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Reconstruction of plasma shape and eddy current profile based on modified cauchy condition surface method in merging spherical tokamak

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ABSTRACT

The spherical tokamak merging start-up is one of the central solenoid-free start-up method. For controlling the merging actively, it is essential to identify the plasma shapes during the merging process. In the present work, the modified Cauchy condition surface method is applied to demonstrate the reconstruction of the plasma boundary shapes as well as the eddy current profiles at three different representative phases in the merging start-up process (a. initial phase, b. merging phase, c. after merging). Profiles of magnetic flux and plasma boundary have been reconstructed accurately using noiseless magnetic sensor signals and reconstructed with a fairly good accuracy using sensor signals with 3% noise. The eddy current profile have been also reconstructed with a fairly accuracy.

1. Introduction

The idea to reduce the aspect ratio or the spherical tokamak (ST) concept [1] has the capability of attaining high-β plasma, and is expected as a candidate of compact fusion reactor. In a ST reactor, central solenoid (CS) coil must be miniaturized or eliminated because of narrow space in the central region of the ST device. Thus, establishment of CS-free start-up scheme is strongly required. Various types of start-up methods, such as introductions of the electron cyclotron waves, the electron Bernstein waves [2,3], the lower hybrid wave [4], the coaxial helicity injection [5–8], the induction by vertical field [9–11], and the merging technique [12,13], are being developed in many experimental devices.

The started-up ST plasma should be completely sustained by some non-inductive additional heating and the current drive methods using the RF waves and/or the neutral beam injection (NBI) [14]. Thus, in the ST plasmas initiated without using CS coils, the parameters of plasma, such as the plasma current, the density, and the temperature, should take values suitable for the RF/NBI power absorption.

The merging start-up method has the advantage of achieving high plasma temperature and density because it involves the reconnection heating and the compression processes. This has been demonstrated in the START, MAST (UKAEA) [15], TS-3, TS-4 (Univ. Tokyo) [12] in which in-vessel poloidal field (PF) coils are utilized to form the initial two STs inductively. In the UTST device (Univ. Tokyo) [13], all the PF coils are located outside the vacuum vessel and successfully initiate two STs with inductive electromotive force across the vessel wall. In each case, the plasma current is driven by the toroidal electric field generated by the swinging-down of the PF coil currents. In order to achieve optimal merging conditions, the initial two ST plasmas should have an identical plasma current and shape, and then move symmetrically toward the center of the device with appropriate velocity. This merging process is caused by the repulsion forces between the plasma current and the reversed PF coil currents. However, the PF coil current waveforms are provided by the LC-circuits or the pre-programmed power supplies in the present experiments. Thus, one requires an active feedback control of the plasma currents, the positions, and the shapes of the two initial ST plasmas to optimize the merging process for achieving higher plasma parameters.

To realize the active feedback control and optimize the plasma parameters described above, the shape of the last closed flux surface (LCFS) or the plasma boundary shape is highly important. Such information should be deduced from signals of magnetic sensors located near the vacuum vessel wall, since the direct measurement of physical quantities inside the plasma is usually difficult. The Cauchy condition surface (CCS) method [16–23] is one such idea for reconstructing the magnetic flux profile outside the plasma and hence the plasma boundary shape. The method has already been established for operating control and diagnosis of JT-60U [16], a tokamak-type device. The application of the method has been expanded to other devices such as KSTAR [17], JT-60SA [18] and QUEST [19]. Further, Itagaki et al. developed the 3D CCS method [20–22] to reconstruct 3D magnetic field

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profile outside the non-axisymmetric plasma in the LHD. In these methods, the CCS, where both the Dirichlet and the Neumann conditions are unknown, is hypothetically placed in a domain that can be supposed to be inside the plasma. The CCS plays the same role as the plasma current in causing the field outside the plasma.

As a difficulty in the authors' research field, the initial STs in the merging start-up phase do not satisfy the equilibrium condition, however, it is fortunate that the CCS method is effective in the shape reconstruction without introducing any information on the MHD equilibrium.

Another difficulty that hampers the reconstruction is the effect of the large eddy currents generated on the vessel wall during the merging start-up period, since the initial two STs are formed inductively. These eddy currents should also be evaluated for a reliable reconstruction of magnetic field/flux structure. Recently, Itagaki et al. proposed an advanced method [23] for the RELAX, a reversed field pinch (RFP) device, where the eddy current effect on the vessel wall is incorporated into the original CCS method algorithm. In more detail, the eddy current term is given by a boundary integral along the vessel in the poloidal direction. The eddy current profile on the vessel is not given in advance but completely unknown before one starts the analysis. That is, the Cauchy conditions and the eddy current values on the vessel nodes are solved simultaneously using only the signals from magnetic sensors. Here, the authors give this advanced method [23] the name "the modified Cauchy condition surface method (the M-CCS method)". The authors believe that the M-CCS method is also suitable for the reconstruction of the magnetic field structure in the UTST, especially in the ST merging start-up period.

In the present work, the M-CCS method is applied to demonstrate the reconstruction of the plasma boundary shapes as well as the eddy current profiles at three different representative phases of plasma merging process (a. initial phase, b. merging phase, c. after merging) in limiter configurations of the UTST device. This paper is arranged as follows. The outline of the M-CCS method is given in Section 2. The modelling and the calculation conditions for the present UTST analyses are described in Section 3. Reconstruction of the poloidal flux profiles and the plasma boundaries are reported in Section 4. Section 5 describes the reconstructed results of eddy current profiles. In both Sections 4 and 5, the effects of sensor signal noise are also discussed. Section 6 gives the conclusion. The present research results demonstrate the effectiveness of the M-CCS method in the reconstruction analyses of ST merging process.

2. Method

2.1. The modified cauchy condition surface (M-CCS) method

In the present study the authors adopted the M-CCS method for the reconstruction. Schematic of this method is shown in Fig. 1. The CCS and the vacuum vessel boundary are located to describe the plasma current effect and the toroidal eddy current, respectively. Then this is an 'inverse problem' that aims to infer the Dirichlet and the Neumann conditions on the CCS as well as the toroidal current on the vacuum vessel, based on the observation of the magnetic sensor signals outside the plasma. Three types of boundary integral equations to be solved are described as shown below [23].

(a) For poloidal flux sensors at points i

$$\psi_i - W_i^{\psi} = \int_{\Gamma_{CCS}} \left(\frac{\psi^*}{r}\frac{\partial\psi}{\partial n} - \frac{\psi}{r}\frac{\partial\psi^*}{\partial n}\right)d\Gamma + \mu_0 \int_{\Gamma_{VV}} j_{VV}(\mathrm{r}_{VV})\psi^*(\mathrm{r}_{VV} \to \mathrm{r}_i)d\Gamma(\mathrm{r}_{VV}) \tag{1}$$

(b) For magnetic field sensors at points i

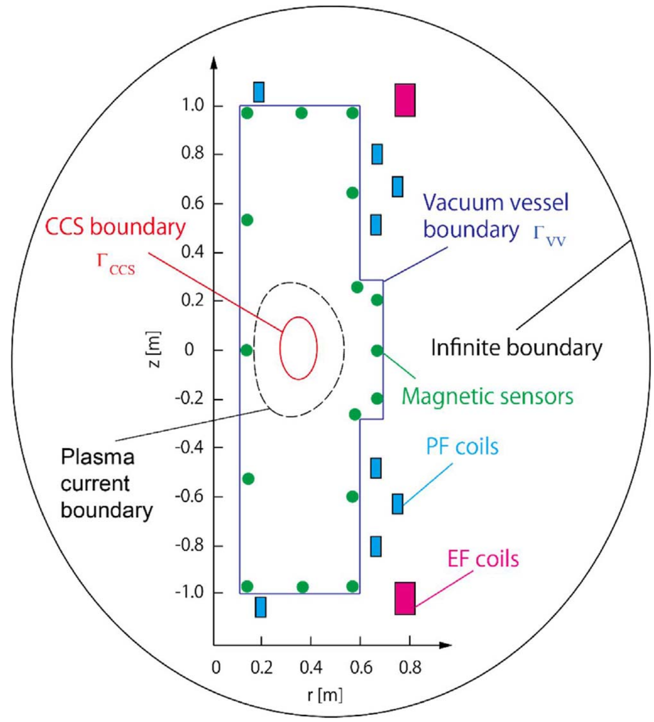

Fig. 1. Schematic of M-CCS method.

$$B_i - W_i^{B} = \int_{\Gamma_{CCS}} \left(\frac{B^*}{r}\frac{\partial\psi}{\partial n} - \frac{\psi}{r}\frac{\partial B^*}{\partial n}\right)d\Gamma + \mu_0 \int_{\Gamma_{VV}} j_{VV}(\mathrm{r}_{VV})B^*(\mathrm{r}_{VV} \to \mathrm{r}_i)d\Gamma(\mathrm{r}_{VV}) \tag{2}$$

(c) For points i on the CCS

$$-W_i^{CCS} + c_i\psi_i = \int_{\Gamma_{CCS}} \left(\frac{\psi^*}{r}\frac{\partial\psi}{\partial n} - \frac{\psi}{r}\frac{\partial\psi^*}{\partial n}\right)d\Gamma + \mu_0 \int_{\Gamma_{VV}} j_{VV}(\mathrm{r}_{VV})\psi^*(\mathrm{r}_{VV} \to \mathrm{r}_i)d\Gamma(\mathrm{r}_{VV}) \tag{3}$$

where ψ means the magnetic flux function [Wb/rad], and c_i is a constant that depends on the local boundary geometry on the CCS [24]. In Eqs. (1)–(3), W_i^{ψ}, W_i^{B} and W_i^{CCS} are the contributions of the external coil current to the point i. In each equation, ψ^* is the fundamental solution which satisfies the equation

$$-\left\{r\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\right) + \frac{\partial^2}{\partial z^2}\right\}\psi^* = r\delta(r-a)\delta(z-a) \tag{4}$$

where $\delta(r-a)\delta(z-a)$ is Dirac's delta function. Eq. (4) describes the axisymmetric poloidal flux function for an arbitrary field point (r, z) caused by a toroidal current spike at the coordinate (a, b). Then the fundamental solution ψ^* is given by

$$\psi^* = \frac{\sqrt{ar}}{\pi k}\left[\left(1 - \frac{k^2}{2}\right)K(k) - E(k)\right] \tag{5}$$

with

$$k^2 = \frac{4ar}{(r+a)^2 + (z-b)^2} \tag{6}$$

where $K(k)$ and $E(k)$ are the complete elliptic integrals of the first and the second kind, respectively. The quantity $B^*(\mathbf{r}_{VV} \to \mathbf{r}_i)$ means $B^* = -\mathbf{n_0}\cdot\nabla\psi^*/r$ with $\mathbf{n_0}$ being the assigned vector normal to the direction of the 'magnetic probe' located at the point i. The quantity $\mathbf{r}_{VV}$ denotes an arbitrary point on the vacuum vessel. $j_{VV}(\mathbf{r}_{VV})$ shows the linear density [A/m] of the toroidal eddy current on the vacuum vessel.

In each of Eqs. (1)–(3) the first term on the RHS comes from the