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Consequences of the technology survey and gap analysis on the EU DEMO R&D programme in tritium, matter injection and vacuum

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HIGHLIGHTS

- The inner fuel cycle architecture of DEMO is developed in a systems engineering approach as a functional break-down diagram, driven by the need for inventory minimisation.
- Technologies to fulfil the required functions are discussed and ranked.
- Prime technologies are identified and an associated R&D programme is developed.
- The core challenges of a DEMO fuel cycle beyond those already addressed in ITER are discussed.

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ABSTRACT

In the framework of the EUROfusion Programme, EU is preparing the conceptual design of the inner fuel cycle of a pulsed tokamak DEMO. This paper illustrates a quantified process to shape a R&D programme that exploits as much as possible previous R&D. In an initial step, the high-level requirements are collected and a novel DEMO inner fuel cycle architecture with its three sub-systems vacuum pumping, matter injection (fuelling and injection of plasma enhancement gases) and tritium systems (tritium plant and breeder coolant purification) is delineated, driven by the DEMO key challenge to reduce tritium inventory. Then, a technology survey is carried out to review potential existing solutions for the required process functions and to assess their maturity and risks. Finally, a decision-making scheme is applied to select the most promising candidates. ITER technology is exploited where possible. As a primary result, a fuel cycle architecture is suggested with an advanced tritium plant that avoids full isotope separation in the main loop and with a Direct Internal Recycling path in the vacuum systems to shorten cycle times. For core fuelling, classical inboard pellet injection technology is selected, in principle similar to that proposed for ITER but aiming for higher launch speeds to achieve deep fuelling of the DEMO plasma. Based on these findings, a tailored R&D programme is shaped that tackles the key questions until 2020.

1. Introduction

EU is currently working on a pre-conceptual design of a pulsed demonstration fusion power plant (DEMO) to implement the “Roadmap to the realisation of fusion energy” [1], which is currently being updated to reflect the results of the review of the ITER overall schedule and associated resources, and other recent developments in the worldwide fusion programme. This European roadmap sets out the strategy to achieve the goal of generating fusion electricity by 2050. DEMO adds three roles that cannot be addressed in ITER: first, it will demonstrate self-sufficiency by breeding its own tritium fuel in situ; second, it will utilise materials that are able to withstand radiation doses over periods of several years; third, DEMO will convert fusion energy into electricity and feed it into the grid. The latter aspect requires a potentially high availability and promising commercial attractiveness of DEMO in view of future fusion power plants. This marks another difference between DEMO and ITER: ITER is an experimental device which has been designed in such a way that a wide operational window is possible which allows for parametric variation of physics and technology parame-

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ters during experimental campaigns, whereas the design of DEMO routine operation will be focused on one single operational point and the operational window is only defined by an uncertainty and control stability frame around this operational point. However, this point will have to be identified to a significant extent by experiments. It is obvious that this fundamental difference asks for a new development approach beyond that taken for ITER.

The roadmap elaborates eight strategic missions to tackle the major challenges. The inner fuel cycle (together with its three sub-systems tritium processing (except tritium generation and extraction from the blankets), matter injection, and vacuum) is deeply involved in two of them. Mission 4 (Tritium self-sufficiency) addresses the tritium plant systems: DEMO will substantially benefit from the experience gained in the operation of the ITER fuel cycle system [2,3], but a development in the field of removal and processing of tritium from candidate breeder blanket systems in large scale will be needed to reduce the processing time, thereby improving system availability. Mission 6 (Integrated DEMO design and system development [4,5]) adds the fuelling and pumping systems. The need for a self-sufficient tritium fuel cycle and hour long scale plasma pulse durations requires systems with performance characteristics beyond those considered for ITER. The proper analysis of DEMO requirements, system modelling and design integration of the various systems that form the DEMO plant is key to the success of Mission 6.

Some assumptions have been made about the operation of the DEMO inner fuel cycle in order to undertake this work:

- DEMO will operate in a pulsed mode (according to the current EU reference configuration with a pulse length of 2 h) [6].
- Fuel injection is able to take a mixed deuterium-tritium input rather than separate isotopic feeds, negating the need for isotope separation for this purpose.
- The tritium plant will consist of as few systems as possible—to reduce cost and complexity and ensure reliability.
- Minimisation of tritium inventory is a prime requirement. This strongly prefers continuous technologies over batch processes, wherever possible and utilizes the idea of continuous Direct Internal Recycling (DIR) [7], which introduces shortcuts within the fuel cycle directly from exhaust to fuelling, thus, avoiding complete D-T separation of the fusion exhaust gas.
- There is a trade-off between the cost of re-use of plasma enhancement gas (PEG) and the cost of purchase in case the PEGs are dumped, together with increased loading on exhaust detritiation.

This paper is an overview paper with more detailed publications on the individual sub-systems to come. The paper will delineate in a staged systems engineering approach the content of a coherent R&D programme for the complete inner fuel cycle of DEMO, separately for the three sub-systems. Once the requirements are determined, functional needs will be derived that would fulfil the requirements. In a follow-up step, technologies are screened that have the potential to fulfil the required functions. In a last step, the technologies were then ranked against specific criteria to finally identify the ones which are 'best' suited, and also, to reveal existing gaps on the way to DEMO, considering already existing R&D for ITER. The outcome of these analyses will then be taken as the basis to define specific R&D actions for the DEMO inner fuel cycle development within the Work Package TFV (Tritium, Matter injection and Vacuum) of the EUROfusion Consortium.

2. Functional break-down of the inner fuel cycle

The fuel cycle on an abstract level is seen as a system that has to provide certain functions to fulfil certain user requirements. This is illustrated in Fig. 1 that highlights the chain and associated growth of details on the systems engineering path from top to bottom. It is important to note that in our approach functions follow requirements and technologies follow functions. Consequently, to start from an existing plant break-down structure and plant architecture, such as for ITER, and to íbendí it to fulfil a functional break-down structure for DEMO is in our understanding incorrect.

In the following, we address the functional break-down structure (FBS) of the sub-systems (see also [9,10]).

An integral function of the fuel cycle is to ensure safety by (i) confining radioactivity (to confine source terms, to confine and detritiate tritiated gases) and (ii) limiting exposure to ionizing radiation. Another integral function of the DEMO fuel cycle is to support economic attractiveness of the produced electric energy by (i) providing a sufficiently good RAMI performance (Reliability–Availability–Maintainability–Inspectability), (ii) providing a sufficiently short dwell time, and (iii) reducing capital expenditure (CapEx) and operational cost (OpEx). Furthermore, it is an integral function to protect investment of the DEMO machine, and to help to satisfy the stakeholder and DEMO user requirements by appropriate translation of these to what it means for the fuel cycle.

The function of the tritium plant is to (i) supply hydrogen isotopes to the machine, (ii) treat, store and supply tritium gas, (iii) to manage gas intake from the tritium extraction system of the breeding blankets, (iv) to provide purification (tritium recovery) of the breeding blanket coolants, and (v) to recover tritium from the exhaust detritiation system, maintenance activities and tritiated waste.

The function of the matter injection system is to ensure plasma burn operation by (i) enabling plasma density ramp-up and maintaining core density by matter injection, (ii) mitigating ELMs and disruptions, (iii) providing plasma enhancement gases (radiative seeding, metal wall confinement recovery), and to ensure plasma dwell operation by injection of support gases such as hydrogen or helium for glow discharge cleaning and wall conditioning.

Finally, the function of the pumping system is to ensure plasma burn operation by (i) helium ash exhaust, by (ii) pump-out of unburnt fuel at a rate and pressure so that divertor detachment can be sustained, and (iii) by maintaining the required vacua of the diagnostics, service and heating systems. Plasma dwell operation must be ensured by providing the necessary dwell pressure, and machine operation has to be supported in any other non-burn phase (wall conditioning, ultimate pump-down after interventions, etc.).

We have performed a functional analysis first, which is completely solution-neutral und un-biased by pre-conceived ideas, followed by a technology survey which is completely solution-specific. To have an unbiased approach in finding the 'best' technology, we developed a list of criteria which were then ranked by a procedure called pairwise comparison to weight the criteria for application to technology solutions candidates. This was also done to make sure that the R&D programme is strictly driven by needs of the DEMO plant design and not primarily by scientific challenges as such. In a final step to define the most efficient R&D programme, we added existing managerial and resource constraints.

2.1. Tritium functional architecture

To meet the FBS above, the tritium plant is given the following capabilities:

- An intake gas processing capability for vacuum pumping exhaust gas, the outputs of which are three separate streams comprising (i) a mixed purified tritium/deuterium stream for direct reinjection into the tokamak, (ii) a separate purified stream of mixed

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