Levitated Superconductor Ring Trap (Mini-RT) Project - A New Self-Organized Structure with Strong Plasma Flow –

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Abstract: Mahajan-Yoshida has theoretically developed a new relaxation state under the condition of a strong plasma flow, and proposed a possibility for confining high beta plasmas. In this self-organized state, two fluids (electron and ion) would relax to the condition given by the relation $\beta + (V/V_A)^2 = const.$. An internal coil device is suitable for studying a self-organized structure with strong plasma flow, because a strong toroidal flow is easily induced by introducing an appropriate radial electric field. We are constructing a Mini-RT device, which is equipping a floating coil with a high temperature superconductor (HTS) coil (*R*=0.15m, *Ic*=50kAturns). The magnetic field strength near the floating coil is around 0.1 T, and the plasma production with 2.45 GHz Electron Cyclotron Heating is planned. We are preparing several techniques to build up the radial electric field in the plasma such as the direct insertion of the electrode and so on. The utilization of direct orbit loss of high energy electrons produced by ECH might be an interesting method. The orbit calculation results show that the electrons with the energy of more than 10 keV would escape at the outer region of the plasma column, yielding the build-up of the radial electric field. The engineering aspect of the HTS coil is in progress. We have fabricated a small HTS coil (*R*=0.04 m and *Ic*= 2.6 kAturns), and succeeded in levitating it during four minutes with an accuracy of a few tens of micrometers. Since the HTS coil is excited by the external power supply, the persistent current switch for the HTS coil has been developed. The HTS coil system with the PCS coil has been fabricated and the excitation test has been carried out. We have succeeded in achieving a persistent current, and it is found that the decay constant of the coil current is evaluated to be around 40 hours and 6.5 hours at 20 K and 40 K, respectively.

1. A Self-Organized Structure with Strong Plasma Flow

A plasma, evolving under strong coupling of the velocity and magnetic fields, may self-organize into stable macroscopic structures that are not accessible by a flow-less plasma [1]. The relaxed state is represented by the double Beltrami (DB) field [2], a linear combination of two Beltrami vortices (each Beltrami field is a force-free magnetic field with parallel flow), which, despite the simple mathematical structure, includes a variety of plasma states that is far richer than the conventional Taylor state. The DB equilibrium is shown to be capable of confining a high-beta plasma. The generalized Bernoulli condition, implying that the energy density of the field is fully relaxed, gives a simple relation among the flow velocity, potential and the static pressure. When we drive a strong flow (of order unity in the Alfvenic units), very high-beta equilibrium may be

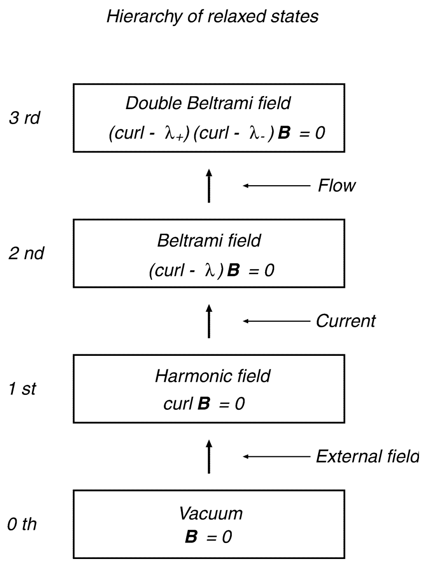

Fig. 1 Hierarchy of relaxed states

obtained. On the other hand, when diamagnetism is imposed (as a jump condition at the boundary), a flow and electric field naturally emerge to sustain the pressure. The self-consistency of the fields and pressure is the defining attribute of the DB self-organized states.

In Fig. 1, we may see a hierarchy determined by the increasing complexity of the final state. In supplying a magnetic field, current, and flow to the plasma, the energy of the system rises successively with the harmonic, the first, and the second Beltrami fields. To access the DB state, one must drive and sustain an appropriate flow. It is equivalent to giving an internal electric field. In the DB self-organized state, two fluids (electron and ion) should relax to the conditions; $\vec{V} - \nabla \times \vec{B} = a\vec{B}$, $\vec{B} + \nabla \times \vec{V} = b\vec{V}$, resulting in a relation given by $\beta + (V/V_A)^2 = const.$.

To study a self-organized structure with strong plasma flow, we have introduced an internal coil device. The idea is schematically shown in Fig. 2. By introducing a radial electric field with appropriate methods discussed later, we could drive a toroidal plasma flow given by $V_t = E_r / B_p$. Going away from the internal coil, the poloidal magnetic field decreases, resulting in the increase of the plasma flow velocity, if the radial electric field changes slower than the magnetic field. We expect to confine a high beta plasma by utilizing this fast plasma flow.

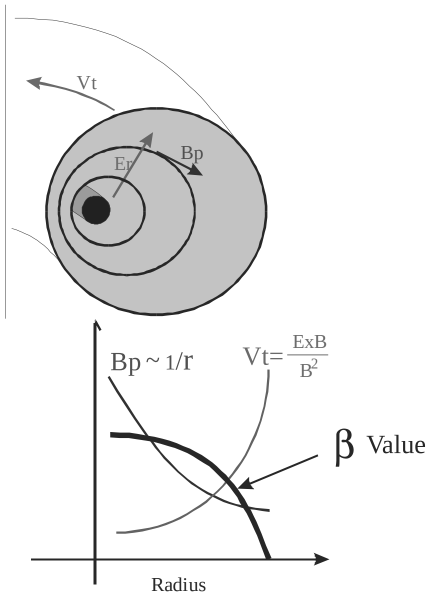

Fig.2 Schematic drawing of the high beta plasma confinement with an internal coil device.

To promote our project, we have constructed an internal coil device Proto-RT[3] with a normal conductor, and have successfully produced an electron plasma by injecting electron beam through chaotic orbits across the magnetic separatrix. The 2-D contour of the plasma potential has been measured, and the radial electric field of a few kV/m has been confirmed. The built-up potential is sufficient to drive an Alfvenic flow velocity.

We are now constructing an internal coil device Mini-RT with a floating superconductor coil[4,5]. The Mini-RT experiment is an important step we must take to eliminate the feed-through and mechanical structures for the internal conductor. The device, employing an internal conductor and a toroidal magnetic field coil, is designed to study a variety of magnetic configurations encompassing from a tokamak-like magnetic shear profile to a dipole field. The coupling of magnetic shear and flow shear will be the central theme of the experiment. The plasma confinement in a dipole field will be related with space plasma physics.

2. The Mini-RT Device and Experimental Plan

The internal coil device Mini-RT is equipping a levitated ring with a high temperature superconductor (HTS) coil, where the major radius of the HTS coil is 0.15 m and the coil current is 50 kAturns. The specification of the HTS coil is listed in Table I. The operation temperature of the HTS coil is 20 K, and we expect a plasma exepriment during the period of the temperature increase from 20 K to 40 K. The GM cryocoil is cooled down to 20 K by introducing a 20 K helium through the removable check valve.

Table I. Specification of the floating HTS coil.

Major/Minor radius	150 mm / 28 mm
Total current	50 kAturns
Number of turns	428
Nominal coil current	117 A
Supperconductor	Ag-sheathed Bi-2223
Cable width/thickness	4.3 mm / 0.26 mm
Silver ratio	1.57
Critical current (77K, s.f., 1μV/cm)	108 A
Stored magnetic energy	598 J
Max. magnetic field	0.51 T(perp.) / 0.76 T(para.)

The vacuum chamber is 1 m in diameter and ~ 0.7 m in height. The magnetic field strength near the floating coil is around 0.1 T, and the plasma production with 2.45 GHz Electron Cyclotron Heating(ECH) is planned. Typical magnetic configuration is shown in Fig. 3. The weight of the floating coil is 20 kg, and the coil current of the levitation coil set at the upper region of the vacuum vessel is 15 kAturns. In addition, the vertical coil is equipped so as to modify a magnetic surface, as shown in Fig. 3.

A strong plasma flow in toroidal direction is expected by introducing a radial electric field. In order to build up the radial electric field in the plasma, we are preparing several techniques. The injection of electrons through the separatrix region might be promising, as demonstrated in the experiments of the Proto-RT device[6]. The direct insertion of the electrode inside the plasma would be possible candidate to drive the radial electric field, as demonstrated by the CCT tokamak for achieving H-mode plasmas[7]. These experiments are planned in the Mini-RT device.

The 2.45 GHz ECH is very useful for plasma production in the density range of $n = 10^{16\text{-}17}$ m^{-3}, and the production of high energy electrons with an energy more than a few tens keV might be expected[8,9]. Since the magnetic field strength is very weak at the outer region of the torus, as shown in Fig. 3, the high energy electrons would escape from the magnetic surface through the separatrix region due to its large Larmor radius; e.g., $\rho_e = 7.5$ cm at $E = 50$ keV and $B = 0.01$ T. This reminds us that the direct orbit loss of the high energy ions might be responsible for the transition of L- to H-mode in tokamak experiments[10], where it seems that the direct ion loss might induce the radial electric field at the edge pedestal region. Similarily, the utilization of direct orbit loss of high energy electrons produced by ECH might be feasible, so as to build up the radial electric field.

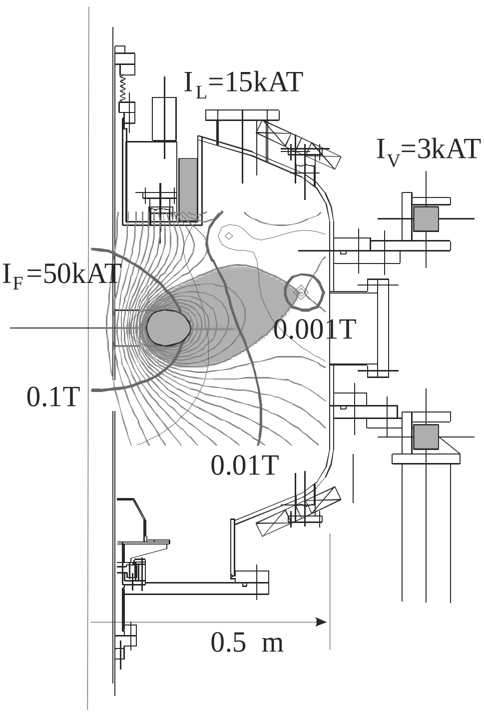

Fig. 3 Typical magnetic configuration and magnetic field strength in the Mini-RT device

The orbit loss of high energy electrons has been calculated. The high energy electron produced by the ECH is launched at the electron cyclotron resonance position (i.e., Bp = 0.0875 T; R ~ 0.18 m and Z ~ 0.07 m in Fig. 4). The orbit loss depends on the initial position of the launched electron and the electron energy. The escaping region of high energy electrons with an energy of 50 keV is shown in Fig. 4. Approaching the separatrix position, the maximum energy of confined electrons decreases drastically. We could, therefore, expect that the radial electric field might be produced at the outer region of the plasma column, if the ECH could produce the high energy electrons with the energy of more than a few keV.

By assuming that $\beta = 0$ at the plasma surface, the relation between the plasma beta value and the radial electric field is given by $E_r / B = V_A \sqrt{\beta}$. If we assume the plasma parameters that $n=10^{17}$ m^{-3} and $\beta = 100$ %, the necessary radial electric field E_r is 690 kV/m and 6.9 kV/m for $B_p = 0.1$ and 0.01 T, respectively. Since the poloidal magnetic field strength changes drastically in the plasma region, the necessary radial electric field might be, therefore, a few tens kV/m in the Mini-RT device; i.e., the build-up of the radial potential around a few kV is required because the plasma minor radius is around 10 ~ 20 cm. Here we should remark that the the amount of escaping electrons so as to build up a necessary radial electric field is quite small; e.g., $\Delta n/n \sim 10^{-4}$.

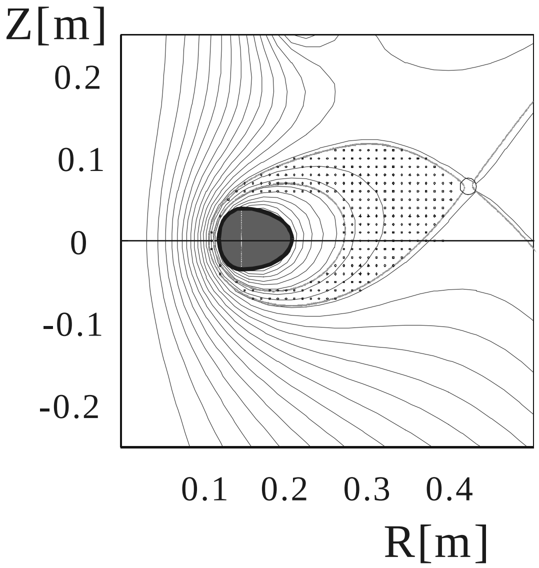

Fig. 4 Loss region of high energy electron with an energy of 50 keV(shown by dotted region). High energy electron is launched at the electron cyclotron resonance position with an perpendicular energy.

3. Progress of the HTS Coil System

Several R&D issues on the HTS coil are in progress. The position control of the floating HTS coil is an important issue. We have fabricated a small HTS coil (0.04 m in radius and 2.6 kAturns), and immersed it with liquid nitrogen. The coil position is measured with the laser detector, and the levitation coil current is controlled with the PD feedback system. Dynamic constant of this system is a few ten Hz. We have succeeded in levitating it during four minutes with an accuracy of ~ 30 micrometers[11].

Instead of the induction method, the coil current is directly charged by the power supply through the removable current feed-through. Attachments for this purpose are equipped in the floating coil. In addition, so as to achieve the persistent current mode during the floating phase, the development of the persistent current switch (PCS) is indispensable, as well. The tape Bi-2223 (Ag-0.3wt%Mn sheathed) is adopted, and the turn-off resistance is designed to be 0.27 Ω at the elevated temperature.

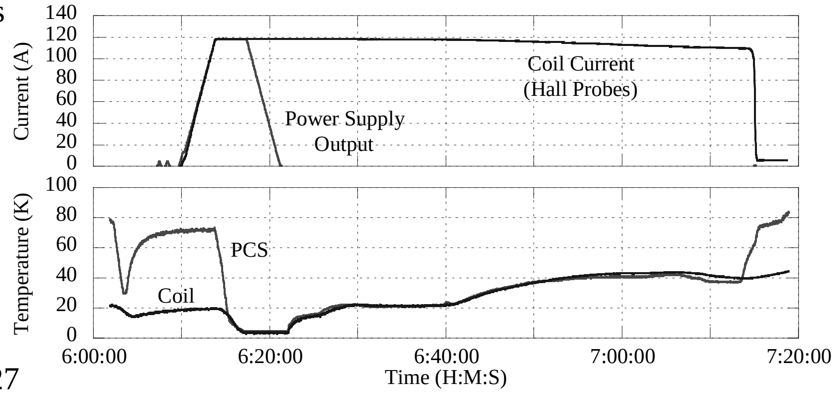

Fig. 5 Excitation test of HTS coil. The time scale denoted by 6:20:00 means 6 o'clock 20 minutes 00 second. The currents of the power supply and HTS coil, and the temperatures of HTS coil and PCS are shown.

The excitation test of the HTS floating coil has been carried out with the cryostat chamber[12]. Figure 5 shows the waveforms of the output current of the power supply, coil current and temperatures of the HTS coil and the PCS. Here the coil current is evaluated by measuring the magnetic field with a Hall probe. Initially the HTS coil is cooled down to 20 K, while the PCS is kept at the elevated temperature around 70 K, so as to hold the switch-off condition. During this period the coil current is supplied by the external power supply within a few minutes. When the coil current is increased up to the nominal value (i.e., Ic = 118 A), the PCS is quickly cooled down to 20 K or less, expecting the transition to the turn-on condition. Then, the current of the power supply is gradually decreased, resulting in the replacement of the power supply current with the PCS one. In Fig. 5 we can see that the persistent current mode is achieved around the time 6:20:00.

We have measured the decay constant (e-holding time) of the persistent current for various temperatures. At the temperature of 20 K, the decay constant is estimated to be 40 hours, while that is to be 6.5 hours at 40 K. Since we are expecting a floating period of a few hours, this result might be satisfactory.

The HTS coil is equipped in the vacuum vessel, and the cooling down of the coil has been started. It has taken about 15 hours to cool down the coil system to 40 K.

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