Study of the Ultra Low Aspect Ratio Tokamak, ULART

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ABSTRACT

We investigate experimentally and theoretically the global MHD characteristics of an ultra-low aspect ratio tokamak (ULART). Since the ULART requires a substantially smaller toroidal field current, I_{tf}, than conventional tokamaks, it has important reactor advantages. By fully utilizing the TS-3 merging spheromak facility with a slender center conductor, we have carried out an experimental study of the ultra-low aspect ratio tokamak with aspect ratio reaching as low as 1.05. The ULART is found to be similar to the spheromak in its strong paramagnetism and magnetic helical pitch. In this extreme limit, we investigate the transition of the spheromak ($q_a = 0$, $I_{tf} = 0$) to a ULART plasma ($q_a = 5$-20, $I_{tf} < I_p$). It is observed that a small current at the center conductor can significantly improve the overall stability of the formed plasmas by effectively stabilizing the tilt mode. We identify a threshold of $I_{tf} << I_p$ with $q_{cyl}(a) << 1$ for global tilt/shift modes. This initial observation is in agreement with a global MHD theory.

1. Introduction

Low-aspect-ratio tokamak(LART) configurations offer possibilities for a cost-effective, high-performance plasma regime which could lead to compact volumetric neutron sources as well as high beta advanced fuel reactors[1]. They can confine high beta plasmas with large natural elongation in the first stability regime. The recent results from START have shown that their confinement properties are as good as conventional aspect ratio tokamaks[2]. To extend the parameter range of the low-aspect-ratio tokamak regime, a new class of 1 MA level devices is being considered(e.g., NSTX [3]). Among various low-aspect-ratio tokamak (LART) regimes, it is important to explore the ultra low aspect ratio tokamak regime(ULART) with aspect ratio($A= R/a$) less than 1.5, since this may afford the highest advantages for MHD stability and for compact reactor design.

The ULART configuration with $A \leq 1.5$, is similar to the spheromak[4,5] in its strong paramagnetism and magnetic helical pitch. As the aspect ratio and plasma configuration approach this extreme limit, the features of the magnetic well (average minimum B), the shear, and their effects on the plasma's MHD stability should deviate from those of standard tokamaks and the MHD characteristics are expected to change drastically. Since ULART requires a substantially smaller toroidal field current ($I_{tf} << I_p$) than conventional tokamaks ($I_{tf} >> I_p$), it has significant reactor advantages over regular tokamaks. In this paper, we study the global MHD stability characteristics of ULART by comparing theoretical results with the experimental data obtained in the Tokyo University TS-3 device.

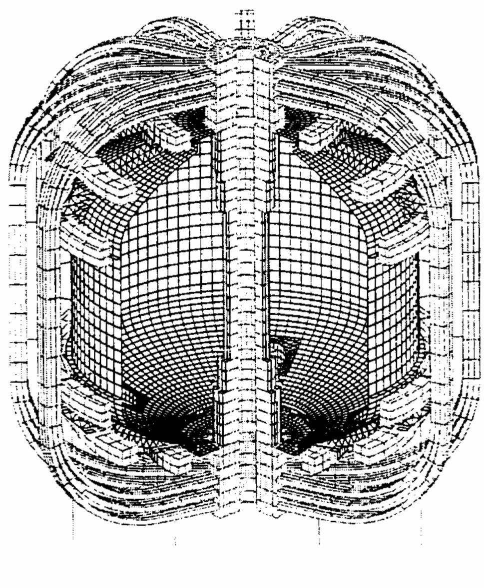


Fig.1 Schematics of NSTX design[3]

2. Background of the present research

The present research has its origins in colliding spheromak experiments, in which local and global MHD physics issues for magnetic reconnection have been extensively investigated in 3-D geometry[6,7]. In these experiments, the three-dimensional features of magnetic reconnection were found to be quite different from conventional two-dimensional features depending on whether the plasma toroids have co-helicity or counter-helicity magnetic fields. Evidence of driven reconnection has been observed and a quantitative dependence of reconnection rate on external force documented. A new plasma acceleration mechanism accompanied by significant ion heating has been indicated during the 3D reconnection process. The results have proved that a double spheromak geometry is well-suited configuration for basic studies of magnetic reconnection. More comprehensive studies of local and global characteristics on the TS-3 device[7] at the Univ. of Tokyo and MRX device[6] at PPPL will give a full picture of magnetic reconnection in three dimensions.

Recently it has been recognized that the experimental apparatus for the merging spheromak experiments is well suited for an experimental study of ULART. A slender center conductor has been inserted into the TS-3 device to create the ULART configuration. In this paper, we report the most recent investigations in this important area; investigating both experimentally and theoretically MHD characteristics of the ULART regime (A ≈ 1.05 - 1.6), which have not been intensively studied before.

3. Study of the MHD Equilibrium of ULART

MHD equilibrium calculations show that the ULART plasmas with edge safety factor of q(a) > 3 (q is the inverse of the rotational transform of field lines) are characterized by high maximum toroidal beta, low poloidal beta, high natural elongation, strong paramagnetism, and a large ratio of plasma current to toroidal-field-coil current. Figure 2 presents poloidal flux contours and poloidal magnetic field profiles of a q(a)=3 tokamak for 3 different aspect ratios of A=1.05, 1.5 and 2.0.

The paramagnetism is seen to increase as A decreases. In the low aspect ratio limit, the field line pitch resembles that of a spheromak in the outer radial edge of toroidal plasma, but it has a large toroidal field component in the inner radial edge, just like in a tokamak. The global stability of the ULART is determined by the magnetic well depth(not always present) and the shear of the configuration. One of the most important global modes is m=1/n=1 tilt/shift mode.

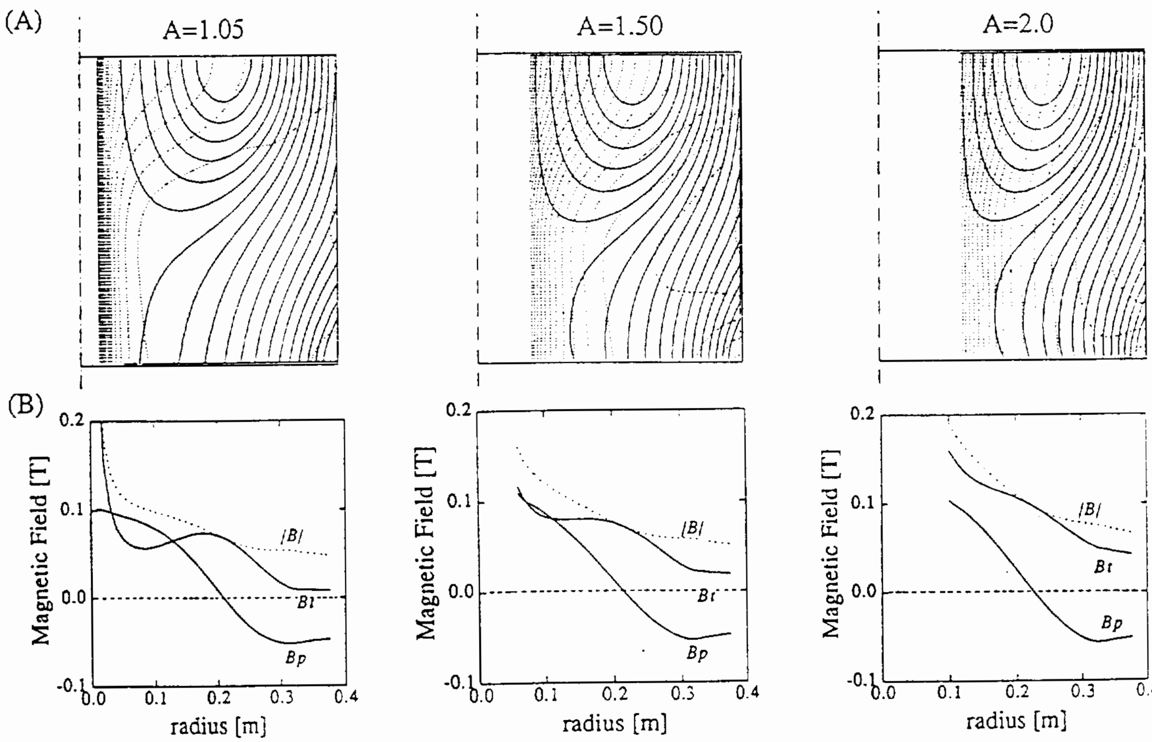


Fig. 2. MHD equilibria of low aspect ratio tokamaks for 3 different aspect ratio A=1.05, 1.5, 2.0. (a) poloidal flux plots and (b) radial magnetic field profiles of toroidal and poloidal field B_t and B_p and B_{norm} for q(a) = 3.

Since the ULART requires a very small toroidal field coil current to generate the necessary toroidal field for tokamak confinement configuration, it has important reactor advantages over regular tokamaks. We have calculated the required toroidal field coil current for typical ULART configurations using (1) analytical approximate calculation and (2) computer equilibrium code calculation based on the Grad-Shafranov equation. Our analytical calculation is based on a simplified model in which q is predominantly determined by the field line pitch in the inner edge of ULART [8];

$$B_t = \mu_o I_{tf} / 2\pi R_{tf}, \qquad (1a)$$

$$B_p \approx \mu_o I_p / 2 L_p, \qquad (1b)$$

$$q(a) \approx (B_t L_p) / (B_p 2\pi R_{tf}), \qquad (1c)$$

where L_p and R_{tf} are vertical length of the plasma and major radius of the inner leg of the toroidal field coil. By combining equations (1a), (1b), and (1c), we obtain

$$I_{tf} / I_p \approx 2\, q(a)\, (\pi R_{tf} / L_p)^2. \qquad (2)$$

With a relationship between aspect ratio A and the plasma's major radius $R_p(= a + R_{tf})$ and minor radii, a; $A = 1 + R_{tf} / a$, we obtain an analytical approximation for the toroidal coil current, as

$$I_{tf} / I_p = 2\, q(a)\, (\pi a / L_p)^2\, (A - 1)^2. \qquad (3)$$

Fig. 3. Required toroidal coil current (I_{tf} / I_p) versus aspect ratio A for ULART equilibrium with q(a) = 3 and for κ= 1.67 and κ=4.17.

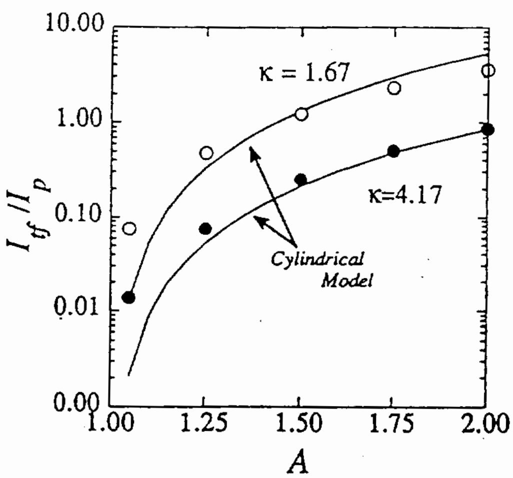
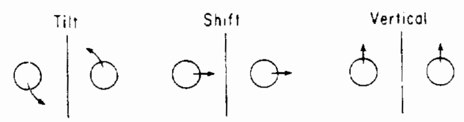


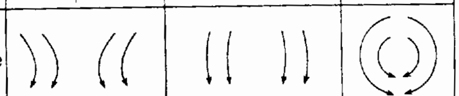
Fig. 3 presents ratios of (total) toroidal field coil current (I_{tf}; Ampere-turns) to plasma current (I_p) versus aspect ratio ranging from 1.05 - 2.0 for q(a)=3 and κ=L_p /2a = 1.67 and 4.17. The curves shown in Fig. 2 are from Eq.(3) and agree well with more exact calculation based on the Grad-Shafranov equation. One notices that ULART requires substantially smaller toroidal field current ($I_{tf} \ll I_p$) than conventional tokamaks ($I_{tf} \gg I_p$), and that the ratio (I_{tf} / I_p) can be as small as 0.1 for an ultra low aspect ratio tokamak with A=1.1 and q(a)=3.

4. Experimental study of global stability of ULART

A spheromak configuration which confines low-aspect-ratio toroidal plasma without requiring a linked toroidal coil structure can offer many reactor advantages. But a serious drawback of the spheromak configuration is its susceptibility to global MHD instabilities with low mode numbers in the absence of near-by conductors. It has been known that the spheromak's tilt mode can be stabilized either by passive stabilizers and/or figure 8 coils[9]. The shaping of the equlibrium field is also an important parameter for global MHD stability. The basic characteristics of the gross n=1 MHD modes with respect to the equilibrium field indices, $n^* = -(R/B_{EF})(\partial B_{EF}/\partial R)$, are summarized in Table 1, which does not include the effect of toroidal field. As shown in the table, at least one type of gross mode is unstable in any given field shape. Stabilizing conductors are thus required in speromaks[5.9]to prevent all of the n=1 gross modes.

Table 1. Stability characteristics of gross n=1 modes of toroidal plasma



Index	$n_i < 0$	$0 < n_i < 1$	$1 < n_i$
Field Shape			
Tilt	Unstable	Unstable	Stable
Shift	Stable	Unstable	Unstable
Vertical	Unstable	Stable	Stable

Insertion of a thin passive center conductor is ineffective in stabilizing the tilt/shift modes because the image currents generated are small. However, by driving a current through a thin central conductor, thereby generating an external toroidal field, the spheromak can be converted into a tilt/shift stable ULART . The question arises, then, of what amount of external toroidal field is necessary to stabilize the n=1 tilt mode in this new configuration.

By introducing a slender current-carrying condu¢tor assembly ($R_{tf} \geq 1$ cm) through the geometric center axis of the TS-3 device, we have generated ULART configurations with extremely low aspect ratio of 1.05-1.5. In this extreme limit we have investigated the transition of the spheromak (q(a) = 0, $I_{tf}=0$) to a ULART plasma (q(a) = 2-20). The plasma current is in the range of 25 kA-35 kA with variable toroidal field of 0-1 kG for R_p=18 cm, a$\leq$ 16 cm. The evolution of the current and magnetic profile [q(R), B(R), Ψ(R)] is monitored by an array of magnetic probes inserted into the plasma. Fig. 4 presents the basic geometry of the TS-3 device[10].

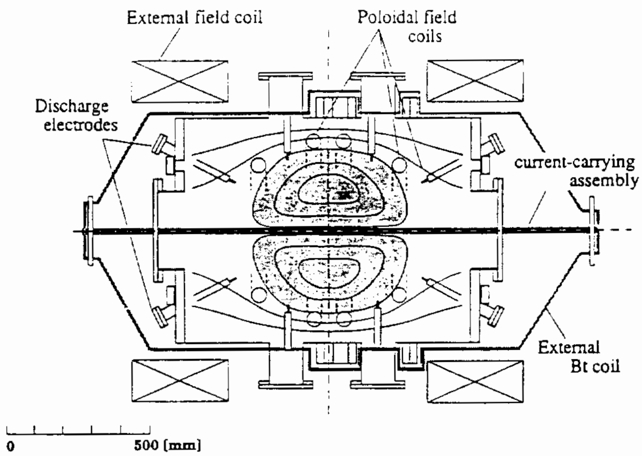


Fig. 4 TS-3 apparatus for ULART experiments.

A significant observation is the effectiveness of the central toroidal field current against tilt and kink modes. It is observed that a small axial current (I_{tf}<<I_p) in the center conductor can significantly improve the overall stability of the plasmas. An important question is at what I_{tf} the plasma becomes stable in suppressing the n=1 tilt/kink mode. Fig.5 depicts the growth rate of n=1 modes due to tilt/shift or kink modes versus toridal field coil currents at the center conductor for 3 dfferent aspect ratios.

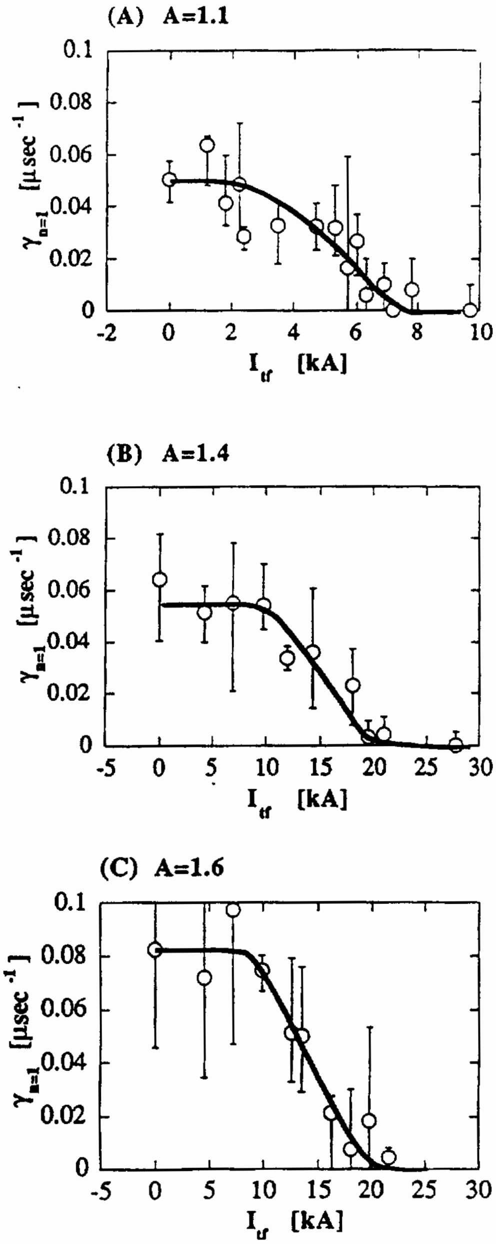


Fig.5 Growth rate of the n=1 toroidal mode vs. I_{tf} in the TS-3 ULART regime with A= 1.1, 1.4 and 1.6.

It is observed that the growth rate of n=1 mode decreases drastically as the toroidal field coil current is raised or q increases. The threshold value of I_{tf} for n=1 global stability decreases substantially from about 30 kA to 6.0 kA as A is reduced from 1.6 to 1.1. These threshold cases correspond to q = 2 - 3 at the plasma edge. A simple MHD theory predicts $\langle B_t \rangle \geq \langle B_p \rangle$ for external tilt stability in a large aspect ratio limit, which is easily satisfied in conventional tokamak configulations. If we apply the same criterion to the ULART, the threshold value for tilt mode stability would be $q_{cyl}(a) = a/R_p \sim 1$ (where $q_{cyl}(a)$ denotes cyclindrical q value) or $I_{tf} \geq I_p$. But our experiment has demonstrated that notably smaller I_{tf} is required for n=1 tilt/shift global stability. In Fig. 4 stable regime is shown by $I_{tf} \geq 0.2\ I_p$ for A=1.1. As the aspect ratio increases, the higher I_{tf} is required to stabilize n=1 modes, while I_p is kept around 35-30 kA.

4.Theoretical study of tilt intability in ULART

A stability criterion and growth rates for the external mode can be estimated by approximating the plasmaas a rigid low-aspect-ratio toroidal ring[5,11]. Assuming a tilt angle θ, with respect to the horizontal axis, the tilt moment due to the force on plasma from the equilibrum vertical field is

$$M_1 = 2I_pB_z \sin\theta \int_{-\pi/2}^{\pi/2} \cos\varphi \cdot R_p^2 \cos\varphi d\varphi$$

$$= \pi R_p^2 I_p B_z \theta \qquad (1),$$

where I_p, B_z, and R_p are the toroidal plasma current, vertical eqilibrium field, and the major radius of the plasma, respectively; φ is toroidal angle.

The radial magnetic field component also generates the tilt moment

$$M_2 = -2I_pB_RR_p^2 \int_{-\pi/2}^{\pi/2} \cos^2\varphi d\varphi$$

$$= -\pi I_p B_R R_p^2 . \qquad (2)$$

With $B_z = \frac{\mu_o I_p}{4\pi R_p} C_L$ and $B_R = n^* \cdot \theta \cdot B_z$, we can calculate the tilit moment from the equilibrium field

$$M_p = \frac{\mu_o I_p^2}{4}\left(1-n^*\right)\theta \cdot R_p \cdot C_L \qquad (3)$$

Where C_L represent a coefficient (~ 1) for calculation of self-inductance for plasma current in the rectangular cross-section plasma[13], and n* denotes the field index at the magnetic axis defined by $n^* = -(R/B_z)(\partial B_z/\partial R)$.

$$C_L \Rightarrow \ln\frac{8R}{a} + \Lambda - \frac{3}{2} \text{ for large aspect limit.}$$

The stabilizing tilt moment from the toroidal field is made on the basis of force on the inner surface of the low aspect-ratio toroidal plasma[11].

The stabilizing moment by I_{tf} is written by

$$M_t' = \frac{-b^3}{2} \cdot \frac{\mu_o I_{TF}^2}{4\pi R_{TF}^2}\theta \qquad (5)$$

From (3) and (5), the total tilt moment is derived as

$$M_{Tilt} = \frac{\mu_o I_p^2}{4}\theta R_p \left[\left(1-n^*\right)C_L - \frac{1}{2\pi}\left(\frac{I_{tf}}{I_p}\right)^2\left(\frac{b}{R_{TF}}\right)^2\left(\frac{b}{R_o}\right)\right] \qquad (6)$$

Thus, stability condition is

$$\frac{I_{TF}}{I_p} \geq \left[2\pi\left(1-n^*\right)C_L\frac{R_p}{b}\right]^{1/2} \cdot \left(\frac{R_{tf}}{b}\right)$$

$$= \left[2\pi\left(1-n^*\right)C_L A\right]^{1/2} \cdot \frac{A-1}{\kappa^{3/2}}, \qquad (7)$$

where A and κ are the aspect ratio and the elongation factor(=b/a), respectively.

If we write $X = \left(\frac{I_{TF}}{I_p}\right)$, the threshold of toroidal field current for tilt stability can be expressed by

$$X_{th} = \left(2\pi C_L A\right)^{1/2}(A-1)/\kappa\sqrt{\kappa} \qquad (7a)$$

The growth rate of the tilt mode can be also straightfowardly derived using the present approximation[11] and the results will be reported elsewhere in the near future.

5. COMPARISON OF THEORY WITH EXPERIMENTAL DATA

To compare our theoretical values for required toroidal coil current for stabilizing n=1 tilt modes with the experimental data from TS-3, normalized threshold currents are plotted with respect to aspect ratio A in Fig.6. The excellent agreement between the data and the rigid conductor model suggests that the ULART is sturdy configuration against global MHD instabilities.

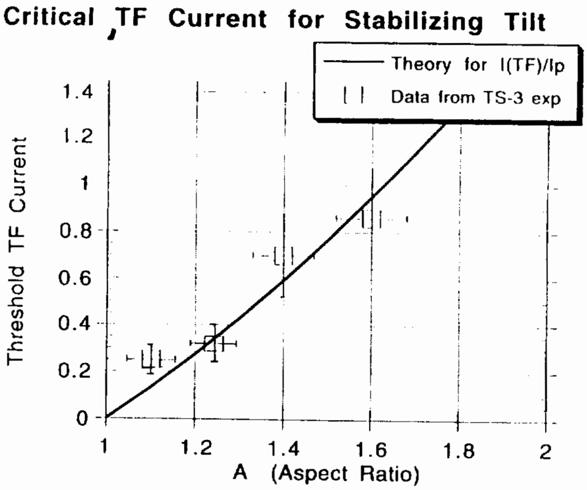


Fig.6 Threshold toroidal field current for stabilizing n=1 tilt/shift modes: Comparison of theory and experiments.

The present result from the ULART experiment on TS-3 is also consistent with the CDX result in which a significant enhancement of m=1-2/n=1 internal MHD modes is observed as the q(a) is decreased[12]. We expect a coupling of low-n internal modes with external modes. A further extensive investigation with aid of MHD numerical stability codes will clarify this important issue and reveal many more unique MHD characteristics of the ULART configuration.

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Note;

A part of results in this paper will be presented in the Ph. D thesis by A. Morita.

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