Recent status of the PAX and APEX projects toward the formation of electron-positron plasma

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We aim to create magnetically-confined electron-positron plasma and experimentally investigate its unique properties as pair-plasmas

- Matter-antimatter plasmas are novel and unique research subjects[1]
  - Pair-plasma consists of light and perfect equal-mass particles, $m_{e-}=m_{e+}$
  - Novel stability[2] and wave propagation properties[3] are predicted
  - Potential contribution to understand astrophysical phenomena

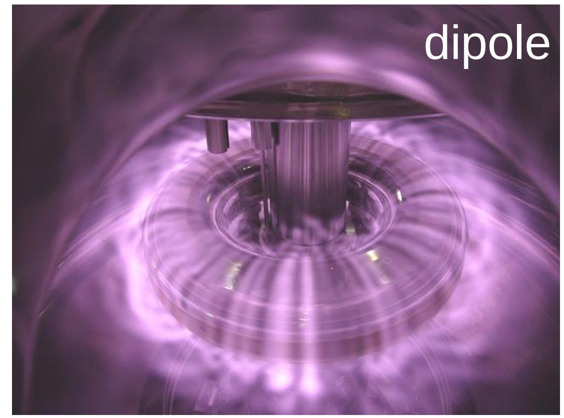
- Very few experiments[4] (no e+ e- plasmas in laboratories) so far[5]
  - Confined electron-positron plasmas have never been realized
  - Simultaneous trapping of e+ & e-: conventional non-neutral traps not applicable
  - Very strong positron source (and accumulator) is needed

1. T. Sunn Pedersen et al., New J. Physics 14, 035010 (2012)
2. P. Helander, Phys. Rev. Lett. 113, 135003 (2014)
3. V. Tsytovich and C. B. Wharton, Comm. Plasma Phys. Cntr. Phys. 4 91 (1978)
4. W. Oohara, D. Data, and R. Hatakeyama, Phys. Rev. Lett. 95, 175003 (2005)
5. C. M. Surko and R.G. Greaves, Phys. Plasmas 11, 2333 (2004)

Toroidal plasma traps and accumulator are planned for operation at NEPOMUC, the world strongest moderated positron source

- Toroidal magnetic configurations, instead of linear non-neutral plasma traps
  - applicable to the confinement of plasmas at any non-neutrality (no open ends)
  - stable trapping of electron plasmas was realized in CNT* and RT-1** (>300 s)

*T. Sunn Pedersen & A. H. Boozer, PRL 88, 205002 (2002)



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

P1-13 Nishiura, P1-14 Kawazura, O-8 Sato

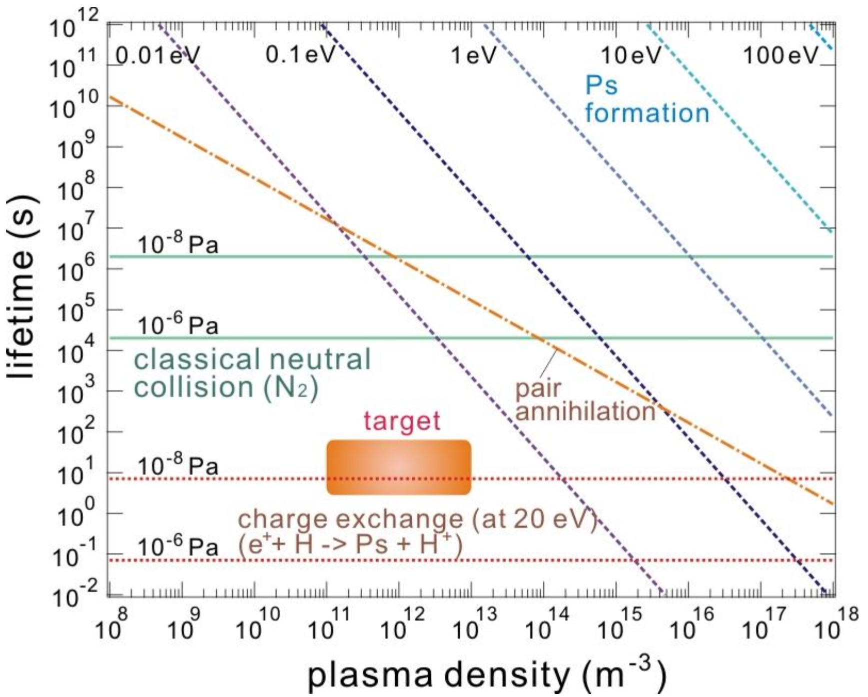
- NEPOMUC positron source***
  - NEutron-induced POsitron source MUniCh
  - reactor (20MW) based source
  - moderated >10^9 /s e+ at 1keV
  - further remoderated beam available

***C.Hugenschmidt et al., New J. Physics 14, 55027 (2012)

Target parameters to realize pair plasmas are a realistic goal: Charge-exchange neutral collisions would set the lifetime

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

Target parameters: n_e >~10^{11}m^{-3}, T_e~1eV ➡ λ_D< 2cm



- For these parameters, lifetimes, set by several processes, are longer than time scales of plasma phenomena* **

- Here efficient injection and long trapping time are essentially important
  - total e+ number of N > 10^9 is needed
  - NEPOMUC beam intensity $\Gamma \sim 10^9$ /s

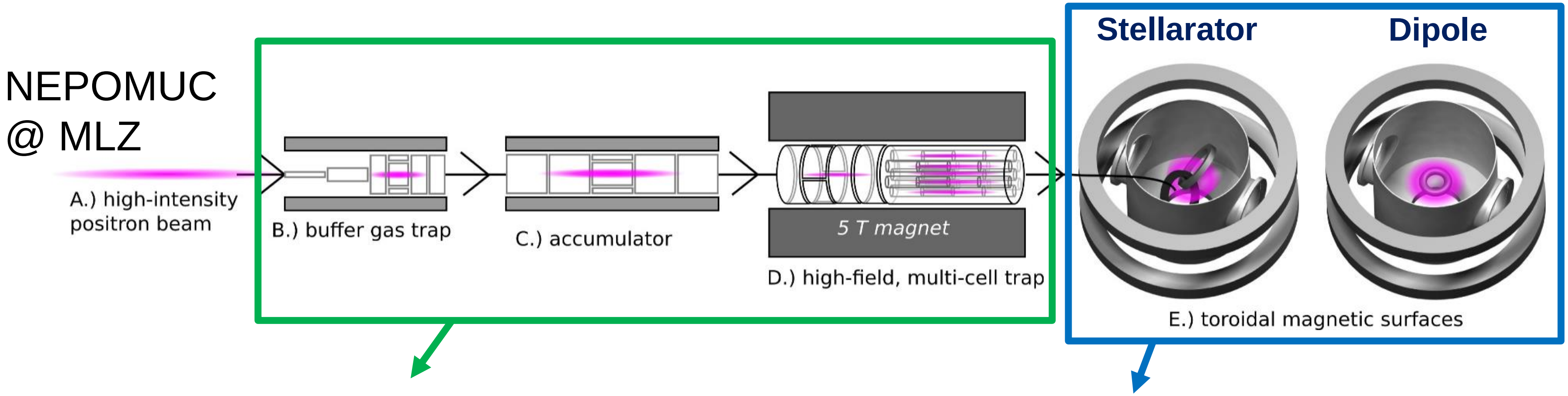
  $N = \alpha\tau\Gamma$ α: injection efficiency
  τ: confinement time (s)

  - Use of accumulator, instead of steady injection scheme, may be a solution

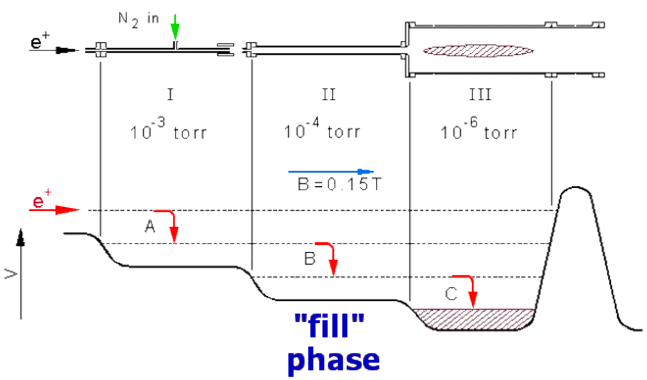
*R. G. Greaves & C. M. Surko, in NNPP IV (2002)

**S. Zhou et al., PRA 55, 361 (1997)

Development of PAX accumulator and APEX confinement projects is ongoing in Greifswald and Garching

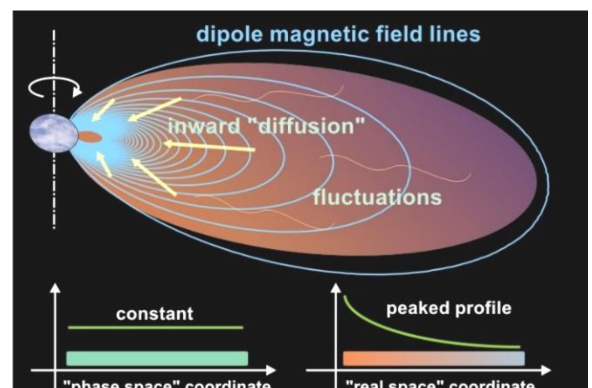


- Positron Accumulation eXperiment
  - accumulation of $10^{11\text{-}12}$ e+
  - bridge between NEPOMUC and APEX
  - cooled in buffer gas trap with N_2*



  - then e+ stored in multi-cell trap

- A Positron-Electron eXperiment
  - simultaneous trapping of e+ and e-
  - toroidal magnetic configuration
  - we have started with dipole (APEX-D)



*M. R. Natisin, J.R. Danielson,& C.M. Surko, PoP 22, 033501 (2015)

Status of PAX/APEX development projects

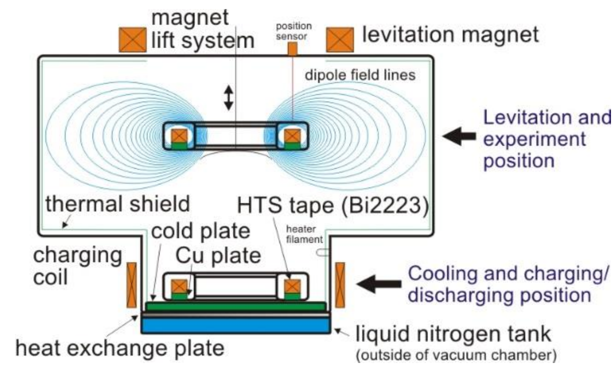
PAX (IPP Greifswald)

- First Point Scientific system
- high field trap and electrodes

- ☑ cooling and accumulation of e+ (Na^{22})
- ☑ phosphor screen responses to e+ and e-
- ☑ e- experiments with high-field (5T) trap
- ☐ development of multi-cell trap

SC toroidal traps

- APEX-D and APEX-S
- closed field lines
- now design phase

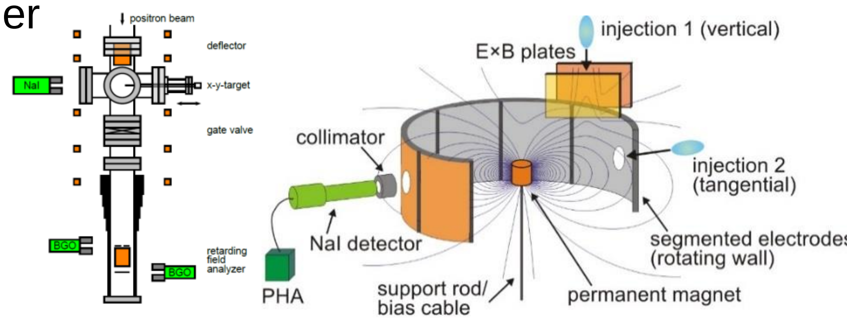


- ☑ levitation system
- ☐ optimized SC magnet
- ☐ cooling/excitation system
- ☐ plasma experiments…

SC coils from NIFS

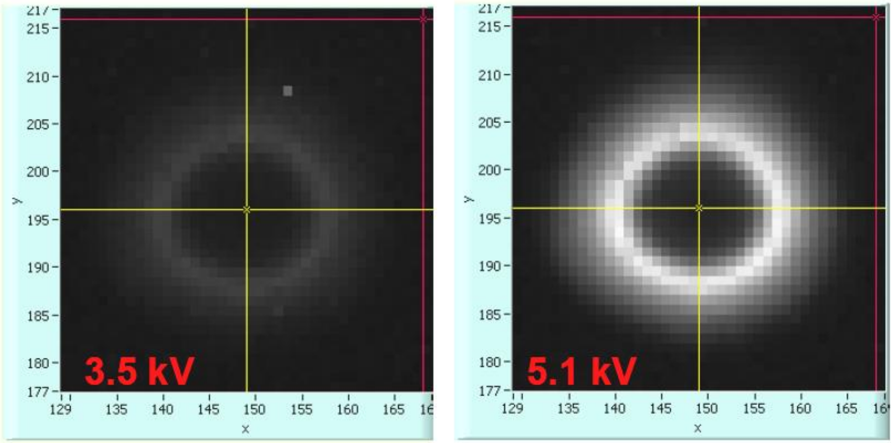
APEX (NEPOMUC Hall / IPP Garching)

- Retarding Field Analyzer
- prototype dipole trap

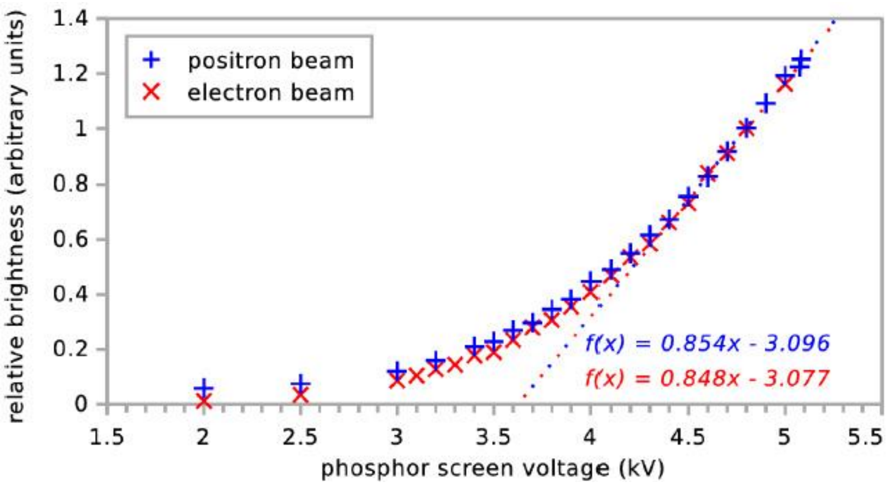


- ☑ beam energy profiles measurements
- ☑ injection (drift, Ps) development
- ☐ design of SC dipole/stellarator

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



Phosphor screen images of positrons

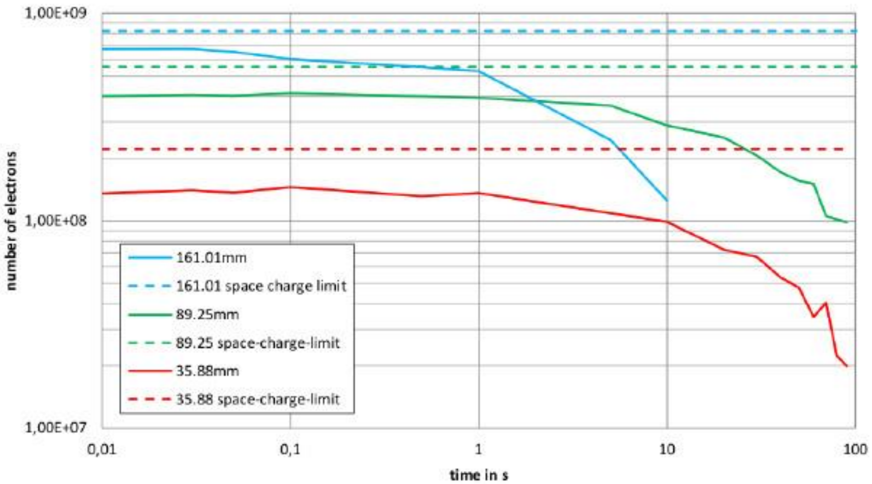


Phosphor screen response to e+ and e-

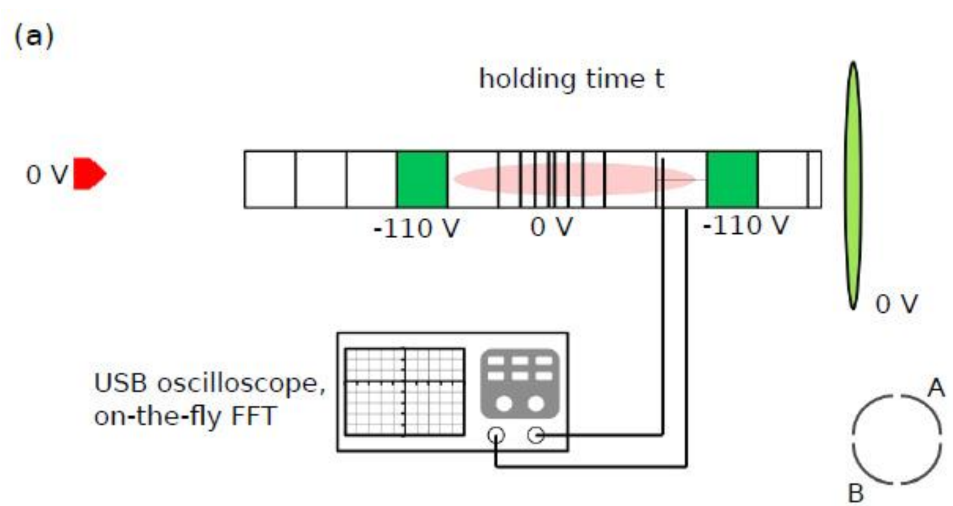
* E.V. Stenson et al., to be published (2015)

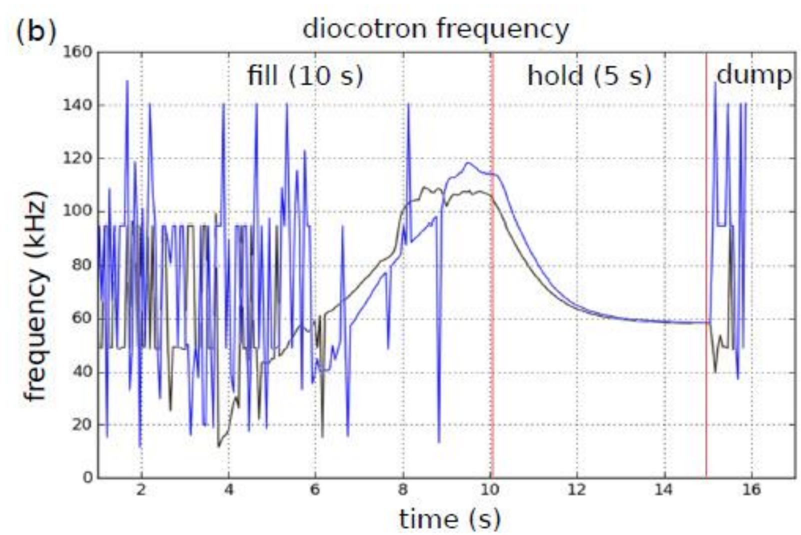
- e+ beam extraction (with Na^{22})
  - commissioning of neon moderator
  - moderation (energy spread: some eV)
- Imaging with phosphor screen
  - raw beam
  - e+ in buffer-gas trap
  - guiding efficiency will be improved
- Phosphor screen response to e+
  - previously, no clear studies done
  - comparison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

Experiments with electron plasma were conducted in high-field trap (up to 5 T) to explore design parameters of multi-cell trap



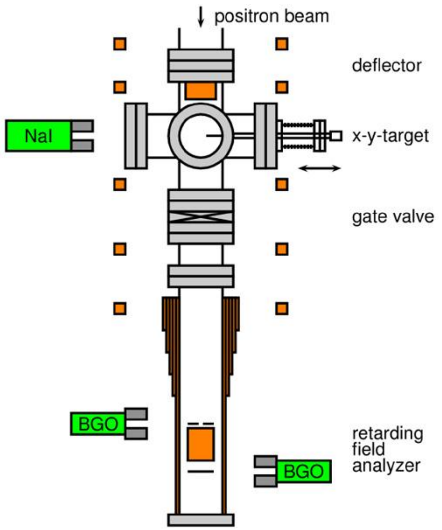
- e- confinement in Penning-Malmberg trap
  - trapping time longer than 1 hour
  - dependence on length, etc.
- Evolution of m=1 diocotron mode
  - also used for diagnostics
  - frequency corresponds to ~10^9 e-

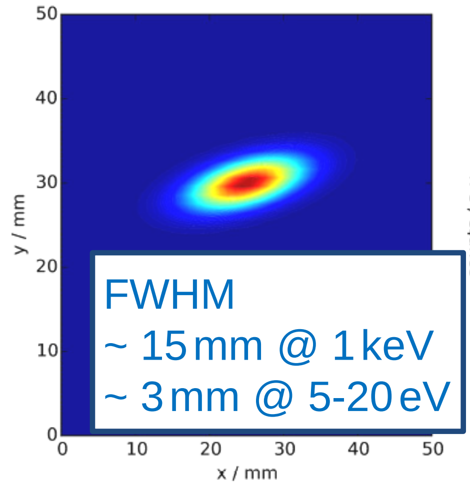


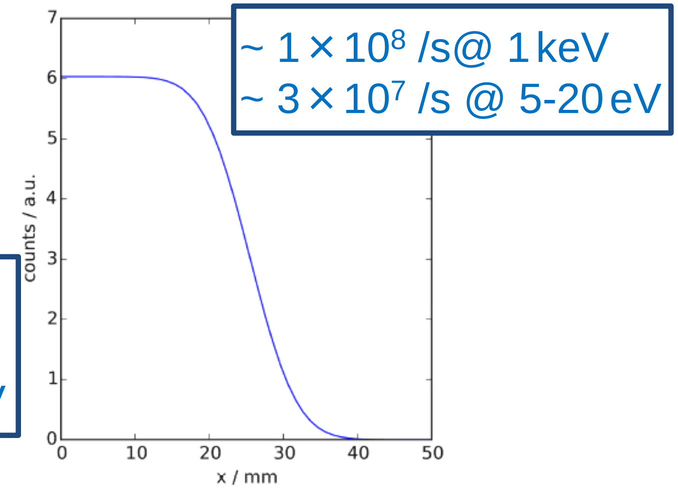


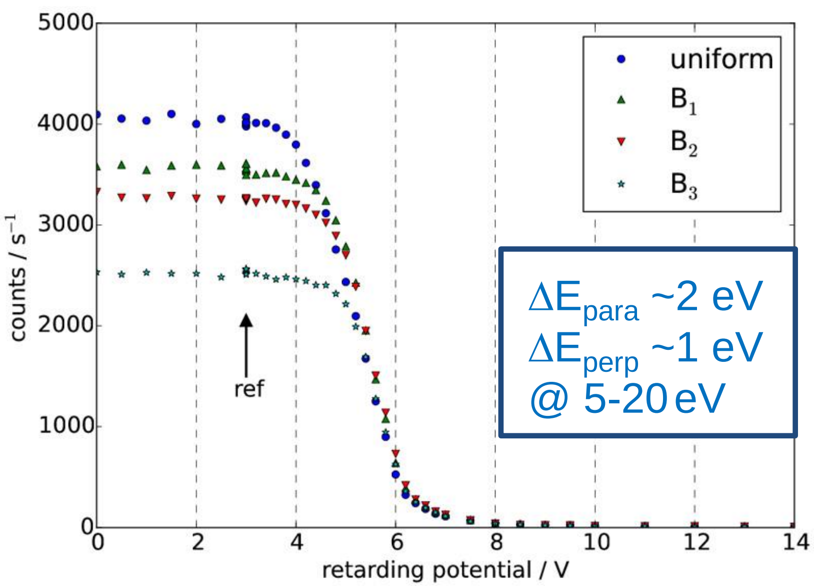
* *H. Niemann, U. Hergenhahn, et al.*

Intensity, spatial profiles, and energy spreads of positron beam were measured at the open beam port of NEPOMUC





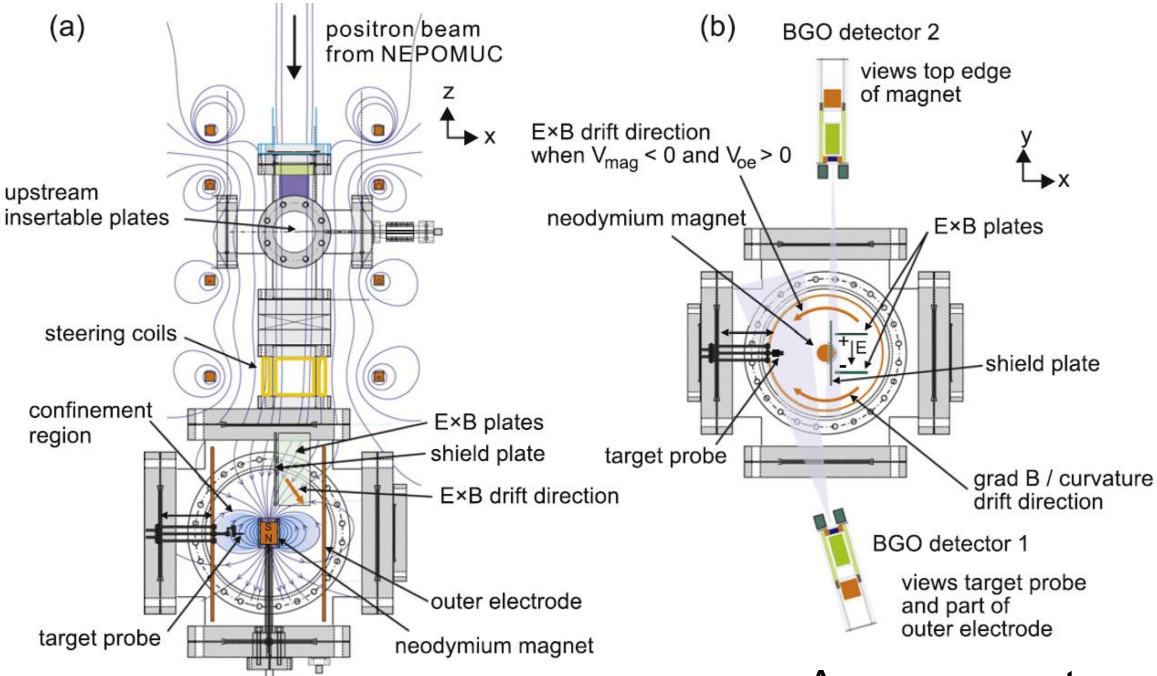


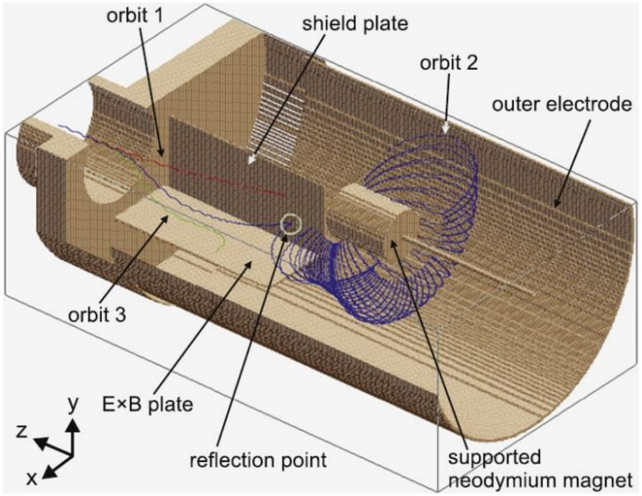


- Spatial profile measurements
  - MCP + phosphor camera image
  - movable targets + BGO scintillator-PMTs
- RFA with variable field strength
  - both parallel and perpendicular energies
  - important parameters for buffer-gas trapping
- Measurements done for several conditions

** J. Stanja et al., to be published (2015)*

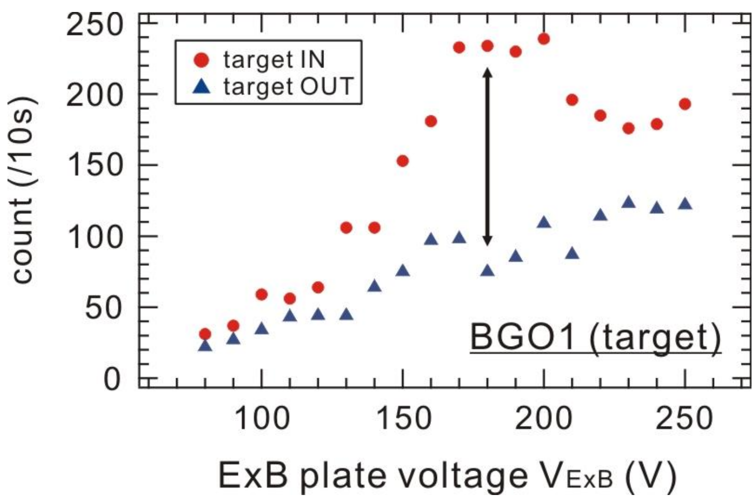
Prototype dipole field trap with a permanent magnet was operated at NEPOMUC for proof-of-principle experiments on injection and trapping



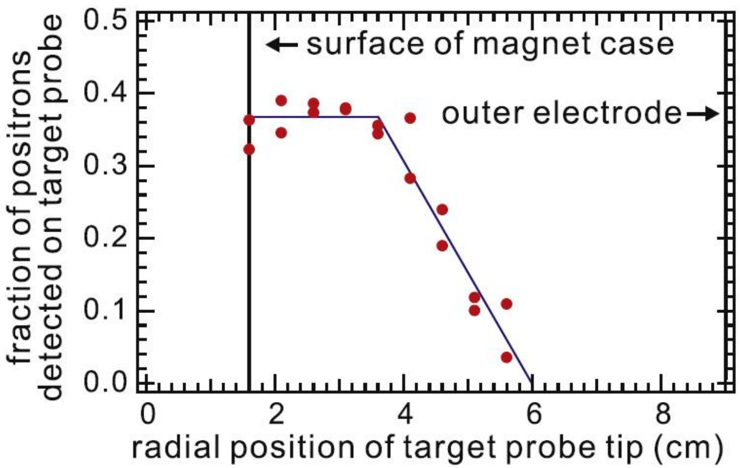


- A permanent magnet device with…
  - ExB and shield plates, steering coils
  - magnet and outer wall electrodes (E_r)
- ExB drift injection was numerically optimized
- Diagnostics
  - BGO scintillator-PMTs to detect 511 keV γ-rays
  - target probe + current amplifier

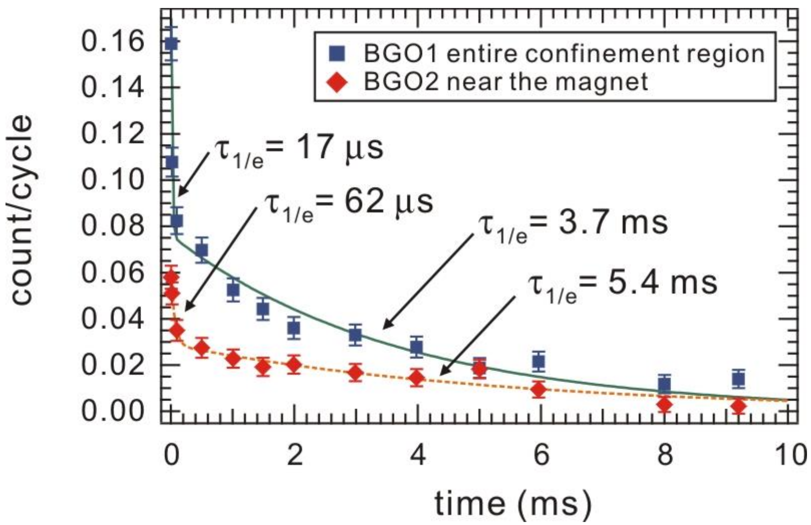
Efficient injection (~ 38%) and relatively long confinement (~ 5 ms) of positrons were realized at NEPOMUC



Detection of 511keV γ in the confinement region



Spatial profile of positron current at movable target



Decay of γ after stopping positron injection

- ExB drift injection of NEPOMUC beam
  - steering, ExB bias, E_r optimization
  - injection and 180° rotation confirmed
- Confinement
  - order of ~1ms in strong field region
  - improvement is expected in SC dipole

** H.Saitoh et al., New J. Physics 17, 103038 (2015)*

Summary and future work

- The PAX/APEX collaboration is conducting development research aimed at the creation and experimental study of electron-positron pair-plasmas

- Present status and results obtained so far:
  - moderator, buffer gas trap, and accumulator systems were assembled
  - trapping of e+ in buffer-gas trap and beam imaging by phosphor screen
  - long trapping and diagnostics with diocotron mode of e- in high-field trap

  - basic e+ beam properties at open beam port of NEPOMUC obtained
  - efficient (~38%) injection of intense 5eV e+ beam into dipole field
  - relatively long (~5ms) confinement in the prototype trap

- Future work
  - application of rotating wall to control radial transport of particles
  - development of more efficient injection schemes (remoderator, Ps)
  - further development: levitated SC dipole / stellarator and multi-cell trap

Backup Slides

Background

Unique properties of electron-positron pair-plasma

- "perfect" equal-mass and light mass (high frequency mode)
- absence of several modes: Faraday rotation, drift and sound waves
- unique stability properties*

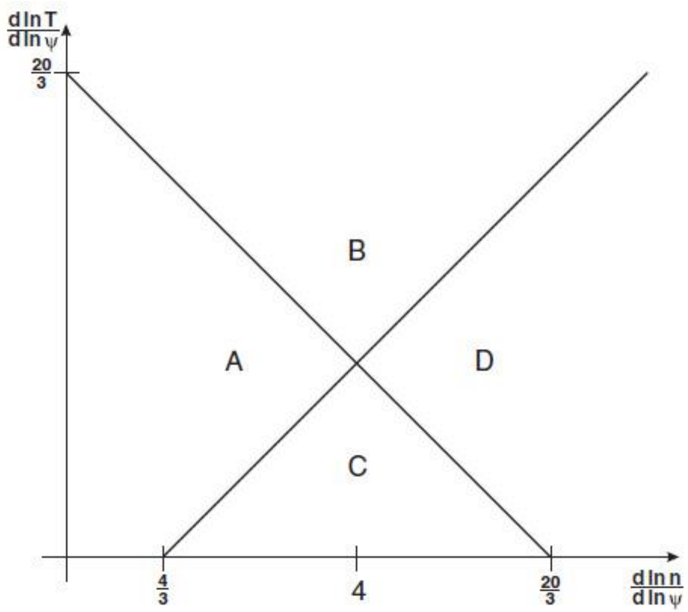


FIG. 1. Stability diagram of an electron-positron plasma in a dipole magnetic field. Regions *A* and *B* are stable to electrostatic modes, while regions *B* and *D* are unstable to MHD interchanges.

- electrostatic stability condition

$$\frac{d\ln(n/T)}{d\ln\psi} < \frac{4}{3} \qquad \text{(A and B)}$$

- MHD modes are unstable when

$$\frac{d(pU^{5/3})}{d\ln\psi} > 0 \Rightarrow \frac{d\ln(nT)}{d\ln\psi} > \frac{20}{3} \qquad \text{(B and D)}$$

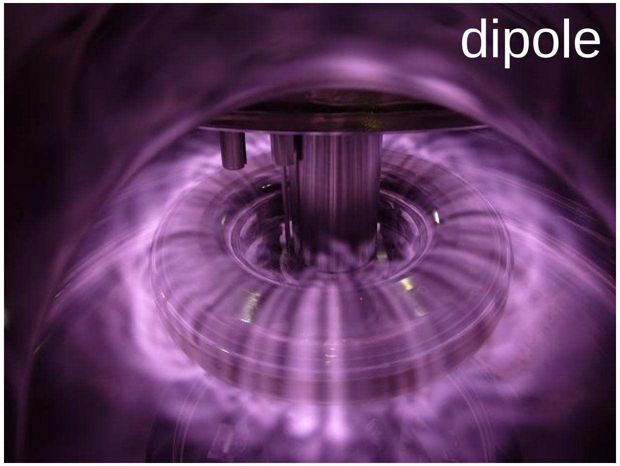
** P. Helander, Phys. Rev. Lett. 113, 135003 (2014)*

We plan to use toroidal configurations that enable 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

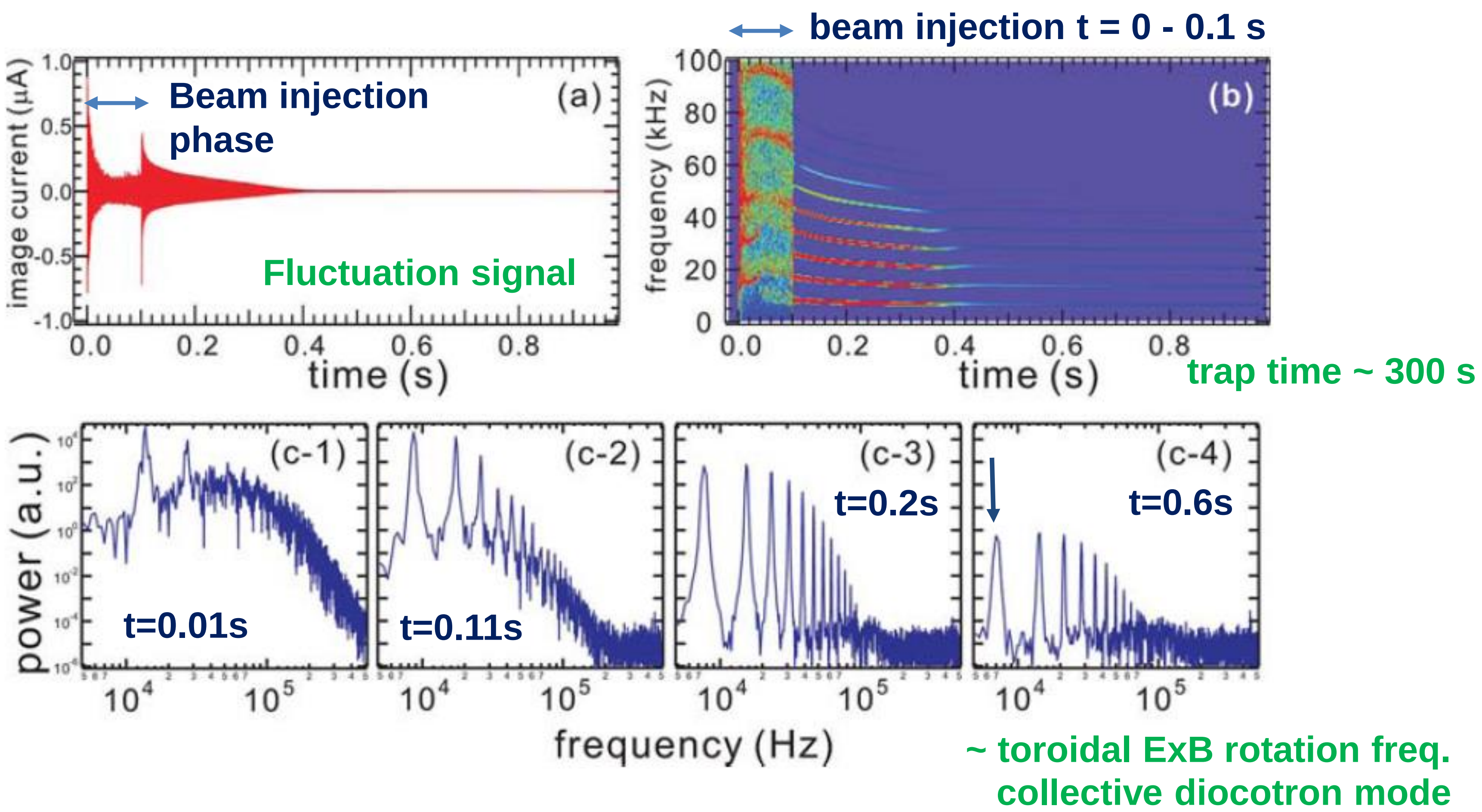
- Toroidal configurations without using plasma currents
  - Applicable to the confinement of plasmas at any non-neutrality
  - Stable trap of electron plasma has been realized in CNT* and RT-1**



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

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

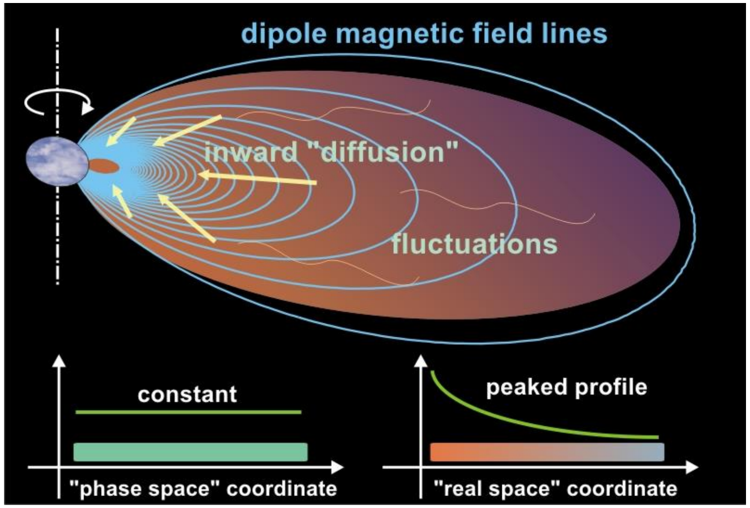
Previous work on pure electron plasma in RT-1, which clearly showed injection, trap, and collective phenomena of charged particles in dipole

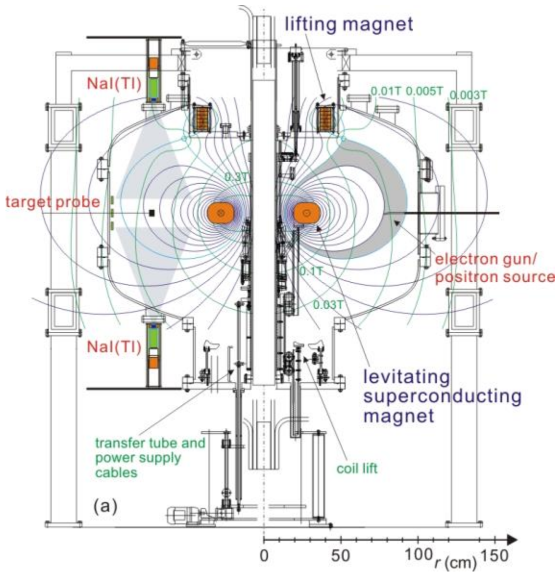


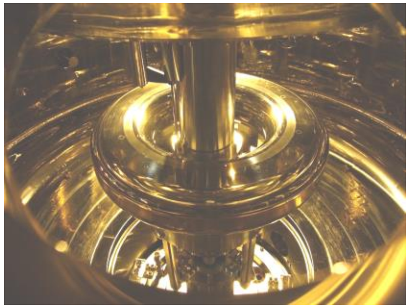
- Plasma is transported inward during turbulent-like phase, then rigid-rotating state is spontaneously generated after stabilization

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

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







RT-1

- Most simple and ubiquitous configuration in laboratory and the Universe
- Closed and axis-symmetric field lines without plasma current
- Inward transport of neutral and non-neutral plasmas has been observed in planetary magnetospheres and experiments, RT-1* and LDX**

***2010 Yoshida *et al*., Phys.Rev.Lett. 104, 235004; 2009 Ogawa *et al*., Plasma Fusion Res. 4, 020.**

***2010 Boxer *et al*., Nature Phys.Rev.Lett. 6, 207.**

Required parameters

Development of efficient injection scheme into toroidal configurations is essential for the trapping of positrons as plasma

Target parameters: $n_e > 10^{11\text{-}12}\ m^{-3}$, $T_e \sim 1eV$ $\lambda_D <$ system size

- Assuming that the volume of confinement region V ~ 10L, we need to trap at very least $N \sim 10^9$ positrons

- For steady-state filling-up, we have $N = \alpha\tau\Gamma$, where

  α: injection efficiency
  τ: confinement time (s)
  Γ: beam intensity (/s) ~ 10^9 at NEPOMUC

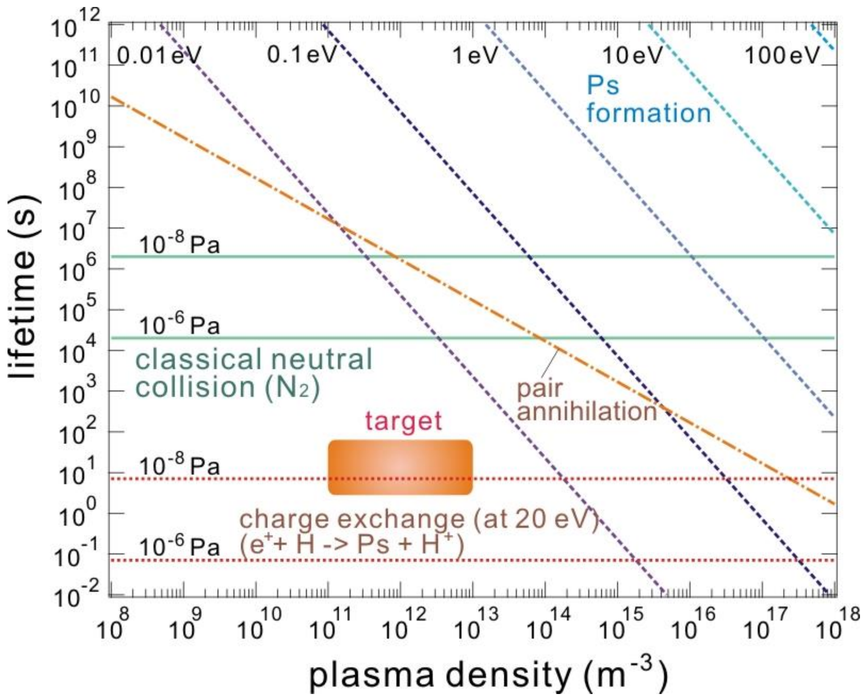
- We need to realize

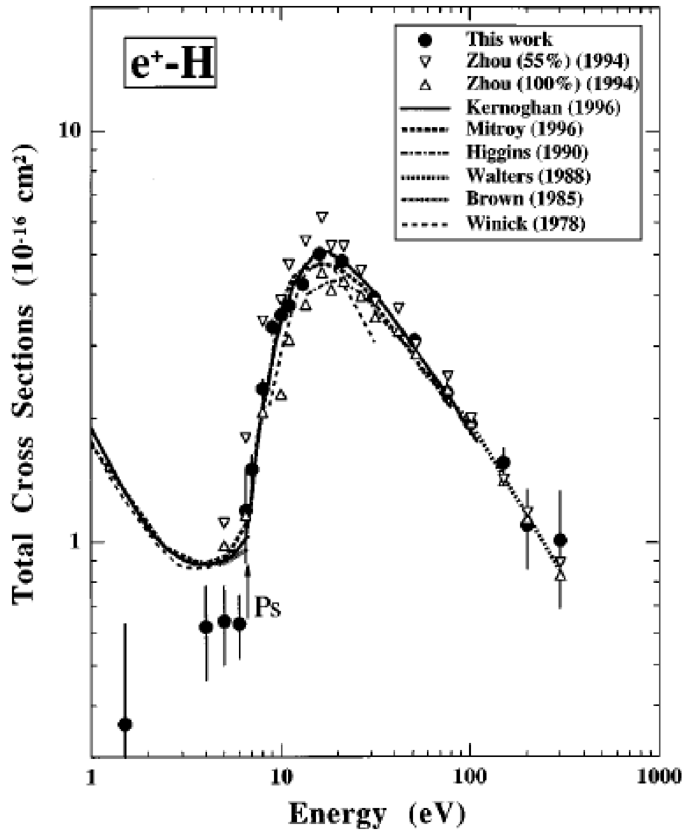
  - Very long (more than 1s) confinement time
  - Very efficient (close to 100%) injection into closed toroidal geometries

- Injection scheme is also important when injecting from multi-cell trap

Life time of electron-positron plasmas

- pair annihilation (e+ + e- -> 2g) $\Gamma = \pi r_0^2 c n_e$
- Ps formation (2e- + e+ -> Ps* + e- : three body, etc.) $\Gamma_{Ps} \simeq A n b^2 v_{th} (n b^3)$
- classical neutral collision (annihilation) $\Gamma = \pi r_0^2 c n_n Z_{eff}$
- charge exchange neutral collision (e+ + H -> Ps +H+) : would be dominant





*R. G. Greaves & C. M. Surko, in NNPP IV (2002)

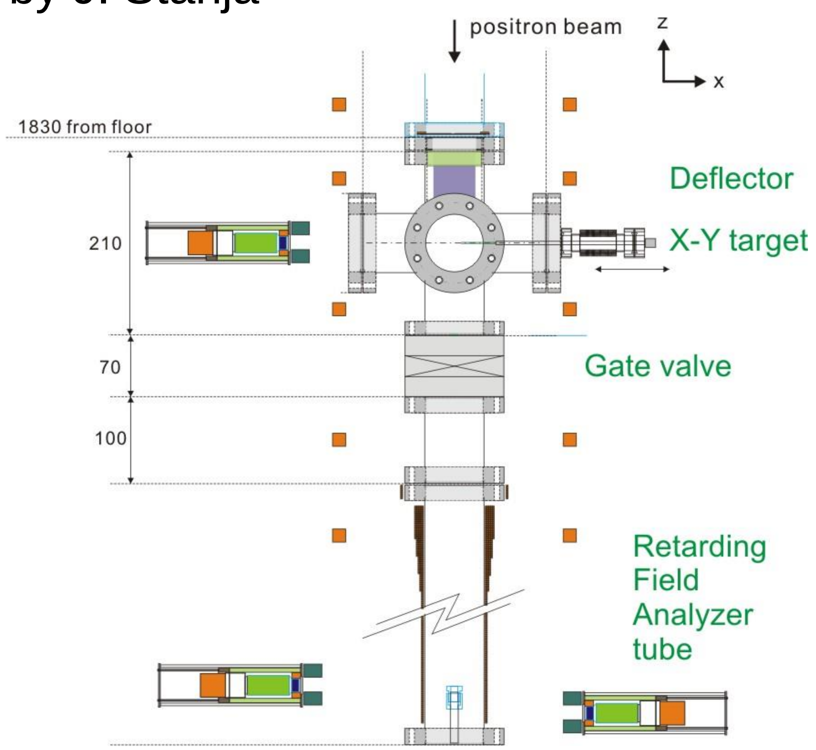
**S. Zhou et al., PRA 55, 361 (1997)

Instruments and Diagnostics

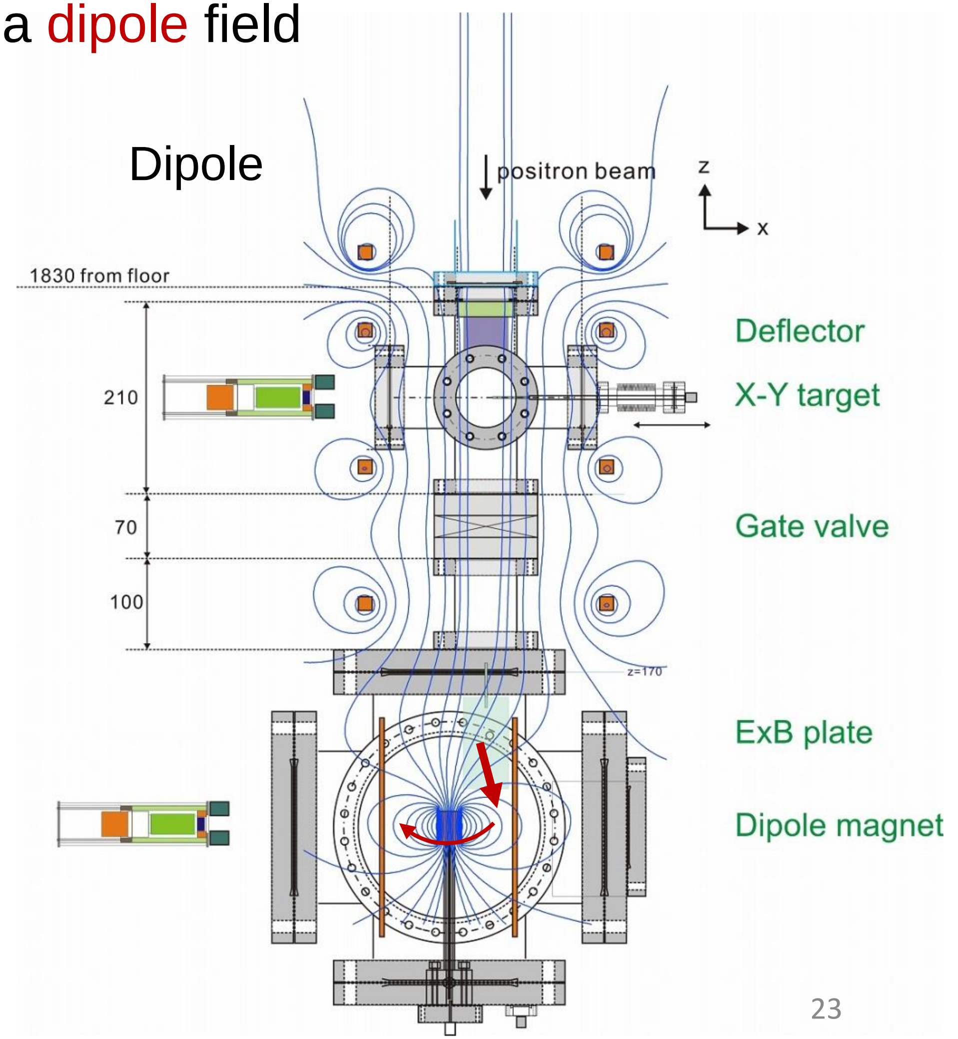
APEX experiments installed at the open beam port of NEPOMUC (13 + 9 days of beamtimes in 2014 and 2015)

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

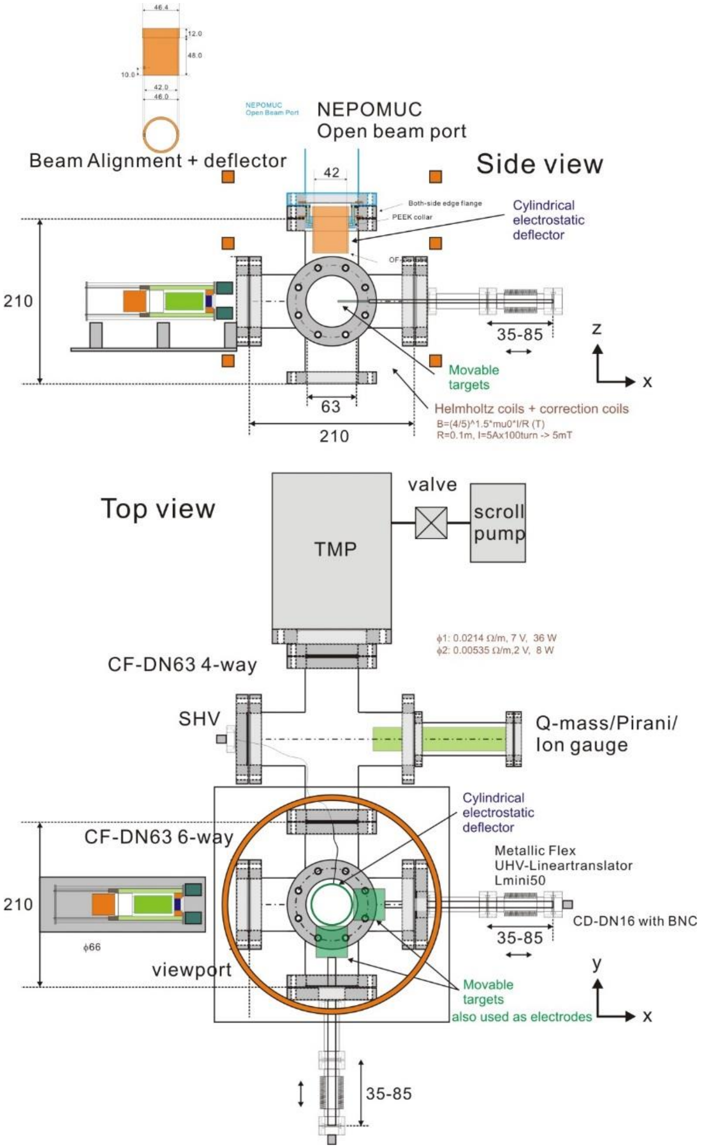
RFA, to be presented by J. Stanja

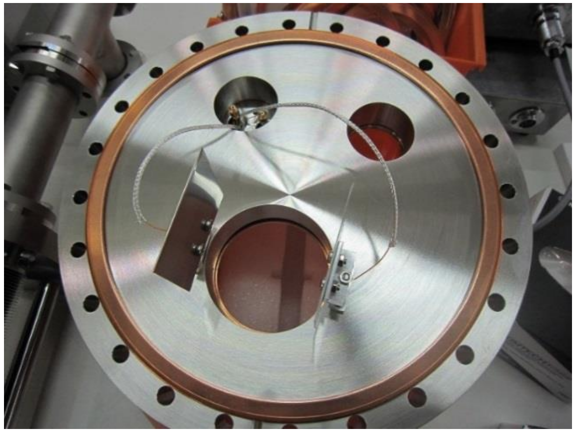


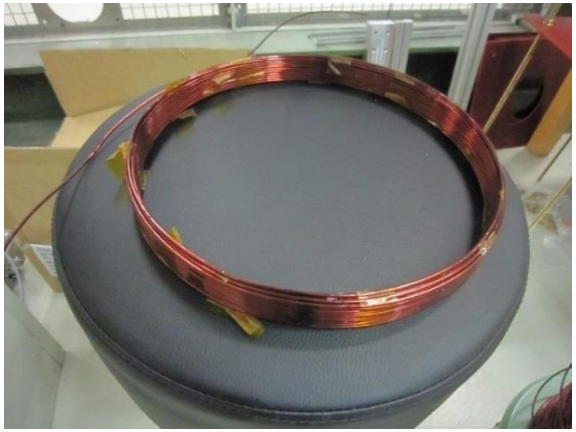
Dipole

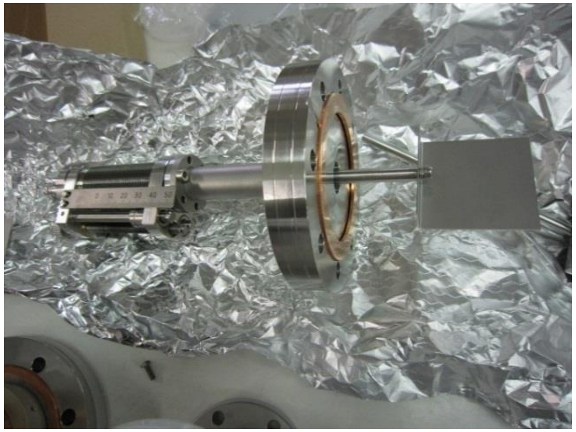


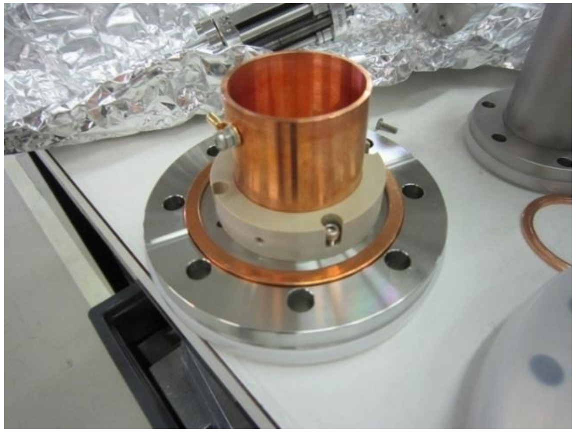
Construction of each of the components of dipole experiment







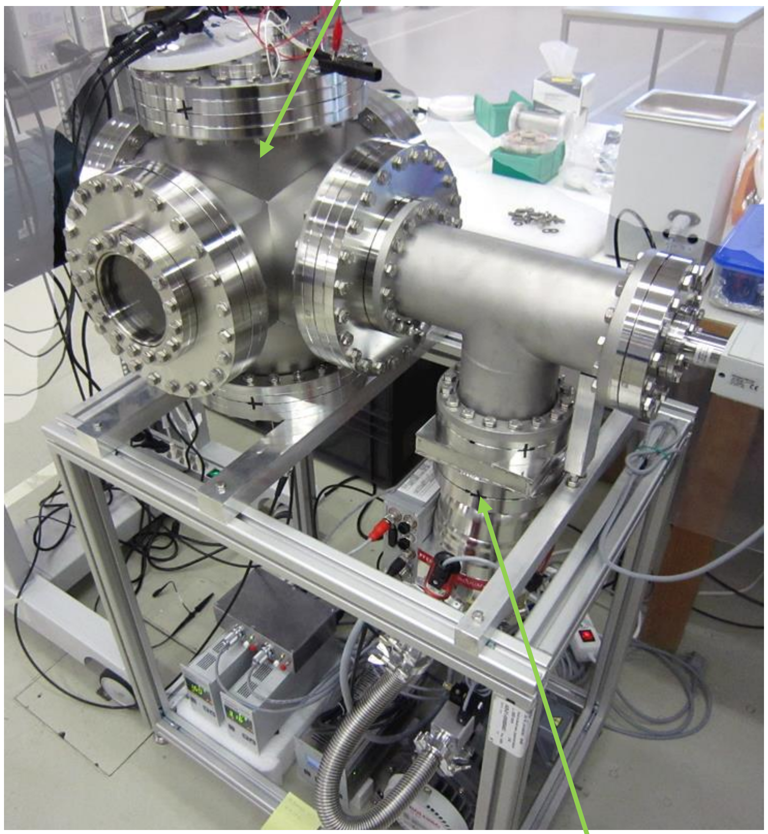


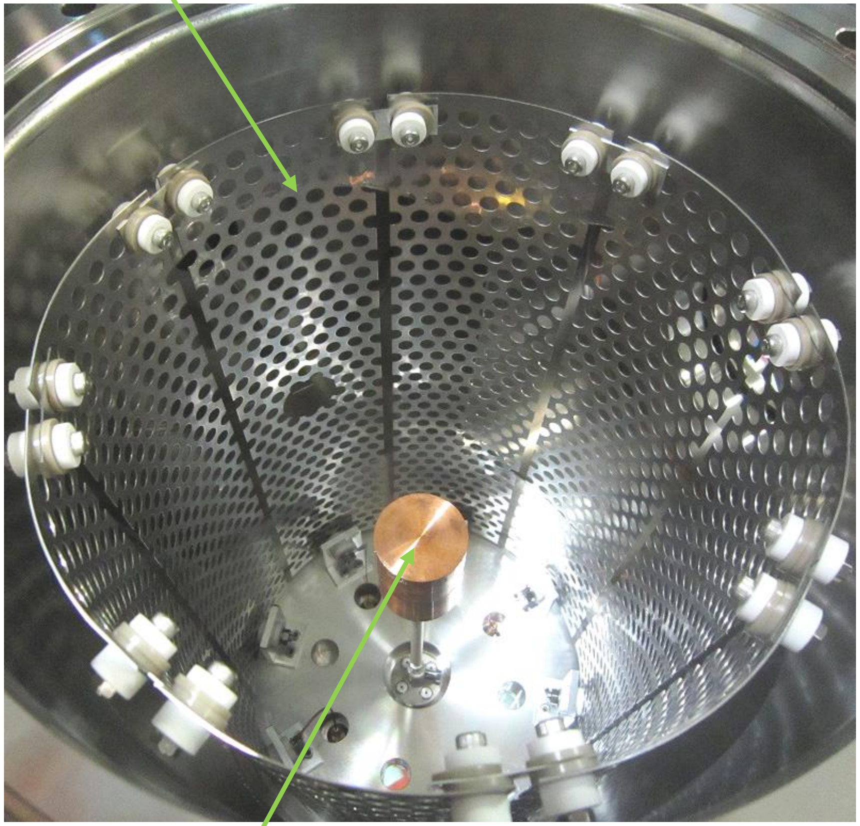


External and internal views of the prototype dipole field trap

trapping region

outer electrode (8-segmented)



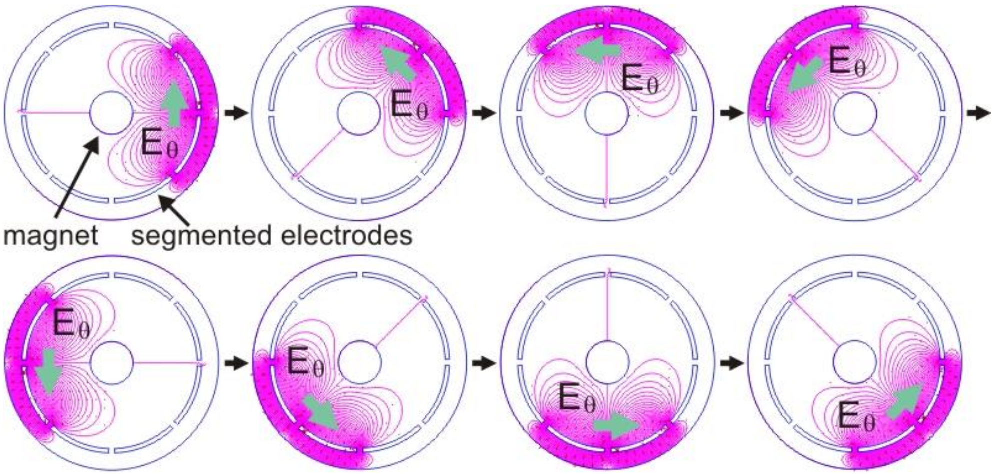


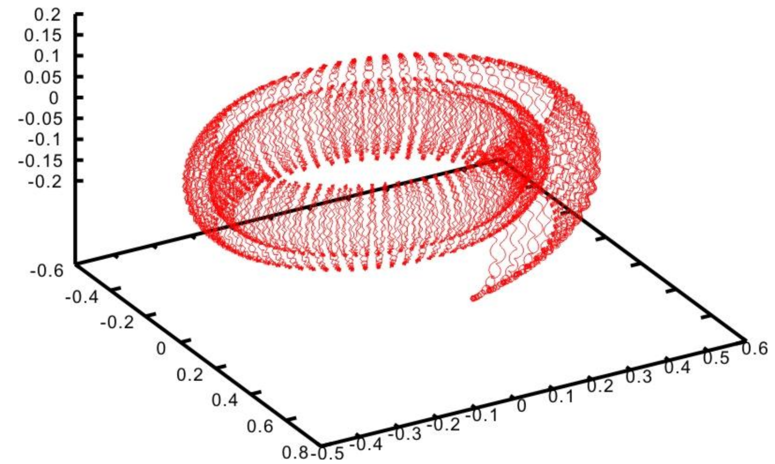
TMP

neodymium magnet ~ 0.6T
(inside copper case)

CF-DN200 (10’’) 6-way, 1.8e-7 Pa

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





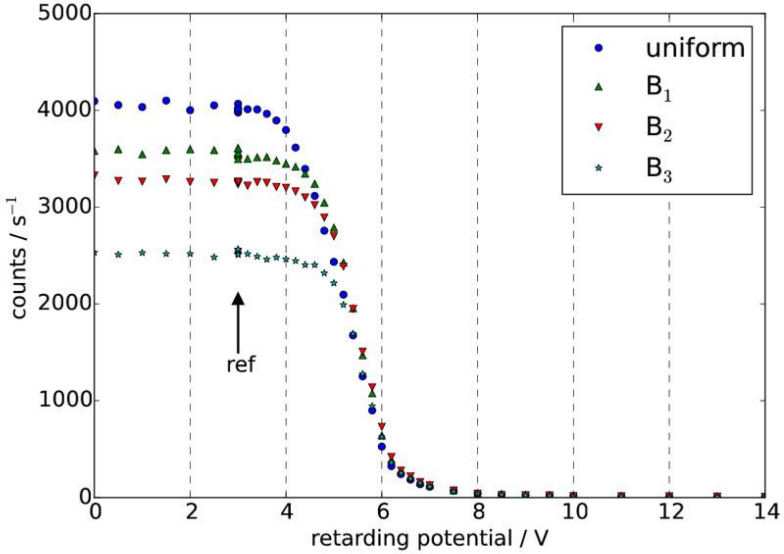
- Rotating **E** is applied in the azimuthal direction
- RW freq. is synchronized with grad-B/curvature drift frequency
- Effects of E_r will also be investigated

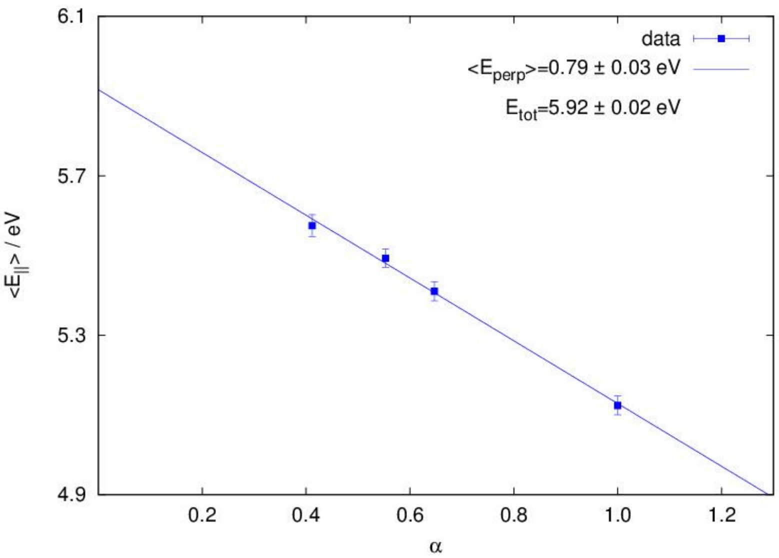
Transverse energy spread measurements of NEPOMUC beam

$$E_{\parallel f} = E_{\parallel i} + \left(1 - \frac{B_f}{B_i}\right) E_{\perp i}$$

$$\langle E_{\perp i} \rangle = -\frac{d\langle E_{\parallel f}\rangle}{d\alpha} \qquad \alpha := B_f / B_i$$

** S. Pastuszka et al., J. Appl. Phys. 88, 6788 (2000), for example.*

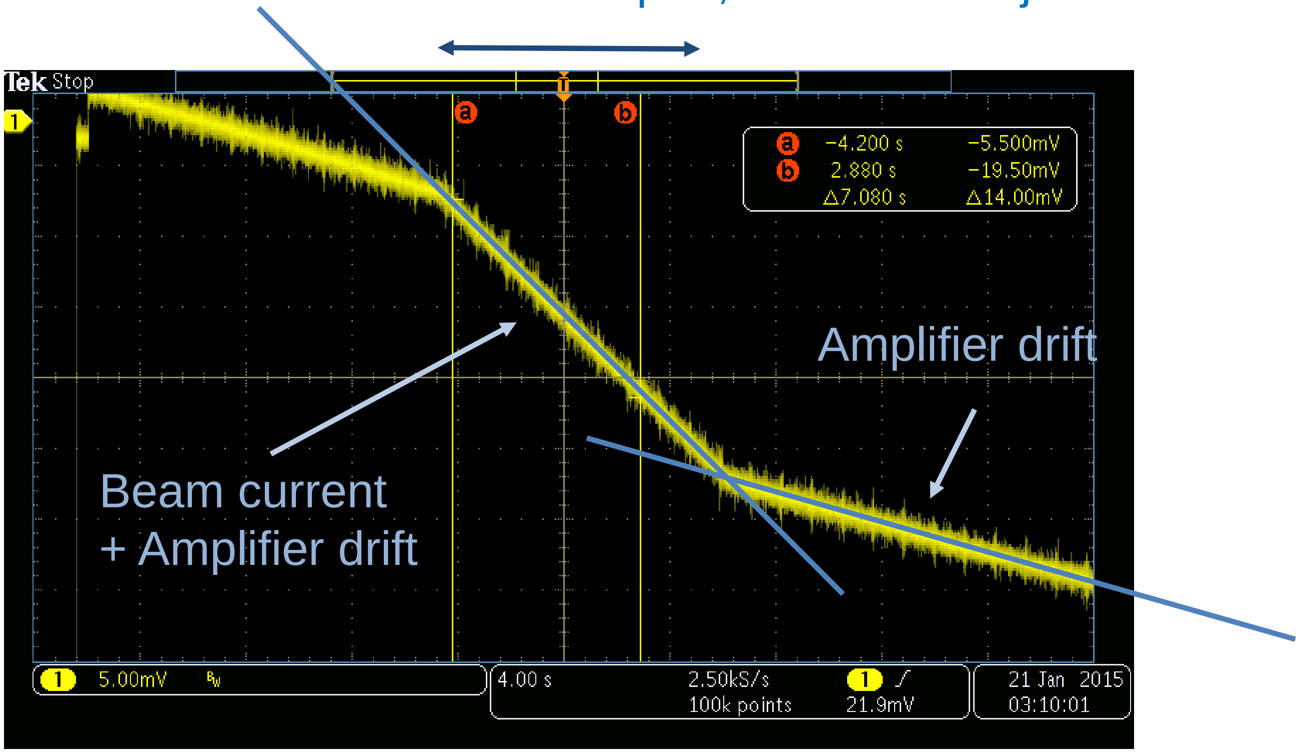




** J. Stanja et al., to be published (2015)*

Direct positron current measurement with charge amplifier

Gate valve open, beams are injected



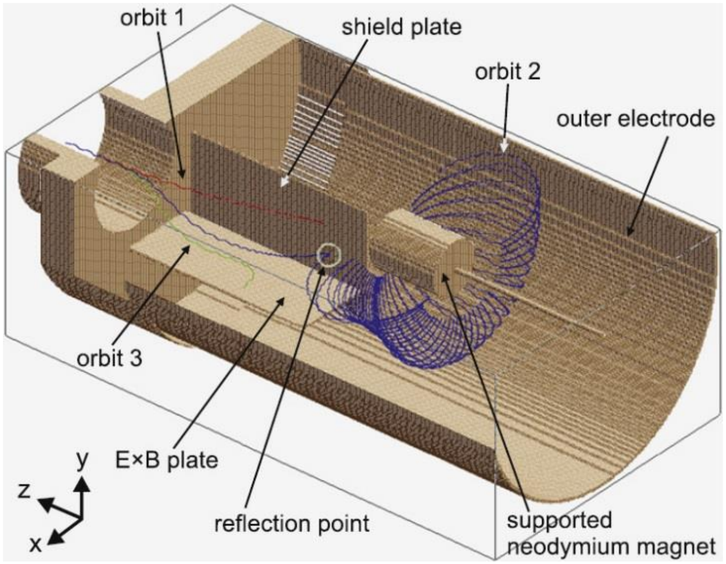
20eV beam, 4s/div, 5mV/div

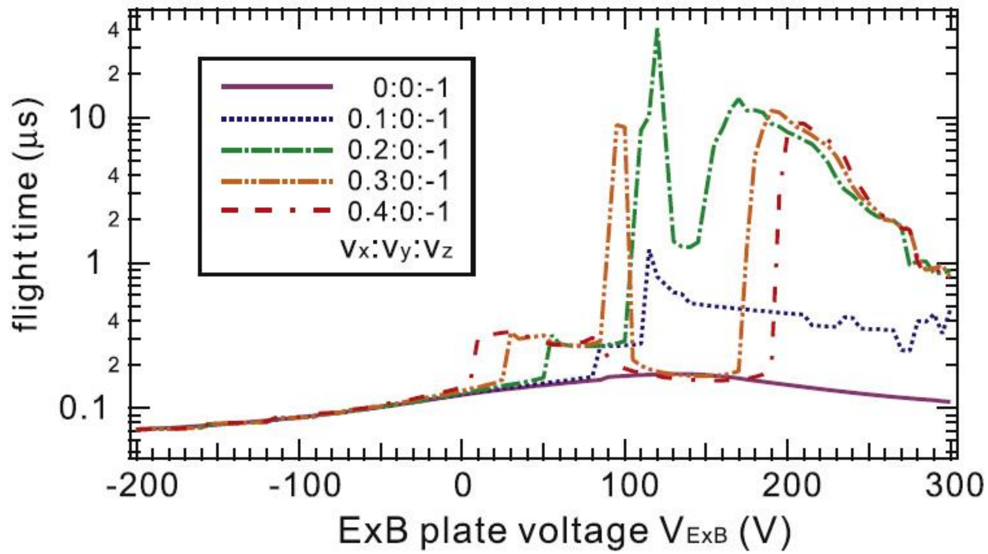
Positron current was integrated by a charge amplifier, giving intensity of beam intensity;

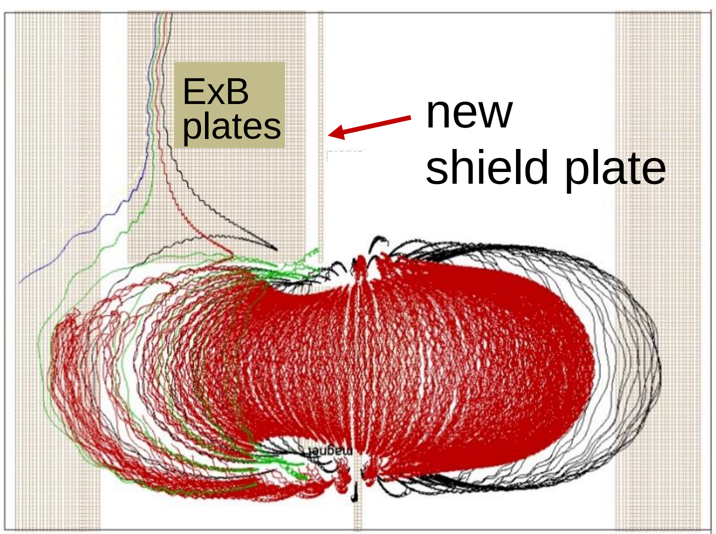
Total injection beam flux was 2.2e7/s at 5 eV

Injection scheme

Injection investigation by orbit analysis with SIMION







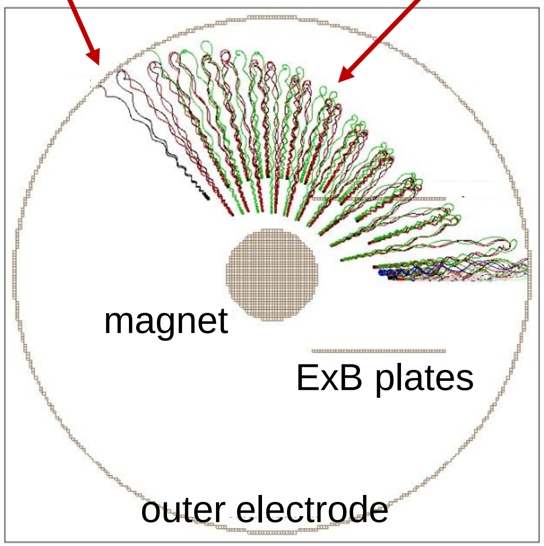
- single orbit analysis with different V_{ExB}
- injection is realized with wide V_{ExB} range
- finite v_{perp} is important for mirror trapping
- shield plate reduces error field, realizing long orbits in the trapping region

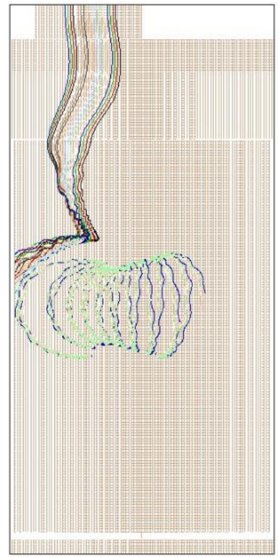
** H.Saitoh et al., New J. Physics 17, 103038 (2015)*

Electrostatic shield plate was installed in order to reduce error field between the ExB plates and (mainly) outer electrode

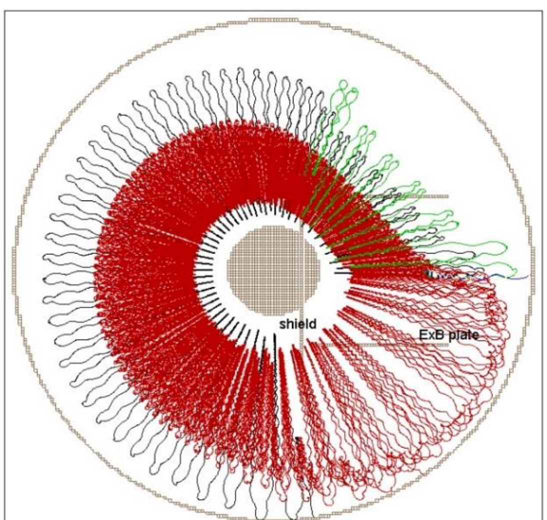
Loss on outer electrode

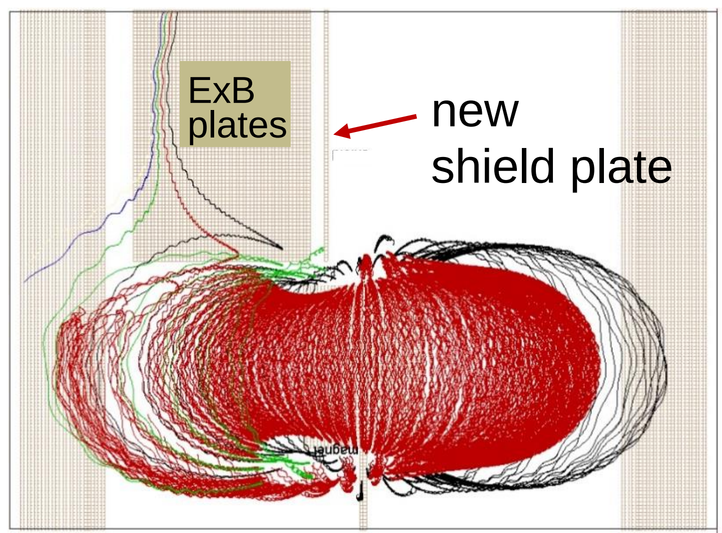
Slow expansion of orbit





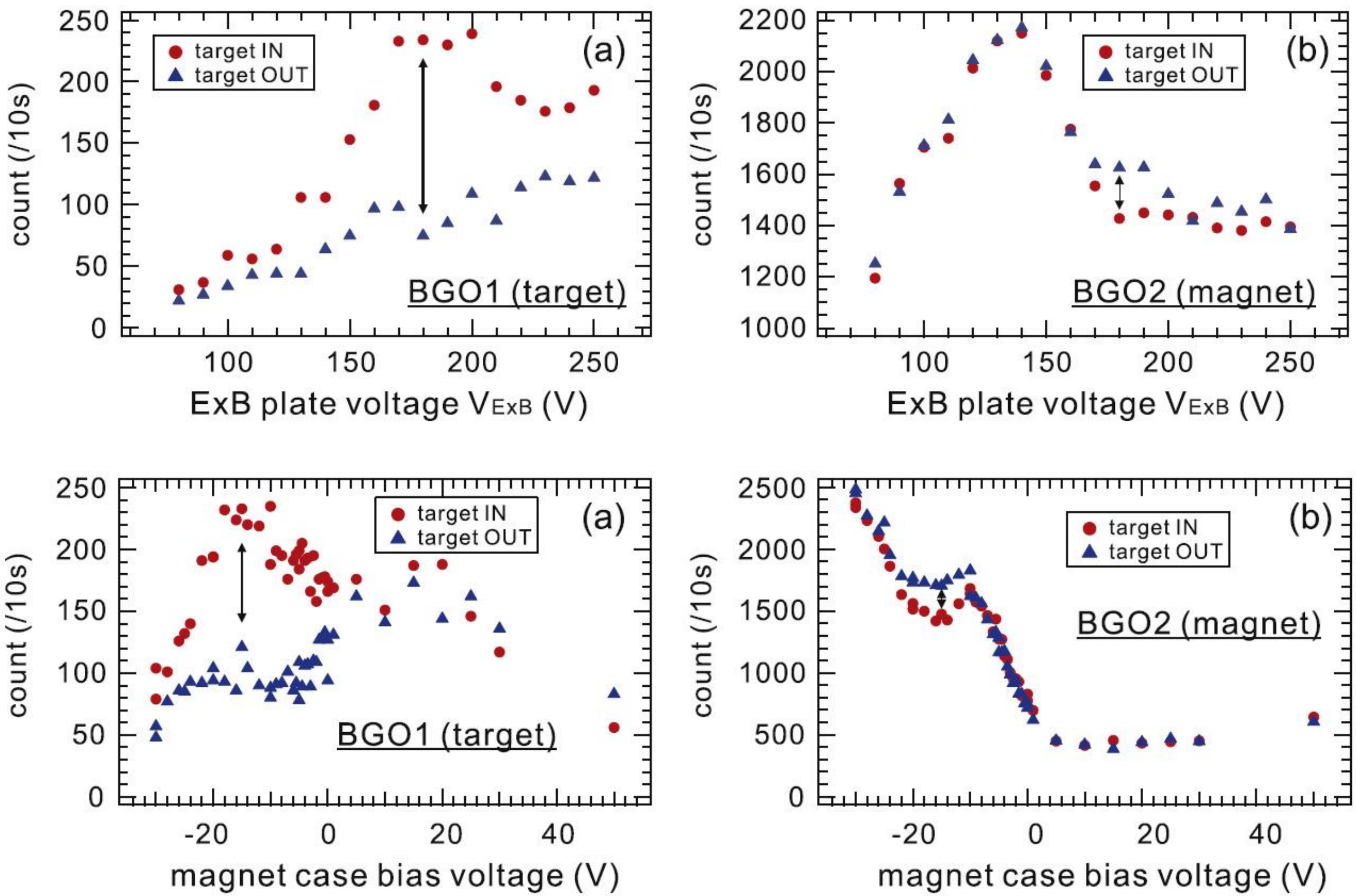
Particle loss is reduced by eliminating error fields using an electrostatic shield plate





new
shield plate

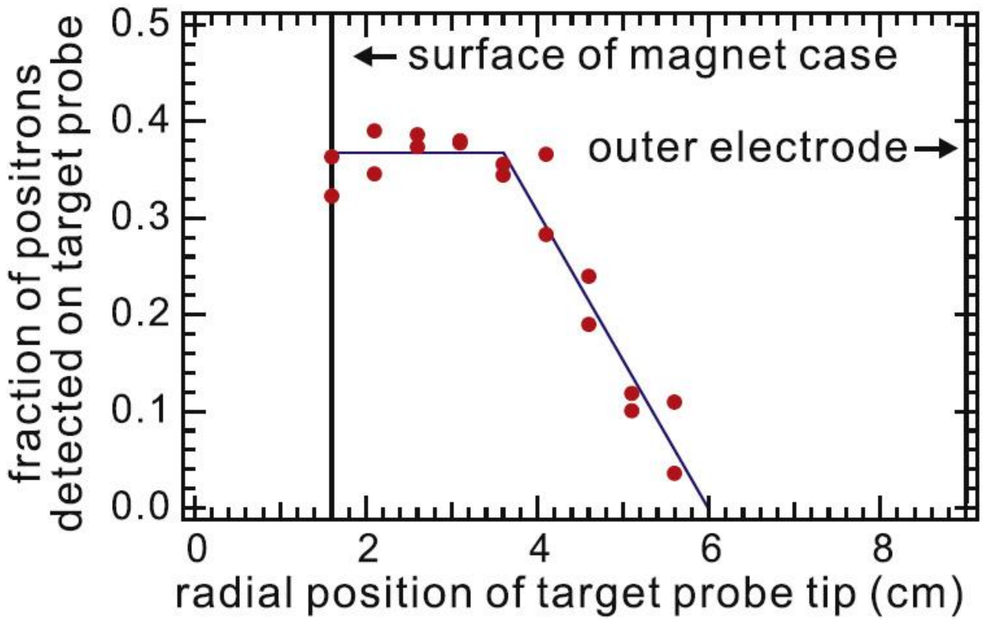
511 keV signals at target and magnet show evidence for injection and at least 180° toroidal rotation of NEPOMUC beam in a dipole field

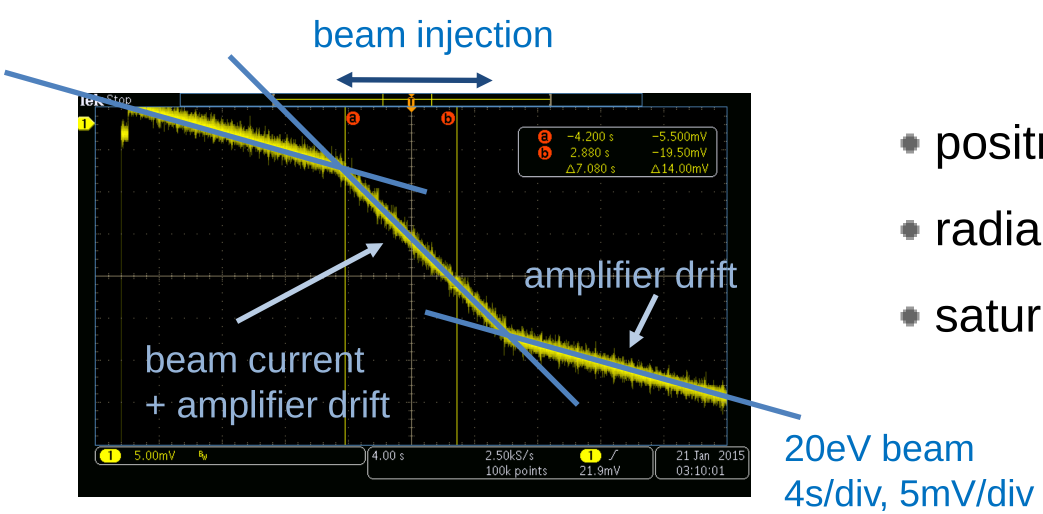


Important control parameters are

- steering coil currents: beam injection position
- V_{ExB}: formation of appropriate drift motion
- E_r: balancing grad-B/curvature and ExB drifts

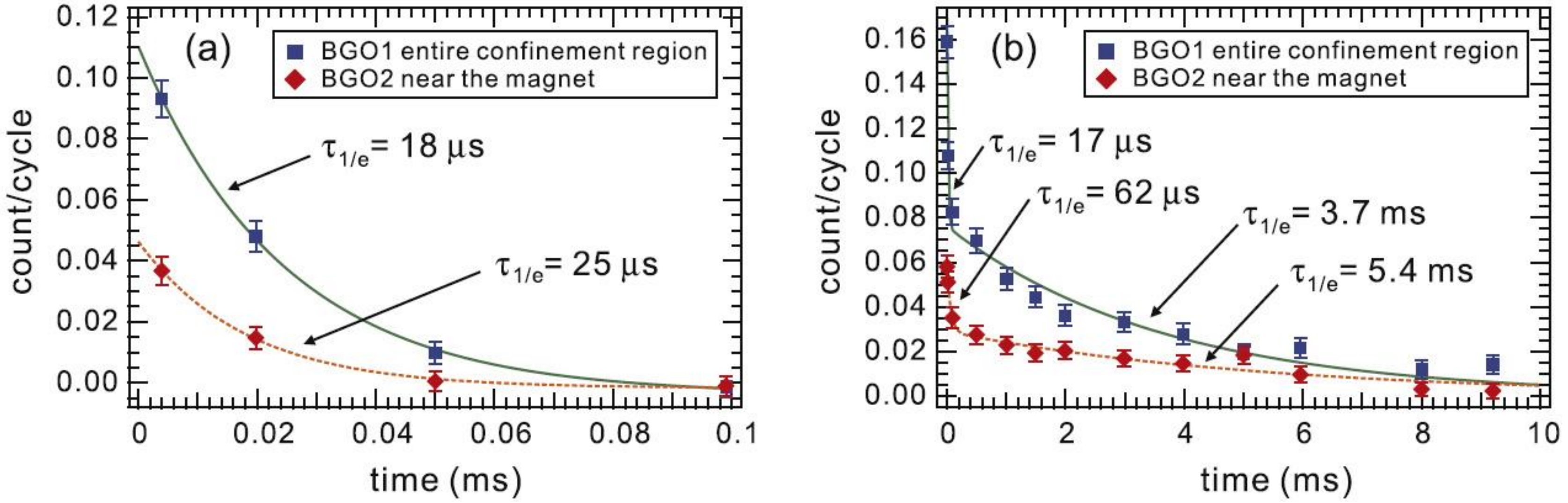
Injection efficiency was evaluated by direct measurements of positron current at insertable probe and target probe





- positron current measurements
- radially integrated signals are obtained
- saturated at 38% of injected beam current

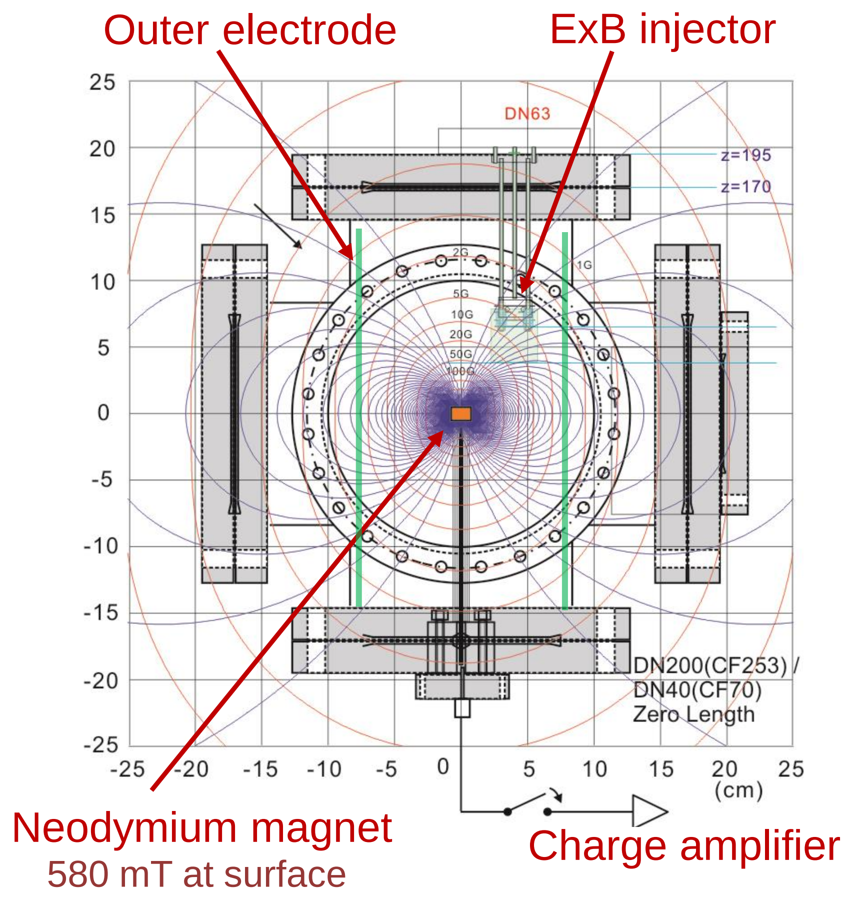
By reducing error electric field in trapping phase after injection phase, relatively long confinement (~ 1 ms) was observed

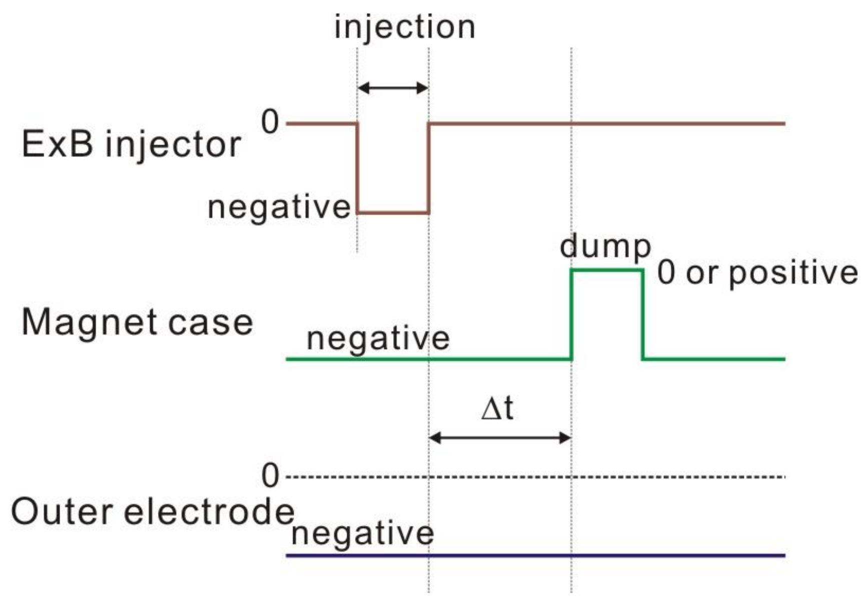


- beam was injected steadily (left) or turned off after injection (right)
- decay with two time constants, suggesting trapped and untrapped particles
- longer confinement times in stronger field region

Electron Exp.

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



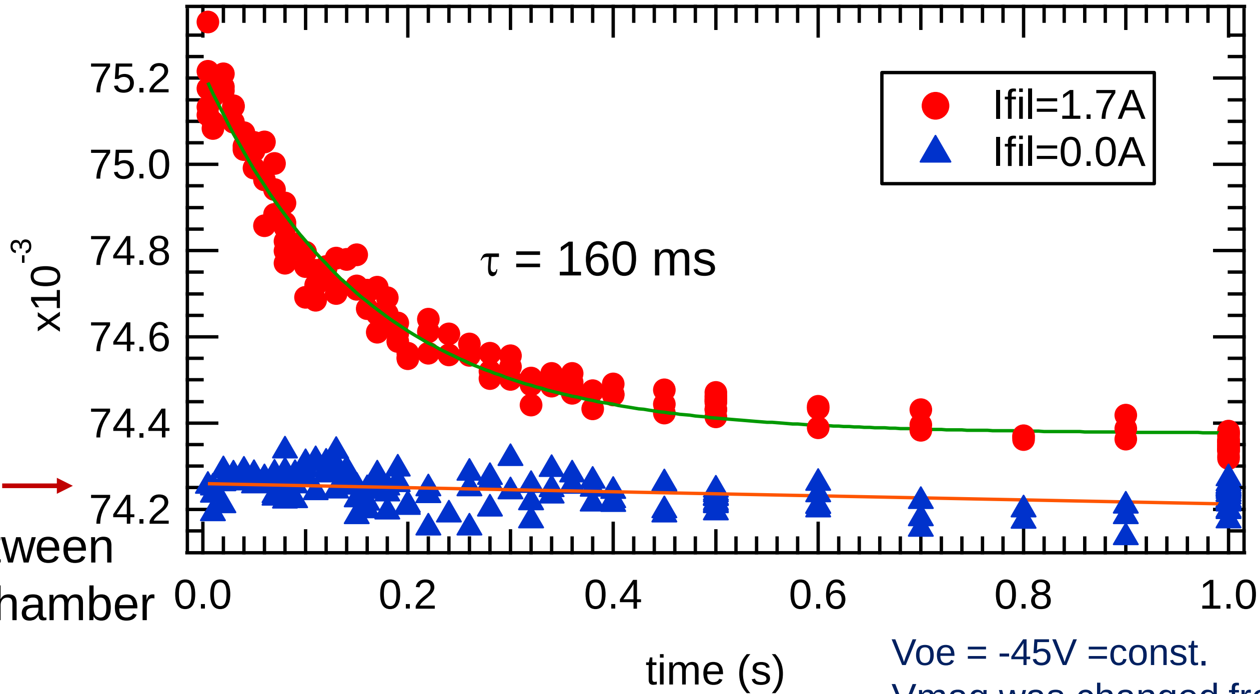


Injection, trap, and dump cycle

B ~ 100-5 mT in the confinement region

Field lines intersect the permanent magnet

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



offset due to capacitance between electrode and chamber

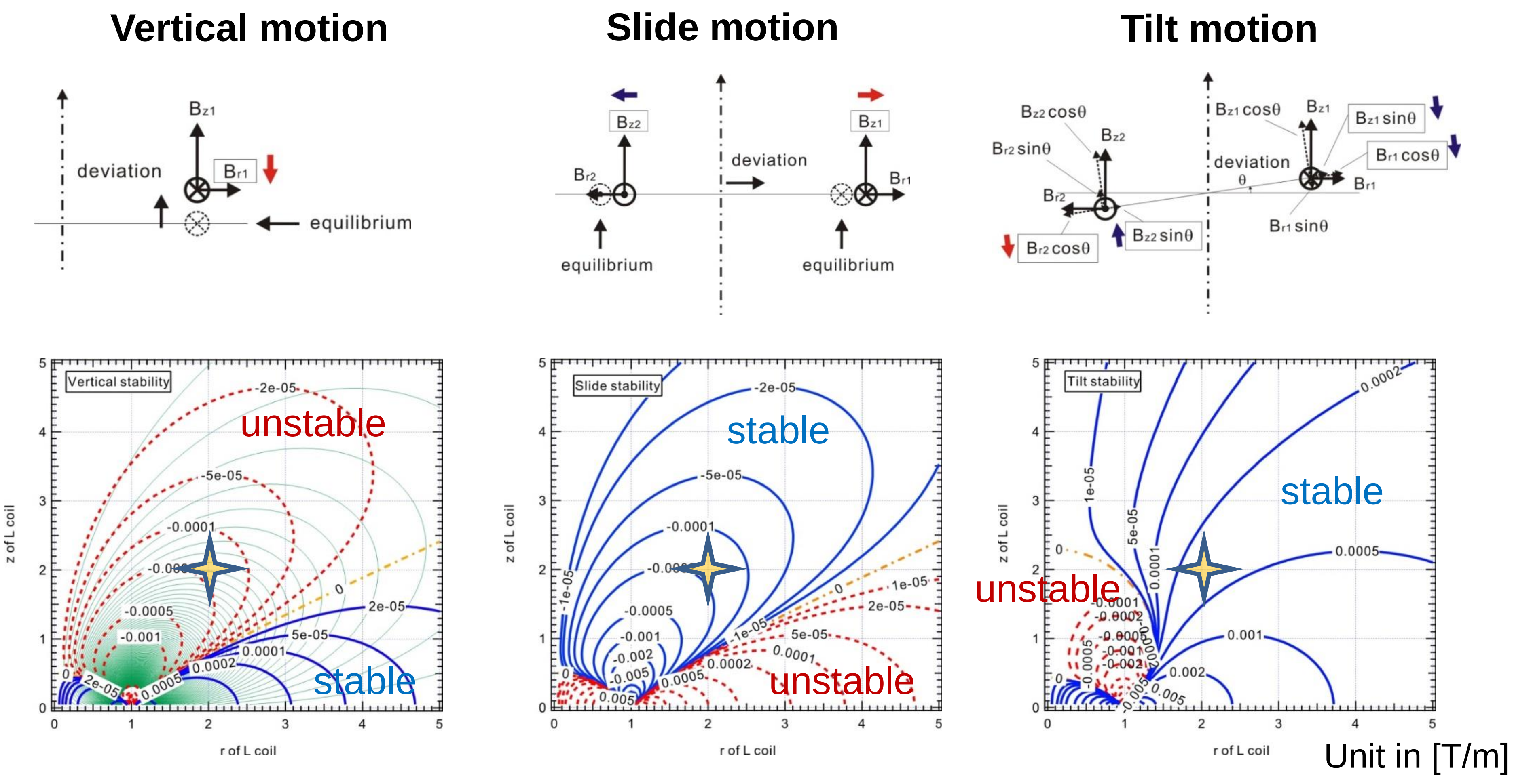
Voe = -45V =const.
Vmag was changed from -20V to 0V.

- 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).

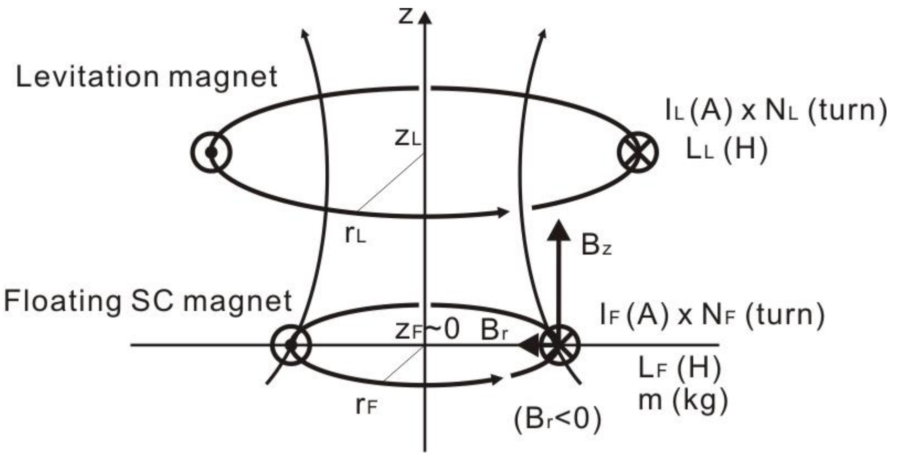
Levitated dipole

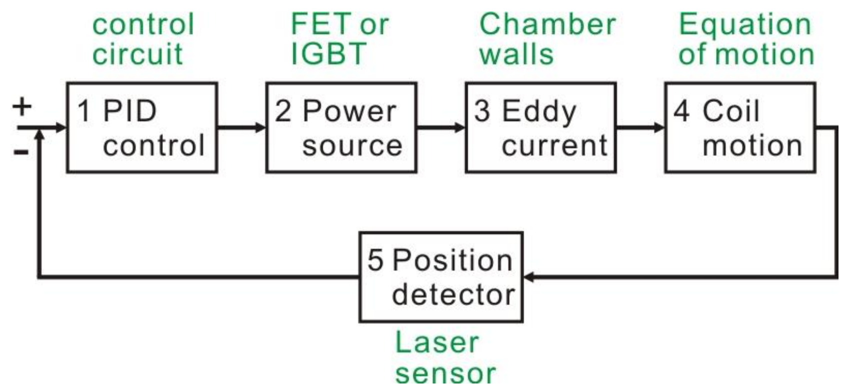
Magnet stability analysis for proposed parameters: Levitation control reduces to one dimensional stability problem



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

The stability condition of the levitation system is analyzed by a transfer function method





1-4: $$\frac{G}{1+GH}=\frac{\frac{\gamma P}{320}\left(1+\frac{D}{P}s\right)}{(1+s/100)^2(s^2/78.4-1)+\frac{\gamma P}{16}\left(1+\frac{D}{P}s\right)}.$$

1-5: $$\begin{aligned} G &= P\left(1+\frac{D}{P}s\right)\times\frac{\gamma}{(1+s/100)^2}\times\frac{1}{320}\frac{1}{s^2/78.4-1} \\ &= \frac{\gamma P}{320}\left(1+\frac{D}{P}s\right)\frac{1}{(1+s/100)^2(s^2/78.4-1)}. \end{aligned}$$

Because

$$1+GH=\frac{s^4}{7.84\times10^5}+\frac{s^3}{3920}+\frac{s^2}{79.0}+\left(\frac{\gamma D}{16}-0.02\right)s+\left(\frac{\gamma P}{16}-1\right),$$

the characteristic function of the system is given by

$$a_0s^4+a_1s^3+a_2s^2+a_3s+a_4=0,$$

Stability conditions from the Routh-Hurwitz stability criterion are

$$a_n>0.$$

$$\begin{vmatrix} a_1 & a_3 \\ a_0 & a_2 \end{vmatrix}=a_1a_2-a_0a_3>0.$$

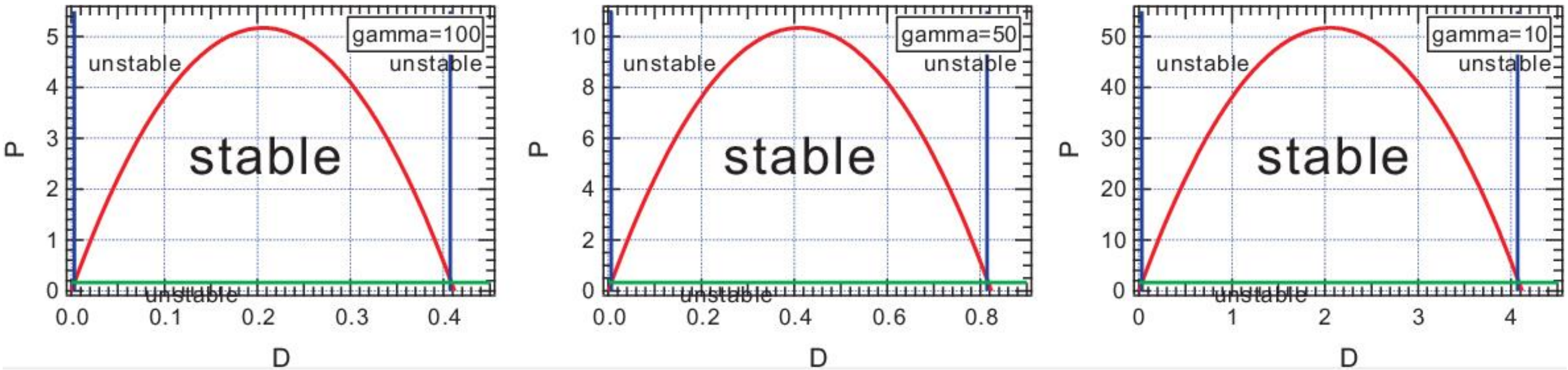
$$\begin{vmatrix} a_1 & a_3 & 0 \\ a_0 & a_2 & a_4 \\ 0 & a_1 & a_3 \end{vmatrix}=a_1a_2a_3-a_0a_3^2-a_1^2a_4>0.$$

$$0.32/\gamma<D<40.73/\gamma,$$

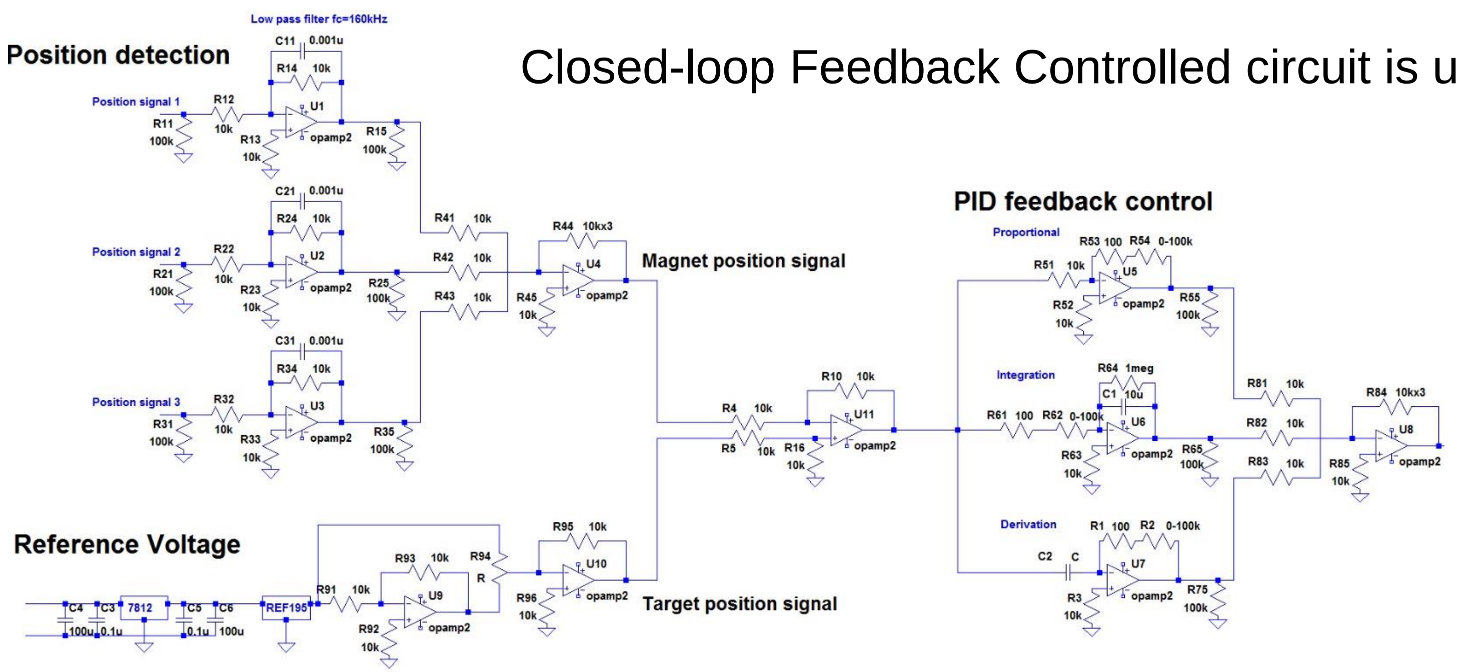
$$16/\gamma<P,$$

$$P<-1.22\gamma D^2+50.24D+0.0719/\gamma.$$

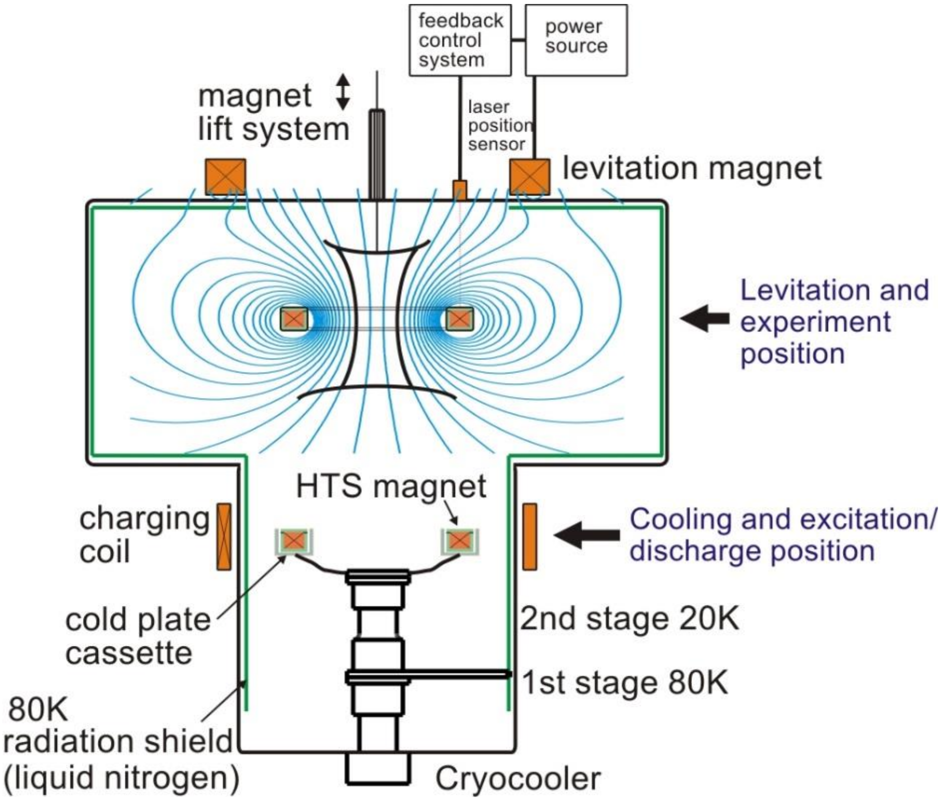
The proposed levitation system has a wide range of stability regions for P and D component of the feedback-controlled circuit



Closed-loop Feedback Controlled circuit is under design



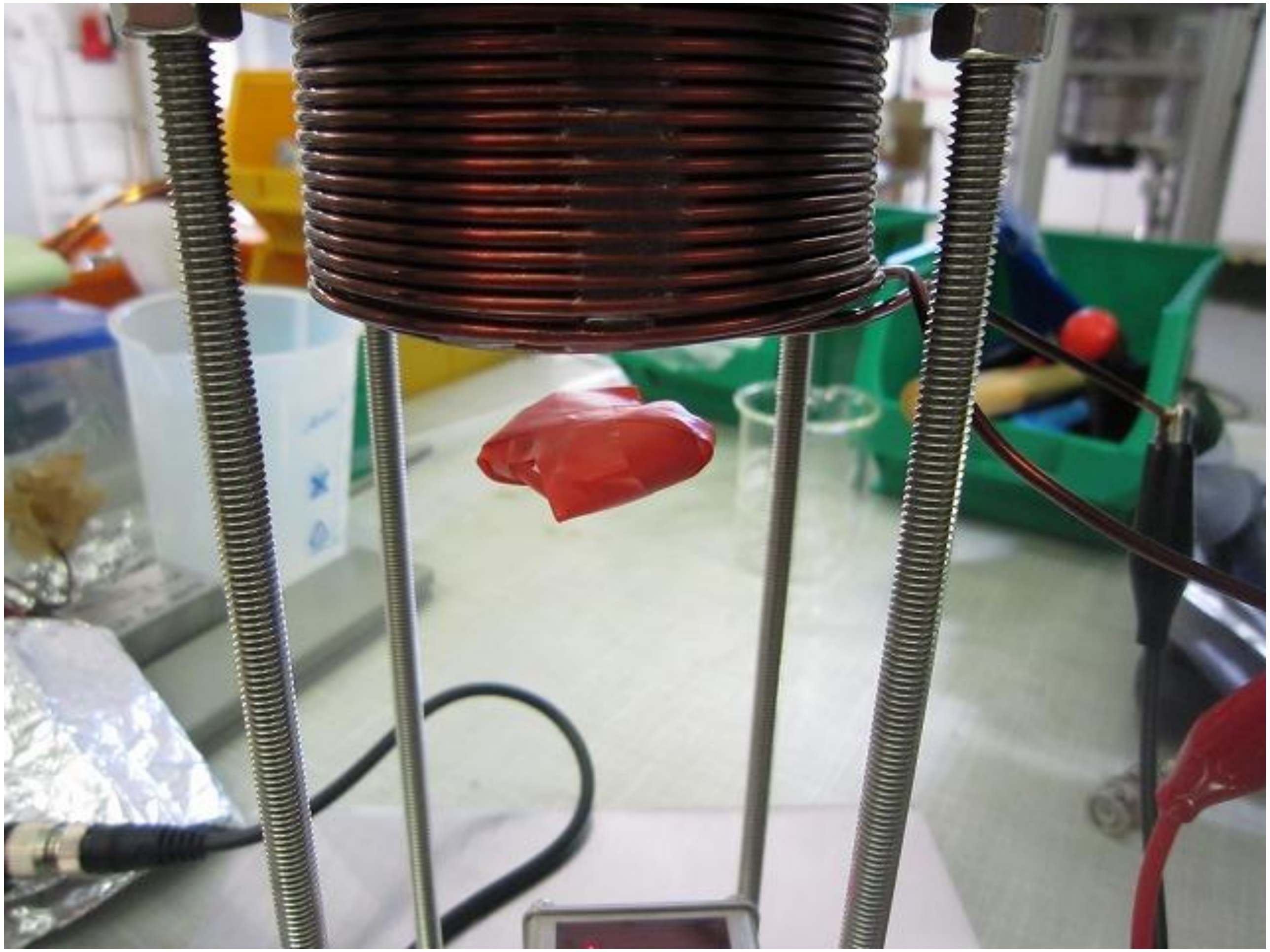
Construction Plan for SC APEX-D: Levitated operation of magnet is needed for the creation of dipole pair plasmas



	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

Levitation test experiment



- A permanent magnet was levitated using a feedback-controlled system