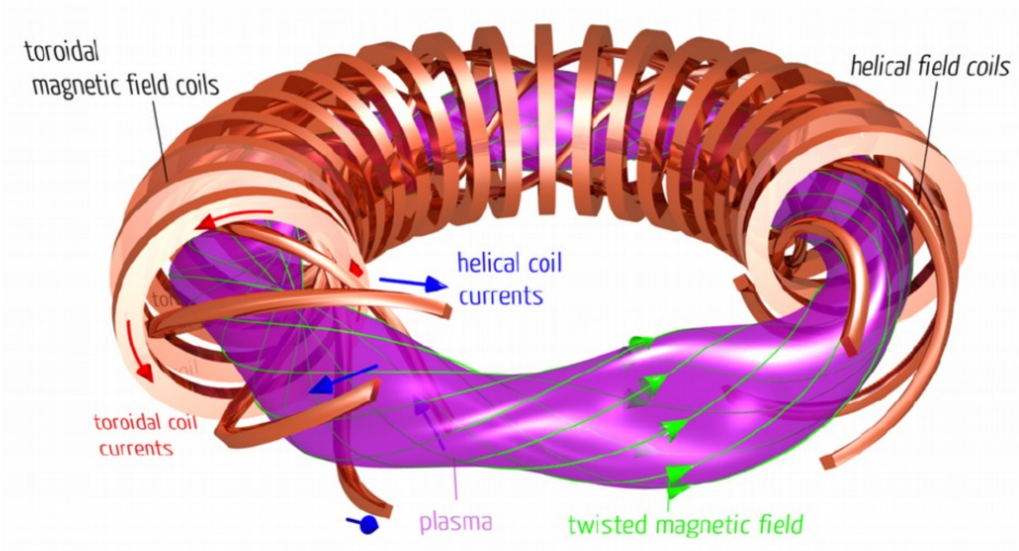


Step 3 (version B):
Combine positrons with electrons in an optimized stellarator.

Companion devices for confining pair plasmas



levitated dipole trap



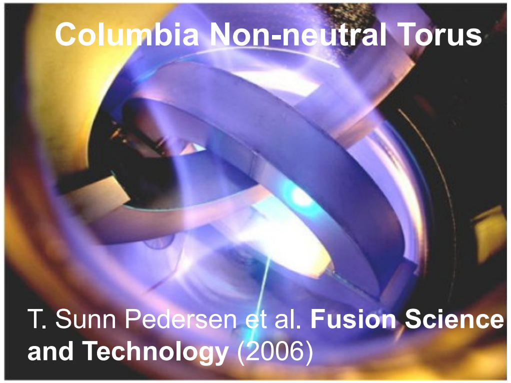
stellarator

image from Lukas-Georg Böttger's Ph.D. thesis

Companion devices for confining pair plasmas

Both the levitated dipole and the stellarator:

- are steady state, purely magnetic, requiring no internal currents
- can confine either non-neutral or quasi-neutral plasmas



Companion devices for confining pair plasmas

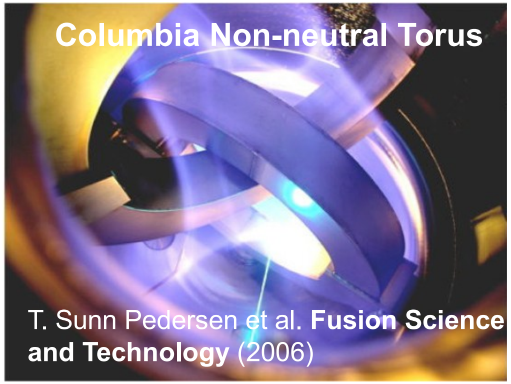
Both the levitated dipole and the stellarator:

- are steady state, purely magnetic, requiring no internal currents
- can confine either non-neutral or quasi-neutral plasmas

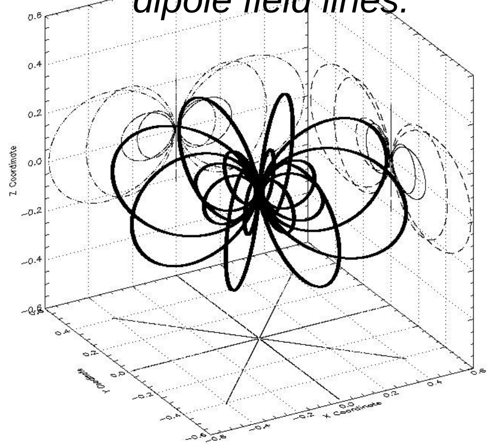
Disparate magnetic topologies
→ **vastly different (but complementary) physics.**

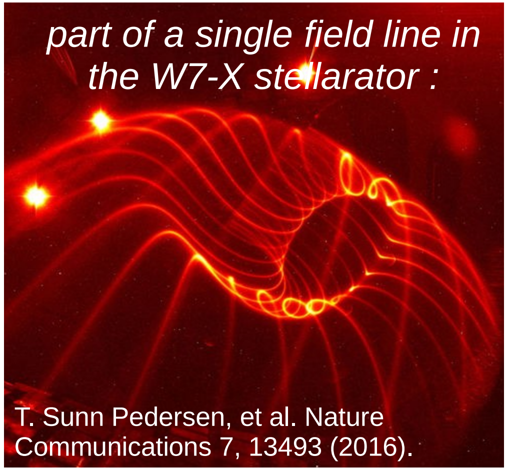
(Complementary technical aspects, strengths/weaknesses, as well.)

Developing both in parallel(ish) will multiply dramatically what we learn.



16 individual dipole field lines:





The APEX grand scheme

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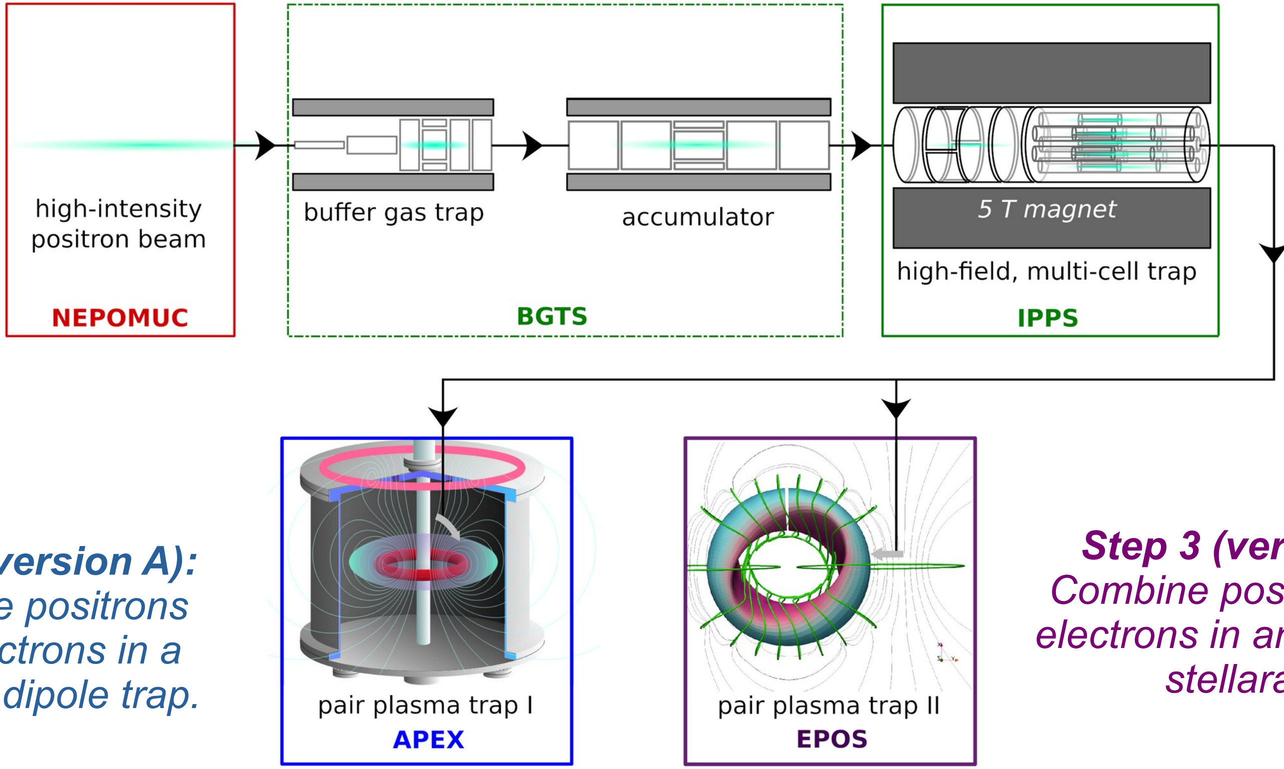

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Step 3 (version A):
Combine positrons with electrons in a levitated dipole trap.

Step 3 (version B):
Combine positrons with electrons in an optimized stellarator.

Step 4: *Study transition to the regime of collective, quasineutral behavior; stability (indeed turbulence-free?), transport (what limits confinement time?), robustness (e.g., to T asymmetry, ion contamination), . . .*

Outline

I. Introduction
- the compelling goal of laboratory pair plasmas
- approaches to making them

II. The APEX Grand Scheme
- sufficient positrons
- suitable traps
- the parts in between

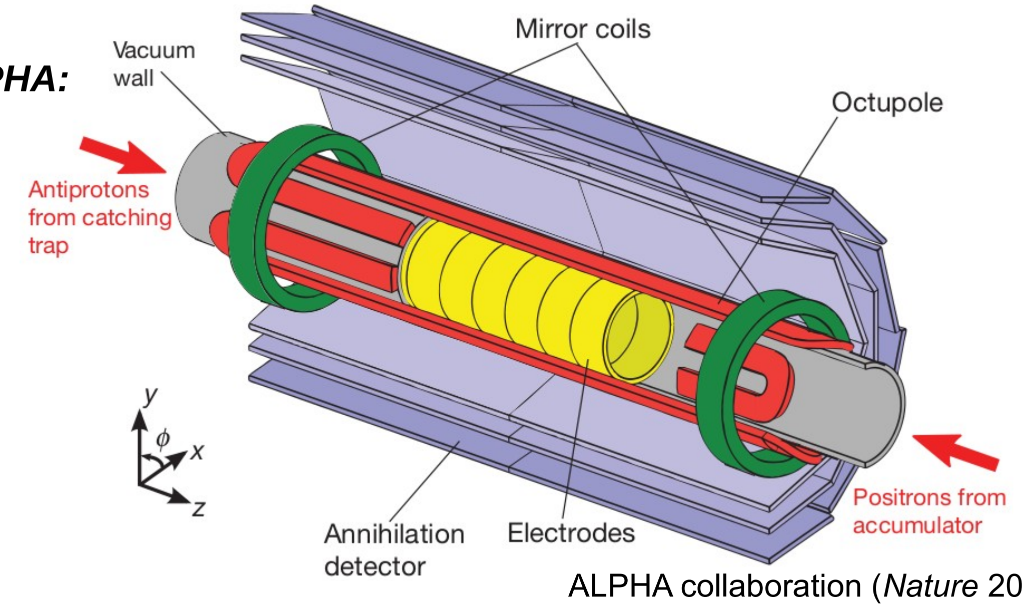
III. Recent progress
- key questions answered in prototype set-ups
- assembly and commissioning of new devices
- moving into higher fields and collective behavior

IV. Coming attractions

Key question #1: how to get 'em in there?

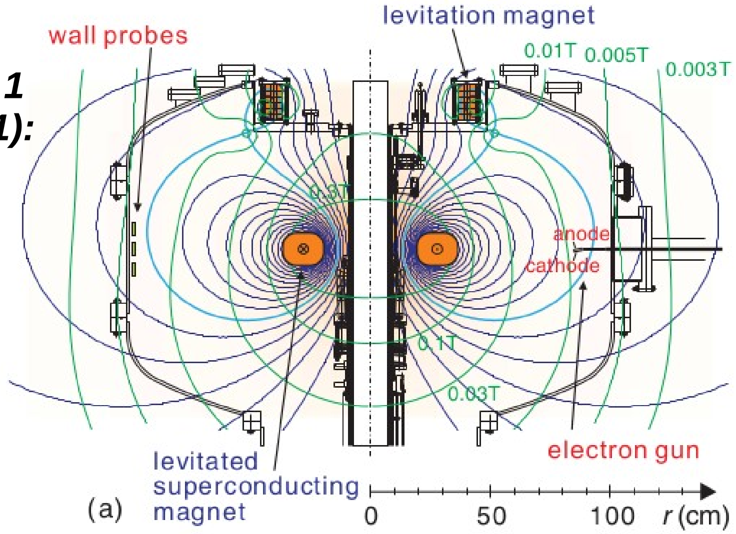
- **antimatter + toroidal device = new problem**
  - *linear devices:* B connection to center of trap
  - *ion-electron plasmas:* ionize in confinement region
  - *e- experiments:* collective effects already present; also, e- are "cheap"

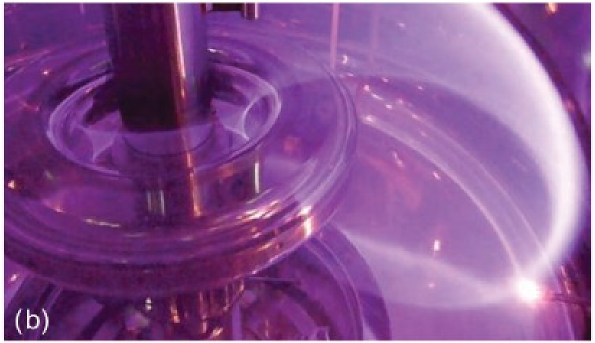
ALPHA:



ALPHA collaboration (*Nature* 2010)

Ring Trap 1 (RT-1):





Z. Yoshida, H. Saitoh, et al. (*PRL* 2010)

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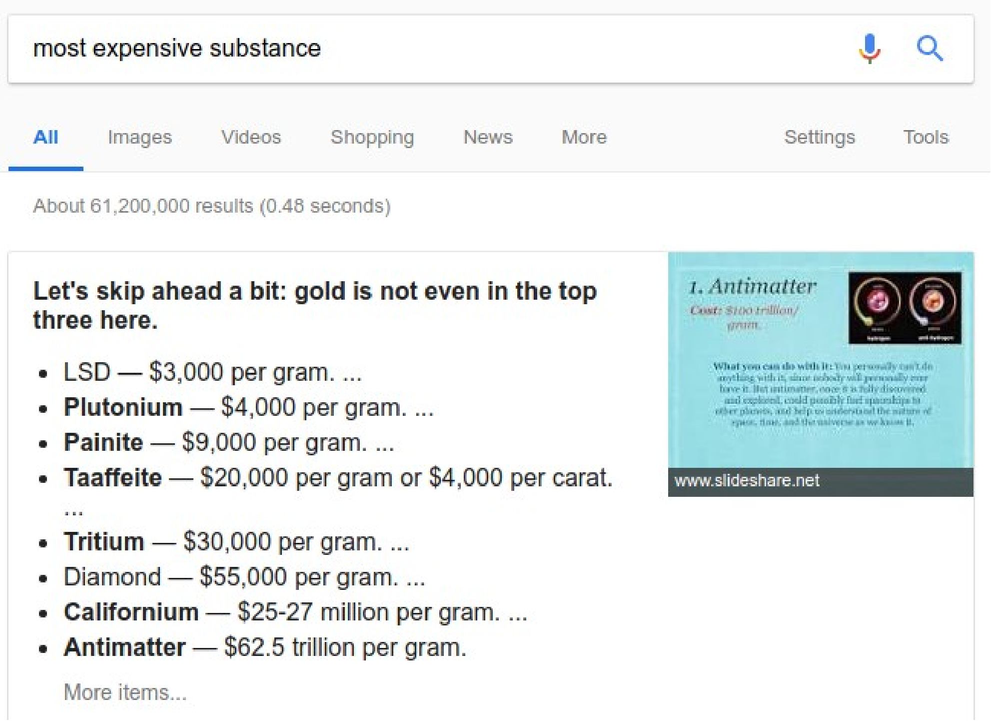
  - *e- experiments:* collective effects already present; also, e- are "cheap"

    (whereas e+ are not)

10^9 e+/s ⟷ **160 pA**

Google confirms:



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- **preliminary simulations** suggested ExB drift could be the solution . . . but also high sensitivity to initial conditions

$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

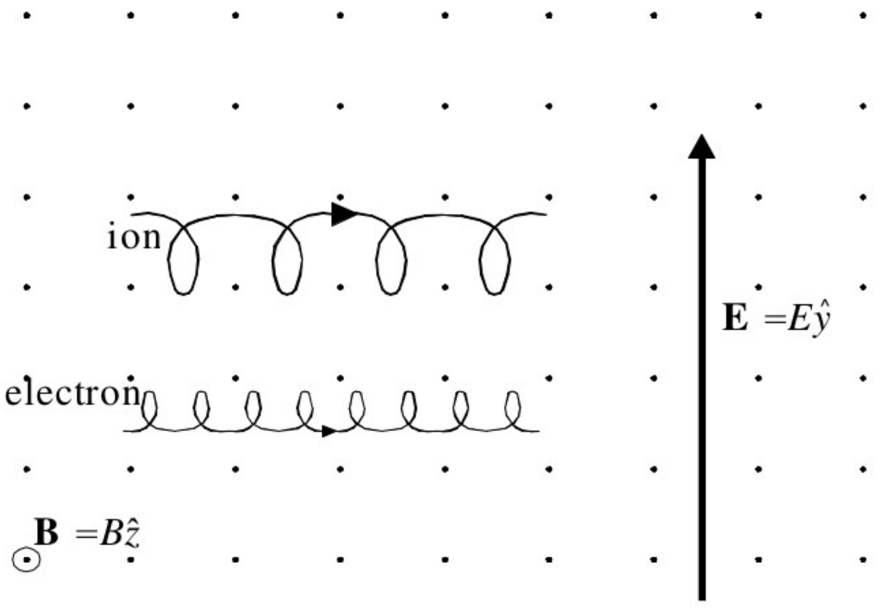

Figure 3.3: E x B drifts for particles having finite initial energy

Paul M. Bellan. *Fundamentals of Plasma Physics.* Cambridge University Press.

Key question #1: how to get ’em in there?

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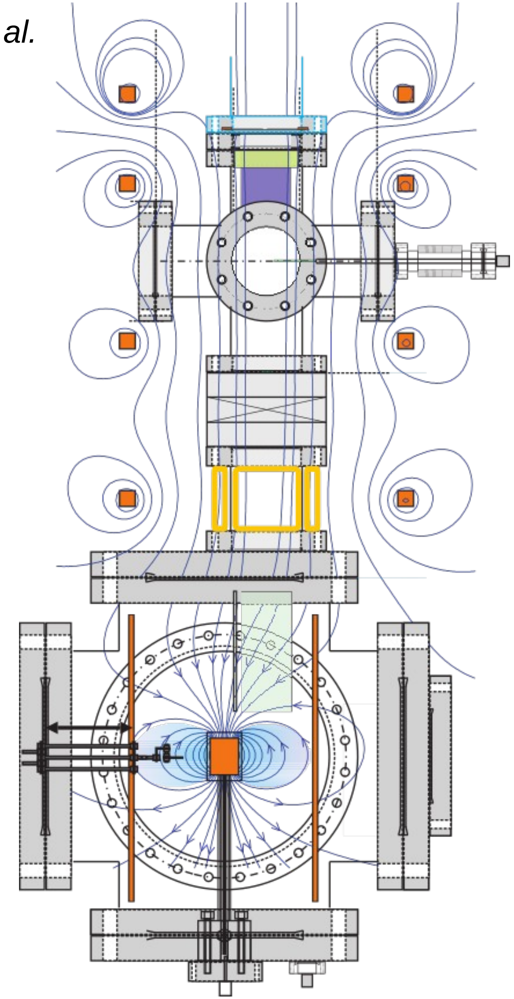
- **preliminary simulations** suggested ExB drift could be the solution . . . but also high sensitivity to initial conditions

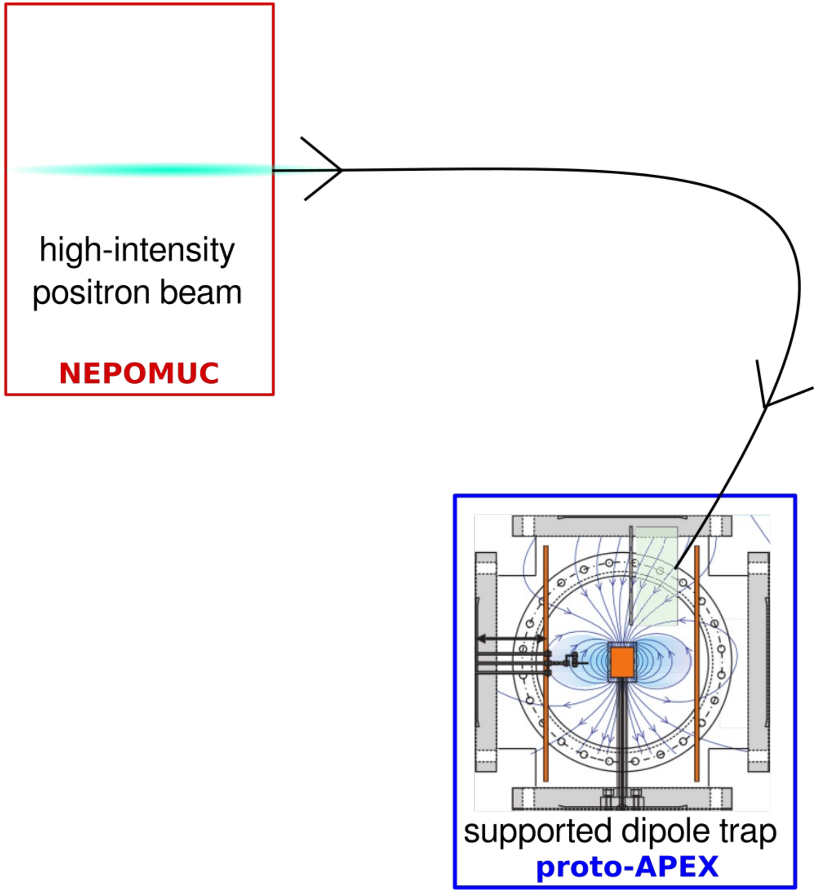
- **“real world” e+ beam** has small but finite:
  - spatial spread
  - energy spread

➡ **Experiments needed to establish the viability of drift injection.**

H. Saitoh, et al. NJP (2015).



Prototype trap to answer key questions



- ✓ Can we move positrons from the guide field of beam line, across B surfaces, into our trap?
- ✓ Without losing too many of them in the process?

H. Saitoh, J. Stanja, et al. NJP 17: 103038 (2015).
E. V. Stenson, S. Nissl, et al. PRL 121, 235005 (2018).
S. Nissl, E. V. Stenson et al. PoP 27, 052107 (2020).

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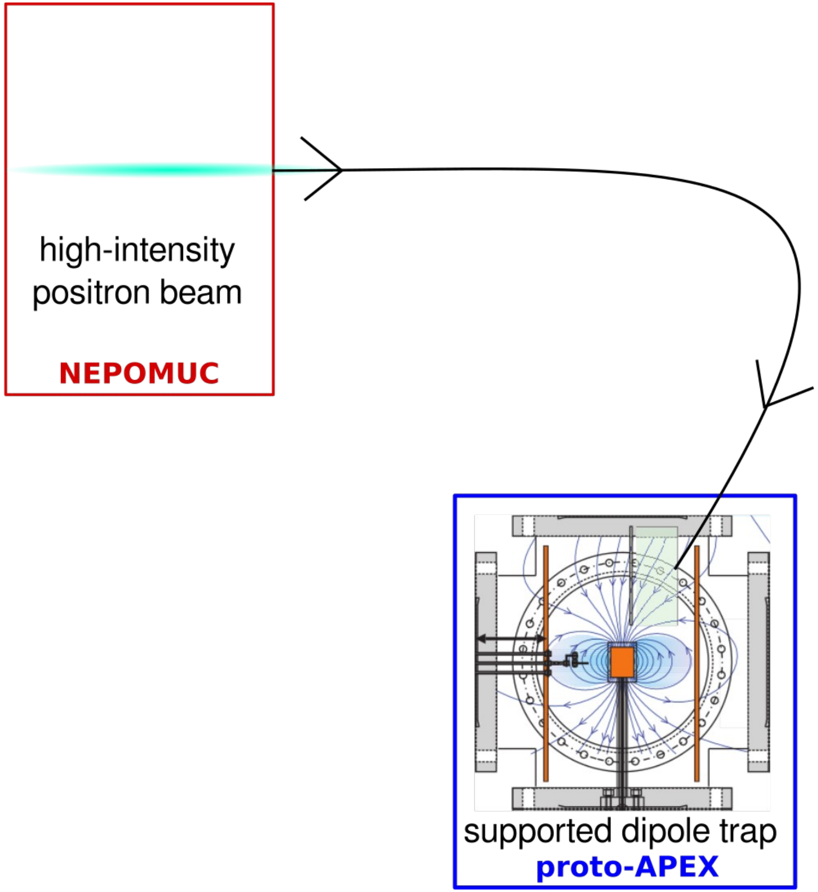

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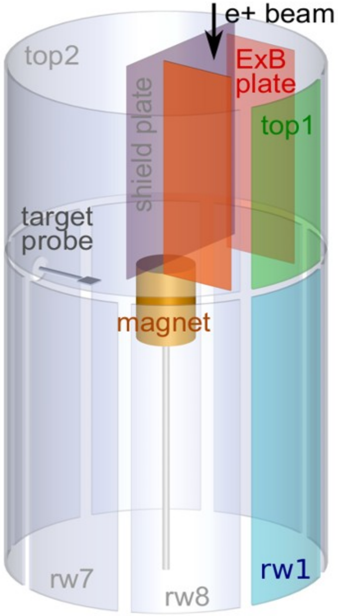

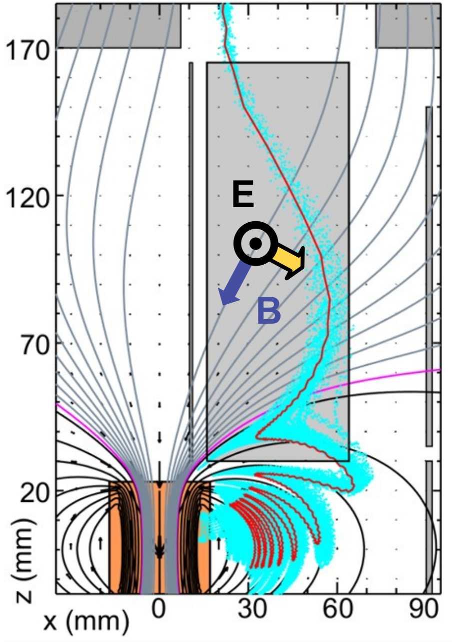

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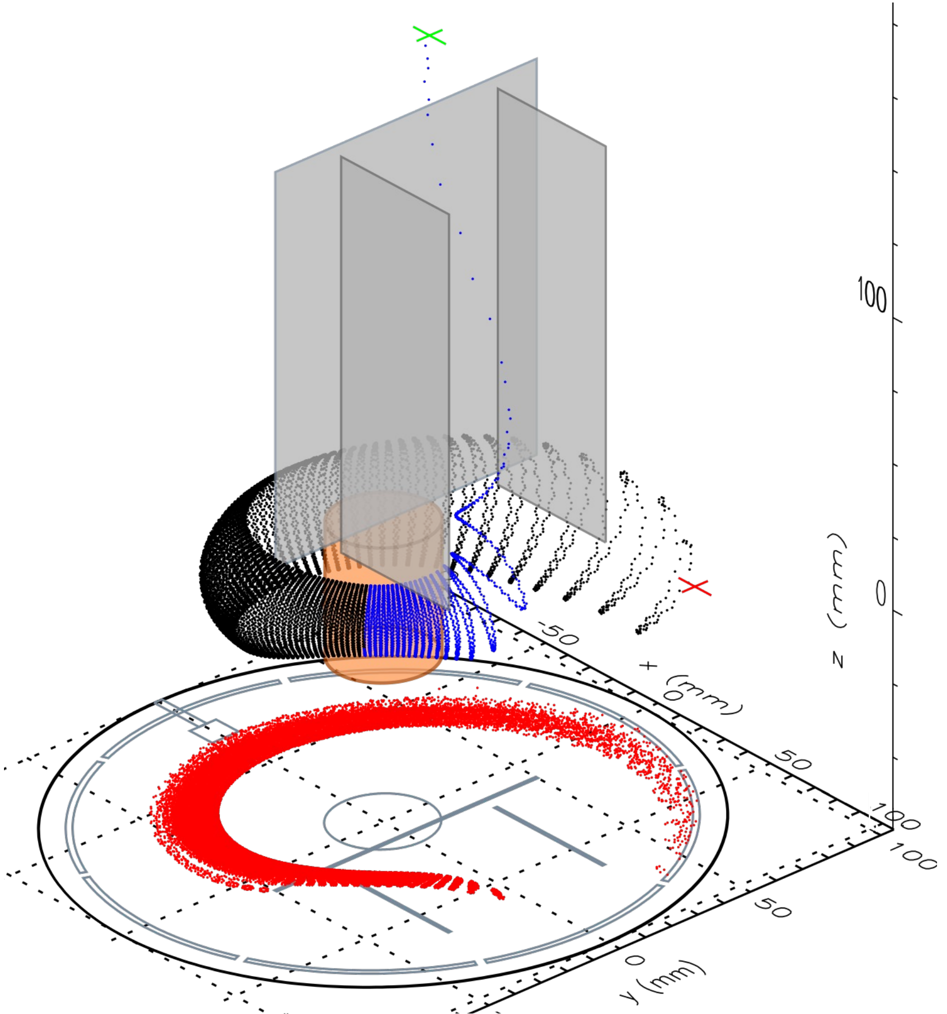
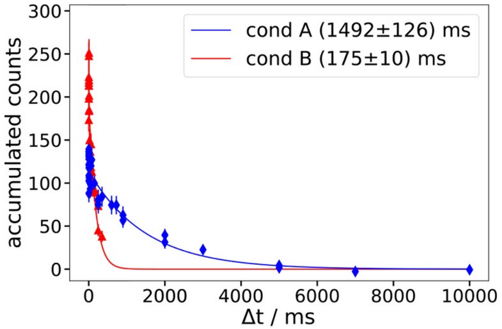


- ✓ Can we move positrons from the guide field of beam line, across B surfaces, into our trap?
- ✓ Without losing too many of them in the process?
- ✓ And then keep them there for awhile?



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J. Horn-Stanja, S. Nissl, et al. PRL 121, 235003 (2018).
J. Horn-Stanja, E. V. Stenson, et al. PREX 2, 015006 (2020).

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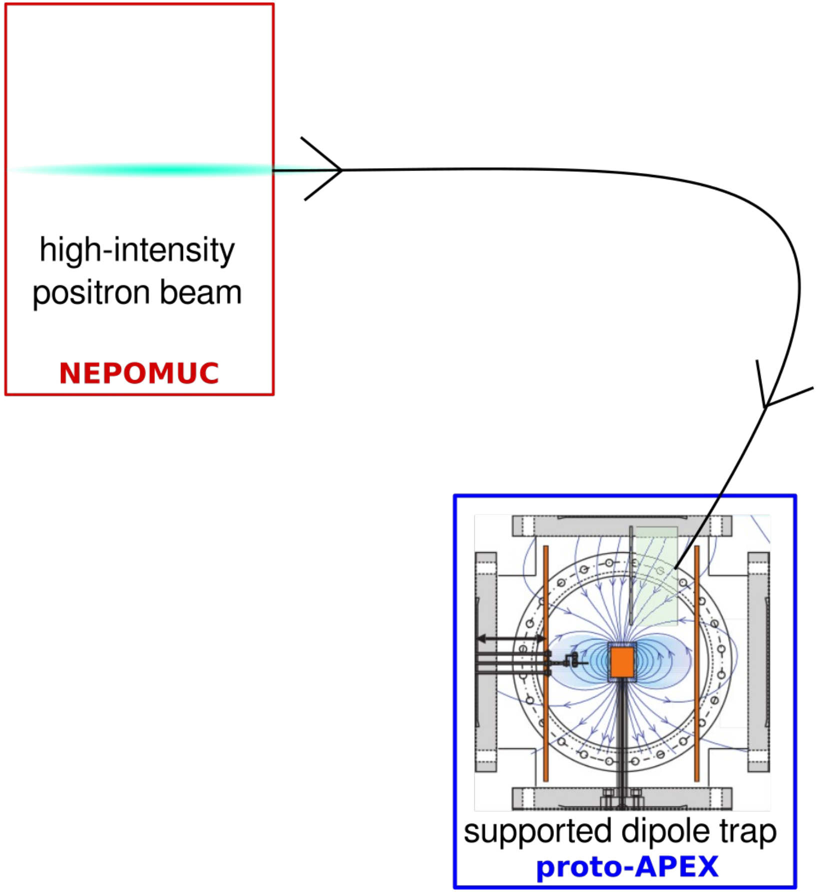

- ✓ Can we move positrons from the guide field of beam line, across B surfaces, into our trap?
- ✓ Without losing too many of them in the process?
- ✓ And then keep them there for awhile?
- ✓ Does it still work when there is a significant e-space charge already in the trap?

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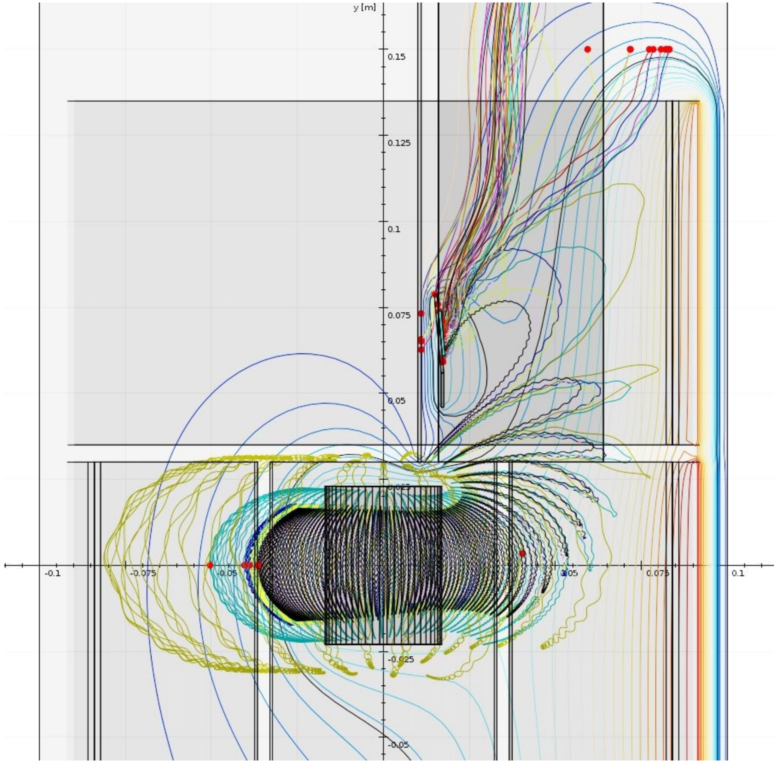
M. Singer, M. R. Stoneking, et al. PoP 28, 062506 (2021).

Prototype trap to answer key questions



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- ✓ Without losing too many of them in the process?
- ✓ And then keep them there for awhile?
- ✓ Does it still work when there is a significant e- space charge already in the trap?
- ✓ And in combination with remoderation (potentially needed if, e.g., the incoming e+ have way too much kinetic energy)?

H. Saitoh, J. Stanja, et al. NJP 17: 103038 (2015).
E. V. Stenson, S. Nissl, et al. PRL 121, 235005 (2018).
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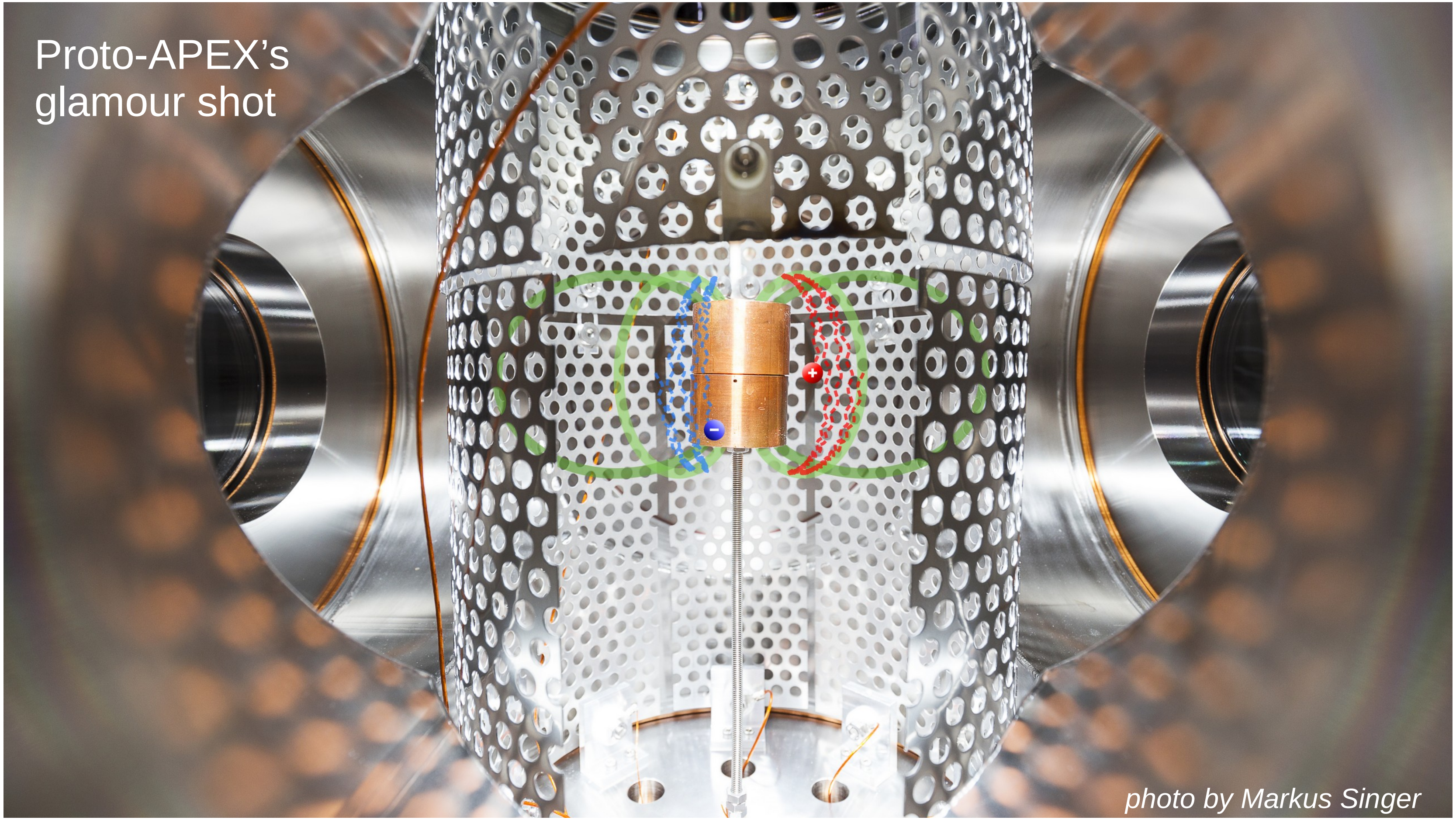
U. Hergenhahn, J. Horn-Stanja, et al. Submitted to PR Research.

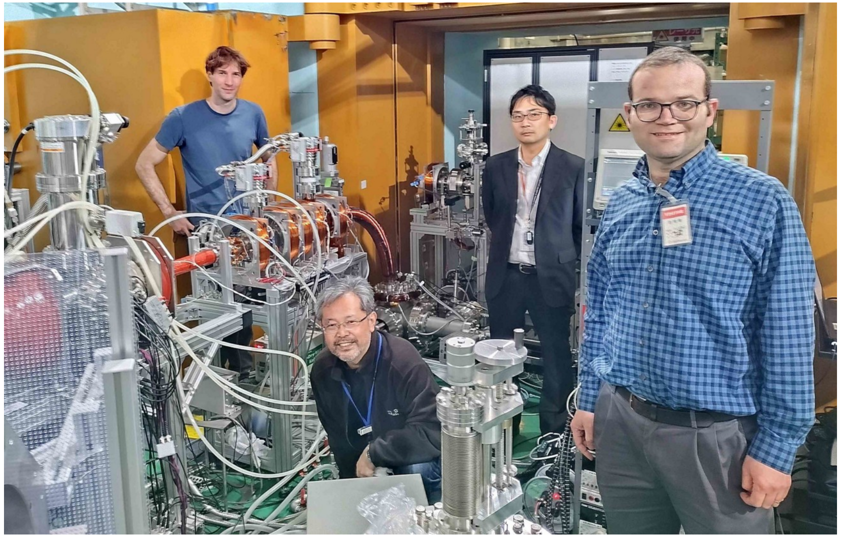
Prototype trap to answer key questions

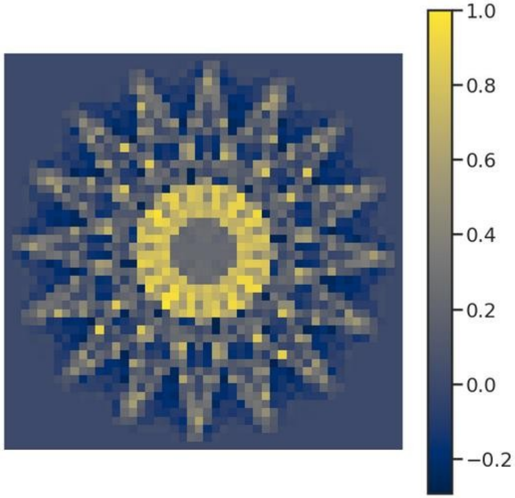


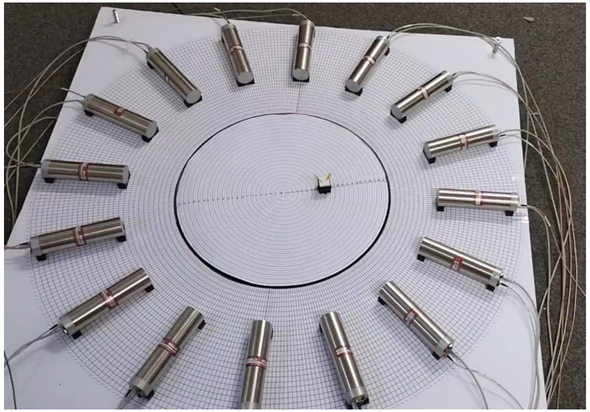
Proto-APEX continues to be a valuable “sand box”

future confinement experiments:

- diffusion/transport studies with e-
- longer trapping times for e+
- injection, confinement, and stacking of e+ pulses







- testing much more advanced gamma diagnostic techniques
- enabled by new detectors + electronics, as well as collaboration with U. Tokyo to do experiments at AIST in 2023

von der Linden, Deller, Saitoh, Higaki

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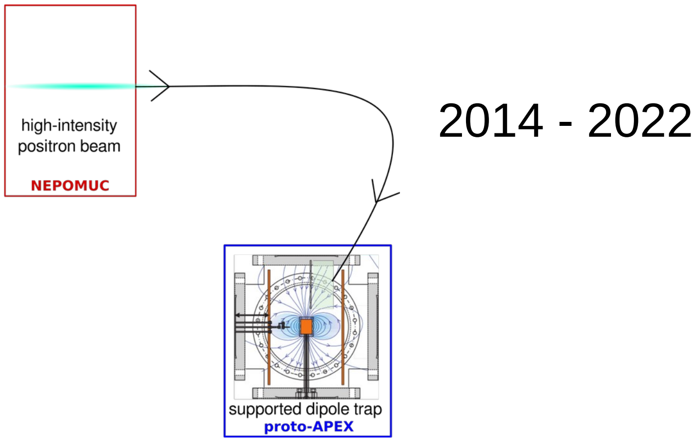
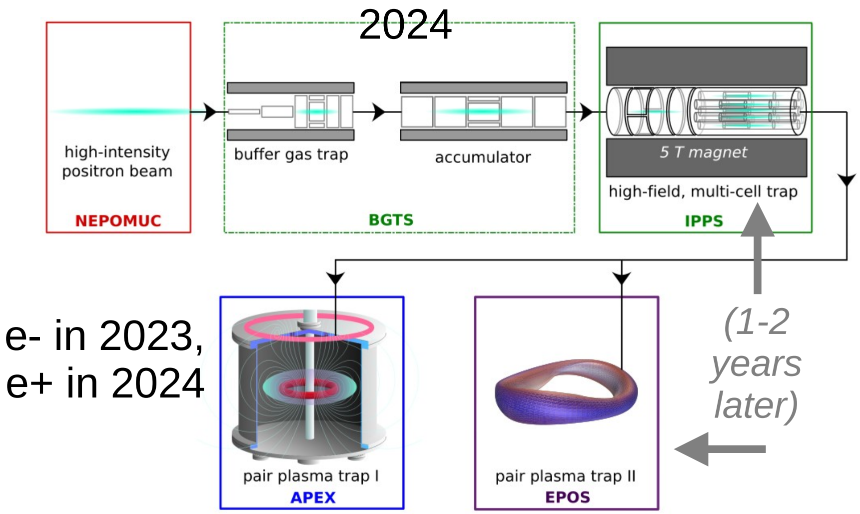
Summary

- **Laboratory e+e- pair plasmas are a compelling frontier in fundamental plasma physics.**

- **The APEX collaboration has a plan to achieve these and has made great progress in the last few years:**
  - key scientific and proof-of principle questions answered by prototype set-ups
  - design, construction, and commissioning of core experiments

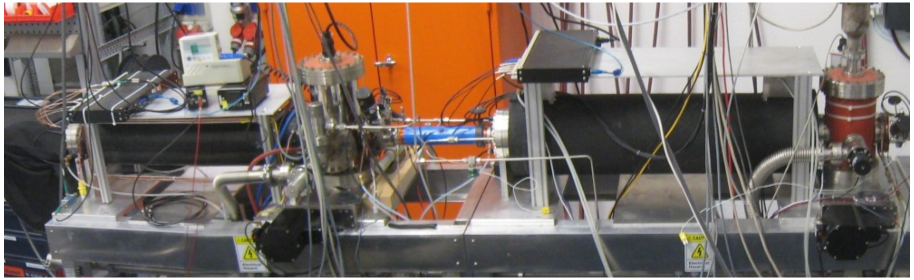
- **The next few years are expected to be exciting!**
  - significantly improved diagnostic capabilities
  - orders of magnitude more trapped e+ (and e-)
  - installation at FRM II



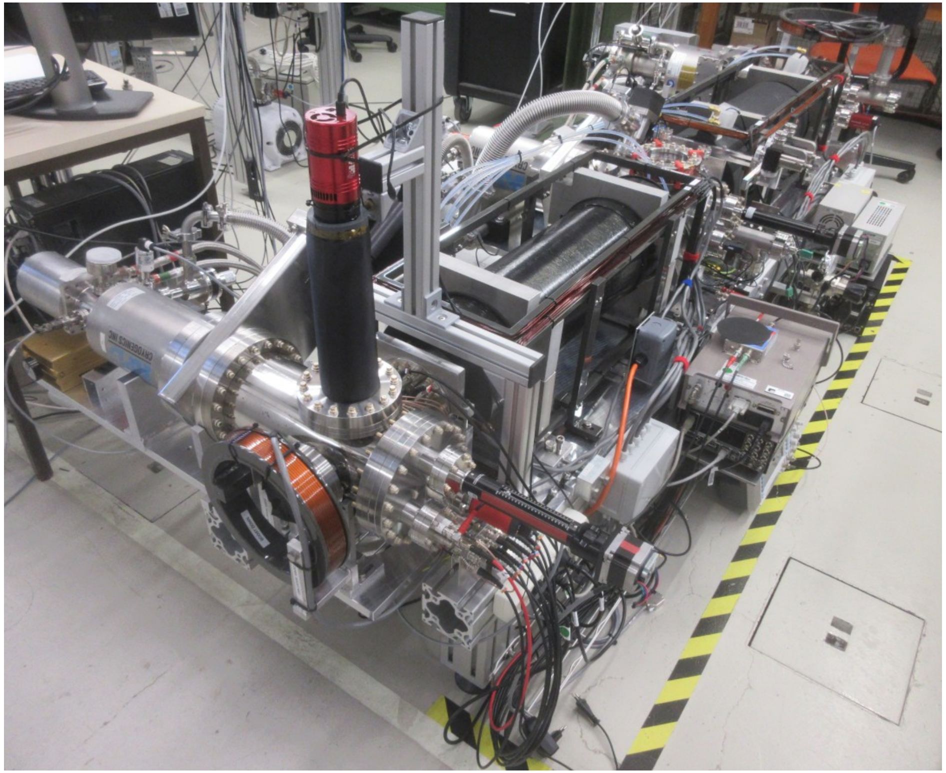


The buffer-gas trap

previously (2013):



now:

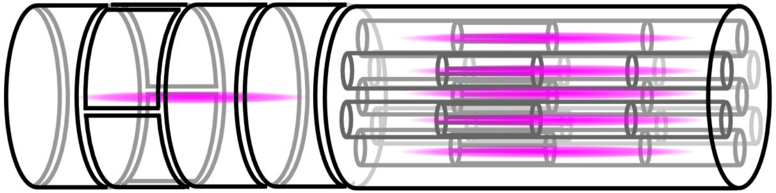


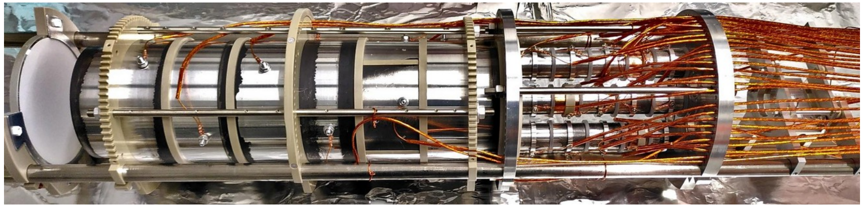
- standard technique for trapping, accumulating e+
- produces dense, tailorable pulses
- major, multi-year upgrade/rebuild (of aging, well-traveled system) complete
- e- commissioning highly successful

project leader: A. Deller
refs: Surko PRL ‘88; Murphy, PRL ‘92; Surko Varenna I (2010); Danielson RMP '15
Masters thesis: C. W. Rogge (2023)

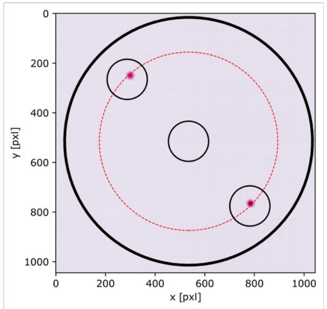
next stop: FRM II

Multi-cell trap, toroidal equilibria calculations





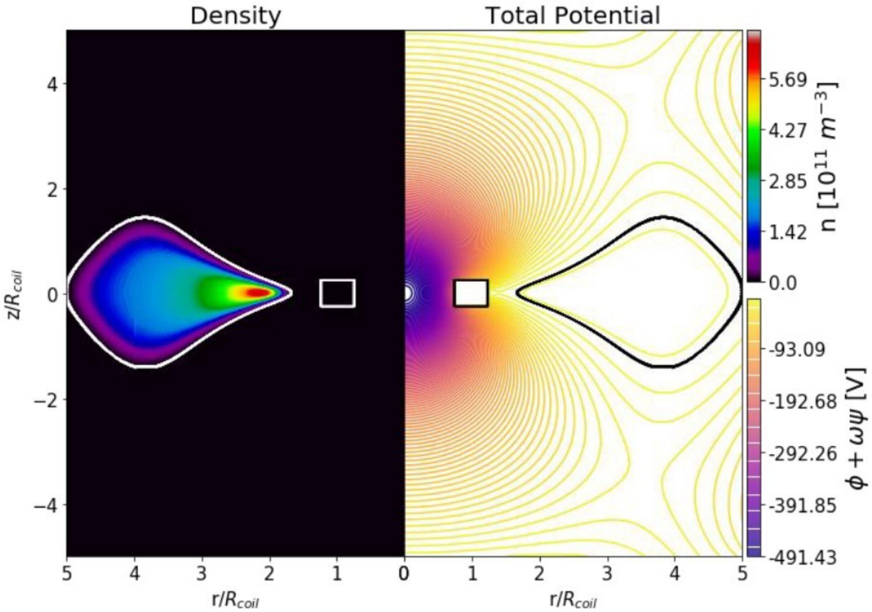
- master cell + 3 test storage cells in operation in 3.1 T in Greifswald
- simultaneous off-axis storage of e- achieved



→ **planned to come to FRM II within the next 1-2 years**

Martin Singer

pure e- (or e+) plasma in levitated dipole trap:



- equilibria and transport for non-neutral plasmas in toroidal devices

Patrick Steinbrunner

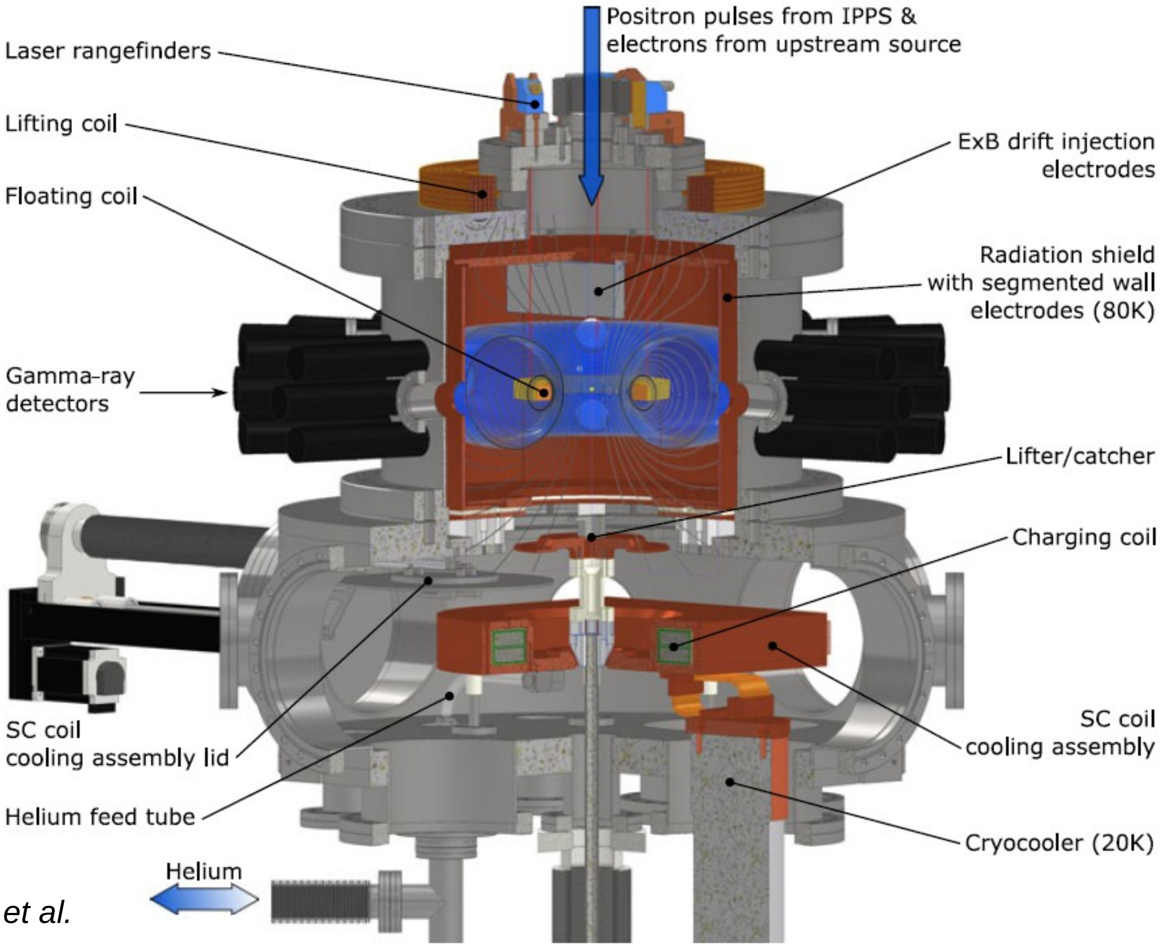
The levitated dipole trap

- ✓ design complete
- ✓ assembly nearing completion
- ✓ HTS coils (THEVA) received . . .

↑ *floating coil*

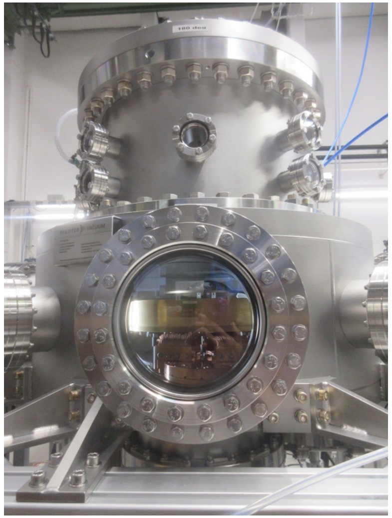
← *charging coil*

Stoneking, Card, et al.

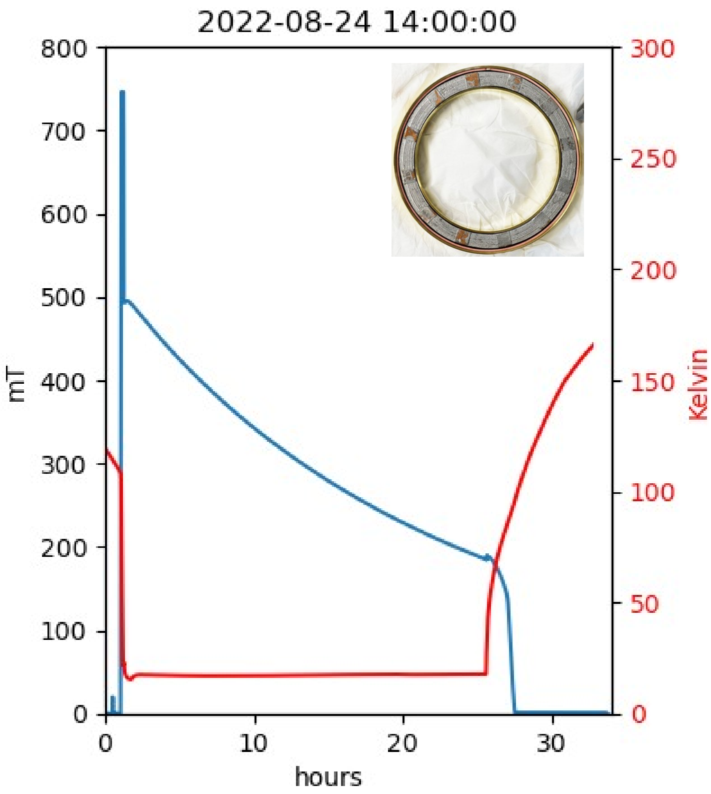


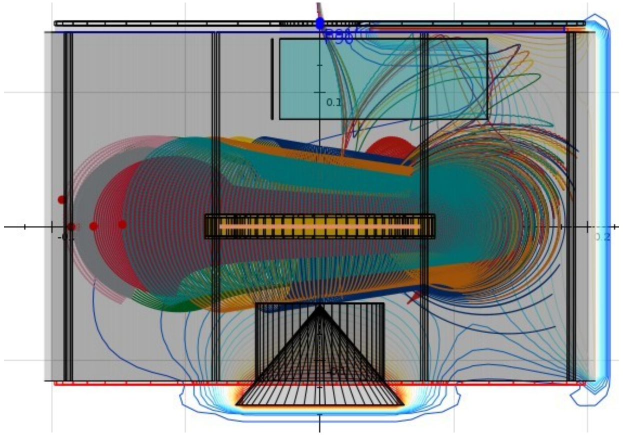
The levitated dipole trap

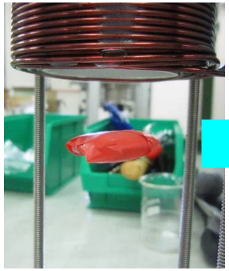
- ✓ design complete
- ✓ assembly nearing completion
- ✓ HTS coils (THEVA) received & successfully tested
- ✓ levitation hopefully very, very soon
- ✓ drift injection scheme (simulation)



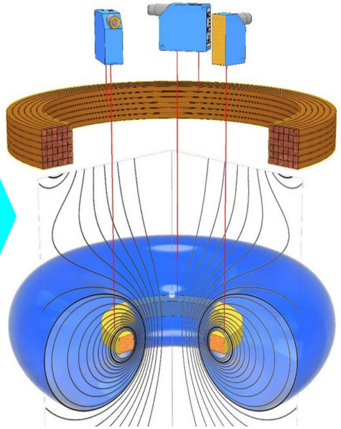
levitated dipole's HTS "F coil" ---
photo + first induction results:







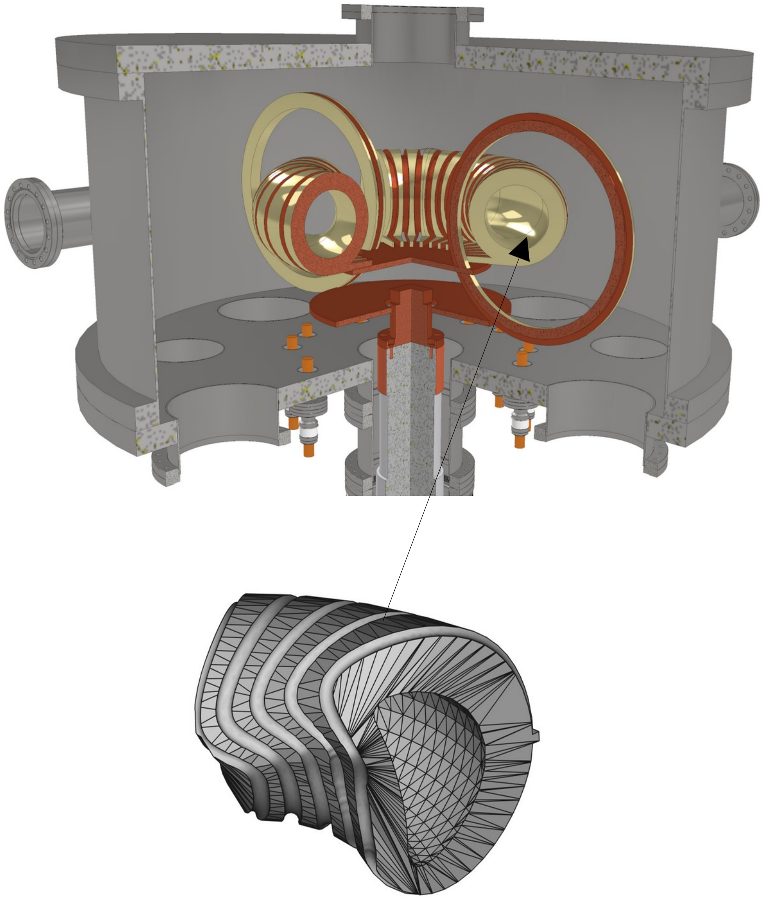
movie



Designing a pair plasma stellarator

- **coils need not be modular**

  (wind & solder HTS tapes on 3D-printed metal, which is cryogenically cooled inside a simply connected vacuum chamber)



Designing a pair plasma stellarator

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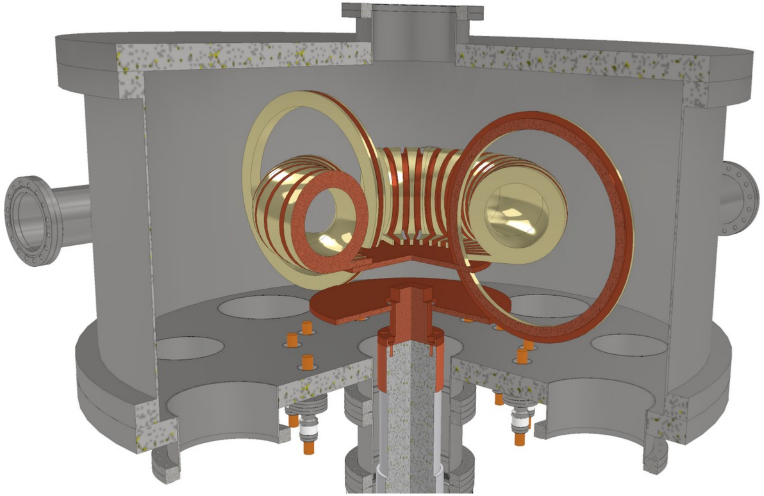
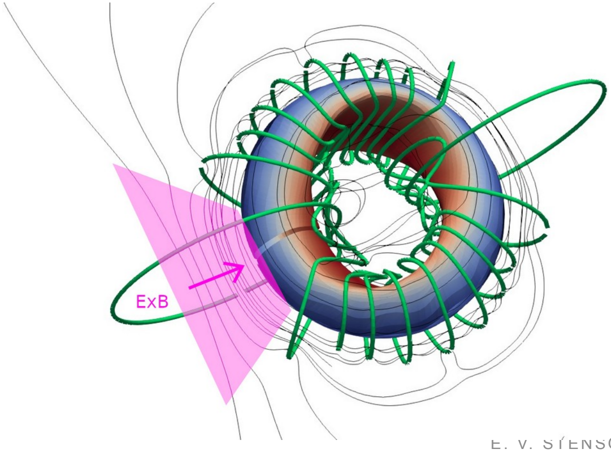
  (wind & solder HTS tapes on 3D-printed metal, which is cryogenically cooled inside a simply connected vacuum chamber)

- **a couple big gaps/openings are needed, though**

  for e+ (and e-) injection & diagnostics (flux surface measurements, probes @ boundary, gas jet, imaging, . . .)





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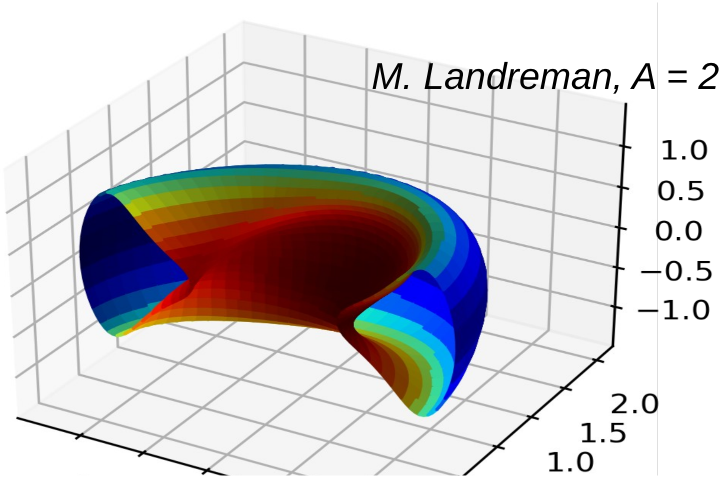
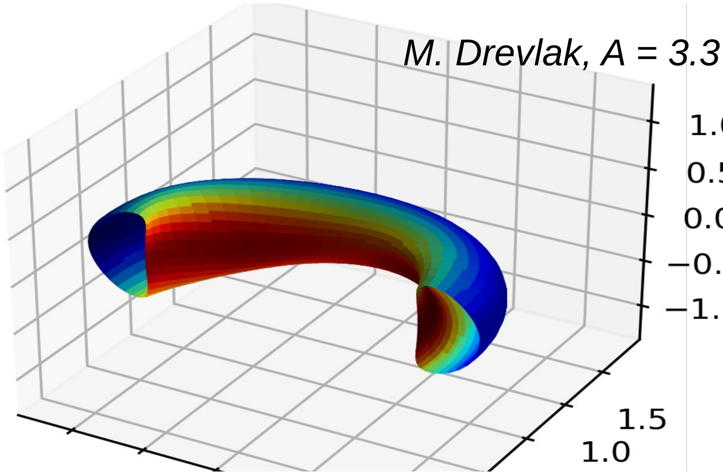
- **quasisymmetric & low aspect-ratio**

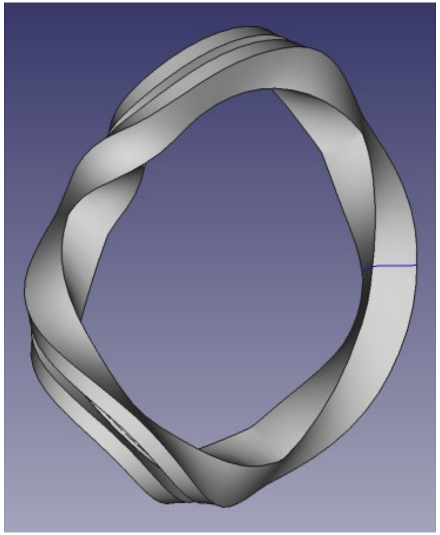
  (but just how much QS is needed? can we really ditch the magnetic well? and could it also be max-J? . . .)

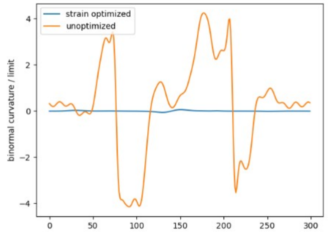


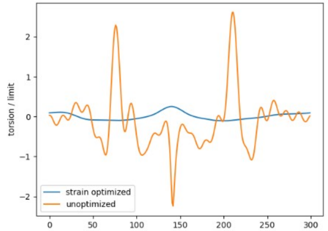


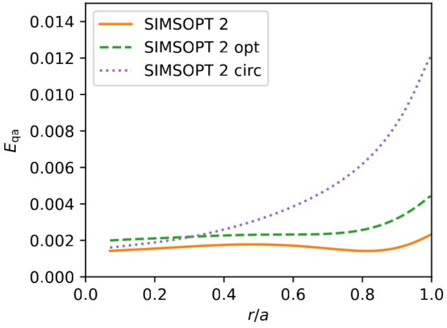
Designing a pair plasma stellarator

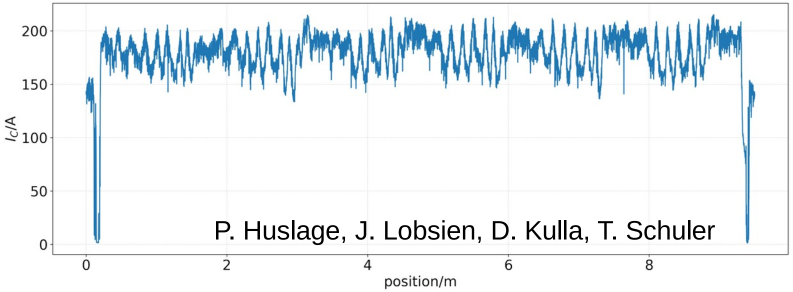
- working with a variety of low-aspect-ratio candidate configurations (and, in turn, coil sets)
- figuring out how to accommodate the “on ramp” (to enable e+ injection from beam line)
- optimizing tape orientation to minimize strain
- figuring out how many coils we want/need, and how precisely we need to build them
- engineering tests: winding HTS into non-planar coils, soldering them into a metal frame











Smoniewski, Gil, Huslage

bonus slides

The regime of non-neutral plasmas

$r_L \ll \lambda_D \ll$ device size $\ll$ plasma skin depth

- cyclotron cooling can be a powerful experimental tool

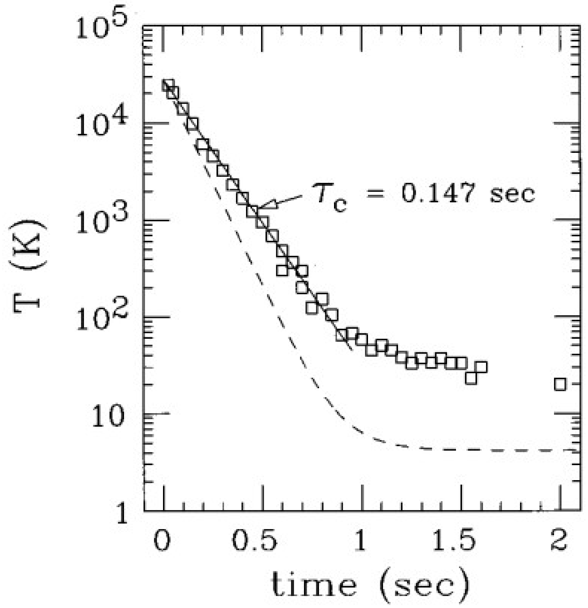


FIG. 3. Measured plasma temperature vs. time for a magnetic field of 61.3 kG. The dashed curve is a plot of Eq. (5).

B. R. Beck, J. Fajans, and J. H. Malmberg, Physics of Plasmas 3, 1250 (1996).

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    - but the (perpendicular) temperature doesn't actually go to zero

      (due to heating + parallel-to-perp energy transfer)

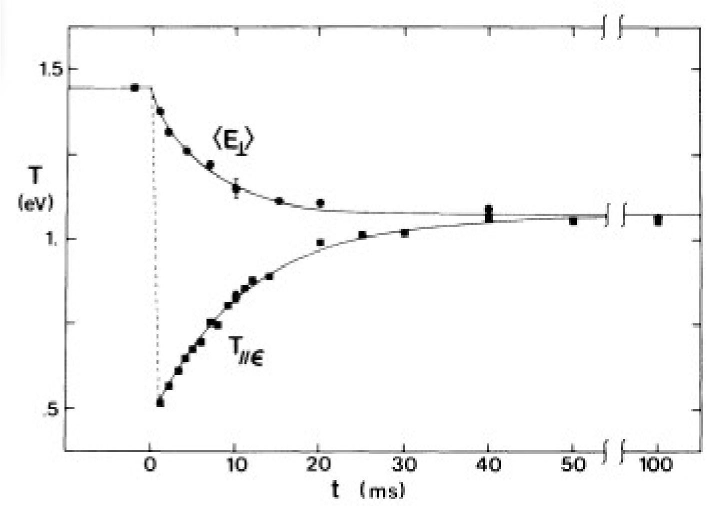
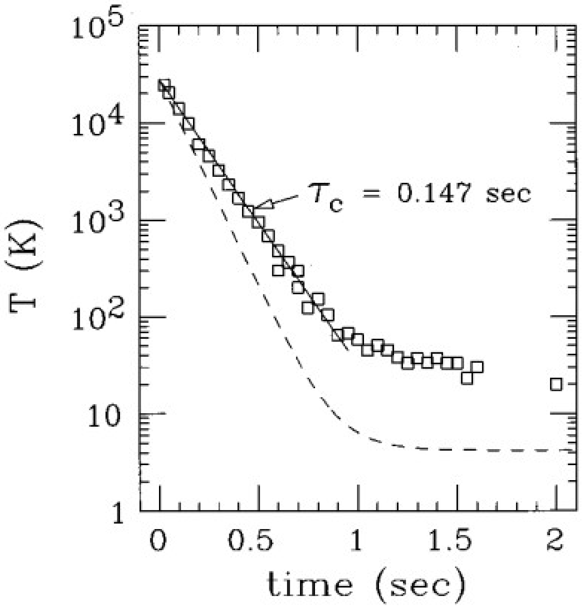


FIG. 2. Data showing the creation and subsequent relaxa-



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  - e-/e+: long-range & mu-conserving

***New work by Kennedy & Helander** (JPP 2021):*

"Coulomb collisions in strongly anisotropic plasmas I. Cyclotron cooling in electron-ion plasmas"

"Coulomb collisions in strongly anisotropic plasmas II. Cyclotron cooling in laboratory pair plasmas"

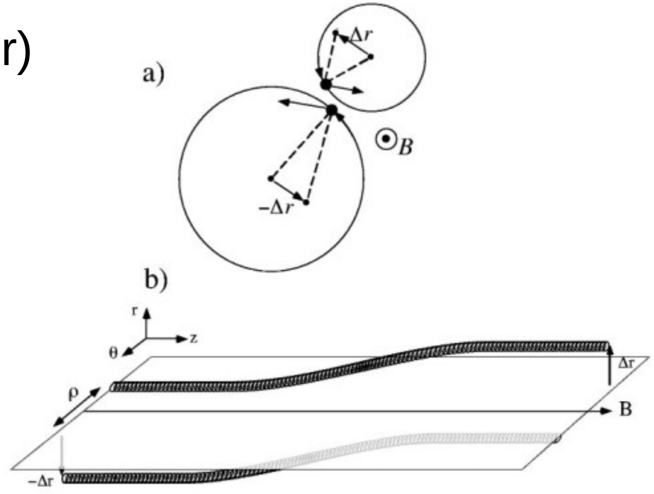

FIG. 1. (a) Classical velocity-scattering collisions with impact parameters $\rho \lesssim r_c$. (b) Long-range **E×B** drift collisions with $r_c < \rho < \lambda_D$.

C. F. Driscoll et al. Phys. Plasmas, Vol. 9, No. 5, May 2002

The regime of non-neutral plasmas

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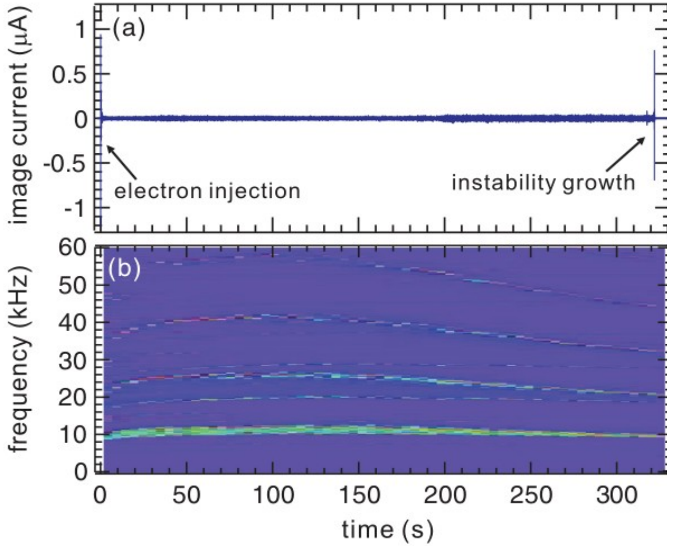
- NNPs known for extremely long confinement times --- e.g., days or weeks in linear traps, 300 s in dipole

electrostatic fluctuations during long confinement in RT-1:



Yoshida et al. PRL 104, 235004 (2010)

The regime of non-neutral plasmas

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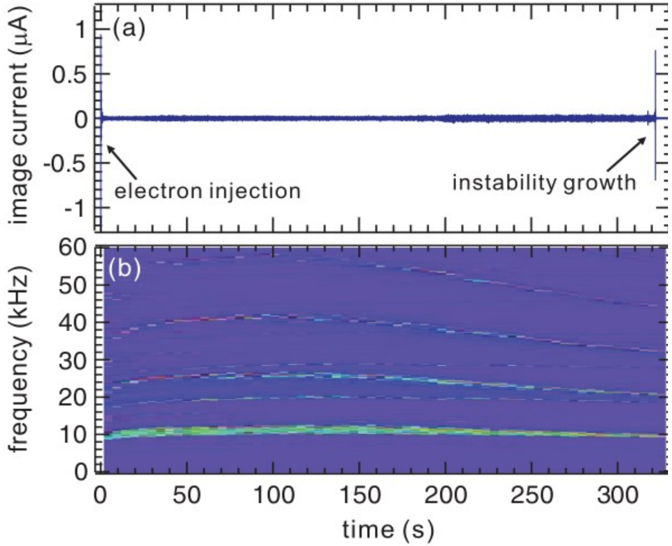
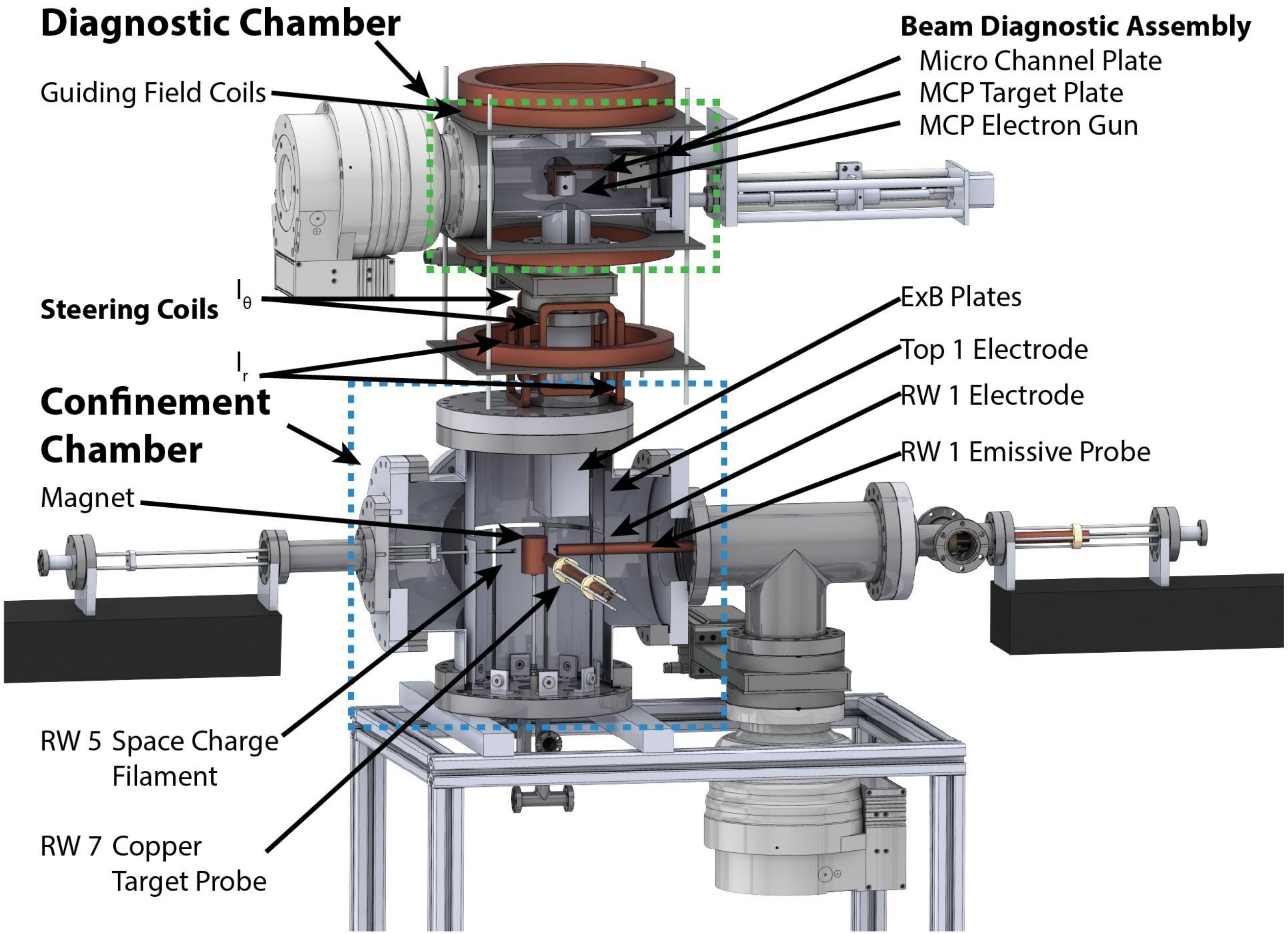


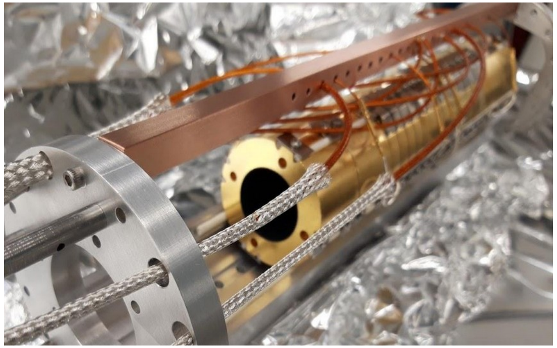
Yoshida et al. PRL 104, 235004 (2010)

If we optimize our traps for this regime, how long can they confine a pure-electron --- or e-e+ --- plasma?

Prototype trap to answer key questions

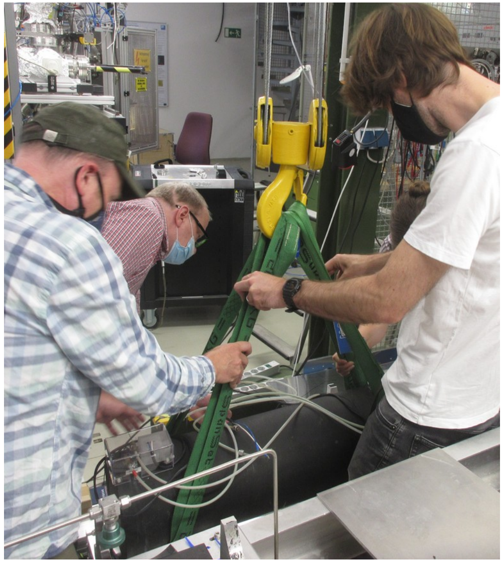


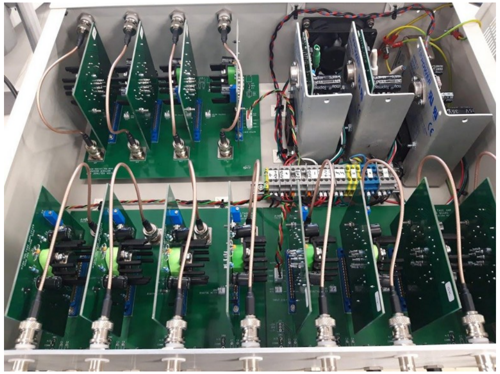
The buffer-gas trap



- ✓ mounted on new Al-profile frame
- ✓ new magnet for storage stage
- ✓ electrode rewiring, graphite coating
- ✓ improvements to electrical and electronics systems
- ✓ new cooling water circuit
- ✓ cryopumps refurbished, 1 added
- ✓ new vacuum components
- ✓ new experiment control and data acquisition software
- ✓ e- commissioning in progress

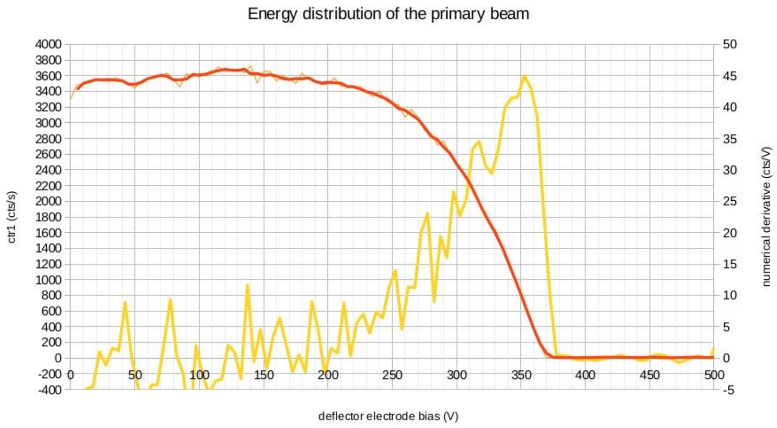
(funding: USDOE, UCSD Foundation)

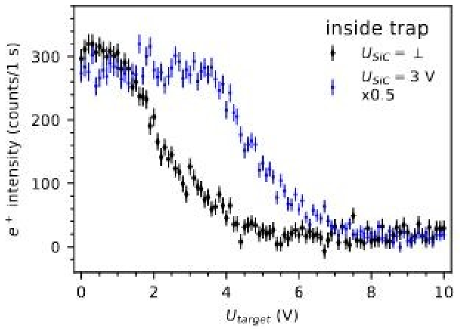




In situ remoderation

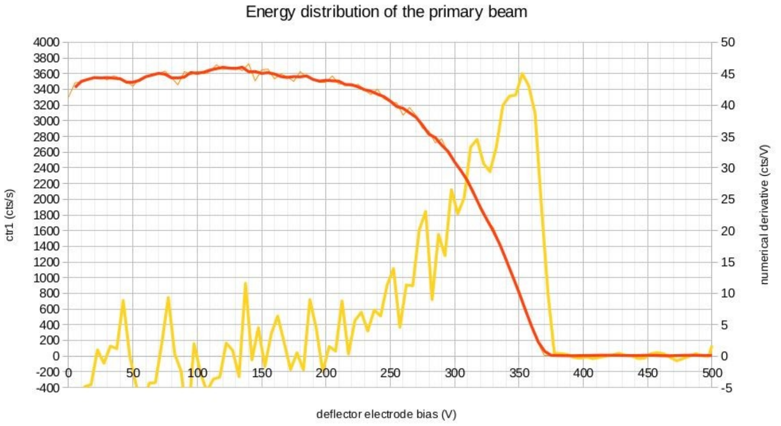
2017 experiments . . .

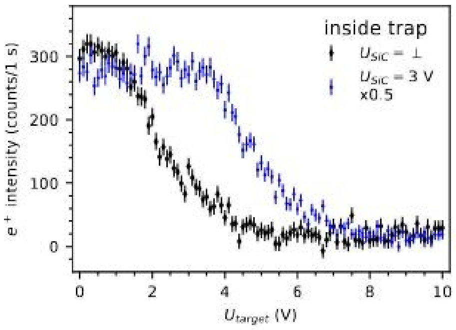


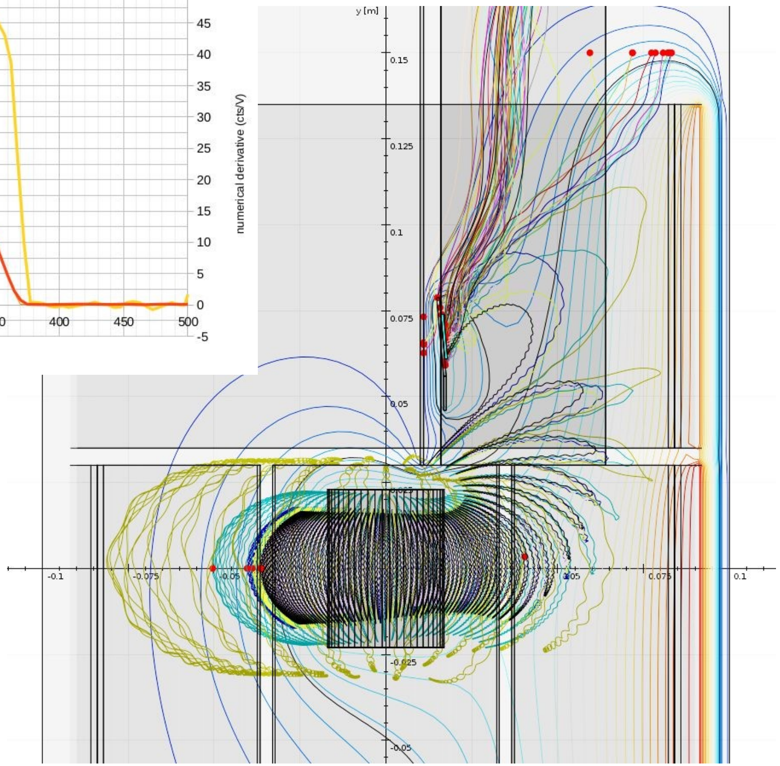


In situ remoderation

2017 experiments . . . rounded out with 2022 simulations







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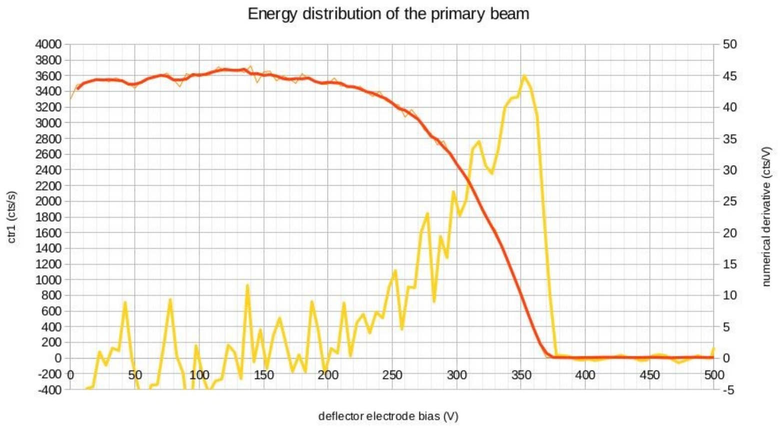
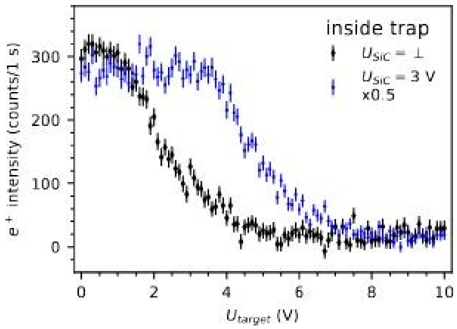
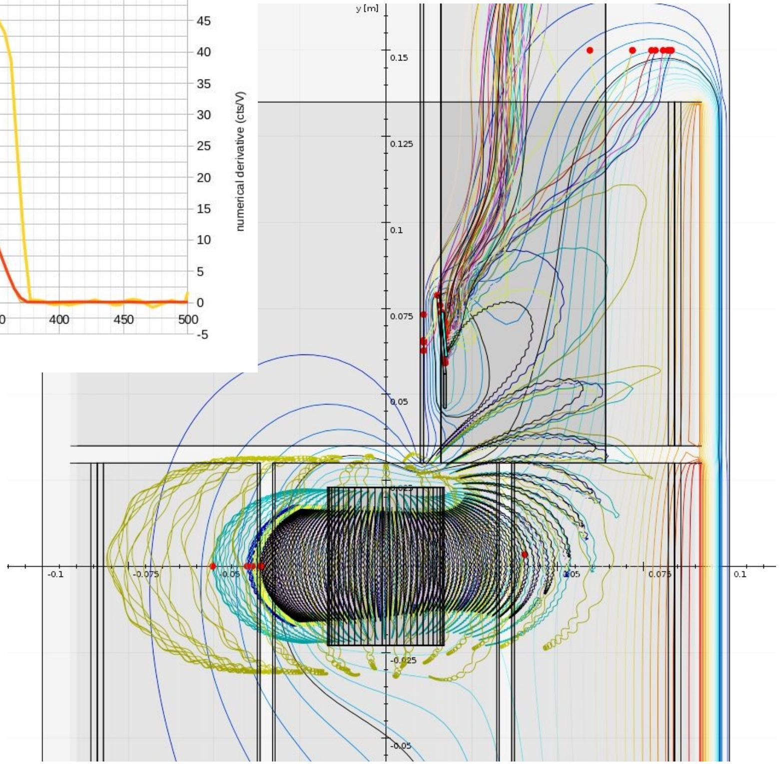






~ 4×10^8 e^+/s @ BM2

between $\frac{1}{2}$ & $\frac{1}{3}$ lost in beam line

1.5 to 2.5×10^8 "e^+"/s @ MCP

~$\frac{1}{4}$ of those are actually 2ndary e^-

1.3×10^8 actual e^+ @ MCP

10-15% don't hit the SiC at all

~ 1.1×10^8 @ SiC

60-65% not remoderated

~ 4×10^7 e^+ "launched" from SiC

~28% go back up the beam line

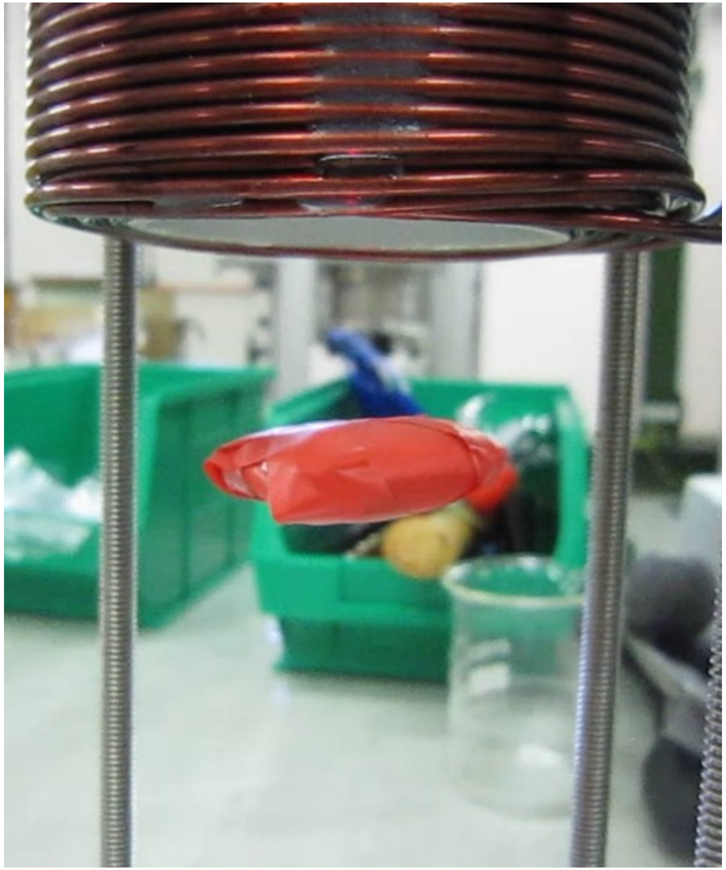
~15% hit the SiC again

?

~ 2×10^7 make it to the probe

Prototype levitation control circuit in action

Stability:



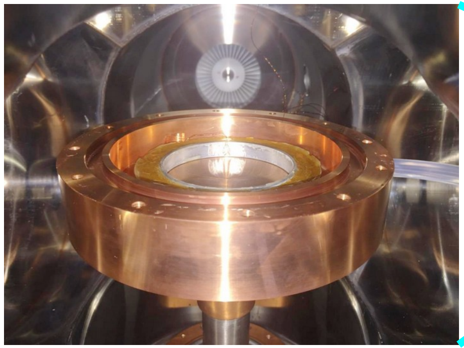
movie

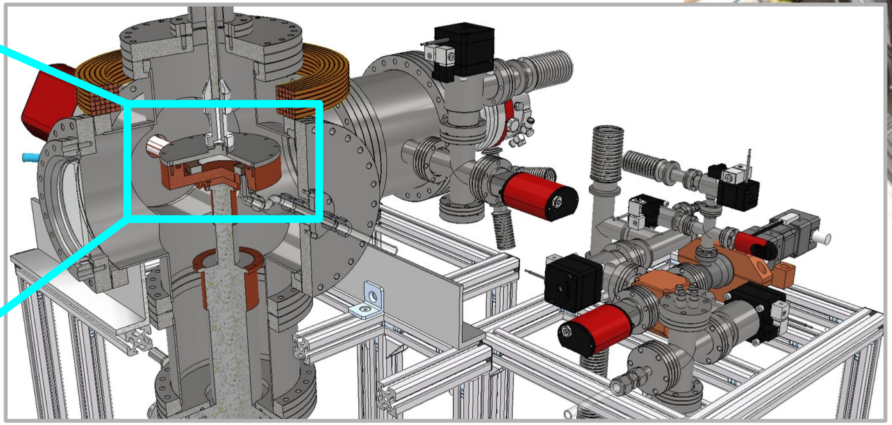
Take-off and landing:

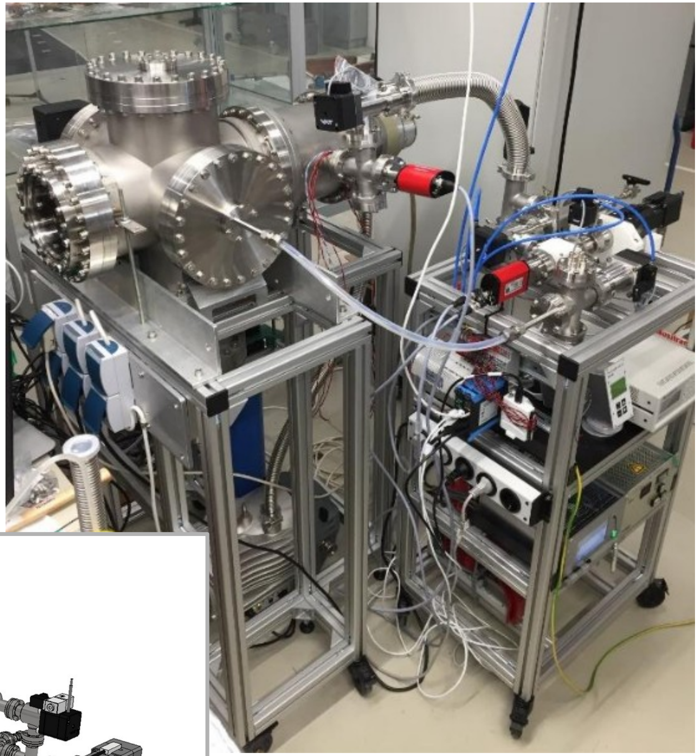
movie

Coolingstack Prototype EXperiment (CPEX)

- ✓ Does a He-gas-filled "chamber within a chamber" generate the thermal contact needed to cool the floating coil from a cold head?
- ✓ Without the pressure in the main chamber of the experiment going too high?
- ✓ Without anything incompatible with repeated re-cooling cycles in the levitated dipole trap (e.g., seals that break or freeze, unreasonably large mechanical force)?

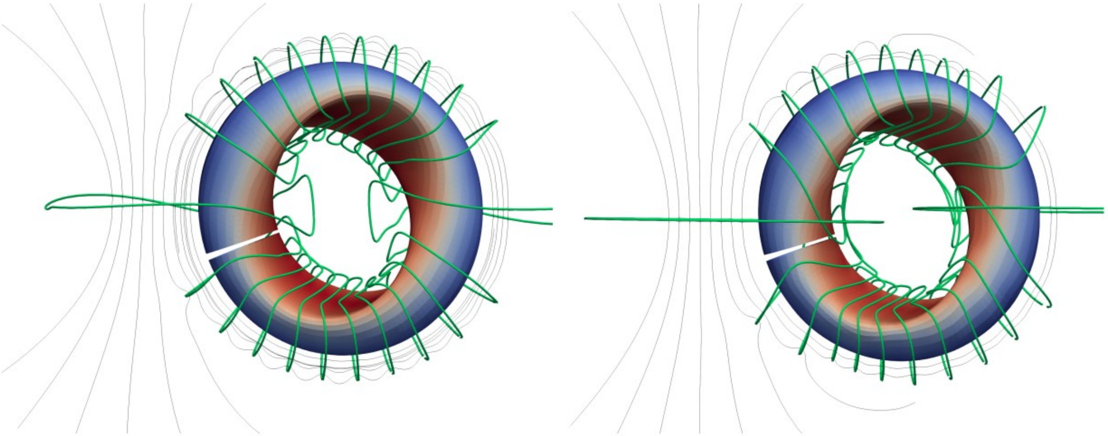


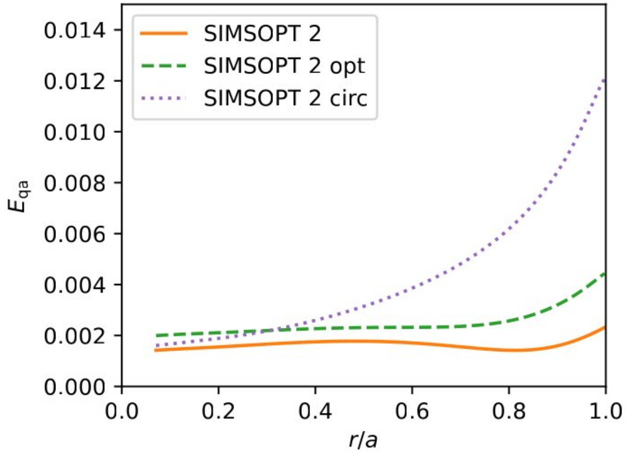


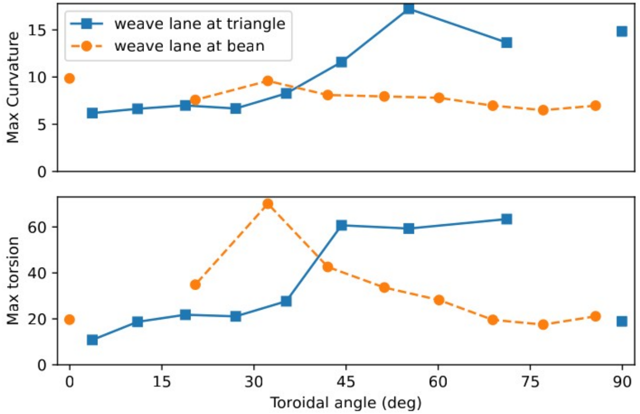


highly successful test stand operated in the GLADIS hall 2020-2021

Weave lane for charged particle injection







- Shaped weave lane coils $\rightarrow$ good QS.
- Weave lane affects other coils.
    - Current affects coil-coil distances.
    - Location affects curvature and torsion.

Designing EPOS, the pair plasma stellarator

The pair plasma perspective: Disparate magnetic topologies → opportunity to learn even more about pair plasmas

- e.g., remarkable stability to microturbulence in suitably chosen configurations and parameter regimes

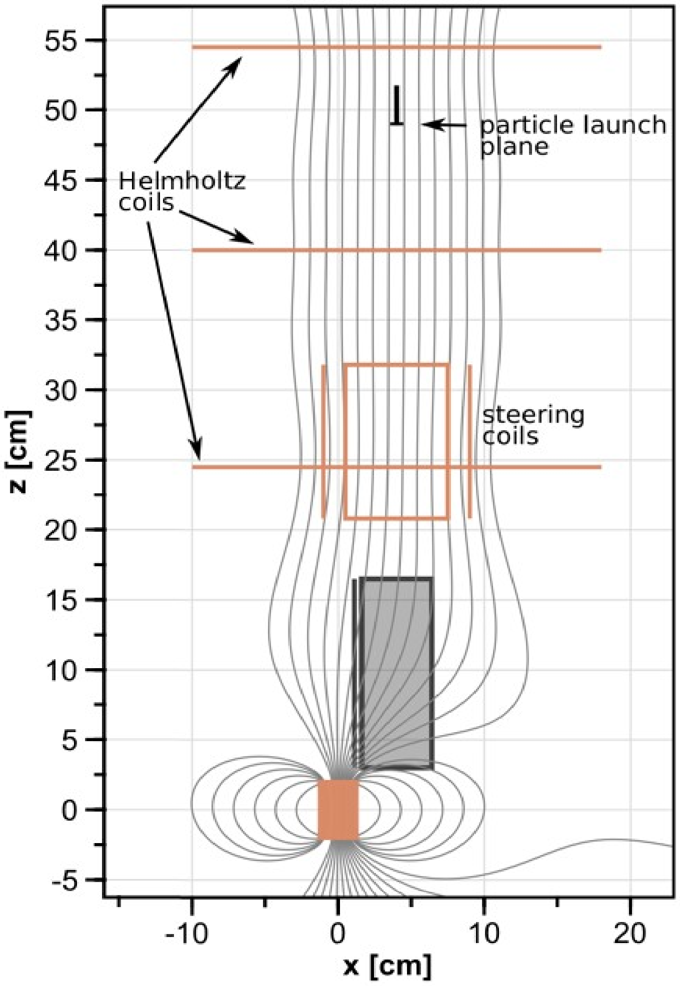
The optimization perspective: An electron-positron pair plasma offers a uniquely sensitive test of neoclassical optimization.

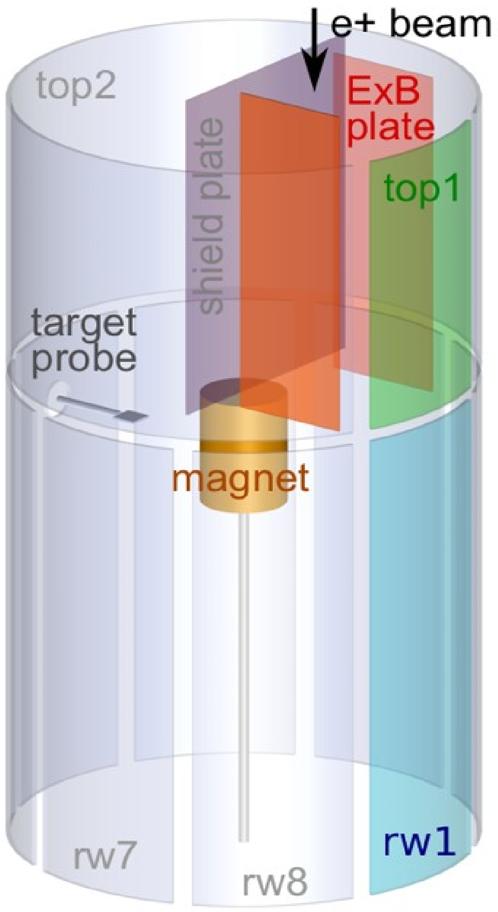
- turbulence-free (in suitably-chosen configurations and parameter regimes)
- no ambipolar fields to "heal" drift orbits
- e+ are a very sensitive probe of what one's charged particles do (gamma detection)

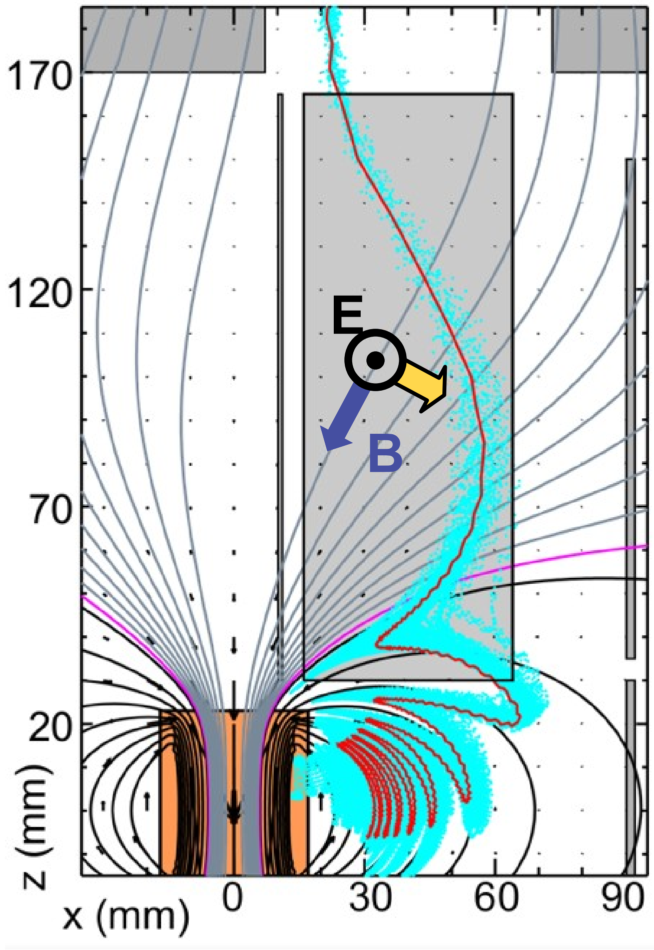
If we have success in make a remarkably “boring” confined pair plasma, there are plenty of options for how to shake things up again:

- de-optimizing the magnetic configuration
- turn down B (to turn off cyclotron cooling, increase the gyroradius)
- ion contamination
- departures from quasineutrality
- departures from $T_{e+} = T_{e-}$

Proto-APEX experiment set-up





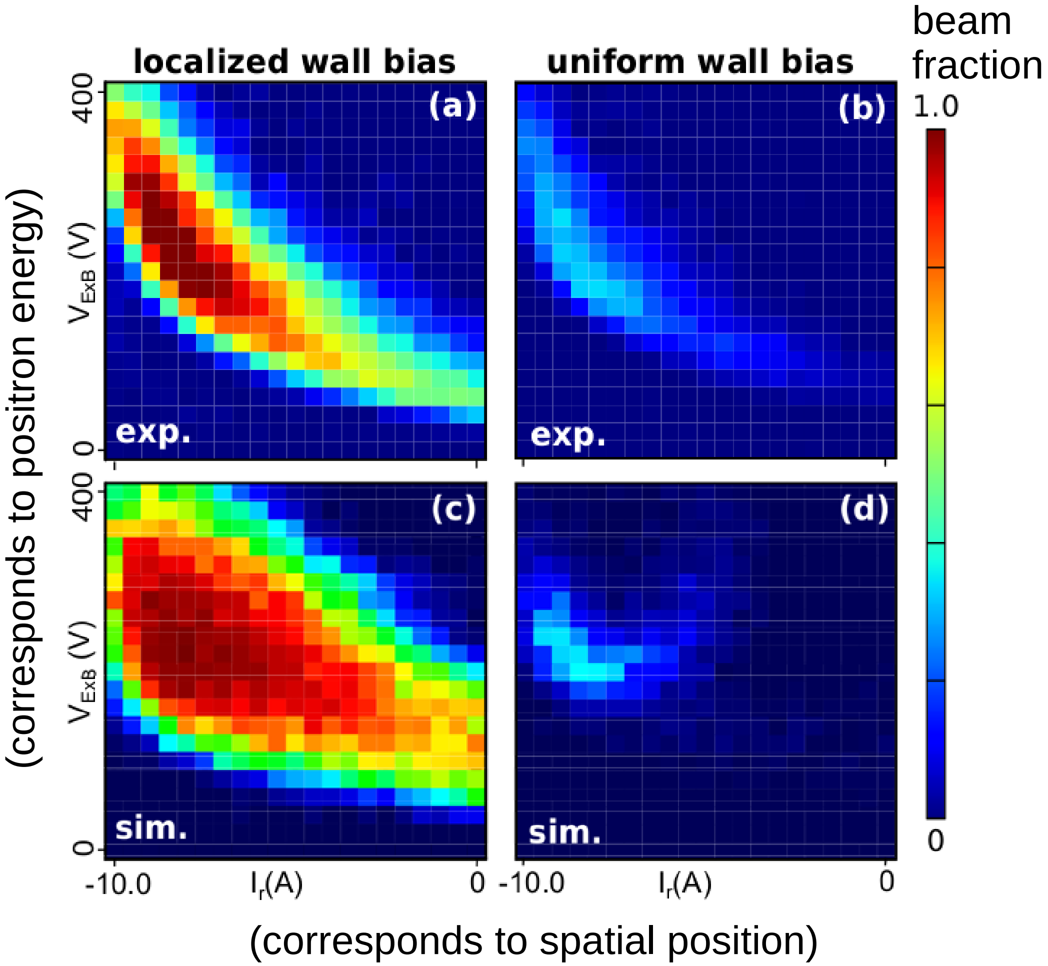


Highlights of injection studies

- lossless injection achieved (by strategically tailoring the effective potential energy well)

- best injection conditions: when the injection region is localized (asymmetric)

- high efficiencies for large regions of the parameter space



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- high efficiencies for large regions of the parameter space

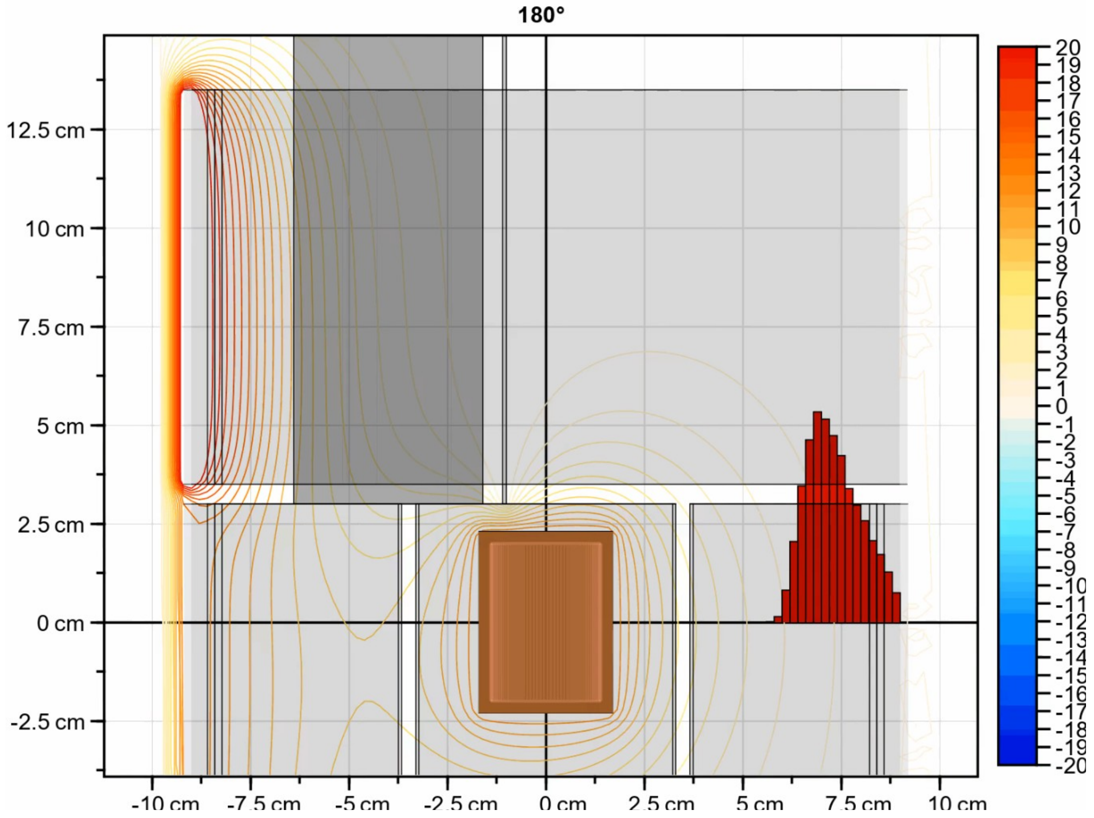
- next-generation trajectory simulations

→ synthetic diagnostic (reproduces data)

→ track individual particles and ensembles

→ excellent synergy with experiment

radial distribution of injected positrons after half of a toroidal transit around the dipole, plus electrostatic potential contours:



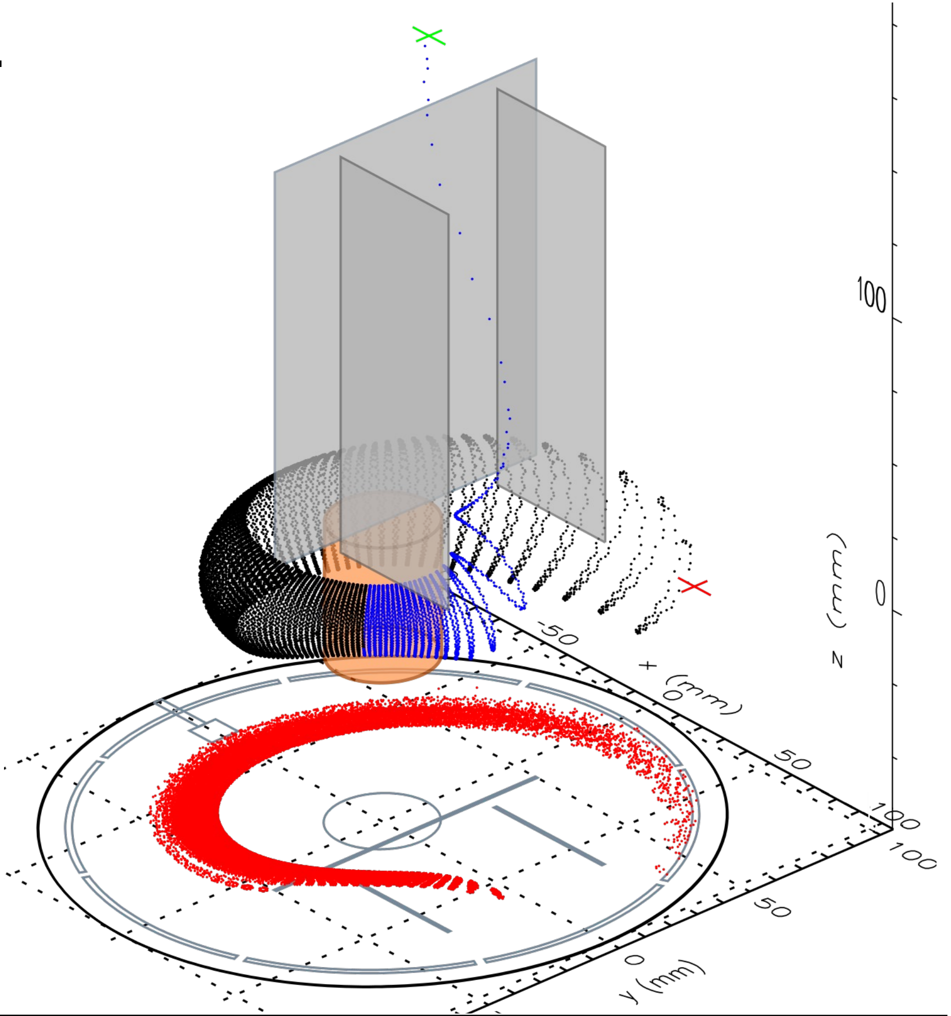
movie

H. Saitoh et al. New Journal of Physics, 17: 103038 (2015).
E. V. Stenson, S. Nissl, et al. PRL 121, 235005 (2018)
S. Nissl et al. Physics of Plasmas 27, 052107 (2020).

But can you keep them in there?

Not if you leave the injection potentials on steady-state.

→ positrons remain in trap for only 10-20 us



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J. Horn-Stanja, S. Nissl, et al. PRL 121, 235003 (2018).

But can you keep them in there?

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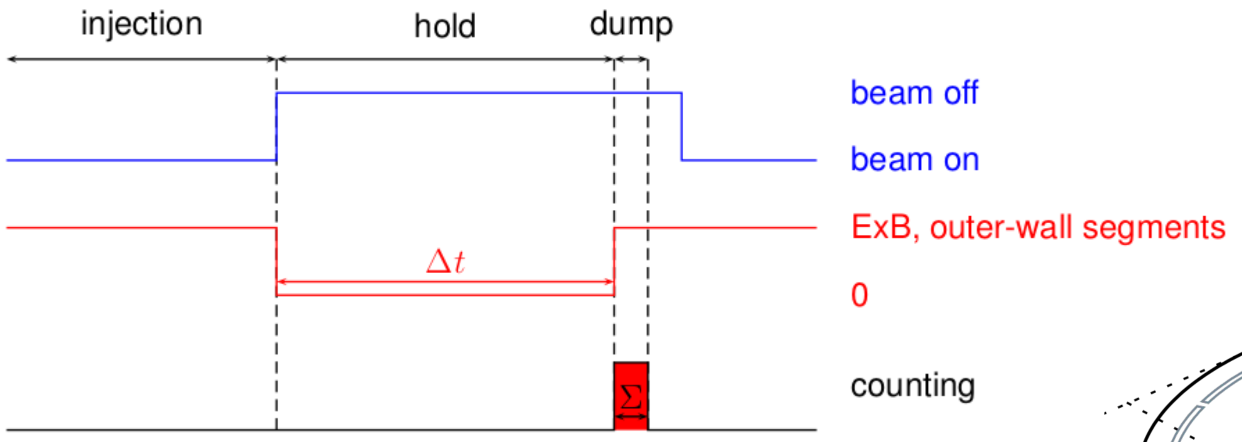
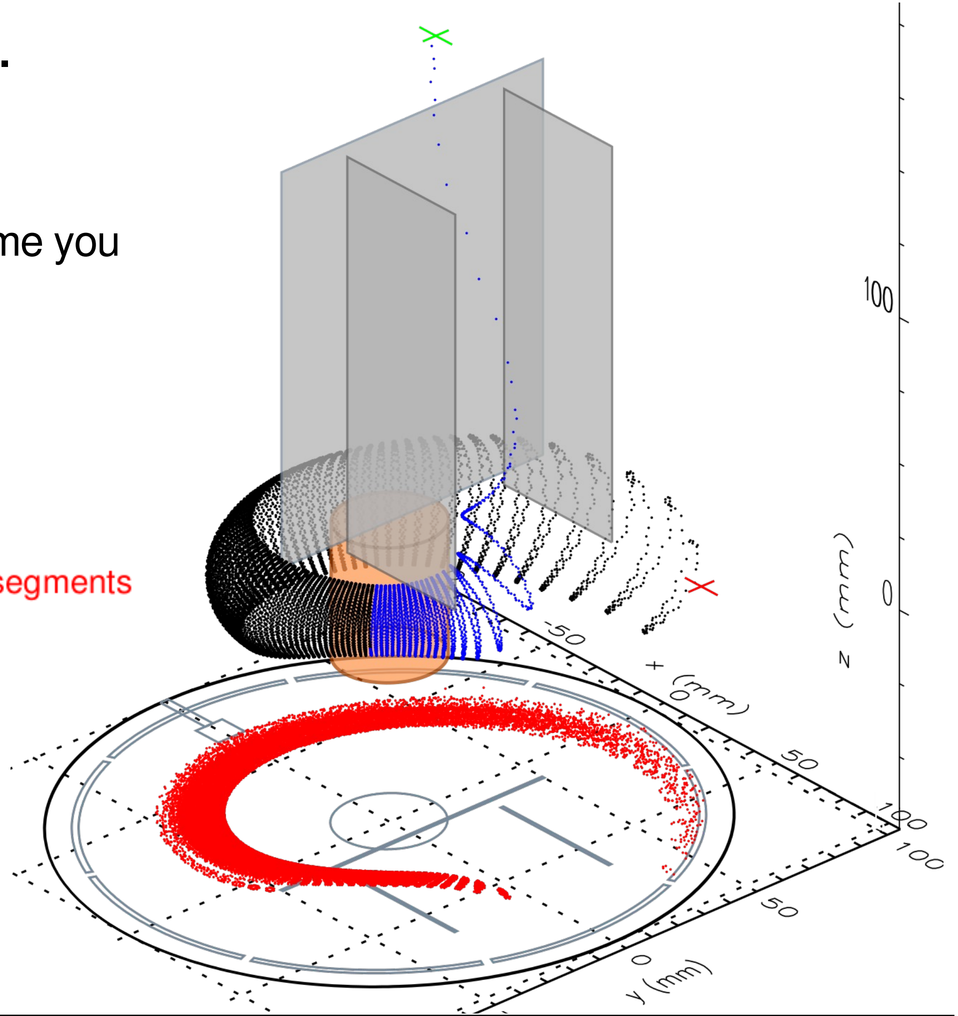
$\rightarrow$ positrons remain in trap for only 10-20 us

However, if you turn off the injection potentials at the same time you turn off the beam . . .





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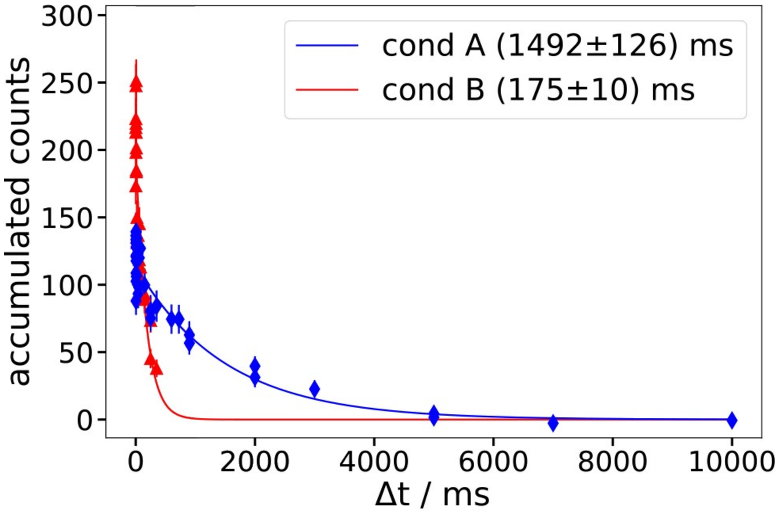
J. Horn-Stanja, S. Nissl, et al. PRL 121, 235003 (2018).

Confinement times are long

- after drift injection is turned off, e+ remain in the trap for up to
  A) tens to hundreds of thousands (with magnet bias)
  B) thousands (without magnet bias)

  of toroidal transits around the magnet



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  1) scattering into loss cone onto the magnet
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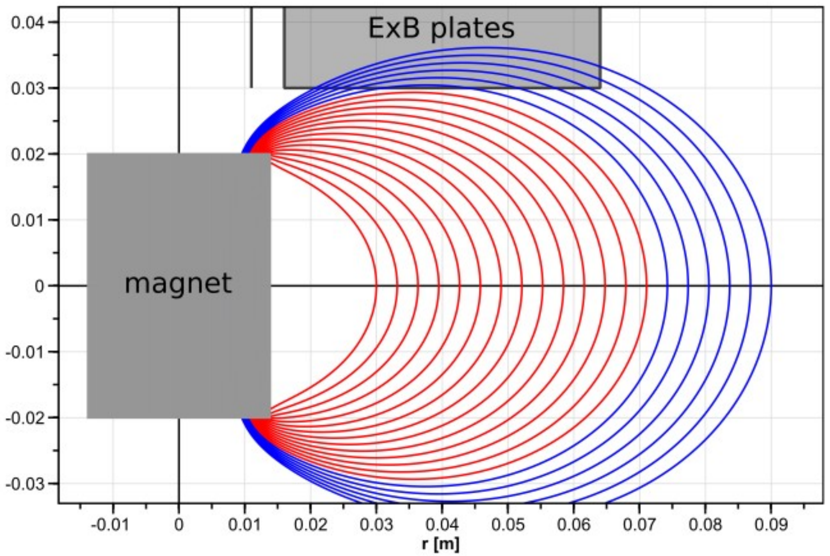

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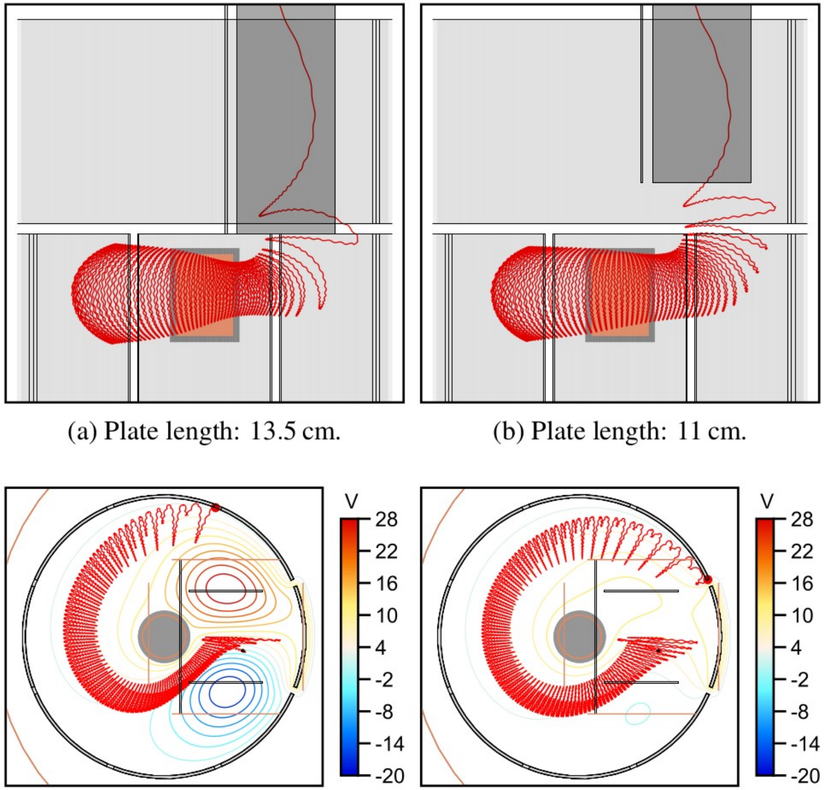
- not a factor for future experiments, due to:
  - a) closed field lines in the levitated dipole
  - b) lossless injection also achievable with much shorter ExB plates

Drift injection is a highly efficient method of moving e+ across flux surfaces and is also compatible with subsequent long confinement.

shorter ExB plates have since been installed:



(a) Plate length: 13.5 cm.
(b) Plate length: 11 cm.
(c) Plate length: 13.5 cm.
(d) Plate length: 11 cm.

J. Horn-Stanja, S. Nissl, et al. PRL 121, 235003 (2018).
S. Nissl et al. Physics of Plasmas 27, 052107 (2020).

Some of the next things to address

- number of trapped e+ (a few hundred), compared to number needed for 10 Debye lengths (>10^9)

How to stuff more particles into the trap?

- feasibility of "stacking" pulses of e+

Can particles be added to the trap in multiple batches?

- influence of collective effects on drift injection

Can we inject into a pre-existing space charge?

Can we inject dense pulses of non-neutral plasma?

- transition to next generation confinement devices

Can drift injection work with a coaxial beam line?

Can drift injection work for a stellarator?

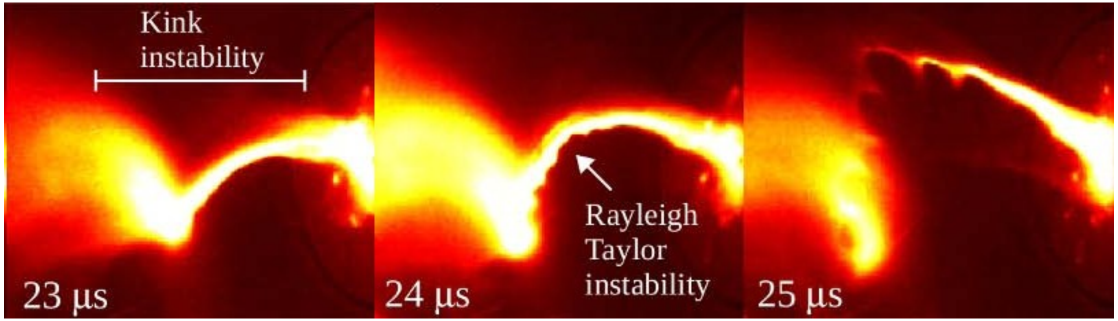
Why "do the experiment"?

- Sometimes terms expected to be important turn out not to be (and vice versa).
- Sometimes the experiment works better (or worse) than anticipated.
- Sometimes, a system may start in one regime and evolve to cross a boundary into another.
- Practical benefits:
  - diagnostic accessibility
  - repeatability
  - knobs to turn

" **Experiment can simulate computation:** Resolves all scales, includes all correlations, includes all MHD and kinetic effects, 'CPU time' < 1 second "

Stewart Prager,
CMPD/CMSO winter school

e.g., a transition from ideal MHD to magnetic reconnection

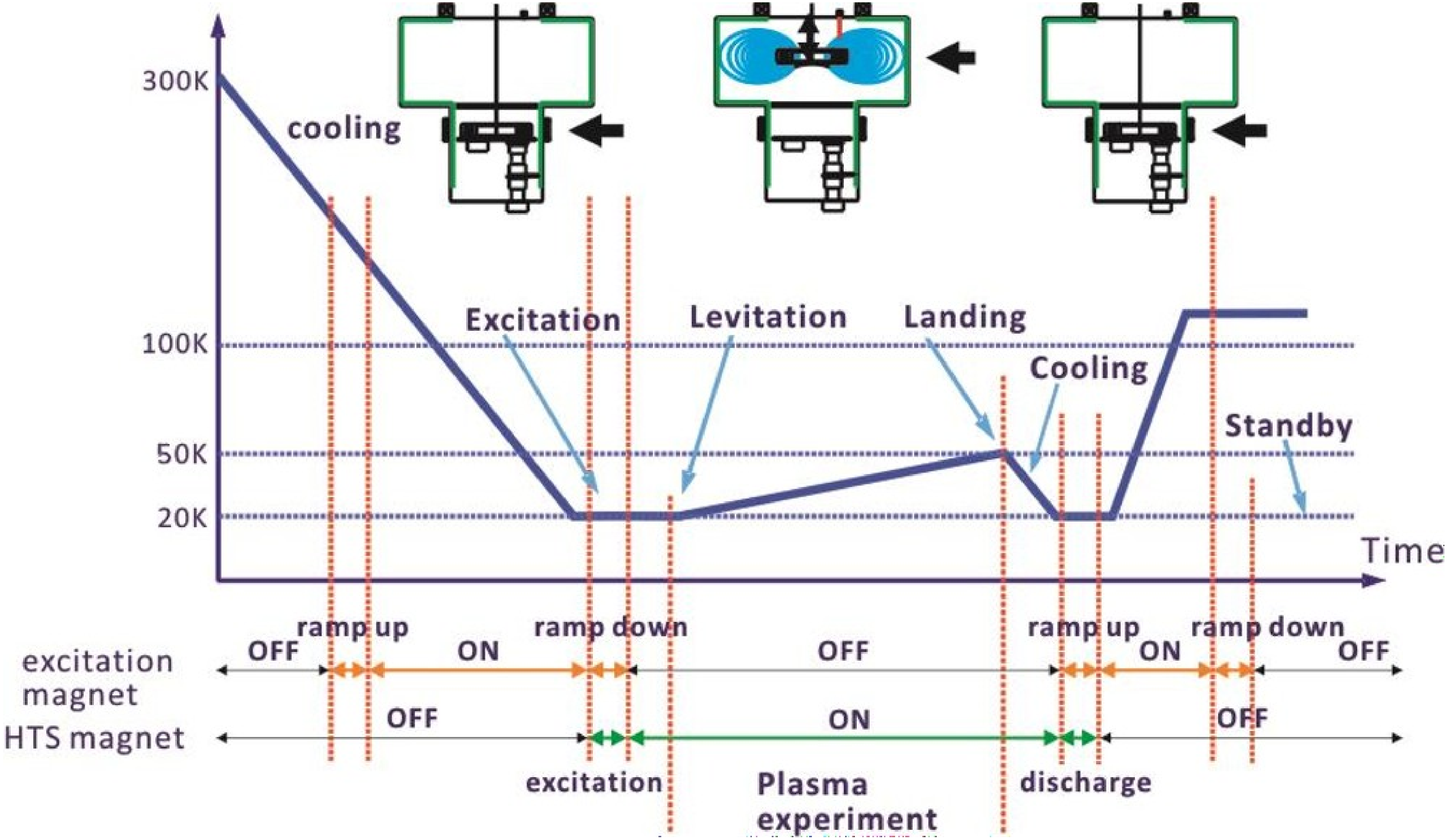


A. L. Moser & P. M. Bellan. Nature 482, 379–381 (2012)

Levitated dipole development

- Compared to other levitated dipoles, APEX will be smaller and lighter and have much less heat load.

- Predicted levitation time: at least tens of minutes



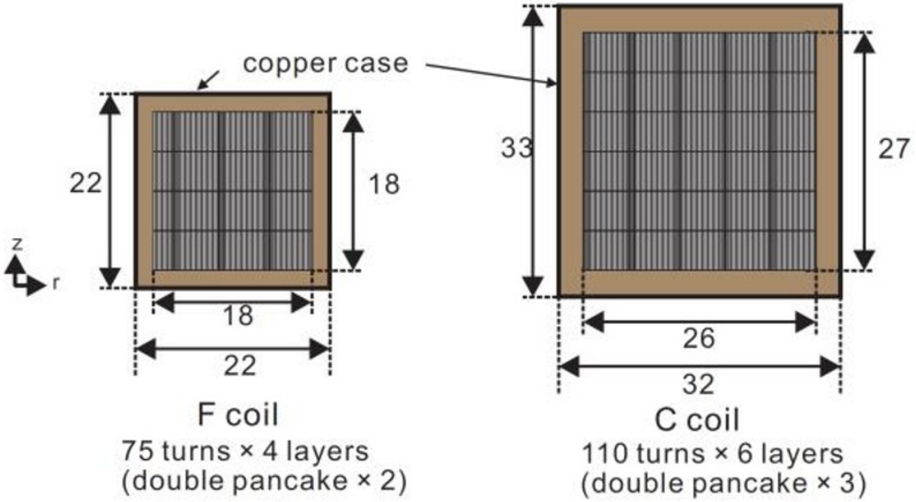
Saitoh et al. "A note on levitation techniques toward construction of a superconducting levitated dipole experiment." Technical Report IPP 17/52, MPI for Plasma Physics, 2016.

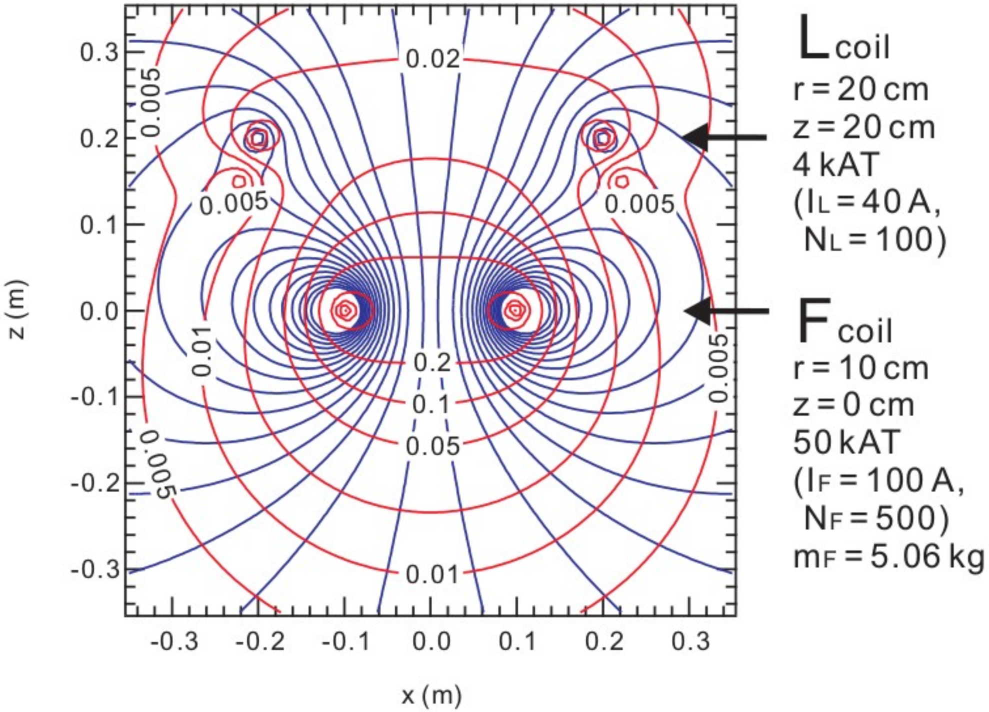
Design and construction of optimized coil set

After solving a non-trivial optimization problem . . .

- excitation vs. size of confinement region
- more windings or more shielding → more weight
- T_c decreases with I, B
- plasma parameters . . .

. . . floating and charging coils are decided and have been wound:

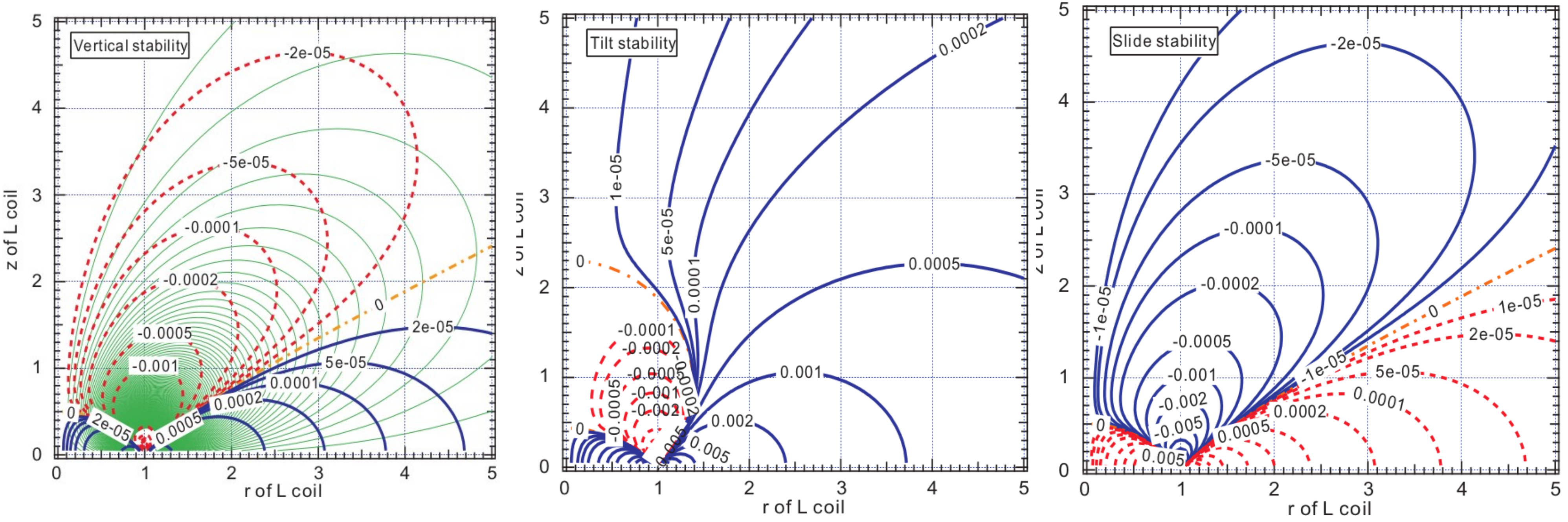




Levitation control system

- no stable equilibrium
- with judicious parameter choices, simplifies to 1D stability problem

Haruhiko Saitoh, et al. *A note on levitation techniques toward construction of a superconducting levitated dipole experiment.* IPP Report (on Pinboard).



Plasma existentialism

When does a collection of charged particles become a plasma?

Popular criteria: multiple Debye lengths, skin depths

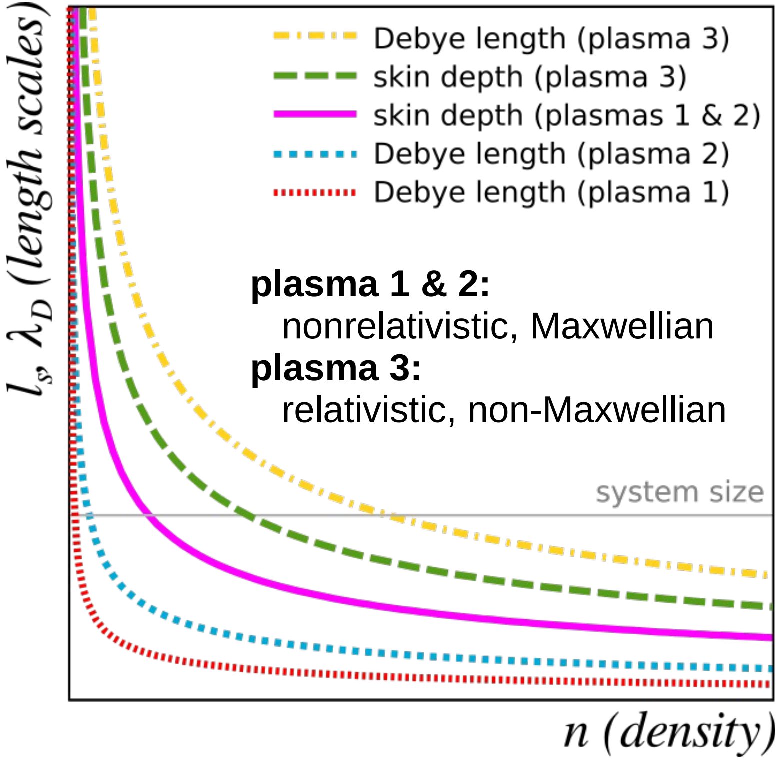
Debye length: $$\lambda_D = \sqrt{\frac{\epsilon_0 \kappa T_e}{2 n_e e^2}}.$$ (pair plasma, Maxwellian)

plasma skin depth: $$l_s = \frac{c}{\omega_p} = \frac{c}{\sqrt{2}\omega_{pe}}$$ (pair plasma, non-relativistic)

where $$\omega_p = \sqrt{\frac{2 n_e e^2}{\epsilon_0 m_e}} = \sqrt{2}\omega_{pe}$$

ratio of the two: $$\frac{l_s}{\lambda_D} = \sqrt{\frac{m_e c^2}{\kappa T_e}}.$$

Compare length scales to system size:



Stenson et al. J. Plasma Phys. 83 (1), 2017

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Debye length > system:

- Quasi-neutrality cannot be assumed (for anything smaller than the whole system).
- Self-generated electrostatic potentials cannot "compete" with thermal effects.

plasma skin depth > system:

- Some wave physics (useful for reflectometry, e.g.) is not accessible.
- Any wave that "fits" in the system involves faster time scales than Debye shielding.

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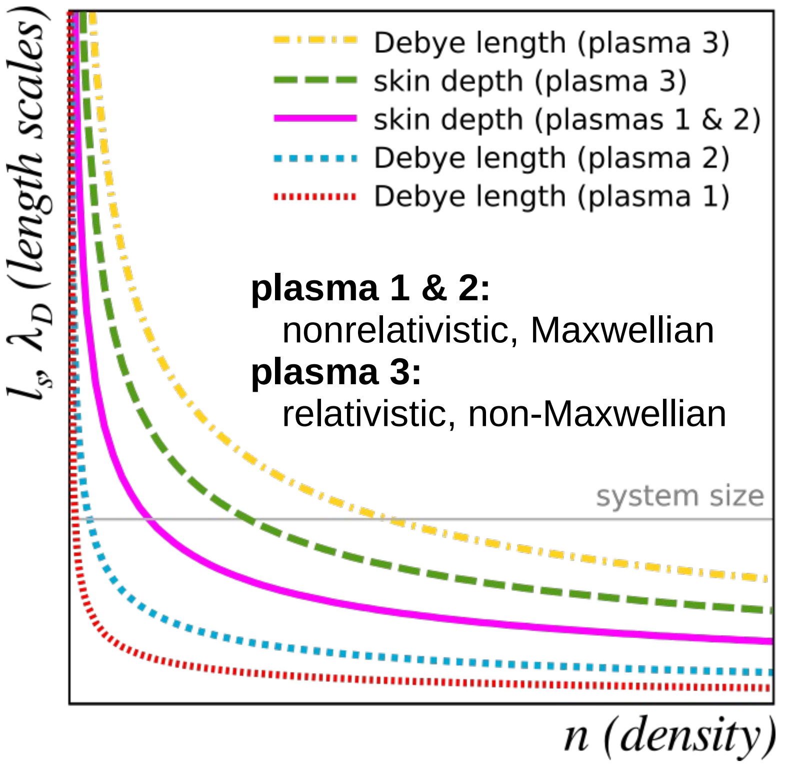

Stenson et al. J. Plasma Phys. 83 (1), 2017

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Collective phenomena can also occur below these thresholds (e.g., non-neutral plasmas, beam-beam instabilities).

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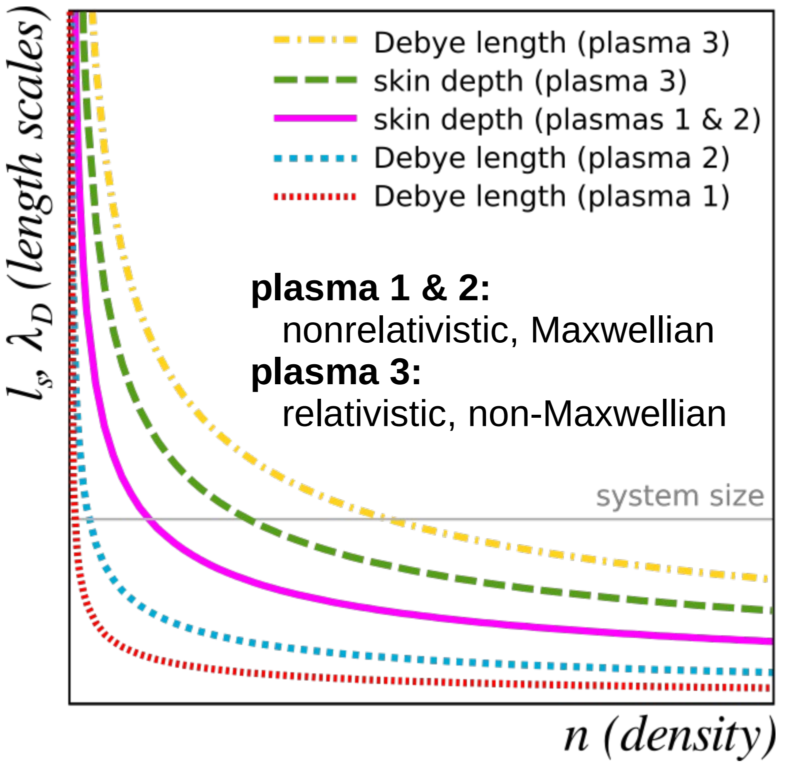

Stenson et al. J. Plasma Phys. 83 (1), 2017