21PA-038

Two-fluid Flowing Equilibrium of Spherical Torus with Density Gradient Caused by Multi-pulsing Coaxial Helicity Injection

マルチ・パルス同軸ヘリシティ入射によって引き起こされる密度勾配を有する球状トーラスの流れのある2磁気流体平衡

Takashi Kanki[1)] and Masayoshi Nagata[2)]

神吉隆司[1)], 永田正義[2)]

[1)] *Japan Coast Guard Academy 5-1 Wakaba, 5-1 Kure, Hiroshima 737-8512, Japan*

[1)] 海上保安大学校 〒737-8512 広島県呉市若葉町5-1

[2)] *Graduate School of Engineering, University of Hyogo 2167 Shosha, Himeji, Hyogo 671-2280, Japan*

[2)] 兵庫県立大学大学院工学研究科 〒671-2280 兵庫県姫路市書写2167

Two-fluid flowing equilibrium of spherical torus with density gradient caused by multi-pulsing coaxial helicity injection has been numerically determined using the nearby-fluids procedure. The numerical results show that the toroidal magnetic field becomes from a diamagnetic to a paramagnetic profile in the closed flux region due to the increase of the poloidal ion flow velocity in the direction of the current between the open flux column and closed flux regions as the negative density gradient steepens there. The increase of the poloidal ion flow velocity is due to the fact that the ion diamagnetic drift velocity is changed in the same direction as the $\boldsymbol{E}\times\boldsymbol{B}$ drift velocity through the negative ion pressure gradient.

1. Introduction

Solenoid-free non-inductive current start-up and steady-state current drive techniques in the spherical torus (ST) have been studied using the coaxial helicity injection (CHI). Recently, a new approach of the CHI operated in multi-pulsing CHI (M-CHI) has been proposed [1]. The M-CHI scenario is that after the plasma current partially decays, a new CHI pulse is applied and the cycle process is repeated to achieve simultaneously a quasi-steady sustainment and good confinement. To examine the dynamo current drive of ST by the M-CHI, we started the double-pulsing operations in the HIST device, observing that the steep density gradient between the open flux column (OFC) and closed flux regions causes not only the $\boldsymbol{E}\times\boldsymbol{B}$ drift but also the ion diamagnetic drift to exhibit the two-fluid effect and Hall dynamo [2]. The purpose of this study is to investigate the effect of the steep density gradient on the two-fluid equilibrium configurations.

2. Numerical Model

Firstly, let us assume axisymmetry about HIST geometric axis in cylindrical coordinates (r, θ, z). Using the dimensionless variables, an axisymmetric two-fluid flowing equilibrium can be described by a pair of extended Grad-Shafranov equations for the ion surface variable $Y \equiv \psi + \varepsilon r u_\theta$ and the electron surface variable ψ [3]

$$\bar{\psi}_i' r^2 \nabla\cdot\left(\frac{\bar{\psi}_i'}{n}\frac{\nabla Y}{r^2}\right) = \frac{r}{\varepsilon}\left(B_\theta \bar{\psi}_i' - n u_\theta\right) + n r^2\left(H_i' - T_i S_i'\right), \quad (1)$$

$$r^2\nabla\cdot\left(\frac{\nabla\psi}{r^2}\right) = \frac{r}{\varepsilon}\left(B_\theta \bar{\psi}_e' - n u_\theta\right) - n r^2\left(H_e' - T_e S_e'\right), \quad (2)$$

and an extended Bernoulli equations for the number density n,

$$\frac{\gamma}{\gamma-1} n^{\gamma-1}\exp[(\gamma-1)S_i] + \frac{u^2}{2} + \phi_E = H_i, \quad (3)$$

$$\frac{\gamma}{\gamma-1} n^{\gamma-1}\exp[(\gamma-1)S_e] - \phi_E = H_e. \quad (4)$$

Here $\boldsymbol{u}$, $\boldsymbol{B}$, T_α, ϕ_E, and γ are the ion flow velocity, magnetic field, temperature of species (α=i, e), electrostatic potential, and adiabatic constant, respectively. The two-fluid parameter ε is defined by the ratio of the ion skin depth $\ell_i = \sqrt{m_i/(\mu_0 n e^2)}$ (m_i and e are ion mass and electron charge, respectively.) to the system length scale R (the effective radius of the flux conserver (FC) used in the HIST, R=0.45 m), and ε=0.0716 is given by using $\ell_i = 3.2\ \mathrm{cm}$ through $n = 5.0\times10^{19}\ \mathrm{m}^{-3}$ observed in the HIST experiment. The value of γ is assumed as 5/3 in the calculation. Note that ψ corresponds to the familiar poloidal flux function. The poloidal flow stream function $\bar{\psi}_\alpha$, total enthalpy function H_α, and entropy function S_α are arbitrary surface functions of their respective surface variables. The three arbitrary functions $\Lambda_\alpha (\equiv \bar{\psi}_\alpha')$, H_α, and S_α for each species must be assumed so as to reflect the experimental results. Equations (1) and (2) have terms of order $1/\varepsilon$ on the right-hand side, and they cause singularities. We employ the nearby-fluids procedure to eliminate the singularities [3].

Next, we consider the boundary conditions for Eqs. (1)-(4). No magnetic flux penetrates the FC, central conductor, and entrance port of the FC. Therefore, ψ is fixed at 0 at the FC wall and surface of the central conductor and entrance port. The bias flux is given by assigning fixed values of ψ to grid points corresponding to the right open end. These values are calculated using a quadratic function of r. The vacuum toroidal field $B_{t,v}$ is produced by a toroidal field coil current I_{tf} along the geometric axis inside the central conductor. Under the above assumptions and boundary conditions, the equilibrium is numerically determined by using a successive over-relaxation method for updating ψ and a Newton-Raphson method for updating n [4].

3. Numerical Results

We steepen the density gradient around the separatrix by decreasing n in the closed flux region as shown in Fig. 1. This behavior of density is caused when the CHI pulse is applied again during the partial decay of plasma current. The toroidal magnetic field then becomes from a diamagnetic to a paramagnetic profile in the closed flux region as shown in Fig. 2. The poloidal ion flow velocity is increased in the direction of the current between the OFC and closed flux regions as shown in Fig. 3, because the ion diamagnetic drift velocity is changed in the same direction as the $\boldsymbol{E}\times\boldsymbol{B}$ drift velocity through the negative ion pressure gradient as shown in Fig. 5. The poliodal flow shear is enhanced in the closed flux region. The ion diamagnetic drift velocity is comparable to the $\boldsymbol{E}\times\boldsymbol{B}$ drift velocity, but the ion inertial drift velocity is small. The toroidal ion flow velocity is increased from negative to positive values in the closed flux region as shown in Fig. 4, enhancing the paramagnetic poloidal field. Here, the negative ion flow velocity is the opposite direction to the current. Both the poloidal and toroidal magnetic fields tend to become from diamagnetic to paramagnetic profiles, because both the poloidal and toroidal ion flow velocities tend to contribute the plasma currents. The effect of steep density gradient leads the increase of plasma currents and magnetic flux.

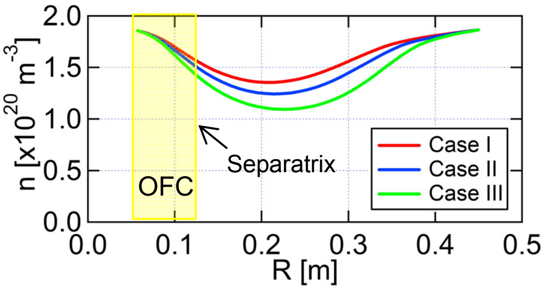

Fig.1. Radial profiles of the number density n at the midplane

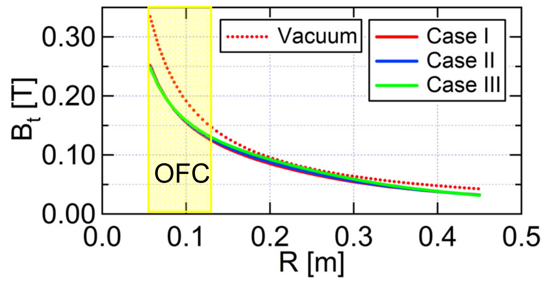

Fig.2. Radial profiles of the toroidal magnetic field B_t at the midplane

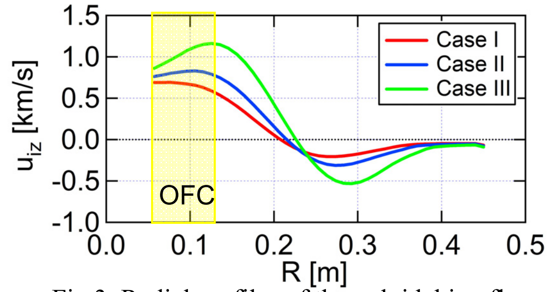

Fig.3. Radial profiles of the poloidal ion flow velocity u_{iz} at the midplane

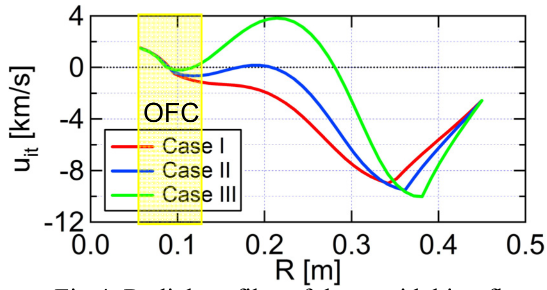

Fig.4. Radial profiles of the toroidal ion flow velocity u_{it} at the midplane

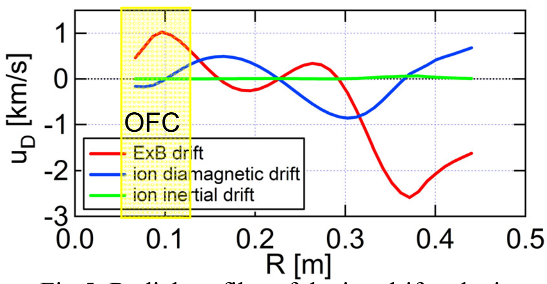

Fig.5. Radial profiles of the ion drift velocity u_D in the poloidal direction at the midplane in the case III

References

[1] E.B. Hooper: Plasma Phys. Control. Fusion **53** (2011) 085008.

[2] M. Nagata *et al.*: *Proc. 24th IAEA Fusion Energy Conf.*, *2012*, *San Diego*, ICC/1-1Rb.

[3] L.C. Steinhauer and A. Ishida: Phys. Plasmas **13** (2006) 052513.

[4] T. Kanki *et al.*: Plasma and Fusion Res. **3** (2008) S1066.