New Control Abilities on EAST PCS for Steady-State Operation

Q. P. Yuan, B. J. Xiao, K. Wu, R. D. Johnson, Y. Huang, Y. Guo, and R. R. Zhang

***Abstract*— To accomplish experimental advanced superconducting tokamak (EAST) physical targets, the plasma control system (PCS), adapted from DIII-D PCS and deployed on EAST in 2005, keeps in continuous development. Some new control abilities for steady-state operation have been achieved. To avoid the integrator linear drift in long pulse discharge, the linear rate for each integrator channel is precalculated and used to decrease the effect of the acquired raw data during shots. Another strategy applied for long pulse operation is real-time data archiving using data segment technology of MDSplus, which provides the possibility to save all data in segments without increasing the computer memory or reducing the saving frequency. For plasma high-performance and noninductive operations, the plasma beta and loop voltage control was implemented in PCS. Using low hybrid wave, the control algorithm was successfully verified in 2016 EAST campaign. Besides, another two control algorithms are integrated to reduce the divertor heat flux. One is radiation power control, which is successfully feedback controlled by using divertor inert gas puffing and mid-plane supersonic molecular beam injection. The other is quasi-snowflake shape control using PEFIT/ISOFLUX, which shows significant heat load reduction to divertor target according to the experimental result. The present EAST PCS has become a huge system capable of long pulse, high-performance advanced plasma control operation, which is ready to demonstrate ITER-like control contents.**

***Index Terms*— Long pulse operation, loop voltage control, PEFIT/ISOFLUX control, plasma beta control, radiation control.**

I. Introduction

EXPERIMENTAL advanced superconducting tokamak (EAST), a toroidal device with a D-shaped poloidal cross section, aims at high confinement and steady-state operation with plasma current up to 1 MA and pulselength to 1000 s. In 2016, EAST achieved over 60s fully noninductive long-pulse H-mode plasmas under radio frequency heating and ITER-like tungsten divertor operations. For further high-performance and steady-state operations, EAST needs effective noninductive current and heat load control. To satisfy the control needs, the plasma control system, EAST plasma control system (PCS) [1], keeps in continuous development with joint efforts from the DIII-D and EAST plasma control groups. In Section II, the strategies for solving integrator linear drift of acquired raw data and data archiving in long pulse discharge is introduced. For plasma high-performance and noninductive operations, the plasma beta and loop voltage control were integrated in PCS. The implementation detail and experimental results are presented in Section III. To reduce the heat load on the divertor target, the radiation power control using divertor inert gas puff and mid-plane supersonic molecular beam injection (SMBI) is realized in PCS. Besides, the new advanced plasma quasi-snowflake (QSF) shape [2] is controlled using PEFIT/ISOFLUX [3], [4], which shows significant heat load reduction to divertor target. These control algorithms and experimental results are discussed in Sections IV and V. With the integration of above control contents, the present EAST PCS has become a huge system capable of long pulse, high-performance advanced plasma control operation.

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Q. P. Yuan, Y. Huang, Y. Guo, and R. R. Zhang are with the Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China (e-mail: qpyuan@ipp.ac.cn; yaohuang@ipp.ac.cn; yguo@ipp.ac.cn; rrzhang@ipp.ac.cn).

B. J. Xiao is with the Department of Science Island of USTC, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China, and also with the University of Science and Technology of China, Hefei 230026, China (e-mail: bjxiao@ipp.ac.cn).

K. Wu is with the Department of Science Island of USTC, University of Science and Technology of China, Hefei 230026, China (e-mail: wukai@ipp.ac.cn).

R. D. Johnson is with General Atomics, DIII-D National Fusion Facility, San Diego, CA 92121 USA (e-mail: johnsonb@fusion.gat.com).

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II. Long Pulse Data Acquisition and Archiving

Long pulse is not only an extension of the discharge time but also it has unique problems that need to be solved, for example, the drift of integrator and the memory limitation for data storage due to long-time operation. In this section, the solution for eliminating integrator linear drift and data storage memory limitation will be introduced.

A. Integrator Linear Drift Processing

On EAST, many magnetic diagnostic data are differential signals, such as plasma current, poloidal flux, and field around the flux loops and magnetic probes, and currents of poloidal field (PF) coils. In order to retrieve these signals, the integrators are deployed before data acquisition. In long pulse operation, the drift of integrator will cause the measurement error and affect the plasma control performance. Thus, a software processing method for deducting linear drift of integrator is proposed and implemented. The main principle is eliminating the linear drift from the acquired raw data by using precalculated linear rate in each control cycle. The linear

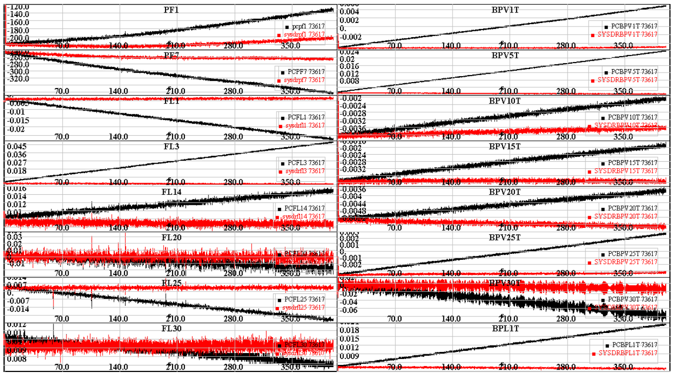


Fig. 1. Comparison between raw data and process data after deducting linear drift of integrator for 400 s shot at 73617, in which black line is for raw data and red line for processed data.

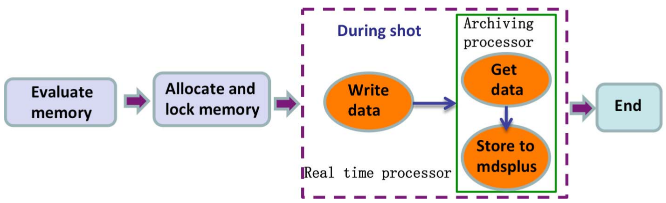


Fig. 2. Real-time archiving mode during a shot.

drift rate of each integrator channel is fit using integrator test shot data and then saved in a file. Such long pulse integrator test shot is run routinely at operation test phase of everyday. During normal operation, the rate data are read from the file and used to calculate the linear drift value to be subtracted from raw data in PCS. Then, the processed data are used for plasma real-time control.

Fig. 1 shows the result of deducting linear drift of integrator channels in a 400 s shot. Some typical signals are selected, such as the PF coil current "PF1," "PF7," some flux loop signals with point name starting with "FL," and magnetic probe signals beginning with "BP." Compared the raw data in black line to the processed data in red line in Fig. 1, it is obvious that the software processing method for deducting linear drift of integrator is effective, which ensures the accuracy of magnetic diagnostic data for plasma control in long pulse operation.

B. Real-Time Segmental Archiving

In current PCS, all data including target vector, acquired raw data, control error vector, and command vector are saved in the computer memory during shot and then stored into MDSplus tree one time after shot. Such after shot archiving mode needs more memory when the discharge shot length extends and increases the network transmission load. To avoid these limitations for long shots, data can be "offloaded" during the shot and archived outside of the real-time processor.

The real-time archiving mode is realized in PCS. As shown in Fig. 2, each archiving processor is corresponding to a real-time processor. The memory used in the real-time processor to store samples is recycled so that there is no limit on the number of samples that can be saved. An offloading buffer area is defined on both real-time and archiving processors.

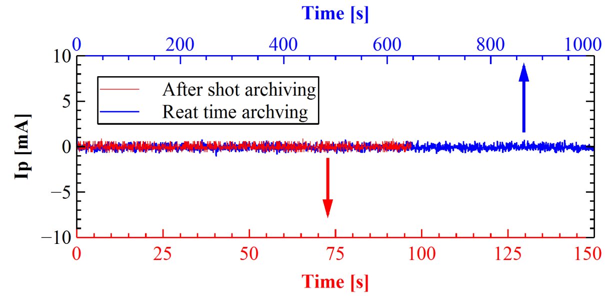


Fig. 3. Comparison for two archiving modes in 1000-s long pulse discharge.

When the real-time data in memory increase to the preset size of a slice or control phase changed, the real-time processor will offload the data to the buffer area and send the data slice to the corresponding archiving processor. Then the data that are offloaded are archived to MDSplus in segments allowing any number of samples to be saved.

Later versions after MDSplus 2–1, segmented records were added to MDSplus to support the ability to append data to an MDSplus signal node and to retrieve subsampled data without retrieving the entire signal from the MDSplus data file [5]. This feature is particularly useful for EAST long pulse experiments. With segmented records, data can be stored in blocks incrementally. These segments can be retrieved individually so it is no longer necessary to retrieve the entire data set for a node. Such feature can be used for real-time data display and analysis, which provides the possibility to adjust the control scenario during the plasma discharge in long pulse shot.

The real-time segmental archiving mode is tested in 1000-s long pulse discharge without plasma. The acquired raw data for plasma current is compared. As shown in Fig. 3, without reducing the data saving frequency or increasing the computer memory, 1000 s data in blue line are stored to MDSplus successfully in real-time archiving mode, while in after shot archiving mode, only 100 s data in red line are stored.

Since the memory in real-time archiving mode is recycled, the required size for the real-time memory is only connected with the size of the slice data and has no relationship with the time length of the discharge. Thus, the segmental archiving strategy solves the memory limitation problem perfectly for long pulse and future steady-state operation.

III. Plasma Beta and Loop Voltage Control

In order to realize stable performance and noninductive current drive, the plasma pressure beta and loop voltage control algorithm are implemented in PCS. The system overall design and experimental results are discussed in this section.

A. System Overall Design

For EAST steady-state operation, a great effort has been made to upgrade the heating and current drive systems. At present, there are two lower hybrid wave (LHW) systems, one is at the frequency of 2.45 GHz with a total power of 4 MW, and the other is at the frequency of 4.6 GHz

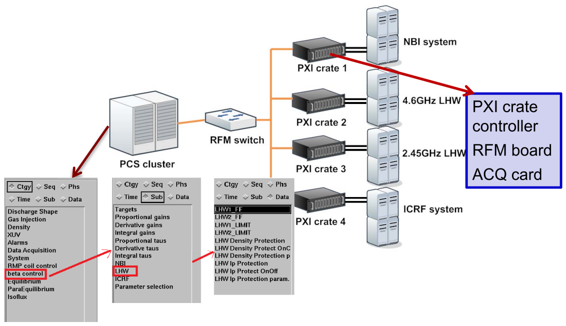


Fig. 4. Hardware connection layout among PCS and auxiliary heating systems for plasma beta and loop voltage control.

with 6 MW power. The NBI system is successfully constructed with two sources in co/counter direction each with 4 MW. In addition, EAST is equipped with an ICRF system consisting of two double-strap antennas, each delivering 3 MW power. These auxiliary heating systems are used as actuators in plasma beta and loop voltage control.

The heating systems are settled far away from PCS. To achieve distortion-free data transmission in long distance, the reflective memory (RFM) network [6] is applied among PCS and each actuator system as shown in Fig. 4. There is a PXI crate configured with RFM board and digitizer at the local site of each actuator system. During each control cycle, the data written to the RFM by PCS is put to the same address on all the RFM boards connected in the RFM data output network. Each system can read the needed data using RFM API function from the corresponding memory offset. At the same time, some on-site signals are acquired in real time and transmitted back to PCS through another RFM network called data input network, which is physically separated from the RFM data output network. All the interface for target, control parameters, and system protection setting is realized on PCS host computer. While the control algorithm based on PID controller executes on PCS real time computing node, which is connected with RFM switch to exchange data with actuator systems.

B. Control Algorithm Implementation

The plasma beta, loop voltage, plasma current, and plasma self-inductance control are classified into the same control category "beta control" in PCS according to the control actuators. Each control item has individual target and PID parameter setting. During each control cycle, the plasma parameter from direct measurement or reconstruction result is compared to target to generate error vector. Then the PID controller works with the inputted error vectors and preset control parameter. The result from PID controller for each item will multiple the "M matrix," as shown in Fig. 5. The power needed for each heating system is the sum of each item multiplying result on that row. Such "M matrix" defines which actuator is used for which item control flexibly. At last, the calculation result is flipped to the allowed power range, and then outputted to the corresponding actuator system.

	betaN	Vloop	Ip	li
NBI1L	0.	0.	0.	0.
NBI1R	0.	0.	0.	0.
NBI2L	0.	0.	0.	0.
NBI2R	0.	0.	0.	0.
LHW245	0.	0.	0.	0.
LHW46	1000000.00	0.	0.	0.
ICRF1	0.	0.	0.	0.
ICRF2	0.	0.	0.	0.

Fig. 5. M matrix in PCS for plasma beta and loop voltage control.

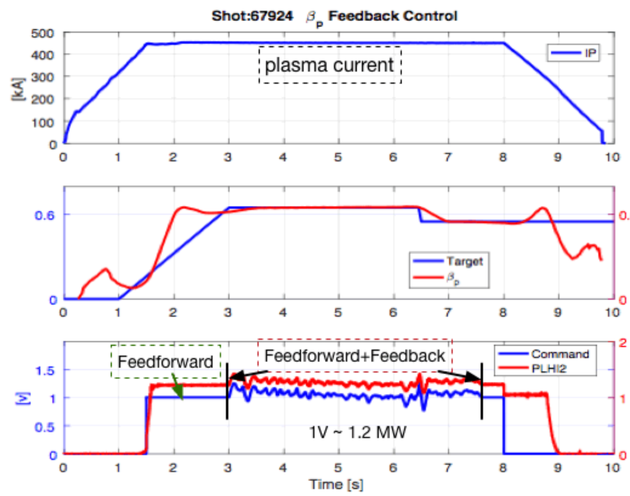


Fig. 6. Plasma beta control result using LHW 4.6 GHz at shot 67924.

C. Experimental Result

In 2016 EAST experiment, the plasma beta and loop voltage control is demonstrated using LHW 4.6 GHz. As shown in Fig. 6, the beta target is in blue line in the second plot. From 1.5 to 3 s, the command output is according to the feedforward waveform of LHW 4.6 GHz, which is about 1.2 MW in the shot 67924. The feedback control period is from 3 to 7.5 s, during which the command is composed of feedforward setting value plus feedback control result as shown in the third plot. The real injection power of LHW 4.6 GHz is drawn in red line which follows the command in blue line quite well. The difference after 8 s is because the LHW system always has a threshold power output when the system is ON. When the plasma current is lower than the protection value set in PCS, a shutdown signal is sent to actuator system. In shot 67924, LHW 4.6 GHz was shut down near 9 s when the plasma current protection worked. As a result, the plasma beta is controlled perfectly during the feedback control period as shown in red line in the second plot.

The loop voltage control result is shown in Fig. 7. The target is set to 0 for noninductive plasma operation. From 2.1 to 7.5 s, the command is composed of feedforward setting value plus feedback control result as shown in blue line in the third plot.

As shown in the second plot, the loop voltage in red line is well controlled to follow the target in blue line during this feedback control period. The control algorithm has been verified and shows good control ability using LHW 4.6 GHz.

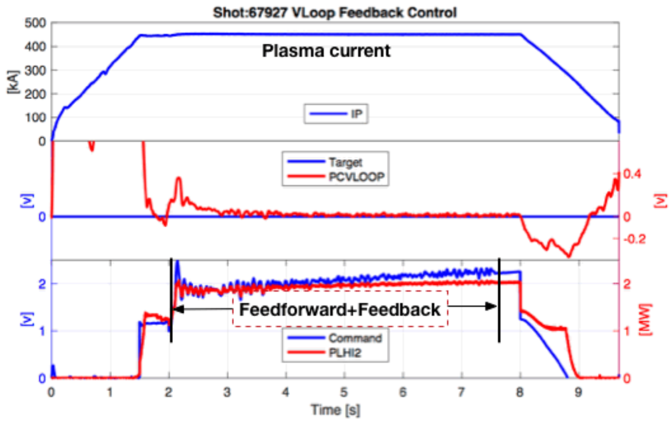


Fig. 7. Plasma loop voltage control result using LHW 4.6 GHz at shot 67927.

Other heating systems, such as NBI and ICRF will be used for plasma beta, self-inductance, and loop voltage control in the future.

IV. Plasma Radiation Control

Impurity seeding has been adopted as a common technique for stationary heat flux control in present tokamak experiments, which is mandatory for high-power and long-pulse operations [7]. On EAST, a multipurpose gas puffing system has been constructed, which allows gas fueling from many different divertor and main chamber locations, i.e., inboard/outboard mid plane, inner/outer target, and dome at both top and bottom divertors. Such gas system, combined with impurity puffing, provides an effective means to actively control power and particle fluxes to the divertor target plates, by generating radiative divertor plasmas.

For the radiation feedback control, the essential process is calculating radiation power using diagnostic data. In EAST, there are 64 absolute extreme ultraviolet (AXUV) channels coving the whole vacuum chamber for measuring the radiative intensity [8]. With AXUV diagnostic data and plasma boundary information, the radiation power can be evaluated in real time by integrating the effective AXUV signal at the plasma region. A subprocessing system is configured with digitizer DTACQ 196 which is a 96-channel synchronous acquisition card, and RFM board for data transmission with PCS, as shown in Fig. 8. The interface and control calculation is realized in PCS as "radiation control" loop. When the radiation power is lower than target, the gas puffing command will be sent to gas system through RFM. Then the impurity gas will be injected into plasma to increase the radiation.

The response speed of AXUV to gas puffing pulse from SMBI, located on the mid plane of low field side, and divertor piezoelectric (PE) valve, located on divertor targets, was tested and compared for actuator selection. According to the test result [9], the delay time including command transfer, valve action, pipe delay, and gas diffusion, is about 7 ms for SMBI and 120 ms for PE value at the divertor location. Therefore, the PE valve at the divertor target is used as feedforward puffing, while the SMBI is for radiation feedback modulation. In 2016 EAST experiment, the impurity gas neon was injected

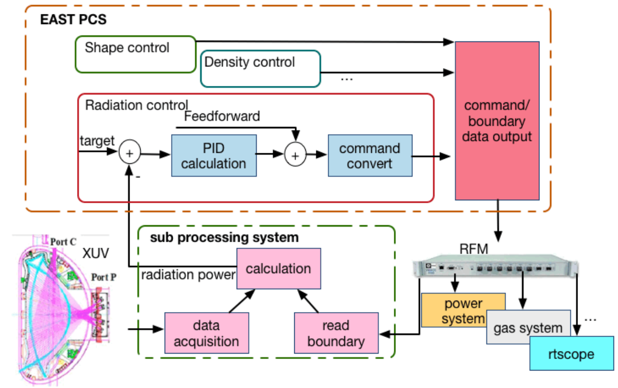


Fig. 8. Diagram of radiation feedback control system.

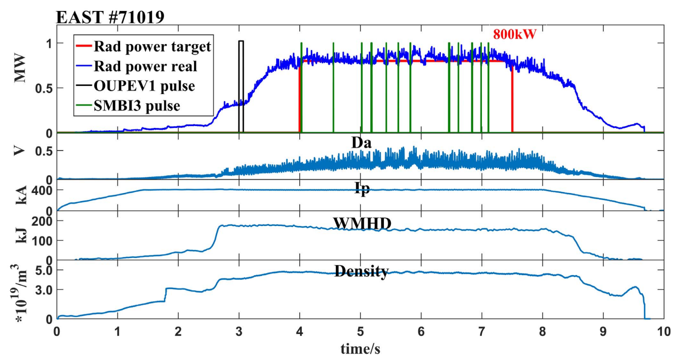


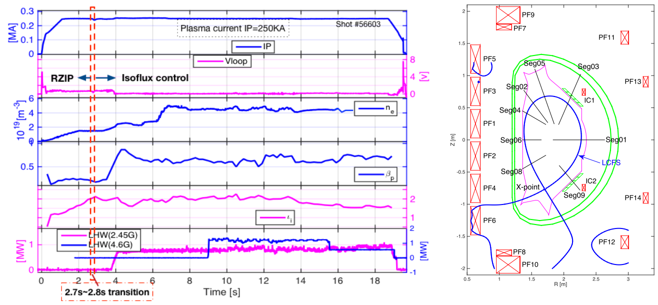
Fig. 9. Radiation power feedback control result using divertor PE valve as feedforward plus SMBI in mid plane as feedback injection actuator at shot 71019.

as one feedforward gas puffing by divertor valve "OUPEV1" plus "SMBI3" modulation injection for radiation feedback control. The experimental result is shown in Fig. 9 in which the radiation power target was set in red line about 800 kW. The measured radiation power in blue line followed the target quite well. The excellent control performance illustrates that the radiation control is successfully integrated in PCS using SMBI as feedback actuator.

V. QSF Shape Control Using PEFIT/ISOFLUX

Advanced magnetic divertor configuration is one of the attractive methods to spread the heat fluxes over divertor targets in tokamak. Due to poloidal coil system limitation, the exact snowflake (SF) shape is hard to achieve on EAST. However, we found an alternative way to operate EAST in a so-called QSF or X-divertor configuration, characterized by two first-order nulls with primary null inside and secondary null outside the vacuum vessel. Both modeling and experiment showed this QSF can result in significant heat load reduction to divertor target [2]. In order to explore the plasma operation margin and effective heat load reduction under various plasma conditions and QSF shape parameters, the QSF control algorithm is implemented in PCS combined with PEFIT providing reconstructed plasma parameters.

In equilibrium reconstruction code, the vacuum chamber is divided into small grids for mutual coefficient calculation. Usually, finer spatial grids have smaller discreteness error,



(a) (b)

Fig. 10. (a) QSF shape control result using PEFIT/ISOFLUX control technique at shot 56603. (b) Target configuration of QSF shape.

but take much more calculation time. To satisfy the real-time reconstruction need for shape control, RTEFIT [10] takes 33 by 33 grids. In addition, the main code in RTEFIT is divided into two portions, fast loop which generates control errors in 250 μs, and slow loop which provides data set for fast loop in about 2 ms for each iteration. In order to accelerate the calculation with higher spatial resolution, a new parallel equilibrium reconstruction code PEFIT [3] was developed based on graphic processing units (GPU) device. Through efficiently making use of the abundant parallel computing cores of GPU, PEFIT could complete an equilibrium reconstruction iteration in 220 μs with a 65×65 grid number.

The PEFIT is integrated in PCS for plasma shape control in 2013. The data interface between PEFIT and PCS was designed [4]. The PEFIT running on GPU exchanges data with PCS through RFM network during each real time control cycle to provide flux errors on control points, and X-point position errors for shape control, and also get magnetic diagnostic data from PCS for reconstruction.

EAST has achieved accurate control of plasma shapes, i.e., upper singer null, DN, or lower single null, using the advanced PEFIT/ISOFLUX control technique. And the QSF control algorithm is developed based on single null algorithm with additional outside secondary X-point or flux expansion control. In shot 56603, QSF shape as shown in Fig. 10(b) is achieved with PF6/PF12 following preset waveform from simulation, and other coils used for plasma current and shape control. There is a transition period from 2.7–2.8 s for RZIP control changing to ISOFLUX control, which reduces the control jitter at algorithm changing point [11]. As shown in Fig. 10(a), up to 19-s long-pulse QSF discharge with LHW current drive has been obtained, from top to bottom: plasma current (MA), loop voltage (V), line integral average density (m^{-3}), poloidal beta, internal inductance, and2.45- and 4.6-GHz LHW power (MW).

VI. Summary and Future Works

The linear rate for each integrator channel is used to eliminate the influence of linear drift of integrators in long pulse shots. Another strategy is about the segmental archiving in real time which solves the memory limitation problem perfectly for long pulse and future steady state operation. Using LHW 4.6 GHz, plasma beta and loop voltage feedback control is demonstrated. And the active feedback control of radiation power is realized, which shows a reliable control capability using divertor gas puffing as feedforward and SMBI in mid plane as feedback actuator. The QSF shape was achieved on EAST using PEFIT/ISOFLUX control method. The conclusion is that the present EAST PCS has become a huge system capable of long pulse, high-performance advanced plasma control operation, which is ready to demonstrate ITER-like control contents.

Future work on real-time data analysis and control scenario switching is ongoing. In real-time segmental data archiving mode, all data in real-time processor memory can be offloaded and archived to MDSplus. The segmental archived data can be retrieved individually, which can be used for real-time data display and analysis. When some control parameters set in PCS are not suitable, the adjustment can be input to PCS for tuning the parameters even changing the control sequence. Another work needs to be done is improving flexibility and robustness of QSF shape control. In current single-input single-output (SISO) controller, it is difficult to physically decouple plasma control parameters and PF coils current. The multi-input multi-output decoupling controller [12], aimed to overcome the intrinsic limitations of SISO controller, will be studied and implemented in PCS in the future.

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