Axisymmetric Tri-Magnetic-Islands Equilibrium of Strongly-Reversed-Shear Tokamak Plasma: An Idea for the Current Hole

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(Received 5 November 2002 / Accepted 18 November 2002)

The idea of a new equilibrium of a strongly-reversed-shear tokamak plasma with a current hole is proposed. This equilibrium configuration called “Axisymmetric Tri-Magnetic-Islands (ATMI) equilibrium” has three islands along the R direction (a central-negative-current island and two side-positive-current islands) and two x-points along the Z direction. The equilibrium is stable with the elongation coils when the current in the ATMI region is limited to be small.

Keywords: axisymmetric equilibrium, tri-magnetic-islands, reversed shear, current hole, tokamak

The aim of this report was to propose the idea of a new equilibrium of a strongly-reversed-shear (str-RS) tokamak plasma with a so-called “current hole”. Because this plasma has a very high confinement performance and is one of the candidates for advanced-tokamak-fusion-reactor core plasma, its physical properties have to be clarified. A current hole at the central core region, in which the current density \( j \) becomes very small compared with the averaged current density, was found experimentally in JT-60U [1,2] and JET [3,4]. The central \( j \) decreases with the reduced toroidal electric field \( E_t \), which decrease results from the increase of the off-axis non-inductive current, such as the bootstrap current and externally driven current. Though \( E_t \) can become largely negative, the central \( j \) hardly becomes negative because of the MHD equilibrium limit; the magnitude of poloidal-field asymmetry \( \varepsilon \Lambda = \varepsilon (\beta_p - 1 + l/2) \) increases beyond unity near the \( B_p = 0 \) surface (\( \varepsilon \): inverse aspect ratio, \( \Lambda \): poloidal-field asymmetry coefficient, \( \beta_p \): poloidal beta value, \( l \): internal inductance, \( B_p \): poloidal magnetic field) [5]. Analysis of the stored energy inside the internal transport barrier (ITB) of str-RS plasmas showed that the core region of these plasmas is really governed by the MHD equilibrium limit condition (i.e., \( \varepsilon \beta_p^\text{core} \sim 1 \)) [6]. In addition to this limit, the negative \( j \) plasma column is directly pulled outside the torus by the vertical magnetic field \( B_v \), while the positive \( j \) column is balanced by the hoop force and the \( j \times B_t \) force. Even in a cylindrical system, a plasma with a negative central \( j \) is not stable. An axisymmetric low-m resistive MHD mode is unstable at a \( q = \infty (B_p = 0) \) magnetic surface [7]. For the \( m = 1 \) case, the mode behaves like an \( m=1/n=1 \) sawtooth at a \( q = 1 \) surface in a normal shear plasma (\( m \): poloidal mode number, \( n \): toroidal mode number, \( q \): safety factor). In any case, there is no known stable axisymmetric equilibrium of a tokamak plasma with a single magnetic axis and a central negative \( j \).

The major cause of the loss of equilibrium for a single-magnetic-axis and central-negative-\( j \) plasma is the existence of a \( B_p = 0 \) magnetic surface. Once the multi-magnetic axes and magnetic-island structure are taken into account, a new type of axisymmetric equilibrium with a central-negative-\( j \) region can be formed. The \( B_p = 0 \) surface is condensed to the x-points in this equilibrium. When the force balance in a toroidal system is considered, a group of three magnetic islands with three magnetic axes and two x-points seems stable. We call this new equilibrium configuration “Axisymmetric Tri-Magnetic-Islands (ATMI) equilibrium”. As is shown in Fig. 1, the central island has a negative \( j \) and the two of the islands, one on either side, have positive \( j \). These
Axisymmetric Tri-Magnetic-Islands Equilibrium

islands stand in the R direction (R arrangement: R-ar), and the two x-points stand in the Z direction. The outward $j \times B$ force on the central-negative-$j$ island is canceled by the repulsion force between the positive-$j$ island at the outer side. On the other hand, when the three islands stand along $Z$ (Z arrangement: Z-ar) and the two x-points along $R$, the central-negative-$j$ island is pulled outside the torus and this Z-ar configuration is broken.

Here, a possible scenario of the formation of ATMI equilibrium is presented. The tri-magnetic-islands configuration, which has mainly an $m=2|n|=0$ component, can be formed through the nonlinear magnetic-reconnection process of $m=1|n|=0$ MHD activity. The rotation from the unstable Z-ar to the stable R-ar is not simply explained by the MHD theory. In the central region with very small $B_p$, the large radial electric field $E$ induced by the large ion-orbit size can rotate the plasma from Z-ar to R-ar configuration. Once the central plasma is rotated to the stable R-ar, each of the three magnetic islands has a closed magnetic surface, and the electrostatic potential becomes uniform on each surface. The $E \times B$ drift rotation is now on the surface, and it does not change the magnetic configuration of the stable R-ar.

Next, the current relation and the current limit are estimated. The ratio of absolute current value in a side-positive-$j$ island $I_t$ to that in a central-negative-$j$ island $I_c$ is determined from the existence of x-points around the top and bottom of an ATMI configuration. Assuming concentrated current channels at magnetic axes for simplicity, we obtain the relation

$$2I_t/I_c \approx (1 + \kappa_1^2)/\kappa_1^2,$$

where $\kappa_1 = z_j/r_1$ is the ATMI effective ellipticity ($2z_j$: distance between x-points, $r_1$: interval between magnetic axes). The ellipticity can take a value $1 < \kappa_1 < 2$, and the ratio is bounded as $2 > 2I_t/I_c > 1.25$. Although a negative-current channel is apt to be pushed away vertically by the repulsion force from side-positive-current channels, the horizontal magnetic field from the elongation coils (or divertor coils) with the coil current $I_\ell$ at $Z = \pm Z_c$ can stabilize the vertical movement of a central-negative-$j$ island. The destabilizing repulsion force is $F_\delta \sim 2I_\ell \delta/r_1^2$ for a small displacement $\delta$, and the stabilizing force by the elongation coils is $F_\kappa \sim 2I_\ell \kappa Z_c^2$. The stability, $F_\delta > F_\kappa$, is maintained only for a low current in the ATMI region: $I_c < I_t(r_t/Z_c)^2$ or the total current $I_{\text{ATMI}} \geq 2I_\ell - I_c(r_t/Z_c)^2$ where $\kappa_1$ is replaced with $(1 + \kappa_1^2)/2$. The effective safety factor at the surface of the ATMI configuration $q_{\text{ATMI}} = 2\pi \kappa r_t^2 B/\mu \rho R_{\text{ATMI}}$ is very large in the stable condition

$$q_{\text{ATMI}}/q_a > \kappa_1^2 Z_c^2/a_p(Z_c - Z_a),$$

where $q_a = 2\pi \kappa a_p B/\mu \rho a_p$ is an engineering safety factor at the surface of a whole plasma with a minor radius $a_p$. The position of an x-point (or x-points) $|Z| = Z_c$ is determined as $I_t/I_p = (Z_c - Z_a)/Z_c$. Owing to the above current relation, eq. (1), and the current limit, eq. (2), the central current is hardly driven in either a negative or a positive direction, as shown in JT-60U electron-cyclotron-current-drive experiments [1,2]. For a typical JT-60U str-RS plasma ($q_a = 4$, $Z_c = 2$ m, $a_p = 0.8$ m, and $Z_c - Z_a = 0.5$ m) the value of $q_{\text{ATMI}}$ exceeds 40, which is consistent with the experimental results.

If the ATMI configuration really exists, the non-flat structures of plasma density, temperature, and rotation can be observed in the central current hole region. The profile can sometimes be wavy along $R$ due to the three magnetic islands [8]. It is expected that the ATMI equilibrium configuration will be confirmed by the experiments.

I am indebted to Dr. T. Fujita for discussion on the experimental results of JT-60U RS plasmas. I would like to thank Dr. S.V. Neudatchin for suggesting the existence of a hump in the electron temperature profile near the ITB shoulder in JT-60U [8]. I also acknowledge Dr. V. Shafranov for discussion on the possibility of ATMI equilibrium.


