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Technological and Engineering Challenges of Fusion

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Abstract

The current fusion development scenario in Europe assumes the sequential achievement of key milestones. Firstly, the qualification of the DEMO/reactor physics basis in ITER, secondly, the qualification of materials for in-vessel components in IFMIF and, thirdly, the qualification of components and processes in DEMO. Although this scenario is constrained by budgetary considerations, it assumes the resolution of many challenges in physics, technology and engineering.

In the first part of the paper, the technological and engineering challenges to be met in order to satisfy the current development scenario will be highlighted. These challenges will be met by an appropriate share of the work between ITER, IFMIF, DEMO and the necessary accompanying programme, which will have to include a number of dedicated facilities (e.g. for the development of H&CD systems).

In the second part of the paper, the consequences of a considerable acceleration of the fusion development programme will be discussed. Although most of the technological and engineering challenges identified above will have to be met within a shorter timescale, it is possible to limit the requirements and expectation for a first fusion power plant with respect to those adopted for the current fusion development scenario. However, it must be recognised that such a strategy will inevitably result in increased risk and a reduction in the economy of the plant.

1. The European Fusion Development Scenario

The current European fusion development scenario assumes that all information required to start construction of the first Fusion Power Plant (FPP) will be provided by a single step after ITER. The main device to be built during this step is called DEMO and it must be supported by an appropriate accompanying programme.

This so-called “fast track” scenario has been assessed in three key papers in Europe in 2000 [1], 2001 [2] and 2005 [3]. Despite the differences between them, there are some strikingly similar conclusions in terms of the timescale in which a commercial fusion reactor could be constructed and on how this programme could be accelerated. However, the analysis in each of these three papers has essentially been focused on physics, with consideration of technological issues essentially limited to materials and blanket.

Following completion of the European Power Plant Conceptual Study [4], the reference development scenario has been reassessed taking into account all the technological issues that need to be resolved prior to the construction of the first FPP.

1.1 Technological and Engineering Challenges

The technological and engineering challenges of fusion can be identified by an analysis of the gap in fusion technology between the present status and the status required by a Utility in order to consider investing in the construction and operation the first fusion power plant (FPP).

Fusion technology will be mature when the following overall objectives have been satisfied:

(i) Qualification of prototypes of all fusion-specific reactor-relevant systems. For the scenario shown in Fig. 1, it is assumed that the internal components will have operated successfully in DEMO up to a fluence of 50dpa before start of design and of 100dpa before licensing/start of operation. This assumption, together with the availability and neutron wall loading, determines the length of DEMO operations before the start of the first FPP construction.

(ii) Validation of the reactor architecture and qualification of the remote handling procedures for the complete replacement of the internal components (blanket and divertor).

(iii) Successful qualification in IFMIF of structural materials for the blanket and divertor.

To start of construction of an FPP, the following milestones have to be achieved:

(a) Qualification of materials in IFMIF, (120/150dpa (steel in FW) for blanket materials, 40/60dpa for divertor materials);

(b) Qualification of in-vessel components, including welding, brazing and hipping, in DEMO (at least 100dpa (steel in FW) for blanket and 40dpa for divertor);

(c) Qualification of tritium systems;

(d) Qualification of H&CD systems;

(e) Qualification of ex-vessel components and systems if and when required (e.g. high temperature superconductors (HTS), Balance of Plant (BoP) components (if the FPP is cooled with helium);

(f) Validation of the overall reactor architecture – in particular the segmentation of the internal components, and demonstration of remote handling procedures during a shutdown at the end of the first phase of DEMO operations.

Prior to the construction of a DEMO able to achieve the above objectives the following milestones have to be achieved:

(g) Demonstration of physics scenario for DEMO/Reactor (compatible with (h) below);

(h) Qualification of DEMO/Reactor relevant Plasma Facing Components made of tungsten;

(i) Validation of blanket functional performance (thermo-hydraulic, thermo-mechanical, TBR);

(j) Validation of divertor functional performance (thermo-hydraulic, thermo-mechanical);

(k) Qualification of materials, including welding, brazing and hipping (around 80dpa – steel in FW – for blanket materials, around 30dpa for divertor materials);

(l) Qualification of tritium technology;

(m) Demonstration of feasibility of H&CD systems able to satisfy the DEMO requirements in terms of efficiency, duty cycle and reliability;

(n) Demonstration of an accumulated body of experience in using Remote Handling systems in the maintenance of ITER (it is expected that this would be attained to a satisfactory level after completion of the ITER programme up to the end of the Phase1/Phase 2 shutdown);

(o) The successful completion of an 80dpa irradiation programme in IFMIF.

Apart from the obvious dependence on exploitation of the ITER operational programme, some of these milestones depend on focused parallel activities as part of an ITER accompanying programme.

Moreover, to guarantee the required DEMO availability, a suitable breeding blanket concept should be installed to ensure its tritium self-sufficiency. This includes the prior qualification of the technology necessary for tritium production, extraction and control, and the qualification of Plasma Facing Components (PFCs). Similarly, always to guarantee the required DEMO availability, a divertor concept and ad-hoc H&CD systems should be developed and qualified.

In addition to satisfying the above requirements, both DEMO and an FPP will have to satisfy a number of requirements in the areas of safety, public acceptance and economics. Some of these requirements are fundamental, e.g. the non-evacuation criteria following any accident driven by in-plant energies (DEMO and FPP) and the economic viability of the project (FPP). The discussion in this paper is however limited to technological and engineering issues.

The objective of IFMIF (International Fusion Materials Irradiation Facility) is the testing of fusion materials under reactor-relevant conditions to characterise their use in fusion power plants. The confirmation of structural materials data at 80dpa for DEMO is a key milestone to achieving this objective. For the reference scenario considered in this paper, the characterisation of materials at 120/150dpa is also required prior to the start of the FPP start of operation, and the achievement of this objective is another IFMIF key milestone.

The objectives of the two phases of ITER operation are defined in the ITER Technical Basis [5]. The first phase covers a decade and is aimed principally at confirmation of the physics objectives together with a limited amount of blanket module testing (in principle sufficient for the DEMO blanket design). The second phase is not yet fully developed, but is intended to have an emphasis on performance optimisation and reliable operation to produce high neutron flux and fluences, principally for blanket module testing.

At present, the confirmation of DEMO physics is envisaged within the second phase of ITER operation, but this confirmation is a critical link with the DEMO programme and the reference scenario considered in this paper differs in assuming that the bulk of the critical issues of DEMO physics will be confirmed during the first phase of ITER operation. A key part of the early programme in the second phase would then be to validate the DEMO physics in the presence of a tungsten first wall[1]. The qualification of all key systems required for DEMO should also take place during the second phase of ITER operation.

1.2 DEMO Availability

Among the requirements to be satisfied for their qualification, reactor-relevant systems will have had to operate reliably and in relevant conditions for a duration comparable with their expected lifetime. For a number of systems, in particular the internal components and the H&CD systems, this qualification can only be achieved in DEMO because of the neutron flux required. If we consider that the internal components must have operated successfully up to a

[1] Tungsten is presently the reference material for the DEMO and FPP first wall and divertor material.

fluence of 50dpa (steel of first wall) in order to start the design, then the time required for this qualification depends on the anticipated average availability and neutron wall loading. With a neutron wall loading of $2MW/m^2$, 8 years (resp. 6 years) are required to achieve approximately 50dpa[2] with an average availability of 33% (resp. 50%).

Individual systems need to operate with a much higher availability than the target DEMO availability. Assuming DEMO to be broken down into 10 independent key systems (namely two for H&CD, blanket, divertor, tritium systems – including purification and extraction, power supplies, power generation, vacuum, cryogenic, and balance of plant), an availability of 90% is required for each individual system to ensure an overall availability of around 33%[3].

1.3 Objectives for ITER Phase 2 Operations

The proposed fusion development scenario assumes that the confirmation of the bulk of the critical issues of DEMO physics is demonstrated during ITER Phase 1 operations. The scenario also identifies a number of technological objectives which need to be achieved during the second Phase of ITER operations to provide input which is critical to the DEMO programme. These objectives include:

(a) Validation of the breeder blanket technology in terms of thermo-hydraulic, thermo-mechanical and TBR properties, such that DEMO would be self-sufficient in tritium production[4] from its start of operations.
(b) Validation of divertor functional performance in terms of thermo-hydraulic and thermo-mechanical properties.
(c) Qualification of the required tritium technology.
(d) Qualification of the required technology for H&CD systems.
(e) Qualification of relevant PFCs: the only suitable first wall material for DEMO and an FPP identified to date is tungsten, and the reference scenario implicitly assumes that DEMO has a 100% tungsten first wall from Day 1 of operation. Therefore the DEMO physics scenario can only be considered fully validated in ITER by operation with a tungsten first wall.
(f) It will be imperative to operate DEMO safely and to control a number of parameters. To be FPP relevant this will have to be achieved with a limited number of very reliable diagnostic systems. These diagnostics should be identified and qualified during ITER Phase 2 operations.

Although many of the above objectives could be achieved in ITER, a number of facilities will be very useful, if not necessary, to ensure a timely start of DEMO without overloading the ITER programme. Others facilities would be useful to accelerate the overall fusion development programme or to reduce its development risk.

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[2] A flux of 14MeV neutrons of 4.5×10^{17}n/s·m^2 corresponds to a neutron wall load of $1MW/m^2$ and to 3×10^{-7}dpa/s (Fe) at the first wall. Therefore, a neutron fluence of 1MW/y·m^2 corresponds to 9.5dpa (Fe) at the first wall.

[3] If the individual systems availability is only 80%, then DEMO overall availability is reduced to 11% (0.9^{10} = 0.348, 0.8^{10} = 0.107).

[4] Approximately 350g of tritium per day is required to sustain 2,000MW of DT fusion reactions.

1.4 Fusion Development Scenario

The scenario developed based on the assumptions made in the previous sections is shown in Figure 1.

2. Alternative Scenario – Acceleration of the Fusion Development Programme

2.1 Reduction of Risks

The scenario outlined above depends on a number of objectives being achieved in a timely fashion. There are risks associated with achieving these objectives, some of which are technical and some non-technical. While some of the non-technical risks, e.g. programmatic decisions not being made on time, are difficult to mitigate, the technical risks can be assessed and supporting programmes of work implemented to reduce specific risks. The economic aspects of such activities must be considered as part of the overall risk mitigation strategy.

Amongst the specific facilities that could be considered, the following should be considered with particular attention: facilities for the development and qualification of H&CD systems and facilities for the development and qualification of DEMO and FPP-relevant remote maintenance procedures.

The advantages of constructing a specific facility for testing in-vessel components in relevant neutronics conditions should also be considered. The main difficulty is to conceive a facility with a suitable neutron fluence but which would be, overall, simpler and considerably cheaper than DEMO. In this case, the operation of this facility might replace, in toto or in part, the objectives of DEMO phase 1.

2.2 Acceleration of the Programme with an Early DEMO (EDEMO)

To accelerate the current reference programme and provide an opportunity for fusion to make an earlier contribution to the increasing global demand for environmentally friendly energy [6], a new paradigm is necessary [7]. This implies dropping the main condition underlying the reference scenario, i.e. where DEMO construction starts after the establishment of the DEMO/reactor physics basis at the end of ITER Phase 1.

Moreover, the objectives of the “reference” DEMO, namely steady-state, “high” availability and demonstration of economic acceptability, must be reduced.

EDEMO Objectives

Under a new paradigm, the “Early DEMO” (EDEMO) objectives could be reduced as follows:

- “Simpler” physics basis that what is currently assumed;
- Reduce some technological constraints, in particular the loads on the plasma facing components (divertor and FW) and the power required for H&CD.

Both of the above can be achieved by considering a pulsed rather than a steady-state machine.

EDEMO Pulsed Device

The reduced EDEMO objectives could be achieved by considering EDEMO as a large, pulsed tokamak device, conceived as a reactor. It should have a pulse length of at least 5 hours, (preferably 10 hours), and a dwell time of less than 15 minutes. Current ITER technology would be utilized as far as possible. The device would be water-cooled and, therefore, rather inefficient in terms of thermodynamics, and it would operate with a limited availability.

It remains to be confirmed whether the drawback of pulsed operation can be mitigated with pulses of adequate length. With a total number of pulses of around 20-30,000, there will be little or no problem associated with material creep, little or no problem associated with cyclic fatigue, and a thermal storage system could mitigate the problems associated with thermal cycling effects.

Design work on such a device could start almost immediately. The construction could be expected to start in 10 years and operations in 20 years. The benefits of such a device should be measured considering either a reduction in the development risk and/or a speeding up the overall schedule.

References

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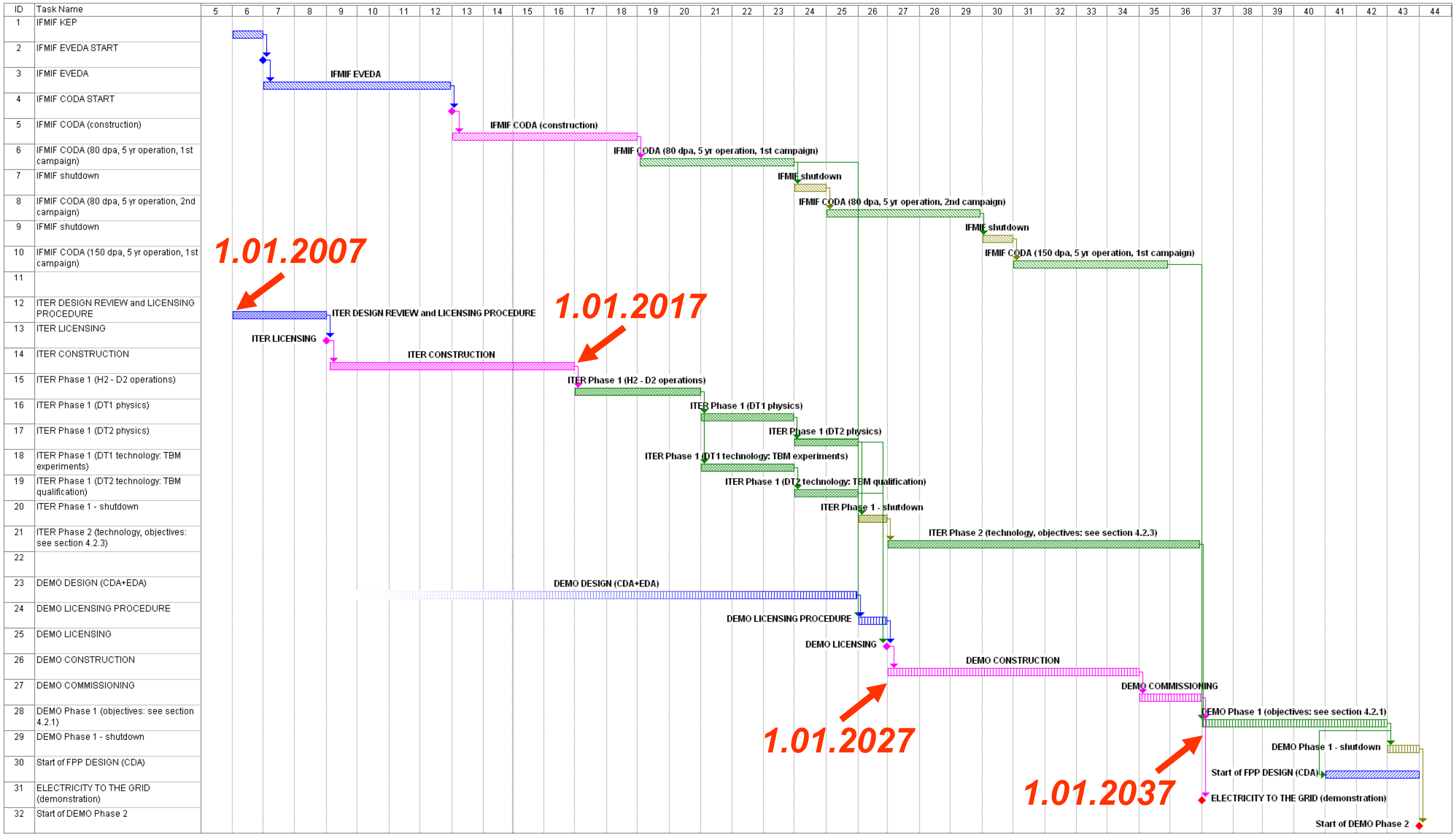

Figure 1 – "Reference" Fusion Development Scenario. The key assumption is that the DEMO construction starts only after the establishment of the DEMO physics basis during ITER Phase 1 operations.