Magnetosphere-like Plasma Produced by Ring Trap 1 (RT-1)
-- A New Approach to High-Beta Confinement --

Z. Yoshida 1), Y. Ogawa 2), J. Morikawa 1), M. Furukawa 1), H. Saitoh 1), M. Hirota 1), D. Hori 1), J. Shiraishi 1), S. Watanabe 1), Y. Yano 1)

1) Graduate School of Frontier Sciences, The University of Tokyo, Chiba 277-8561, Japan
2) High Temperature Plasma Center, The University of Tokyo, Chiba 277-8568, Japan

e-mail contact of main author: yoshida@k.u-tokyo.ac.jp

Abstract. The Ring Trap 1 (RT-1) is a novel plasma device constructed to explore ways to the advanced-fuel fusion that requires a very high beta value. A super-conducting ring, levitated in the vacuum chamber, produces a magnetic field that traps high-temperature plasma, creating a magnetosphere-like configuration. Giving a radial electric field yields a strong flow whose hydrodynamic pressure can balance the thermal pressure. The mechanism of plasma confinement is based on the theory of high-beta equilibrium that is self-organized in a flowing plasma. The first experiment (performed in January 2006) succeeded in producing plasma with energizing and levitating the super-conducting coil and injecting an 8.2 GHz microwave.

1. Introduction

The physics of “flowing plasmas” is still immature, and there remain many unknown structures produced by flow-field couplings. The governing equations of flowing plasmas include some fundamental mathematical difficulties that fortunately degenerate in static plasmas. The equilibrium equations have singularities that bring about interactions of different scale hierarchies. Shock is a well-known example of the creation of singularity, which hosts many interesting multi-scale phenomena such as particle acceleration. The analysis of magnetohydrodynamic (MHD) equilibrium of a flowing plasma is an involved nonlinear problem. The theory of waves and instabilities in flowing plasmas is also a challenging area of theory. Because of the non-Hermitian property of the generator (the operator governing the evolution), transient phenomena are far richer than those in a Hermitian system; the latter may be analyzed invoking the standard dispersion relations (spectral analysis), while the former are far beyond the scope of the spectral analysis. The existence of various continuous spectra is also making the analysis very difficult.

The Ring Trap 1 (RT-1) project is aiming at exploring various effects of flow-field couplings as described above. The RT-1 device produces a magnetosphere-like plasma –the most common configuration in the universe. A super-conducting ring magnet is levitated in the vacuum chamber, which produces a dipole magnetic field to trap high-temperature plasma. Giving a radial electric field yields a strong plasma flow whose hydrodynamic pressure can balance the thermal pressure. Such a structure simulates Jupiter’s magnetosphere that is known to be confining a very high-beta plasma. While a “magnetosphere” is geometrically simple, it has rather strong inhomogeneity in various parameters, which creates extremely rich structures through some self-organization processes.

In this paper, we describe the theoretical background and predictions underlying this project (section 2), the outline of the RT-1 device, and the present status of the experiment (section 3).

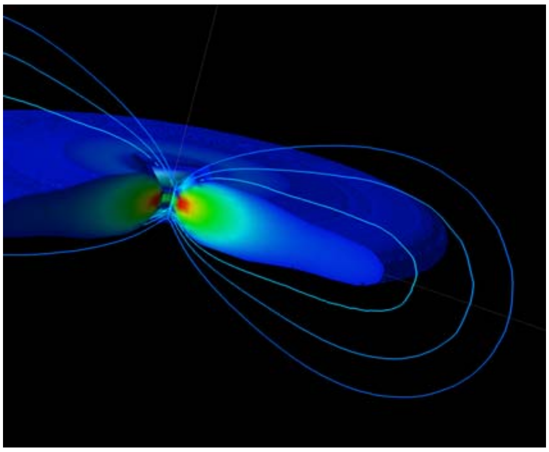

FIG.1. Theoretical model of Jupiter's magnetosphere [3]. The planetary dipole magnetic field traps a high-pressure plasma.

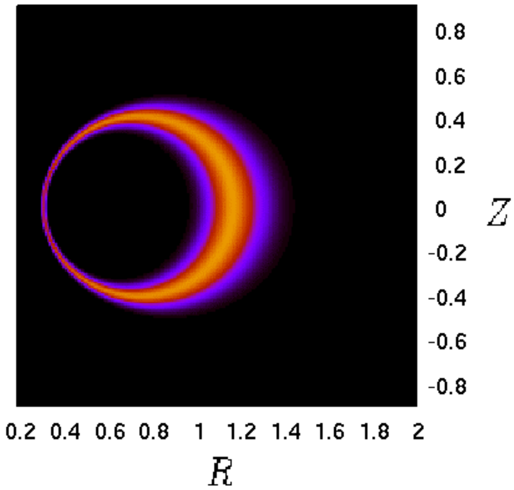

FIG. 2. New type of Hall-MHD equilibrium in the RT-1 configuration [4]. Unlike the standard MHD equilibrium of a rotating plasma, the core of the plasma shifts inward when the rotation speed is increased.

2. Equilibrium and Stability Theory

2.1. Equilibrium of Flowing Plasmas

The RT-1's mechanism of plasma confinement is based on the theory of self-organized states in flowing plasmas [1,2], which predicts that the hydrodynamic pressure in a fast plasma flow can balance the thermal pressure (Bernoulli's law) creating a relaxed state with an appreciably high-beta value. The equilibrium state produced by this device simulates Jupiter's magnetosphere. Figure 1 shows a theoretical model of a high-beta magnetosphere that is the minimum energy "relaxed state" under the restrictions of the helicity and canonical angular momentum [3]. The RT-1 experiment may produce a larger variety of configurations that are dominated by the collision-less Hall effect [4] (see FIG. 2) and/or self-electric field [5,6] (see FIG. 3).

The fundamental structure of the nonlinear flow-field coupling can be represented by the "double Beltrami" solution [1,2] to the nonlinear Hall MHD equations, which is a combination of two eigenfunctions of the curl operator. The Beltrami fields, eigenfunctions of the curl operator, represent essential characteristics of sheared, spiral, chiral or helical structures in various vector fields. A general solenoidal (divergence-free) vector field, such as a magnetic field or an incompressible flow, can be decomposed into an orthogonal sum of Beltrami fields (eigenfunctions) [7]. Nonlinear dynamics of a plasma induces complex couplings among these Beltrami fields. In an MHD plasma, however, the energy of the system tends to condensate into a single Beltrami magnetic field $\boldsymbol{B}$, resulting in the self-organization of a force-free equilibrium, that is the Taylor relaxed state [8] satisfying $\nabla \times \boldsymbol{B} = \lambda \boldsymbol{B}$. It is remarkable that, in the Hall MHD model, a more general relaxed state is given by a pair of two different Beltrami fields [1]; the magnetic and flow fields ($\boldsymbol{B}$ and $\boldsymbol{v}$, respectively) are given by

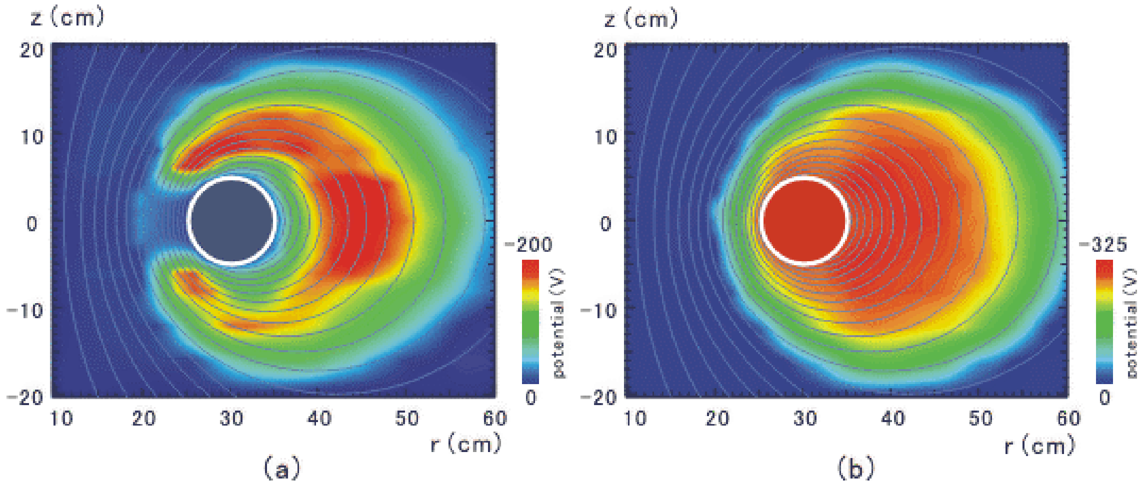

FIG. 3. Two different types of equilibria of non-neutral (pure electron) plasma (data from the Proto-RT experiment [6]). The color contours show the electric potential.

$$\boldsymbol{B} = C_+\boldsymbol{G}_+ + C_-\boldsymbol{G}_-, \quad \boldsymbol{V} = C_+'\boldsymbol{G}_+ + C_-'\boldsymbol{G}_- \qquad (\nabla\times\boldsymbol{G}_\pm = \lambda_\pm\boldsymbol{G}_\pm).$$

This new set of relaxed states includes field structures far richer than the conventional single Beltrami states.

In the double Beltrami fields, un-separable scale hierarchies are represented by the coupling of the two scale Beltrami fields [9]. The eigenvalue λ of the curl derivative is the reciprocal length scale of the corresponding vortex eigenfunction. A double Beltrami field, thus, includes two distinct scales. The coupling is primarily due to the Hall term that acts as a “singular perturbation”, a term including a higher-order derivatives and multiplied by a small factor ε. The ε is scaled by the collision-less ion skin depth $c/\omega_{\rm pi}$. In the limit of ε = 0, one component of the double Beltrami field converges to the single Beltrami solution of the ideal MHD, while the other is singular. The former component, thus, represents the “universality class” of the scale-free structures, which is always accompanied by a small-scale (order ε) component that is omitted by the macroscopic ideal model.

The physical role of the Hall term is to introduce a dispersive effect that unfolds the singularity. Singularities in the ideal MHD model are naturally removed by the higher-order degree of freedom introduced by the Hall term [10,11].

2.2. Stability of Flowing Plasmas and Casimir Invariants

The stability analysis of a flowing plasma encounters the problem of non-Hermitian generator of dynamics, where the method of “dispersion relations” does not apply. Von Neumann's theorem of the spectral resolution for Hermitian operators allows us to transform $\partial_t \to -i\omega$ in the evolution equation, converting the initial-value problem into an eigenvalue problem, viz., the solution to the initial-value problem can be constructed by summing (integrating) over the particular solutions of the form of $u(x,t) = \exp(-i\omega t)\phi_\omega(x)$ (the inverse Laplace transform). Since we do not have an equivalent spectral resolution of general non-Hermitian operators, we may no longer start with assuming exponential behavior of the perturbation.

Indeed, a variety of complex transient phenomena are observed in non-Hermitian systems [12-14].

It is well known that a linear operator (matrix) in a finite-dimension vector space can be cast into Jordan's canonical form. Then, some degenerate eigenvalues (overlapping frequencies) may cause “nilpotent”, and the “resonance” among independent (generalized) eigenvectors results in secular (algebraic in time) amplification of the mode amplitudes. In an infinite-dimension phase space of plasma dynamics, however, the generator may have continuous spectra. The overlapping of the continuous spectra brings about coupling of the corresponding singular eigenfunctions, and very complicated transient phenomena that may not be decomposed into a finite degree of freedom. A rigorous theory of singular eigenfunctions has been constructed by invoking the hyperfunctions [14].

One may assume a variety of pathological non-Hermitian operators. However, some classes of non-Hermitian operators, which are relevant to physics, have special interesting natures. For ideal fluids and plasmas, the model equations have the conservative property (for example, the “energy” must be a constant of motion), and can be cast in (non-canonical) Hamiltonian form. The analysis of the equilibrium and also the stability of the “Beltrami-class” of solutions, such as the single or double Beltrami fields, have a strong relation to the Hamiltonian structure.

A non-canonical Hamiltonian system is characterized by a non-canonical Lie-Poisson bracket { , } that may have a null space V_n. This null space is not dynamically accessible by any orbit $u(t)$ in the phase space. If there is a “Casimir invariant” $C(u)$, i.e., $\{H(u), C(u)\}$ for all $H(u)$, the orbit is limited on the level-set of $C(u)$, and hence, the gradients of the Casimir are included in V_n. Adding such Casimir invariants $C_j(u)$ to the Hamiltonian $H(u)$ does not change the dynamics;

$$\frac{d}{dt}F(u) = \{H, F\} = \{H + \sum \alpha_j C_j, F\} .$$

This fact can be used to find a set of equilibrium points; the variational principle

$$\delta F(u) = \delta\left(H(u) + \sum \alpha_j C_j(u)\right) = 0$$

yields equilibrium points characterized by parameters α_j. If we take the helicities as the Casimirs, we obtain the Beltrami fields [2]. For this class of equilibria, the functional $F(u)$ works as a Lyapunov function, and the convexity (coercivity) of $F(u)$, with respect to some norm of the perturbation, warrants the stability of the critical point [15]. Hence, this Hamiltonian structure gives a strong method of analysis of the equilibrium and stability of flowing plasmas [16].

3. RT-1 Experiment

3.1. Magnetosphere-like System

To explore high-beta plasma confinement that may enable the advanced-fuel fusion energy, we have constructed a new device, Ring Trap 1 (RT-1), which confines a plasma in a magnetosphere-like field produced by a super-conducting magnet levitated in a vacuum

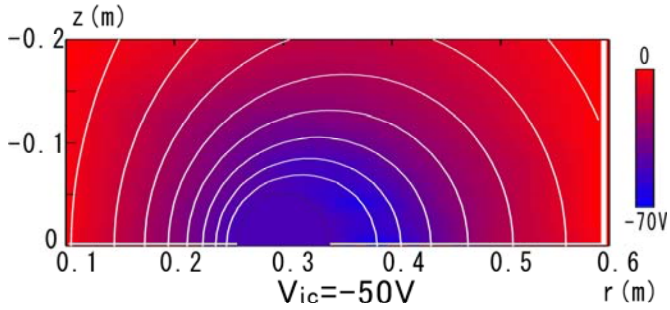

FIG. 4. Potential (flow) distribution in the Proto-RT device. The surface of the ring conductor was biased at –50V to produce a radial electric field driving a supersonic flow.

chamber. The physics and technology of RT-1 is based on the developments and experiments done in the preceding Proto-RT and Mini-RT projects. Proto-RT was the first magnetospheric device, which proved the basic concept of the flowing-plasma confinement [5,17]. Mini-RT was constructed to develop a super-conducting levitated coil system using the Bi-2223 high-Tc conductor [18]. To extend and improve the total performance of the system, some technical challenges and developments were needed in the construction of RT-1.

The "dipole fusion" is also exploring a high-beta confinement with a similar magnetic-field configuration [19], while it does not emphasize the flow effect. The LDX experiment developed by MIT takes this approach [20].

On the Proto-RT device, we have demonstrated generation of a supersonic flow with biasing the surface of the internal conductor [21]. Figure 4 shows the internal structure of the electrostatic potential. The internal electric field was of order 10^3 V/m and the corresponding $\boldsymbol{E} \times \boldsymbol{B}$ drift speed was 10^5 m/sec, which is much larger than the ion sound speed (electron temperature was of order 10 eV). The equi-potential surfaces coincide with the magnetic surfaces.

3.2. Super-Conducting Ring Magnet System

The confining magnetic field of the RT-1 device is produced by a super-conducting magnet levitated in the vacuum chamber (FIGS. 5-7 and TABLE 1). The magnet employs a high-Tc superconductor (Bi-2223). The field strength in the confinement region varies from 0.3T to 0.03T.

FIG. 5. The view of the RT-1 device.

FIG. 6. The super-conducting ring magnet supported by the lifter. The catcher system is installed on the center column.

TABLE I: RT-1 machine parameters.

levitated magnet	Size	R=250mm, cross section (casing): *w*=195mm, *h*=150mm
	Current	250kA (2160turns)
	Weight	110kg
	operating temperature	20K – 32K
lifting magnet	Current	88kA (68turns)
	dynamic range	f < 10Hz (feedback controlled)
chamber	Size	R = 1000mm, h=560mm
RF (1)	Frequency	8.2 GHz
	Power	100kW (1sec pulse)
RF (2)	Frequency	2.45GHz
	Power	20kW (2 sec pulse)

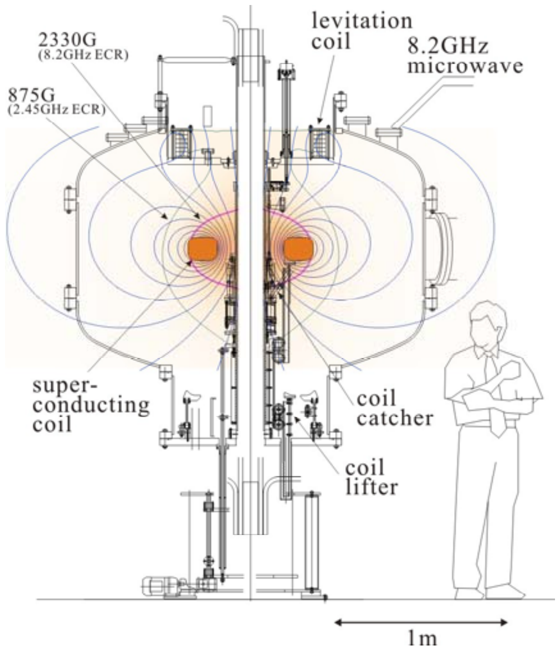

FIG. 7. Schematic view of the RT-1 device (with the computed magnetic surfaces).

The conductor is first cooled to 20K in the maintenance chamber (located at the bottom of the plasma chamber), and, then, charged to 0.25MA (the coil consists of 12 pancakes and has a total of 2160 turns). After detaching the current leads and coolant (He gas) transfer tubes, the ring is moved up to the mid-plane of the plasma chamber and is then levitated by a feedback-controlled magnet installed on the top of the device. We can continue the super-conducting operation for 7 hours before the coil temperature increases to 30K. Current decay is less than 1% after 7 hours [23-25].

Three-cord laser sensors measure the position of the levitated ring. We have succeeded to levitate the magnet stably. The fluctuation of the coil poison is less than 100μm. To eliminate the tilt of the coil due to the geomagnetic field, collections coils are installed outside the chamber.

In case when the control of the levitation system is lost, a “catcher” system operates to hold the ring magnet within 100msec before the floating coil drops 5cm (FIG. 6).

3.3. First Plasma Experiment on RT-1

We have performed the first plasma experiment in January of 2006. The plasma was produced by 1.5kW ECH (FIG. 8). The pulse duration was 1sec. The superconductor ring was levitated about 30mm over the lifter. In this condition, the plasma still interacts with the lifter, so the input power was limited. Experiments with completely detached condition wait further mechanical testing of the emergency catcher system. Optimization of the plasma and measurements of parameters will start after finishing detailed evaluations of the machine performances.

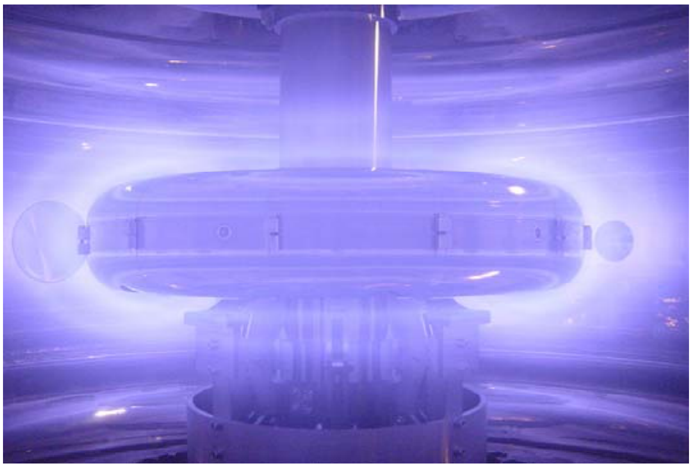

FIG. 8. First plasma produced by the RT-1. The plasma is produced by ECH using an 8.2GHz microwave.

4. Summary

We have completed the construction of the RT-1 device, and have started plasma experiments with the levitated super-conducting magnet. This device will serve as a laboratory system where we can explore interesting phenomena simulating space and astronomical systems. RT-1's "magnetosphere" can host a variety of plasmas such as a non-neutral (single spices) plasma, spinning plasma like Jupiter's magnetosphere, mirror-trapped plasma in a dipole magnetic field, or double Beltrami-like Hall MHD plasma. "Flow-field coupling" is the central theme of the research. A flowing plasma can create a tremendously variegated and rich structure that is degenerate in a static picture of plasmas.

Acknowledgements

This work was supported by Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture No. 14102033.

REFERENCES

[1] MAHAJAN, S. M. and YOSHIDA, Z., "Double curl Beltrami flow: Diamagnetic structures", Phys. Rev. Lett. **81** (1998) 4863.
[2] YOSHIDA, Z. and MAHAJAN, S. M., "Variational principles and self-organization in two-fluid plasmas", Phys. Rev. Lett. **88** (2002) 095001.
[3] SHIRAISHI, J., et al., "Relaxation of a quasisymmetric rotating plasma: A model of Jupiter's magnetosphere", Phys. Plasmas **12** (2005) 092901.
[4] SHIRAISHI, J. FURUKAWA, M. and YOSHIDA, Z., "A new-type equilibrium of flowing plasma dominated by the Hall effect", Plasma Fusion Res. (to be published).
[5] YOSHIDA, Z., et al., 17th IAEA Fusion Energy Conference, Yokohama, 1998, IAEA-CN-69/ICP/10.
[6] SAITOH, H., et al., "Confinement of pure-electron plasmas in a toroidal magnetic-surface configuration", Phys. Rev. Lett. **92** (2004) 255005.
[7] YOSHIDA, Z. and GIGA, Y., "Remarks on spectra of operator rot", Math. Z. **204**

(1990) 235.
[8] TAYLOR, J. B., “Relaxation of toroidal plasma and generation of reverse magnetic fields”, Phys. Rev. Lett. **33** (1974) 1139.
[9] YOSHIDA, Z., MAHAJAN, S. M., and OHSAKI, S., “Scale hierarchy created in plasma flow”, Phys. Plasmas **11** (2004) 3660.
[10] SHIRAISHI, J., OHSAKI, S., and YOSHIDA. Z., “Regularization of the Alfvén singularity by the Hall effect”, Phys. Plasmas **12** (2005) 092308.
[11] YOSHIDA, Z., et al., “Beltrami fields in plasmas: High-confinement mode boundary layers and high beta equilibria”, Phys. Plasmas **8** (2001) 2125.
[12] CHAGELISHVILI, G. D., ROGAVA, A. D., and TSIKLAURI, D. T., “Compressible hydromagnetic shear flows with anisotropic thermal pressure: Nonmodal study of waves and instabilities”, Phys. Plasmas **4** (1997) 1182.
[13] VOLPONI, F., YOSHIDA, Z., and TATSUNO, T., “Shear-flow induced stabilization of kinklike modes”, Phys. Plasmas **7** (2000) 2314.
[14] HIROTA M., TATSUNO, T., and YOSHIDA, Z., “Degenerate continuous spectra producing localized secular instability – an example in a non-neutral plasma”, J. Plasma Phys. **69** (2003) 397.
[15] YOSHIDA, Z., OHSAKI S., ITO A., and MAHAJAN, S. M., “Stability of Beltrami flows”, J. Math. Phys. **44** (2003) 2168.
[16] OHSAKI S. and YOSHIDA Z., “Lyapunov function of relaxed states in two-fluid plasmas: Stability of double-Beltrami flows”, Phys. Plasmas **10** (2003) 3853.
[17] YOSHIDA. Z., et al., 20th IAEA Fusion Energy Conference, Vilamoura, 2004, IC/P6-16.
[18] OGAWA, Y., et al., “Construction and operation of an internal coil device with a high temperature superconductor”, J. Plasma Fusion Res. **79** (2003) 643.
[19] HASEGAWA, A., et al., “A D3-He fusion reactor based on a dipole magnetic field”, Nucl. Fusion **30** (1990) 2405.
[20] KESNER, J., et al., 17th IAEA Fusion Energy Conference, Yokohama, 1998, IAEA-CN-69/ICP/09.
[21] SAITOH, H., et al., “Potential structure of a plasma in an internal conductor device under the influence of a biased electrode”, Phys. Plasmas **11** (2004) 3331.
[22] YOSHIDA, Z., et al., “First plasma in the RT-1 device”, Plasma Fusion Res. **1** (2006) 008.
[23] TOSAKA, T., et al., “Development of Persistent-current Mode HTS Coil for the RT-1 Plasma Device”, IEEE Trans. Appl. Supercond. **16** (2006) 910.
[24] MIZUMAKI, S., et al., “Development of the Magnetically Floating Superconducting Dipole in the RT-1 Plasma Device”, IEEE Trans. Appl. Supercond. **16** (2006) 918.
[25] TOSAKA, T., et al., “First Experiement on Levitation and Plasma with HTS on the RT-1 Plasma Device”, Proc. Applied Superconductivity Conference 2006, Seattle (2006), 4LH04.