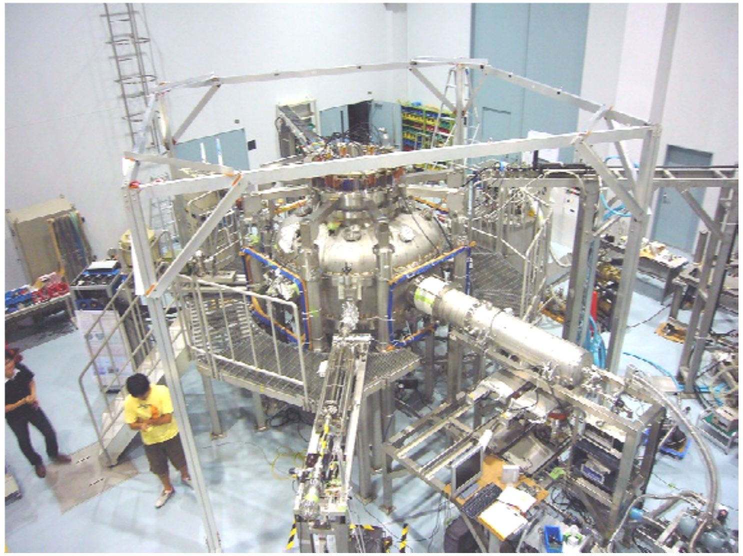
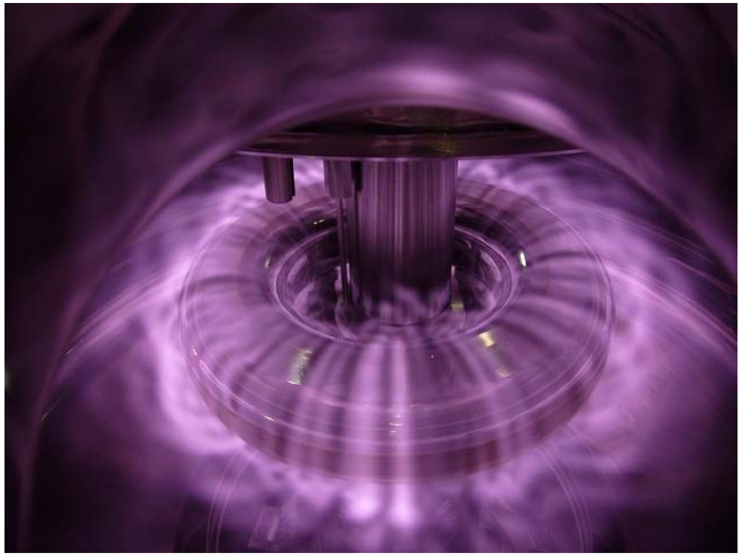
A-04

2nd APTWG Meeting, May 15-18 2012, Chengdu, China

Spontaneous formation of peaked density profile in a dipole plasma



RT-1: Magnetospheric plasma experiment



Magnetospheric plasma confined in RT-1

The RT-1 Experiment, GSFS, University of Tokyo

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Outline

1. Introduction
   - Structure formation and conserved quantities in plasmas
   - Observations of particle pinch in dipole plasmas

2. Particle pinch effects in the dipole plasma experiment RT-1
   - Plasma experiments in dipole field configuration
   - Formation of high-β ECH plasma and peaked density profiles
   - Long confinement of pure electron plasma and inward diffusion

3. Dipole plasma structures in phase space and real space
   - Charged particle motions in a dipole field
   - Relaxed states governed by adiabatic invariants

4. Summary

1. Introduction

➢ Structure formation and conserved quantities in plasmas

- Plasmas have a wide variety of turbulent transport mechanisms.

- When the total energy is the only conserved quantity in the system,
  ➡ the system relaxes to the Boltzmann distribution.

$$f(x,v) = Z^{-1} e^{-\beta H}$$

- However, if there is another conserved quantity *G* during the turbulent transport processes, ➡ the maximum entropy state is realized when

$$f(x,v) = Z^{-1} e^{-\beta H - \gamma G} ,$$

  in stead of the thermal equilibrium states.

- According to time and spatial scales of our observations, plasmas have various conserved quantities, realizing self-organization of a wide variety of structures.

➢Some examples of structure formation and conserved quantities

- In MHD plasmas, magnetic helicity $K = \int \mathbf{A} \cdot \mathbf{B} d\mathbf{x}$ is the first pointed-out conserved quantity to decide plasma structures.

- By calculating the variation of *K* and magnetic energy $E = \int B^2 d\mathbf{x}$,

$$\delta(E - \mu K) = 0 \ ,$$

  J. B. Taylor* derived the force-free relaxation state: $\nabla \times \mathbf{B} = \mu \mathbf{B}$.

- Importance of conserved quantities, as binding conditions on relaxation processes with turbulent transport, was clearly shown.

- Later, A. Hasegawa** stated that "selective dissipation" processes on conserved quantities play important role on the self-organization of various structures in plasmas.

***1974 J.B. Taylor, Phys. Rev. Lett. 33, 1139.**

****1987 A. Hasegawa Comm. Plasma Phys. Cntr. Fusion 11, 147.**

➢ Particle pinch observed in dipole plasmas

- Among many transport and self-organization processes in various plasmas, we focus on the pinch effects in dipole plasmas.

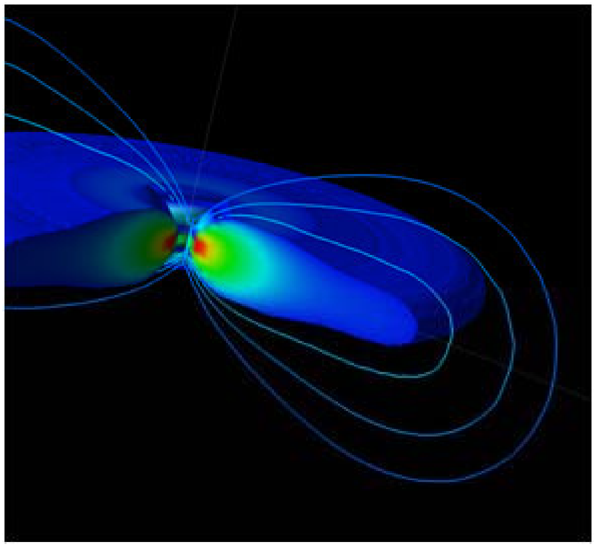
- Dipole field is one of the simplest and most common field in the Universe, yet its strongly inhomogeneous field yields many interesting transport and structure-formation phenomena.

- In the Earth's magnetosphere, fluctuation-induced diffusion drives charged particles inward, generating peaked density profiles:

  ➡ particle acceleration, substorm, aurora, etc.

- This is opposite to the "usual" direction of diffusion (that flattens density gradients).

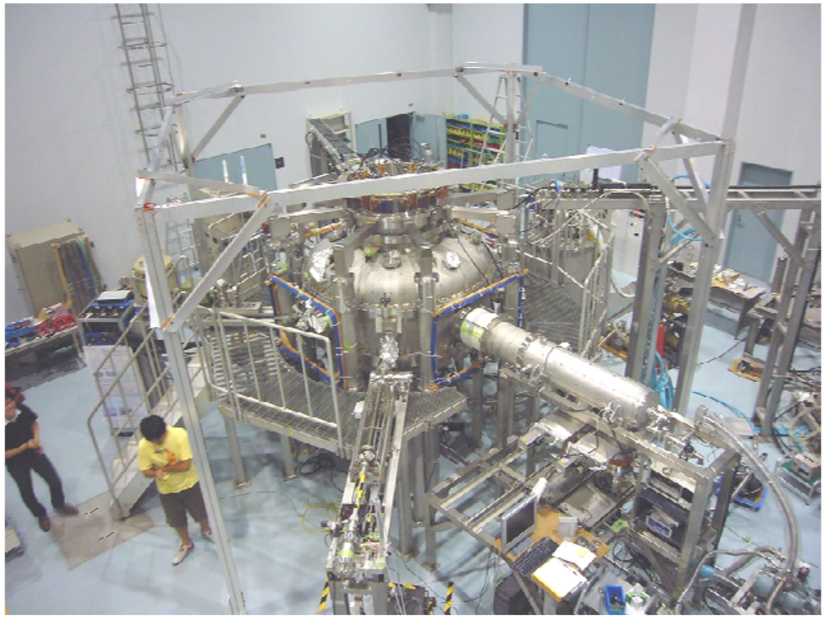
What is the mechanism to decide the inward diffusion (pinch) in dipole plasmas?



High-β plasma near Jupiter

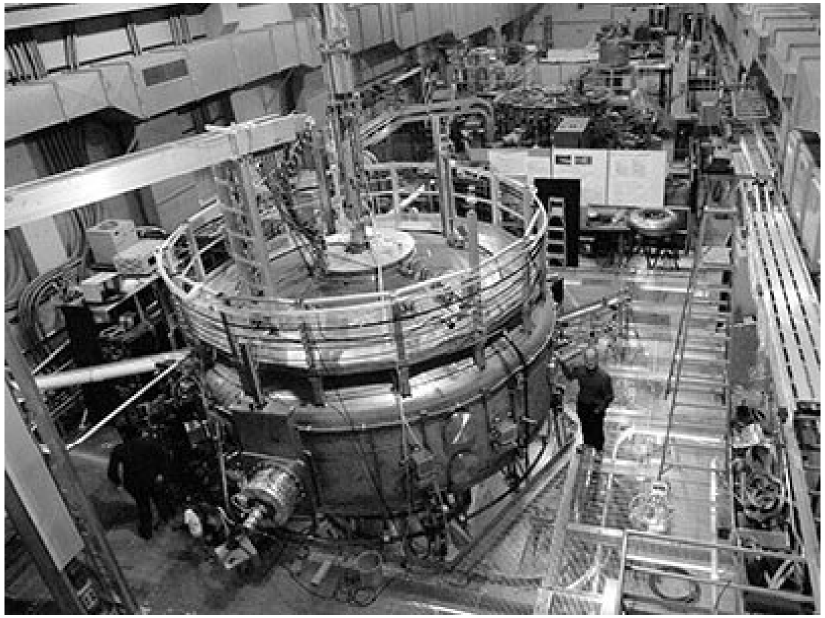
➢Laboratory experiments on pinch in dipole field

Dipole plasma experiments (RT-1: U.Tokyo, Japan, LDX: MIT, USA)



U.Tokyo RT-1（Proto-RT->Mini-RT->...）

Hasegawa *et al.*, Nucl. Fusion **30**, 2405 (1990).
Yoshida*et al.*, PRL **104**, 235004 (2010); PFR **1**, 008 (2006).



MIT/Columbia Levitated Dipole eXperiment

Garnier*et al.*, Phys. Plasmas **13**, 056111 (2006).
Boxer*et al.*, PRL **6**, 207 (2010).

- Primary research goal is the demonstration of formation of high-β (~1) plasma suitable for advanced fusion using D-D and D-^{3}He.

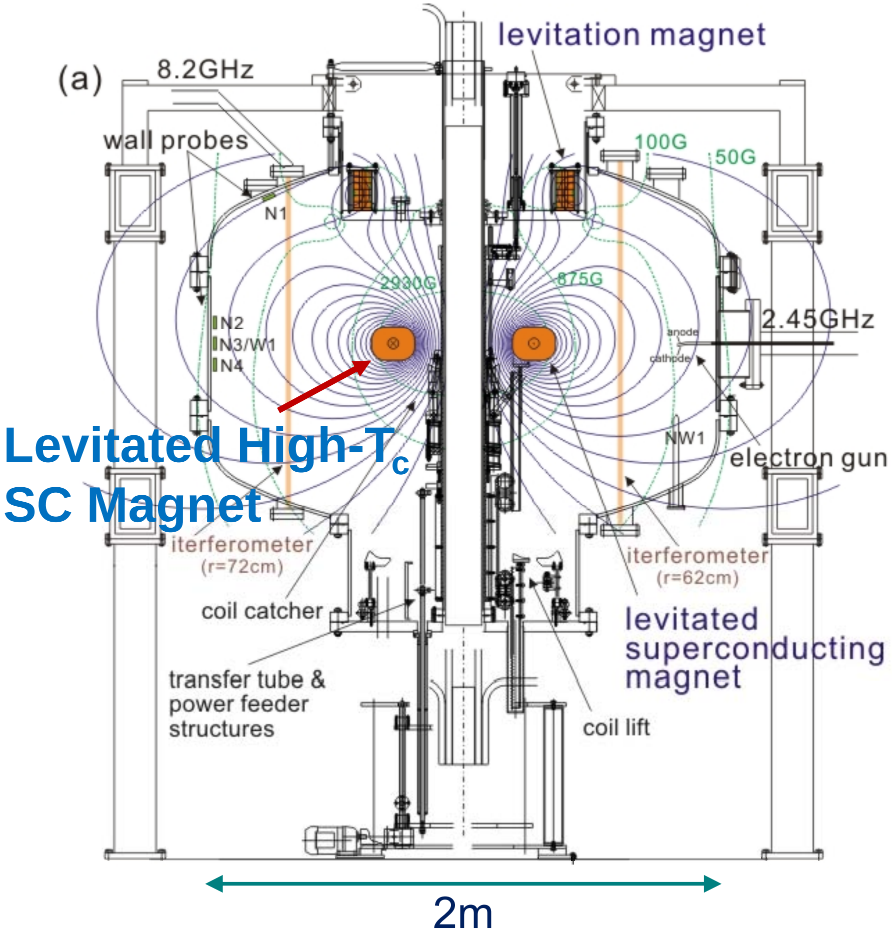
- In high-β (local β~70%) hot electron plasma, spontaneous formation of peaked density profiles were observed.

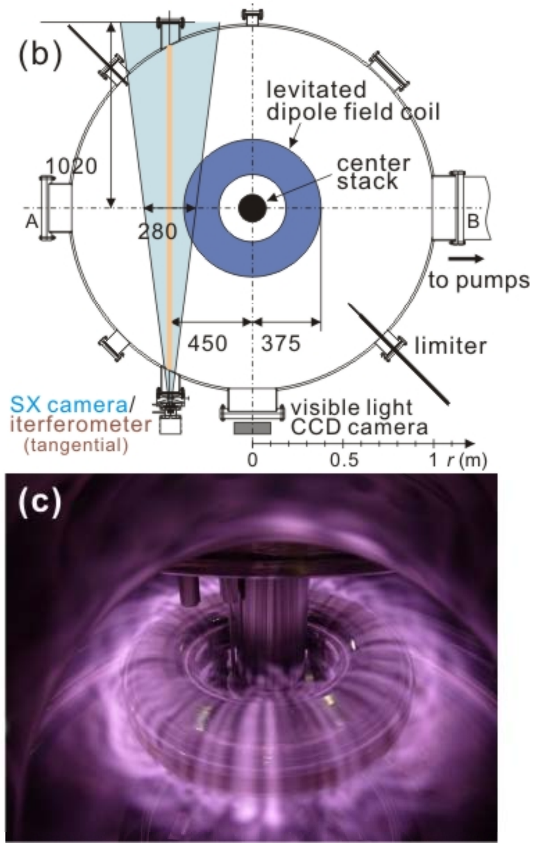
- Relaxation based on adiabatic invariants may explain this observation.

2. Results on dipole plasma experiments in RT-1

- Plasma confinement in dipole field configuration
- Formation of high-β ECH plasma and peaked density profiles
- Long confinement of pure electron plasma and inward diffusion

RT-1 has succeeded to generate high-β ECH plasma and to stably confine toroidal non-neutral (electron) plasma





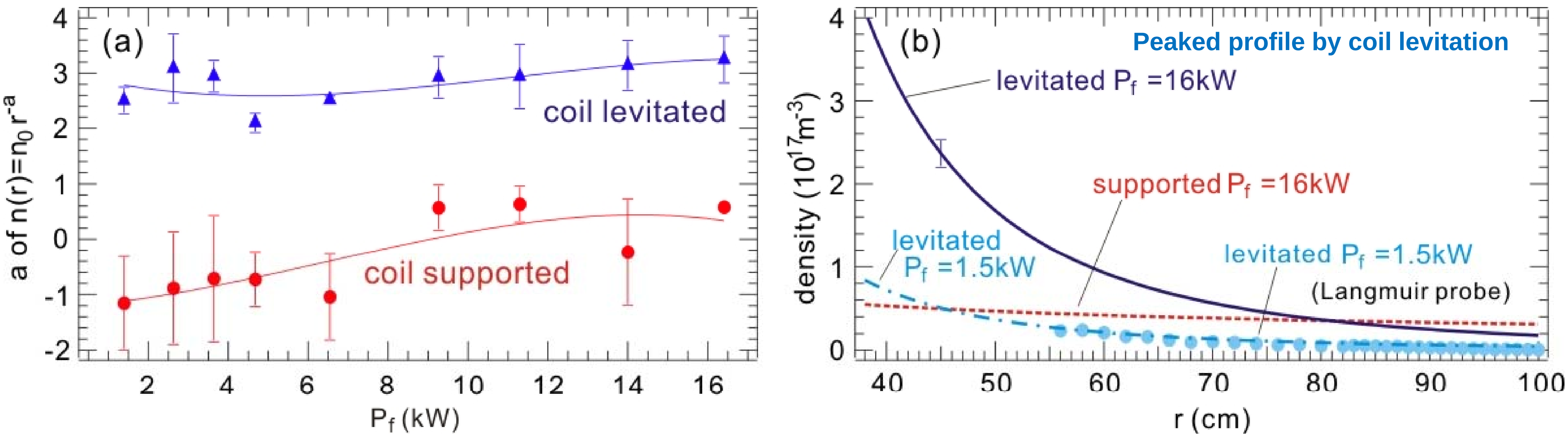
- HTS Bi-2223 magnet
  0.25MA, 112kg
  magnetically levitated
  (reduce perturbations)
- Microwaves
  8.2GHz (25kW) and
  2.45GHz (20kW)
- Electron gun
  LaB_6 cathode

Magnetospheric plasma Experiment, RT-1

2009 Ogawa *et al*., Plasma Fusion Res. 4, 020.

- **High-β plasma for advanced fusion**
  70% local β, formation of peaked density profile by magnetic levitation
- **Toroidal non-neutral (pure electron and positron) plasma**
  300s long confinement, rigid-rotating steady state, inward diffusion

ECH Plasma has peaked density profiles in strong field region when superconducting magnet is levitated



Radial density profiles [coefficient a of $n(r)=n_0r^{-a}$] of ECH plasma in RT-1

- When the magnet is not levitated (strong disturbance due to support),

  ➡ plasma has rather flat density profiles

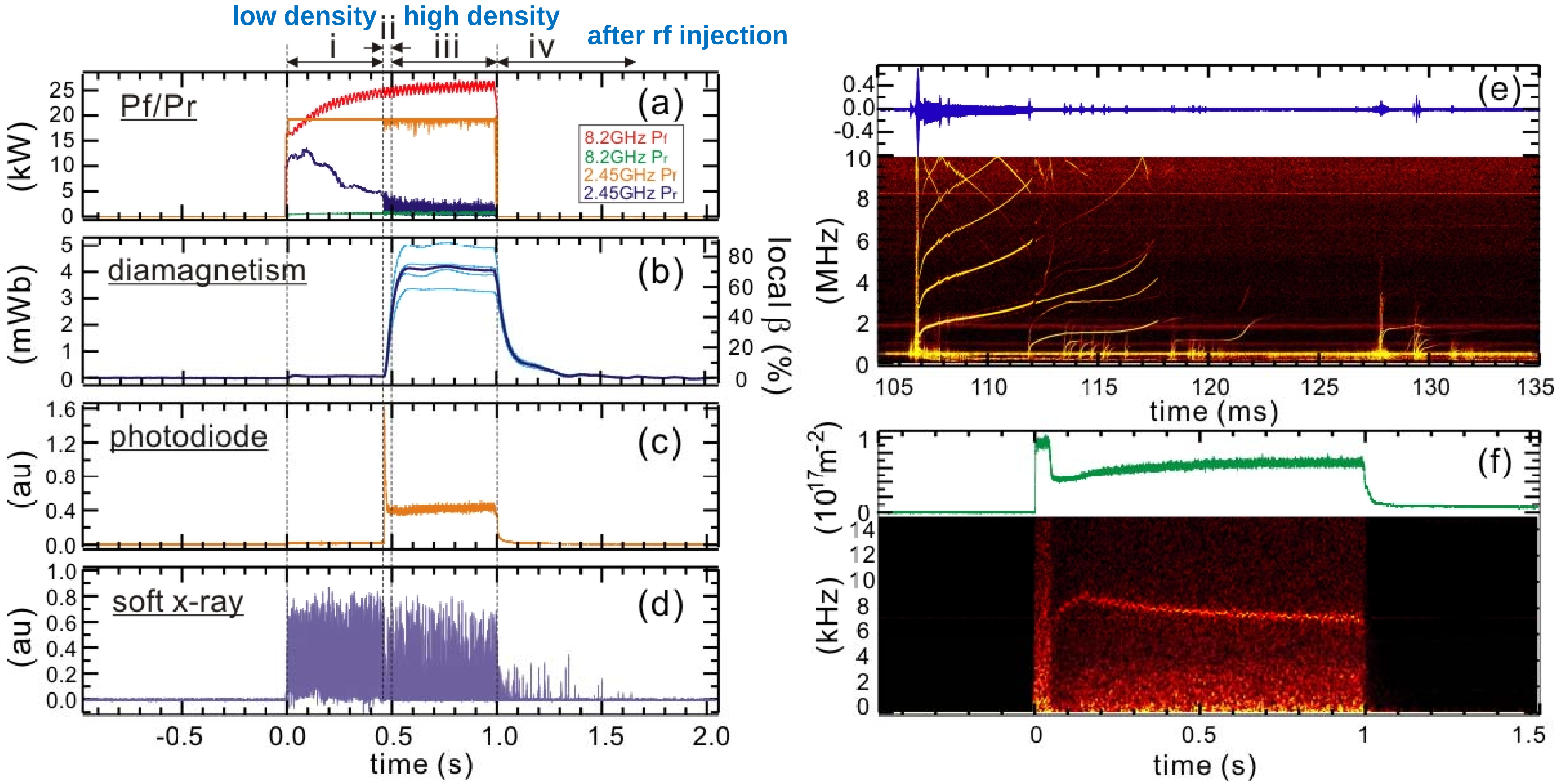
- By coil levitation (disturbance eliminated),

  ➡ Peaked density profiles are spontaneously generated*

Profiles weakly depend on plasma formation conditions

***2011 H. Saitoh, Z. Yoshida et al., Nucl. Fusion 51, 063034.**

High β ECH plasma in RT-1 has several kinds of fluctuations (time scale ~ toroidal drift period of charged particles)



Typical waveforms of high-β plasma and electromagnetic fluctuations in RT-1

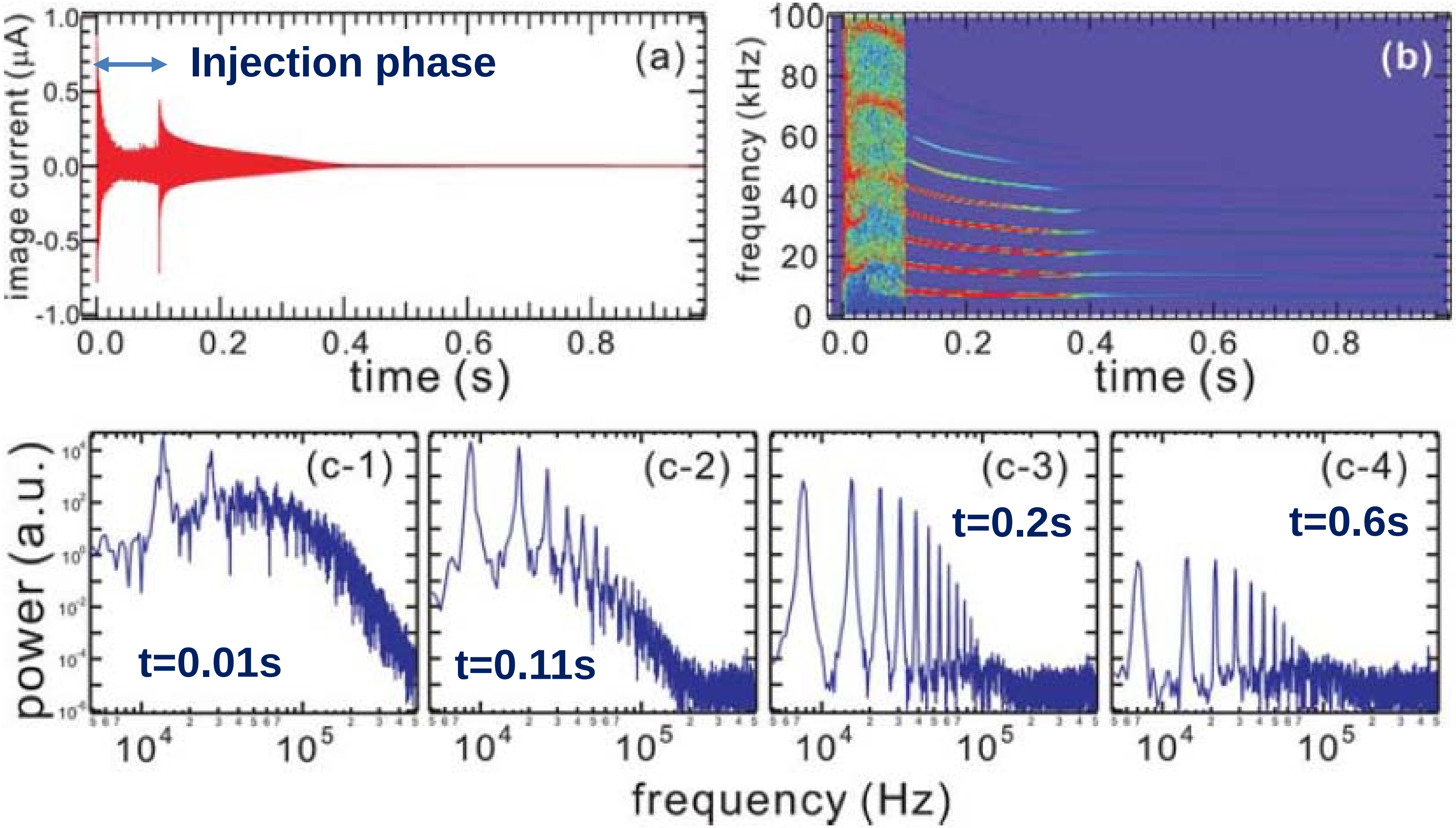
- High-β state is characterized by large stored energy, strong x-ray, and depression of visible light strength and fluctuations: **hot electron plasma**

- Plasma has several kind of fluctuations ~ toroidal drift frequencies

  - Effects of hot electrons are possible reasons for the onset of instability*

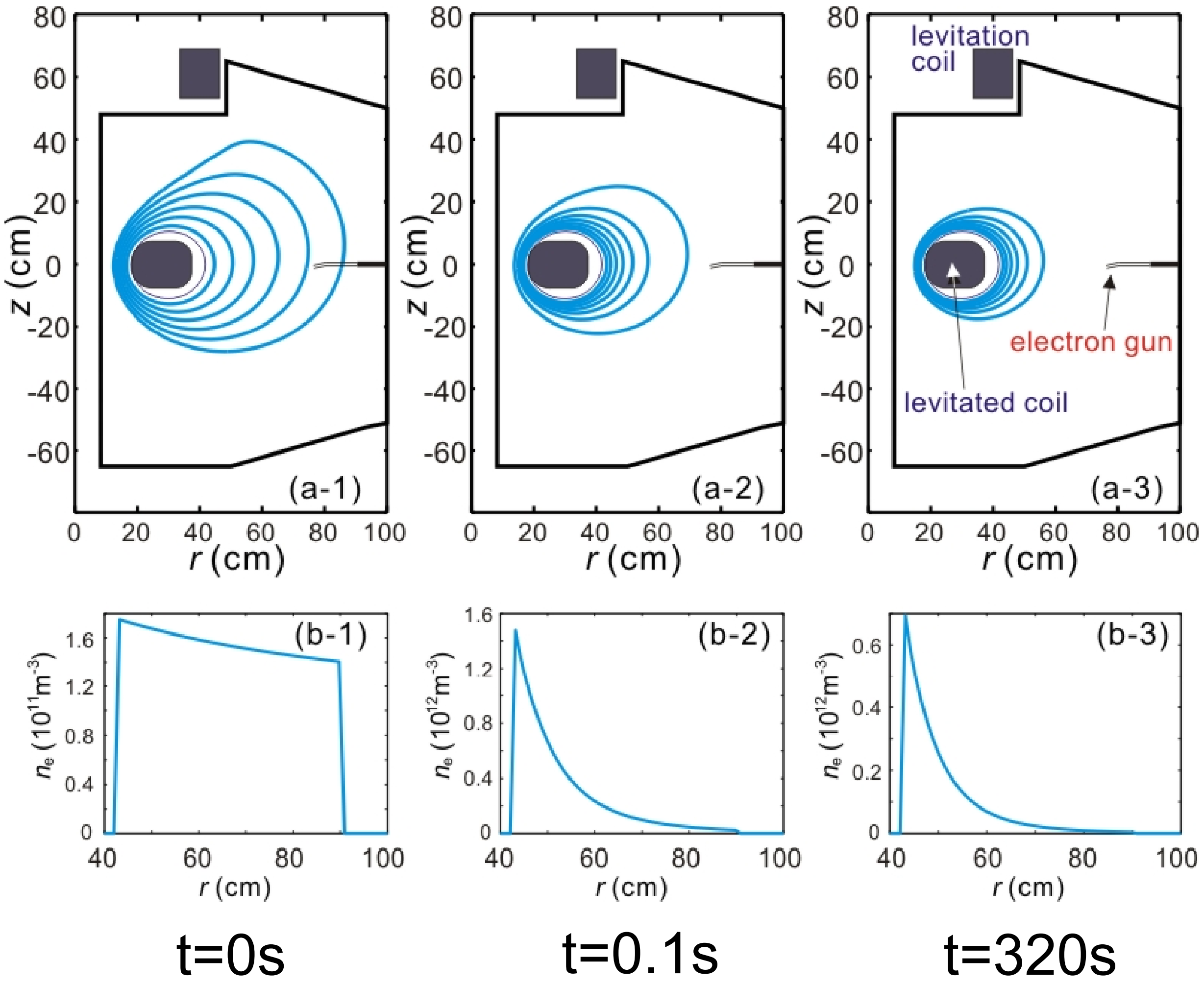
*2012 H. Saitoh, Z Yoshida *et al*, accepted for publication in PoP.

Pure electron plasma (PEP) formation process in RT-1: Electron beam injection and stabilization of fluctuations



- Electrons were injected from edge confinement region from a gun.
- Turbulent-like component is stabilized after injection phase, realizing stable diocotron (Kelvin-Helmholtz) mode. Confinement time ~300s.

Inward particle diffusion and formation of stable peaked profiles: Plasma diffuses inward to strong field region



Density profiles of PEP
(a) during beam injection,
(b) after beam injection,
(c) before confinement ended.

- The confinement region shifts inward to the strong field region.
- Peaked density profiles are stably sustained in the stable confinement phase.

2011 Saitoh, Yoshida *et al*., PoP 18, 056102.

Experimental observations:

- Peaked profiles are spontaneously generated in dipole plasmas.
- It is commonly observed in planetary magnetospheres, laboratory experiments (both ECH plasma and NNP), at various formation conditions.
- Especially in formation phase, plasma has fluctuations (~ toroidal drift frequency) that can destroy the . conservation of third adiabatic invariant $J_3 \sim e\Psi = erA_\theta$.

3. Dipole plasma structures in phase space and real space

- Charged particle motions in a dipole field
- Relaxed states governed by adiabatic invariants

Charged particle motion in a dipole field and adiabatic invariants

- Particle orbit consists of three periodic motions: gyromotion, bounce motion along field lines, and toroidal drift motion.

- Associated with these periodic motions, three adiabatic invariants are defined as actions for magnetized charged particles.

$$J_1 = 2\pi m {v_\perp}^2 / \omega_c \propto m {v_\perp}^2 / 2B = \mu$$

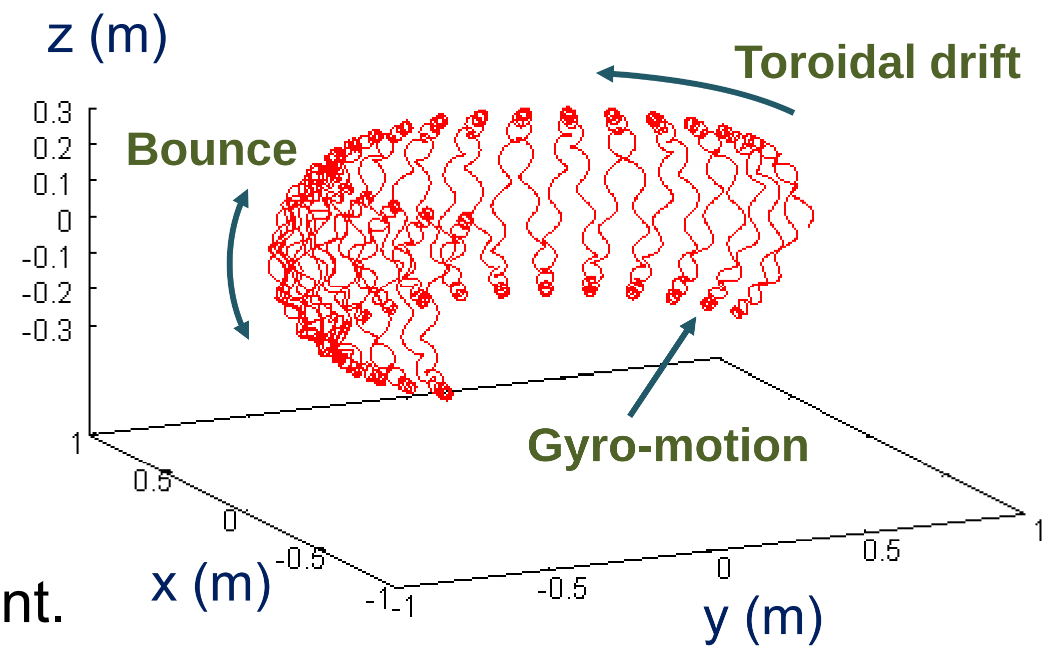
$$J_2 = m/2\pi \int v_{//} dz$$

$$J_3 = 1/2\pi \int P_\theta dq \sim e\Psi/2\pi$$

- When the system is axisymmetric and J_3 is conserved

particles are trapped on magnetic surfaces, realizing stable confinement.

(long confinement phase)



Typical charged particle orbit in a dipole field

Relaxed states governed by adiabatic inbariants

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

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

which is constant for charge neutral systems.

- Including the conservation of invariants, density profiles of dipole plasma should be derived.

- Among three invariants, fluctuations can easily destroy the symmetry and conservation of J_3 ($\propto \Psi$). In fact, radial transport was experimentally confirmed in RT-1. Then we have

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

assuming that only μ and J are robust invariants.

- By evaluating Jacobian, density profile is given by

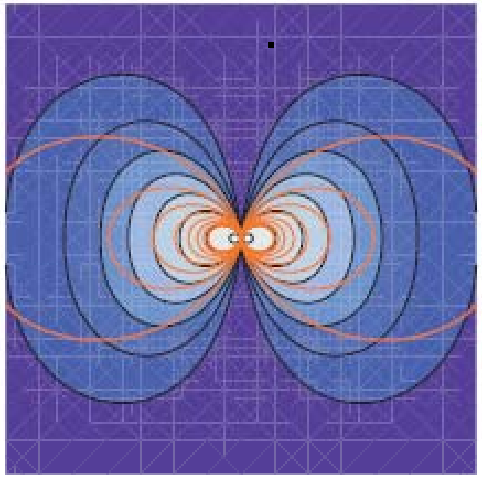
$$\rho(x) = \int f \frac{2\pi\omega_c d\mu}{m} \frac{dJ}{mL_{//}(\Psi)} dv_d \quad \propto \frac{\omega_c(\mathbf{x})}{m^2} \int f \frac{e^{-(\beta\omega_c+\alpha)\mu} d\mu}{\beta\sqrt{2\omega_c\mu/m} + \gamma L_{//}(\Psi)}$$

where $L_{//}(\Psi) = \sqrt{2\Omega_c(\Psi)/\Omega_c''(\Psi)}$

Scale of field strength variation along field lines

$$\omega_c = \Omega_c(\Psi) + \Omega_c''(\Psi) z^2/2$$

cyclotron frequency along longitudinal bounce



Magnetic surfaces (blue) and density profiles (red)

- In the limit of r->∞ (point dipole) and β->0 (ignoring temperature effects), density profile is proportional to

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

- This model generates peaked profiles that agree with observations.

Z. Yoshida, to be published.

Summary

- Observation of pinch in dipole plasma experiments in RT-1

  - Formation of high-β ECH plasma
    local β ~ 70%, hot electron induced fluctuations

  - Long confinement of pure electron plasma
    confinement time ~300s, diocotron (Kelvin-Helmholtz) fluctuations

  Inward diffusion and particle pinch were commonly observed

- Relaxed states governed by adiabatic invariants

  - Structure formation decided by adiabatic invariants

  Conservation of μ and J, but not Ψ
  ➡ Steep density gradient in strong field is given as a relaxed state

  In β->0 limit, density per flux tube is constant, which is qualitatively agrees with observations in RT-1