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Physics of the conceptual design of the ITER plasma control system

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HIGHLIGHTS

- ITER plasma control system conceptual design has been finalized.
- ITER's plasma control system will evolve with the ITER research plan.
- A sophisticated actuator sharing scheme is being developed to apply multiple coupled control actions simultaneously with a limited set of actuators.

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ABSTRACT

The ITER plasma control system (PCS) will play a central role in enabling the experimental program to attempt to sustain DT plasmas with $Q = 10$ for several hundred seconds and also support research toward the development of steady-state operation in ITER. The PCS is now in the final phase of its conceptual design. The PCS relies on about 45 diagnostic systems to assess real-time plasma conditions and about 20 actuator systems for overall control of ITER plasmas. It will integrate algorithms required for active control of a wide range of plasma parameters with sophisticated event forecasting and handling functions, which will enable appropriate transitions to be implemented, in real-time, in response to plasma evolution or actuator constraints.

In specifying the PCS conceptual design, it is essential to define requirements related to all phases of plasma operation, ranging from early (non-active) H/He plasmas through high fusion gain inductive plasmas to fully non-inductive steady-state operation, to ensure that the PCS control functionality and architecture will be capable of satisfying the demands of the ITER research plan. The scope of the control functionality required of the PCS includes plasma equilibrium and density control commonly utilized in existing experiments, control of the plasma heat exhaust, control of a range of MHD instabilities (including mitigation of disruptions), and aspects such as control of the non-inductive current and the current profile required to maintain stable plasmas in steady-state scenarios. Control areas are often strongly coupled and the integrated control of the plasma to reach and sustain high plasma performance must apply multiple control functions simultaneously with a limited number of actuators. A sophisticated shared actuator management system is being designed to prioritize the goals that need to be controlled or weigh the algorithms and actuators in real-time according to dynamic control needs. The underlying architecture will be event-based so that many possible plasma or plant system events or faults could trigger automatic changes in the control algorithms or operational scenario, depending on real-time operating limits and conditions.

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1. Introduction

The conceptual design review of the ITER plasma control system (PCS) took place in November 2012. The design was well received by the review panel and the formal approval of the design by the ITER Organization is expected by the end of June 2013. This paper gives an overview of the main physics concepts on which the PCS design is based. The PCS is the central control system for ITER operation and will control nearly all aspects of plasma operation [1,2] to achieve the main goals of the ITER research plan, which include reaching $Q = 10$ for 300–500 s fusion burn as well as long pulse near steady-state operation with $Q \sim 5$ for up to 3000 s. The PCS will take inputs from most of the ITER diagnostic systems and apply control algorithms to drive actuators [3] to set up the necessary conditions for plasma operation, initiate the plasma, raise the plasma current, control the plasma position and shape, fuel and heat the plasma to thermonuclear burn conditions, control plasma exhaust and instabilities, handle plasma and plant system events to optimize plasma performance as well as to avoid or mitigate possible damage to in-vessel components, and control the exit from the fusion burn and safely ramp down the plasma current.

The PCS conceptual design sets out to ensure that all aspects of plasma operation are considered including preparing suitable wall conditions for plasma operation, early operation in H, He, and D, as well as high performance DT operation and long pulse near steady-state DT operation. In this way, the PCS architecture is designed taking into account all foreseen operational conditions to ensure sufficient flexibility to perform effectively under all conditions. No attempt has yet been made to define the detailed control algorithms that will be required as the preliminary and final design for 1st plasma progress in preparation for ITER operation. The conceptual design team includes the authors of this paper as well as a number of plasma control experts from the ITER Member states and many members of the International Tokamak Physics Activity (ITPA). This joint effort has produced a solid PCS conceptual design with broad agreement of the plasma physics community.

The PCS physics functional breakdown structure includes wall conditioning and tritium removal, axisymmetric magnetic control, kinetic control, MHD and error field control, and disruption and runaway electron control as the main control areas. Kinetic control is further broken down into core fuelling and impurity control, first wall and divertor heat flux control, temperature, current density, and rotation profile control and burn control. Each of these main physics functions is covered in the following sections of this paper, except axisymmetric magnetic control is covered in a separate paper [4]. Technical aspects of the PCS conceptual design are described in separate papers [5–8].

2. Wall conditioning

ITER requires wall conditioning techniques to desorb and pump away impurities as well as hydrogen isotopes from the plasma facing components (PFCs) to reduce plasma radiation, to control the plasma density, and to control tritium inventory. Baking and glow discharge cleaning (GDC) will be used on ITER for wall conditioning. The PCS will not include control of such wall conditioning methods, but some wall conditioning methods require control of multiple systems that make the involvement of the central control system mandatory. Ion cyclotron (IC) and electron cyclotron (EC) wall conditioning [9,10] require coordinating a number of plant systems including the heating system itself as well as gas input and possibly poloidal field, which requires the PCS. ICWC is expected to require 1–5 MW of power at 40 MHz with a duty cycle 1 s on/30 s off in a D or H plasma at 5.3 T or 2.65 T in a plasma with $n_e \sim 10^{17}$–10^{18} m^{-3} and $T_e \sim 5$–10 eV. ECWC may require 1–10 MW at 170 GHz with a similar duty cycle at an order of magnitude higher electron density. Limited tritium inventory requirements will probably require tritium removal during an experimental campaign between discharges with dedicated tritium removal techniques that minimize impact on subsequent high performance plasma operation.

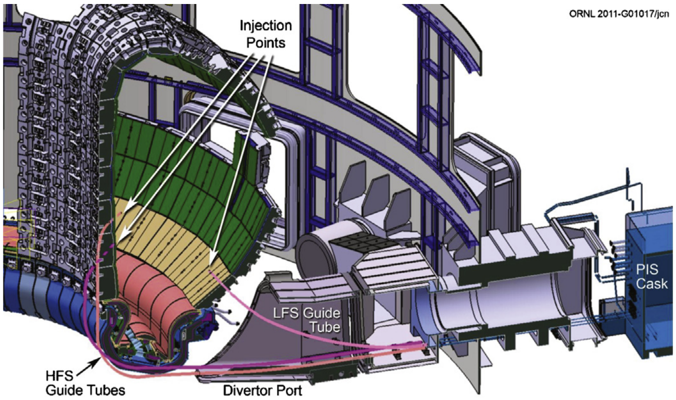

Fig. 1. 3D cutaway view of ITER showing the locations of the two high field side (HFS) and one low field side (LFS) guide tubes for pellet injection.
This figure is courtesy of L. Baylor ORNL.

3. Axisymmetric magnetic control

Axisymmetric magnetic control comprises functionality that is standard in today's machines and is fundamental to operate a tokamak [1,11,12]. It includes plasma initiation, vertical and radial position and shape control, and inductive plasma current control. The actuators include the central solenoid (CS), poloidal field (PF), and in-vessel vertical stability (VS) coil systems and their power supplies as well as the gas injection system (GIS) and the electron cyclotron heating (ECH) system to setup the conditions for plasma initiation and achieve breakdown and burnthrough of the plasma current rise. The conceptual design for axisymmetric magnetic control in the ITER PCS is described in detail in a separate paper [4].

4. Fuelling and impurity control

The main tasks of fuelling and impurity control include reaching and sustaining the required core density, controlling the minority species for ICRF heating, controlling the main impurity level, controlling the D/T mixture, controlling the edge density, and pellet pacing for ELM control [13–15]. Fuelling and impurity gases will be injected from 4 upper and 6 lower gas valve boxes with a choice of H, T, D, He^4, N, Ar, and Ne gases. He^3 has not yet been approved, but will be needed for ICRF heating schemes in H and DT plasmas. Initially 2 with a possible upgrade up to 6 H, D, and DT pellet injectors will be installed with up to 16 Hz fuelling pellets. A dedicated <60 Hz pellet injector may also be installed for ELM pacing. Two guide tubes will be installed from the high field side and one from the low field side (Fig. 1). In addition, one impurity injector will also be installed.

The hot and dense edge of ITER plasmas will ionize the gas far into the scrape-off-layer so that most of the gas will not reach the separatrix, which makes gas fuelling very inefficient. Core fuelling will then require pellet injection [16]. The control of the core D/T ratio will also then be weakly dependent on edge DT recycling and depend mainly on the relative fraction of D and T pellet injection. Thus, core and edge fuelling will have nearly separate control schemes. The timescales for fuelling are long with ~1 s for gas injection and ~3 s required to double the rate of pellet injection, but these timescales are comparable to the confinement time.