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Construction of a Toroidal Plasma Confinement Device with a Floating Internal Coil for Studying High Beta Plasmas

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Abstract

A new relaxation theory for high-beta plasma configuration has been proposed by Mahajan-Yoshida. For exploring this new relaxed configuration, we are constructing an internal coil device, called Mini-RT, with a high temperature superconductor (HTS) coil. Typical machine parameters are as follows; the major radius of the internal coil is 0.15 m and the coil current is 50 kA·turn. The vacuum chamber is 1 m in diameter and ~ 0.7 m in height. We are planning to produce a neutral plasma with 2.45 GHz Electron Cyclotron Heating system. A strong plasma flow in toroidal direction is expected by introducing a radial electric field E_r. A persistent current switch should be equipped in the floating coil, because the floating coil current is charged with the demountable electrode. Here A Ag-sheathed Bi-2223 HTS tape with 0.3 wt% Manganese has been successfully tested for the persistent current switch. The levitation control of the HTS coil is another important issue. We have fabricated a small HTS coil (0.04 m in radius, and 2.6 kA·turn), and succeeded in levitating it during a few minutes with an accuracy of 20~30 micrometers.

Keywords:

two fluid relaxation, high beta plasma, internal coil device, high temperature superconductor, levitation, persistent current switch

1. Introduction

Mahajan-Yoshida has found a new relaxation state by taking a two-fluid effect into account, and pointed out the possibility of a new type of configuration for a high beta plasma confinement [1]. To explore this new relaxation theory, a toroidal device with an internal coil is suitable, where the high beta plasma would be confined with the dynamic pressure of the plasma flow in toroidal direction. The toroidal plasma flow can be driven by the radial electric field by the $\boldsymbol{E} \times \boldsymbol{B}$ force. We are expecting to induce the radial electric field by producing a non-neutralized plasma.

In the past several devices with a floating coil (e.g., Spherator, Levitron) have been constructed, where a low-temperature superconductor coil has been employed [2]. In these devices the plasma is confined at the inner side of the torus so as to study several MHD concepts such as Min-B and so on, while in our device the plasma is produced and confined at the outer region of the torus

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for exploring a new relaxed state.

We adopt a high temperature superconductor (HTS) wire for the floating coil, expecting easy/reliable operation and maintenance. In addition, the HTS coil is preferable for plasma experiments, because long pulse and/or high power heating experiments might be available due to the high thermal stability and large heat capacity of the HTS wire.

The persistent current switch should be equipped in the floating coil, because the floating coil current is charged with the demountable electrode. Here the Bi-2223 HTS tape with 0.3 wt% Manganese is adopted for the persistent current switch. The floating coil should be controlled with an accuracy of a few tens of micrometers for plasma experiments. The levitation experiments with a small HTS coil have been carried out.

In this manuscript, the construction of the internal coil device called Mini-RT is described, and expected plasma parameters and experimental plan are discussed. The development of the persistent current switch and levitation experiments of the HTS coil are described, as well. This is a first challenge to apply the HTS coil for a plasma confinement device, as well as the levitation experiment of the HTS coil.

2. Design of a Floating Coil Ddevice (Mini-RT)

Schematic drawing of the internal floating coil device Mini-RT is shown in Fig. 1, where a vacuum chamber is 0.5 m in radius and ~ 0.7 m in height. A levitation coil is put at the top of the vacuum vessel. Since the floating coil is unstable to the vertical motion, the levitation coil current is feedback-controlled to keep the floating coil position. The floating coil is re-cooled at the bottom of the vacuum vessel through the demountable pipe, and the coil current is recharged directly by the power supply with the demountable electrode, as well.

The HTS wire is Ag-sheathed Bi-2223. The specification of the floating coil is listed in Table 1. The maximum magnetic field strength appears at the surface of the coil and is that $B_z = 0.75$ T and $B_r = 0.57$ T. To evaluate the residual voltage of the HTS wire, it is assumed that the n-value defined by $V = V_c\,(I/I_c)^n$ is 10. Operation temperature of the HTS wire is initially 20 K, and increases up to ~ 40 K. Taking the decrease of the decay constant of the coil current at the elevated temperature into account, we expect to keep the floating coil during a few hours for plasma experiments. In this floating coil system we need no quench protection system.

3. Plasma Parameters Expected in Mini-RT

In order to produce non-neutral (or non-neutralized) plasmas, the injection of electrons through the separatrix has been proposed, where the inward diffusion of

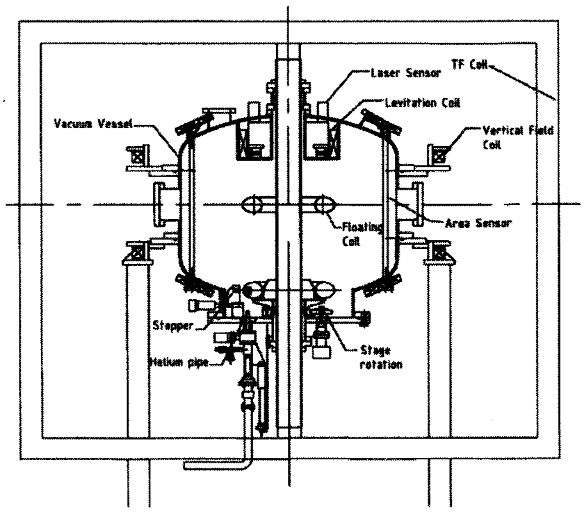

Fig. 1 Schematic Drawing of the internal coil device Mini-RT, where a floating coil are re-cooled and charged at the bottom of the torus.

Table 1 The Specification of the Floating Coil Made of HTS Wire.

Parameters	Values
Major and minor radii	$R = 0.15$ m and $a = 0.028$ m
Operation current of the coil	$I_{op} = 117$ A
Magneto-motive force (total coil current)	$I_{tot} = 50{,}000$ A (428 turns)
Critical current of the HTS wire	$I_c = 108$ A at 77 K, s.f., 1 μV/cm
Residual voltage and inductance of the coil	$R_\Omega = 1.66 \times 10^{-5}$ V, $L = 0.091$ H
Weight of the coil	W ~ 20 kg

electrons is expected at the separatrix, by taking the chaotic motion of electrons at the magnetic null point into account [3].

We are planning to produce a neutral plasma in the range of $n \sim 10^{16\text{-}17}$ m^{-3} with 2.45 GHz Electron Cyclotron Heating system. As shown in Fig. 2, the contour of the magnetic field strength of 0.1 T is located around the outer side of the floating coil. We expect the neutral plasma will be produced in the neighborhood of the contour of B = 0.1 T. Since the ECH could produce high energy electrons more than a few tens keV [4], this might be helpful to produce a high beta plasma. In addition, some part of the extremely high energy electrons might escape from the magnetic surface through the separatrix region. This might yield a bulk plasma to non-neutralize. To examine the compatibility between high energy electron production and non-neutralization by the orbit loss, an orbit of a high energy electron has been calculated for the magnetic configuration given in Fig. 2. An electron with a perpendicular energy of a few tens keV is initially launched at the resonance position (i.e., at the location of B_t = 0.0875 T). Only at the magnetic surface far away from the internal coil, a direct orbit loss of a high energy electron takes place; for example, an electron with an energy more than 80 keV is not confined at a hatched region shown in Fig. 2.

Mahajan-Yoshida has found a MHD relaxation state in two-fluid plasmas, and derived the following Beltrami/Bernoulli condition [1]; i.e., $\beta + (V_P/V_A)^2$ = constant, where β is the ratio of the plasma pressure to the magnetic pressure, and the velocities V_P and V_A are plasma flow velocity and Alfven velocity, respectively. When the plasma velocity is increasing as the plasma radius, high beta plasmas can be confined at the core region of the plasma column. If the radial electric field is introduced in the torus plasma with the internal coil, the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity is an increasing function of the plasma minor radius. This is the reason why the internal coil device is suitable for studying high beta plasmas based on two-fluid MHD relaxation theory.

By assuming that $\beta = 0$ at the plasma surface, the relation between the plasma beta value and the radial electric field can be derived as follows;

$$\frac{E}{B} = \sqrt{\frac{B^2}{\mu_0 n_i m_i}}\,\sqrt{\beta}\,,$$

where n_i and m_i are ion density and mass, respectively. This gives plasma parameters necessary for studying high beta plasmas, and typical values are listed in Table 2.

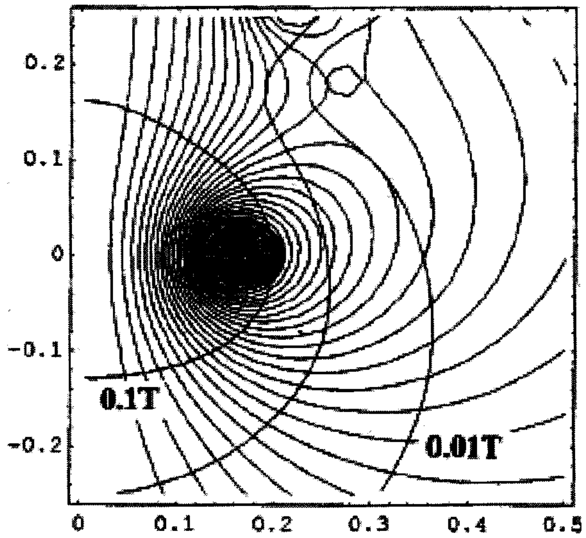

Fig. 2 Magnetic field configuration only with the levitation coil and the contour of the magnetic field strength. At the hatched region a high energy electron with a perpendicular energy more than 80 keV is lost.

Table 2 Typical Plasma Parameters to study High Beta plasma Experiments.

Beta value	Temperature	Radial electric field
100% (at B = 0.1T)	T = 124 keV	690 kV/m
10% (at B = 0.1T)	T = 12.4 keV	220 kV/m
100% (at B = 0.01T)	T = 1.24 keV	6.9 kV/m
10% (at B = 0.01T)	T = 0.12 keV	2.2 kV/m

The low density plasma needs a high plasma temperature and a large radial electric field. We might expect a high beta plasma at the outer region of the plasma column, because the magnetic field strength drastically decreases, as shown in Fig. 2.

It is not so easy to predict the plasma confinement time in this internal coil device. Here we roughly estimate the energy confinement time necessary to achieve these plasma parameters. When the ECH power is assumed to be 10 kW, the energy confinement time to achieve the plasma with β = 100% is estimated to be 4.1 msec.

4. Engineering Progress of the HTS Coil

We employ the method to drive the HTS coil current through the demountable electrode. This has some advantages in comparison with the induction drive; e.g., the induction coil is not necessary, and the power supply system becomes quite simple. However, it is necessary to introduce the persistent current switch (PCS) made of the HTS wire in the floating coil. There are few experiences of the PCS with the HTS wire in the past. We use the Ag-sheathed Bi-2223 tape with 0.3 wt% Manganese, which gives high electric resistance at the elevated temperature (the turn-off resistance of 0.27 Ω at the critical temperature). We have measured the characteristics of the HTS-PCS tape for various temperatures, and confirmed the performance as the PCS for the floating coil [5].

The levitation of the HTS coil is another important issue. We cannot expect the pinning effect for the HTS coil, because the HTS wire is composed of multi-filaments, in comparison with the bulk HTS material. The feedback control is, therefore, indispensable. In addition, we particularly pay attention to the position control of the floating coil, because the fluctuation of the coil position induces an error field, resulting in the disturbance of the magnetic surface for the plasma confinement. In plasma experiments, the position of the floating coil should be controlled within a sufficiently high accuracy (e.g., less than 100 micrometers).

We have fabricated a small HTS coil (4 cm in radius and 2.6 kA·turn) and carried out the levitation experiment [6]. The coil is covered with the casing made of polycarbonate and immersed in liquid nitrogen. The total weight is approximately 321 g with liquid nitrogen. The HTS coil current is induced by the field-cooling method. The detected signals of the floating coil position are transferred to the feedback system, which is composed of a proportional and differential feedback control (the so-called PD feedback control). The HTS coil position can successfully be controlled within an accuracy of 25~30 μm, and levitated for 4 min or more.

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