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Progress and improvement of KSTAR plasma control using model-based control simulators

Sang-hee Hahn[a,*], A.S. Welander[b], S.W. Yoon[a], J.G. Bak[a], N.W. Eidietis[b], H.S. Han[a], D.A. Humphreys[b], A. Hyatt[b], Y.M. Jeon[a], R.D. Johnson[b], H.S. Kim[a], J. Kim[a], E. Kolemen[c], D. Mueller[c], B.G. Penaflor[b], D.A. Piglowski[b], G.W. Shin[d], M.L. Walker[b], M.H. Woo[a]

[a] National Fusion Research Institute, 169-148 Gwahak-ro, yuseong-gu, Daejeon, Republic of Korea
[b] General Atomics, San Diego, CA, USA
[c] Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[d] University of Science and Technology, Daejeon, Republic of Korea

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ABSTRACT

Superconducting tokamaks like KSTAR, EAST and ITER need elaborate magnetic controls mainly due to either the demanding experiment schedule or tighter hardware limitations caused by the superconducting coils. In order to reduce the operation runtime requirements, two types of plasma simulators for the KSTAR plasma control system (PCS) have been developed for improving axisymmetric magnetic controls. The first one is an open-loop type, which can reproduce the control done in an old shot by loading the corresponding diagnostics data and PCS setup. The other one, a closed-loop simulator based on a linear nonrigid plasma model, is designed to simulate dynamic responses of the plasma equilibrium and plasma current (I_p) due to changes of the axisymmetric poloidal field (PF) coil currents, poloidal beta, and internal inductance. The closed-loop simulator is the one that actually can test and enable alteration of the feedback control setup for the next shot. The simulators have been used routinely in 2012 plasma campaign, and the experimental performances of the axisymmetric shape control algorithm are enhanced. Quality of the real-time EFIT has been enhanced by utilizations of the open-loop type. Using the closed-loop type, the decoupling scheme of the plasma current control and axisymmetric shape controls are verified through both the simulations and experiments. By combining with the relay feedback tuning algorithm, the improved controls helped to maintain the shape suitable for longer H-mode (10–16 s) with the number of required commissioning shots largely reduced.

1. Motivation

Tokamak operation costs are high, even for the tokamaks with full superconducting coil capability: annual operation requires dedicated machine preparation process longer than the time for the conventional tokamaks, including the cool-down procedure [1]. As a consequence, the practically allowed runtime for plasma experiments is usually 8–12 weeks per year for KSTAR tokamak [2–4]. The experiment schedule for applying any novel designs in the plasma control is more demanding and risk-taking if the design is not practically verified within the existing control constraints of the diagnostics and actuators. Control software development benefits if we have a suitable simulation environment to test newly developed algorithms against the known constraints. The constraints can be either from possible conflicts with the existing algorithms during the development, or from the hardware limits that could give the control an immediate stop if violated. The ability to check against the plant system limitations is especially efficient when dealing with the superconducting coil actuators, for preventing loss of superconductivity which is usually caused by accumulated coupling AC loss through excessive PF coil current drive and current saturations at the end of the discharge.

The complexity of the plasma control system (PCS) is also a good reason to implement a future shot designer, which is a user interface that can save desired plasma control system settings for future applications to an incoming experiment shot. Usually the number of available control setpoints is huge for a tokamak. The number of feedback items for the KSTAR PCS increased to more than 30 items from the 4 items in the first year [5]. Practically the operators need to set up more than 100 entries for a shot design from scratch.

Hence an approach of offline optimization methods using simulations becomes essential for better utilizing controls in the limited runtime slot. The first attempt using a model-based approach has been taken for improving the axisymmetric magnetic controls to

* Corresponding author. Tel.: +82 42 879 5123.
E-mail address: hahn76@nfri.re.kr (S.-h. Hahn).

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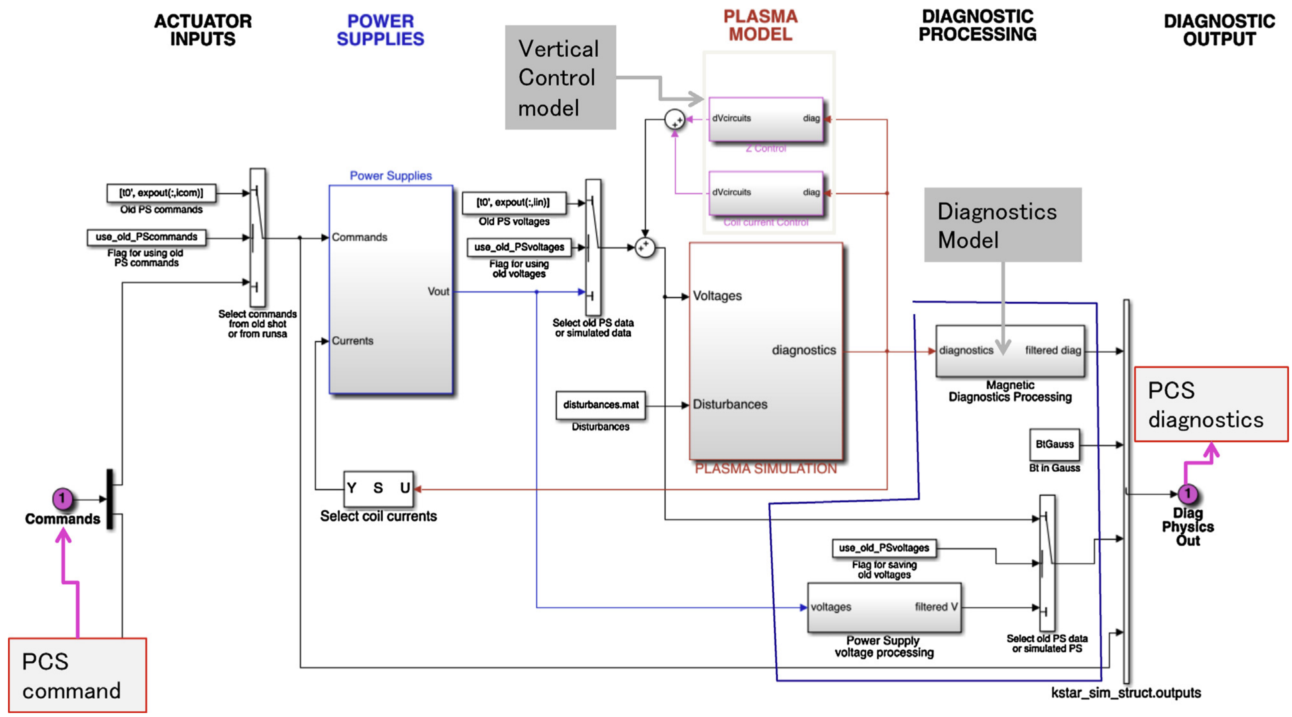

Fig. 1. Structure of the closed-loop simulator for axisymmetric plasma magnetic controls. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

maintain the diverted shape for a longer H-mode discharge. In the next section, the structure and the verifications of the simulators are summarized. Application highlights of the developed simulator are described in Section 3.

2. Structure and validations of simulators

2.1. The open-loop simulator

Two kinds of the PCS simulator have been implemented for KSTAR. The first one is an open-loop type, called as “data simserver”. The data simserver provides archived data of a shot to the PCS software in place of diagnostics input, hence the PCS software re-runs the old shot to recalculate the output of the PCS under a new algorithm or operator setup. The data simserver has been most frequently used to rerun the PCS for old shots to check if we can get better shot setup for the particular shot with the modified operator setup. For example, it is used to test and give a working real-time EFIT [6] snap setup when given diagnostics hardware constraints are changed during the operations.

Another advantage of the data simserver is that the PCS users can verify their ideas through the PCS software even when a useful plasma model is not available. The data simserver helps to develop and analyze hardware-related algorithm changes. For example, it can be used to add a new physics parameter estimator (like radial position estimator used in [5]) using existing diagnostics, hence it can help to add/change a control output of the actuator according to the new criterion that the estimator gives.

2.2. The closed-loop simulator

On the other hand, the closed-loop simulator resembles the plant more in a sense of that it provides system responses of plant/plasma caused by the PCS commands as a form of corresponding diagnostics. Hence it is possible to design and simulate the feedback loop using this type of simulator. An axisymmetric magnetic response model is implemented in this closed-loop type simulator (typically called as “simserver”) in order to give the PCS data representing simulated changes of the plasma due to prior PCS commands.

2.2.1. Structure and implementations

Following the method originally developed in DIII-D control simulator [7,8], the simserver is written using Simulink software under Matlab/TokSys [9] environment. Fig. 1 shows the structure of the Simulink simulator redesigned in 2012. When the simulation is controlled by the PCS, the PCS commands come to the input port in the left. The blue block, ‘Power Supplies (PS)’, simulates each power supply voltage responses to a given voltage command in time. A linear response model accounting for the pure delays/rise time is implemented in the block for the PS voltage output. A state-space plasma response model is implemented in the red block, using the coil power supply voltages as the input. The plant model consisting of 70 toroidal conductors are included in the model to generate the current responses due to the given voltages. The gray blocks, “Vertical control model”, are an idealized model of the vertical position control, including the estimator of the vertical position and the PD loop. Simulated diagnostic input is fed to the diagnostics model blocks, representing signal-conditioning apparatus (e.g. hardware filters) in the diagnostics data acquisition system. Most channels are modeled as low-pass filter boxes with different corner frequencies based on the measured frequency response of each component.

A setup script is also written using Matlab in order to provide user inputs essential to build the component models. The inputs for building the response model are provided from a user-specified old shot through an automated Matlab script under the TokSys environment. The script gets the user-specified inputs such as shot number, set of magnetic equilibria, and the diagnostics data vectors in time. After reading the inputs, the script analyzes the equilibrium set to extract information necessary to build a linear, non-rigid plasma response model [10] inside the red block. This model also needs the magnetic responses by perturbations on both the plasma energy (β_p) and plasma current distribution, characterized using

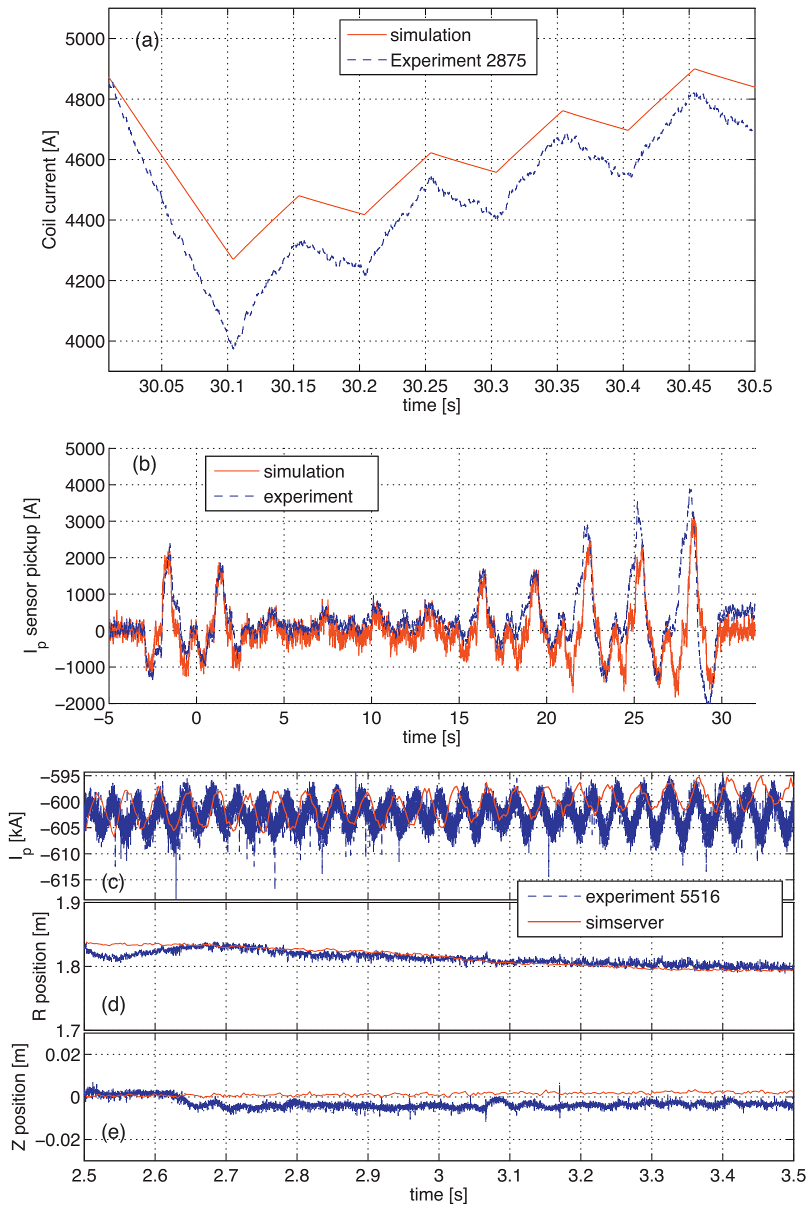

Fig. 2. Examples of validation process. (a) Power supply model verification with the coil current measurement excited by ±50 V of feedforward voltage step commands. (b) Toroidal vacuum model validation by magnetic diagnostics. Comparison on a toroidal Rogowski signal (PCRC03) pickup by individual PF current swing by ±500 A/turn is shown here. Measurement result (blue) matches to the simulated diagnostics (red). Validations of plasma model on the closed-loop simulator are shown using a slowly varying plasma shot: comparison is shown on the simulated (red) (c) plasma current, (d) radial position and (e) vertical position of the current centroid with measurements by shot 5516 (blue dashed). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

internal inductance (l_i), the corresponding state-space term is also provided as “disturbances” by analyzing the old shot within the script.

The simulator becomes an executable using the Real-Time Workshop, a real-time code generator from Matlab/Simulink, and the compiled PCS software. The executable is directly connected to the PCS for the simulation. The input/output port interfaces are automatically associated with the current PCS software configuration. The setup and simulation results obtained by the simserver run are stored to the MDSplus [11,12] as a simulated shot so that the operator setup data for this shot can be easily restored to the PCS for an experiment.

2.2.2. Component-based validations

Reliability of the closed-loop simulator is guaranteed by its accuracy achieved during validations. Before building the real-time code, a few self-validation routines execute inside the setup script using (i) conductor currents, (ii) measured voltages or (iii) stored PCS commands from the old shot. The most useful routine is the conductor current simulation, which will work even if the power supply model prediction of voltage is not accurate.

A component-based validation approach [13] was taken to make sure that the Matlab simulator can give reasonable responses for static/dynamic responses made by the controller. Ideally the individual block at Fig. 1 has to be verified. And the plasma block (red) verification is in the last because the plasma block always needs the other blocks to run. The crucial plant parts for verifications are (1) the power supply model, (2) the vacuum conductor model and (3) the diagnostics model.

The plant model can be verified by comparing with dedicated vacuum shot results. Fig. 2(a) and (b) shows the result of such vacuum shots. For Fig. 2(a), known open-loop voltage step commands was programmed for a dedicated run of the PF3U coil: and the measured coil current per turn is compared with the simulations. The voltage responses of the model were adjusted to give the measured voltage output. A matching frequency response on the coil current is obtained by adjusting the effective inductance/resistances of the circuit. For the vessel model verification, a specially designed vacuum shot is used to verify the resistance of individual passive toroidal conductors and the PF coils. Each coil is perturbed by ±500 A/turn in the initial magnetization [14] state so that one can relatively easily obtain the Green's function estimates from the specific coil to magnetic diagnostics measurements. An optimization code was applied to adjust the effective resistance on individual passive conductors to match the simulated response to the measurement. Application to a Rogowski coil is shown in Fig. 2(b).

After verifying the plant components, a discharge with a slowly varying plasma parameters was chosen to check that the simulator reproduces the experimental result. Fig. 2(c)–(e) shows comparisons on the measured plasma current (I_p) and the position of the plasma current center (R and Z). In the case of shot 5516, the oscillation amplitude of the I_p matches with the experimental result, as shown in Fig. 2(c). The differences in the radial position of the centroid between the simulation and the experiment are within ±2 cm. The idealized Z control model is supposed to have very small Z errors, but in this case, the Z position differences are smaller than ±1 cm.

3. Experimental applications of the closed-loop simulator

The simulators have been successfully utilized through the 2012 plasma campaign. The closed-loop simulator is mostly used to develop new setup by the PCS operators for the next-day experiment. By adding the relay feedback tuning technique [15], the software reduced the time required to tune the experimental setup for sophisticated plasma experiments.

3.1. Improvement of I_p and shape controls

Control of the shape is usually coupled with the plasma current control by the characteristic coil geometry of tokamaks. Hence a scheme of decoupling the shape control from the influence of the I_p feedback is essential. In the KSTAR case this is very important, because the distances between the plasma control points and the superconducting PF coils are high, hence a PF coil could affect more control points than wanted. Before the simulators were developed, there was no optimized controller able to drive properly plasma current and plasma shape at the same time.

A redesign of the I_p controller was suggested to minimize the conflicts with the SISO shape control. A preliminary test was done by replacing the old I_p controller with the new one, and rerunning shot 5516 with the closed-loop simulation to produce simulated shot 995035. The result shown in Fig. 3 indicates that the new decoupled design on I_p can improve the position controls too. By changing the I_p controller, the disturbances at the radial position feedback are reduced from ±10 cm to ∼1 cm without changing the radial position control scheme. In the 2012 experiment, the best working I_p control is a design to use all the PF coils as the actuators in order to minimize the magnetic field (less than ∼1 G) inside the plasma area.

The simulator gave useful limitation check in utilizing a PID tuning technique known as "relay feedback" [15]. Based on the Ziegler–Nichols method [16], the algorithm generates a series of steps in the PF coil current target, which makes the controlled shape oscillate. An example of the experimental application is shown in Fig. 4 for PF1UL, the innermost center stack coil, at the shot 6981

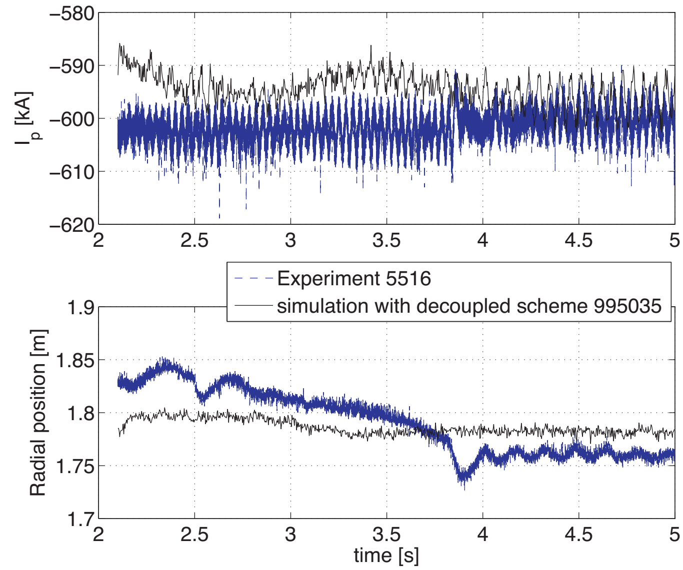

Fig. 3. Improvement is shown and predicted on decoupling plasma current and shape control using a simulation of old experiment. Experiment 5516 (blue) is rerun in a closed-loop simulation 995035 (black) using different decoupling I_p control scheme. The setup for the radial position (R) estimator is not changed in both shots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

and the response of the inboard flux error denoted as SEG07. A step command with amplitude 2h results in periodic responses with period P_u and amplitude 2A. The optimized PID gains are given by the following equation:

$$[G_p, G_i, G_D] = \frac{4h}{\pi A} \times \left[0.6, \frac{2}{P_u}, \frac{P_u}{8}\right]$$

The closed-loop simulator was used to compute the working 2h and 2A ranges in order to reduce limitation violations when the relay feedback algorithm is applied in experiment.

3.2. Extension of the plasma performances

Using many techniques described above, the I_p and shape feedback gains have been redesigned frequently during operations for

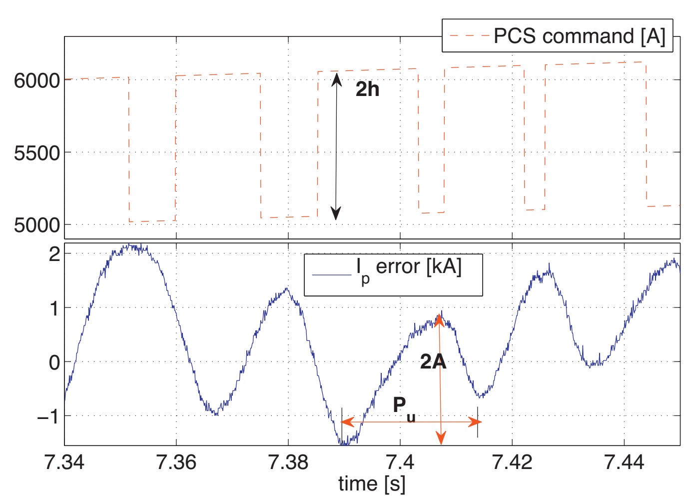

Fig. 4. Experimental example of applying the relay feedback. The most influential coil for ohmic flux, PF1UL, is requested to perturb by 2h in the coil current command in the top plot. The response on the plasma current (I_p) control error is shown in the bottom plot.

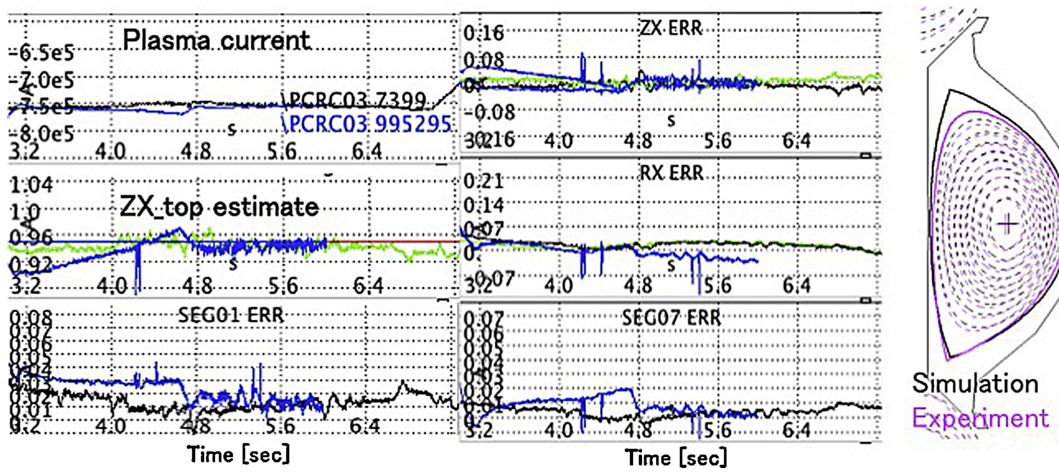

Fig. 5. Direct application of the simulation result to the experiment. The shot setup made in simulated shot 995295 (blue) was loaded into the PCS setup for experiment 7399, and the executed experiment showed a very close reproduction of the simulation. Comparison for plasma current, vertical position of the top X-point, flux error of the midplane gap (left), errors on vertical(ZX)/radial(RX) position of the top X-point, and the flux error for midplane outboard gap. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

optimizing a set of controllers to be used widely in the future. Since operational runtime is very limited for testing control algorithms, the control improvement was demonstrated through a series of mini-session (2–3 shots per day). In these shots, a setup for possible improvement predicted by the simulations was saved prior to the session and was restored as the PCS setup for the next shot. Once an improvement was confirmed, the best shot was used to rebuild the simulator for the next scheduled mini-session. Since the simulator requires at least an equilibrium from EFIT or real-time EFIT, the model-based approach worked only the phases where a good reconstruction was available.

Fig. 5 shows one of those direct applications of the simulated setup to an experiment targeting a $I_p = 750\,\mathrm{kA}$, diverted plasma discharge; the responses of I_p and defined control points, the

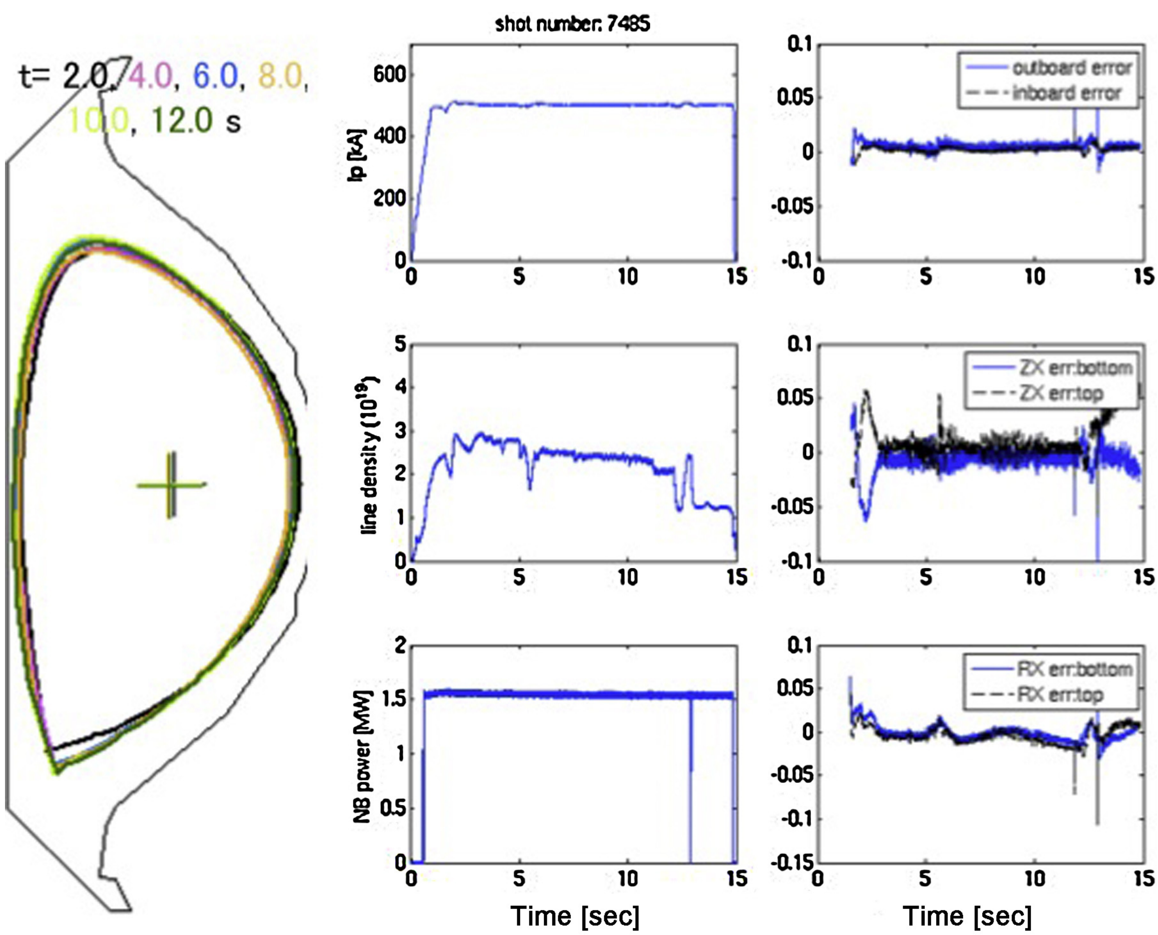

Fig. 6. A diverted discharge of 10 s has been obtained in the shot 7485. Real-time reconstruction verifies the shape control works until $t = 12.0$ s (left). The pulse length is 15 s total, and the H-mode was sustained until one of the coil actuators (for X-point) reached to its current limit.

inboard/outboard flux errors and the radial/vertical X-point positions, are shown. The experimental and simulated results are very close except the radial position of top X-point (RX). The differences between predicted/measured errors are within 2 cm in the geometry. As shown in the reconstruction comparison, the LCFS estimate is different from the one in the experiment; the asymmetry might be due to a previously observed up/down asymmetry of the conducting material distributions because of the presence of the Cryostat. Through the mini-sessions, a full axisymmetric magnetic controller for driving both I_p and 6 control points are constructed, using 11 PF independent coils and an anti-symmetric pair of in-vessel vertical control coils. As shown in Fig. 6, the controller works for a full diverted shape maintaining errors within ±2 cm or 0.01 Wb in the flux errors for the inboard/outboard gaps. Using full real-time EFIT/isoflux [17] control, the controller enabled a ∼10 s of H-mode discharge with only one neutral beam (approximately 1.4 MW for injected power): the average pulse length in 2012 has been enhanced by 100% as well. Additional extension of the pulse was attempted using similar setup later, which made a ∼16 s H-mode shot using 2 NBIs [18].

4. Conclusion

Two kinds of the KSTAR plasma control simulators have been developed in order to improve the axisymmetric magnetic controls within the given operation time constraints. The developed tools are used on a daily basis to verify the prepared setup of the day before the operations. An open-loop type simulator provides a method to rerun the shot with newer software to check the integrity of the output. For the closed-loop type model simulator, a model-based Matlab simserver has been developed using a nonrigid plasma model for the dynamic plasma responses. Essential plant components are also modeled and verified through a series of vacuum shot experiments. The plasma model is verified by the response comparison to discharges with slow-varying plasma properties. The simulators helped to redesign the KSTAR magnetic controls with full applications of real-time EFIT/isoflux to enhance the H-mode pulse duration, which doubled in 2012.

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