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Injection and trapping of electrons in a dipole magnetic field: towards the formation of an electron-positron plasma

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*T. S. Pedersen *et al*, NJP **14**, 035010 (2012).
C. Hugenschmidt *et al*, NJP **14, 055027 (2012).
***D. B. Cassidy *et al*., Phys. Rev. Lett. **106**, 133401 (2011).

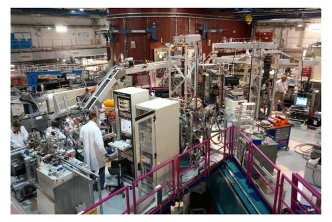
◆ Motivation and the PAX/APEX project*

Electron-positron mixture as a pair-plasma

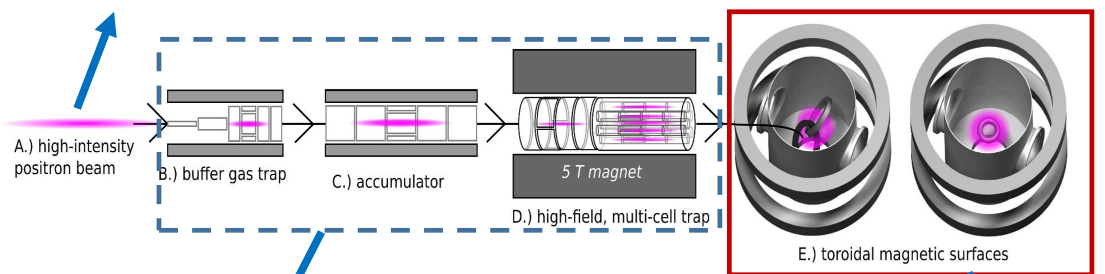
- Matter-antimatter plasma experiment; new research subjects
  - Unique plasma properties on stability, wave propagation (e.g. no Faraday rotation)
  - Application to astrophysical phenomena in pulsars and active galaxies
  - Very few experiments so far – problems on particle source, confinement

- Advantages of electron-positron pair plasma
  - Quick response to external electric and magnetic fields ($m_e = m_{C60}/2.2\times10^5$)
    - ➡ Suitable for studies of waves in both high- and low- frequency ranges
  - "Perfectly" equal-mass particles ($m_{e-} = m_{e+} = 9.10938291\times10^{-31}$kg)
    - ➡ No effects of remaining small mass unbalance
  - Precise measurements by using annihilation γ rays
    - ➡ Detailed understanding of general properties of toroidal non-neutral plasmas

The project



NEPOMUC positron source**
- FRM II @TUM（20MW neutron source)
- DC positron ~10^9/s by using prompt γs
- East Hall is under construction ~2015



E. V. Stenson, P4.130

Positron Accumulation eXperiment
PAX positron accumulator
- Buffer gas trap + multi-cell type trap
- target parameter: cold 10^{12} e+ accumulation

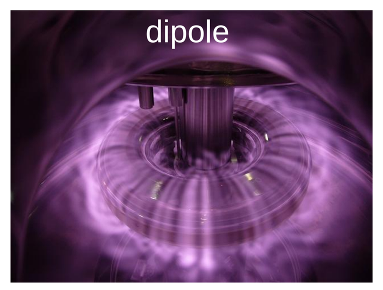
A Positron Electron eXperiment
APEX Toroidal trap
- **Confinement of e+ and e-**
- **Stellarator or Dipole**

◆ APEX: toroidal confinement concept

Toroidal confinement of particles

- Linear configurations:
  - Plugging electric field along magnetic field lines
  - Suitable for the confinement of single-component non-neutral plasmas
  - ➡ Positively and negatively charged particles are not simultaneously trapped in a finite region as a plasma
- Toroidal configurations for non-neutral plasmas
  - Stable trapping of pure electron plasma has been realized in CNT and RT-1
  - Applicable to the confinement of plasmas at any non-neutrality

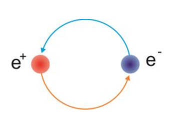
P. W. Brenner and T. S. Pedersen, Phys. Plasmas **19**, 050701 (2012).



Z. Yoshida et al., Plasma Phys. Cntr. Fusion **55**, 014018 (2013).

Particle injection schemes

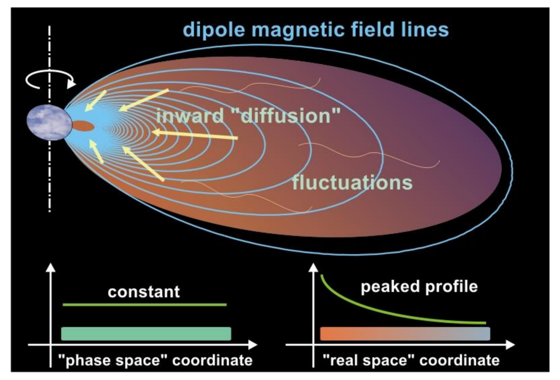
- By using positronium re-emission process on solid materials***
  positrons are converted into positronium atoms and freely transported into the confinement region, then photo-ionized using lasers



- Drift injection by using external electric fields (to be started with electrons)

◆ Dipole trap for APEX and target parameters

Two-step development of APEX dipole



Proof-of-principle experiment with a permanent magnet device 2014 1Q-
- Small trap with a neodymium dipole magnet
  Confinement and injection properties

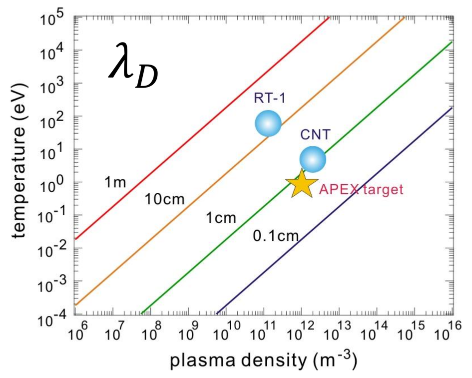
  Electron beam exp.
  - Efficient injection method development with drift injection with external electric fields

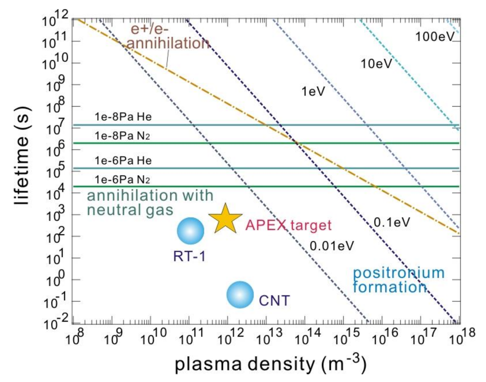
  Positron beam exp.
  - Drift injection and γ detection with PHA

➡

APEX Levitated dipole 2015-
- Superconducting dipole field magnet
- Closed and unperturbed field lines
- Long confinement of e+
- Simultaneous confinement of e- and e+
- Excitation and detection of waves
- Dispersion relation measurements

Target parameters and expected life times





- To observe collective phenomena, scale length must be larger ($a > \sim10\lambda_D$) than the Debye length $\lambda_D = \sqrt{k_B T_e / n_e e^2}$

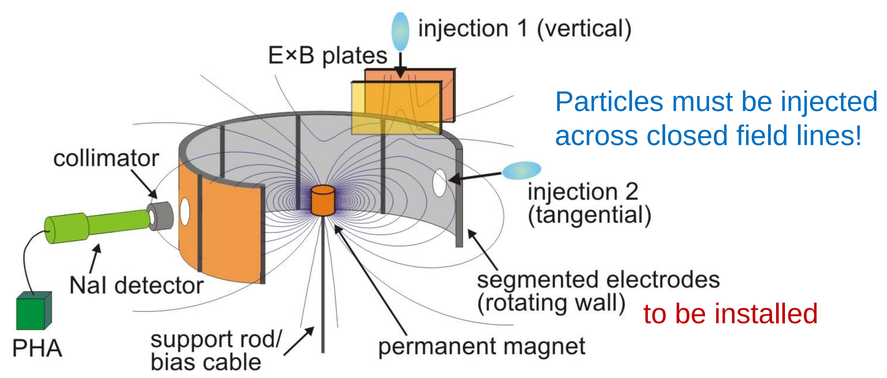
  Target parameters: $n_e \sim 10^{12}$m^{-3}, $T_e \sim 1$eV ➡ $\lambda_D \sim 1$cm

- For trap volume $V \sim 10^{-2}$ m^{-3} and DC beam, required confinement time is ~10 s; rather hard target ➡ importance of PAX

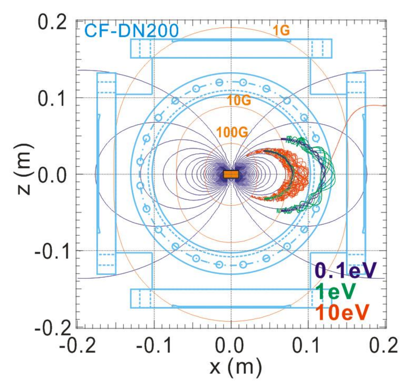
- In these parameters, loss channels are expected to be small
  (Plasma effects; instabilities, turbulence, etc. are not considered here)

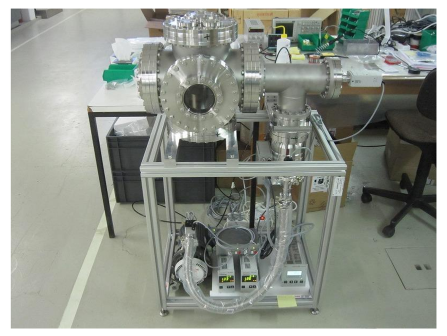
◆ Prototype APEX trap and drift injection schemes

Compact dipole device with a permanent magnet



Schematic of the experiment, including the supported neodymium magnet, E × B plates for vertical injection, rotating wall for tangential injection, and diagnostics.

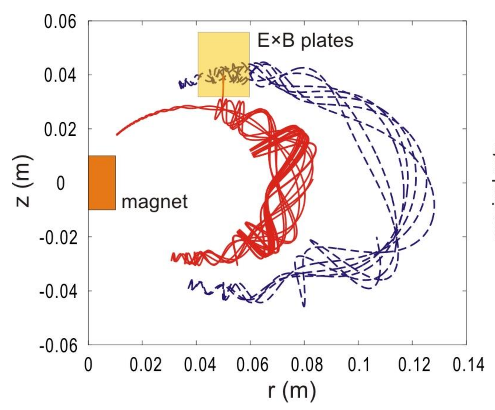


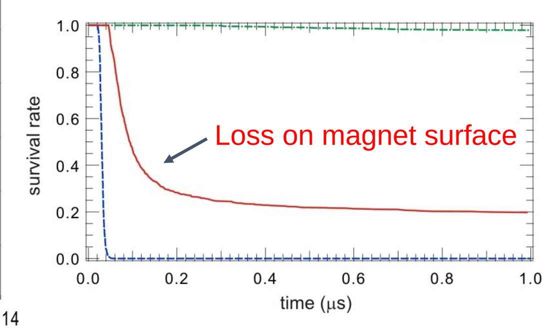


Small energy spread is important for efficient confinement in a trap system.

Drift injection schemes

Injection method 1: vertical injection
- the **E** × **B** drift motion induced by a local crossed electric field
- High injection efficiency when the permanent magnet is biased

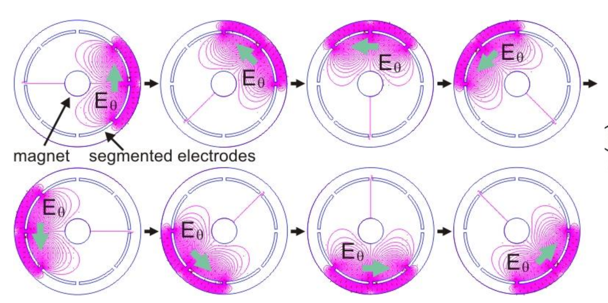


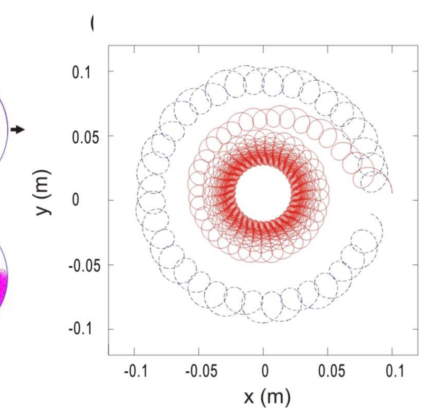


(left) Typical positron orbit projected onto the *r-z* cross section when electric field is applied (solid line) and not applied (dot line). Electric field of **E** = 1 × 10^3 V/m was applied in the marked region from t=0 to 0.1ms.

(right) Ratios of remaining positrons after injection without **E** (dot line), with the application of **E** (solid line), and when the magnet was also biased (chain line).

Injection method 2: tangential injection (to be installed)
- Rotating **E** is applied in the azimuthal direction
- RW freq. is synchronized with grad-B/curvature drift freq.
- Efficiency will be tested in a real system



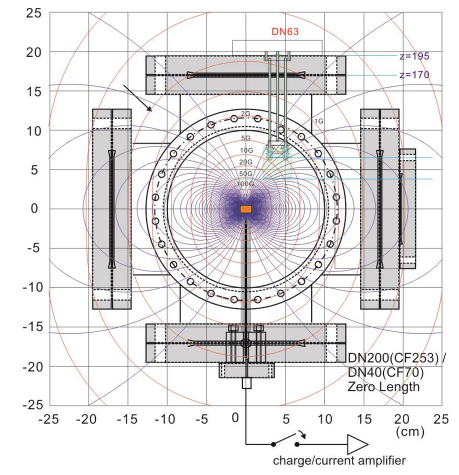


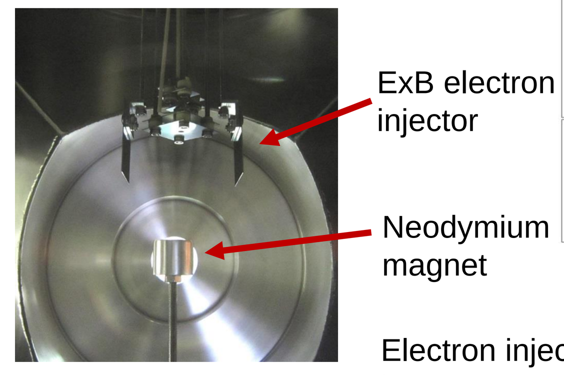
(left) Schematic view of a rotating wall and equipotential contours generated by the segmented electrodes.

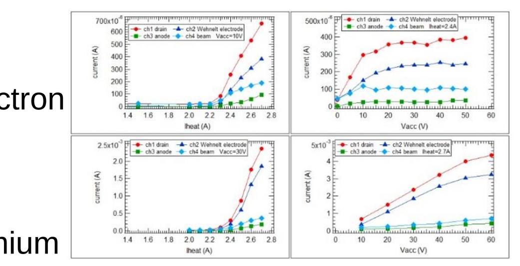
(right) Typical positron orbits with (dot line) and without (solid line) the application of synchronized rotating wall.

◆ Proof of principle experiment in Proto-APEX

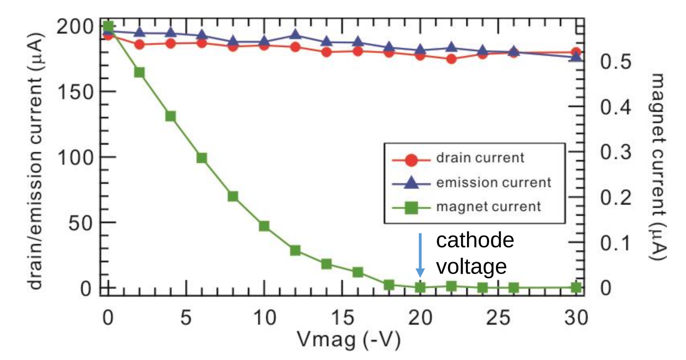
Drift Injection of electrons

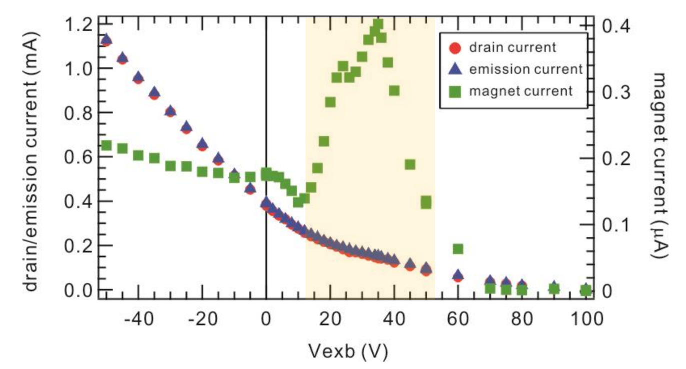






Electron injection into a dipole field generated by a permanent magnet



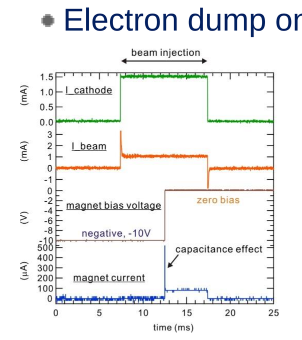


Electrons are effectively guided into the confinement region by using external electric field.

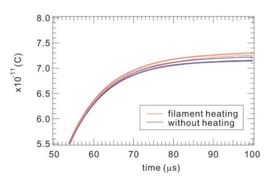
Diagnostics and initial results

- Fixed current probe
  - Electron emitting filament located just outside the confinement region
  - Emission current (~10 nA) is controlled by external circuit
  - Plasma potential is estimated according to the filament voltage

- Electron dump onto the magnet

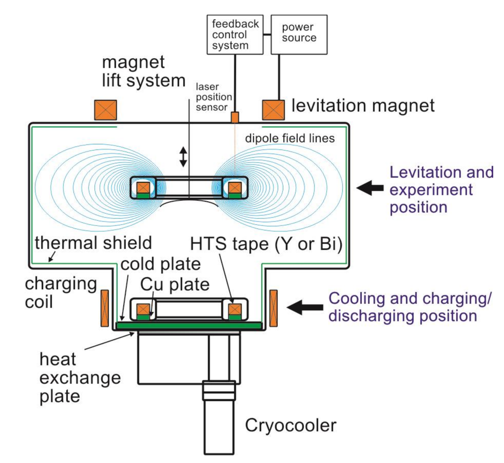


- During/after injection, electrons are dumped onto magnet along field lines.
- So far good S/N level is not realized



◆ Future works

Superconducting levitated dipole trap

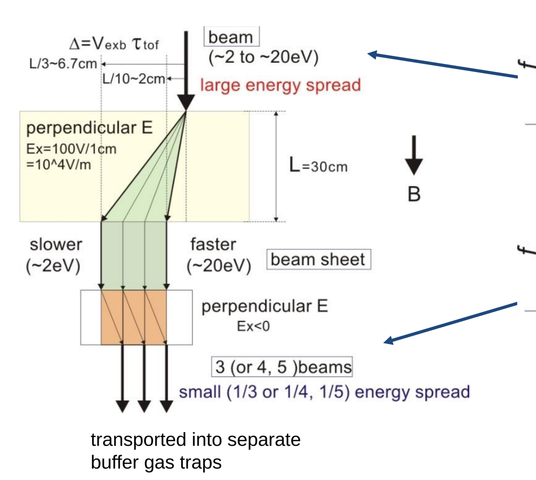


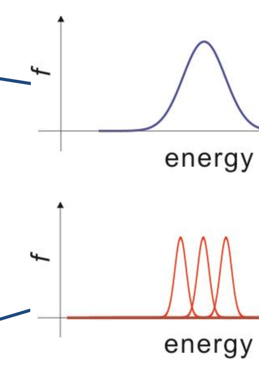
	RT-1	Mini-RT	LDX	APEX dipole
SC material	Bi-2223	Bi-2223	Nb3Sn	Bi or Y
magnet major radius	250 mm	150 mm	300 mm	100 mm
coil current	116 A	117 A	1820 A	100 A
turn	2160 turn	430 turn	714 turn	500 turn
total current	250 kA	50 kA	1300 kA	50 kA
operation temperature	20-30 K	20-40 K	4 K	20-40 K
coil weight	110 kg	20 kg	580 kg	10 kg
Coil cooling	He gas	He gas	He cooling	conduction
excitation	direct	direct	induction	induction
thermal shield	coil	coil	coil (He)	chamber

- Closed and unperturbed field lines are required for the confinement of pair-plasmas
- This will be realized with a levitated HTS magnet

ExB separation of positron beams

J. Stanja, T. S. Pedersen et al.





- Small energy spread is important for efficient confinement in a trap system
- This may be realized by two sets of ExB drift plates