3.7 Identification of Plasma Boundary and Position for TdeV Tokamak

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Knowledge of plasma position and shape is essential for controlling tokamak operation and for further investigation of plasma confinement and MHD instability. Various methods have been proposed[1]. The method called filament current approximation[2] seems to be the one most freguently applied to tokamaks. The method uses several filament current to replace plasma current. Although it is based on a simple approximation, the method reproduces plasma shape comparatively well using only magnetic measurements. In contrast, method based on an exact analytical solution of partial differential equation, such as the Legendre-Fourier expansion gives poor identification for plasmas with certain current profile[3]. This is due to the small number of sensors. In this paper, using virtual-case principle and least-square fit of the poloidal fields, plasma shape, plasma current centroid, X-point and edge safety factor are identified.

The contribution to the magnetic flux in the vacuum area from plasma current is divided into two parts. One is from plasma centroid. The other is from the multipole moments of the plasma current generating magnetic flux in a polynomial form, which is a solution of the Glad-Shafronov equation. Since the polynomial is a complete system, there is no limitation for any configuration. However, the position of the centroid and the coefficients in the polynomial are unknow, which could be obtained by the virtual-case principle and the least-square fit.

1 Formulation of the physical problem

The MHD equilibrium inside the plasma is governed by the Glad-Shafranov equation:

$$R^2\nabla\cdot R^{-2}\nabla\psi=-\mu_0 Rj_{\varphi}(R,Z) \qquad (1)$$

where j_{φ} is the plasma current density and outside the plasma governed by the equation:

$$R^2\nabla\cdot R^{-2}\nabla\psi=-\mu_0 R\sum_{R=1}^{N}I_k\delta(R-R_k)\delta(Z-Z_k) \qquad (2)$$

where I_k is the current flowing in the kth coil. The poloidal magnetic field in the axisymmetric system is given by

$$\boldsymbol{B}_p=\nabla\Psi\times\nabla\varphi \qquad (3)$$

All the measurements are performed outside plasma. Firstly, we form a solution in

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the vacuum area which satisfies Eq. (2) and consider the influence from the plasma current,

$$\Psi(R,Z) = \sum_{k=1}^{N} I_k \Psi_0(R_k, Z_k, R, Z) + I_p \Psi_0(R_p, Z_p, R, Z) + \Psi_{poly}(R,Z) \quad (4)$$

where the first term represents the coil current contribution, second term stands for the plasma current centroid, and the last term is the contribution from the multipole moments of the plasma current. R_p and Z_p is the position of the centroid, which are obtained by virtual-case principle and reiterative method. The Ψ_{poly} is a homogeneous solution of Eq. (2)[4] with undetermined unknowns which are called adaptive parameters,

$$\Psi_{poly}(R,Z) = \sum (\alpha_n P_n + \beta_n Q_n) + \beta_1 Z + \beta_3 R^2 Z \quad (5)$$

where

$$P_2 = \frac{1}{2} R^2,\ Q_2 = \frac{1}{2} Z^2 + \frac{1}{4} R^2 - P_2 \ln R$$

$$P_4 = \frac{1}{2} R^2 Z^2 - \frac{1}{16} R^4$$

$$Q_4 = \frac{Z^4}{4!} + \frac{1}{8} R^2 Z^2 - \frac{5}{4^3} R^4 - P_4 \ln R$$

$$P_6 = \frac{1}{3 \cdot 4^2} R^2 Z^4 - \frac{1}{2^5} R^4 Z^2 + \frac{1}{3 \cdot 2^7} R^6$$

$$Q_6 = \frac{Z^6}{6!} + \frac{R^2 Z^4}{4 \cdot 4!} - \frac{5}{2^7} R^2 Z^2 + \frac{5}{3^2 \cdot 2^7} R^6 - P_6 \ln R$$

the last two terms in Eq. (5) represent the rigid and slip displacements[5], and the up-down asymmetry in the equilibrium. The adaptive parameters are determined by the lease-square fit of the poloidal magnetic field.

We set a functional:

$$J = \sum_{i=0}^{M} (B_i - B_i^M)^2 + \lambda \sum_{j=1}^{k} \gamma_j^2 \quad (6)$$

where B_i is the calculated value of the magnetic field from Eq. (4) either in R or in Z direction, B_i^M the measured value. M is the number of sensors. γ_j stands for the adaptive parameters. λ is the regularization factor. The adaptive parameters can be obtained from minimization of the functional J. The essence of the problem is to get information inside the plasma from the measurements outside. It belongs to Fredholm equation of first class, which is improperly proposed. The regularization is needed[6].

Once the adaptive parameters are obtained, the plasma boundary can be acquired, which passes the nearer X point. Virtual-case principle is employed to calculate the position of the current centroid.

It is assumed that an ideal supperconductor shell is put on the plasma boundary. There is surface current, which generates the same magnetic field as one by plasma current outside the plasma boundary and cancels the containing magnetic field inside the plasma boundary.

The virtual-case current

$$j_s = \boldsymbol{n} \times B_p \cdot e_\varphi = \frac{1}{\mu_0 R} \frac{\partial \Psi}{\partial n} \quad (7)$$

Position of the current centroid is obtained by integrals along plasma boundary,

$$Z_c = \frac{1}{I_p} \oint_b j_s Z \mathrm{d}l \quad (8)$$

$$R_c = \frac{1}{I_p} \oint_b j_s R \mathrm{d}l \quad (9)$$

The new position of centroid will replace the old in Eq. (4). It is a reiterative procedure until the distance between old and new is less than a small parameter ε, for example, 10^{-4}. The surface current gives containing magnetic field in the plasma region, for example, vertical magnetic field at the current center,

$$B_{\perp} = \oint_b j_s B_z(R_c, Z_c, R, Z)\,dl \qquad (10)$$

where B_z is the magnetic field in Z direction generated by unit surface current. Using the Shafranov formula[7] for the vertical field:

$$B_{\perp} = \frac{\mu_0 I_p}{4\pi R}\left[\ln\frac{8R}{\alpha} + \beta_p + \frac{l_i}{2} - \frac{3}{2}\right] \qquad (11)$$

we can estimate the parameter $\beta_p + \frac{l_i}{2}$ and further the beta value.

2 Application of TdeV

TdeV is the tokamak de varennes in Canada, 25 kirometers away from Montreal. Biasing divertor plate to improve the confinement is one of the feutures[8]. For reconstruction of the equilibrium configuration and improvement of the active feedback, 18 pick-up coils are placed at inner wall of vacuum vessel of TdeV.

For the shot 9626, the divertor case, we obtain the adaptic parameters: $\alpha_2 = 7.07 \times 10^{-2}$, $\beta_2 = 0.18$, $\alpha_4 = -10.20$, $\beta_4 = 12.00$, $\alpha_6 = -8.18$, $\beta_6 = 0.60$, $\beta_1 = 4.00 \times 10^{-2}$, $\beta_3 = -7.07$.

The X point is $R_x = 0.67$ m and $Z_x = 0.27$ m. The current centroid is $R_c = 0.865$ m and $Z_c = 0.005$ m. The edge safety factor q_a is 2.80. $\beta_p + \frac{l_i}{2}$ is 1.048, for the parabolic distribution of plasma current density[8] $l_i = 0.916$ and $\beta_p = 0.59$. The plasma configuration is shown in Fig. 1. It is in good agreement with TV image taken by camera with a toroidal view. It is a little flat. The elongation is 0.96. The triangularity is 0.18. One

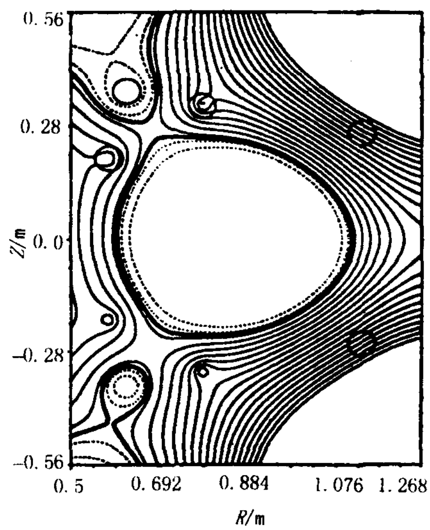

Fig. 1 Reconstruction of the MHD equilibrium of TdeV

X-point is connected with the last close magnetic surface and the other is a little far away. $Z_c = 0.005$ m represents that the plasma is up shifted. The relative error is

$$E_R = J\Big/\sum_{i=1}^{M}(B^M)^2 = 3\% \qquad (12)$$

It needs two minutes to reconstruct a configuration using the VAX computer. We can process the data between the shots. For large computer, it can be fast enough for active control of equilibrium.

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3.8 The Influence of Magnetic Turbulence on the Electron Distribution Function in LHCD①

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Key words LHCD Magnetic turbulence Electron distribution

The transport of electron energy out of tokamak plasma is well known experimentally that its order of magnitude is greater than that predicated by classical and neoclassical theories, whereas ion energy transport is approximately neoclassical. Theoretically, a very small nonaxisymmetric perturbation to the flux surface can lead to magnetic field lines randomly wandering out to the plasma edge and the fast transport of electrons parallel to the magnetic field is thus coupled to radial transport [1,2].

1 Radial magnetic perturbation

Radial magnetic perturbations in a magnitude of $b_r/B \sim 10^{-4}$ have been measured in plasma edge[3]. But in the core the magnitude has not been measured, the magnetic field turbulence may be intense, in some cases, perhaps it can be $b_r/B \sim 10^{-2}$ as the turbulence being in $q=1$ sawtooth relaxation[4] and in RFP, which is much larger than that generally measured in plasma edge. It has been suggested that the rapid transport of electrons relative to ions gives rise to a positive ambipolar electric field, adjusting the electron flow rate to equal the ion flow rate.

Based on the assumption above, the loss of the fast electrons caused by magnetic field turbulence has been taken into account. The analysis shows that this loss can make the electron density decrease by 5% ~ 7%, fit-

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