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Three-Dimensional Dynamics of an Accelerated Compact Toroid in a Cylindrical Conductor

SUZUKI Yoshio, WATANABE Tomohiko, SATO Tetsuya and HAYASHI Takaya
National Institute for Fusion Science, Toki 509-5292, Japan

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Abstract

A compact toroid (CT) plasmoid injection is considered to be one of the most promising schemes for central fueling of a fusion device. However, there is the possibility that the device magnetic field leaking to the gun region (the leakage magnetic field) prevents the CT from entering the fusion device. By using magnetohydrodynamic (MHD) numerical simulations, we investigate three-dimensional dynamics of an accelerated CT in a cylindrical conductor and examine the effect of the leakage magnetic field on the CT penetration.

Keywords:

compact toroid (CT), fueling, MHD simulation

1. Introduction

A compact toroid (CT) plasmoid injection is considered to be one of the most promising methods for central fueling of a fusion device, because the injection speed of fuel by this scheme is much faster than that by any other schemes (up to 2000km/s). So far, the CT injection method has been discussed in several experiments [1-5] and theoretical models [6-8]. However, the dynamics of the injected CT has not been well examined. Also, the dynamics of the CT in the coaxial gun has not been well understood. Especially for a reactor grade device, there is the possibility that the device magnetic field leaking to the gun region (the leakage magnetic field) may prevent the CT from entering the fusion device. By using magnetohydrodynamic (MHD) numerical simulations, we investigate three-dimensional dynamics of an accelerated CT in a cylindrical conductor and examine the effect of the leakage magnetic field on the CT penetration.

2. Simulation Model

The simulation model is similar to that in our previous papers [9,10]. Because we examine the CT dynamics in a coaxial gun, the simulation region is given by a cylindrical coaxial conductor (Fig. 1). The radius and the length of this cylinder are respectively L_r and L_z. The relative lengths of the sizes are given by $L_r : L_z = 1 : 32$. The radius of the inner electrode is $L_r^{\rm in}$. We employ a perfectly conducting wall for the boundary condition. The governing equations are given by MHD

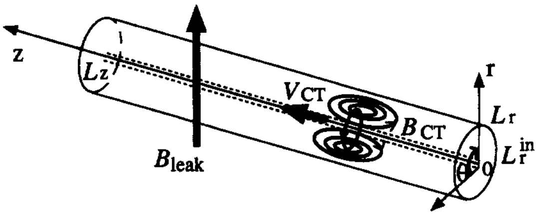

Fig. 1 The schematic diagram of the simulation region.

Corresponding author's e-mail: suzukiy@fusion.naka.jaeri.go.jp

equations which have a non-dimensional form. The explicit finite difference method with second-order accuracy and the Runge-Kutta-Gill method are used to solve the basic equations numerically. We carry out four simulation runs as shown in Table 1.

3. Simulation Results

Figure 2 shows the spatial structure of magnetic field lines and the high density plasma in the case 1. The high density plasma confined in the CT magnetic field is accelerated up to the maximum velocity V_{CT} at $t = 2L_r/V_{CT}$. At $t = 20\ \tau_A$, the CT has penetrated into the region dominated by the leakage magnetic field. In this process, the CT suffers from a tilting instability, which is accompanied by magnetic reconnection between the CT magnetic field and the leakage magnetic field. As a result, the magnetic configuration of the CT is disrupted, by which the CT high density plasma diffuses ($t = 40\ \tau_A$). At $t = 50\ \tau_A$, the leakage magnetic field goes back to the uniform configuration, which pushes back the CT high density plasma.

Figure 3 shows the time evolution of the CT penetration depth L_p which is defined by $\int_{\rho>\rho_c} \rho z \mathrm{d}V / \int_{\rho>\rho_c} \rho \mathrm{d}V - L_0$, where L_0 is the initial position of the CT and ρ_c is half of the maximum CT density. The region $L_p > 2\ L_r$ is dominated by the leakage magnetic field. In this figure, the penetration depth without the leakage magnetic field (case 2) is also plotted. By comparing these cases, we can see that the CT penetration depth in the case with the leakage magnetic field becomes shorter than that without it. It is considered that when the leakage magnetic field exists, the CT slows down much more by the compressibility of the plasma through which the CT kinetic energy is converted to the magnetic energy of the leakage magnetic field [10].

In this figure, CT penetration depths in cases with the inner electrode whose radius is 0.1 L_r (case 3 and case 4) are also plotted by broken lines. When we compare these depths with those in cases without it, we can see that the CT penetration depth is not sensitive to the existence of the inner electrode.

4. Discussion

It should be noticed that the CT is decelerated even when the leakage magnetic field does not exist. In the simulation, the gun region is filled with the plasma, while it is an almost vacuum in the real experiments, which would cause such a deceleration. In our previous papers [9,10] we have shown that the CT penetration depth is sensitive to the background density and

Table 1 Several parameters in four different simulation runs. L_r^{in}, V_{CT}, B_{CT}, ρ_{CT}, B_{leak}, ρ_{leak}, P_{com}, η, μ, and κ are the radius of the inner electrode, the maximum CT velocity, the maximum strength of the CT magnetic field, the maximum CT density, the leakage magnetic field, the background density, the pressure which has the same value both in the background and the CT region, the resistivity, the viscosity, and the conductivity, respectively.

case	L_r^{in}	V_{CT}	B_{CT}	ρ_{CT}	B_{leak}	ρ_{leak}	P_{com}	η, μ, κ
1	0	0.3	1	10	0.1	0.1	0.1	1×10^{-3}
2	0	0.3	1	10	0	0.1	0.1	1×10^{-3}
3	0.1	0.3	1	10	0.1	0.1	0.1	1×10^{-3}
4	0.1	0.3	1	10	0	0.1	0.1	1×10^{-3}

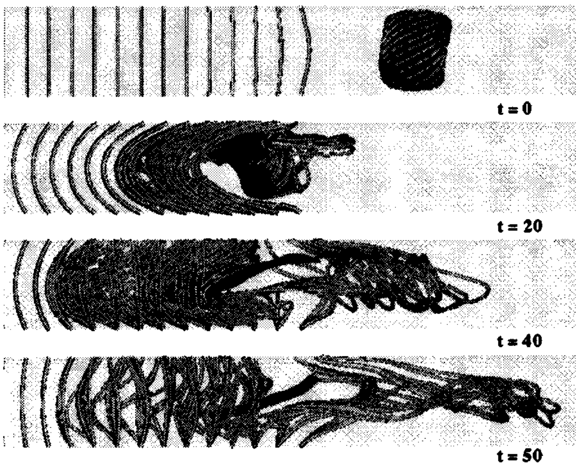

Fig. 2 The spatial structure of magnetic field lines and the high density plasma viewed from $\theta = 0$ at t = 0, 20, 40, and 50 τ_A in the case 1.

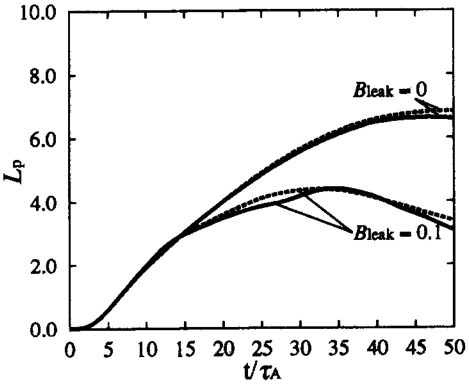

Fig. 3 The time evolution of the CT penetration depth, which is plotted by solid lines in cases with L_r^{in} = 0, and broken lines in cases with L_r^{in} = 0.1.

pressure and becomes longer for lower density and lower pressure. Therefore, it is needed to examine the dependence of these quantities on the CT dynamics as well as the CT penetration depth. Also, when the radius of an inner electrode is larger (for example, in JFT-2M experiments, $L_r^{in}/L_r \sim 0.5$), the leakage magnetic field line-tied on it increases, which would cause the stronger deceleration. The dependence of L_r^{in} on the CT penetration depth in such cases with larger L_r^{in} should be examined. These dependences will be reported in the future work.

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