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Observation of poloidal current flowed to the vessel after failure of vertical position feedback control in EAST Tokamak*

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Plasmas with vertically elongated cross-sections tend to be unstable to an axis-symmetric instability. This paper studies the magnetohydrodynamic equilibria in elongated plasmas after failure of vertical feedback control by using magnetic data for EAST device. Vertical forces on the vessel due to the induced polodial and toroidal currents are evaluated. The maximum force of the $Fz_{\rm pol}$ in vertical displacement events for EAST designed parameters is given.

Keywords: equilibrium reconstruction, vertical stability, scrape-off layer
PACC: 5255, 5235P, 5255G

1. Introduction

Plasmas with vertically elongated cross-sections tend to be unstable to an axis-symmetric instability.[1] This stability is generally maintained by a feedback control system, which involves control of coil inside and outside the vacuum vessel. When the feedback system fails to keep plasma in its original position, a vertical displacement event (VDE) develops. During the vertical motion of the plasma, the vessel wall experiences a vertical reaction force to slow down the plasma motion.[2,3] This vertical force can be large enough to be concerned.

Such forces were observed in JET,[4] PBX-M[5] and DIII-D,[6−8] when the control system could not maintain this stability. These forces result from the interaction between currents in the vacuum vessel and the magnetic field. An understanding of these forces is important for avoiding damage to the vessel and related structures in future experiments.

As a vertically moving discharge comes into contact with the vessel wall, some of the plasma current flows partially in the plasma and partially in the vessel. Reference [5] reported that the net vertical force of $\boldsymbol{J} \times \boldsymbol{B}$ could be quite large because the poloidal vessel current is not uniform. A method of this equilibrium with attached currents was described in an earlier paper[9] and then introduced in magnetohydrodynamic (MHD) equilibrium reconstruction.[10] A purpose of the present study is to investigate the vessel forces due to the induced poloidal and toroidal vessel in EAST device.

Many EAST discharges were disrupted after failure of feedback control of the vertical instability. Measurements of probes at different toroidal locations show that plasma shapes during this event are close to axis-symmetric. Poloidal currents flowing in the scrape-off layer (SOL) are introduced by allowing the FF' term in the Grad–Shafranov equation to be nonzero outside the last closed flux surface. Details of this will be presented in Section 2. Section 3 gives the results of the analysis using EAST data. A summary is given in Section 4.

2. Equilibrium technique

In an axis-symmetric toroidal system, the MHD equilibrium Grad–Shafranov equation can be written

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as

$$\Delta^* \psi = -\mu_0 R J_{\rm t},$$
$$J_{\rm t} = RP'(\psi) + \frac{\mu_0 FF'(\psi)}{4\pi^2 R} G, \quad (1)$$

where R is the cylindrical radial co-ordinate, $J_{\rm t}$ is the toroidal current density, and ψ is the polodial magnetic flux per radian. $G(R, Z)$=1 if (R, Z) is inside the vacuum vessel; Otherwise, $G(R, Z)$=0. In Ref.[11], by using a set of basis functions, y_n, the two stream functions $P'(\psi)$ and $FF'(\psi)$ are represented in terms of a number of linear parameters, α_n and γ_n, as

$$P'(\psi) = \sum_n \alpha_n y_n(x), \quad (2)$$

$$FF'(\psi) = \sum_n \gamma_n y_n(x). \quad (3)$$

The unknown parameters α_n and γ_n are then determined from all available magnetic data M_i by minimizing

$$\chi^2 = \sum_i \left(\frac{M_i - C_i}{\sigma_i} \right)^2, \quad (4)$$

where σ_i is the uncertainty associated with the ith magnetic measurement, C_i is the calculated values by mutual-inductance. A key assumption is that plasma currents carried by the main body of the plasma, i.e. the plasma does not intersect the vacuum vessel. $x = (\psi - \psi_0)/(\psi_1 - \psi_0)$ is the normalized poloidal magnetic flux, ψ_0 and ψ_1 are the poloidal magnetic flux at the magnetic axis and at the plasma boundary, and $0 \le x \le 1$. However, during VDEs, current can flow along the open magnetic field lines outside of the plasma boundary. This is modelled using an attached current model by letting $x = (\psi - \psi_0)/(\psi_\mu - \psi_0)$ in the FF' term.[10] Here, ψ_μ is a poloidal flux parameter to describe the open field line attached current region outside of the plasma boundary, which is defined as

$$\psi_\mu = \psi_v + \mu(\psi_1 - \psi_v), \quad (5)$$

where ψ_v is the lowest value of the poloidal flux at the external separatrix in the SOL outside the main body of the plasma. Here $\mu = 1$ corresponds to the case where the plasma current only in the main body, while $\mu = 0$ corresponds to the case where part of the plasma current is permitted to flow in the SOL.

3. Results analysis

EAST device has a major radius R_0 of 1.75 m and a midplane halfwidth of 0.5 m. The reconstructions typically utilize data from magnetic diagnostics including PF coils currents, 37 flux loops, 76 magnetic probes (tangential and normal direction together) and a Rogowski coil measuring the total toroidal current of the plasma. Figure 1 shows the polodial cross-section of the EAST device, illustrating the diagnostics, vacuum vessel, PF coils and typical single-null configuration from fixed boundary calculation.

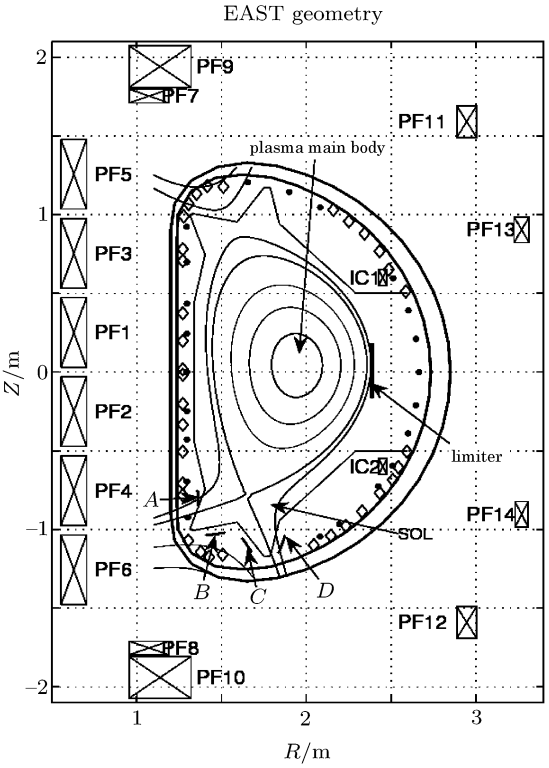


Fig.1. Cross-section of the EAST device, showing the locations of all the 14 PF coils, the flux loops (close circle) and the magnetic probes (open diamond). (A, B, C and D are the locations of Rogowski loops for the halo current).

A set of measured vacuum flux loop and magnetic probe signals obtained by powering the PF coils in the absence of plasma are compared with the predicted values using the EFIT code. To ensure that no current is induced in the vacuum vessel, the currents in the PF coils are held at their flat-top values for a period much longer than the resistive skin time of the vessel (∼15 ms). As shown in Fig.2, most of the predicted and the measured values agree with each other. Details of testing the adequacy of the method used to reconstruct attached equilibria are well documented in Ref.[10]. As part of the EAST magnetic diagnostic system, Rogowski loops have been installed behind the supporting structure of divertor plate and dome (A, B, C, and D in Fig.1). They measure the poloidal current flowing through the supporting structure, which corresponds to part of halo current. The raw signal

from each Rogowski loop is passed through an active integrator to obtain a voltage which is proportional to the current linked by the loop.

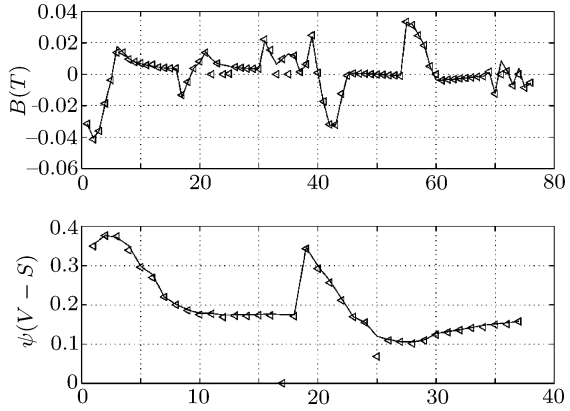


Fig.2. Comparison of the measured magnetic signals (triangle) with the predicted values (curve) for a EAST vacuum shot 4442# with no plasma.

Time traces for a vertically elongated discharge which ended in a vertical instability are shown in Fig.3. The plasma current in the figure was from the standard Rogowski loop inside the vessel. Major parameters of this shot before VDEs are given in Table 1. The midplane soft x-ray, and the poloidal magnetic field from magnetic probes located at two different poloidal positions (top and bottom) indicate that the discharge began to move downward at about 4526ms. Partial toroidal current started to flow in the SOL between the plasma main body and the vessel wall.

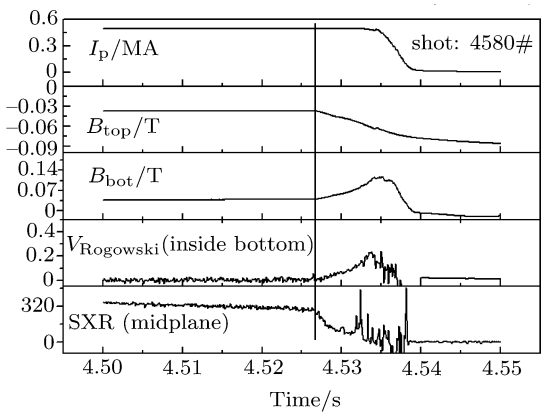


Fig.3. Time traces for an ohmic discharge 4580, which ended in a vertical instability (B_T=2 T, I_p=0.5 MA). The traces shown are: plasma current, magnetic probes located on the top and bottom, and soft x-ray viewing the midplane.

Table 1. Major plasma parameters for EAST discharge 4580 at 4520ms before disruption.

plasma current I_p	0.5 MA
major radius R	1.81 m
minor radius a	0.47 m
elongation ratio κ	1.69
upper triangularity δ_U	0.33
upper triangularity δ_L	0.39
internal inductance l_i	1.04
toroidal field B_T	2.0 T

In Fig.4, the χ^2 values at several time slices after disruption are presented with various values of the attachment parameter μ in the range $0 \le \mu \le 1$ fitting the available magnetic data. For values of $0 \le \mu \le 0.5$, the χ^2 values vary very slowly. However, for $\mu > 0.5$, χ^2 increases very quickly. No satisfactory fitting to the magnetic data can be obtained for $\mu = 1$ with the critical value $\chi^2 = 60$, showing that the poloidal current flowing in the SOL can not be ignored in the reconstruction. By using EFIT code, Fig.5 shows the poloidal current in the SOL, I_{pol}, the toroidal vessel current, I_v, and the vessel vertical forces due to the toroidal and the polodial currents flowing in the vessel, $Fz_{pol} = J_p \times B_\phi$, $Fz_{tor} = J_\phi \times B_p$ (the subscripts p and ϕ represent the poloidal and toroidal direction respectively), with the parameter μ for EAST discharge 4580 at 2532 ms. As shown in this figure, I_{pol} in the SOL and I_v in the vessel are found to be rather insensitive to the width chosen (μ) for the SOL. However, the vertical force Fz_{pol} on the vessel is a stronger function of μ values because it depends on the distribution of currents in the vessel.

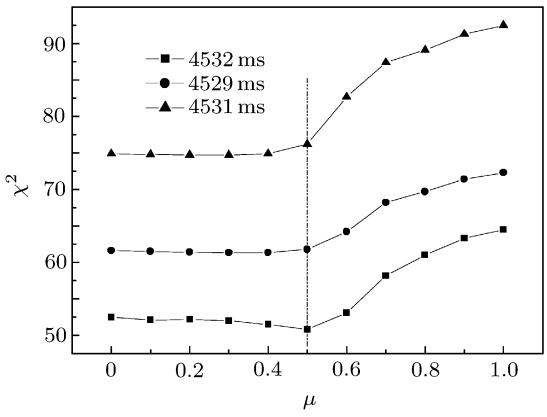


Fig.4. Comparison of χ^2 with various values of μ at three time slices after the plasma has lost its vertical stability for EAST shot 4580.

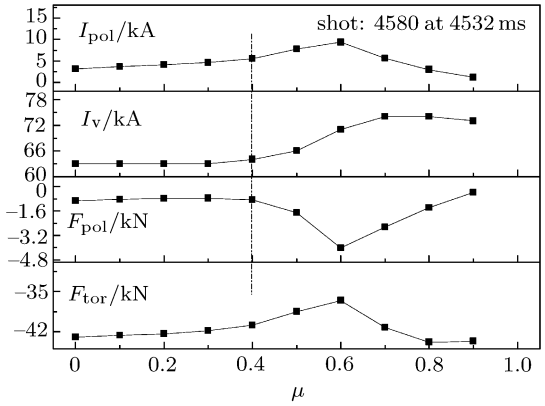


Fig.5. Variation of the poloidal current in the SOL, I_{pol}, the toroidal currents in the vessel, I_v, and the vessel vertical forces due to the toroidal and the polodial currents flowing in the vessel, Fz_{pol}, Fz_{tor}, as a function of the parameter μ in the equilibrium reconstruction for EAST discharge 4580 at 4532 ms.

Several equilibrium plots illustrating the plasma disruption are shown in Fig.6. As the plasma moves downward, the poloidal current region of the SOL becomes wider (dashed line away from the plasma main body gradually). Figure 7 shows the time evolution of I_{pol}, I_v, Fz_{pol} and Fz_{tor}. Note that no satisfactory fitting results are shown in the figure after 4535ms. The major source of this problem in the reconstruction is, of course, the lack of probes information behind the divertor. The magnetic probes are more sensitive to changes in the plasma conditions than the flux loops.[10,12] The equilibrium calculation indicates that the vertical forces decrease monotonically due to the calculated poloidal current. However, the peak point of the vertical forces (40 000 N) due to the toroidal current appears at 4532 ms. The force due to the poloidal current is always downward, while the force due to the toroidal current changes signs during the vertical instability.

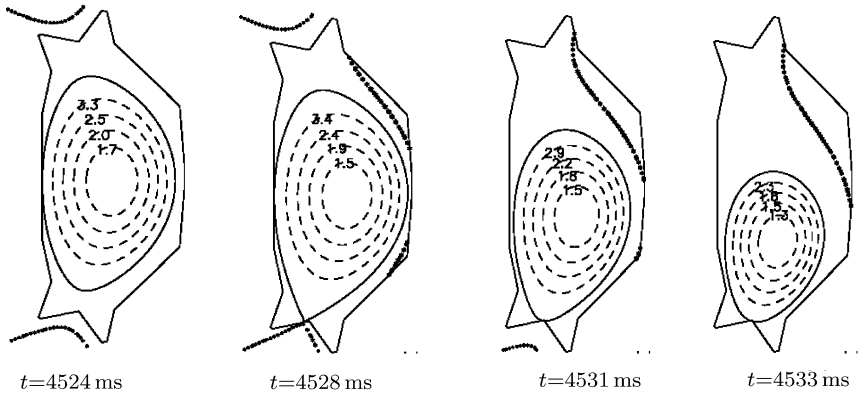


Fig.6. Reconstructed flux surfaces at several time slices after the plasma has lost vertical stability for EAST shot 4580.

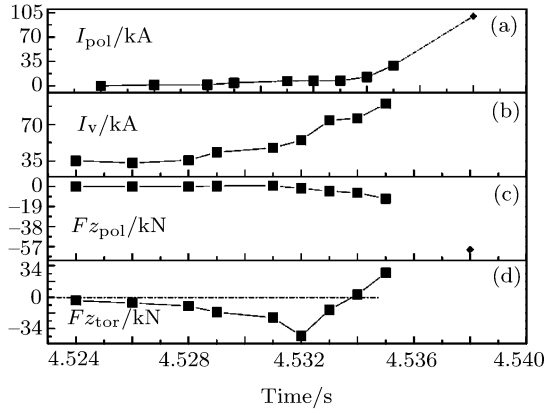


Fig.7. Time evolution for EAST discharge 4580 after failure of vertical position feedback control. (a) Poloidal current (calculated by EFIT) in the SOL. (b) Toroidal current in the vessel wall. (c) and (d) Vertical force on the vessel wall produced by poloidal and toroidal currents. The diamond point shown in the figure is computed by the model.

The poloidal current was measured by the Rogowski loops surrounded on the supporting legs behind the plate. It is difficult to measure all poloidal current in SOL because of room limitation to mount Rogowski loops on all supporting legs behind the plate. All mounted Rogowski loops (A, B, C, and D), which measured the poloidal currents are presented in Fig.8(a–d). We note that the sum of the currents is not zero. The absolute value of current A plus B is higher than that of C and D due to asymmetric distribution in poloidal direction. The poloidal current determined from the MHD equilibrium fits is in agreement with the value from the more direct Rogowski loop ($A+B$) measurements before 4533 ms, as seen in Fig.8(e). This implies that most poloidal current flows through these two legs and the relative narrow region

of SOL. As the region of SOL becomes wider, the currents measured by these two Rogowski loops represent only partial poloidal currents and hence were smaller than those calculated. All current flow from the SOL to the structure will be measured by full set of the magnetic diagnostics with the new built in-vessel structure and components in the next experiment.

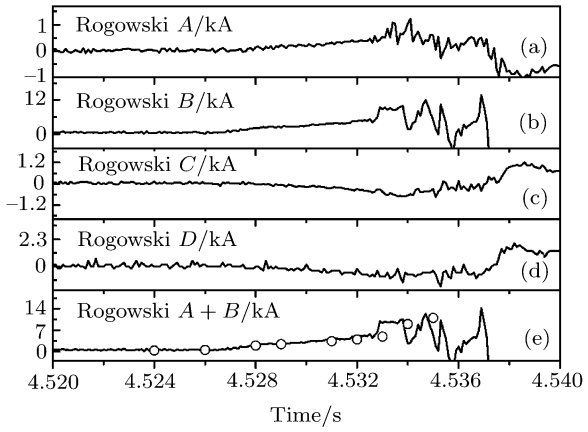


Fig.8. Currents in Rogowski loops A, B, C and D (a–d) during discharge 4580. Comparison (e) of measured (loops A and B) and calculated poloidal scrape off layer current.

We further reckon the maximum force due to the poloidal current in the SOL. According to the model developed in Ref.[13], the force on the vessel due to the poloidal current is $Fz_{\rm pol} \sim aI_{\rm pol}B_{\rm T}$, here a is the characteristic length for the current flow through the vessel, typically assumed to be the plasma minor radius and the maximum poloidal current driven $I_{\rm pol}$ is about 20% of the pre-disruption plasma current.[6,8,13] So the peak force due to the poloidal current is 60,000N by this model for the shot 4580 (see the diamond point in Fig.7). For the designed EAST parameters ($I_{\rm p}$=1 MA, $B_{\rm T}$=3.5 T, a=0.45 m), the maximum force due to the poloidal current in the SOL will be up to 315000N in VDEs.

4. Summary

In summary, the analysis of results based on the reconstruction of MHD equilibria using magnetic data shows that a current may flow along the open field lines in the SOL between the plasma main body and the vacuum vessel wall. One Rogowski loop installed behind the structure partly measured the existence of attached currents in SOL. The peak force due to the poloidal current calculated by the model indicates that this force can be very large for uncontrolled vertical motion discharges. New and upgraded diagnostics are installed. All these are expected to help understanding the SOL current and related phenomena.

References

[1] Wesson J A 1978 *Nucl. Fusion* **18** 87
[2] Hofmann F, Dutch M J, Favre A, Martin Y, Moret J and Ward D J 1998 *Nucl. Fusion* **38** 399
[3] Jardin S C and Park W 1981 *Phys. Fluids* **21** 721
[4] Noll P, Aigle R, Browne M and Corbyn D in: 1985 *Fusion Engineering* (*Proc. 11th Symp.* Austin, TX) Vol. **1** (New York: IEEE) p33
[5] Kugel H W, Asakura N and Bell R in: 1989 *Controlled Fusion and Plasma Physics* (Proc. 16th Eur. Conf. Venice), Vol. **13B** Part I, European Physical Society 199
[6] Schaffer M J and Leikind B J 1991 *Nucl. Fusion* **31** 1750
[7] Reis E E and Baxi C B in: 1987 *Fusion Engineering* (Proc. 12th Symp. Montery, CA) Vol. **1** (New York: IEEE) p212
[8] Strait E J, Lao L L, Luxon J L and Reis E E 1991 *Nucl. Fusion* **31** 527
[9] Jensen T J and Chu M S 1989 *Phys. Fluids* B **1** 1545
[10] Lao L L and Jensen T H 1991 *Nucl. Fusion* **31** 1909
[11] Lao L L, St. John H and Stambaugh R D 1985 *Nucl. Fusion* **25** 1611
[12] Strait E J 2006 *Rev. Sci. Instrum.* **77** 023502
[13] Kellman A G, Ferron J R and Jenson T H in: 1991 *Proc. 16th Symposium on Fusion Technology* (London 1990) (Asmterdam: Elsevier) vol. **2** p1045