Electron Plasmas and Positron Bunches in Levitating and Supported Magnetic Dipole Traps

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for the APEX Collaboration

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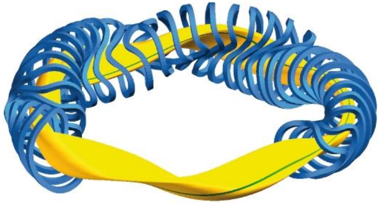
What do plasma physicists care about?

PLASMA = charged particles with sufficiently high density and low temperature to exhibit ***collective behavior.***

phys.org

- Trapping, equilibria and transport (of particles, momentum, and energy).
- Wave propagation, resonances, cutoffs, and mode conversion.
- Instabilities and nonlinear cascade to broadband turbulence.
- Wave-particle interactions, particle acceleration, beam instabilities, …
- Understanding astrophysical phenomena: solar flares, accretion disks, dynamos, magnetic reconnection, …
- Enabling other physics studies: neutral antimatter production, wakefield acceleration, gaseous electronics, …
- Applications for society/industry: fusion energy, plasma chemistry, semi-conductor manufacturing, lighting, medicine, …



Max-Planck Institut
für Plasmaphysik

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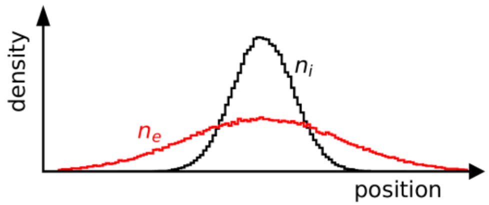
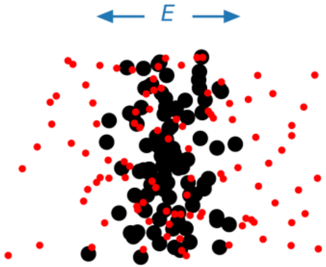
Mass-asymmetry is the source of instability in magnetized plasmas

- In ion-electron plasmas, the spatial and temporal scales for ion and electron dynamics differ by ~ two orders of magnitude due to mass asymmetry.
- Mass asymmetry is source of instabilities that lead to turbulence and transport.





Example: coupling of density and electric potential fluctuations.

Light electrons leave a density perturbation faster, creating an electric field.

In magnetized plasmas with density gradient → drift wave (or “universal”) instability.

Hypothesis (supported by much theory): A mass-symmetric magnetized plasma will be much more stable and therefore better confined than a mass-asymmetric plasma.

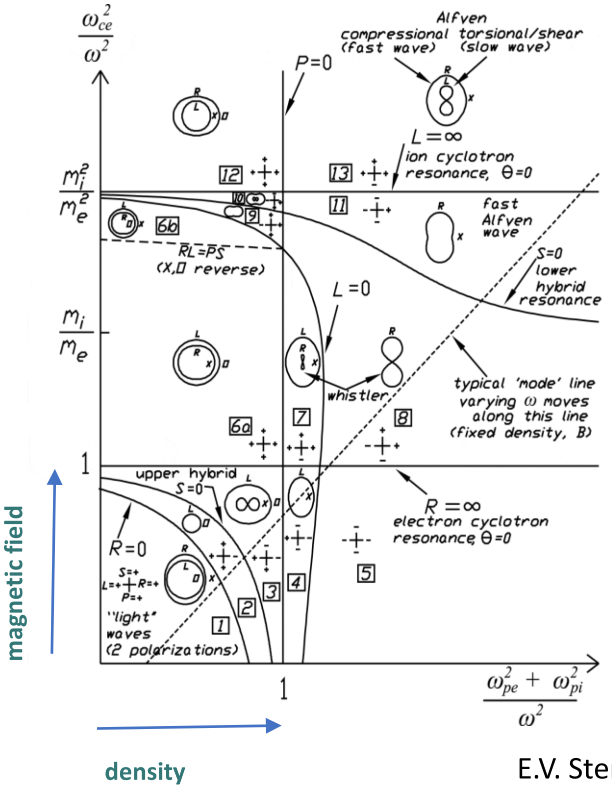
M.R. Stoneking, et al., J. Plasma Phys. **86**, 155860601 (2020).

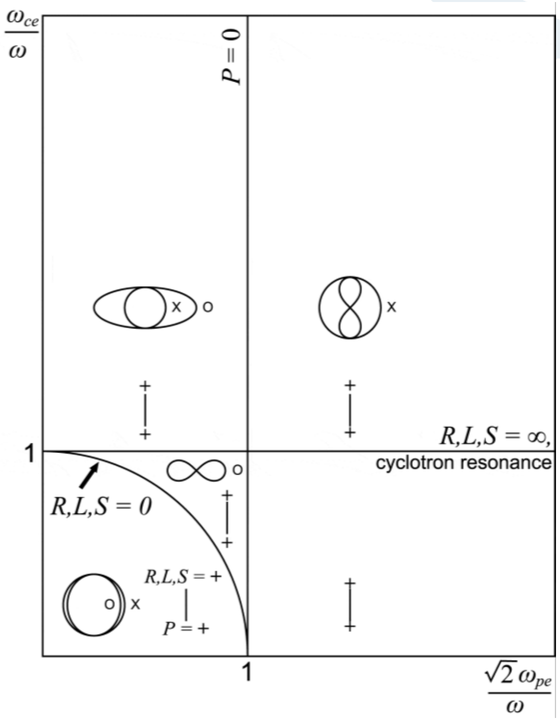
Wave physics of mass-symmetric plasmas is predicted to be simple.

CMA diagram

$m_{ion} \gg m_e$

Mass asymmetry is a source of complexity and instability in ion-electron plasma.





Pair plasma

$m_+ = m_-$

Mass symmetry reduces complexity and eliminates sources of instability.

E.V. Stenson, et al., J. Plasma Phys. **83**, 595830106 (2017)

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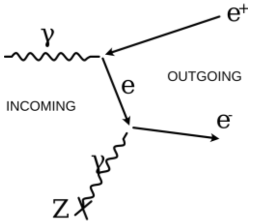
Choosing electron-positron plasma

- Exact mass symmetry
- Light particles are easily magnetized.
- Positrons are available

  → sometimes in some places.



wikipedia.org

Dirac equation:

$$i\hbar\gamma^{\mu}\partial_{\mu}\psi - mc\psi = 0$$

Electron	Anti-electron (positron)	
e^- ●	● e^+	$m_{e^+} = m_{e^-}$ $q_{e^+} = -q_{e^-}$

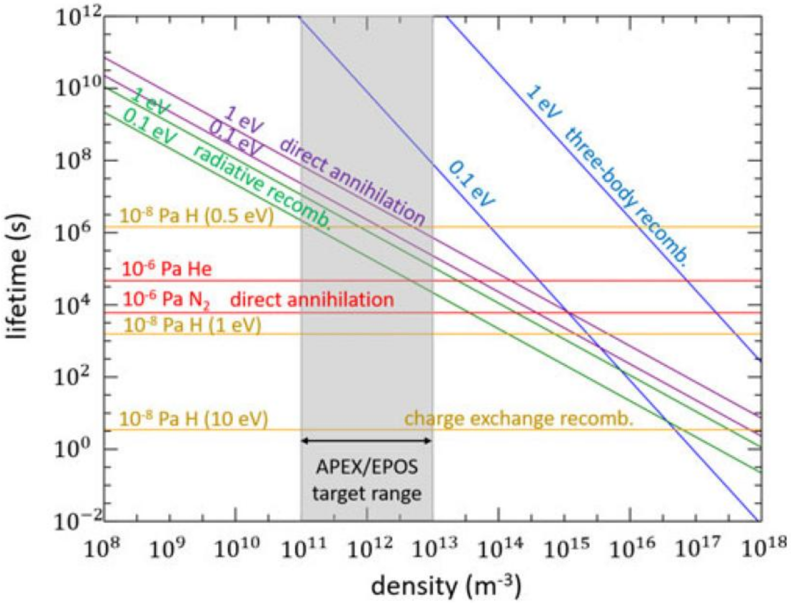
> *“We should not expect to find [anti-electrons] in nature, on account of their rapid rate of recombination with electrons, but if they could be produced experimentally in high-vacuum they would be quite stable and amenable to observation.”* P.A.M. Dirac (1931)

Small numbers of positrons can be confined / are stable for > 3 days.
- Haarsman, Abdullah, and Gabrielse, PRL **75**, 806 (1995).

Annihilation is not an impediment to doing plasma physics with electrons and positrons

- Radiative recombination / Ps formation → annihilation limits timescales to hours at low temperatures.

- Charge exchange Ps formation → annihilation could limit timescales to seconds at higher temperatures (and bad vacuum conditions).



direct annihilation

$$e^+ + e^- \rightarrow 2\gamma \text{ (511 keV)}$$

charge exchange

$$e^+ + X \rightarrow X^+ + Ps$$

3-body recombination

$$e^+ + e^- + e^\pm \rightarrow \text{Ps} + e^\pm$$

radiative recombination

$$e^+ + e^- \rightarrow \text{Ps} + \gamma$$

M.R. Stoneking, et al., J. Plasma Phys. **86**, 155860601 (2020).

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Need ~10^{10} low energy (<10 eV) positrons with low energy spread (< 1 eV).

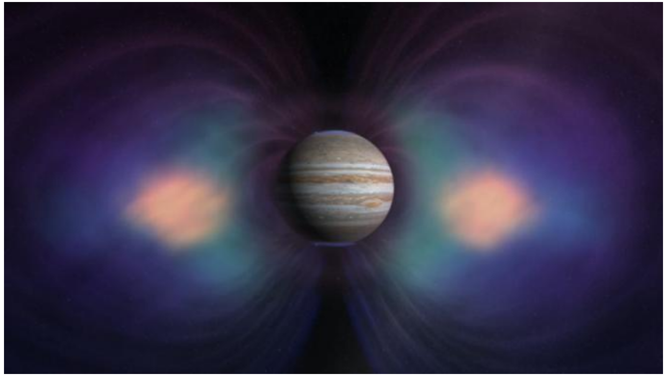
Target parameters:

- Density, typical of non-neutral plasma experiments: $n \sim 10^{13}\ \mathrm{m}^{-3}$
- Temperature: low (to increase collective effects): $T \sim 1\ \mathrm{eV}$
- Plasma size: small (to reduce required number of positrons while reaching collective regime), but not too small (to make it difficult to diagnose): $a \sim 20\ \mathrm{cm}$
- Magnetic field: large (to magnetize plasma and enhance cyclotron cooling): $B_{max} \sim 1\ \mathrm{T}$
- Number of positrons required: $N_+ \sim 10^{10}$

Two options for magnetic traps

From nature:

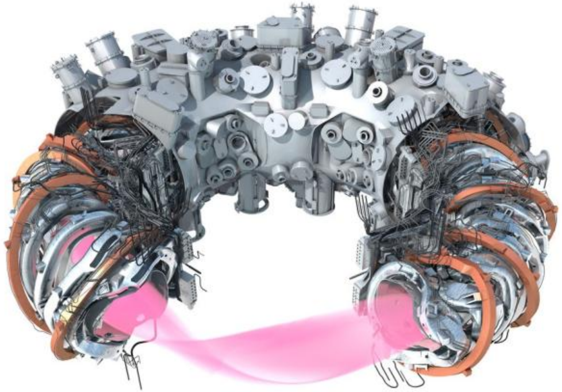
magnetic dipole/magnetosphere



https://www.missionjuno.swri.edu/jupiter/magnetosphere/

From fusion:

stellarator



Max Planck Institute for Plasma Physics

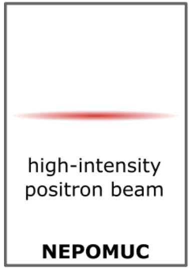
These configurations:

1) Do NOT require plasma currents
2) Can confine un-neutralized combinations of charged particles

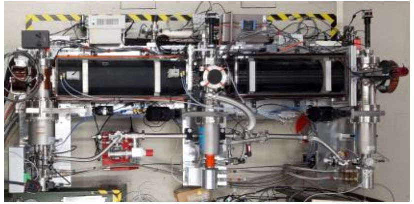
A Positron Electron eXperiment (APEX): Grand Scheme

$5 \times 10^7\ e^+$/s @ 5-20 eV

8 pA, DC, 2-3 mmϕ

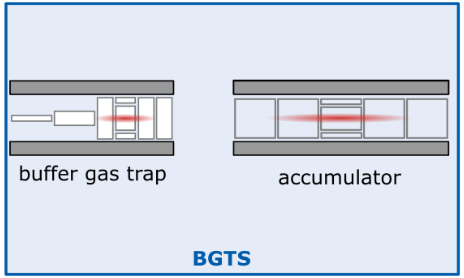


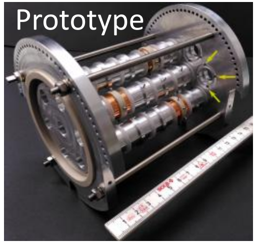
Surko trap & accumulator



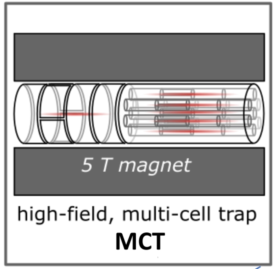
$10^6\ e^+$ per pulse (1 Hz)

$10^8\ e^+$ per pulse (1/min)



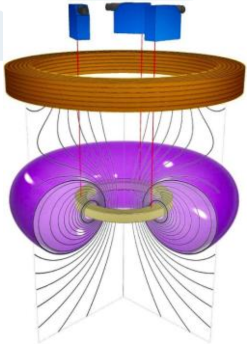


$10^{10}\ e^+$ delivered at 1/hour



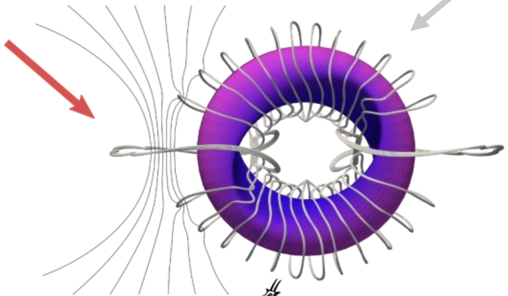
Accumulation in traps with increasing confinement time & space-charge capacity

APEX-LD



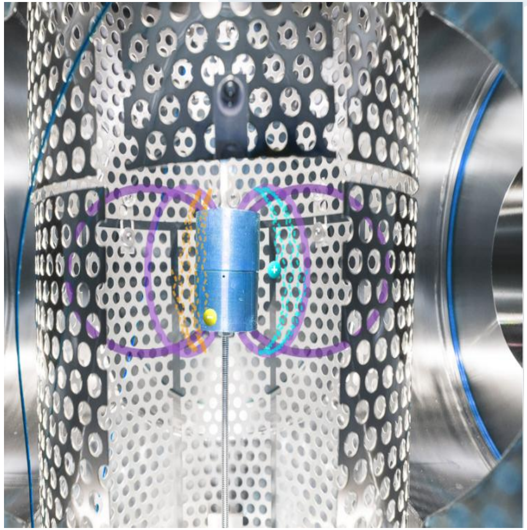
e^-

EPOS



Experiments in a Permanent (Supported) Magnetic Dipole Trap

- Efficient injection of a DC positron beam.
- Good confinement of a gated DC positron beam.
- Injection of DC positron beam into a pre-formed electron plasma.
- Efficient injection and confinement of positron pulses.
- Resolving positron transport and positronium formation rates in dipole trap.



Proto APEX. *Photo: Markus Singer*

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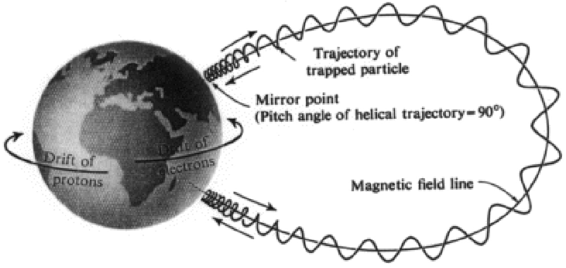
Appleton, Wisconsin

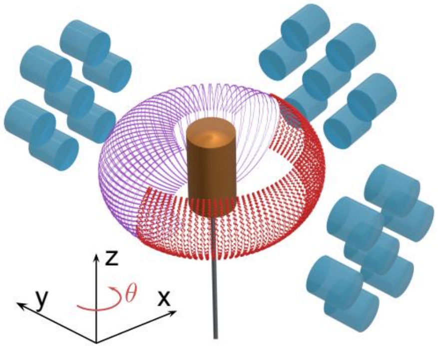
Charged Particle Motion in a Dipole Field

Frequency scales:

Slow ←→ Fast

Single-particle motion:	Magnetosphere	Laboratory
• Gyration about the magnetic field	kHz	GHz
• Poloidal bounce/mirror	Hz	MHz
• Toroidal drift	mHz	kHz





Dipole moment is adiabatically conserved: $\mu = \frac{mv_{\perp}^{2}}{2B}$

Stronger field at poles produces an effective potential energy:

$$U_{eff} = \mu|B|$$

Some particles escape (loss-cone in velocity space).

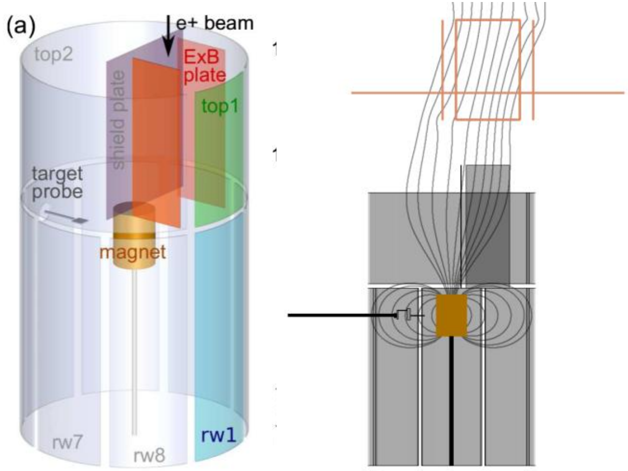
In lab, biasing the magnet plugs the loss cone electrostatically:

$$U = e\phi$$

ExB drift technique for injection

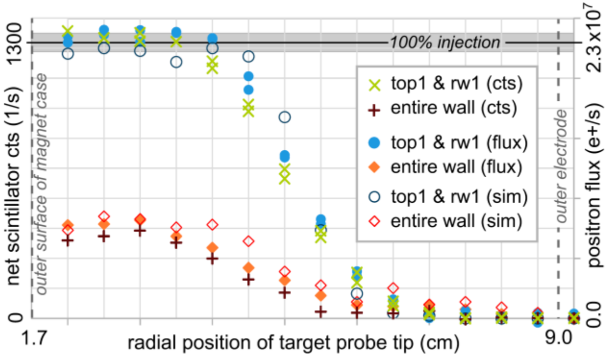
Nearly 100% of positrons can be injected onto orbits that drift 180° toroidally.

DC positron beam from NEPOMUC



Annihilation gammas detected with collimated BGO detectors viewing target probe.

- Highest efficiency requires (positive) bias on the magnet AND on electrodes localized to injection azimuth.
- Gamma diagnostic and direct charge flux measurements agree on location of orbits.
- Simulations reproduce measured signals.



E. V. Stenson, *et.al.*, Phys. Rev. Lett. **121**, 235005 (2018).

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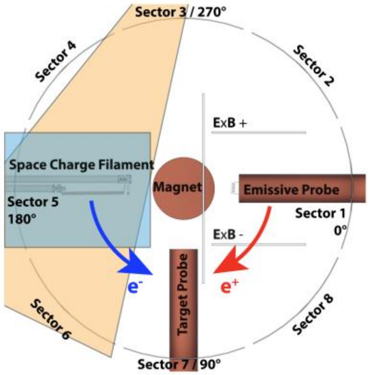
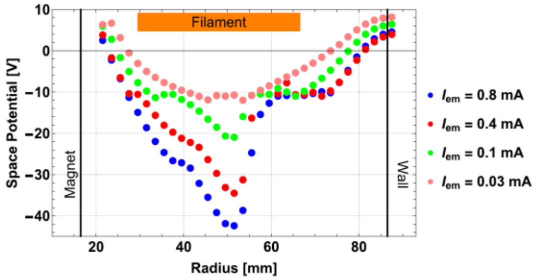
The presence of an electron space charge does NOT impede positron injection

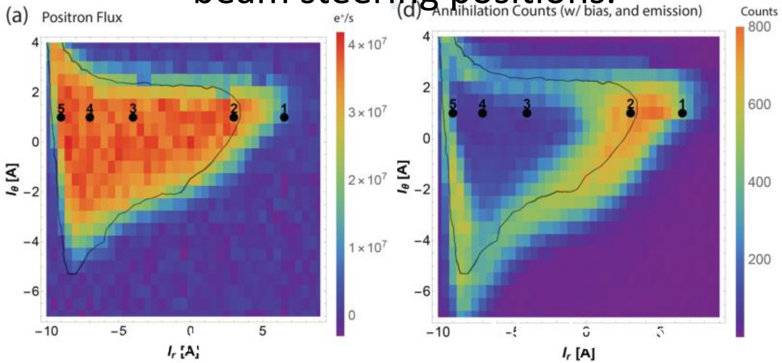


- Electron cloud generated with tungsten filament.

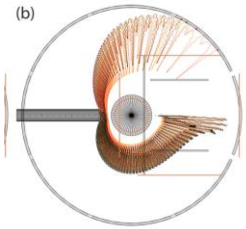


- Substantial space charge measured on other side of device.

Annihilation signal for different e+ beam steering positions.



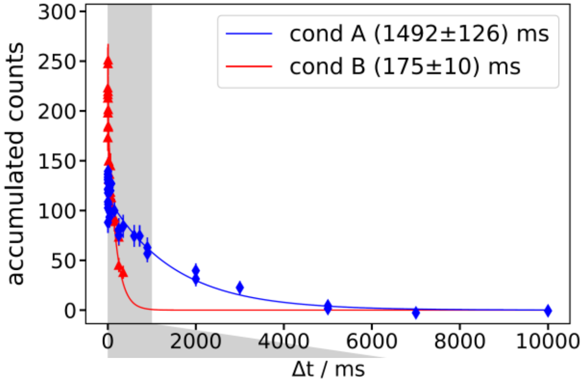
- Positrons are still efficiently injected!



M. Singer, et. al., Phys. Plasmas **28**, 062506 (2021).

Confinement of positrons in a supported dipole trap → switch off the ExB potentials

Gated DC (NEPOMUC) e$^+$ beam



A = magnet biased to +8 V, plugging loss cone
B = magnet grounded

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

AIST Slow-Positron Facility

Tsukuba, Japan

Electron source

67 kV, 100 mA, 40 Hz

LINAC

40 MeV, 80 mA, 40 Hz

Slow positrons

Ta converter & W moderator

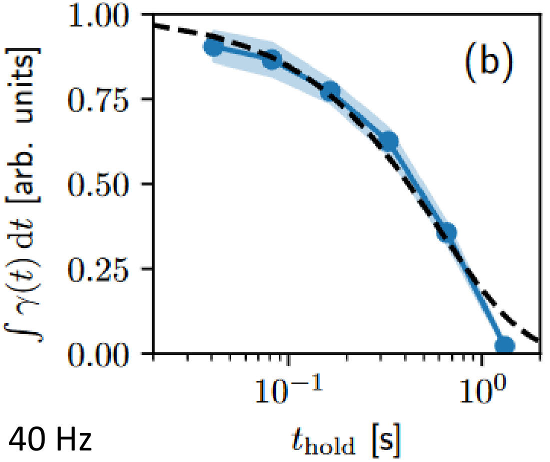
30 eV, ~6 ×10^6 e^+/s (1 pA), 2 us, 40 Hz

Buffer-gas trap

N=10^5 e^+/ pulse, ~7 eV, ~100ns, 0.3 Hz

H. Higaki *et al.* (2020) *Appl. Phys. Express* **13** 066003

Pulsed (AIST) e+ beam



J. Von der Linden, A. Deller, et al., *in preparation for publication (2026).*

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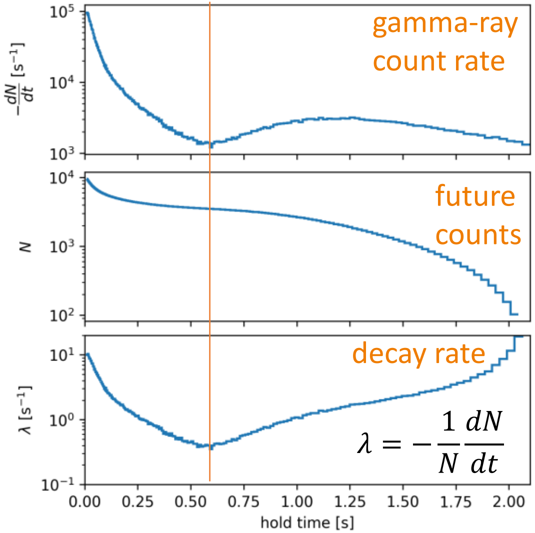
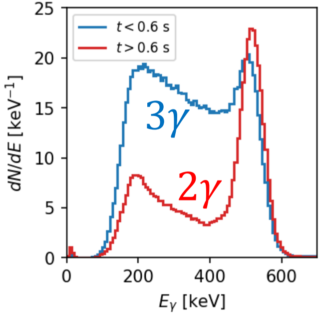
Positron pulses → using annihilation signal to observe positronium formation

Pulsed (AIST) e+ beam

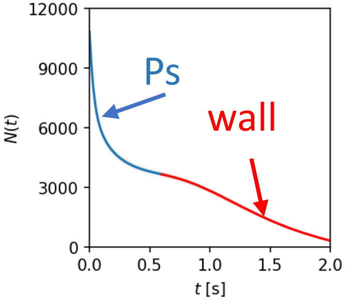


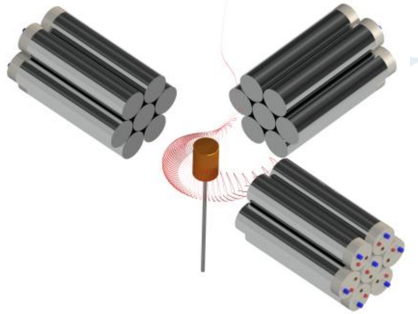
- Spectrum from early gamma signal is dominantly 3γ due to Ps formation by charge exchange on residual gas.
- Later, cooler e$^+$ population diffuses to wall, due to elastic scattering on residual gas, resulting in 2γ spectrum dominated by 511 keV peak.

energy spectrum



positron population





- Positron cooling rate (and diffusion due to elastic scattering) can be enhanced by introduction of CF4.

J. Von der Linden, A. Deller, et al., *in preparation for publication (2026).*

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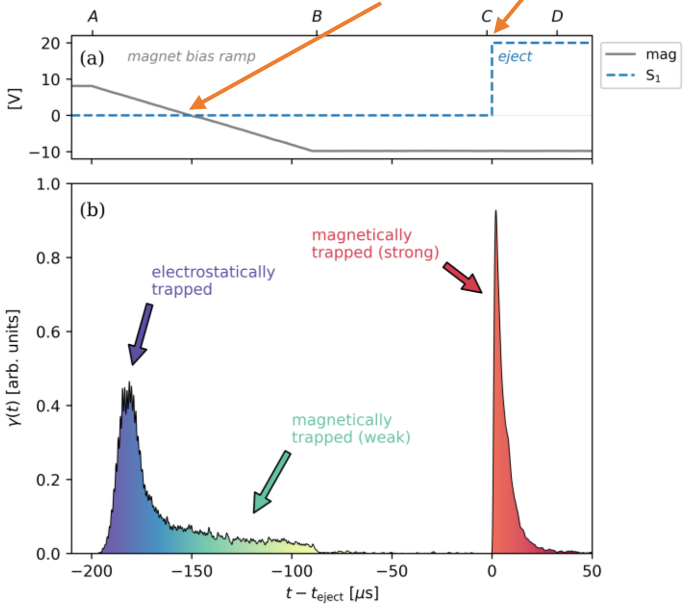
Positron pulses → using annihilation signal to diagnose distinct trapped populations

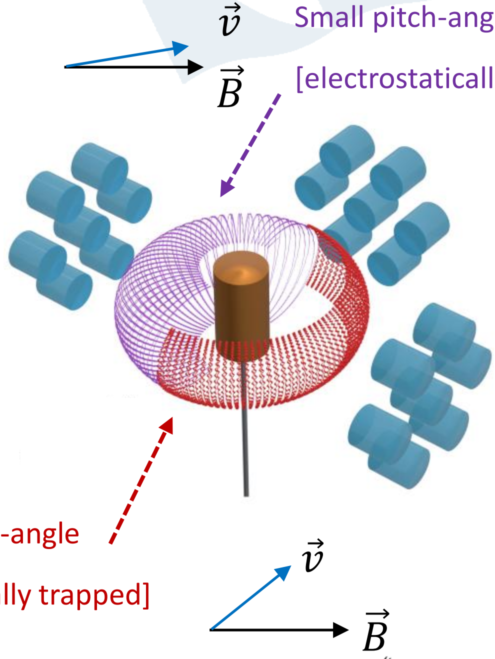


slowly ramp magnet bias

ExB plates ON

- Ramping the magnet bias allows electrostatically trapped particles to escape/annihilate.

- Turning on ExB plate bias ejects remaining, magnetically trapped particles.



Small pitch-angle

[electrostatically trapped]

Large pitch-angle

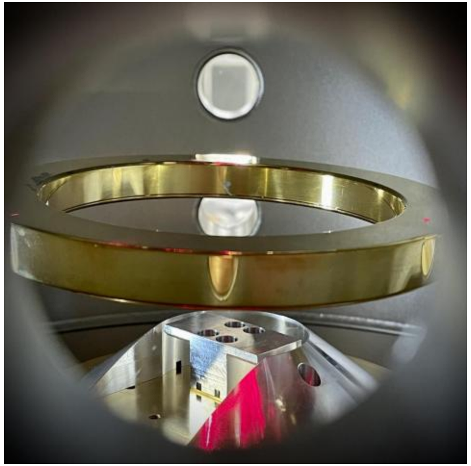
[magnetically trapped]

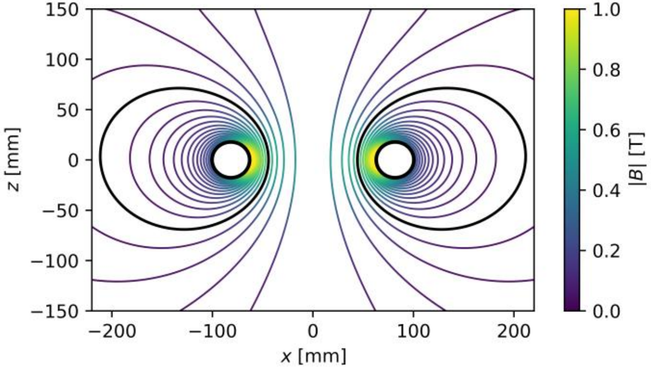
J. Von der Linden, A. Deller, et al., *in preparation for publication (2026).*

Levitating dipole → allow passing orbits

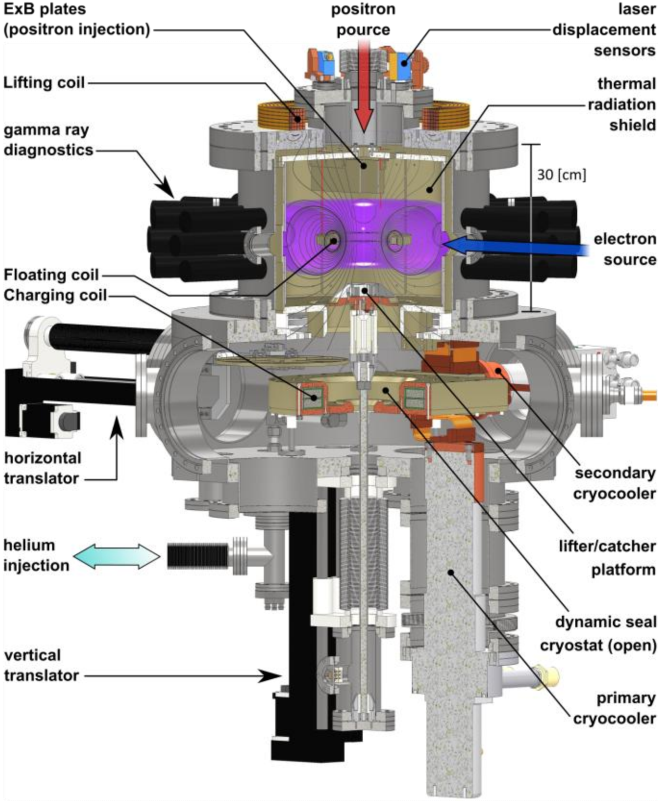
Levitated Dipole Trap

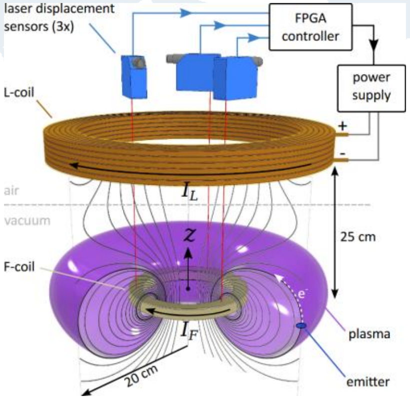
- Poloidal field lines wrap around current ring.
- Levitation eliminates supports that would interrupt the confinement volume.
- Good confinement for neutral and non-neutral collections of charge.





Design and operation of a levitating dipole trap





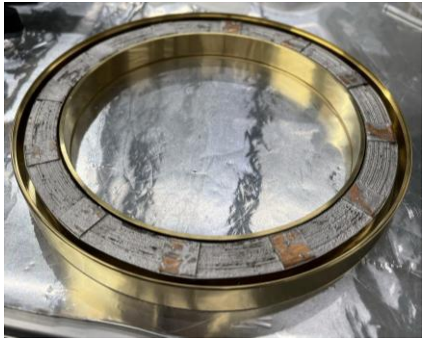
HTS Floating coil

A. Card, et al., Rev. Sci. Instrum. **97**, 023501 (2026).

High-temperature Superconducting Coils

Floating coil

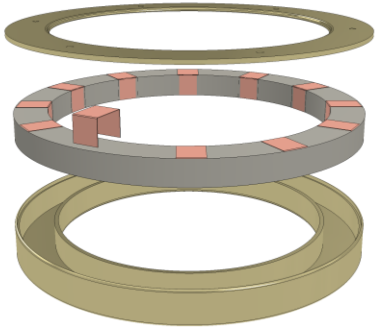
- *<u>No-insulation</u>* ReBCO tape (12 mm).
- 150 turns.
- Single pancake coil with 12 return bands.
- Inductively charged.

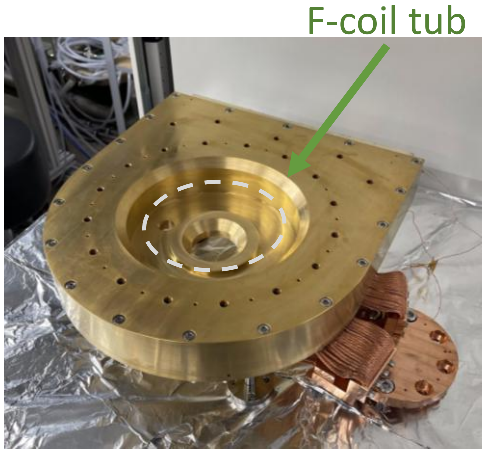


150 mm

Charging coil

- Insulated, copper-laminated HTS ReBCO tape (12 mm).
- 450 turns.
- Double-pancake coil.
- Epoxy encased.
- DC powered.





260 mm

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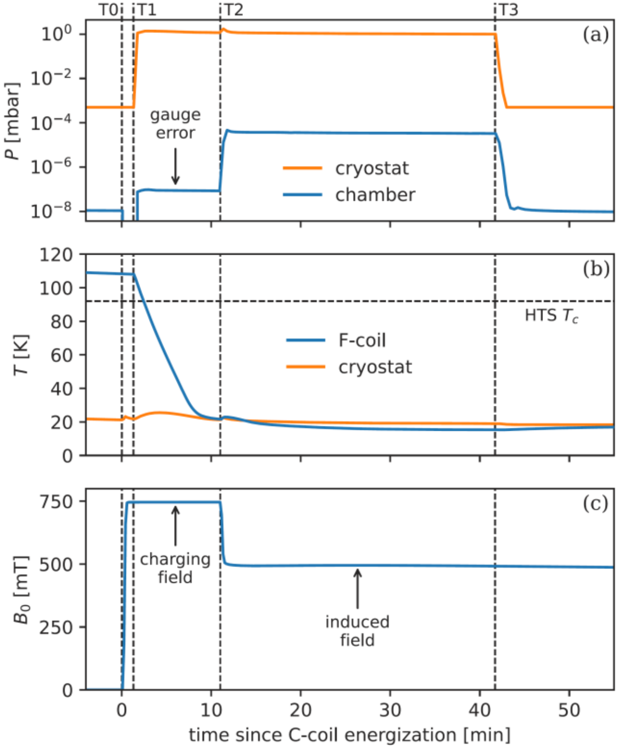
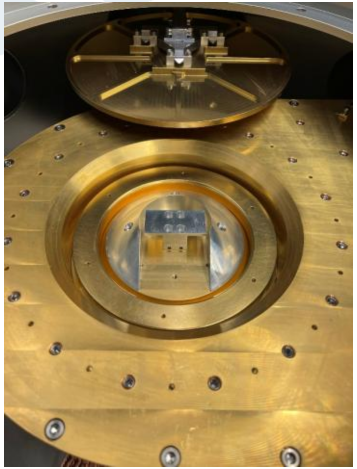
Cooling and Charging the F-coil

- C-coil is maintained below 45 K and is energized while F-coil is above SC transition (110 K).
- He gas is introduced into sealed enclosure, cooling F-coil below SC transition.
- C-coil current is ramped down to induce F-coil current (60 kA-t) which persists for 24 hours (if maintained at 20 K).



Cooling and charging enclosure



Maximum on-axis field is 0.5 T
Exceed 1 T near the coil

A. Card, et al., Rev. Sci. Instrum. **97**, 023501 (2026).

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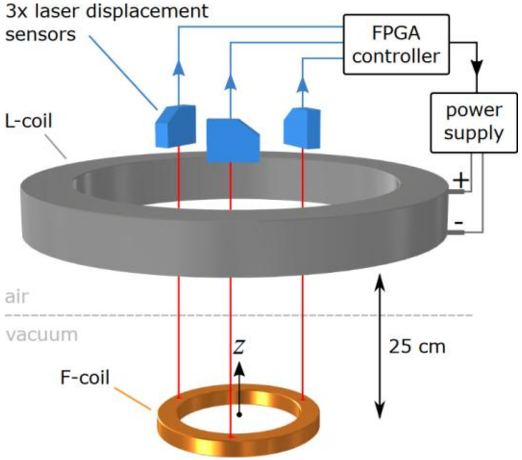
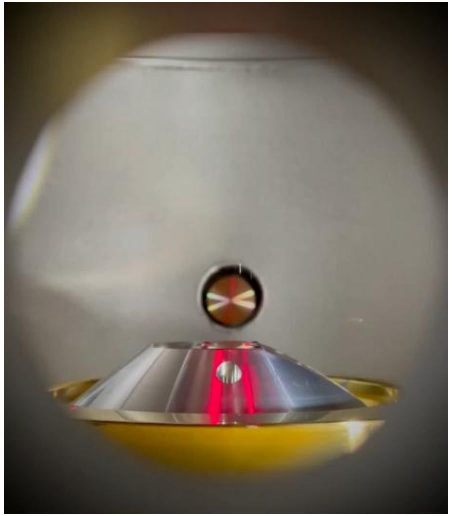
Stabilizing the Levitation

- A PID feedback, implemented on an FPGA controller, manipulates lifting coil current, based on 3 laser range finder signals to stabilize the vertical position.



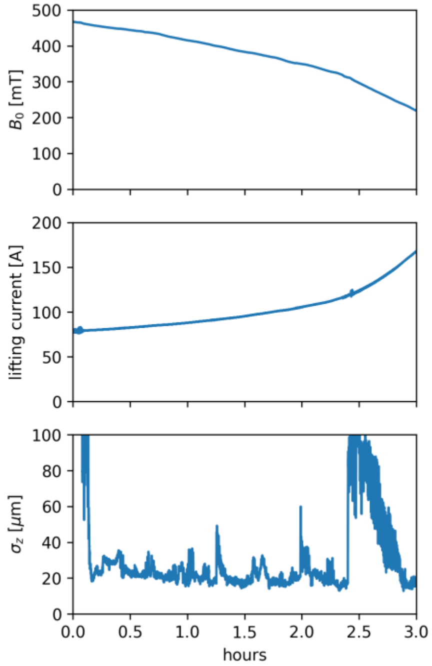
APEX-LD: LAUNCH



- Tilt and slide displacements are inherently stable in this configuration.

3 hours of stable levitation

~20 μm vertical stability



A. Card *et al.*, (2024), *IEEE Trans. Appl. Supercond.*, 1–9

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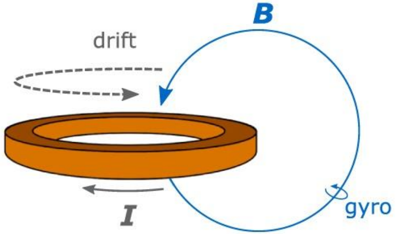
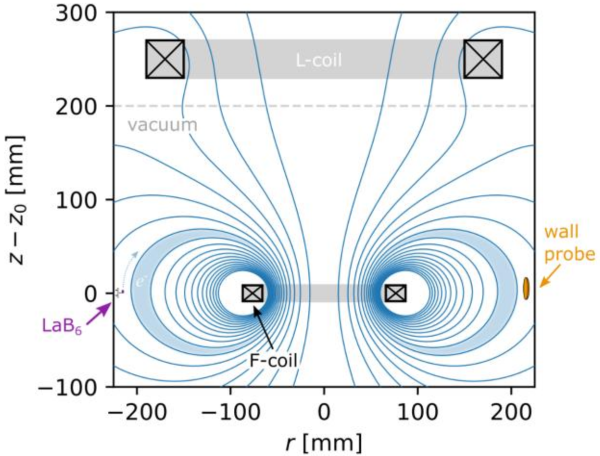
Visualizing Field Lines and Particle Motion using Helium

- Electrons emitted from a thermionic emitter excite He gas.
- Single particle trajectories are visualized.

Electron orbits in Helium

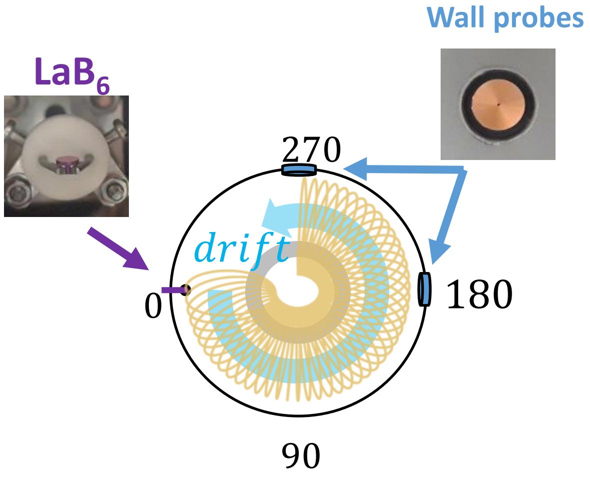
LaB$_6$

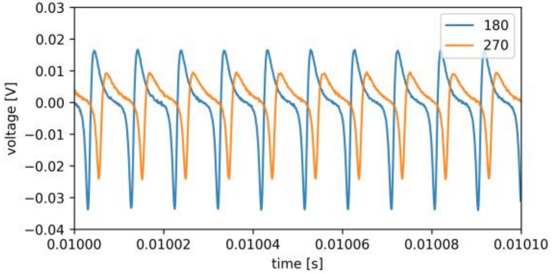




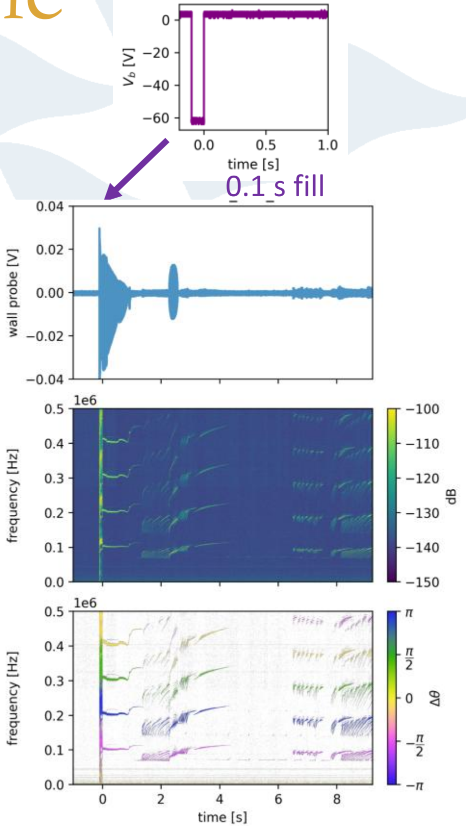
A. Deller et al. Plasma Phys. Control. Fusion 67 015030 (2025).

Electron plasma experiments in the levitating trap





- Electrons are injected from edge-localized thermionic emitter.
- After early turbulent phase (during injection), a coherent mode emerges, diagnosed with capacitive wall-probes.
- Mode has one toroidal wavelength (m=1), but exhibits complicated frequency chirping.
- This is evidence of collective behavior of a confined electron plasma.



A. Deller, et al, submitted to Phys. Plasmas (2026).

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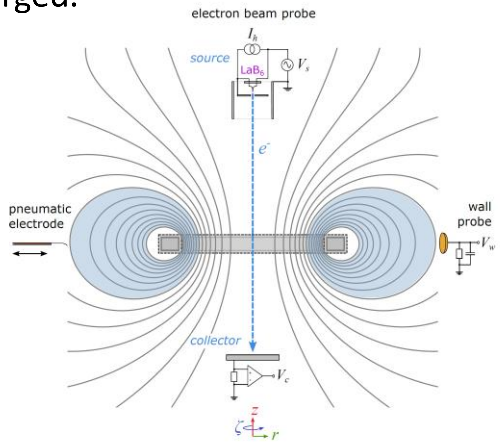
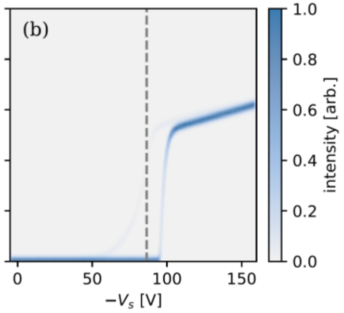
Diagnosing the electron plasma equilibrium with an electron beam probe

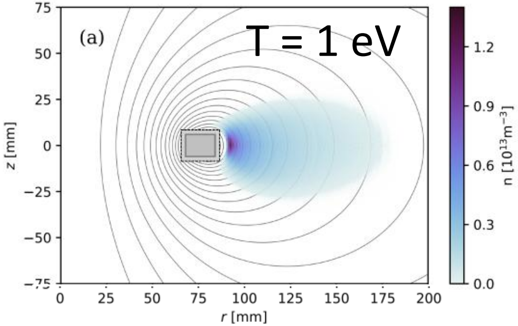
- Diagnostic e-beam is sent down the axis.
- Beam energy is ramped and transmitted current is collected on lifter.
- Clear indication that F-coil becomes charged.



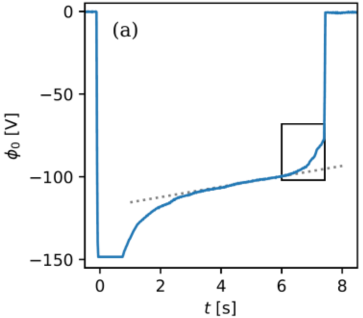
A. Deller, et al, submitted to Phys. Plasmas (2026).

- Sample transmitted current vs. beam energy.





- Beam stopping potential is measured during confinement, and as reciprocating probe is inserted.



- The trapped charge distribution can be backed out from the measured stopping potential as the probe is inserted (assuming a temperature).

Electrons and Positrons in an Optimized Stellarator (EPOS)

Motivation:

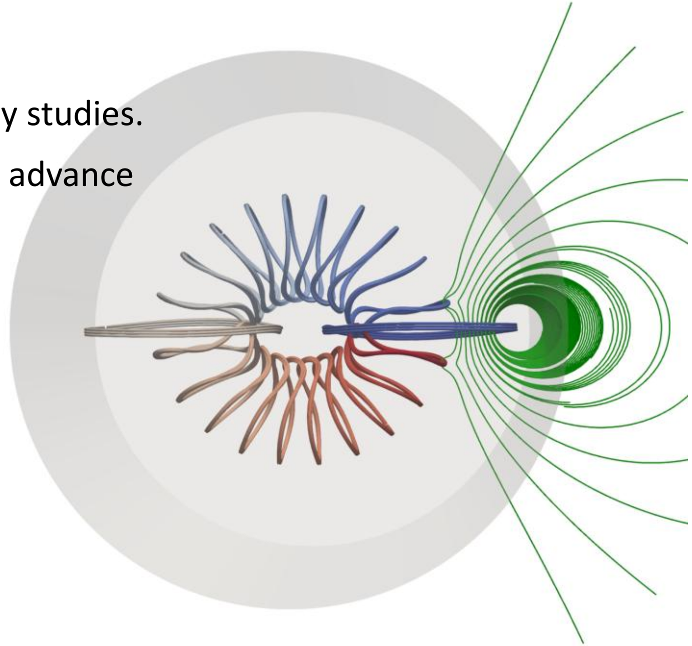
Exploit technologies developed for APEX-LD (e.g., HTS coils, positron traps, drift injection) to investigate pair plasma confinement in a compact stellarator.

Goals:

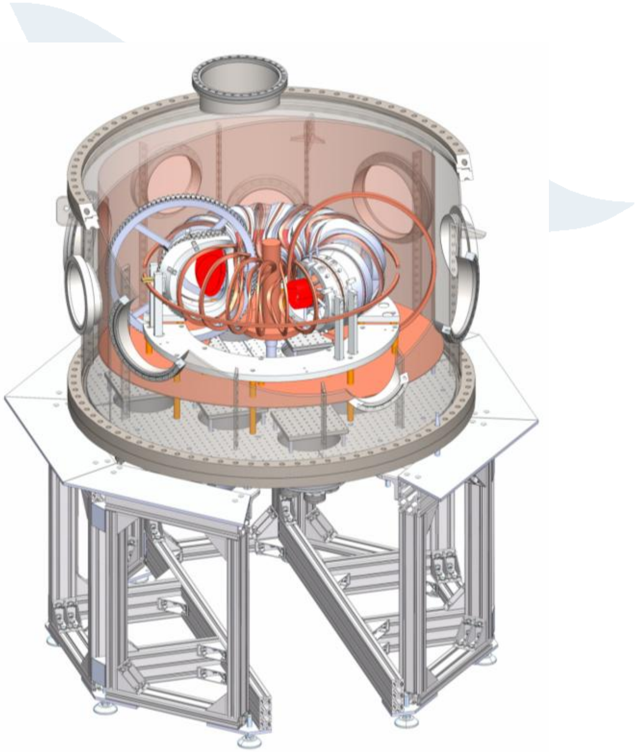
- Confine a low-energy electron-positron plasma for transport and stability studies.
- Experimentally **validate** state-of-the-art stellarator coil optimization and advance non-planar HTS coil technologies.

Requirements:

- Small volume (limited number of positrons).
- Good confinement (low neoclassical transport).
- Drift injection access (weave lane).
- High B-field for cyclotron cooling (HTS).
- Buildable tolerances (HTS strain).



EPOS stellarator



Target Specifications

- Quasi-axisymmetric
- 2 field period
- 20 cm major radius
- $a/\lambda > 10$
- B ~ 2 T on axis
- Stray fields for positron injection

Results

- 22-coil design
- Field error < 0.04%
- HTS strain < 0.1%
- QS error < 0.1%
- Iota = 0.06
- Feasible tolerances: ~ 1 mm

Engineering considerations:

- Cryogenic cooling (20K)
- Ultra-high vacuum
- Diagnostic access (gamma-rays)
- Thermal expansion
- Magnetic forces
- Feasible tolerances and windable coils
- Machinability and material cost

1st test coil in the CNC

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APEX collaboration

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Cliff Surko, 1941 - 2024

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