

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

TAKIZUKA Tomonori

Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Ibaraki 311-0193, Japan

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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 $\varepsilon \Lambda = \varepsilon (\beta_p - 1 + l_i/2)$ increases beyond unity near the $B_p = 0$ surface (ε : inverse aspect ratio, Λ : poloidal-field asymmetry coefficient, β_p : poloidal beta value, l_i : 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., $\varepsilon \beta_{p,core} \sim 1$) [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 $j \times B_v$ 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

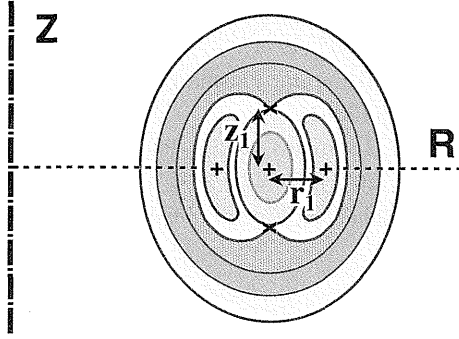


Fig. 1 ATMI equilibrium. Red regions have positive j , while blue region has negative j . Three magnetic axes are located along R with interval r_1 and two x-points along Z at $Z = \pm z_1$. Surrounding deep-red region has large bootstrap current.

islands stand in the R direction (R arrangement: R -ar), and the two x-points stand in the Z direction. The outward $j \times B_v$ 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_+ to that in a central-negative- j island I_- 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

$$2I_+/I_- \approx (1 + \kappa_1^2)/\kappa_1^2, \quad (1)$$

where $\kappa_1 = z_1/r_1$ is the ATMI effective ellipticity ($2z_1$: 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 $2 > 2I_+/I_- > 1.25$. 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_c at $Z = \pm Z_c$ can stabilize the vertical movement of a central-negative- j island. The destabilizing repulsion force is $F_d \sim 2I_+I_- \delta_z / r_1^2$ for a small displacement δ_z , and the stabilizing force by the elongation coils is $F_s \sim 2I_c I_- \delta_z / Z_c^2$. The stability, $F_s > F_d$, is maintained only for a low current in the ATMI region; $I_+ < I_c(r_1/Z_c)^2$ or the total current $I_{\text{ATMI}} = 2I_+ - I_- < I_c(r_1^2/\kappa_1 Z_c^2)$ where κ_1 is replaced with $(1 + \kappa_1^2)/2$. The effective safety factor at the surface of the ATMI configuration $q_{\text{ATMI}} \approx 2\pi\kappa_1 r_1^2 B_t / \mu_0 R I_{\text{ATMI}}$ is very large in the stable condition

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

where $q_a \approx 2\pi\kappa a_p^2 B_t / \mu_0 R I_p$ 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) $|Z| = Z_x$ is determined as $I_c/I_p = (Z_c - Z_x)/Z_x$. 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 $Z_c - Z_x = 0.5$ m) the value of q_{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.

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