ITER Control System

Wolfgang Treutterer
Max-Planck Institute for Plasma Physics

Disclaimer: This presentation is based on personal experience of the author. Views and opinions expressed herein do not necessarily reflect those of the ITER organization!
Overview

• DEMO relevant ITER control goals
• Actuator and Diagnostics comparison
• ITER control system
• DEMO control system
• Conclusions
ITER Research Plan

Reference (4-stages)

ITER Overall Project Schedule
43N7X7

- First Plasma (2025 ..)
- Pre-Fusion Power Operation I (2028 ..)
- Pre-Fusion Power Operation II (2032 ..)
- Fusion Power Operation (2035 ..)
ITER Research Plan: Preparation

Accompanying programme:
- ELM control
- MHD stability
- Disruption/Runaway electron mitigation
- Error field correction
- Scenario development
  - Ramp-up
  - Safe termination

Update of the ITER Research Plan, TPMLHZ
First Plasma:
- ECRH assisted breakdown and burnthrough
- Minimum control capability
- Engineering operation
  - Commissioning with plasma
  - Circular H or He plasma

Update of the ITER Research Plan, TPMLHZ
Pre-Fusion Power Operation -1:
- Full magnetic control
- Density and impurity control
- Divertor heat flux control
- Disruption prediction, detection and mitigation (including runaway electrons)

Update of the ITER Research Plan, TPMLHZ
Pre-Fusion Power Operation-2:
• H&CD control
• ELM suppression and control
• Integrated heat flux control
• Core MHD control
• Actuator management
• Disruption and runaway electron mitigation
• Robust H-mode access and exit

Update of the ITER Research Plan, TPMLHZ
Fusion Power Operation:

- High power/current H-mode in D, DT
- Long pulse H-mode
- Tune control
- Use/ Optimize control
  - Integrated control
  - Burn control
  - Exception Handling

Update of the ITER Research Plan, TPMLHZ
Shape control - Plasma shape controlled variables

- The shape geometrical/physical variables to be controlled have an impact on the controller architecture, implementation and performance, and on the diagnostics.
- Possibility of changing indicators during the pulse.
- Shape is imposed by controlling the position of the points where the plasma separatrix intersects control segments

\[ \psi(g) = \psi_B \]

 Flux control – limiter phase \[ \psi(g_{ref}) - \psi_L = 0 \]

 Flux control – limiter to diverted \[ \psi(g_{ref}) - \psi_X = 0 \]

 Gap control – diverted phase \[ g_{ref} - g = 0 \]

A set of plasma shape descriptors adopted in the proposed simulations are defined according to 29 control segments

G. Ambrosino (CREATE), PCS PDR, U44DHV
ITER study: DEMO Power Exhaust

- DEMO power exhaust problem is 4-5 times more serious than ITER
- Conventional divertor relies on keeping $P_{\text{sep}}^{\text{DEMO}} \sim P_{\text{sep}}^{\text{ITER}}$ through $P_{\text{rad,core}}$ (maintaining $P_{\text{sep}} > P_{\text{L-H}}$)

<table>
<thead>
<tr>
<th></th>
<th>ITER Q=10</th>
<th>DEMO1 A=2.6</th>
<th>DEMO1 A=3.1</th>
<th>DEMO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ [$m$]</td>
<td>6.2</td>
<td>9.5</td>
<td>9.1</td>
<td>7.5</td>
</tr>
<tr>
<td>$S$ [$m^3$]</td>
<td>683</td>
<td>1895</td>
<td>1428</td>
<td>1253</td>
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<tr>
<td>$V$ [$m^3$]</td>
<td>831</td>
<td>4174</td>
<td>2502</td>
<td>2217</td>
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<tr>
<td>$P_{\text{fus}}$ [MW]</td>
<td>500</td>
<td>2074</td>
<td>2037</td>
<td>3255</td>
</tr>
<tr>
<td>$t_{\text{hum}}$ [h]</td>
<td>0.1</td>
<td>2</td>
<td>2</td>
<td>inf</td>
</tr>
<tr>
<td>$I_p$ [MA]</td>
<td>15</td>
<td>24</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td>$B_T$ [T]</td>
<td>5.3</td>
<td>3.8</td>
<td>5.7</td>
<td>5.6</td>
</tr>
<tr>
<td>$\beta_{N,\text{tot}}$ [%]</td>
<td>1.8</td>
<td>2.9</td>
<td>2.6</td>
<td>3.8</td>
</tr>
<tr>
<td>$T_e0$ [keV]</td>
<td>11.5</td>
<td>26.8</td>
<td>27.4</td>
<td>34.7</td>
</tr>
<tr>
<td>$n_e0$ [$10^{19}$ m$^{-3}$]</td>
<td>12.5</td>
<td>8.2</td>
<td>10.1</td>
<td>12.2</td>
</tr>
<tr>
<td>$P_{\text{rad,core}}$ [MW]</td>
<td>47</td>
<td>318</td>
<td>331</td>
<td>694</td>
</tr>
<tr>
<td>$P_{\text{CD}}$ [MW]</td>
<td>70</td>
<td>50</td>
<td>50</td>
<td>133</td>
</tr>
<tr>
<td>$q_{\text{NW}}$ [MW/m$^2$]</td>
<td>0.5</td>
<td>0.8</td>
<td>1.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

- $P_{\text{tot}}^{\text{DEMO1}}$ 460 MW
- $P_{\text{sep}}^{\text{DEMO1}}$ 154 MW
- $P_{\text{L-H}}^{\text{DEMO1}}$ 133 MW

A. Loarte, R. Pitts (ITER), Control of power loads, Taming the flame meeting, 2016

- DEMO conventional divertor $\to$ core radiation & impurity control
DEMO relevant ITER control goals

• ITER research plan

• Magnetic control
  – Plasma current and shape
  – Divertor configuration (strike points)

• Kinetic control
  – Heat load
    o ELMs
    o Divertor detachment
  – \( j \) and \( T_e \) profiles
  – \( P_{fus} \)

• Machine protection
  – First wall/divertor heat load protection
  – H-L back-transition avoidance
  – MHD control
  – Disruption avoidance/mitigation
  – Runaway electron avoidance/mitigation

• Exception handling
  – Technical faults
  – Instabilities
  – Impurity events
Actuators

• "Conventional" actuator systems
  – Magnetic coils
    ITER: also in-vessel coils
  – Gas and pellets for fuelling and impurity injection
  – NBI and ECRH for heating and current drive
    ITER: 73 MW (33 MW NBI, 20 MW ECRH, 20 MW ICRH)
  – Disruption mitigation system (DMS)

• Late ITER and DEMO: $\alpha$-heating dominates auxiliary heating

Diagnostics

• ITER: fusion experiment
  – Physics research
  – Model and control evaluation
  – Lots of diagnostics (> 50)
    o safety, protection and control relevant diagnostics (~ 30)
    o neutron fluence rate low
      $\left(10^{20} \text{ n/cm}^2, \text{ DEMO}:10^{22} \text{ n/cm}^2\right)$

• DEMO: fusion reactor
  – Technology maturation/demonstration
  – Only safety, protection and control-relevant diagnostics
  – High neutron fluence rate
    (compatibility, mounting limits)
  – T breeding (space limitations)
<table>
<thead>
<tr>
<th>Control quantity</th>
<th>Operational limits</th>
<th>Diagnostics</th>
<th>Actuators + interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
<td>safety factor limit ($q_{95}$)</td>
<td>magnetic diagnostics</td>
<td>CS coils auxiliary heating</td>
</tr>
<tr>
<td>Plasma position and shape, incl. vertical stability</td>
<td>wall loads (FW and div.) max. $\Delta z$ / VDE disruption</td>
<td>magnetic diagnostics Reflectometry, ECE neutron/gamma diagnostics IR polarimetry/interferometry</td>
<td>PF + CS coils auxiliary heating gas injection</td>
</tr>
<tr>
<td>Plasma (edge) density</td>
<td>density limit</td>
<td>Reflectometry IR polarimetry/interferometry Plasma radiation</td>
<td>pellet injection (fuel)</td>
</tr>
<tr>
<td>Plasma radiation, impurity mixture, $Z_{\text{eff}}$</td>
<td>radiation limit LH threshold</td>
<td>Spectroscopy+radiation meas. $U_{\text{loop}}$</td>
<td>impurity gas injection auxiliary heating</td>
</tr>
<tr>
<td>Fusion power</td>
<td>wall loads (FW and div.) LH threshold</td>
<td>Neutron diagnostics FW/blanket and div. power (for calibration only)</td>
<td>pellet injection (fuel) impurity gas injection auxiliary heating</td>
</tr>
<tr>
<td>Divertor detachment and heat flux control</td>
<td>divertor wall loads LH threshold</td>
<td>Spectroscopy+radiation meas. Thermography Divertor thermo-currents Reflectometry, ECE</td>
<td>gas injection (impurities + fuel) pellet injection (fuel) PF coils pumping system</td>
</tr>
<tr>
<td>(MHD) plasma instabilities</td>
<td>various ($\rightarrow$ disruptions)</td>
<td>Reflectometry, ECE IR polarimetry/interferometry magnetic diagnostics neutron/gamma diagnostics auxilliary heating ECCD PF coils</td>
<td></td>
</tr>
<tr>
<td>Plasma pressure</td>
<td>beta limit</td>
<td>magnetic diagnostics density and temperature meas.</td>
<td>auxiliary heating fuel and impurity injection</td>
</tr>
<tr>
<td>Unforeseen events (impurity ingress, component failure)</td>
<td>various ($\rightarrow$ disruptions)</td>
<td>all</td>
<td>all</td>
</tr>
</tbody>
</table>
## Equilibrium Control

<table>
<thead>
<tr>
<th>Control quantity</th>
<th>Operational limits</th>
<th>DEMO Diagnostics</th>
<th>ITER Diagnostics</th>
<th>Actuators + interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current</td>
<td>safety factor limit ($q_{95}$)</td>
<td>magnetic diagnostics</td>
<td>In-vessel magnetics</td>
<td>CS coils auxiliary heating</td>
</tr>
<tr>
<td>Plasma position and shape, incl. vertical stability</td>
<td>wall loads (FW and div.) max. $\Delta z / VDE$ disruption</td>
<td>magnetic diagnostics Reflectometry, ECE neutron/gamma diagnostics IR polarimetry/interferometry</td>
<td>In-vessel magnetics, Divertor magnetics</td>
<td>PF + CS coils auxiliary heating gas injection</td>
</tr>
<tr>
<td>Error field</td>
<td></td>
<td>In-vessel magnetics</td>
<td></td>
<td>Error Field Correction coils</td>
</tr>
</tbody>
</table>

### Legend:
- Usable/foreseen for DEMO
- Big issues/not feasible in DEMO
- Applicable with restrictions (e.g. resolution, sacrificial)
<table>
<thead>
<tr>
<th>Control quantity</th>
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<th>DEMO Diagnostics</th>
<th>ITER Diagnostics</th>
<th>Actuators + interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma (edge) density</td>
<td>density limit</td>
<td>Reflectometry</td>
<td>interferometer/polarimeter</td>
<td>pellet injection (fuel) gas injection pumping system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IR polarimetry/interferometry</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Plasma radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bolometry: radiated power, Hα, vis. spectroscopy, VUV, X-ray (core + divertor), CXRS, BES</td>
<td></td>
</tr>
<tr>
<td>Plasma radiation, impurity mixture, Z_{\text{eff}}</td>
<td>radiation limit</td>
<td>Spectroscopy + radiation meas. U_loop</td>
<td></td>
<td>impurity gas injection auxiliary heating</td>
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<tr>
<td></td>
<td>LH threshold</td>
<td></td>
<td></td>
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<tr>
<td>Fusion power</td>
<td>wall loads (FW and div.)</td>
<td>Neutron diagnostics FW/blanket and div. power (for calibration only)</td>
<td>diamagnetic loop: plasma energy, neutron flux monitors and cameras, neutron spectrometer: fuel ratio, neutral particle analyzer: fuel ratio, D/T influx: Hα, vis. spectroscopy</td>
<td>pellet injection (fuel) impurity gas injection auxiliary heating</td>
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<td>Spectroscopy + radiation meas. Thermography Divertor thermo-currents Reflectometry, ECE</td>
<td>IR thermography, VIS/IR imaging, pressure gauges, residual gas analysers, Langmuir probes</td>
<td>gas injection (impurities + fuel) pellet injection (fuel) PF coils, pumps</td>
</tr>
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<td></td>
<td>LH threshold</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ELMs</td>
<td>Target overheat</td>
<td></td>
<td>Hα, vis. spectroscopy</td>
<td>ELM pellet inj, ITER: ELM ctr. coils</td>
</tr>
<tr>
<td>Gas pressure in main chamber</td>
<td></td>
<td></td>
<td>pressure gauges</td>
<td>gas injection, pumps</td>
</tr>
<tr>
<td>Te, ne profiles</td>
<td></td>
<td>Thomson scattering, ECE, reflectometry</td>
<td></td>
<td>EC</td>
</tr>
<tr>
<td>Ti profile</td>
<td></td>
<td>X-ray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current profile</td>
<td></td>
<td>MSE, polarimetry</td>
<td></td>
<td>EC, NBI</td>
</tr>
<tr>
<td>Plasma rotation</td>
<td></td>
<td>X-ray, CXRS</td>
<td></td>
<td>NBI</td>
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<td>all</td>
<td></td>
<td>all</td>
</tr>
<tr>
<td>L-H threshold</td>
<td>H-L backtransition</td>
<td>Hα, vis. spectroscopy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disruption trigger</td>
<td>Imminent disruption</td>
<td>In-vessel magnetics: VDE, Wmhd</td>
<td>DMS</td>
<td></td>
</tr>
<tr>
<td>Runaway electron beam</td>
<td>PFC damage</td>
<td>In-vessel magnetics</td>
<td>DMS PF coils</td>
<td></td>
</tr>
</tbody>
</table>
ITER control system

• Controller design
  – Plant Modelling
  – Control strategy
  – Controller dimensioning
  – Simulation and validation

• Control architecture
  – Continuous control – monitoring
  – Control modes and schemes
  – Pulse supervision – exception handling
  – Actuator management

• PCS implementation
  – Real-Time Framework
  – Pulse Scheduling System

Control also implies first level of defence in machine protection:
  • Monitoring
  • Exception Handling
Plasma Control System

• Plasma Control System (PCS)
  – ITER Work Breakdown Structure Project WBS-47
  – Deals with the **functionality** of plasma control
    o Which quantities must be controlled in which way?
      ➔ Physics control modelling
      ➔ Controller design
    o Which strategies are necessary to survive faults and plasma events?
      ➔ Exception Handling
      ➔ Decision Taking (pulse organisation/optimization)
    o How can control functions be organised effectively?
      ➔ Control architecture
      ➔ Flexibility, extensibility, scalability
  – Developed by consortium of experts:
    CCFE, CEA, CREATE, General Atomics, IPP and ITER Organization
  – *Control software is split apart in a separate project (WBS-45, ➔ ITER-RTF)*

ITER only?
DEMO: no experiment, no control system evolution
BUT: traversal through various plasma phases will require **dynamic control scheme adaptation also in DEMO!**
Example: Density control modelling

1D/0D (gas reservoirs) model used to assess density control issues

T. Ravensbergen (TU/e), Nucl. Fusion 58 (2018) 016048
The pre-defined actuator requests are used without ILC optimization. The Dual Robust control request are simply added to the feedforward terms. The dual control is able to track the density reference without the ILC optimization. ILC is still required before the pellet phase ($t<10s$).

S. Bremond, R. Nouialletas (IRFM), PCS PDR, U4AGQ9

ILC: Iterative Learning Control
Architecture: Function Dependency

diagram in vertical hierarchy layout

Functions:
- diagnostic
- reconstruction
- monitoring
- exc. handling
- reference gen.
- basic control
- high level ctr.
- actuator

W. Treutterer (IPP),
PCS CDR, CX9DLY
Architecture: Compact Controller

- Generic component
- Configurable function
- Re-usable

Select controlled variables/control goals

Select control method (PI, state-space, non-linear)

(Smoothly) change control methods

Report control performance and failures

W. Treutterer (IPP), PCS PDR, U4B755
Architecture: Control Scheme

Scheme selectors
Mode selectors

Exception Handling & Reference Generation

Elementary Control Scheme

- Vertical Stab.
- Mag. Perturbation
- NBI Control
- ICRH Control

- Pos., Shape, Current
- Pellet Control
- Gas Control
- ECRH Control

Actuators

Monitoring

Measurement & Reconstruction

W. Treutterer (IPP), PCS CDR, CX9DLY
Exception Handling: Vertical Stabilization

- Vertical control exception aspects common to many instabilities:
  - Accurate metric to quantify proximity to boundary
  - Equilibrium, profile actions that can rapidly prevent loss of control
  - Growth of instability requires disruption mitigation action

- Finite State Machine
  Exception Handling architecture:
  - Enables tracking gradual loss of controllability
  - Responses to nominal, warning, alarm, or termination states
  - Recovery or alternate scenario actions
  - Stability margin $m_S$ proxy for more accurate controllability metrics

- Finite State Machine Exception Handling operational in DIII-D PCS

$$m_S \approx \left[ \frac{1.47}{1.13} \right] \frac{1+e^{-2t_i}}{2} \left[ 1+0.60 \left( \frac{r}{0.1} \right) \right]$$

D. Humphreys (GA), PCS PDR, U44DU3
Architectural Design

Pulse Supervision Module

Override default handling policy
- Override shape/profile references
  - After 2s => Alarm

Change structure
- Override shape weighting
  - After 4s => Warning

Change behaviour
- Change shape weighting
  - After 4s => Warning

Control Scheme

Override most system goals
- Repurpose actuators
  - After 4s => Termination

Minimise risks

Architecture: Exception Handling

Override default handling policy

W. Treutterer (IPP), PCS PDR, U4BCL2
Central Interlock System (CIS)

- CIS (PBS 46) responsible for investment protection
  - shut down pulse upon severe failures (incl. PCS fail) via plant systems
  - authority to trigger Disruption Mitigation System (DMS) injectors for Disruption and RE mitigation

- PCS involvement and view:
  - evaluate continuously
    - RE/DISR state, DMS state
      => DMS sequence + trigger
    - PCS state
      => PCS heart beat
  - terminate pulse
    - upon RE/DISR state as preparatory actions before CIS intervenes and DMS action takes effect
      (if defined in Pulse Schedule)
    - upon termination command CIS > PCS
  - **covered by Exception Handling pattern**
    "change termination segment"

Supplement by intelligent Plasma Investment Protection System (PIPS) under discussion.

G. Raupp (IPP), PCS PDR, U4ANR3
• Preliminary Design Review passed in November 2016
• Final Design for First Plasma Operation ongoing (until 2020)
  – Focused on commissioning and initial plasma (H/He) operation
  – Architecture already designed for high current, burning plasma
• Later stages envisaged to mature functionality before coding in software ➔ ITER Real-time Framework
Plasma Control System Simulation Platform

- Plasma Control System Simulation Platform (PCSSP)
  - Developed as a general purpose tool – not only for ITER
    https://git.iter.org/projects/PCS/repos/pcssp (➡ Luca.Zabeo@iter.org)
  - Targeted for
    o Scenario studies including plasma control
    o Control development
    o Code generation for the ITER Real-Time Framework
    o Pulse Validation
  - Models
    o Plasma Control System (candidates)
    o Diagnostic and Actuator Systems
    o Plasma physics
  - Focus is on rapid development ➡ simplified “control models”
  - Can be coupled with external physics codes for detail simulation
    o e.g. ASTRA, CORSICA, IMAS (, RAPTOR planned)
  - Developed by consortium of experts: CREATE, General Atomics, IPP
Real-Time Framework

• Real-Time Framework (RTF)
  – ITER Work Breakdown Structure Project WBS-45
  – Collaborative work of ITER, CCFE, Cosylab, IPP, NSTX
  – Deals with the software for real-time plasma control
    o Support the control needs of a modern complex fusion device
    o Provide a modular, highly flexible and configurable software basis
    o Provide a software basis that can survive many future hardware technology innovation cycles
    o Encapsulate real-time and multi-thread computing weirdness
    o Enable non-computer-nerds (physicists) to plug-in their algorithms in the control system like “Lego” blocks
  – Also offered for ITER plant systems (e.g. diagnostics)
    ➔ needed early, for commissioning of first ITER diagnostics
  – Could be adopted by other fusion devices as successor of actual control systems approaching their end-of-life
    ➔ ITER can set a new standard
• **What to use from ITER?**
  - Integrated control
    - Initial burn control
    - Divertor heat load control
  - Low/No ELM H-mode scenarios
  - Exception Handling
  - Disruption Detection, Avoidance and Mitigation
  - Machine Protection Systems (Control – Interlock - Safety)

• **What to develop for DEMO?**
  - Robust scenario (different operation point than ITER)
  - Model-based/predictive, robust control ➔ Eugenio Schuster
  - Burn control ➔ Filip Janky
    - Control fusion power without isotope mix
    - Control with limited actuator efficiency
  - Equilibrium control without magnetics ➔ Sang-hee Hahn
Conclusions

• ITER is dedicated to pave the way for DEMO
  – ITER control system development
    o to operate ITER
    o to develop, and test control strategies for burning plasma (DEMO)
  – Operation conditions for ITER and DEMO are different
    o Plasma confinement, power/neutron-flux, instrumentation, control margins
    o Not all ITER solutions will be scalable/portable to DEMO
  – ITER control prepares essential controls for DEMO
    o Machine protection:
      ELM control, heat load control, exception handling
    o Fusion performance:
      Burn control
    o Scenarios:
      H-mode scenario with no/low MHD instabilities, Robust ramp-up/down,
    o Control system design:
      Models, simulators, control schemes, integrated control, adaptive control, control architecture
The Beginning of a Success Story ...

Thank you.
for your attention