Confinement of toroidal non-neutral plasma in Proto-RT

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Outline:
- Toroidal geometries for charged particle trap
- First step experiment in Prototype-Ring Trap (pure electron plasma)
- Particle injection into magnetic surfaces
- Summary

Toroidal geometry for non-neutral plasmas

- Trap geometry without the use of a plugging electric field

  ⇒ • Simultaneous confinement of multiple particles with different charges

  “Overlap” region of particles is not limited due to the Debye length

- Observation of various new plasma phenomena*

  Creation of antihydrogen plasma, positron-electron plasma, etc.

  Basis for the realization of the experiments on astrophysical phenomena, as well as in the fields of atomic and plasma physics

- Potentially useful for the efficient production of antimatters

- Confinement of plasmas at any degree of non-neutrality

  Fundamental properties of non-neutralized flowing plasmas:

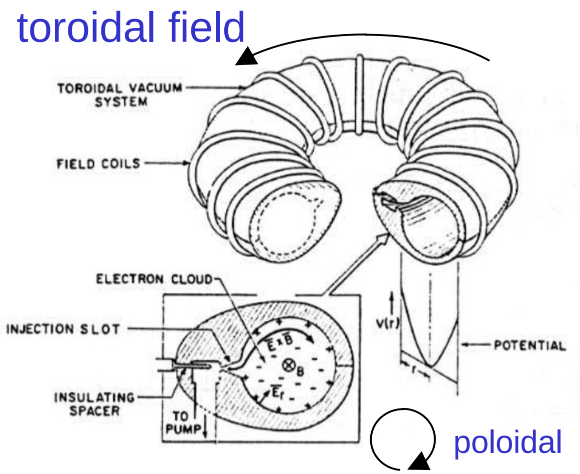
  Non-neutralization of plasmas ⇒ Radial electric field *or* Flow

  Plasma pressure is balanced by dynamic pressure (double Beltrami state**)

*V. Tsytovich & C. B. Wharton, Comment. Plasma Phys. Control. Fusion **4** 91 (1978).

** S. M. Mahajan & Z. Yoshida, PRL **81** 4863 (1998); Z. Yoshida & S. M. Mahajan, PRL **88** 095001 (2002).

Non-neutral plasma in a pure toroidal field configuration



1950~ Toroidal electron plasma in a pure toroidal field

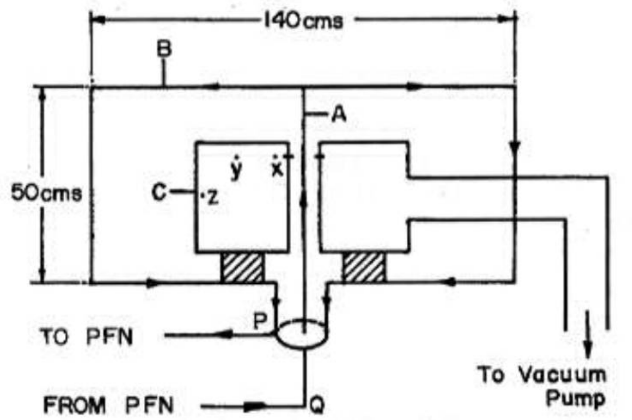
Ion storage, creation of relativistic electron beams*

- Confinement without "rotational transform"
  (without the addition of a poloidal field)
- Electron cloud of up to ~400kV
- Instability caused by the ionization

D. Daugherty et al., Phys. Fluids **12**, 2677 (1969).

1990~ "Low aspect ratio" torus

- Equilibrium with external electric field
- Electron injection by using drift orbit
- Electron plasma is confined for ~100μs
  (10^{-7}Torr, 100G, ϕ~100V)



P. Zaveri et al., PRL **68**, 3295 (1992).

Equilibrium of toroidal electron plasma is successfully demonstrated,
⇒ Confinement and stability properties

*D. Daugherty et al (1969); A. Mohri et al. PRL **34**, 574 (1975).

Magnetic-surface configuration for non-neutral plasmas

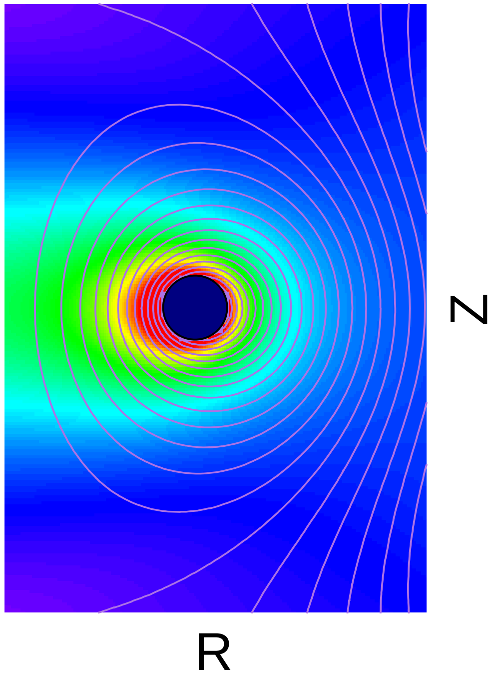
- **Particle motion in a poloidal field**

  Poloidal Magnetic surfaces: $\psi(\mathbf{r}) = const.$ planes,
  where magnetic field lines lie on $\psi(\mathbf{r}) = const.$

  Particles in an axis-symmetric system
  ⇒ Conservation of canonical angular momentum
  ⇒ Deviation of particle motion from magnetic surface
  is approximately (poloidal) Larmor radius

  Ignoring the mechanical momentum (stronger magnetic field)
  ⇒ Particle motion may be limited on magnetic surfaces

  - Improvement of the confinement properties
  - Simultaneous confinement of multiple charges



Example of magnetic surfaces (thin lines) and field strength

- **Possible applications of magnetic surface configurations**

  - Experimental test on the equilibrium of a flowing plasma*

    Advanced fusion concept, space plasma phenomena…

  - Simultaneous confinement of multiple charges**

    Antihydrogen plasmas, electron-positron plasmas, etc.

* S. M. Mahajan & Z. Yoshida, PRL **81** 4863 (1998); Z. Yoshida & S. M. Mahajan, PRL **88** 095001 (2002).
** Z. Yoshida et. al., in *Non-neutral Plasma Physics III*, 397 (1999), T. S. Pedersen & A. H. Boozer, PRL **88**, 205002 (2002).

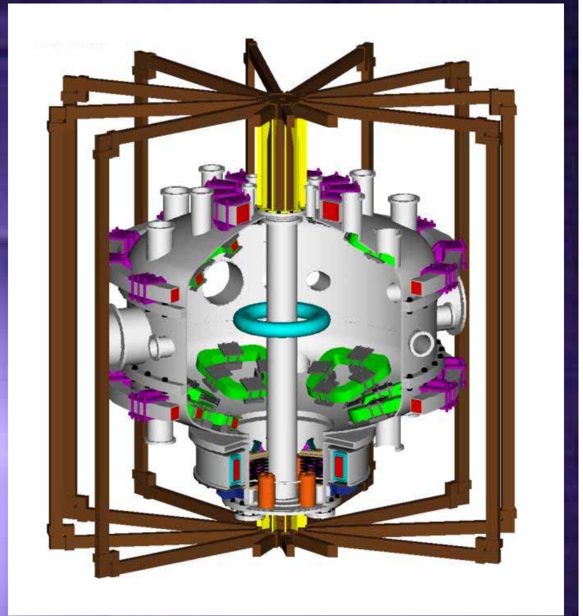
Non-neutral plasma research at UT －Ring Trap project*－

Proto-RT 1998-

- Normal-conducting coil with support structures
- Coil radius R_{coil}=30cm
- Coil currrent I_{coil}=10kAT(DC)

Mini-RT 2003-

- Superconducting (Bi-2223) levitated dipole field coil
- R_{coil}=15cm, I_{coil}=50kAT



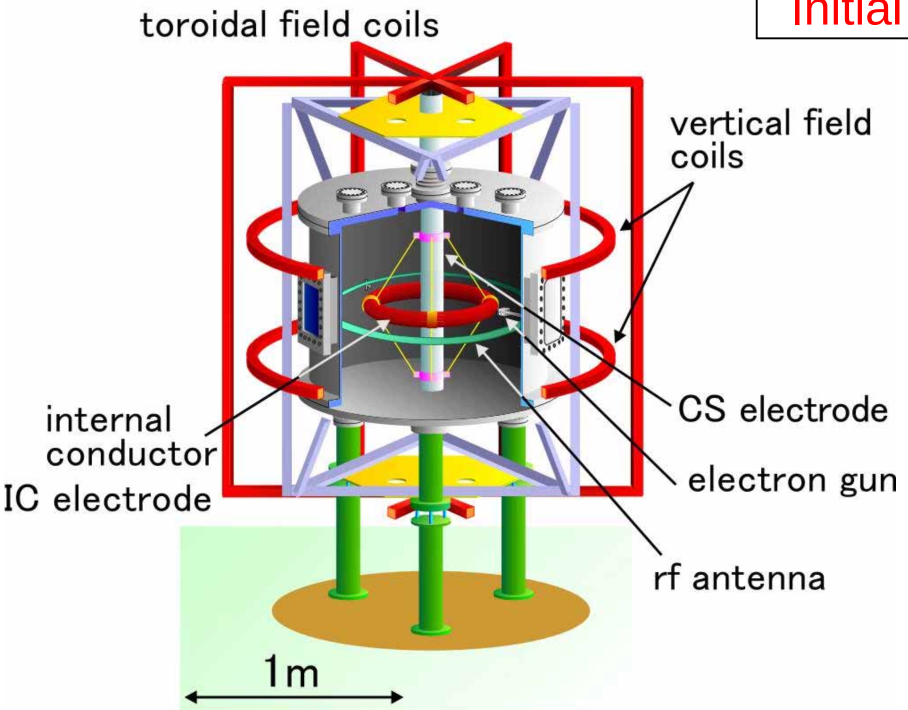
RT-1 2005-

Ring Trap: Non-neutral plasma in a dipole magnetic field
axis-symmetric toroidal magnetic surface configuration

- Equilibrium and stability of flowing non-neutral plasma on magnetic surfaces
- Injection of charged particles into magnetic surfaces via magnetic neutral loop
- Chaos-induced resistivity of plasmas and applications to industrial plasmas

* Z. Yoshida et al., Y. Ogawa wt al., H. Himura et al., in *Non-neutral Plasma Physics III*, 397 (1999).

The Proto-RT (Prototype-Ring Trap) device



vacuum vessel	**inner radius**	**59 cm**
	height	**90 cm**
	base pressure	**5×10^{-7}Torr**
internal conductor	**major radius**	**30 cm**
	minor radius	**4.3 cm**
	coil current	**10.5 kAT**
vertical field coil	**major radius**	**90 cm**
	coil current	**5.25kAT × 2**
vertical field coil	**coil current**	**30 kAT**

Bird-eye view and machine parameters of Proto-RT

Initial experiment with toroidal electron plasma

- **Toroidal magnetic surface configuration**
  - Internal conductor (dipole field coil)
  - A pair of vertical field coils
  - Toroidal field coils (for magnetic shear)

⇒ Trap of particles on magnetic surfaces

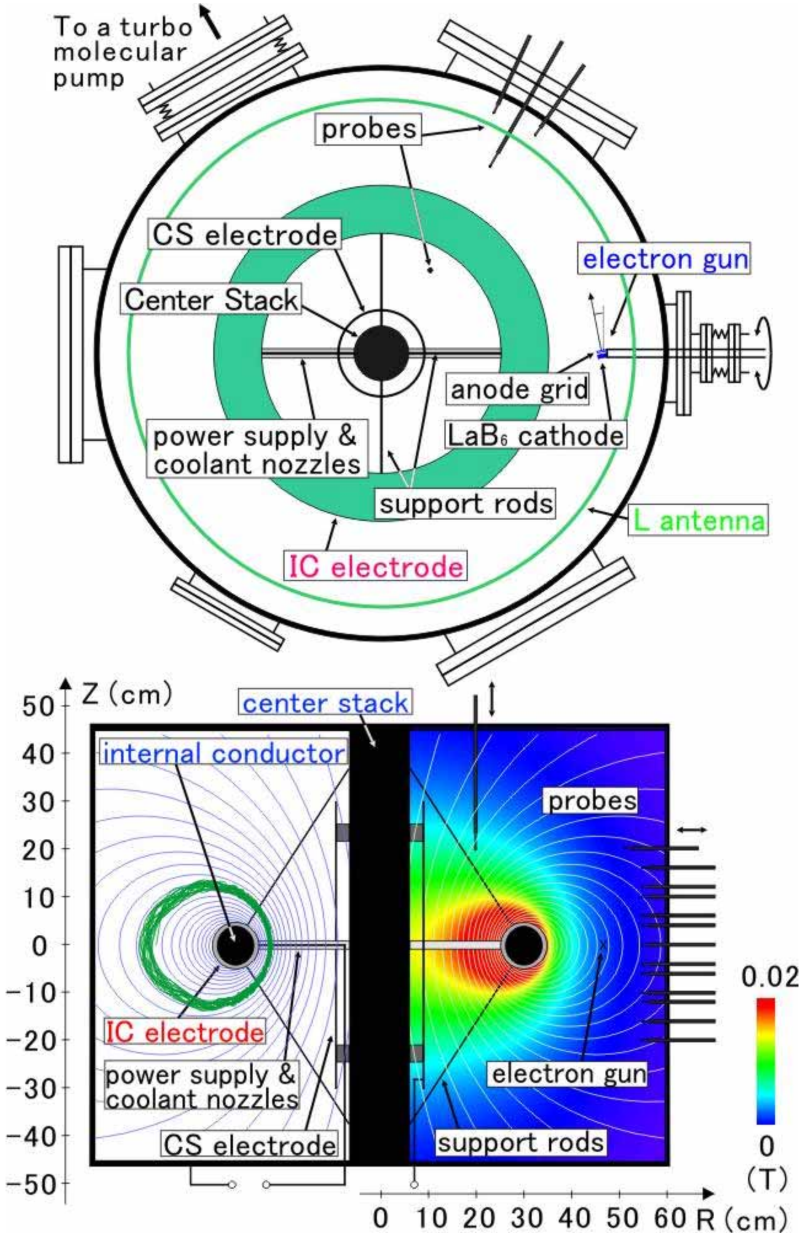
- **External plasma bias**
  - Torus electrode on the internal conductor
  - Cylindrical electrode on the center stack

⇒ Potential optimization, radial electric field

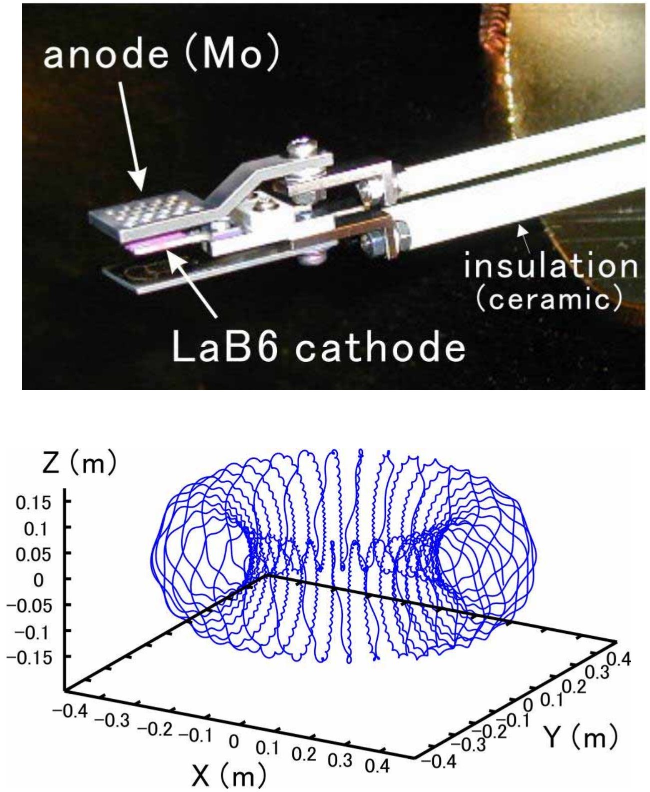
- **Formation of electron plasma**
  - Electron gun with LaB6 cathode

- **Diagnostics**
  - Emissive Langmuir probe array
    space potential distributions
  - Wall probes
    electrostatic fluctuations, charge decay

Experimental setup and electron injection



Top view and poloidal cross section of Proto-RT

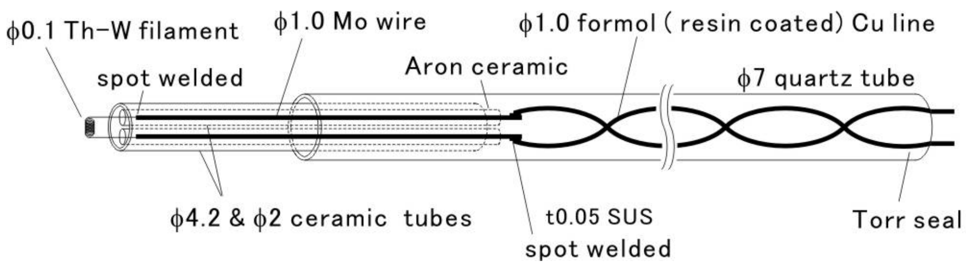


Electron gun and the typical beam orbit

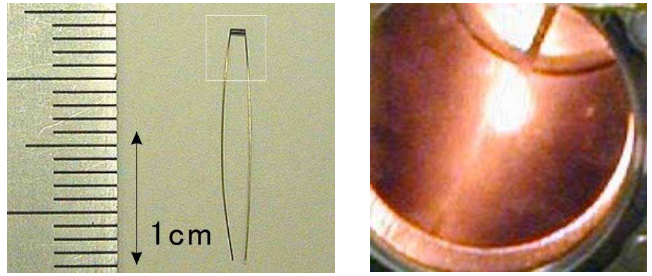
- Electron injection into DC magnetic field
- Toroidal symmetry of the field warrants the trap of charged particles on the magnetic surfaces

Diagnostics: potential profile and fluctuation measurements

- **Emssive Langmuir probes***



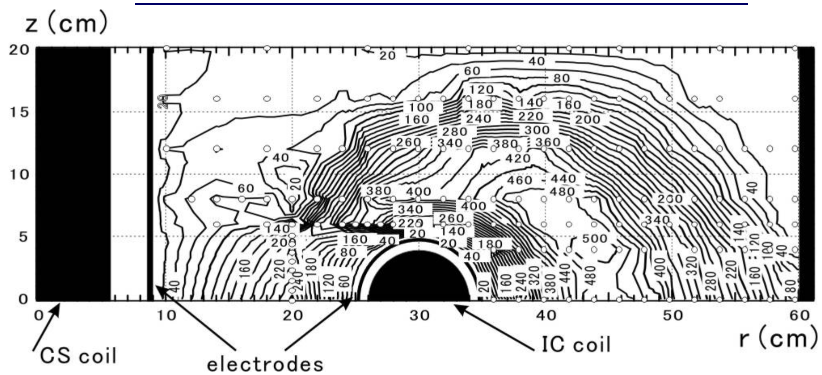
Emissive Langmuir probe construction



Probe filament and electron emission

Potential distributions with fine resolution
(during electron injection phase)

Two-dimensional profiles are measured
by the use of a probe array



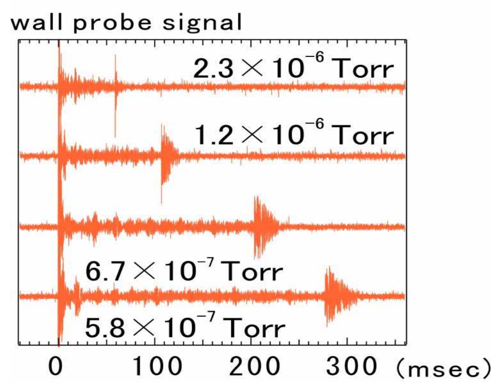
Measuring points (○) and reconstructed distribution

- **Wall probes***

Electrostatic fluctuations: diocotron mode, disruption…

Trapped charge: confinement time of plasmas

Measurements during the confinement phase
(without destruction of plasmas)



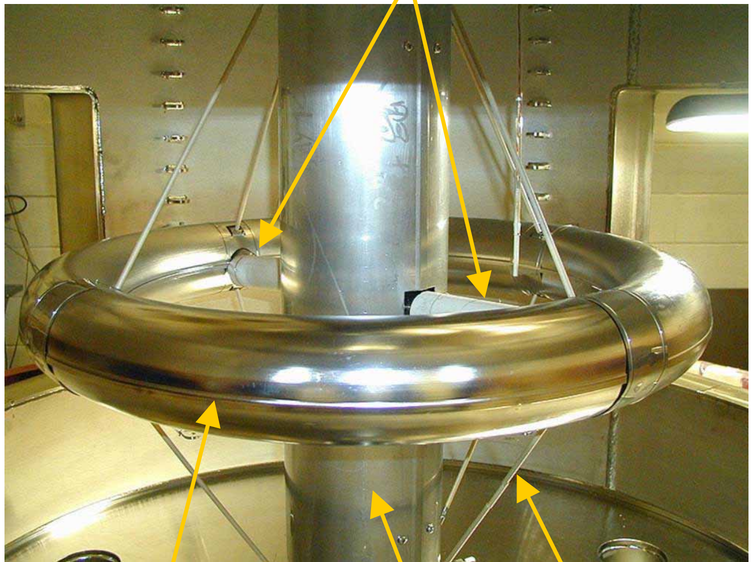
Wall probe signals

* R. F. Kemp et al., RSI **37**, 455 (1966), H. Himura et al., Phys. Plasmas **8**, 4651 (2001). ** J. D. Daugherty et al., Phys. Fluids **12**, 2677 (1969).

Internal view of Proto-RT

Coil current feed & cooling structures

Langmuir probes



Coil support

Electron gun
LaB6 cathode and anode

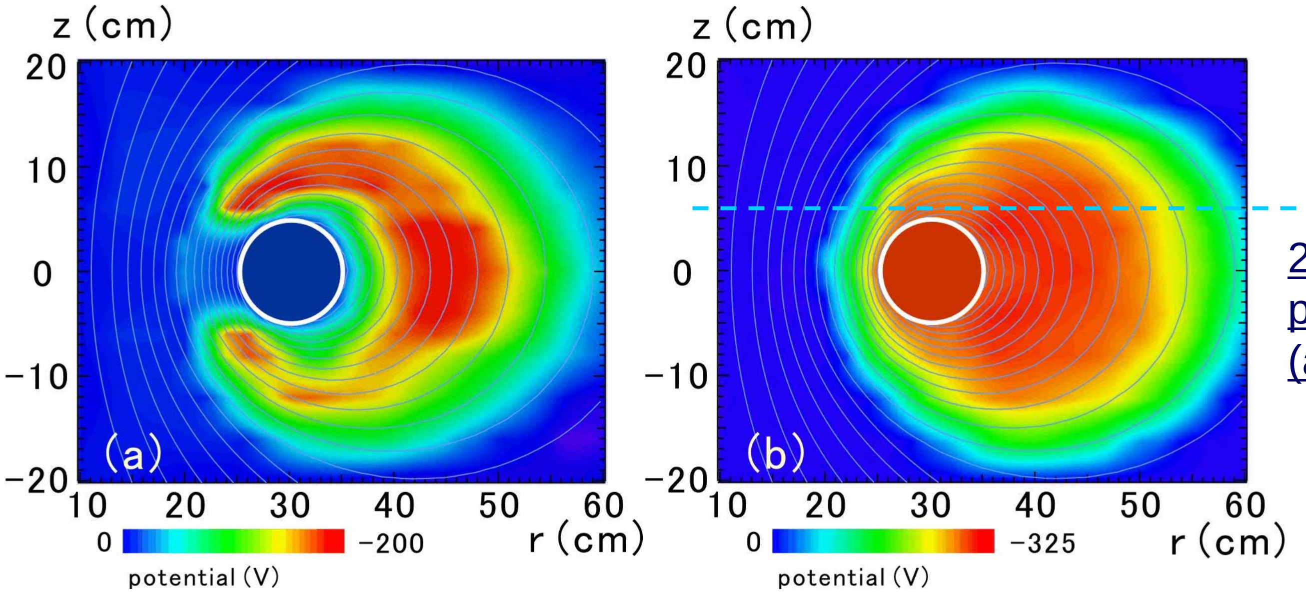
Internal conductor (IC)
(dipole field coil)
and electrode

Center stack (CS)
(toroidal field coil)
and electrode

<u>Photographic view inside the Proto-RT device</u>

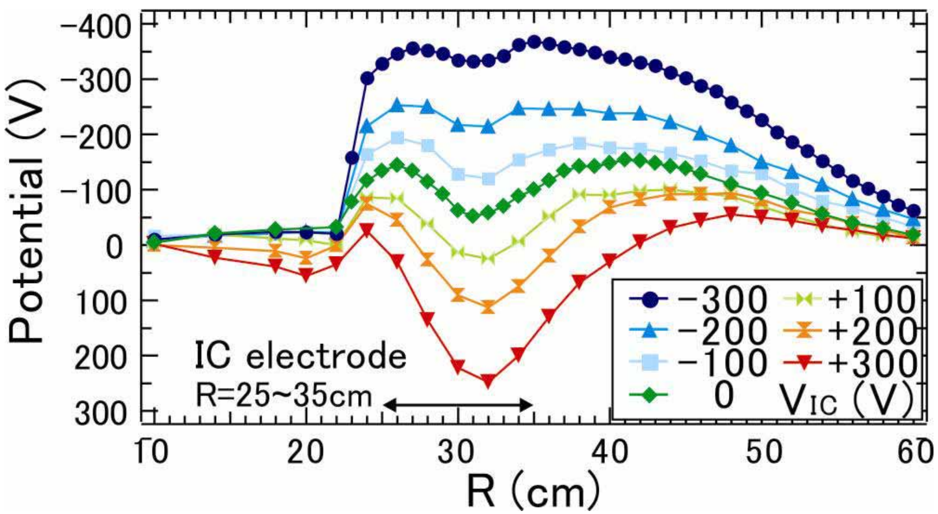
Magnetic field coil for dipole field, electrodes for plasma bias on IC and CS, electron gun, and diagnostic probes for potential measurements

Potential structures of a toroidal electron plasma



2-d potential profiles in the poloidal cross section when (a) Vic=0V and (b) Vic=-300V.

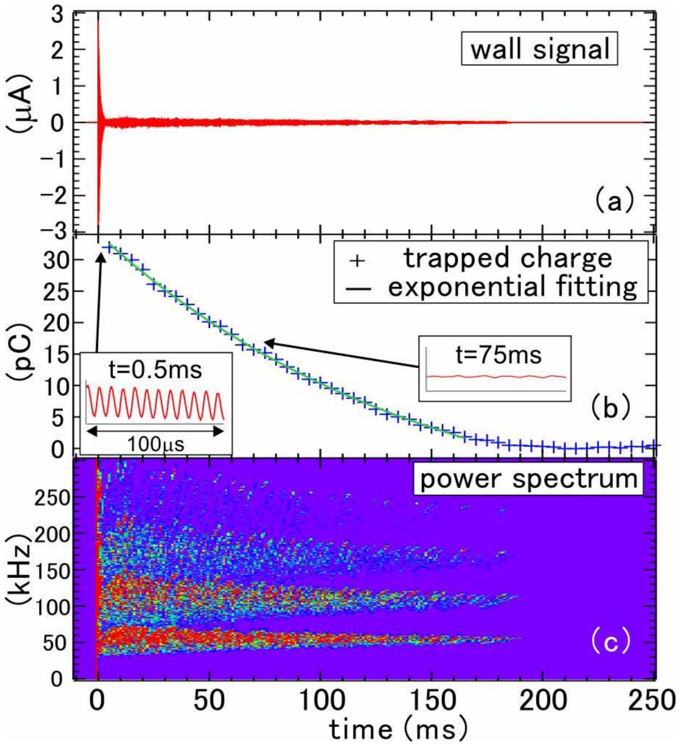
Reconstructed from 254 data points.
Thin lines show magnetic surfaces.



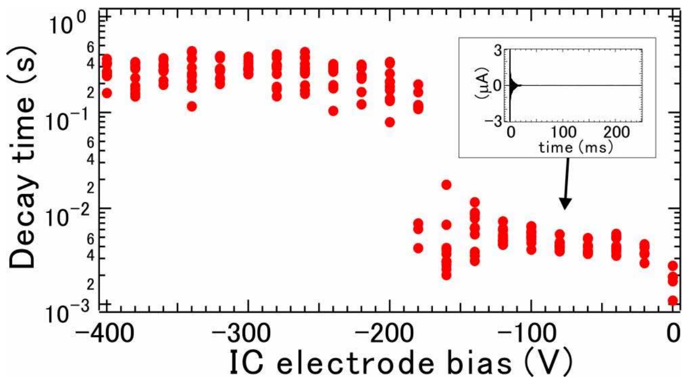
Radial potential profiles at Z=+6cm in the variation of bias voltage of the IC electrode (Vic)

- No bias (Vic=0V) or positively biased:
  - -Disagreement of **ψ** (magnetic surface) and **Φ** (potential) contours
  - -Sheared E×B flow, energy source for the diocotron instability
- No bias (Vic=0V) or positively biased:
  - -**ψ** contours are close to **Φ** contours
    $\mathbf{B}\cdot\nabla\phi = 0$ is approximately satisfied
  - -Potential hall structure is eliminated

Stabilization by potential optimization, confinement time



Fluctuation signal of toroidal electron plasma



Confinement time in the variation of Vic

Experimental procedure:

Electron injection (V_{acc}=300V, t=-100μs~0s) into DC magnetic field by I_{IC}=7kAT and radial electric field by V_{IC}=-300V.

Confinement properties:

Stop of e-gun at t=0 (electron plasma of ~10^{-8}C)

⇒ Trapped charge at t=1ms: ~5×10^{-9}C

Without potential control (V_{IC}=0V) :
Plasma is not stabilized, fast decay in ~ms.

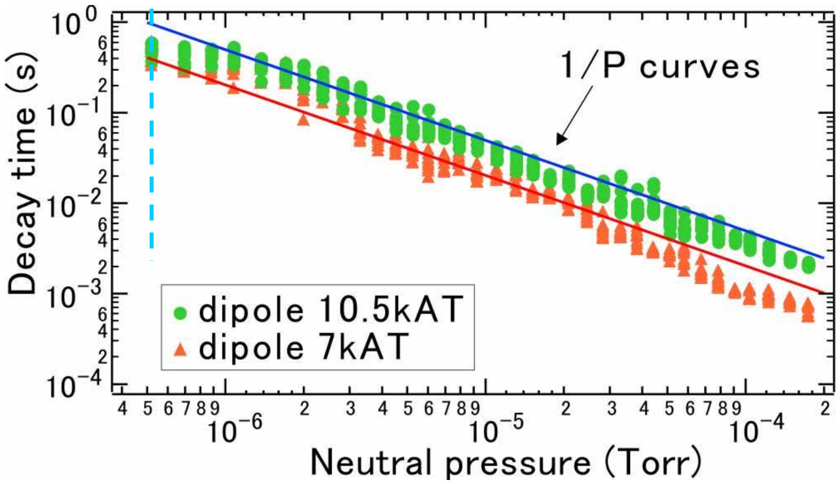
With potential control (V_{IC}<~-200V) :
Stable oscillation mode is realized,
fluctuation amplitude at t=0.5ms: ~10%
at t=75ms: <1%

(normalized by the fluctuation amplitude at t=-50μs)

Magnetic surfaces of dipole field
~ Equi-potential contours of the plasma

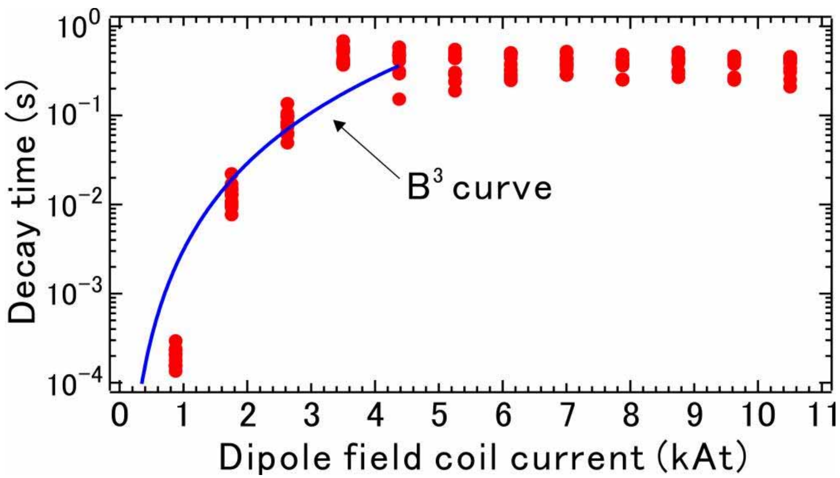
Elimination of Hollow potential structures

Confinement time scalings



τ in the variation of the back pressure P

(addition of hydrogen gas, in the dipole field of I_{ic}=7kAT)



τ in the variation of magnetic field strength B

(at the base pressure of B=5×10^{-7} Torr)

Dependence on P and B:

Measurement of the confinement time τ
in the poloidal (dipole) field configuration

Dependence on
- neutral gas pressure P
- magnetic field strength B

Force balance of electrons:

$$qn(\mathbf{E}+\mathbf{v}_e\times\mathbf{B})-m_e n_e \nu_{en}\mathbf{v}_e=0$$

$$0=qn_e v_r B - m_e n_e \nu_{en}(v_t - v_n)$$ in the toroidal direction.

Trap time caused by neutral collisions is

$$\tau_D \sim a/v_r = \frac{qaB^3}{m_e n_e \sigma E^2} \propto P^{-1}B^3,$$

where a~0.1m is the minor radius of the plasma.

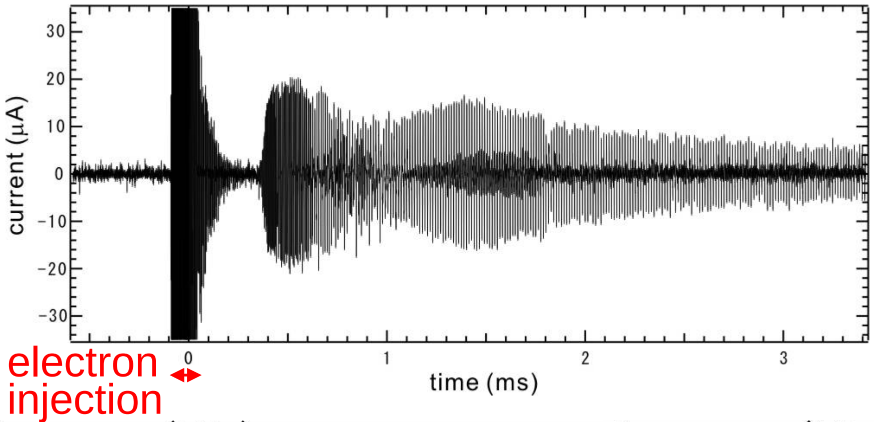
Rough estimate of the confinement time
In the present experiment:

B~50G, P=5×10^{-7}Torr, etc. ⇒ ~1s

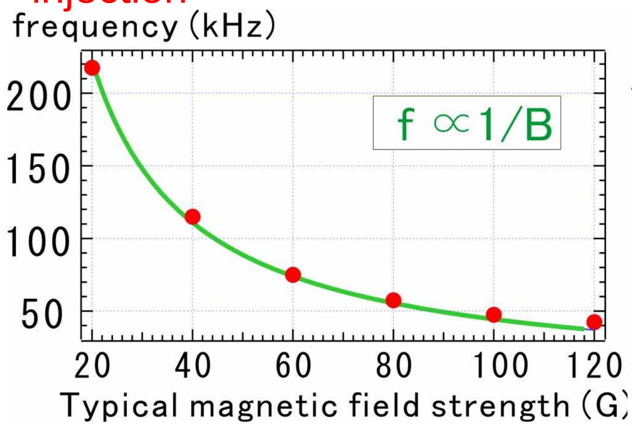
~Comparable to the observed confinement time τ
Dependence on P and B as $\propto P^{-1}B^3$

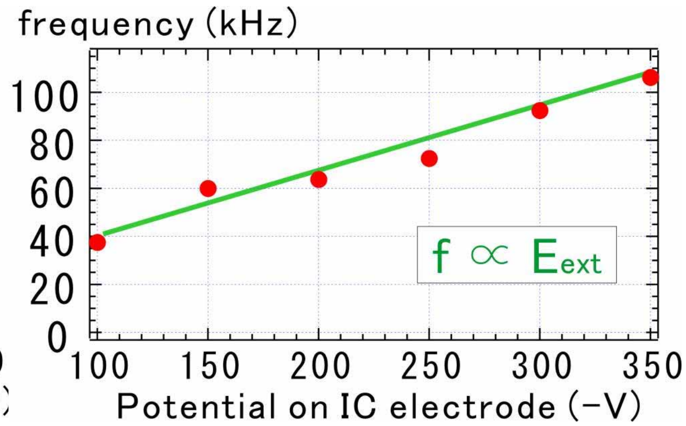
Stable confinement is realized in Proto-RT, trap time is limited by neutral collisions.
However, deviation from $P^{-1}B^3$ curves at low P.

Diocotron mode frequency



Example of the electrostatic fluctuation of Toroidal electron plasma

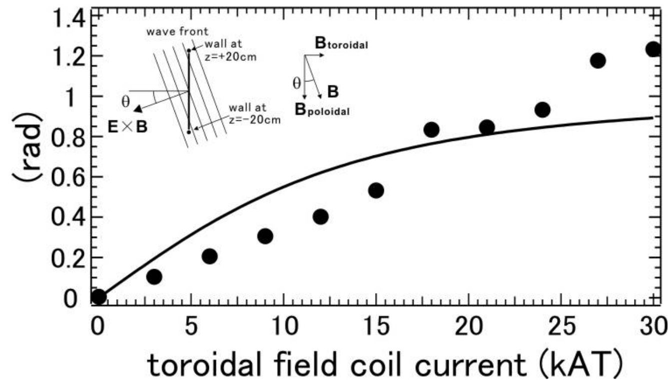




Frequency dependence on magnetic field B and external bias voltage Vic

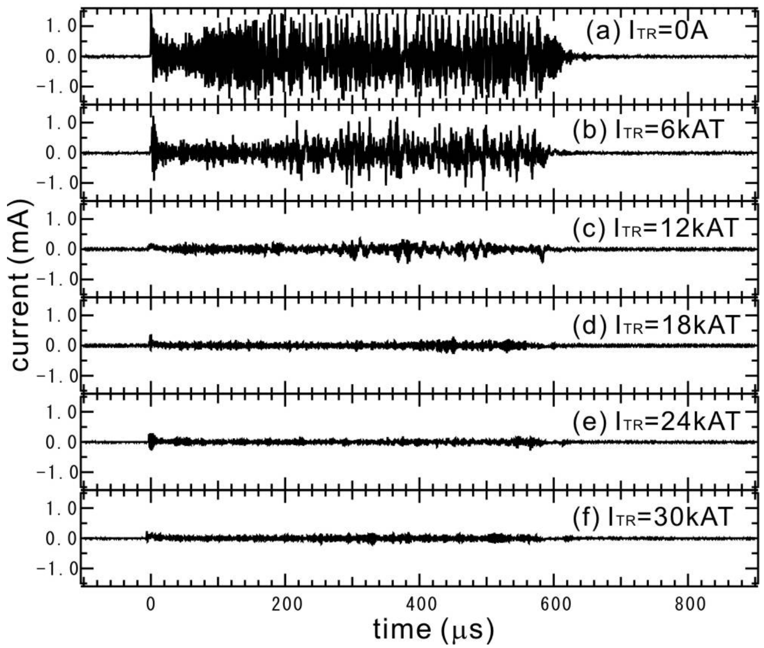
Temporal evolution, frequency, propagating direction
⇒ diocotron mode in a curved (dipole) field

Electron plasma of density: ~10^6cm^{-3} and
total trapped electrons: ~10^{11}
confinement time is ~1s (B~50G, P=5×10^{-7}Torr)



Phase shift between two walls

Stabilizing effects of magnetic shear

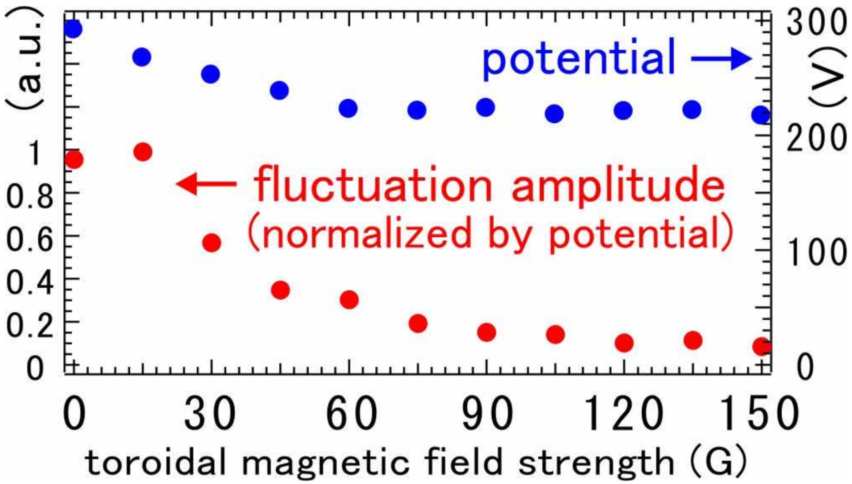


Fluctuation signal of toroidal electron plasma

Stabilization of diocotron mode by the addition of (magnetic shear) toroidal field*

Confinement properties,
precise measurements, etc….

Stronger toroidal field, while
dipole field strength is constant



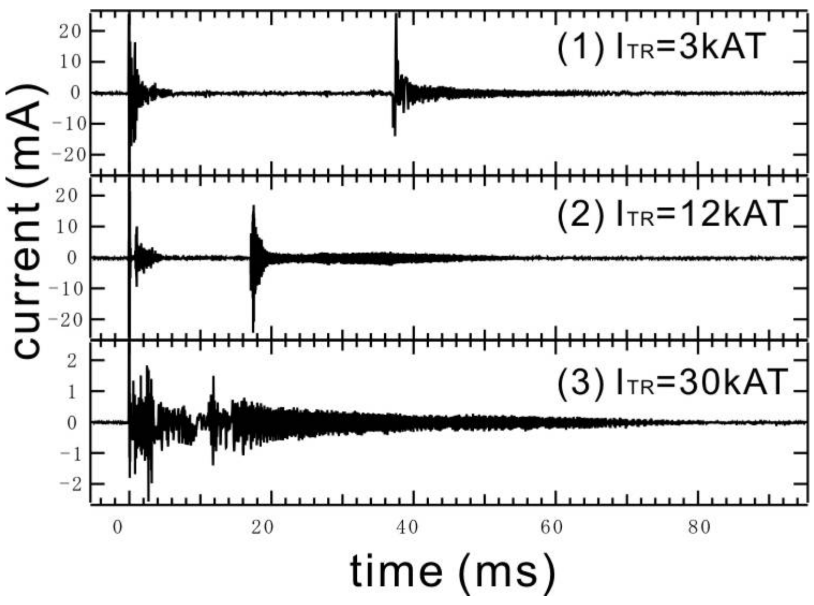
Fluctuation signal of toroidal electron plasma

Amplitude of the electrostatic fluctuation in the diocotron frequency range is stabilized,
while the generated plasma potential
is approximately constant.

(during the electron injection)

* S. Kondoh, T. Tatsuno, Z. Yoshida, Phys. Plasmas **8** 2635 (2001)

Effects of magnetic shear on a toroidal plasma



Fluctuation signals with the addition of toroidal field

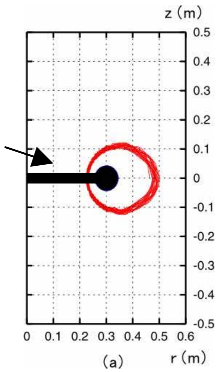
When a toroidal field is added, the plasma tend to disrupt during the trap phase.

(Although fluctuations are stabilized during the electron injection)

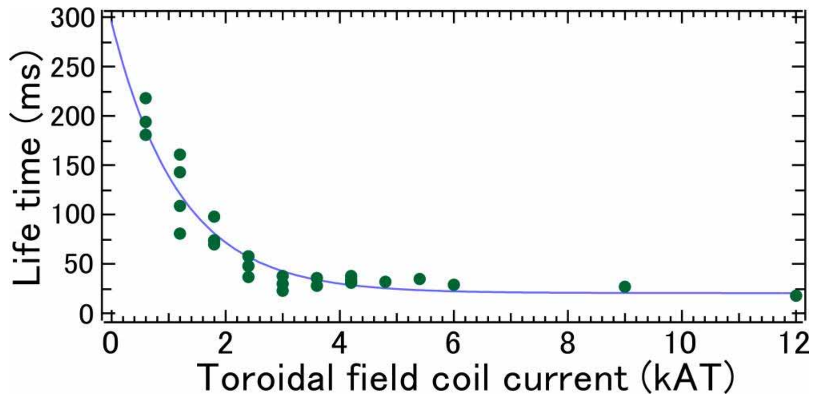
Disturbance due to the support structure

⇒ Possibly improved in future experiments with super-conducting levitated coil

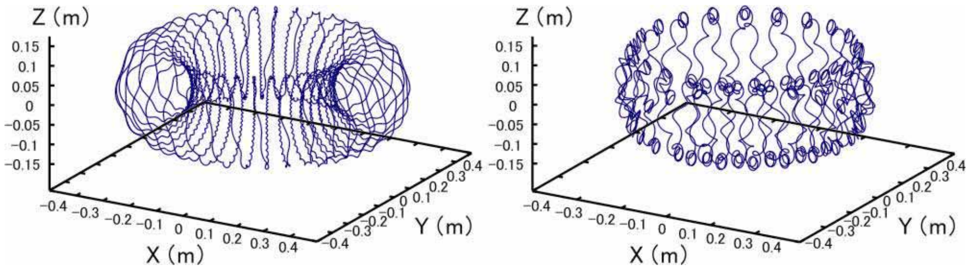
coil and support



Projection of orbit on R-Z crosssection



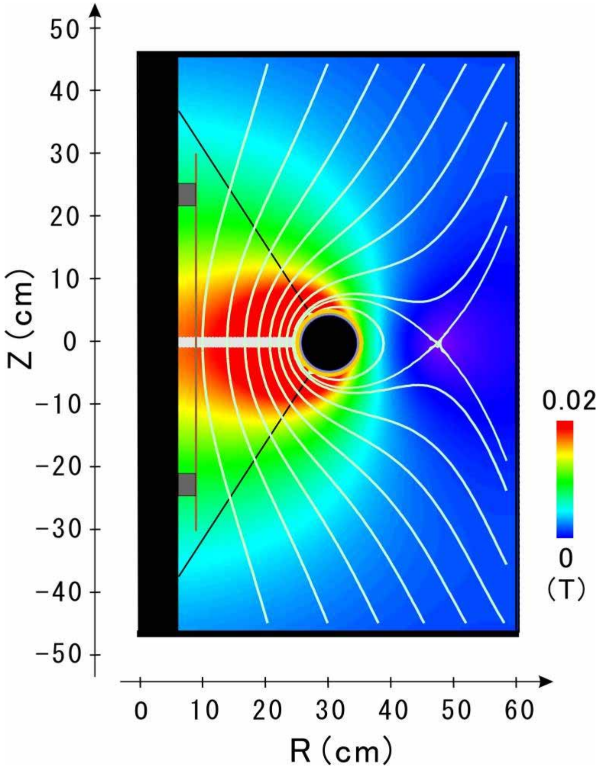
Stable confinement time of electron plasma



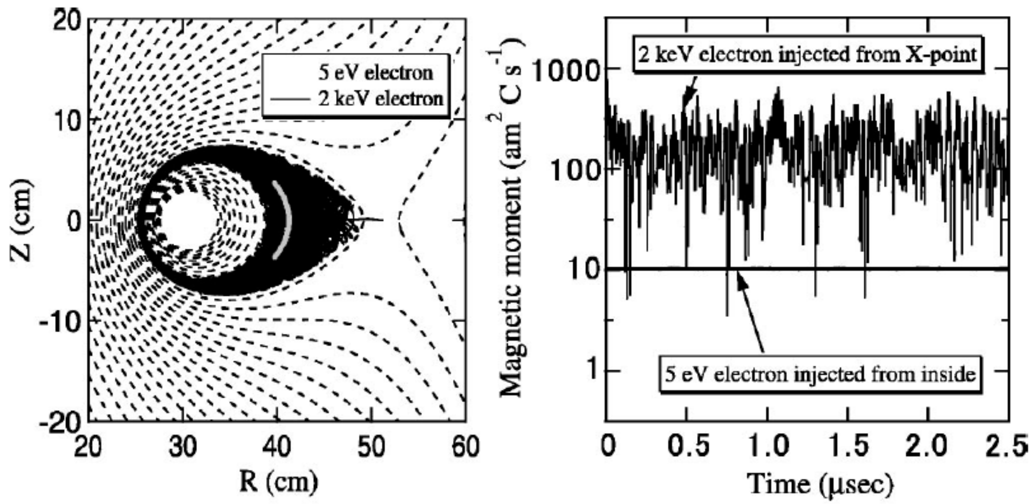
“Passing” and “trapped” orbit of particles

Particle injection using chaotic orbit

For the creation of multi-component plasmas: particle injection methods



X-point field configuration



* C. Nakashima, Z. Yoshida et al. PRE **65**, 036409 (2002)

Chaotic orbit of particle and injection into closed surfaces

Dipole magnetic field + vertical field

⇒ "X"-point magnetic surface configuration
magnetic null at "X", chaotic orbit.

Charged particles are successfully injected from edge region of the plasma

Stored electrons + positron injection

Stored positrons + antiproton injection

to form multi-component plasmas

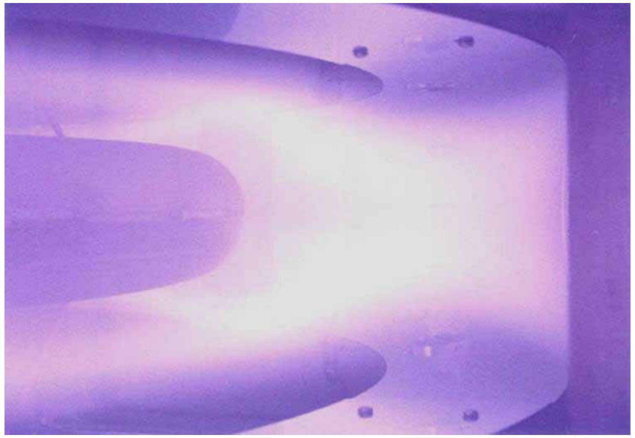
Non-neutral plasmas experiments on magnetic surfaces

- Fundamental test on multi-component non-neutral plasmas:

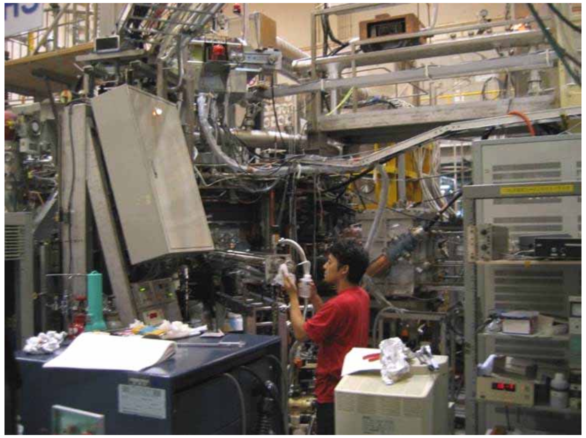
  Wave excitation and measurements of dispersion relations
  Relaxation to the equilibriua state

- Future experiments:

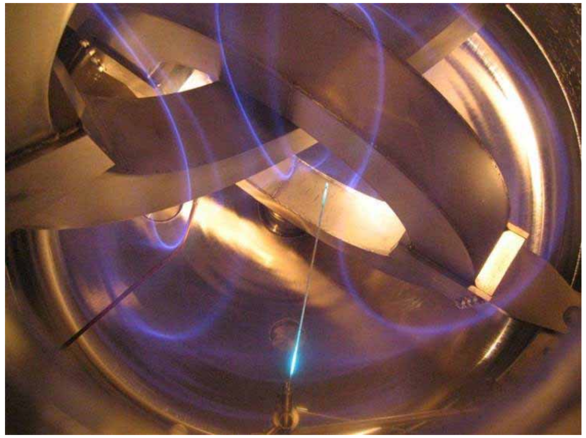
  Flowing non-neutralized plasma in a superconducting levitated ring device
  Formation of matter-antimatter plasmas in helical systems



Proto-RT (Prototype-Ring Trap)*
University of Tokyo, Japan, 1998-



CHS (Compact Helical System)**
National Inst. Fusion Science, Japan, 2003-



CNT (Columbia Non-neutral Torus)***
Columbia University, US, 2005-

Non-neutral plasma experiments on magnetic surfaces −dipole field and stellarator traps−

* Z. Yoshida et al., Y. Ogawa wt al., H. Himura et al., in Non-neutral Plasma Physics III, 397 (1999).
** H.Himura et al., Phys. Plasmas **11**, 492 (2004).
*** T. S. Pedersen and A. H. Boozer, Phys. Rev. Lett. 88, 205002 (2002).

Summary

- Confinement of non-neutral plasma on toroidal magnetic surfaces of the Proto-RT device, in dipole field with magnetic shear

- Trap time ~1s, electron plasma of ~10^6cm^{-3} and total number : ~10^{11} in B~50G (dipole field) and P=5×10^{-7}Torr (due to neutral collisions)

- Stabilization by the addition of toroidal field

- Injection of particles using chaotic orbits near a magnetic null line

- Basis for application of toroidal non-neutral plasmas:

  Creation of antimatter multi-component plasmas
  Fundamental test on plasma physics (pair-plasmas, etc.)
  Container for several kinds of charged particles
  Equilibrium and stability of flowing plasmas (double Beltrami state)