§21. Numerical Study of Particle Transport in Field-reversed Configuration Plasma

Takahashi, T., Hashimoto, A. (Gunma Univ.),
Mizuguchi, N.

Field-reversed configuration (FRC) plasma is sustained by the poloidal field that is generated by the diamagnetic toroidal plasma current. As a result, it has a high-volume-averaged beta value of about 0.8, which is advantageous for designing nuclear fusion reactors[1].

The transport properties of FRCs, however, are still unclear[2, 3]. Several studies have reported the particle lifetime due to classical transport in FRCs. Clemente *et al.* calculated the radial particle flux employing the simplified Ohm's law[4, 5].

The aforementioned studies, however, neglect the kinetic nature of high-beta FRCs. The ion orbit patterns of FRCs can be of three types: betatron, figure-8, and small-gyroradius drift orbits[6]. In particular, the gyroradius of betatron particles are comparable to the field-null radius; they are quite kinetic in nature and cannot be described by a fluid model.

In the present report, we calculate the particle loss rate through the end of confinement region by using a particle-tracking method. Since ions are initially loaded inside the separatrix and over a wide range in a velocity space, we consider the particle effects of kinetic ions. In addition, as the transport process, we consider pitch angle scattering.

We use an equilibrium FRC state that satisfies the Grad–Shafranov equation for the particle-tracking calculation. The external magnetic field is maintained constant for the entire calculation; therefore, the plasma pressure is also constant. The ion temperature is two times as high as the electron temperature and is assumed to be uniform inside the separatrix.

Because of pitch angle scattering, plasma ions leave the separatrix and move to the open-field region. Eventually, they move through the mirror end, which is defined as the axial position $z = z_M$. The end-loss ions are counted, and the ratio increases with time.

Because the plasma pressure is constant for all the calculations, the classical diffusion coefficient is proportional to $T^{-1.5}$. The particle confinement time derived from classical physics, therefore, increases with temperature. However, the result of the calculation is considerably different from the classical prediction based on a fluid model; we attribute this difference to the high-beta nature of FRCs. When kinetic ions in betatron and figure-8 orbits are subject to pitch angle scattering, the step size of the diffusion process is comparable to the separatrix radius. To clearly show the effect of the finite Larmor radius (FLR) on particle transport, the conventional kinetic parameter s is introduced. The FLR parameter is

$$s = \int_R^{r_s} (r/\rho_i)\, dr / r_s \quad , \tag{1}$$

where ρ_i is the ion Larmor radius. For our approximation, $\rho_i = \sqrt{2m_i T_i}/(q_i B)$, where m_i and q_i are the mass and charge of plasma ions, respectively. In the neighborhood of the field-null, ρ_i increases with $1/B$. Since the gyroradius of betatron particles is limited to the field-null radius, our estimate of s is less than a statistically averaged value of s by probably a factor of 2 to 3. Suppose the number of plasma ions exponentially decreases with time, then we can estimate the particle decay time from the end-loss ratio. Its relation to the FLR parameter s is shown in Fig. 1. Although the temperature range in our present calculation is similar to typical experimental conditions, the entire range of the FLR parameter s is in the kinetic regime. The data shown in Fig. 1 are fit to

$$\tau_N \propto s^{4.74}. \tag{2}$$

The above scaling has a much stronger dependence on the plasma temperature ($\sim T^{-2.37}$) than the Bohm scaling ($\sim T^{-0.5}$). The classical transport rate, however, is much smaller than the Bohm rate; thus, the particle decay time is on the order of milliseconds. The discrepancy between our classical scaling and the empirical scaling[7] suggests the presence of more active fluctuations induced by FRC plasma instabilities. Exploratory research on inherent instabilities that cause proper radial transport scaling will be focused in the future study.

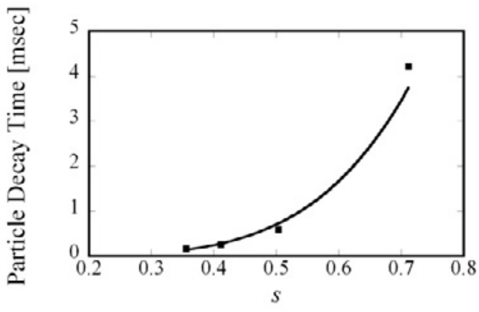

Fig. 1. Particle decay time versus the finite Larmor radius effect parameter s.

1) Momota, H. et al. : Fusion Technol. **21** (1992) 2307.
2) Tuszewski, M. : Nucl. Fusion **28** (1988) 2033.
3) Steinhauer, L. C. : Phys. Plasmas **18** (2011) 070501.
4) Clemente, R. A. and Grillo, C. E.: Phys. Fluids **27** (1984) 658.
5) Clemente, R. A. and Freire, E. M.: Plasma Phys. Control. Fusion **28** (1986) 951.
6) Finn, J. M. and Sudan, R. N.: Nucl. Fusion **22** (1982)1443.
7) Hoffman, A. L. and Slough, J. T.: Nucl. Fusion **33** (1993) 27.