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Plasma position and current control system enhancements for the JET ITER-like wall

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HIGHLIGHTS

- JET plasma position and current control system enhanced for the JET ITER like wall.
- Vertical stabilization system enhanced to speed up its response and to withstand larger perturbations.
- Improved termination management system.
- Implementation of the current limit avoidance system.
- Implementation of PFX-on-early-task.

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ABSTRACT

The upgrade of Joint European Torus (JET) to a new all-metal wall, the so-called ITER-like wall (ILW), has posed a set of new challenges regarding both machine operation and protection. The plasma position and current control (PPCC) system plays a crucial role in minimizing the possibility that the plasma could permanently damage the ILW. The installation of the ILW has driven a number of upgrades of the two PPCC components, namely the Vertical Stabilization (VS) system and the Shape Controller (SC). The VS system has been enhanced in order to speed up its response and to withstand larger perturbations. The SC upgrade includes three new features: an improved termination management system, the current limit avoidance system, and the PFX-on-early-task. This paper describes the PPCC upgrades listed above, focusing on the implementation issues and on the experimental results achieved during the 2011–12 JET experimental campaigns.

1. Introduction

The installation of the ITER-like wall (ILW) [1] has driven a number of upgrades to the JET plasma position and current control (PPCC) system. The overall design objective was the avoidance of overheating the ILW due to plasma thermal loads and hence the prevention of permanent damage to the wall surface.

The PPCC system is composed of two subsystems, namely the Shape Control (SC) system, which regulates the plasma current and controls the plasma shape, and the Vertical Stabilization (VS) system that stabilizes the JET elongated plasmas.

The VS system was upgraded in 2009–10, before the ILW installation, and hence has been tested with the carbon wall, as part of the commissioning strategy, before use on the more fragile metal wall [2].

A further package of activities was launched within the project Protection of the ITER-like wall (PIW) in 2011. Amongst these activities the SC was upgraded to include three new features: an improved termination management system, the Current Limit Avoidance system (CLA), and the PFX-on-early-task (POET). Before these enhancements, one of the key problems for machine protection was that the termination of a pulse under fault conditions was limited to a predefined set of global responses, tailored for safe plasma landing or for reducing the vessel forces in case of plasma disruptions. Indeed, one of the possible force reduction strategies consists of pushing the plasma against the inner wall, which for the ILW, conflicts with the requirement that localised heat fluxes in the wall components should be avoided. The enhancement requires the

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[1] See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA.

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update of several systems that are key to the machine operation, such as PPCC, the plasma density plant manager, and the additional heating systems. The new termination management system allows these subsystems (including PPCC) to dynamically adapt their responses according to the experimental conditions at the time of the stop request and during the termination itself. Such a solution is one of the first attempts to have a programmable pulse schedule (for two other examples, see [3] and [4]), which is one of the challenges for the ITER plasma control system [5]. The CLA avoids the current saturations in the poloidal field (PF) coils when the eXtreme Shape Controller is used to control the plasma shape.

This paper deals with all these recent enhancements of the JET PPCC system, and also reports on some significant experimental results obtained during the first ITER-like wall campaigns at JET, in 2011–2012. The remainder of the paper is structured as follows: the next section gives a brief overview of the overall JET PPCC system. A detailed description of the recent enhancements for both the VS and SC, together with the relevant experimental results are presented in Sections 3 and 4, respectively.

2. Overview of the jet plasma position and current control system

The PPCC system is in charge of the axisymmetric magnetic control [6]. When dealing with the control of the current, position and shape of the plasma column inside the vacuum vessel, the problem is typically considered axisymmetric, and the following three control issues are considered: the vertical stabilization, the plasma shape control, and the plasma current control.

On almost all existing machines, a frequency separation approach is adopted to solve the three aforementioned control problems. Following this approach, at JET the plasma is first vertically stabilized on a *fast* time scale, according to the constraints imposed by the passive structures and the actuator. Afterwards, the current and shape controller is designed on the basis of the stable system obtained taking into account the vertical stabilization controller. For the JET tokamak, the time constant of the unstable mode is ~2 ms, while the settling time of the current and shape controller is about 0.7 s.

According to the frequency separation approach, the PPCC system has a distributed architecture which includes the two following subsystems

- the Vertical stabilization (VS) system, which stabilizes the plasma by controlling the plasma vertical velocity;
- the Shape control (SC) system, which controls both plasma current and shape (and hence also its position).

The VS and the SC systems are deployed on two different hardware platforms. The SC system runs with a 2 ms cycle time on a ten years old VME board, which mounts a 400 MHz PowerPC® CPU and executes the VxWorks™ OS. On the other hand, the VS system is deployed on a more recent ATCA/PCIe architecture, with a Intel® Core2Quad CPU that runs Linux®-RTAI, with a cycle time of 50 μs.

These two heterogeneous hardware architectures are connected to the JET Real-Time Data Network [7], which is a ATM/AAL5 communications on 155 MHz fiber-optic. Each of the connected system sends application-specific datagrams into the network. For cross-platform interoperability, the datagrams have a fixed-size and structure, based on 32-bit integer or IEEE-754 floating point fields, with a simple header (sample number, sample time) and trailer (datagram version). The network switch distributes the datagrams to whichever system needs the information. Currently the JET Real-Time Data Network connects more than 30 systems, exchanging 40 datagram types and a total of more than 500 signals.

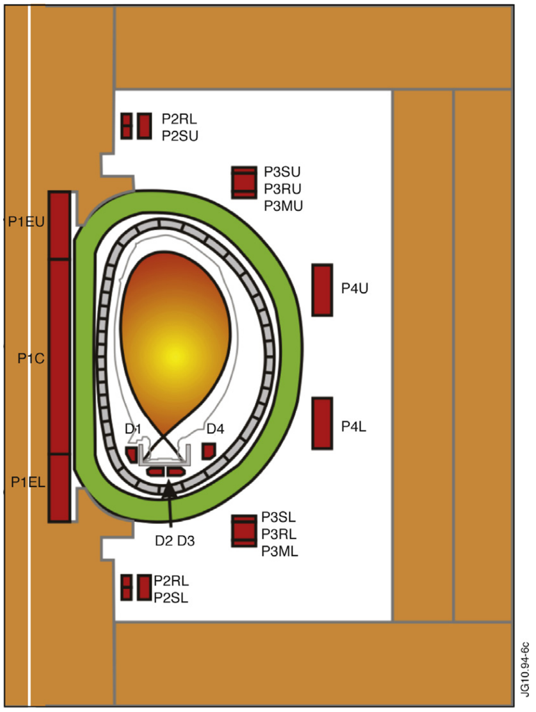

Fig. 1. The JET poloidal field coils system. The radial field circuit connects the P2RU, P3RU, P2RL, and P3RL, and is fed by the *Radial Field Amplifier* (*RFA*). This amplifier is used by the VS system to vertically stabilize the plasma column. The *P1* circuit includes the elements of the central solenoid P1EU, P1C, P1EL, as well as P3MU and P3ML. The series circuit of P4U and P4L is named *P4*, while the circuit that creates an imbalance current between the two coils is referred to as *IMB*. *SHA* is made of the series circuit of P2SU, P3SU, P2SL, and P3SL. The central part of the central solenoid contains an additional circuit named *PFX*. Finally the four divertor coils (*D1* to *D4*) are driven separately each by one power supply.

As far as the real-time software is concerned the VS system has been developed using the MARTe framework [8], while the SC system exploits the MARTe's ancestor, called *JETRT* [9].

The actuators used by the PPCC system are the PF coils shown as red squares in Fig. 1. These coils are linked together into 10 circuits, named *P1*, *P4*, *IMB*, *SHA*, *PFX*, *D1*, *D2*, *D3*, *D4* and *Radial Field* circuit, each driven by independent power supplies. In particular, the *P1* circuit is controlled by SC system and enables both the plasma inductive formation and the control of the plasma current. Furthermore, the SC system controls also *P4*, *IMB*, *SHA*, *PFX*, *D1*, *D2*, *D3*, and *D4* to perform plasma shape control. The VS system stabilizes the plasma by controlling the current in the *Radial Field* circuit fed by the *Radial Field Amplifier* (*RFA*).

The block diagram in Fig. 2 shows both the VS and SC systems. The VS system stabilizes the plasma column by controlling to zero its vertical velocity $\dot{z}_p(t)$. It tries also to minimize the control effort by controlling to zero the current flowing in the *Radial Field* circuit $I_{RFA}(t)$; furthermore keeping $I_{RFA}(t)$ small also allows the system to withstand bigger disturbances when they occur. As a matter of fact, The VS control law provides a proportional action on plasma velocity and a proportional-integral action on the actuator current.

The two main components of the SC system, namely the *Shape and Plasma Current Controller* and the *PF Current Controller*, are also shown. The former computes the PF currents needed to counteract the disturbances and track the desired values for both the plasma current $I_{P_{ref}}(t)$ and of the plasma shape.[2]

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[2] The plasma shape is usually specified via a vector of geometrical descriptors $\mathbf{shape}_{ref}(t)$ that includes gaps, strike points and X-point positions (see also Tutorial 7 in [10]).