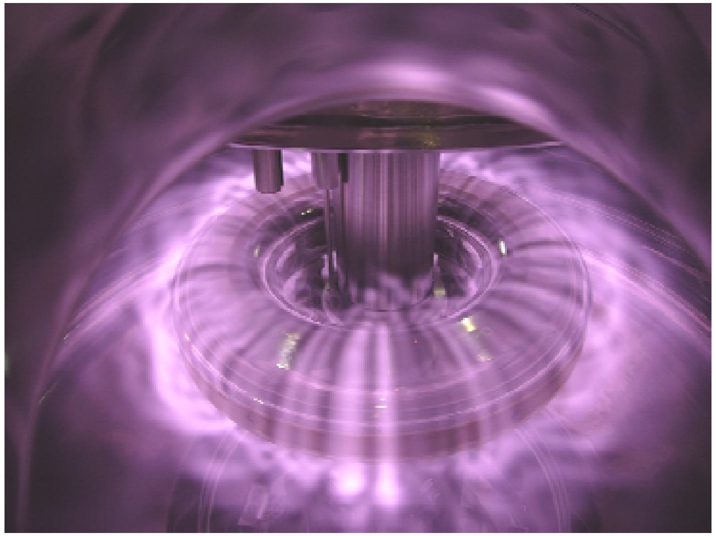
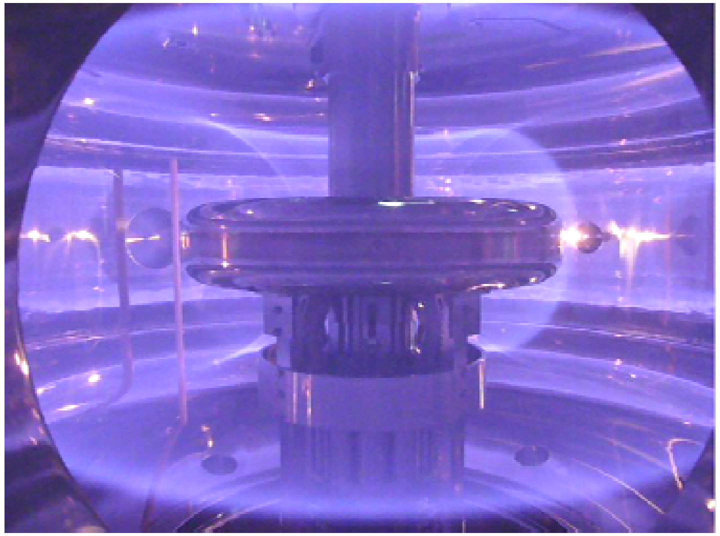
磁気圏型配位RT-1における密度ピーキングの観測



High-β hot electron ECH plasma



Non-neutral pure electron plasma

2012年1月13日　輸送研究会@NIFS

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Transdisciplinary
Sciences, GSFS

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Outline

- Introduction:
  - Dipole fusion concept, motivated by high-β magnetospheric plasmas

- Radial diffusion in dipole field:
  - Self organization of peaked profiles in strongly inhomogeneous field
  - Adiabatic invariants and fluctuation-induced transport

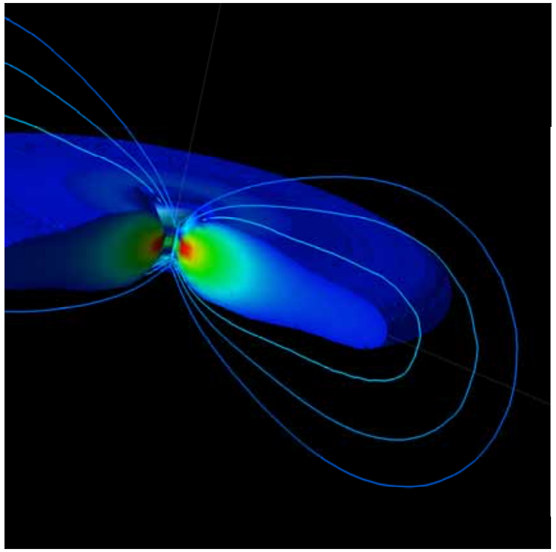
- Experimental setup:
  - Dipole plasma experiment RT-1 (comparison with LDX)

- Experimental results 1:
  - Formation of high-β ECH plasma and spatial structures

- Experimental results 2
  - Stable confinement (~300sec) of electron plasma and spatial structures

- Summary and next step

Introduction: Observation of high-β, peaked-profile plasmas in planetary magnetospheres



High-β flowing plasma

J. Shiraishi *et al*., PoP 12, 092901 (2005).

- High-β plasma in Jovian and earth's magnetospheres (spacecraft observations):
  - Flowing high-β (>100%) state, absorption of solar wind with substorms, whistler, chorus.
  - Effects of flow, Hall-MHD, inward diffusion, particle acceleration, etc.

- Stability conditions for interchange mode:

$$\frac{dP}{dU} < \gamma \frac{P}{|U|} \qquad U = -\oint \frac{dl}{B}$$

- For a point dipole, field strength $B \propto 1/r^3$, field line length $\propto 1/r$, then

$$-\frac{d \ln P}{d \ln r} < 4\gamma = \frac{20}{3}$$

- $P \propto 1/r^{-20/3}$ in geomagnetosphere, satisfying stability condition.

MHD交換型モードに対する安定性

プラズマを含む磁力管の体積は $V = \oint S dl = \Phi \oint \frac{dl}{B}$

$\Phi = SB$ **は磁力管の磁束であり，磁力線に沿って一定** (β<<1)．

磁力管が断熱的に変位する時，磁力管内部の圧力変化は

$dP = -\gamma P \, \delta U / U$ $\quad U = -\oint \frac{dl}{B}$ $\quad \delta V / V = \delta U / U$

であり，この値が，これを取り巻くプラズマの圧力変化

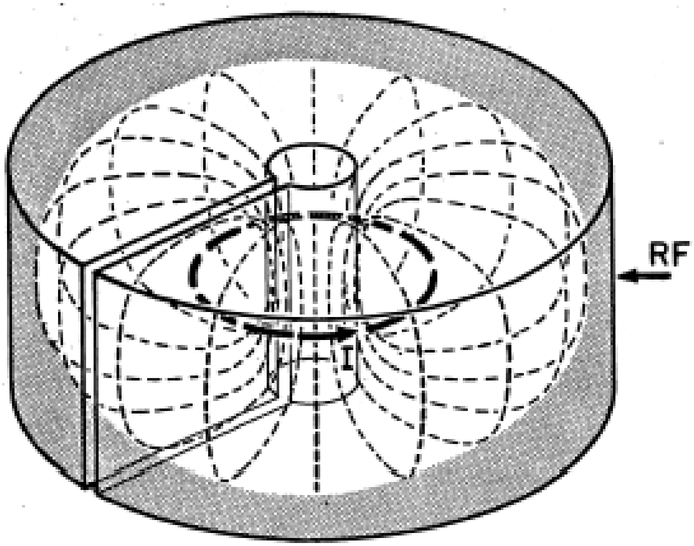
$dP/dU \, \delta U$ **よりも小さい時には，プラズマは浮力を受けて変位を続ける．**

よって，交換型不安定性に対する安定化の条件は $\frac{dP}{dU} < \gamma \frac{P}{|U|}$

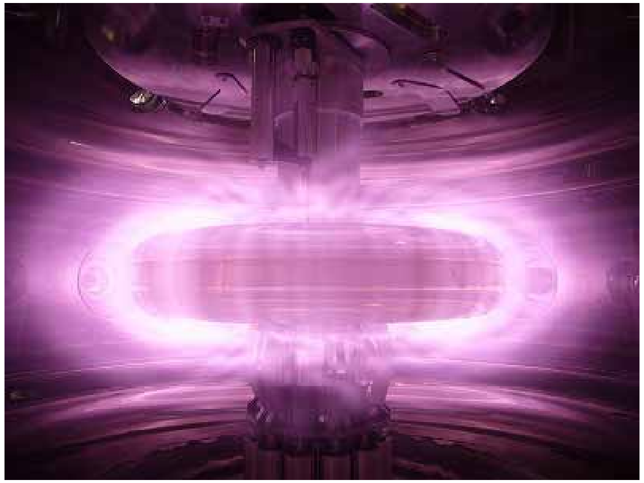
プラズマ圧力P**を考慮しているため，**good/bad curvature**とは一致しない．**

Dipole fusion concept, inspired by observations of high-β planetary magnetosheres

A. Hasegawa, Comm. Plasma Phys. Contr. Fusion 11, 147 (1987).



- Application of RF ~ toroidal drift frequency
  - Strongly inhomogeneous dipole field induces inward particle diffusion
  - Adiabatic plasma heating by the conservations of μ and J
  - Possibility of stable high-β state suitable for burning D-D, D-^{3}He



Magnetospheric plasma in RT-1

- Recent renewed interest in dipole fusion
  - Levitated superconducting magnet

RT-1: 2010 Yoshida *et al*., PRL 104, 235004.
LDX: 2010 Boxer *et al*., Nat. Phys. 6, 207.

Effects of field fluctuations and transport

For a particle distribution function $f = f(\mu, J, \Phi; t)$, written by using adiabatic invariants μ, J, Ψ,

number of particles located in a phase space volume μ±dμ, J±dJ, Ψ±dΨ is given by $dN = f(\mu, J, \Phi; t) d\mu dJ d\Phi$.

By using $P(\mu, J, \Phi; \Delta\mu, \Delta J, \Delta\Phi)$, probability that mean change $\Delta\mu, \Delta J, \Delta\Phi$ takes place per unit time, the distribution function averaged over three periodic particle motions are

$$
\begin{aligned}
f(\mu, J, \Phi; t) = \iiint d(\Delta\mu) d(\Delta J) d(\Delta\Phi) \\
f(\mu - \Delta\mu, J - \Delta J, \Phi - \Delta\Phi; t) \\
P(\mu - \Delta\mu, J - \Delta J, \Phi - \Delta\Phi; \Delta\mu, \Delta J, \Delta\Phi)
\end{aligned}
$$

Spjeldvik, Rothwell, “The radiation belts”
1971 M. Walt, Space Sci. Rev.

The Fokker-Planck equation is then obtained by expanding f and P in Taylor series around the unperturbed quantities:

$$\frac{df}{dt} = -\frac{\partial}{\partial \mu}\left(\frac{\langle \Delta\mu \rangle}{\Delta t} f\right) - \frac{\partial}{\partial J}\left(\frac{\langle \Delta J \rangle}{\Delta t} f\right) - \frac{\partial}{\partial \Phi}\left(\frac{\langle \Delta\Phi \rangle}{\Delta t} f\right)$$

$$+\frac{\partial^2}{\partial \mu^2}\left(\frac{\langle (\Delta\mu)^2 \rangle}{2\Delta t} f\right) + \frac{\partial^2}{\partial J^2}\left(\frac{\langle (\Delta J)^2 \rangle}{2\Delta t} f\right) + \frac{\partial^2}{\partial \Phi^2}\left(\frac{\langle (\Delta\Phi)^2 \rangle}{2\Delta t} f\right)$$

$$+\frac{\partial^2}{\partial \mu \partial J}\left(\frac{\langle \Delta\mu\Delta J \rangle}{2\Delta t} f\right) + \frac{\partial^2}{\partial \mu \partial \Phi}\left(\frac{\langle \Delta\mu\Delta\Phi \rangle}{2\Delta t} f\right) + \frac{\partial^2}{\partial J \partial \Phi}\left(\frac{\langle \Delta J\Delta\Phi \rangle}{2\Delta t} f\right)$$

$$\langle \Delta i \rangle = \iiint d(\Delta\mu) d(\Delta J) d(\Delta\Phi) P(\mu, J, \Phi; \Delta\mu, \Delta J, \Delta\Phi) \Delta i$$

$$\langle \Delta i \Delta j \rangle = \iiint d(\Delta\mu) d(\Delta J) d(\Delta\Phi) P(\mu, J, \Phi; \Delta\mu, \Delta J, \Delta\Phi) \Delta i \Delta j$$

$$i, j = \mu, J, \Phi$$

The above equation is greatly reduced by recognizing that

- Violation of one adiabatic invariant is uncorrelated with the process that violate another invariant:

$$\left\langle \Delta\mu\Delta J \right\rangle = \left\langle \Delta\mu\Delta\Phi \right\rangle = \left\langle \Delta J\Delta\Phi \right\rangle = 0$$

- In the absence of sources and losses, diffusion would proceed until all gradients will vanish, and for each diffusion mode

$$\left\langle \Delta i \right\rangle - \frac{\partial}{\partial i}\frac{\left\langle (\Delta i)^2 \right\rangle}{2} = 0$$

and we have

$$\frac{\partial f}{\partial t} = \sum_i \frac{\partial}{\partial i}\left(\frac{\left\langle (\Delta i)^2 \right\rangle}{2\Delta t}\frac{\partial f}{\partial i} \right) = \sum_i \frac{\partial}{\partial i}\left(D_{ii}\frac{\partial f}{\partial i} \right) \qquad i = \mu, J, \Phi$$

Transformation to other variable, such as ϕ_1, ϕ_2, ϕ_3 , is realized by

$$\frac{\partial f}{\partial t} = \sum_i \frac{1}{G}\frac{\partial}{\partial \phi_j}\left(D_{\phi_j\phi_j} G \frac{\partial f}{\partial \phi_j} \right) \qquad G = G(\mu, J, \Phi; \phi_1, \phi_2, \phi_3)$$: Jacobian

Radial diffusion of plasma in dipole field

Low frequency fluctuations can violate the conservation of Ψ, while preserving the μ, J invariants. Radial diffusion equation becomes

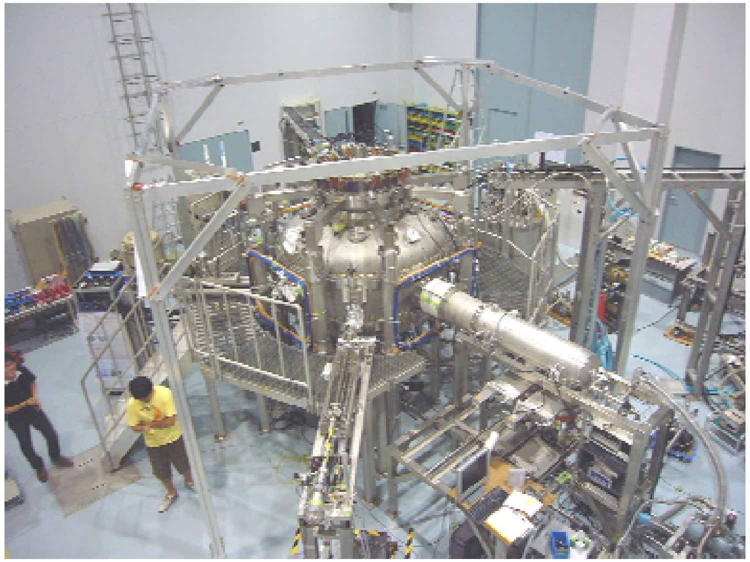
$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial \Phi}\left(D_{\Phi\Phi} \frac{\partial f}{\partial \Phi} \right) + S - L$$

This relation says that, when source and loss terms are neglected, stationary density state $\frac{\partial N}{\partial t} = \int d\mu dJ \frac{\partial f}{\partial t} = 0$ is realized when particle number within a flux tube, N, is constant $\frac{\partial N}{\partial \Phi} = \int d\mu dJ \frac{\partial f}{\partial \Phi} = 0$

The flux tube volume of point dipole satisfies $\int \frac{dl}{B} \propto r^4$, then the above relation gives density profile of $n \propto r^{-4}$

If the density profile is flatter than this equation, diffusion due to the destruction of Ψ results the inward transport.

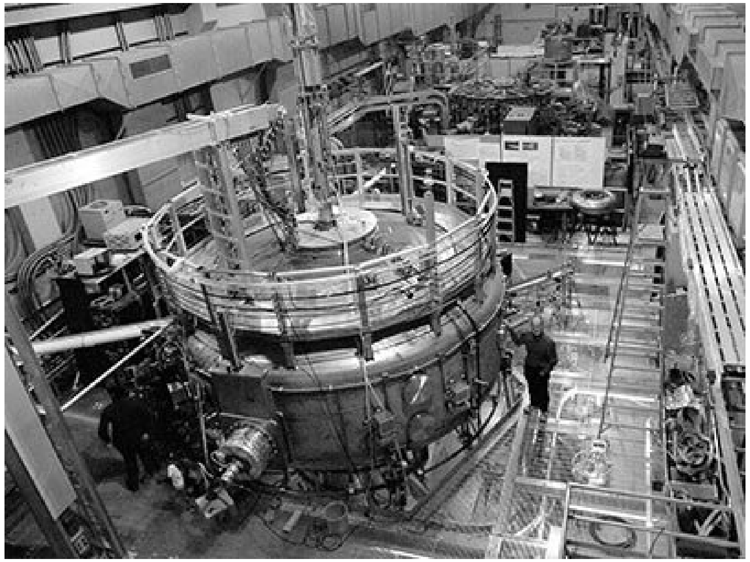
Radial diffusion of plasma in dipole field



東大RT-1 (Proto-RT->Mini-RT->…) **

*Hasegawa *et al.*, Nucl. Fusion **30**, 2405 (1990).

Yoshida*et al.*, PRL **88, 095001 (2002); PFR **1**, 008 (2006).



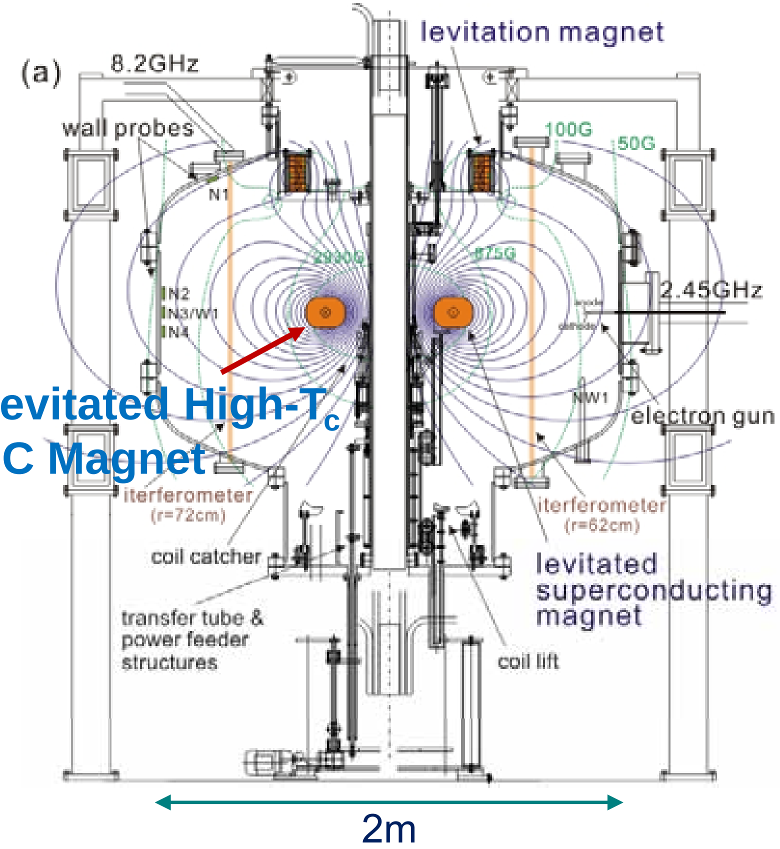
MIT/Columbia: Levitated Dipole eXperiment***

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

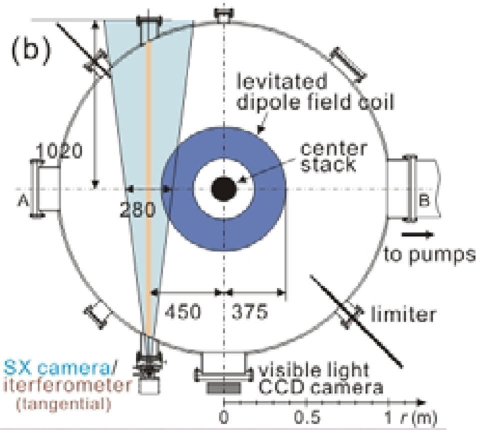
- Is high-β stable confinement state realized in dipole devices?
- What kind of density/pressure profiles are generated in equilibrium states?
- Is it consistent with the simplified (source free) model?

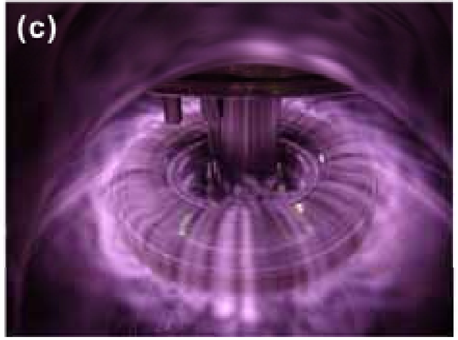
particle number within a flux tube is spatially constant

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



Levitated High-T_c SC Magnet





- HTS Bi-2223 magnet
  0.25MA,112kg
  magnetically levitated

- Microwaves
  8.2GHz (25kW) and
  2.45GHz (20kW)

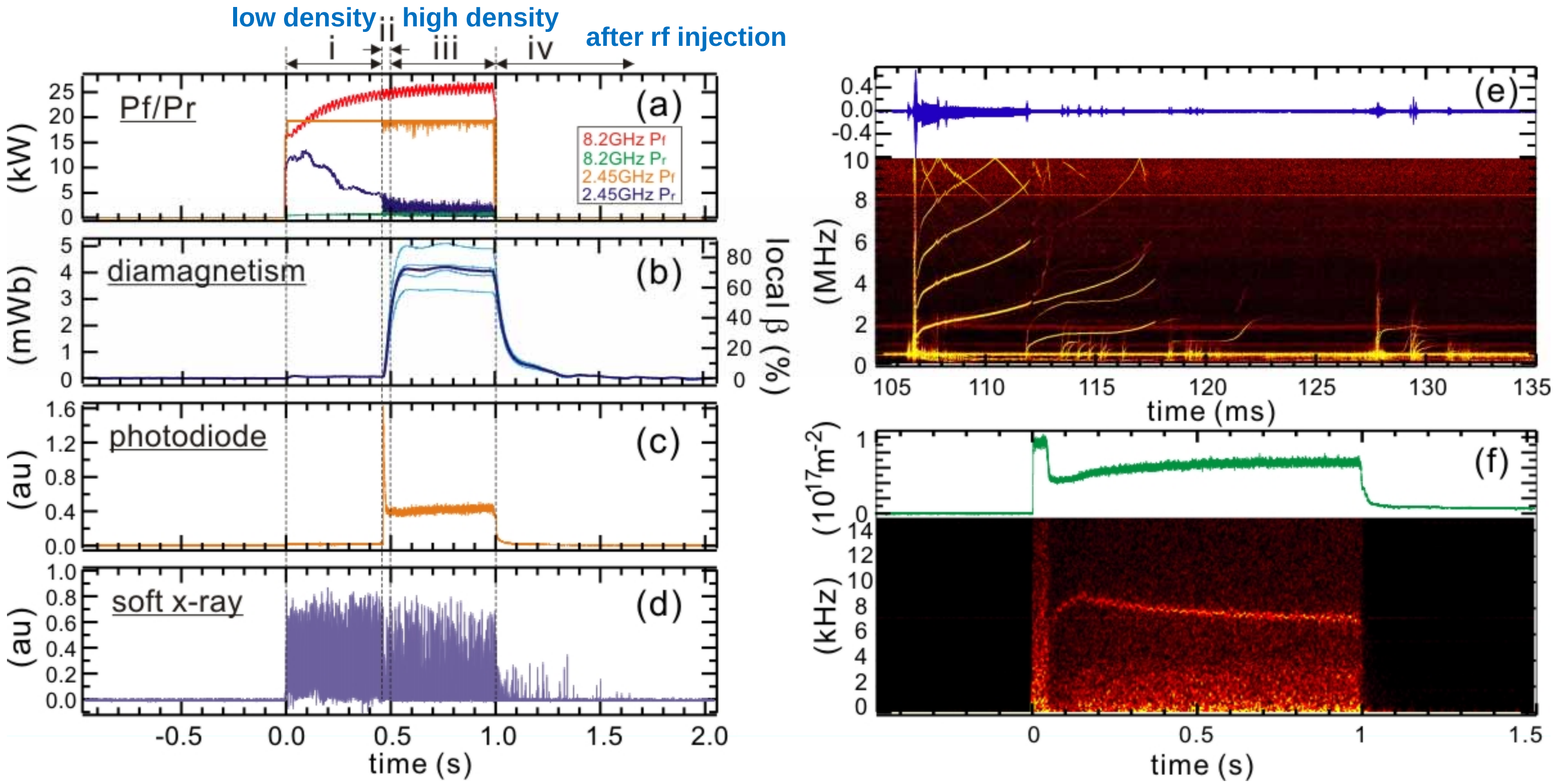
- Electron gun
  LaB_6 cathode

Magnetospheric plasma
Experiment, RT-1

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

- **High-β plasma for advanced fusion**
  70% local β, confinement time ~0.5s, peaked density profile
- **Toroidal non-neutral (pure electron) plasma**
  300s long confinement, rigid-rotating steady state, inward diffusion

High β ECH plasma is generated with optimized formation conditions, avoiding the onset of instabilities



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

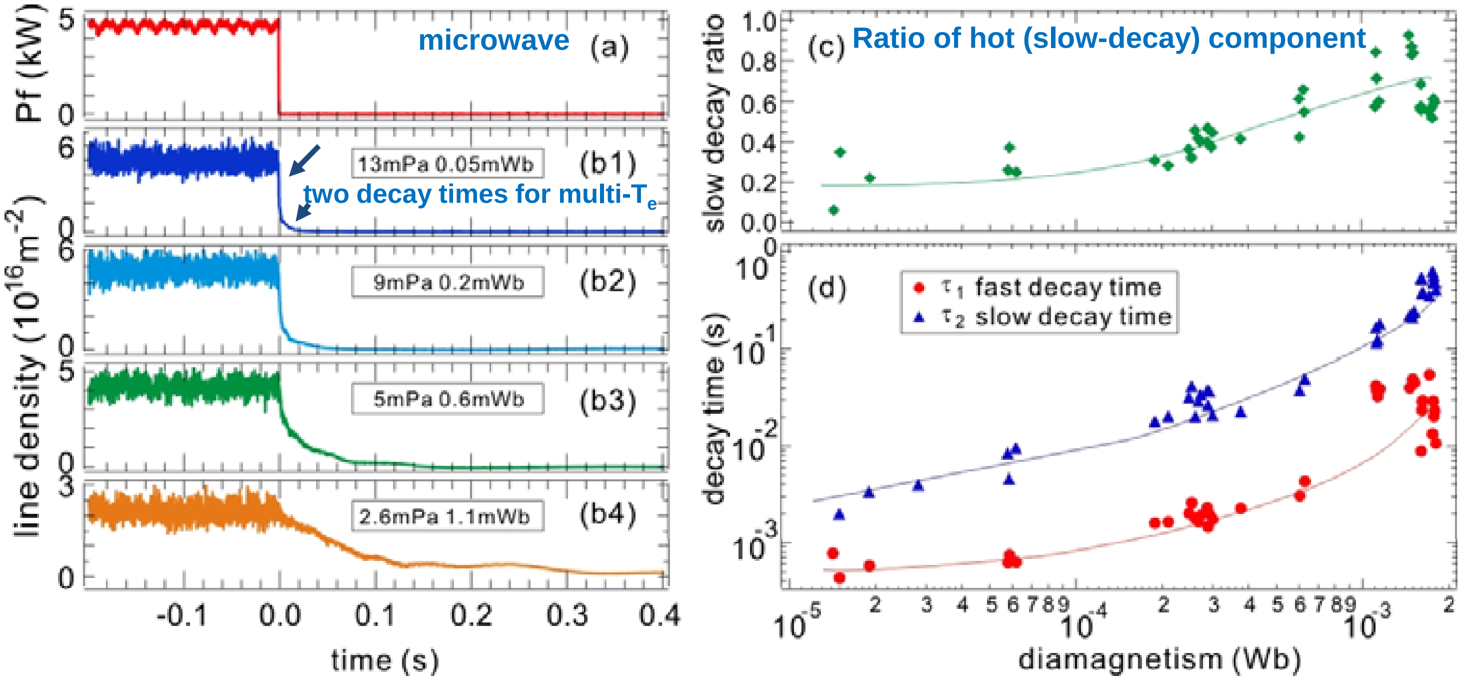
- High-β state is characterized by large stored energy, strong x-ray, and depression of visible light strength and fluctuations: **hot electron plasma**

- In phase (i), thin (~10^{15}m^{-3}) hot plasma has large electromagnetic fluctuations, which are stabilized after higher density formation in phase (iii)

  - Effects of hot electrons are possible reasons for the onset of instability[*1]

1. **2006 Garnier *et al.*, PoP 13, 056111.**

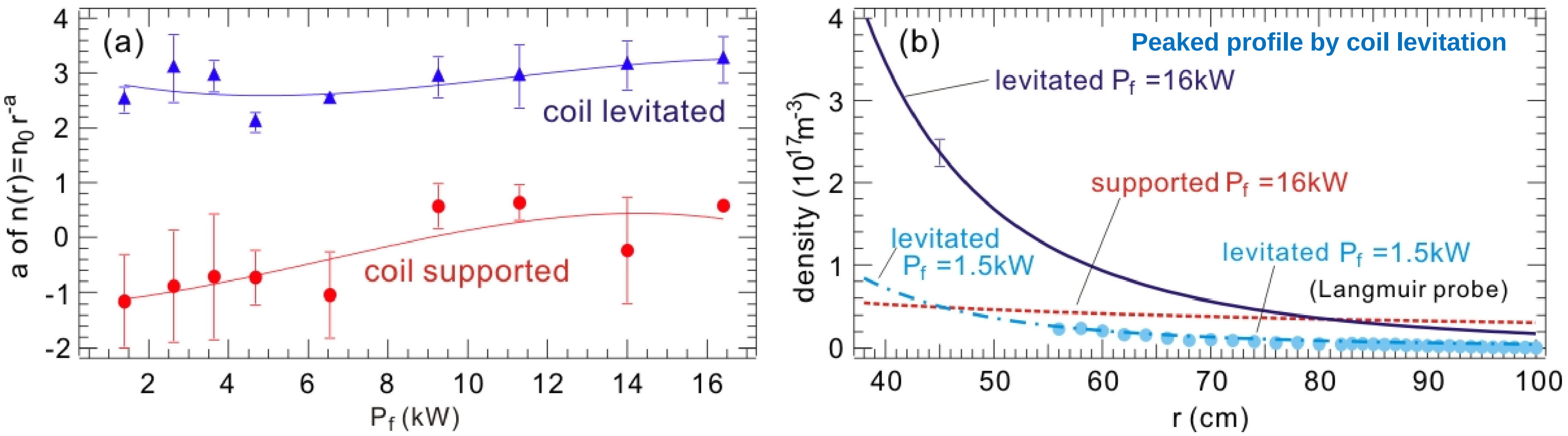
Electrons of high beta plasma consists of majority of hot (up to ~50keV) component, and τ_p~0.5s



Decay of line density and estimated ratio of hot-electron component and confinement time

- Electrons consists of majority (~60%) of hot (~50keV) and cold (~10eV) populations
- Confinement time of hot electron component is τ_p=0.5s cf) τ_{Bohm}~1.4μs
- Energy confinement time τ_E is comparable to τ_p, suggesting that temporal variation of T_e is relatively small after RF stopped (consistent with x-ray measurements)

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

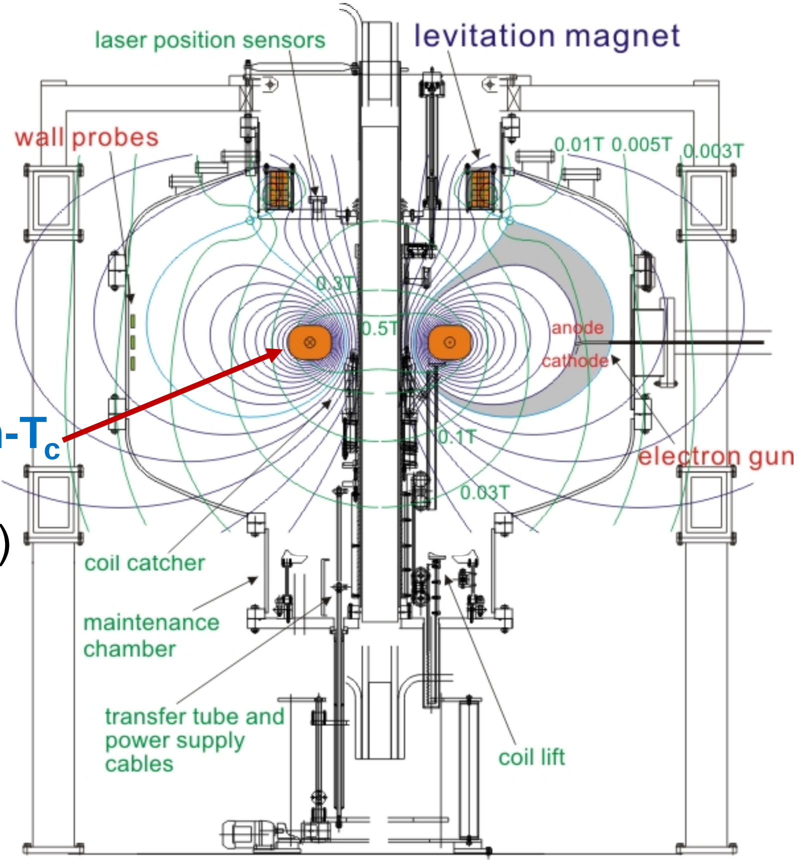


Radial density profiles [coefficient *a* of $n(r)=n_0r^{-a}$] with and without coil levitation

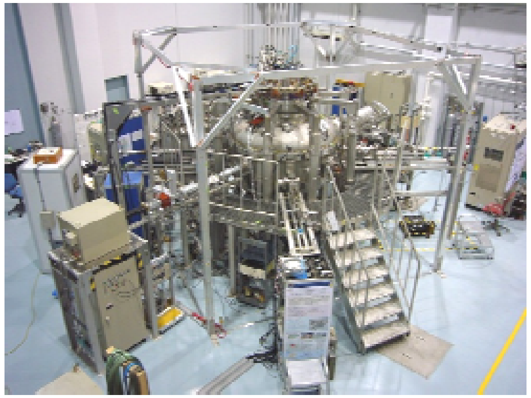
- Density profiles were estimated by multi-cord measurements of interferometer, assuming $n(r)=n_0r^{-a}$ on z=0 plane and density is a function of magnetic surface
- When the superconducting coil is levitated, plasma has peaked density profiles
- This result is similar to previous report in LDX*[1] and consistent with Hasegawa's prediction*[2] that turbulent-induced diffusion occurs until plasma density per flux tube becomes constant: $\partial/\partial\psi \iint f(\mu,J,\psi)d\mu dJ = 0$

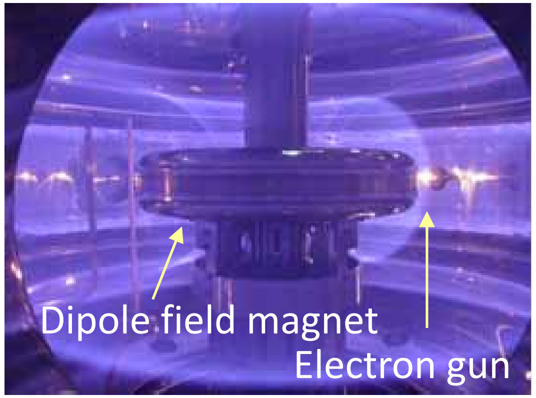
1. 2010 Boxer *et al.*, Nature Phys. 6, 207. 2. 1987 Hasegawa, CPPCF 11, 147.

RT-1, a magnetosheric configuration generated by a levitated dipole field magnet, stably confines toroidal non-neutral (electron) plasma



Levitated High-T_c SC Magnet
(0.25MA,112kg)





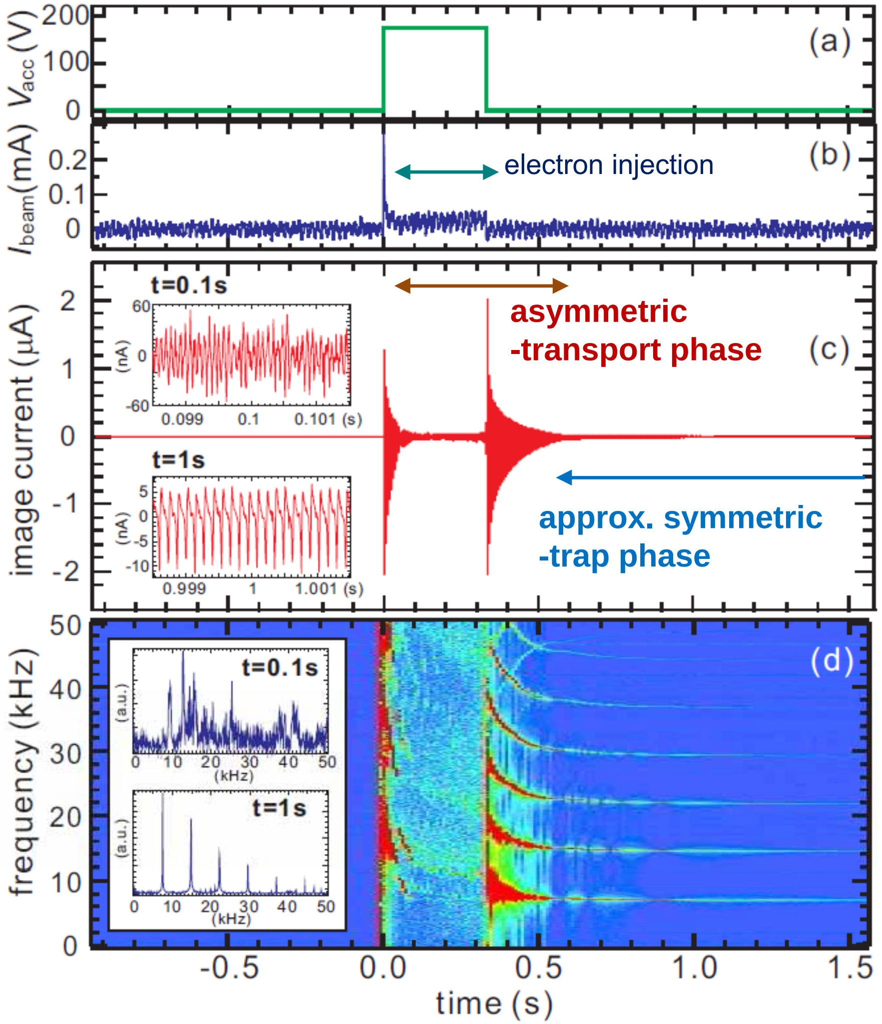
2009 Ogawa, Yoshida *et al*., Plasma Fusion Res. 4, 020.

- **High-β ECH plasma for advanced fusion**
  70% local β, confinement time ~0.5s, peaked density profiles

2011 Saitoh, Yoshida *et al*., Nuclear Fusion 51, 063034.

- **Toroidal non-neutral (pure electron) plasma**
  300s long confinement, rigid-rotating steady state, inward diffusion

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

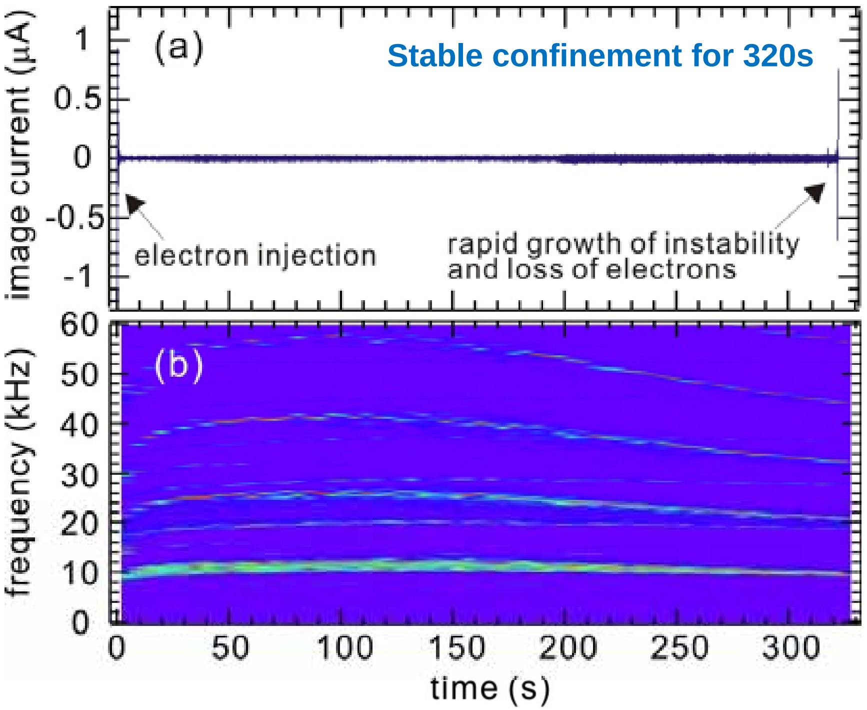


Formation and sustainment of toroidal PEP in RT-1.
(a) V_{acc}, (b) beam current, (c) electrostatic fluctuation, and (d) its frequency power spectrum.

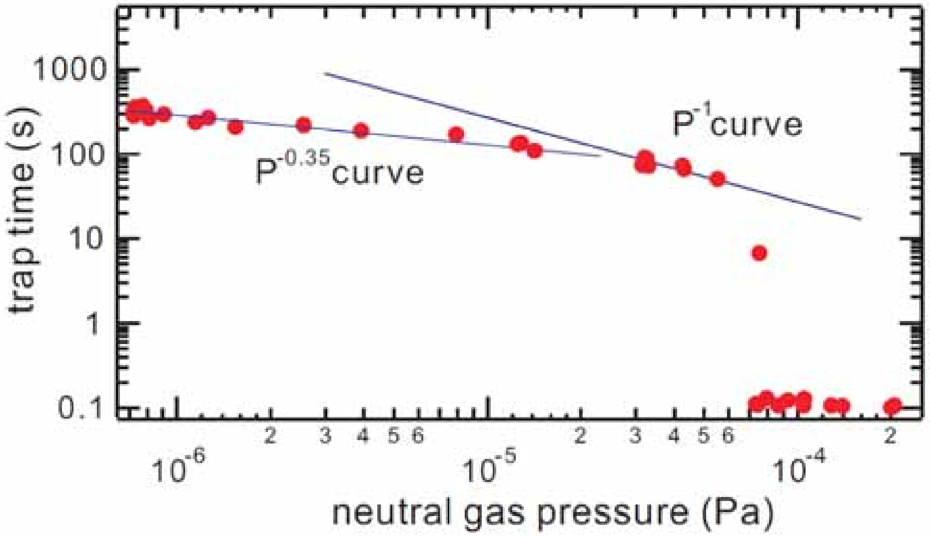
- Electrons are injected with a gun located at edge confinement region.
- Soon after the start of beam injection, a charged cloud is created, which repels the beam and diminished the beam current to about 10^{-5}A.
- When the beam current is stopped, plasma becomes turbulent, and then relaxes into a quiescent state.
- Frequency spectrum is sharply localized in this phase. The observed f~10kHz is comparable to the toroidal ExB rotation frequency.

2010 Yoshida *et al*., PRL 104, 235004.

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



Stable confinement for 320s

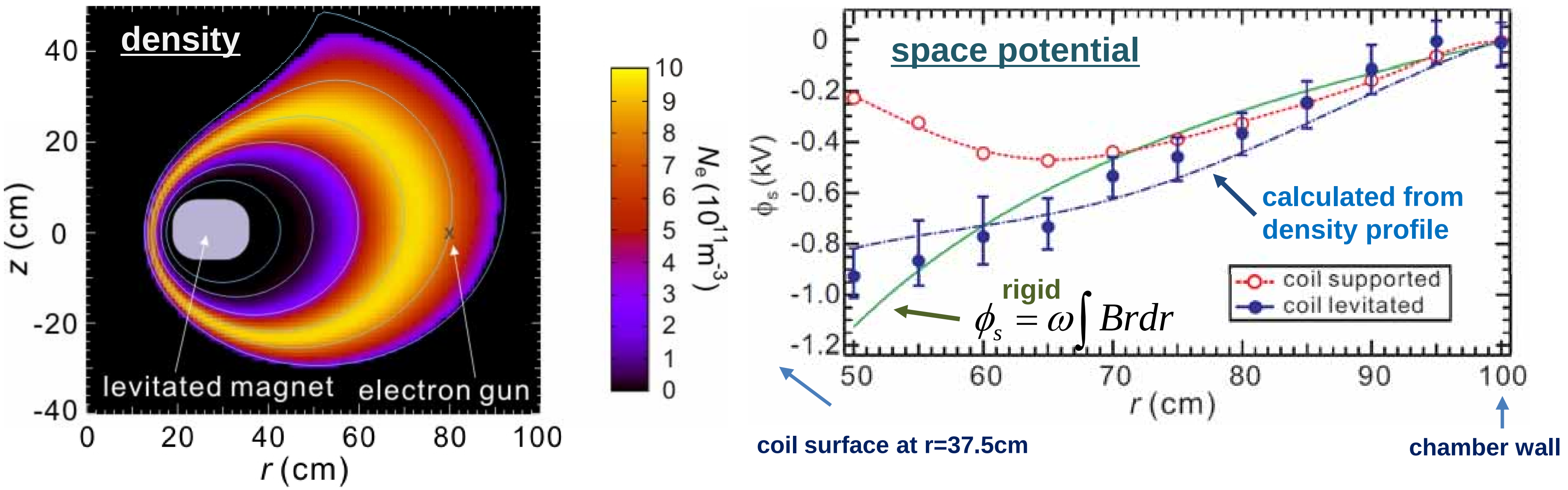


Temporal evolutions of electrostatic fluctuation and stable trap time in variation of neutral gas pressure

- The stable confinement time τ^* strongly depends on the neutral gas pressure P_n.
- The nonlinear relation ($\tau^* P_n \neq$const.) indicates that electron-neutral collisions do not simply decide the trap time of PEP.
- Confinement ends with onset of instability, possibly due to ion resonance effects.

2010 Yoshida *et al*., PRL 104, 235004.

Spontaneous formation of rigid-rotating state and inward diffusion: Density and potential profiles are consistent with semi-rigid motion



calculated from density profile

rigid $\phi_s = \omega \int Brdr$

coil surface at r=37.5cm

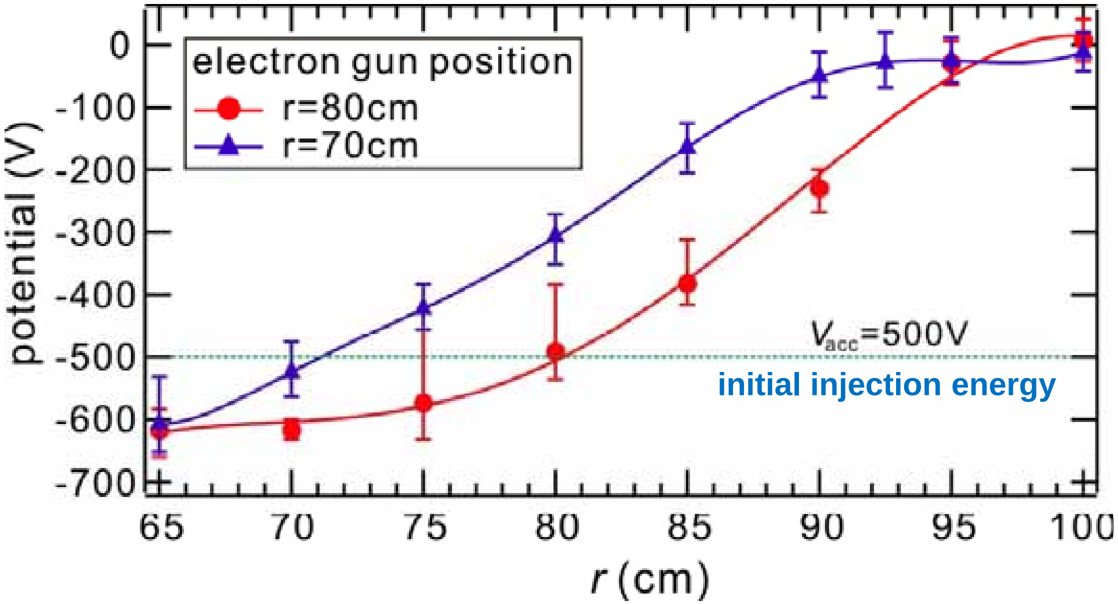
chamber wall

Radial density profile and space potential profiles during beam injection, measured with Langmuir probes. Electron gun accelelation voltage V_{acc}=500V.

- During electron beam injection, the levitated superconducting magnet is spontaneously negatively charged up.
- Density profiles that generate semi-rigid toroidal rotation are self-organized.
- Measured and calculated (from density profiles) potential profiles are consistent.

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

Observation of inward particle diffusion 2:
Space potential exceeds initial electron energy in strong field region

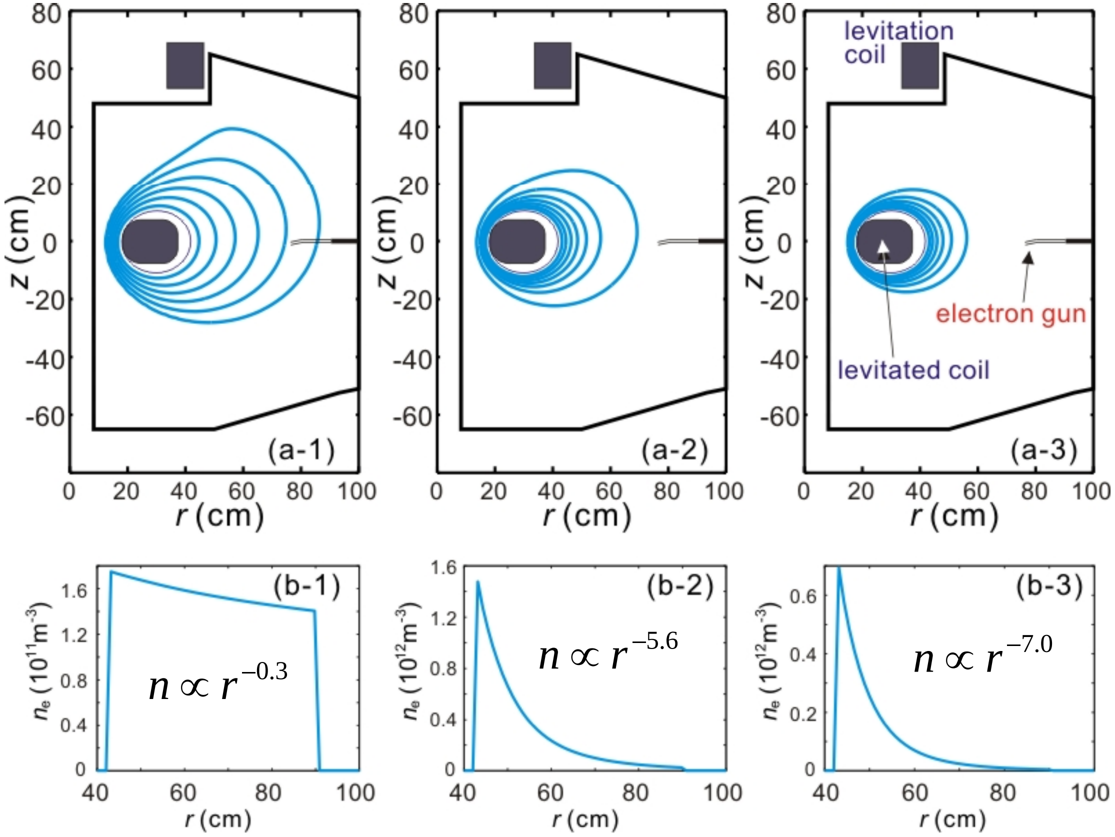


Radial spatial potential profiles with different radial positions of gun. V_{acc}=500V.

- Potential profiles indicate radial transport and acceleration of particles
  - At $r=r_{gun}$, space potential agrees well with V_{acc}
  - Space potential at $r<r_{gun}$ (in the stronger field region) is lower than V_{acc}.

➡ Some particles are accelerated and radially transported inward,
while thermal relaxation time (~400s) is much longer than beam injection time.

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



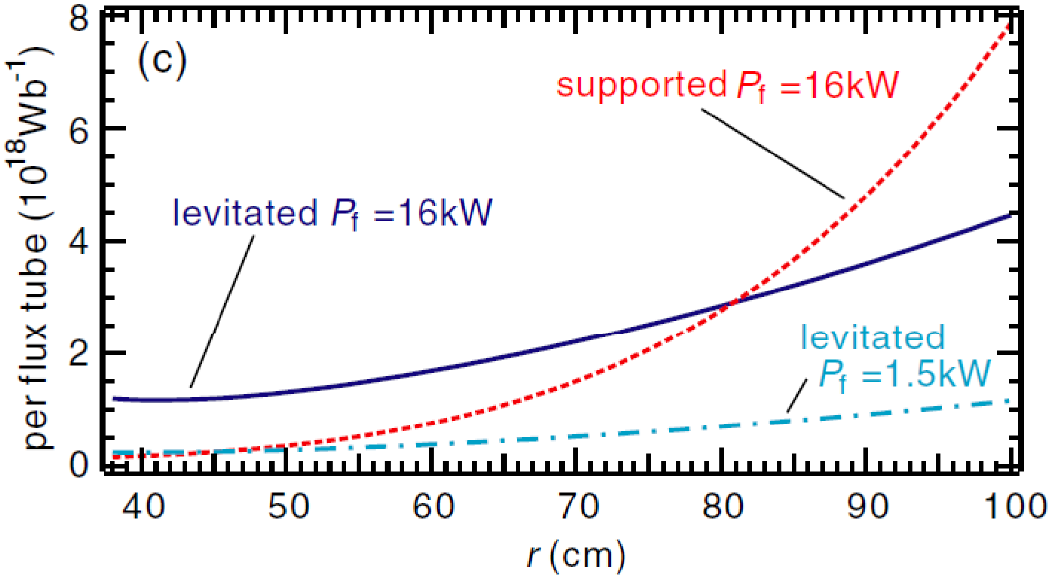
t=0s t=0.1s t=320s

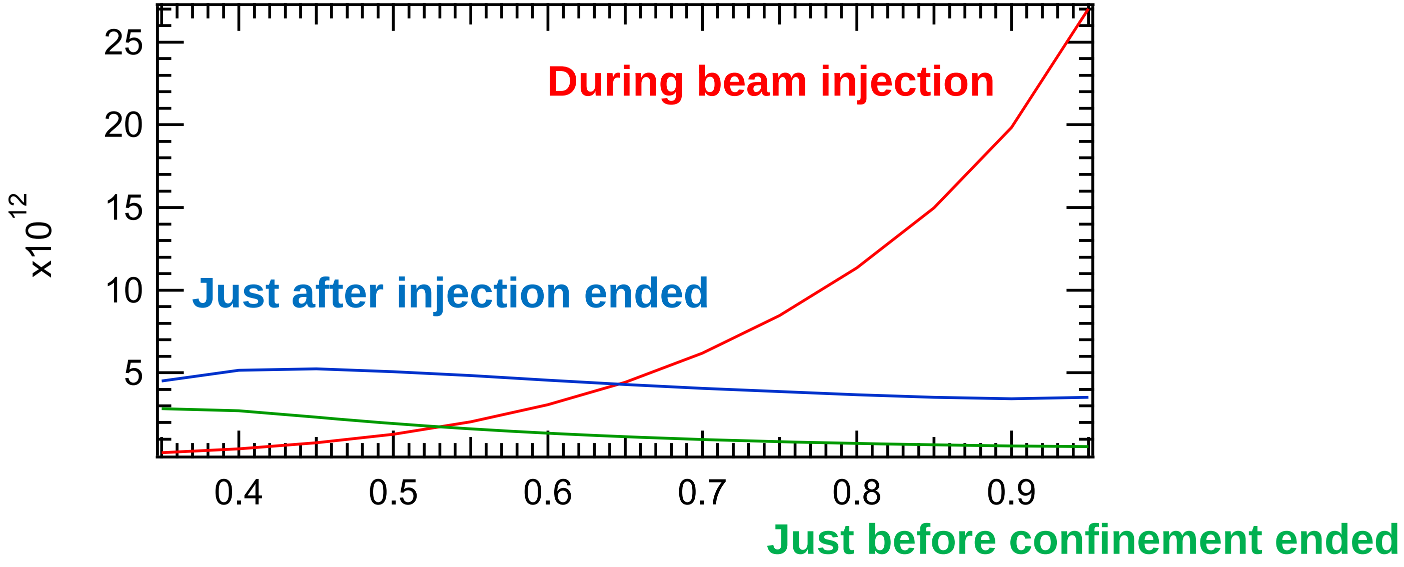
Estimated density profiles of PEP
(a) during electron beam injection,
(b) just after beam injection ended,
(c) just before confinement ended.

- 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.

Flattening of particle density per flux tube by magnet levitation





まとめと今後の課題

□ RT-1装置において，磁気浮上させたdipole磁場コイルの
作り出す磁気圏型配位中で，8.2GHz及び2.45GHzのマイクロ波による
ECHプラズマと純電子による非中性プラズマの生成実験を行ない，
特にその空間構造を調べた．

□ ECHプラズマ実験の現状： 高温電子による高βプラズマ
超電導マグネットの磁気浮上の効果により，性能が格段に向上
Ne $8\times10^{17}\mathrm{m}^{-3}$ local β >70% (~3.5mWb) τ_e ~100ms

□ 非中性プラズマ実験の現状： 純電子の300秒以上の安定閉じ込め
剛体回転する安定な平衡状態
Ne $1\text{-}10\times10^{11}\mathrm{m}^{-3}$ τ>300s 安定閉じ込め中にコヒーレントな揺動

□ いずれの場合も，マグネットの磁気浮上により擾乱を抑制した時に，
磁束管当たりの粒子数が空間的に平坦化する傾向が見られる．

□ 今後の課題
- 輸送研究の定量化 (計測システム，輸送モデル)
- ICRHによるイオン加熱 (現状のECHではイオンは~eV)
- 非断熱的な輸送機構の，陽電子を用いた実験研究