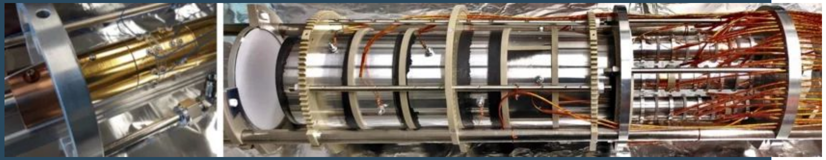
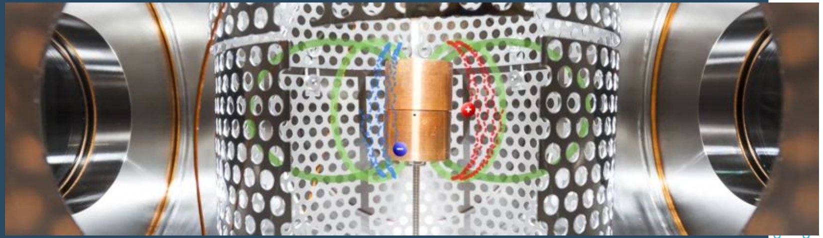
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Highlights from the path to confined pair plasmas

APEX

E. V. Stenson (Max Planck Institute for Plasma Physics),
on behalf of the APEX Collaboration

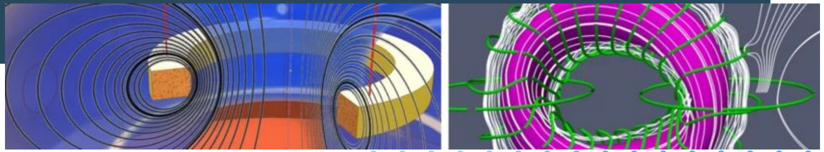




15th International Symposium for Space Simulations (ISSS-15)

16th International Workshop on the Interrelationship between
Plasma Experiments in the Laboratory and in Space (IPELS-16)

9 August 2024 ○ Garching



HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DFG
Deutsche
Forschungsgemeinschaft

erc
European Research Council
Established by the European Commission

UCSD
Foundation

Alexander von Humboldt
Stiftung / Foundation

Outline

I. Introduction & motivation

- the APEX Collaboration
- the compelling goal of laboratory pair plasmas
- our “grand scheme”:
  - ➜ sufficient positrons
  - ➜ suitable traps
  - ➜ the parts in between

II. Latest progress & coming attractions

- answering key questions in prototype set-ups
- next-generation experiments
- putting the pieces together

A Positron Electron eXperiment (APEX) collaboration

Max Planck Institute for Plasma Physics

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S. Nißl[4]

Martin Singer[1]

P. Steinbrunner[1]

P. Huslage[5]

P. Gil[5]

V. C. Bayer

A. Zettl, D. Schmeling, E. von Schoenberg, D. Orona

E. Buglione-Ceresa, D. Mendonça

stellarator theory: P. Helander[1], A. Mishchenko, P. Costello

Lawrence University

M. R. Stoneking

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

Technische Universität München

C. Hugenschmidt

A. Card

University of Greifswald

L. Schweikhard

University of California San Diego

C. M. Surko, J. R. Danielson

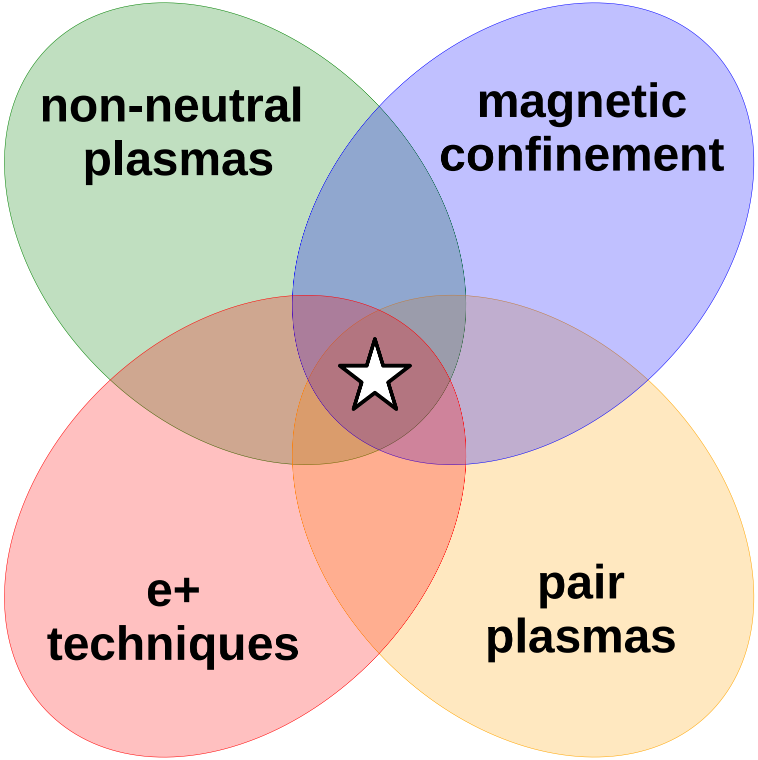
The University of Tokyo

H. Saitoh

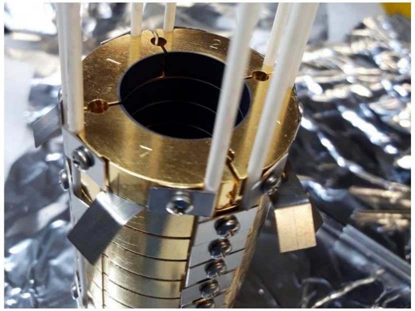
+ a growing contingent of alumni
(U. Hergenhahn, D. Kennedy, S. König, J. Horn-Stanja, C. W. Rogge, T. Sunn Pedersen, Markus Singer, et al.)

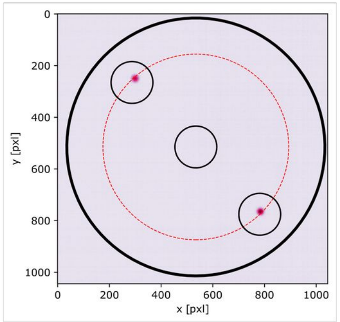
+ project-focused collaborations & co-authors

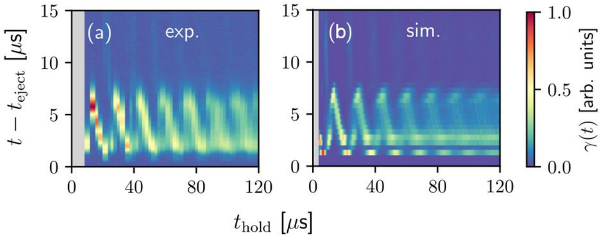
The APEX Collaboration’s research areas

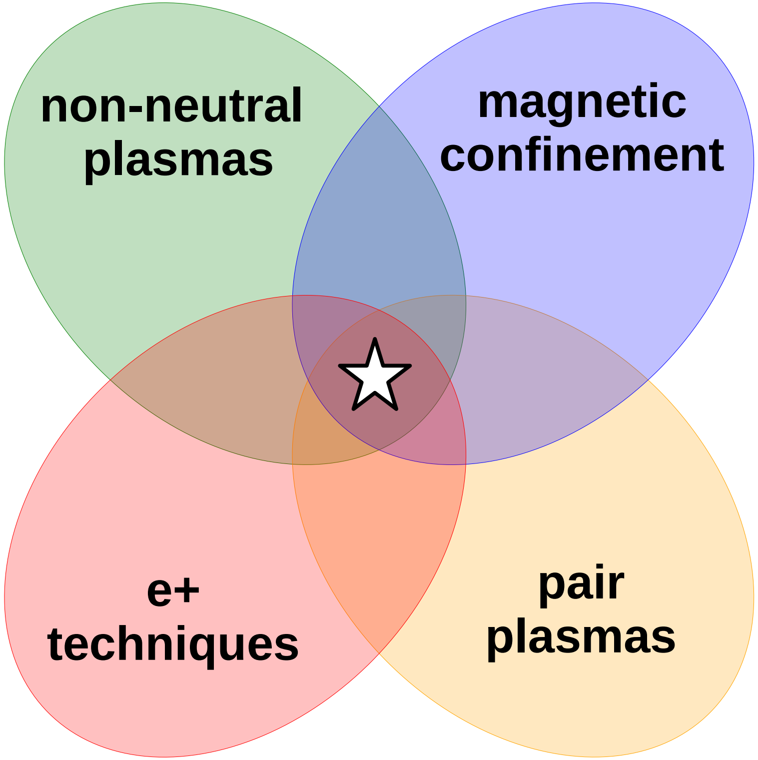


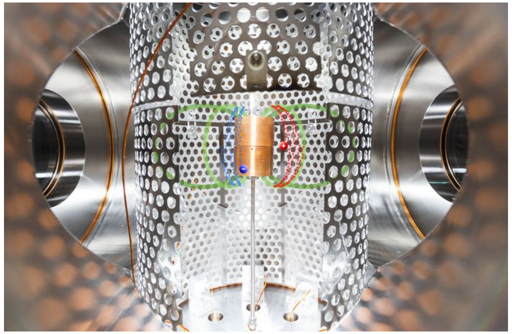
The APEX Collaboration's research areas

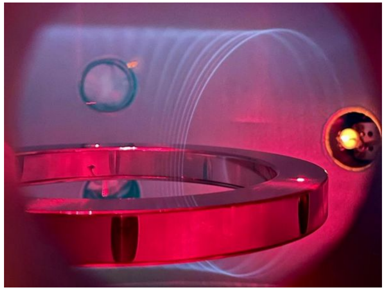


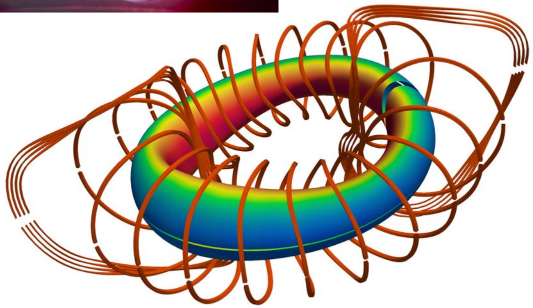












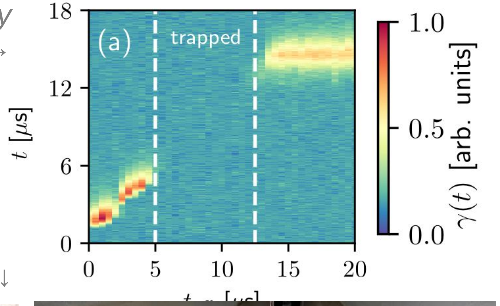
What we're working on, in a single slide

The APEX Collaboration seeks to:

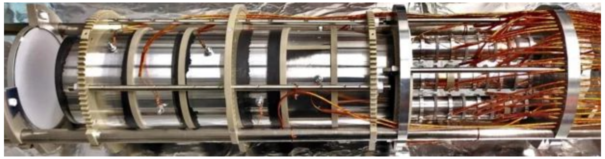
- Accumulate positrons in record numbers (for our purposes and for others').
- Create and investigate uniquely simple, symmetric quasi-neutral plasmas (potentially turbulence-free!).
- Use the plasmas/positrons as sensitive probes for fundamental plasma processes (e.g., transport, regime-crossing,...).
- Contribute to the advancement of the state-of-the-art science/technologies we are using (e.g., non-neutral plasmas, e+ science, HTS coils, stellarator design, etc.).

snapshots from current & recent projects:

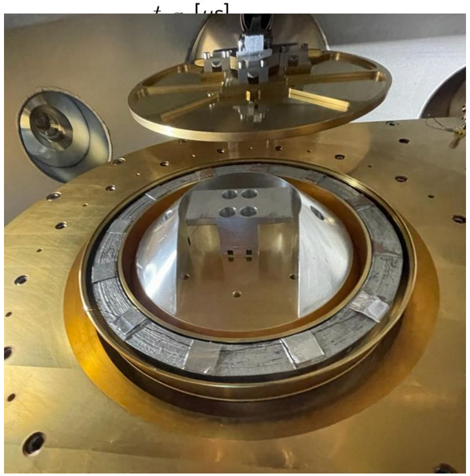
using gammas to study transport/losses →



multi-cell, non-neutral plasma tap ↓



3d-printed winding frame for a nonplanar, HTS coil →



"floating coil" (sitting in cryostat, ready for cooling/quench tests)

Space (& simulation) connections

courtesy of P. Steinbrunner

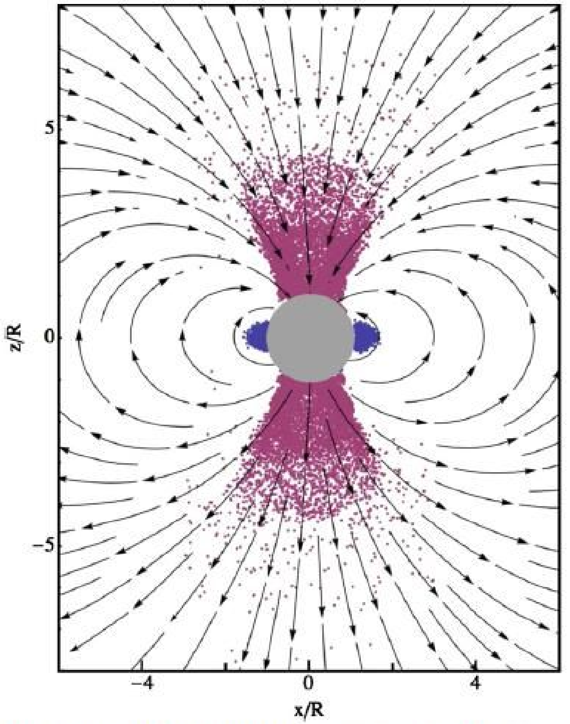


Figure 2. Slice through the 3D charge-separated magnetospheric solution showing disk–dome configuration. The magnetic field (arrows) does not change from the initial dipole outside of the star. Electrons are blue, positrons are red.
(A color version of this figure is available in the online journal.)

Philippov & Anatoly Spitkovsky. "Ab Initio Pulsar Magnetosphere: Three-dimensional Particle-in-cell Simulations of Axisymmetric Pulsars." ApJ Lett. 785, Issue 2, L33 (2014).

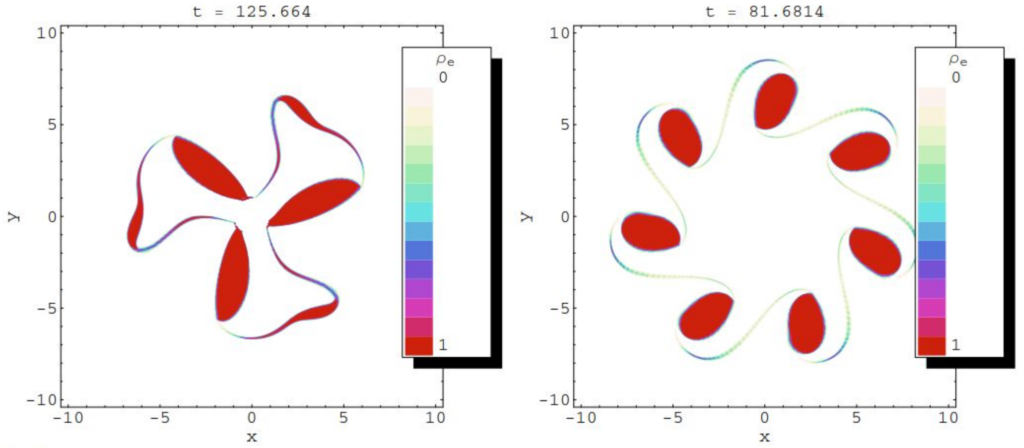


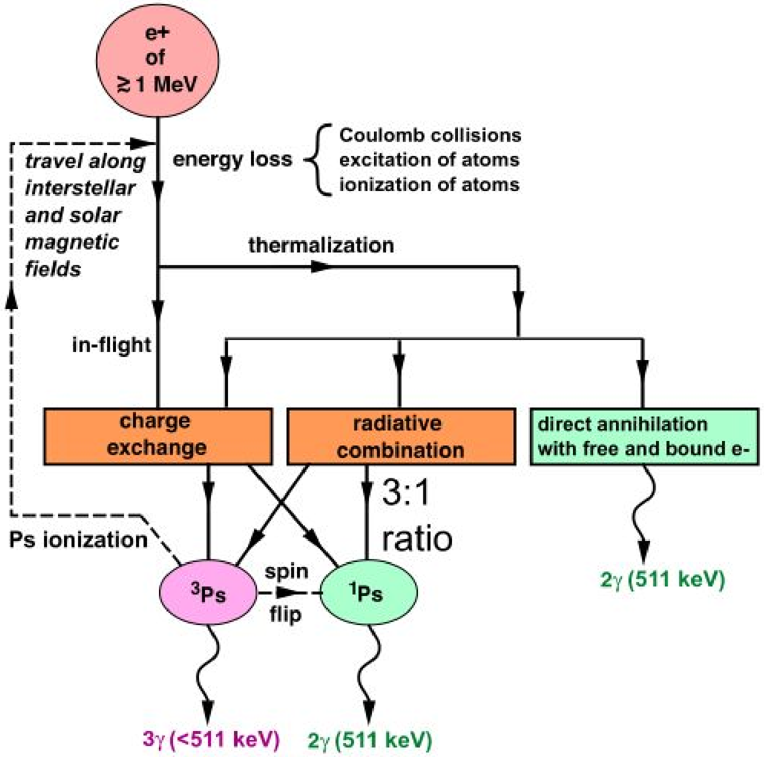
Fig. 2. Snapshot of the charge density in the plasma column showing the $m = 3$ pattern (*on the left*) and the $m = 7$ pattern (*on the right*). The chosen time corresponds to the transition between the linear phase and the beginning of the non-linear regime, associated with the total electrostatic energy curves discussed in Fig. 1.

J. Pétri, "Non-linear evolution of the diocotron instability in a pulsar electrosphere: two-dimensional particle-in-cell simulations." A&A Volume 503, Number 1 (2009).

Space (& simulation) connections

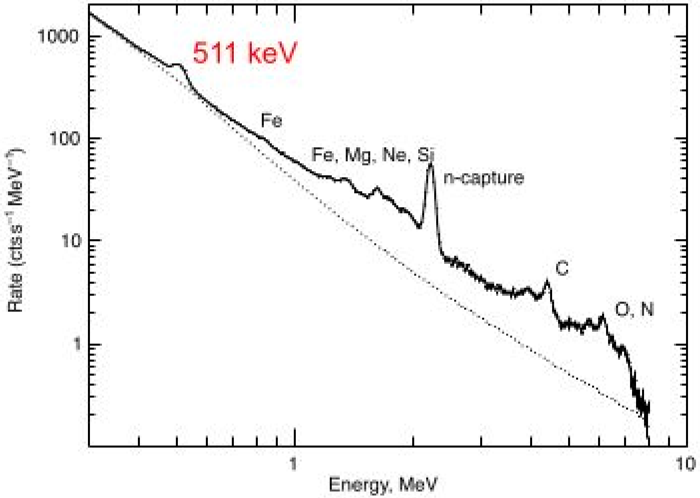
Life of positrons in interstellar media and solar chromosphere

courtesy of J. von der Linden



Modified figure from Murphy et al. (2005) Astro.phys. J. Supp.

Gamma spectra of solar flares



Can we relate the ratio of the 2-gamma line and the 3-gamma continuum to the chromospheric media by understanding the contributions of Ps formation, direct annihilation, spin-flip, and Ps ionization?
figure from Murphy (2007) Space Sci. Rev.

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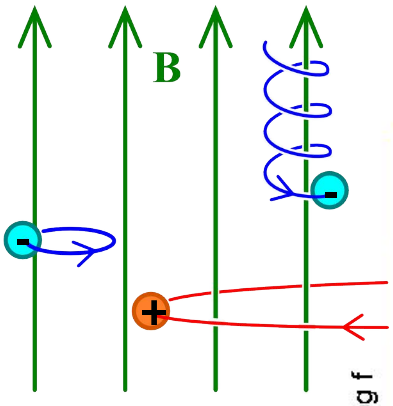
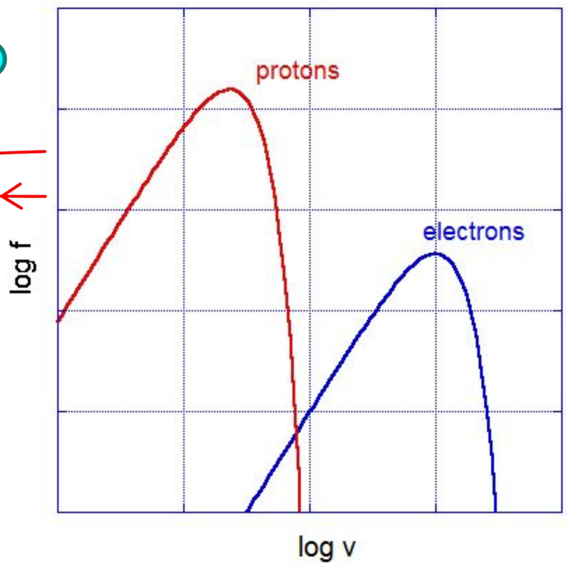
Pair plasmas: an exciting frontier

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



ion/electron mass ratio ≥ 1836



Pair plasmas: an exciting frontier

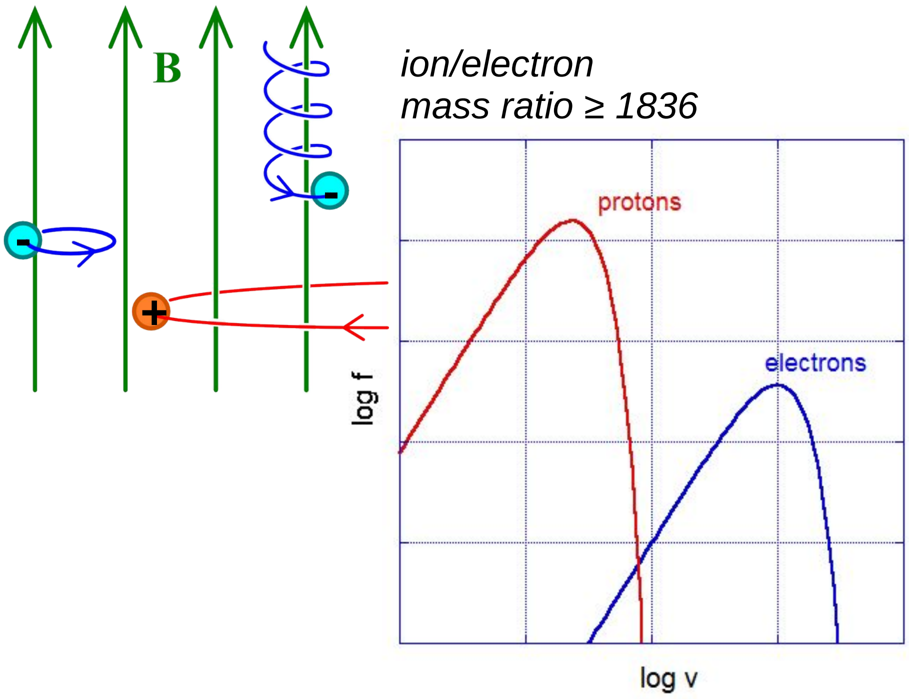
Mass asymmetry is a cornerstone of the physics of quasi-neutral plasmas . . .

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

➡ ~1000 papers on "pair plasmas"

(but experimental side still in its nascence)

ion/electron
mass ratio ≥ 1836



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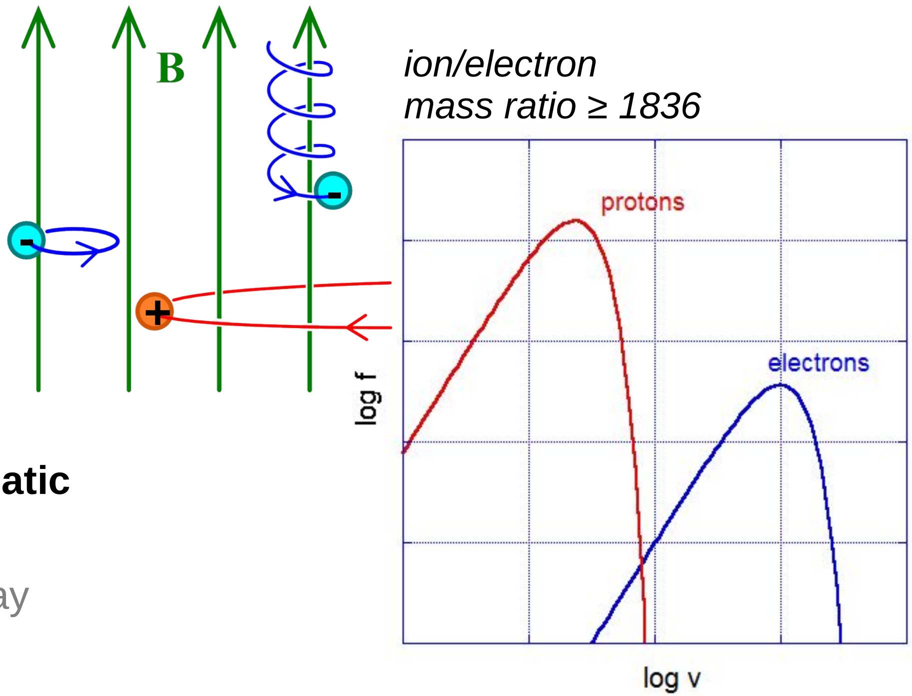


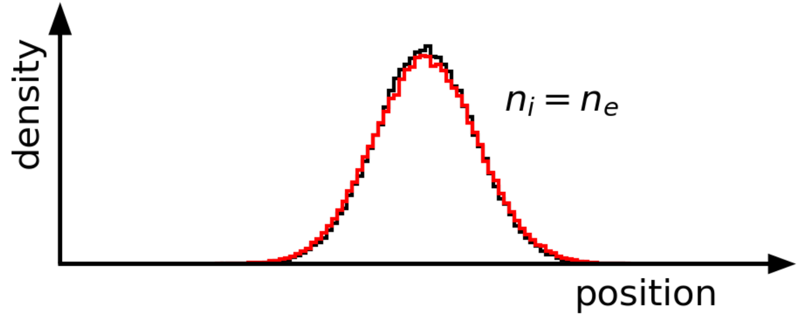
In comparison to electron/ion plasmas, certain dramatic changes to plasma properties are predicted:

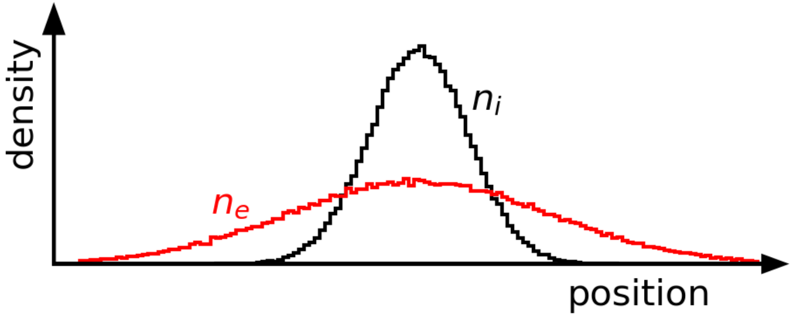
- disappearance of some phenomena (sheaths, Faraday rotation, whistler waves, lower hybrid waves . . .)
- changes in characteristic properties with regard to others (reconnection, turbulence, soliton solutions . . .)
- “remarkable stability properties” in certain geometries and parameter regimes → turbulence-free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

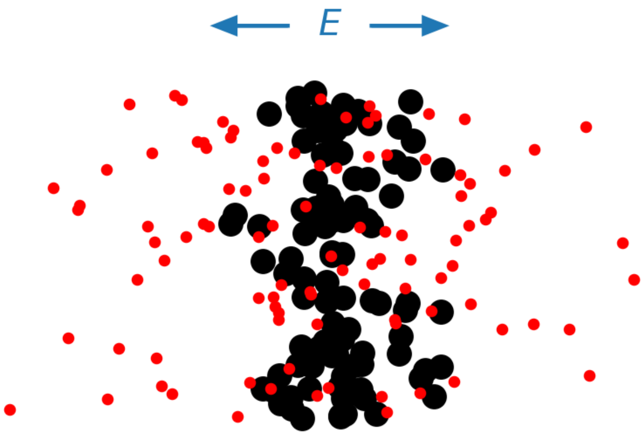
References:

Tsytovich & Wharton (*CPPCF* 1978)
Sarri et. al. (*JPP* 2015)
Helander (*PRL* 2014)
Mischenko (*JPP* 2023)
and many more . . .

Mass asymmetry → coupling between p and E







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

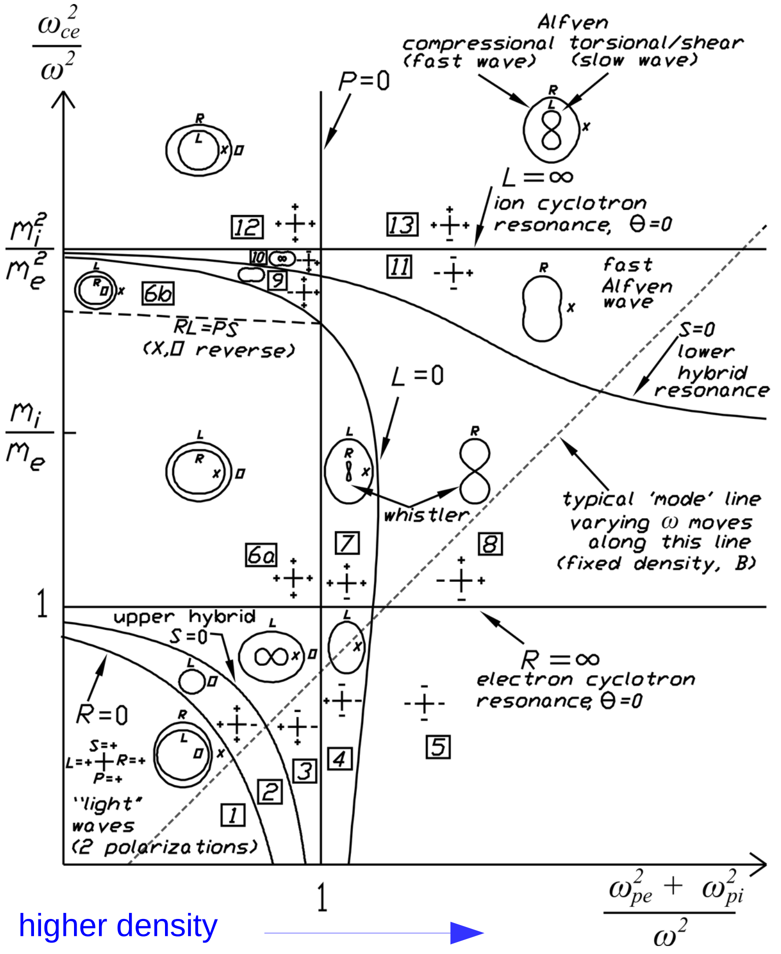
e-p+ movie

vs.

e-e+ movie

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

The landscape of basic plasma waves

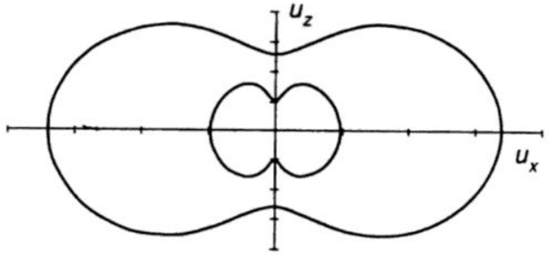


higher density →

standard CMA diagram
(Bellan)

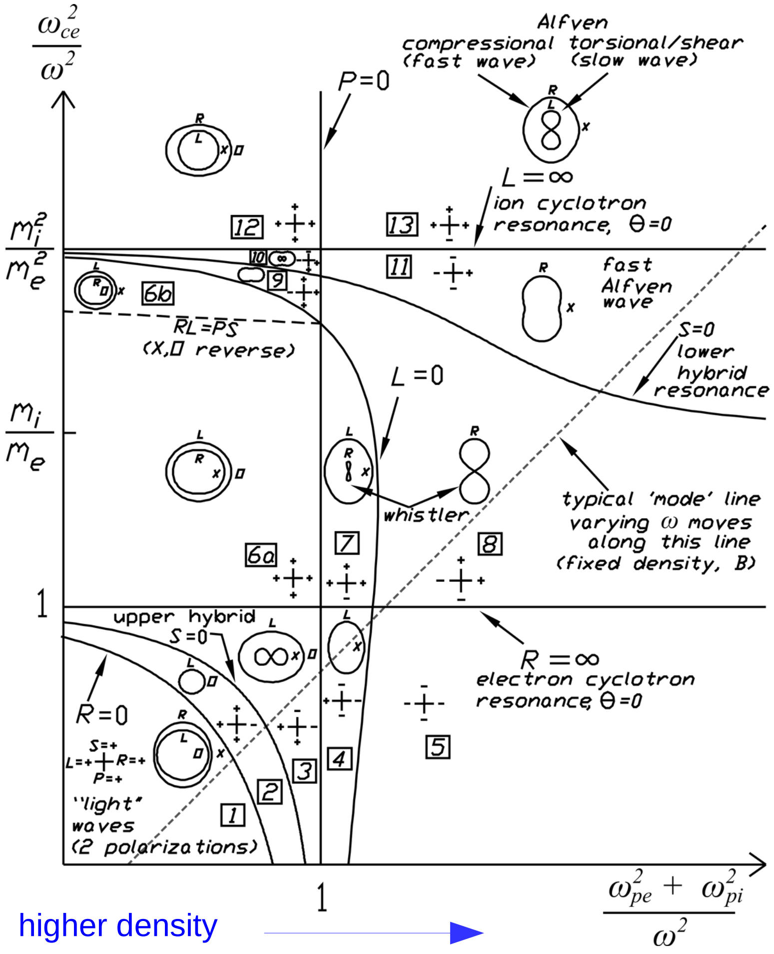
larger magnetic field ↑

- “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

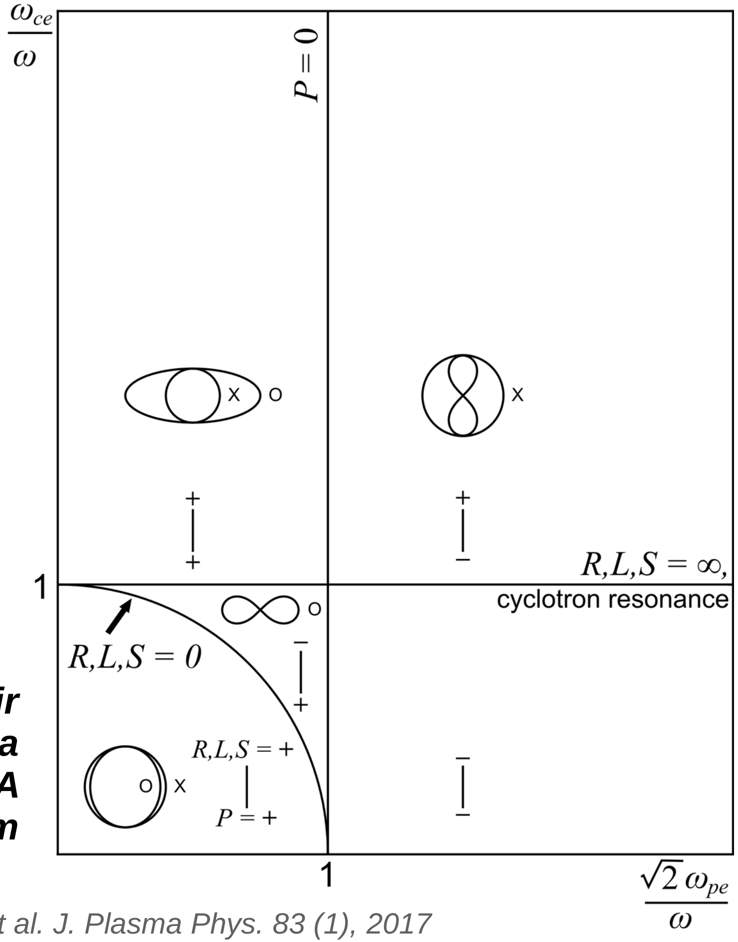


standard CMA diagram *(Bellan)*

larger magnetic field

higher density

pair plasma CMA diagram



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

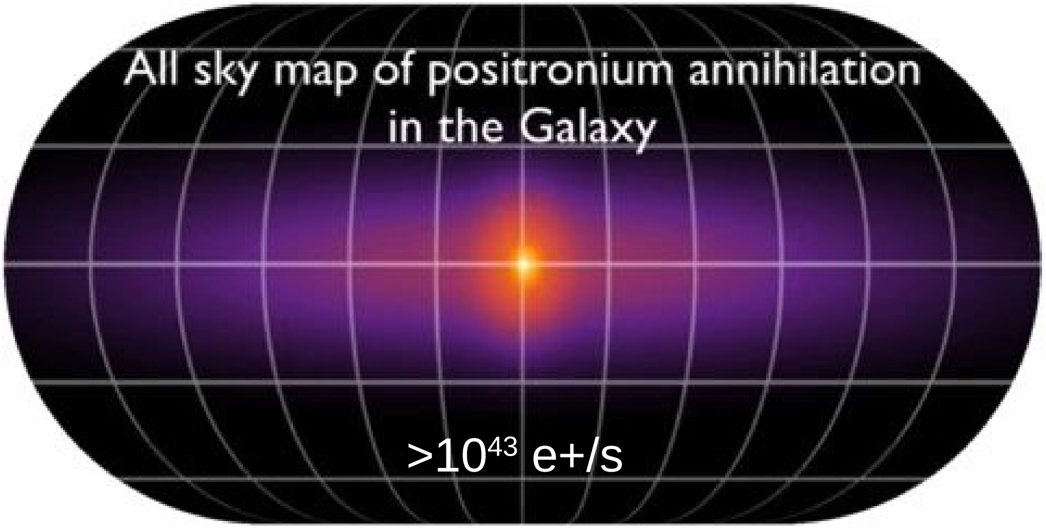
Why pursue pair plasma experiments?

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.**

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

- **Our understanding of our universe.**
  - Lepton Epoch = 1-10 s post-Big-Bang
  - more recent phenomena involving e+e- plasmas: gamma ray bursts, pulsars, 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.

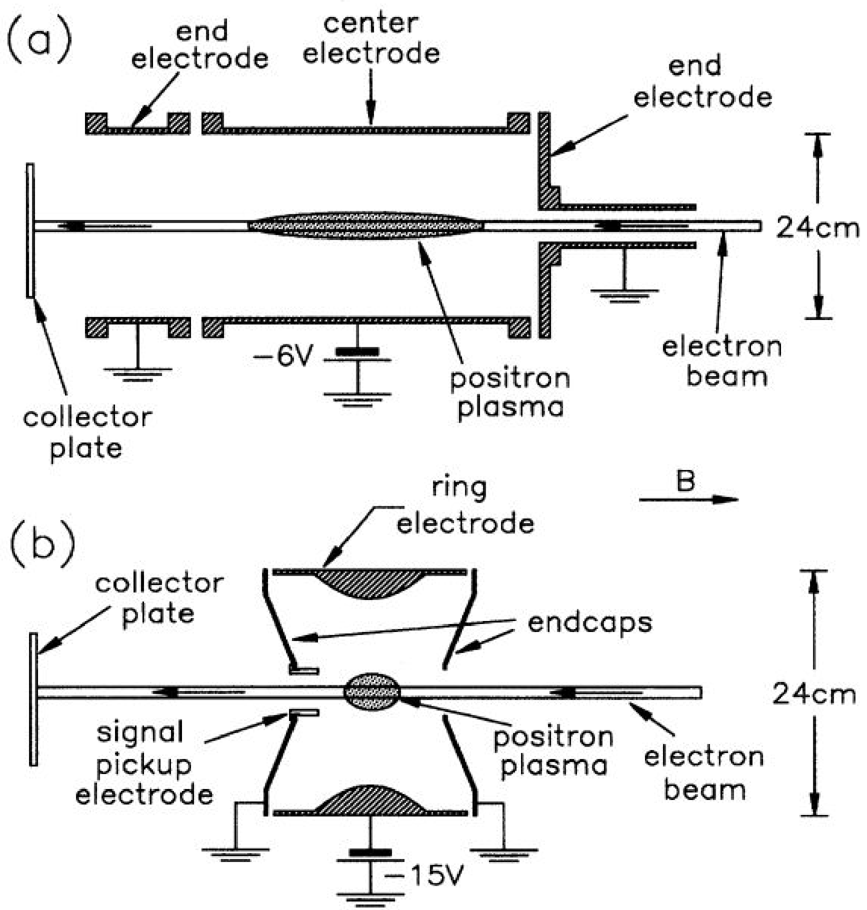
Siegert et al. "Gamma-ray spectroscopy of positron annihilation in the Milky Way". A&A 586, A84 (2016)

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

Approaches to lab pair plasmas

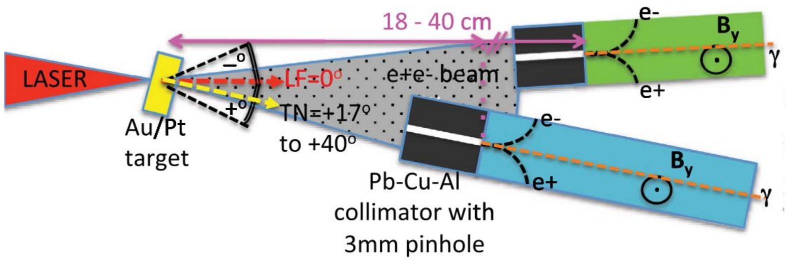
- **Pure positron plasma + electron beam**

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

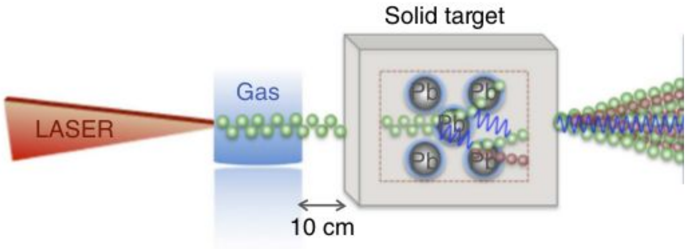


Approaches to lab pair plasmas

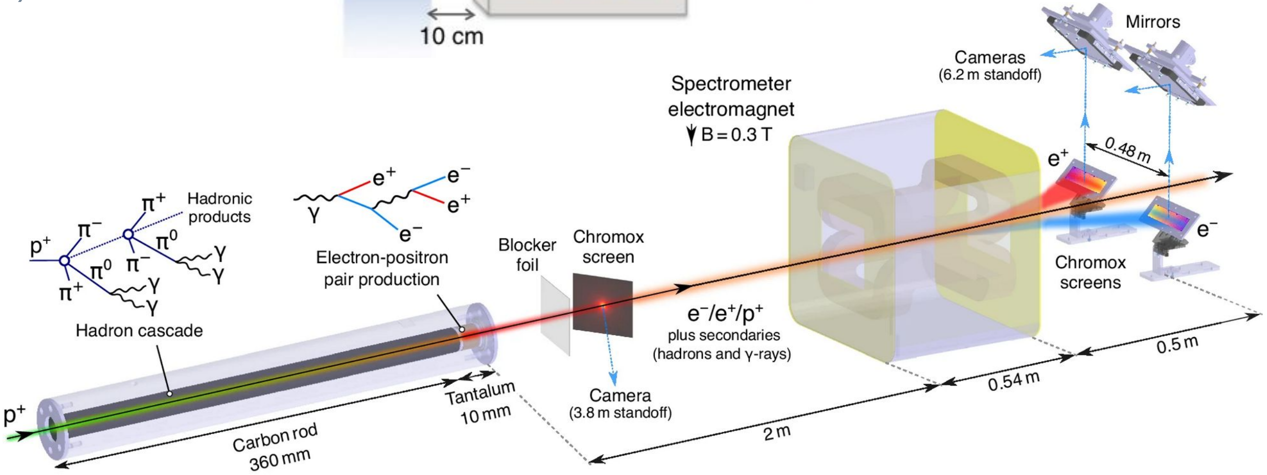
• Pure positron plasma + electron beam



• **Generation of relativistic pairs**



Chen, H., et al. ***Phys. Rev. Lett.*** *102:105001 (2009).*
Liang, E. et al. ***Scientific Reports****, 5, 13968 (2015).*
Sarri, G. et al. ***Nat. Comm*** *6:6747, (2015).*
Arrowsmith, C.D. et al. ***Nat. Comm.*** *15: 5029 (2024).*



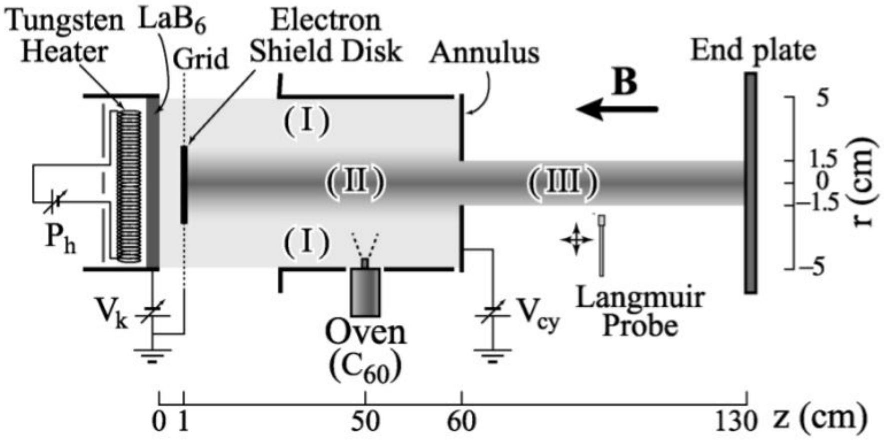
Approaches to lab pair plasmas

- Pure positron plasma + electron beam

- Generation of relativistic pairs

- **Fullerene pair plasmas**

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



Approaches to lab pair plasmas

- Pure positron plasma + electron beam
- Generation of relativistic pairs
- Fullerene pair plasmas
- **Low-temperature e-e+ plasmas in toroidal traps**

*T. S. Pedersen, et al., **NJP** 14, 035010 (2012).*
*Stoneking et al. **JPP** 86, Issue 6, 155860601 (2020).*

Goals:

many Debye lengths,
both species magnetically confined
(as long as possible)

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

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

(Another option: magnetic mirror trap)

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

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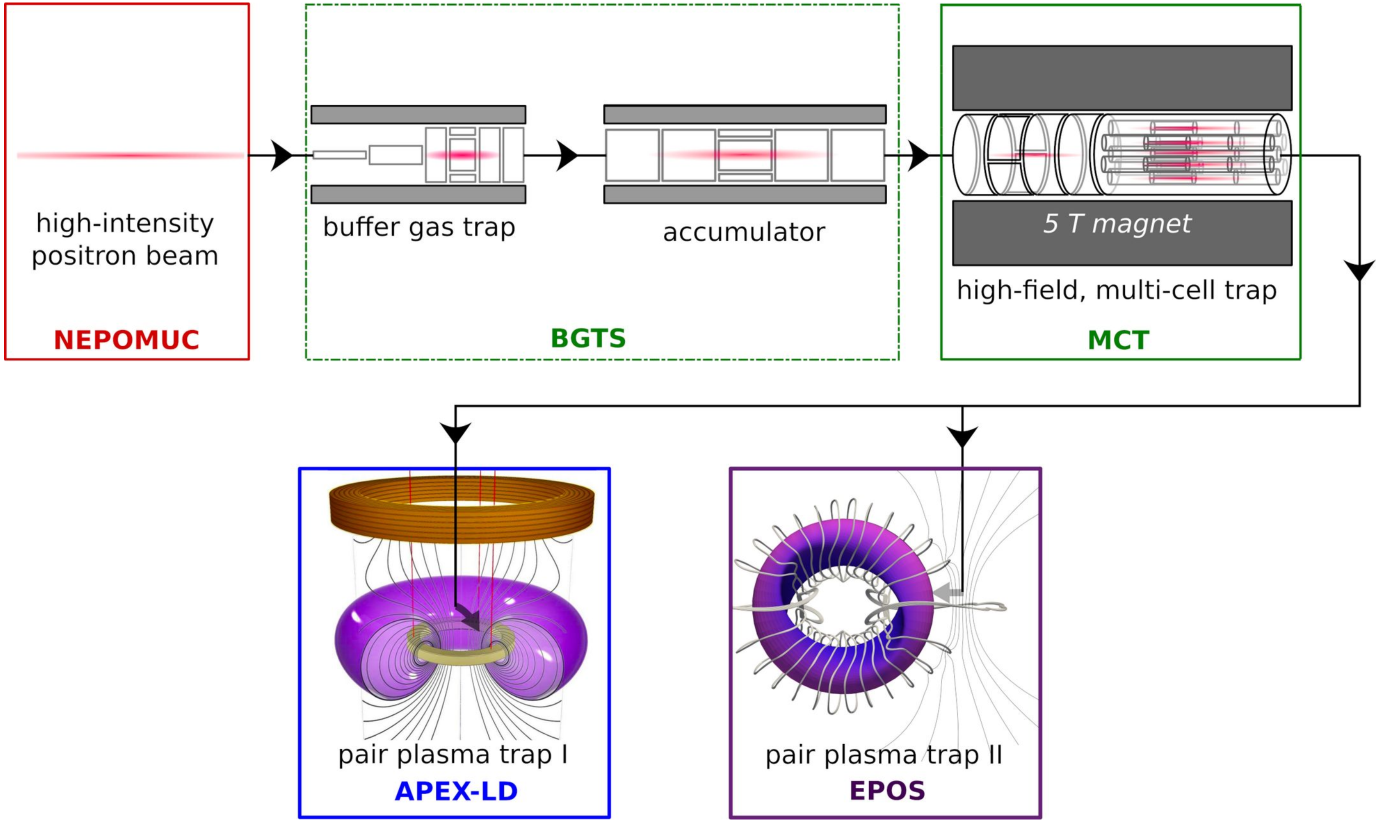
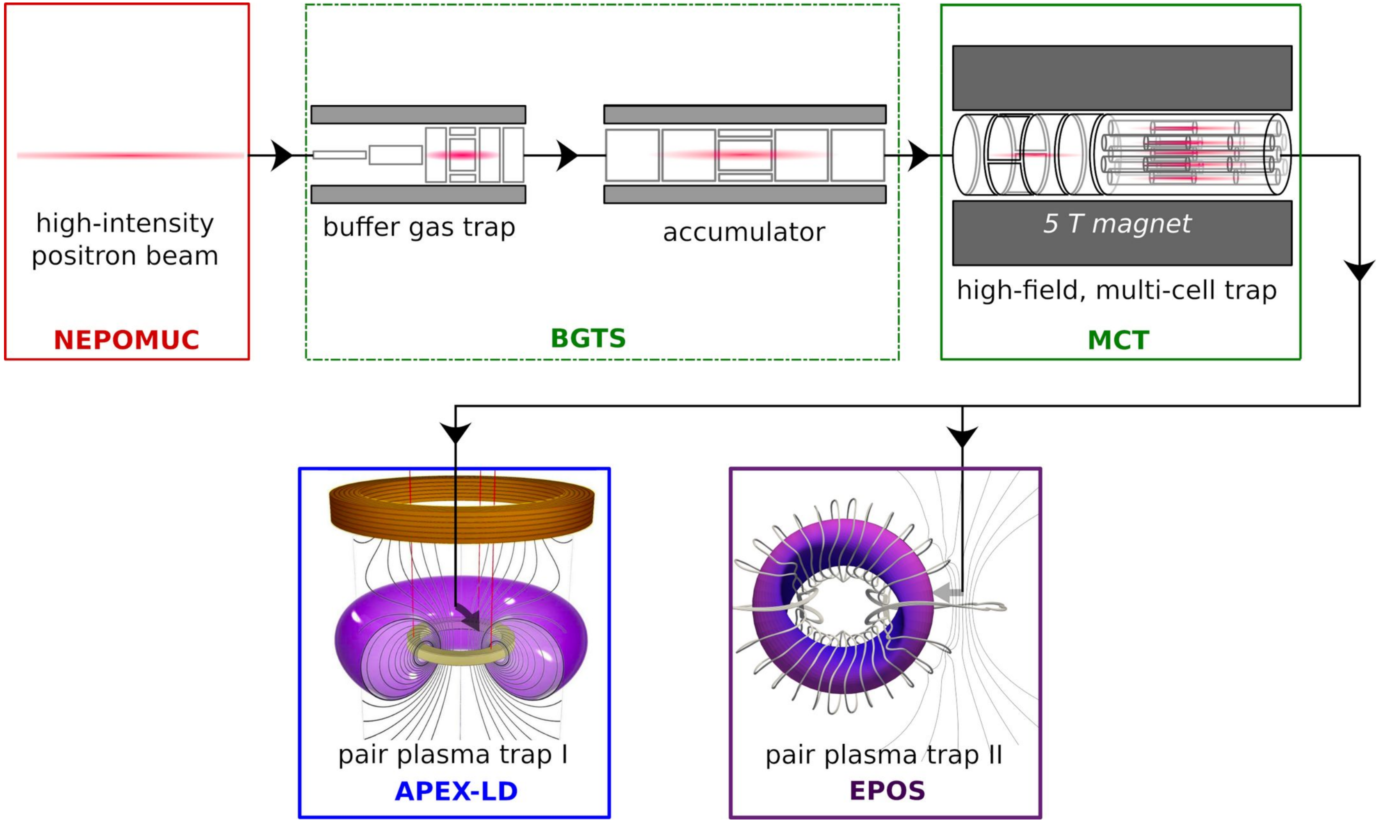
The APEX grand scheme

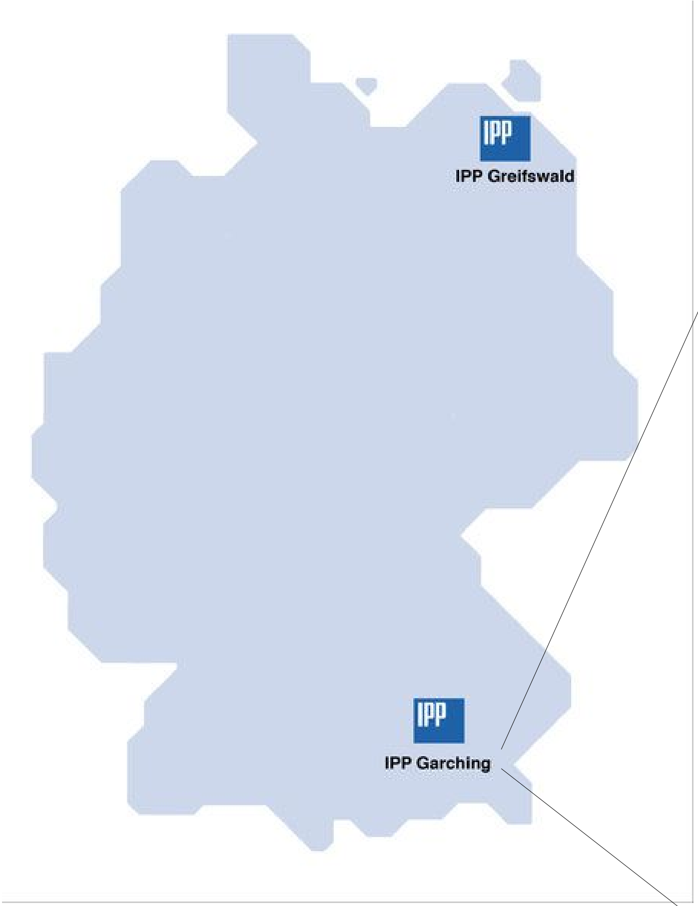


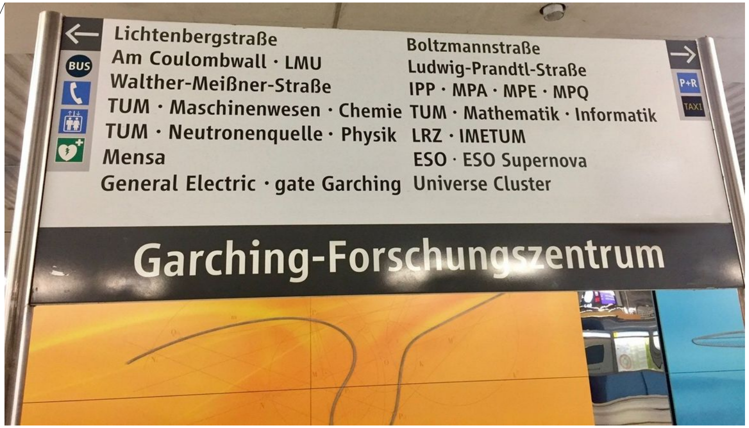
The APEX grand scheme

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



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

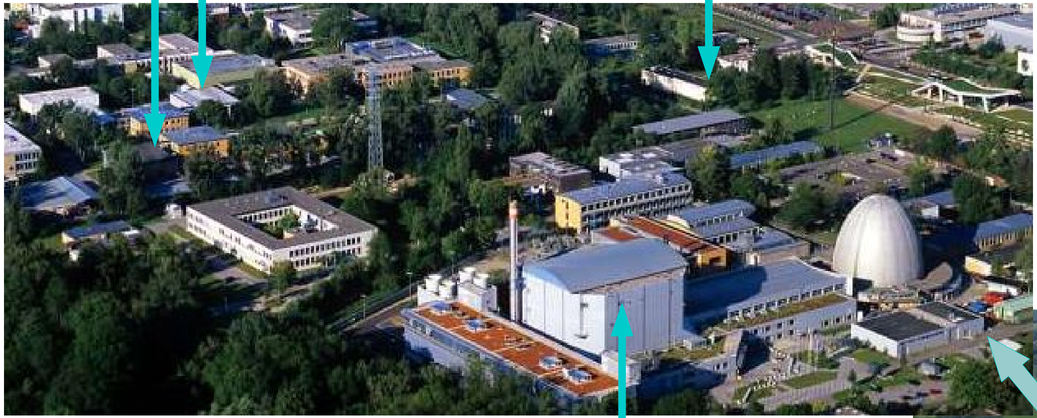




Garching: home of a world-class e+ source

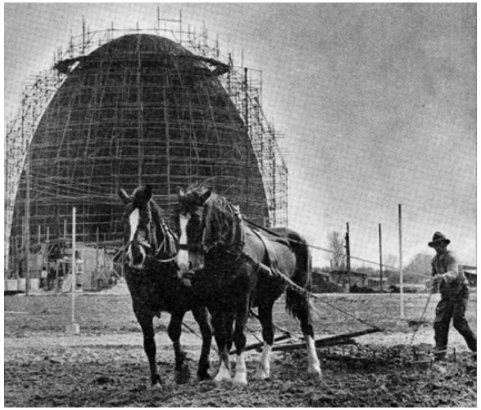
labs @ IPP

offices @ IPP



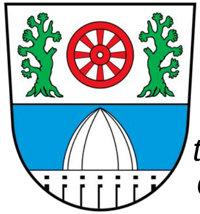
FRM-II:
Forschungs-
Neutronenquelle
Heinz Maier-Leibnitz

(started operation in 2004)



Forschungsreactor München (FRM) in 1957

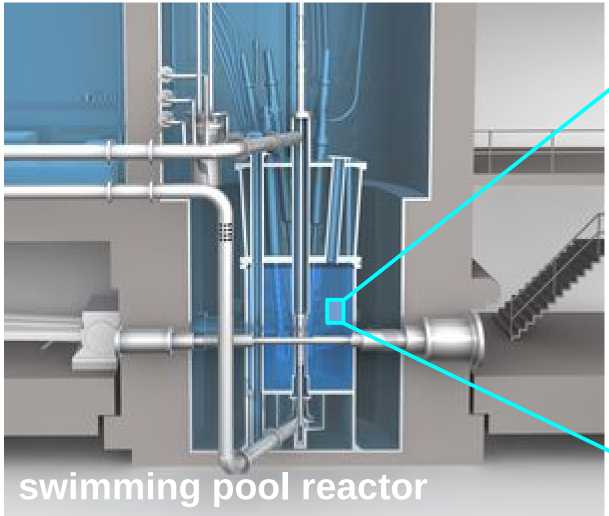
(operated 1957-2000)



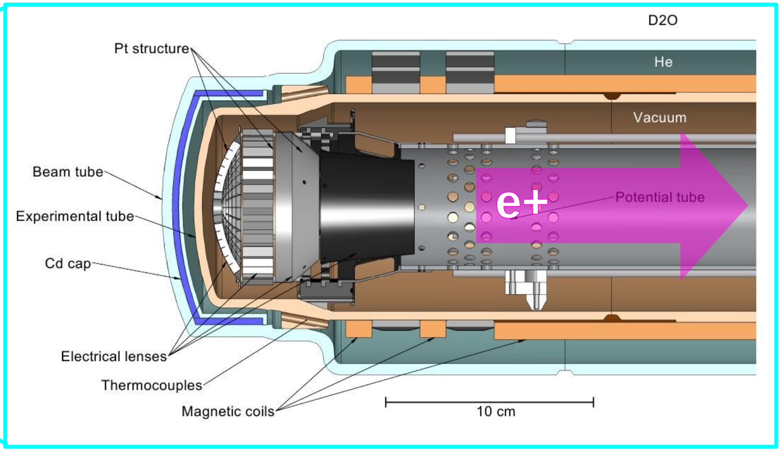
coat of arms for the city of Garching

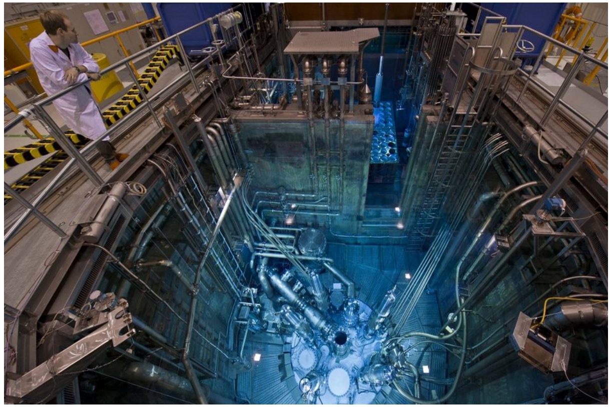
https://mlz-garching.de/aktuelles-und-presse/from-behind-the-sciences/als-vor-dem-atom-ei-noch-geackert-wurde.html

NEutron-induced POsitron source MUniCh



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



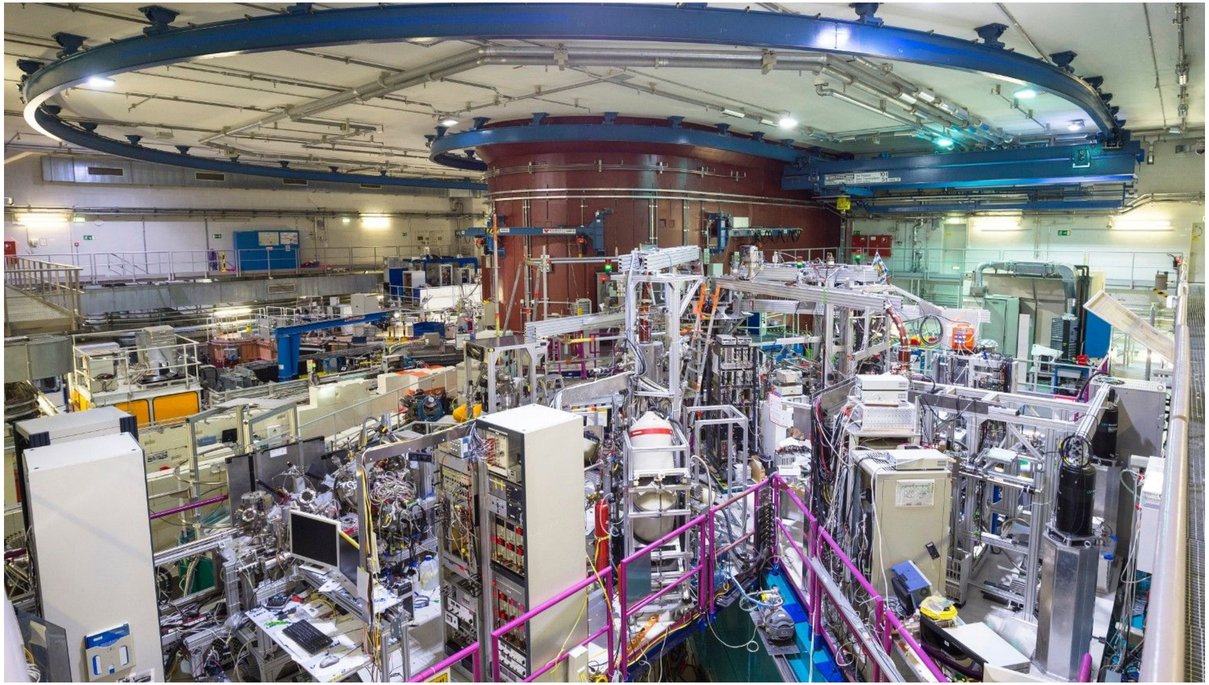


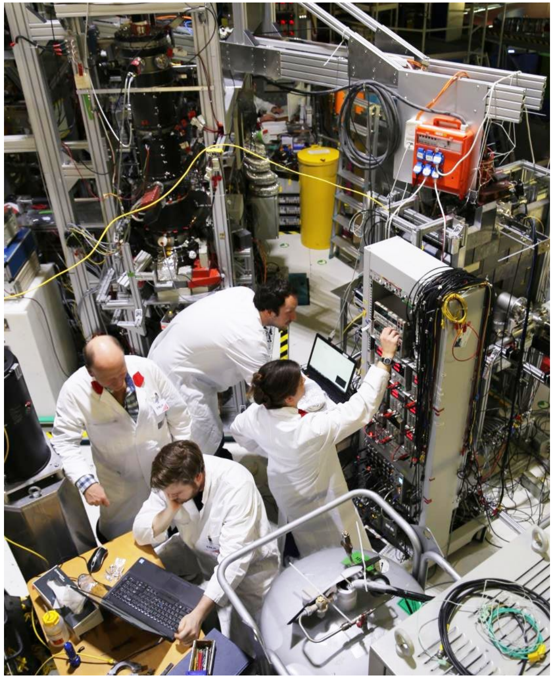
→ **primary beam** (10^9 e+/s @ 1 keV)

→ **remoderated beam** (5×10^7 e+/s @ 20 eV)

C. Hugenschmidt, et al. New J. Phys. 14 055027 (2012).
M. Dickmann, et al. Acta Phys Polonica A 137, 2, 149 (2020).

NEutron-induced POsitron source MUniCh





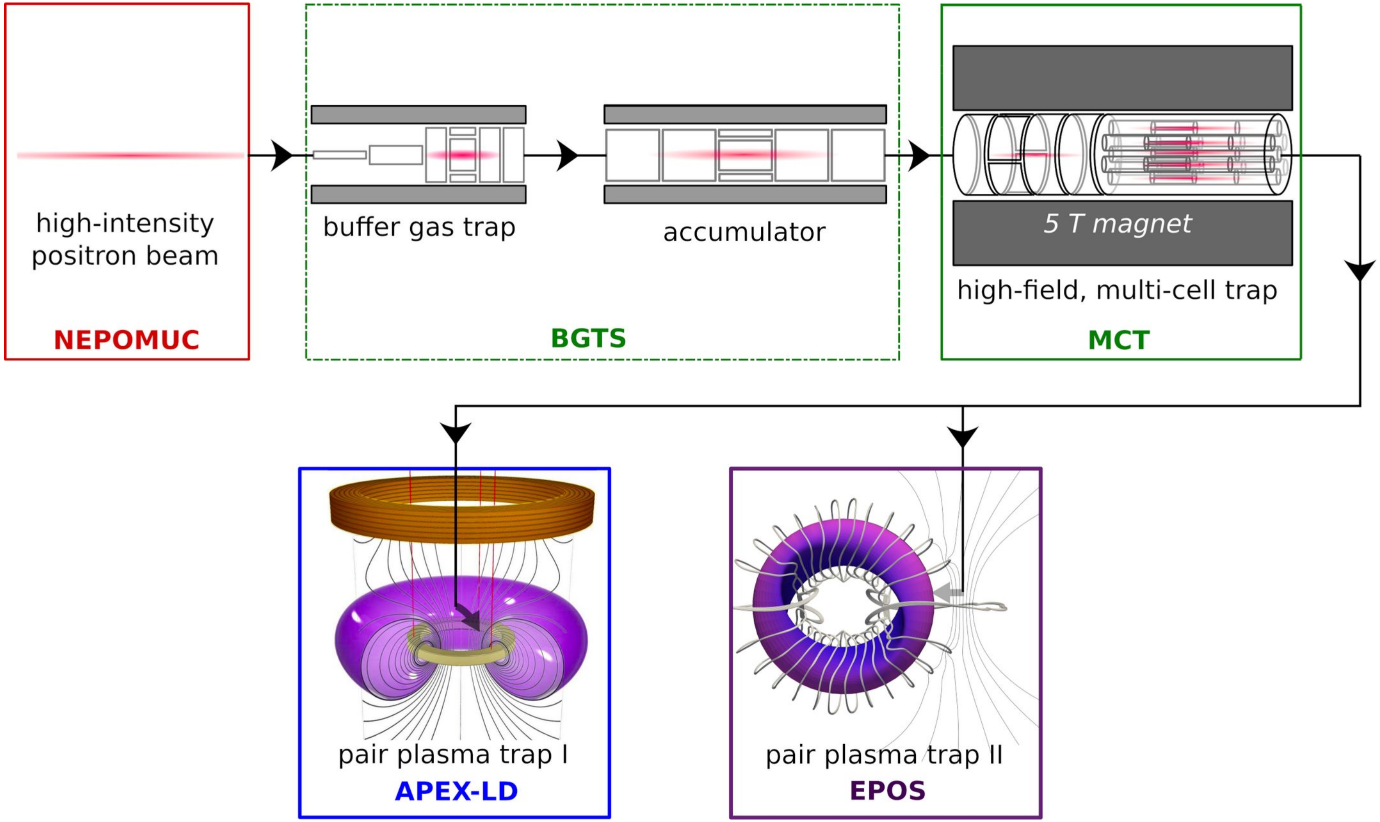
- five-way switch → different experiment stations
- myriad applications in materials & surface science, AMO & antimatter physics, among other areas

→ 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)



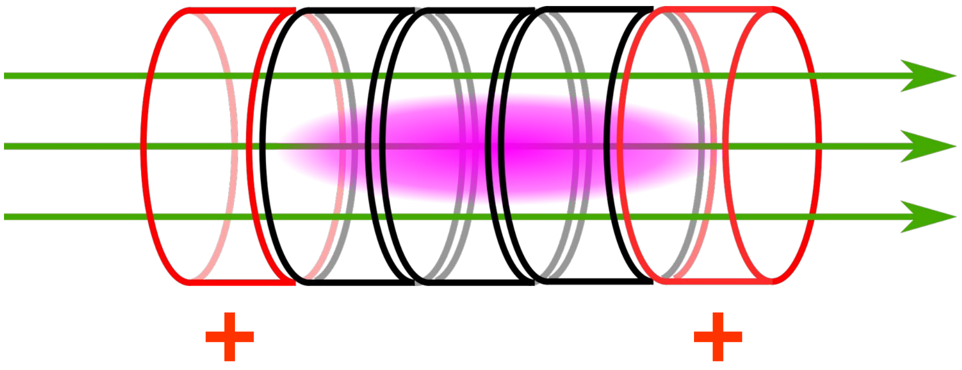
Step 2:
Use a series of non-neutral plasma traps to collect positrons, until we have enough to make a plasma.

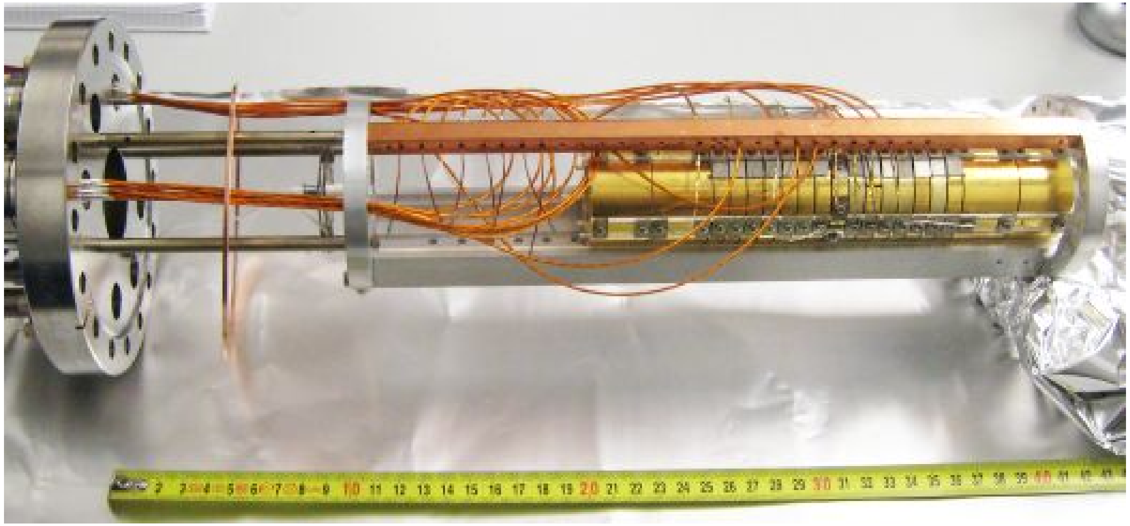
Highly effective traps for a single sign of charge

uniform B
+
axial potential well
+
UHV

=

non-neutral
plasma trap



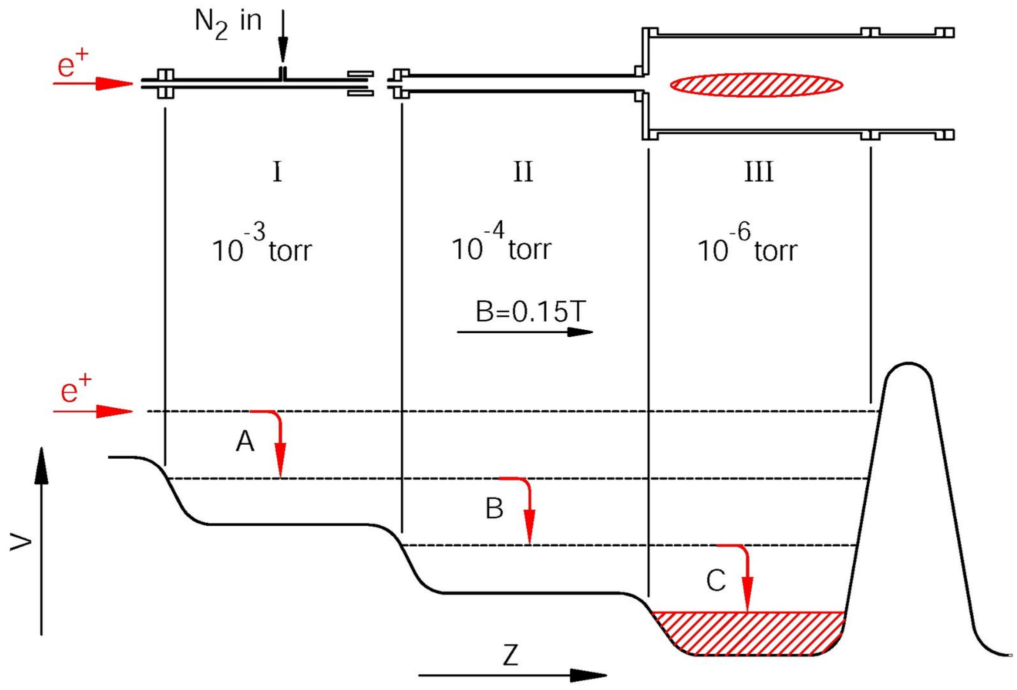


recent reviews:
Fajans & Surko, Phys. Plasmas 27, 030601 (2020).

J. R. Danielson, D. H. E. Dubin, R. G. Greaves, and C. M. Surko. Rev. Mod. Phys. 87, 247 (2015).

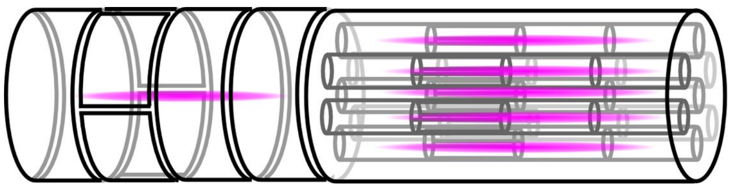
Variations on the basic non-neutral plasma trap

buffer-gas trap:



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

multi-cell trap:



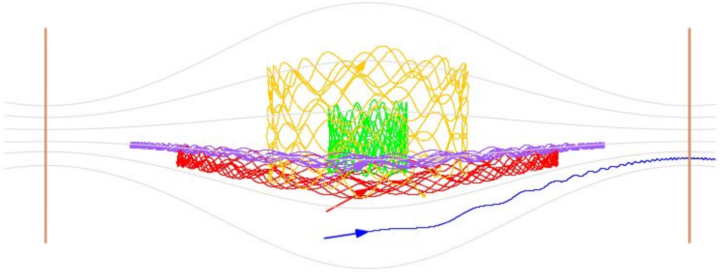
(array of traps to increase the total number of e+ you can stuff into the available volume)

Surko et al. PRL ‘88; Murphy et el. PRL ‘92; Surko Varenna lecture (2010); Danielson et al. RMP '15

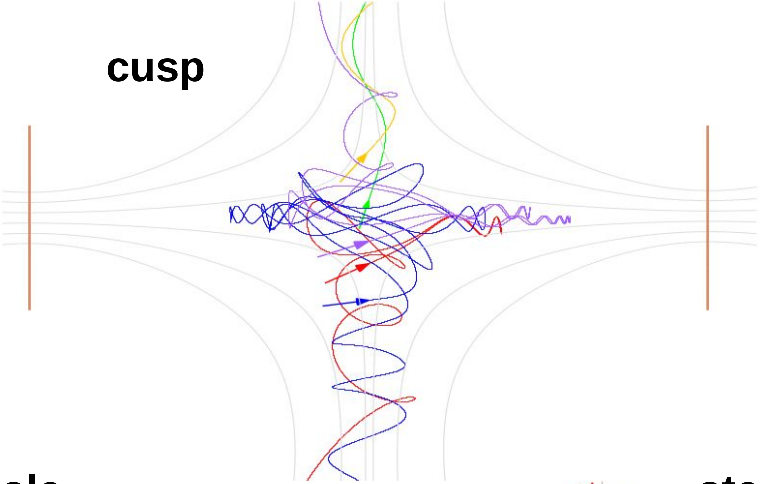
More “exotic” geometries for confining NNPs

when you add electrodes and space charge (not included here)

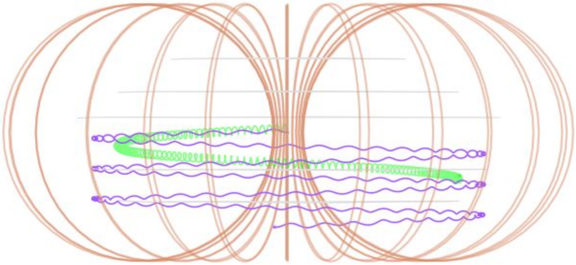
mirror



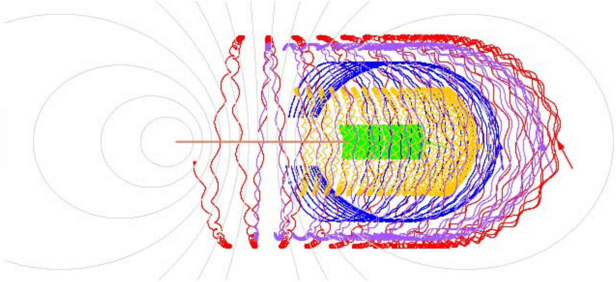
cusp



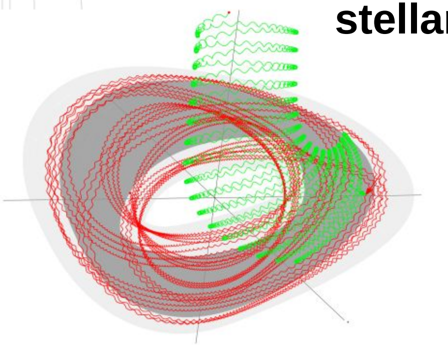
toroidal field



dipole



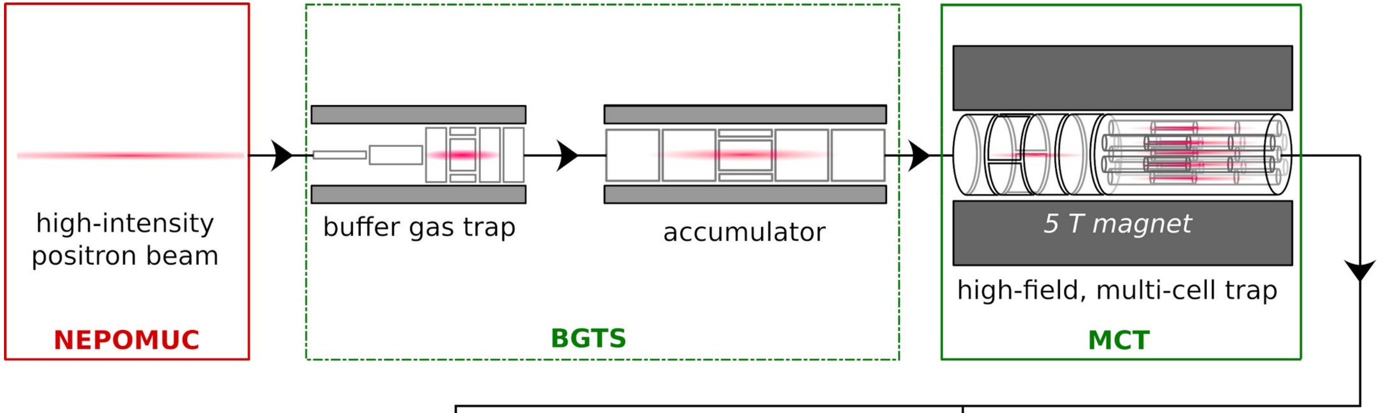
stellarator



Maero, Hunter, Murtagh, Stenson, “Fundamental physics and other applications using nonneutral plasma,” Advances in Physics: X Volume 9, Issue 1, 1-36 (2024).

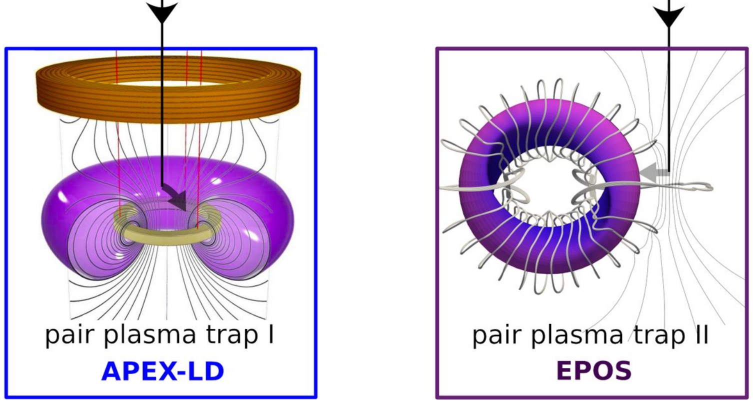
The APEX grand scheme

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



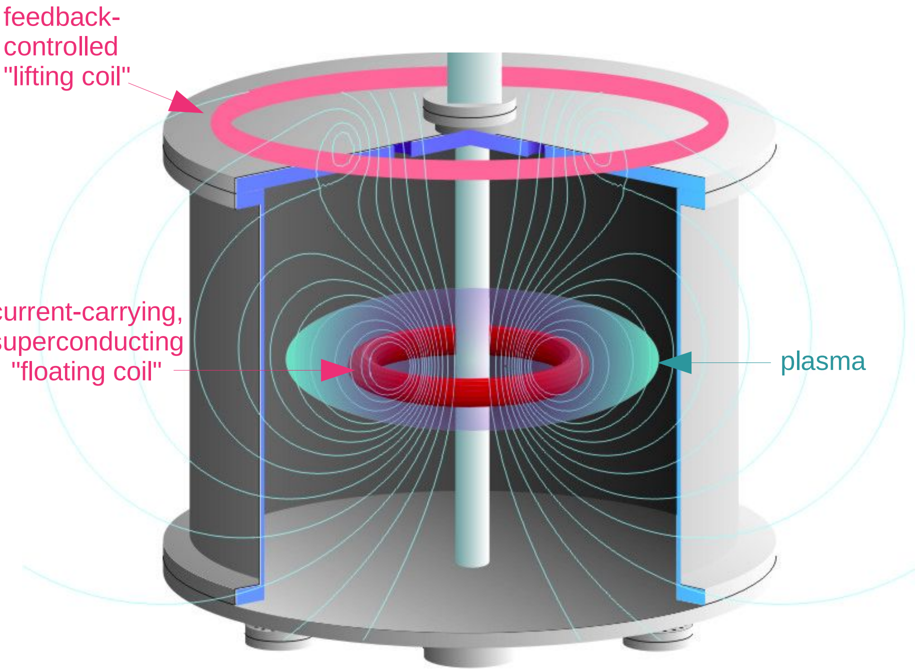
Step 2:
Use a series of non-neutral plasma traps to collect positrons, until we have enough to make a plasma.

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



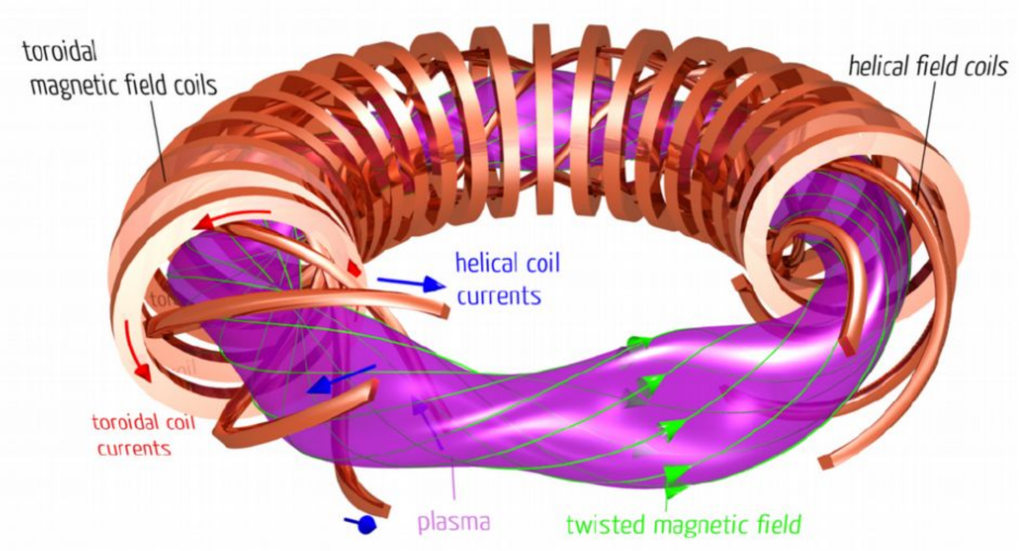
Step 3 (version B):
Combine positrons with electrons in an optimized stellarator.

Companion devices for confining pair plasmas



levitated dipole trap

(other recent examples: LDX, RT-1, . . .)



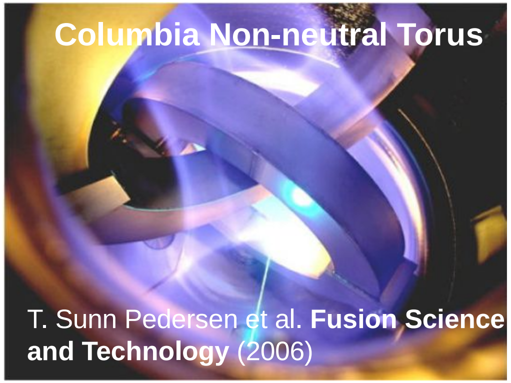
stellarator

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 (no plasma current required)
- can confine either non-neutral or quasi-neutral plasmas



Companion devices for confining pair plasmas

Both the levitated dipole and the stellarator:

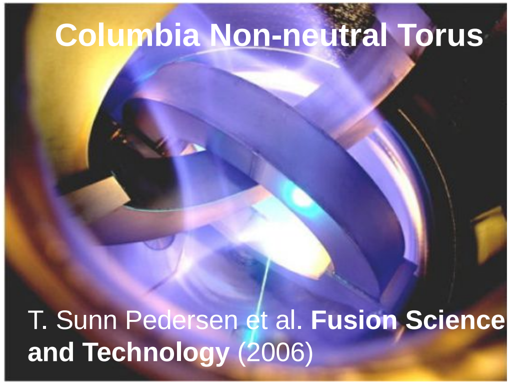
- are steady state, purely magnetic (no plasma current required)
- can confine either non-neutral or quasi-neutral plasmas

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

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

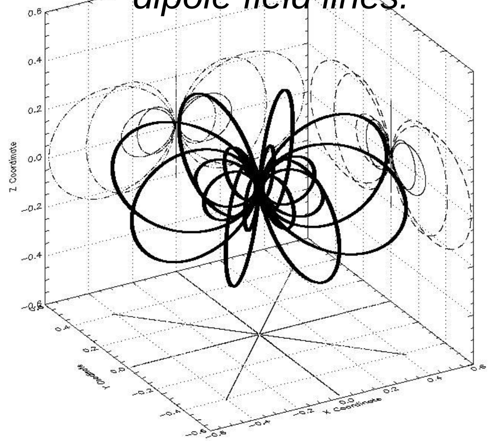
Developing both in parallel(ish) will multiply dramatically what we learn.

Z. Yoshida et al **Phys. Rev. Lett.** (Jun 2010)

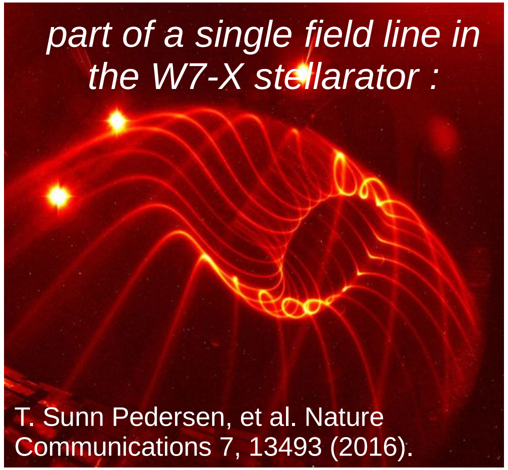


T. Sunn Pedersen et al. **Fusion Science and Technology** (2006)

16 individual dipole field lines:



part of a single field line in the W7-X stellarator :



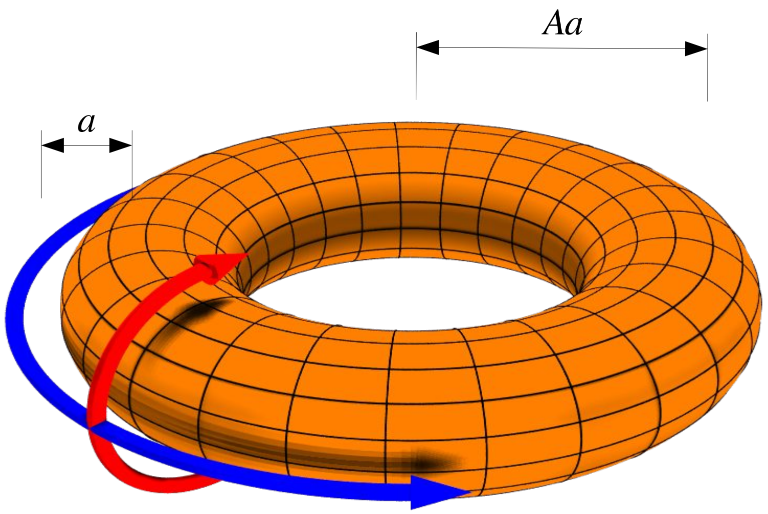
T. Sunn Pedersen, et al. Nature Communications 7, 13493 (2016).

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



target N ~ 10^{10} (or more)

target T ~ 1 eV (or less)

*T. S. Pedersen, et al., **NJP** 14, 035010 (2012).*

By DaveBurke - Own work, CC BY 2.5

Expected plasma properties/parameters

- **"tabletop-sized"**
- **steady-state high magnetic field**
- **very low plasma densities**
- **low plasma temperatures**

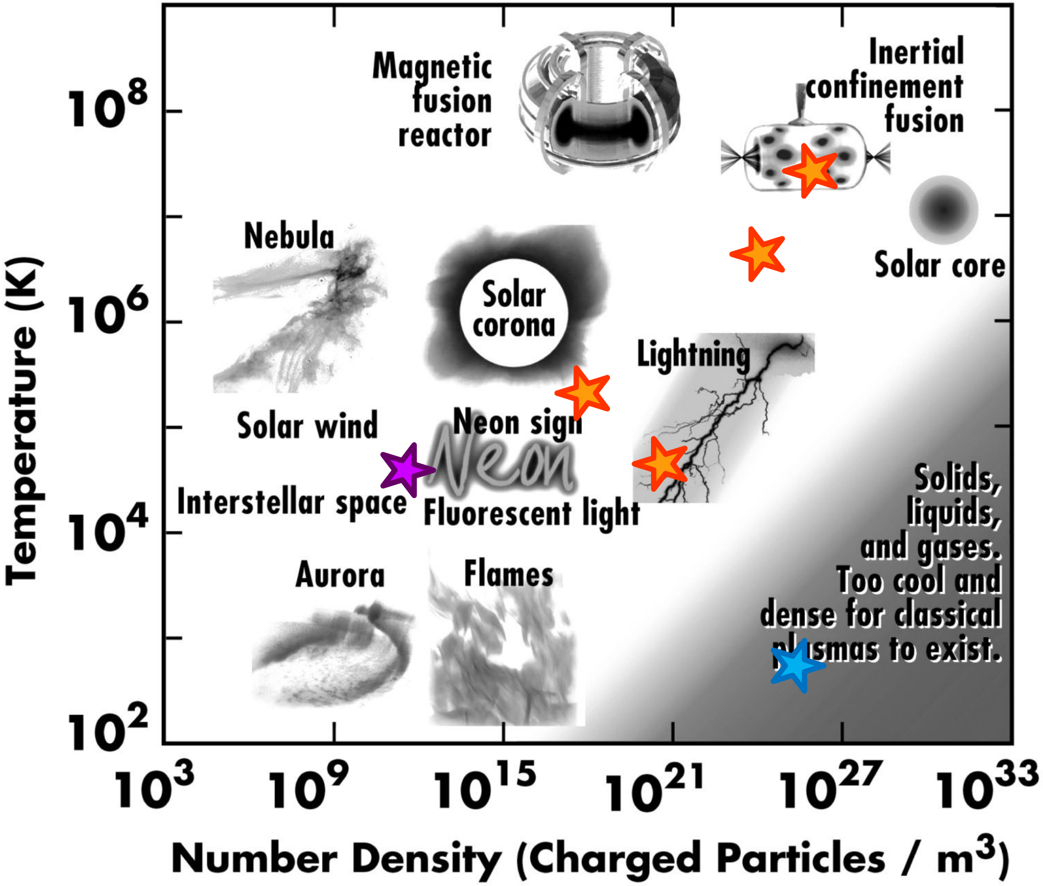
$r_L \ll \lambda_D \ll$ device size $\ll$ plasma skin depth

(strongly magnetized, weakly coupled regime)

volume:	10 – 20 L
major radius:	10 – 20 cm
minor radius:	5 – 10 cm
aspect ratio:	2 – 5
B-field:	up to 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} %

Our place in the plasma universe

In other words:
We're aiming to make a symmetric, quasi-neutral plasma in the "non-neutral plasma regime".



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The APEX grand scheme

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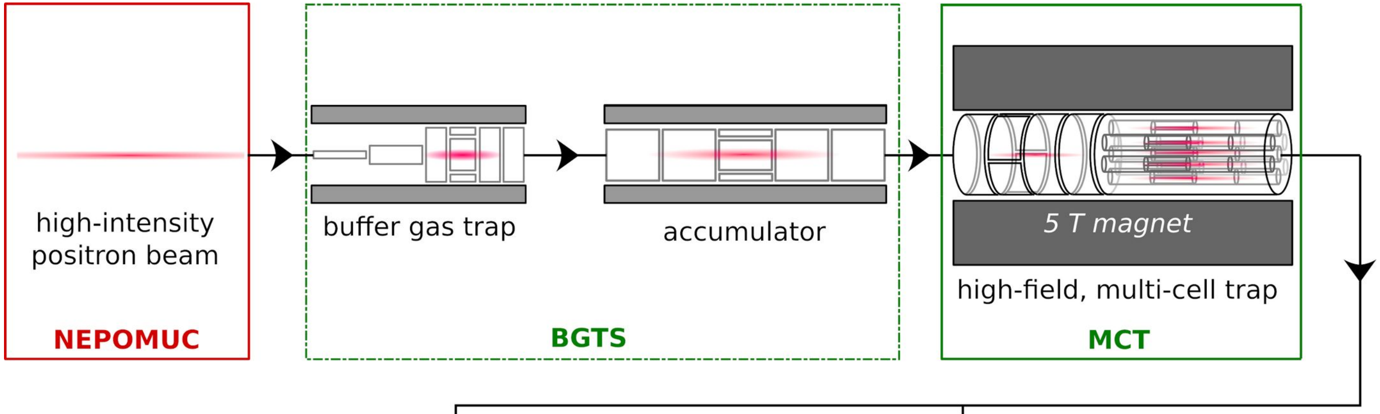

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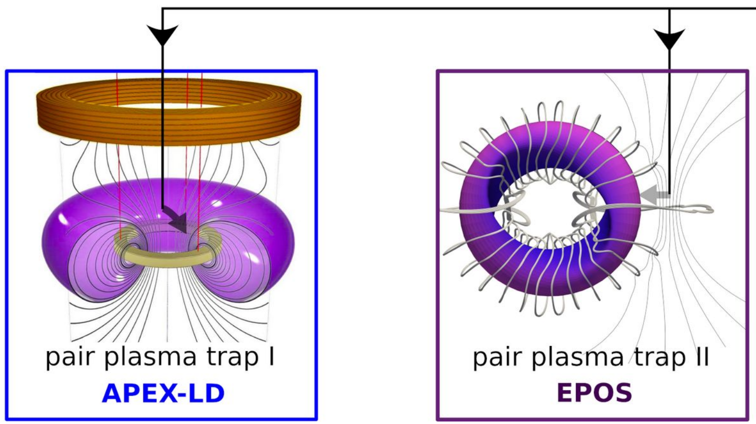


Step 3 (version B):
Combine positrons with electrons in an optimized stellarator.

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), . . .*

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), τ > 1 s was limited by elastic scattering off residual neutrals.
- (quasi-)symmetry of the traps?

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

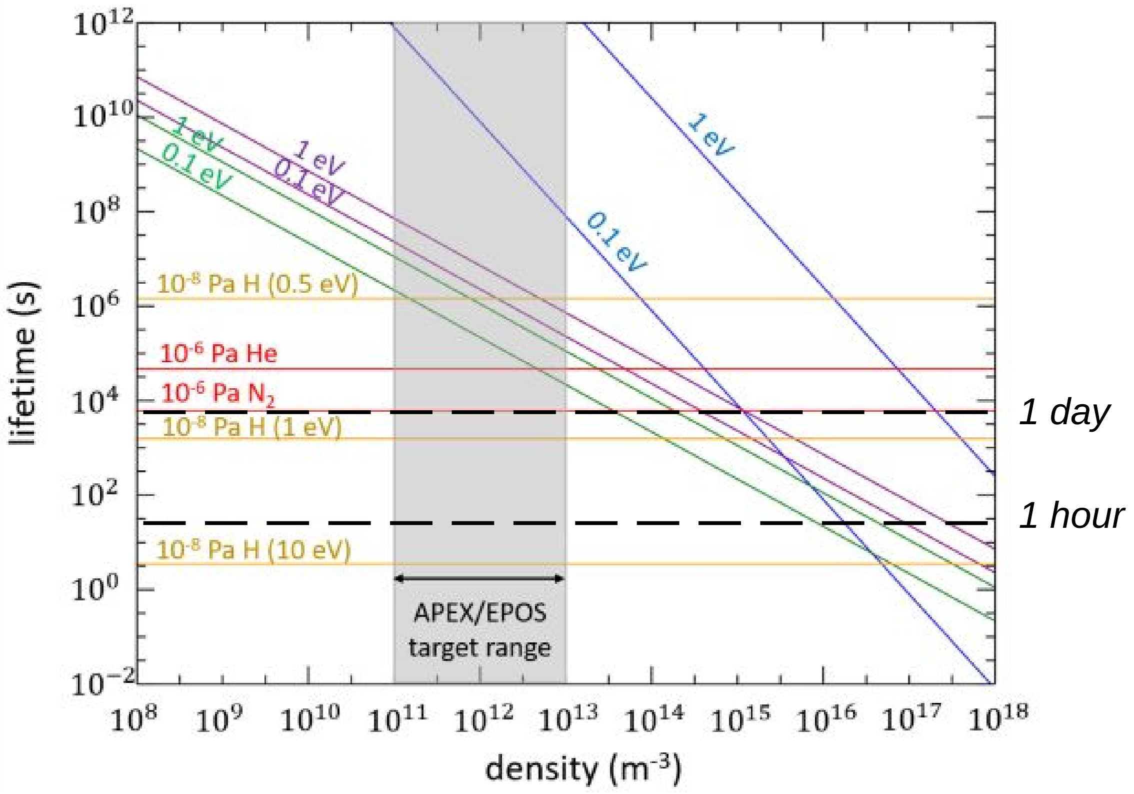
purple: direct annihilation with plasma electrons

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).

Outline

I. Introduction
& motivation

- the APEX Collaboration
- the compelling goal of laboratory pair plasmas
- our “grand scheme”:
  - ➜ sufficient positrons
  - ➜ suitable traps
  - ➜ the parts in between

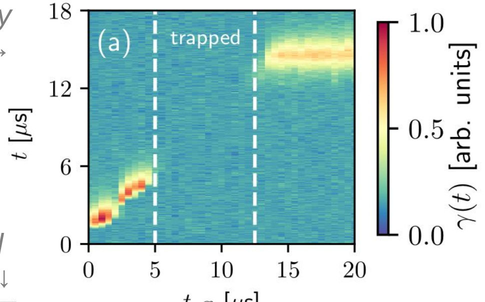
II. Latest progress
& coming attractions

- answering key questions in prototype set-ups
- next-generation experiments
- putting the pieces together

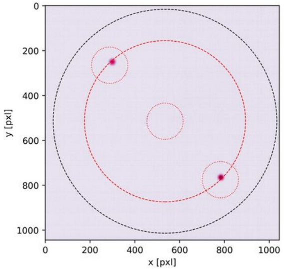
Themes and highlights of recent work

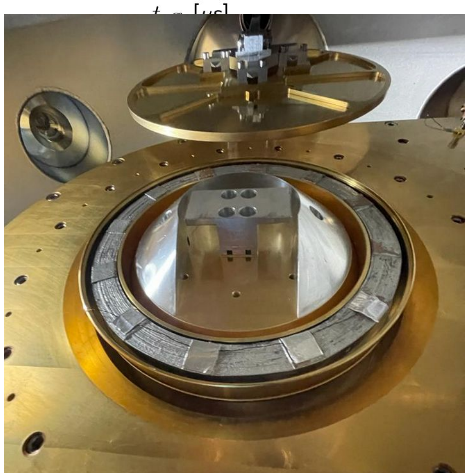
- **orders of magnitude more e+** trapped together in a dipole
- **e- plasmas**, experimental and numerical, both for their own sake (50% of future pair plasmas) and as stand-ins (for commissioning e+ **accumulation experiments**)
- **HTS coils** for the **levitated dipole** & **stellarator** (non-planar)
- **stellarator optimization** that builds on and contributes to fusion efforts
- **diagnostic development** for non-neutral and pair plasmas

using gammas to study transport/losses →



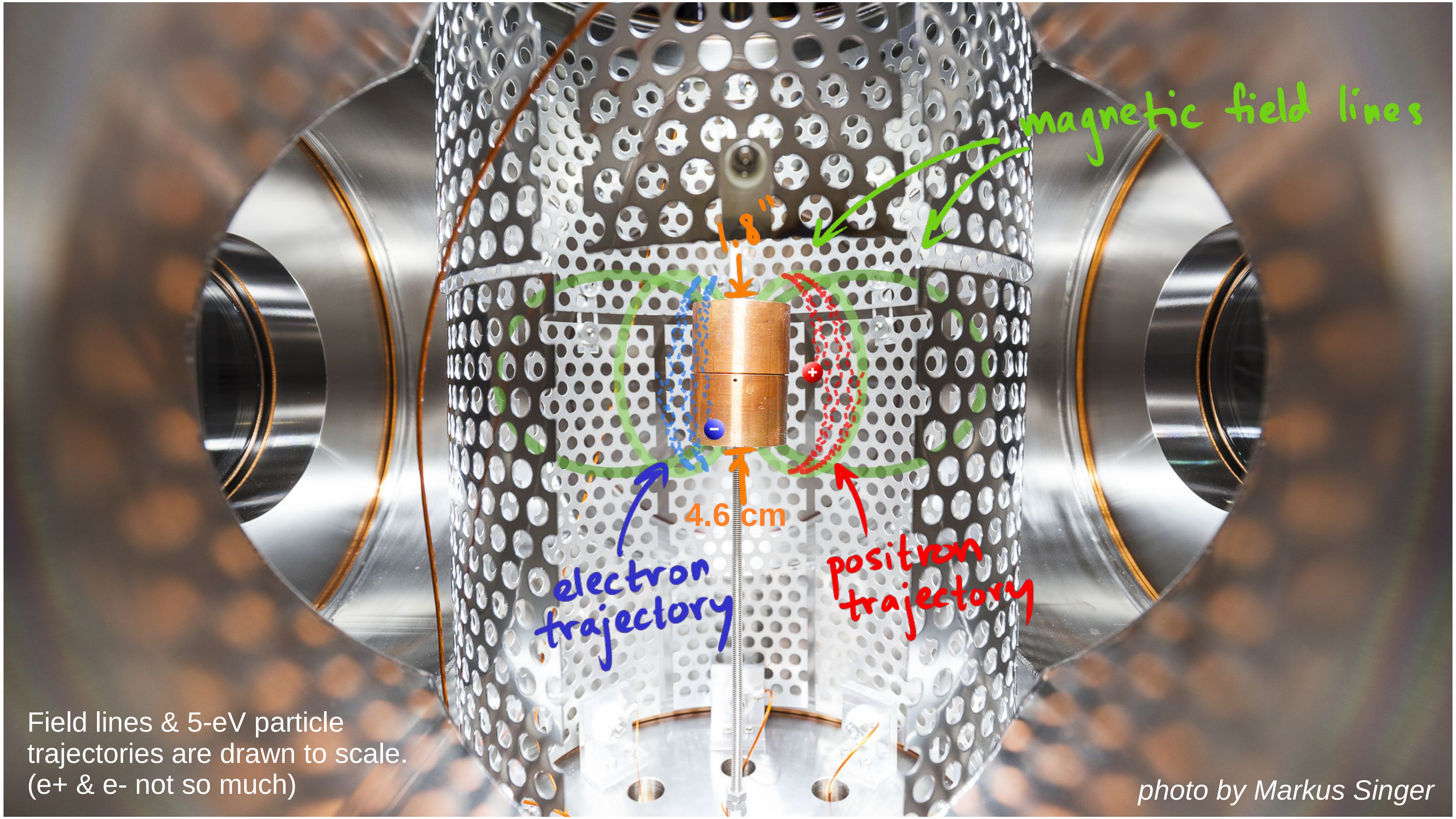
two trapped e- plasmas ↓





"floating coil" (sitting in cryostat, ready for cooling/quench tests)

Using a “terrella” as our “sandbox”



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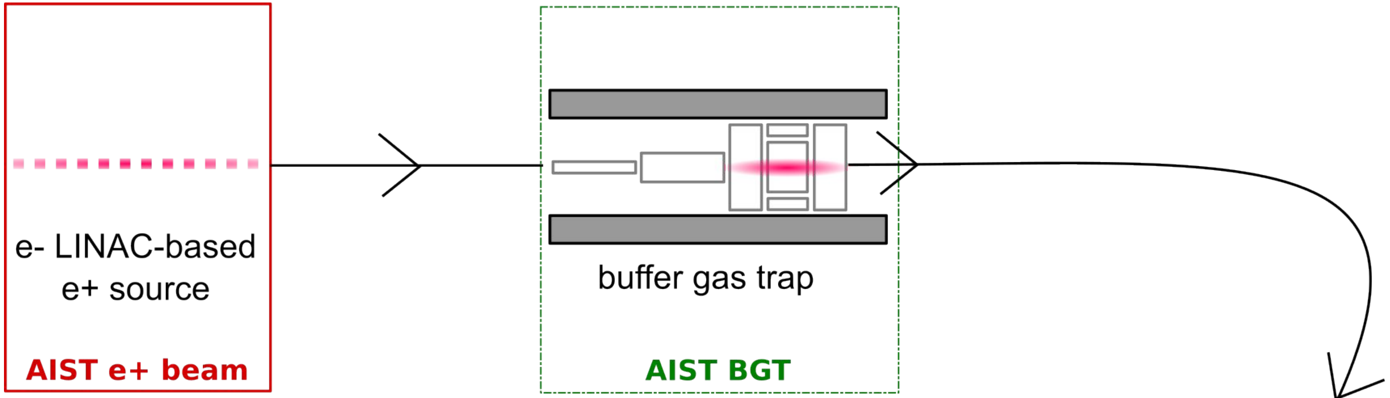
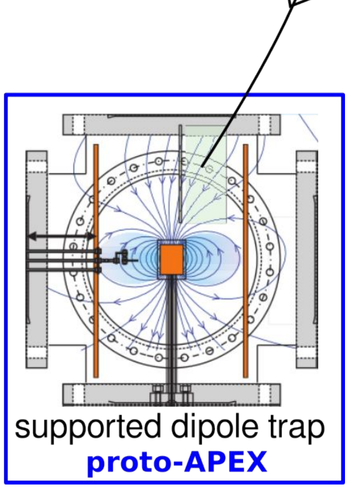




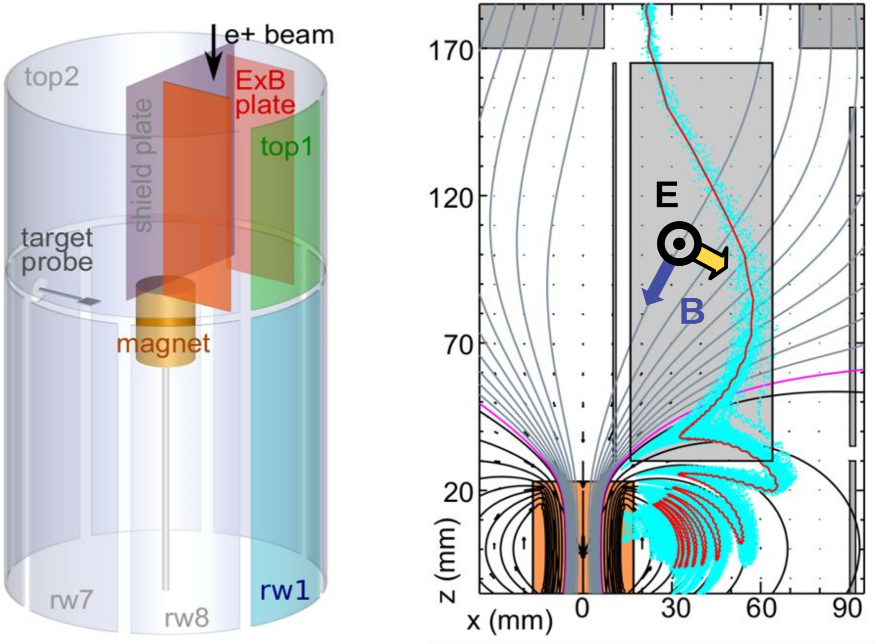
Higaki, Michishio, et al. Accumulation of LINAC based low energy positrons in a buffer gas trap. Applied Physics Express 13, 066003 (2020).

A sensitive probe for particle dynamics & transport

recent results from von der Linden, Deller, Nißl, Higaki, Michishio, Saitoh, et al.

- inject a bunch of positrons

bias electrodes to make positrons ExB drift into the trap:



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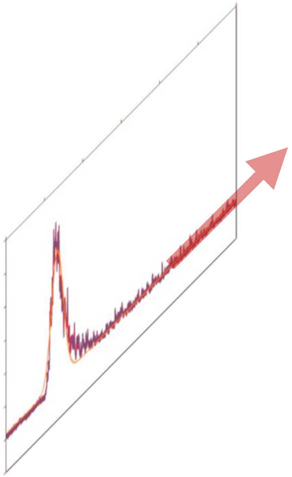
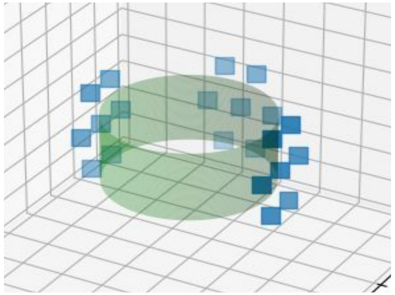
- inject a <u>bunch</u> of positrons



positions of 21 gamma detectors, surrounding the supported dipole trap

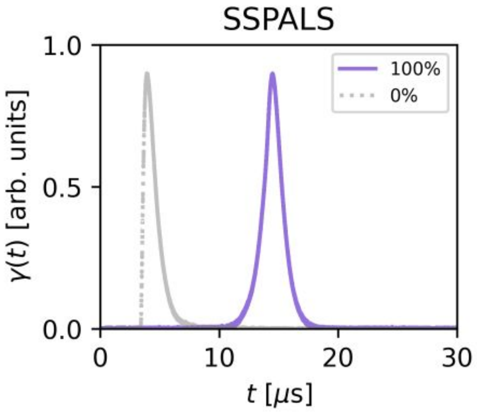


A sensitive probe for particle dynamics & transport

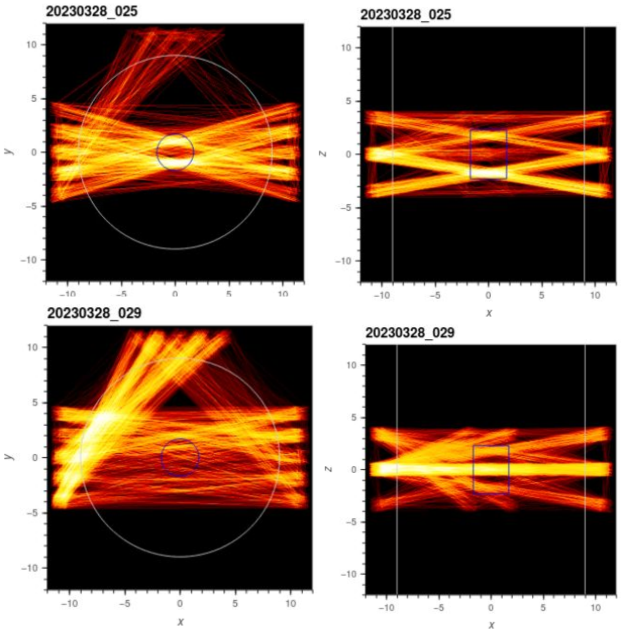
recent results from von der Linden, Deller, Nißl, Higaki, Michishio, Saitoh, et al.

- inject a bunch of positrons
- use the details of their annihilation

when they annihilate:



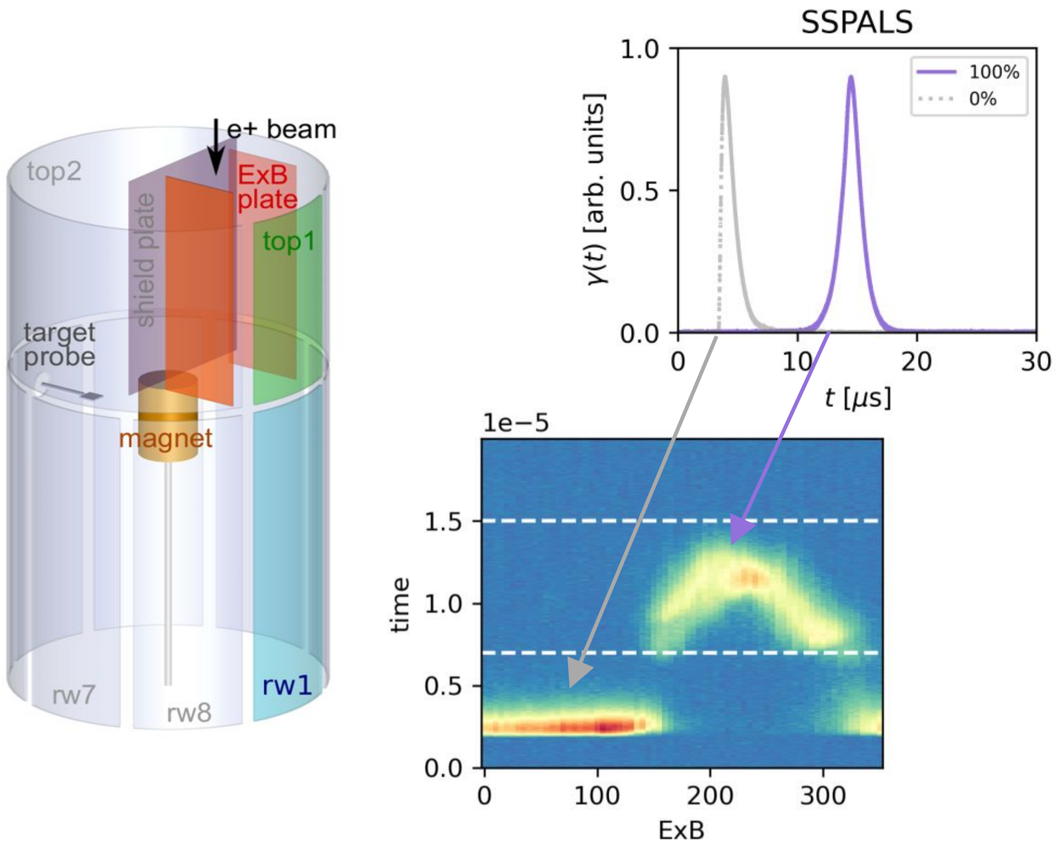
where they annihilate:



A sensitive probe for particle dynamics & transport

recent results from von der Linden, Deller, Nißl, Higaki, Michishio, Saitoh, et al.

- inject a bunch of positrons
- use the details of their annihilation to “see” things like . . .
  - if they were well-injected



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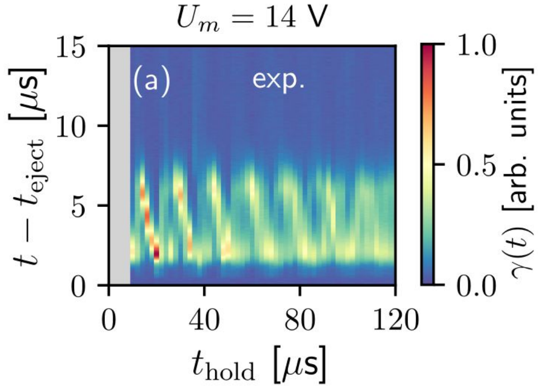
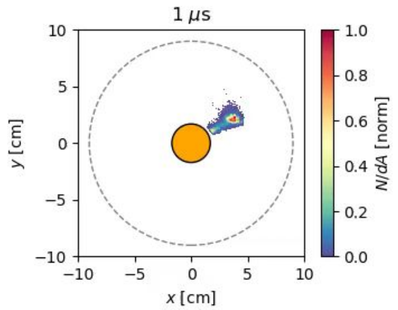
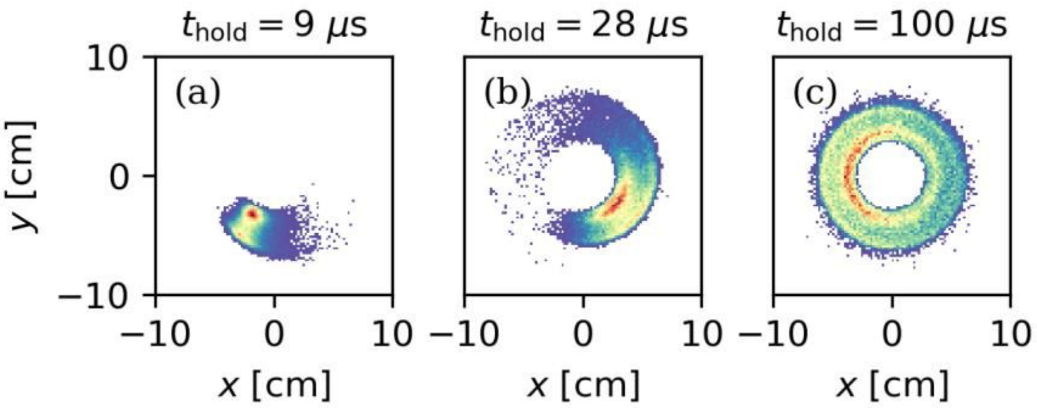
- inject a bunch of positrons
- use the details of their annihilation to “see” things like . . .
  - if they were well-injected
  - motion and evolution of the bunch (which depend on its distribution function)

toroidal spreading of e+ pulse, as seen in dump signals:





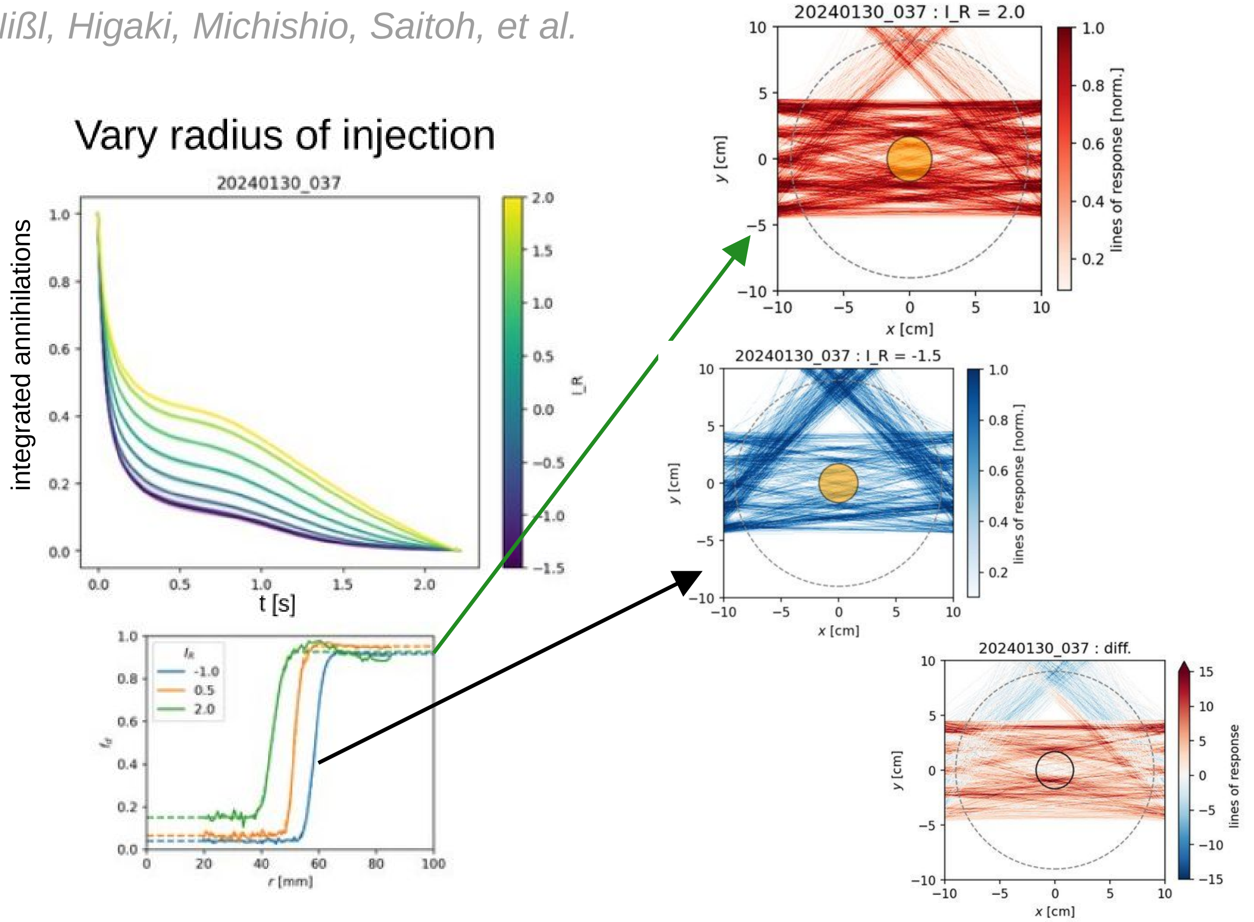


A sensitive probe for particle dynamics & transport

recent results from von der Linden, Deller, Nißl, Higaki, Michishio, Saitoh, et al.

- inject a bunch of positrons

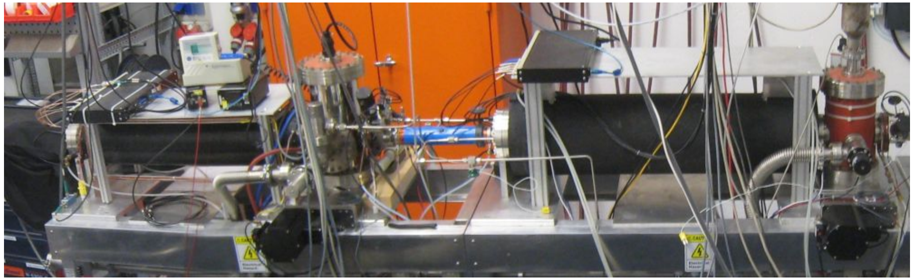
- use the details of their annihilation to “see” things like . . .
  - if they were well-injected
  - motion and evolution of the bunch (which depend on its distribution function)
  - how long the e+ stay in the trap
  - where they come out



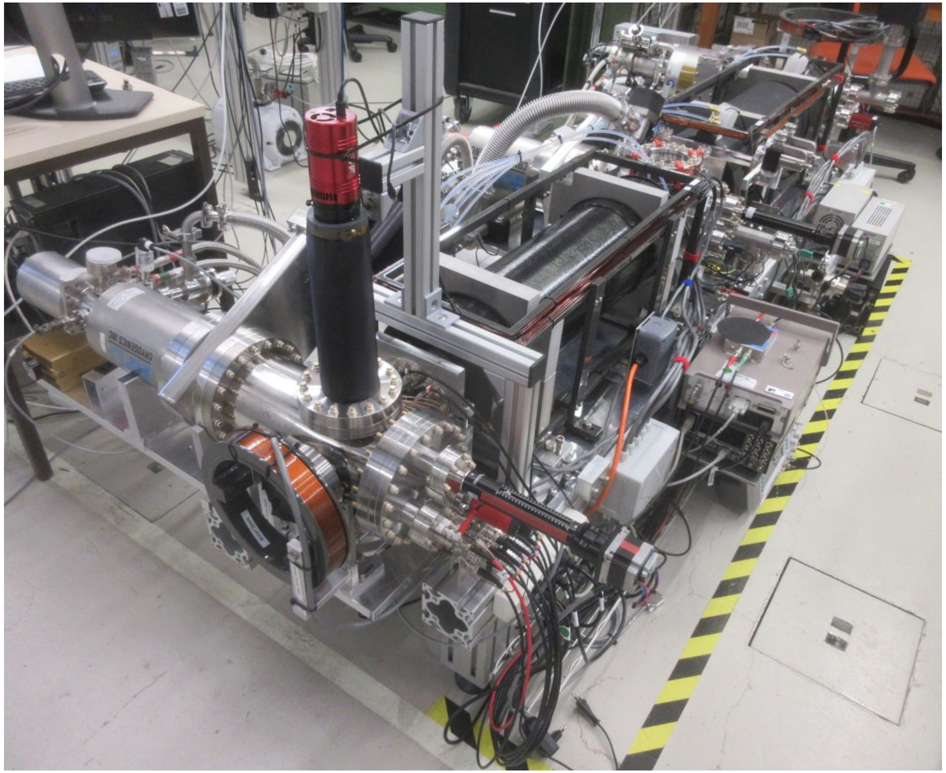
Our own buffer-gas trap: rebuilt & ready for NEPOMUC

- standard technique for trapping, accumulating e+
- produces dense, tailorable pulses
- major, multi-year upgrade/rebuild complete (collaboration with UC San Diego)

previously (2013, Greifswald):



now (Garching):

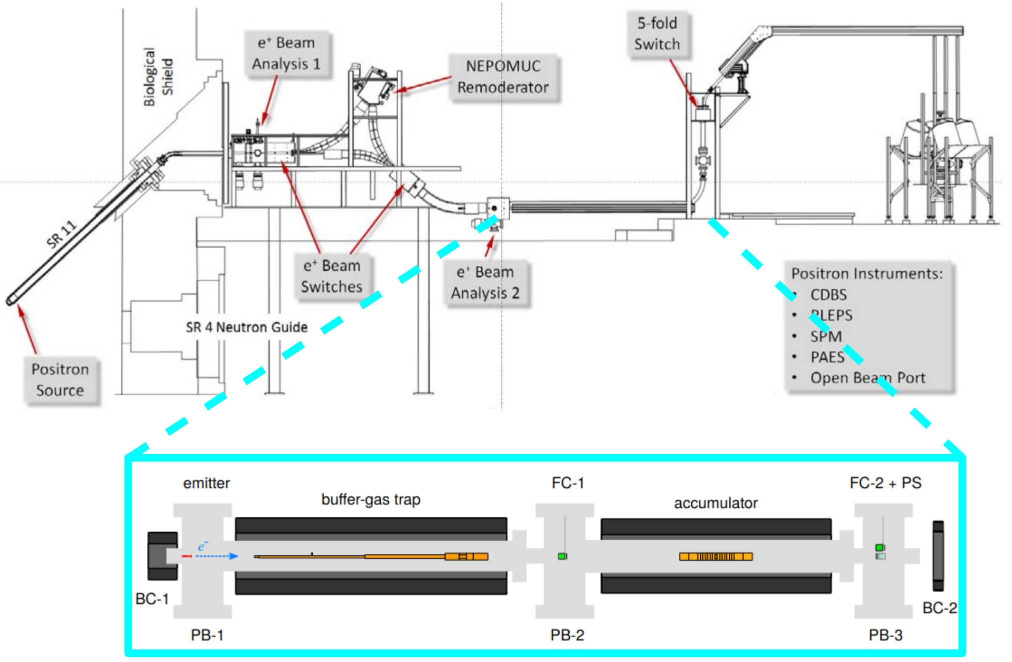


project leader: A. Deller
refs: Surko PRL ‘88; Murphy, PRL ‘92; Surko Varenna I (2010); Danielson RMP '15
Masters thesis: C. W. Rogge (2023)

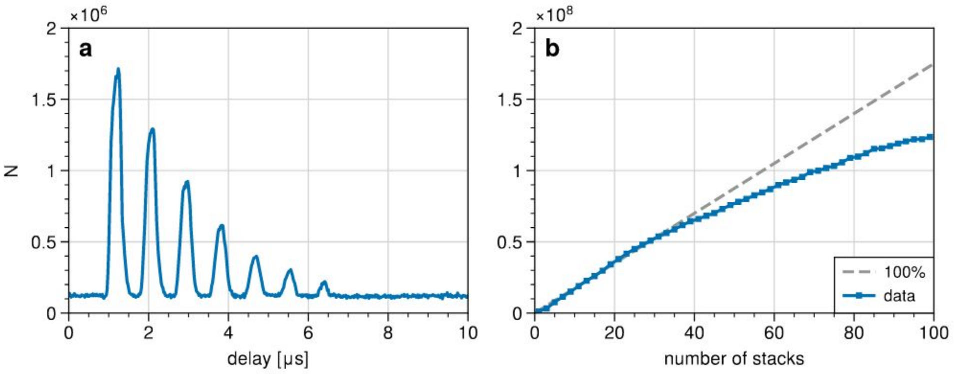
Our own buffer-gas trap: rebuilt & ready for NEPOMUC

- standard technique for trapping, accumulating e+
- produces dense, tailorable pulses
- major, multi-year upgrade/rebuild complete (collaboration with UC San Diego)
- commissioning (with e-) highly successful

Where it will go in the NEPOMUC beam line:



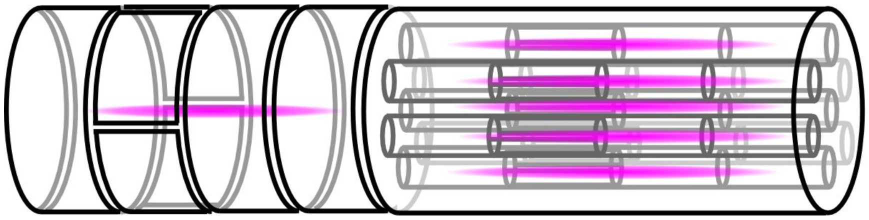
***BGT → accumulator:** pulse transfer timing & stacking*



A. Deller, C. W. Rogge, et al. JPP. 89, 935890602 (2023).

next stop: FRM II
(first half of 2025)

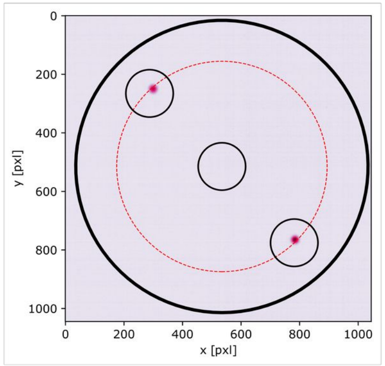
Multi-cell trap has advanced the NNP frontier



← *MCT concept*

Martin Singer, A. Zettl

simultaneous e- plasmas in storage cells → (phosphor screen image)



- concept for accumulating and storing record amounts of (charged) antimatter
- in operation (with e-) in 3.1 T

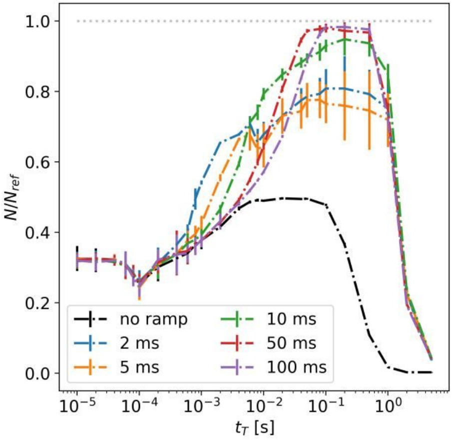
developing lossless transfer from master cell to a storage cell ↓

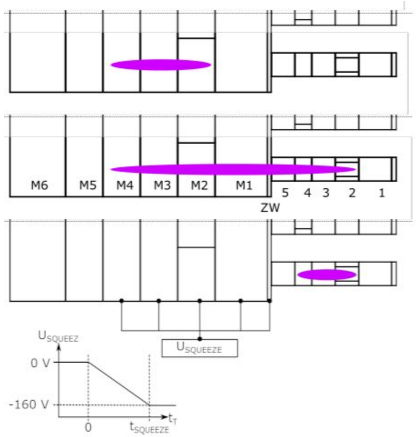
✓ **long confinement in master cell**

✓ **lossless transfer to storage cells**

✓ **simultaneous off-axis trapping**

✓ **"strong drive regime" reached**

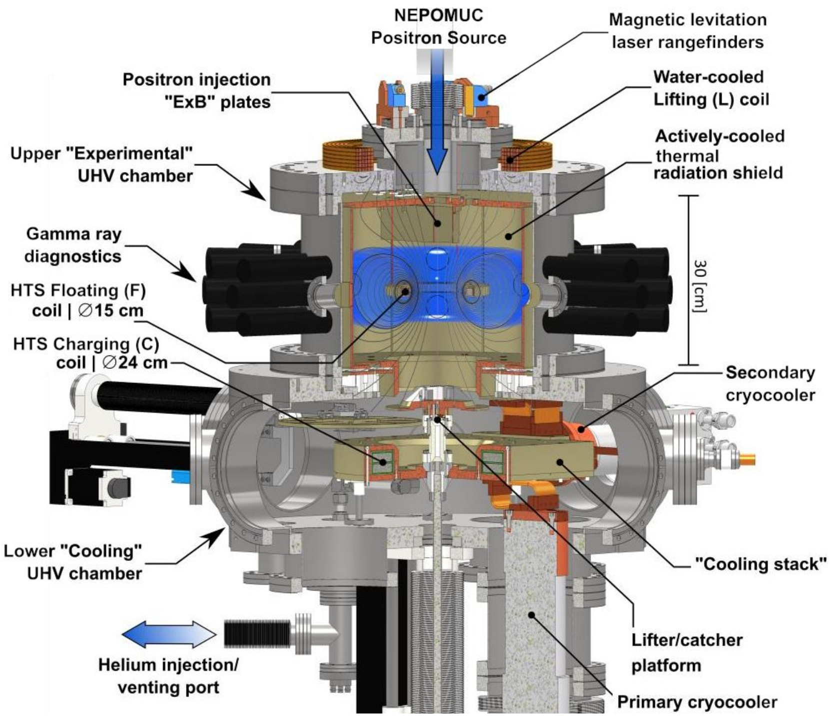


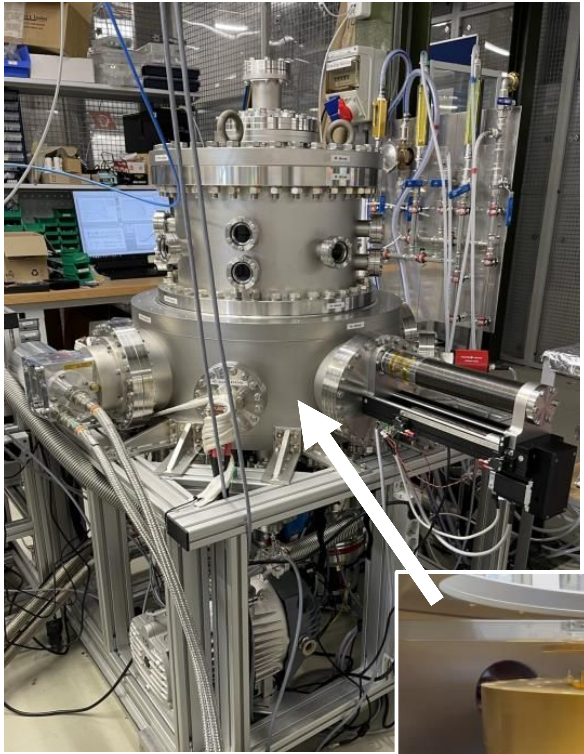


M. Singer, S. König, et al., RSI 92, 123504 (2021).
M. Singer, J. R. Danielson, et al., JPP 89, 935890501 (2023).

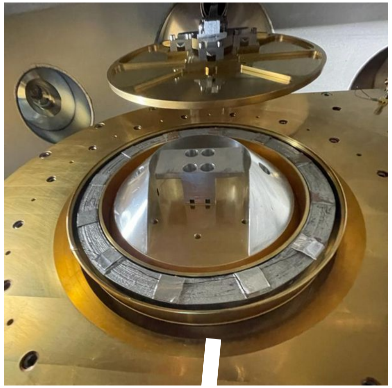
Compact levitated dipole trap: designed & built

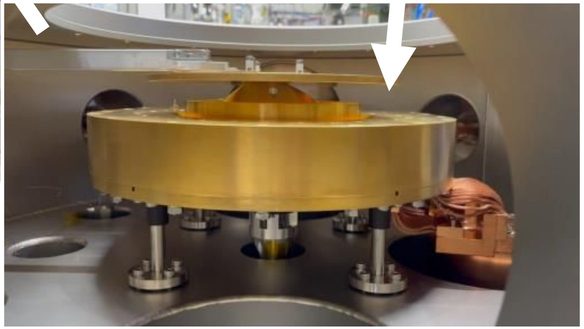
- ✓ engineering based on cooling test setup
- ✓ HTS coils floating & charging coils (THEVA)





The F coil is cooled with He in a "chamber within a chamber" located in the middle of the C coil.



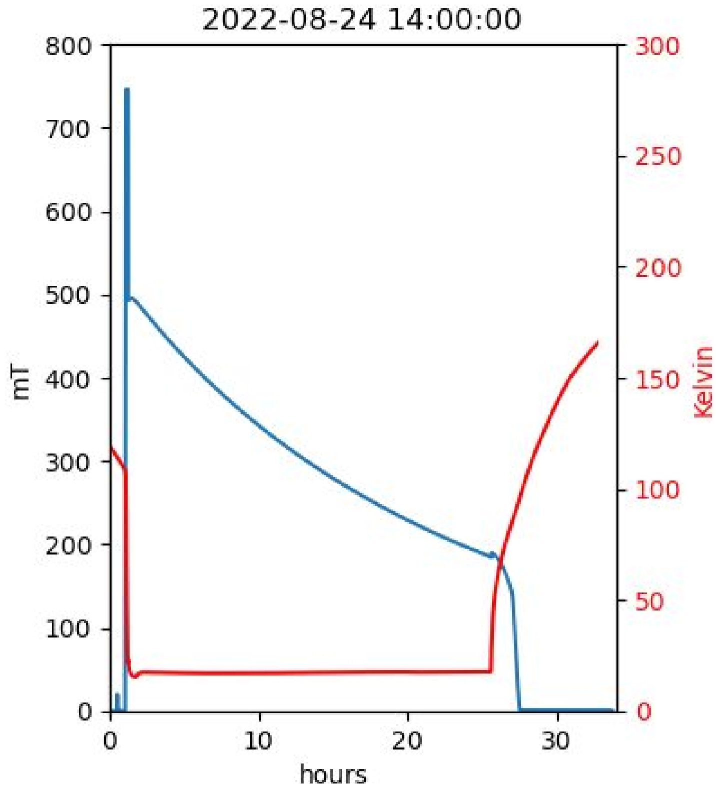


A. Card, M. Stoneking, et al. In preparation.

Compact levitated dipole trap: commissioned

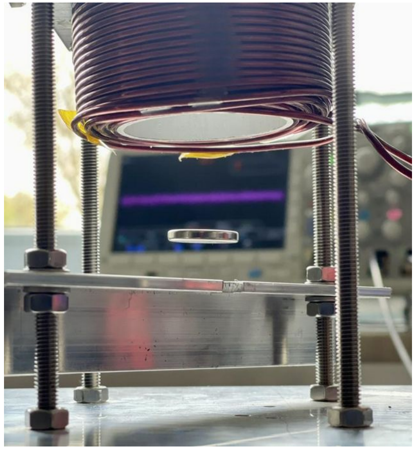
- ✓ engineering based on cooling test setup
- ✓ HTS coils floating & charging coils (THEVA)

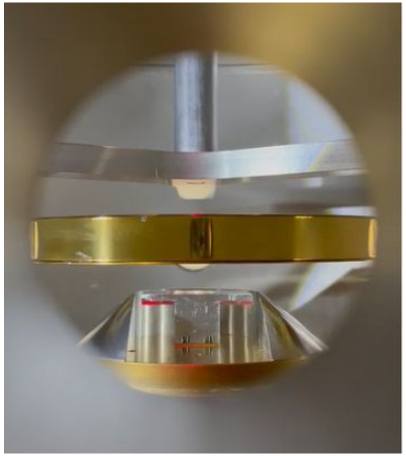
successful F coil cooling, excitation, current decay over the course of a day, then deliberate quench:



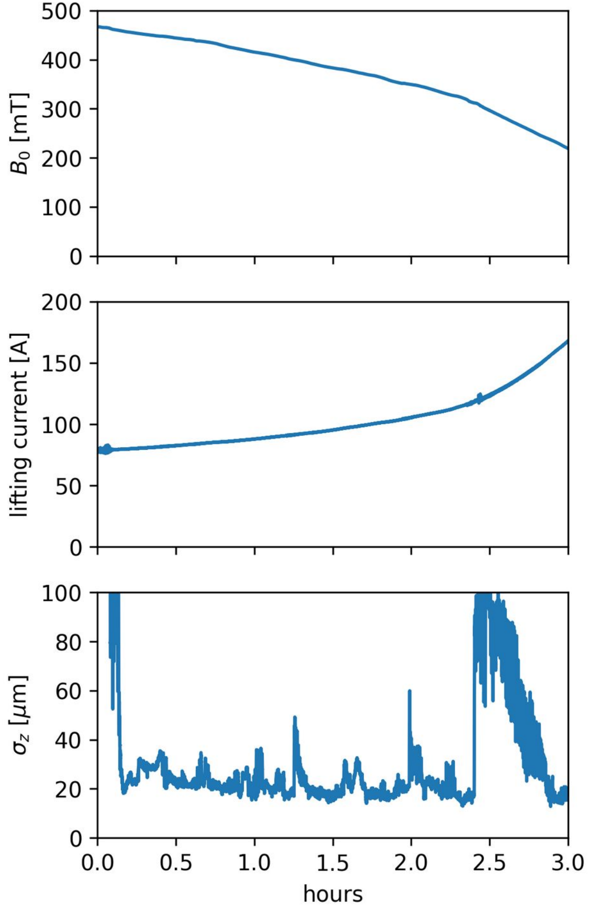
Compact levitated dipole trap: commissioned

- ✓ engineering based on cooling test setup
- ✓ HTS coils floating & charging coils (THEVA)
- ✓ levitation feedback system





> 3 hours of levitation/cycle:

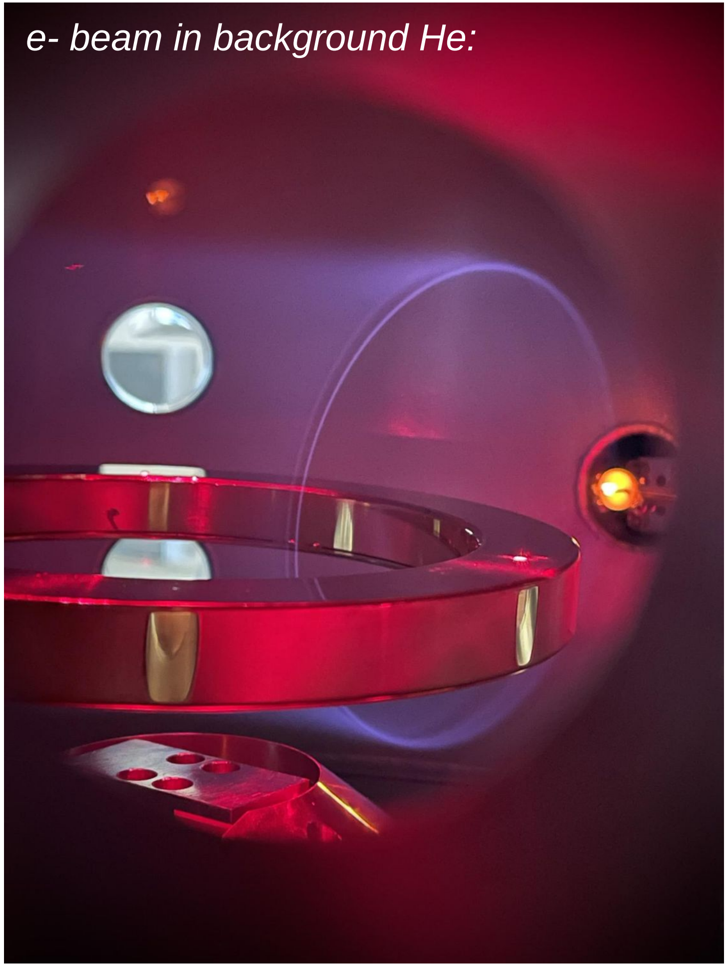


YouTube video

A. Card, A Deller, et al.
Submitted to IEEE
Appl. Superconductivity

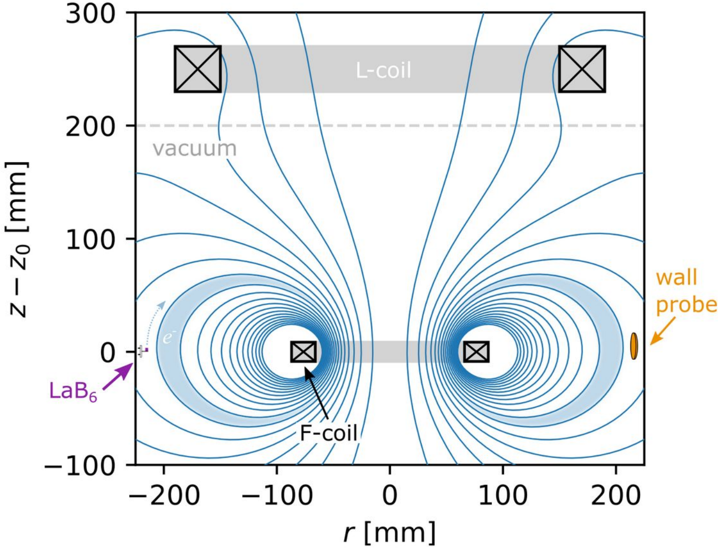
Compact levitated dipole trap: up and running!

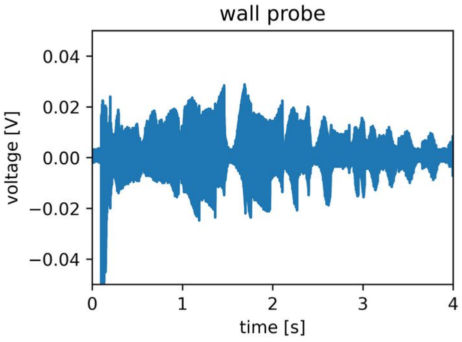
- ✓ engineering based on cooling test setup
- ✓ HTS coils floating & charging coils (THEVA)
- ✓ levitation feedback system
- ✓ field line imaging



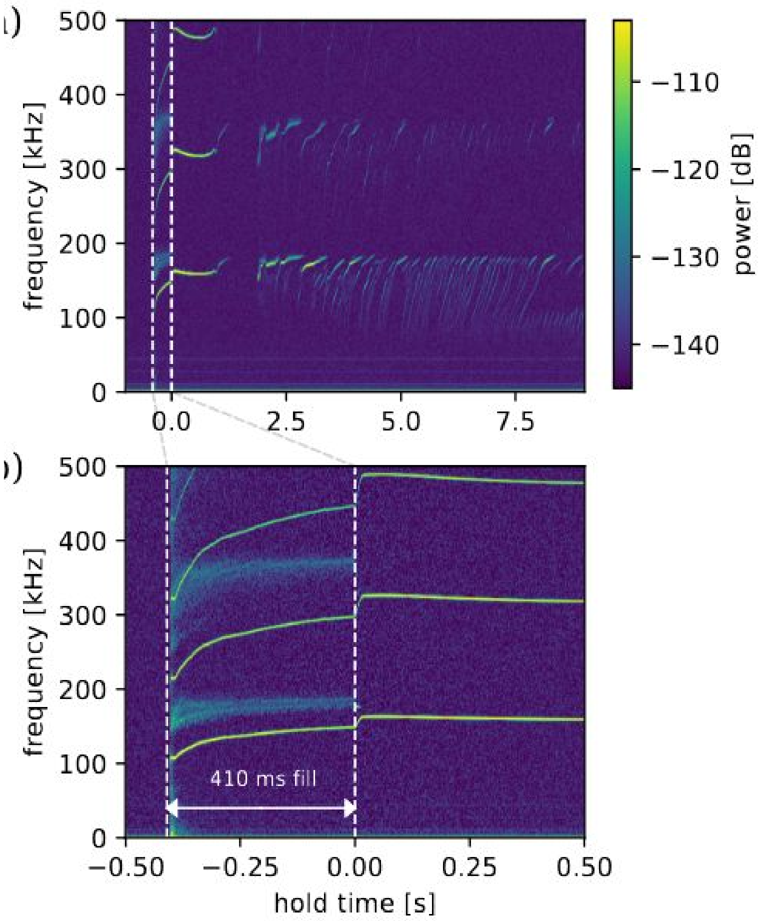
Compact levitated dipole trap: up and running!

- ✓ engineering based on cooling test setup
- ✓ HTS coils floating & charging coils (THEVA)
- ✓ levitation feedback system
- ✓ field line imaging & e- plasma experiments





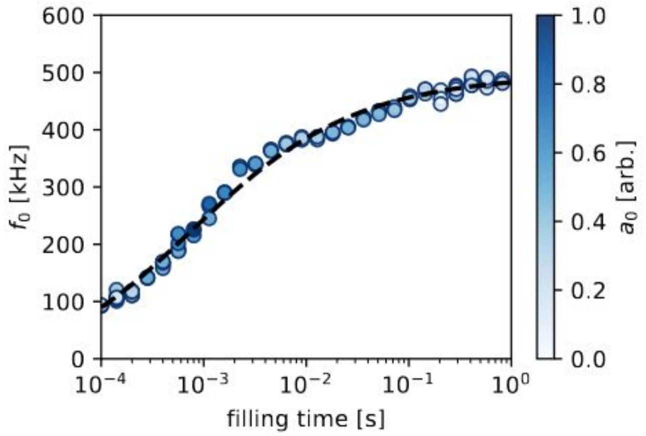
Deller, Steinbrunner, et al.
In preparation.

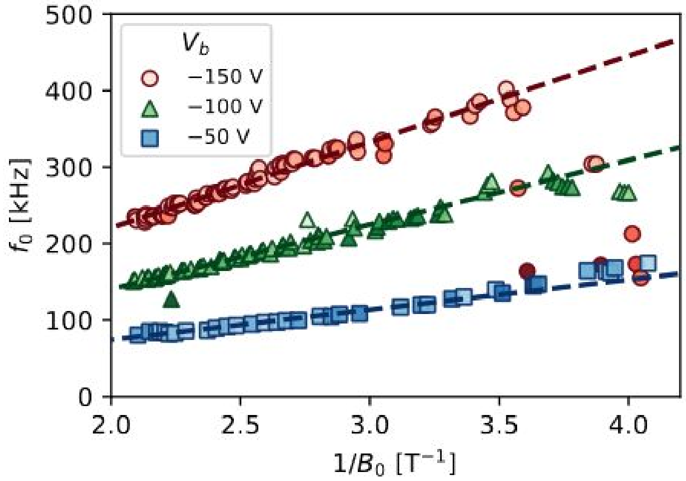


Compact levitated dipole trap: up and running!

- ✓ engineering based on cooling test setup
- ✓ HTS coils floating & charging coils (THEVA)
- ✓ levitation feedback system
- ✓ field line imaging & e- plasma experiments

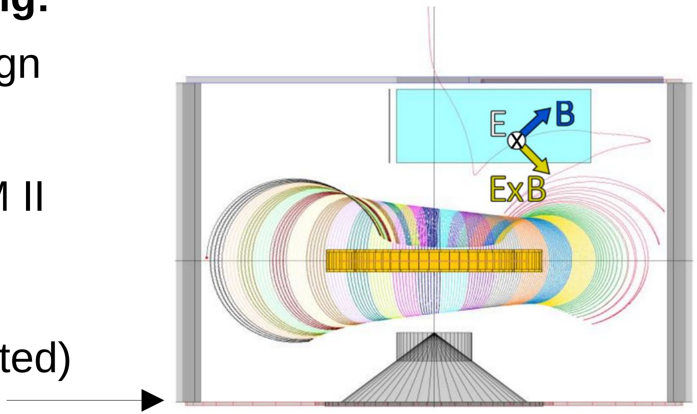
Dependence on space charge and B field:





ongoing & upcoming:

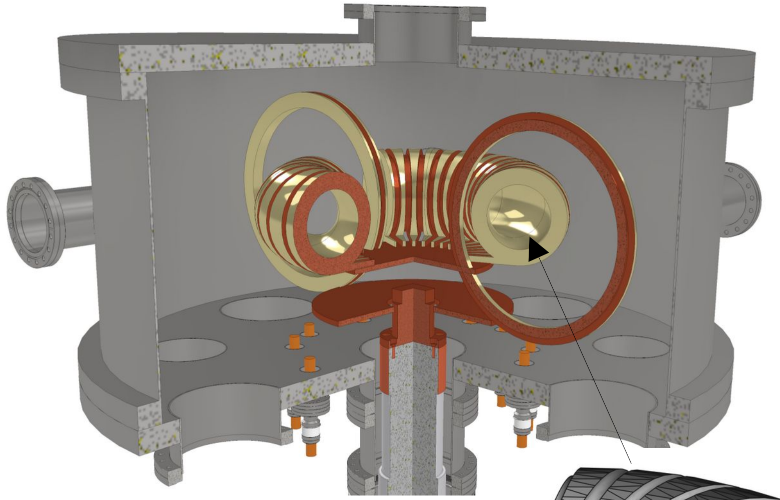
- e- plasma campaign
- radiation shield
- installation at FRM II (2025)
- e+ drift injection (previously simulated)

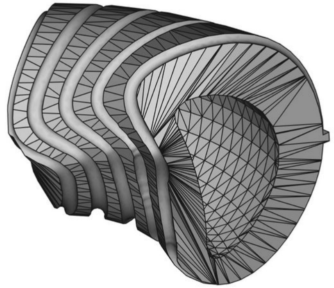


Tabletop stellarator: design in full swing

Use common resources . . .

- e+ accumulation systems
- gamma diagnostics & NNP creation/measurement
- HTS/cryo experience

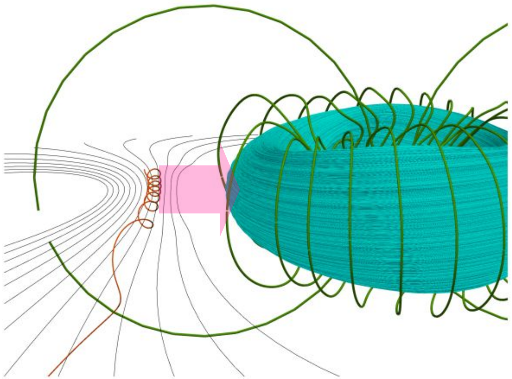




. . . in order to compare/contrast two very different (complementary) magnetic geometries:

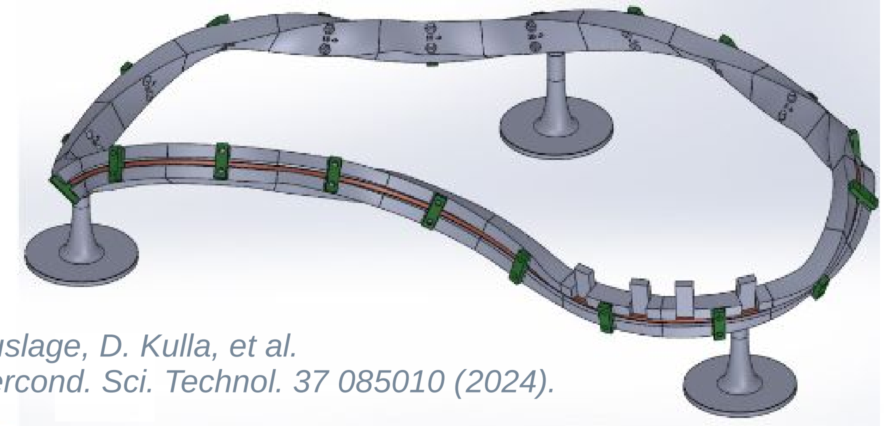
- axisymmetry vs. quasi-symmetry
- poloidal vs. primarily toroidal B field
- short vs. long B-field connection lengths

(also: B field, vacuum, cycling . . .)



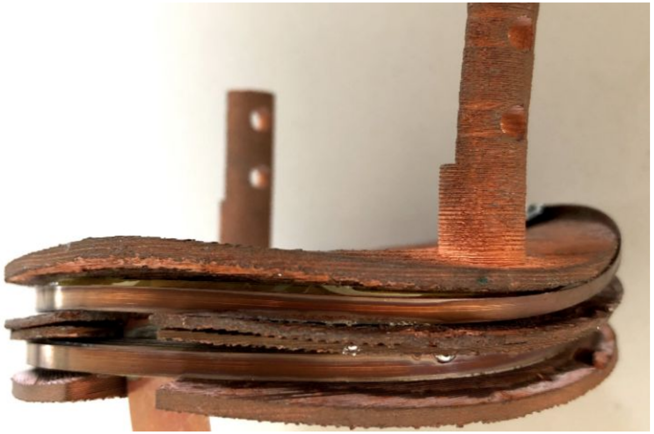
Our first non-planar HTS coils

Student-organized "Project Stellar" (Huslage, Kulla, Lobsien, Schuler):



P. Huslage, D. Kulla, et al.
Supercond. Sci. Technol. 37 085010 (2024).

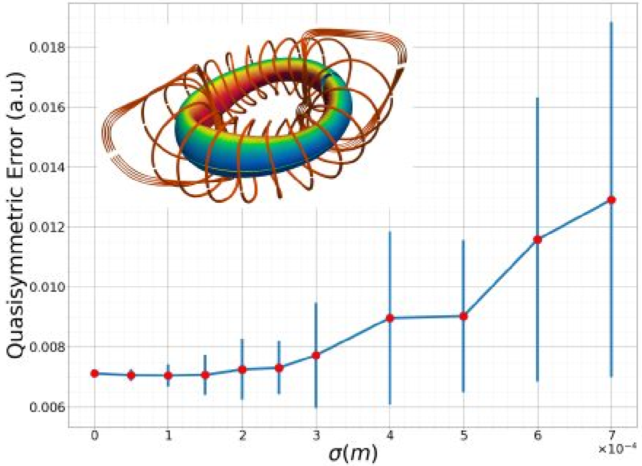
order of magnitude smaller and soldered together:

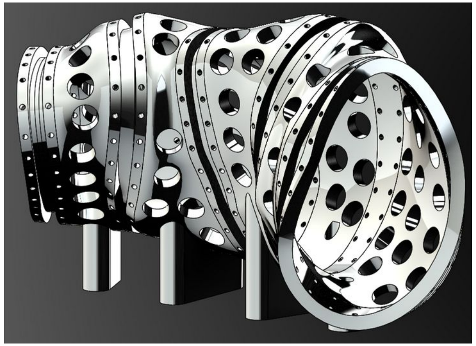


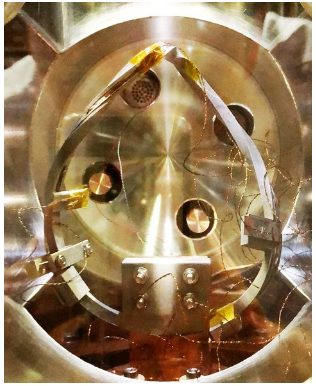
EPOS: configuration & engineering in parallel

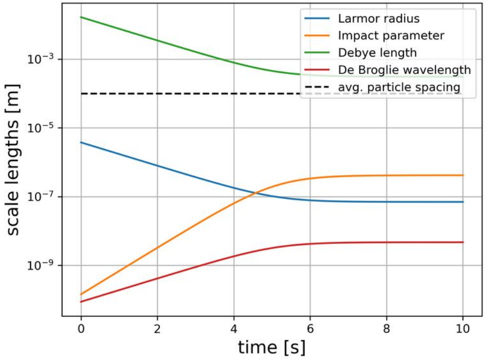
Current work / coming attractions:

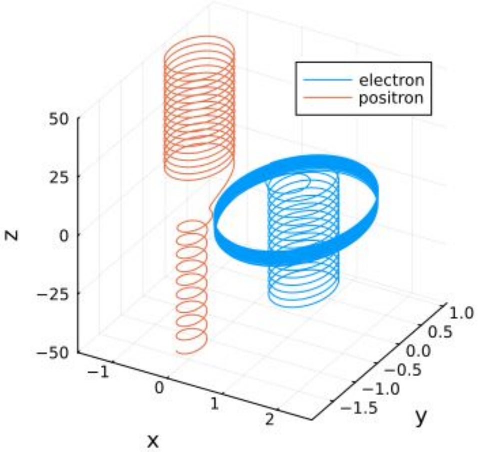
- stochastic, single-stage, HTS-compatible optimization
- qualification of 3D-printed metal structures
- tests with high current, coldhead-cooled
- injection simulations with KORC (with M. Beidler, ORNL)
- “neoclassical transport” in the e+e- parameter regime
  (collision operator more interesting than originally anticipated)







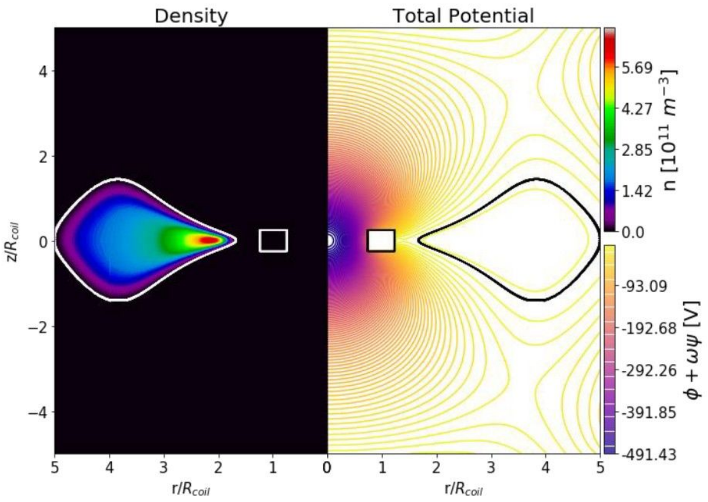




Non-neutral plasmas in toroidal geometries

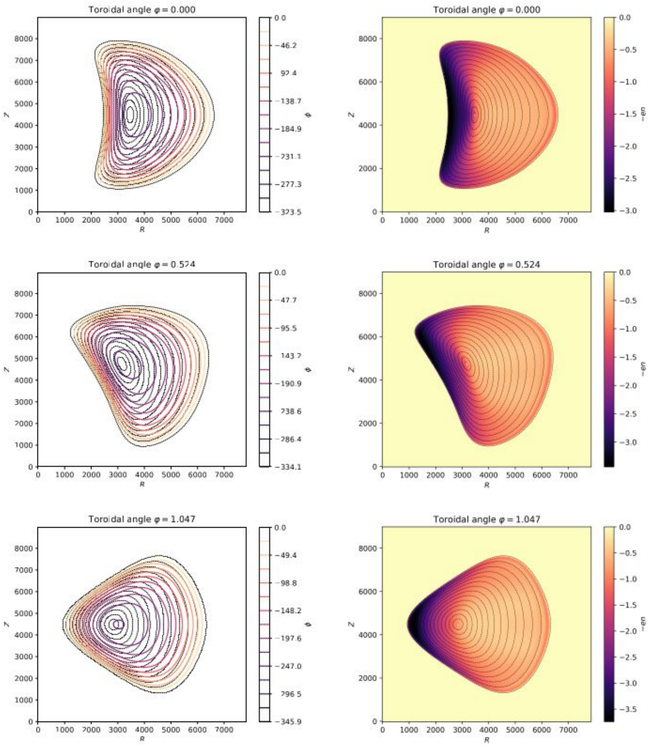
- studies in dipole, stellarator, and other geometries
- fluid equilibria
  (zero- and finite-temperature cases)
- gyrokinetic applications
- EUTERPE simulations
- stability theorem

latest: fluid modes
(of a NNP annular cylinder around a straight wire)



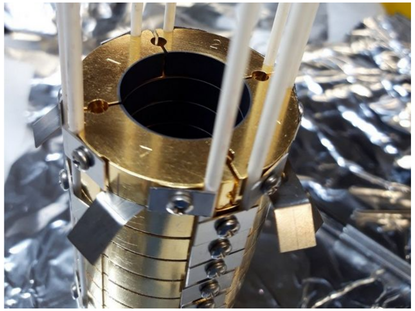
↑ pure e- (or e+) plasma in a levitated dipole trap (global thermal equilibrium)

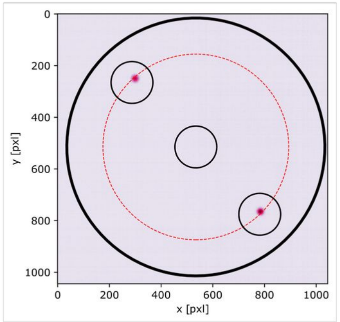
equilibrium electrostatic potential and charge density alongside the magnetic surfaces in an A = 4 QA stellarator →

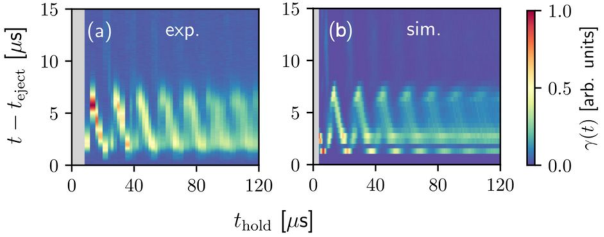


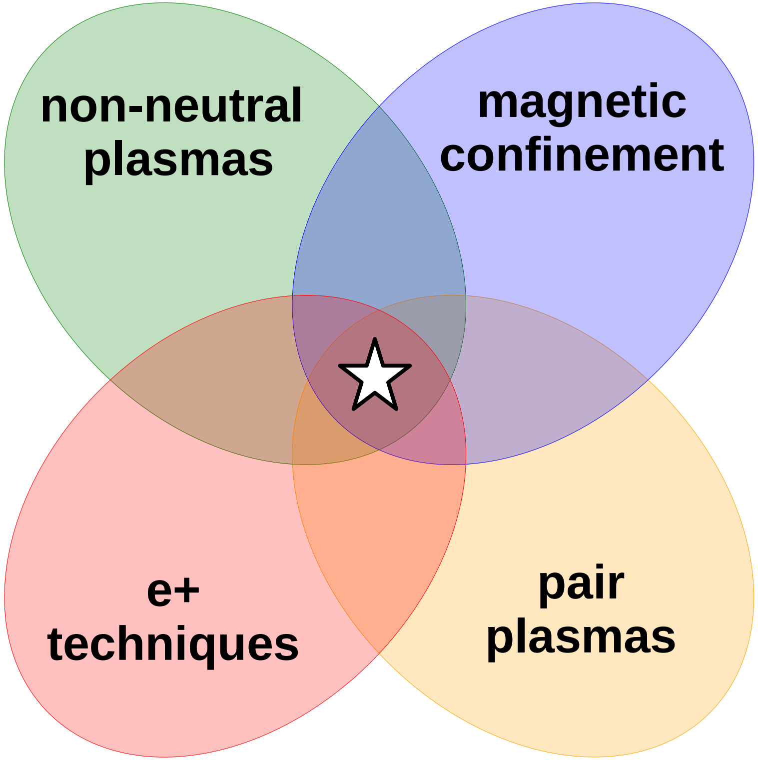
P. Costello Masters thesis.
Costello & Helander. JPP 89, 935890402 (2023).
P. Steinbrunner, et al. JPP 89, 935890401 (2023).
A. Mischenko et al. JPP 89, 935890403 (2023).

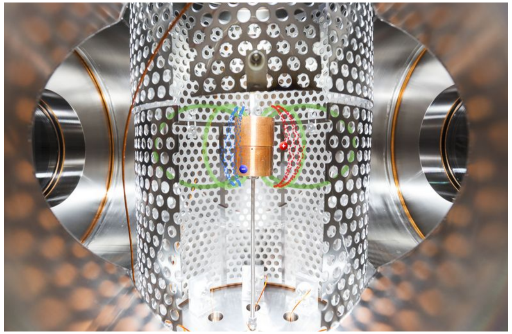
The APEX Collaboration’s research areas

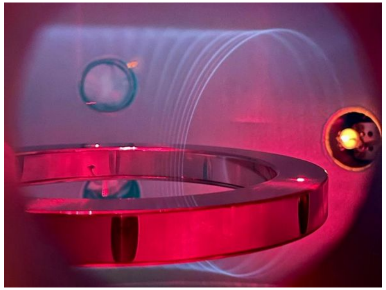


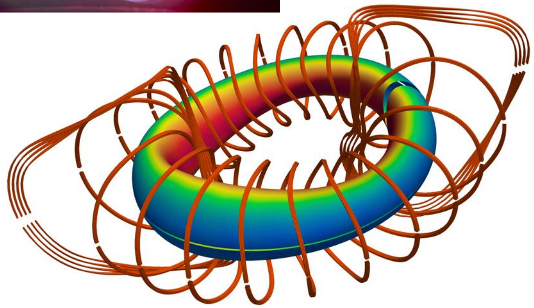






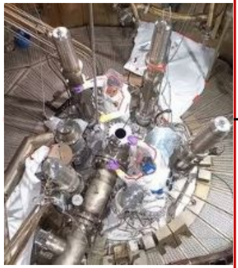




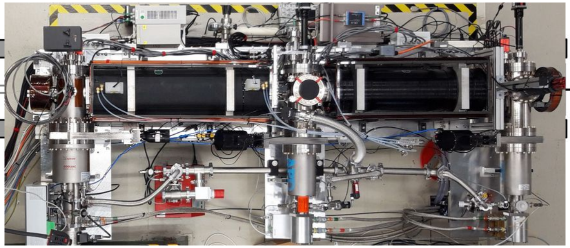


The APEX grand scheme

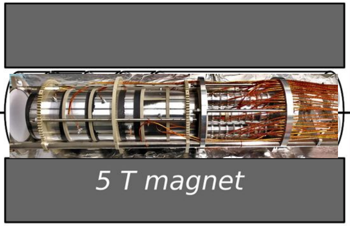
Step 1:
Obtain positrons from world-class source (up to 10^9/s)



NEPOMUC



BGTS

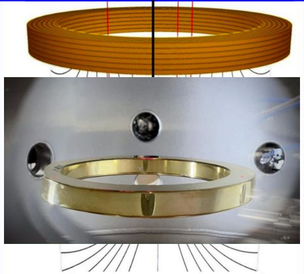


high-field, multi-cell trap

MCT

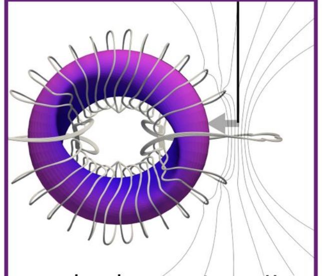
Step 2:
Use a series of non-neutral plasma traps to collect positrons, until we have enough to make a plasma.

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



pair plasma trap I

APEX-LD



pair plasma trap II

EPOS

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), . . .*

Key points & coming attractions

Laboratory e+e- pair plasmas are a compelling frontier in fundamental plasma physics with strong interdisciplinary ties (incl. materials, anti-H, AMO, . . .).

The APEX Collaboration "grand scheme" has made great progress in the last few years:

- prototypes for "risk retirement" (& also "surprises")
- design, construction, operation of core experiments
- new physics with e- plasmas and e+ pulses
- significantly improved diagnostic capabilities

The next few years are expected to be exciting!

- installations planned for 2025 & beyond