Diagnostic Data Handling in the ITER Plasma Control System

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ITER Organization

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Outline

• Plasma Control System (PCS) Introduction and Status
• Diagnostics dedicated to the PCS functions
• Integration within the PCS
• Example use cases
• Few remarks on relevant frameworks (PCSSP & RTF)
• Conclusions
Plasma Control System - PCS

• PCS controls all aspects of ITER pulsed operation: pre-charging of PF/CS coils and pre-fill, plasma initiation, ramp-up, flattop, ramp-down, controlled termination throughout the control of all the available actuators.

• Relevant diagnostics and plant systems data are combined to generated inputs for the loops and event handling.

• The PCS implements the first line of defense for investment protection. PCS aims to avoid interlock action by CIS.

• The PCS development plan is aligned with the ITER stage approach.
PCS: functional breakdown

**System Architecture**

- **Control Functions**
  - Wall conditioning and T removal
  - Axisymmetric Magnetic Control
    - Core Fueling and Impurity Control
    - First Wall Heat Flux and MARFE Control
    - Divertor Heat Flux and Edge Impurity Control
    - Burn Control
  - Kinetic Control
    - Current Density Profile Control
    - Rotation Profile Control
    - Stored energy control
    - Temperature and Pressure Profile Control
  - MHD and Error Field Control
  - Disruption and Runaway Electron Control
  - Exception Handling
  - Actuator Management
  - Basic Control Functions
    - Forecasting
    - Boundary reconstruction
    - Equilibrium Reconstruction
    - Error field topology

- **Support Functions**

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PCS status and plan

The next phase of the PCS design aims at the final design for ITER 1st plasma:

- **PCS architecture for the full scope of ITER.**
- **Exception handling for the first plasma.**
- **Development of controllers for first plasma up to 1MA:**
  - Control of the power supply (for breakdown) including protection.
  - ECH from 0.8 to 6.7MW for assisted breakdown.
  - Gas fueling including feedback for pre-fill.
  - Initial plasma current, position and vertical stability as well as boundary reconstruction, in preparation of subsequent operation.
  - Interface completion including data exchange.
- **Develop commissioning plan and procedures**
- **Control assessment done in PCSSP.**
- **Design description in PCS Database.**
ITER Diagnostics

- ITER is equipped with many diagnostics (~50) providing a large number of measurement (~100). The majority will be available in real-time.

- Measurements provide plasma parameters as well as machine conditions (in combination with operational instrumentation provided by plant systems).

- Measurements have roles for Machine Protection, Basic and Advanced Control and Physics.

- Key aspect: each diagnostic contributes to one or many measurements requiring a careful integration schema.
PCS and Diagnostics

Diagnostic delivers validated data used directly as input

Diagnostic delivers data requiring processing to generate input

Diagnostic delivers validated data but integration is required for robustness

Diagnostic delivers validated data but integration is required for generating additional plasma parameters
Requirements summary

- Not really demanding on time resolution for feedback control (1ms is probably the extreme case) but for event detection the resolution might be higher (e.g. ELM with a total duration of 1-2ms)

- Relatively demanding on accuracy (e.g. plasma shape 1cm or NTM island few cm).

- Low latency in particular on parameters related to investment protection.

- Robustness and on-line consistency/validation.
Representative Use cases

- Magnetics probes
- Density measurements
- Visible/IR Cameras
- Prediction/forecast
Magnetics

• Representative example where a large number of data from diagnostics need to be integrated to generate a large set of data output.

• More than 700 probes (field and flux but > 1000 in total) to provide all the magnetic information. From plasma shape and equilibria to plasma current and MHD modes.

• Data used in subsets or as a all. Robustness and flexibility. Fault recognition and replacement.
Magnetics

Probes → Acquisition → Data characterization → Validation → Process (linear combinations) → Real-time network → PCS → Data processing → Actuators and alarms
Magnetics output

- Multiple plasma parameters from linear interpolation of multiple probes: plasma current, vertical velocity, plasma energy ($\beta_p$), loop voltage etc.
- Equilibrium and/or boundary reconstruction: gaps, isoflux and $q(r)$ profile
- MHD modes information: modes number, amplitude, frequency etc.
- Implementation shared between diagnostic and PCS
Density

• Representative example where different diagnostics eventually based on a different principle provide a single plasma parameters.
• Provides the full compliance with all the requirements eventually for all the expected plasma scenarios
• Improves robustness especially for the parameters used for control.
• It benefits from diversified solutions less vulnerable from a common failure mode
Density

Interferometer
Spectroscopy
Thomson Scattering
Polarimetry

Real-time network

Additional parameters

Best density

Data validation

PCS

Actuators and alarms

Additional parameters
Density

Interferometer (main diagnostic for line integrated density),
Polarimeter (requires correction from the magnetic field),
Thomson Scattering (provide profile),
Bremsstrahlung (extract density from radiation)

At the same time this parameter can be input to additional processing for generating other plasma parameters (e.g. more accurate equilibrium reconstruction)
Vis/IR Cameras

- Representative example where data interpretation is not trivial especially if expected to be in real-time for the PCS and/or other monitoring or control activities.
- Data-processing is extremely complex and eventually requiring integration with other diagnostics for comparison, calibration and validation.

(Presentation from M. Kocan)
Vis/IR Cameras

Diagnostic main roles:
• Detection of local overheating ("hot spots")
• RF antenna spark detection
• UFO/pellet tracking
• Part of runaway monitoring scheme

Real time analysis:
• Real-time ROI-based analysis (local maxima, profiles, etc.)
• Real-time event-based analysis (pattern recognition algorithms)

Foreseen machine protection function Implementation:

Will generate ~100 GB/s of data BUT bandwidth of CODAC network limited to 25-100 MB/s → use of simple "thresholds", but may be too "simplistic" (risk of false positives) → will learn from operation of IR monitoring systems in current long-pulse experiments (e.g. W7X)
Model based control and supervision

Additional data processing will be developed within the PCS scope to allow:

• Model based control
• Plasma status forecast
• Prediction (i.e. disruption)
• Plasma evolution alternative paths (i.e. as part of Event Handling)
PCS – Interlock data integration

High reliability and robustness is expected for the data related to *machine protection*. Monitoring data are provided by diagnostics (e.g. cameras) allowing first line of defense from the PCS.

*From simple parameters to more complex prediction and forecast* input to the system as result of data integration:

- shine-through (estimation and monitoring)
- electromagnetic forces at the coils
- heat load at the in-vessel components
- vertical moments for VDE detection
PCSSP & RTF

Development of controls will strongly rely on simulations:

• *Controllers and algorithms* will be tested before to be deployed in the real-time infrastructure.

• In order to perform the better simulations the plasma and plant systems behaviors have to be properly simulated. That includes also diagnostic simulation.

• Not only control loop but also simulations of plasma control functions as part of the event handling are expected.
PCSSP is a Matlab/Simulink platform based tool that allows simulation of plasma control functions and event handling policy.

More realistic the simulation, better control design. Plant systems as well as diagnostics should be simulated accurately as needed.
The Real-Time Framework is now under development (*).

It will equip both the PCS and plant systems. It is also proposed to be used for data processing both within the diagnostic and in the between with the PCS.

Highly modular will allow fast deployment of applications.

Portable to many platforms.

It is possible to deploy modules in the RTF if they have been developed in PCSSP.

(*) IAEA-TM on Control, Data Acquisition and Remote Participation for Fusion Research Greifswald, Germany
Conclusions

• PCS is aiming at the Final design for the first plasma.
• A large set of diversified diagnostics will provide all the needed parameters input for the control loops and event handling.
• Integration of the diagnostics is mandatory to fulfil the requirements from the PCS. Quality is not the only requirement from the PCS. Robustness and availability are even more stringent especially when approaching the nuclear phase.
• Integration of diagnostics with other plant systems and Interlock is also strategic for the success of ITER.
• Optimized allocation of the data processing between diagnostic and PCS.
• Simulation platform including synthetic data and plant systems simulators are expected for the design of controllers (PCSSP).
Backup slides
### ITER Diagnostics list

#### Magnetic sensors
- Vessel Magnetics
- In-Vessel Magnetics
- Divertor Magnetics
- External Rogowskis
- Diamagnetic Loop
- Halo Current Sensors

#### Neutron diagnostics
- Radial Neutron Camera
- Vertical Neutron Camera
- Microfission Chambers
- Flux Monitors
- Gamma-ray Spectrometers
- Activation Systems
- Lost Alpha Detectors

#### Operational diagnostics
- IR Cameras – Visible / IR TV
- Thermocouples
- Pressure Gauges
- Residual Gas Analysers
- IR Thermography
- Langmuir Probes

#### Spectroscopic diagnostics
- Charge Exchange Resonance Spectroscopy
- H Alpha Spectroscopy
- Impurity Monitor for Main Plasma
- Divertor
- Impurity/Influx Monitor
- X-Ray Crystal Spectrometer
- Visible Continuum Array
- Neutral Particle Analysers
- Motional Stark Effect

#### Optical diagnostics
- Thomson Scattering (Core)
- Thomson Scattering (Edge)
- Thomson Scattering (X-point)
- Thomson Scattering (Divertor)
- Toroidal Interferometry/Polarimetry
- Poloidal Field Measurement System

#### Microwave diagnostics
- Electron cyclotron emission
- Reflectometry for the main plasma
- Reflectometry for plasma position
- Reflectometry for the divertor

#### Bolometric diagnostics
- Bolometry
### Required plasma parameter for first plasma

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>55.A0</td>
<td>Magnetics System Electronics &amp; Software</td>
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<tr>
<td>55.A1</td>
<td>Continuous External Rogowski</td>
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<td>55.A3/A4/A9</td>
<td>Outer Vessel Coils</td>
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<tr>
<td>55.A5/A6</td>
<td>Steady State Sensors</td>
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<td>55.A7/AE/AI</td>
<td>Flux Loops</td>
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<tr>
<td>55.AA/AB/AC</td>
<td>Inner Vessel Coils</td>
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<tr>
<td>55.AF/AG/AH</td>
<td>Diamagnetic Sensors</td>
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<td>55.E2</td>
<td>H-alpha Vis in EPP12</td>
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<tr>
<td>55.E3</td>
<td>Vacuum UltraViolet Survey</td>
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<td>55.E6</td>
<td>Visible Spectroscopy Reference System (partial)</td>
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<td>55.ED</td>
<td>X-Ray Crystal Spectrometer</td>
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<td>55.EE</td>
<td>Hard X-ray Monitor</td>
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<td>Vis/IR Equatorial in EP16 (temporary)</td>
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<td>55.GB</td>
<td>Stray ECH detector</td>
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<td>55.GF</td>
<td>TF Mapping (one-off activity)</td>
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<td>55.GL</td>
<td>In-Vessel Lighting</td>
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<tr>
<td>55.GT</td>
<td>Tokamak Structural Monitoring system</td>
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<tr>
<td>55.FA</td>
<td>Density Interferometer Polarimeter (partial)</td>
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</table>

This list is only reporting what it is necessary for achieving the first goal of this phase of ITER operation. More diagnostics might be beneficial to better understanding of the machine conditions and plasma breakdown but they are not mandatory.