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Upgrade of the COMPASS tokamak real-time control system

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HIGHLIGHTS

- An upgrade of the COMPASS real-time system has been made to generally improve the plasma performance.
- Stability of discharges in SNT configuration has been increased.
- Plasma flat-top phase length has been extended.
- Central solenoid protection has been developed.
- Plasma position estimation has been improved.

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ABSTRACT

The COMPASS plasma control system is based on the MARTe real-time framework. Thanks to MARTe modularity and flexibility new algorithms have been developed for plasma diagnostic (plasma position calculation), control (shaping field control), and protection systems (central solenoid protection). Moreover, the MARTe framework itself was modified to broaden the communication capabilities via Aurora.

This paper presents the recent upgrades and improvements made to the COMPASS real-time plasma control system, focusing on the issues related to precision of the real-time calculations, and discussing the improvements in terms of discharge parameters and stability. In particular, the new real-time system has given the possibility to analyze and to minimize the transport delays of each control loop.

1. Introduction

COMPASS [1] is a tokamak with an ITER-like magnetic configuration, which currently operates with the parameters listed in Table 1.

The simplified scheme of the poloidal field coils and of the corresponding power supplies [2] is shown in Fig. 1.

The Magnetizing Field Power Supply (MFPS) is used to drive the current in the central solenoid made by the MA and MB windings reported in Fig. 1). The central solenoid generates the loop voltage needed to drive the plasma current. The shaping magnetic field elongates and shapes the plasma, in order to achieve different configurations. This additional field is generated by the Shaping Field Power Supply (SFPS). The horizontal magnetic field, which vertically stabilizes the plasma is generated by the Fast Amplifier for Radial Field (FABR), while the vertical magnetic field used to horizontally control the plasma has two different sources. The "slow" one generated by the Equilibrium Field Power Supply (EFPS) and the "fast" one is generated by Fast Amplifiers for the Vertical Magnetic field (FABV). Both fast amplifiers (FABR and FABV) operate with a frequency response of 40 kHz.

1.1. Feedback control

Present-day tokamaks, in particular those with divertor configuration, need a robust real-time control system to keep a predefined and stable magnetic configuration. Fig. 2 shows the block scheme of the COMPASS real-time control system. All power supplies are

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Table 1
COMPASS parameters.

Major radius	0.56 m
Minor radius	0.18–0.23 m
Plasma current	<300 kA
Magnetic field	0.9–2.1 T
Triangularity	0.5–0.7
Elongation	1.8
Pulse length	<0.5 s
P_{NBI}	2 × 0.3 MW

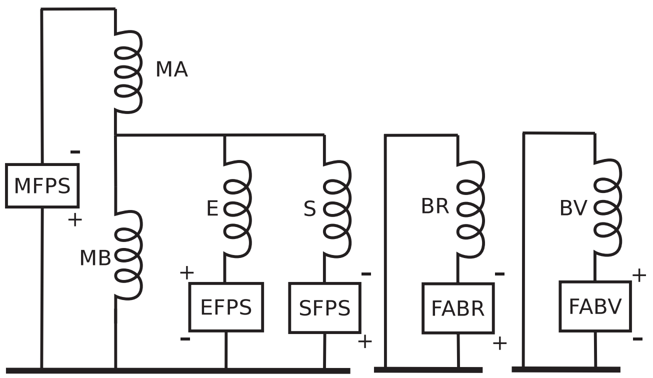

Fig. 1. Simplified scheme of coils connection between magnetizing, equilibrium and shaping filed power supplies.

controlled in real-time by using the Multi-threaded Application Real-Time executor (MARTe) [3,4]. The MARTe system runs on two Advanced Telecommunications Computing Architecture (ATCA) crates [5]. Each ATCA crate is equipped with Data Acquisition (DAQ) boards having a Field-Programmable Gate Array (FPGA) [6], whose firmware can be programmed either to acquire data at 2 Msps, or to control experiments in real-time with MARTe. Data are digitized by the analogue–digital converters assembled on the DAQ boards. For real-time control, the data are down-sampled by the on-board FPGA and then streamed to MARTe in 50 μs cycles. The ATCA crate has a carrier board which connects every DAQ board to the motherboard, where MARTe runs at dedicated isolated CPU cores, via the Peripheral Component Interconnect Express cable (PCIe) [7].

Each ATCA crate is synchronized by the timing unit with 2 MHz clocks. The timing unit sends triggers to each ATCA crate to start acquiring data and provides triggers for diagnostics to start measurements, when required.

The real-time control on COMPASS operates in two different ways. Parameters can be controlled either with predefined waveforms or with a feedback control loop applied to the measured

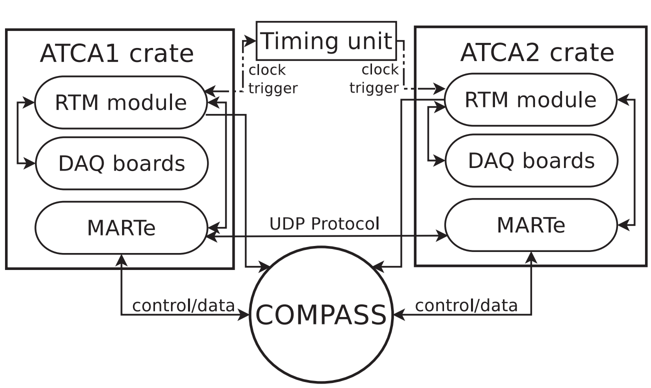

Fig. 2. Block scheme of the real-time control. Timing unit sends triggers and clocks to synchronize the ATCA boards. MARTe analyses data from COMPASS and controls the experiment according to measured signals.

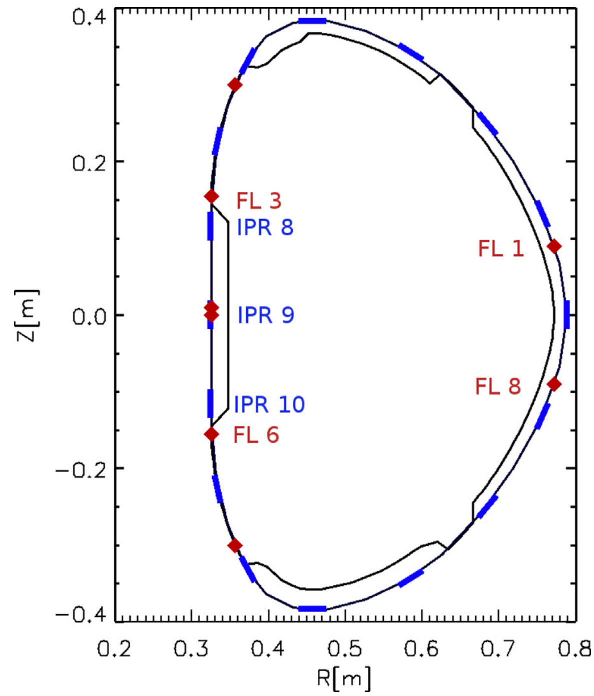

Fig. 3. Position of sixteen internal partial Rogowski coils (IPR1–IPR16) and eight flux loops (FL1–FL8) used as magnetic sensors for real-time control. Named IPR coils and flux loops are used for calculating horizontal position.

signal. These two methods can be combined for any controlled parameter.

1.2. Recent upgrades

During the commissioning phase, the COMPASS tokamak was successfully operated with a circular plasma cross-section by using the control system already described in [8,5,9]. However, the existing control system appeared not to be fully efficient in broadening the operational scenarios to D-shaped plasmas, which are required in order to achieve the H-mode. In particular, the vertical stability of elongated plasmas was rather poor, mainly because of the vertical displacement events (VDE) [10–12], and development of a more robust feedback system appeared to be urgent.

Several improvements have recently been implemented to ensure plasma stability and consequently the reproducibility of the plasma discharges. These upgrades are described in the following sections. Improved estimation of the horizontal plasma position is described in Section 2. An upgrade of the EFPS control, which suppresses oscillations in the horizontal plasma position is mentioned in Section 3. The main problem with vertical plasma position stability, caused by time delays between measurements of the data and acting on plasma with the actuators, is treated in Section 4. Overshooting of a controlled parameter and connection between feedback and the predefined control system is described in Section 5. Newly developed plasma shape control is described in Section 6. Furthermore, protection of the central solenoid against overheating during the discharge is discussed in Section 7. The last Section 8 is devoted to the upgrade of the real-time control MARTe software and the control FireSignal software.

2. Improved calculation of the horizontal plasma position

The location of the magnetic sensors, which are used for real-time control is shown in Fig. 3. The setup is made of sixteen internal