DEMO diagnostics and impact on controllability

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Today’s fusion experiments are amply equipped with diagnostic systems …

… the situation on DEMO will look much different!
DEMO control: Requirements and challenges

Top level requirements for DEMO diagnostic & control

1. Stable machine operation in compliance with safety requirements
   - Significant safety issues arising from control failure must be completely excluded
   - Passive safety of the machine in case of severe incidents

2. Avoid machine damage, keep safe distance from all operational limits
   - no full energy disruptions (< 1 / fpy), no strong off-normal events (melting of wall)

3. Optimised fusion performance, minimum aging of components
   - e.g. erosion, cyclic loads, neutrons

Severe limitations for implementation of a reliable plasma control

- Adverse effects on diagnostic components
  - High neutron and gamma flux (ITER x 3 … 6) and fluence (ITER x 50 … 100)
  - High fluxes and fluences of CX neutrals, gross erosion ~ 1 t / fpy (Brooks, Kotov)
  - High temperatures of FW and blanket

- Limitation of openings and space (TBR > 1, wall integrity, cost limitation)
  - → scarce diagnostics with limited accuracy
  - → weak, slow and/or indirect actuators (heating, shaping, fuelling/pumping)

Limitations for control may limit the achievable plasma scenario
DEM0 control challenges (1): Disruptions

A **disruption** should be seen as a **failure of plasma control**

Current status: **JET disruptivity ~ 10^-2 ... 10^-3 /sec.**

Extrapolation of disruptions to DEMO 1:

- \( R_0 = 9 \) m, \( a = 2.5 \) m, \( P_{th} = 1.7 \) GW
- \( W_{\text{therm}} \sim 3 \) n \( k_B T \ V_{\text{Plasma}} \sim 1 \) GJ
- \( W_{\text{ind}} \sim 0.5 \) L \( l^2 \sim 1 \) GJ
- **Thermal quench** releases \( W_{\text{therm}} \) within \( t_{TQ} \sim 1 \ldots 3 \) ms to
  - **(unmitigated case) divertor target** \( A_{\text{eff}} \sim 30 \) m\(^2\)  
    \( \rightarrow \eta \text{ above melt threshold} \)
  - **(mitigated case) first wall** \( A_{\text{eff}} \sim 1200 \) m\(^2\)  
    \( \rightarrow \eta \text{ near melt threshold, + cracking!} \)
- **Current quench** releases inductive energy \( W_{\text{ind}} \) within \( t_{CQ} \sim 10 \ldots 30 \) ms
- **Possible runaway beam generation** \( A_{\text{runaway}} \sim 3 \) m\(^2\)  
  \( \rightarrow \text{deep melting if impinging on wall} \)

**High energy disruptions on DEMO**

- High risk of major wall damage, vessel inspection may be required before restart
- Economic reactor operation requires very low disruption rate (< 1 / fpy)

\( \rightarrow \text{improvement of control reliability needed by factor of } 10^5 \text{ as compared to today} \)
Melt motion starts at 'vertical cracks'.

QSPA plasma gun exposure of a tungsten target (J. Linke et al., FZJ)
Diagnostic challenges (2): lifetime issues

Combined Risk Assessment - Results

D. Thomas et al., ITER_D_2MPTR6

Results for 35 systems range from critical (e.g. 9 shots for VUV mirror in divertor) to effectively risk-free (e.g. several equatorial systems with lifetimes greater than assumed ITER lifetime (4700 hrs))

<table>
<thead>
<tr>
<th>DD-ID</th>
<th>First Mirror at Risk</th>
<th>Location risk class</th>
<th>Wavelength risk class</th>
<th>Solid angle risk class</th>
<th>Time to 1/4 (%) ITER lifetime</th>
<th>Time to 1/4 (% ITER shots)</th>
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First mirror lifetime \( t \sim \frac{\text{wavelength}}{\text{particle flux} \times \text{etendue}} \)

\( \rightarrow \) No high efficiency spectroscopy or imaging systems on DEMO/fusion reactor

\( \sim 1 \text{ year} \)
Diagnostic lifetime issues (2): ionising radiation

Neutron fluence and activation on DEMO behind the blanket will be comparable to the situation at the ITER first wall

(F Orsitto et al.)

A significant lifetime of diagnostic components on DEMO can only be expected when installed behind the blanket
DEMO diagnostics and control implementation

- **High availability + reliability**
  - Main control system should work maintenance-free for several full power years → only install diagnostic systems which have a sufficient lifetime
  - Vulnerable diagnostic components only behind the blanket or divertor; proper shielding of diagnostic components against radiation and particles
  - Routine exchange of diagnostic front end components together with divertor or blanket replacement
  - Provide maintenance access for (occasional) diagnostic repair, e.g. via endoscope-like mounting of diagnostics through vacuum vessel wall from backside

- **High Tritium Breeding rate TBR > 1, cost optimisation**
  - Implementation of diagnostic and heating components with minimum impact on the TBR, integrated into the blanket/divertor, (avoid large voids or shielding blocks)
  - Allow for standardisation of blanket and divertor (cost optimisation)

- **Option: additional startup diagnostic**
  - Installation of a limited set of additional diagnostics with higher accuracy may → facilitate the commissioning phase
    → fine-tune the operational scenario
    → train the more coarse main control system
Essential measurement & control issues on DEMO

- Plasma current  
  ($\rightarrow q_{95}$ limit)
- Plasma density  
  ($\rightarrow$ density limit)
- Plasma beta  
  ($\rightarrow$ beta limit; depending on the chosen plasma scenario)
- Plasma position and shape  
  ($\rightarrow$ limited wall loads)
- Divertor heat flux  
  ($\rightarrow$ limited wall loads)
- Fusion power  
  ($\rightarrow$ limited wall loads)
- Radiated power, $Z_{\text{eff}}$, impurity mixture  
  ($\rightarrow$ limited wall loads // radiation collapse)
- Wall + blanket temperature  
  ($\rightarrow$ material properties)
- Plasma instabilities  
  ($\rightarrow$ disruption avoidance, ELMs, …)
- Runaway electrons  
  ($\rightarrow$ disruption mitigation, q profile control)
- D/T ratio  
  ($\rightarrow$ burn control)
- Dust, Tritium retention  
  ($\rightarrow$ safety)
- Radial profiles: n, T, $P_{\text{rad}}$, $v_{\text{rot}}$, j  
  ($\rightarrow$ scenario control/optimisation if needed)
- In-vessel inspection  
  ($\rightarrow$ maintenance)

The plasma scenario is only feasible if all those quantities which are related to operational limits can be reliably controlled
Candidate diagnostic systems for DEMO

Diagnostics which are most likely feasible:

- Reflectometry, ECE, tangential polarimetry, neutron spectroscopy
  - n, T, q profiles + plasma position/shape in main plasma
  - Instabilities in main plasma (mainly via microwave diagnostics)
  - Plasma position and shape and strike point in divertor plasma
- (Passive) radiation measurements / spectroscopy with low etendue
  - Prad, Zeff, impurity mixture (low performance, low time resolution)
- Magnetic diagnostics behind the breeding blanket / shield
  - measurement of \( I_p, U_{\text{Loop}}, E_{\text{Dia}} \) (plasma position and shape?)
- FW and divertor coolant temperature, flow and pressure
  - absolute measurement of thermal power (slow and low spatial resolution)
- Current density / voltage measurement at divertor target plates (t.b.c.)
  - Perspective for detachment control
- Measurement of gas/beam/pellet fuelling and gas exhaust
  - Neutral pressure in divertor, impurity gas composition, D/T ratio

Important gaps and problems

- Monitoring of 1st wall + divertor integrity (no imaging diagnostics?)
- Control of the divertor plasma (detachment control) + heat fluxes
- Erosion, dust, tritium retention
- Plasma instabilities, modes etc.
Integrated plasma diagnostics processing & control

- Plasma controller: perform control actions based on full plasma state knowledge
- Plasma state reconstruction: derive plasma state by merging measurements from several diagnostics
- Fault detection: classify unexpected measurements (e.g. off-normal events, faulty signals)
- Diagnostic redundancy in number of channels and number of methods facilitates handling of faults (the better the model, the less measurements are needed)

(F. Felici, see poster)
Dynamic observer for tokamak plasma state

- Run tokamak simulation in parallel with plasma evolution
- Correct simulated state estimate based on difference between predicted and true measurements
- Detection & classification of excessive discrepancies
- The plasma controller may initiate fast rampdown or disruption mitigation if a discrepancy cannot be resolved otherwise

(F. Felici, see poster)
Controllability of DEMO plasma scenarios

Major diagnostic/control problems for all scenarios

- Divertor (lifetime; spatial resolution and coverage) → driver for PEX programme
- fast modes/instabilities (coverage; temporal and spatial resolution)
- First wall loads in main chamber → increased clearance between separatrix and first wall

Additional issues for advanced scenarios (profile control if needed)

- electron temperature profile
  → measurement by ECE, seems feasible but with limited accuracy
  → control actuator: ECR heating (weak, slow)
- electron density profile
  → measurement via reflectometry + tangential polarimetry, seems feasible
  control actuator: gas inlet, pellet injection, (NBI has too small particle flux)
- current density profile
  → direct measurement only with start-up diagnostic → scenario limitation
  → indirect measurement via correlation reflectometry t.b.c.
  → indirect control actuator: ECR heating
Control issues for highly radiative scenarios

(A. Kallenbach)

- Highly radiative scenarios tend to be unstable: \( L_Z \) rises when \( T_e \) decreases
- Measurement of plasma radiation only available at low performance
- Only low auxiliary heating power may be available to counteract
- Plasma density can only be slowly reduced
- Thorough stability analysis / dynamic simulation needed before concluding on the scenario
Example: Control of fusion power

Fusion power is not very sensitive to the D/T ratio

- control of D/T ratio via measurements of fuelling and gas exhaust
- optional local D/T measurement via NPA (Petrov et al)

\[ P_{\text{el, net}} \approx 340 \text{ MW} \]

\[ P_{\text{el, net}} \approx 410 \text{ MW} \]

DEM01: Variation of D/T ratio

- DEMO simulation \( P_{\text{ext}} = 100 \text{ MW} \)
- DEMO simulation \( P_{\text{ext}} = 50 \text{ MW} \)

- quadratic

\[ R_0 = 9 \text{ m} \]
\[ a = 2.49 \text{ m} \]
\[ H = 1.1 \]
\[ N_{\text{GW}} = 1.2 \]
\[ q_{95} = 3 \]
\[ P_{\text{div}} = 146 \text{ MW} \]

\( c_{\text{Ar}} \) is varied to keep \( P_{\text{Sep}} \) constant
Example: Control of fusion power (2)

R_0 = 9 m
a = 2.49 m
H = 1.1
N_{GW} = 1.2
q_{95} = 3
P_{div} = 146 MW

c_{Ar} is varied to keep P_{Sep} constant

**DEMO1: Variation of D/T ratio**

- DEMO simulation P_{ext} = 100 MW
- DEMO simulation P_{ext} = 50 MW

\[ f_D = \frac{n_D}{n_D + n_T} \]
Diagnostic/control accuracy and disruptions

\[ \tau_E / s = 0.173 \, H_H \, I_M^{0.93} \, R_0^{1.39} \, a^{0.58} \, k^{0.78} \, n_{20}^{0.41} \, B_0^{0.15} \, P_M^{-0.69} \]

In DEMO design studies, the operational point is often chosen quite near the limits.

- But, for a given accuracy of the measurement and control system, \( \sigma \), how much distance should the plasma scenario keep from the operational limits?

\[ \Rightarrow 3 \, \sigma \ldots 5 \, \sigma ? \]

P de Vries *NF 49* (2009) 055011
Impact of introducing control margins on the DEMO operational point

Compare two cases for the DEMO 1 model (system code calculation):
\( R_0 = 9 \text{ m}, \ a = 2.49 \text{ m}, \ P_{\text{ext}} = 50 \text{ MW}, \ P_{\text{Div}} = 146 \text{ MW} \)

a) Reference case

b) The same but with 10% reduction („control margin“) both in confinement quality, plasma density and plasma current

<table>
<thead>
<tr>
<th>Case</th>
<th>( H_H )</th>
<th>( n/n_{GW} )</th>
<th>( q_{95} )</th>
<th>( \text{Zeff} )</th>
<th>( P_{\text{therm}} / \text{MW} )</th>
<th>( P_{\text{electr}} / \text{MW} )</th>
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Assuming just 10% control margin for confinement quality, plasma density and safety factor, we obtain 50% reduction of electrical output power
### DEMO control requirements table (a few details)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Diagnostics</th>
<th>Actuators + interactions</th>
<th>Interactions</th>
<th>Control accuracy</th>
<th>Spatial resolution</th>
<th>Control time response</th>
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</thead>
<tbody>
<tr>
<td>Main plasma density</td>
<td>Polarimetry, Reflectometry, Bremsstrahlung, Soft x-ray, Neutrons</td>
<td>Gas inlets, Pumping system</td>
<td>Wall and divertor, temperatures (outgassing)</td>
<td>2 % - 5%</td>
<td>a/10 in core, a/20 in edge</td>
<td>0.1 ... 1 s for 10% increase, 1 ... 5 s for 10% decrease</td>
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<td>Main plasma temperature</td>
<td>ECE, Soft x-ray, Bremsstrahlung</td>
<td>Plasma heating</td>
<td>Main plasma density</td>
<td>5% - 10%</td>
<td>a/10 in core, a/20 in edge</td>
<td>Several s for increase, A few ms for decrease</td>
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<td>Plasma position and shape</td>
<td>Reflectometry, ECE, Magnetic behind blanket</td>
<td>PF coils, CS coils, Plasma heating</td>
<td>Confinement (beta)</td>
<td>a/50</td>
<td>a/50 - a/20</td>
<td>1 s (PF coils) &lt; 0.1 s (confinement)</td>
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<tr>
<td>Zeff</td>
<td>Bremsstrahlung, Soft x-rays</td>
<td>Impurity gas inlet, FW and Div fluxes</td>
<td>0.2 - 0.5</td>
<td>Integral or a/5</td>
<td>1 s</td>
<td></td>
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</tbody>
</table>

The numbers entering into this table will be result of:
- Analysis of achievable diagnostic and actuator properties
- DEMO control simulation

This table will serve as:
- Reference specification for diagnostic and actuator designers
- Reference für plasma scenario definition
Elements of the R&D programme for DEMO diagnostic and control

- Develop a DEMO integrated control requirements table (realistic numbers!)
  - Serve as a guiding tool (1) for all diagnostic/control R&D
  - **important interface to plasma scenario development** and system integration unit
  - Define limits for all relevant parameters to which the plasma scenario must be adapted to
  - „living“ document, to be updated whenever new results are obtained (design iterations)

- Develop simulation tools for DEMO control, including realistic accuracies and response times for both diagnostics and actuators
  - Serve as a guiding tool (2) for all diagnostic/control R&D
  - Serve as test bed to prepare the later integrated DEMO control system

- Set up a list of candidate diagnostic systems and assess/validate their performance
  - Develop and test relevant prototypes
  - Validation experiments on JET, JT-60 + ITER (individual diagnostics and full control)

- Set up a list of actuators and assess/validate their performance

- Develop implementation schemes for diagnostics and actuators (integration into the blanket and divertor)
Stellarator-DEMO control issues

Background: Stellarators – 3D magnetic confinement facility
- + External $B_\theta$ generation, stable configuration w/o current, reversed shear
- + steady-state
- + no disruptions; radiation collapse slower than tokamak disruptions
- + high-density operation possible
- - 3D engineering – integration and maintenance
- - concept development one generation behind the tokamak – many unknowns

About stellarator DEMO control
- + less effort needed for real time control of current and plasma position
- + milder instabilities
- + smaller fluxes
- - plasma scenario to be explored (confinement, impurity control)
- - burning plasma effects unknown
- - divertor operation and detachment control to be explored
Interfaces relevant for DEMO diagnostic & control

- Safety relevance of DEMO control (passive safety?)
- Scenario definition depending on control margins (machine protection)
  - to be defined according to the achievable control accuracy (diagnostic+software+actuator)
- Diagnostic (and heating) implementation+maintenance:
  - Blanket
  - Divertor
  - Vacuum vessel
  - Remote handling
- Main actuators:
  - PF, CS and corrections coils
  - H&CD systems
  - Fuelling and gas exhaust systems
- Resilience of first wall, divertor materials, diagnostic and heating components against disruptions

→ Development of diagnostic and control system must go in parallel with overall DEMO design
Summary and conclusions:

- Requirements for stable control on DEMO are much higher than on ITER
  - Disruptions and other transient events could potentially cause severe damage
- Only limited set of diagnostics and actuators available on DEMO
  - Lifetime and performance issues
- Novel integrated control techniques may (partially) compensate the shortfalls on the diagnostic/actuator side
- Feasibility of control system may limit the operational space for the plasma scenario → realistic control margins needed
- Outline of future R&D programme on DEMO control:
  - Develop control requirements table and control simulation tools to obtain realistic numbers
  - Specific validation experiments on diagnostics, actuators and full control system
  - Work on the interfaces to other parts of the DEMO design work