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Current status and prospect of plasma control system for steady-state operation on QUEST

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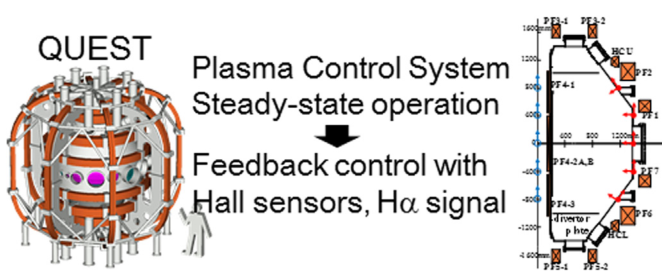
HIGHLIGHTS

- Overall configuration of plasma control system on QUEST are presented.
- Multi core system and reflective memories are used for the real-time control.
- Hall sensors are used for the identification of plasma current and its position.
- Repetitive gas fueling with the feedback control of Hα signal is implemented.

GRAPHICAL ABSTRACT



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ABSTRACT

The plasma control system (PCS) of QUEST is developed according to the progress of QUEST project. Since one of the critical goals of the project is to achieve the steady-state operation with high temperature vacuum vessel wall, the PCS is also required to have the capability to control the plasma for a long period. For the increase of the loads to processing power of the PCS, the PCS is decentralized with the use of reflective memories (RFMs). The PCS controls the plasma edge position with the real-time identification of plasma current and its position. This identification is done with not only flux loops but also hall sensors. The gas fueling method by piezo valve with monitoring the Hα signal filtered by a digital low-pass filter are proposed and suitable for the steady-state operation on QUEST. The present status and prospect of the PCS are presented with recent topics.

1. Introduction

One of the major purposes of QUEST (Q-shu University Experiment with Steady-State Spherical Tokamak) [1–3] is to develop the particle recycling control with high temperature wall (>600 K) for the steady state operation on spherical tokamaks (STs). The plasma control system (PCS) of QUEST is also developing according to the progress of QUEST project in order to control the plasma with a high degree of accuracy for the long pulse plasma discharge. In this paper, we would like to introduce the recent topics and future prospects of the PCS on QUEST. In Section 2, the overall configuration of PCS is introduced. The identification and the control of plasma shape are introduced in Section 3. Another identification method with hall sensors and the gas fueling method for the steady-state operation are presented in Sections 4 and 5, respectively. The summary is in Section 6.

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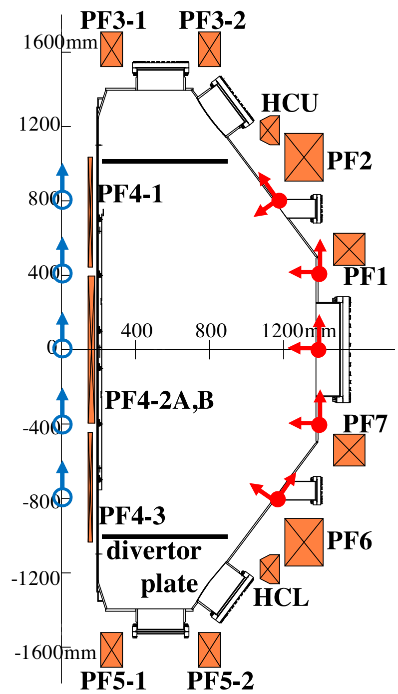

Fig. 1. PF coils on QUEST, and installed positions of hall sensors with the measuring direction of magnetic fields. Z-axis sensors with ±1600 G (open circle) and triaxial sensors with ±220 G and ±1600 G in TF direction (closed circle).

2. Overall configuration of PCS

The PCS of QUEST is composed of the workstation (WS) and its subsystem (SS). The WS and SS are the PXI systems based on the LabVIEW real-time operating system (OS) of National Instruments Corporation, and several threads of main loop, hardware control loop, and magnetic analysis loop are executed in parallel with the multicore CPU in each system. The WS and SS are connected each other with an optical fiber via reflective memories (RFMs). With these RFMs, the 128 double-precision floating-point numbers (DBLs), namely 1 kB are shared between them in 4 kHz. The SS acquires experimental data, especially the magnetic signals, and transfers the important and/or calculated experimental data to the WS. The WS communicates with other peripherals systems of the central control system, coil power supply systems, RF power supply systems, and fuel supply systems. The central control system informs the WS about the discharge sequence information of shot number, sequence status, and the discharge time, and monitors the status of the WS.

The poloidal field (PF) coils of QUEST are shown in Fig. 1. In typical connection of PF coils on QUEST, PF coils positioned symmetrically against equatorial plane are connected serially to make vertical magnetic fields. In one instance, PF1 and PF7 are connected serially and this pair is called as PF17 coil. On the other hand, the HCU and HCL coils are connected oppositely to make horizontal magnetic fields for the control of the vertical position of plasma. On the QUEST, the WS controls 8 coil power supplies to drive the PF coil currents and the toroidal field (TF) coil current. Signals to control the RF power are sent from the WS to three RF power supply systems. The RF power of one system is up to 50 kW with 2.45 GHz, and others are up to 200 kW with 8.2 GHz. The WS also sends control signals in order to control four piezo valves for fueling gases. One piezo valve is for puffing of helium gas, and others are for puffing of hydrogen gas. The locations of hydrogen fueling are the mid-plane of the center stack (CS), downside of CS, and top divertor plate, respectively.

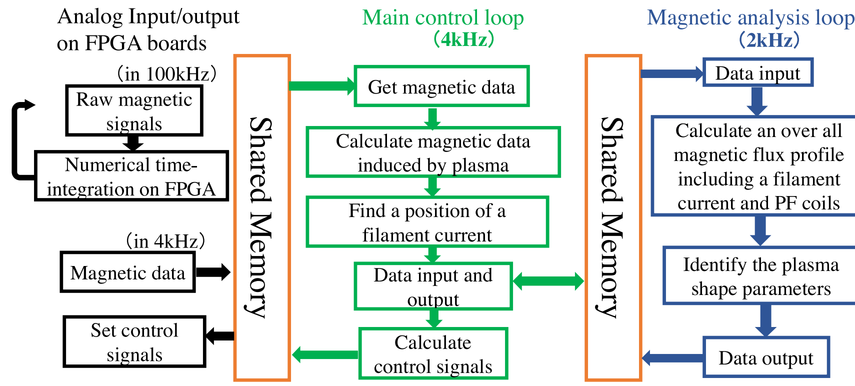

Fig. 2. Flowchart of plasma shape identification in real time. The calculation processes are executed in parallel with a multicore of the WS.

3. Real-time identification and control

Plasma position and its shape have to be identified in real time for the control of them. On QUEST, the Cauchy condition surface method [4,5] and general equilibrium calculation codes are tested to identify them. Another method is to assume the plasma current as a filament current located on the inside of the vacuum vessel. Fig. 2 shows the flowchart of this method. In this calculation, the numerical time-integration with 100 kHz against 32ch magnetic raw signals are executed to calculate magnetic fluxes in real-time with field-programmable gate array (FPGA). On main control loop executed in 4 kHz, the plasma-induced magnetic fluxes are extracted with the consideration of coil-induced eddy current effect by applying the digital low-pass filters to PF coil currents, and the filament position is determined with the least-square method between measured flux signals and pre-calculated data arrays [6]. On magnetic analysis loop executed in 2 kHz, the plasma shape is identified in real time with the calculation of the total magnetic flux profile induced by all PF coil currents and a filament current as a plasma current [7], where the last closed flux surface (LCFS) is searched by widening the area of the LCFS gradually from the filament position with referring to the magnetic flux profile and its position. The search is stopped when the searching position touches the vacuum vessel or the saddle point of the magnetic flux profile. The former and the latter cases mean the limiter configuration and the divertor configuration, respectively. The shaping parameters of aspect ratio, triangularity, and plasma edge positions are defined with this LCFS.

The plasma shape control is executed as the plasma edge position control. Fig. 3 shows the result of inside plasma edge position control by PF4 in order to sustain the divertor configuration from limiter configuration [7]. This control is executed by a proportional-integral-derivative (PID) control loop of the deviation between the actual inside position and target inside position. The PF4 coil current increases gradually after the start of the inside edge position control to move the inside edge position outward during 2.0 and 2.5 s. After that, the PF4 coil current is adjusted automatically in order for the actual edge position to correspond to the target edge position. The change of the PF4 coil current affects not only the inside edge position but the overall plasma equilibrium, and the other edge positions are also changed. In future, the control of other positions such as the outside, top, and bottom edge positions will be tried with other PF coils, and the plasma shape control on QUEST will be done by increasing its control positions.

The real-time equilibrium calculation code which treats the plasma current as not a filament current but the some current profile is also developed [8]. In this calculation, the iteration to converge a solution with one dataset is eliminated as other real