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Kinetic equilibrium reconstruction on EAST tokamak

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Abstract
Plasma equilibrium is an important basis for tokamak plasma research. The equilibrium reconstructed from experimental diagnostics is a key element for experiments analysis and for theory study. The kinetic equilibrium has the profiles information (current or safety factor profile, kinetic pressure profile), which are key issues for some studies of physics. With the constraints of magnetic measurements, pressure profile and edge current profile, we achieved the first reconstructed kinetic equilibrium on EAST tokamak. The pressure and edge current profiles are based on the diagnostics and theoretical bootstrap current model. The kinetic equilibrium has the pedestal structure for H-mode plasma, which the magnetic reconstruction missed. This improved equilibrium is an important basis for some experimental analysis and theory studies on EAST.

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

1. Introduction

Plasma equilibrium is an important basis for tokamak research. Equilibrium has the plasma geometry and important profiles (pressure, current, safety factor, etc). These geometry and profiles are basic issues for theory and experimental studies, such as the magnetohydrodynamic (MHD), transport process, heating and current drive. To get the equilibrium from experiments, the so-called equilibrium reconstruction method is used, i.e. yield the experimental equilibria from the diagnostic data such as magnetic field and the kinetic pressure profiles. Equilibrium reconstruction has been widely studied [1–7].

The reconstruction is essentially to find a measurement compatible solution to the well-known Grad–Shafranov (G–S) equation:

$$\Delta^*\psi = -\mu_0 R J_\varphi, \quad J_\varphi = RP'(\psi) + \frac{FF'(\psi)}{\mu_0 R}. \qquad (1)$$

In this paper, the EFIT code [1, 2] is used to get the reconstructed equilibria on EAST tokamak [8]. EFIT is an efficiency code to reconstruct the equilibrium. It has been widely used in almost all the major tokomaks in the world. In EFIT, two stream functions $P'(\psi)$ and $FF'(\psi)$ are represented with a set of basis function y_n in terms of a number of coefficients α_n and β_n as

$$P'(\psi) = \alpha_n y_n(\psi), \quad FF'(\psi) = \beta_n y_n(\psi). \qquad (2)$$

The basis function could be polynomial or tension spline functions [9]. Then the coefficients α_n and β_n are determined by the Picard's method to iteratively find the G–S equation solution and minimize the error quality function [2]:

$$\chi^2 = \sum_i \left(\frac{M_i - C_i}{\sigma_i}\right)^2. \qquad (3)$$

Here M_i, σ_i and C_i are the ith measurement value, the corresponding uncertainty and the computation value, respectively.

There are three kinds of diagnostic data to constrain the equilibrium reconstruction. Table 1 shows the three kinds of diagnostics, the corresponding constraints added to the reconstruction and the yielded equilibrium quantities. The magnetic diagnostics are basic diagnostics on every tokamak. The magnetic equilibrium reconstruction could get the plasma shape and some global plasma information. On

Table 1. Three kinds of diagnostics, the corresponding constraints added to the reconstruction and the yielded equilibrium quantities.

	Diagnostics	Constraints	Yield
Magnetic	Magnetic loops and probes	I_p, poloidal flux, external magnetic field	Plasma current, plasma shape, internal inductance, betap, edge current profile
Current	Motional Stark effect or Li Beam, SXR, etc	Internal magnetic field or flux surface	Magnetic surface, current profile, safety factor profile
Kinetic	Thomson scattering, ECE, CER, XCS, FADI, nubeam calculation, etc	Pressure profile (from T_e, T_i, n_e, Z_{eff}, P_f profiles)	Pressure profile

EAST, the magnetic reconstruction has been successfully used for the plasma control system (PCS) and some experiment analysis [10]. It was widely accepted [4, 11] that with the magnetic diagnostics we can only achieve some integral parameters of internal plasma profiles such as the total plasma current I_p, the internal inductance l_i and the poloidal beta β_p. Here $l_i = \int_\Omega dV B_p^2/(B_{pa}^2\Omega)$ is the index of the current profile peakedness, which is the global internal current profile information; $\beta_p = 2\mu_0 \int_\Omega dV P/(B_{pa}^2\Omega)$, where Ω is the plasma volume, $B_{pa} = \mu_0 I_p / \int_\Gamma dl$ is an average poloidal magnetic field for normalization, and Γ denotes the plasma surface bounding Ω. However, recently it was showed that the magnetic reconstruction can also get the edge current profile information, and the reconstructed edge current aligns the calculated current (bootstrap current plus Ohmic current) [7, 12]. Besides the magnetic diagnostics, we need the current diagnostics to constrain the current (or q) profile and the kinetic diagnostics to constrain the pressure profile. Then we can get all the information of the equilibrium.

To get a complete reconstructed equilibrium, we should have all the three kinds of diagnostics to perform the equilibrium reconstruction. However, diagnostics for current and kinetic profiles are not easy. And the reconstruction process is not easy either. In most tokmaks, only the magnetic equilibrium reconstruction are routinely operated.

2. Kinetic equilibrium reconstruction on EAST tokamak

EAST (Experimental Advanced Superconducting Tokamak) is the first non-circle superconducting tokamak in the world. In 2006, EAST got the first plasma and drew a lot of attention in the magnetic confinement fusion community. In the following years, the plasma parameters of EAST were gradually improved and EAST begun to play role. However, previously EAST only had the magnetic diagnostics and very limited kinetic diagnostics, and only the magnetic equilibrium reconstruction was performed. But a lot of experiments analysis requires the profile information that the magnetic equilibrium reconstruction cannot give. Recently some kinetic profile diagnostics were installed on EAST. It is time for us to do the kinetic equilibrium reconstruction for EAST. We will add the kinetic pressure and current constraints as much as possible we can get.

2.1. Kinetic pressure constraint

To get the kinetic pressure profile, we have to have the diagnostics for the profiles of electron density n_e, electron temperature T_e, main ion density n_i, main ion temperature T_i, impurity density n_z (or the effective Z) and the pressure contributed from the fast ion p_f. Then we get the pressure profiles with the formula

$$P(x) = n_e T_e + (n_i + n_z)\, T_i + P_f. \tag{4}$$

In the formula, the impurity temperature is taken to be same as the main ion temperature. At present on EAST, T_e and n_e profiles are from Thomson scattering measurement [13, 14]. T_i profiles are from the x-ray imaging crystal spectrometer (XCS) [15, 16]. n_i and n_z are from n_e, the quasi-neutrality condition and the Z_{eff} measurement.

These measurements data are all discrete points in different spatial locations. Before we evaluate the pressure profile, we should first map the data into the flux surface coordinates (in this study the ρ coordinate is used, where ρ is the square root of normalized toroidal magnetic flux) using the magnetic geometry from the previous magnetic equilibrium or from previous iteration, then fit them with smooth functions.

Figure 1 shows the measured data and the fitted profiles for EAST discharge 38300 at time 3900 ms. The T_e profile is fitted with a tension spline function [9]. The XCS measurement on EAST only has the central region data, so T_i is scaled from T_e to match the XCS data at the central region and match $T_i = T_e$ at the edge region. Currently on EAST, T_i and T_e at the edge region are relatively low and the collision frequency is large, so the $T_i = T_e$ assumption is reasonable. n_e profile is also fitted with the tension spline function. In these profile fittings, the knot locations are chosen to make the fitted profile monotonic and smooth. The fitted density profile is also checked with the line average density measurement.

For the n_i and n_z profiles, we calculated them with the n_e and Z_{eff} profiles by using the quasi-neutral condition and the definition of Z_{eff}. The target plate material of EAST divertor is carbon, so the major impurity in plasma is carbon and the $Z_i = 6$. For the Z_{eff} profile, currently EAST only has the line average Z_{eff} measurement, so a flat profile is assumed and $Z_{eff} = 2.5$ for this time slice. Generally the Z_{eff} at the edge region is higher than the central region. But the Z_{eff} profile does not change the total pressure much. Actually we tried Z_{eff} from 2.5 to 3.5, there was about 9% decrease for the kinetic pressure at the pedestal shoulder.

P_f is the pressure contributed by the fast particles. At present, EAST does not have the neutral beam injection (NBI) yet, so the P_f is omitted. In the next campaign the NBI will be installed on EAST and the P_f contribution could be obtained by the numerical code such as NUBEAM [17] or directly by

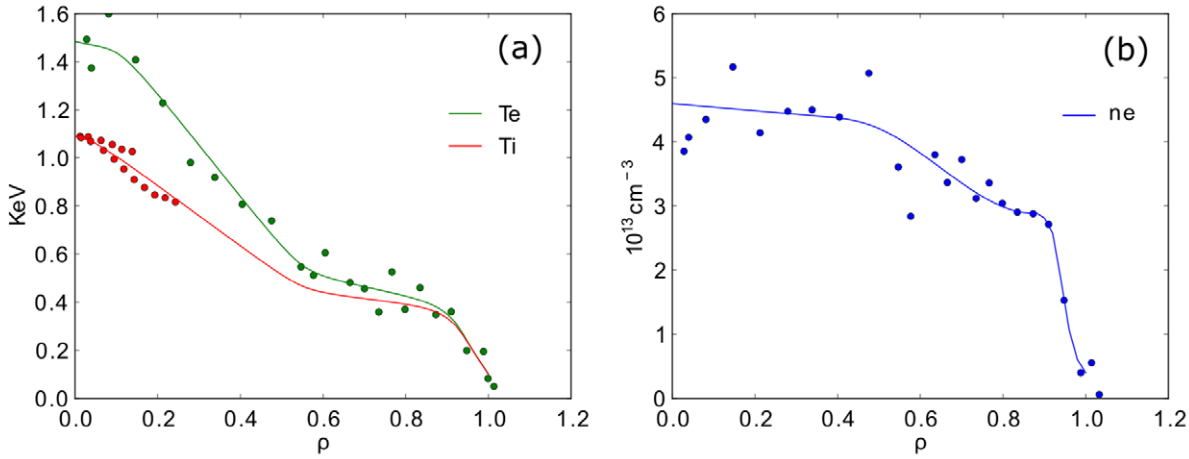

Figure 1. The diagnostic data and fitted profiles. (*a*) The electron temperature and the ion temperature. (*b*) The electron density.

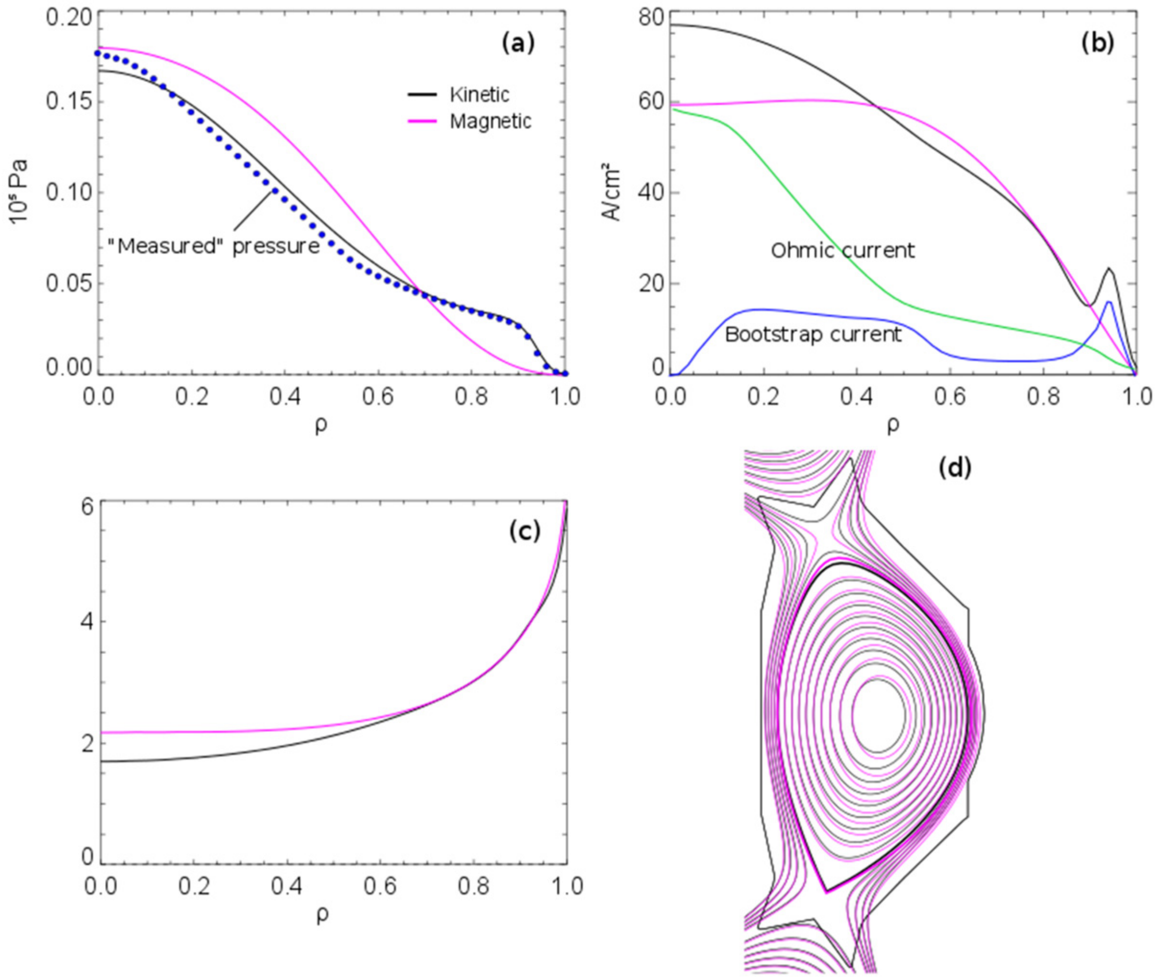

Figure 2. The profiles and the plasma configuration from kinetic reconstruction and magnetic reconstruction. (*a*) Pressure profiles. The 'measured' pressure points are also plotted. (*b*) Flux surface averaged parallel current density profiles $(j \cdot B)/B_0$. Also the bootstrap current and Ohmic current profiles are plotted. (*c*) Safty factor profiles. (*d*) Plasma configuration.

some diagnostic such as fast ion $D\alpha$ imaging (FIDA) [18] if it is available.

With all the fitted and assumed kinetic profiles, we use formula (4) to calculate the 'measured' pressure profile. Then the measured pressure profile is used as a constraint for reconstruction. In our reconstruction, 51 pressure points are selected as pressure constraint (See figure 2(*a*) for the 'measured' pressure). The uncertainty of the 'measured' pressure is artificially set as 10%. The uncertainty is just for calculating the χ^2 with equation (3). Actually, it is hard to evaluate the uncertainty, since we do not have all the kinetic profile measurements.

2.2. Edge current constraint

Based on the kinetic profiles described above, we found the kinetic pressure profile, which could be added to the constraints of equilibrium reconstruction. Another important constraint is the current profile. Currently EAST does not have the current profile diagnostics yet. On the other tokamaks, generally motional Stark effect (MSE) diagnostic are used to measure the magnetic field pitch angle to constrain the poloidal field [19]. But even with the MSE, the current profile are still not easy to accurately get, especially at the pedestal region of H-mode plasma. At the narrow pedestal region the profiles change dramatically, so the space resolution of MSE is not easy to catch the details of the current profile structure. However we can use the bootstrap current to constrain the current profile at the edge region. This constraint is especially important for H-mode plasma. Generally the current has three components,

$$j = j_{\mathrm{Ohmic}} + j_{\mathrm{CD}} + j_{\mathrm{BS}}, \tag{5}$$

where the j_{Ohmic}, j_{CD} and j_{BS} are Ohmic current, auxiliary driven current and bootstrap current, respectively. At the edge region of H-mode plasma, the current is dominated by the bootstrap current and a local current density peak is generated. This has been confirmed by the experiments analysis [12, 20, 21].

In this paper, the Sauter model [22, 23] was used to calculate the bootstrap current. Also the Ohmic current was calculated with a simple model [12, 22]

$$\langle j_{\mathrm{Ohmic}} \cdot B\rangle = \sigma_{\mathrm{neo}}\langle E \cdot B\rangle \approx \sigma_{\mathrm{neo}} \frac{V_{\mathrm{loop}}}{(2\pi R_0)} \frac{\langle B\rangle^2}{B}. \tag{6}$$

Here V_{loop} is the loop voltage measured by flux loop, σ_{neo} is the neoclassical resistivity described in reference [22]. On EAST, the low hybrid wave is used to drive current. The calculation on EAST showed generally the driven current is inside $\rho = 0.7$ [24]. So the auxiliary driven current at the edge region could be omitted. Then the calculated bootstrap current and Ohmic current were used to constrain the edge current. The bootstrap current and Ohmic current calculations relies on the kinetic profiles (T_e, T_i, n_e and Z_{eff}).

2.3. The results of kinetic equilibrium reconstruction

With the constraints of magnetic diagnostics, pressure profile and edge current profile, we ran the EFIT code and got the kinetic equilibrium. For H-mode plasmas, the tension spline function representation for stream function (2) is used. Generally, the magnetic surface of kinetic reconstruction is different from the magnetic reconstruction result. Since the diagnostic data is from the fixed point in real space, we should do the profiles fitting again with the new equilibrium. In our experience, twice iteration is enough.

In this reconstruction, for the magnetic diagnostics, there are 27 magnetic probes, 26 flux loops and 1 Rogowski loop. The error quality function $\chi^2_{\mathrm{mag}} = 15.3$. For 51 pressure points, the error quality function $\chi^2_{\mathrm{p}} = 12.8$. The reconstruction quality seems good.

Figure 2 shows the reconstructed pressure profile, current profile, q profile and the plasma configuration. Both the magnetic reconstruction and kinetic reconstruction results are showed. We can see the profiles are quite different, especially at the edge region. Compared with the kinetic results, the magnetic reconstruction missed the important pedestal structure: no steep pressure profile, no local peaked current profile. However, the plasma shape and the magnetic surface does not have much difference. In figure 2(*b*), also the bootstrap current profile is plotted. At the edge region, the total current is aligned with the calculated bootstrap current and Ohmic current.

The reconstructed equilibrium, the pressure profile was from the diagnostics and some reasonable assumption. The edge current profile was based on the theoretical bootstrap current and Ohmic current model. However, the current profile at the core region only has the constraint of l_i from the magnetic diagnostic, it is a weak constraint of current distribution tendency. So the core current profile is not as reliable as the edge region.

3. Conclusion and discussion

With the constraints of magnetic diagnostics, pressure profile, edge current profile, we found the first reconstructed kinetic equilibrium on EAST tokamak. The pressure profile and edge current profile are based on the diagnostics and theoretical model. The kinetic equilibrium has the steep edge pressure profile and local peaked edge current profile, which the magnetic reconstruction missed. The improved equilibrium is an important basis for some experimental analysis and theory study on EAST.

The edge current reconstruction is based on the theoretical bootstrap current and Ohmic current model. So the question is how is the reliability of the bootstrap current model at the edge region? The experiments analysis on DIII-D and on ASDEX-U gave us a positive answer. On DIII-D, the MSE measurement analysis [20] and the lithium beam measurement analysis [21] separately confirmed that the edge current is dominated by bootstrap current. The newly developed reconstruction technique on ASDEX-U [7, 12] gave us more confidence. With the technique, the edge current reconstruction can only rely on the magnetic measurements. Generally the external magnetic measurements are more accurate and reliable then other measurements. In [12], it is showed that the reconstructed edge current aligns the theoretical calculated current (bootstrap current plus Ohmic current).

For our reconstruction the error quality function χ^2 seems good. However, based on our present diagnostics and technique, it is hard to give the real variances of the pressure and current profiles. These are the quantities people care for. The variance of edge current may be large, because the bootstrap current calculation relies on the kinetic profile's differentiations, which will amplify the measurement errors in the kinetic profiles [6] developed a method, could systematically analyze all the variances. We planned to implement the technique. With these new technique and improved diagnostics, we can get more reliable equilibrium.

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