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ADP012575

TITLE: Design of a Toroidal Device with a High Temperature  
Superconductor Coil for Non-neutral Plasma Trap

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This paper is part of the following report:

TITLE: Non-Neutral Plasma Physics 4. Workshop on Non-Neutral Plasmas  
[2001] Held in San Diego, California on 30 July-2 August 2001

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# Design of a toroidal device with a high temperature superconductor coil for non-neutral plasma trap

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**Abstract.** The non-neutral plasma confinement device with a floating internal coil is under construction, where the high temperature superconductor (HTS) Ag-sheathed BSCCO-2223 is employed as the floating coil. We have two topics with this device; one is a trap of a non-neutral plasma consisting of one species, and another is an exploration of a high beta plasma based on two-fluid MHD relaxation theory. In the latter case the plasma should be non-neutralized in order to drive the plasma flow in the toroidal direction. The expected plasma parameters are discussed. Key elements of engineering issues have already developed. In addition, we have fabricated a small HTS coil and succeeded in levitating it within an accuracy of 25 ~ 30  $\mu\text{m}$  for 4 min or more.

## INTRODUCTION

An internal coil device with a normal conductor (called Proto-RT) has been constructed, and trapping/confinement of non-neutral plasmas in a toroidal device has been intensively promoted [1]. There are, however, some restrictions for the normal conductor device; i.e., the current feeder and the coil support are intersecting with the magnetic surface, resulting in the deterioration of the plasma confinement. In addition, the high magnetic field seems not to be easy, because of the low current density of the normal conductor. To overcome these issues we are now constructing a toroidal device with a floating coil wound with a superconductor, called Mini-RT.

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.

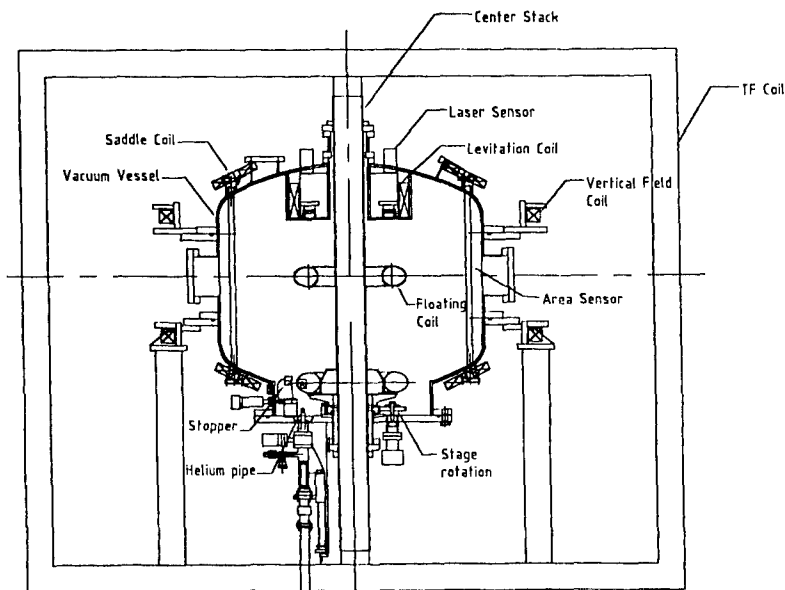
In this Mini-RT device, we are expecting to study two topics; one is a trap of a pure electron (or positron) plasma in a toroidal device. From the viewpoint of trapping experiments, the strong magnetic field might make it possible to confine relatively high energy charged particles.

Another purpose is an exploration of a new type of MHD relaxation by producing a non-neutralized plasma. Recently, 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 high beta plasma [2]. To explore this new relaxation theory, the 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  $E \times B$  force. We are expecting to produce the radial electric field by producing a non-neutralized plasma.

In this manuscript, the design of the internal coil device called Mini-RT is described, and expected plasma parameters are discussed. Test of HTS wire has been started, and levitation experiments with a small HTS coil have been successfully carried out [3]. This is a first challenge to apply the HTS coil for plasma confinement devices, as well as the levitation experiment of the HTS coil.

## DESIGN OF A FLOATING COIL DEVICE (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  $\sim 0.7$  m in height. A levitation coil is



**FIGURE 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.

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, as well.

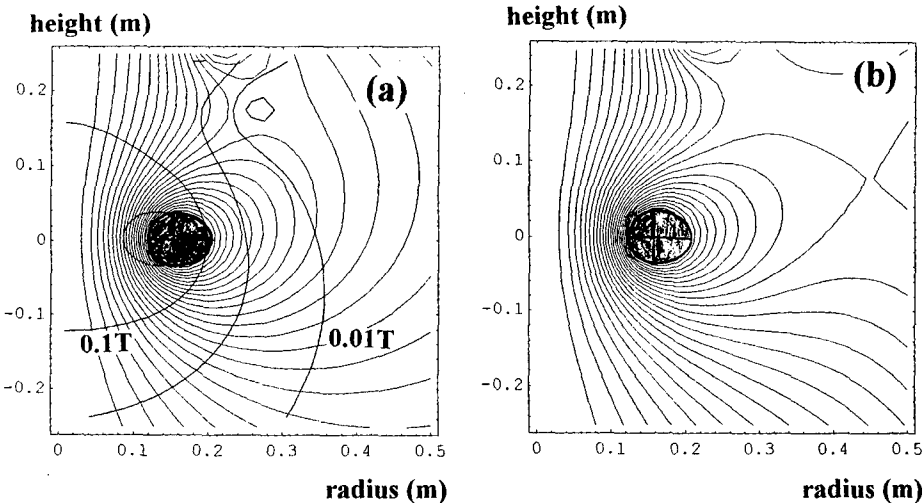
The HTS wire is Ag-sheathed BSCCO-2223. The specification of the floating coil is listed in Table 1.

**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               | $I_{op} = 115$ A                                  |
| Magneto-motive force (total coil current)   | $I_{tot} = 50,000$ A (435 turns)                  |
| Critical current of the HTS wire            | $I_c = 108$ A at 77 K, s.f., $1 \mu\text{V/cm}$   |
| Residual voltage and inductance of the coil | $R_\Omega = 1.66 \times 10^{-5}$ V, $L = 0.091$ H |
| Decay constant of the coil current          | $\tau = 174.4$ hours at 20 K                      |
| Weight of the coil                          | $W \sim 20$ kg                                    |

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  $\sim 40$  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.

In addition to the floating coil, there are other magnetic field coils made of normal conductors. With the combination of the levitation coil, the nested magnetic field lines can be produced as shown in Fig. 2(a). To levitate the floating coil, the coil



**FIGURE 2.** Magnetic field configuration (a) only with the levitation coil and (b) the levitation and vertical coils. The contour of the magnetic field strength is also shown in the case (a).

current of the levitation coil is 15.3 kA·turn. We should pay attention to the clearance at the inner side of the torus; e.g., the distance between the separatrix magnetic field line and the inner surface of the coil is 22 mm. This clearance is sufficiently large for electrons; i.e., the Larmor radius of electrons with the energy of 100 keV is 3 mm at the inner side of the torus ( $B = 0.35$  T), but is marginal for ions.

A pair of the vertical field coil made of the normal conductor is put outside the vacuum vessel so as to modify the magnetic surface. In Fig. 2(b) the closed magnetic surface with the separatrix outside of the torus is also presented, where the coil current of the vertical field coil is 2.7 kA·turn.

## PLASMA PARAMETERS EXPECTED IN A MINI-RT DEVICE

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 electrons is expected at the separatrix, by taking the chaotic motion of electrons at the magnetic null point into account [4]. In a Proto-RT device, the production of a non-neutral plasma with a potential of a few hundreds of eV has been succeeded [1]. In a Mini-RT device, we expect to apply this technique, as well.

We are planning to produce a neutral plasma in the range of  $n \sim 10^{16-17} \text{ m}^{-3}$  with 2.45 GHz Electron Cyclotron Heating system. As shown in Fig. 2(a), 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 [5,6], 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.

Mahajan-Yoshida has found a MHD relaxation state in two-fluid plasmas, and derived the following Beltrami/Bernoulli condition [2]; i.e.,  $\beta + (V_p / V_A)^2 = \text{constant}$ , where  $\beta$  is the ratio of the plasma pressure to the magnetic pressure, and the velocities  $V_p$  and  $V_A$  are plasma flow velocity and Alfvén 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 so-called  $E \times B$  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;

$$\frac{E}{B} = \sqrt{\frac{B^2}{\mu_0 n_i m_i}} \sqrt{\beta}, \quad (1)$$

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.

**TABLE 2. Typical Plasma Parameters to study High Beta plasma Experiments.**

| Beta Value and Magnetic Field | Plasma Density and Temperature                  | Radial Electric Field |
|-------------------------------|-------------------------------------------------|-----------------------|
| 100 % at $B = 0.1$ T          | $n = 10^{16} \text{ m}^{-3}$ and $T = 1240$ keV | 2200 kV/m             |
| 100 % at $B = 0.1$ T          | $n = 10^{17} \text{ m}^{-3}$ and $T = 124$ keV  | 690 kV/m              |
| 10 % at $B = 0.1$ T           | $n = 10^{17} \text{ m}^{-3}$ and $T = 12.4$ keV | 220 kV/m              |
| 100 % at $B = 0.01$ T         | $n = 10^{17} \text{ m}^{-3}$ and $T = 124$ keV  | 6.9 kV/m              |
| 10 % at $B = 0.01$ T          | $n = 10^{17} \text{ m}^{-3}$ and $T = 1.24$ 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(a).

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  $\beta = 100\%$  is estimated to be 4.1 msec.

## ENGINEERING PROGRESS OF THE HTS COIL

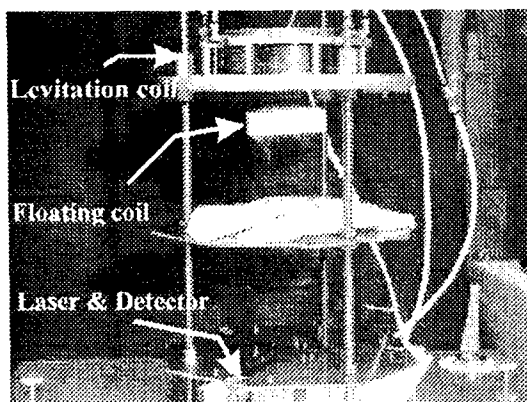
We employ the method to drive the HTS coil current through the demountable electrode. This has some advantages in comparison with the induction drive; e.g., the induction coil is not necessary, and the power supply system becomes quite simple. However, it is necessary to introduce the persistent current 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 Mn-doped HTS wire, which gives high electric resistance at the elevated temperature. We have measured the characteristics of the Mn-doped HTS wire, and confirmed the performance as the PCS for the floating coil.

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).

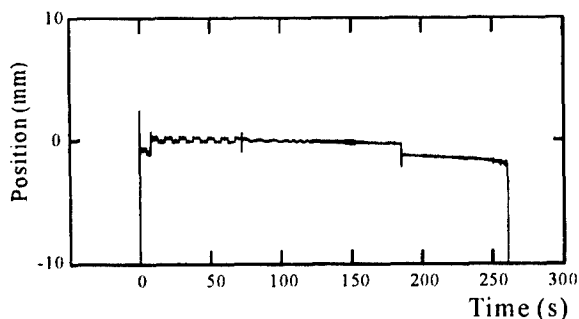
We have fabricated a small HTS coil (4 cm in radius and 2.6 kA·turn) and carried out the levitation experiment [3]. The coil is covered with the casing made of polycarbonate and immersed in liquid nitrogen. The total weight is approximately 321 g with liquid nitrogen. The HTS coil current is induced by the field-cooling method.

Figure 3 shows the levitation experimental setup using the reflection method. Nitrogen vapor can be seen, because the HTS coil immersed in liquid nitrogen is open. The laser light injected from the bottom of the HTS coil is sometimes interrupted by this nitrogen vapor, making the position control worse. 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 position data of the HTS coil is shown in Fig. 4, where the coil position is artificially changed so as to examine the dynamic response of the coil. The HTS coil position can successfully be controlled within an accuracy of 25–30  $\mu\text{m}$ , and levitated for 4 min or more.



**FIGURE 3.** Setup of levitation experiment of a small HTS coil. Laser light is irradiated from the bottom, and reflected light is measured at the bottom by the CCD camera.



**FIGURE 4.** Feedback control experiments of the HTS floating coil. The coil position is artificially changed, in order to examine the dynamic response of the floating coil.

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