The Preliminary Design of the ITER Plasma Control System

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PCS Design Evolves with ITER Research Plan

- Conceptual Design was approved June 2013
- Preliminary Design 2014 – 2016 concentrated on 1st plasma and early plasma operation in H/He ➔ Approved in April 2017
- Final Design for 1st Plasma PCS 2017 – 2020 (de Vries O-20)
- Final Design for PFPO-1 Phase PCS 2021 - 2023
- Final Design for PFPO-2 Phase PCS 2023 – 2030
- Final Design for FPO Phase PCS 2030 - 2034
- PCS will evolve along with the ITER Research Plan
ITER Plasma Control System Functional Breakdown

PlasmaControl

System Architecture (SA)
- Communication Concept
- Functional Architecture
- Wall conditioning and T removal (WC)
- Axisymmetric Magnetic Control (AMC)
- Kinetic Control (KC)
- MHD and Error Field Control (MHD)

Control Functions (CF)
- Disruption and Runaway Electron Control (DRC)
- Event detection and Exception handling (EH)
- Actuator Management (AM)
- Basic Control Functionality (BC)
- Support Functions (SF)

Control Simulator (CS)
- Model Development (MD)
- Code Development (CD)
- Pulse Validation Simulator (VS)
- Real-time Simulator (RT)

O-18 Treutterer
O-19 Raupp
O-16 Walker

Plasma Control Database
PCS Requirements for 1st Plasma & Early Operation

- Basic PCS architecture
- Plasma control simulator and detailed modelling of stray fields, plasma initiation, current rise, basic RE mitigation
- Initial plasma control algorithms
  - Plasma initiation (premagnetization, PF null, pre-fill neutral pressure feedback, ECH assist), current rise, vertical stability, position, shape, X-point formation, divertor operation
  - Initial density control (gas puffing, no pellets)
  - Basic ECH control and ECH overheat in-vessel protection algorithms
- Support functions for stray field topology and real-time plasma boundary reconstruction flux maps
- Initial event handling for essential plant system faults and disruption protection
Relatively simple PCS logic needed for 1\textsuperscript{st} Plasma

- Gas control (ffwd)
- ECH control (ffwd)
- Coils controls (ffwd+fdbk)
- SNU control

- Full power when Ip high enough
- Shut off EC if on too long & no Ip
Extensive Plasma Initiation Simulations for ITER

- Low startup electric field \( \approx 0.3 \) V/m
- High stray fields due to eddy currents
- Large volume and neutral fueling source increase required power and limit the allowed neutral prefill range
- Ohmic startup is predicted for a small range of \( p(0) < 10^{-5} \) Torr \( \Rightarrow \) RE’s?
- \( P_{EC} > 3 \) MW probably required for robust startup with short pulses (~100 ms) to limit damage to in-vessel components
- Feedback on neutral pressure timed with ECH pulses, the poloidal field null, and vertical field swing for robust breakdown control
- Require extensive plasma initiation simulations including eddy currents

Simulated Ohmic Burnthrough in ITER

H T Kim, PPCF 2013
• **Test of integrated control response to density perturbations shows good density recovery:**
  - Brief (< 1 sec) impurity influx pulse
  - Density regulation with ideal fueling supply, 1 sec valve delay time

• **Integrated control provides acceptable decoupling:**
  - $I_p$, shape, density all experience disturbance, but acceptable amplitudes
  - Recovery of quantities on density response timescale

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**Graphs:**
- $I_p$ [MA]
- Gap in [m]
- Gap out [m]
- $n_e$ [m$^{-3}$]
- $W_{th}$ [MJ]
Advanced Density Control Model for ITER

- Density control model includes:
  - Heuristic 1D particle transport
  - Large neutral inventory in vacuum
  - Ionization, recombination, pumping
  - Wall source/sink neutral exchange, gas, pellet, and NBI source terms
  - One controller also handles diverted plasmas and transport delays

- Iterative Learning Control (ILC) tracks a trajectory to remove trial-and-error

- Valve time delay and > 20 m long gas pipe \( \rightarrow \) ILC valuable for robust density control

T Ravensbergen, submitted to NF
Support Functions Include RT Boundary Reconstruction

- 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

- Several plasma boundary and equilibrium reconstruction codes are being considered for ITER including RT-EFIT, EFIT++, IAIA, RT-LIUQE, CCS that require proper handling of eddy currents particularly for reconstructing very low plasma current early in the current rise

- 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
PCS has an Important Role in Investment Protection

- The PCS will operate with plasma and plant system parameters within the **green operation zone** and may push limits up to the **Pulse Control Allowables (PCA)**

- If the PCS exceeds the PCA and reaches the **Interlock limit**, the Central Interlock System (CIS) will intervene forcing a controlled rampdown of the plasma or trigger the Disruption Mitigation System (DMS) to ensure investment protection

- Should the CIS fail to intervene in plasma situations that could affect personnel or environmental safety, then the CSS will trigger the Fusion Power Shutdown System to stop the plasma within 3 s, resulting in a safety incident
## Disruption Avoidance, Prediction, and Detection

### Avoidance
- Designing pulses to avoid parameter ranges with high disruption risk
- Measures for active avoidance to be put in place
- PCS to react on any deviation:
  - Recovery scenarios
  - Termination scenarios
- Actuators: heating, fuelling, MHD control, impurity control,…

### Prediction
- Forecasting a thermal quench
- Solely to trigger the Disruption Mitigation System (DMS)
- Two approaches:
  - Threshold tests of multiple parameters
  - Complex data-driven approaches
- Subsystem of PCS to decide on the disruption scenario (sequence, injection type) and request CIS to trigger DMS

### Detection
- Detection of an ongoing disruption
  - Vertical Displacement Event
  - Loss of plasma stored energy
  - Current spike
- Current quench detection needs to be reliable & robust
- Timescales for plasma vertical displacement are > 100 ms sufficient to trigger DMS
Investment Protection at High Plasma Current/Energy

- The PCS plays an important role in investment protection when there is significant plasma current \( I_p > 2 - 4 \) MA or plasma stored energy.
- When \( I_p > 5 - 7 \) MA, close proximity of the plasma to the wall can soon exceed melting limits of Be tiles \( \Rightarrow \) good gap control.
- Average thermal quench disruption loads > 5 MW/m\(^2\) will also melt Be tiles \( \Rightarrow \) disruption mitigation system (DMS) is required.
- A high runaway electron current will also melt Be tiles.
- Disruption prediction algorithm required to predict disruptions with \( > 30 \) ms warning time to trigger the Disruption Mitigation System.
- When PCS determines a disruption is imminent, it will request CIS to trigger the DMS when \( I_p > I_p^{\text{min}} \) or \( W_{\text{plasma}} > W_{\text{plasma}}^{\text{min}} \).
- A range of plasma stop scenarios have been defined and will be implemented in the PCS and CIS algorithms depending on the event and corresponding timescale to act.
Disruption Mitigation Function – Role of PCS/CIS/DMS

**Responsibilities**

**PCS:** DMS trigger, sequence

**CIS:** execute sequence, DMS trigger on plant fault or other safety interlock

**DMS:** injector status, activate injectors, pre-pulse configuration (via CODAC)
Disruption Mitigation Function – Injection Sequence

- Each barrel of the DMS can be fired individually in real time
- The **injection sequence** is an array of injection times for each of the individual barrels, relative to $t_0$ (arrival of DMS request in CIS)
- PCS generates and updates the injection sequence based on input from diagnostic signals, plant system status, DMS injector status
- CIS keeps default sequences if an interlock event activates the DMS

*Time constraints for updating the sequence*

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**Diagram:***

- Event detection in DMS local control
- Propagation delay DMS local control to CIS
- CIS Processing
- Propagation delay CIS to PCS
- PCS Processing

**Latency:***

- $\text{latency} \leq 1\text{ ms}$
- $\text{latency} \leq 0.5\text{ ms}$
Summary of the PCS Investment Protection Role

- PCS is the first line of defense for machine protection
- CIS shall always backup the PCS for machine protection even for complex functions and safety incidents during plasma operation
- When a plant system fault or accident occurs during plasma operation that can impact plasma operation, the PCS should know the time available and the expected impact on plasma operation
- The PCS will implement automatic event handling to choose the optimum emergency termination in real-time depending on the time available before a disruption will occur and the plasma state
- Timescales to impact plasma operation for all fault and accident scenarios of interfacing plant systems will be defined in interfaces
- Simplified plant system models required
  - To model impact of plasma operation on plant systems and plant system operation on plasma operation to validate operational scenarios
  - For control scheme testing, real-time monitoring, and to anticipate events
Key Elements of PCS Architecture

PCS architecture designed to contain ITER complexity

Architecture key elements:
- Modular components
- Compact controllers of the same actuators with control modes
- Goal-driven execution
- Pulse supervision control
- Continuous control
- Exception handling

Architecture includes:
- Elementary control functions for plant system commissioning & basic control
- Integrated control functions
- Phase dependent & dynamically changing control objectives
- Actuator sharing management
Methods change control:

1) **behavior**
   Of a single controller
   - adapt parameters / IO / algorithm

2) **structure**
   Of controllers with connected objectives
   - adapt modes or references

3) **goal**
   Of the overall system
   - new choice of functionality

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**Pulse Supervision Control** monitors Pulse Continuous Control and may change control

1) **Behavior**
2) **Structure or**
3) **Goal**

in an increasing hierarchy, depending on the changes required by the exception conditions

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Plasma Control Database to Manage PCS Design

- Systems engineering approach to manage complexity
- Database of control functions and strategies
- Tracks user & system requirements, diagnostic and actuator specifications to carry out control functions
- Includes operational scenarios expressing alternatives, repeated behavior, parallel branches, and exceptions
- Technical and physics limitations of control actions
- Coordinated with architecture to justify design choices
Plasma Control Simulator

- PCS requires a simulator for:
  - Architecture test and validation
  - Control scheme development
  - Offline scenario preparation
  - Pre-pulse validation of control schemes and operation scenarios
  - Real-time comparison of actual performance against models

- PCS simulator must include:
  - Time-dependent simulation of plasma evolution, control, and interlock actions
  - Synthetic diagnostic models to simulate expected signals
  - Simplified plasma and plant system models to predict approaching limits
  - Simulated off-normal events and Exception Handling responses
  - Simulated CIS-PCS interactions


RAPTOR: (Maljaars, Felici, Nucl. Fus. 2015)
rapid plasma transport model available in PCSSP
Conclusions

- ITER PCS Preliminary Design approved that concentrates on 1st plasma and early plasma operation
- Modeling of magnetic and early kinetic control demonstrates feasible control schemes for 1st plasma and early operation
- Real-time plasma boundary reconstruction requires good eddy current model for accurate reconstruction
- PCS is first line of defense for investment protection with disruption avoidance, prediction, detection, and exception handling (O-19 Raupp) backed up by the CIS and DMS for ultimate protection
- PCS architecture (O-18 Treutterer) designed with a systems engineering approach and a plasma control database
- Plasma control system simulation platform in Matlab/Simulink established to develop, test, and validate control schemes to include simplified plasma transport and plant system models
- 1st Plasma PCS Final design to begin later this year (O-20 de Vries)