2D MHD Study of the Plasma Formation Using the Induction of In-Vessel Poloidal Field Coils inside the Spherical Tokamak

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The formation and merging of the ST plasmas in the spherical tokamak have been studied by the means of the 2D toroidal MHD simulation for the two cases with a single and double PF coils. The following results were obtained: (i) during the ST plasmas formation, an internal toroidal flux is injected to the ST plasmas, (ii) this internal flux increases strongly during the plasma merging, and (iii) the internal toroidal flux damps after the merging.

In the last decades, magnetic reconnection has been investigated as a heating method in various devices such as the TS-3 [1, 2], TS-4 [3], TS-6 [4], ST-40 [5], and MAST [6]. In these merging experiments, two spherical tokamak (ST) plasmas are formed inductively due to the swinging down of the two in-vessel poloidal field (PF) coils. At the pinch off ($I_{PF} = 0$), the ST plasmas separate from the coils and move toward the mid-plane to merge. Note that a pair of EF coils maintains the radial balance.

Figure 1 illustrates the schematic view of the ST plasmas formation around the in-vessel PF coils along with the currents wave-form. Experimental studies of merging revealed the presence of an internal toroidal flux. As there is no numerical work studying plasma formation, this work plans to study the generation of the internal toroidal flux during the plasma formation and merging by using the 2D Hall-MHD model.

The current simulation was written in the BOUT++ which is a C++ framework for writing plasma simulations in curvilinear geometry [7]. This simulation was arranged on a $N_R \times N_Z = 64 \times 128$ finite element domain.

Our MHD simulation has the pre-merging temperature value $T_0 = T_i = 10\,\mathrm{eV}$, density $n_0 = 5 \times 10^{18}\,\mathrm{m}^{-3}$, the normalized resistivity $\eta = 5 \times 10^{-6}$, initial magnetic field is a toroidal magnetic field $B_{T0} = \frac{0.5}{R}$ [T], and the normalized viscosity $v = 5 \times 10^{-4}$ inside a toroidal domain with an inner radius of $0.2\,\mathrm{m}$, major radius of $1\,\mathrm{m}$ and $Z = \pm 1.1\,\mathrm{m}$. Note that the perfect conducting boundary condition is assumed in this work. The used plasma parameters are received from the common merging experiments in the spherical tokamak [7, 8].

When the PF coils current decreases in the ramp-down phase, the plasma is formed inductively around the coils.
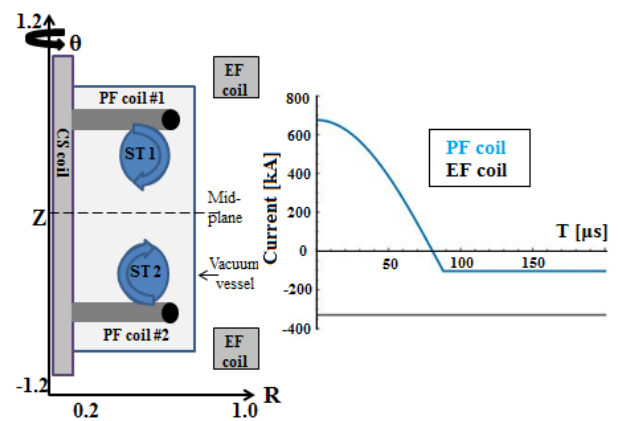

Fig. 1 The PF/EF coils current wave-forms along with the schematic view of the ST plasma formation and merging.

Figure 2 shows the poloidal flux contour Ψ and toroidal field B_t in the case of two PF coils. At the pinch-off, the ST plasmas separate from the coils and gradually move toward the mid-plane. Soon after, the repulsion force between the PF coils/plasma currents and the ST plasmas mutual attraction drive the merging resulting in the formation of a single ST as shown in Figs. 2 (b) and (c).

As mentioned before, the experimental measurements of the magnetic field during the merging proposed the presence of a toroidal flux inside the ST plasmas [9]. Figure 4 illustrates the time evolution of the generated toroidal flux inside the separatrix (hence it is referred to as the internal toroidal flux) produced by poloidal plasma current in the case of double PF coils [10].

At the plasma formation stage, the internal toroidal flux gradually increases forming the ST plasmas with the toroidal flux confirming the experimental results. During the dynamic merging process, the internal toroidal flux

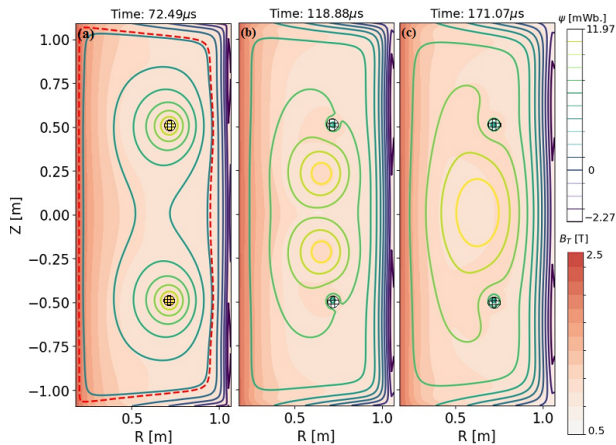*author's e-mail: tara@ts.t.u-tokyo.ac.jp*

Fig. 2 Time evolution of the poloidal flux contours Ψ and toroidal field B_t at 72.49 μs (a), 121.78 μs (b), and 171.07 μs (c) for a pair of PF coils. Red dotted line indicates the separatrix.
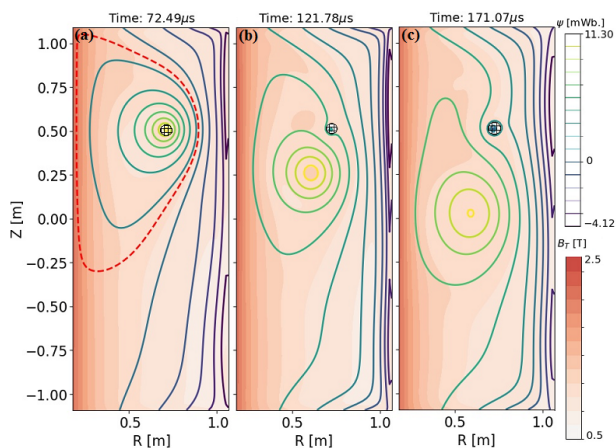
Fig. 3 Time evolution of the poloidal flux contours Ψ and toroidal field B_t at 72.49 μs (a), 121.78 μs (b), and 171.07 μs (c) for a single PF coil. Red dotted line indicates the separatrix.

increases strongly to maintain the pressure balance; yet, soon after at the end of merging, the internal toroidal flux damps, possibly due to the dissipation and the plasma relaxation process.

Figure 3 shows the formation of a ST plasma by using a single PF coil. Note that the single PF and double PF coils cases have equal amount of vacuum magnetic energy. Similar to the previous case, the plasma is formed inductively around the PF coil (Fig. 3 (a)). After the ST plasma pinches off from the coil, it gradually moves toward the mid-plane as presented in Figs. 3 (b) and (c).

Figure 4 shows the internal toroidal flux during the plasma formation and movement toward the mid-plane in the case of a single PF coil. The separated plasma contains an internal toroidal flux; yet, its magnitude is smaller than the case with a pair of PF coils due to the absence of merging. In this case, as soon as the single ST plasma reaches steady equilibrium state the internal toroidal field damps.
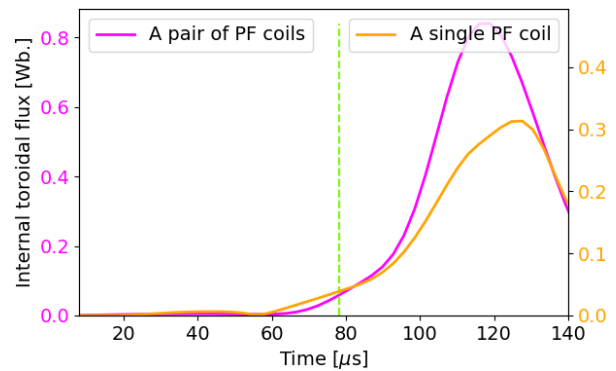

Fig. 4 Time evolution of the internal toroidal flux inside the separatrix for two cases. Green line indicates the pinch-off.

It was found that the internal toroidal flux is generated inside the ST plasmas in the cases of single and double PF coils configurations. The toroidal flux is generated due to the increase in the poloidal current during the plasma formation and the merging. Yet, the poloidal current itself is generated due to the shrinking of flux surfaces which is higher during the merging [10].

In conclusion, we study the ST plasmas formation and merging by swinging a pair of in-vessel PF coils using 2D MHD simulation. The PF coils current ramp down, forming two ST plasmas around the coils inductively. After the ST plasmas separate from the coils, they move toward the mid-plane due to the expanding force of the internal toroidal field which initially drives the merging.

It was shown that the internal toroidal flux is also formed during the plasma formation in the case of a single PF coil during the plasma formation. The internal toroidal flux in the case of two PF coils is twice as much as the case with a single PF coil, indicating the effect of merging and compression on the toroidal flux generation.

In the both cases, the internal toroidal flux generates due to the changes in the poloidal current which consequently resulted from the shrinking of the poloidal flux lines during the plasma formation and merging. Note that in spite of the rise in the internal toroidal flux, the toroidal flux itself is conserved inside the flux surface.

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