学位論文

Experimental Analysis of the Magnetic Field Structure on the High-Beta Plasmas in the Magnetospheric Plasma Device

(磁気圏型プラズマ閉じ込めにおける高βプラズマの

磁場構造の実験的解析)

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Chapter 1

Introduction

1.1 Nuclear Fusion

1.1.1 Fusion Energy for Future Energy

It is thought that nuclear fusion will be a strong candidate of the supply of energy in future, because nuclear fusion reaction produces huge amount of energy without carbon dioxide emissions. And fuels of nuclear fusion reaction are deutelium, tritium and helium-3, etc.: it's possible to recover from seawater or atomic reactors (semi-infinity). Although fusion reaction produces some amount of radioactive waste, it's said that the radioactive level of the waste is less than those which is produce in fission reaction. For these desireable reasons the realization of nuclear fusion reactor is strongly expected and fusion research is conducted in all over the world.

1.1.2 Difficulty of Fusion Reaction

On the other hand, there're many challenges to be overcome for the realization. Fusion reaction is a kind of nuclear reactions as fission reaction is: mass defect ($E = \Delta mc^2$, where E, Δm, m and c denote produced energy, mass different before and after reaction and light speed in vacuum, respectively.) before and after reaction is conversed to electricity. We must collide light nucleus each other and produce heavy nucleus after reaction. It is necessary for fusion reaction to approach nucleus less than the distance working nuclear force with overcoming Coulomb repulsive force. Probability of fusion reaction is given by the function of kinetic energy of nucleus, more than 5 keV of nucleus energy is needed for sufficiently high fusion reaction cross section. Thus in order to energize nucleus high temperature, fuels must be ionized. These charged particles are called plasma [16]. In order to use fusion reaction for power generation, we must confinement sufficiently high density of nuclei for sufficiently long time. The criterion for producing nucler reactor was evaluated by J. D. Lawson, so it's called Lawson criterion [17]. The criterion is given by $n \cdot \tau = 10^{20}$ m^{-3} in case of D-T reaction (which is easiest to achieve), where n and τ denote plasma density and confinement time of plasma.

1.1.3 Concepts of Fusion Reactor

To achieve the criterion there're two concepts of the fusion reactor, in other words two concept of the confinement of plasma. One is magnetic confinement and the other is inertial confinement. In the magnetic confinement the lower density ($\sim 10^{20}$ m^{-3}) plasma is confined for a longer time ($\sim$ 1.0 s), while in the inertial confinement the higher density ($\sim 10^{31}$ m^{-3}) plasma is confined for a shorter time ($\sim 10^{-11}$ s). Both of the confinement needs a giant devices surrounded by a number of frontier apparatuses. In the inertial confinement a fuel ice pellet is radiated by several hundreds of intense laser in order to achieve a extremely high density plasma. On the other hand, strong magnetic field is applied to interrupt the particle loss to perpendicular direction in magnetic confinement.

1.2 Magnetic Plasma Confinement

Magnetic field restricts the motion of charged particle because the charged particle in magnetic field receive a force perpendicular to the motion, the Lorentz force, then the particle is forced to move helically along magnetic field line. Most of the plasma confinement device is toroidal shapes and the field lines are closed so that one charged particle is easily confined. Tokamaks and stellarators are the major methods for magnetic plasma confinement. They have the closed toroidal magnetic configuration and the magnetic field is twisted in order to neutralize a charge separation. Tokamaks twist the magnetic field by applying a toroidal current in the plasma itself, on the other sterallators twist the field by twisting external field coils.

1.2.1 Issues for Magnetic Confinement

Because it is necessary to confinement "high temperature plasma ($\sim$ 10 keV)" "in high vacuum chamber" "with complex magnetic configuration" "for a long time ($\tau_E \sim 1$ s)" , there're a lot of physical and technical issues to be overcome in order to realize the fusion reactor [18] [19]. In a physical point of view, plasma equilibrium and its stability are the most crucial issues. The operation mode of the reactor depends on transport phenomena as typified by L-H and H-L transition and ELM physics. Disruption phenomena should be understood and supressed because heat load resulted from plasma disruption seriously damages the wall structure facing the plasma. Also advanced material development is required in order to protect from the extremely high heat load from plasma and to suppress high-Z impurity penetrations from the wall.

1.2.2 The ITER Project

ITER, which adopts a tokamak magnetic configuration, is explained by a shorthand for the word "International Thermonuclear Experimental Reactor" or the "road" in latine. It is a world-wide project to progress fusion reactor realization. The aim of the ITER project is to achieve 500 MW of fusion energy output which is equivalent to typical commercial power reactor. And the steady operation of burning plasma whose energy multiplication constant is more than 10 will be conducted in ITER. The studies of α particles which are ash of nuclear fusion reaction will be under intense investigation including measurement system and exhausting method from the plasma core, etc., because ITER will achieve a nuclear burning plasma and producing a lot of α particles. There're another technical issues which are investigated in ITER for realization of fusion reactor for example development of superconducting coils, plasma heating and current-driving method and remote-robot system for maintenance, etc.

1.2.3 High Beta Plasma

Beta value is defined as the ration plasma and magnetic pressure

$$\beta = \frac{\sum n_s \kappa T_s}{B^2/2\mu_0} \tag{1.1}$$

where subscript 's' denotes the species and κ is the Boltzmann constant and plasma density ,temperature and magnetic field strength are denoted by n, T and B, respectively. In this notation the plasma pressure is written in numerator and the magnetic pressure is written in dominator. If the plasma pressure is higher for the same magnetic field strength, the beta value becomes larger. High beta plasma means therefore the relatively high pressure plasma, which is the product of plasma density and pressure, is confined in a weak magnetic field. And achievement of higher beta plasma result in advantage of the economics of commercial reactors, surppression of a cyclotron radiation from plasma and realization of an advanced fuel fusion which uses D and ^{3}He as fuels and needs higher plasma temperature than D-T reaction. The final goal of this work, the Ring Trap project, is to investigate very high beta, order of unity, plasma confinment in application of magnetospheric configuration by using a levitating dipole magnet.

1.3 Outline of This Research

This work deals the confinement characteristics of magnetospheric plasma, Ring Trap-1 (RT-1). Here the confinement characteristics mean the estimate of the beta value and the energy confinement time, etc. Firstly Chap. 2 provides the progress of the magnetospheric plasma research in past and present including Ring Trap project. Chapter 3 describes the optimization of the levitation system in RT-1. Typical high beta plasma observed in RT-1 is introduced in Chap. 4. Chapter 5 denotes the estimate of the local beta value in RT-1 by comparing the equilibrium code and the flux loop measurement. Chapter 6 describes the estimate of the plasma pressure profile and the energy confinement time which are measured by using the magnetic probes. Finally in Chap. 7 this experimental research is concluded.

Chapter 2

Magnetospheric Plasma

Magnetospherical plasma is a plasma which is confined in the magnetosphere-shaped magnetic field. The magnetosphere is the most common magnetic structure, which is called a dipole field, in the universe [39]. In spite of its bad curvatures, the magnetospheric plasma has possibilities to confine a very high beta plasma whose beta value is more than unity. But the detailed mechanics of the high beta confinement, why so high beta plasma is stable, is not known so far. The RT-1 device, which has a levitated superconducting magnet, is one of the magnetospheric plasma experimental device to investigate high beta plasmas confined in the magnetosphere. In this chapter, the historical background of the magnetospheric plasma and the goal of the Ring Trap project and purposes of this research is mentioned.

2.1 Internal Coil Device in the 1970s.

To realize a magnetosphere in a laboratory, a simple ring-shaped coil is usually adopted. Then the ring coil generates a dipole field. When the plasma is discharged in this configuration, the ring coil is surrounded by the plasma without doubt. The plasma experimental device with a dipole field is therefore called an internal coil device. There are two prominent types of internal coil devices. One uses normal conductor as an internal conductor, and the other applies superconducor. Without the internal coil made of superconductor, feedthroughs from a power supply or cooling tubes should pass across the plasma. These structures can be the parallel loss channel of plasma particles and the plasma confinement become depleted. If we adopt a superconducting conductor as a internal conductor, the particle loss parallel to a magnetic field is completely eliminated by levitating the coil, which is called a levitated dipole.

In the 1970s, several internal coil plasma experiments including the levitated dipole were conducted such as a spherator[44] [47] [55], a levitron [43] and an octapole [20]. The main purposes of these earlier internal coil devices were focused on neoclassical transport and MHD physics (an averaged minimum-B and magnetic shear), etc. And the main confinement regions of these experiment were in the inner regions of the tori; they were not like "a magnetosphere" who has huge confinement volume outside of a torus. The comparison drawing between the earlier internal coil device and the recent one is shown in Fig. 2.1. As mentioned above, these researches in the 1970s dealt with the basic characteristics of the plasma confined in the magnetic field and they achieved a certain result. But this type of internal coil device faded out because of the difficulties in the sense of application to the fusion reactor.

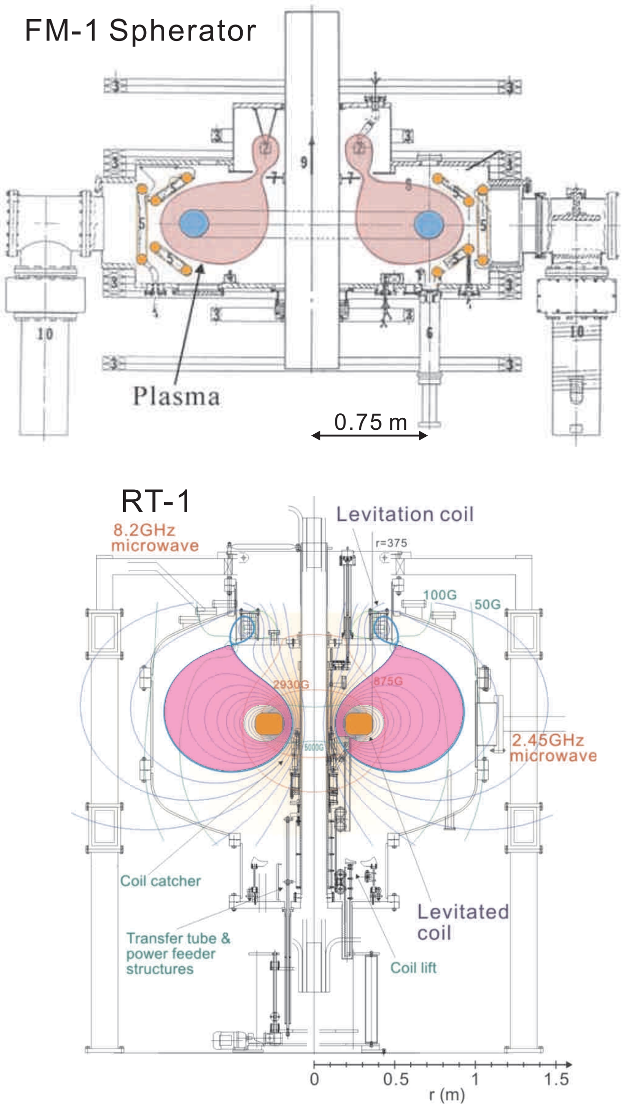

Figure 2.1: Comparison drawing of the magnetic field configurations of FM-1 Spherator and RT-1. Because the floating magnet in FM-1 Spherator was unstable to tilting direction, unlike that of RT-1, there're tilt stabilizing coils in FM-1 [after Ogawa (2009) [67]].

2.2 High Beta Plasma in Jovian Magnetosphere

Jupiter is known as the largest planet in the solar system. Jupiter has a geomagnetic field as the earth has, and strength of the magnetic field of the Jovian magnetosphere is very strong. There were several project to observe the plasma confined in the Jovian plasma, for example, Pioneer [17], Voyager [3] [27] [28] and Ulysses [35-38]. They observed the Jovian plasma by the various of measurements like electrostatic and magnetic probes, microwaves, etc. Finally they found that very high beta plasma, order of unity, is confined in the Jovian magnetosphere and the Jovian plasma has interesting structures in real space and velocity space. The Jovian plasma model from the observations is shown in Fig. 2.2. The structure of the Jovian plasma is governed by the relation between the solar wind flow direction and the attitude of the magnetosphre. Hot plasma (more than 10 keV) region is confined in the inner plasmasphere ($R < 50\ R_j$, where R_j denotes the radius of the Jupiter). And very fast plasma flow (about 1000 kilometers per second) is found in outer region of the magnetosphere. The plasma flow is caused by the rotation of Jupiter because the flow direction is co-rotational. The rotation period of Jupiter is 10 hours, which is shorter than that of the earth, and the rotation axis is tilted to the solar equatorial plane, which results in the very fast plasma flow. The typical observation results of high beta plasma in Jovian magnetosphere, such as electron and ion densities and magnetic field strength, are shown in Fig. 2.3. In Fig. 2.3, the satellite Voyager 1 was inbound way to the Jupiter located at $R = 25\ R_j$ and crossing the plasma sheet at the time of minimum magnetic field strength. It seems reasonable that the magnetic field depression is due to the diamagnetic effect of the plasmasheet. The theoretical model of the Jovian magnetosphere is shown in Fig. 2.4. The magnetosphere is stretched outward by the effect of fast flow and the tail of the magnetosphere has a disk-like shape, which corresponds with the practical structure of the nightside Jovian magnetosphere.

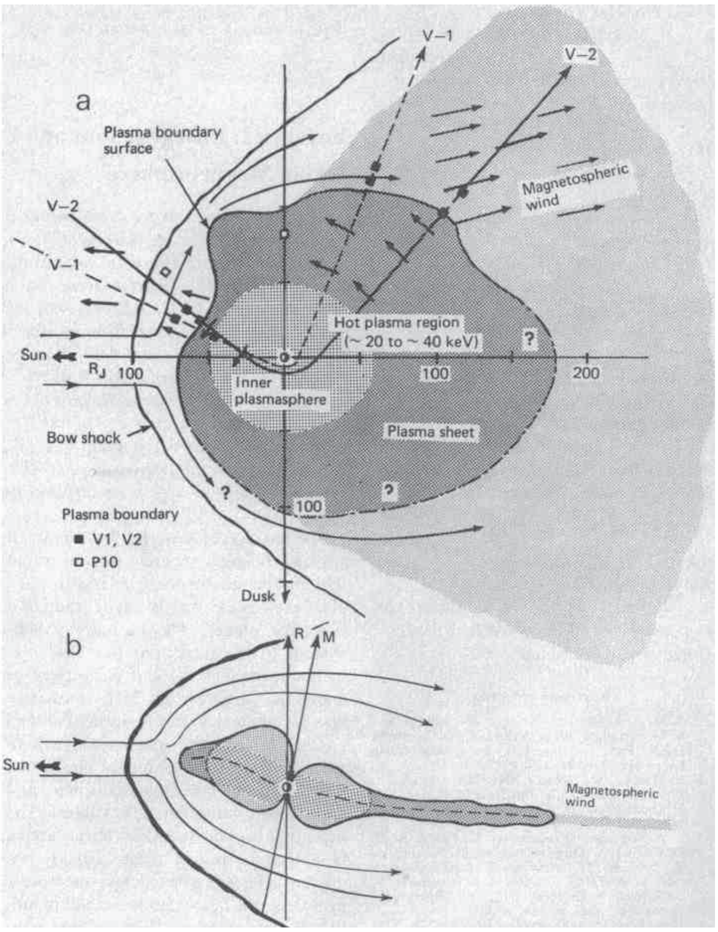

Figure 2.2: Plasma model of the Jovian magnetosphere in (a) the equatorial and (b) the meridional planes. The model emphasizes the hot plasma regions. Question marks indicate areas of uncertainty. The long arrows indicate solar wind flow direction [after Krimigis (1979) [3]].

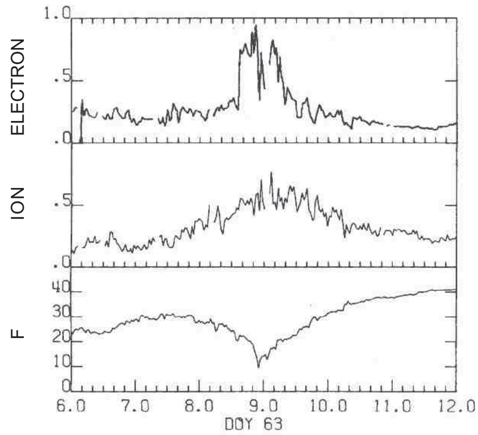

Figure 2.3: Typical observation example of the Jovian plasma. Shown are electron densities and the nominal ion densities and the field strength F. The field strength decreases at the time of maximum particle densities. This field depression is due to the plasma diamagnetic effect [after Bridge (1979) [21]].

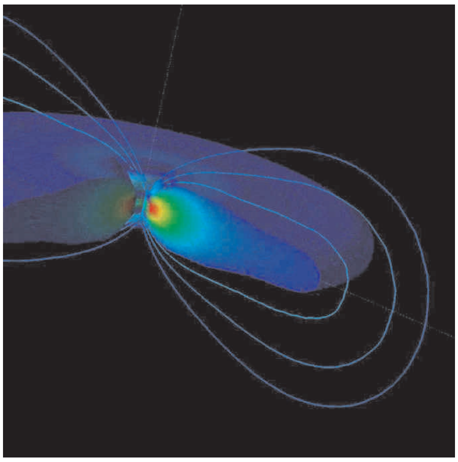

Figure 2.4: The theoretical model of the Jovian magnetosphere. This model explains that the plasma flow causes the disk-shaped plasma observed in Jupiter [after Shiraishi (2005) [22]].

2.3 Recent Dipole Experiment

The plasma confined in a dipole magnetic field is likely to be considered unsuitable for a fusion reactor, because most of the magnetic field lines are bad-curvatures which trigger interchange instability. But satellite observations of the high beta plasma which is confined in the Jovian magnetosphere revived the research of the internal coil device as a candidate of the fusion reactor which uses the advanced fuels such as D and ^{3}He [10].

The dipole fusion concepts was proposed by Akira Hasegawa who was motivated by observations of planetary magnetosphere [9]. Since then, two project of the dipole plasma confinement have started. One is the Ring Trap project in University of Tokyo and the other is the Levitated Dipole eXperimental (LDX) device as a joint work project between Massachusetts Institute of Technology and Columbia University [23-25] [29] [53] [54] [57] [59]. Both of the project have been inspired by high beta plasma in the Jupiter. And both set a final goal of the realization of the advanced fusion reactor by taking the advantage of high beta plasma obtained in the dipole configuration. But the focused physics about the stabilization effect of Jovian high beta plasma are a little different. In RT-project, we are interested in the relaxation theory of fast flow in the plasma. On the other, the LDX group is focusing on the plasma compressibility.

2.3.1 Levitated Dipole eXperimental Device

The LDX group has concept that the dipole plasma is stabilized by the theory which is mentioned below. From ideal MHD, a plasma confined in bad curvature will be in a marginally stable state when the pressure profile, $p(\psi)$ satisfies the adiabaticity condition,

$$\delta(pV^{\gamma}) = 0, \tag{2.1}$$

expanded by

$$p_0/p_{sol} = (V_{sol}/V_0)^{\gamma} \tag{2.2}$$

where $\gamma = 5/3$ and plasma pressure, flux tube volume, core values and edge, or scrape-off-layer, values are denoted by p, V, subscript "0" and "sol", respectively. Then the stability requirement can also be written as

$$d \equiv -d\ln p/d\ln V < \gamma. \tag{2.3}$$

What is important is that eq. 2.3 teaches us a limit on the pressure gradient and not on the pressure itself. In this way, a large enough dipole configuration can stabilize a arbitrarily large local beta values and at these high beta values the magnetic field is largely excluded from the region of the pressure peak on the outer midplane, like the diamagnetic effect shown in Fig. 2.3. They also showed that when a high beta dipole plasma is stable to interchange mode it will also be stable to ideal balooning modes.

To achieve the high beta dipole plasma in laboratory they constructed the Levitated Dipole eXperimental device in MIT. The schematic drawing of the LDX device is shown in Fig. 2.5. They succeeded in levitation about one and a half year after we succeeded in levitation in RT-1. At present they observed a couple of dozens percents of beta in levitation plasma, which is the same order to us, and the LDX plasma exhibits the same characteristics as the RT-1 plasma.

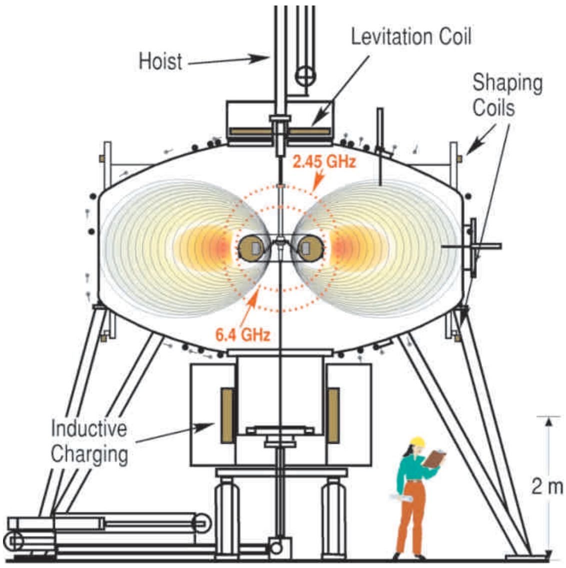

Figure 2.5: Schematic drawing of the LDX device [after Garnier (2006) [57]]. The camber radius is about 2.5 m and the volume of the plasma is designed large to obtain the stabilization effect of the plasma compressibility.

2.3.2 Ring Trap Project

Basic Theory

In addition to the plasma compressibility mentioned in previous subsection, we are interested in the self-organization with restrictions of magnetic energy and magnetic helicity. For example of self-organization of the plasma is force-free configuration which is supposed by Taylor [15]. Taylor state is explained as a minimum energy state which conserves the magnetic helicity. The magnetic helicity is defined as

$$K \equiv \int A \cdot B \mathrm{d}^3 x, \tag{2.4}$$

where A and B denote the vector potential and the magnetic field strength, respectively. Taylor proved that the turbulent plasma system will settle down to the configuration which makes the magnetic energy (which is given by $\int (B^2/2\mu_0)\mathrm{d}^3x$) minimum. That force-free configuration, or single Beltrami state, is given by

$$\nabla \times B = \mu B. \tag{2.5}$$

In addition to this theory, S. M. Mahajan and Z. Yoshida has extended the taylor state by adding a plasma flow [1][2]. Flowing plasma will relax to minimum energy state with restriction that the total of magnetic and generalized helicity is constant. This state is called "double Beltrami state" and it predicts that very high beta plasma confinement is possible with fast flow.

The fluid equations of two charged particles (electrons, and ions) are

$$m_e n_e \frac{\mathrm{d}v_e}{\mathrm{d}t} = -en_e(E + v_e \times B) - \nabla p_e \tag{2.6}$$

and

$$m_i n_i(\partial v_i \partial t + v_i \cdot \nabla v_i) = -en_i(E + v_i \times B) - \nabla p_i. \tag{2.7}$$

By neglecting the electron inertia,

$$0 = E + v_e \times B - \frac{p_e}{en_e}. \tag{2.8}$$

With the convective term expanded, Eq. (2.7) can be written as

$$\frac{\partial v_i}{\partial t} - \frac{e}{m_i}E - v_i \times (\frac{e}{m_i}B + \nabla \times v_i) = -\frac{1}{m_i n_i}\nabla(p_i + \frac{m_i n_i v_i^2}{2}). \tag{2.9}$$

Length, time, magnetic field and pressure is normalized by ion skin depth ($_i = \frac{c}{\omega_{pi}} = \frac{V_A}{\Omega_i}$), ion cyclotron frequency Ω_i, typical magnetic field strength B_0 and $p = \frac{B^2}{2\mu_0}\hat{p}$. Electric scalar potential and velocity are normalized by $\phi = \frac{m_i V_A^2}{e}\hat{\phi}$ and $v = V_A\hat{V}$, respectively, where V_A and V_T denote Alfvén velocity and thermal velocity, respectively. Equations (2.8) and (2.9) are normalized by the relationships $E = -\frac{\partial A}{\partial t} - \nabla\phi$, $v_i \sim v$, $v_e - \frac{j}{en}$ and $j = \mu_0^{-1}\nabla \times B$ as

$$\frac{\partial A}{\partial t} - (v - \times B) \times B = \nabla(\frac{1}{2}p_e - \phi), \tag{2.10}$$

and

$$\frac{\partial(A+v)}{\partial t} - v \times (B + \times v) = \nabla(\frac{1}{2}v^2 + \frac{1}{2}p_i + \phi). \tag{2.11}$$

Magnetic and generalized helicity are defined as

$$\frac{1}{2}\int \mathrm{d}^3x A \cdot B, \tag{2.12}$$

and

$$\frac{1}{2}\int \mathrm{d}^3x (A+v) \cdot (B + \nabla \times v), \tag{2.13}$$

respectively. The double Beltrami state is given by

$$B = a(v - \nabla \times B), \tag{2.14}$$

and

$$(B + \nabla \times v) = bv, \tag{2.15}$$

where a and b are some constants. Finally Eqs. (2.10) and (2.11) can be written as

$$\frac{1}{2}p_e - \phi = \text{Const.}, \tag{2.16}$$

and

$$\frac{1}{2}v^2 + \frac{1}{2}p_i + \phi = \text{Const.}. \tag{2.17}$$

By adding these two equations, the simple formula is obtained

$$v^2 + \beta^2 = \text{Const.}, \tag{2.18}$$

where β is defined in Eq. 1.1. From this two fluid theory we expect that high beta plasma whose beta value is about unity is obtained with Alfvénic plasma flow.

Experimental Progress

The final goal of the Ring Trap project is to confinement high beta plasma with driving a fast plasma flow. Before the Ring Trap-1 device is completed, three experimental devices are constructed. In the Proto-RT device, basic physics of plasma confined in a dipole configuration including the driving method of a fast plasma flow by adding the electric field are investigated [14] [49]. In the Feed Back- Ring Trap (FB-RT) device, the levitation control technique is developed [6] [32]. And remarkable progress in high-temperature superconducting (HTS) conductors enabled us to construct the Mini-RT device which has the HTS floating magnet and the Mini-RT device is the first fusion experimental device which produces the field with HTS conductor [12] [13] [30] [31] [33] [64-65]. Mini-RT also developed a number of engineering techniques related to the HTS applications, such as cooling and energizing, etc. On the successes of those experiments the Ring Trap-1 device has been constructed in Jan. 2006 [5] [49] [61] [66-74]. And we have conducted a high beta plasma experiment during levitation and the order of 10 percents of high beta plasma was achieved with electron cyclotron heatings (ECH), the details are mentioned later.

2.4 The Ring Trap-1 Device

The Ring Trap-1 (RT-1) device is the magnetospheric plasma confinement device [5]. To realize a magnetosphere on the earth we levitate a superconducting magnet in the vacuum chamber. The "magnetosphere" is generated by the high-temperature superconducting coil (the F-coil) which is hung by the lifting coil (the L-coil) from above. We succeeded to control the position of the F-coil by a PID negative feedback control system. The photograph and the drawing of the RT-1 device are shown in Fig. 2.6 and Fig. 2.7. The principle parameters of RT-1 is shown in Table 2.1.

The F-coil consists of many leading-edge apparatuses and the total weight of the coil is about 112 kg. The wire of the F-coil is made of high temperature superconductor (Bi-2223). The F-coil can be charged to 116 A per 1 turn and the coil has a total of 2160 turns, the F-coil has therefore 250 kA as a total current.

Table 2.1: Principal parameter of RT-1

Vacuum vessel	Inner radius	1000 mm
	Height	560 mm
HTS ring coil	Major radius	250 mm
	Outside radius	375 mm
	Inside radius	180 mm
	Height	150 mm
	Coil wire	2160 turns (Bi-2223)
	Excitation current	116 A
	Magnetic field strength	0.005 T - 0.3 T
	Mass	112 kg
	Operation temperature	20-30 K
	Self inductance	3.3 H
	Stored energy	22 kJ
Levitation coil	Major radius	400 mm
	Coil wire	68 turns (copper)
	Power supply	1500 A-DC / 150 A-AC
	Resistance	28 mΩ
	Self inductance	4.6 mH
RF heating1	Frequency	8.2 GHz
	Max. Power	25 kW (100 kW)
	Pulse width	1 second
RF heating2	Frequency	2.5 GHz
	Max. Power	20 kW
	Pulse width	2 seconds
Coil catcher	Response speed	0.1 second

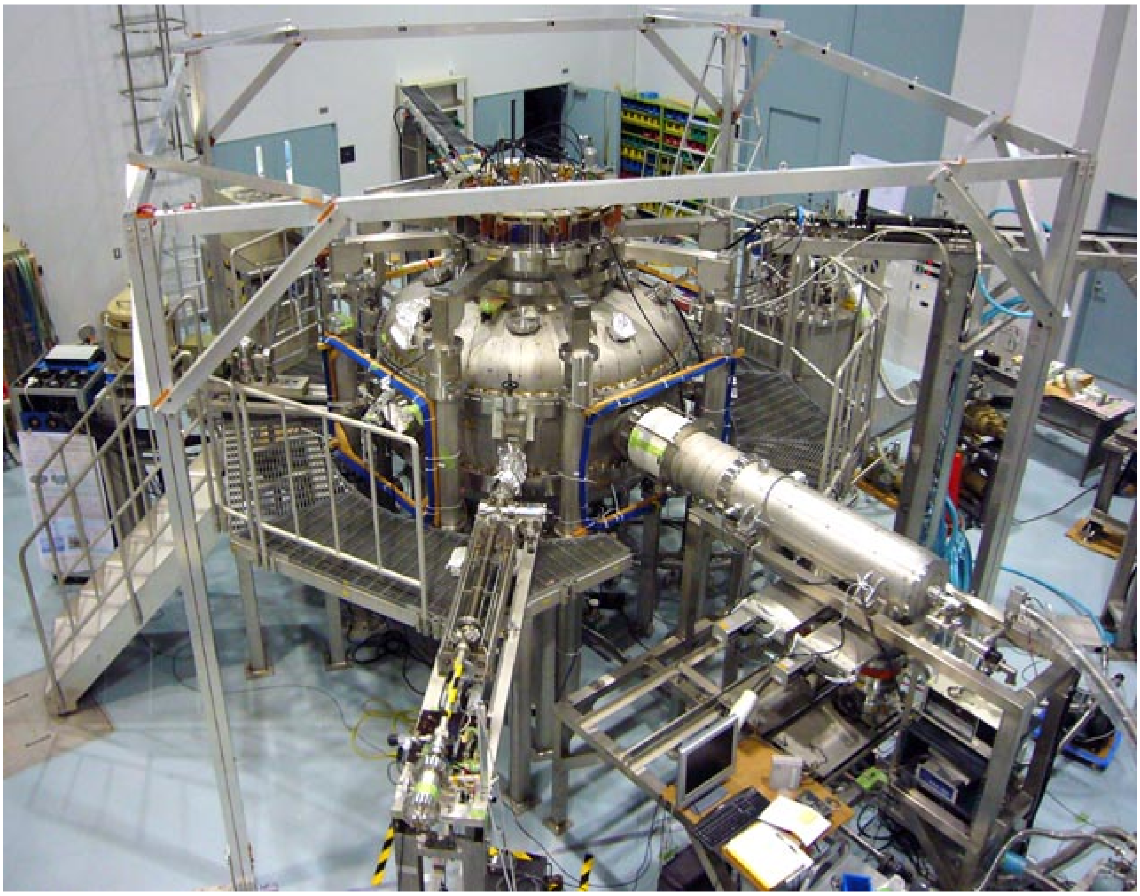

Figure 2.6: Photographic view of the RT-1 device

Because the magnetosphere has approximately a dipole magnetic field the magnetic field strength in the confinement region varies very much from 0.3 T to 0.005 T. An outside radius of the coil is 0.375 m and an inside radius is 0.18 m and a radius of a current center is 0.25 m. The F-coil has many leading-edge apparatuses inside the coil case, which relate to the operation of cooling, energizing and monitoring, etc.

The levitation coil is made of copper. The coil has a total of 68 turns and the coil current is about 440 A per 1 turn in the usual levitating operation, the L-coil has therefore a total current of 30 kA. A radius of a current center of the L-coil is 0.40 m. A designed current of a power supply of the L-coil is 1500 A-DC and 150 A-AC. In the usual levitation condition, the magnetic field of levitation coil is about 0.01 T near the F-coil and 0.003 T -0.03 T in the plasma confinement region.

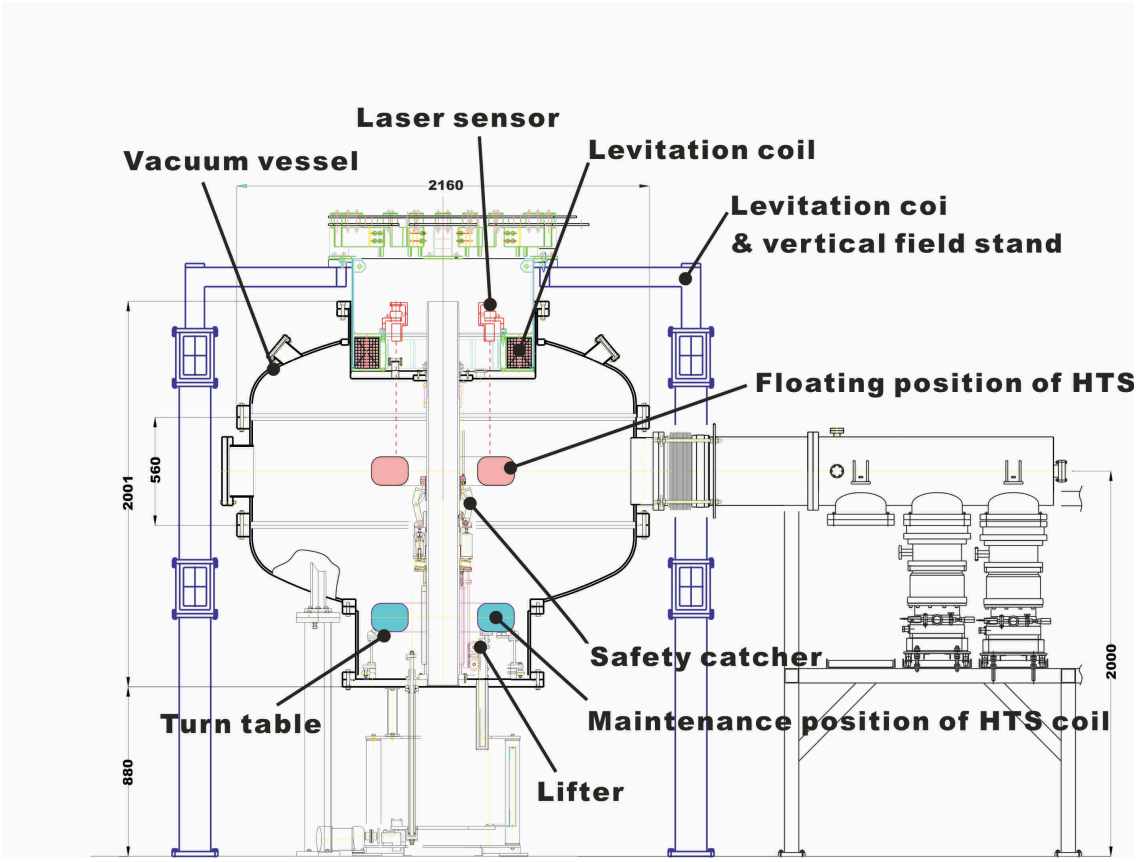

Figure 2.7: Schematic view of the dipole plasma confinement device RT-1. This device is able to generate a plasma with the superconducting internal conductor which is magnetically levitated by the lifting coil.

The arrangement drawing of the F-coil, the L-coil and the position detectors is shown in Fig. 2.8. The center of the F-coil is located at $z = 0$ mm and the center of the L-coil is located at $z = 612$ mm. The vacuum field is calculated from the position relation of the coils. The calculated results of magnetic field are shown in Fig. 2.9, Fig. 2.10 and Fig. 2.11. There are two typical magnetic configurations in RT-1. One is pure-dipole field which is produced by using only the F-coil (supported) and the other is separatrix configuration (supported or levitated). Both of the innermost magnetic surfaces (black lines) of two configurations are limited at the inside radius of the coil case. The outermost surfaces (black lines) of the pure-dipole configuration

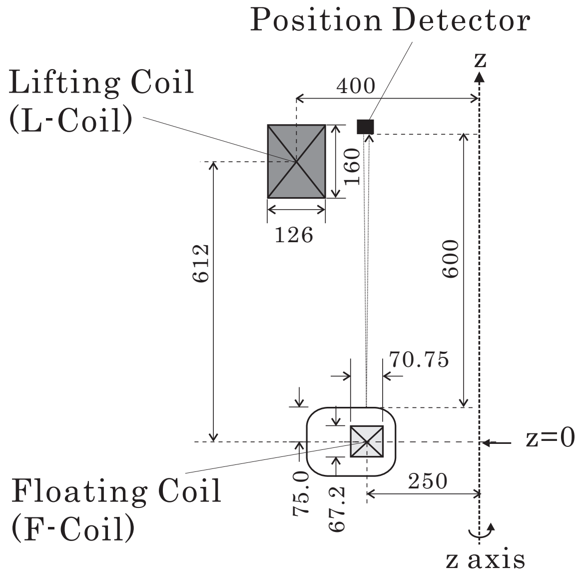

Figure 2.8: The schematic veiw of the arrangement of the F-coil, the L-coil and the position detectors.

is limited by the chamber wall touching at (R, Z) = (1.0 m, 0.0 m). The outermost surfaces (black lines) of the separatrix configuration is limited by X-point which is located at (R, Z) = (0.51 m, 0.49 m) is crossing at R= 0.92 m on the mid-plane. The resonance surfaces of electron cyclotron resonance heating for frequencies of 2.45 GHz (|B| = 875 G) and 8.2 GHz (|B| = 2929 G) are shown by a blue line and a red line, respectively.

The cooling and energizing of the superconductor of the F-coil is conducted in the maintenance chamber which is located at bottom. In the maintenance chamber, the're two coolant transfer tubes and two current leads and three monitoring connectors. The superconductor of the F-coil is first cooled to 20 K from room temperature by helium gas provided by the GM-type refrigerator. The coolant gas is transferred through detachable tubes connected to the F-coil inside the maintenance chamber. After we finish cooling (it takes about 48 hours), the F-coil is fed current up to 250 kA by detachable current leads. The connection and detachment of the transfer tubes and current leads can be performed by remote manipulation systems inside the maintenance chamber.

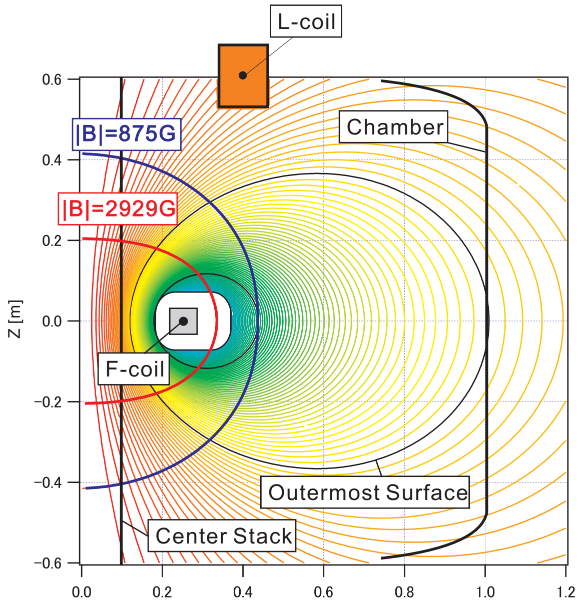

Figure 2.9: Magnetic field configuration of RT-1. When the L-coil current is turned off: pure dipole configuration. The magnetic field is exactly symmetrical about the mid-plane.

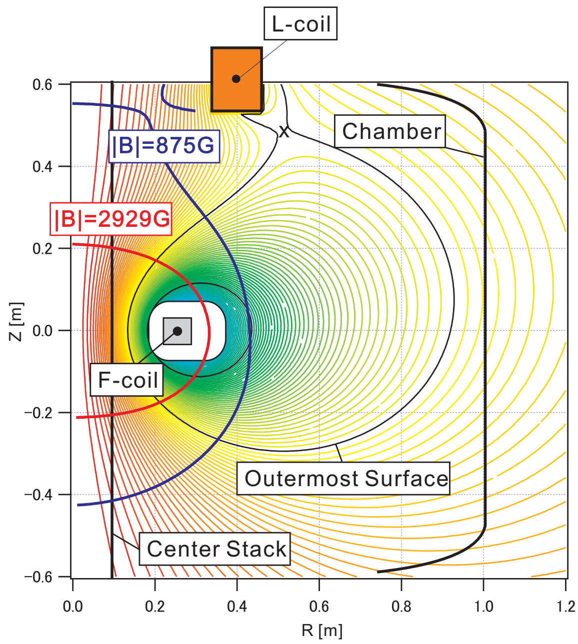

Figure 2.10: Magnetic field configuration of RT-1. When the F-coil is levitating: separatrix configuration. The magnetic field is stretched upward by the L-coil current.

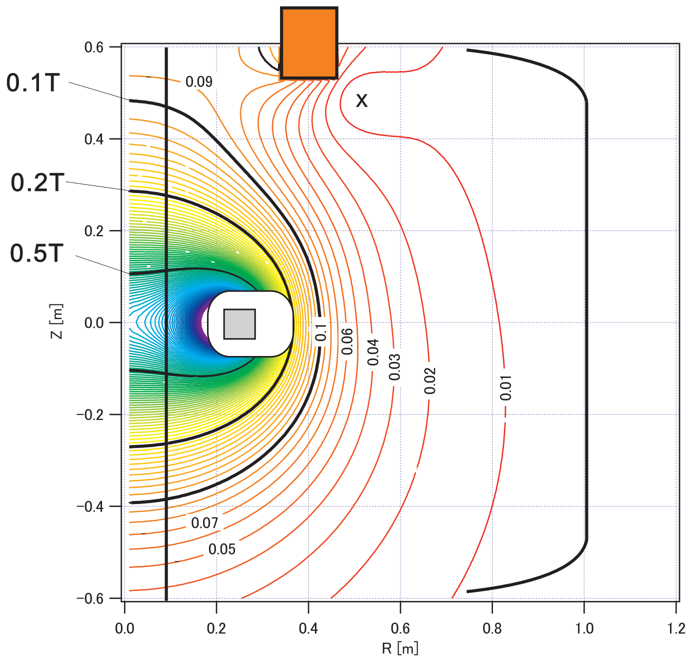

Figure 2.11: Magnetic field strength of the RT-1 configuration. When the F-coil is levitating: separatrix configuration. The unit is given in tesla.

After energizing, the F-coil is lifted up to the center of the vacuum chamber, where the plasma experiment and levitation is done, by a mechanical lifter. The plasma experiment and levitation is operated about 6 hours which is determined by length of time it takes the F-coil to increase in temperature to 30 K. In the plasma experiment in RT-1, plasmas is electron-cyclotron-heated by either-or-both of 2.45 GHz and/or 8.2 GHz of frequencies (shown in Table 2.1). After experiment, the F-coil is recovered by the mechanical lifter in order to eliminate the current in superconductor and the F-coil is again cooled to 20 K by the experiments carried out the following day. The schematic drawing of the RT-1 maintenance chamber and the mechanical lifter is shown in Fig. 2.12. We have a safety catcher system which can open in case of accident, such as electricity failure or earthquake or loss of control, in order to protect the F-coil from the impact with the vacuum chamber. The safety catcher system is necessary for us to proceed to the levitation with the lifter completely removed, which we call "the full levitation". The safety catcher system is installed at Z = - 50 mm. The photograph of the catcher system is shown in Fig. 2.13. The continuous photographs of the opening test of the catcher is shown in Fig. 2.14. This movies was took by the video camera whose frame speed is 8.3 ms and a red-colored LED flushed for 100 ms after the emergency signal was transmitted. We have confirmed that the catcher can surely open in 100 ms.

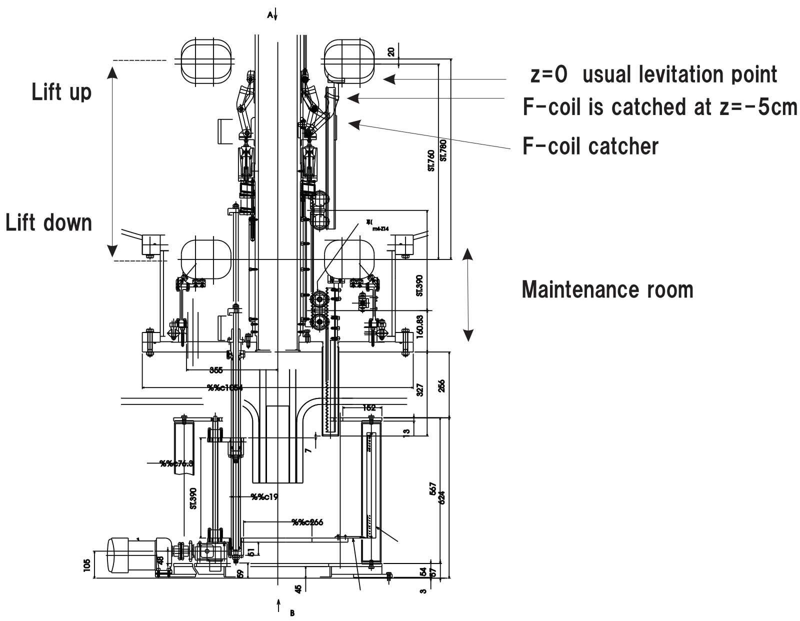

Figure 2.12: Schematic drawing of the RT-1 center stack structure. The mechanical lifter brings up and down the F-coil between the experiment room and maintenance chamber. The safety catcher can open within 0.1 second before the F-coil falls down 50 mm.

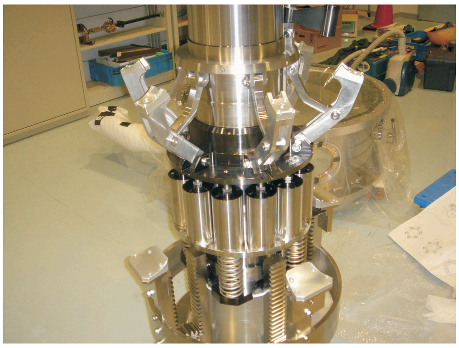

Figure 2.13: A photograph of the safety catcher. The catcher is opened in this photograph.

Figure 2.14: A sequence of photographs of the opening of the safety catcher. The pulse duration of the red-colored LED is set to 100 ms. The catcher certainly opens in 100 ms.

2.5 Purposes of This Research

The purposes of this thesis which is named " Experimental Analysis of the Magnetic Field Structure on the High-Beta plasmas in the Magnetospheric Plasma Device" are to experimentally investigate the various confinement characteristics of the magnetospheric plasma RT-1. Here the various confinement characteristics mean the estimate of the local beta value, the evaluation of the energy confinement time, the analyses of the pressure profile and the discharge-condition dependencies of them. In order to investigate them, the several magnetic measurement systems are developed in RT-1. The change of the magnetic signal of plasma, or plasma diamagnetism, means the change of the confined plasma pressure or energy. So analysis of the magnetic field structure of the high beta plasma directly contributes to the estimate of the profile of the plasma pressure, or beta value, which resembles to the satellite observations shown in Fig. 2.3.