DPG Spring Meeting, Hannover, 01.03. 2016, P 12.7

Progress toward the creation of magnetically confined pair-plasmas

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Motivation

We aim to create magnetically confined electron-positron plasma in a laboratory. These pair-plasmas are important as

- **Unique research subjects in plasma physics**

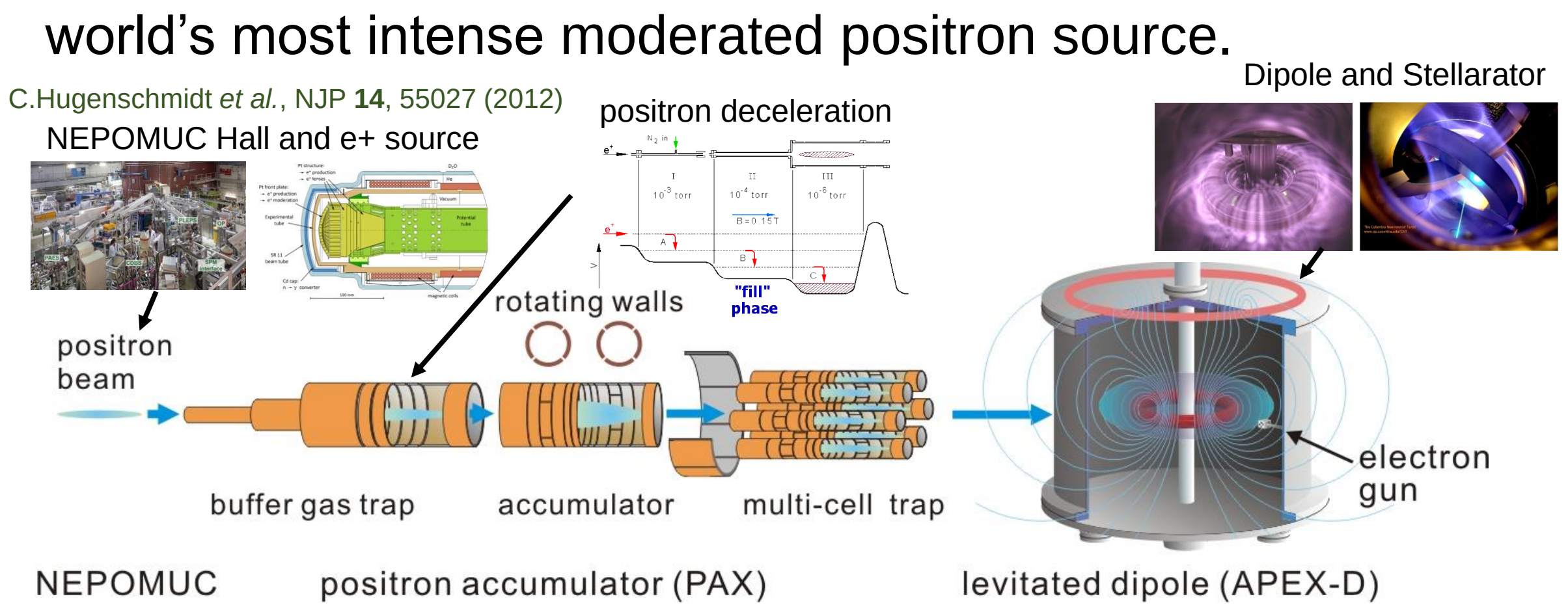
  Because of the mass symmetry, pair-plasmas are predicted to exhibit unique properties, which are fundamentally different from conventional ion-electron plasmas. These examples include remarkable wave and stability properties, enhanced soliton behaviour, the lack of Faraday rotation, and strong nonlinear Landau damping effects.

- **Insight into astrophysics and scientific applications**

  Electron-positron plasmas are believed to exist ubiquitously in the environments of high-energy density objects, such as pulsar magnetospheres and active galaxies. Also, realization of a large number of stored positrons and stable confinement of plasmas at any non-neutrality is a basis for the formation of a large number of positronium (Ps) atoms and their Bose Einstein condensation (BEC), development of an intense γ-ray source, efficient antihydrogen atom production, and formation of antihydrogen plasma and further complicated matter-antimatter plasmas.

Methods

In order to create pair-plasmas, we plan to develop the PAX and APEX experiments and operate them at NEPOMUC, the world's most intense moderated positron source.



C.Hugenschmidt *et al.*, NJP **14**, 55027 (2012)

The grand scheme of the electron-positron plasma experiment

The PAX (Positron Accumulator eXperiment) consists of a so-called Surko-type buffer gas trap and multi-cell trap cells. Accumulation of 10^{10-12} positrons and fast injection of them into APEX is the purpose of the PAX.

APEX (A Positron Electron eXperiment) is a toroidal magnetic trap for the simultaneous confinement of positrons and electrons as plasmas. We plan to start with a levitated dipole experiment (APEX-D). A stellarator (APEX-S) is another promising trapping geometry.

Main results

- Positron moderation, buffer gas trapping, and accumulation system from *First Point Scientific* was installed and operated.
- As important diagnostic tools, response of phosphor screens against electrons and positrons were precisely compared.
- Confinement of electron plasmas for 1 hour and observation of collective mode were realized in a Penning-Malmberg trap.
- Positron beam characterization was done at the open beam port of NEPOMUC at various kinetic energies.
- With a prototype dipole trap with a permanent magnet, an E×B drift injection scheme of positrons was developed.

Future plans

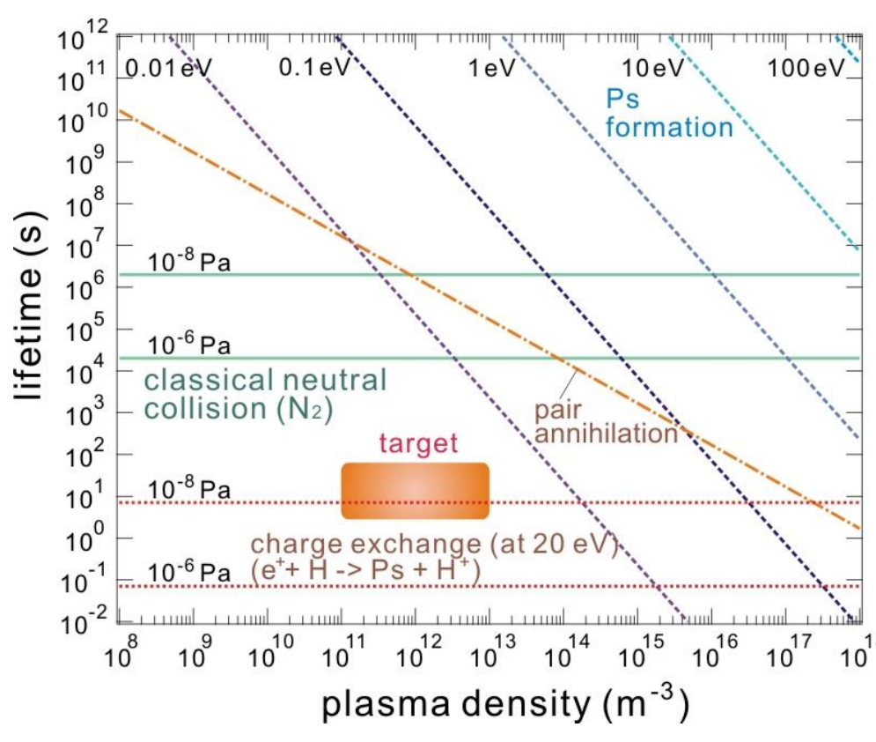
- Development of multi-cell trap, and accumulation and fast extraction of a large number of positrons.
- Development of a superconducting levitated dipole trap.
- Efficient transport and simultaneous confinement of positrons and electrons as a plasma in the levitated dipole trap.

T. Sunn Pedersen *et al.*, New J. Phys. **14**, 035010 (2012).

Target parameters

Creation of electron-positron plasmas is a challenging but realistic research goal

- To observe collective phenomena, the Debye length $\lambda_D = \sqrt{k_B T_e / n_e e^2}$ must be smaller than system size.
- Target: n_e >~10^{11}m^{-3}, T_e~1eV ➡ λ_D< 2cm

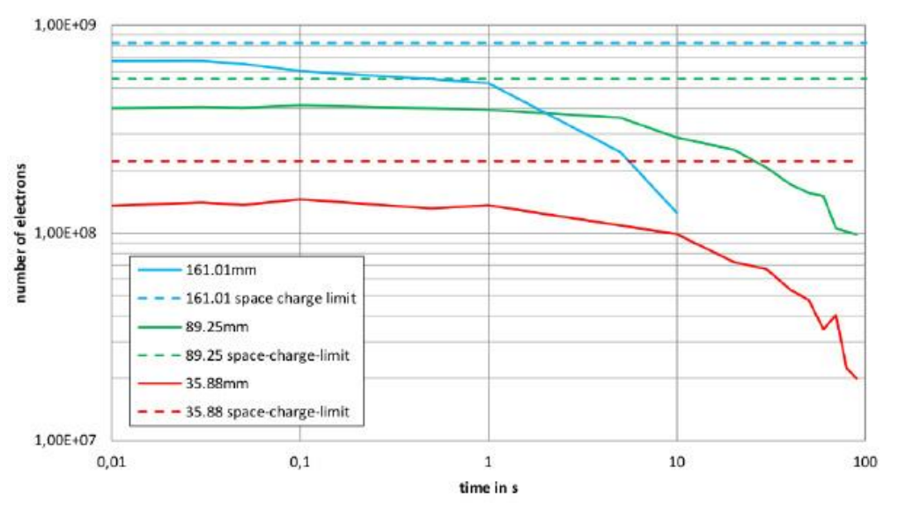


Lifetimes of positrons set by several processes

- For these parameters, lifetimes, set by several processes, are longer than time scales of plasma phenomena.
- Charge exchange Ps formation process is most important.

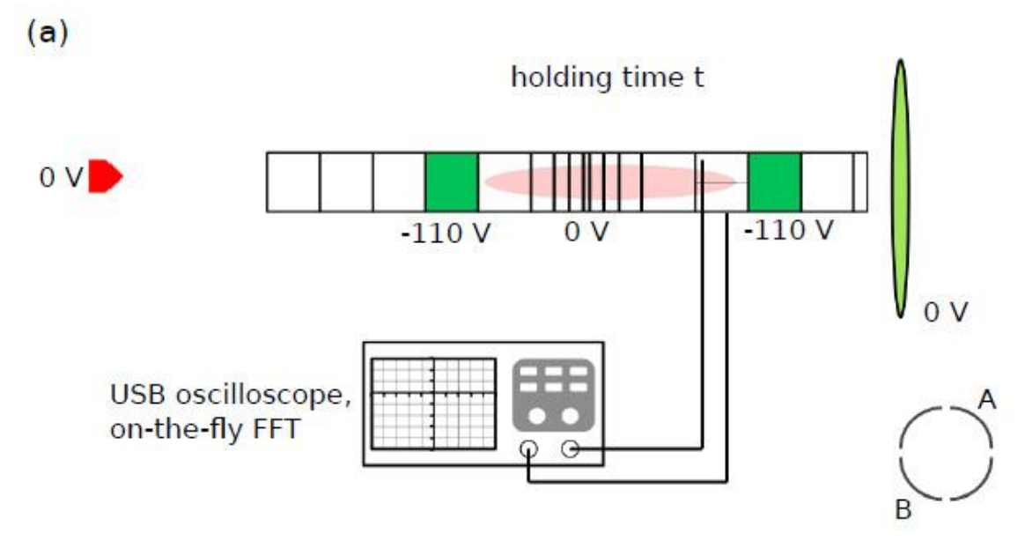
High field trap experiments

Experiments with electron plasmas were conducted in a high-field trap (up to 2.3 T) to explore design parameters of the multi-cell trap

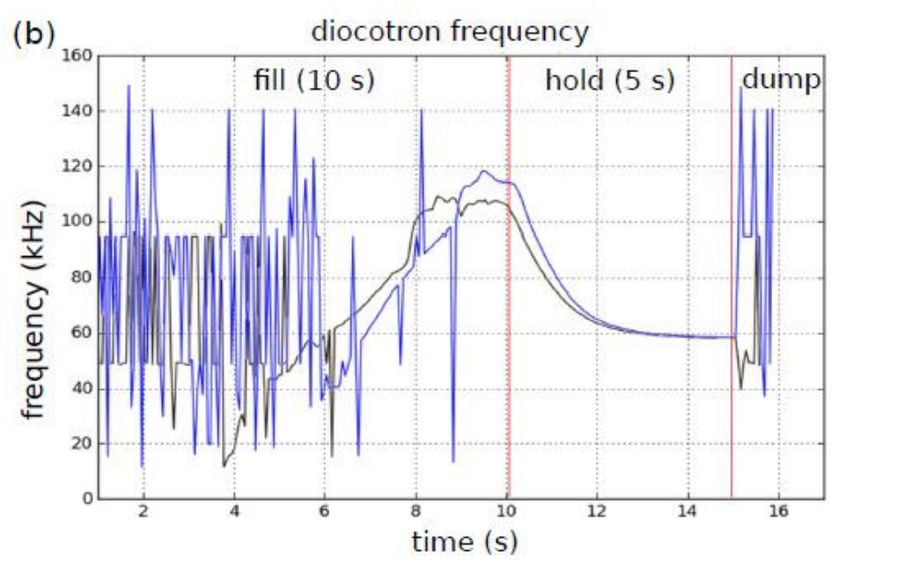


Temporal evolution of dumped charge

- e- trapping in a Penning-Malmberg trap
  - trapping time longer than 1 hour
  - dependence on length, etc. measured
- Evolution of m = 1 diocotron mode
  - also used for diagnostics
  - mode frequency corresponds to ~10^9 e-



Experimental setup for electron confinement

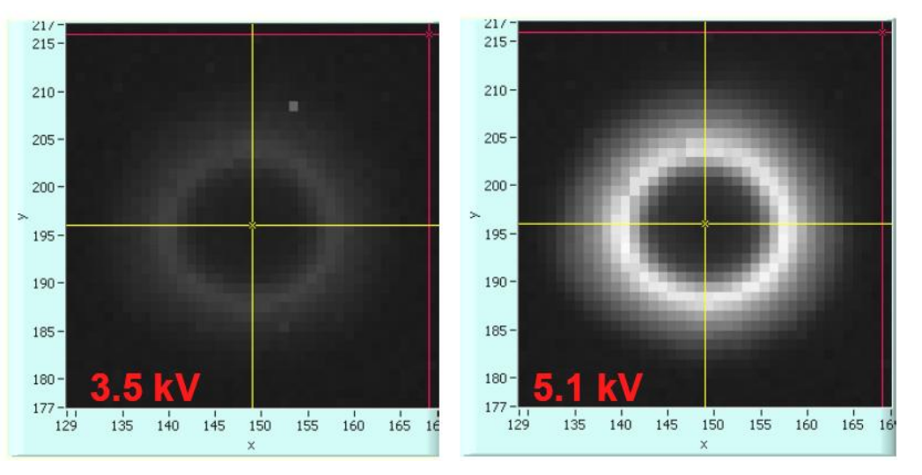


Temporal evolution of the mode frequency

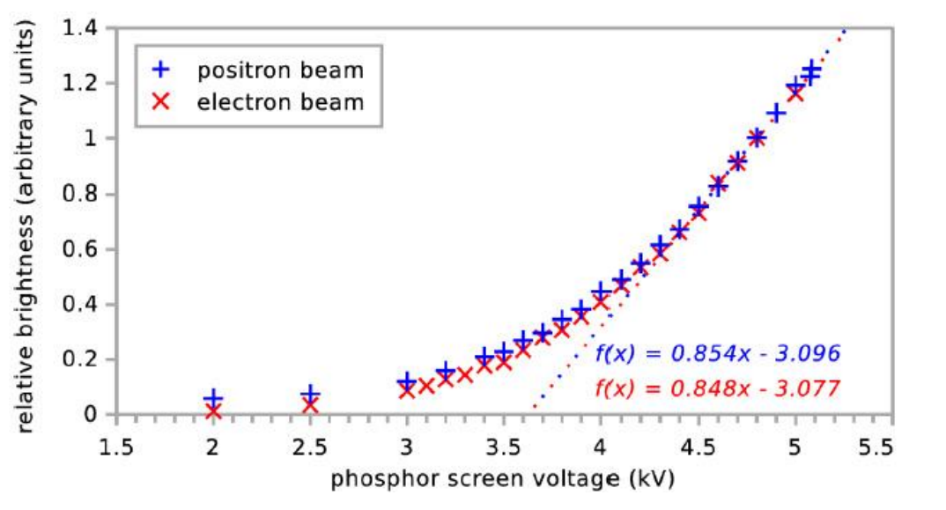
* H. Niemann and U. Hergenhahn, *et al.*

Positron system and diagnostics

Moderator, buffer gas, accumulator system was assembled, and positron beam was extracted and measured with phosphor screen



Phosphor screen images of positrons



Phosphor screen response to e+ and e-

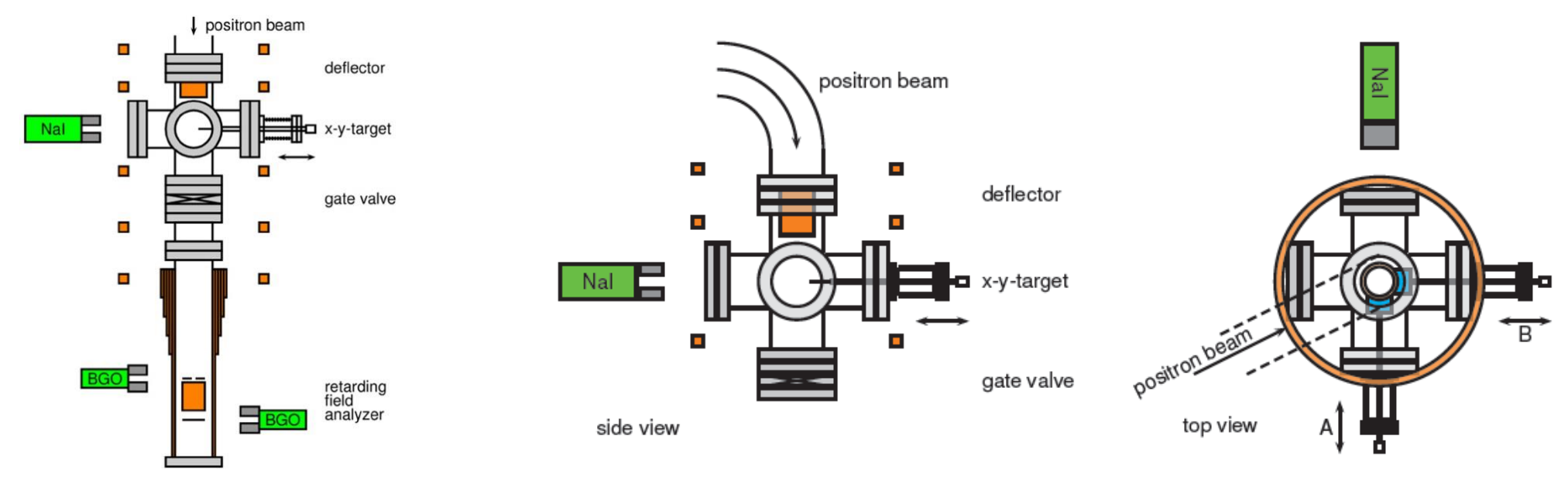
- e+ beam extraction (with Na-22)
  - commissioning of neon moderator
  - moderation (energy spread: some eV)
- Imaging with phosphor screen
  - raw beam
  - e+ in buffer-gas trap
  - guiding efficiency will be improved
- Phosphor screen response to e+
  - previously, no clear studies done
  - comparison with e- for the first time
  - direct measurements of e+ current

E.V. Stenson *et al.*, to be published (2016).

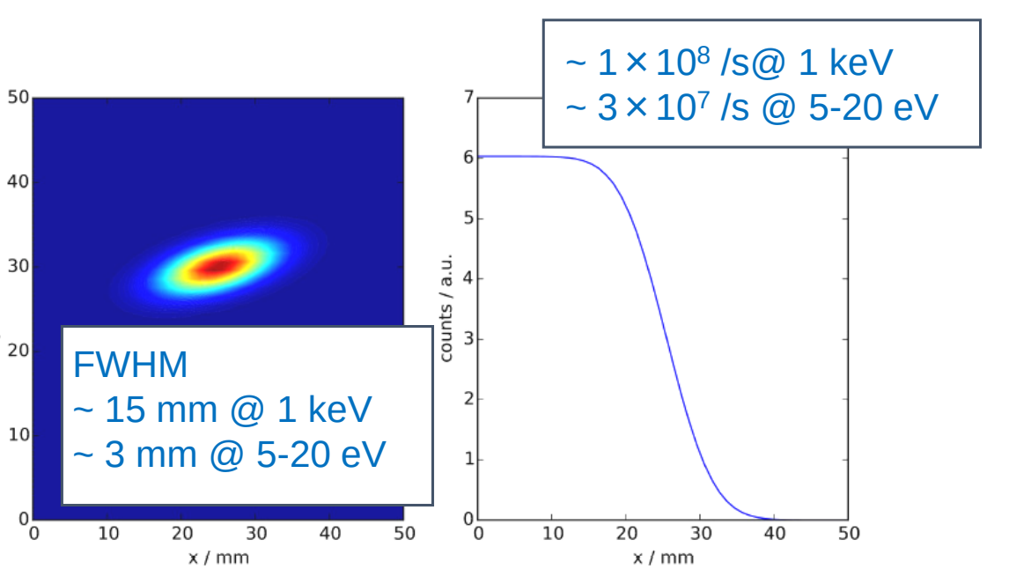
Positron beam characterization at NEPOMUC

Talk by J. Stanja, P 7.6

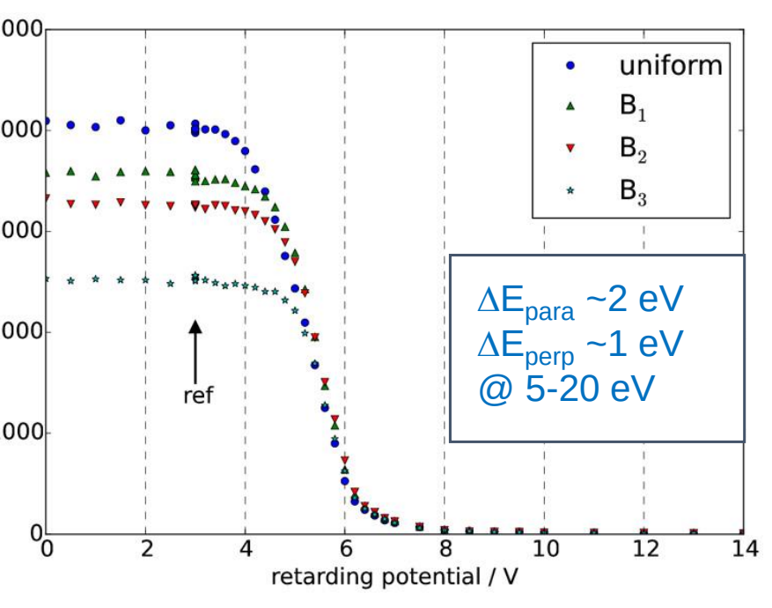
Intensity, spatial profiles, and energy spreads (both parallel and perpendicular) of positron beams were measured at the open beam port of NEPOMUC



Schematics of the retarding energy analyzer and a set of target plate



MCP image and one dimensional profile measured by target plate



RFA data with different field gradient

- Spatial profile measurements
  - MCP + phosphor (only images)
  - targets + BGO scintillator-PMTs
- RFA with variable field strength
  - both parallel and perpendicular energies (RFA with field gradient)
  - important parameters for efficient capture in a buffer-gas trap
- Measurements were done for several conditions at the open beam port

energy / eV	$\langle E_{\parallel,i}\rangle$ / eV	$\Delta E_{\parallel}$ / eV	$\langle E_{\perp,i}\rangle$ / eV	$\langle E_{tot}\rangle$ / eV
5	5.18(2)	1.84(5)	0.75(3)	5.94(2)
12	11.82(3)	2.45(7)	1.17(6)	12.98(4)
22	20.80(3)	3.12(7)	1.3(1)	22.05(7)

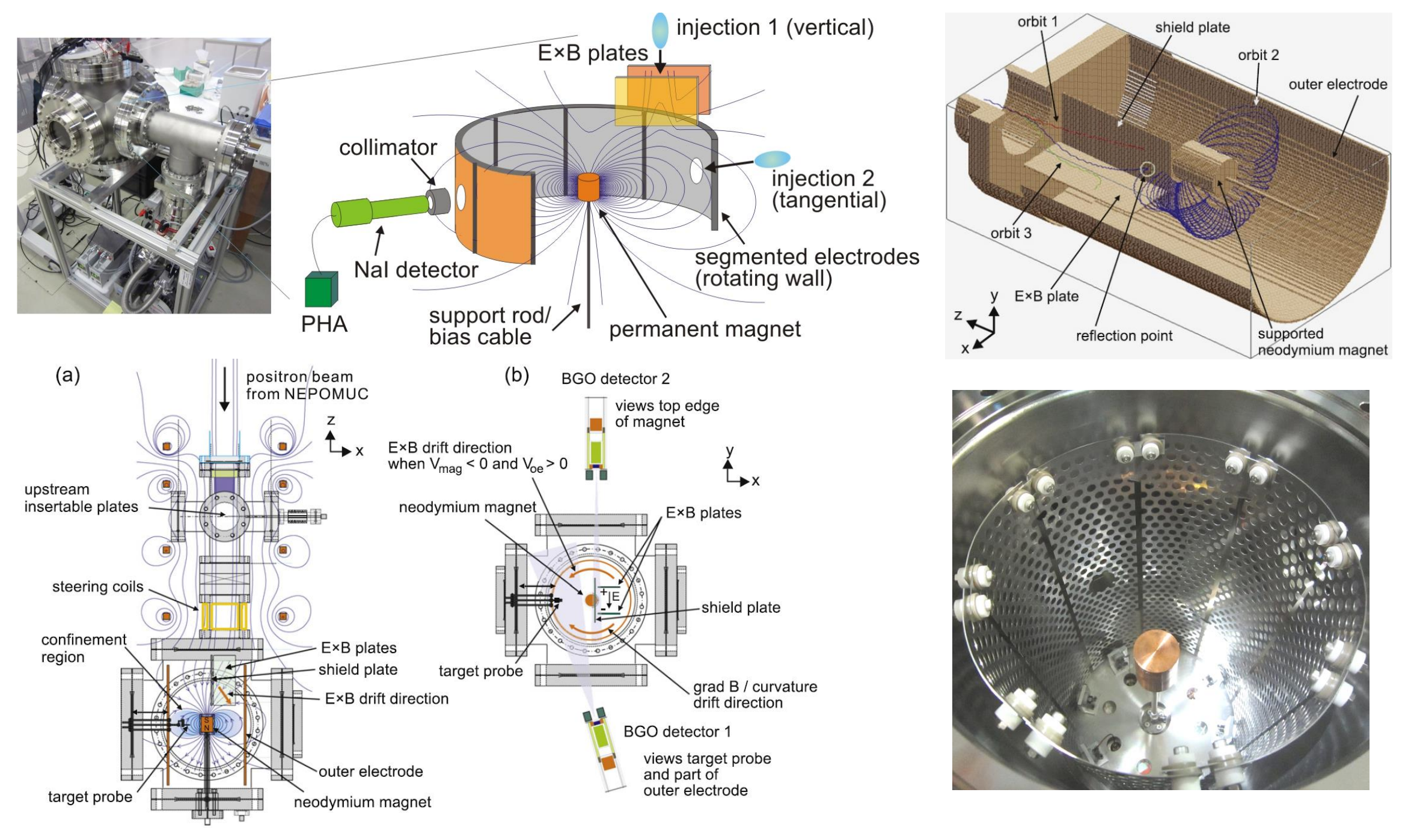
Typical parameters of moderated positron beams at NEPOMUC

* J. Stanja *et al.*, to be published (2016)

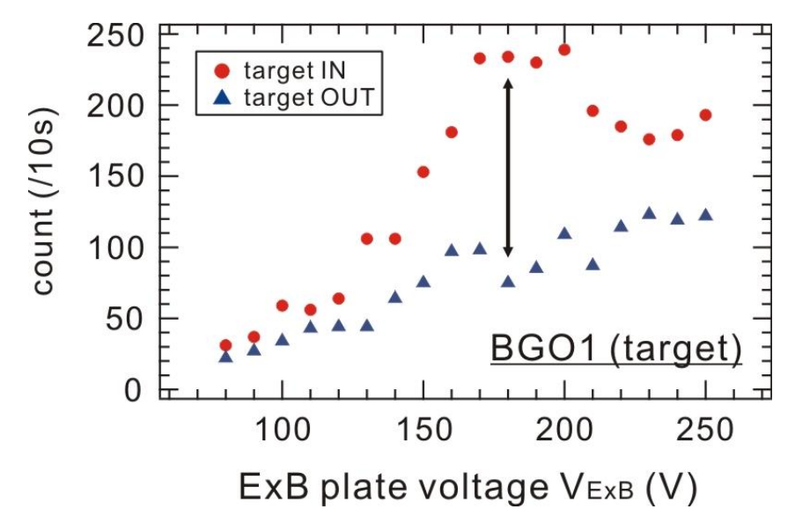
Efficient injection of positron beam into dipole field

In a prototype supported dipole experiment, we employed ExB drift and magnetic steering, and guided the positron beam of NEPOMUC with a high efficiency of 40%

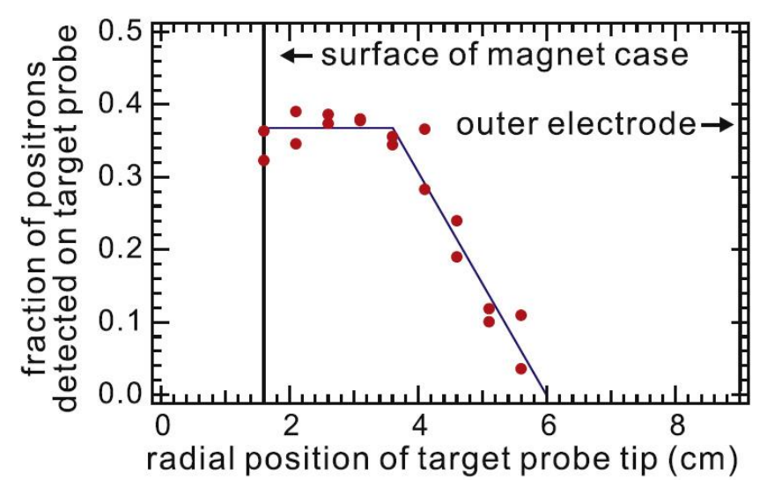
- Effective injection conditions were found
- Toroidal rotation of positrons were confirmed



External and internal views of the prototype dipole experiment and the ExB injection scheme



Detection of 511keV γ in the confinement region



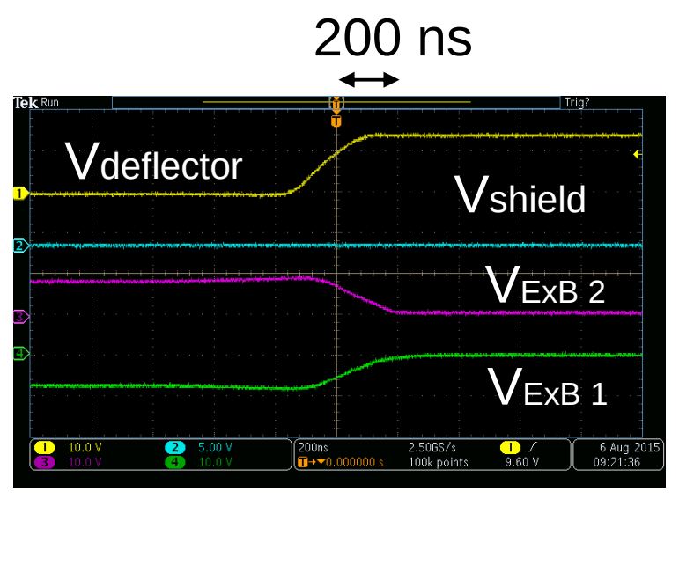
Spatial profile of positron current at movable target

* H. Saitoh *et al.*, NJP **17**, 103038 (2015).

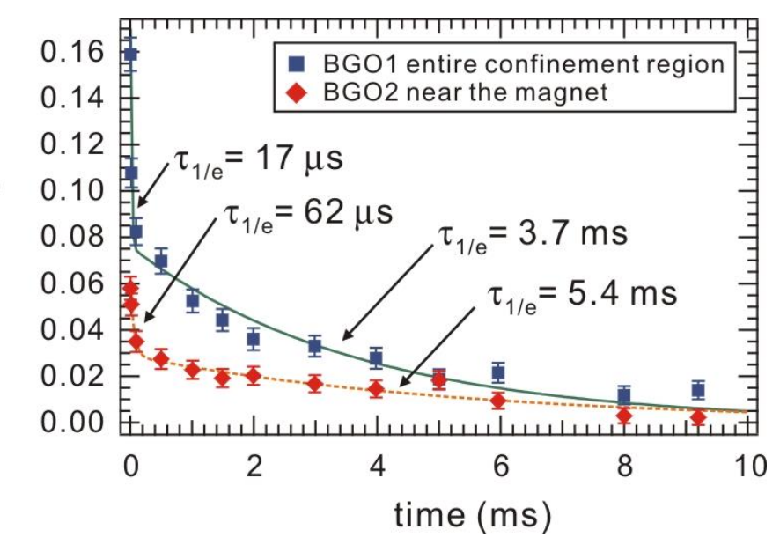
Trapping of e+ in dipole

Positron confinement in the supported dipole experiment

- fast switching of V_{ExB} to reduce error fields
- order of ~1ms trapping is realized in strong field region



Fast blocking of positrons and V_{ExB}

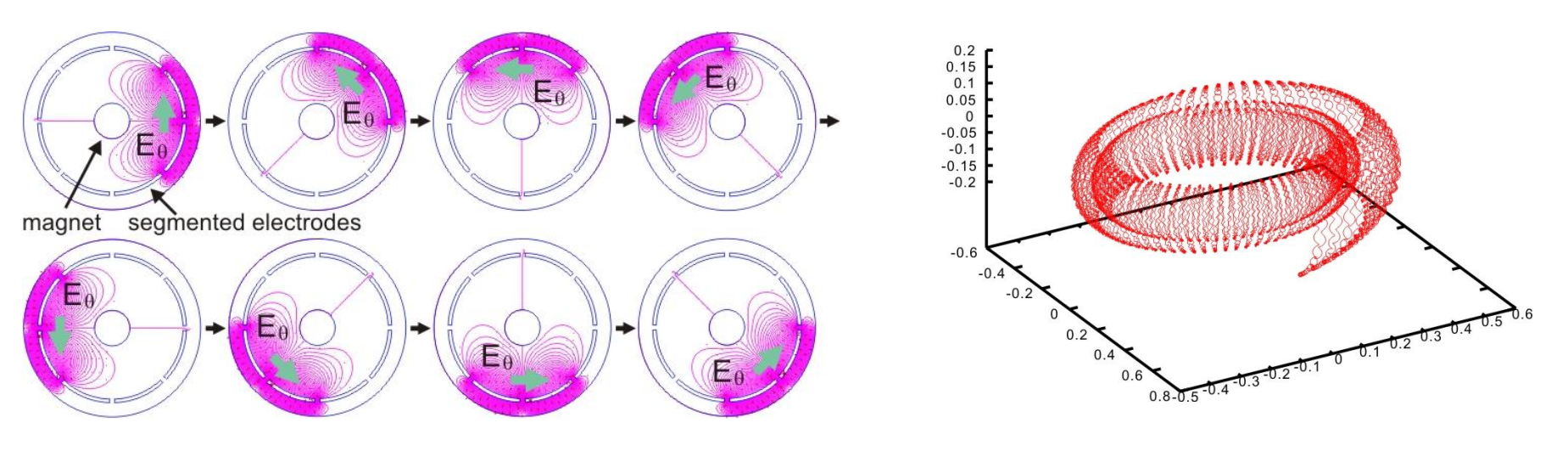


Decay of γ after stopping positron injection

Application of rotating wall

Trial of plasma compression in a toroidal geometry

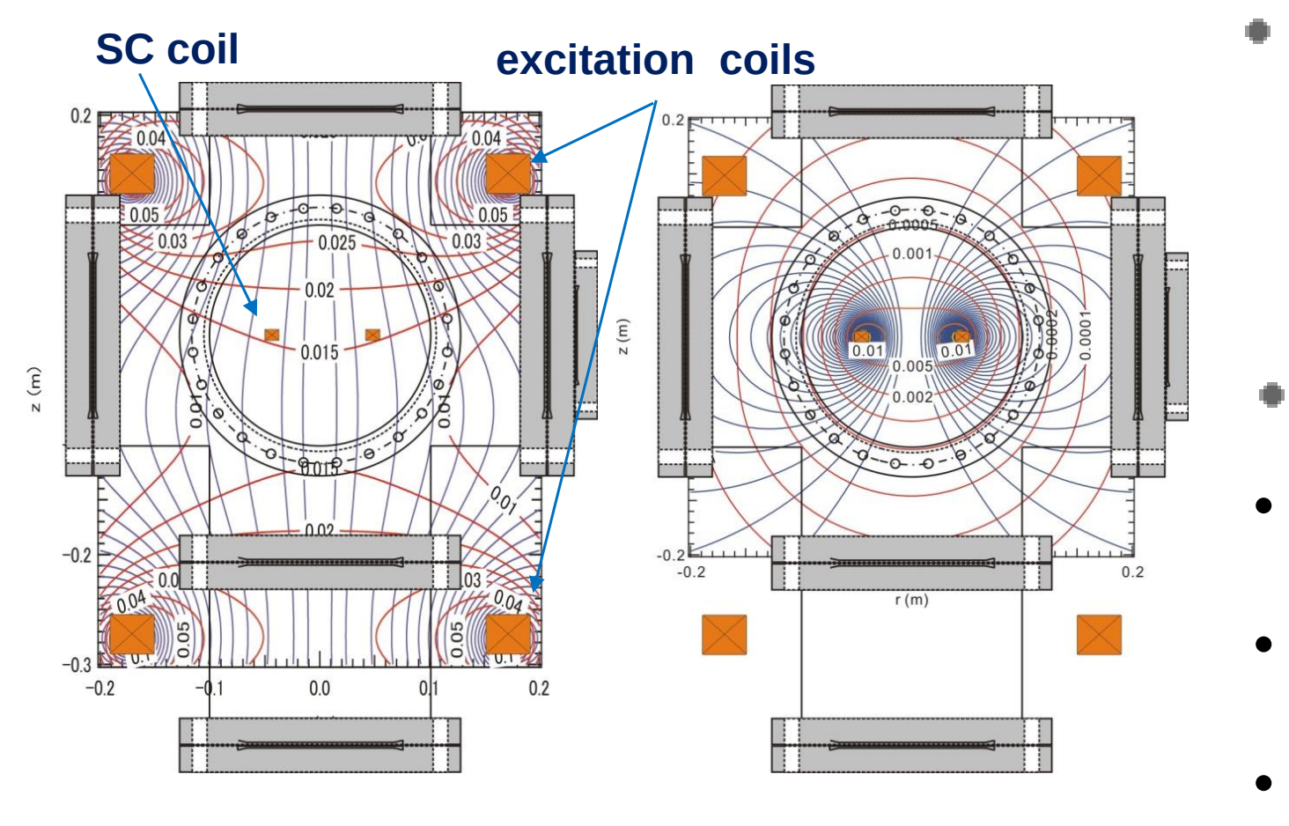
- so far compression was not yet observed
- optimization of configurations is a future work



Application of the rotating electric field (left, top views) and typical particle orbit

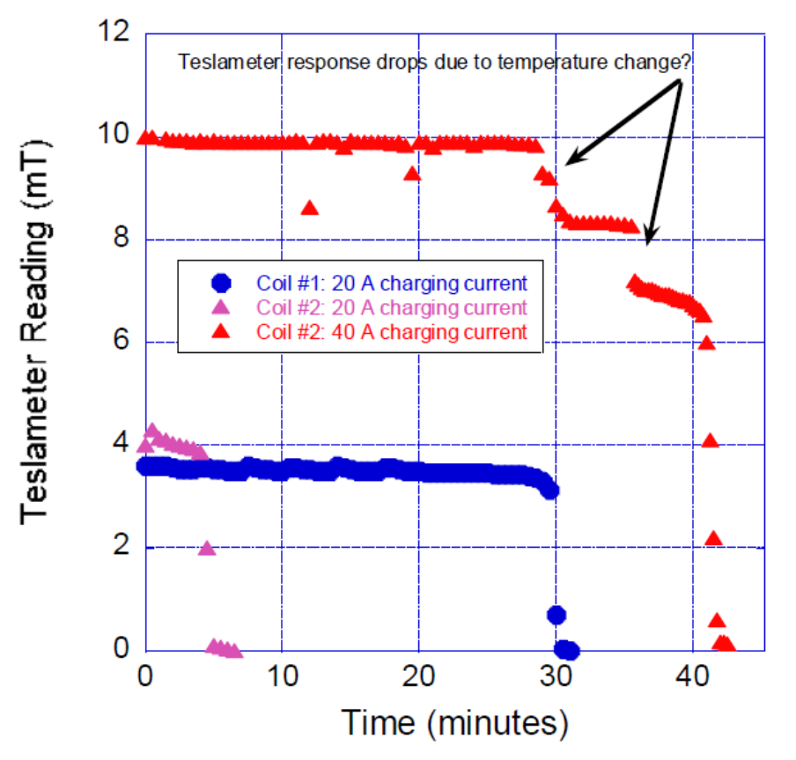
Forthcoming experiments with SC coil

Development of SC dipole coils are ongoing toward the next positron beam experiment at NEPOMUC in 2016



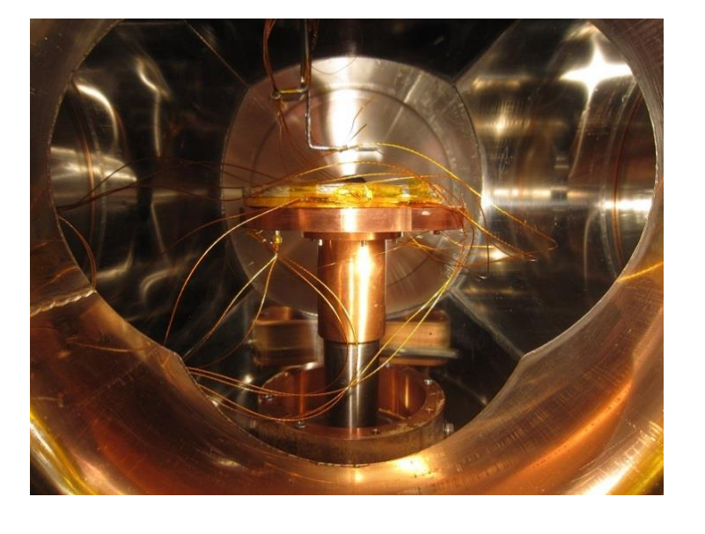
Field lines and strength (in T) generated by excitation coils and SC coil

- Closed and unperturbed magnetic field lines, which cannot be realized with a permanent magnet, are required for simultaneous confinement of e+ and e-.
- "Inductive" excitation of the SC coil
  - Excitation coil current 0 -> I_E at T_{SC}>T_C
  - After cooling to T_{SC}<T_C, I_E -> 0
  - SC coil current 0 -> I_{SC} (flux conservation)



Excitation of SC coil cooled with liquid nitrogen

Bi-2223 SC tape winding (from NIFS)

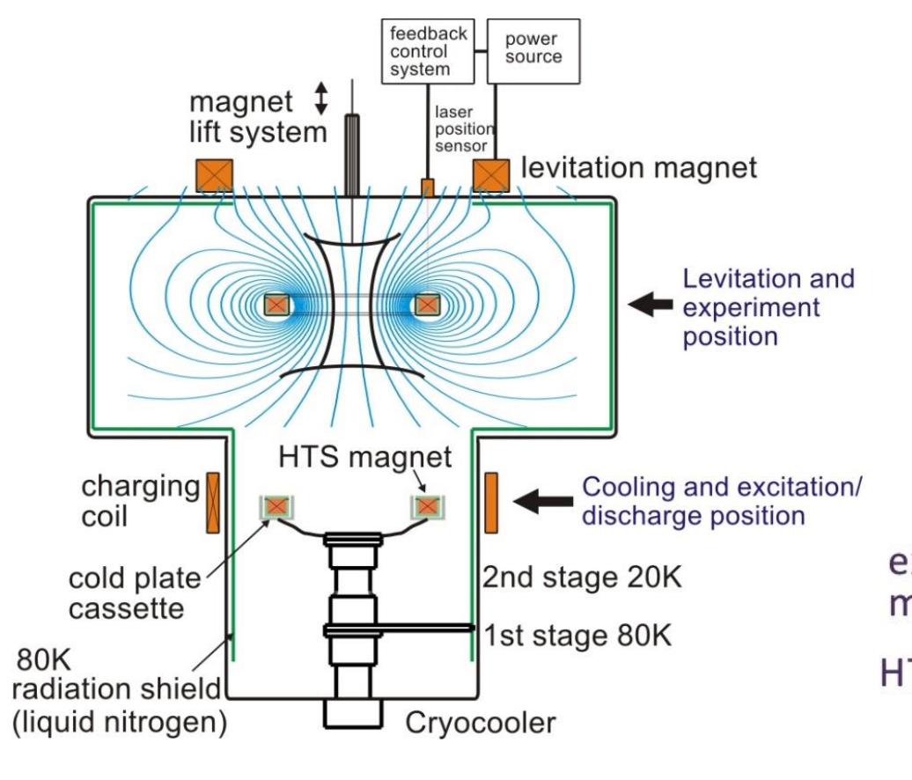


Cryocooler test in vacuum environment

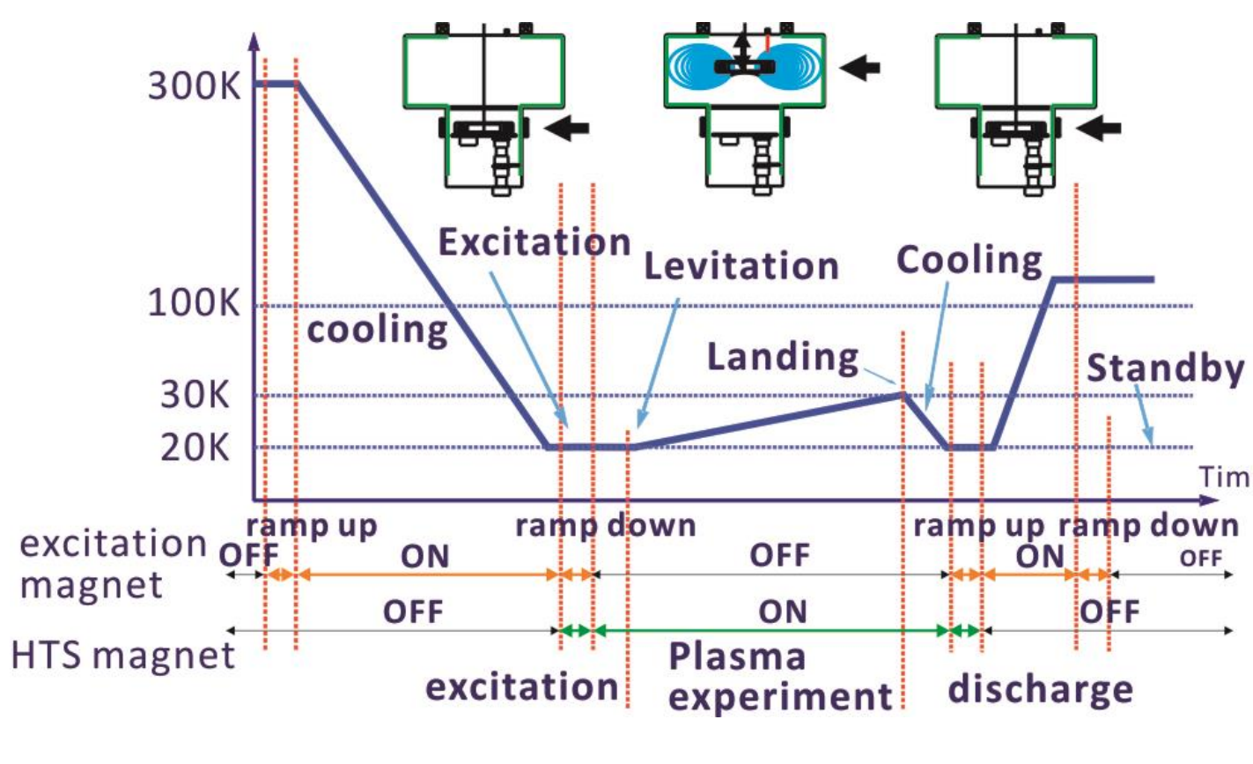
- SC coil excitation was realized with N_2 cooling
- Test with a cryocooler system is ongoing

Design studies on SC levitated dipole

We are developing SC APEX-D, consisting of SC (Bi-2223 HTS) coils, cooling system, and feedback-controlled levitation system.

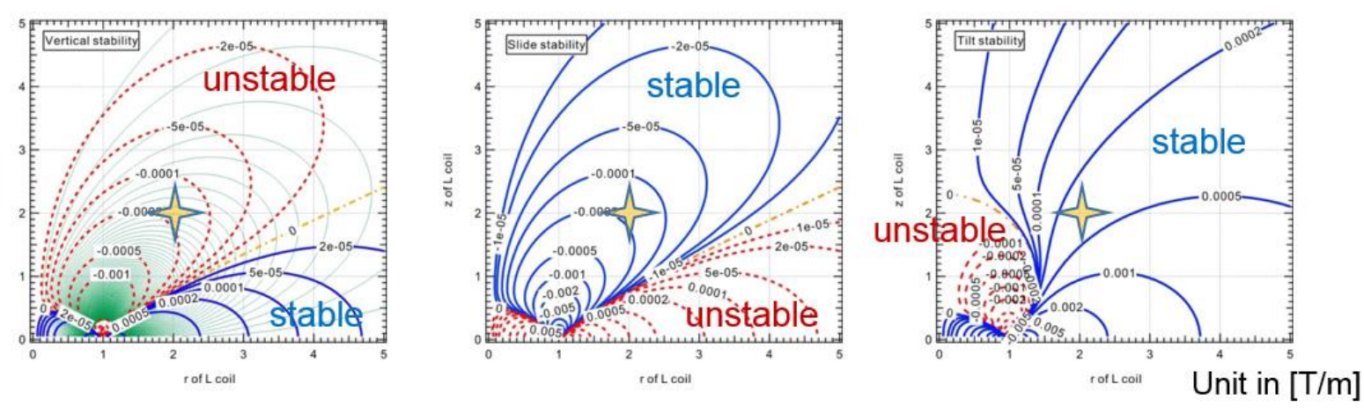


Schematic of APEX-D levitated dipole

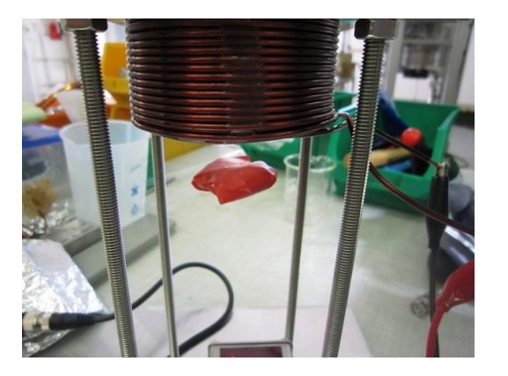


Magnetic excitation and operation scheme of APEX-D

- Basic design is now fixed, and considerations on optimized parameters and operation scenario are ongoing



Stability analysis of vertical, slide, and tilt motions of a levitated SC coil



Levitation of a permanent magnet

- Feedback circuit was developed and used for permanent magnet levitation