Equilibrium Reconstruction and Its Integration in J-TEXT

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Abstract The equilibrium fitting code (EFIT) and its application in the J-TEXT tokamak are integrated by the Matlab language. The function of analysis and visualization to the results is added. In addition, the experiment data measured by soft X-ray (SXR) are used to calculate plasma equilibrium as a constraint condition. The improved EFIT code is used for J-TEXT discharge and the profiles of plasma parameters such as flux function, safety factor $q$, pressure and current density are obtained from the reconstructed configurations.

Keywords: EFIT, integrated operation, equilibrium reconstruction

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(Some figures may appear in colour only in the online journal)

1 Introduction

The reconstruction of plasma equilibrium is an important research topic in discharge experiments of a tokamak. To get the inner parameters of plasma in a tokamak, many efficient methods and numerical codes have been developed. Among them, the equilibrium fitting code (EFIT) is the widely used one [1−4]. The basic equation of the EFIT code is the Grad-Shafranov equation for the flux function $\psi$, and it can be written as:

$$R \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_0 R^2 p'(\psi) - \mu_0^2 F(\psi) F'(\psi),$$

(1)

where $F$ is the poloidal current flux function, $R$ and $Z$ are radial and axial co-ordinates in a cylindrical co-ordinate system respectively, and $P$ is the pressure [5]. In actuality, calculating the above equation is usually taken in the following form [6]:

$$R \frac{\partial}{\partial R} \left( \frac{1}{R} \frac{\partial \psi}{\partial R} \right) + \frac{\partial^2 \psi}{\partial Z^2} = -\mu_0 R j_\psi,$$

(2)

$$j_\psi = R p'(\psi) + \frac{\mu_0}{R} F(\psi) F'(\psi),$$

(3)

where $j_\psi$ is the toroidal component of the plasma current density. The EFIT code can be run in either the equilibrium mode or the fitting mode. In the equilibrium mode, it acts as an equilibrium solver, and in the fitting mode, it performs magnetic fittings to get the information about the plasma, such as plasma shaping, peaking of current profile and so on.

J-TEXT is a circular cross section tokamak with an iron-core transformer [7]. The facility’s major radius is 1.05 m, the minor radius is 0.27 m. A schematic cross-section of J-TEXT is shown in Fig. 1. The (1) in Fig. 1 is the toroidal coils, which produce the toroidal magnetic field. The (2) is the Ohmic coils for inducing toroidal plasma current and heating the plasma. The (3) is the vertical field coils, essential to maintaining plasma equilibrium. The (4) is the horizontal field, which controls the vertical position of the plasma. The (5) is the limiters. In addition, the dots in the vacuum vessel denote the magnetic probes, which get the magnetic data for equilibrium reconstruction. We have not considered the eddy current effect of magnetic probes in this paper because the eddy current has little effect on the magnetic probes in plasmas equilibrium state [8].

![Fig. 1 Schematic cross-section of J-TEXT. (1) Toroidal field coils, (2) Ohmic coils, (3) Vertical field coils, (4) Horizontal field coils, (5) Limiters](image-url)
2 The design and implementation of the integrated EFIT code

The original EFIT code has been modified to match the iron core by using the spool model [9], but it is tedious and inefficient using this EFIT code to reconstruct the plasma parameters from the magnetic measurement signals in J-TEXT. On one hand, most magnetic data retrieved from the MDSplus database need to be disposed, and then they need to be written in an input file manually. On the other hand, it is inconvenient to analyze and store the results.

In order to resolve these problems, we develop a set of interface and analysis programs combined with the EFIT code. This program structurally integrates four parts: measured data retrieval, input file generation, magnetic fittings, and visualization. In addition, the program is installed on the server, which can be accessed remotely [10], conveniently.

The flowchart of the program is shown in Fig. 2, and the details are described below.

The Data catch module is able to retrieve the diagnostic data from the MDSplus database. Currently, the diagnostic data consist of the plasma current, the vertical field current, the horizontal field current, the ohmic field current and the magnetic probes data. Among them, the magnetic probes data need to be integrated as well as correcting the zero drift [11]. For example, 1\textsuperscript{st} probe signal of shot 1037012, the correction of zero drift is shown in Fig. 3.

The Data_write module can generate the input file, which will be read by the EFIT code [12]. The input file is named after the shot number, and it contains many variables which are stored as a namelist format. When the magnetic fittings program begins to run, the Data_write module can upgrade the file by writing the magnetic data in the appropriate place, then the file will be supplied to the EFIT code.

The Calculate module is able to call the EFIT code for the magnetic fittings. It can control the display format of the results and also can compute the results for multiple time slices in one run, which is convenient to collect and analyze the fittings result.

Visualization [13] of the results can be done by the Data_out module. It can plot graphics for the magnetic surfaces, fitting qualities and various profiles such as plasma current density, safety factor and so on.

A simple interface is provided for this program, as shown in Fig. 4. The equilibrium reconstruction can be completed as long as we input the discharge number and the time slice into the interface.

![Fig.4](image)

The program interface, ISHOT is the discharge number, ITIME is the time slice

3 Illustrative examples

J-TEXT discharge #1037012 serves to illustrate the equilibrium reconstruction process by the integrated EFIT program. The curve of measured magnetic data for shot #1037012 is shown in Fig. 5, including the total toroidal plasma current \( I_p \), the ohmic coil current \( I_{ohp} \), the vertical field coil current \( I_{vfp} \), and the horizontal field coil current \( I_{hfp} \). The calculated region is set between \( R = 0.7 \) m to \( R = 1.4 \) m and \( Z = -0.35 \) m to \( Z = 0.35 \) m in a mesh of 65×65 grid points in \( R \) and \( Z \).

Besides, we also add the position of the \( q = 1 \) surface to the program as a constraint condition, and the data are measured by soft X-ray (SXR) [14] as shown in Fig. 6.

Fig. 7 demonstrates the evolution of the plasma configuration. In this figure, the red dashed lines represent the limiters, and the plasma center and the last closed flux surface are marked by blue dots. It shows that the plasma configuration evolves as time.

Fig. 8 shows the variation of the iteration convergence error and the variance of the least square fitting during magnetic fittings. The results indicate that the iteration convergence error of magnetic fittings is about \( 1 \times 10^{-3} \), and the variance of the least square fitting is
less than 100, which meet the conditions of equilibrium convergence and the least square fitting.

\begin{equation}
q(a) = \frac{2\pi a^2}{\mu_0 R} \frac{B_T}{I_p},
\end{equation}

where $a$ is the minor radius, $R$ is the major radius, $B_T$ is the toroidal magnetic field ($B_T = 1.8$ T, #1037012) and $I_p$ is the total toroidal plasma current. In Fig. 9, we compare the value of $q(a)$ at different time slices between EFIT results and the results of Eq. (4). The red data are estimated by Eq. (4), and the blue data come from magnetic fittings. The difference between them.

**Fig.5** The waveform of measured magnetic data, #1037012

**Fig.6** Position of $q=1$ surface from SXR

**Fig.7** Reconstructed equilibrium configurations at different time slices of shot #1037012

**Fig.8** The convergence error and the variance at $t=150$ ms, $t=390$ ms and $t=550$ ms
does not exceed 7%. The result of equilibrium reconstruction obtained from the integrated EFIT program is authentic.

Some profiles of plasma parameters, such as the safety factor and plasma current, can be obtained through equilibrium reconstruction \cite{15}. In Fig. 10, the profiles of the flux function, the safety factor \( q \), the plasma current density and the pressure at \( t = 200 \text{ ms} \) are presented. In this figure, the dotted line represents the calculation results without using SXR data while the solid line represents the calculation results with the SXR data. The SXR data play an important role to accurately calculate the equilibrium of plasmas.

The time consumed at different modules of this improved EFIT program are shown in Table 1 and Table 2. Table 1 shows the time consumed for equilibrium reconstruction for different discharges, while Table 2 shows the time consumed for the multiple equilibrium reconstruction for discharge \#1027383. As shown in the two tables, the time of Data\_catch relates to the internet connection speed, while the time of the others is stable. The total computing time has a significant reduction compared to the previous manual EFIT calculation.

### Table 1. Time consumed for different shots

<table>
<thead>
<tr>
<th>Shot number</th>
<th>Data_catch</th>
<th>Data_write</th>
<th>Calculate</th>
<th>Data_out</th>
<th>Total</th>
<th>Total (manual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1027339</td>
<td>3.4473 s</td>
<td>0.0985 s</td>
<td>0.2038 s</td>
<td>4.6252 s</td>
<td>8.3748 s</td>
<td>5 min</td>
</tr>
<tr>
<td>1027091</td>
<td>3.0315 s</td>
<td>0.1000 s</td>
<td>0.2063 s</td>
<td>4.5717 s</td>
<td>7.9095 s</td>
<td>4 min</td>
</tr>
<tr>
<td>1027389</td>
<td>3.4265 s</td>
<td>0.1127 s</td>
<td>0.2044 s</td>
<td>4.0819 s</td>
<td>7.8255 s</td>
<td>5 min</td>
</tr>
<tr>
<td>1034350</td>
<td>3.6061 s</td>
<td>0.0992 s</td>
<td>0.2041 s</td>
<td>3.8867 s</td>
<td>7.7961 s</td>
<td>5 min</td>
</tr>
<tr>
<td>1035355</td>
<td>3.7468 s</td>
<td>0.0967 s</td>
<td>0.2014 s</td>
<td>3.8926 s</td>
<td>7.9375 s</td>
<td>4 min</td>
</tr>
</tbody>
</table>

### Table 2. Time consumed for \#1027383

<table>
<thead>
<tr>
<th>Compute times</th>
<th>Data_catch</th>
<th>Data_write</th>
<th>Calculate</th>
<th>Data_out</th>
<th>Total</th>
<th>Total (manual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5435 s</td>
<td>0.1011 s</td>
<td>0.2047 s</td>
<td>4.0695 s</td>
<td>7.9188 s</td>
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</tr>
<tr>
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<td>3.1543 s</td>
<td>0.0971 s</td>
<td>0.2040 s</td>
<td>3.7361 s</td>
<td>7.1915 s</td>
<td>4 min</td>
</tr>
<tr>
<td>3</td>
<td>3.0682 s</td>
<td>0.1011 s</td>
<td>0.2049 s</td>
<td>4.0885 s</td>
<td>7.4627 s</td>
<td>4 min</td>
</tr>
<tr>
<td>4</td>
<td>3.0495 s</td>
<td>0.0980 s</td>
<td>0.2015 s</td>
<td>3.9195 s</td>
<td>7.2685 s</td>
<td>4 min</td>
</tr>
</tbody>
</table>

### 4 Summary

In this paper, the integrated EFIT program is developed to reconstruct the plasma configuration in J-TEXT tokamak, and the experiment data measured by SXR are used as a constraint condition. Some internal plasma parameters are reconstructed by the magnetic fittings, such as the profiles of the safety factor \( q \), the plasma current density and so on. The results indicate that the integrated EFIT program can satisfy the basic needs for the equilibrium reconstruction in the J-TEXT tokamak. To further reconstruct the current profile, internal information \cite{16}, such as the magnetic measurement by the laser polarimeter-interferometer system (POLARIS) \cite{17}, should be added as a constraint condition for the equilibrium reconstruction. So the integrated EFIT program will be improved in the coming J-TEXT tokamak experiment with the diagnostic upgrade.

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