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Research on High-Beta Plasmas Based on Two-Fluid Relaxation Theory

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Abstract

Relaxation phenomena have been observed in many plasma experiments, and some theoretical explanations have been presented. Recently Mahajan-Yoshida has discovered a new relaxation state based on two-fluid plasma theory, and proposed a possibility for confining high-beta plasmas. In this theory two fluids (electron and ion) should relax to the conditions; $\boldsymbol{V} - \nabla \times \boldsymbol{B} = \alpha \boldsymbol{B}$, $\boldsymbol{B} + \nabla \times \boldsymbol{V} = \beta \boldsymbol{V}$, resulting in a relation given by $\beta + (V/V_A)^2$ = constant. This is called Beltrami/(generalized) Bernoulli condition. To explore this new relaxation state experimentally, a toroidal device with an internal coil is suitable, where strong plasma flow in the toroidal direction is induced by $\boldsymbol{E} \times \boldsymbol{B}$ drift by introducing a radial electric field. Since the $\boldsymbol{E} \times \boldsymbol{B}$ flow velocity increases as the minor radius is increased, a high-beta plasma could be confined in the core region. A torus device called S-RT is planned with a floating superconductor coil. This paper describes its engineering design and discusses expected plasma parameters. At present, a device with a normal conductor, called Proto-RT, has been constructed, and experiments of electron injection have been carried out. In addition, a small-scale torus device with a superconductor coil, called Mini-RT, are under construction, where a high-temperature superconductor (HTS) made of Bi-2223 tape is employed as a floating coil. This is the first challenge to explore the feasibility of HTS coils for fusion plasma devices.

Keywords:

High-beta plasma, two-fluid relaxation theory, plasma flow, internal coil device, high temperature superconductor (HTS)

1. Introduction

Relaxation plays an important role in plasma dynamics. In Reversed Field Pinch (RFP) plasmas the force-free condition (i.e., $j \parallel B$) is established and J.B. Taylor has theoretically explained by the energy minimum condition with the constraint of the helicity conservation [1]. While, tokamak plasmas do not relax to the so-called Taylor state due to the strong toroidal magnetic field. In REPUTE-1 device (R=0.82 m, a=0.22 m, B_t=0.35 T, I_p=400 kA) a new relaxation state has been discovered experimentally at the parameter region between RFP and tokamak (i.e., $0 < q(a) < 1$), and is called as Ultra-low-q (ULQ) configuration [2]. In ULQ

Corresponding author's e-mail: ogawa@plasma.q.t.u-tokyo.ac.jp plasmas the profile of the safety factor is not monotonical, but has a pitch minimum in the outer region of the plasma column ($r/a \sim 0.7$). This is very similar to the negative shear configuration in tokamak plasmas [3]. ULQ plasmas are categorized into a kind of relaxed plasmas, and many interesting phenomena related with the dynamo effect have been observed [4,5].

In the Taylor state, the plasma current becomes parallel to the magnetic field; namely the relaxation between the electron flow (plasma current) and the magnetic field takes place. Recently a relaxation theory including the plasma flow (i.e., ion flow) has been developed, and a new relaxation state has been identified [6,7]. Hereafter let us call this two-fluid (electron and ion flows) relaxation.

In Taylor's one-fluid relaxation state, the pressure gradient perpendicular to the magnetic surface should be zero, yielding a quite low beta plasma, if some improvements were not taken into account. While, in the two-fluid relaxation state, the plasma pressure could be sustained by the dynamic pressure due to the plasma flow, resulting in a confinement of an ultra high-beta plasma. To study this new relaxation state experimentally, a toroidal device with an internal coil is suitable, where strong plasma flow in the toroidal direction is induced by $\boldsymbol{E} \times \boldsymbol{B}$ drift by introducing a radial electric field.

A. Hasegawa has also developed another new relaxation theory, and proposed a dipole field configuration with an internal coil [8]. In his theory the plasma relaxes to a high beta state under the constraints of the conservations of two adiabatic constants (μ and J) [9]. To explore this concept, MIT/Columbia group is now constructing a large-scale torus device called as Levitating Dipole eXperiments (LDX) [10].

As mentioned above, Mahajan-Yoshida and Hasegawa have proposed new relaxation theories. Although these two relaxation phenomena are independent with each other, the internal coil device is suitable for studying these relaxation theories. To explore these new relaxation phenomena, it is planned to construct a torus device with a floating superconductor coil called Superconductor-Ring Trap (S-RT). Prior to large-scale experiments a normal conductor device called Proto-RT has been constructed [11,12]. The confinement time of plasmas is, however, quite limited due to the support structures of the internal coil. A small-scale torus device with a superconductor coil, called Mini-RT, is now under construction, where a high-temperature superconductor (HTS) made of Bi-2223 tape is employed as a floating coil [13]. This is the first challenge to explore the feasibility of HTS coils for fusion plasma devices.

In this paper the two-fluid relaxation theory is briefly explained, and an idea how to apply this relaxation theory for a torus device with an internal coil is presented. Next the engineering design of the S-RT device and expected plasma parameters are discussed. Finally, the present status of the Proto-RT device is reviewed and the design of the Mini-RT device is presented.

2. Two-Fluid Relaxation Theory and Application for a Torus Device with an Internal Coil

Equations of motion of the electron fluid and the ion one are given as follows;

$$\boldsymbol{E} + \boldsymbol{V}_{\mathrm{e}} \times \boldsymbol{B} + \frac{1}{en}\nabla p_{\mathrm{e}} = 0, \tag{1a}$$

$$\frac{\partial \boldsymbol{V}_{\mathrm{i}}}{\partial t} + \left(\boldsymbol{V}_{\mathrm{i}} \cdot \nabla\right) \boldsymbol{V}_{\mathrm{i}} = \frac{e}{M}\left(\boldsymbol{E} + \boldsymbol{V}_{\mathrm{i}} \times \boldsymbol{B}\right) - \frac{1}{Mn}\nabla p_{\mathrm{i}} \tag{1b}$$

Here an inertial term is omitted for electron equation, and the ion flow velocity is retained for the ion equation. Conventional notations are employed. These two-fluid equations can be easily modified as follows;

$$\frac{\partial \tilde{\boldsymbol{A}}}{\partial t} = \left(\tilde{\boldsymbol{V}} - \nabla \times \tilde{\boldsymbol{B}}\right) \times \tilde{\boldsymbol{B}} + \nabla\left(\tilde{p}_{\mathrm{e}} - \phi\right), \tag{2a}$$

$$\frac{\partial}{\partial t}\left(\tilde{\boldsymbol{V}} + \tilde{\boldsymbol{A}}\right) = \tilde{\boldsymbol{V}} \times \left(\tilde{\boldsymbol{B}} + \nabla \times \tilde{\boldsymbol{V}}\right) - \nabla\left(\frac{1}{2}\tilde{\boldsymbol{V}}^2 + \tilde{p}_{\mathrm{i}} + \phi\right), \tag{2b}$$

where the electric field $\boldsymbol{E}$ is replaced with vector and scalar potentials ($\boldsymbol{A}$ and ϕ). The magnetic field $\boldsymbol{B}$, the plasma flow velocity $\boldsymbol{V}_{\mathrm{P}}$ and electron/ion pressure $p_{\mathrm{e}}/p_{\mathrm{i}}$ are normalized by $\boldsymbol{B}_0$, $\boldsymbol{V}_{\mathrm{A}}$, magnetic pressure, respectively.

Mahajan-Yoshida has examined these two equations at the steady-state condition and derived the following conditions as a new relaxation state [7].

$$\tilde{\boldsymbol{B}} = a\left(\tilde{\boldsymbol{V}} - \nabla \times \tilde{\boldsymbol{B}}\right), \tag{3a}$$

$$\tilde{\boldsymbol{B}} + \nabla \times \tilde{\boldsymbol{V}} = b\tilde{\boldsymbol{V}}. \tag{3b}$$

These are corresponding to the so-called force-free conditions; i.e., the first terms of the right hand side in eqs. (2a) and (2b) should be zero. This is corresponding to the Beltrami condition of a vortex dynamic system. We should notice that the first condition includes the Taylor state, when the plasma flow $\tilde{V}$ is zero; i.e., $\tilde{B} = a(\tilde{V} - \nabla \times \tilde{B}) = -a\nabla \times \tilde{B} = \lambda \tilde{j}$.

This force free conditions yield the following relations;

$$\tilde{p}_e - \phi = const. , \tag{4a}$$

$$\frac{1}{2}\tilde{V}^2 + \tilde{p}_i - \phi = const. . \tag{4b}$$

By combining these two relations, the following condition is obtained;

$$\tilde{V}^2 + \beta = const. . \tag{5}$$

This is called as Beltrami/(generalized) Bernoulli condition. This means that the sum of the dynamic pressure $\tilde{V}^2$ and the static pressure p is constant, and is very similar to the Bernoulli law. Here we should notice that this condition is satisfied for the radial direction (i.e., the perpendicular direction to the plasma flow), as well, while the Bernoulli law is valid only along with the flow.

In the case of no plasma flow, this gives the condition that β = constant, yielding a low/zero beta plasma because of the low/zero beta at the plasma surface. While, we could confine a high beta plasma in the core region if the plasma flow is induced in the outer region of the plasma column.

Here a torus device with an internal coil is introduced, to explore this new relaxation state. Figure 1 shows the schematic drawing of the magnetic field produced by the internal coil, where the dipole magnetic field with the separatrix is shown. Going away from the poloidal magnetic field coil, the poloidal magnetic field strength $\boldsymbol{B}_p$ by the internal coil is monotonically decreasing. If a radial electric field is induced in the inner region of the plasma column, the plasma begins to flow in the toroidal direction due to the $\boldsymbol{E}\times\boldsymbol{B}$ drift. The drift velocity becomes faster in the outer region of the plasma column, because the amplitude of the drift velocity is given by E_r/B_p. This results in confining a high beta plasma in the core region, if the relation $\tilde{V}^2 + \beta = const.$ is realized. This is the reason why we are utilizing a toroidal device with an internal coil to study a two-fluid relaxation theory experimentally.

Several devices with a floating superconductor coil (e.g., Spherator, Levitron) have been constructed in the past, where many interesting physics issues such as Min-B concept have been verified, and very good plasma confinement characteristics have been discovered [14]. In these devices the plasma is confined in the inner region of the torus (i.e., good curvature region), while in our device the plasma is produced and confined in the outer region of the torus (i.e., bad curvature region). We expect to realize a new relaxed state predicted by two-fluid relaxation theory under the condition of the strong toroidal plasma flow. In general, the interchange mode is unstable at the bad curvature region, but the stability is not so clear for the plasma accompanied by a strong plasma flow. Stability of the new relaxed state is important, and theoretical study is under way.

Next let us discuss on the radial electric field E_r. In tokamak H-mode plasmas the radial electric field seems to play an important role at the plasma boundary. Mahajan-Yoshida has extended two-fluid relaxation theory for the pedestal region of tokamak H-mode plasmas, and found a good agreement between experimental characteristics and theoretical predictions [15].

In the torus device with an internal coil we are considering several methods to produce the radial electric field. Most straight forward method is the insertion of the electrode inside the plasma column, just as demonstrated by the CCT device [16]. While, in L-H transition phase the role of high energy ion loss is pointed out to explain the build-up of the radial electric field [17]. This idea might be applicable for the internal coil device, as well. The Electron Cyclotron Heating

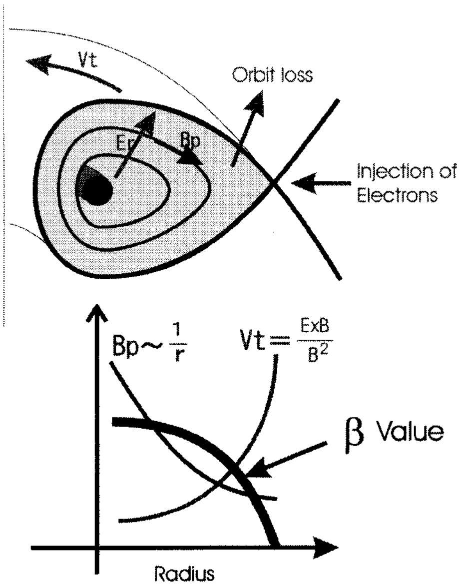

Fig. 1 Schematic drawing of an idea for confining a high beta plasma with an internal coil device.

(ECH) is planned to produce a high temperature plasma, and could yield a high energy component at a low density plasma [18]. The poloidal magnetic field is very weak in the outer region of the plasma column, and become zero at the separatrix point, as shown in Fig. 1. We could, therefore, expect an orbit loss of high energy electrons, yielding a radial electric field.

In addition, by considering that the magnetic field is zero at the separatrix, an interesting idea has been proposed for injecting an electrons into the torus plasmas. At the separatrix region the electron has a chaotic motion because of the non-conservation of the adiabatic constant. By utilizing this chaotic motion, some part of electrons can travel into the torus [19].

3. Design of the Torus Device with an Internal Coil

Figure 2 shows a bird's-eye view of the device, which is composed with floating internal ring coil, several poloidal field coils and toroidal field coil. Feedback coils are located inside the vacuum vessel, and charging coil is put at the bottom of the torus. The diameter and height of the vacuum vessel is 3 m and 2.5 m, respectively.

The basic specification of the levitated internal ring coil is as follows; the major radius of the coil is 40 cm, and the coil current is 500 kAturns. The minor radius of the coil might be around 8 cm. The maximum magnetic field strength is estimated to be ~ 3 T around the conductor. It is expected that the internal ring coil is levitating during a few hours or more.

The toroidal field coil is also equipped in order to introduce a magnetic shear, because some instabilities related with flow shear and non-neutralized plasmas might be stabilized by the magnetic shear. The total current of the toroidal field coil is 1.4 MAturns, which produces the toroidal magnetic field B_t to be 0.7 T at $R = 0.4$ m.

The internal ring coil produces the dipole magnetic field. By combining external poloidal field coils, several magnetic field configurations are available; for example, the plasma confinement configuration bounded with the magnetic separatrix located in the outer (or top/bottom) region of the torus can be produced. The typical magnetic configuration is shown in Fig. 3. The levitation coil current is 120 kAturns, and the vertical coil current located upper and lower positions is 50 kAturns. The separatrix is produced in the outer region of the torus around $R = 1.2$ m.

The maximum magnetic field becomes larger than 2 T at the conductor, and is around 1 T in the core plasma region. In the outer region of the torus the magnetic field decreases rapidly, and becomes around 0.1 T at $R = 0.7$ m. If the plasma relaxes to the two-fluid relaxation state, the relation $(V_p/V_A)^2 + \beta$ = constant is satisfied at the whole region of the plasma column. Here the plasma velocity V_p is given by E_r/B_p. By assuming that the beta value is set to be zero at the plasma

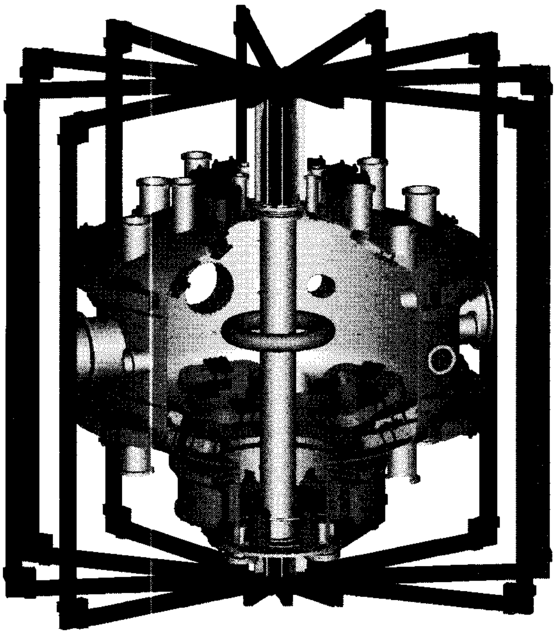

Fig. 2 A Bird's-eye view of an internal coil device with an superconductor floating coil, called S-RT.

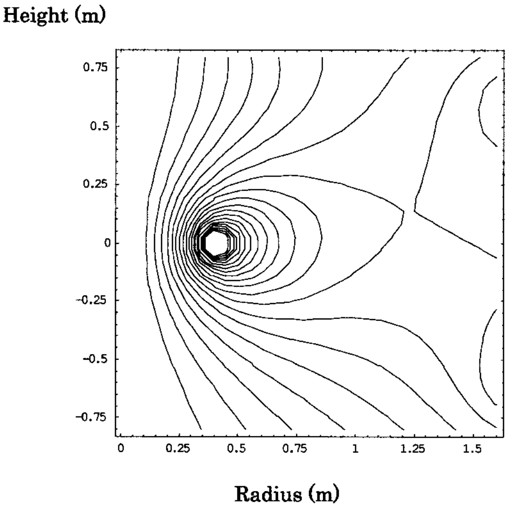

Fig. 3 Typical magnetic configuration of the S-RT device.

Table 1 Expected Plasma Parameters of the S-RT device at B=0.1T and $n_i = 10^{18}$ m^{-3}.

Beta value: β	100 %	10 %
Temperature: T_i	12 keV	1.2 keV
Radial electric field: E	220 kV/m	69 kV/m
Nonneutrality: $\Delta n/n$	2.4×10^{-5}	0.76×10^{-5}
confinement time: τ_{Ei}	120 msec	12 msec

boundary and the flow velocity is zero at the plasma center, the necessary radial electric field E_r is given with the relation. $E_r/B_p = V_A\sqrt{\beta}$. Expected plasma parameters are estimated in Table 1. Here it is assumed that the magnetic field strength B is 0.1 T, and the plasma minor radius is 0.5 m. The plasma nonneutrality $\Delta n/n$ to induce this radial electric field is also evaluated, as shown in Table 1. When the heating power is assumed to be P=100 kW, the necessary energy confinement time to realize above-mentioned plasma parameters is evaluated to be 12 ~ 120 msec.

Low-Tc and high-Tc superconductor coils are taken into account for the floating coil. There were, in the past, several experiences of construction and operation of the low-Tc superconductor floating coil, and a new large device is now under construction in MIT [20]. There is no experience of the high temperature superconductor (HTS) coil in the fusion plasma experiments. If the HTS coil could be employed as a floating coil, it seems to be quite attractive from the viewpoints of plasma experiments and machine operation.

In the case of low-Tc superconductor coil, three superconductor cables NbTi, Nb_3Sn and Nb_3Al are compared, and Nb_3Al is selected because of its large temperature margin and mechanical stress. It is estimated that the current decay time of the floating coil is quite long (50 days).

The design of the HTS coil has been carried out, as well. Advantages of HTS coils are summarized as follows;

* Large heat capacity; i.e., specific heat capacity at 20–40 K is around 100 times as high as that at 4 K, results in the remarkable improvement of the thermal stability of the superconductor coil, giving a chance of high power and/or long pulse plasma heating experiments.

* High cooling efficiency of refrigerators; i.e., the efficiency of refrigerators at 20–40 K is around 10 times as high as that at 4 K, results in easy maintenance and remarkable reduction of the operation cost.

A Bi-2223 Ag-sheathed multifilamentary wire, at present, seems to be a most promising candidate for the high magnetic field coil. For example, a 7T solenoid coil with an averaged major radius of 17.6 cm and a coil current of 1.5 MAturns has already been constructed [21]. Bi-2223 is a thin tape and the critical current density strongly degrades as the magnetic field is increased at the relatively high temperature regime (e.g., $T > 40$ K). There exists a residual voltage of the HTS coil, and n-value around the critical current density is relatively small. We should, therefore, pay attention to the coil current decay due to the residual voltage.

Operation temperature regime is set to be between 20 K to 40 K. During levitating operation for a few hours the heat input to the levitated internal coil should be compensated with the temperature increase of the structural materials of the coil. So as to increase the heat capacity of the coil itself, some heat reservoir with a large heat capacity should be equipped; e.g., lead, cooled helium and cooled nitrogen.

Based on these considerations, it is concluded that the levitation during a few hours could be available with the HTS coil.

4. Present Status of High Beta Plasma Study with Small Devices

A normal conductor device called Proto-RT has been constructed [12], equipping an internal coil with a major radius of 30 cm and the coil current of 10 kAturns. The electron injection through the separatrix has been carried out to examine the feasibility of the build-up of the radial electric field. Experimentally the radial potential of ~ 1 kV has been established, yielding a radial electric field of ~ 10 kV/m or more. The electron density is estimated to be of the order of 10^{14} m^{-3}, which is close to the Brillouin density limit of an electron plasma.

In the Proto-RT device the support structure of the internal coil and the current feeder are crossing the magnetic surface of the dipole field, which might be afraid of causing a loss of plasma. In addition, the magnetic field is relatively weak due to the limitation of the coil current. To overcome these problems, a small size device with a floating internal coil called Mini-RT is now under construction. The detail of the Mini-RT device is described in ref. [13].

The Mini-RT device is equipping a HTS floating coil (R=0.15 m). The Ag-sheathed Bi-2223 tape with a coil current of 117 A (50 kAturns in total) is employed. The magnetic field strength at the plasma confinement region is around 0.1 T, giving a plasma production and heating by 2.45 GHz ECH system. In order to drive a radial electric field, the loss of high energy electrons produced by the ECH might be a useful technique, in addition to the electron injection through the separatrix.

This is the first challenge to apply the HTS coil for a fusion plasma confinement device. Several engineering developments for the HTS coil are required. At first, the persistent current switch (PCS) with the HTS tape is requisite, because the HTS coil current is directly driven by the demountable electrode in the Mini-RT device. There are few experiences for the PCS with the HTS tape. Here the Ag-sheathed Bi-2223 with 0.3wt% Manganese is adopted, because this gives a sufficiently high resistance at the elevated temperature (0.27 Ω at the critical temperature). We have measured the characteristics of this PCS-HTS tape, and confirmed that this tape is satisfactory for the PCS [22].

Next, the levitation of the HTS coil itself is very challenging. A small HTS coil (4 cm radius, 2.6 kAturns) has been fabricated and the levitation experiment has been carried out. The HTS coil is immersed with liquid nitrogen, and the coil current is kept during the evaporation of the liquid nitrogen. The levitation coil is located at the upper region of the floating coil. In this situation, the floating coil is unstable for the vertical motion. The coil position is detected by the laser sensor, and the levitation coil current is controlled with PID feedback system. It has been demonstrated that the HTS coil has successfully floating during a few minutes with a positioning accuracy of ~ 30 μm [23].

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