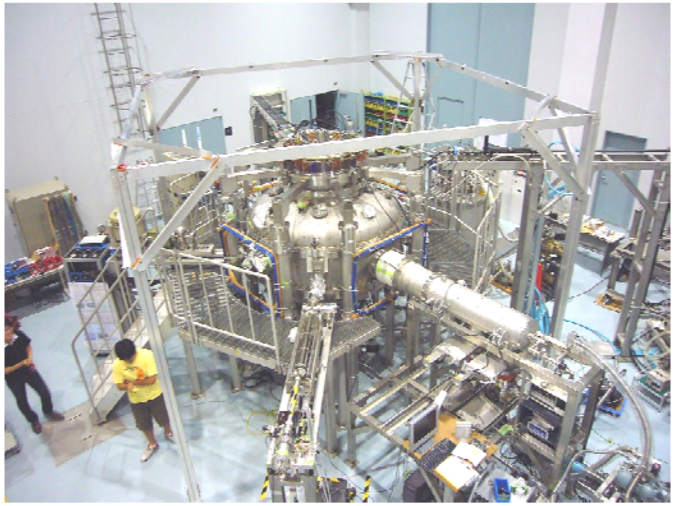
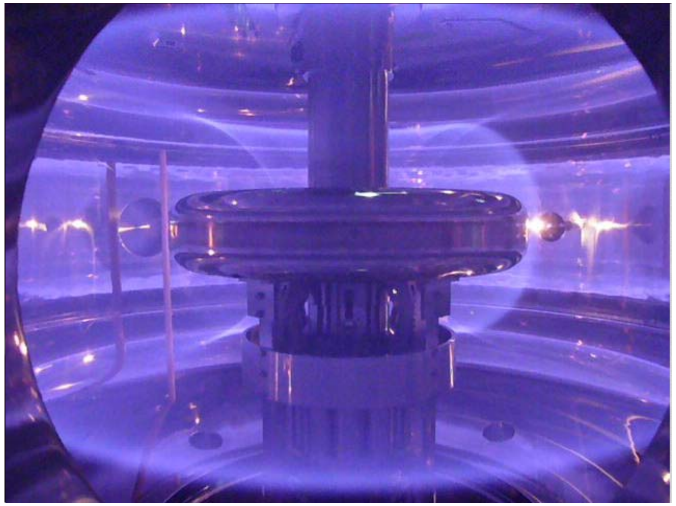
Confinement of toroidal non-neutral plasma in magnetic dipole



RT-1: Magnetospheric plasma experiment



Visualized magnetic surfaces

The RT-1 Experiment, GSFS, University of Tokyo
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Outline

1. Introduction
   - Toroidal non-neutral plasmas in dipole field configuration
   - Adiabatic invariants and relation to self-organization process

2. Pure electron plasma confinement
   - Injection and stabilization of electrons, trapped as plasma
   - Long confinement, observation of the onset of instability
   - Spatial profiles, inward diffusion and density peaking (pinch)

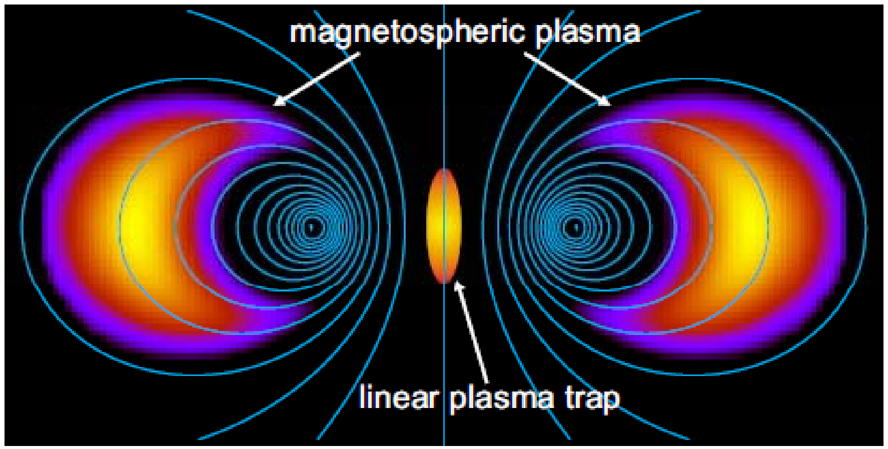
3. Initial experiments on positron injection and trapping
   - Numerical analysis on chaotic behavior of positrons
   - Injection/detection of positrons using small (1MBq) Na-22 source

4. Summary and future tasks

1. Introduction: Toroidal confinement of non-neutral plasmas in a dipole field configuration

- Toroidal configurations use no plugging electric fields
  - ➡ Potentially applicable to high energy charged particles, independent of their electric signs and charges

- Creation of antimatter plasmas, such as positron plasma and electron-positron plasma is one of challenging tasks to be realized in toroidal configurations



- Dipole non-neutral plasma
  - Axi-symmetric magnetic surfaces

    As well as scientific applications,

  - Self organization of stable state in strongly inhomogeneous field
  - Injection across closed surfaces

Adiabatic and non-adiabatic behaviors of particles in dipole field

- Magnetized particle orbit in dipole field consist of three periodic motions
  - ➡ Three adiabatic invariants are defined as actions, orbit is integrable

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

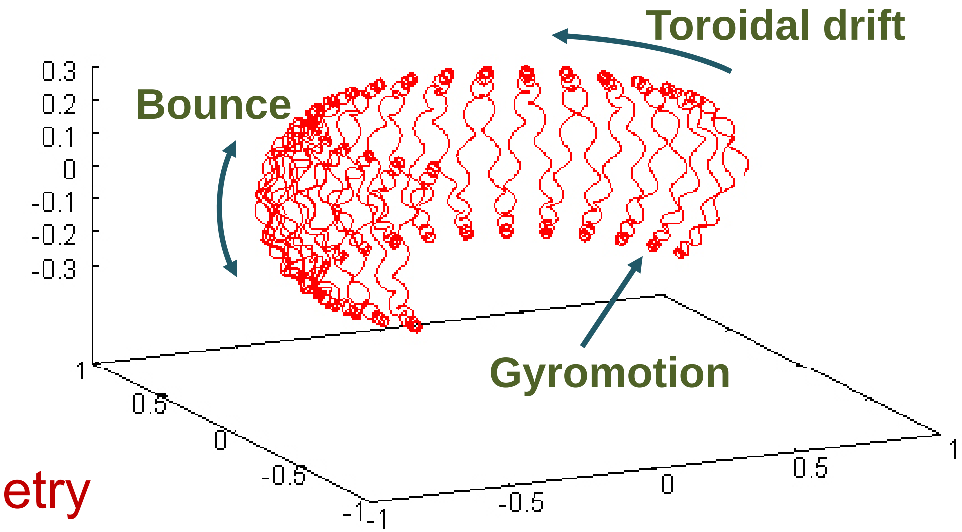
- In axisymmetric trap, H (energy) and P_θ (canonical angular momentum) are constant

$$H = \frac{P_r{}^2}{2m} + \frac{(P_\theta - qrA_\theta)^2}{2mr^2} + \frac{P_z{}^2}{2m} = const.$$

$$\dot{P}_\theta = -\frac{\partial H}{\partial \theta} = 0$$

➡ $$P_\theta = \frac{\partial L}{\partial \dot{\theta}} = mr^2\dot{\theta} + qrA_\theta = const.$$

Φ conservation is due to axi-symmetry



- Adiabatic Invariants are often not conserved due to various reasons

destroyed by

- magnetic moment $\mu = v_\perp{}^2/B$
- action integral $J = \int v_{//} ds$

large Larmor radius, fast fluctuations

- magnetic flux $\Phi = \int BdS \sim P_\theta$

trap asymmetry, slow fluctuations

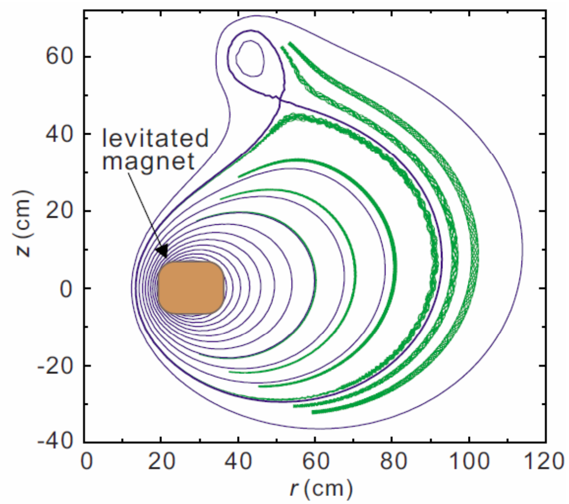
➡ Particle motion in a simple dipole field is non-integrable

stable phase (toroidal symmetric)

- **Conservation of invariants**

Particles trapped on magnetic surfaces

Stable confinement



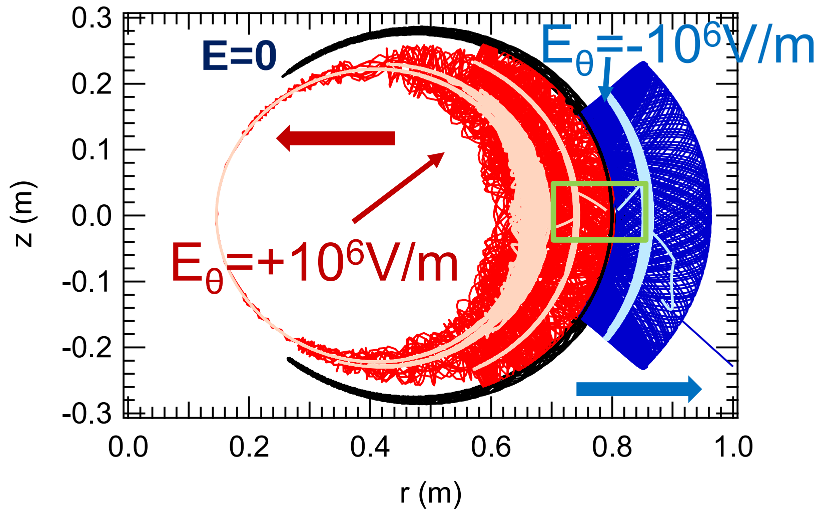
turbulent phase (asymmetric)

- **Breakdown of invariants (Φ)**

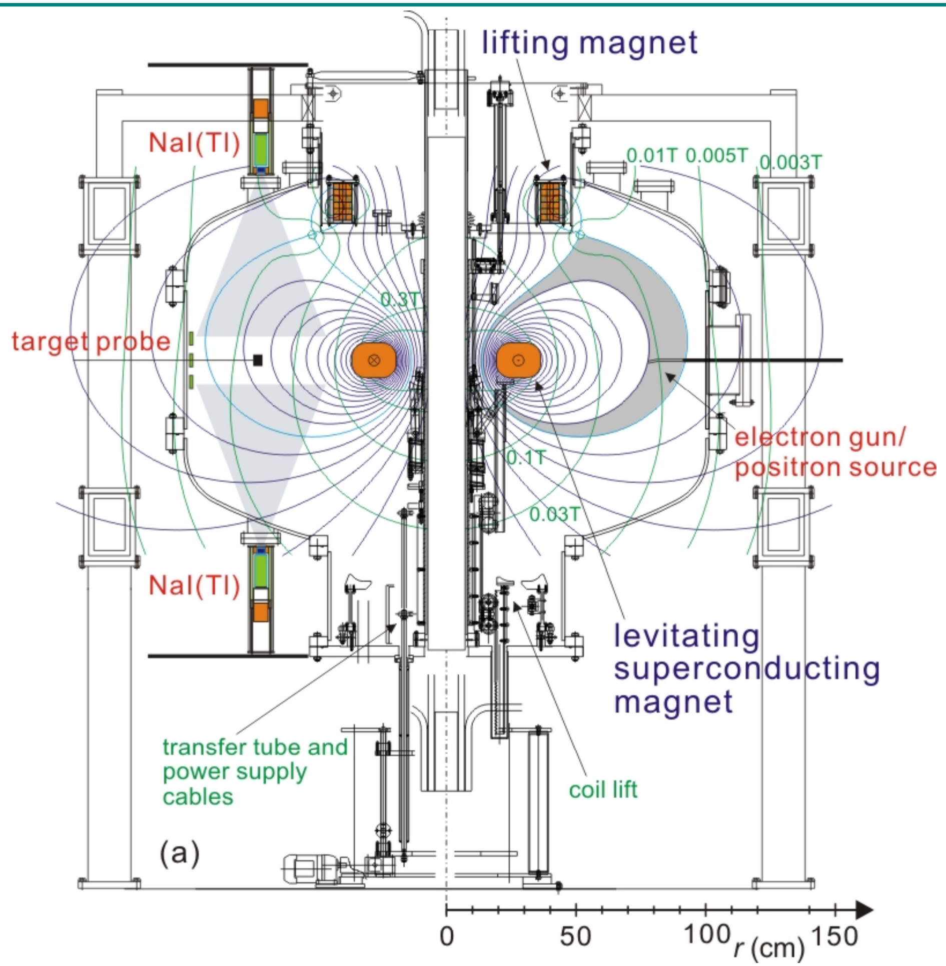
Diffusion across magnetic surfaces

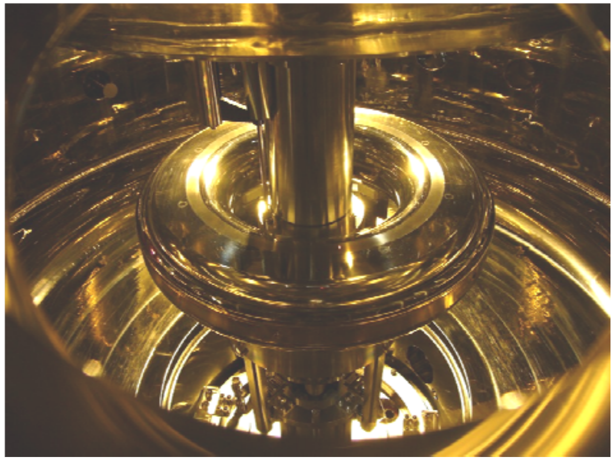
Profile reconstruction (relaxation)

What kind of state is generated?



RT-1 (Ring Trap 1) is a dipole field configuration generated by a levitated superconducting magnet





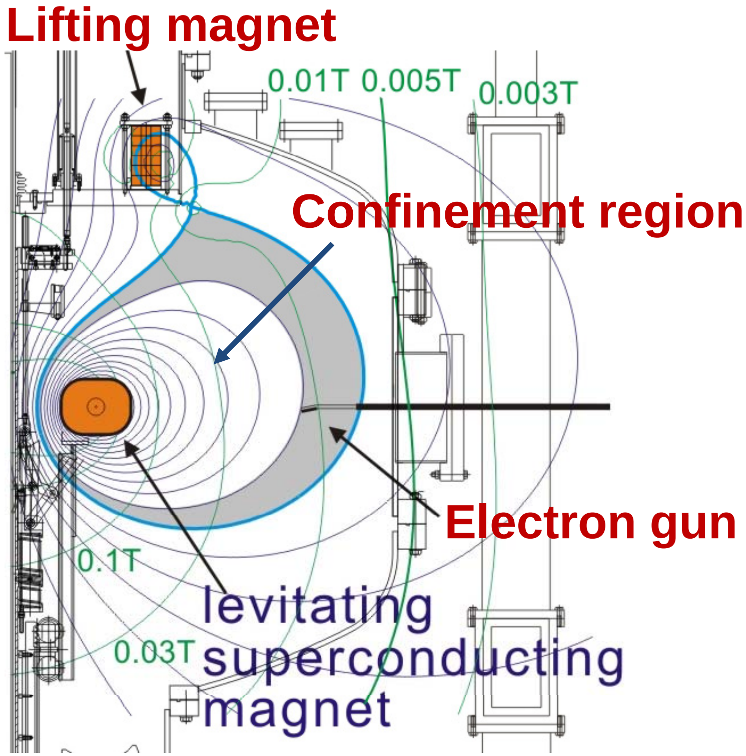
- HTS Bi-2223 magnet
  0.25MA,112kg
  magnetically levitated, without cooling during 6 hours operation

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

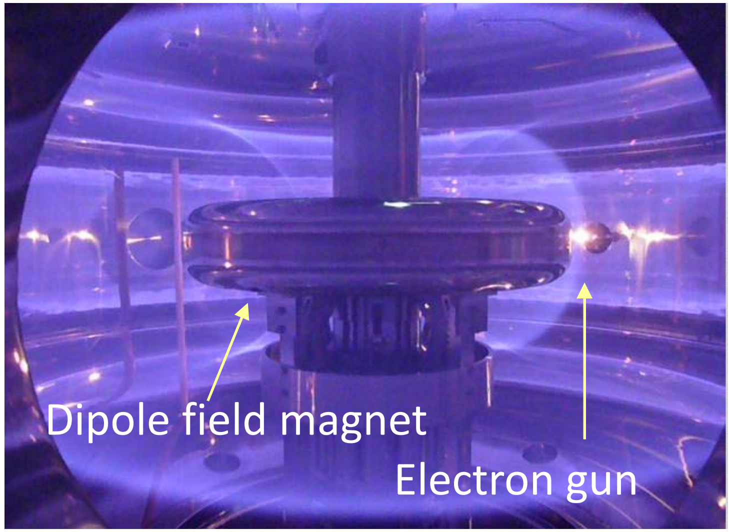
- **Toroidal non-neutral plasmas**
  Self-organization states, inward diffusion, positron trapping
- **High-β ECH plasma**
  70% local β, confinement time ~0.5s; fusion-oriented studies

2. Pure electron plasma experiment in RT-1

Electrons injection from a gun located at edge weak-field region



Separatrix configuration

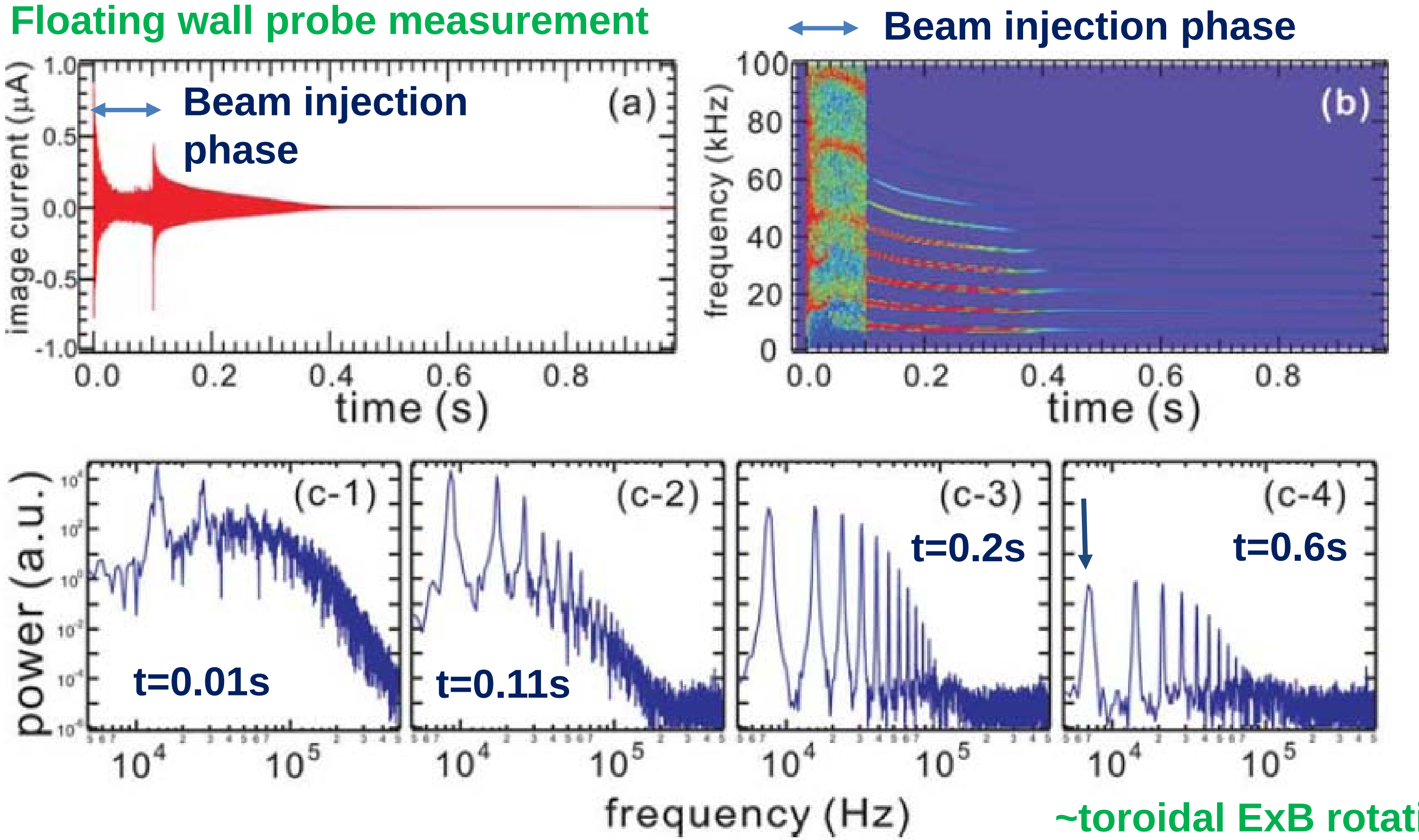


Visualized magnetic surfaces

- Electrons are injected by a movable electron gun with a LaB_6 cathode
  - Beam injection from edge region ➡ Plasma formation in confinement region
  - After beam injection, cathode heating current is also turned off (to ensure that electron supply is certainly turned off)

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

Floating wall probe measurement

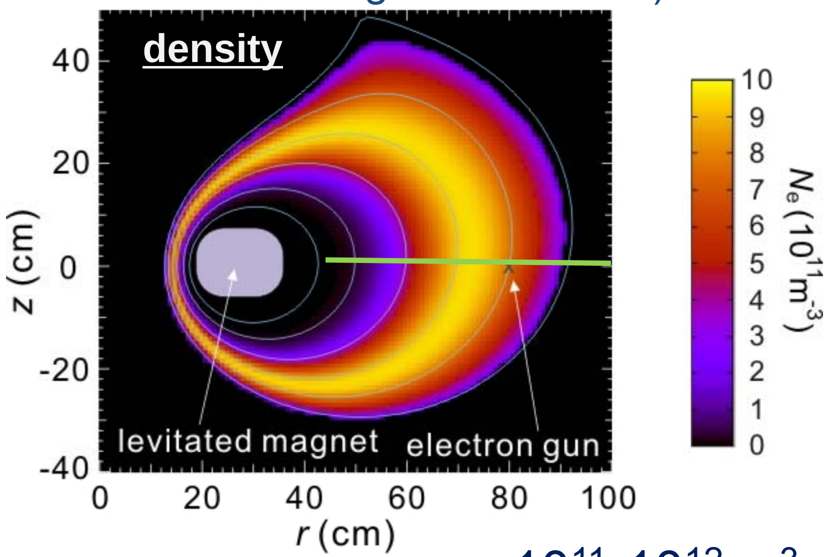


~toroidal ExB rotation freq.
collective moe

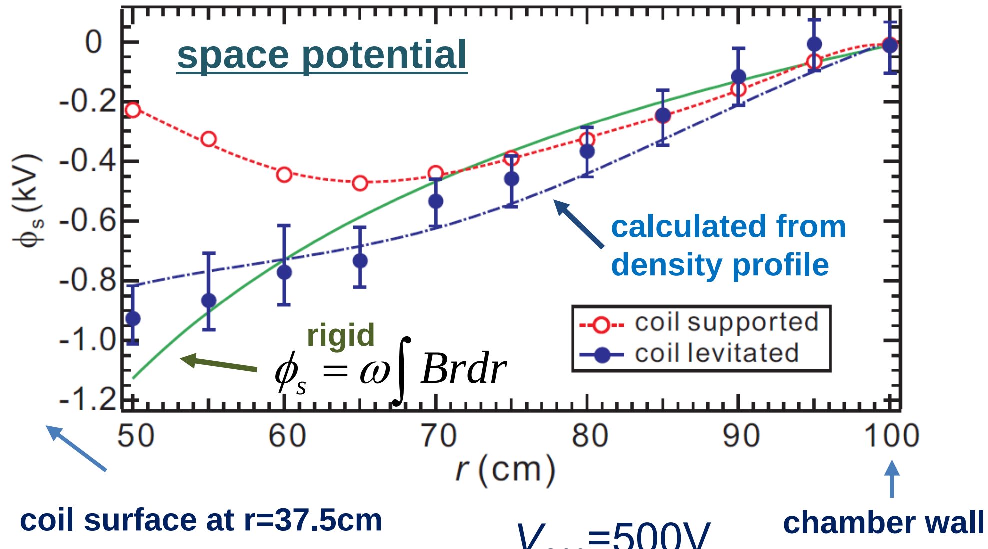
- The electron gun was operated from t=0 to 0.1s.
- Plasma has turbulent-like fluctuation component in injection phase, and is stabilized after the end of beam injection.

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}



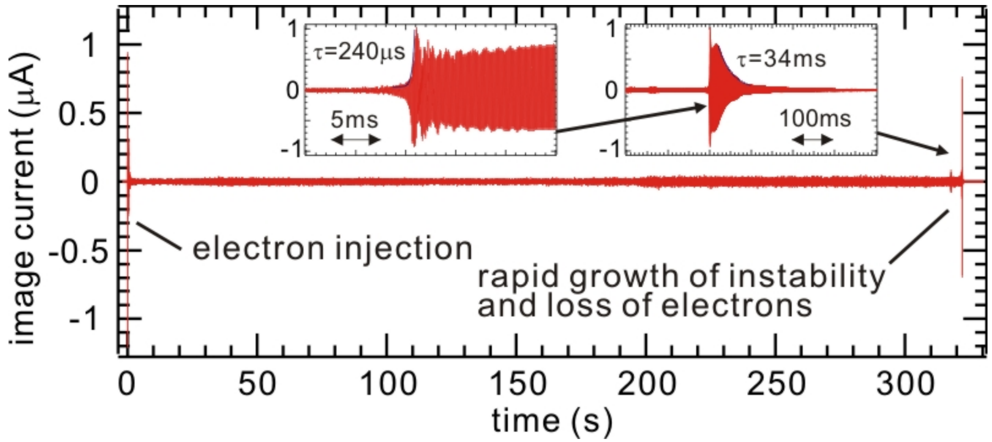
- When the magnet is not levitated
  - Potential profiles (○) are hollow ➡ plasma has strong shear flow

    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.

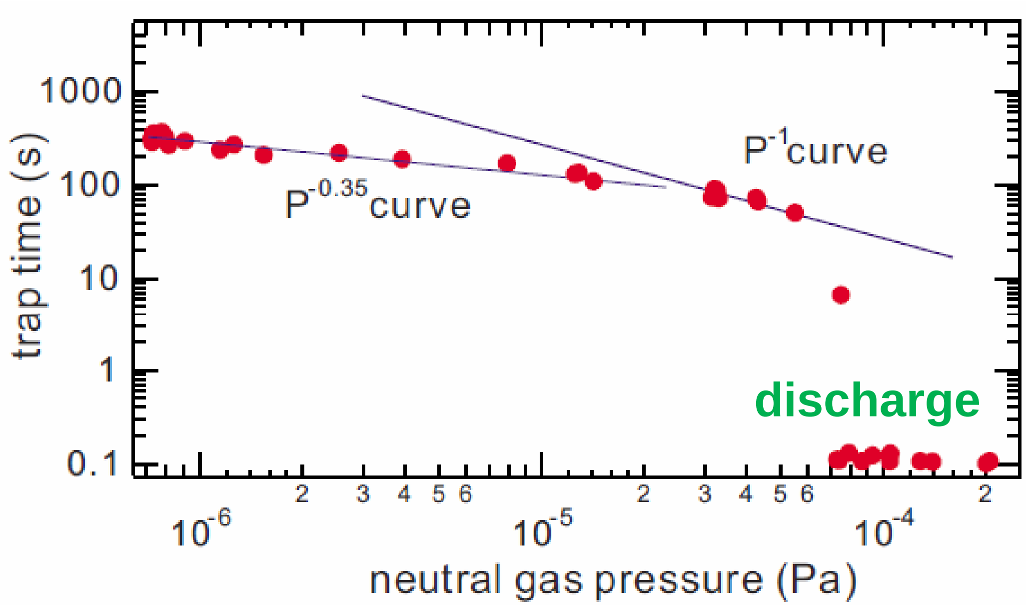
Stable confinement of PEP for more than 300s is realized, trap time comparable to the diffusion time due to neutral collisions

Floating wall probe measurement



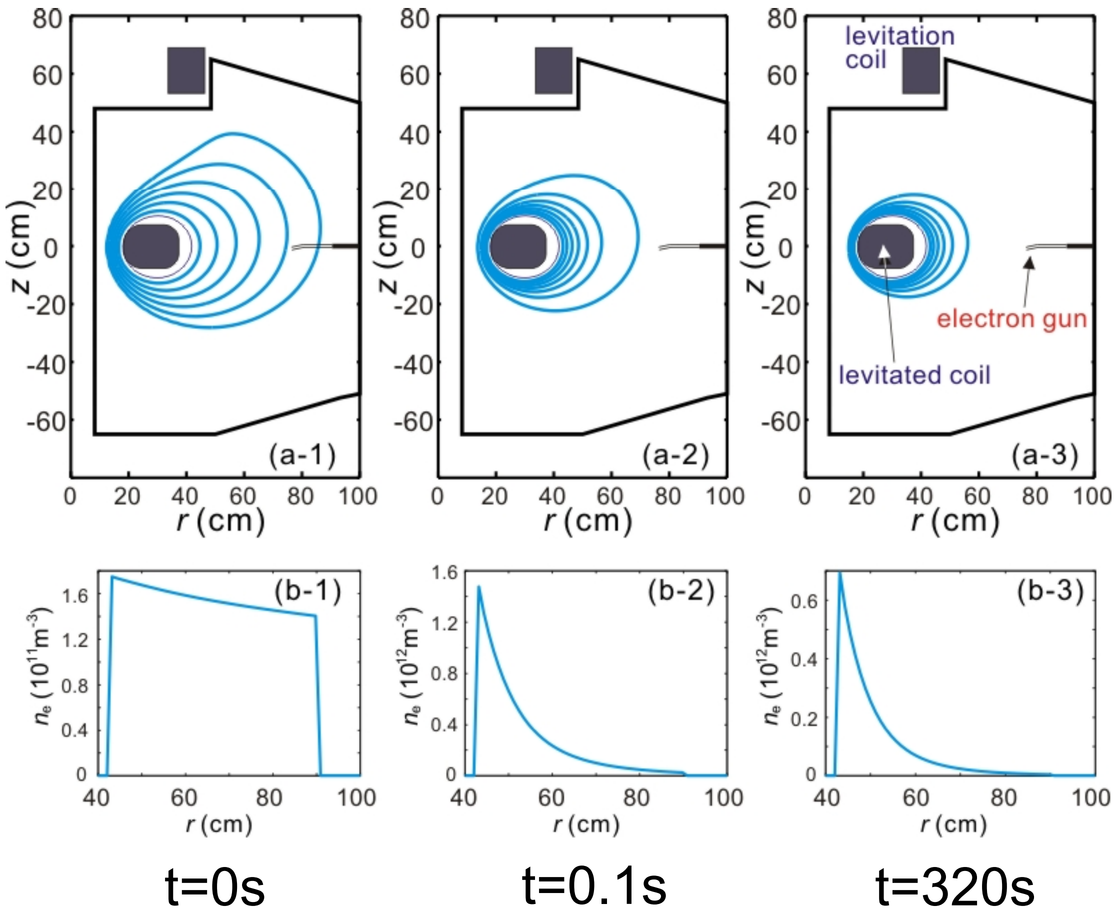
- Long confinement is realized by the magnet levitation

- Instability does not grow, until the end of confinement



- The nonlinear relation (τ*P_n≠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

(a) during beam injection,

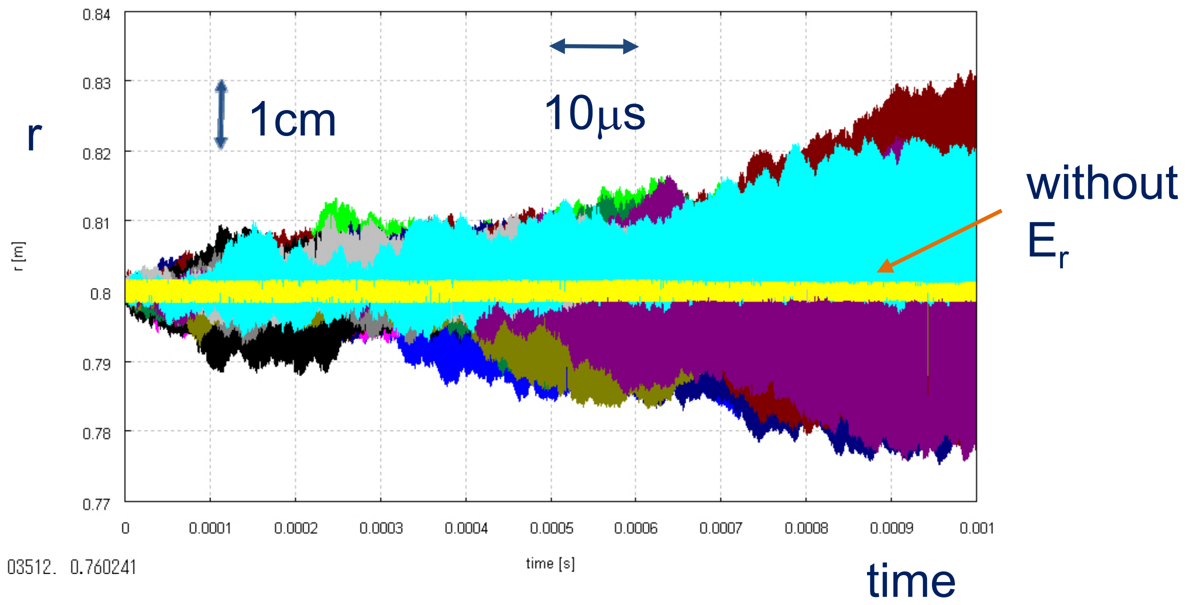
(b) after stabilization,

(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

Test particle simulation suggests that effective radial diffusion is realized during beam injection phase

- Test particle simulation in random fluctuating electric field



Randum field of 10^3V/m ➡ ~10cm/ms of tansport

- P_θ is not conserved due to asymmetry, leading to radial particle transport
- Large electrostatic fluctuations in the relaxation phase can work as a driving force to create relaxed states of dipole plasmas.

Relaxed states governed by adiabatic invariants

***Z. Yoshida, N. Kasaoka, to be published.**

- For Boltzmann distribution $f(x,v) = Z^{-1}e^{-\beta H}$, corresponding density is

$$\rho(x) = \int f d^3 v \propto \exp(-\beta\phi),$$

thermal equilibrium, which is constant for charge neutral systems.

- Conservation of invariants, in addition to the total energy *H*, leads to more complex (or realistic) density profiles of dipole plasmas.

Low frequency (diocotron range)

- Fluctuations can easily destroy the symmetry and conservation of P_θ ($\propto\Psi$).

- Assuming that μ and *J* are robust invariants, distribution function is

$$f(x,v) = Z^{-1}\exp(-\beta H + \alpha\mu + \gamma J)$$

- It was shown that density per flux tube is constant for neutral limit

$$\rho(x) = \int f \frac{2\pi\omega_c d\mu}{m} \frac{dJ}{mL_{//}(\Psi)} dv_d \propto \omega_c / L_{//}(\Psi) \propto r^{-4}$$

- Cases with non-neutral plasma is will be conducted*

3. Initial results on positron injection into dipole

- Electron plasma successfully trapped in dipole field, applicable to the confinement of positrons simultaneously, in principle

very weak beam current, especially after moderation

- In a toroidal dipole field configuration,
  - High energy charged particles can be trapped
  - Trapped particles may be cooled by radiation in strong field regions

  ➡ Possibility of the direct trap of positrons from sources in dipole field

- Issues to be solved for toroidal confinement of positron plasma
  - Reduction of return current to the source
  - Radial inward transport across closed magnetic surfaces

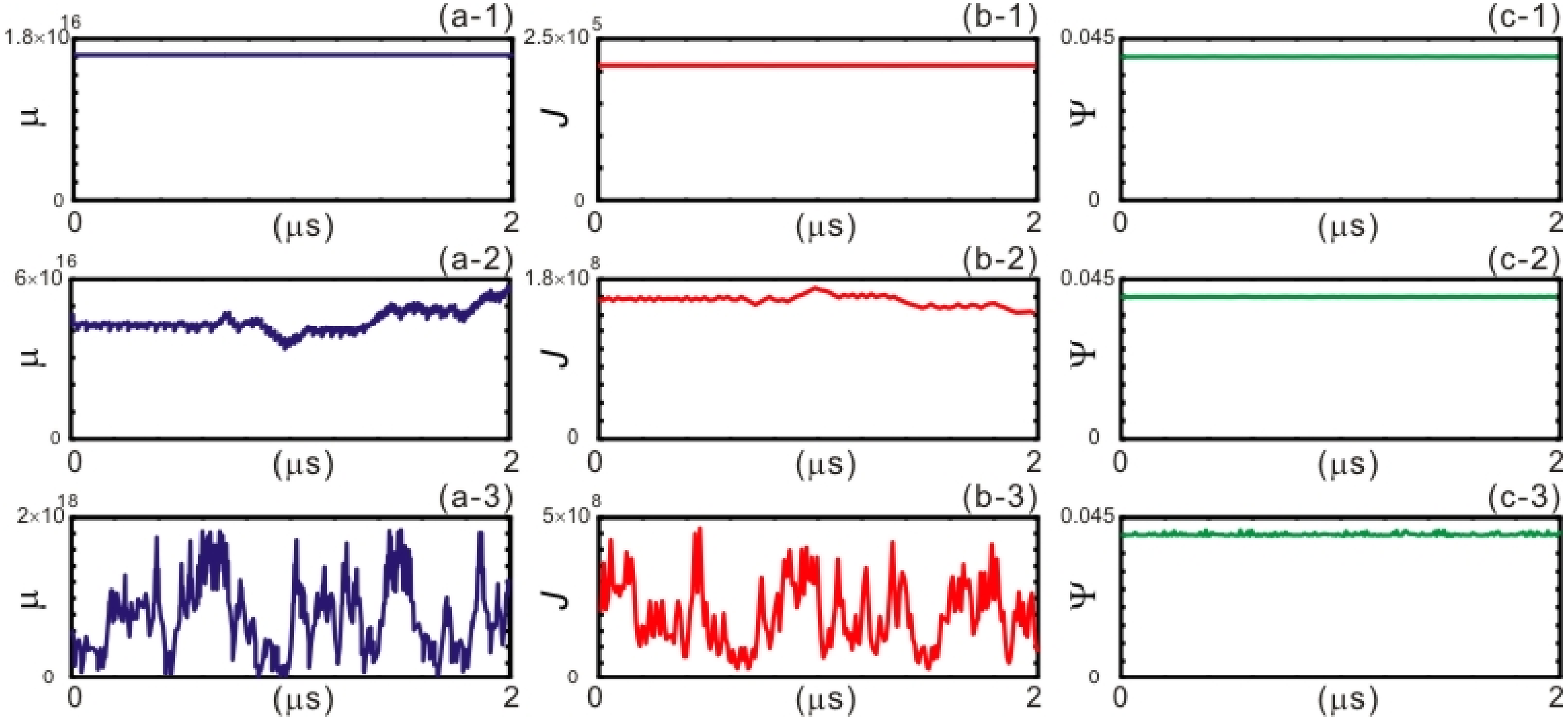
- Temporal evolution of "adiabatic invariants" of positrons in RT-1

$\mu = v_\perp{}^2 / B$ $J = \int v_{//} ds$ $\Phi = \int B dS \sim P_\theta$

1keV

10keV

100keV

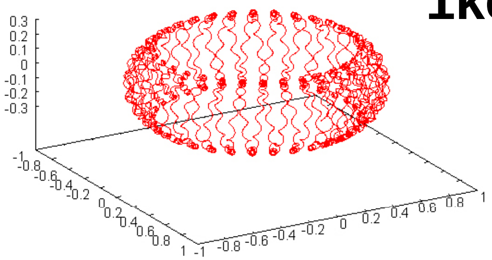


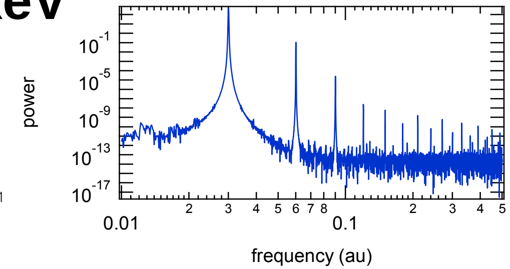
• μ and J are not conserved for high energy positron in RT-1

• Φ is generally conserved (due to the symmetry of trap system)

- Low energy magnetized particles have four constants of motion

1keV





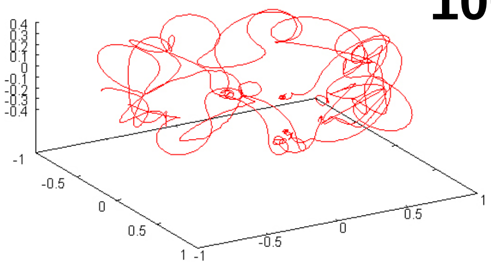
- Orbit is integrable
- Periodic motions

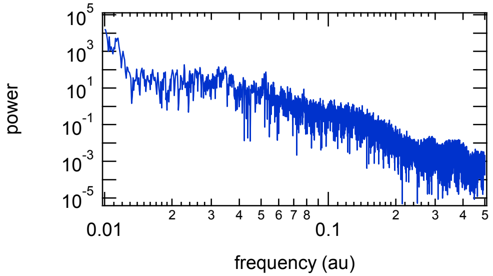
Positrons go back to a source in short times

Typically after one bounce

- High energy particles have only two constants of motion (E and Φ)

100keV

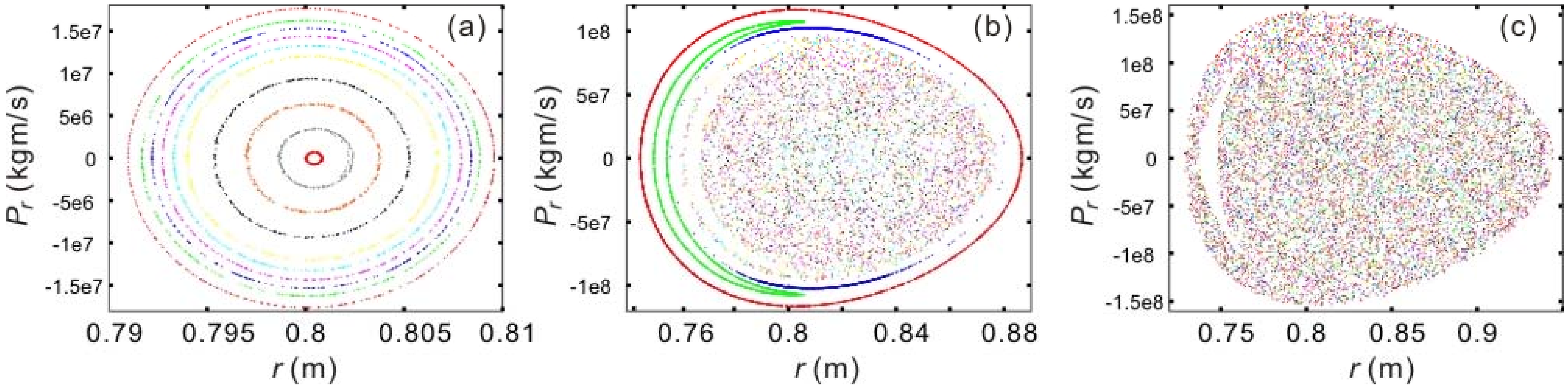




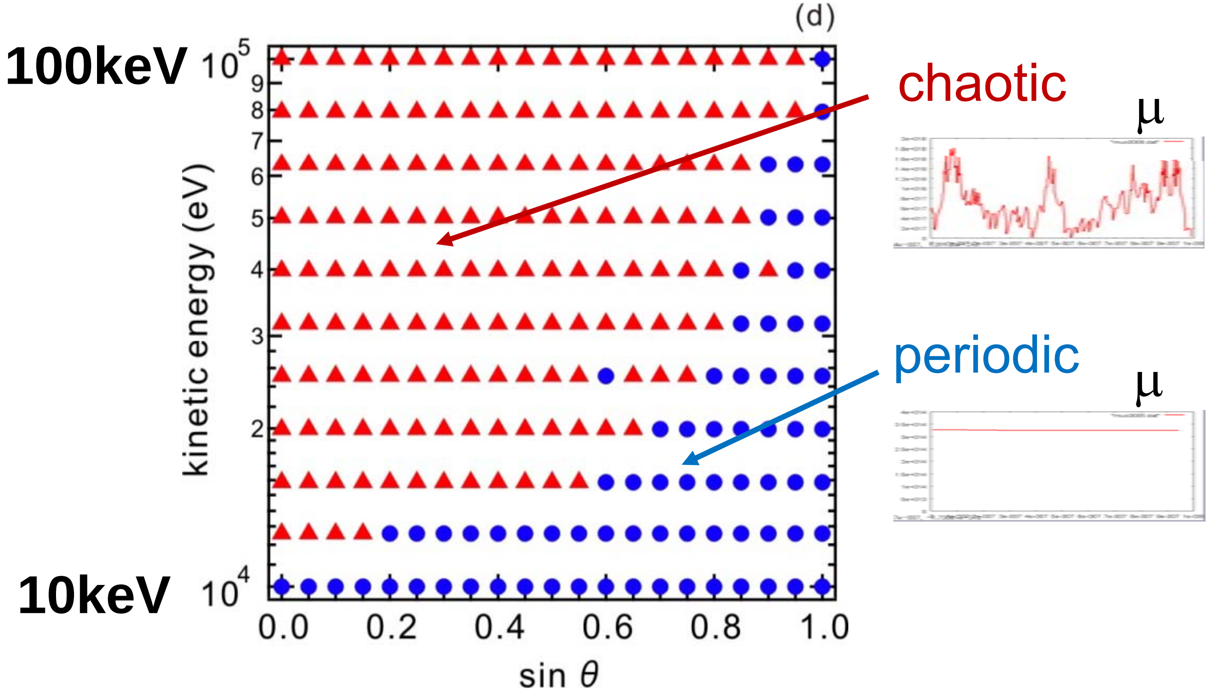
- Orbit is non-integrable
- Non-periodic motions

Long orbits before hitting the source, long life time

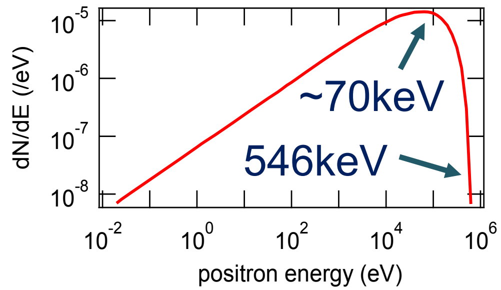
1keV **10keV** **100keV** **Poinceré plot**



Considerable ratio of positrons from a Na-22 source has chaotic orbits in a dipole field of RT-1



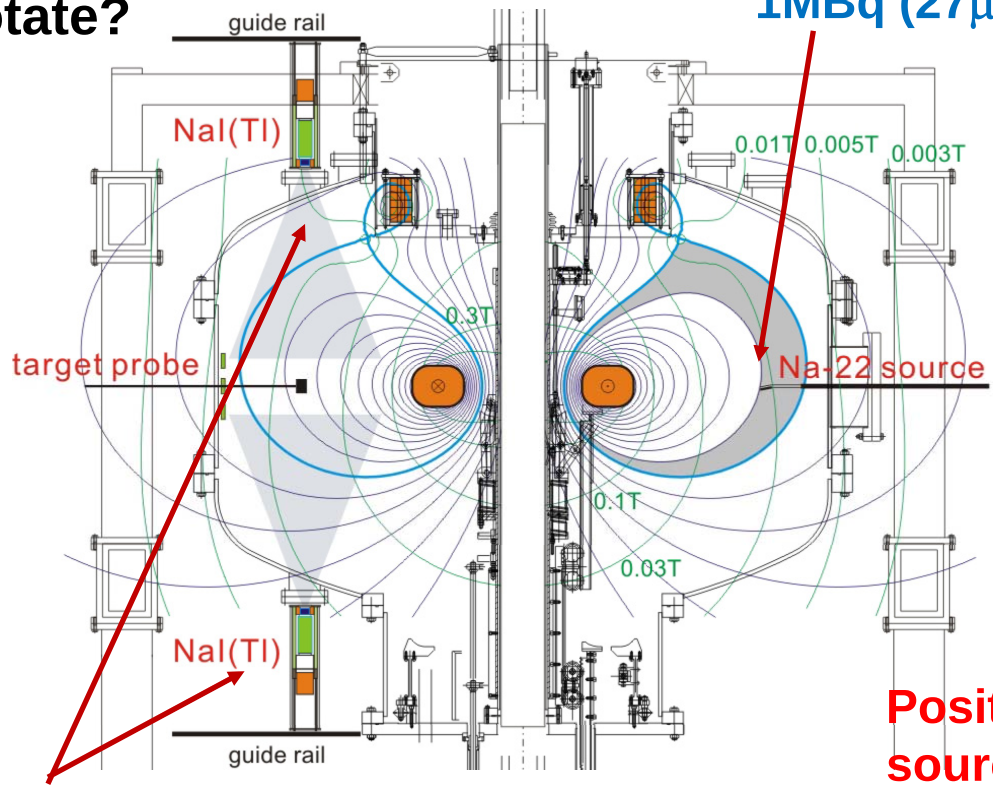
Positron energy spectrum from a Na-22 source



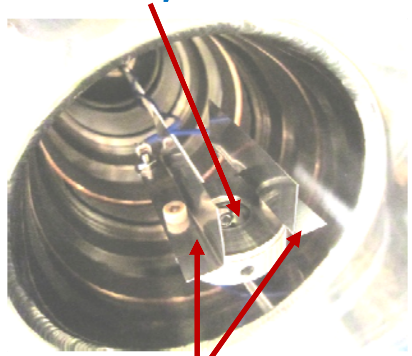
- Positron orbit is **periodic** or **chaotic** (whether μ is conserved or not) depending on kinetic energy and pitch angle
- In RT-1, approximately 70% of positrons from Na-22 source takes chaotic and long orbits (~100 toroidal rotation)
- By applying azimuthal electric field in this phase, positrons may be transported inward to the strong field region.

Detection of injected positrons by a target (preliminary experiment)

- **Positrons rotate?**
- **E_θ works?**



1MBq (27μCi) Na-22 β+ source

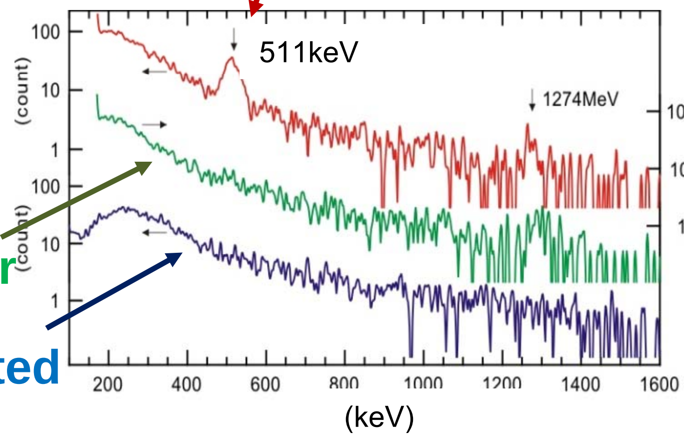


electrodes

NaI(Tl) scintillator-photomultiplier systems

- annihilation 511keV γs on a movable target
- PHA (pulse height analysis) and coincidence

Positrons travelling from source to target

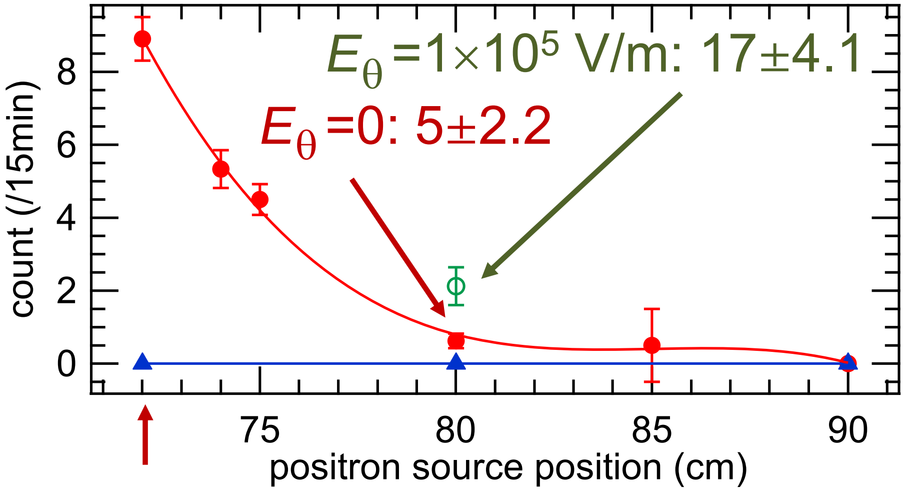


target outside chamber

dipole field magnet not operated

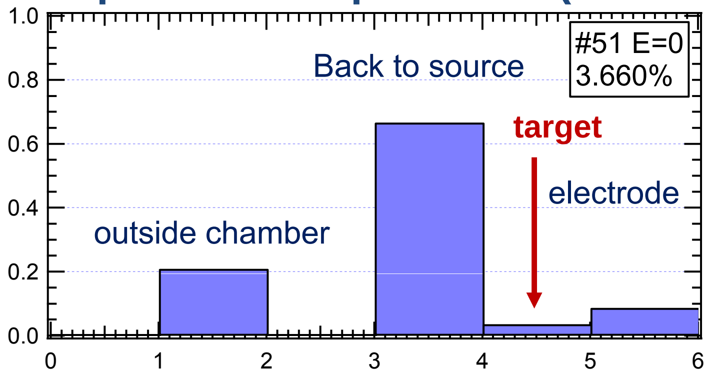
Detection of annihilation γ-ray and effects of azimuthal field

- Approximately 5% of injected positrons hit the target
- Effects of the application of edge field were confirmed

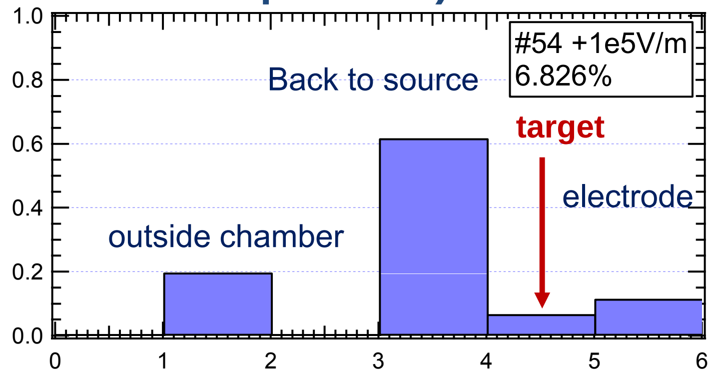


Scintillator located at r=72cm

Lost positions of positrons (calculation with 2000 test particles)



Without E_θ at edge region



E_θ =1×10⁵ V/m applied

Summary

- Pure electron plasma confinement in RT-1
  - Long confinement by the levitation of dipole field magnet
  - Spontaneous formation of stable (possibly rigid-rotating) states
  - Approx. 10^{11} electrons trapped for more than 300s
  - Inward diffusion and peaked relaxed state
- Initial results on positron injection and trapping
  - Chaotic motion and long orbit of high energy positrons
  - Toroidal rotation and effects of E_θ were confirmed
- Future tasks
  - Injection of positrons from strong field regions, RF application
  - Development of efficient positron injection method into dipole field