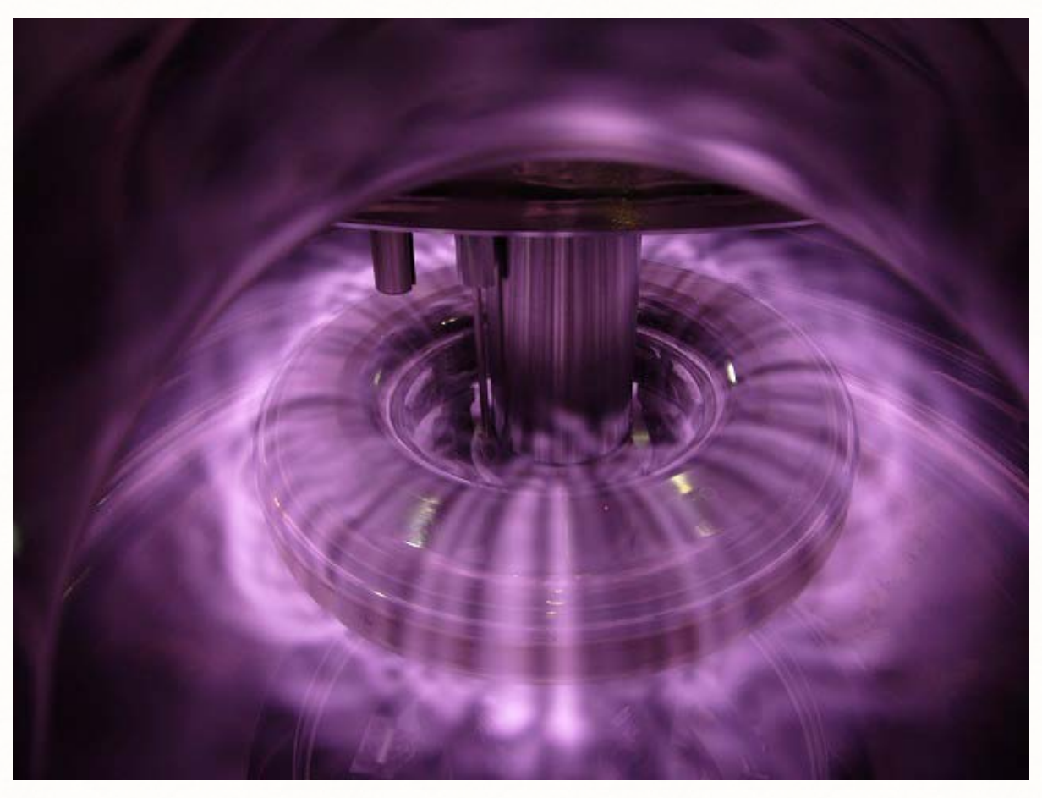
EXC/9-4Rb
23rd IAEA FEC
11-16 Oct. 2010

High-Beta Plasma Confinement and Inward Particle Diffusion in the Magnetospheric Device RT-1

H. Saitoh, Z. Yoshida, J. Morikawa, Y. Yano, T. Mizushima, Y. Ogawa, M. Furukawa, K. Harima, Y. Kawazura, K. Tadachi, S. Emoto, M. Kobayashi, T. Sugiura, and G. Vogel

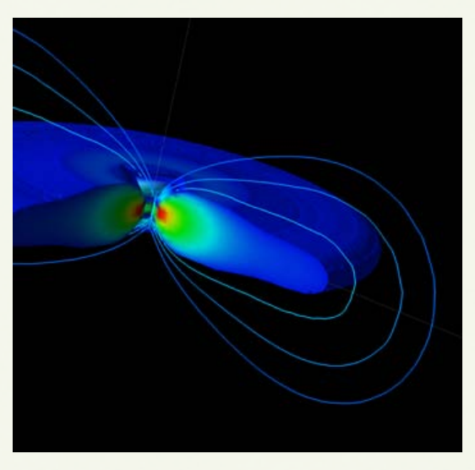
Graduate School of Frontier Sciences, University of Tokyo, Kashiwa, Chiba, JAPAN

- RT-1 is a magnetospheric configuration generated by a levitated superconducting (Bi-2223) magnet.
- High-β hot-electron ECH plasma is generated and stably sustained in RT-1.
- The maximum local β is 70% and pressure profiles have steep gradient near the levitated magnet.
- Electrons of high-β plasma typically consist of 70% of hot (~50keV) and the rest of cold populations.
- Confinement time of the hot-component high-β plasma τ_p~0.6s > $10^5\tau_{Bohm}$.
- Inward particle diffusion to strong field region was confirmed by pure electron plasma experiment.



Introduction

- Stable high-β plasma confinement is essential for realizing advanced fusion burning D-D and D-^{3}He.
- Dipole fusion* was proposed by taking a hint from the Jovian magnetosphere, where high-β plasma is stably confined.
- The mechanism of high-β state is theoretically explained by hydrodynamic pressure of fast flow (double Beltrami state**).



High-β flowing plasma near Jupiter

- Study of high-β flowing plasma is important for understanding the fundamental physics of self-organization of magnetized charged particles, as well as for the realization of advanced fusion concept.
- Diversity of plasma structures can emerge by two-fluid effects***:

From equation of motion $q_j(\tilde{\mathbf{E}}_j+\mathbf{v}_j\times\tilde{\mathbf{B}}_j)=0$ where $\tilde{\mathbf{E}}_j=-\partial_t\tilde{\mathbf{A}}_j-\nabla\tilde{\phi}$ and $\tilde{\mathbf{B}}_j=\nabla\times\tilde{\mathbf{A}}_j$, equilibrium condition of two-fluid system normalized for the ion inertia scale is

$$\nabla\left(\phi-h_e-\varepsilon\frac{v_e^2}{2}\right)=\mathbf{v}_e\times\left[\nabla\times\left(\frac{\mathbf{A}}{\delta_i}-\varepsilon\mathbf{v}_e\right)\right] \text{ and } \nabla\left(\phi+h_i+\frac{v_i^2}{2}\right)=\mathbf{v}_i\times\left[\nabla\times\left(\frac{\mathbf{A}}{\delta_i}+\varepsilon\mathbf{v}_i\right)\right].$$

where $\varepsilon=m_e/m_i$, $\delta_i=\Delta_i/L_0$, $\Delta_i=v_A/\omega_{ci}=\sqrt{m_i/\mu_0ne^2}$: ion inertia length, and L_0: plasma scale.

Standard MHD equilibrium equation is obtained in the limit of $\delta_i\to0$, satisfying $\mathbf{V}_i\times\mathbf{B}=0$.

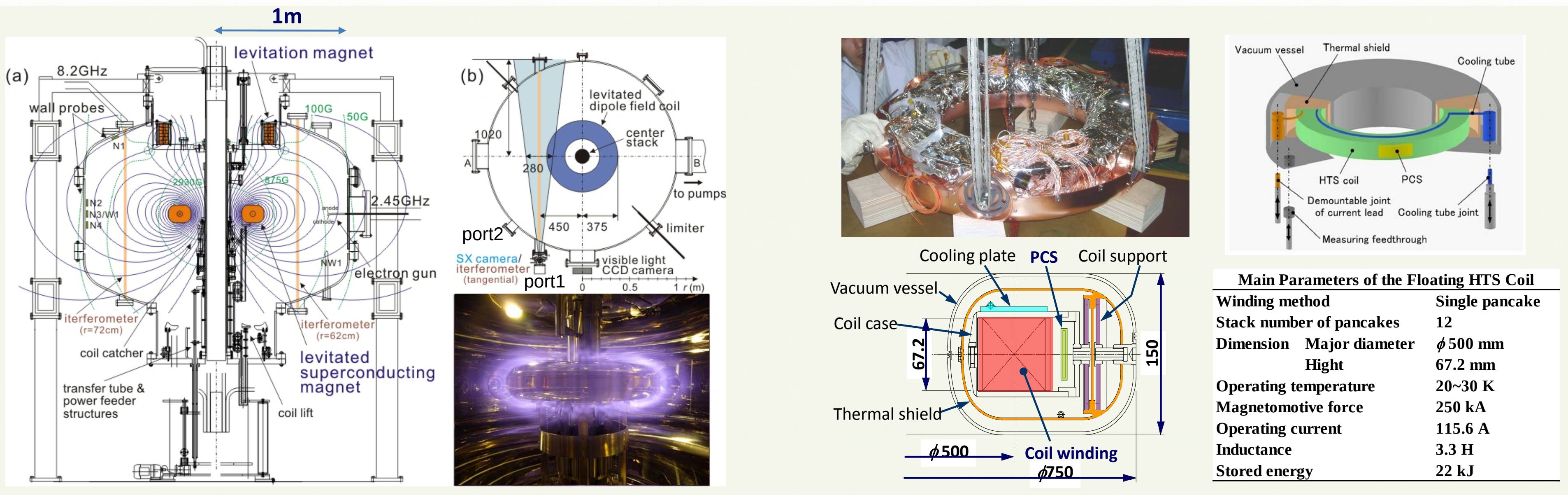
In magnetospheric plasma in RT-1, $\Delta_i\sim1\mathrm{m}$ and $L_0\sim0.1\mathrm{m}$, resulting $\Delta_i>1$.

Decoupling of ion and electron fluids causes many interesting phenomena, for example strong ion flow due to ion diamagnetism, which are not treated by MHD.

---

* 1987 Hasegawa, CPPCF **11**, 147. RT (Tokyo) and LDX (MIT/Columbia) are operating dipole fusion experiments.
1998 Mahajan Yoshida, PRL **81, 4863; 2005 Shiraishi *et al.*, PoP **12**, 092901. ***2010 Yoshida, PoP, to be published.

Experimental Setup: Ring Trap 1 (RT-1)



Main Parameters of the Floating HTS Coil		
Winding method		Single pancake
Stack number of pancakes		12
Dimension	Major diameter	ϕ500 mm
	Hight	67.2 mm
Operating temperature		20~30 K
Magnetomotive force		250 kA
Operating current		115.6 A
Inductance		3.3 H
Stored energy		22 kJ

Cross sections of RT-1*, visible light image of plasma, and construction of superconducting magnet.

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

- Dipole field magnet: Bi-2223 high-temperature superconducting coil, 250kAT (116A),112kg.
- Plasma is generated and heated by electron cyclotron resonance heating (ECH) with 2.45GHz magnetron (20kW, 2s) and 8.2GHz klystron (25kW(→100kW in the future), 1s).
- Diagnostic system consists of: 75GHz interferometer, visible light spectroscopy, magnetic loops and probes, Si(Li) and CdTe x-ray detectors, soft x-ray CCD camera, and edge Langmuir probes.

Proto-RT (1998-)

Normal conducting Magnet (10kA)

Mini-RT (2003-)

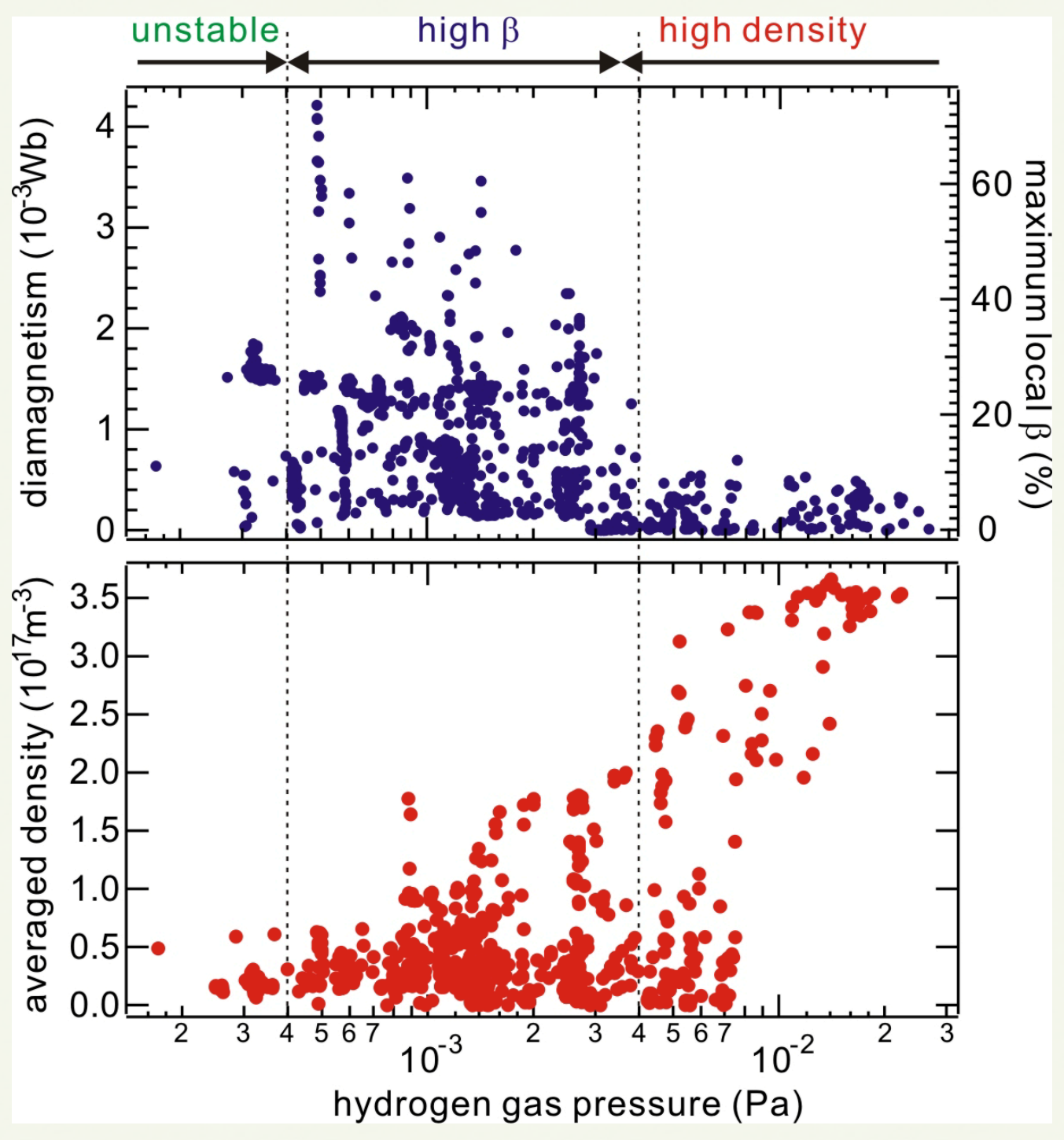
Superconducting Magnet (50kA)

RT-1 (2006-)

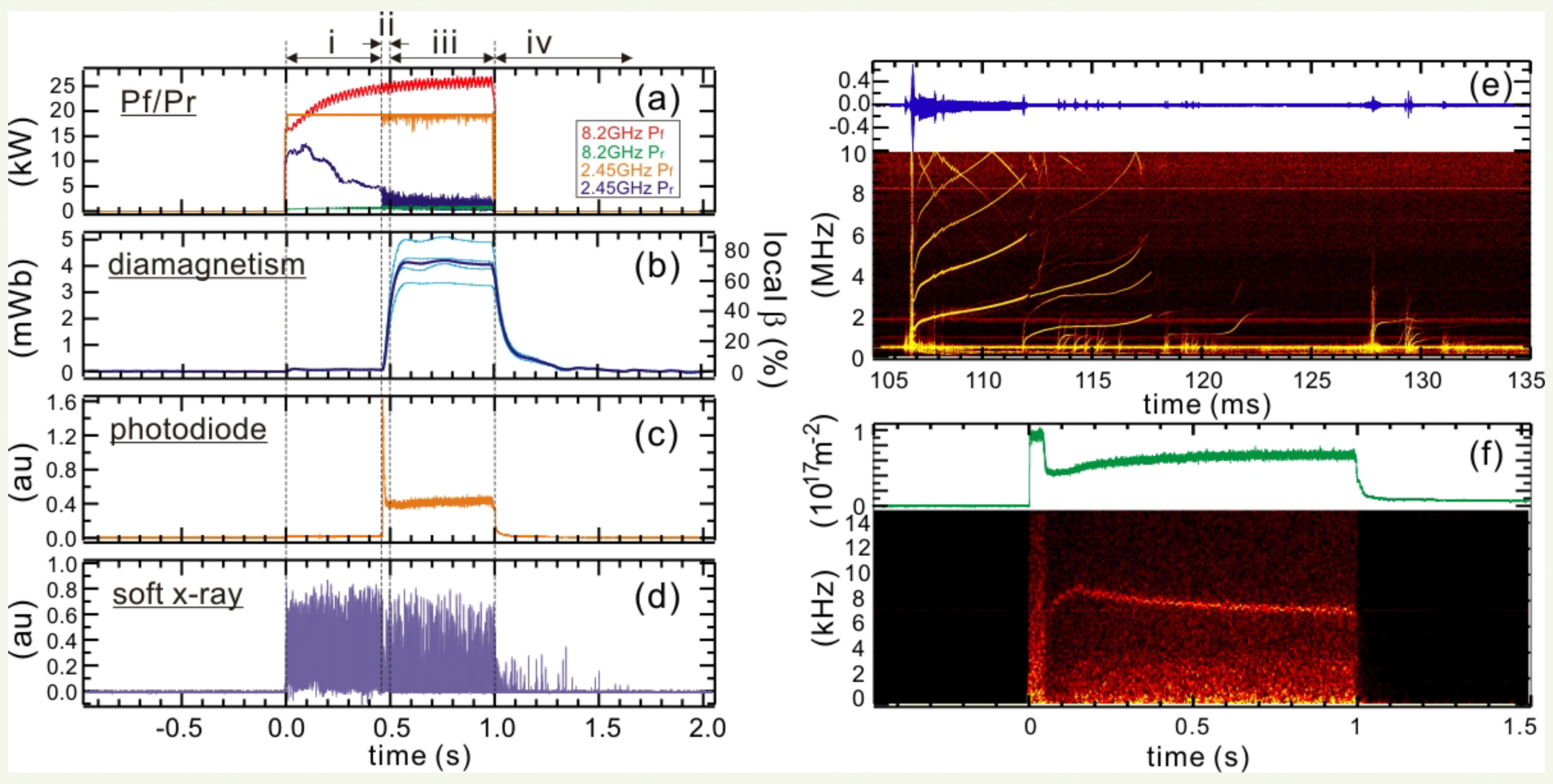
geomagnetic field compensation coil

RT Experiments at University of Tokyo, JAPAN

Improved High-β Stable State



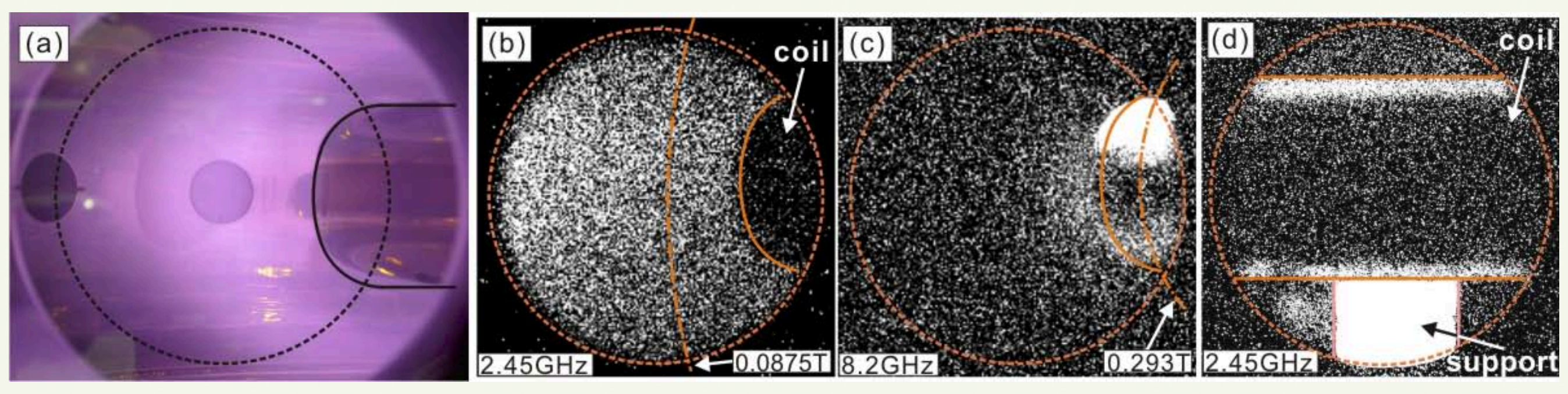
Diamagnetism and maximum local β, and (b) line density in variation of gas pressure.



Typical waveforms of high-β (local β~70%) plasma formation (left). Magnetic and density fluctuations observed in low-density and unstable mode of plasma.

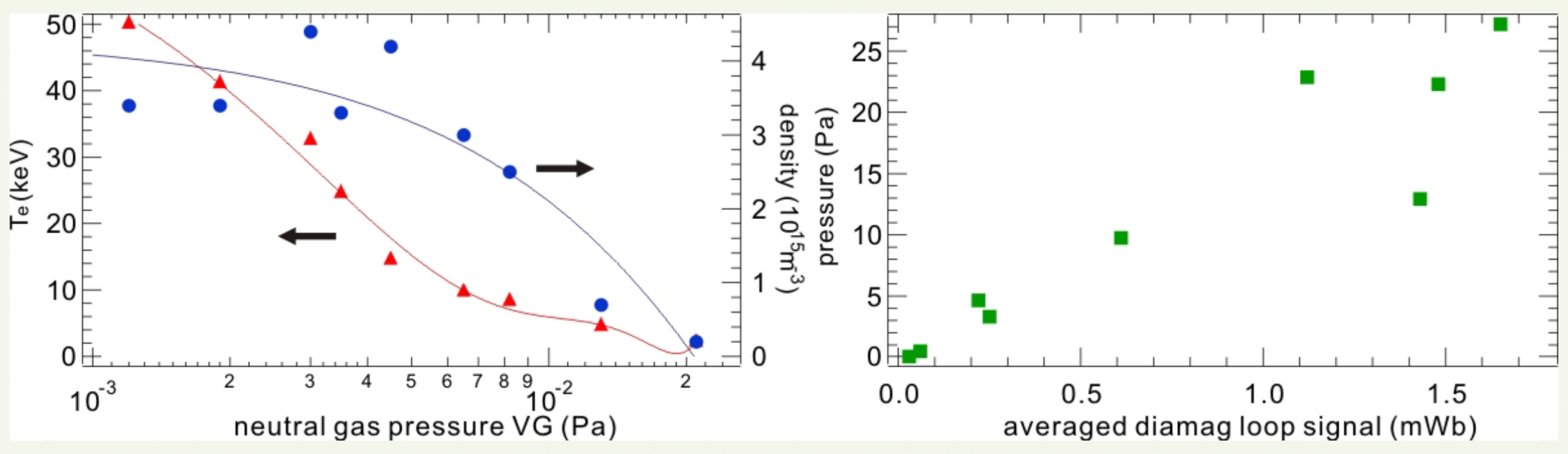
- High-β (maximum local β~70%) and high density (>n_{cutoff}, possibly due to EBW) plasma is generated.
- Parameter ranges are designated as high-density (4mPa<P_n), high-β (0.4mPa<P_n<4mPa), and unstable states (P_n<0.4mPa) according to the filling neutral gas pressure.
- High-β state is characterized by large stored energy, strong x-ray, and depression of visible light strength.
- In phase (i), thin plasma has large electromagnetic fluctuations, which are stabilized in steady state in (iii).

X-ray Measurements



(a) Visible light image and typical x-ray images* of plasmas generated by (b) 2.45GHz and (c) 8.2GHz ECH from port1. (d) X-ray image from port2.

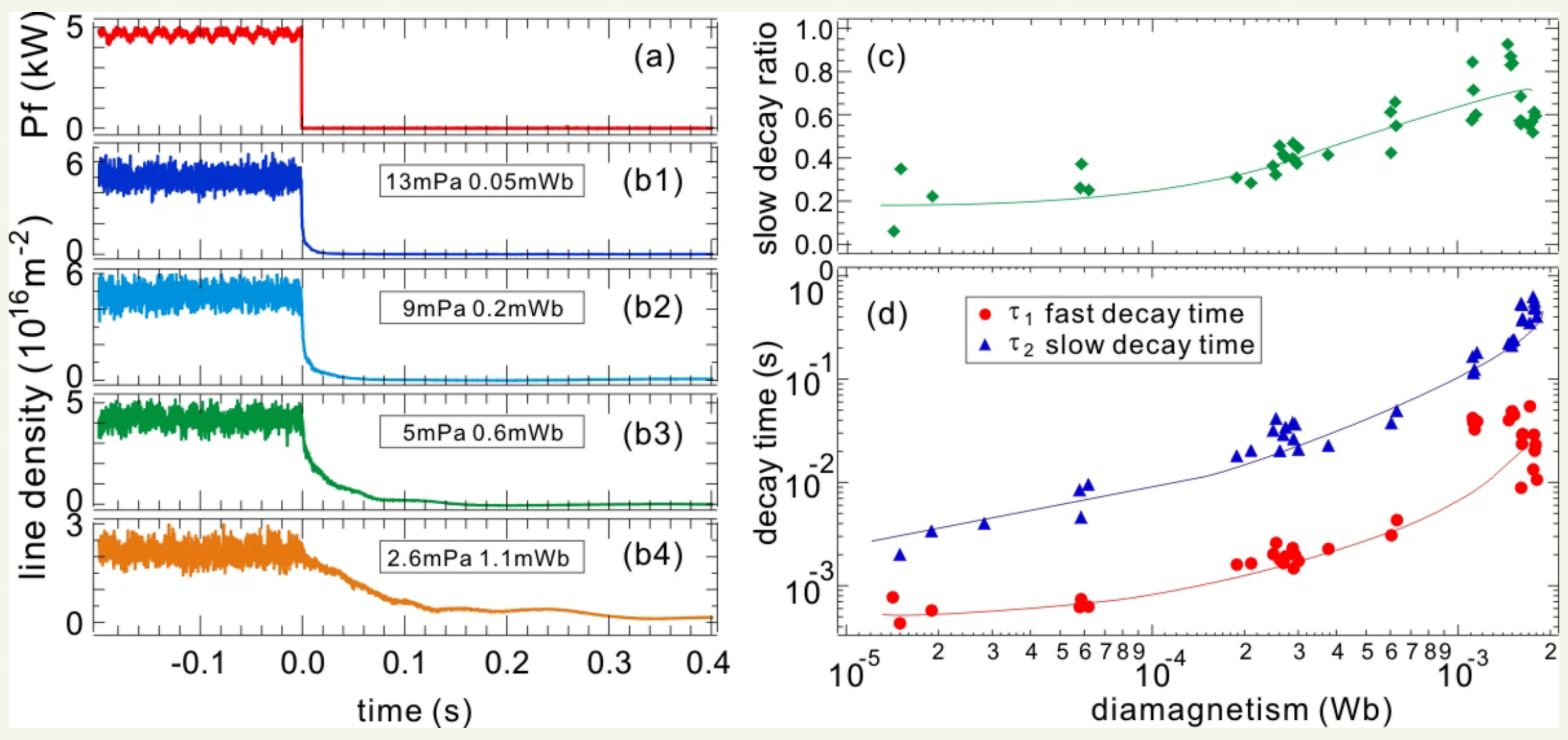
*2009 Saitoh *et al.*, Plasma Fusion Res. **4**, 050.



Temperature and density of hot electrons in variation of filled neutral gas, and hot electron pressure $P_h=n_hT_h$ in variation of diamagnetic signal.

- High-β plasma pressure is mainly resulted from hot electrons.
- Plasma has hot component electrons of T_h~50keV.
- Strong correlation between $P_h=n_hT_h$ and diamagnetism suggests hot component is the main component of electrons in high-β cases.

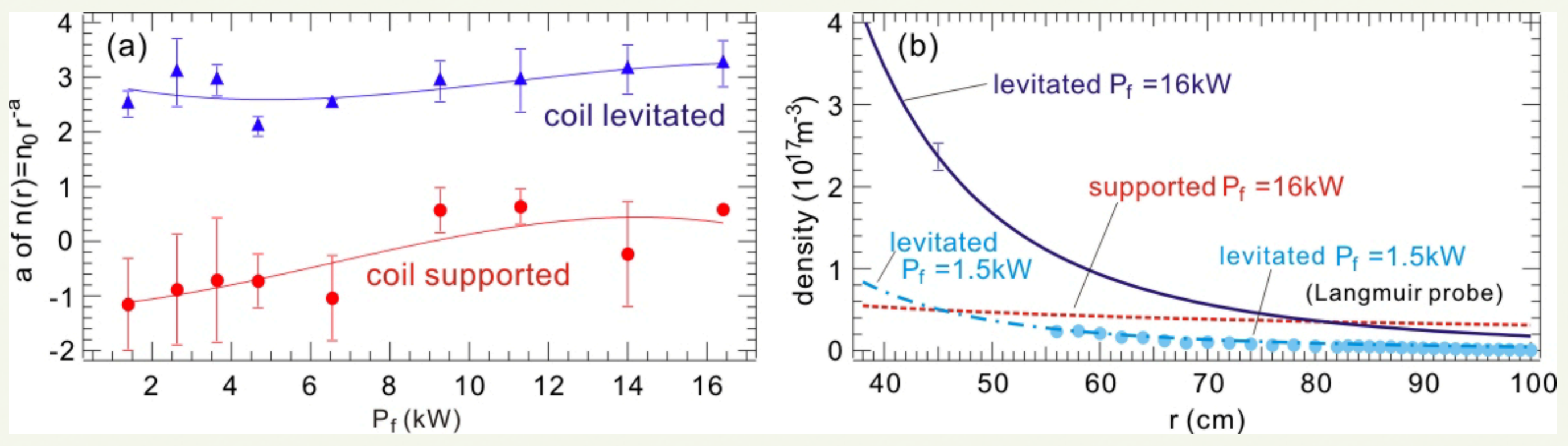
Confinement Properties



(a) Injection power of 2.45GHz microwave and (b) temporal decay of line density after the termination of microwave at t=0s with different neutral gas pressures. (c) Ratio of slow decay component electrons and (d) time constants of decay times in variation of neutral gas pressure.

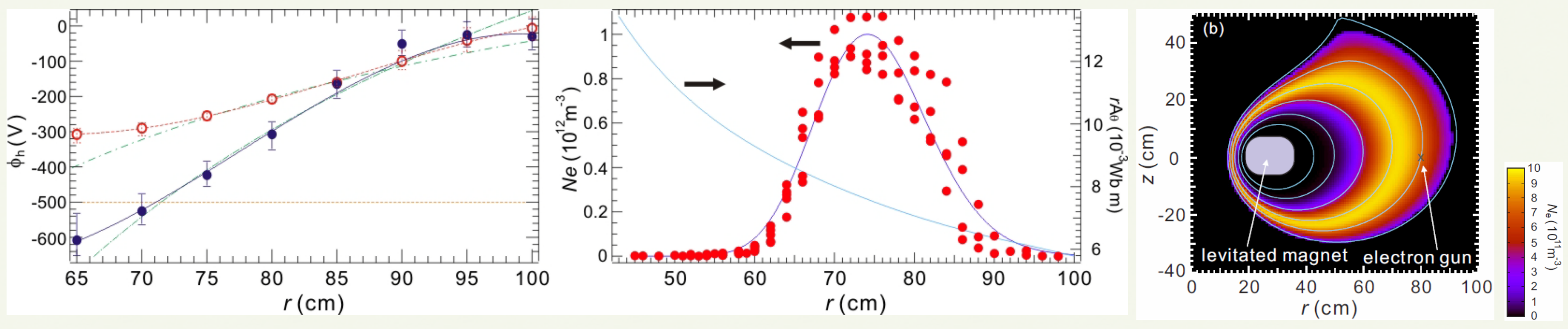
- Electrons consists of hot (~50keV) and cold (~10eV) populations, and hot-component has relatively long lifetime due to its small cross section of Coulomb collisions.
- Line density signals have two different decay times, corresponding to two components.
- By optimizing neutral gas pressure, increase in the ratio of hot component (~80%) and decay time (τ_p=0.6s) was observed. cf) τ_{Bohm}=1.4μs $\tau_{classical}$=3000s.
- Energy confinement time τ_E is comparable to τ_p, suggesting that temporal variation of is relatively small in afterglow phase.

Peaked Density Profiles



Coefficient *a* of $n(r)=n_0r^{-a}$ and estimated radial density profiles with and without coil levitation.

- When the superconducting coil is levitated, plasma has peaked density profiles.



Radial profiles of electrostatic potential with (closed circle) and without (open circles) coil levitation, and radial and 2d profile of electron density, of non-neutral (pure electron) plasma.

- Electrons injected from edge region are transported inward and stably trapped (>300s)*.
- These observation is consistent with Hasegawa's prediction**, turbulent-induced radial diffusion occurs until plasma density per flux tube becomes constant.

*2010 Yoshida *et al.*, PRL **104**, 235004. **1987 Hasegawa, CPPCF **11**, 147.