Plasma Shape Feedback Control on EAST

Q.P. Yuan 1), B.J. Xiao 1), Z.P. Luo 1), M.L. Walker 2), A.S. Welander 2), A. Hyatt 2), J.P. Qian 1), D.A. Humphreys 2), J.A. Leuer 2), R.D. Johnson 2), B.G. Penaflor 2), D. Muller 3)

1) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
2) General Atomics, DIII-D National Fusion Facility, San Diego, CA, USA
3) Princeton Plasma Physics Laboratory, Princeton, New Jersey

Email: qpyuan@ipp.ac.cn

Abstract. The shape feedback control was realized for diverted plasma using RTEFIT for the plasma equilibrium reconstruction and ISOFLUX control method in EAST PCS (EAST Plasma Control System). In a typical divertor plasma discharge, the plasma shape is feedback controlled from circular shape to elongated and fully diverted shape using different control algorithms. The smooth shape transition is essential for volt-seconds saving and plasma disruption avoidance. In order to achieve such aim, there is a trajectory used in EAST PCS for switching the control methods. The implementation details and experiment results are presented in this paper. Now, EAST has obtained stable double-null plasma operation for longer than 60 seconds with auxiliary heating and current drive by Low Hybrid Wave.

1. Introduction

EAST (Experimental Advanced Superconducting Tokamak) is the first tokamak with ITER-like fully superconductive poloidal and toroidal coils. As shown in FIG. 1, it is a toroidal device with a poloidal D-shape cross section and double-layer vacuum vessel. In the EAST tokamak, there are twelve poloidal field coils available to the plasma control system. The PF7 and 9 (PF8 and 10) are connected in series, which is treated as one coil. Each poloidal coil is driven by an individual power supply. Besides, two normal copper coils (IC1 and IC2) connected in anti-series are installed inside the vacuum vessel to provide vertical stabilization for elongated plasma.

For plasma control in tokamak, accurate magnetic measurement and effective reconstruction are essential, since the plasma position and shape parameters can't be measured directly but only reconstructed from magnetic data. In EAST, 38 poloidally aligned magnetic probes measuring tangential field and 35 flux loops measuring poloidal flux are mounted on the vacuum vessel as shown in FIG. 1. And the plasma current and poloidal coil currents are measured by rogowski coils. In the plasma shape control system, the real-time equilibrium reconstruction code (RTEFIT) [1] is applied for the plasma shape calculation. The comparison results of RTEFIT and offline EFIT are presented in the paper.

Since the first plasma was obtained in 2006 [2], EAST has achieved stable plasma current and position control, and diverted plasma operation. The control logic in EAST PCS and experiment results are discussed in section 2 and 3. In a typical divertor plasma discharge, the plasma is feedback controlled from circular shape to elongated and fully diverted shape using different control algorithms. The smooth shape transition is essential for volt-seconds saving and plasma disruption avoidance. The shape transition trajectory and some experiment results are reported in section 4.

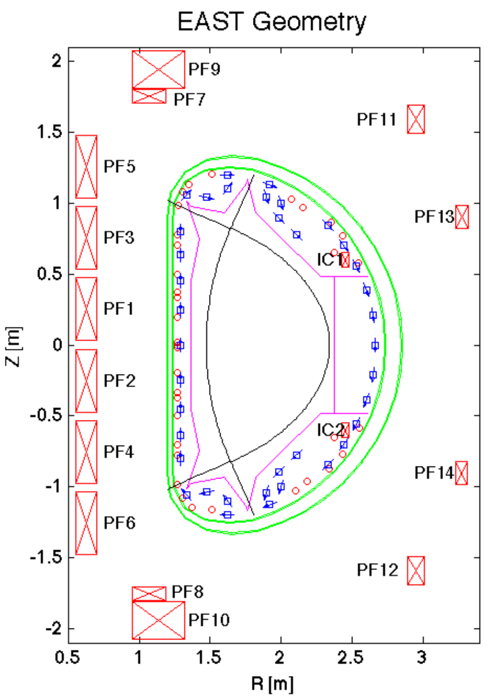


FIG. 1. EAST cross section and magnetic diagnostics distribution with flux loops (circle) and magnetic probes (square).

2. Plasma current and position control

Tokamak discharge relies on good plasma control system (PCS). EAST PCS, adapted from DIII-D plasma control system [3-5], has served all the EAST operation campaigns and is still being developed to satisfy the experimental needs [6-8].

The plasma current and position control is called RZIP control in EAST PCS. The control parameters are feedback controlled by adjusting the current in poloidal field (PF) coils. The requested PF coil current is composed of feedforward part and the feedback part. The control logic is shown in FIG. 2.

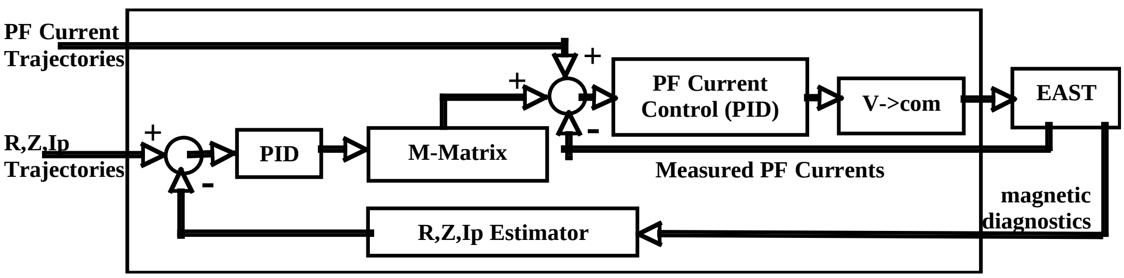


FIG. 2. Control logic of EAST RZIP algorithm

In a control cycle, the plasma current Ip is measured directly from rogowski coil, but the radial and vertical position of plasma current center can only be calculated by the estimator using magnetic diagnostic data [9]. With PID operation and decoupling calculation, the requested adjust value for PF coil current is achieved. Then the corresponding command for power supply is generated with PF current PID calculation.

In EAST experiment, the plasma current is mainly controlled by PF1-8, while the plasma position is controlled using PF11-14. Besides, the inner coils are used for plasma fast vertical movement control. FIG. 3 shows the achieved position control performance. We set a triangle wave target for R or Z on the current flattop in two separate shots, shot 10112 and shot 10113. The vertical position of plasma center followed the target perfectly with control error in 1 mm. Due to the time for magnetic field penetration into the vacuum vessel, plasma radial position followed the target a little bit slower. But after the target was traced, the R control error was in 2 mm. Such RZIP control algorithm has obtained stable and excellent control performance in EAST experiment.

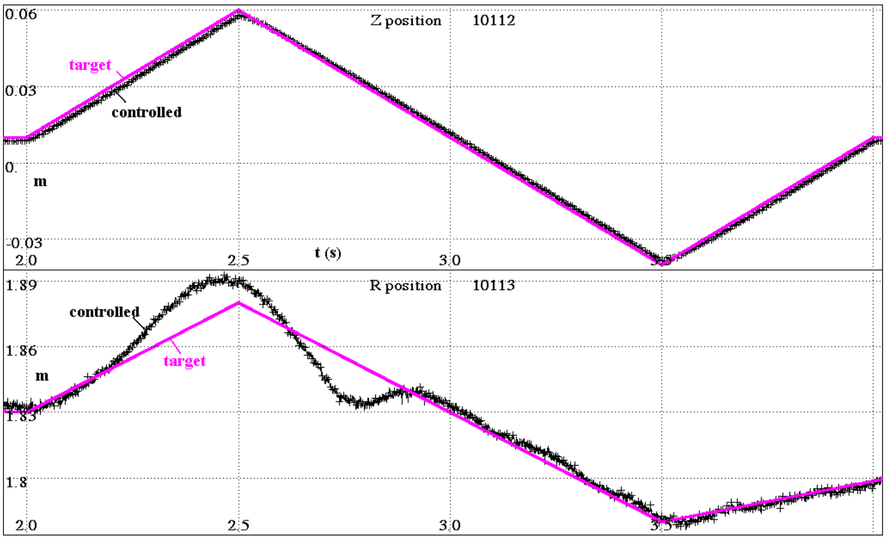


FIG. 3. Plasma R, Z control result for EAST shot 10112 and 10113, target in magenta solid line and controlled result in black cross.

3. Plasma shape control

Precise shape control is essential to avoid the first wall damage from high energy plasma and obtain better coupling between plasma and RF wave. On EAST, the shape feedback control is realized using the ISOFLUX control method. As the key concept of ISOFLUX control, plasma target shape is interpreted as a set of control points, and the flux at each control point is controlled to be equivalent [10]. Usually, one of the control points is chosen as reference point which is on limiter in a limited configuration or X points in a diverted configuration. Thus the plasma boundary is controlled by adjusting the PF coil current to eliminate the flux error between the reference point and other control points. Since the plasma shape cannot be measured directly but only reconstructed from magnetic data, fast and accurate equilibrium reconstruction is essential for the plasma shape control.

3.1. Equilibrium reconstruction

The EFIT reconstruction provides a least square best fit to the diagnostic data and satisfies the model given by the Grad-Shafranov equation [11]. From such full reconstruction calculation, the plasma pressure, current flux function, poloidal beta, internal inductance and the parameters of plasma shape and position can be obtained. However such heavy computation is not fast enough for plasma control, so the RTEFIT algorithm modified from offline EFIT is used for the fast equilibrium solution in PCS [1].

The real-time reconstruction algorithm consists of a fast loop and a slow loop running on two CPUs separately. The fast loop does the fitting calculation for poloidal current source including external coils and plasma current in each grid. Then the flux error on each control point compared with the reference flux is transferred to the ISOFLUX control algorithm. And the slow loop completes the steps required in the reconstruction iteration to prepare a new data set including response vector and normalized flux for fast loop.

3.2. Comparison between RTEFIT and offline EFIT

For RTEFIT code, the most important modifications to offline EFIT are the one iteration calculation and the reuse of the data set in fast loop. Each time the fast loop is executed with a new set of diagnostic data, but the same data set is reused until a new one is updated by the slow loop.

The RTEFIT has reasonable accuracies in DIII-D and NSTX [1]. The comparison for RTEFIT and offline EFIT is also done on EAST. Firstly, the one iteration solution based on a chosen reference time and a well-converged solution from offline EFIT was compared [12]. The results show that one iteration solution is close enough to the well-converged reconstruction when the change of normalized flux is small.

Secondly, using the same snap setting and magnetic diagnostic data, the reconstructed results were compared. FIG. 4 (a) shows the flux distribution on grids with size 33x33 for both the RTEFIT (blue contour) and offline EFIT (red contour) at time 2.39 s of shot 21143. The result shows perfect consistency especially for the plasma boundary. And the calculated results on magnetic diagnostics are shown in FIG. 4 (b). The bad signals were eliminated, such as FL12, FL33, FL34 for flux loops and BP11, BP19 and so on for probes, since they were not used in RTEFIT calculation for the shot. The calculated diagnostic data from the two reconstruction codes matched well. Although there are few differences of some reconstructed parameters [12], the RTEFIT result is accurate enough for plasma shape control.

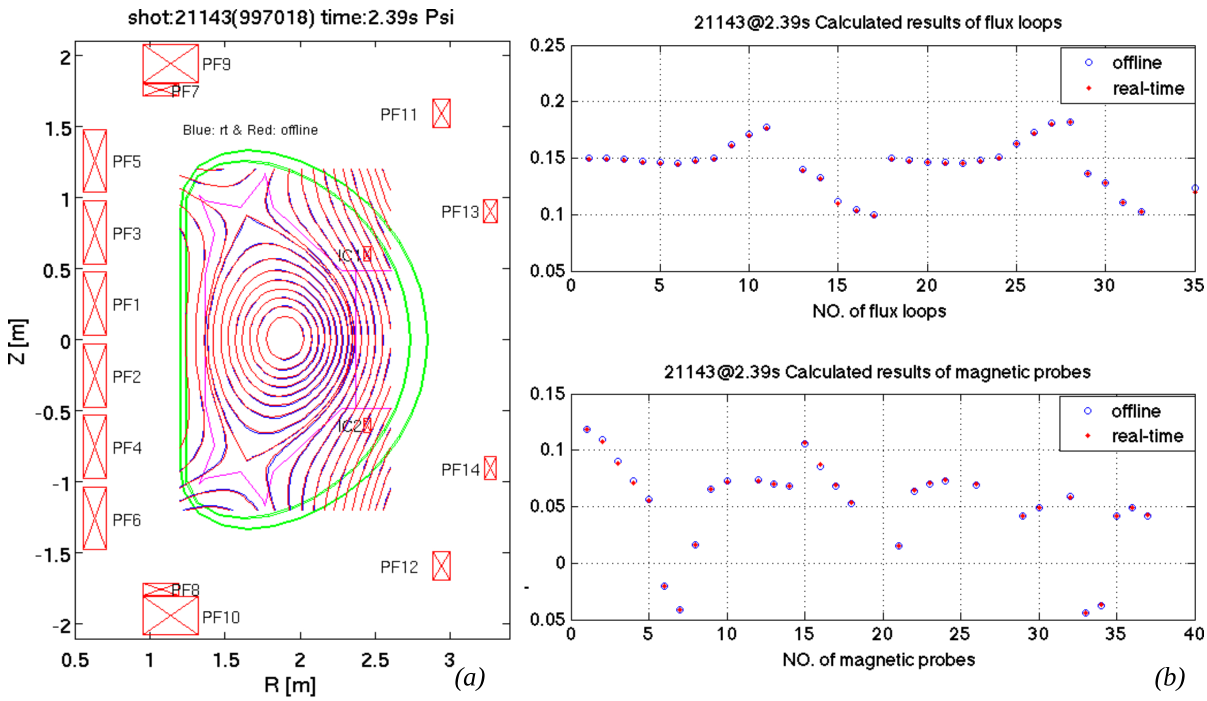


FIG. 4. Comparisons between RTEFIT and offline EFIT at 2.39 s of EAST shot 21143. (a) Flux distribution comparison; (b) Reconstruction result for flux loops in unit of web/radian and magnetic probes in unit of Tesla.

3.3. ISOFLUX control algorithm

In EAST PCS, there are two ISOFLUX control algorithms called ISO-elong and ISO-dnull algorithm for elongated limiter and double null diverter plasma shape control. The basic control logic of the algorithms is shown in FIG. 5.

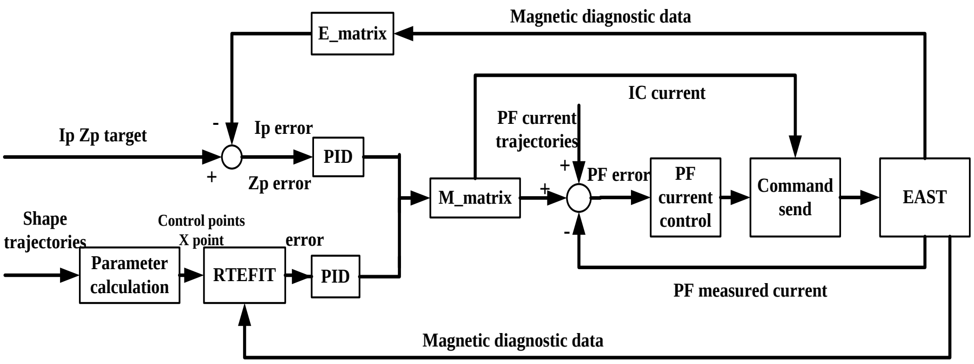
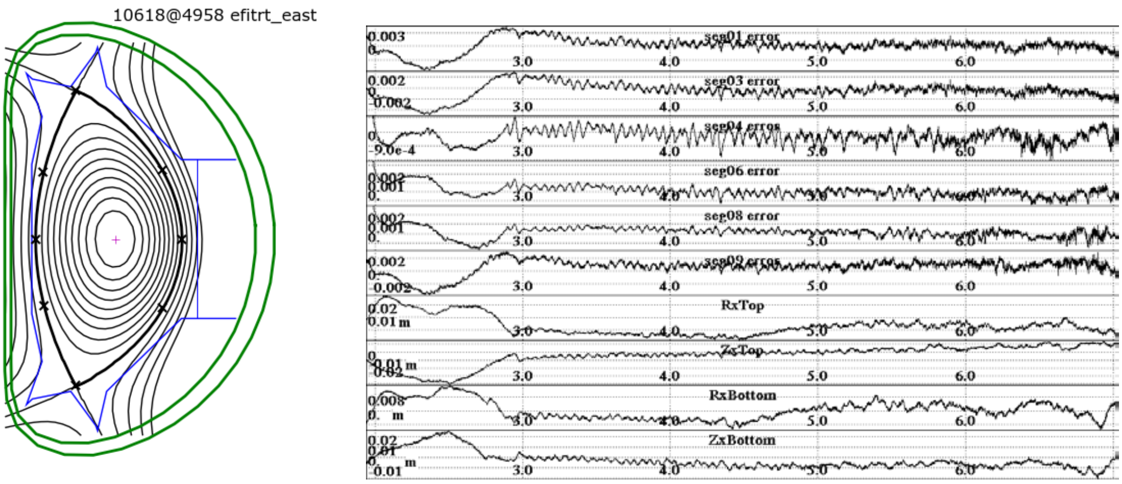


FIG. 5. Control logic of EAST ISOFLUX algorithm

When the plasma shape is reconstructed, the position of characteristic points such as the X points or limiter point is found. The maximum flux of the characteristic points is used as reference flux. Then the ISOFLUX algorithm uses the errors between the flux at each control point and the reference flux as input to a PID controller as shown in FIG. 5. Each control point is controlled by one or two nearby PF coils. And the plasma current is mainly controlled using PF1-6. The required PF coil current is obtained after decoupling calculation and adding the feedforward current. Then the corresponding power supply voltages are determined after the PF coil current control loop.

On EAST, typical growth rate for the discharge up to now is about 200-300/s. For a higher elongation and higher plasma parameters, the growth rate might be above 1000/s [13]. This requires fast vertical position calculation and fast response power supply to provide the vertical stabilization. Thus, in the ISOFLUX control algorithm the plasma vertical position is estimated in the same way as RZIP control algorithm and controlled using inner coils.

Taking shot 10618 for example, it is a typical double-null shape discharge with elongation 2.0 and plasma current up to 250 kA. The ISO-dnull algorithm took control after 2.7 s. And the plasma shape is perfectly controlled as shown in FIG. 6 (a) drawn in data display tool EAST VIEWER [14]. The plasma boundary crossed with each control point and two X points. The flux control errors on each selected segment are shown in the first 6 plots of FIG. 6 (b), while the X points control errors are shown in the last 4 plots. After t=3 s, the flux control error is less than 0.001 Vs/radian and X point control error is less than 1 cm during the whole plasma flat top. Such results indicate that the plasma shape is controlled accurately and stably using ISOFLUX control method.



(a) *(b)*

FIG. 6. (a) The controlled plasma shape for EAST shot 10618 at time 4.958s. (b)The control errors on each segment and X points during shot 10618

4. Shape transition trajectory

In a plasma discharge, the basis position control is applied after initial breakdown using the RZIP control algorithm, and then switched to the shape control using ISOFLUX control algorithm. As a result, the plasma starts at a limited configuration, and then gradually be expanded, elongated and finally forms a diverted configuration. A smooth shape transition is essential for volt-seconds saving and plasma disruption avoidance. In order to achieve such transition, there is a trajectory used in EAST PCS for switching the control methods. The control commands to poloidal filed power supply can be combined with RZIP control commands and ISOFLUX commands at some ratio. Then the control methods are transitioned by varying the ratio from 0 to 1 in a preset time. Besides, the ISO-elong control is often used to be a transition phase for RZIP control to ISO-dnull control, since the plasma shape is gradually elongated from limited to diverted configuration.

In EAST shot 13928, the transition period was set from 0.5 s to 0.6 s. After the transition period, ISO-elong took the overall control from RZIP control at plasma ramp-up phase where the plasma current was about 150 kA and the plasma was circular. Then the plasma was gradually elongated and current was about 300 kA. At time=1.8 s, the ISO-dnull algorithm was used for plasma double null shape control. The plasma shape evolution during the shot is shown in FIG. 7. The plasma shape transition is rather smooth. And the shape is stably controlled during the whole plasma flat top with plasma current about 300 kA and elongation 2.0. In shot 14865, we reached long pulse discharge up to 62 seconds for plasma current of 250 kA with the low hybrid wave power up to 600 kW. And bias single null discharge is realized using ISO-dnull algorithm by controlling the gap at mid-plane for two separatrixes.

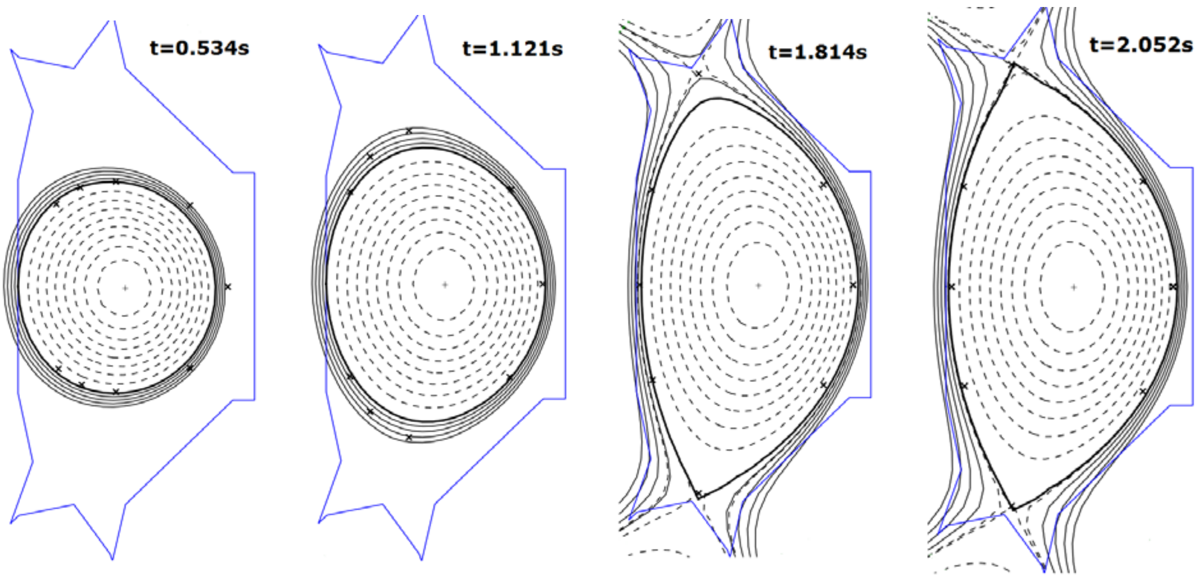


FIG. 7. The plasma shape evolution for shot 13928 at time=0.534 s, 1.121 s, 1.814s, 2.052 s

5. Summary

Good shape feedback control has been realized. The plasma shape is transitioned from limited to diverted configuration smoothly. The single null diverted plasma control algorithm has been implemented in EAST PCS. The algorithm verification and optimization of control parameters are going to be carried out in the coming EAST campaign.

Acknowledgement

This work is supported by National Nature Science Foundation of China with contract number. 10835009, the Key Project of Knowledge Innovation Program of Chinese Academy of Sciences with project number KJCX3.SYW.N4, the National 973 Project with number 2009GB103000 and the Knowledge Innovation Program of Hefei Institutes of Physical Science, project number 085FCQ0128.

Reference

[1] J.R. Ferron, M.L. Walker, L.L. Lao, et al., "Real time equilibrium reconstruction for tokamak discharge control", Nuclear Fusion, Vol. 38, pp1055-1066, 1998

[2] B. J. Xiao, et al., Proc. 34th European Conf. Plasma Physics, Warsaw, 2007 edited by Pawel Gasior and Jerzy Wolowski (European Physical Society, 2007) vol. 31F, paper O4_014, http://epsppd.epfl.ch/Warsaw/pdf/O4_014.pdf

[3] M.L. Walker, J.R. Ferron, D.A. Humphreys, R.D. Johnson, et al., "Next-generation plasma control in the DIII-D tokamak", Fusion Engineering and Design, 2003, Vol. 66-68, pp749-753

[4] D. Humphreys, et al., "DIII-D Integrated Plasma Control Solutions for ITER and Next-Generation Tokamaks", 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research, 4 - 8 June 2007, Inuyama, Japan

[5] B. Penaflor, J.R. Ferron, M.L. Walker , et al., "Worldwide Collaborative Efforts in Plasma Control Software Development", 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research, 2007, Inuyama, Japan

[6] Q. P. Yuan, B.J. Xiao, B.G. Penaflor, D.A. Piglowski, et al., "New achievements in the EAST Plasma Control System", 2010, Fusion engineering and design, vol. 85, p474

[7] B.J. Xiao, D.A. Humphreys, M.L. Walker, A. Hyatt , J.A. Leuer, B.G. Penaflor, D.A. Pigrowski, R.D. Johnson, A. Welander, Q.P. Yuan, H.Z. Wang, et al., "EAST plasma control system", Fusion engineering and design, 2008, vol.83, p181

[8] Q.P. Yuan, B.J. Xiao, M.L. Walker and H.Z. Wang, "Implementation of Gas Control Algorithm in the EASTPCS", Plasma Science and Technology, 2009, Vol.11, No.2, pp231-235

[9] D.A. Humphreys, J.A. Leuer, M.L. Walker, "EAST, KSTAR PCS Control Design Using EPG Matlab Codes", General Atomics Engineering Physics Memo: EPMdah070111a-EPCSCtrlDes2, 2007

[10] M.L. Walker, D.A. Humphreys, J.R. Ferron, "Control of plasma poloidal shape and position in the DIII-D tokamak", 1997, Proc of the 36th IEEE CDC, San Diego, CA

[11] L.L. Lao, H.St. John, R.D. Stambaugh, A.G. Kellman, W. Pfeiffer, "Reconstruction of current profile parameters and plasma shapes in tokamaks", Nuclear Fusion, 1985, Vol. 25, pp1611-1622.

[12] Z.P. Luo, B.J. Xiao, Q.P. Yuan, Y. Guo, "Verification of EAST Plasma Equilibrium Reconstruction Using RT and Offline EFIT", EAST Plasma Control Memo: PCMlzp20100822, 2010

[13] Liu Lei, Xiao Bingjia and Luo Zhengping, "Simulation of the Growth Rate of Vertical Displacement Events and the Requirement of Active Feedback Power Supply in EAST", Plasma Science and Technology, 2009, Vol. 11, No.1, pp28-32

[14] R.R. Zhang, "Instructions for EAST-VIEWER", EAST internal documents, rrzhang@ipp.ac.cn