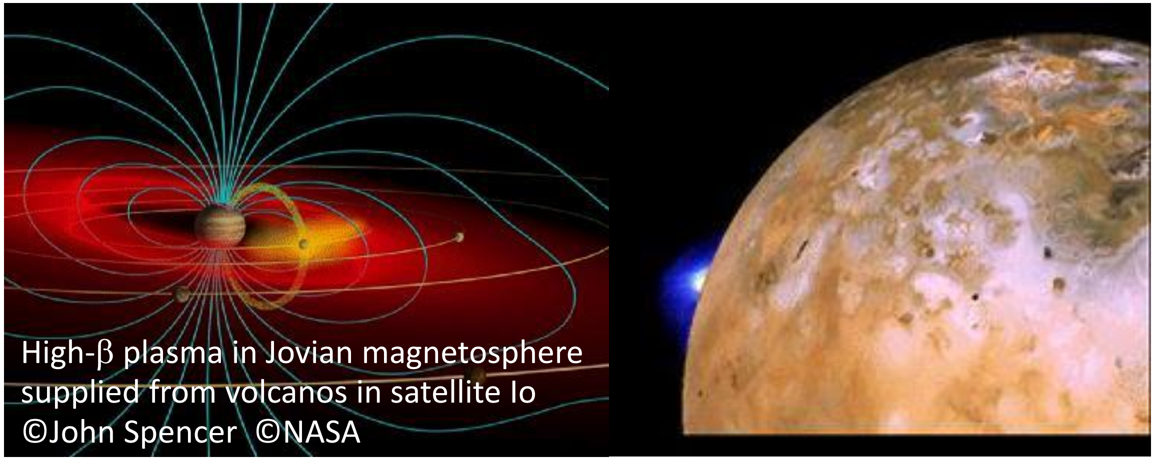
# Trapping properties of magnetic-dipole fields

**H. Saitoh[1], T. S. Pedersen[1], U. Hergenhahn[1], E. V. Stenson[1],
N. Paschkowski[1], C. Hugenschmidt[2], and the PAX/APEX team**

**1 Max Planck Institute for Plasma Physics, Greifswald and Garching, Germany
2 FRM-II and Physics Department, Technical University Munich, Garching, Germany**

# Dipole magnetic field is the most simple and ubiquitously observed field in the Universe



High-$\beta$ plasma in Jovian magnetosphere supplied from volcanos in satellite Io
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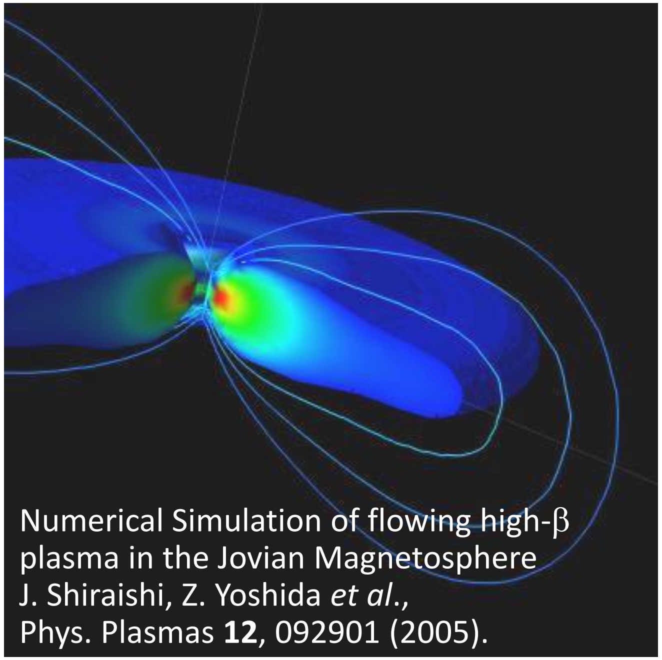


Numerical Simulation of flowing high-$\beta$ plasma in the Jovian Magnetosphere
J. Shiraishi, Z. Yoshida *et al.*,
Phys. Plasmas **12**, 092901 (2005).

- Good approximation of many objects; pulsars, magnetospheres (Jupiter, earth)

1987 Hasegawa., Comm. Plasma Phys. Fusion **1**, 147.

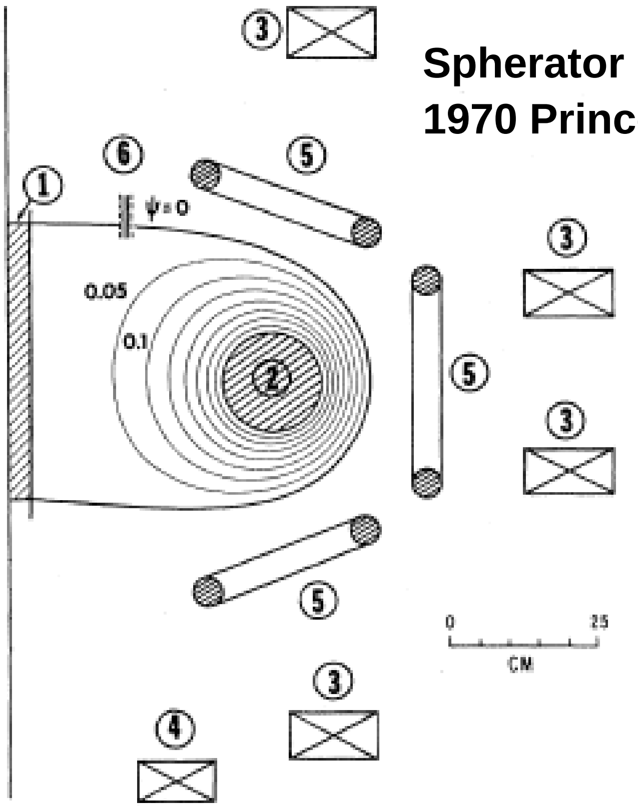
2002 Yoshida and Mahajan, PRL **88**, 095001.

- Space craft observations of magnetosphere of Jupiter
  - High-$\beta$ ($\beta$>100%) flowing plasma
  - Stable against several instabilities (compressibility of field lines)

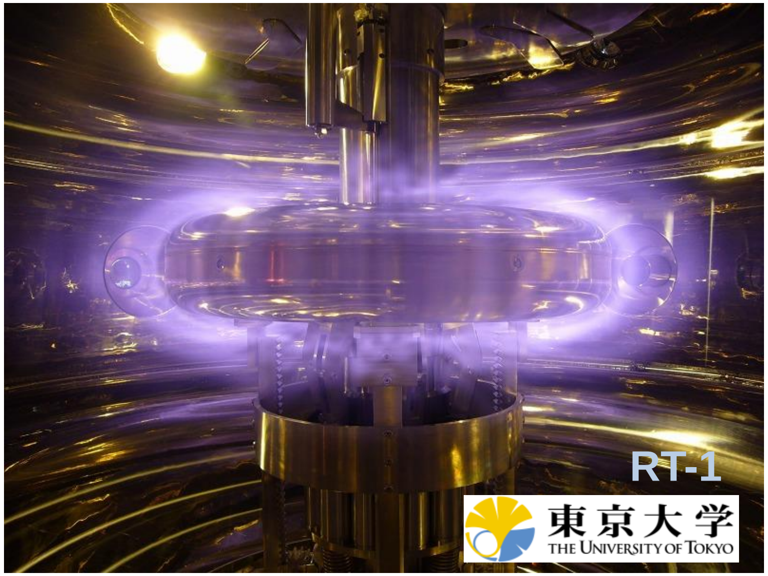
$\beta$ = Plasma pressure / magnetic pressure

- Physics of dipole plasmas: Self-organization, inward “diffusion” etc.

# There has been a renewed interest in laboratory studies on dipole plasmas: by using superconducting levitated coils



**Spherator**
**1970 Princeton**



- Dates back to early fusion studies with Spherators and multi-pole traps

1971 Freeman *et al*., PRL **26**, 356.

(averaged) Min-B concept: still working in fusion studies

- Recently, RT-1 (Tokyo) and LDX (MIT/Columbia) were constructed, by taking a hint from the Jovian magnetosphpere

2006 Garnier*et al.*, Phys. Plasmas **13**, 056111.

- Scientific applications: advanced fusion, matter-antimatter plasmas

# Outline

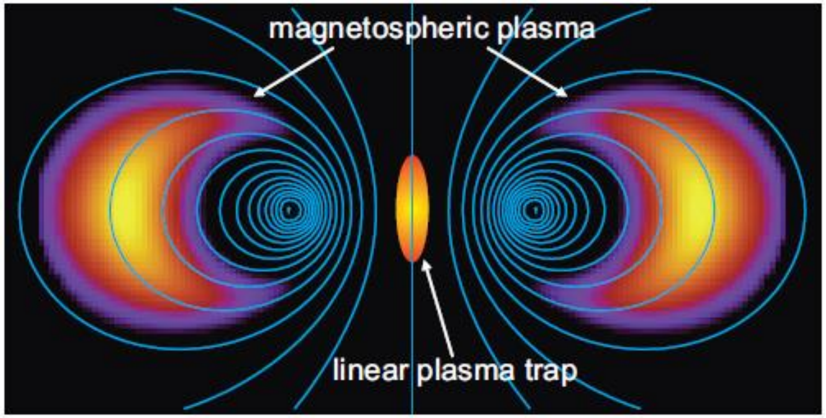
- Properties of particle motion in the dipole field
  - Conservation of adiabatic invariants and its breakdown

    Stable confinement ⟺ efficient inward transport
  - Advantages for trapping e-p plasmas: axi-symmetric totoidal configuration

- Recent results on dipole non-neutral (pure electron) plasmas
  - Long time confinement and its properties
  - Spatial profiles and conditions for good confinement

- Application to electron-positron plasmas in a dipole field
  - Planned small experiments with superconducting magnet
  - Experiments on superconducting dipole field trap

# Characteristics of dipole field trap and its advantages for the confinement of plasmas



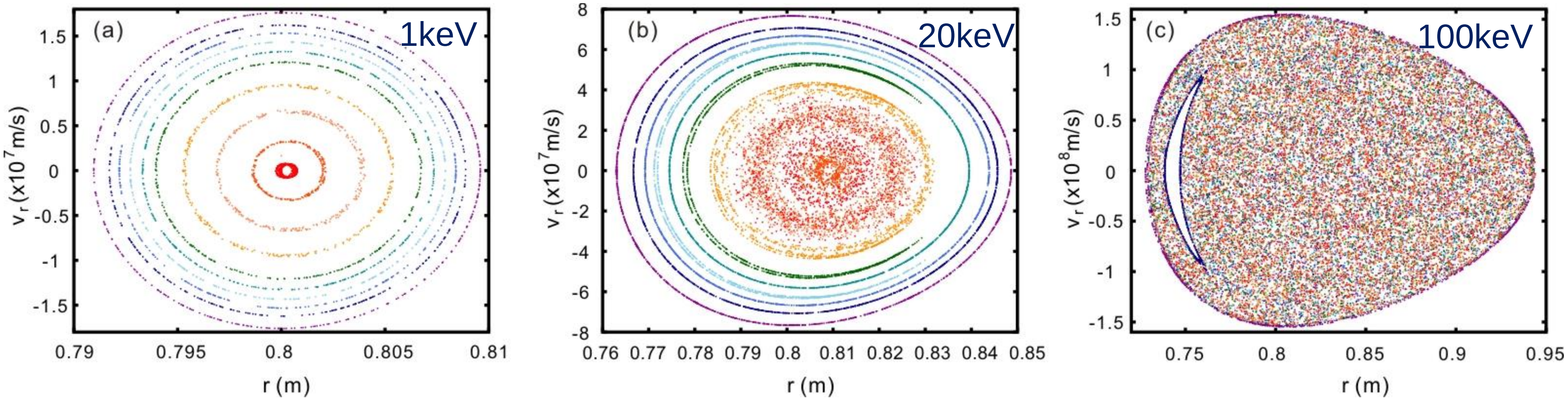
**Comparison of linear and dipole traps**

- Toroidal configuration enables confinement of plasmas at arbitrary non-neutrality

- In an axi-symmetric trap, canonical angular momentum of a charged particle is well conserved.

➡ Good confinement is expected

- Injection methods (breakdown of invariants) are key issues



**Poincaré plots of positron orbit in a dipole field: Motions are not always integrable !**

# Confinement of plasmas in a dipole field is realized through the conservation of adiabatic invariants

- Charged particle motions in an axi-symmetric dipole field:

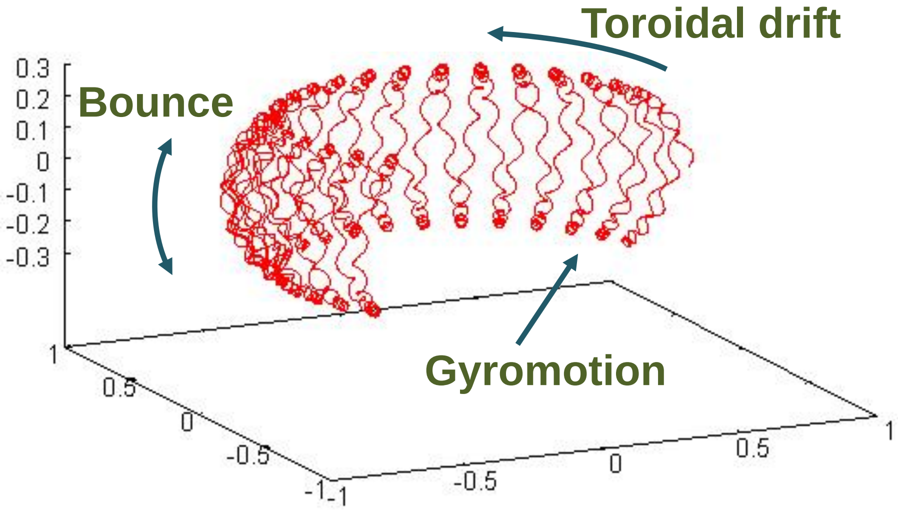
  When three adiabatic invariants are conserved, motions are integrable

| | Adiabatic invariants | periodic motions |
|---|---|---|
| • magnetic moment | $\mu = v_{\perp}{}^{2} / B$ | gyromotion |
| • action integral | $J = \int v_{//} ds$ | bounce along field lines |
| • magnetic flux | $\Psi = \int BdS \sim P_{\theta}$ | toroidal drift motion |

Canonical angular momentum

- When the system is quiescent, charged particles are trapped on magnetic surfaces due to symmetry

- Stable confinement is expected for plasmas at any non-neutrality, and for high-energy particles



# Radial transport of particles are realized by breaking the conservations of adiabatic invariants

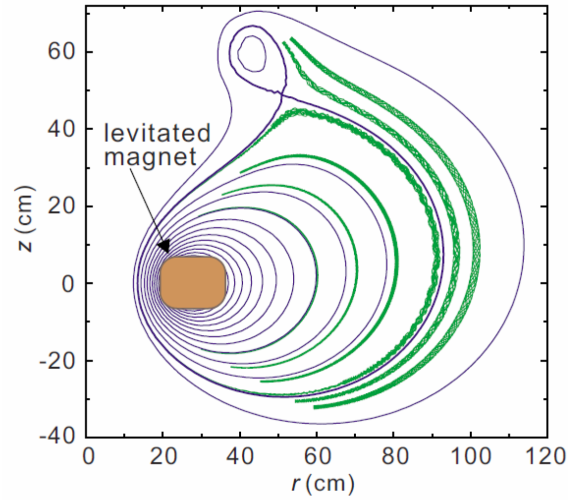
- $\mu$ and $J$ are not conserved when charged particles are not magnetized
- When the system is not axially symmetric, $\Psi$ is not conserved
- Temporally changing fields can also destroy the conservations of invariants

$\tau_{\mathrm{gyro}} < \tau_{\mathrm{bounce}} < \tau_{\mathrm{drift}}$ ➡ Even slow fluctuations can easily destroy $\Psi$

## Conservation of invariants

Particles trapped on magnetic surfaces

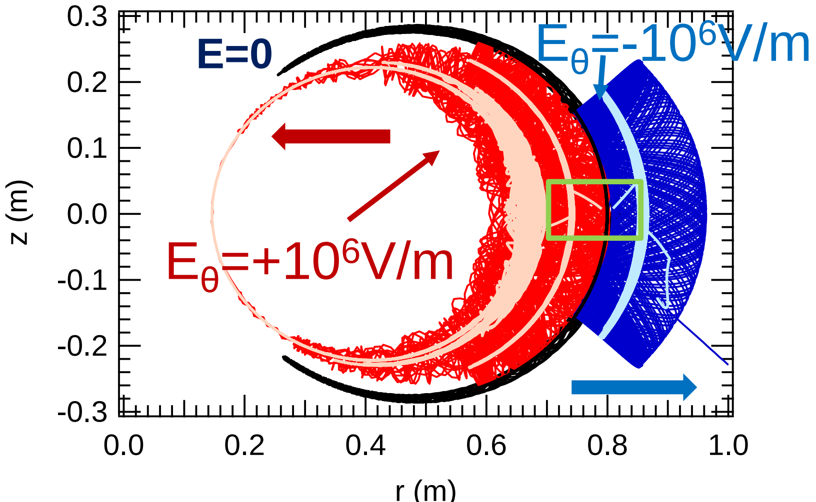
**stable confinement due to symmetry**



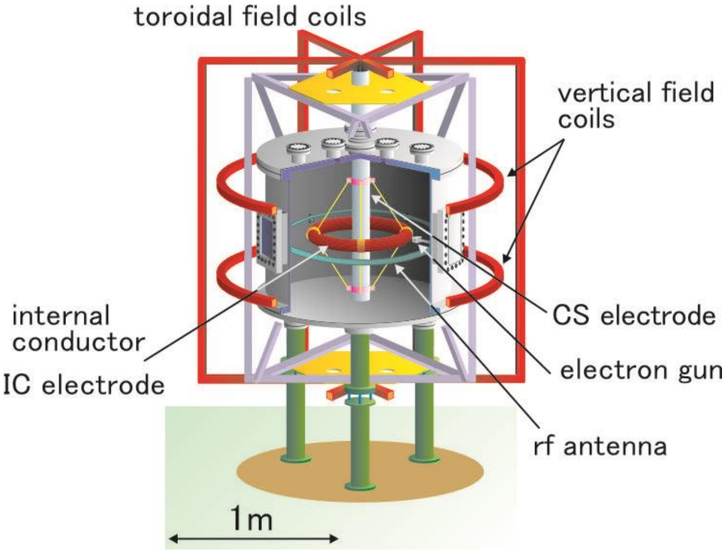
## Breakdown of invariants ($\Psi$)

Diffusion across magnetic surfaces

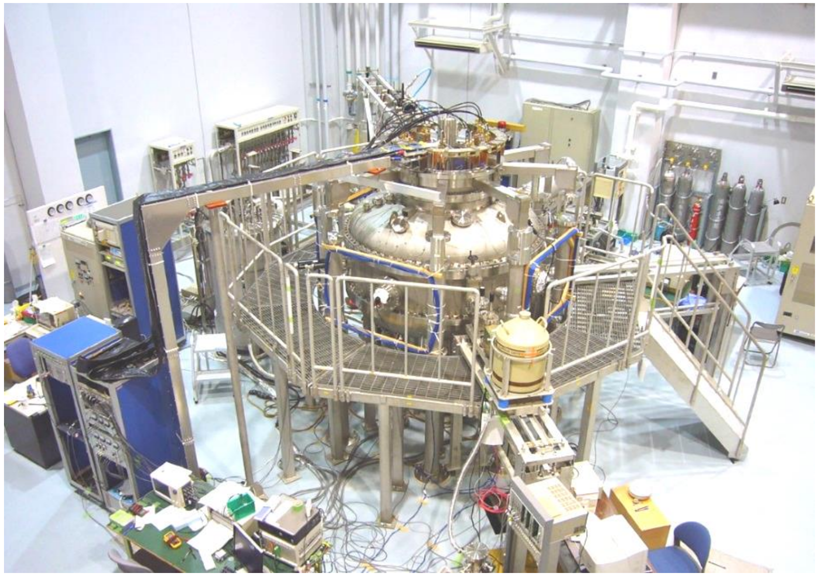
**Profile reconstruction (relaxation)**



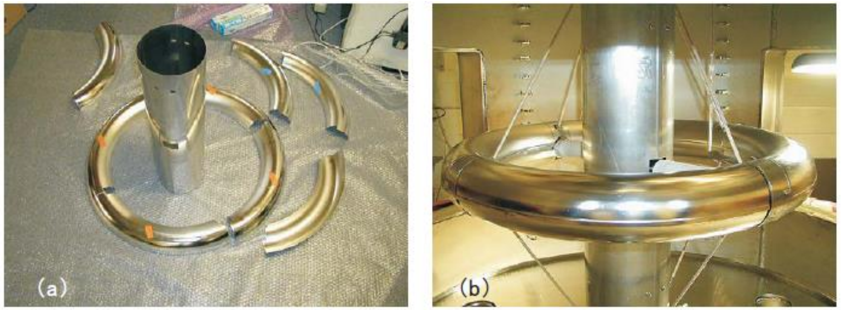
# Two experiments had been conducted by using supported and levitated dipole field trap



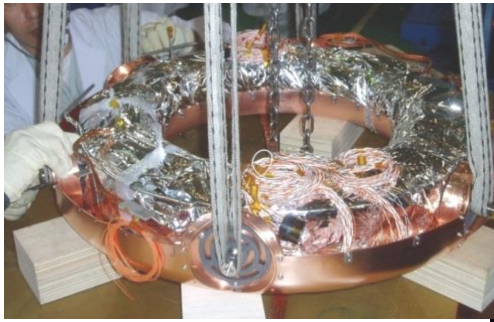
**Proto-RT (1998-2005) supported coil**

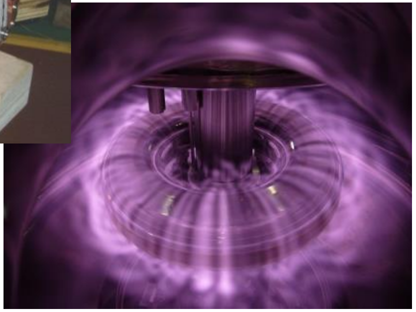


**Superconducting Ring Trap 1 (RT-1) (2006-)**



**Potential control by using torus electrodes**



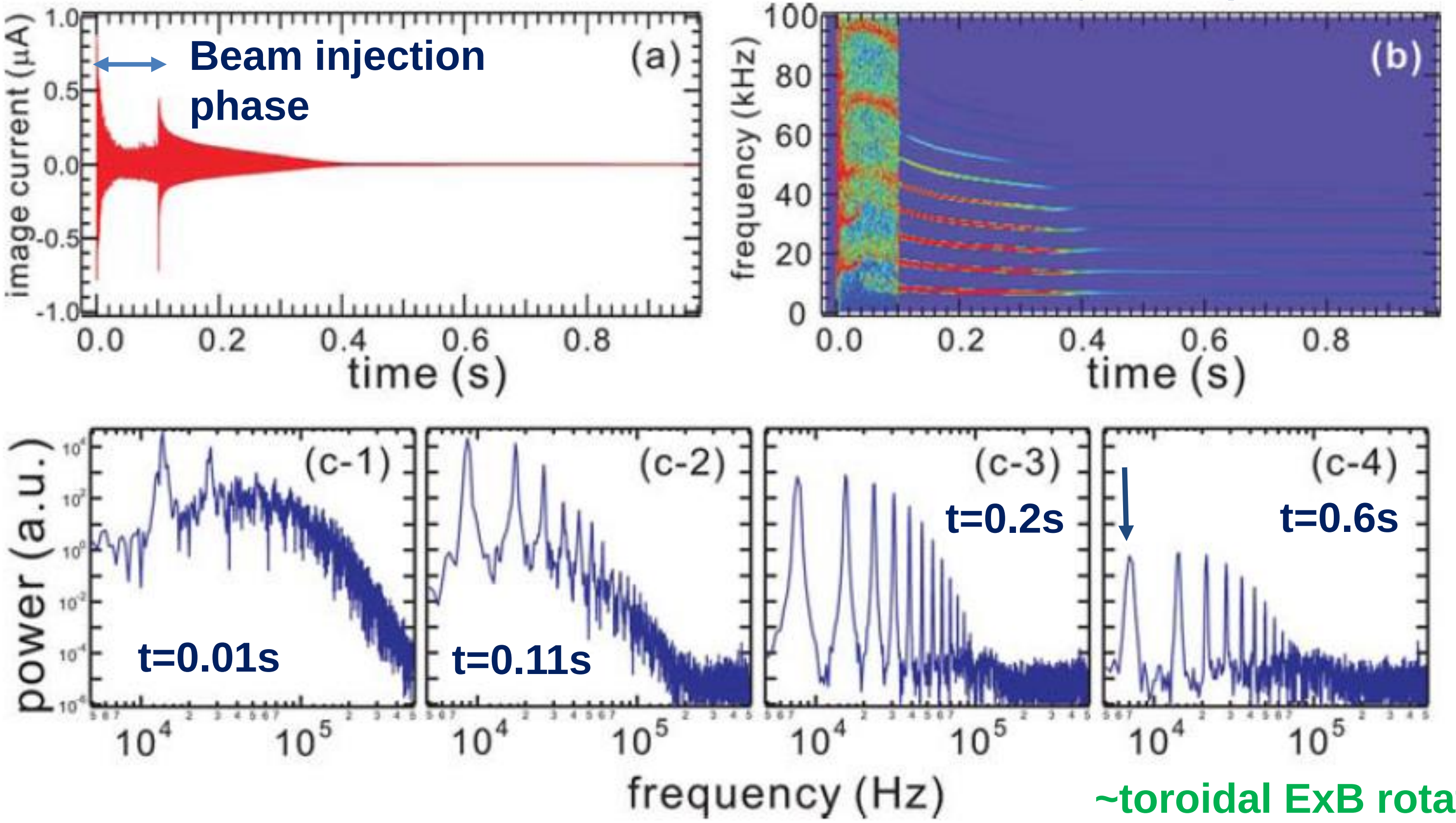


**Magnet levitated**

**Minimizing perturbations**

# **Formation phase**: plasma has large turbulent-like fluctuations during beam injection, which are stabilized after the end of beam supply

**Floating wall probe measurement**



Beam injection phase

Beam injection phase

t=0.01s

t=0.11s

t=0.2s

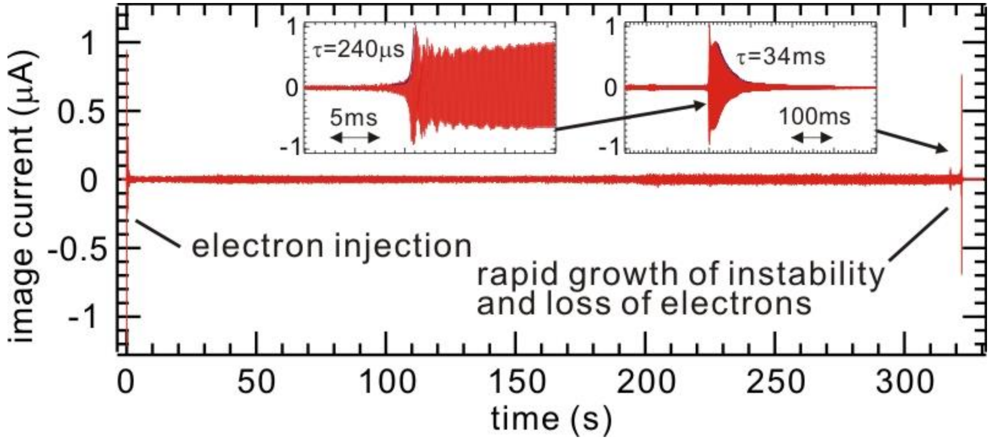
t=0.6s

~toroidal ExB rotation freq.
collective diocotron moe

- The electron gun was operated from t=0 to 0.1s.
- Plasma has turbulent-like fluctuation component in injection phase, and is stabilized after the end of beam injection.

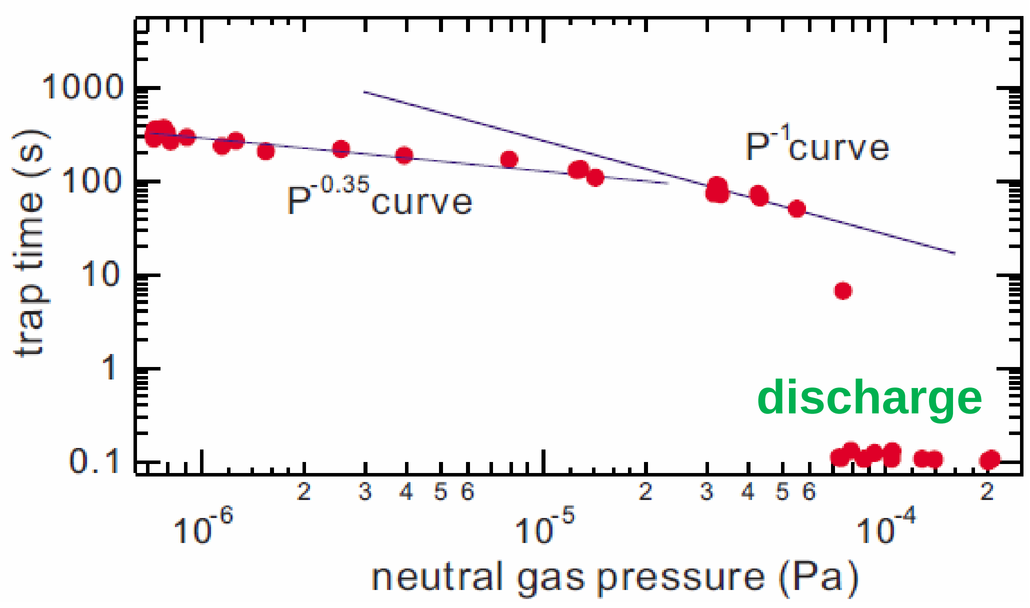
# Stable confinement of PEP for more than 300s is realized, trap time comparable to the diffusion time due to neutral collisions

**Floating wall probe measurement**



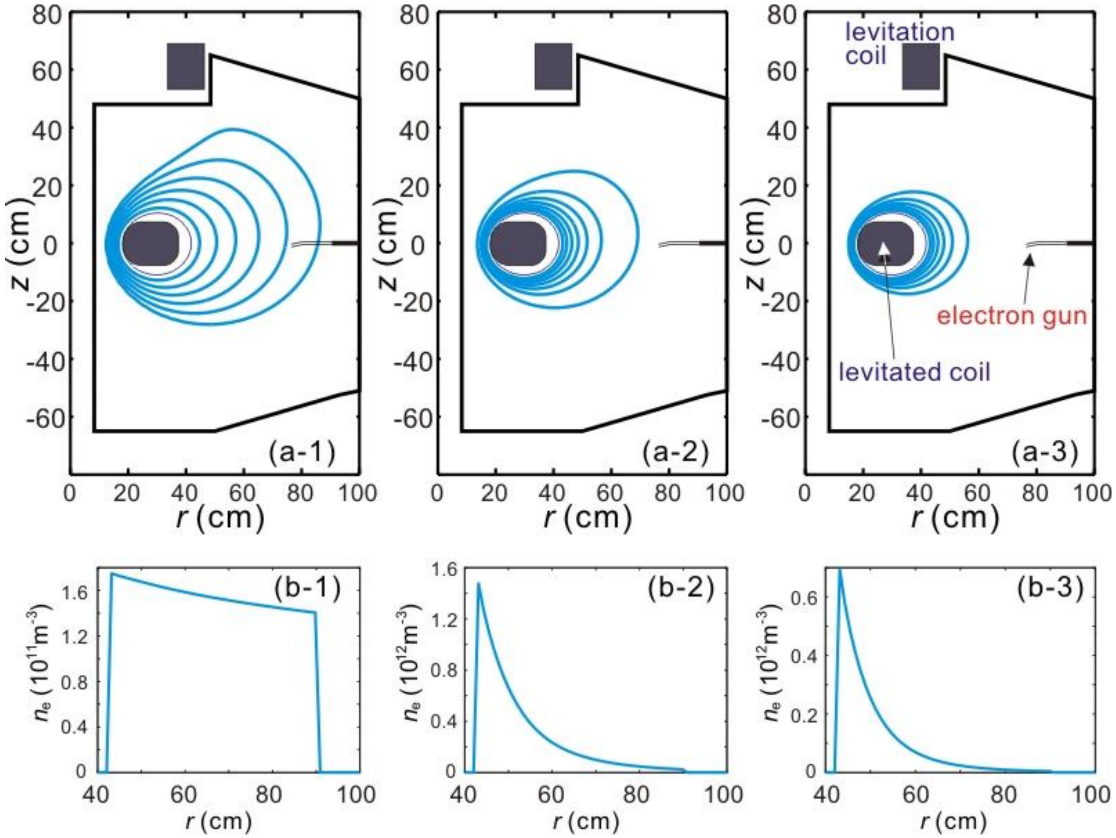
- Long confinement is realized by the magnet levitation

- Instability does not grow, until the end of confinement



- The nonlinear relation ($\tau^{*}P_n \neq$const.) indicates that electron-neutral collisions do not simply decide the trap time of PEP.

# Density profiles: Pinch toward strong field region estimated by using a wall probe array in stable confinement phase



Density profiles of PEP

t=0s
t=0.1s
t=320s

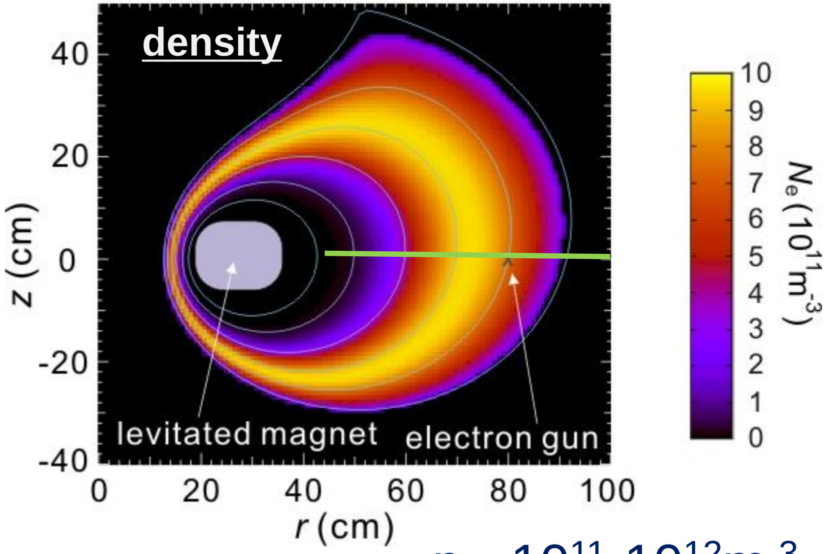
(a) during beam injection (b) after stabilization (c) before confinement ended

- Radial transport to strong field region is realized during beam injection.
- After stopping electron supply, in the stable phase, plasma relaxes to strongly peaked density profile

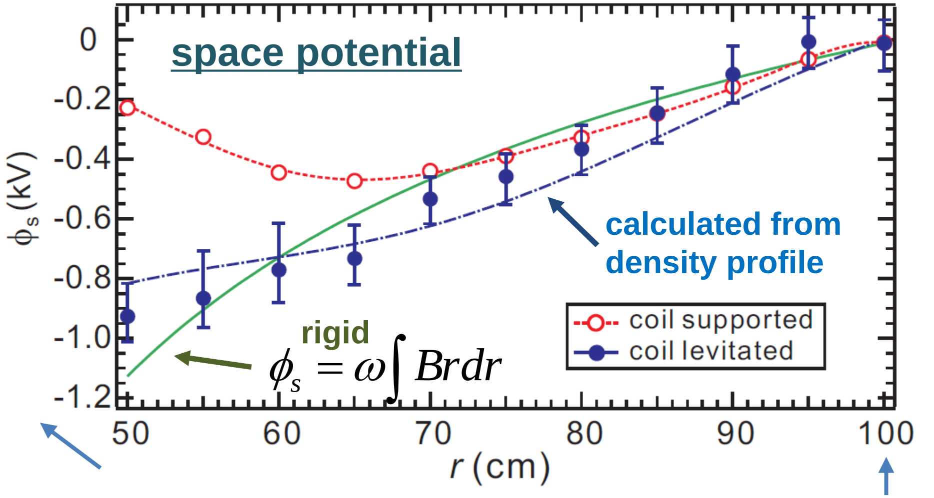
**2009 Saitoh *et al*., Plasma Fusion Res. 4, 054.**

# Semi rigid-rotating state is spontaneously generated during beam injection, measured density and potential profiles are consistent

(1D data, assuming density is constant on magnetic surfaces)



$n_e$~$10^{11}$-$10^{12}$m$^{-3}$



**coil surface at r=37.5cm**

$V_{acc}$=500V

**chamber wall**

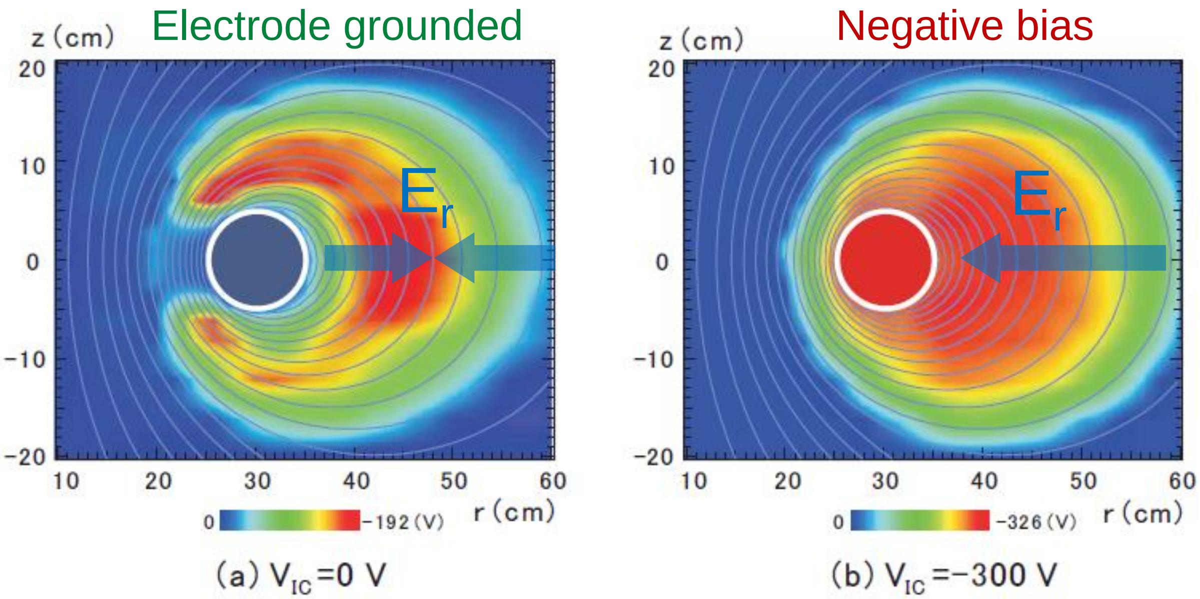
- When the magnet is not levitated
  - Potential profiles (○) are hollow ➡ plasma has strong shear flow

**toroidal ExB rotation**

- By the levitation of dipole field magnet
  - Potential profiles (●) are close to that of rigid rotation (—)
  - Density (--) and potential measurements are consistent

**2010 Saitoh, Yoshida *et al.*, PoP 17, 112111.**

# The confinement properties strongly depend on the internal potential structure (Proto-RT)

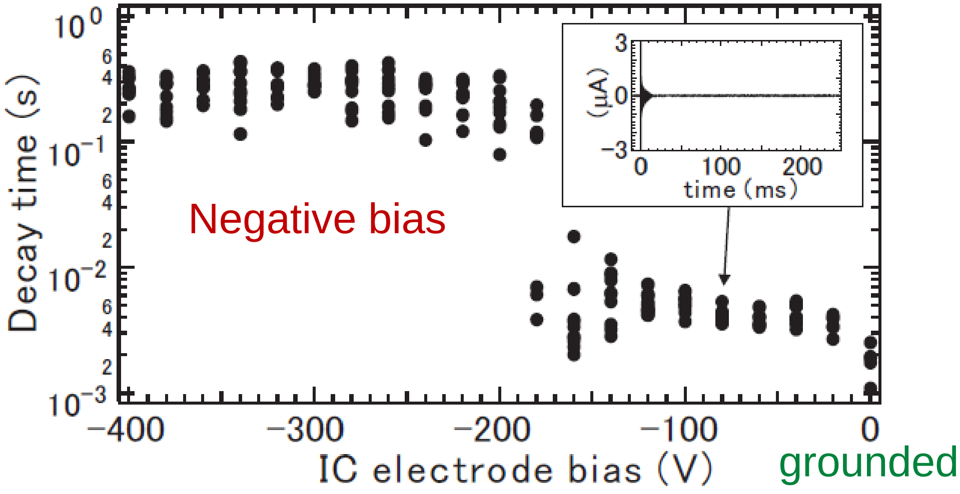


(a) $V_{IC}=0$ V

(b) $V_{IC}=-300$ V

**2-d space potential profiles of PEP in Proto-RT**

- When the torus electrode is grounded (or weakly negatively biased):
  - Potential profile has a peak in a plasma
  - Strong toroidal shear flow
  - Short confinement time



**Confinement time vs torus electrode bias voltage**

- When the torus electrode is negatively biased:
  - Flow shear reduced
  - Long stable confinement
- Instability?
- Effects of support?

# Toward the positron confinement in the dipole field; Common and different properties with electrons

- Basically, similar confinement properties are expected for positrons

- Efficient injection methods should be developed for positrons
  - Inward transport should be externally controlled for weak beam

    cf) Electron injection: Fluctuation-induced spontaneous inward "diffusion"
  - Two methods have been proposed*, should be tested
    - Drift injection scheme with external electric fields*
    - Novel methods by using positronium*

- For the confinement of positrons and electrons simultaneously
  - What will happen in the mixing phase of positrons and electrons?

    Potential control required?  Two fluid instabilities?

*T. S. Pedersen *et al*, NJP **14**, 035010 (2012).

# Toward the positron confinement in the dipole field; Common and different properties with electrons

**NEPOMUC positron source***

Using prompt $\gamma$-rays, $10^9$ $e^+$/s

**PAX positron accumulator****

Consists of Multicell-type trap

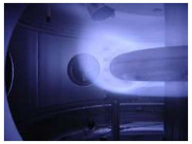
- confinement of $10^{11}$ cold positrons
- fast extraction within milliseconds

**E. V. Stenson *et al*.,**

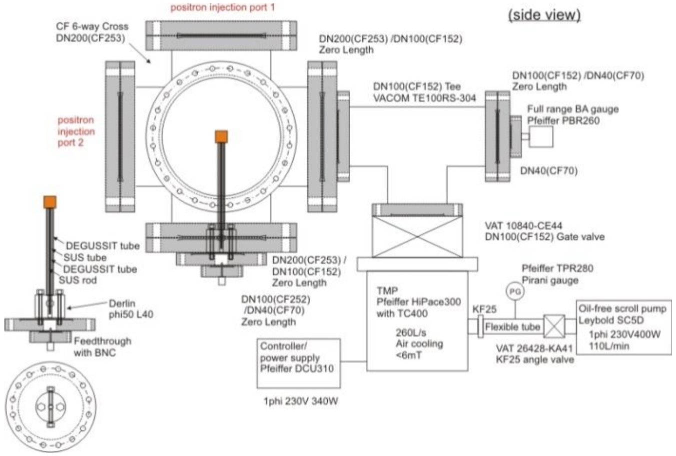
**APEX Toroidal trap**

- Superconducting dipole field magnet
- Realization of long confinement

- Long confinement of e+
- Simultaneous confinement of e- and e+
- Excitation and detection of waves
- Dispersion relation measurements



**Proof-of-principle experiment in 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 rift injection with external electric fields

Positron beam exp.

- Efficient injection by using positronium atoms

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

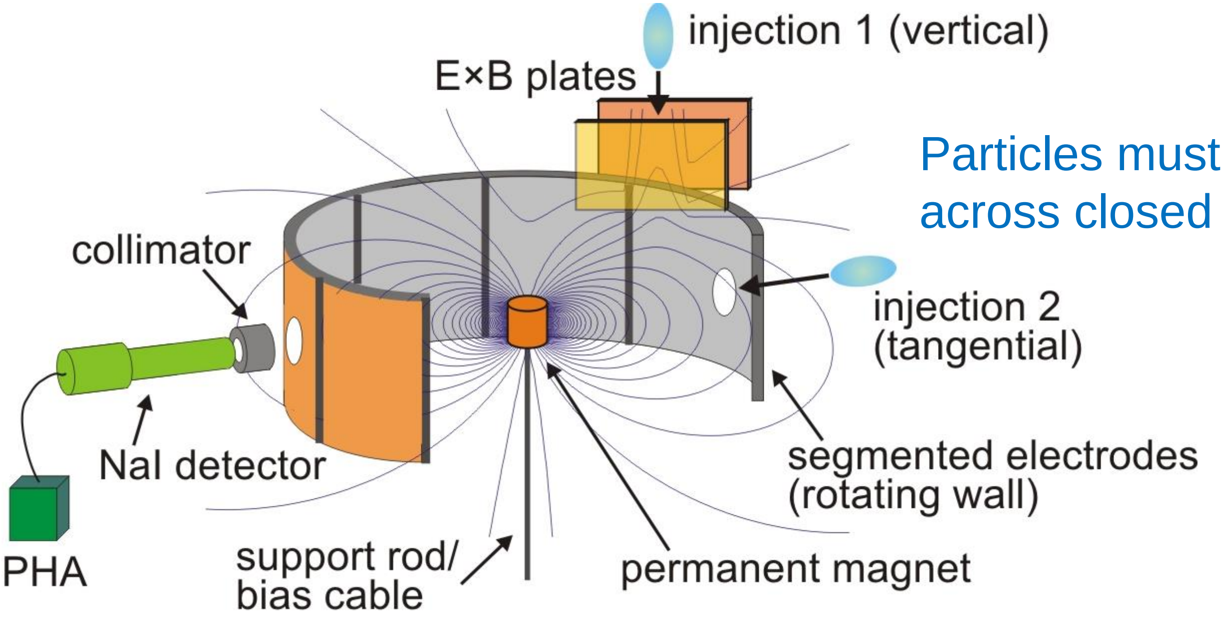
# Proposed proof-of-principle experiment

## Development of particle injection schemes

- By using positronium reemission process on solid materials*

  positrons are converted into positronium atoms and freely transported into the confinement region, where they are photo ionized

- By using external electric fields (to be started with electrons)



Particles must be injected across closed field lines!

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

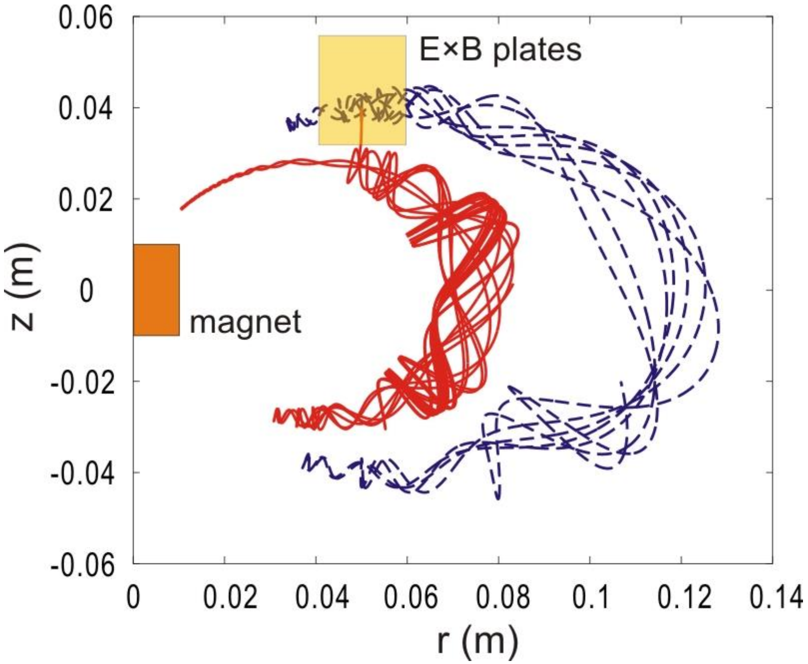
*D. B. Cassidy *et al.*, Phys. Rev. Lett. **106**, 133401 (2011); T. S. Pedersen *et al.*, (2012).

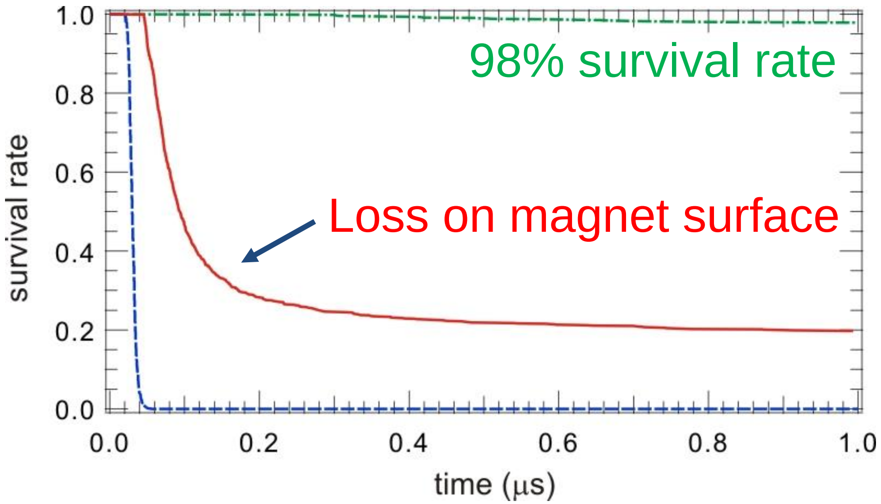
**C. Hugenschmidt *et al.*, Nucl. Instrum. Meth. Phys. Res. A **554**, 384 (2005).

# Positron injection by using external electric field 1

## 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





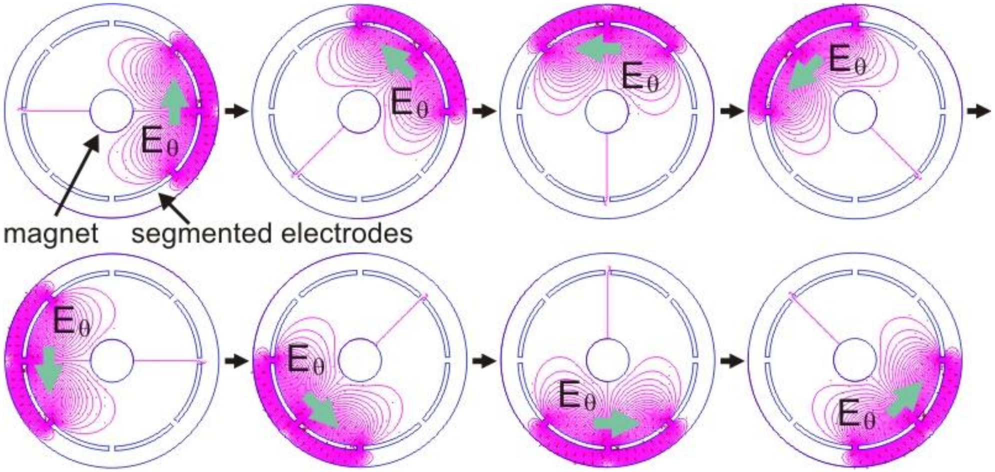
(left) Typical positron orbit projected onto the *r*-*z* cross section when the electric field is applied (solid line) and not applied (dot line). Electric field of $\mathbf{E} = 1 \times 10^3$ V/m was applied in the marked region from t=0 to 0.1ms.

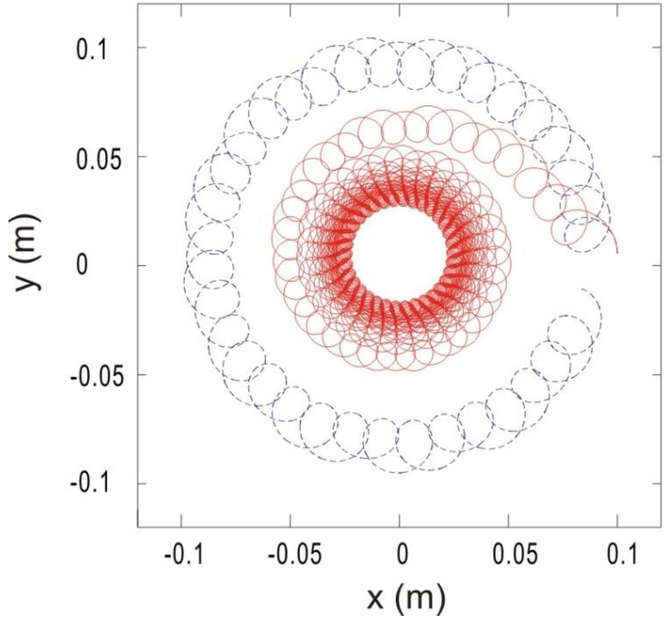
(right) Ratios of remaining positrons after injection without **E** (dot line), with the application of **E** (solid line), and when the magnet was also biased (chain line).

# Positron injection by using external electric field 2

## Injection method 2: tangential injection

- 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

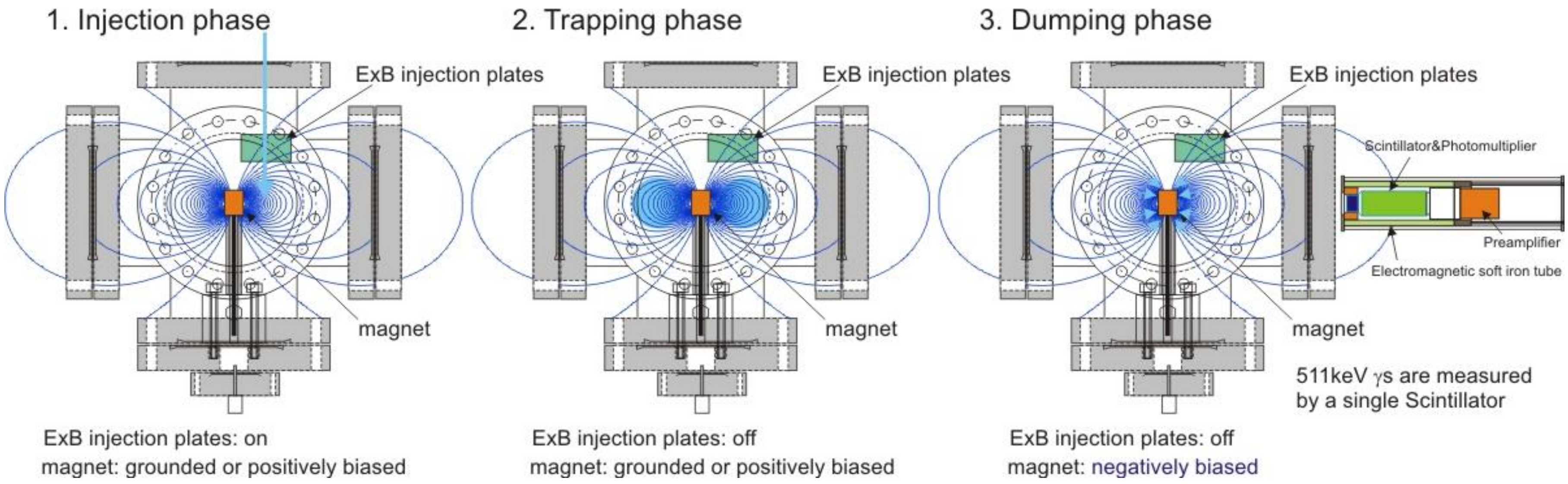




(left) Schematic view of a rotating wall and equipotential contours generated by the segmented electrodes.

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

# Injection, confinement, and detection schemes with positrons



1. Injection by external fields

2. After transported inward, positrons are expected to relax into an equilibrium state in the dipole field.

3. For the diagnostics of the injected number of positrons, finally the magnet is negatively biased so that trapped positrons are dumped onto the magnet surface. The g rays from annihilation are counted by a scintillator detector with a pulse height analysis system.

# Summary of pure electron plasma experiments in RT-1 and prospects toward the creation of electron-positron plasmas

## ➢ Dipole confinement and experimental results obtained so far

- Dipole magnetic field is a possible candidate as a trap configuration of electron-positron plasmas (toroidal axi-symmetric trap)

- Stable confinement of single-component non-neutral plasmas is realized in the axisymmetric dipole field configuration

- In turbulent phase, adiabatic invariants are not conserved, resulting spontaneous particle diffusion and formation of peaked density profiles

## ➢ For the future electron-positron experiments

- Injection methods of particles are key issues, as well as stable confinement of electrons, positrons, and their mixtures

- Prior to levitated dipole machine, we plan to conduct small experiment with a permanent magnet, by using both electrons and positrons (drift injection methods and by using positronium)