TSC Simulation and Prediction of Ohmic Discharge in EAST

Yong Guo 1), Bingjia Xiao 1), Bin Wu 1), Chengyue Liu 1)

1) Institute of Plasma Physics, Chinese Academy of Science, Hefei, 230031, China

E-mail: yguo@ipp.ac.cn

Abstract: EAST is the full superconducting tokamak with D-shaped cross-section, which forms different plasma shape with elongation of 1.5-2.0, triangularity of 0.3-0.5, major radius of 1.8 m and minor radius of 0.4 m. The Tokamak Simulation Code (TSC), a two-dimensional time dependent free boundary simulation code, has been a very useful tool both in analyzing experimental data and designing future tokamaks for many years. It has been used to model the time dependence of ohimc discharges in the EAST experiment for several years. The simulation results follow the experimental PF current, plasma current and position to a very good accuracy. Neoclassical resistivity gives good match with the measured surface voltage. On the basis of one good simulation, several predictions with different higher plasma current have been done by TSC. These predictions results are confirmed by the followed experiment. It proves the ability of TSC as predictive tool for EAST plasma discharge, and gives us a good confidence to predict 1MA ohmic discharge on EAST.

1. Introduction

Experimental Advanced Superconducting Tokamak (EAST) is the full superconducting tokamak with D-shaped cross-section (FIG. 1). Twelve superconductive poloidal field coils (PF7 and PF9, PF8 and PF10 connect together, respectively) can be individually charged to form different shapes with elongation of 1.5-2.0, triangularity of 0.3-0.5, major radius of 1.8 m, and minor radius of 0.4 m. The Tokamak Simulation Code (TSC) [1] is a numerical model of axisymmetric tokamak plasma and the associated control system. It has been used many years for analyzing experimental data and designing future tokamaks. In general, good agreement with a wide range of experimental data in simulating EAST discharge give us a great confidence in using TSC as predictive tools for the further experiment.

The paper briefly presents the models used for ohmic discharge simulation. On the EAST rectangular computational grid, the code evolves the experimental plasma current and position, PF current wave, and central temperature trajectory. On the basis of good simulations, several predictions of different plasma shape discharge have been done by TSC. With the help of PCS, the plasma follows the predictive evolution. It directly proves TSC as predictive tool to direct EAST discharge. Further, 1MA ohmic discharge on EAST is simulated, and the requirements of PF coils are estimated.

2. TSC Simulation Mode

TSC evolves a two dimensional time dependent free boundary simulation code, which advances the MHD equations describing the transport time-scale evolution of axisymmetric magnetized tokamak plasma. It solves the initial free boundary equilibrium on the rectangular computational grid for the given PF current, plasma current, plasma pressure, and plasma density profile. Then, the equilibrium evolution is done by solving the MHD equation, the electron and ion temperatures are evolved by flux surface-averaged Coppi-Tang transport mode [2][3]. The free parameters in the transport equations are in the form of the electron and ion thermal conductivities χ_e and χ_i, which are of the form:

$$\chi_e = f_m\left(\chi_{TEM}^2 + \chi_{\eta i}^2\right)^{1/2} F(\Phi)\cdot\left|\nabla\Phi\right|^{-2} \tag{1}$$

$$\chi_i = a_{126}\cdot\chi_e \tag{2}$$

where $F(\Phi)$ is a function of toroidal flux function Φ, χ_{TEM} and $\chi_{\eta i}$ are the thermal conductivities in the ohmic heating region and in the auxiliary heated regime, respectively, which are presented in reference [4].

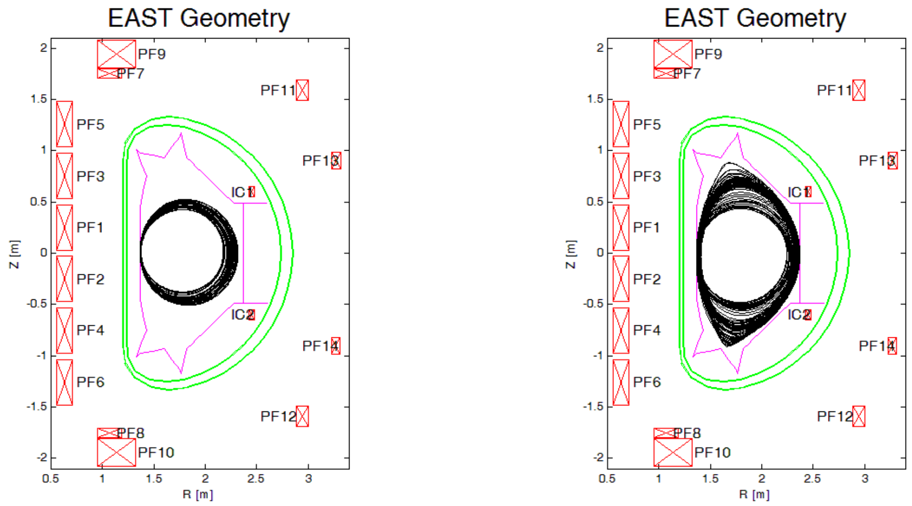
In EAST with superconducting PF coil system, ramping-up rate of the plasma current is essentially much slower than normal tokamak. It leads to lower q(0) on magnetic axis, and tends to occurrence of sawtooth activity for ohmic discharge, and flatten the temperature inside the q=1 surface. A time averaged sawtooth model [4], which enhances the resistivity and thermal conductivity inside q=1 surface, is used in the simulations.

3. Simulation of Ohmic Discharge

We report on the success of the TSC simulation model in reproducing the time dependence of several ohmically heated discharges in EAST. These discharges, including limiter discharge (such as shot 16028, FIG. 1(a)) and divertor discharge (such as shot 17126, FIG. 1 (b)), whose plasma current is about 250 KA, and line average density ranges from 0.60e+19 to 1.60e+19 m^{-2}.

For shot 16028, plasma current ramps up to 250 KA at 1.2 sec. The TSC simulates the plasma evolution from 0.2 sec, when the plasma has breakdown and rt-EFIT could proved reliable parameters for TSC initiation, to 5.3 sec, when the plasma current has ramped down to 100 KA. The line average density rises to 1.60e+19 m^{-2} at 2.0 sec, and keeps around this value to 5.0 sec. PF currents, which provide the volt-second to sustain the plasma energy consumption for ohmic discharge and the equilibrium field used to shape the plasma, is simulated by TSC. The results follow the measurements well (FIG. 2).

As we known, the plasma shape is not a directly measurable quantity and thus can only be evaluated using diagnostic data. EFIT [5] has been successfully used to evaluate plasma shape in EAST for several years. The comparison of TSC simulation results and the EFIT calculated data of major radius, minor radius, elongation, and plasma current is shown in FIG. 3(a). After 0.2 – 0.9 sec vibration, TSC better simulates the course of plasma major radius reduces from 1.187 m at 0.90 sec to 1.787 m at 2.051 sec, then slowly move to 1.82 m at 4.51 sec, while traces the elongation and plasma current of EFIT results.



(a) (b)

FIG. 1. The evolution of plasma boundary (black line) of (a) shot 16028 (limiter), and (b) shot 17126 (divertor) plot in the EAST geometry. The green lines sign EAST double layer vacuum vessel, and the magenta line is the EAST limiter components.

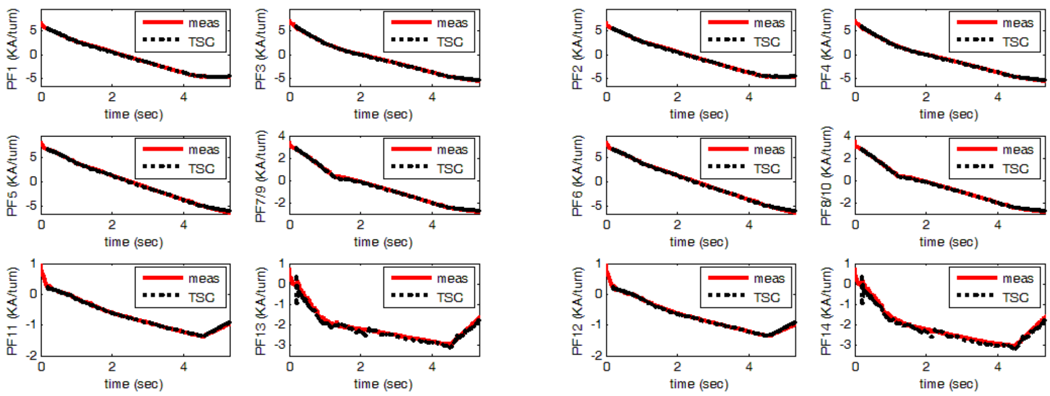
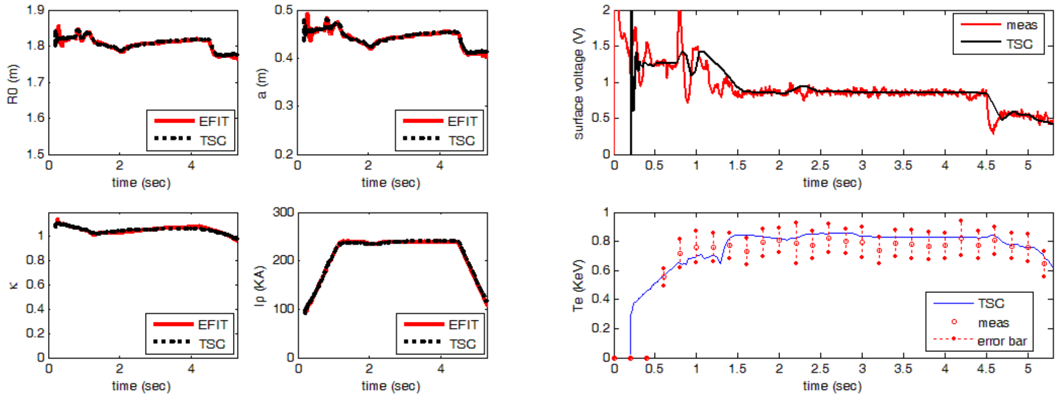


FIG. 2. Shot 16028 PF current (KA/turn) versus time (sec). (left) PF coils with the odd number, (right) PF coils with even number. PF7 and PF9, PF8 and PF10 connected together, respectively. In the figure, the measurements are shown by red line and the TSC simulated data by black dot line.

The surface voltage (FIG. 3(b) top) is used to estimate the ability of plasma volt-second consumption. The agreement between TSC output and measurements is well, especially at the flattop. The electron temperature is measured by a set diagnostic system of soft X-ray energy spectrum based on a high performance Silicon Drift Detector (SDD) linear array [6] in EAST. The measured electron temperature at (1.90m, 0.0), where is close to the plasma center, is signed by circular (FIG. 3(b) bottom). The dot line shows the measurements error bar. Considering the measurement error, the TSC output at this point (blue line) traces the measurements well. It proves the transport model is suitable for EAST ohmic discharge.



(a) (b)

FIG. 3. Shot 16028. (a) The major radius (top left), the minor radius (top right), the elongation (bottom left) and plasma current (bottom right) versus time. Comparison of the TSC simulation data (black dot) and the EFIT calculated data (red line) is shown. (b) surface voltage (top): TSC simulated data (black line) fit experimentally measured values (red line) well, and electron temperature (bottom) at (1.90 m, 0.0), Te trajectory at this point simulated by TSC (blue line) follows the soft x-ray measurements(red circular) well considering the measurement error bar (dot line).

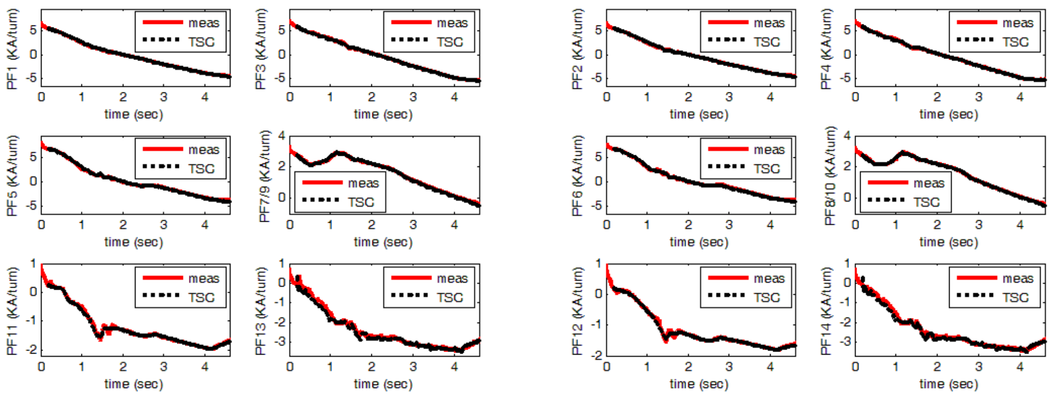
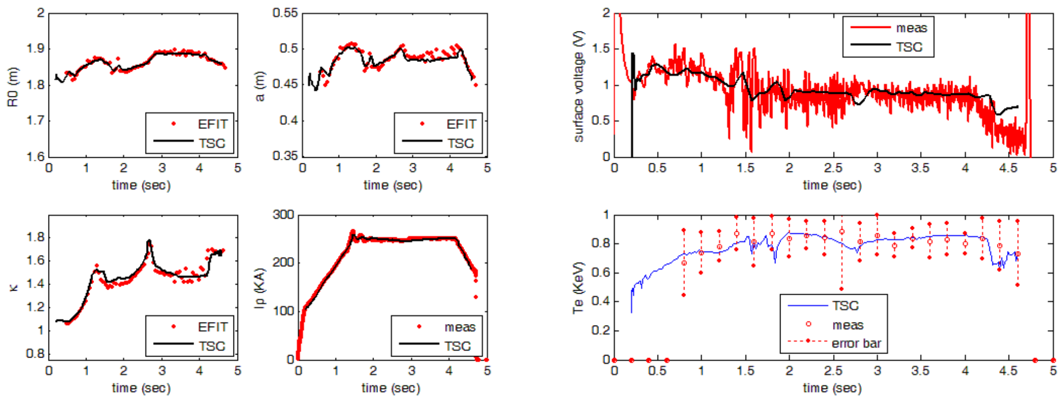


FIG. 4. Shot 17126 PF current (KA/turn) versus time (sec). (left) PF coils with the odd number, (right) PF coils with even number. PF7 and PF9, PF8 and PF10 connected together, respectively. In the figure, the measurements are shown by red line and the TSC simulated data by black dot line.

For shot 17126, the plasma current ramp up to 250 KA at 1.40 sec, when the elongation is 1.55. The plasma diverts between 2.8 sec and 3.2 sec, and then becomes elongated limiter configuration. The plasma current begins ramping down at 4.0 sec. The line average density rises to 0.90e+19 m^{-2} at 1.8 sec, and keeps around this value to end of simulation. The PF current trajectories simulated by TSC are shown in FIG. 4. Good agreements of major radius, minor radius and elongation between TSC and EFIT (FIG. 5(a)), prove the TSC simulation follows shot 17126 plasma shape evolution well. TSC also output good agreements of plasma current, surface voltage and electron temperature at (1.90 m, 0.0) (FIG. 5) with the according measurements.



(a) (b)

FIG. 5. Shot 17126. (a) The major radius (top left), the minor radius (top right), the elongation (bottom left) and plasma current (bottom right) versus time. (b) surface voltage (top): TSC simulated data (black line) fit experimentally measured values (red line) well, and electron temperature (bottom) at (1.90 m, 0.0), Te trajectory at this point simulated by TSC (blue line) follows the soft x-ray measurements(red circular) well considering the measurement error bar (dot line).

4. Prediction of Ohmic Discharge

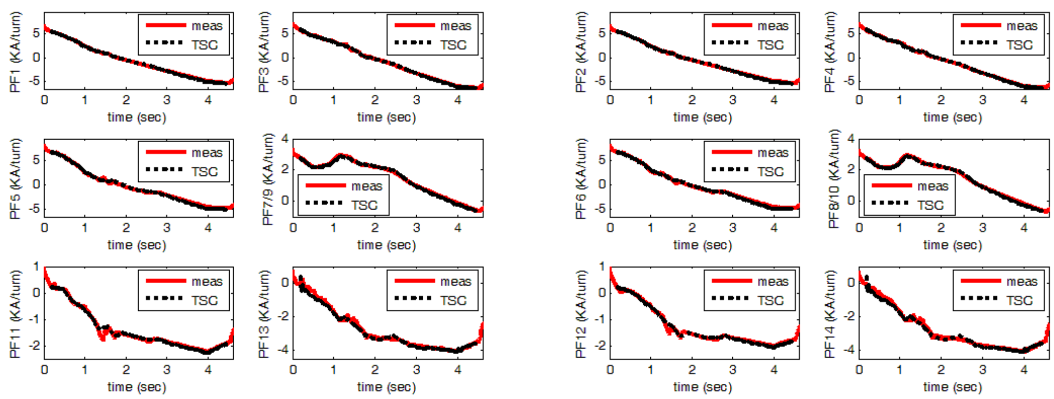


FIG. 6. Shot 17127 PF current (KA/turn) versus time (sec). (left) PF coils with the odd number, (right) PF coils with even number. PF7 and PF9, PF8 and PF10 connected together, respectively. In the figure, the measurements are shown by line and the TSC predictive data by dot line.

The agreements of previous EAST experiment data and TSC simulation results benchmark the TSC model for EAST. For shot 17126 and shot 17127, they have the similar experiment condition. The difference between two shots is plasma current at the flattop (300KA for shot 17127, while 250 KA for shot 17126). On the base of good simulation of shot 17126, the TSC is used to predict shot 17127, while Plasma current, density, and observations pairs are replaced by shot 17127 experiment data at corresponding time-slice. Due to the effect of TSC control system, the plasma shape evolution and plasma current trajectory follow the real experiment (FIG. 7a). The PF currents are corrected by the feedback of TSC RZIp control to satisfy the MHD equations. The predictive PF currents (dot line) basically follow the experimental data (line), shown in FIG. 6. Within the measurement error bar, the electron temperature at (1.90 m, 0.0) predicted by TSC fit the diagnostic data well (FIG. 7b). The surface voltage basically follows measurement, although there is a slight bias from 2.5 sec to 3.5 sec. In the view of Spitzer resistivity $(\sim Z_{eff} \cdot T^{-3/2})$, the bias could be viewed as the misestimate of effective Z (Zeff).

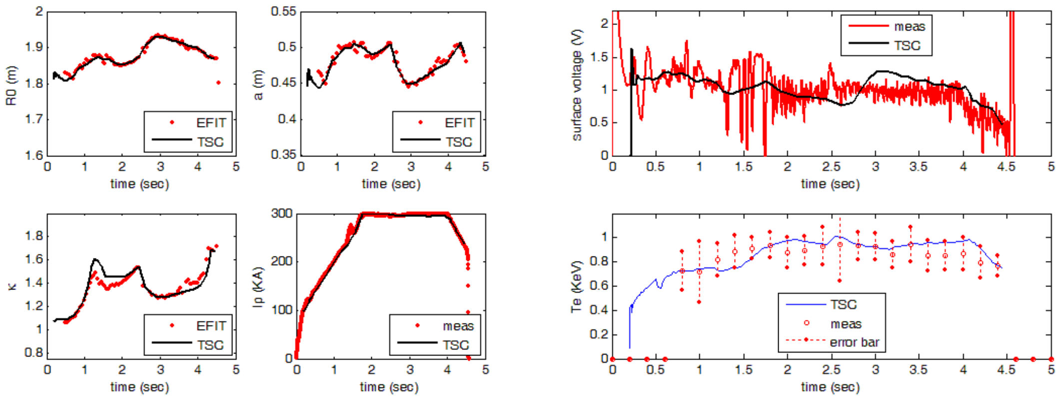
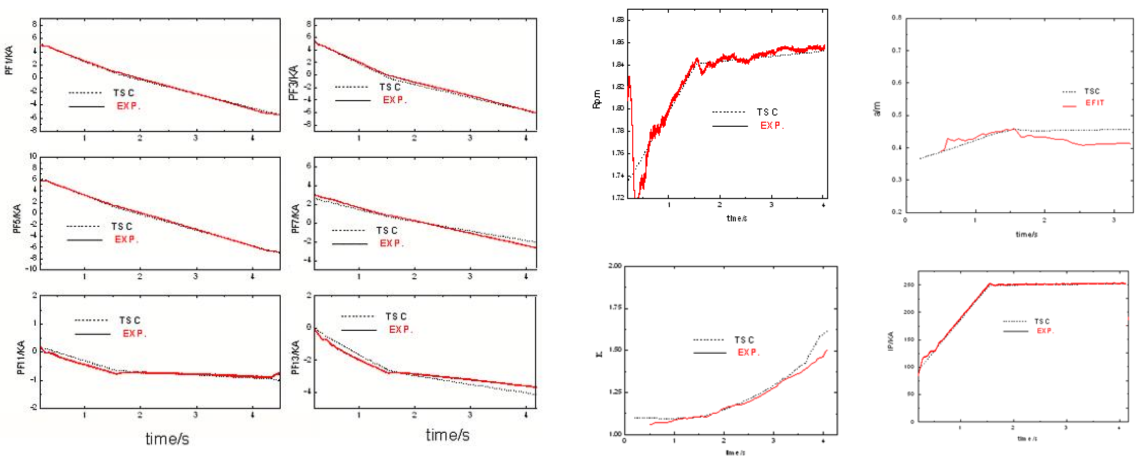


FIG. 7. Shot 17127. (a) The major radius (top left), the minor radius (top right), the elongation (bottom left) and plasma current (bottom right) versus time. TSC predicted data (black line) fit experimentally measured values (red line) well due to TSC control system. (b) surface voltage (top):and electron temperature (bottom) at (1.90 m, 0.0) (bottom).

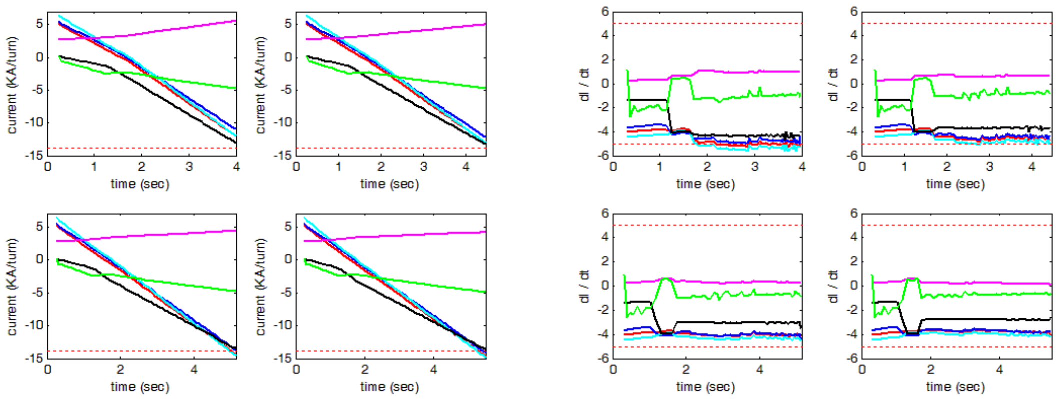


(a) (b)

FIG. 8. Shot 14189 (reference 7) takes TSC predictive data as reference wave. (la) PF currents with odd number, due to symmetry mode used in TSC, PF currents with even number are same to the corresponding coils. (b) The major radius (top left), the minor radius (top right), the elongation (bottom left) and plasma current (bottom right) versus time

We also have tentatively explores the way using TSC to direct EAST experiment [7]. TSC is used to predict the trajectories of PF currents, plasma current, major radius and minor radius. These data are taken as the reference wave for PCS (Plasma Control system). RZIp control system of PCS is used to fix the PF current error mainly induced by the uncertainty of experiment condition (such as Zeff, impurity distribution). The plasma (shot 14189) evolves basically along the prediction of TSC (FIG. 8).

These acceptable results encourage us to predict the ability of 1 MA ohmic discharge for EAST by TSC under current experimental condition. Because TSC could not be used for breakdown calculation, the plasma parameters of shot 17126 at 0.20 sec are used to initial TSC simulation, which breakdown with lower PF current (~ 7 KA/turn for PF1-PF6). Based on the EAST main parameters, the target plasma is double null configuration with R0 = 1.87 m, a = 0.48 m, elongation = 1.80, and triangularity = 0.45. From the view of EAST device, the realization of EAST 1 MA discharge is decided by two factors: (1) do not excess the 95% of maximum value of PF current (~ 13.77 KA/turn), and (2) do not excess the maximum change rate of PF current (5 KA/turn per sec) set by PCS system for superconductor protection. The plasma current ramp up in 4.00 sec, 4.16 sec, 5.14 sec, and 5.50 sec are simulated by TSC. As we known, when plasma current ramp up to 1 MA, the slower ramp-up means more flux consumption and slower PF current derivative rate (FIG 9). For ramp time of 5.14 sec and 5.50 sec, PF1-PF6 current obviously over the red dot signed 95% maximum PF current, although the PF change rate is smaller than 5 KA/turn per second. For 4.0 sec ramp-up time, the PF change rate is over 5 KA/turn per second setting for superconductor protection. Under the assumed situation, EAST could ramp up to 1MA in 4.46 sec which PF coils could sustain.



(a) (b)

FIG. 9. (a) PF current trajectories (PF1-red, PF3-blue, PF5-cyan, PF7/9-megenta, PF11-black, PF13-green) versus time for ramp-up time 4.0 sec (top left), 4.46 sec (top right), 5.14 sec (bottom left), and 5.50 sec (bottom right). 95% PF current limitation is signed by red dot. (b) PF currents change rate trajectories (same setting to Fig. 9(a)) versus time for the fourth condition. The maximum PF change rate is signed by red dot.

When the plasma current ramp up to 1 MA at 4.46 sec, the PF1 – PF6 currents are close to the limitation. It seems no more volt-second to sustain 1 MA flattop. But, we need emphasize that The TSC predictions start from lower PF currents. It means there is more volt-second unused. It will help to prolong the flattop by breakdown at higher PF currents. Zeff (~ 2.5) is higher for 1 MA simulation. Reducing the impurity would help to save volt-second at ramp-up stage to prolong flattop.

5. Summary

TSC has been used to simulate several EAST ohmic shots and the results are in reasonably good agreement with experimental data. Taking shot 17126 as basis, the prediction for higher plasma current has been verified by experiment. It shows the power of TSC predictive ability, and gives us confidence to predict 1MA ohmic discharge on EAST. The predictive calculation shows the possibility of 1 MA ohmic discharge on the condition of PF coils limitations.

Acknowledgements

The authors would like to thank C. E. Kessel in PPPL for TSC direction and Xu Ping for providing electron temperature measurements. This work is supported by the Major State Basic Research Development Program of China (973 program, No. 2009GB103000), National Nature Science Foundation of China (No. 10835009), the Key Project of Knowledge Innovation Program of Chinese Academy of Science with grant ID of KJCX3.SYW.N4, and the Knowledge Innovation Program of Hefei Institutes of Physical Science (No. 085FCQ0128).

Reference:

[1] Jardin S.C., Pomphrey N., Delucia I., ‘Dynamic Modeling of Transport and Position Control of Tokamak’, J. Comput. Phys. 66 (1986) 481

[2] Coppi B., ‘Nonclassical Transport and the principle of the profile consistency’, Comments Plasma Phys. Cont. Fusion, 5 (1980) 261

[3] Tang W. M., ‘microinstability-based model for anomalous thermal confinement in tokamaks’, Nucl. Fusion 26 (1986) 1605

[4] Jardin S. C., Bell M. G., Pomphrey N., ‘TSC simulation of Ohmic discharge in TFTR’, Nucl. Fusion 33 (1993) 371

[5] Lao L L, St John H, Stambaugh R D, et al., ‘reconstruction of current profile parameters and plasma shapes in Tokamaks’, Nucl. Fusion, 25 (1985) 1611

[6] Xu Ping, Lin Shiyao, Hu Liqun, et.al., ‘Soft X-ray PHA diagnostic for the electron temperature measurements on EAST’, Plasma Science and Technology, 11 (2009) 468

[7] Liu Chengyue, Xiao Bingjia, Wu Bin, et. al., ‘EAST plasma current and position prediction by TSC and experimental verification’, Plasma Science and Technology, 12 (2010) 156