Theory and MHD simulation of fuelling process by compact toroid (CT) injection

Y. SUZUKI 1), T. HAYASHI 2), Y. KISHIMOTO 1)

1) Plasma Theory Laboratory, Department of Fusion Plasma Research,
Naka Fusion Research Establishment, Japan Atomic Energy Research Institute,
Naka 311-0193, Japan
2) Theory and Computer Simulation Center, National Institute for Fusion Science,
Toki 509-5292, Japan

e-mail contact of main author: suzukiy@fusion.naka.jaeri.go.jp

Abstract. The fuelling process by a spheromak-like compact toroid (SCT) injection is investigated by using MHD numerical simulations, where the SCT is injected into a magnetized target plasma region corresponding to a fusion device. In our previous study, the theoretical model to determine the penetration depth of the SCT into the target region has been proposed based on the simulation results, in which the SCT is decelerated not only by the magnetic pressure force but also by the magnetic tension force. However, since both ends of the target magnetic field are fixed on the boundary wall in the simulation, the deceleration caused by the magnetic tension force would be overestimated. In this study, the dependence of the boundary condition of the target magnetic field on the SCT penetration process is examined. From these results, the theoretical model we have proposed is improved to include the effect that the wave length of the target magnetic field bent by the SCT penetration expands with the Alfvén velocity. In addition, by carrying out the simulation with the torus domain, it is confirmed that the theoretical model is applicable to estimate the penetration depth of the SCT under such conditions. Furthermore, the dependence of the injection position (the side injection and the top/bottom injection) on the penetration process is examined.

1. Introduction

As one of the advanced fuelling methods for a fusion reactor, the compact toroid (CT) injection has been studied experimentally [1,2,3,4,5,6,7,8,9,10] and theoretically [11,12,13,14]. This method would have advantages especially for a large-grade fusion device like ITER, since the injection velocity of the CT is much faster than any of the other conventional fuelling methods. However, the penetration depth of the injected CT, which directly affects the fuelling efficiency, remains as one of the unsolved questions. To reveal this, so far, we have carried out MHD numerical simulations, where the SCT is injected into magnetized target plasmas [15]. From these results, we have proposed the theoretical model to determine the penetration depth of the injected SCT, which indicates that the SCT is decelerated not only by the magnetic pressure force but also by the magnetic tension force [16]. However, since both ends of the target magnetic field are fixed on the conducting boundary wall in the simulation, the deceleration caused by the magnetic tension force would be overestimated.

In this study, by improving the boundary condition of the target magnetic field, the dependence of it on the penetration process of the SCT in the device region is examined. From these results, the theoretical model we have proposed [16] is improved. Furthermore, the theoretical model is applied to the simulation with the torus domain, in which the target magnetic field has the toroidal one and decreases in inverse proportion to the major radius.

case	V_{SCT}	$\langle\rho_{SCT}\rangle$	$\langle B_{SCT}\rangle$	ρ_{target}	$B_{target}(\alpha)$	P_{com}	position
1	0.3	5.5	0.46	0.1	0	0.1	
2	0.3	5.5	0.46	0.1	0.1	0.1	
3	0.3	5.5	0.46	0.1	0.3	0.1	
4	0.3	5.5	0.46	0.1	0(0)	0.1	side
5	0.3	5.5	0.46	0.1	$0.1-0.2(1.6)$	0.1	side
6	0.3	5.5	0.46	0.1	$0.3-0.6(4.8)$	0.1	side
7	0.3	5.5	0.46	0.1	0(0)	0.1	top/bottom
8	0.3	5.5	0.46	0.1	$0.075-0.15(1.2)$	0.1	top/bottom
9	0.3	5.5	0.46	0.1	$0.225-0.45(3.6)$	0.1	top/bottom

TAB. I. Several parameters in nine different simulation runs. In case 1, 2 and 3 the target region is given by the square corresponding to a part of fusion device. In case 4, 5 and 6 the target region is given by the toroidal geometry with the side injection of the SCT. In case 7, 8 and 9, the injection position of the SCT is top/bottom.

2. Simulation model

The simulation region is given by the combination of the cylinder with the cylindrical coordinates (r, θ, z) and the square with the Cartesian coordinates (X, Y, Z), which correspond to the gun region and a part of device region, respectively. The governing equations are given by MHD equations with a non-dimensional form, where the density, the magnetic field, the velocity, the length and the time are normalized by onetenth of the maximum SCT density $\rho_0(\equiv 0.1\rho_{SCT})$, the maximum strength of the SCT magnetic field $B_0(\equiv B_{SCT})$, the characteristic Alfvén velocity $V_A(\equiv B_0/\sqrt{\mu_0\rho_0})$, the scale of the cylinder radius L_r and the Alfvén transit time $\tau_A(\equiv L_r/V_A)$, respectively. The explicit finite difference method with second order accuracy and the Runge-Kutta-Gill method are used to solve the basic equations numerically.

Furtheremore, to investigate the SCT dynamics in more realistic condition, two cylinders, which are perpendicularly connected with each other and correspond to a gun region and a whole device region, respectively, are used as the simulation domain We use the cylindrical coordinates (R, Θ, Z) for the device region. The radius and the height of the device region is given by $8L_r < R < 16L_r$ and $0 < Z < 4L_r$, respectively. The target magnetic field is given by the toroidal magnetic field: $B_{target} = \alpha/R$, where α is constant. In addition, to examine the dependence of the injection position on the penetration process of the SCT, two cylinders, which are connected by shifting their axes are used as the simulation domain where the height of the target region is extended to $8L_r$. We have carried out totally nine simulation runs as shown in Table I.

3. Simulation results and improvement of NS model

Firstly, we indicate the simulation results in case 1, 2 and 3, where the target region is given by the square, and compare them with the previous simulaiton results [15,16]. From the simulation, we can observe two important phenomena: magnetic reconnection between the SCT magnetic field and the target one and the bending of the target magnetic field in the SCT penetration direction, which have been observed in the previous simulation

[15]. However, the amplitude of the bent target magnetic field in the current simulation is smaller than that in the previous simulation. From these results, it is considered that in the case with the periodic boundary the bending of the target magnetic field is relaxed after such imformation reaches the boundary. Therefore, by assuming that both ends of the bent target magnetic field expand with the Alfvén velocity determined by the target magnetic field and the target density, the theoretical model (we call the non-slipping sphere (NS) model) we have proposed [16] is improved by replacing the size of the target region ,which is given by R in the previous paper [16] to the Alfvén transit length. As a result, the NS model is improved as follows:

$$\rho \frac{\partial V_z}{\partial t} = F - \frac{\partial}{\partial z}\frac{B^2}{2\mu_0} - \frac{B^2 \pi^2 (L_p + L_{SCT})}{2\mu_0 L_w^2} \ , \tag{1}$$

where z is taken as the penetration direction, L_p is the penetration depth and L_{SCT} is the half size of the SCT. L_w is the Alfvén transit length defined by

$$\begin{aligned} L_w &= L_r && \text{for } t < t_0 \ , \\ L_w &= L_r + \frac{B_{target}(R = 16 L_r)}{\sqrt{\rho_{target}}}(t - t_0) && \text{for } t \geq t_0 \ , \end{aligned} \tag{2}$$

where t_0 is given by the time when the quarter of the SCT penetrates the target region. F is estimated from the case with null target magnetic field to examine strictly the effect of the deceleration due to the existence of the target magnetic field [16].

4. Discussion

To examine applicability of the improved NS model to the simulation with more realistic condition, we have carried out simulations with the torus domain, where the target magnetic field has the toroidal one and decreases in inverse proportion to the major radius. Figure 1 shows the spatial structure of the SCT high density plasma and magnetic field lines at $t = 0$ and $30\tau_A$ in case 5 and 6. It can be seen that the same phenomena, namely magnetic reconnection and the bending of the target magnetic field, are observed in these cases. Figure 2 shows the time evolution of SCT penetration depths in these cases and in the improved NS model. It can be seen that penetration depths in these cases well coincide with those estimated from the NS model, respectively. In addition, it is confirmed that fluctuations in these cases propagate with Alfvén velocity, which coincide with those estimated from the NS model. Furthermore, to examine the dependence of the injection position of the SCT on the penetration process, we have carried out simulations, where the SCT is injected from the top/bottom direction (case 7, 8 and 9). As a result, penetration depths in these cases well coincide with those estimated from the NS model, respectively.

Next, we compare the side injection and the top/bottom injection based on the improved NS model, where we assume that the injection velocity is 200 and $300 km/s$ and the strength of the target magnetic field at the magnetic axis is $0.8T$ [8]. By using the current simulation domain, the injected SCT experiences the target magnetic field increasing form $0.6T$ to $1.2T$ in the side injection and being constant with $0.8T$ in the top/bottom injection. It is revealed that the penetration depth in the side injection is longer than that in the top/bottom injection when the injection velocity is $200 km/s$ but the former is shorter than the latter when it is $300 km/s$. It is because while the gradient of the

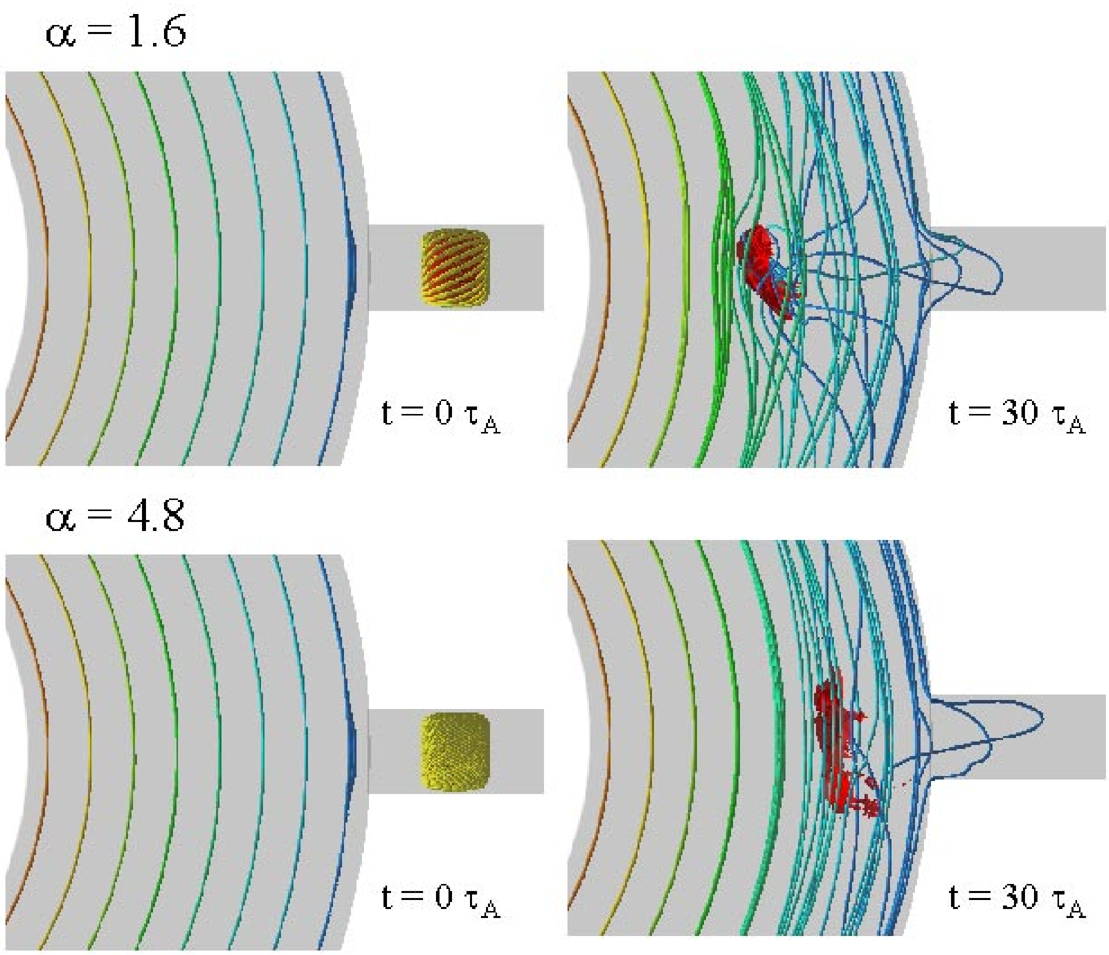

FIG. 1. The spatial structure of magnetic field lines and the SCT high density plasma at $t = 0$ and $30\tau_A$ in case 5($\alpha = 1.6$) and 6($\alpha = 4.8$).

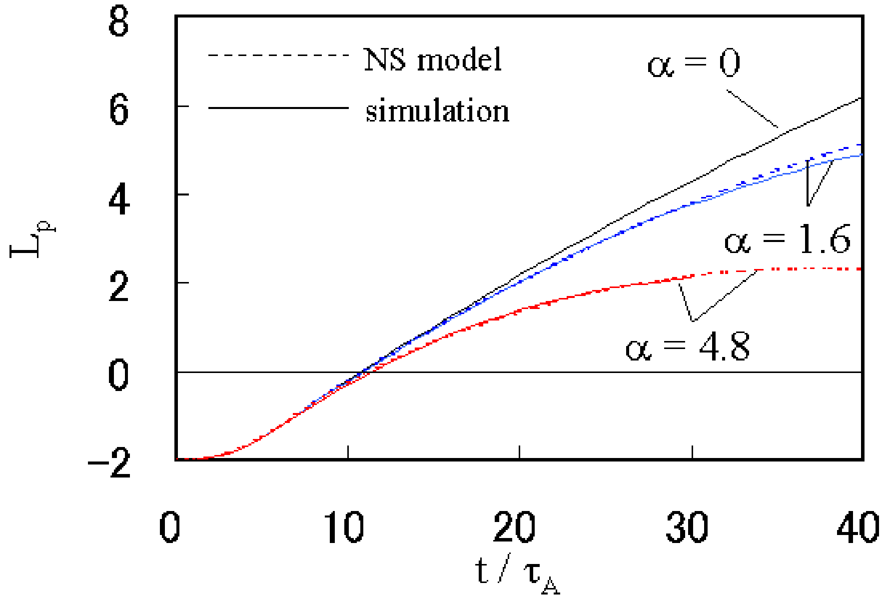

FIG. 2. The time evolution of penetration depths in the simulation (case 4, 5 and 6) and the NS model. In case 6, the simulation is stopped at $t = 30\tau_A$, since the numerical error increases.

magnetic pressure near the gun region effectively decelerates the SCT when the injection velocity is slower, that in the target region does when the injection velocity is faster.

5. Summary

By improving the target region in the simulation from the cylinder [15,16] to the square, the dependence of the boundary condition of the target magnetic field on the penetration process of the SCT is examined. From the simulation results, it is found that the wave length of the bent target magnetic field expands with the Alfvén velocity determined by the magnetic field and the density in the device region, which leads to the relaxation of the magnetic tension force. By improving the theoretical model to include this effect and applying it to the simulation with more realistic condition, it is confirmed that the model is applicable to estimate the penetration depth of the SCT under such conditions. Finally, the dependence of the injection position of the SCT on the penetration process is discussed.

Acknowledgements

We acknowledge Prof. A. Kitsunezaki, Prof. M. Azumi, Prof. T. Sato and Prof. M. Wakatani for fruitful suggestions. We thank Prof. T. Uyama, Prof. M. Nagata, Dr. N. Fukumoto, Prof. H. Yamada, Dr. J. Miyazawa, Prof. T. Ogawa and Dr. T. Miyoshi for useful discussion. We also thank JAERI Information Systems Operating Division group for using JAERI vector parallel processor.

References

[1] BROWN, M.R., BELLAN, P.M., Nucl. Fusion **32** (1992) 1125.
[2] RAMAN, R., *et al.*, Phys. Rev. Lett. **73** (1994) 3101.
[3] RAMAN, R., *et al.*, Nucl. Fusion **37** (1997) 967.
[4] RAMAN, R., *et al.*, in Controlled Fusion and Plasma Physics (Proc. 24th Eur. Conf. Berchtesgaden, 1997), Vol. 21A, Part I, European Physical Society, Geneva (1999) 293.
[5] RAMAN, R., *et al.*, in Proceedings of the 17th IAEA Fusion Energy Conference, Yokohama, Japan, October 1998.
[6] GOUGE, M.J., *et al.*, in Fusion Energy 1996 (Proc. 16th Int. Conf. Montreal, 1996), Vol. 3, IAEA, Vienna (1997) 481.
[7] FUKUMOTO, N., *et al.*, Bull. Am. Phys. Soc. **42** (1997) 1961.
[8] OGAWA, T., *et al.*, Nucl. Fusion **39** (1999) 1911.
[9] SLOUGH, J.T., HOFFMAN, A.L., in Fusion Energy 1996 (Proc 16th Int. Conf. Montreal, 1996), Vol. 2, IAEA, Vienna (1997) 237.
[10] YEE, J., BELLAN, P.M., Nucl. Fusion **38** (1998) 711.
[11] PARKS, P.B., Phys. Rev. Lett. **61** (1988) 1364.
[12] PERKINS, L.J., HO, S.K., HAMMER, J.H., Nucl. Fusion **28** (1988) 1365.
[13] NEWCOMB, W.A., Phys. Fluids B **3** (1991) 1818.
[14] HWANG, D.Q., RYUTOVA, M., MCLEAN, H., Phys. Plasmas **6** (1999) 1515.
[15] SUZUKI, Y., *et al.*, Nucl. Fusion **40** (2000) 277.
[16] SUZUKI, Y., *et al.*, to be published in Phys. plasmas.