§20. Simulation of Field-reversed Configuration Plasma with Extended Fluid Model

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Field-reversed configurations (FRCs) have open field region, which works as a natural diverter. A high-beta plasma is confined inside the separatrix that is the boundary between open and closed field region. Although the field-null x-points are present on the separatrix and geometric axis, even electrons can be trapped unless their guiding center coincides with the geometric axis. To obtain an equilibrium state of the FRC plasma, we often employ the solution to the Grad-Shafranov (G-S) equation. Because the pressure is the only function of the poloidal flux, a G-S equilibrium pressure is constant along the field line even in the open-field region. However, the edge plasma suffers from anisotropic transport processes, such as end-losses and/or adiabaticity breaking processes near the x-points [1]. Consequently, the spatial pressure profile may deviate from the G-S equilibrium state especially in the open-field region. In the present paper, we will check if the G-S equilibrium state survives for a longer duration than the Alfvén time by the hybrid (ion particle and electron fluid) simulation [2].

In our calculations, we model our FRC plasma on the NUCTE (Nihon University Compact Torus Experiment) - III device [3]. The external magnetic field is 0.4 T, and the radius and half-length of calculation region are 0.17 m and 1 m, respectively. The ion and electron temperatures are 100 eV and 50 eV, and the field-null density is $2.7\times10^{21}\,\mathrm{m}^{-3}$. As a result, the Alfvén speed for deuterium ions estimated by the field null density and external field is about 120 km/s, and its radial propagation time is approximately 1.4 μs.

The equilibrium state, which is used as initial simulation condition, is obtained from the Grad-Shafranov equation. The pressure is a cubic function of the poloidal flux inside the separatrix, whereas the outside pressure is expressed by the exponential function[4]. Then the time evolution of FRC magnetic and electric field are obtained by calculating the hybrid model, where the ions in the FRC are treated as particles, while the electrons are treated as a fluid, assuming quasi-neutrality.

The electric field is calculated from the generalized Ohm's law,

$$\mathbf{E} = -\mathbf{u}_\mathrm{e}\times\mathbf{B} - \frac{1}{en_\mathrm{e}}\nabla p_\mathrm{e} + \frac{\mathbf{R}_\mathrm{ei}}{en_\mathrm{e}} \qquad (1)$$

where $\mathbf{u}_\mathrm{e}$, n_e, p_e, and $\mathbf{R}_\mathrm{ei}$ are respectively the flow velocity, density, and pressure of electrons, and the resistive force between the ion particles and electron fluid, which is obtained by calculating the equation of motion for magnetized plasmas. In each time step, after the ion's motion is calculated, the ion velocity is calculated by the PIC method. Then the electron velocity is given by the definition of current density, where the electron density is assumed to be equal to the ion density obtained from the PIC method to fulfill the quasi-neutrality. Finally, by integrating Faraday's law, we obtain the magnetic field needed for the next time step.

Deuterium ions as super-particles are initially distributed uniformly in *r-z* plane of the cylindrical coordinate system. The weight of particles is assigned by the initial density that is calculated from the pressure in the G-S equilibrium state and assumption of uniform temperature. We assume initial velocity distribution for ions is Maxwellian.

We present the two-dimensional pressure profile indicated by the color contour in Fig. 1. We found rapid decrease in the pressure of the open-field plasma. On the other hand, internal structure seems robust until 3.75 μs. This is because that the particle flow rate due to cross-field transport inside the separatrix is much slower than the end loss rate. Resultantly, the pressure profile at 3.75 μs in Fig. 1(b) deviates from the G-S equilibrium state.

This rapid transition process finishes by about 4 μs, because the exterior pressure decrease gradually slows down and other equilibrium state seems to be formed in the open field region. The open field equilibrium would be sustained by the particle balance between the supply from the closed region and the end-loss. On the other hand, the G-S equilibrium state persists for longer duration than typical Alfvén time (about 1.4 μs).

From our simulation results, we conclude that the Grad-Shafranov equilibrium state is not the best initial state to simulate FRCs. Therefore, we need to consider effects of end-loss ions to reproduce an equilibrium state of FRCs numerically.

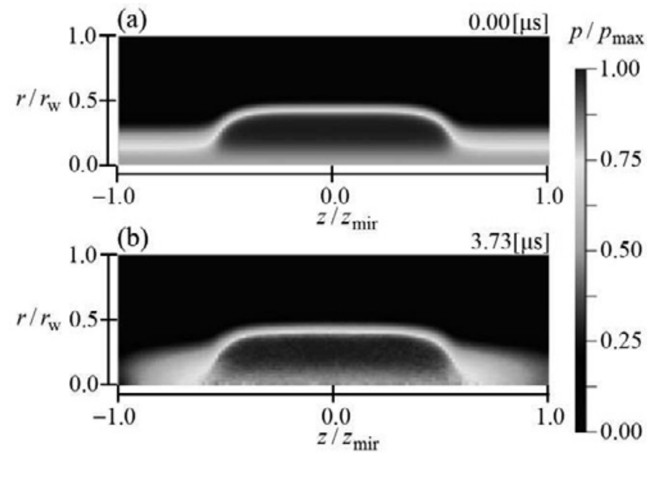

Fig. 1. Contour plots of the pressure normalized by its maximum value at (a) t=0, and (b) t=3.75 μs.

1)Takahashi, T. et al. : Phys. Plasmas **4** (1997) 4301.
2)Watanabe, T. et al. : Plasma Fusion Res. **7** (2012) 2405042.
3) Asai, T. et al. : Phys. Plasmas **13** (2006) 072508.
4) Takahashi, T. et al. : Phys. Plasmas **11** (2004) 3131.