B-I15

Injection and manipulation of positron beam in a dipole magnetic field toward the creation of electron-positron pair plasmas

H. Saitoh[1,5], J. Horn-Stanja[1], E.V. Stenson[1], U. Hergenhahn[1], T. Sunn Pedersen[1,6], M. Singer[2], M. Dickmann[2], C. Hugenschmidt[2], M.R. Stoneking[3], and J.R. Danielson[4]

[1] Max Planck Institute for Plasma Physics (IPP), Greifswald and Garching, Germany,
[2] Technische Universität München (TUM), Garching, Germany,
[3] Lawrence University, Appleton, USA,
[4] University of California at San Diego, USA
[5] The University of Tokyo, Kashiwa, Japan,
[6] Ernst-Moritz-Arndt-Universität, Greifswald, Germany,

1st Asia-Pacific Conference on Plasma Physics, 20 September 2017, Chengdu, China

PAX (Positron Accumulation eXperiment)/APEX (A Positron-Electron eXperiment) collaboration for pair-plasma studies

Members and collaborators of PAX/APEX*

Max Planck Institute for Plasma Physics (IPP), DE
T. Sunn Pedersen
P. Helander
U. Hergenhahn
J. Horn-Stanja
H. Niemann
S. Nißl
N. Paschkowski
H. Saitoh
E.V. Stenson

Ernst Moritz Arndt Universität Greifswald, DE
L. Schweikhard
G.H. Marx

Lawrence University, US
M.R. Stoneking

Technische Universität München (TUM), DE
C. Hugenschmidt
M. Dickmann
C. Piochacz
M. Singer
S. Vohburger

University of California, San Diego
C.M. Surko
J.R. Danielson

NIFS, JP
N. Yanagi
T. Mito

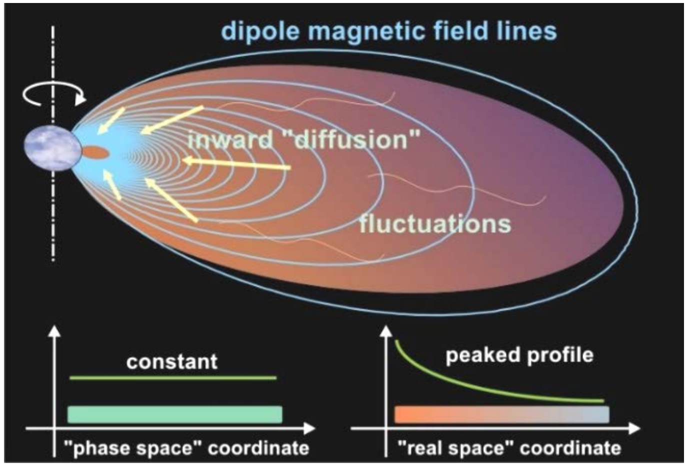
The University of Tokyo, JP
Mini-RT (Y. Ogawa) and RT-1 (Z. Yoshida)

*Work supported by European Research Council (T. Sunn Pedersen ERC-2016-ADG), Germany Research Society (DFG), Max Planck Institute for Plasma Physics, NIFS Collaboration Research Program, Japan Society for the Promotion of Science (JSPS), and the UCSD Foundation

Outline of the talk

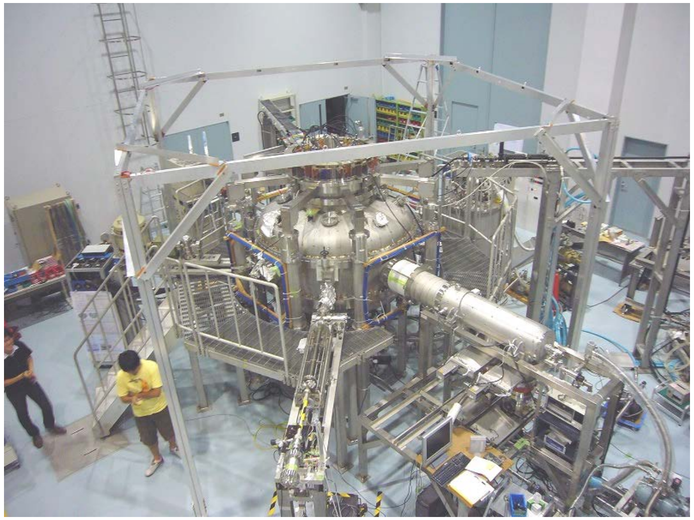
- Introduction:
  - laboratory plasma studies in a dipole magnetic field configuration
  - magnetically-confined electron-positron "pair plasmas"
- Overview of the Pair-Plasma project
  - past and ongoing efforts to create pair-plasmas in a laboratory
  - what is challenging? – and our solutions
  - grand scheme of the experiment and development status
- Positron experiments with a prototype dipole trap
  - high-efficiency injection of positron beam into dipole field
  - long time trapping of positrons
  - manipulation of positron orbits in the trap
- Summary and future work

Renewed interest on plasmas in a magnetic dipole field

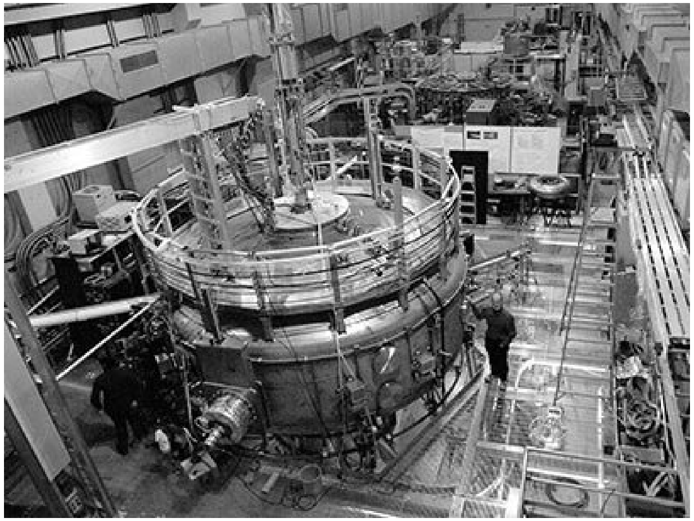


- High-β plasmas in Jovian magnetosphere
- Ultra high-β plasma (effects of flow: β>1)
- Application to D-D and D-^{3}He fusion
- Self-organization of plasmas in a strongly inhomogeneous dipole field:
  inward "diffusion" driven by fluctuations

1987 A. Hasegawa, Comm. Plasma Phys. Ctr. Fusion **11**, 147.
2013 Z. Yoshida+, Plasma Phys. Control. Fusion **55**, 014018.

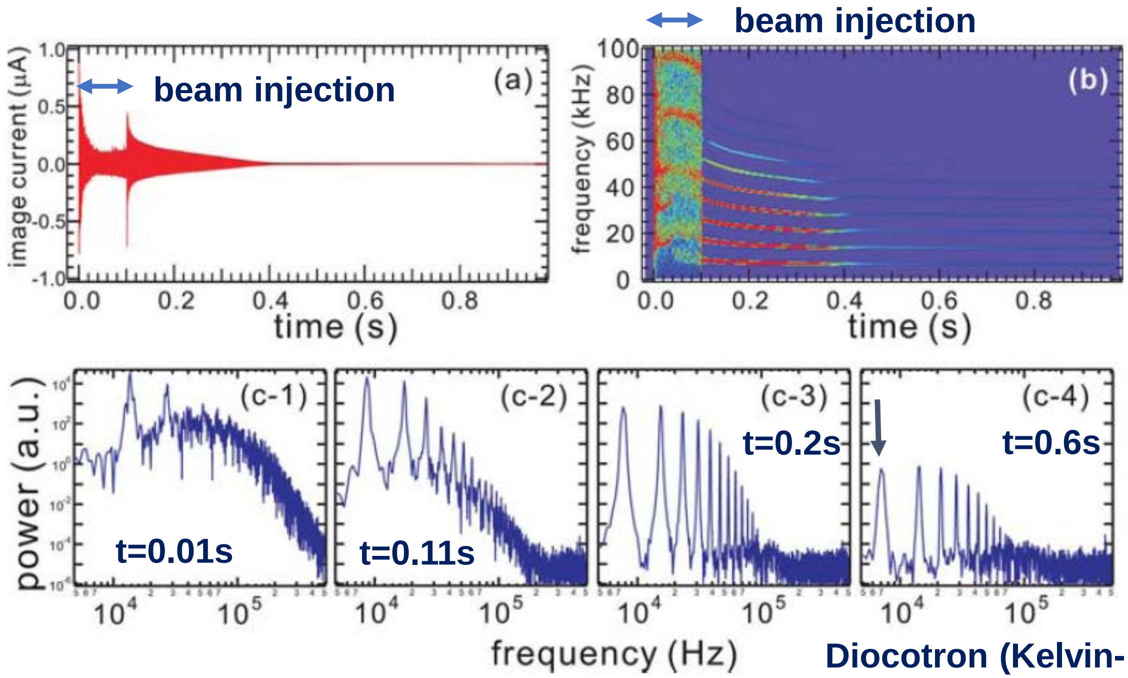


Tokyo: RT-1（Proto-RT->Mini-RT->...）
2010 Z. Yoshida+, Phys. Rev. Lett. **88**, 095001.
S-I3 M. Nishiura

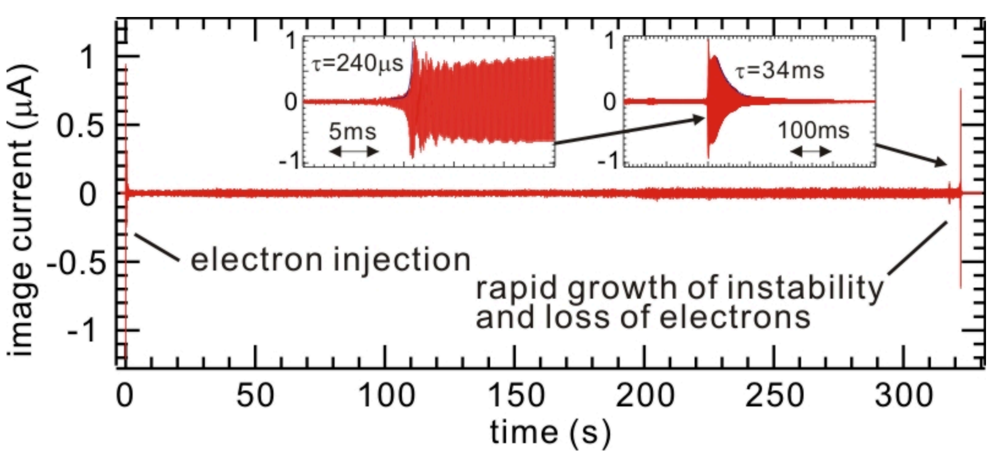


MIT/Columbia: Levitated Dipole eXperiment
2010 A.C. Boxer+, Nature Phys. **6**, 207.
S-I2 M. Mauel

Toroidal dipole field geometry enables excellent confinement for various plasmas at any non-neutrality



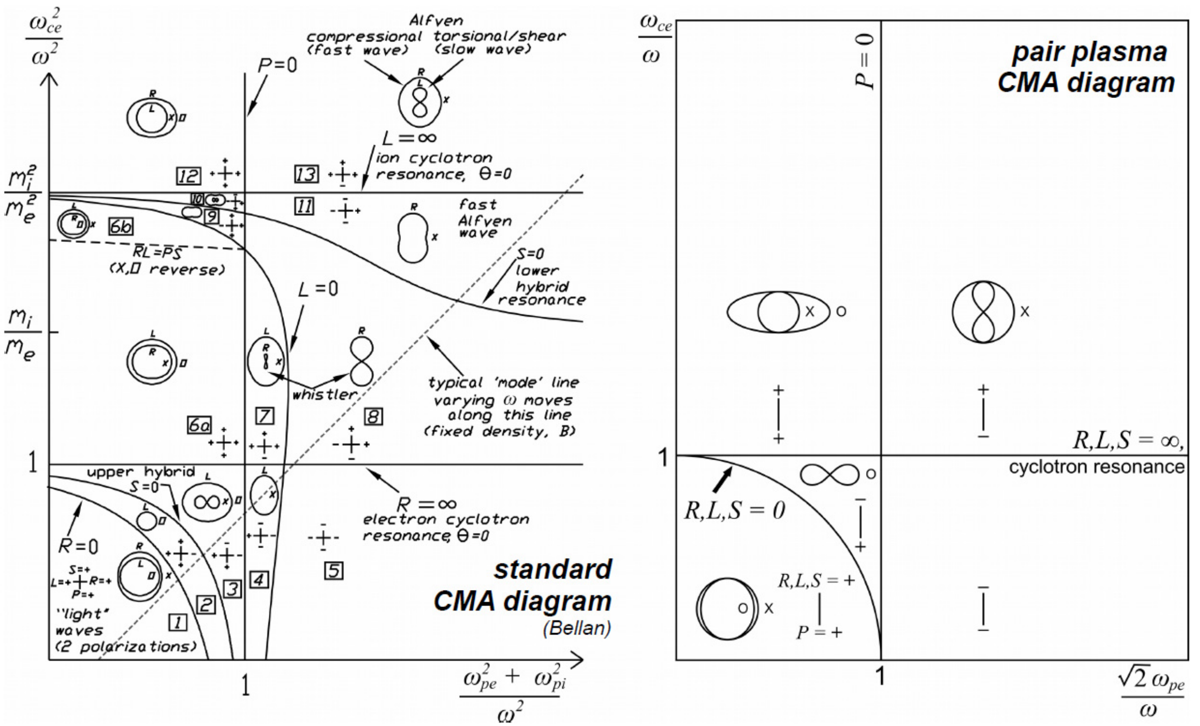
Diocotron (Kelvin-Helmholtz) mode



- Confinement of both fusion-oriented high-temperature plasmas* and non-neutral plasmas**
- Measurements on the fluctuations of pure electron plasmas clearly demonstrated:
  - self-organization of stable equilibrium structure
  - very long (>300s) trapping of electron plasmas
- In principle, we can confine electrons and positrons simultaneously as a plasma in a dipole magnetic field

*2015 M. Nishiura+, Nucl. Fusion **55**, 053019.
2010 Z. Yoshida+, Phys. Rev. Lett. **88, 095001.

Motivations for studies on electron-positron pair-plasmas



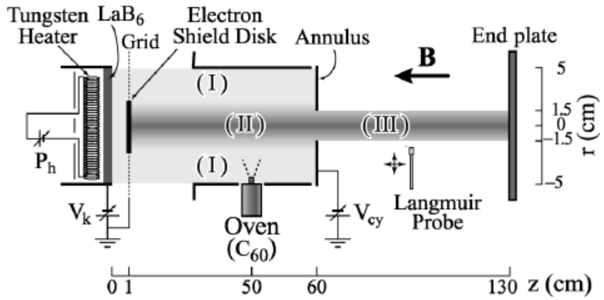
2017 E.V. Stenson+.

- Unique behaviors as pair-plasmas consisting of equal-mass particles*
  - Remarkable stability** and wave propagation*** properties
  - Potential contribution to understand astrophysical phenomena
- Application of many positrons, clusters, Positronium Bose Einstein Condensation
- A lot of theoretical and numerical studies, but very few experiments

*2012 T. Sunn Pedersen+, New J. Physics **14**, 035010; 2017 E.V. Stenson+, J. Plasma Phys. **83**, 595830106.
2014 P. Helander, PRL **113, 135003. ***1978 V. Tsytovich & C. B. Wharton, Comm. Plasma Phys. Cntr. Phys. **4**, 91.

History and state of the art of pair-plasma experiments

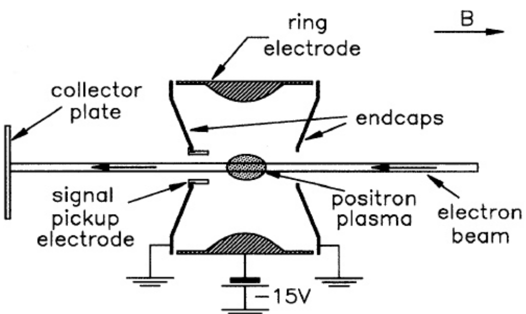
- Weakly-ionized pair-plasmas were generated with fullerene (C60+/C60-)



- electron attachment -> C60-
- electron impact ionization -> C60+
- separated with electrons by r_L difference

2003 W. Oohara and R. Hatakeyama, PRL **91**, 205005.

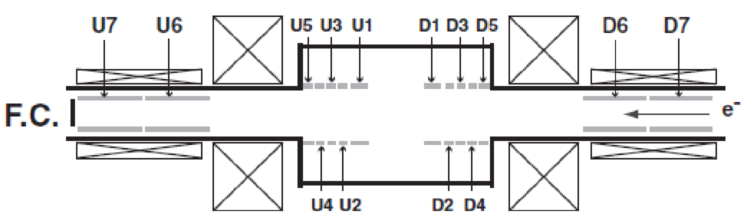
- Positron plasma / electron beam experiments in linear Penning traps

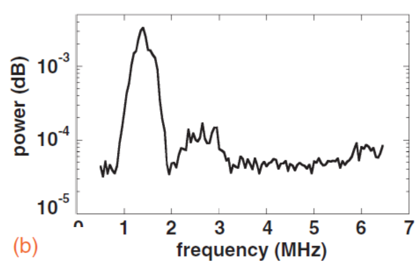


- first interaction of electrons and positrons
- two stream instability observed

1995 G. Greaves and C.M. Surko, PRL **75**, 3846.

- Pure positron / electron confinement in magnetic mirror traps





- trapping of ~ 40 ms for e+/e-
- plasma mode detection

1960 G. Gibson+, PRL **5**, 141.
2017 Higaki+, New J. Phys. **19**, 023016.

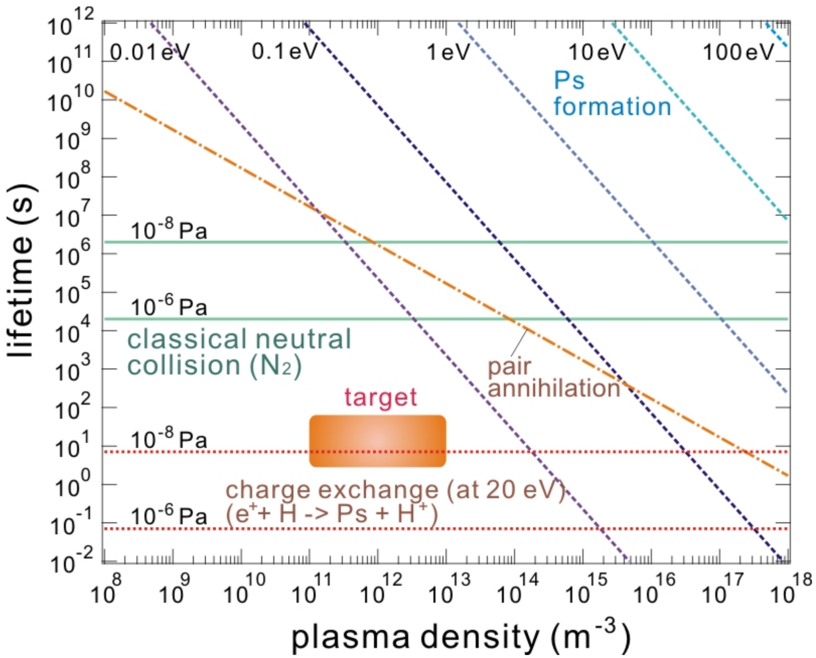
- High-density relativistic electron-positron pairs were created using intense laser

2015 G. Sarri+, Nat. Commun. **6**, 6747.

What is challenging?

- In spite of long history of intensive studies, fully-ionized, perfectly two-component, magnetically-confined pair-plasmas have never been created

  - linear traps: basically only for single-component plasmas, long trapping in mirror?
  - C60+/C60-: low ionization rate, contains electron component, large mass
  - laser: not magnetically-confined at present, Debye length > scale size



Target parameters and lifetimes of e+ and e+/e- set by several processes

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

  Small Debye length is needed in order to observe collective phenomena

- A large number of cold positrons must be trapped with electrons simultaneously

  1. trapping of e+/e- as plasmas

     this is not realized in linear traps

  2. total e+ number of N ~ 10^{10} is needed

     cf) isotope: ~10^6 e+/s , linac: ~10^7 e+/s

How can we solve the problems? 1
ideas from fusion plasmas: toroidal magnetic configurations

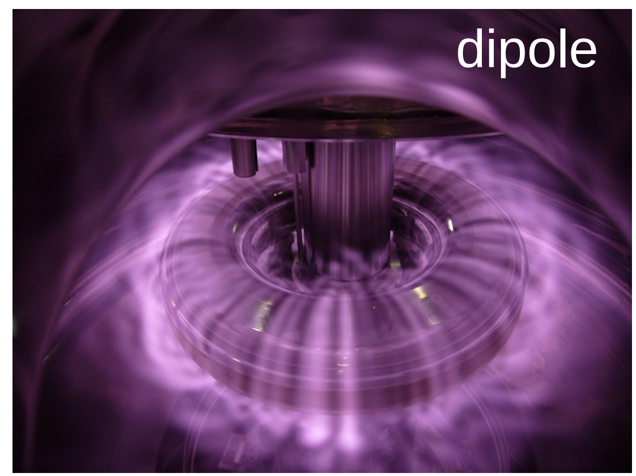
- Linear traps: standard traps for non-neutral plasmas (Penning-Malmberg trap)
  - Plugging electric fields are required along magnetic field lines

➡ Positive and negative particles are not simultaneously trapped as a plasma

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

Steady-state closed magnetic surfaces are generated by interlocked current coils

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



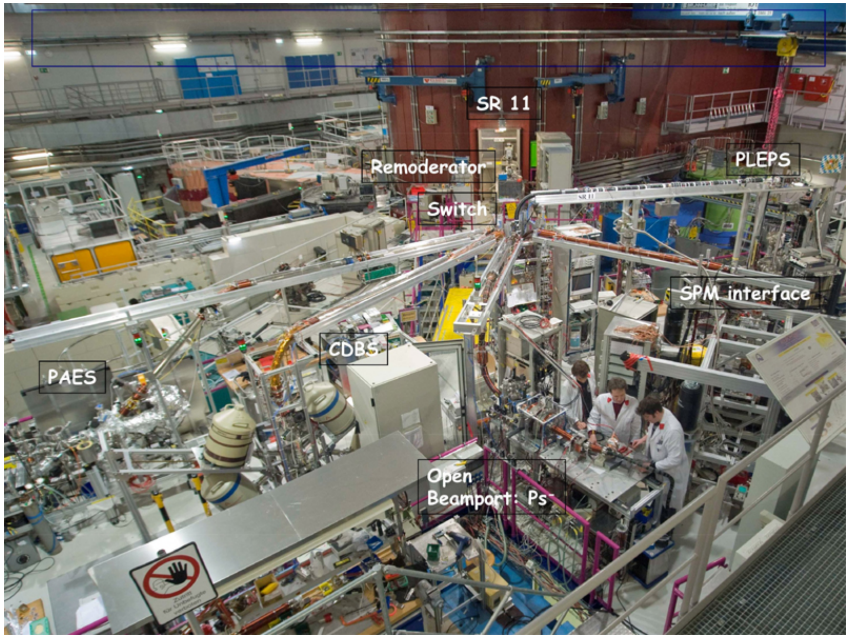
"Inward diffusion" and self-organization in a SC levitated dipole experiment (300 s of e- trapping)**

2010 Z. Yoshida+ PRL **88**, 095001.

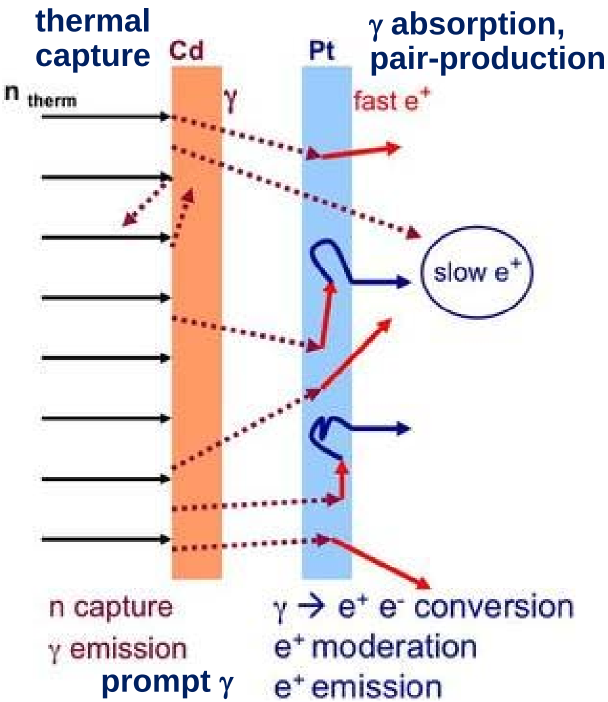
How can we solve the problems? 2
world's strongest slow positron source, NEPOMUC

NEPOMUC (NEutron-induced POsitron source MUniCh)*

- FRM II @Technische Universität München （20 MW neutron source reactor)
- DC moderated beams, 10^9 /s at 1 keV, 10^7 /s at 20 eV, still under improvement



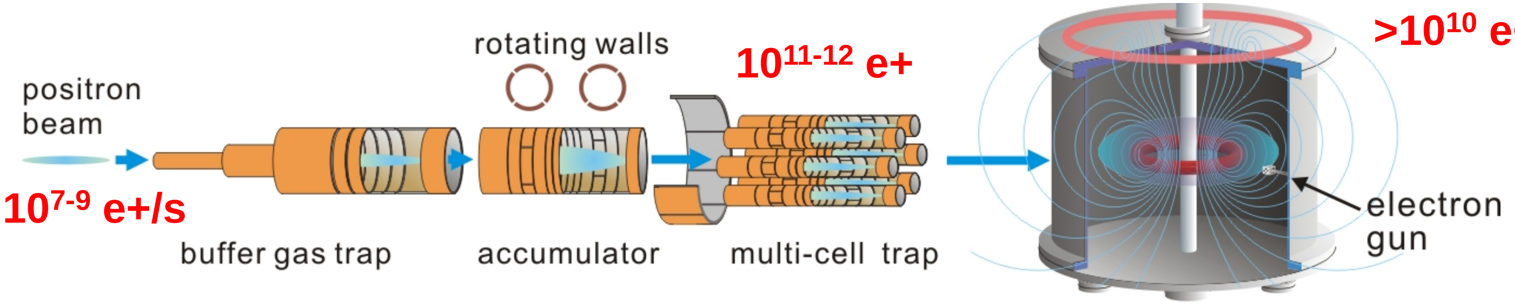
NEPOMUC Hall at FRM II, Garching b. München



*2012 C. Hugenschmidt+, New J. Phys. **14**, 055027.

MLZ Heinz Maier-Leibnitz Zentrum
TUM TECHNISCHE UNIVERSITÄT MÜNCHEN

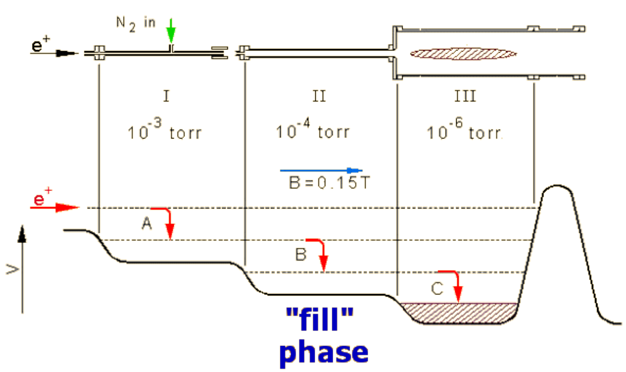
Overview of the PAX/APEX experiment plan: Combination of NEPOMUC, accumulator, and toroidal trap




stellarator

NEPOMUC   positron accumulator (PAX)   levitated dipole (APEX-D)   (APEX-S)

- **P**ositron **A**ccumulation e**X**periment
  - accumulation of 10^{11-12} e+
  - bridge between NEPOMUC and APEX
  - cooled in buffer gas trap with N_2^*



  - then e+ stored in multi-cell trap*

- **A P**ositron-**E**lectron e**X**periment
  - simultaneous trapping of e+ and e-
  - we have started with dipole (APEX-D)
  - particle injection is not straightforward

- prototype device with a permanent magnet
- closed field lines with SC levitated dipole

*2015 J.R. Danielson, D.H.E. Dubin, R.G. Greaves, and C.M. Surko, Rev. Mod. Phys. **87**, 247.

Roadmap of PAX/APEX projects and development status

PAX (IPP Greifswald/Garching)

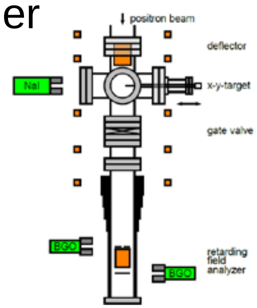
- First Point Scientific system
- high field trap and electrodes

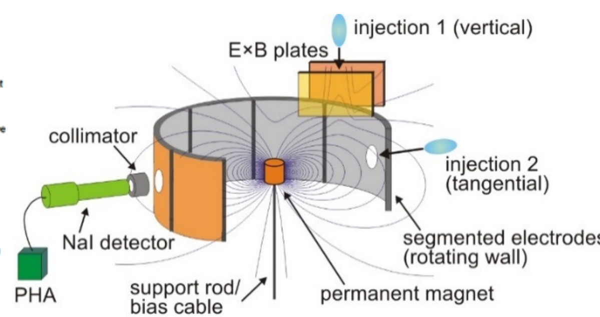
2012-

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

APEX (MLZ NEPOMUC / IPP Garching) 2013-

- Retarding Field Analyzer
- prototype dipole trap

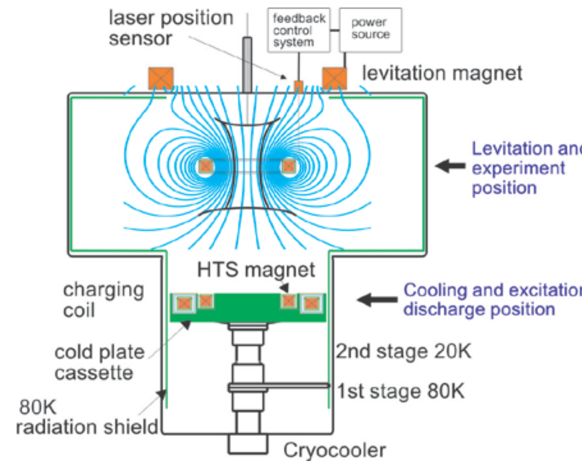




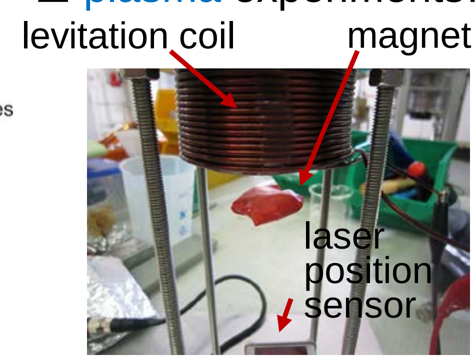
☑ beam energy profiles measurements
☑ injection and trapping studies
☐ design of SC dipole/stellarator

SC toroidal traps 2018-

- APEX-D and APEX-S
- closed field lines
- development work underway



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



Feedback levitation of magnet

Efficient injection scheme and stable trapping of positrons in are essential for pair-plasma production in a toroidal dipole geometry

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

- Assuming that the volume of confinement region V ~ 10L, we need to trap at very least N ~ 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

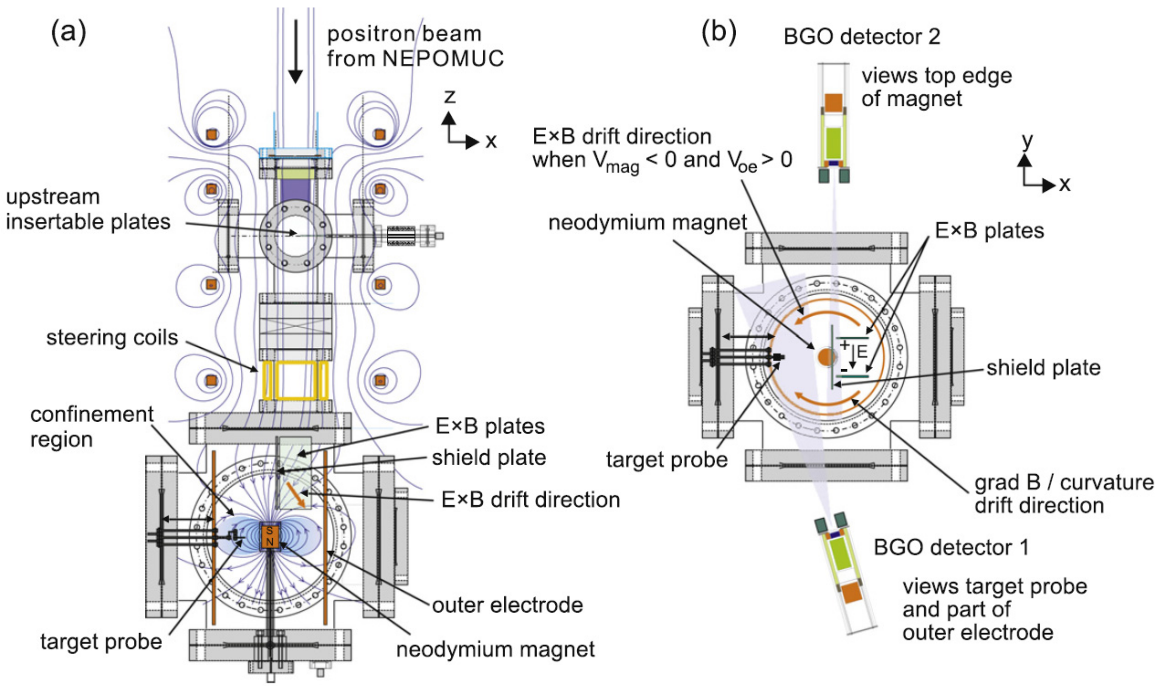
  • Very efficient (close to 100%) injection into closed toroidal geometries

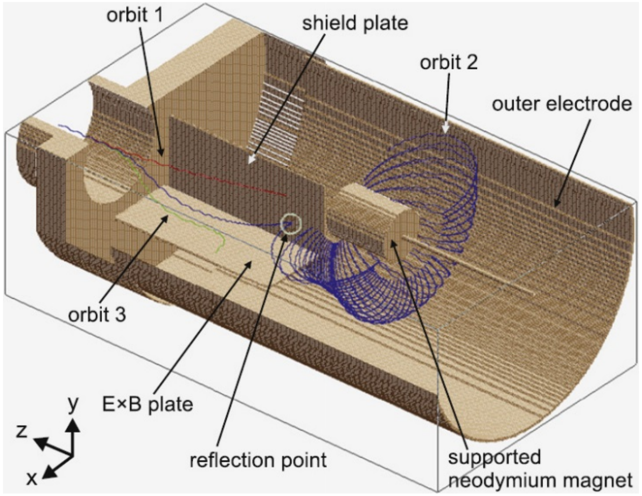
- Excellent confinement properties of dipole is due to its axisymmetry

  ➡ for efficient injection of particles, we need to destroy this symmetry

We started positron injection and trapping experiments with a prototype dipole field trap with a permanent magnet

2016 H. Saitoh+, New J. Phys. **17**, 103038.

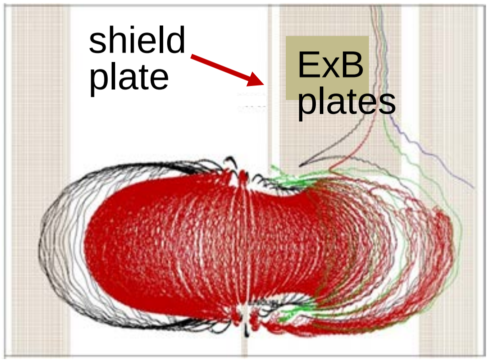




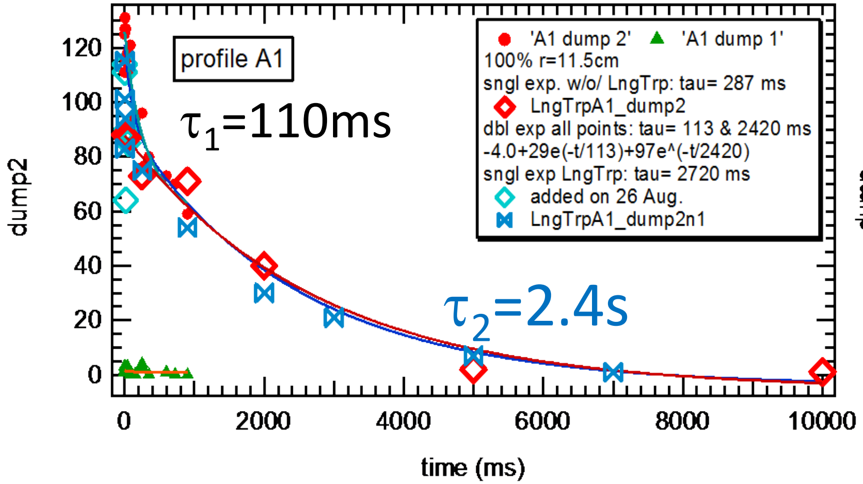
- A permanent magnet device with
  - ExB and shield plates, steering coils
  - magnet and outer wall electrodes (E_r)
- Diagnostics
  - BGO scintillator-PMTs to detect 511 keV γ-ray
  - two target probes + current amplifier
- ExB drift injection was numerically optimized

Loss-less injection and very long trapping (> 1s) of positrons were realized in recent beamtimes

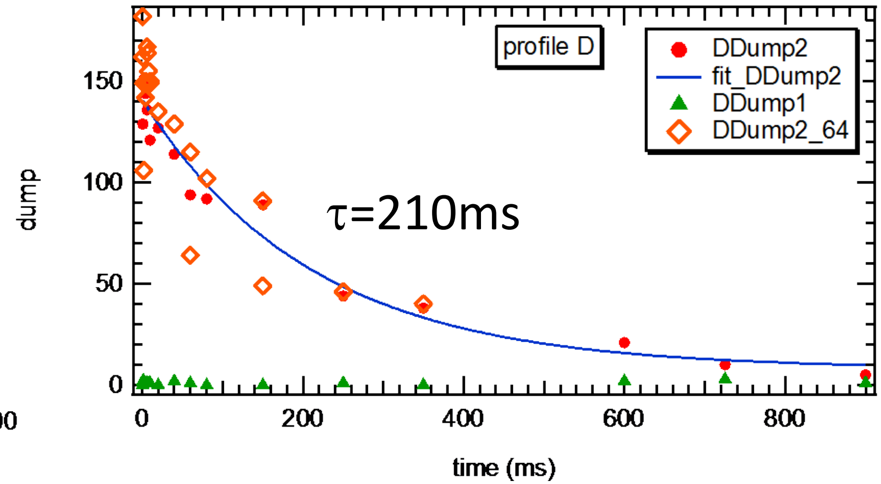
- Complete (close to 100%) injection efficiency by optimized electrode bias with minimizing
  - loss cone toward the magnet
  - loss toward the outer electrodes
- After injection, positrons were trapped for more than 1s in the dipole field



Typical injection orbits of positron into the dipole field trap



Trapping with gating the top electrode voltage



Without gating: no long-lived component

- multiple decay constants of ~100ms and 2-3s in the optimized conditions
- reduction of error fields (bias voltage etc.) and symmetry is very important

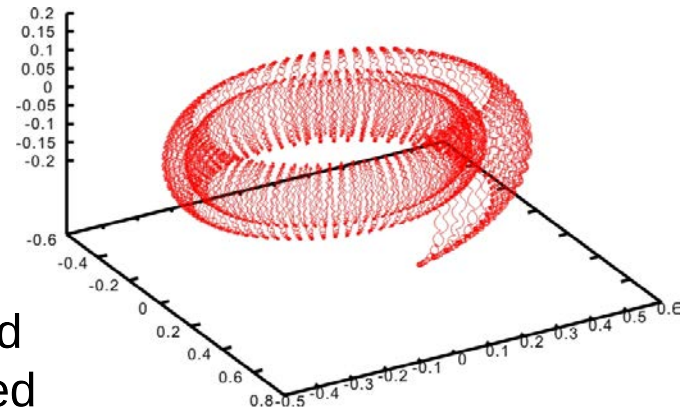
Motivations for the RW experiments in the dipole field

- Add another freedom to the injection scheme
  - sinusoidal voltages on RW electrodes

    E_θ moves particle in the radial direction, resulting in orbit modulation and radial oscillation of beam

  - toward the high-density states of positrons

    by applying RW voltages for a short time on pulsed beam, radial compression of beam orbits is realized

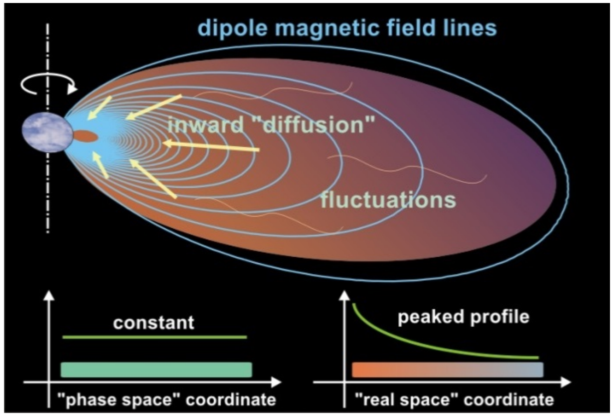


- Inward transport of particles and self-organization of structures
  - "diffusion" in the magnetic coordinate

    corresponds to peaked density profile in strong magnetic field region, in the real space

  - studies on fluctuation induced transport

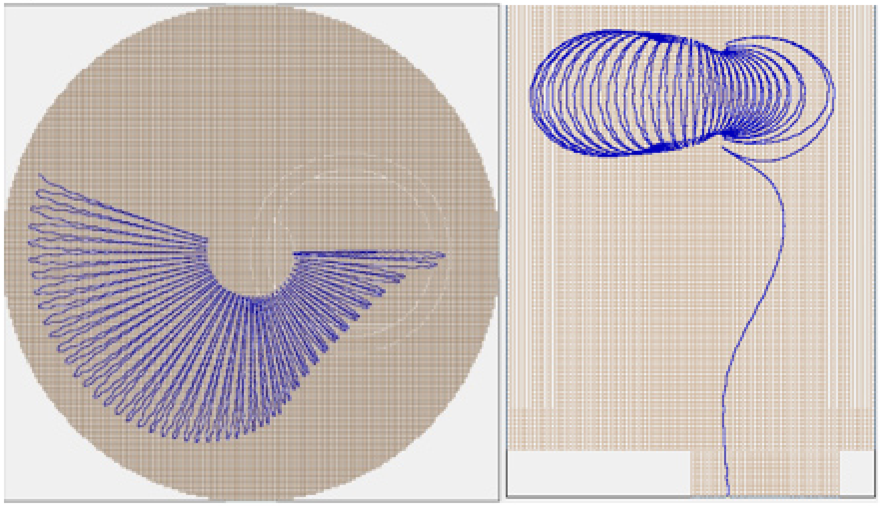
    precise measurements with annihilation γ-rays for phenomena in dipole plasmas



Interaction of fast RW waves with positron orbit

- high frequency RF of 100 MHz (~ gyromotion frequency)

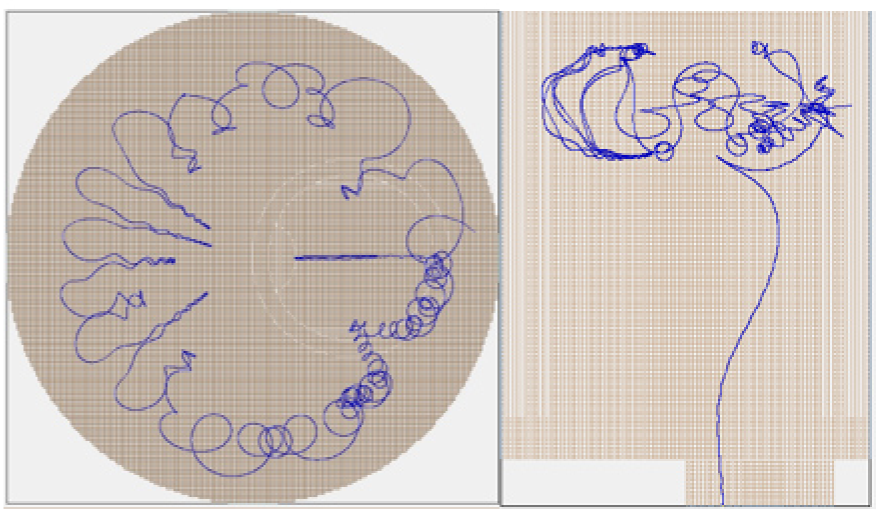
120, 100, 400, 160, -160, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 5, -0.10811487166967, -0.17674489577929, -1
x,y,z,Vexb,-Vexb,oe1,oe2,oe3,oe4,oe5,oe6,oe7,oe8,oetop,Vmag,Te,vx,vy,vz



without RW

- injection and 180-deg rotation

Voe=0V



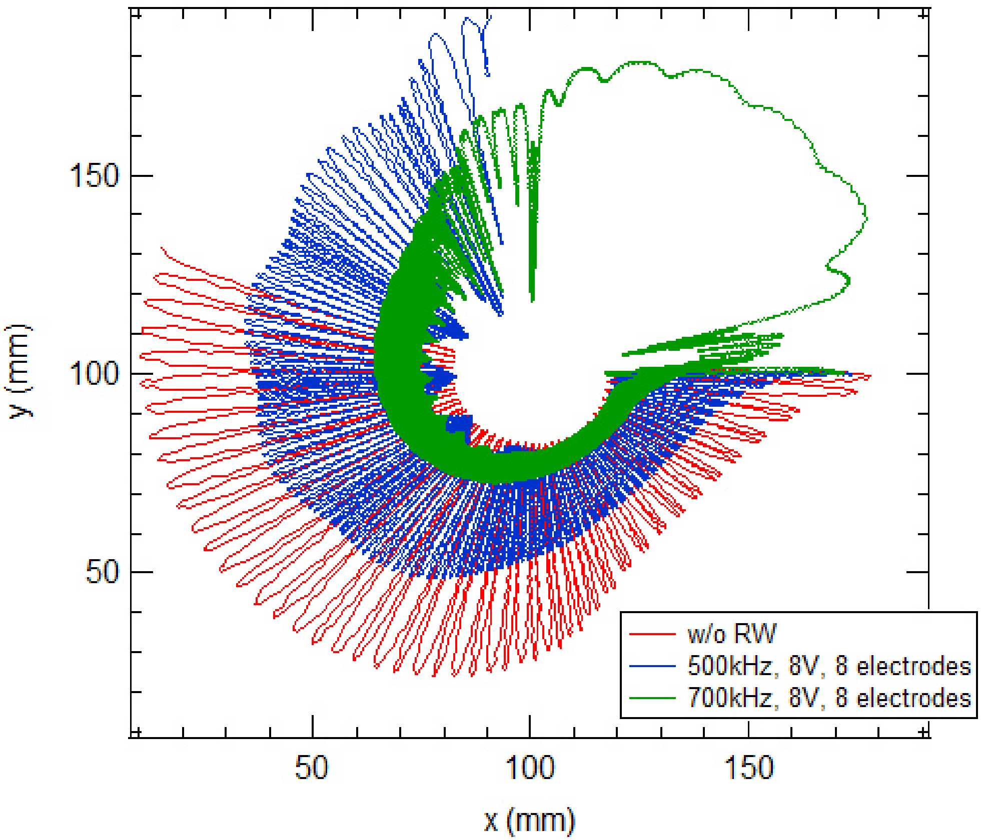
with RW

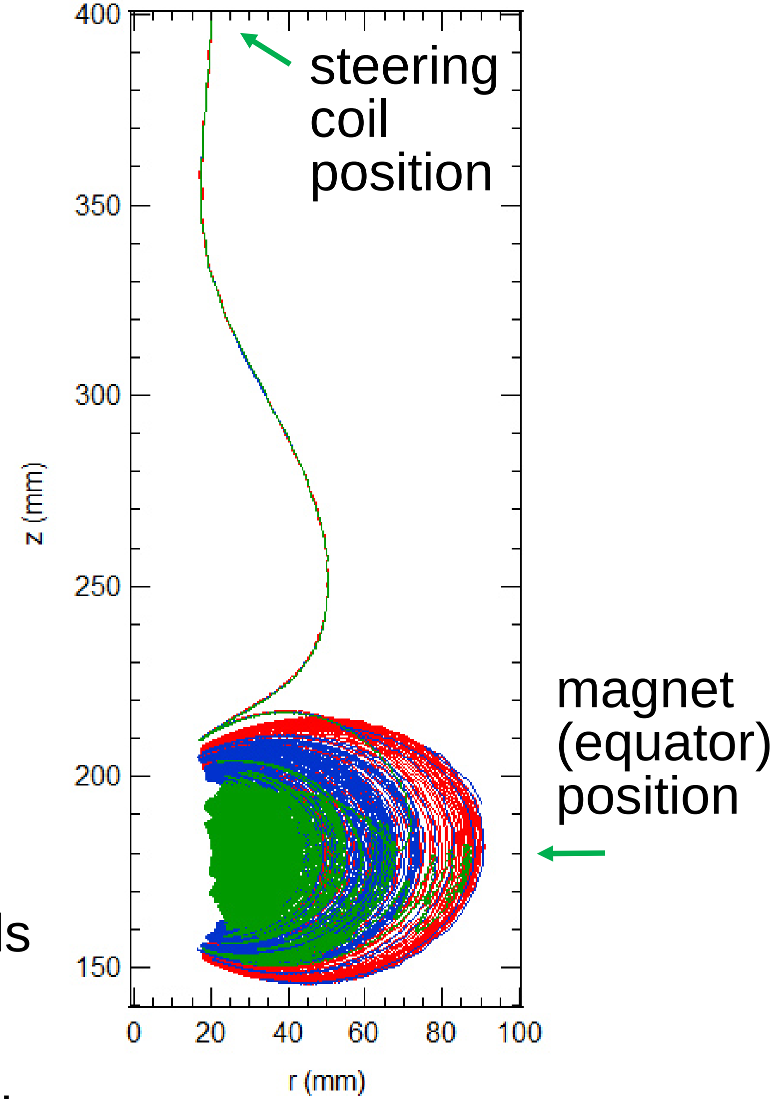
- decoupled with injection
- there are effects, but
- no guiding center transport

100MHz(1e8) 200V rotating E

Interaction of slow (~toroidal circulation) RW with positron orbit

- medium frequency range of ~1MHz (~ vertical bounce frequency)

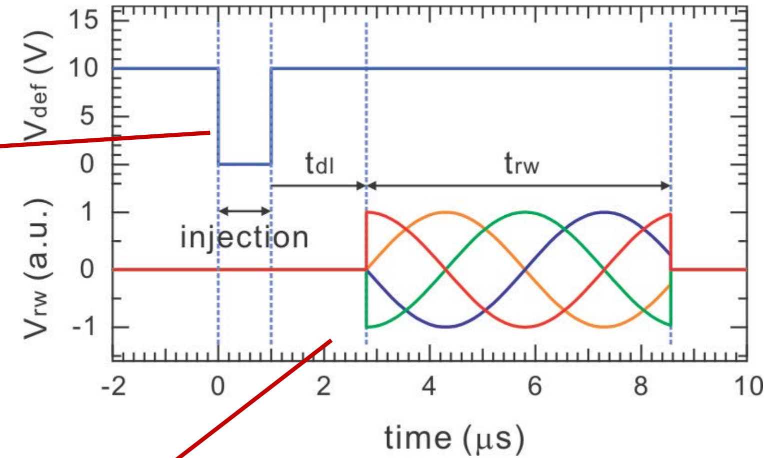


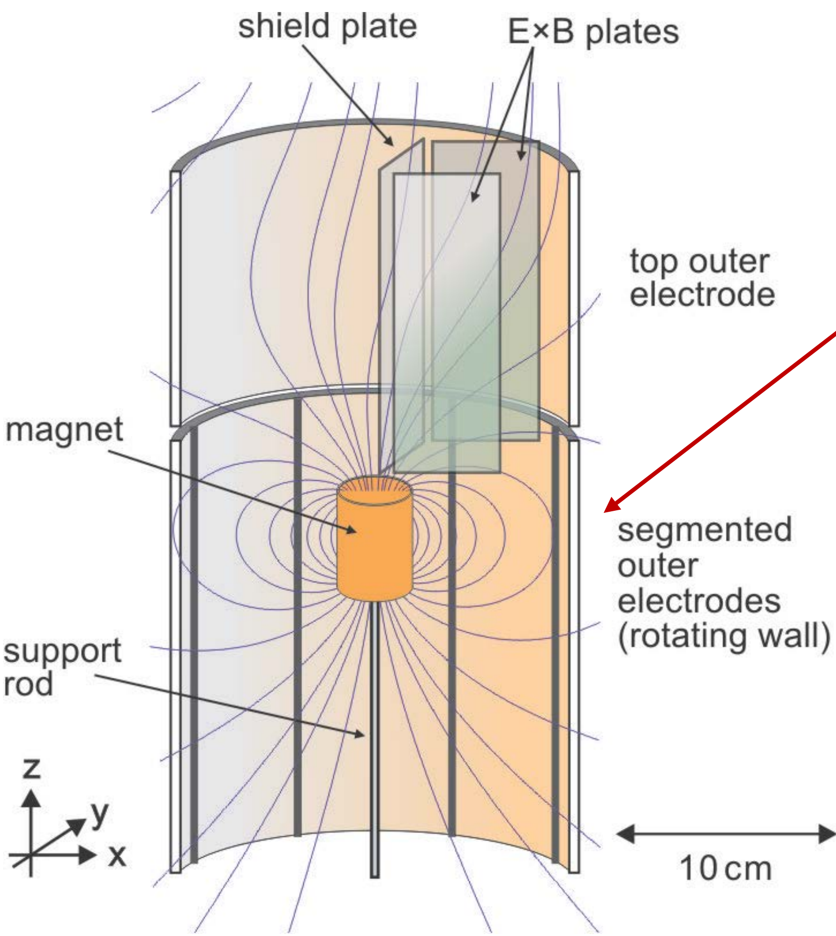


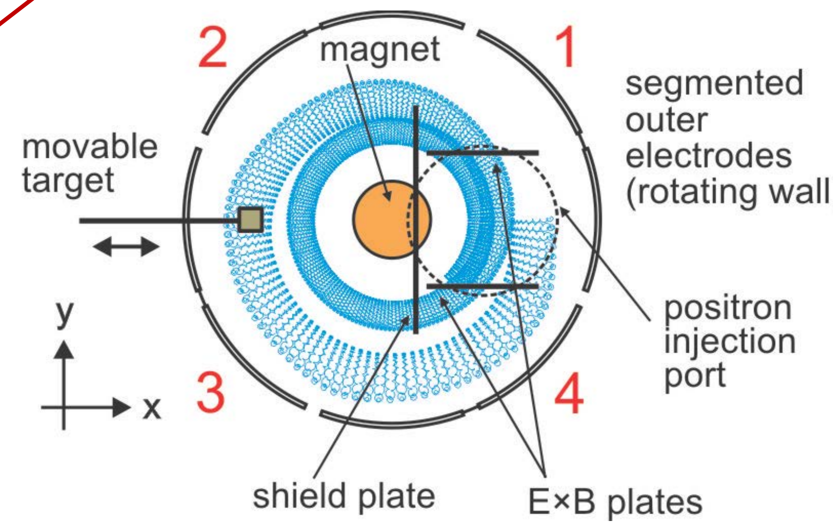
- 5eV positron orbits with or without RW fields
- inward transport with certain conditions
- can be combined with ExB drift injection scheme

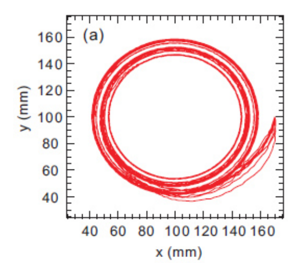
Schematic of the experiment, waveforms, and typical orbit of positrons in the trap

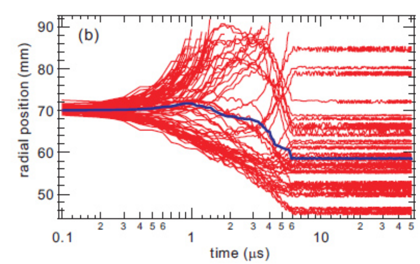
electrostatic deflector
(not shown in the figure)



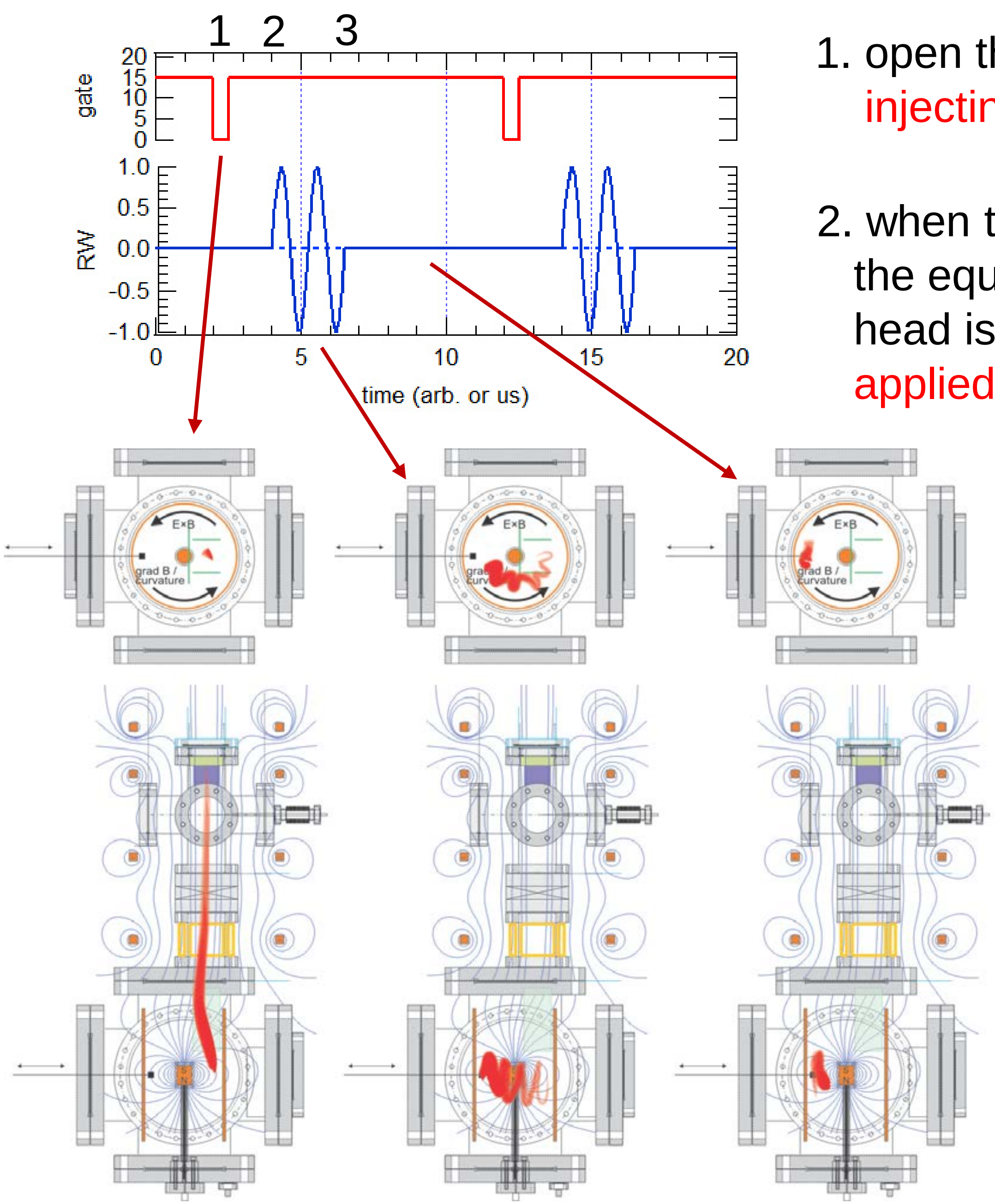








Gated pulse injection of positrons and application of RW fields



1. open the gate (deflector or aperture) injecting short pulse of e+ beam

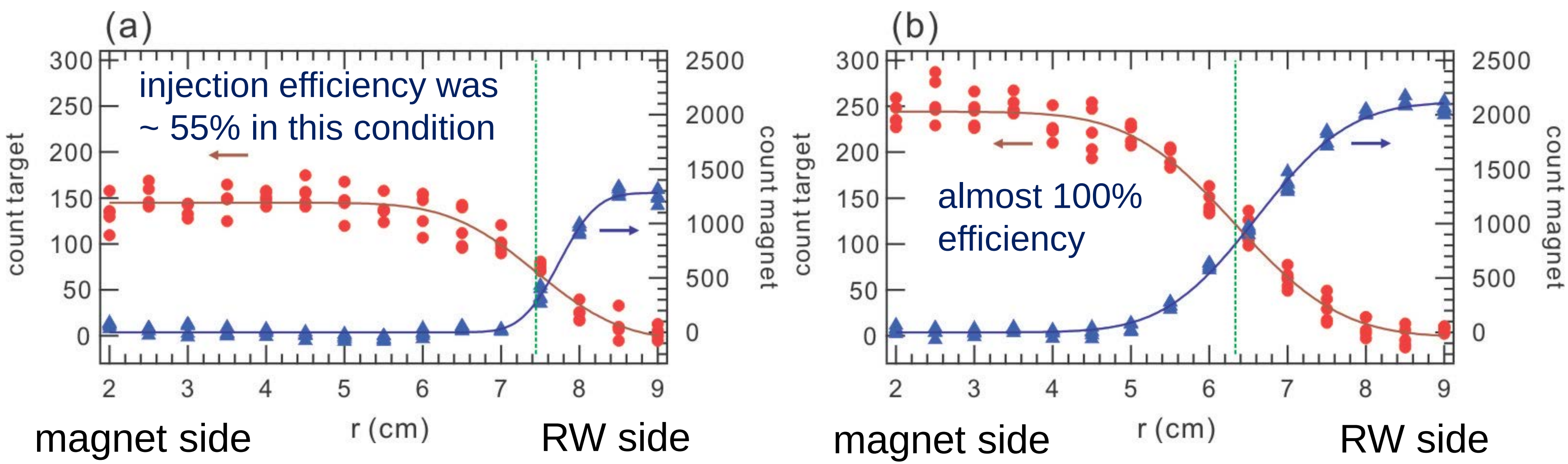
2. when the tail end of the beam reaches the equator ("injected"), (and the beam head is in the trapping region,) RF is applied (or not applied, for comparison)

3. sinusoidal waves stop when the tail end reaches the target (or before), and go back to 0V.

Continue measurements of counts at the target with various r, with and without applying RF waves

Application of gated sinusoidal waves resulted in the inward compression and improved injection efficiency

preliminary results



Without RW

With RW in the circulation direction of positrons

- red curves: 511 keV counts at a target probe (integrated radial profile)
- radial orbit compression and enhancement of injection efficiency

Summary and future work toward e+/e- pair plasmas

- We aim to create and study magnetically-confined electron-positron pair-plasmas in stellarator and levitated dipole devices*

- Results obtained so far (today, mainly dipole activities were reported)
  - characteristics of e+ beam** at the open beam port of NEPOMUC
  - efficient (~100%) injection of intense 5 eV e+ beam into dipole field***
  - long (> 1 s) confinement of positrons in the prototype trap****
  - shaping of radial profiles of positron orbits by RW electric fields

  - e+ system from first point Inc. assembled and operated in IPP
  - first observation of different phosphor screen response to e+ and e-
  - trapping of electron plasma and diocotron mode of e- in high-field trap

- Future work
  - application of RW to control radial inward diffusion of positrons
  - further development: levitated SC dipole / stellarator
  - development of positron accumulator at NEPOMUC

*2012 T. Sunn Pedersen+, New J. Physics **14**, 035010; 2017 E.V. Stenson+, J. Plasma Phys. **83**, 595830106.
2016 J. Stanja+, NIM A **827, 52. ***E.V. Stenson+, to be submitted. ****J. Horn-Stanja+, to be submitted.