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Actuator and diagnostic requirements of the ITER Plasma Control System

J.A. Snipes [a,*], D. Beltran [a], T. Casper [a], Y. Gribov [a], A. Isayama [b], J. Lister [c], S. Simrock [a], G. Vayakis [a], A. Winter [a], Y. Yang [a], L. Zabeo [a]

[a] ITER Organization, St. Paul-lez-Durance 13115, France
[b] Japan Atomic Energy Agency, Naka, Ibaraki-ken 311-0193, Japan
[c] Association EURATOM – Confédération Suisse, Ecole Polytechnique Fédérale de Lausanne (EPFL), CRPP, Lausanne CH-1015, Switzerland

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ABSTRACT

The ITER Plasma Control System (PCS) requires an extensive set of about 50 diagnostic systems to measure the plasma response and about 20 actuators to act on the plasma to carry out its control functions. The specifications and real limitations of the actuators and diagnostics are being assessed as part of the ongoing conceptual design of the PCS to understand the potential impact on plasma control. The actuators include magnetic coils (central solenoid (CS), poloidal field (PF), vertical stability (VS), edge localized mode (ELM), correction coils (CC)), heating and current drive (electron cyclotron (EC), ion cyclotron (IC), neutral beam injection (NBI), and possibly lower hybrid (LH)), glow discharge cleaning, fueling and impurity gas and pellet injection, vacuum pumping, and disruption mitigation systems. Diagnostic systems are prioritized according to their role in machine protection (MP), basic control (BC), advanced control (AC), and physics studies (PS). At the conceptual design phase, detailed control algorithms do not yet need to be specified, but conceptual solutions must be chosen that satisfy the PCS requirements for control within the real constraints of the diagnostics and actuators. The feasibility of the chosen solutions must be proven either through established control schemes on existing machines or through an R&D program to develop them before they will be required on ITER. The diagnostic and actuator requirements of the PCS will evolve from first plasma through the high performance DT phase. A comparison is made of the expected requirements to control vertical stability, sawteeth, neoclassical tearing modes (NTMs), edge localized modes (ELMs), error fields, resistive wall modes (RWMs), Alfvén eigenmodes, and disruptions with the ITER baseline actuator and diagnostic specifications.

1. Introduction

The conceptual design of the ITER Plasma Control System (PCS) is expected to be completed by the end of 2012. Two parallel efforts are ongoing together with experts in the fusion community to assess both the system requirements and the actuator and diagnostic requirements for the PCS to successfully control ITER plasmas to achieve ITER's goals. This paper compares the actuator and diagnostic requirements as specified in the ITER Project Requirements document [1] and individual plant system requirements documents (SRDs) [2] with what fusion community experts think may be required to control ITER high performance plasmas. Some comparisons are made of specific actuator constraints and diagnostic requirements together with a comparison of diagnostic requirements for magnetohydrodynamic (MHD) stability control [3] and actuator requirements for sawtooth control [4] made by the MHD International Tokamak Physics Activity (ITPA) group. This is only part of an ongoing process and much more work will be required to complete the PCS conceptual design.

2. Actuator requirements

There are just over 20 actuator systems that will be used by the PCS to act on the plasma including magnetic field coils [central solenoid (CS1–3U, L), poloidal field (PF1 –6), correction coil (CC), in-vessel vertical stability (VS), and edge localized mode (ELM coil)], electron cyclotron (EC), ion cyclotron (IC), and neutral beam (NB) heating and current drive systems, glow discharge cleaning, fueling and impurity gas and pellet injection, ELM pace making pellet injection, vacuum pumping, and disruption and runaway electron mitigation systems. Table 1 gives a brief description of each of these actuators with one or more of their characteristics that affect plasma control including a global plasma response time. Since the toroidal field coils are limited to 1000 full current cycles due to fatigue in the superconducting strands, there will be no control of

* Corresponding author at: ITER Organization, Route de Vinon sur Verdon, Building 523, 13115 St. Paul-lez-Durance, France. Tel.: +33 4 42 17 65 15; fax: +33 4 42 17 65 00.
E-mail address: Joseph.Snipes@iter.org (J.A. Snipes).

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Table 1
Actuator characteristics including the maximum output, the number of locations, the global plasma response time, and some specific characteristics.

Actuator	Max output	Locations	Response time	Characteristics
Toroidal Field	5.3 T	18	100 s ramp up	Limited to 1000 full current cycles in ITER life, no real-time PCS control during the pulse
Central solenoid	25 MAt @ 12.6 T	6	5–10 s	Current limit 22 MAt @ 13 T on the coil, total vertical force limit 60 MN
Poloidal field (PF1)	12 MAt @ 6.4 T	1	5–10 s	Current limit 10 MAt @ 6.5 T on the coil, vertical force limits 110 to −150 MN
(PF2)	6.3 MAt @ 4.8 T	1	0.5–10 s	Current limit 5.7 MAt @ 5 T on the coil, vertical force limits 15 to −75 MN
(PF3)	10 MAt @ 4.8 T	1	0.5–10 s	Current limit 9.3 MAt @ 5 T on the coil, vertical force limits 40 to −90 MN
(PF4)	9.3 MAt @ 4.8 T	1	0.5–10 s	Current limit 8.5 MAt @ 5 T on the coil, vertical force limits 90 to −40 MN, PF3 + PF4 10, −60 MN
(PF5)	11 MAt @ 5.7 T	1	0.5–10 s	Current limit 7.2 MAt @ 6 T on the coil, vertical force limits 160 to −10 MN
(PF6) (0.4 K subcooled)	24 MAt @ 6.8 T	1	5–10 s	Current limit 18.8 MAt @ 7 T on the coil, vertical force limits 170 to −190 MN
Internal vertical stability (VS) coils	60 kA peak, 10 kA RMS	2	0.1–0.3 s	Using present 4 turn design with 2.3 kV peak, water cooling permits RMS current steady-state but coil overheats at peak current in < 0.3 s
ELM control coils	16 kA peak	27	0.2 s	Using present 6 turn design, up to 5 Hz rotation of peak current
Correction coils (CC)	10 kA	18	1–50 s	Slow control with dynamic error field correction < 1 Hz for at most a few cycles
Electron cyclotron	20 MW	1 EL, 4 UL	1–20 ms	0–100% modulation < 1 kHz, 50–100% <5 kHz, mirror sweep rate 50 cm/s at mid radius
Ion cyclotron	20 MW	2	1–200 ms	Initial 200 ms ramp up time, 50–100% modulation < 1 kHz
Neutral beam	33 MW	2	80 ms	Modulation rate limited by 5 ms max off time to limit thermal fatigue
Glow discharge cleaning	200 A, 3 kV	4–6	~10 s	May be possible to use the steady GDC electrodes at 20–100 kHz during TF
Fuelling gas injection	100 Pa m^3/s	4U, 6L	<1 s	Max. throughput from each of 10 gas valve boxes: $H_2/D_2/He_4$ 100 Pa m^3/s, T2 10 Pa m^3/s
Impurity gas injection	10 Pa m^3/s	4U, 6L	<1 s	Max. throughput from each of 10 gas valve boxes: N_2/Ne/He_3/Ar 10 Pa m^3/s
Fuelling pellet injection	120 Pa m^3/s	3L	<0.1 s	Max. throughput for each injector: H_2/D_2 120 Pa m^3/s, T2 111 Pa m^3/s, up to 16 Hz
ELM pacemaking pellet	120 Pa m^3/s	3L	21 ms	3 staggered injectors up to 16 Hz each provide 48 Hz pellet repetition rate
Impurity pellet injection	10 Pa m^3/s	3L	<0.1 s	Max. throughput: N_2/Ne/Ar 10 Pa m^3/s, once per plasma pulse
Vacuum pumping	65–107 m^3/s	8	5–10 s	~3–4 h regeneration time required each day for 400 s pulses → 40 pulses/day max
Disruption mitigation	0.5–2 kPa	4	10 ms	Thermal quench mitigation 1–2 kPa Ne or 0.5–1 kPa Ar, high pressure gas or shattered pellets
Runaway suppression	1 kPa	2	10 ms	5 repetitive high pressure Ne gas injections in 5–10 ms intervals in the current quench

the toroidal field during a plasma pulse and the toroidal field (TF) current will typically be set at the beginning of a campaign and left at that value throughout an operational campaign during and between plasma pulses.

The CS and PF coils are divided into 3 upper and lower sets as shown in Fig. 1 with current, field, and force limits shown in Table 1. The CS and PF1–PF6 coils are used for plasma current and shape control, which is limited to a slow settling time of about 5–10 s. The CS, PF1 and PF6 coils will be driven by initially one and later 2 converters with 1.05 kV each at full current. Coils PF2–PF5 will be driven by 3 converters of 1.05 kV each at full current. For plasma initiation, CS1 will have 6 kV additional and CS2, CS3, PF1, and PF6 will have 8.5 kV additional voltages from switching network units. Coils PF2–PF5 are combined for faster stabilization of plasma vertical displacements (VS1) with another six 1.05 kV converters, with a settling time that is expected to be down to 0.5 s. For still faster settling time for vertical stability, the water cooled in-vessel VS coils (VS3) will be used with a settling time expected to be down to 0.1–0.3 s. The present 4 turn design has a voltage limit of 2.3 kV with up to 40 kAt RMS in steady-state and up to 240 kAt peak current for at most 0.3 s. The system stabilizing plasma vertical displacements is capable of restoring the plasma to its specified vertical position after a maximum uncontrolled vertical drift of about 16 cm for a nominal full aperture plasma with $l_i(3) < 1.2$ [5]. Modeling indicates adequate performance should be achievable for each of the main ITER scenarios within these limits [6].

There will be 27 water cooled in-vessel ELM control coils located above, below, and centered about the outboard midplane beneath the blanket modules in 9 toroidal sectors providing $n = 3$ or $n = 4$ perturbations. The ELM coils will be used primarily to produce a slowly rotating (5 Hz) resonant magnetic perturbation to the plasma edge to stabilize ELMs, but will also be used for faster error field control when sufficient current head room is available. The slowly rotating perturbation allows the heat load on the in-vessel components to be more equally distributed. The present 6 turn design has a 96 kAt peak current limit with an on-load voltage of 144 V. Extrapolation of experimental results on existing devices and modeling indicate that within the present engineering limits, ELM control should be possible for ITER scenarios [7].

There will be 18 superconducting external correction coils (CC) around the machine toroidally on top, bottom, and at the outboard midplane connected to provide $n = 1$ toroidal mode number error field correction. Maximum values of the converters on-load voltage are 450 V for the midplane CC and 90 V for the top and bottom CC. Within the engineering limits on currents in the CC (200 kAt midplane and 320 kAt top and bottom), they are capable