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Overview of EU DEMO design and R&D activities

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HIGHLIGHTS

- An important objective of the new EU fusion roadmap is to lay the foundation of a DEMO Fusion Power Reactor to follow ITER.
- DEMO should be capable of generating several 100 MW of net electricity and operating with a closed fuel-cycle by 2050.
- The paper outlines the DEMO design and R&D approach recently being undertaken in Europe.
- The paper presents some preliminary design options that are under evaluation as well as the most urgent R&D work needed.
- The R&D on materials for a near-term DEMO is discussed in detail elsewhere.

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ABSTRACT

One important objective of the EU fusion roadmap Horizon 2020 is to lay the foundation of a Demonstration Fusion Power Reactor (DEMO) to follow ITER, with the capability of generating several 100 MW of net electricity to the grid and operating with a closed fuel-cycle by 2050. This is currently viewed by many of the nations engaged in the construction of ITER as the remaining crucial step towards the exploitation of fusion power. This paper outlines the DEMO design and R&D approach that is being adopted in Europe and presents some of the preliminary design options that are under evaluation as well as the most urgent R&D work that is expected to be launched in the near-future. The R&D on materials for a near-term DEMO is discussed in detail elsewhere.

1. Introduction

With the construction of ITER well underway, attention is now turning to the design of a successor device; a Demonstration Fusion Power Plant (DEMO), i.e., the nearest-term reactor design capable of producing electricity, operating with a closed fuel-cycle and to be the single step between ITER and a commercial reactor. Currently, no conceptual design exists for DEMO and work carried out in the past in Europe on fusion reactor design focussed on the assessment of the safety, environmental and socioeconomic aspects of fusion power and less on rigorous technology feasibility assessments [1]. At present, the DEMO reactor design has not been formally selected and detailed operational requirements are not yet available. DEMO is a device which lies between ITER and a power plant, but there is not widespread agreement of where in the range it must lie; motivated in part by the range of options for a power plant design and the timescales on which DEMO should be delivered.

This paper provides an overview of EU DEMO design and R&D activities. Emphasis is on the results of a two-and-a-half year study performed by the EFDA Power Plant Physics and Technology (PPPT) Department focusing on (i) the identification of the DEMO prerequisites, (ii) the main design and technical challenges (physics and technology), (iii) the preliminary assessment of the foreseeable technical solutions and (iv) the prioritization of R&D activities to be launched as part of the new EU fusion roadmap [2,3]. In view of the many uncertainties still involved and recognizing the role of DEMO in fusion development, it is judged undesirable for the initial study effort to focus solely on developing the details of a single design point and there is the need to keep some flexibility in the approach to the conceptual design. However, establishing performance requirements and project development schedules linked to a target start of construction date is expected to be a strong driver in the selection of the technical features of the device;

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favouring more conservative technology choices for near term solutions [2,4].

A system engineering approach is viewed as essential from the early concept design stage [5]: (i) to better understand the problems and evaluate the technical risks of foreseeable technical solutions; (ii) to identify design trade-offs and constraints to address the most urgent issues in physics, technology and design integration; and (iii) to prioritize the R&D needs. Ensuring that R&D is focussed on resolving critical uncertainties in a timely manner and that learning from R&D is used to responsively adapt the technology strategy is crucial to the success of the programme. In general, the progress assessment methodology should be similar to other fields and follow the approach of assigning a technical readiness level (TRL) to the reactor systems and updating the TRL as R&D tasks are completed. There are many examples of TRL scales and their application to systems of varying and evolving maturity. The integration of our expanding physics knowledge into the DEMO conceptual design will also play a crucial role in supporting the design evolution.

Involvement of industry and exploitation of international collaborations on a number of critical technical aspects is highly desirable.

2. Main differences between ITER and DEMO

According to several studies undertaken in Europe in the past (see for example [1,6]) DEMO must:

- Resolve all physics and technical issues foreseen in the plant and demonstrate reactor relevant technologies.
- Demonstrate production of several 100 MW of electricity.
- Achieve *T* self-sufficiency, i.e. DEMO must make its own fuel.
- Achieve adequate availability/reliability operation over a reasonable time span.

The main differences between ITER and DEMO are summarized in Table 1 [7].

Table 1
Main differences between ITER and DEMO [7].

ITER	DEMO
Experimental device with physics and technology development missions	Nearer to a commercial power plant but with some development missions
400 s pulses, long dwell time	Long pulses (>2 h) or steady state
Experimental campaigns. Outages for maintenance, component replacements	Maximize availability
Large number of diagnostics	Only diagnostics required for operation
Multiple H&CD systems	Optimized set of H&CD systems
Large design margins, necessitated by uncertainties and lack of fully appropriate design codes	With ITER (and other) experience, design should have smaller uncertainties
Cooling system optimized for minimum stresses and sized for modest heat rejection	Cooling system optimized for electricity generation efficiency (e.g. much higher temperature)
Unique one-off design optimized for exptl. goals	Move towards design choices suitable for series production
No tritium breeding requirement (except very small quantity in TBMs)	Tritium breeding needed to achieve self-sufficiency
Conventional 316 stainless steel structure for in-vessel components	Nuclear hardened, novel reduced activation materials as structure for breeding blanket
Very modest lifetime n-fluence, low dpa and He production	High fluence, significant in-vessel materials damage
Licensed as nuclear facility, but like a laboratory, not a reactor	Licensing as nuclear reactor more likely
Licensing as experimental facility	Stricter approach may be necessary to avoid large design margins
"Progressive start-up" permits staged approach to licensing	"Progressive start-up" should also be possible (e.g. utilize a "starter" blanket using moderate-performance materials and then switch to blankets with a more advanced-performance material after a few MW-year/m^2)
During design, licensing in any ITER party had to be possible	Fewer constraints

A variety of fusion power plant system designs have been studied in the past across the world, but the underlying physics and technology assumptions were found to be at an early stage of readiness. The recent EU fusion roadmap [2] advocates a pragmatic approach and considers, for the initial design integration studies, a pulsed "low-extrapolation" DEMO that could be delivered in the short to medium term. This should be based on mature technologies and reliable regimes of operation to be, as much as possible, extrapolated from the ITER experience, and on the use of materials adequate for the expected level of neutron fluence [3].

It is argued that by waiting to design DEMO for the ultimate technical solution in each area would postpone the realization of fusion indefinitely. Since the mission requirements of a near-term DEMO put more emphasis on solutions with high technical readiness levels and realistic performance and component reliability, rather than on high-efficiency, the R&D priorities in the Roadmap are defined to achieve these goals. Nevertheless, these goals remain very ambitious and many technological advances and innovations will be required. More advanced technological solutions will also need be developed but on a longer timescale and as part of a parallel long term R&D programme.

3. DEMO design options

The task of choosing an appropriate set of design parameters and engineering technologies involves trade-offs between the attractiveness and technical risk associated with the various design options. One of the crucial points is the size of the device and the amount of power that can be reliably produced and controlled in it. This is the subject of research and depends upon the assumptions that are made on the readiness of required advances in physics (e.g., the problem of the heat exhaust, choice of regime of operation, efficiency of non-inductive Heating and Current Drive (H&CD) systems, etc.), technology and materials developments. An overview of the results of initial analyses is provided elsewhere [4]. Here, we summarize some of the key results on the main device design drivers and how they have been explored in these studies.

Two different DEMO design options are currently investigated, in an attempt to identify a realistic range of possibilities:

- A near-term DEMO (DEMO1) is a rather "conservative baseline design", i.e. a DEMO concept deliverable in the short to medium term (e.g., construction possibly starting ~20 years from now), based on the expected performance of ITER ($Q = 10$) with reasonable improvements in science and technology; i.e., a large, modest power density, long-pulse inductively supported plasma in a conventional plasma scenario. The design of Balance of Plant (BoP) for a near-term DEMO must also make use of mature and reliable technology.
- a more advanced, DEMO design concept (DEMO2) based around more optimistic (but "less mature") physics assumptions, which are at the upper limit of what may be achieved in ITER phase-2, i.e., an advanced higher power density high current drive steady-state plasma scenario. It is clear that this can only be delivered on a longer term (e.g., construction to be started on a much longer time scale assuming that the required significant advances in the