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Poster

Overview of the Preliminary Design of the ITER Plasma Control System

Poster on an Overview of the Preliminary Design of the ITER Plasma Control System to be presented at the 26th IAEA FEC in Kyoto, Japan by J A Snipes.

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Overview of the Preliminary Design of the ITER Plasma Control System

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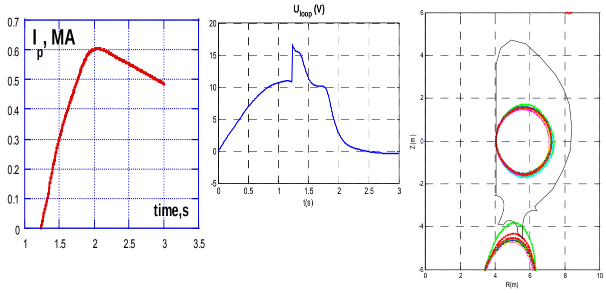
Introduction

The Preliminary Design of the ITER Plasma Control System (PCS) has been carried out since 2014 by the ITER Organization and plasma control experts from CCFE, CEA-Cadarache, CREATE, Efremov, General Atomics, IPP-Garching, and Kurchatov and through a collaboration with Eindhoven University of Technology. This work builds on the 2013 PCS Conceptual Design [1,2] and focusses on 1st plasma and early plasma operation in H/He up to 15 MA with moderate heating in L-mode. The Preliminary Design includes:

- Initial control schemes for plasma initiation, current rise, vertical stability, plasma position and shape, X-point formation, divertor operation, and density control
- Commissioning of the electron cyclotron (EC), ion cyclotron (IC), and neutral beam (NB) heating systems
- Support functions for stray field identification and real-time plasma boundary reconstruction
- Initial event handling schemes for essential plant system faults and initial disruption detection, avoidance, and mitigation schemes
- The PCS architecture for basic control, early plant system and plasma commissioning, and advanced control functions needed for future high performance operation
- Development of a plasma control simulator to test and validate control schemes [3]
- A plasma control database to keep track of all control requirements, including those of the associated diagnostics and actuators needed to carry out the control functions
- Any changes in requirements for advanced control functions since the conceptual design to ensure consistency with the ongoing development of the diagnostics and actuators



DINA simulations of 1st plasma showing the plasma current, loop voltage, and the plasma shape.

Plasma initiation and burnthrough

- Large size & eddy currents in the highly conductive vacuum vessel make plasma initiation challenging
- Low stray field with $B_p < 2$ mT in a large region of minor radius ~1.6 m
- The low toroidal electric field in ITER ~0.3 V/m➔ low neutral pressure of the hydrogen prefill < 1 mPa
- Low impurity content, which will require substantial glow discharge cleaning
- Ohmic breakdown may be possible at very low neutral pressure ➔ risk of runaway electrons
- Robust breakdown requires up to 6.7 MW EC heating at 170 GHz at 1st or 2nd harmonic
- The 1st plasma temporary limiters can withstand disruption forces up to 1 MA@2.65 T or 0.5 MA@5.3 T
- ITER plans to use feedback control of the prefill neutral pressure throughout the plasma initiation phase
- The 1st plasma milestone is to achieve $I_p > 100$ kA for at least 100 ms ➔ possibly ~1 MA for a few sec
- Magnetic feedback control of the current rise requires 5 – 10 seconds and the signal-to-noise ratio of the magnetic diagnostics makes it challenging to control a plasma with $I_p \leq 1$ MA
- From the 2nd plasma campaign, all four upper EC launchers and the equatorial EC launcher will be installed with up to 20 MW injected power
- Any unabsorbed EC power will scatter throughout the vessel and EC sniffer probes at many locations will attempt to ensure that the stray EC power does not damage in-vessel components
- Be+W will change the stray fields and eddy currents at breakdown, require more gas fueling, and reduce the impurity content of the plasma, requiring significant changes to the PF configuration, pre-fill gas feed, and ECH power and timing
- Burnthrough may require several MW of ECH power for ~1 s to heat the plasma sufficiently to overcome impurity radiation as modeled with the DYON code [4], which has been validated with both carbon and ITER-like wall data from JET [5]

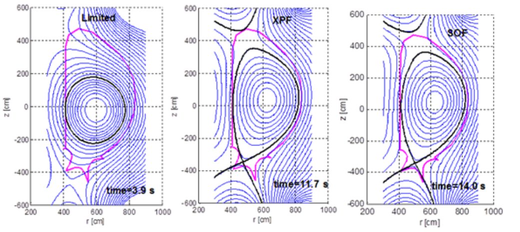
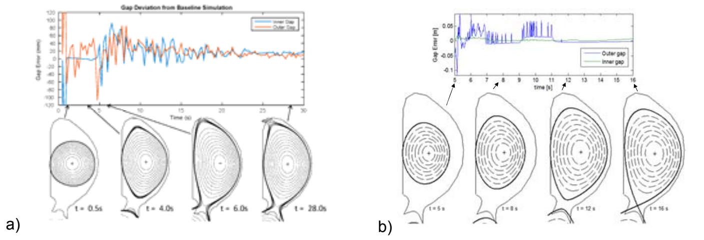


Fig. 2. Plasma equilibria in a limited configuration (t=3.9 s), start of X point formation (t=11.7 s), and start of plasma current flattop (t=14 s) from a 2.65 T/3.2 MA DINA scenario with maximum CS current of 12 kA.

Magnetic control

- Initial pre-programmed plasma volume expansion and increasing elongation up to I_p ~1 MA
- Feedback plasma centroid position while maintaining an inner wall limited discharge up to 1.5 to 2.5 MA
- Above ~3.2 MA, sufficient control of the plasma shape for a diverted configuration
- High heat flux panels on the inner and outer wall can withstand steady-state heat flux up to ~7.5 MA [6]
- Need ~60 - 70 s to reach 15 MA while keeping the maximum magnetic field on the PF6 < 6.4 T
- Max duration 15 MA Ohmic flattop in hydrogen is ~10 – 15 s and with 73 MW, up to ~100 s in L-mode
- Nominal ramp down rate from 15 MA is 0.21 MA/s to avoid operational limits
- DINA emergency termination scenarios from 15 MA found
  - > 6 s required to ramp down to 10 MA at fastest ramp rate 0.83 MA/s
  - > 10 s required to ramp down to 7.5 MA at a rate of 0.77 MA/s
  - > 17 s required to ramp down to 5 MA at a rate of 0.58 MA/s before operational limits are reached

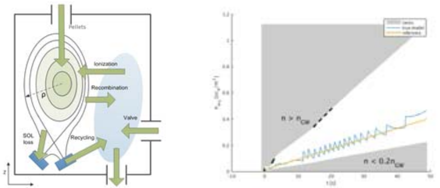


a) b)

Comparison of plasma startup simulations with a) unoptimized RT-EFIT and b) EFIT++ for an ITER 15 MA scenario, plasma equilibria, and inner and outer gap deviations between the plasma and the wall

Support functions

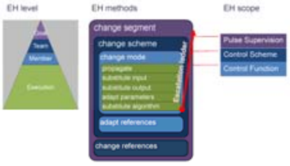
- PCS support functions include error field identification, plasma boundary and equilibrium reconstruction, and real-time forecasting of stability boundaries: vertical stability, l_i vs q limits [7] [8]
- 3D error fields include sources from eddy currents in the vacuum vessel and plasma facing conducting structures, ferromagnetic components near the plasma, coil misalignments, coil feeders
- Several plasma boundary and equilibrium reconstruction codes are being considered for ITER including RT-EFIT [9], EFIT++ [18], IAIA [19], RT-LIUQE [20], CCS [21] that require proper handling of eddy currents particularly for reconstructing very low plasma current early in the current rise



Three reservoir fueling model of the plasma, wall, and vacuum regions; modeled density rise with gas and pellet injection avoiding both low and high density limits shown in gray indicating that the density can be reasonably well controlled to follow the reference request.

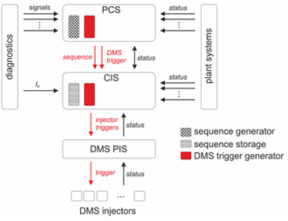
Early Kinetic Control

- Density control is expected to be difficult on ITER due to the delay in the gas injection from > 20 m of pipe and the opacity of the scrape-off-layer with high edge temperatures [11] ➔ pellet fueling will be required
- A three reservoir model including the plasma, wall, and vacuum region including recycling, pumping, ionization, recombination, diffusion, and convection with both gas and pellet injection [13,14]
- ITER constraints have led to a reasonably sophisticated control model including Iterative Learning [15] and Robust Control [16] to successfully control the density ramp up



Actuator Management and Event Handling

- Event handling will deal with plasma and plant system events at different layers of control depending on the potential impact on one or multiple control functions
- substituting inputs, outputs, algorithms, or adapting parameters
- Or the event is handled by a control scheme supervisor that adapts the control scheme accordingly to optimize the response
- Or may require the pulse supervisor to change the entire control segment to an alternative goal such as a backup experiment



Disruption and Runaway Electron control

- PCS will request the central interlock system (CIS) to trigger the Disruption Mitigation System (DMS) to inject massive amounts of impurities to radiate the energy and mitigate disruption loads
- DMS will have 12 shattered pellet injectors to mitigate thermal loads, 15 injectors to mitigate runaway electrons and a massive gas injection system close to the plasma with ~20 ms response
- PCS decides the sequence of which DMS injectors to trigger if it detects or predicts an imminent thermal quench, a current quench, a loss of vertical control, the presence of runaway electrons, or a critical plant system fault

System architecture, control database, control simulator

- The PCS architecture must be flexible enough to support the expected evolution and complexity of all control envisioned from early commissioning through DT inductive, hybrid, and long pulse operation
- A control database with all PCS requirements, control functions, and strategies will manage PCS evolution
- The Plasma Control System Simulation Platform (PCSSP) [3] will aid testing, validation, and troubleshooting of all algorithms and architectural choices

Summary and next phases

- PCS Preliminary Design Review will be in Nov 2016
- PCS design will proceed in stages, anticipating the evolution of the ITER Research Plan [17].
- 1st Plasma PCS Design will include detailed PCS architecture and complete control algorithms required for 1st Plasma operation
- Non-Active (Pre-Fusion) PCS Design review before 1st Plasma in 2025
- Implement just after 1st Plasma including initial plasma control algorithms for H-mode operation
- High Power Non-Active PCS Design including ECRH, ICRF, and NBI up to full power
- Nuclear Operation PCS Design for D and DT operation up to full Q=10 performance
- Long Pulse PCS Design including current density profile and internal transport barrier control
- Each PCS stage to be approved one stage before it is required in operation for implementation, testing, and validation

References

[1] J. A. Snipes, et al., *Fusion Eng. and Design* **89** (2014) 507.
[2] A. Winter, et al., *Fusion Eng. and Design* **89** (2014) 267.
[3] M. Walker, et al, *Fusion Eng. and Design* **96-97** (2015) 716.
[4] H. T. Kim, et al, *Plasma Phys & Cont. Fus.* **55** (2013) 124032.
[5] P. C. de Vries, et al, *Nuc. Fus.* **53** (2013) 053003.
[6] M. Kocan, et al, *Nucl. Fus.* **55** (2015) 033019.
[7] D. A. Humphreys, et al, *Nucl. Fus.* **49** (2009) 115003.
[8] J. A. Snipes, et al, *Nucl. Fus.* **28** (1988) 1085.
[9] J. R. Ferron, et al, *Nucl. Fus.* **38** (1998) 1055.
[10] D. A. Humphreys, et al, this conference.
[11] Andrei S. Kukushkin, et al, *Fus. Eng. Design* **65** (2003) 355.
[12] L. Garzotti, et al, Proc. 43rd EPS Conf. Plasma Phys. Leuven (2016) O4.113.
[13] T. Ravensbergen, et al, Proc. 43rd EPS Conf. Plasma Phys. Leuven (2016) P4.068.
[14] T. Blanken, et al, submitted to *Plasma Physics and Controlled Fusion.*
[15] Federico Felici, et al, IEEE 54th Ann. Conf. on Decision and Control, Osaka (2015) 5370.
[16] Sigurd Skogestad, Ian Postlethwaite, "Multivariable Feedback Control: Analysis and Design", Wiley, 2007.
[17] D. J. Campbell, Proc. 24th IAEA FEC, San Diego (2012) ITR/P1-18.
[18] L C Appel, et al., *33rd EPS Conf on Plasma Phys. Rome, 19 - 23 June 2006 ECA* **Vol.30I** (2006) P-2.184.
[19] Paolo Bettini, Angelo Cenedese, *Fusion Engineering and Design,* **88** (2013) 1150.
[20] J-M Moret, et al, *Fusion Engineering and Design,* **91** (2015) 1.
[21] Masafumi Itagaki, et al., *Plasma and Fusion Research*, **8** (2013) 1402134.

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