Improved Confinement Properties of Plasmas in RT-1 with a Levitated Coil

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Abstract

Ring Trap-1 (RT-1) is a novel device to confine plasmas in a magnetospheric configuration generated by a levitated superconducting coil. The main purpose of the RT-1 project is to explore physics of flowing plasmas (high-β double Beltrami states) and toroidal non-neutral plasmas on magnetic surfaces. In this study, we present the recent progress and status of the RT-1 experiment, especially focusing on the improvements of plasma properties by the coil levitation. In experiments with 8.2GHz ECH hydrogen plasmas, preliminary tests on formation of radial electric field were conducted by using an electron gun. The coil levitation has also realized a long time (~500s) trap of a pure electron plasma in a toroidal geometry.

I. Introduction

Flowing High β plasmas

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

Starting from equations of motion of an electron and an ion

$$\mathbf{E} + \mathbf{v}_e \times \mathbf{B} + \frac{1}{m_e n}\nabla p_e = 0 \quad \text{(inertia term neglected)}$$

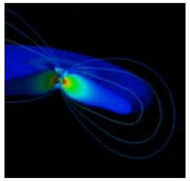
$$\frac{\partial}{\partial t}\mathbf{v}_i + (\mathbf{v}_i \cdot \nabla)\mathbf{v}_i = \frac{e}{m_i}(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \frac{1}{m_i n}\nabla p_i, \quad \text{we have}$$

$$\partial_t \mathbf{A} = (\mathbf{v} - \nabla \times \mathbf{B}) \times \mathbf{B} - \nabla(-\phi + \varepsilon p_e) \quad \text{and}$$

$$\partial_t(\varepsilon \mathbf{v} + \mathbf{A}) = \mathbf{v} \times (\mathbf{B} + \varepsilon \nabla \times \mathbf{v}) - \nabla(\varepsilon v^2/2 + \phi + \varepsilon p_i),$$

by using relations $\mathbf{E} = -\partial \mathbf{A}/\partial t - \nabla\phi$ and $\mathbf{j} = e(\mathbf{v} - \mathbf{v}_e) = 1/\mu_0 \nabla \times \mathbf{B}$.

Taking curl, $\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p$ and $\partial_t \mathbf{B} = \nabla \times [(\mathbf{v} - \varepsilon \nabla \times \mathbf{B}) \times \mathbf{B}]$.



High β rotating plasma in Jupiter's magnetosphere
J. Shiraishi, Z. Yoshida et al., Pop 12, 092901 (2005).

One of the time independent solutions is given by $\mathbf{B} = a(\mathbf{v} - \nabla \times \mathbf{B})$ and $\mathbf{B} + \nabla \times \mathbf{v} = b\mathbf{v}$.

This solution satisfies $v^2/2 + p_i + \phi = const.$ and $p_i - \phi = const.$

Then the generalized Bernoulli condition $\beta + v^2 = const.$ is derived.

Assuming that $\beta = 0$ at the plasma surface and v is given by $\mathbf{E} \times \mathbf{B}$ speed, $E_r/B = v_A \beta^{1/2}$.

➡ Possibility of Ultra-high β (including β >1) equilibrium state of plasmas balanced by the dynamic pressure of plasma flow, when the plasma flow has a fast flow comparable to the alfvén velocity v_A.

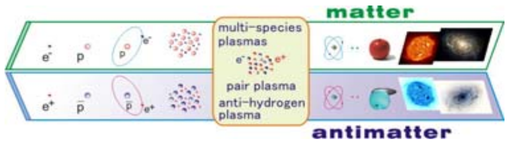
Toroidal non-neutral plasmas on magnetic surfaces

Z. Yoshida et al., *Nonneutral Plasma Physics III*, 397 (1999).
T. Sunn Pedersen and A.H. Boozer, PRL **88**, 205002 (2002).

"Pure magnetic" confinement of non-neutral plasmas without open-ends

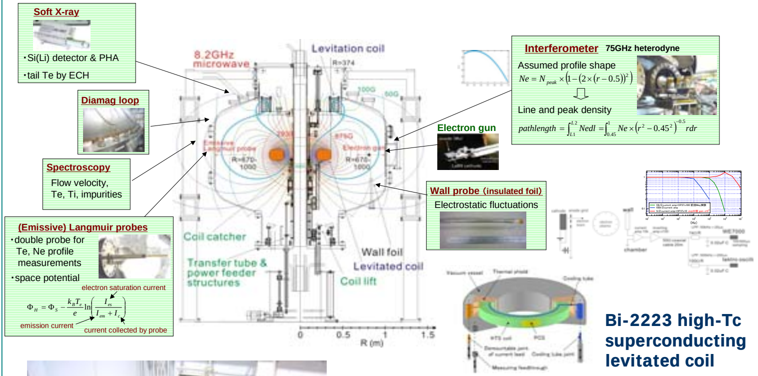
Ring trap: axisymmetric toroidal magnetic surface configuration

➡ Application to trap high energy beam particles or multiple species of charged particles with different charges.



The aim of the RT-1 project is the experimental verification of the novel concepts in non-neutral plasma physics

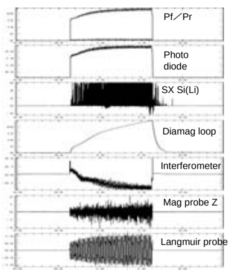
II. RT-1: device geometry and diagnostics



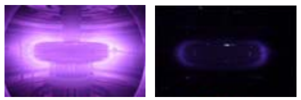
Bi-2223 high-Tc superconducting levitated coil

levitated magnet	Size	R=250mm *w*195mm *h*150mm
	Current	250kA (2160turns)
	Weight	110kg
	Operating temp.	20K – 32K
lifting magnet	Current	88kA (68turns)
	dynamic range	*f*<10Hz (feedback control)
chamber	Size	R = 1m, h=0.56mm 10^{-6}Pa
RF1	Frequency	8.2 GHz
	Power	100kW (1sec pulse)
RF2 (plan)	Frequency	2.45GHz
	Power	20kW (2 sec pulse)

III. 8.2GHz ECH plasmas



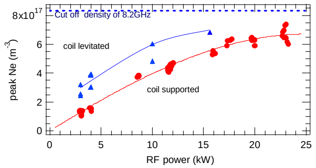
Typical waveform of 25kW 1s discharge



t=0.5s: microwave injection   t=1.1s (afterglow)

Afterglow

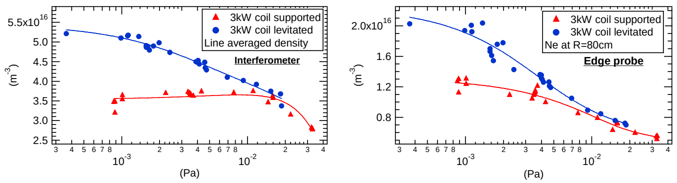
Light emission was observed for ~1s, when electrons have high energy component.



Electron density

Peak density saturates at 25kW (coil supported) and 15kW (levitated), close to the 8.2GHz cut off density.

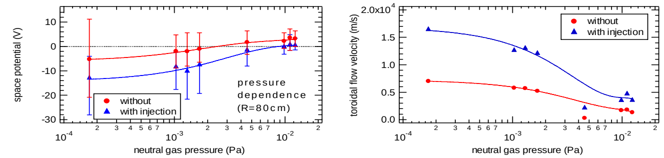
Electron density with and without coil levitation



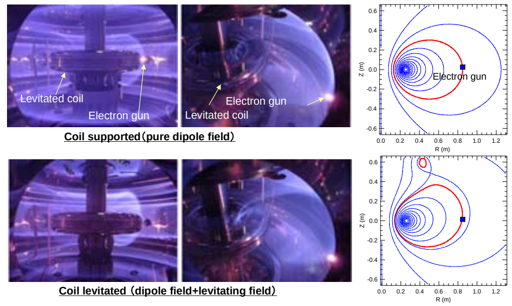
Increase of Ne was clear especially in a low neutral pressure region, lasma loss due to the support structure was minimized by the coil levitation.

Preliminary test for flow formation

We applied a small current (~1A) electron gun for electron injection into a plasma.
Radial electric field of ~100V/m was formed at the edge region.
A new bias electrode with larger area is scheduled to be installed.



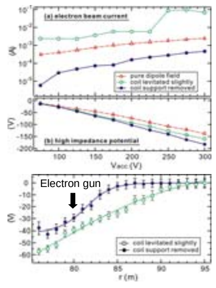
IV. Non-neutral (pure electron) plasmas



Visualization of magnetic surfaces:

500eV electron beam was injected into 1×10^{-2}Pa H_2 gas, and low density hydrogen plasma was generated.

Light emission distributions show good agreement with the calculated magnetic surfaces.

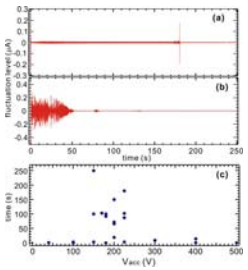


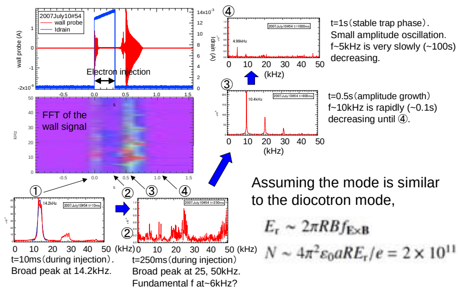
Electron beam current and potential profiles

By the coil levitation, the injected beam current decreased by two orders of magnitude.

Space potential was comparable to the acceleration voltage of the electron gun.

Suggesting excellent trap during the coil levitation.





Assuming the mode is similar to the diocotron mode,

$$E_r \sim 2\pi RBf_{\mathbf{E}\times\mathbf{B}}$$

$$N \sim 4\pi^2 \varepsilon_0 aRE_r/e = 2 \times 10^{11}$$

Stabilization of fluctuation and long confinement

After the stabilization and frequency drop, PEP was trapped for ~500s (close to the classical diffusion time caused by collisions with neutral atoms).