ITER PLASMA CONTROL SYSTEM FINAL DESIGN AND PREPARATION FOR FIRST PLASMA

Joseph A Snipes
on behalf of the ITER PCS Design Team
and
ITER Organization

Disclaimer: The views and opinions expressed herein do not necessarily reflect those of the ITER Organization
Outline

- Plasma Control System (PCS) Final Design for First Plasma
  - Nominal control and Exception Handling
  - PCS Configuration and Architecture
  - Systems engineering and design assessment
  - PCS commissioning

- ITER Research Plan – first operation phase
  - Integrated Commissioning (IC)
  - First Plasma Campaign (FP)
  - Engineering Operation (EO)

- Conclusion
ITER Plasma Control System Final Design Scope

- The PCS is key to integrated ITER operation
- The PCS Final Design for FP was performed by ITER Organization and a team of external plasma control experts from EU, Russian Federation and US, building on the Conceptual and Preliminary designs
- The PCS Final Design for FP includes:
  - Basic magnetic control of Central Solenoid (CS) and Poloidal Field (PF) coils
  - Kinetic control of gas injection system (GIS) & Electron Cyclotron Heating (ECH)
  - Exception handling due to plasma or plant system events
  - Pulse schedule requirements to reconfigure the PCS for each pulse
  - Architecture required for FP up through Fusion Power Operation (FPO)
  - Systems engineering approach and design assessment
  - PCS commissioning plans
Mainly feedforward control of CS/PF power supplies provides electromagnetic breakdown conditions, plasma current, radial position, and nearly circular plasma shape limited on inboard or outboard temporary limiters.

Switching Network Units (SNUs) provide main contribution to the plasma loop voltage limited to < 0.3 V/m by superconducting coils.

Provides a poloidal field null (< 2 mT) over a wide region.

Force limits on temporary stainless-steel limiters require methods to ensure \( I_p < 1 \text{ MA} \) at 2.65 T.

Large currents induced in Vacuum Vessel (VV) ~ 1.5 MA during plasma initiation must be taken into account.

Magnetic diagnostics expect to measure plasma currents down to 10 – 50 kA.

Up to 15% coil voltages may be allocated to feedback control to correct for asymmetries in stray fields due to ferromagnetic materials and non-axisymmetric eddy currents.
**Kinetic Control: Gas Prefill and Initial Density Control**

- FP kinetic control uses only H$_2$ gas for prefills and initial density control.
- Gas Injection System (GIS) has 10 Gas Valve Boxes from 4 upper ports and 6 divertor locations.
- Combined feedforward and feedback GIS control allow triggering SNU at a chosen equilibrated VV prefills pressure.
- Large VV volume (~1700 m$^3$), low toroidal electric field, and long delays in the gas lines (~0.5 s for 18 – 26 m long pipes) make reproducible breakdown challenging.
- Breakdown expected over a very narrow range in neutral pressure 0.5 – 1 mPa.
Kinetic Control: Electron Cyclotron Breakdown Assist

- FP ECH system has 8 gyrotrons at 170 GHz from one upper launcher
- Each gyrotron can inject 0.83 MW
- To protect in-vessel components before Be blanket and W divertor, ECH power reflected off inner wall mirrors into ECH-absorbing beam dump in equatorial port
- Space available for 7 of 8 beams to avoid the mirrors sticking into the plasma – up to 5.8 MW injected
- 4 beams ~40 cm below, 3 beams above midplane
- Beam dump designed for ≤ 300 ms beam pulse
- Absorbed ECH power of single pass at plasma initiation expected to be < a few percent at 2.65 T (2nd harmonic X-mode)
Exception Handling in the Plasma Control System

- Plasma events or plant system faults may occur during plasma operation that require a change in plasma control in real-time.
- The PCS monitors the plasma and plant systems to detect relevant events, identify exceptions, prioritize them, and take appropriate actions.
- FP actions include changing gas flow, turning off coil voltages and ECH power.
Pulse Schedule Reconfigures the PCS for each Pulse

- Pulse Schedule is a software tool to reconfigure all plant systems and the PCS with the data needed to run an ITER commissioning or plasma pulse.

- The pulse schedule includes:
  - Pulse scenario and segments
  - Operational constraints
  - Chosen controller configurations
  - Prescribed waveforms
  - General pulse supervision rules
  - Exception handling policies
  - Configuration information for all operational plant systems
PCS is flexible, extendable, and contains complexity with modular components

Architecture covers FP to FPO

Coupling between control functions requires integrated architecture

Pulse Supervision Controller executes Pulse Schedule, reference waveforms, monitors operation, performs global exception handling

Support functions process inputs, manage actuators, local exception handling

Standardized, modular, and reusable Compact Controller, with dynamic control goal switching, local monitoring, and separation of concerns, including local exception handling

Publish/Subscribe scheme makes information available dynamically from the Synchronous Data Network (SDN) and within the PCS when and where needed, providing configurable functionality through the Pulse Schedule

Actuator management can replace tripped actuators dynamically through a hierarchy of goals
The PCS developed with a systems engineering approach using a PCS database (PCSDB).

The PCSDB:
- Keeps track of all aspects of the design to ensure it satisfies system and performance requirements.
- Aims to achieve full traceability from architectural components and control functions up to high level requirements, down to code testing and commissioning procedures.
- Provides a means to manage changes to the PCS as it evolves, generate reports, and find gaps in the design.
Assessment Shows PCS Design Meets Requirements

- The PCS design was assessed within the PCS Simulation Platform (PCSSP) using simplified models of the plasma, tokamak, actuators, and diagnostics.
- To simulate control functions in closed loop with the PCS implementation in PCSSP.
- The assessment evaluates metrics that quantify the PCS performance.
- Verifies that the metric values are within required performance bounds.
- For a series of test cases that test both nominal control and exception handling.
- Within the limitations of the models, the assessment results confirm that the PCS design meets requirements.
PCS System Commissioning Confirms Basic Functionality

- After PCS implementation, actuator (ECH, GIS, CPSS) tests on dummy loads and diagnostic (magnetics, $H_\alpha$, neutral pressure, hard x ray) tests to check data exchange will be carried out.

- PCS system commissioning must establish basic communications and functionality with interfacing plant systems to be ready for integrated operation.
ITER Research Plan (https://www.iter.org/technical-reports?id=9) begins with

1. Integrated Commissioning
   - Central control systems: CODAC, PCS, Central Interlock System (CIS) and Central Safety System (CSS) must be commissioned to ensure control and protection systems function correctly
   - Integrated Commissioning begins with VV and Cryostat closure, pump down, baking, Gas Injection System and Glow Discharge Cleaning (GDC)
   - Commission magnets and power supplies to half current and half TF of 2.65 T
   - Magnetic diagnostic commissioning
   - Commission ECH

2. First Plasma to achieve $I_p > 100$ kA for $> 100$ ms

3. Engineering Operation to commission magnets to full current
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
- Glow Discharge Cleaning
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
- Glow Discharge Cleaning
- Cryogenic cooling of the magnets
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
- Glow Discharge Cleaning
- Cryogenic cooling of the magnets
- Magnets and Power Supplies
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
- Glow Discharge Cleaning
- Cryogenic cooling of the magnets
- Magnets and Power Supplies
- Magnetic diagnostics
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
- Glow Discharge Cleaning
- Cryogenic cooling of the magnets
- Magnets and Power Supplies
- Magnetic diagnostics
- H$_{\alpha}$, hard x ray, interferometer, and other FP diagnostics
Integrated Commissioning Begins Operation Phase

- Integrated Commissioning begins with VV and cryostat closure
- Vacuum pump down and baking
- Gas Injection System
- Glow Discharge Cleaning
- Cryogenic cooling of the magnets
- Magnets and Power Supplies
- Magnetic diagnostics
- $H_\alpha, \text{ hard x ray, interferometer, and other FP diagnostics}$
- EC heating system

Commissioned with PCS
How to Prepare for Plasma Operation

- Vacuum vessel baked to 200°C with the Primary Heat Transfer System (PHTS) of the Tokamak Cooling Water System (TCWS) to remove water and impurities.
How to Prepare for Plasma Operation

- Vacuum vessel baked to 200°C with the Primary Heat Transfer System (PHTS) of the Tokamak Cooling Water System (TCWS) to remove water and impurities
- Glow discharge cleaning plasma in hydrogen to remove impurities from the vessel walls
- Monitor residual gas analyzer measurements of outgassing impurities to reach necessary vacuum conditions for plasma initiation and burnthrough

Vacuum Vessel Base Pressure vs Time

- Base pressure for H isotopes <10^{-5} Pa
- Base pressure for impurities < 10^{-7} Pa
- Global air leak rate into VV < 2x10^{-7} Pam^3/s
First Plasma Campaign Demonstrates Integrated Operation

- One month is scheduled for the FP campaign to demonstrate integrated operation of the main ITER plant
- Milestone is \( I_p > 100 \text{ kA} \) for > 100 ms at \( B_T = 2.65 \text{ T} \), but may reach up to 1 MA for a few seconds for a nearly circular plasma
- Low toroidal electric field (~0.3 V/m), large VV volume and neutral source increase required power and limit neutral pressure range to 0.5 – 1 mPa of nearly pure \( \text{H}_2 \) gas for successful plasma breakdown
- ECH power up to 5.8 MW for up to 300 ms at 170 GHz (2nd harmonic X-mode) may be added to assist pre-ionization
Engineering Operation Demonstrates Full Current Capability

- EO campaign will commission the TF, CS, PF, and CC magnets to full current to demonstrate capability to achieve nominal plasma current of 15 MA at 5.3 T
- Characterize magnet hydraulic, thermal and mechanical behavior
- Commission quench detection, interlock fast discharge and tokamak systems monitoring structural stresses
- Magnetic axis alignment measurement to position the blanket modules during Assembly Phase II (Pitts, EX/P5-1, Thurs)
- If FP was not achieved at 2.65 T, attempts will be made at 5.3 T with improved breakdown conditions
May Attempt Ohmic Plasma Start-up at 1.8 T

- ECH (170 GHz) 3rd harmonic assist not effective $\rightarrow$ 1.8 T Ohmic start-up with $V_{\text{loop}} \sim 0.3$ V/m?
- Modelled 1.8 T Ohmic plasma start-up OK within narrow pressure window (similar to 2.65 T) [burn-through $\leftrightarrow$ runaway avoidance]

Ohmic plasma start-up in EO Phase $\rightarrow$ decision on 1.8 T ECH assist
Conclusions

- ITER tokamak assembly has begun for first VV sector
- PF coils 5 and 6 are nearly ready to be installed in the cryostat
- The Steady State Electrical Network has been commissioned and Cooling Water System commissioning has begun
- The PCS Final Design for First Plasma was approved
- The ITER Research Plan first operational phase will begin with Integrated Commissioning, First Plasma and Engineering Operation to commission systems for full current operation to demonstrate capability to achieve 15 MA, 5.3 T in later operation phases