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Overview of magnetic control in ITER

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ABSTRACT

ITER is targeting $Q=10$ with 500 MW of fusion power. To meet this target, the plasma needs to be controlled and shaped for a period of hundreds of seconds, avoiding contact with internal components, and acting against instabilities that could result in the loss of control of the plasma and in its disruptive termination.

Axisymmetric magnetic control is a well-understood area being the basic control for any tokamak device. ITER adds more stringent constraints to the control primarily due to machine protection and engineering limits. The limits on the actuators by means of the maximum current and voltage at the coils and the few hundred ms time response of the vacuum vessel requires optimization of the control strategies and the validation of the capabilities of the machine in controlling the designed scenarios.

Scenarios have been optimized with realistic control strategies able to guarantee robust control against plasma behavior and engineering limits due to recent changes in the ITER design. Technological issues such as performance changes associated with the optimization of the final design of the central solenoid, control of fast transitions like H to L mode to avoid plasma-wall contact, and optimization of the plasma ramp-down have been modeled to demonstrate the successful operability of ITER and compatibility with the latest refinements in the magnetic system design.

Validation and optimization of the scenarios refining the operational space available for ITER and associated control strategies will be proposed. The present capabilities of magnetic control will be assessed and the remaining critical aspects that still need to be refined will be presented. The paper will also demonstrate the capabilities of the diagnostic system for magnetic control as a basic element for control. In fact, the noisy environment (affecting primarily vertical stability), the non-axisymmetric elements in the machine structure (affecting the accuracy of the identification of the plasma boundary), and the strong component of eddy current at the start-up (resulting in a poor S/N ratio for plasma reconstruction for $I_p<2$ MA requiring a robust plasma control) make the ITER magnetic diagnostic system a demanding part of the magnetic control and investment protection systems. Finally the paper will illustrate the identified roles of magnetic control in the PCS (plasma control system) as formally defined in the recent first step of the design and development of the system.

1. Introduction

Axisymmetric magnetic control for a tokamak device is the basic control for maintaining the plasma properly shaped (performance) and positioned in the vacuum vessel (avoid close proximity with the internal components at high plasma performance).

In the case of ITER [1], magnetic control will also play an important role in machine protection because of the high plasma energy and electromagnetic forces.

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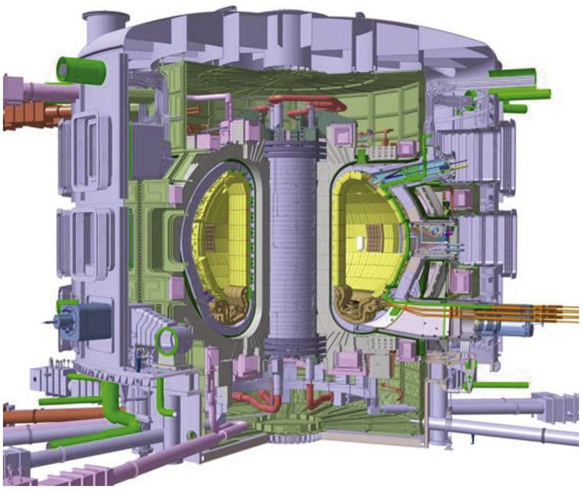

Fig. 1. Layout of the magnetic actuators in ITER. Poloidal field (PF) coils, central solenoid (CS) coils and vertical stabilization systems (VS1 and VS3).

It is a common approach allocating three main actions to the magnetic control areas such as driving the plasma current, control the shape and the position of the plasma [2].

Plasma initiation is also usually included in the magnetic control area by means of requiring the control of the magnetic actuators.

The paper will illustrate the present understanding of the magnetic control in ITER with attention also to the uncertainties and open questions still under investigation. In the paper, space will be given to both the plasma scenarios development and the controller design.

2. Plasma scenario optimization

A wide set of analysis have been performed so far with the primary purpose to validate the capabilities of the ITER machine in achieving the desired plasma performance while still remaining inside the technical limits of the device. Those limitations are on the performance of the actuators (e.g. maximum current and voltage at the coils) and the machine structural integrity (e.g. maximum thermal load on first wall or electromagnetic forces at the coils). Scenarios have been simulated in all the phases from the plasma breakdown, ramp-up, flat-top to ramp-down showing that the present design of ITER is able to pursue its goals. Naturally, in the process of the development of the scenarios, modifications have been made and simulations repeated each time a change in the performance of the actuators or an additional restriction coming from one of the plant system of the machine was identified.

Alternatives and adjustments to the scenarios have been tested in order to verify the largest set of possible conditions that ITER would encounter.

Input for the design includes also specific plasma events and conditions that could compromise the performance of ITER and in some cases jeopardize the controllability of the plasma with the risk of damaging first wall components.

In the following, the main activities in the respect of the scenario design will be reported with a particular emphasis on the magnetic control aspects (Fig. 1).

2.1. Plasma initiation

Plasma initiation in ITER defines the interval of the start of discharge of the central solenoid (CS) followed by the gas breakdown and impurity burn-through till plasma current of about 0.5 MA, when the control of the plasma position is activated. Breakdown occurs under specific conditions [3] such as the applied voltage history, the quality of the field null region and the vertical field evolution. Additionally, a radio frequency source from an EC system is envisaged for ITER [4]. The magnetic system needs to prove the ability to realize a high quality field null region (<∼2 mT) simultaneous with the maximum toroidal electric field (>∼0.3 V/m), followed by the correct evolution of the magnetic field to provide stable radial and vertical plasma equilibrium for the rising plasma current. Usually performed with pre-programmed actions, optimization in the magnetic distribution will be probably required by means of a feedback control. Optimization is also desired in order to maximize the flux at the breakdown leaving more flux for sustaining the long in ITER.

The analyses have been carried out by means of simulations with different codes. Transport and equilibrium codes have been used together with the purpose to simulate the full conditions for the plasma formation in a realistic way.

A first set of simulations makes use of the TRANSMAK [5] code for approaching the conditions for plasma breakdown and the current ramp-up till about 0.5 MA [6].

In parallel a different set of simulations has also been proposed [7]. That optimizes the set of voltages to apply to the coils prior the breakdown. Then the plasma equilibrium was calculated by using the CREATE-NL [8].

Several representative scenarios of plasma initiation have been studied such as inboard and outboard with partly (∼60 Wb) or fully (∼118 Wb) charged CS and 'first plasma' scenario.

Some important results can be summarized as follows:

- The operating space for Ohmic breakdown is extremely limited. Electron cyclotron assistance is required to guarantee a reliable breakdown and impurity burn-through.
- There is a rather large region of low field (<3 mT in the area with minor radius ∼1.6 m) in which one or more field null points can be found at the breakdown time. Non-axisymmetric eddy currents, ferromagnetic elements closely located to the plasma (ferromagnetic inserts and test blanket modules) and measurement errors in the coil currents could reduce precision in the control of magnetic configuration with the possibility of undesired breakdown.
- The flux loss at breakdown is in the range of 8 Wb for all the cases with an external voltage at the center of the plasma formation region between 12 V and 14 V. An Ip current ramp rate of about 1 MA/s can be achieved up to I_p = 0.5 MA for all the cases.
- PF3–PF5 voltages are fully saturated in most of the cases. CS voltages are used at the maximum of their capabilities leaving a reduced margin of control for the plasma rise.
- Forces and fields in coils remain within the imposed limits although for fully charged CS cases some of them are very close to limits (vertical forces on the coils PF1 and PF6, max field on the CS conductors).
- The present limitation of the grid is on the order of 500 MW, where the analyses show a variation of the required peak power during the breakdown between 400 MW and 800 MW. Optimization is still possible to remain inside the limit.

2.2. From plasma rump-up to termination

The baseline plasma scenarios [1] have been designed and simulated. Two major sets of analysis have been performed in order to provide a representative operational space for ITER within the specifications of the machine. In here we will focus on the axisymmetric magnetic control aspects without disputing the physics results, assuming that the physics target has been achieved. We will report the main results on the 15MA–DT scenario, main goal for ITER, although many others have been simulated.