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DEMO diagnostics and burn control

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HIGHLIGHTS

- An initial concept for the DEMO diagnostic and control system is presented.
- A preliminary list of control functions and candidate diagnostics is developed.
- Challenges regarding disruptions, power exhaust and radiation control are highlighted.
- The need for introducing realistic control margins is emphasized.
- On outline of the future R&D plan is presented.

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ABSTRACT

The development of the control system for a tokamak demonstration fusion reactor (DEMO) faces unprecedented challenges. First, the requirements for control reliability and accuracy are more stringent than on existing fusion devices: any loss of plasma control on DEMO may result in a disruption which could damage the inner wall of the machine, while operating the device with larger margins against the operational limits would lead to a reduction of the electrical output power. Second, the performance of DEMO control is limited by space restrictions for the implementation of components (optimization of the tritium breeding rate), by lifetime issues for the front-end parts (neutron and gamma radiation, erosion and deposition acting on all components) and by slow, weak and indirect action of the available actuators (plasma shaping, heating and fuelling). The European DEMO conceptual design studies include the development of a reliable control system, since the details of the achievable plasma scenario and the machine design may depend on the actual performance of the control system. In the first phase of development, an initial understanding of the prime choices of diagnostic methods applicable to DEMO, implementation and performance issues, the interrelation with the plasma scenario definition, and the planning of necessary future R&D have been obtained.

1. Introduction and overview

With the construction of the new tokamak experiment ITER making progress, the efforts on conceptual design studies for a follow-up demonstration reactor (DEMO) are pursued with increasing emphasis [1–7]. In the current European roadmap towards fusion power [8] ITER is seen as the key facility, with the main mission of demonstrating a burning plasma with fusion power $P = 500$ MW and energy amplification $Q = 10$ over a significant pulse duration ($t = 400$ s), and testing a number of key technologies. In a subsequent step a DEMO reactor is foreseen with the aim to demonstrate significant net electrical output power, tritium self-sufficiency and high availability, thus opening the perspective for economic fusion electricity.

Reliable operation and control of a magnetic fusion reactor requires a robust plasma scenario combined with an integrated diagnostic and control system. Both elements together, scenario and control have to ensure machine operation in compliance with

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nuclear safety requirements, achieve high plant availability and aim for optimized fusion performance. In view of operational limits, which should not be exceeded due to the risk of machine damage, essential quantities to be measured and controlled in a tokamak reactor (and mostly also in a stellarator) are

- plasma current, position and shape
- plasma density, pressure and fusion power
- plasma radiation, local wall loads and wall temperatures and
- plasma instabilities (MHD)

Furthermore, an event handling system has to be implemented to counteract any unforeseen incidents, e.g. impurity particles falling into the plasma, failure of control components, disruption mitigation and occurrence of runaway electrons.

Except for the fusion power, control schemes for most of the other quantities are already in use and continuously under improvement on all current major tokamak experiments [9–14]. However, already for ITER and even more for a future DEMO fusion reactor, the requirements for the reliability of plasma operation are much more demanding than on any existing device. One significant problem is the stationary power exhaust, where the local power flux densities are near to design limits and must be safely controlled to avoid damage to the target plates [15]. On top of the stationary loads, strong transient events such as large ELMs or disruptions have to be avoided as well, since the crack limit or melt limit of the wall surface may be exceeded [16].

While present magnetic fusion experiments are amply equipped with diagnostic and actuator systems, and a broad range of systems is also foreseen on ITER [17], their implementation on DEMO will only be possible with reduced performance and/or number of systems, due to several reasons: first, the fraction of openings and voids in the breeding blanket has to be minimized in order to achieve a Tritium breeding rate TBR > 1 [18,19]. Second, diagnostic front-end components will be subject to an extremely harsh environment (radiation, forces, temperatures etc.) and thus any vulnerable components may only be installed at some distance behind the first wall or blanket [20–22]. Third, available actuators on fusion reactors such as magnetic field coils (poloidal field and central solenoid), auxiliary heating, gas inlets, pellet injectors and pumping systems can typically only provide slow, indirect or weak actions on the DEMO plasma.

In order to achieve accurate control with high availability over extended periods of operation, an enhanced long-term stability of diagnostic systems and actuators, together with redundancy in terms of number of methods and number of channels, are needed. In addition, plasma modelling and integrated data analysis together with in situ calibration and consistency checking methods have to be developed and implemented into the DEMO control system [23,24]. In view of the expected limitations of control performance on DEMO, the parameters of the plasma scenario and machine design may have to be chosen with sufficiently large margins against any operational limits [25], thus reducing the disruption rate but effectively limiting the achievable overall performance of the reactor. Some of the issues to be solved for DEMO diagnostic and control are overlapping with problems being addressed on ITER [26]. A thorough analysis will be needed to identify which of the solutions being developed for ITER could be transferred to the DEMO diagnostic and control development.

2. DEMO diagnostic and control: challenges

2.1. General requirements for DEMO control

The DEMO control system has to provide stable operation of the DEMO tokamak and the peripheral components according to the following requirements and priorities [27]: first, ensure that the machine is operated in compliance with nuclear safety requirements, where any significant release of radioactive inventory in relation with control failure must be strictly excluded. Second, machine damage has to be avoided by keeping a sufficiently large distance from all known operational limits, in particular avoiding disruptions and any other strong transients like large ELMs or sawteeth. Third, machine performance has to be optimized, maximizing efficiency and availability while minimizing the ageing of components (e.g. via neutron embrittlement, erosion and deposition). Specifically, the control system should be designed to allow for DEMO operation with high reliability over extended periods of several full power years, such that no need for major shutdowns for inspection, maintenance or repair would be generated due to failure of the control system or its components.

2.2. Control quantities on DEMO

The primary list of quantities to be controlled on a DEMO tokamak follows from the general requirements defined above. In the first place, the machine design and plasma scenario definition should be made such that any kind of control failure may not lead directly or indirectly to any safety relevant incidents, even when considering combinations of unlikely events. Specifically, any breaking of the safety boundaries and release of radioactive inventory related to failure of control components or software, external events, human error or misuse of the control system have to be excluded by design. Passive safety features of DEMO would be the preferred case, such that the safe containment is guaranteed in any case of control malfunction. In turn, if perfect passive safety could not be proven, then an accordingly higher level of redundancy and robustness of the control system would be needed. In the second priority, all those quantities which are related to operational limits must be controlled such that any exceeding of those limits is excluded, thereby avoiding termination of the plasma or damage of components. Here the redundancy and accuracy of the control system have to be adapted to the required degree of the overall control reliability. Finally, all quantities which are related to the efficiency and availability of the plant have to be controlled to stay within certain operational margins, maximizing the electrical output power while minimizing the ageing of components.

For the structuring of the various quantities to be controlled, it is convenient to group them into a limited number of “control functions”, which are composed of a number of individual control parameters and quantities that are interrelated with respect to their physics properties, measurements and actuator issues. In the following, we present a tentative list of control functions for a DEMO tokamak. Here, we distinguish between the two cases of a conservative and less demanding pulsed tokamak (DEMO 1) and a more advanced steady-state tokamak (DEMO 2) [6]. A short listing of the control functions and individual quantities to be controlled is presented in Table 1.

For each of these control functions, suitable measurements, actuator actions and control modules (i.e. a quantitative and reliable model for the purpose of control) have to be developed, in order to be able to identify and control the system state on DEMO.

2.3. Plasma disruptions in a DEMO tokamak

In view of the concept development for DEMO control any plasma disruption has to be seen as a loss of control event, where an operational limit has been exceeded, which has to be strictly avoided. To illustrate this requirement, we recall that a disruption in a DEMO tokamak with the parameters major radius $R_0 = 9$ m, minor radius $a = 2.25$ m, elongation $\kappa = 1.7$, plasma density $n_{20} = 1.03$ and temperature $T = 12.9$ keV [6] may release a significant