Max-Planck-Institut für Plasmaphysik

Status of A Positron-Electron Experiment (APEX) towards the formation of pair plasmas

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Outline

- Introduction
  - Motivation for the electron-positron pair plasma experiments
  - The role of APEX and target parameters
  - APEX-D project and development steps
- Recent activities of APEX
  - Injection and trap of electrons in a prototype dipole trap
  - Forthcoming first positron experiment at NEPOMUC
  - Design status of a superconducting levitated APEX-D
- Summary

Motivation to create and study electron-positron pair-plasmas[1]

- Matter-antimatter plasma experiment; new research subjects[2,3]
  - Unique stability[4] and wave propagation properties (e.g. no Faraday rotation)
  - Application to astrophysical phenomena in pulsars and active galaxies

- Advantages of electron-positron pair plasma
  - Strongly magnetized plasmas are expected : $m_e = m_{C60}/2.2\times10^5$
  - Perfectly equal-mass particles: $m_{e-} = m_{e+} = 9.10938291\times10^{-31}$kg
  - Precise measurements by using annihilation γs, loss channels etc.

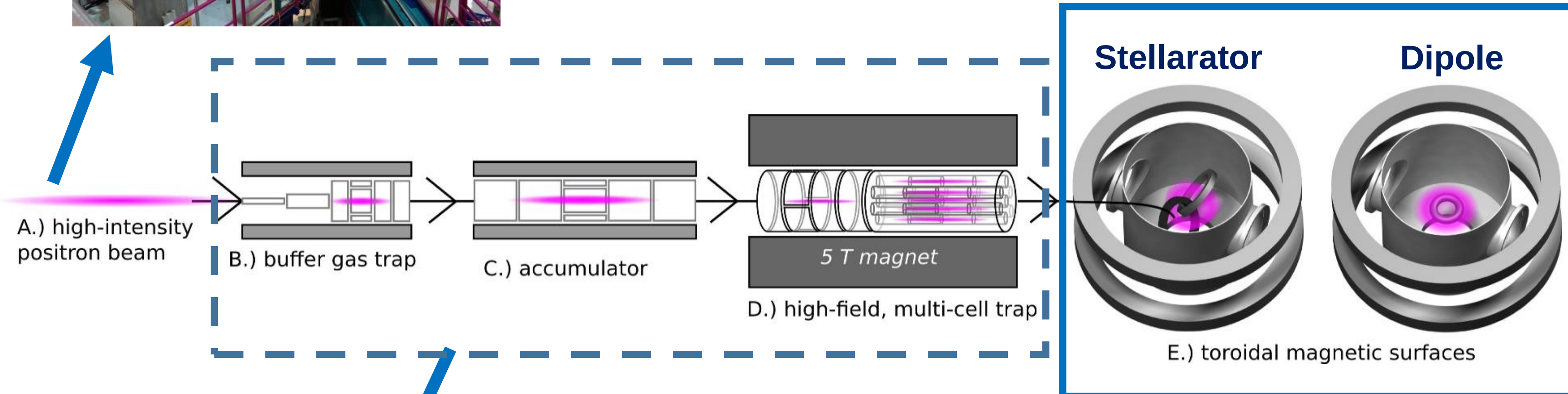
However, very few experiments so far: source and trap problems…

1 T. Sunn Pedersen, J. R. Danielson, C. Hugenschmidt *et al*, NJP **14**, 035010 (2012).
2. V. Tsytovich and C. B. Wharton, Comm. Plasma Phys. Cntr. Phys. **4** 91 (1978).
3. C. M. Surko and R.G. Greaves, Phys. Plasmas **11**, 2333 (2004).
4. P. Helander, Phys. Rev. Lett. **113**, 135003 (2014).

In the project*, APEX focuses on the confinement of positrons and electrons as plasmas in toroidal geometries

NEPOMUC positron source**

- FRM II @TUM, Garching（20MW reactor)
- DC positron ~10^9 /s by using prompt γs
- East Hall is under construction ~2018



Talk of Eve Stenson

Positron Accumulation eXperiment

PAX positron accumulator

- Buffer gas trap + multi-cell type trap
- target parameter: cold $10^{11\text{-}12}$ e^+ accumulation

A Positron Electron eXperiment

APEX Toroidal trap

- Confinement of e+ and e-
- Stellarator and Dipole

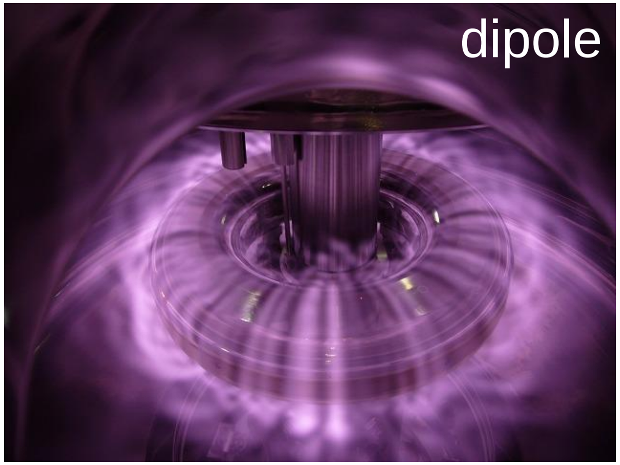
*T. Sunn Pedersen *et al*, NJP **14**, 035010 (2012). **C. Hugenschmidt *et al*, NJP **14**, 055027 (2012).

The use of toroidal configurations enable the simultaneous trapping of positrons and electrons as plasmas

- Linear configurations:
  - Plugging electric fields are required along magnetic field lines

➡ Positively and negatively charged particles are not simultaneously trapped in a finite region as a plasma

- Toroidal configurations for non-neutral plasmas
  - Applicable to the confinement of plasmas at any non-neutrality
  - Stable trap of electron plasma has been realized in CNT* and RT-1**



*P. W. Brenner and T. Sunn Pedersen, PoP **19**, 050701 (2012).

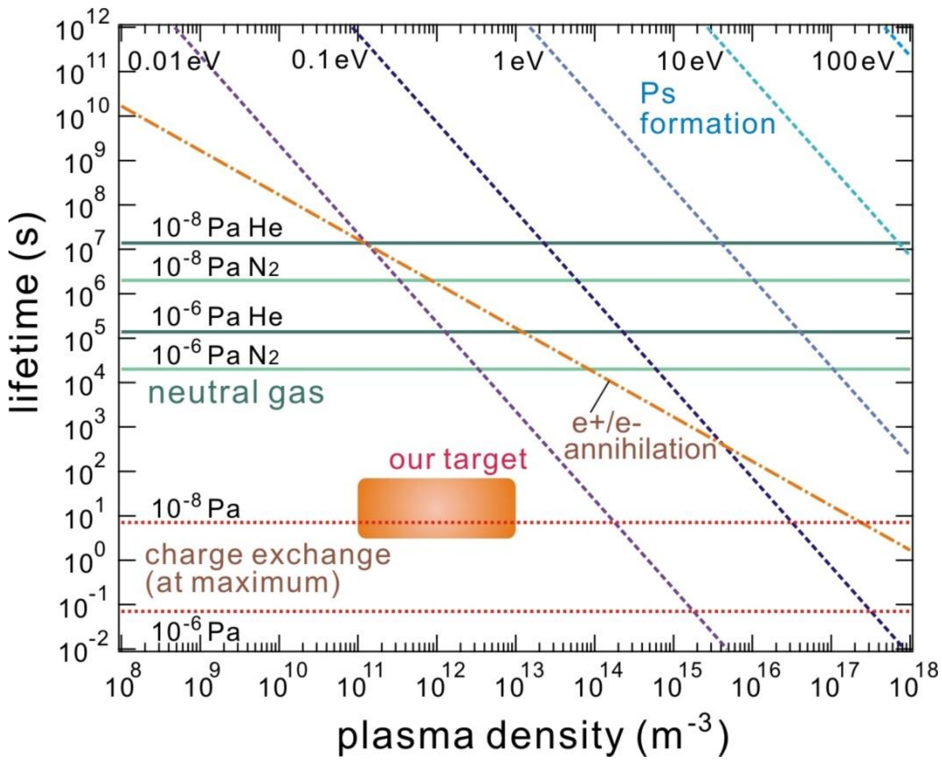
Z. Yoshida *et al.*, PPCF **55, 014018 (2013).

Target parameters of APEX to realize pair plasmas as a realistic goal: Life time vs. charge exchange collisions, Ps formation, annihilation, etc.

- To observe collective phenomena, scale length of the system must be larger ($a > \sim 10\lambda_D$) than the Debye length $\lambda_D = \sqrt{k_B T_e / n_e e^2}$

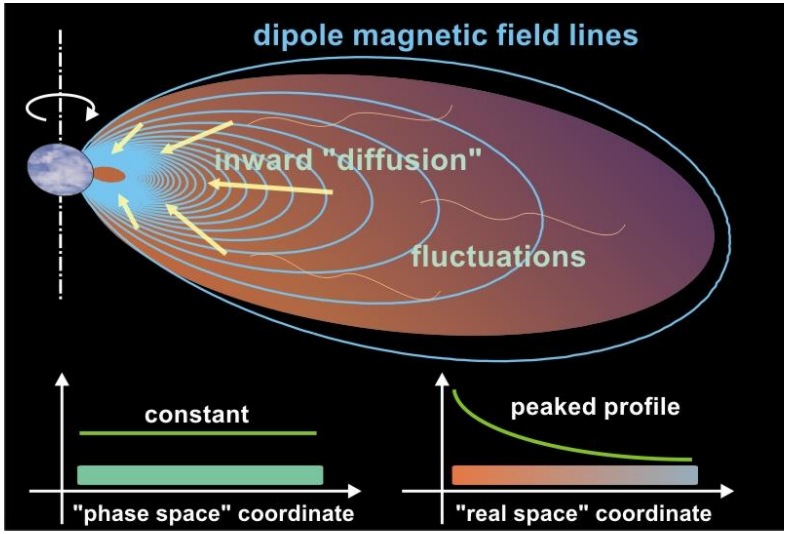
  Target parameters: $n_e \sim 10^{12} m^{-3}$, $T_e \sim 1 eV$ ➡ $\lambda_D \sim 1 cm$

- For these parameters, lifetimes are long enough, i.e., we can expect to observe plasma phenomena



R. G. Greaves and C. M. Surko, in *Non-Neutral Plasma Physics IV* (2002)

Magnetic dipole as one of APEX configurations, where effective inward transport and self-organization of plasmas are realized



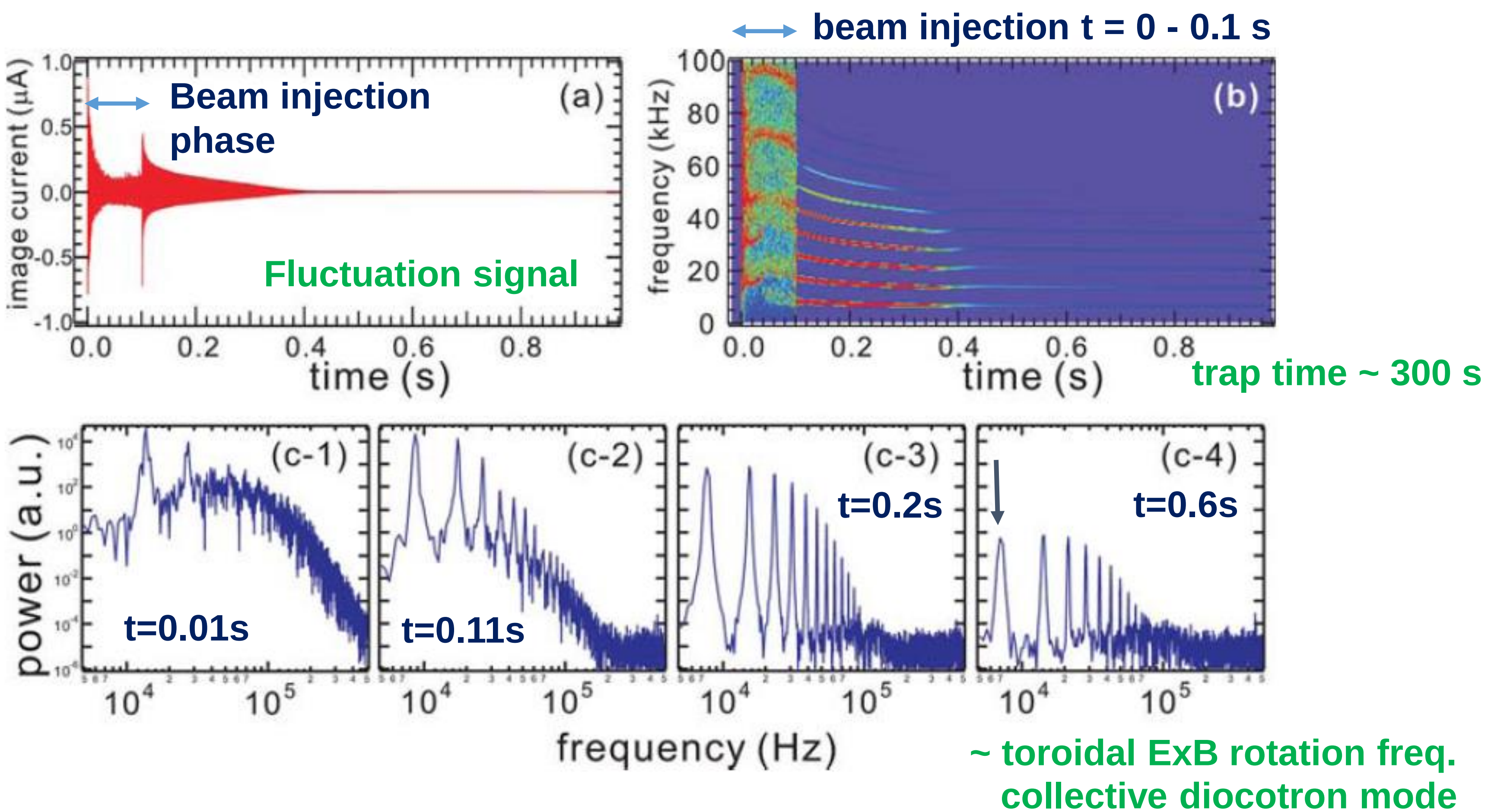
Z. Yoshida et al., PPCF **55**, 014018 (2013).

- Inward transport of neutral and non-neutral plasmas has been observed in planetary magnetospheres and experiments, RT-1 and LDX

- Development of particle injection schemes is one of key issues
  - By using external electric fields (proof of principle studies with electrons)
  - By using positronium re-emission process on metals/crystals*
    positrons -> Ps -> photo-ionized in trap region

*D. B. Cassidy *et al.*, Phys. Rev. Lett. **106**, 133401 (2011); T. S. Pedersen *et al.*, (2012).

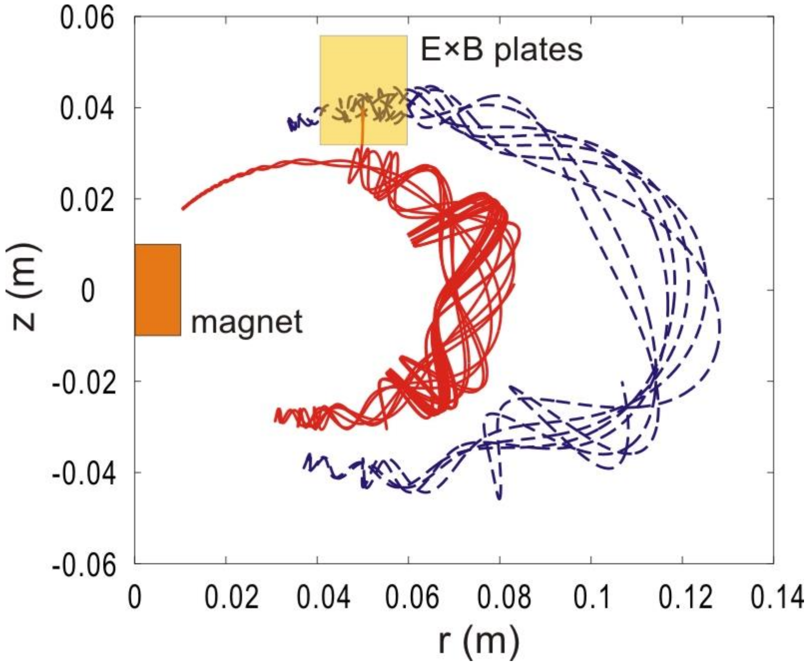
Previous work on pure electron plasma in RT-1, which clearly showed injection, trap, and collective phenomena of charged particles in dipole

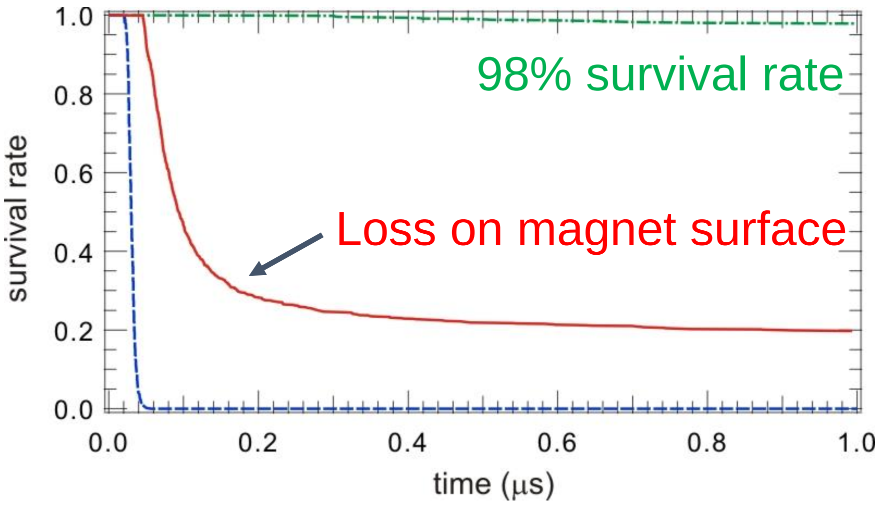


- Plasma is transported inward during turbulent-like phase, then rigid-rotating state is spontaneously generated after stabilization

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

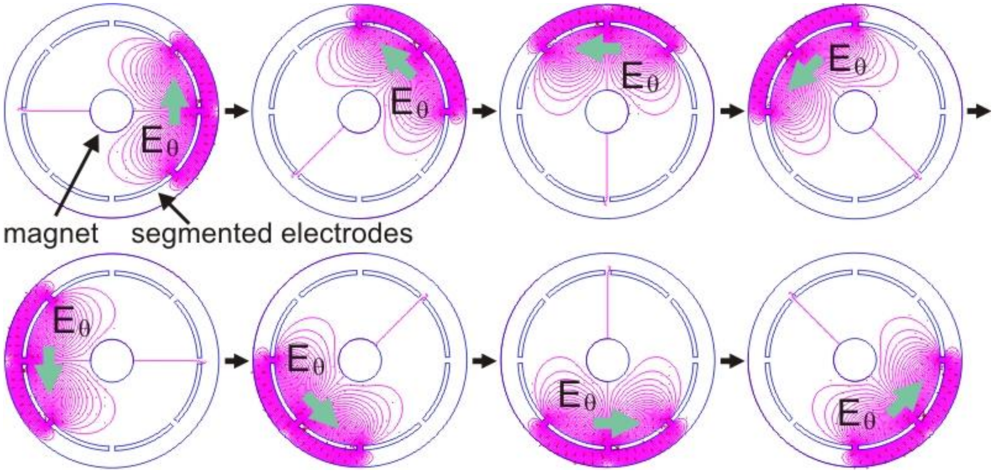
Numerical considerations on injection with external electric field 1: ExB drift toward strong field region across field lines

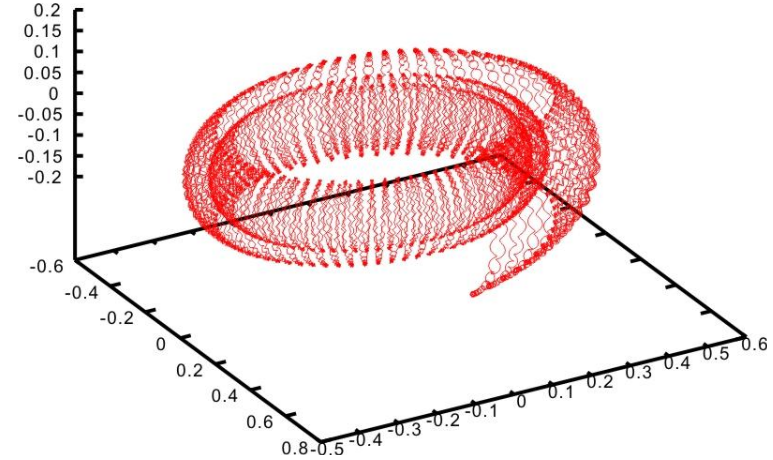




- **E × B** drift motion is induced by a local crossed electric field
- High injection efficiency when the permanent magnet is biased
- More detailed analysis in real configurations is going on

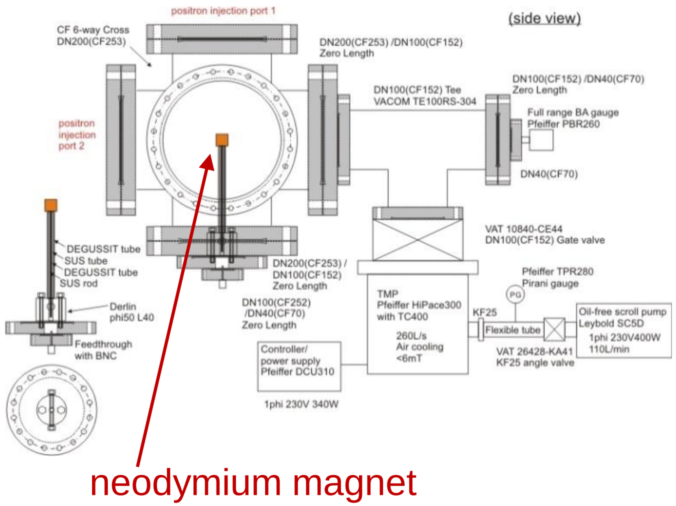
Numerical considerations on injection with external electric field 2: Rotating electric field coupled with dipole magnetic field





- Rotating **E** is applied in the azimuthal direction
- RW freq. is synchronized with grad-B/curvature drift frequency
- Effects of E_r will also be investigated

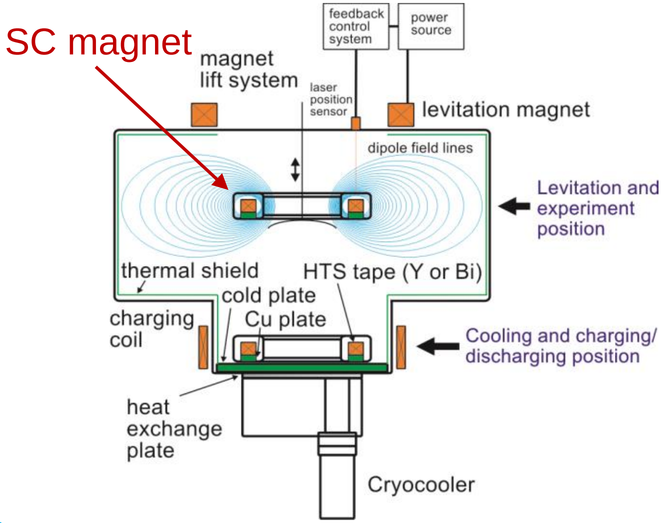
Development steps of the APEX-D project: Prototype experiment and superconducting levitated experiment



Proof-of-principle experiment in a permanent magnet device, 2013-

- Efficient injection method development by drift injection with external electric fields
- Confinement and precise measurements

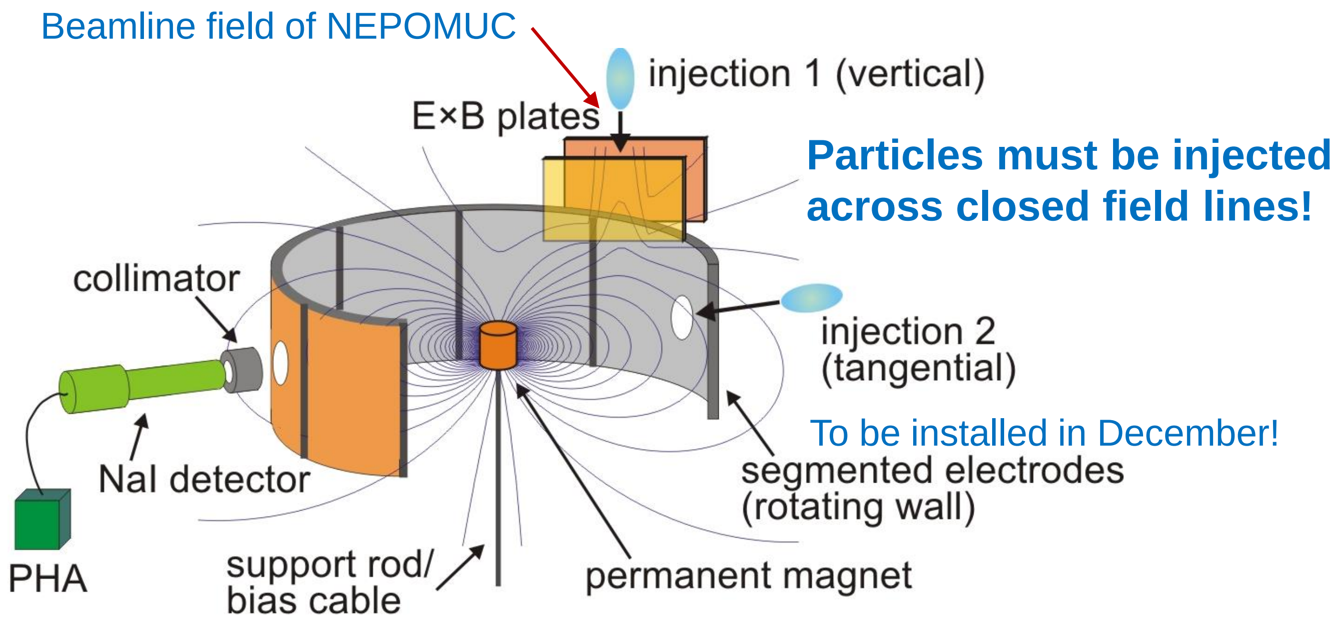
by using both electron and positron beams



Pair plasma formation in APEX-D SC Levitated Dipole

- Closed and unperturbed field lines
- Simultaneous confinement of positrons and electrons and understanding of their properties as final goals

Prior to SC APEX-D, we have constructed a prototype device with a permanent neodymium magnet for proof-of-principle experiments



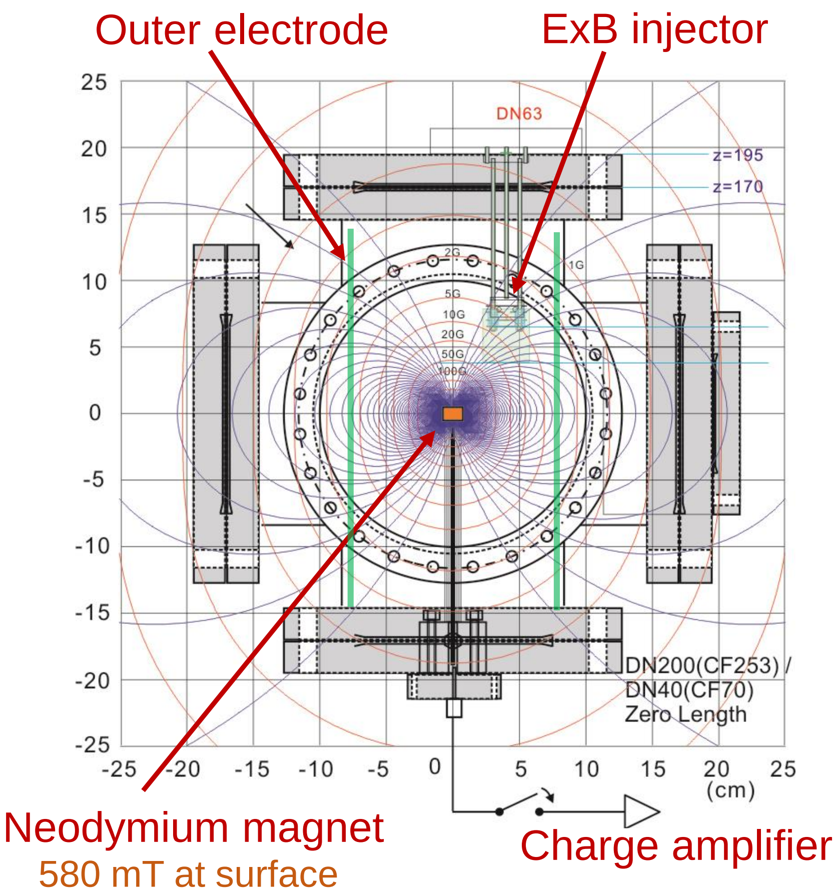
Development and understanding of essential issues for SC APEX-D

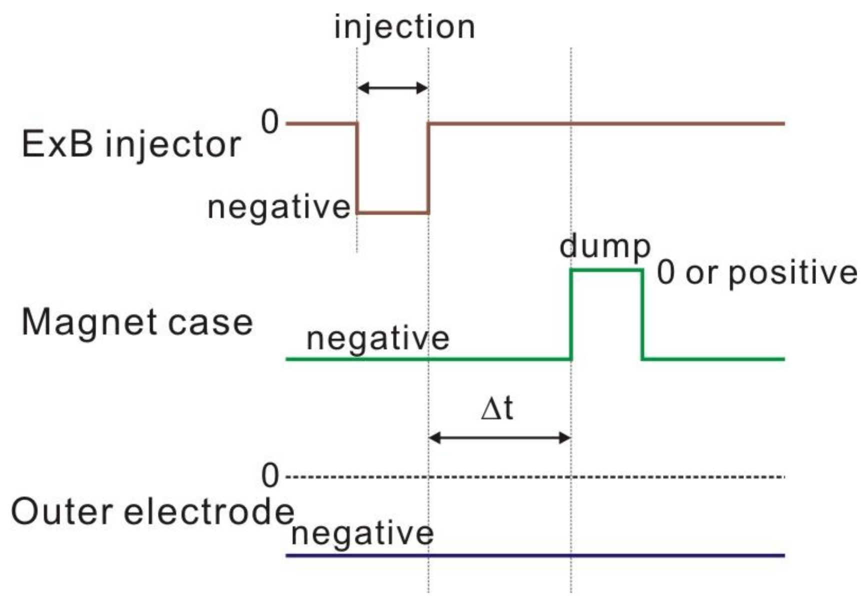
- Injection of charged particles by using external electric fields

  ExB drift injection, rotating wall technique, remoderation by using W crystal

- Confinement properties of both electrons and positrons

Setup of the prototype device for pure electron plasma experiments and operation (injection-trap-dump) scheme





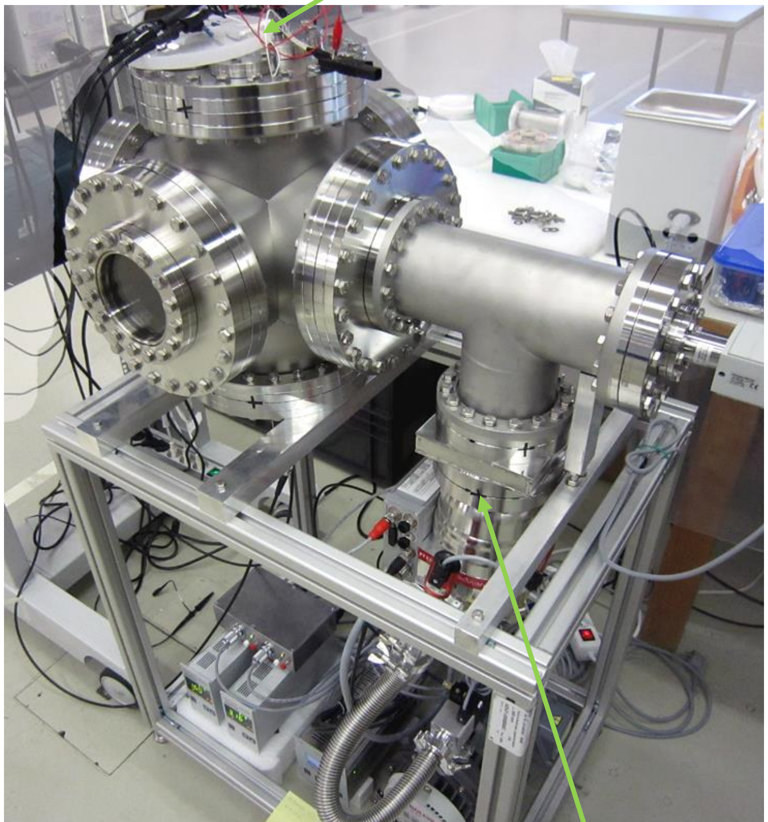
Injection, trap, and dump cycle

B ~ 100-5 mT in the confinement region

Field lines intersect the permanent magnet

External view and inside the vacuum chamber of the prototype device

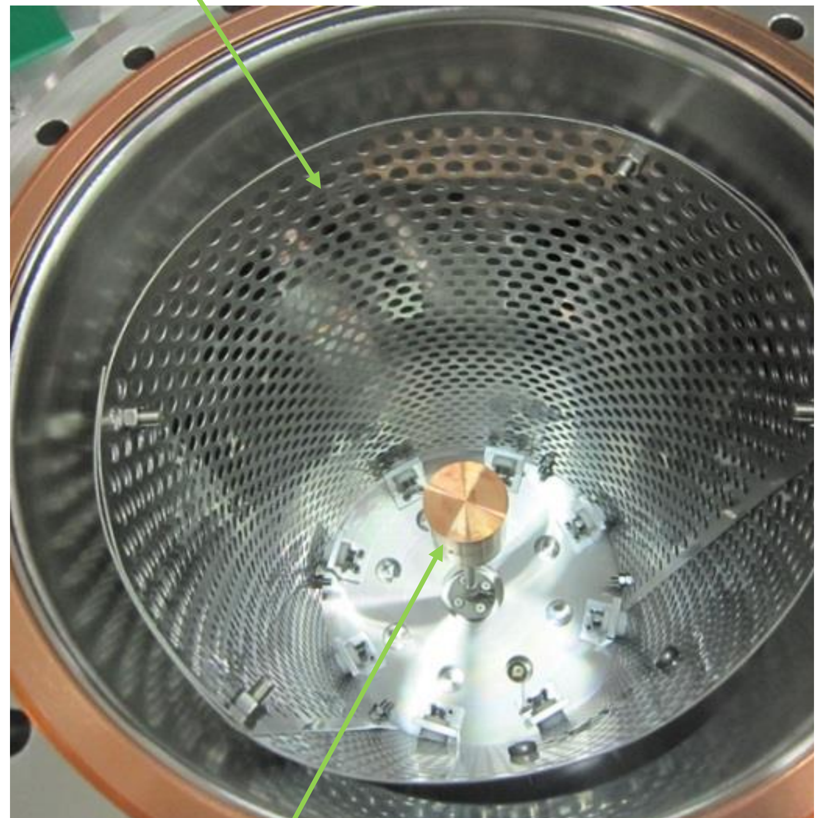
ExB electron injector



TMP

CF-DN200 6-way, 1.8e-7 Pa

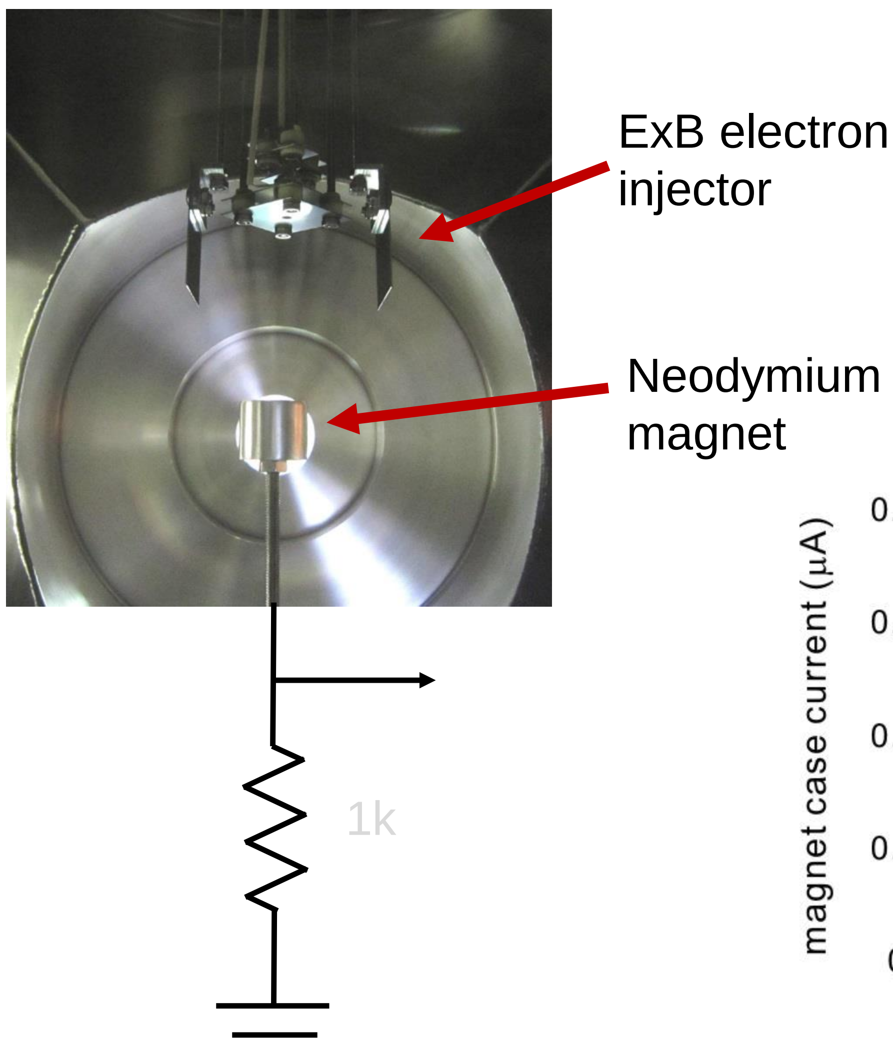
Outer electrode

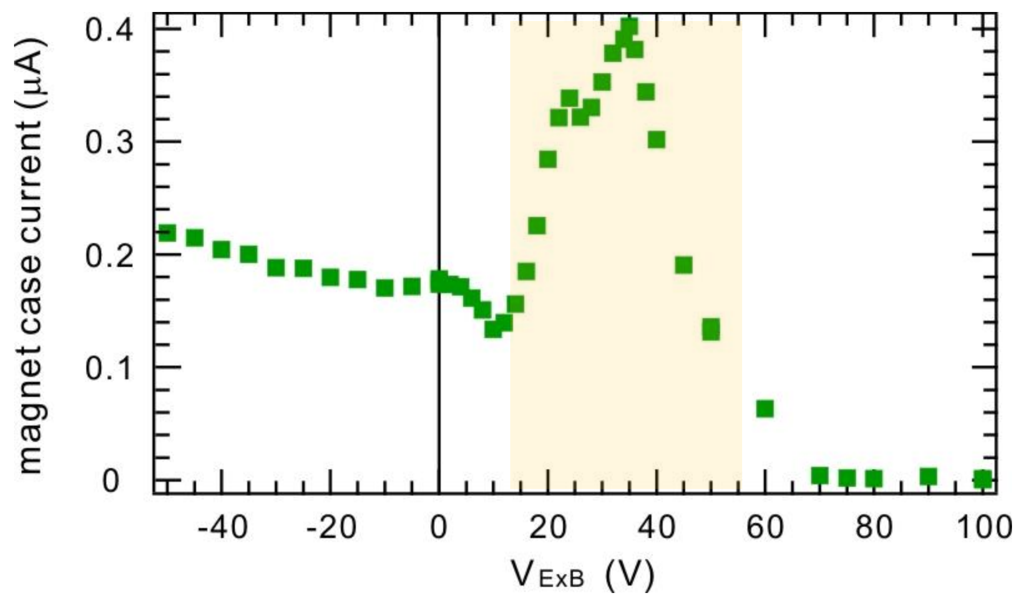


Neodymium magnet
(inside copper case)

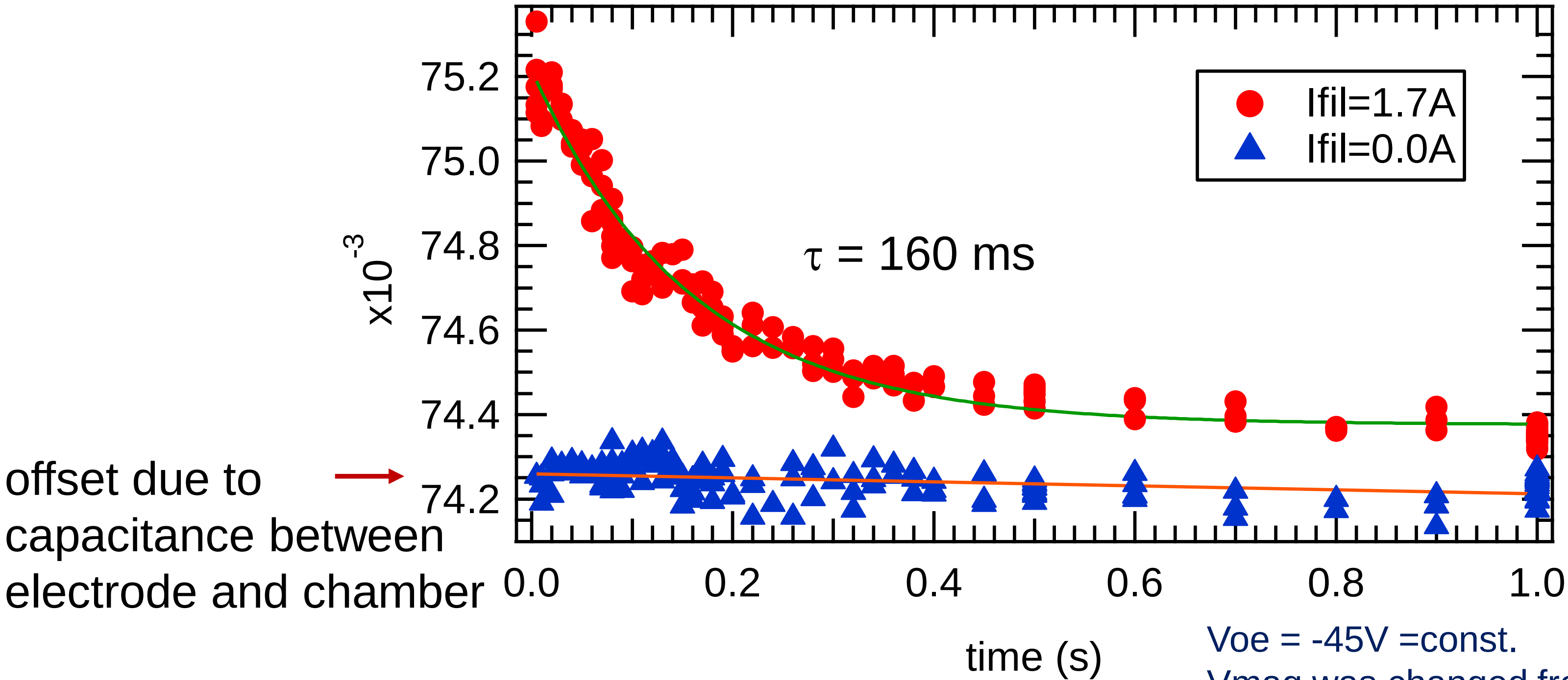
Increase of current arriving at magnet case from electron gun, due to electron transport across field lines

- A part of electrons are guided to strong field region
- Increase in magnet case current by the use of ExB plates





Remaining charge after stopping electron injection: Initial results on confinement of electrons in a dipole trap



Voe = -45V =const.
Vmag was changed from -20V to 0V.

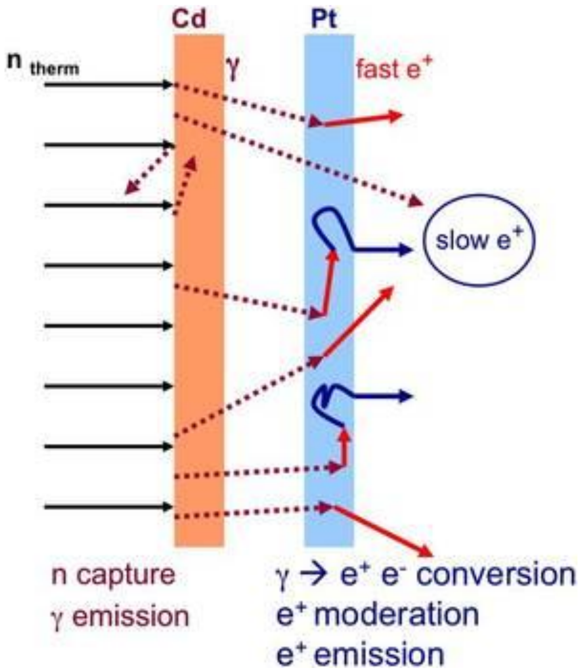
- Electrons were injected into negative potential well
- Dumped charge corresponds to 3×10^7 electrons, decay time $\tau \sim$ 200ms
- Precise measurement (including dependencies of τ etc.) will be done by using fixed current probe*

*P. W. Brenner and T. Sunn Pedersen, PhysPlasmas **19**, 050701 (2012).

First trial to create toroidal positron plasma at NEPOMUC will be conducted from this December

Open Beam Port at NEPOMUC*

- FRM II @Technical University Munich（20 MW neutron source reactor)
- DC moderated beams, 10^9 /s at 1 keV, 10^7 /s at 20 eV

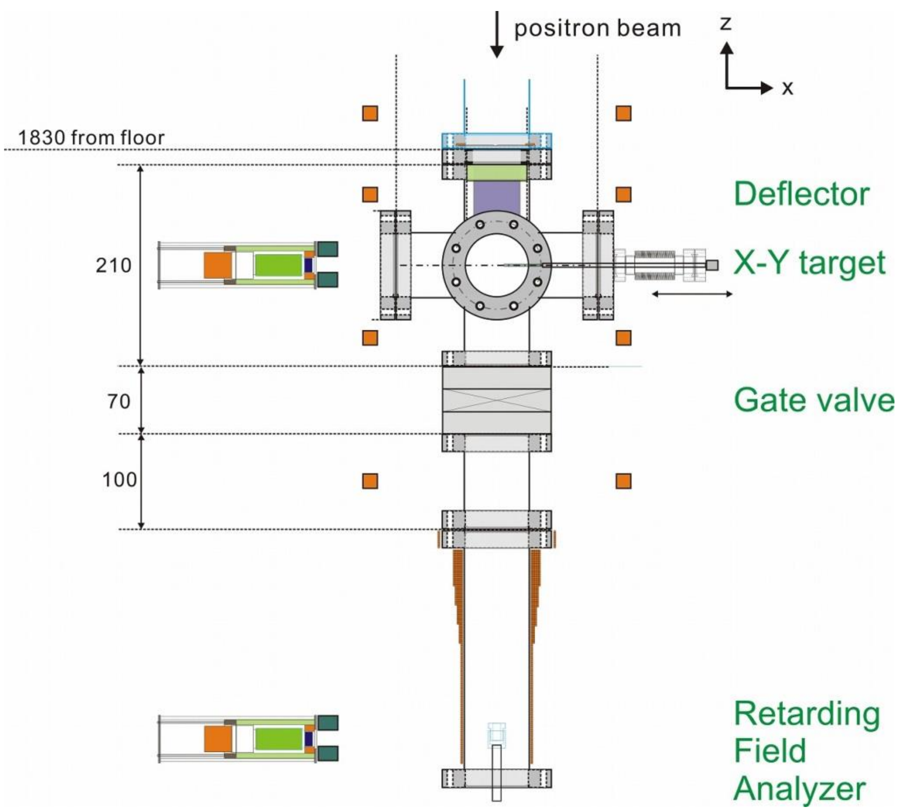


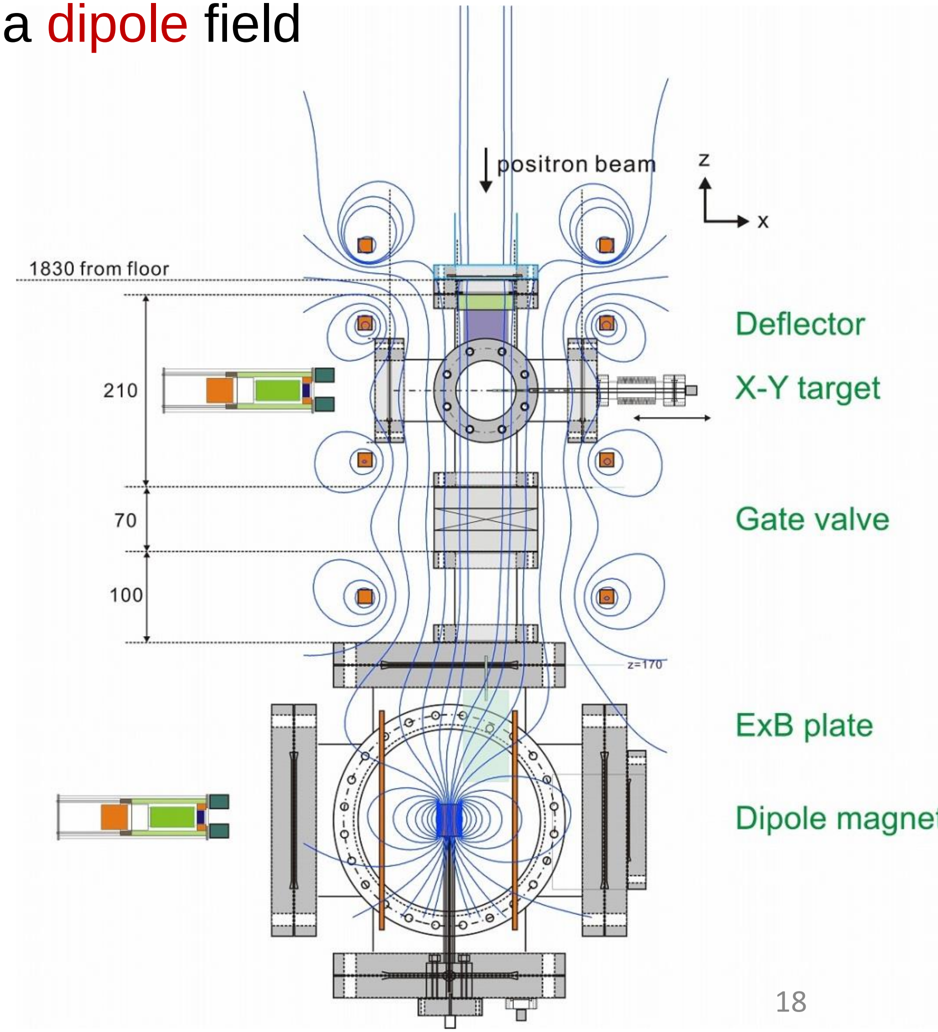
Positrons are generated by pair production from absorption of high-energy prompt gamma-rays after thermal neutron capture in Cd

*C. Hugenschmidt *et al*, NJP **14**, 055027 (2012).

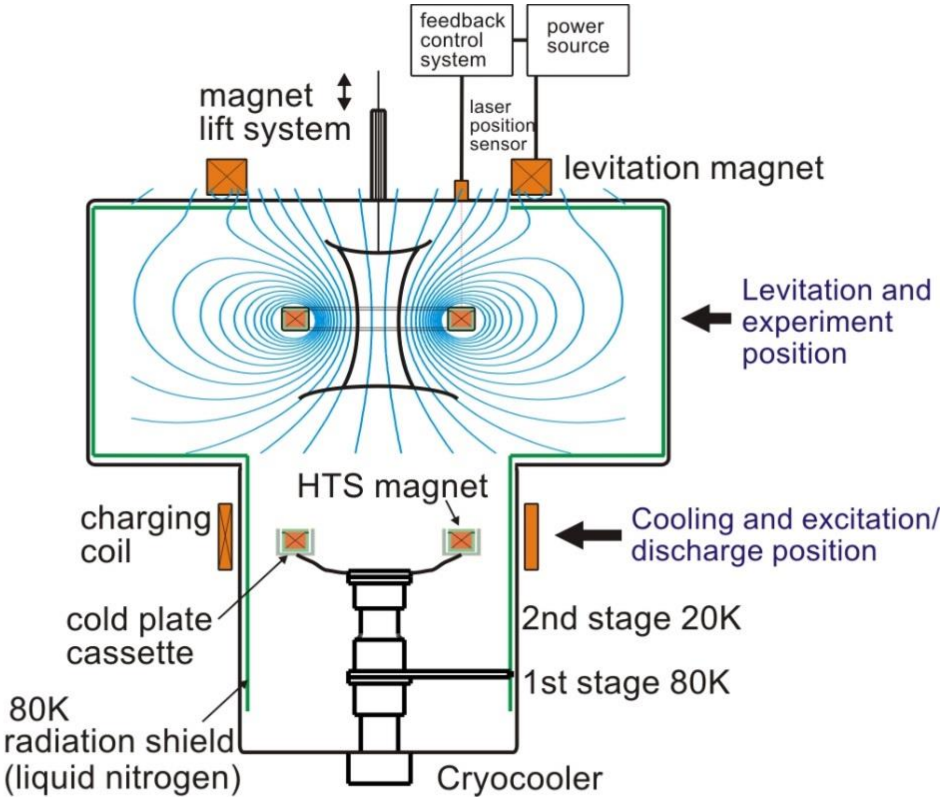
Planned experiments at NEPOMUC in the forthcoming beamtimes in Dec. 2014 and Jan. 2015)

- Particle numbers and diameters of positron beams
- Parallel and perpendicular energy distributions of beams
- Injection, trap, and loss properties in a dipole field





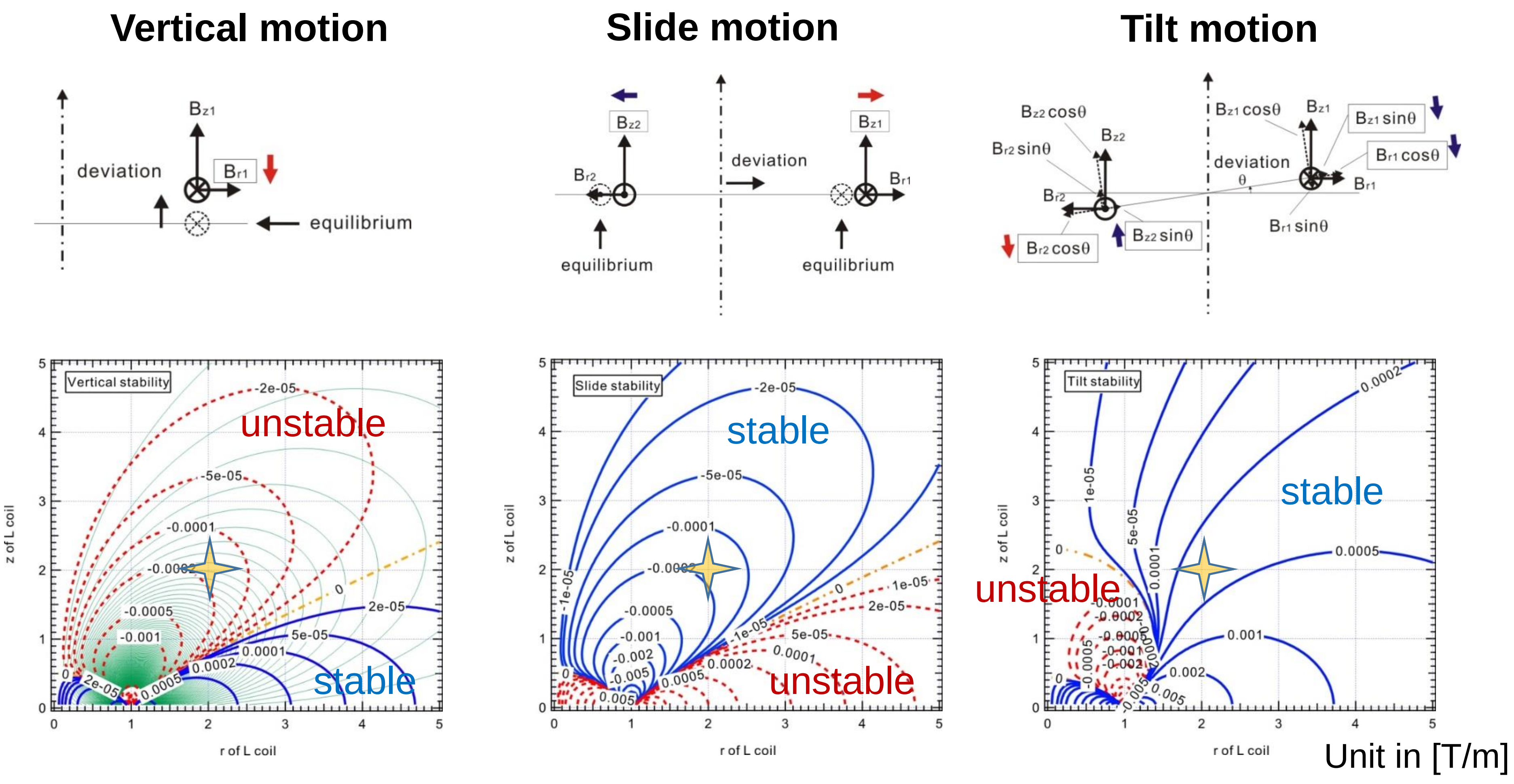
Construction Plan for SC APEX-D: Levitated operation of magnet is needed for the creation of dipole pair plasmas



	LDX	RT-1	Mini-RT	SC APEX-D
SC magnet	Nb3Sn	Bi-2223	Bi-2223	**Bi-2223**
	40 cm	25cm	15cm	**10cm**
	1820 A	116 A	117 A	**100 A**
	714 turn	2160 turn	430 turn	**500 turn**
	1300 kA	250 kA	50 kA	**50 kA**
	4.5-10K	20-30K	20-40K	**20-50K**
	5 hours	8 hours	3 hours	**> 3 hours**
	580 kg	110 kg	20 kg	**10 kg**
Cooling	He cooling (125 atm He)	Cryocooler and He gas	Cryocooler and He gas	**Cryocooler thrm. contact**
Excitation	inductive	direct, PCS	direct, PCS	**inductive**
Shield	coil case	coil case	coil case	**chamber**
Heat input	< 1W	0.9W	< 0.2W	**<0.1W**

- Closed and unperturbed magnetic field lines, which cannot be realized with a permanent magnet, are required for simultaneous confinement
- This is achieved by a levitated dipole; We started design studies

Magnet stability analysis for proposed parameters: Levitation control reduces to one dimensional stability problem



- Magnet motion is simplified to a one-dimensional vertical stability problem
- Based on these basic analysis, design studies are ongoing

Summary of the APEX status and future works

- Aiming for the first creation and study of electron-positron pair-plasmas, we are developing a toroidal trap APEX (Stellarator and Dipole)

- Development of efficient injection methods and understanding of the trap properties of non-neutral plasmas are key issues

- By using drift (ExB) method, injection and relatively short (~100 ms) trap of electrons were confirmed in a prototype device with a permanent magnet

- Properties of charged particles in dipole field will be further investigated in the forthcoming positron beam experiments at NEPOMUC

- Based on these proof-of-principle experiments, we started the design of a SC APEX-D, where dipole field is magnetically levitated