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Overview of the design approach and prioritization of R&D activities towards an EU DEMO

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This paper describes the progress of the DEMO design and R&D activities in Europe. The focus is on a systems engineering and design integration approach, which is recognized to be essential from an early stage to identify and address the engineering and operational challenges, and the requirements for technology and physics R&D. We present some of the preliminary design choices/sensitivity studies to explore and narrow down the design space and identify/select attractive design points. We also discuss some of the initial results of work being executed in the EUROfusion Consortium by a geographically distributed project team involving many EU laboratories, universities, and industries in Europe.

1. Introduction

As an important part of the Roadmap to Fusion Electricity Horizon 2020, Europe is now conducting a conceptual design study on a DEMO plant which considers, for the initial design integration studies, a pulsed "low extrapolation" system based as far as possible on mature technologies and reliable regimes of operation (to be extrapolated from the ITER experience), and on the use of materials suitable for the expected level of neutron fluence. It is argued that delaying the design of DEMO in anticipation of the ultimate technical solutions in each subsystem would postpone the realization of fusion indefinitely. However, it is clear that, to realistically convert this outline concept into a reliable high performance facility, there is a need for significant technical and scientific innovation.

Key to the success of any technology development program is the early and continuous engagement of technology stakeholders to ensure that the work conducted is valuable to the eventual adopters of the technology. EUROfusion is currently engaging experts (e.g., industry, utilities, grids, safety, licensing, etc.) to establish realistic high level requirements for the DEMO plant to embark on a self-consistent conceptual design approach. This will ensure that their perspectives are captured in the initial identification of leading technologies, and the down-selection for the most promising design options.

DEMO in Europe is considered to be the last step before a commercial fusion power plant (see for example [1,2,3]) and capable of: (i) resolving all remaining physics and technical issues foreseen in the plant and demonstrating the necessary reactor relevant technologies; (ii) demonstrating production of several 100's MW of electricity; (iii) achieving T self-sufficiency, i.e. DEMO must make its own fuel; (iv) operating with adequate availability/reliability over a reasonable time span.

At present, the DEMO reactor design has not been formally selected and detailed operational requirements are not yet available. Where exactly DEMO should be located in between ITER and a fusion power plant depends on the resources, the gaps towards a commercial plant as well as the development risks that can be accepted, and the time scale to fusion deployment. The main differences between ITER and DEMO are discussed elsewhere [4].

This paper provides an overview of EU DEMO design and R&D activities.

2. EU DEMO concept design approach

2.1 Outstanding challenges and design drivers

ITER is the key facility in the EU strategy and the DEMO design/R&D is expected to benefit largely from the experience gained with the construction and operation of ITER. Nevertheless, there are still issues beyond ITER requiring a vigorous integrated design and technology R&D programme. Design integration is essential from an early stage to identify requirements for technology and physics R&D. A number of outstanding technology and physics integration issues must be resolved before a DEMO plant concept selection is made. Each of them has very strong interdependencies. They include the selection of: (i) the breeding blanket concept and, in particular, the selection of blanket coolant and the balance of plant (BoP); (ii) the divertor concept and its configuration; (iii) the first wall design and its mechanical and hydraulic integration to the blanket, taking into account that the first wall might see higher heat loads than assumed in previous studies; (iv) the heating and current drive (H&CD) mix; (v) the remote maintenance scheme and; (vi) a compatible plasma scenario.

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. 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. 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 on the assumptions that are made on the readiness of required advances in physics and technologies (e.g. the problem of the heat exhaust,

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choice of regime of operation, efficiency of non-inductive H&CD, etc.).

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. Two operating scenarios are being explored: a 'conservative' design (DEMO 1) that achieves improvements over existing designs (i.e., ITER) through moderate modifications, with a strong emphasis on maintaining proven design features (e.g., using near-ITER technology whenever possible) to minimize technological risks; and an 'advanced', higher-performance (but much less mature physics and technology assumptions), steady-state option (DEMO 2).

Establishing performance requirements and realistic projected cost estimates and development schedules are expected to be a strong driver in the selection of the technical features of the device. Safety also plays important role in the ultimate selection of plant design choices and operating conditions (e.g., choice of materials, coolants). Safety analyses must be constantly updated to match the evolution of the DEMO design.

The development of an advanced design which incorporates significant changes in comparison with existing practice would require more R&D, feasibility tests, very likely additional facilities to be built, and the willingness to take a higher risk. The impact on the overall plant reliability and availability of the various system design options must therefore be analysed in an integrated approach, with testing regimes developed accordingly. In other words, some gaps could remain between some first generation systems of DEMO and what is needed for a commercial fusion power plant. To bridge these potential gaps, DEMO must be capable of testing advanced technical solutions that will be developed in parallel for application in a fusion power plant, thus playing the role of a component test facility. For instance, the design and operation strategy now adopted for the breeding blanket, as recommended in [4], is to obtain licensing approval for operation up to moderate exposures for the 'starter' blanket, while high-dose engineering data for a more advanced materials blanket is being generated. In addition, the benefit of this 'progressive' approach would also include the possibility to start with a less optimized thermo-hydraulic or mechanical design (larger safety margin) to cope with large uncertainties in the overall reactor loadings and performances. Furthermore, it may be decided to extend the purely inductive pulse duration through additional auxiliary H&CD systems to be installed at a later stage. The benefit could be, for example, an extension of the service life of in-vessel components through a reduction of the number of thermal cycles – as a result of an increased pulse duration. Such capabilities have to be properly investigated early in the conceptual design phase of DEMO.

Tritium supply considerations are very important for defining the implementation timeline of a DEMO device, which must breed tritium from the very beginning and use significant amount of tritium (5-10 kg) for start-up. Tritium decays at a rate of 5.47 %/yr. Current realistic forecast of civilian tritium supplies available in the future points to very limited quantities of tritium available after ITER operation and in view of the limits above to start-up only one DEMO reactor this must operate and produce its own tritium around 2050 at the latest [5,6,7]. Increasing supplies of tritium, by either extending the life of Canadian and South Korean CANDU reactors beyond 2030 or building new tritium-producing facilities, is clearly a controversial topic that lies outside of the fusion community's strategical control. In addition, the construction of any intermediate fusion device with a net tritium consumption in any part of the world during the next two decades (e.g., Fusion Engineering Test Reactor - CFETR in China, or a burning plasma stellarator), will further limit the availability of the tritium supply.

2.2 DEMO physics basis

In comparison to the ITER (Q=10) design, the European DEMO design options have significantly higher fusion power and stored energy, higher normalized plasma pressure (i.e., operate close to global stability limits), and higher power radiated from the confined plasma region. Hence, aside from some simplifications of requirements (e.g., as DEMO will be designed for a much narrower range of operational regimes than an experimental device such as ITER), more challenging conditions in various fields will have to be faced. An EU assessment outlined five major 'DEMO physics issues' [8]. These are: (i) steady state operation; (ii) high density operation; (iii) heat exhaust; (iv) plasma disruptions; and (v) plasma control.

The DEMO design must be based as much as possible on the validated physics and technology basis of ITER, which should demonstrate robust burning plasma physics regimes, using a conventional divertor. The feasibility of breeding blanket technologies is also expected to be partially qualified in ITER. In order to clearly identify and resolve DEMO physics challenges beyond ITER, the physics basis of DEMO needs to be developed, especially in areas with issues concerning the feasibility or the performance of the device [9].

2.3 Design point studies and design drivers

System codes representing the full plant by capturing the interactions between (usually relatively simple) models of all the important plant subsystems are used to identify design points based on assumptions about plasma performance and technology. The systems code PROCESS [10] is being used to underpin EU DEMO design studies, and another code (SYCOMORE [11]), which treats some of the relevant aspects differently, is under development. Operating space and the consequences of choosing different target global parameters can be rapidly explored, as described in [9].

The system output is then analysed with state-of-the-art tools allowing a more detailed assessment of individual aspects in several areas (e.g., scenario modelling). In case of significant discrepancy with the system code results, the parameters or modules used in the system code are modified in order to obtain a better match with the more advanced calculations. This interaction is repeated until there is satisfaction with the realism of the design point, which can then be circulated as a ‘stable release’ for wider evaluation of both physics and engineering aspects.

Among technological constraints that strongly impact the design, there are the allowable surface heat loads in the divertor and on the first wall, and the neutron load limits on the first wall and the structural materials of blanket and divertor. Some preliminary physics and engineering parameters are shown in Figure 1, while design features now incorporated in the initial conceptual design work are listed in Table 1. Open design choices where a decision is expected to be made by the end of the concept design work are shown in Table 2.

The machine size (major radius) is driven by various aspects. Among these are the quality of confinement, the edge safety factor, and the aspect ratio. Recently it has been found that the combination of the requirements to protect the divertor and to operate sufficiently above the L-H-threshold affect the machine size [12].

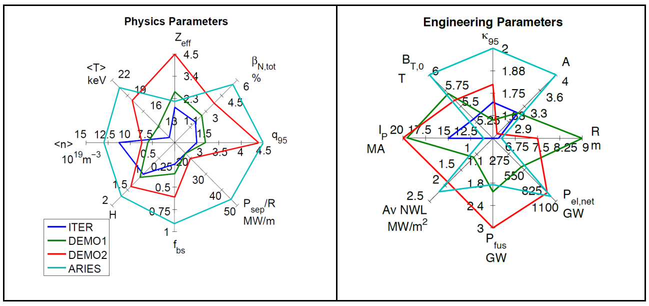


Fig. 1 Physics (left) and engineering (right) parameters of an inductive and steady-state DEMO design option [12]

Table 1 Preliminary design features (EU DEMO 2015):

– 2000 MW_{th} ~ 500 MW_e
– Pulses > 2 hrs
– Single-null water cooled divertor; PFC armour: W
– LTSC magnets: Nb_3Sn
– RAFM (EUROFER) as blanket structure
– Vacuum Vessel made of AISI 316
– Maintenance: Blanket vertical RH / divertor cassettes

Table 2 Open design choices where a selection is expected to be made by the end of the concept design work

– Operating scenario
– Breeding blanket design concept
– Protection strategy first wall (e.g., limiters)
– Advanced divertor configurations and/or technologies
– Energy conversion system
– Specific safety features, e.g., # of PHTS cooling loops
– Diagnostics and control systems

Figure 2 shows the dependence of R on $f_{LH}=P_{sep}/P_{LH;scal}$ ($P_{LH;scal}$ given in Ref. [13]) and P_{sep}/R from a calculation with PROCESS minimizing the major radius at fixed $P_{el;net}$ = 500 MW, and τ_{burn} = 2 h. For each value of P_{sep}/R, f_{LH} has a minimum value corresponding to the highest achievable value of the magnetic field at the inner TF coil leg. To achieve sufficient confinement quality and controllability of the plasma it might be necessary to control f_{LH} towards a higher value, which would lead to a significant increase of R. Also, if the real H-mode threshold were higher than the scaled one, this would result in a corresponding increase in f_{LH}. Hence the significant uncertainty in the H-mode threshold [13] is associated with a significant uncertainty in the major radius of DEMO.

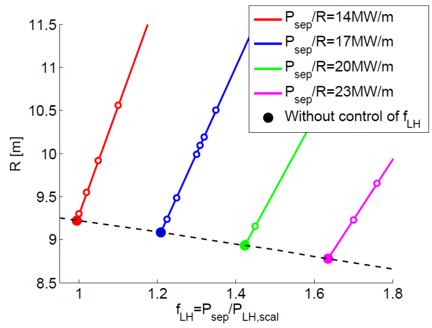


Fig. 2 Dependence of the major radius on f_{LH} and P_{sep}/R from PROCESS calculations

2.4 System code uncertainty and sensitivity studies

The input parameters and also the relations used in system code calculations are subject to important uncertainties. Various sensitivity studies were carried out around initial reference design options to identify the key limiting parameters, to explore the robustness of the reference design to key assumptions, to analyse the impact of uncertainties, and to analyse the trends and improve early design concept optimization. Figure 3 shows the range in effect of a ±10% variation in input parameters on the output performance parameters $P_{el,net}$ and τ_{burn}. The highest relative impact is caused by a variation in the elongation of the device, which is limited by vertical stability considerations [14].

Fig. 3 Range of a ±10% variation in input parameters on the output performance parameters $P_{el,net}$ (yellow) and τ_{burn} (blue)

3. Systems Engineering Framework

3.1 Introduction

A project as large and complex as DEMO certainly warrants a Systems Engineering (SE) approach, especially given the multitudinous number of interdependencies it contains. There are particular reasons however, why Systems Engineering is particularly important given some of the unique characteristics of the DEMO programme, and why a model based system or “framework” is likely the best way of achieving this.

a. Building a framework that accommodates variants, identifies a reference design and facilitates optioneering and decision making simultaneously

The DEMO programme has to do two difficult things at the same time. 1) It has to produce a coherent concept that is fully substantiated and resilient to scrutiny, whilst at the same time 2) accommodate the fact that it exists in an environment where innovation and subsequent technological advancement are progressing continuously. The second point is underlined by the significant time duration between conceptual studies and the completion of detailed design, which might be 15-20 years or more.

A Systems Engineering Framework can accommodate these themes with suitable definition of data and relationships between data points. In a practical sense, DEMO can be thought of as comprising of a Plant Architecture Model (PAM) and a set of System Level Solutions (SLSs). The PAM is essentially the top level design of DEMO, setting out the main machine parameters, their justification, the main architectural features and the reasoning behind their inclusion and then the supporting systems in the form of high level block diagrams with identified performance requirements. The SLSs are then design solutions that respond to the needs of the PAM via a functional structure developed in the SE Framework. The PAM satisfies 1) whilst the SLSs are identified from best available technologies and in this area, variants can co-exist and to some degree be evergreen in alignment with 2). At any particular time it is beneficial to state a reference technology, but this can easily change as refinement of the PAM will lead to changes in the basis of the reference selection, and another variant becoming more favourable. By capturing these relationships in a SE Framework, the relationships between the PAM and associated SLSs can be maintained.

b.Create something useful for the future

One of the most important outcomes of this phase of the DEMO programme must be that it creates something that can be built upon in the next phase. It is essential therefore that we do not just simply record the design output of this phase, but record the thinking behind the design output in addition to purely technical deliverables. Without this context, a future team will take the output at face value and be unable to rationalize the context in which it was derived. Elements of the design will appear over complicated and even unnecessary unless there is traceability. A future team could well conclude the PAM to be unfit for purpose and start again. A SE framework will inherently provide the traceability and justification to preserve the intent and subsequent concept the present team are striving to produce.

3.2 Principle missions, High Level Requirements, and stakeholder engagement

A sequence of activities has been completed with a view to defining a clear mandate and set of principle missions for the current DEMO programme. Before embarking on a stakeholder engagement process, it was felt that the DEMO team could learn from fission development programmes. A number of meetings were conducted and the subsequent lessons are presented in Sect. 3.2. This provided a context for the formation of a Stakeholder Group of individuals. The group was presented with a preliminary set of High Level Requirements for rationalization and prioritization. A Stakeholder Group report has been produced but cannot be distributed. This can be summarized as dictating the principle missions for the current DEMO programme as being: (i) safety and environmental sustainability; (ii) plant performance; and (iii) assessment of economic viability.

3.2 Main differences to Fission and lessons learned from Gen-IV

The following lessons learned are distilled from in-depth discussions with advanced Gen-IV Fission projects ASTRID and MYRRHA. We are very grateful for the advice and observations they have made.

- Fission projects follow a pattern of evolution in each successive plant design, with careful progression in key areas backed up by some operational data. ASTRID has drawn from Superphenix and the Phenix machine before that. MYRRHA has matured from extensive test bed development and operation of the MEGAPIE experiments.
- In both cases clear leadership and design authority of the project is in the hands of persons with good technical and managerial skills.
- Both projects stressed that the plant design should drive R&D and not the other way round.
- It is important to not avoid the fact that fusion is a nuclear technology and as such, will be assessed with full nuclear scrutiny by the regulator. The political downplay of the nuclear element of fusion should not enter the way the project is conducted, reviewed and licensed. To this end, early engagement with a licensing consultant is needed to understand and tackle potential safety implications through design amelioration.
- Both projects underlined the need for a traceable design process with a rigorous Systems Engineering approach. Decisions must be rigorously recorded in order to defend a decision path taken that was correct at the time, but in years to come, may seem wrong. Design choices should be made within a traceable context of functions and requirements so that future lurches from one decision path to another are not made without full understanding of the requirements originally assigned and the potential implications.
- The design of a plant aiming at production of electricity should be the main objective of the DEMO concept design work and supporting R&D – rather than aiming too high and promising something unachievable.
- Both projects emphasised that the technical solution should be based on maintaining proven design features (e.g., using mostly near-ITER technology) to minimize technological risks, but both highlighted the need to take risks when the reward is significant and there is a back-up plan.
- Reliability and maintainability should be key drivers: allow for design margin (overdesign) where

technology limits and budget will allow, since this will increase machine longevity, reliability and capability, when considering enhancements.

- The project should move from a scientific culture to a more project focused culture. It was acknowledged that this is not easily done, but this cultural shift should begin to happen over the course of the pre-concept phase.

3.3 Systems Engineering approach for dealing with uncertainties

A big challenge in the development of a DEMO concept is the combination of many design interdependencies and the inherent uncertainties. The combined effect is that uncertainty propagates through the design, often leading to de-harmonised boundary conditions between sub-systems being studied individually. From a practical perspective, a way forward is to determine some assumptions that allow conceptualizing to proceed, whilst at least being rooted in some sound logic that fits with the philosophy of the conceptual approach. Methods for tackling the challenges that uncertainties pose consist of:

- Tracking assumptions used in the design, their justifications, and where they are used so that at any future time, the basis for concepts derived from these assumptions can be retrieved. As assumptions mature to defined and reasoned values, the cascade of effects this development has on the overall design can be quickly and accurately identified.

- Understanding the relative impact uncertainty around different design points has on the physics design. Eliminating uncertainty is resource heavy and so it is important to work on the high impact uncertainties. By varying input parameters, the effect on key performance metrics can be ascertained.

- Understanding the wider risk uncertainty poses. This extends the sensitivity studies previously described to include other facets of the design such as the safety or maintainability impact, further discussed in section 4.1.

- Tracking uncertainty margins through the design. In order to compensate for uncertainty, margins are often applied to parameter values which if not monitored, can combine to form large multipliers in the boundary conditions of sub-systems.

Further discussion on treating uncertainties is covered in [15].

4. Current main design trade-off studies

A number of studies that have strong implications on machine parameter selection and architectural layout have been initiated. They include:

- Aspect ratio scan
- Investigation of the impact of increasing plasma elongation, k, constrained by vertical stability, through optimising for example PF coils layouts and current distributions.
- Investigation of divertor configurations with a lower X-point height and larger flux expansion.
- Assessment of first wall power handling design limits near the upper secondary null point and assessment of the technology and maintainability requirements of the solutions proposed.
- Investigation of the potential of a double null (DN) configuration: advantages (e.g., higher plasma performance with improved vertical position control, and an accompanying reduced machine size) and disadvantages (e.g., T-breeding, compatibility with proposed blanket vertical maintenance scheme, integration of upper divertor, etc.).
- Investigation of divertor strike point sweeping, including technology issues such as thermal fatigue of the high-heat-flux components, AC losses of the adjacent PF coils, etc.
- Optimise blanket shielding design to minimise vacuum vessel activation [16].
- Investigation of magnetic field ripple: trade-off between RM access, coil size, and NBI access.
- Estimation of the minimum achievable dwell time and evaluate impact of trade-offs on central solenoid design, BoP, pumping, etc.

Due to limitations of space, only a limited number of topics are covered in depth here.

4.1 Results of selected studies

a. Overview of aspect ratio study

The aspect ratio (A=R/a) was identified as one of the most important parameters which was still relatively unconstrained. Studies were carried out in 2014 in various areas to understand the advantages and disadvantages of aspect ratio variations between 2.6 - 4 on the pulsed DEMO design (see Fig. 4). Lower aspect ratio designs implying a larger plasma volume and lower toroidal field have a higher TBR, better vertical stability properties, lower forces on in-vessel components during fast disruption events and more favourable properties in the case of fast TF coil discharges. Larger aspect ratio designs have the advantage that the gap between vessel and outer leg of the TF coil can be dimensioned smaller to achieve the same value of toroidal field ripple. The majority of data from tokamaks is available around an aspect ratio of 3.

Although in depth assessments of some aspects (e.g. cost, maintainability, availability) still need to be carried out, the DEMO aspect ratio was changed from 4 to 3.1 in recognition of a favourable trend towards lower values of A. Investigating multiple design points in the pre-conceptual design phase is vital; more information relating to the choice of DEMO aspect ratio will be collated and may result in a further modification of the baseline design.

	ITER Q=10	DEMO1 A=2.6	DEMO1 A=3.1	DEMO2
R [m]	6.2	9.5	9.1	7.5
S [m^2]	683	1895	1428	1253
V [m^3]	831	4174	2502	2217
P_{fus} [MW]	500	2074	2037	3255
τ_{burn} [h]	0.1	2	2	inf
I_P [MA]	15	24	20	22
B_T [T]	5.3	3.8	5.7	5.6
$\beta_{N,tot}$ [%]	1.8	2.9	2.6	3.8
T_{e0} [keV]	11.5	26.8	27.4	34.7
n_{e0} [10^{19} m^{-3}]	12.5	8.2	10.1	12.2
$P_{rad,core}$ [MW]	47	318	331	694
P_{CD} [MW]	70	50	50	133
q_{NW} [MW/m^2]	0.5	0.8	1.1	1.9

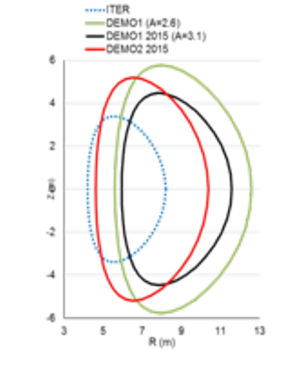


Fig. 4 Key design parameters for pulsed and steady-state design options in comparison to the ITER (Q=10) design point

b. TBR sensitivity analysis

In order to achieve tritium self-sufficiency, the required TBR to be achieved was defined for DEMO as 1.1, in order to compensate for uncertainties, the loss of breeding area due to the integration of auxiliary systems, and tritium losses in the fuel cycle [17]. The total TBR depends on two factors: the fraction of the plasma surface covered by the breeding blanket and the local breeding ratio. The latter is the number of (D, T) source neutrons impinging on the FW panel compared to the number of neutrons hitting the FW panel. This is design-dependent and the current state of the breeding blanket design was considered here. Reasonable modifications of the blanket design and technology have been studied regarding the TBR and the impact was found to be moderate, typically less than a few percent [18]. The fraction of the plasma covered by the breeding blanket plays a more important role, since in DEMO it is the only IVC that breeds tritium. No breeding units are currently incorporated in the DEMO divertor to allow for a simpler design and integration.

A systematic approach was adopted in the DEMO development to determine suitable breeding blanket configurations. In Figure 5 the potential of different poloidal sections is shown to contribute to the total TBR.

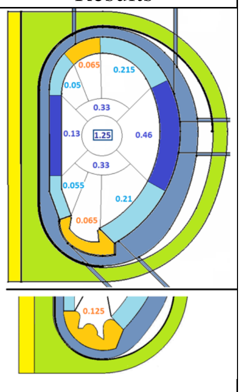
	Options investigated	TBR	Results
1	Full blanket coverage (no divertor)	1.25	
2	Small divertor – single null configuration	1.19	
3	Large ITER-like divertor – SN configuration	1.13	
4	2 small divertors – DN configuration	1.12	

Fig. 5 Predicted potential TBR achieved by the breeding blanket for different IVC configurations.

About 85% of the plasma surface must be covered by the breeding blanket. The result highlights the significant penalty of the earlier DEMO IVC configuration including a large ITER-like divertor. In the recently issued baseline configuration, the divertor size was consequently reduced and the breeding blanket area was increased accordingly, generating a significant gain in TBR of 0.06 – about half of the breeding potential previously lost by implementing an ITER-like divertor. This finding points to the possibility to adopt a double-null configuration with two divertor cassettes, at least from a breeding point of view, see Figure 5 [19].

a. Optimisation of divertor geometry

Investigations of divertor configurations with a lower X-point height and larger flux expansion have been initiated, as they may provide a more favourable compromise between breeding coverage, pumping and power exhaust for DEMO than the vertical target divertor chosen for ITER. Estimates of the required target poloidal length for DEMO should take intoaccount a conservative prediction of the power flux distribution and an estimation of the worst case controllable plasma strike-point displacement. For the divertor footprint, an extrapolation of the present experiment database for attached regimes [20] to DEMO with a peak power flux density of ~20 MW/m^2 has been used. The predicted footprint is of 10 cm for the outer target strike point in the poloidal direction. Giving the uncertainties of the heat flux footprint extrapolation in regimes of interest for DEMO, a safety margin of a factor 2 is considered, allowing a total length required for the density heat flux footprint equal to 20 cm in total (±10 cm respectively for the upward and downward direction).

A preliminary and conservative assessment was done to estimate the loss of plasma vertical position arising from destabilizing events, which a preliminary designed control system can stabilize. The disturbances considered are the predicted plasma internal profile changes, scaled from ITER, i.e. $\Delta_{BetaPOL}$ and Δ_{Li}, to represent ELMs, H-L transitions, mini disruptions and VDE events. The maximum vertical displacement would induce an upward vertical displacement of ~35 cm [16], mainly located in the top part of the plasma boundary, while the movement of the vertical strike point position is limited to a maximum displacement of ~ 10 cm. An allowance of ±25 cm around the strike point position, in both upwards and downwards directions, for a total amount of 50 cm is judged to be reasonably conservative. A total target length of 70 cm is considered (for both inner and outer target plates), which includes the 20 cm space for the heat flux density footprint and the 50 cm allowance for strike point vertical movement in case of the considered destabilizing events.

A 2D field-line tracing study has been performed on the divertor targets and on the interface region between the divertor and the breeding blanket, to optimise the target and adjacent breeding blanket shape and inclination angle (Figure 6a).

The angle between the field lines and the target also needs to be optimised. Several aspects need to be considered here: (i) in favour of minimising the power flux density on the target due to thermal charged particles, the toroidal incidence angle of the field line on a horizontal plane should be minimised up to a limit of about 3° [21]; (ii) as indicated above, the angle has to be chosen in a way that the strike points do not move outside the high heat flux region during a worst case controlled plasma displacement; (iii) if possible the radiation heat load on the divertor targets should be minimised.

An analysis has been started on the consequences of shortening the distance from the X-point to the strike point (Figure 6b), which may contribute to further increasing the breeding area. Several aspects are being considered, such as the beneficial increase of the total flux expansion, with a short distance, which helps to spread the heat power on a larger area. This benefit is limited by the minimum achievable toroidal incidence angle of the field line. Due to their non-linear relation, a reduction of the distance between X-point and strike point from ~1.3 m to ~0.9 m would result in a ~5% reduction in the connection length, with the consequent increase in $T_{e,tar}$ being limited. The disadvantages of the short distance in terms of heat load due to radiation, although reasonable, are not so clear yet, due to the lack of experience in DEMO relevant scenarios in the present experimental machines. Other aspects like the impact on the PF system need to be investigated.

The divertor dome is another aspect of divertor designs that is now under investigation for DEMO. Potential disadvantages of an ITER-like dome are related to the power flux density on the dome surface (mainly due to radiation) and the possibility that the strike points are positioned on the dome during plasma displacements (e.g. during downward VDEs).

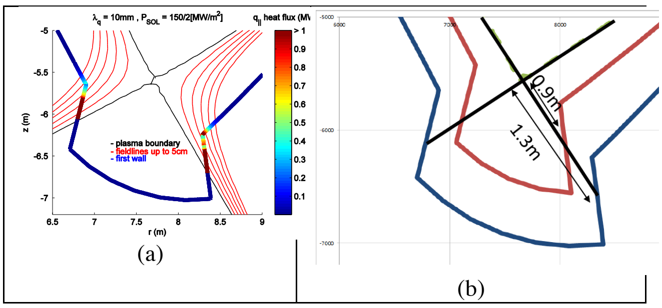


Fig. 6 (a) Example of 2D field-line tracing for the EU DEMO1 2015 baseline design, with the hypothesis of no radiation and P_{SOL} of 150 MW shared between upward and downward direction, and a λ_q~10 mm, to represent far-SOL phenomena; (b) Range of DEMO divertor geometry being analyzed with strike to X-point distance from 0.9 m to 1.3 m.

b. FW protection and architectural implications

The issues and strategies for DEMO in-vessel component integration is described in Ref. [16]. The loads on the FW in DEMO remain poorly characterised [22]. In particular, near the secondary null at the top of the machine, the presently predicted loads exceed the technological capabilities of integrated water and helium cooled FWs. If these loads cannot be sufficiently mitigated in the baseline configuration, they may entail radically different plant architectures – with wide-ranging implications.

Alternative configurations are currently being developed in parallel to the baseline to mitigate the risk of the inadequacy of the baseline; these are: a single null (SN) tokamak with dedicated high heat flux FW panels hydraulically and mechanically de-coupled from the blanket, and a double-null (DN) tokamak [15]. These alternatives present significant integration challenges, negatively affect the TBR (Figure 5), and are likely to have negative consequences for the maintainability and availability, and overall efficiency of the plant.

c. Divertor strike-point sweeping

A parametric study was conducted to evaluate the reduction of divertor target heat flux arising from divertor strike-point sweeping for a set of sweeping frequencies and amplitudes at different levels of incident power heat flux [23]. The results have shown a considerable reduction of the heat flux to the coolant, up to a factor ~4, for 1 Hz and 20 cm sweeping case, for an incident heat flux in the range 15-20 MW/m^2. This allows a larger margin to the onset of the critical heat flux, representing the maximum heat removal capability above which the pipe burns out, resulting in the destruction of the target.

An assessment was carried out on the installed power needed for the sweeping cases considered. For this calculation, two sweeping copper coils were preliminarily considered. These are located 80 cm behind the divertor, to allow the possibility to provide sufficient neutron shielding, and remote maintenance. An alternative solution could be represented by the use of saddle coils in each toroidal sector, integrated in the divertor cassette, and replaceable with the time scale of the DEMO divertor. The results indicated a required active power of up to 3.3 MW, and reactive power up to 16 MVAr, for the 1 Hz/20 cm sweeping. The additional AC losses induced in the closest superconductors as a result of the sweeping were also preliminarily analysed, finding an increase of temperature of 0.1 K, which is comparable with the AC losses due to the DEMO scenario, which are of the order of 0.3 K. Finally, a thermal fatigue analysis on the pipe interlayer has confirmed a reasonable lifetime for the divertor by using the sweeping as a temporary method, i.e. to quickly react to a possible increase of heat flux density above the nominal values, or continuously, provided the frequency is raised to 4 Hz [24].

5. Highlights of Selected R&D

The arrangement of the DEMO conceptual design work in EUROfusion is rather unconventional and different from what is done in other projects. The plant design and physics integration are coordinated centrally whereas the design and R&D of individual systems is executed in geographically-distributed work packages (WPs) – projects in their own rights. The necessary horizontal integration between various WPs is insured by the project leaders and the central team. Below, a brief summary of activities conducted in the distributed WPs is provided listing the projects in alphabetical order.

5.1 Breeding Blanket (WPBB)

Four design options have been progressed utilising He, water, and LiPb as coolants and a solid or LiPb breeder/multiplier [25]. The main design drivers include T self-sufficiency (including all penetrations) [26], thermo-hydraulic efficiency and structural feasibility to withstand the most severe loading conditions due to accidental conditions and disruptions. The power handling requirements of the FW are still subject to large uncertainties, complicating the thermo-hydraulic integration in the primary heat transfer system (PHTS). Work is underway to develop a DEMO wall load specification which will provide poloidally resolved estimates of a wide range of static and transient loads. For the FW design, three architectural options have been proposed: a thermo-hydraulically and mechanically integrated option, a thermo-hydraulically decoupled one, and an option enabling the replacement of selected sections of the FW. The adoption of these different options will depend on the loads acting locally on the FW surface [15,27].

The design of the four blanket concepts was progressed in 2015 focussing on the structural integrity of the breeding modules during the in-box loss of coolant event. In this event the breeding module, which contains either LiPb or a purge gas at low pressure, is internally pressurized to the (high) coolant pressure. The effect of EM loads on the blanket segment structures is under evaluation in all concepts and their potential to achieve the required TBR was shown [26]. In the helium-cooled solid breeder concept, an optimization of the breeding module design was undertaken reducing the size of the internal manifold and increasing the space available for the breeding zone. In the helium-cooled liquid breeder concept, thermo-hydraulic and structural analyses were performed to consolidate the design based on “tie rods”. In particular the behavior of the box in case of an in-box LOCA was assessed according to RCC-MRx. In the water-cooled liquid breeder concept, several options were investigated to improve the design of the blanket manifold to enhance nuclear shielding and thermo-hydraulic performance. In the design of the dual coolant liquid metal concept (DCLL), significant progress was made recently developing an initial design concept with LiPb being operated below 550°C [28]. The DCLL concept is – as the other concepts – based on a multi-module segment (MMS) design, with eight different modules attached to a common back supporting structure. This structure integrates the segment manifold and has supporting, feeding, and nuclear shielding functions. Each DCLL blanket segment implements a poloidal circulation of PbLi in order to extract the power generated in the breeder zone and the FW including He channels for cooling purposes. The breeder zone consists of four parallel PbLi channels, separated by a stiffening grid. These channels include electrically insulating flow channel inserts consisting of a EUROFER-alumina-EUROFER sandwich, in order to prevent large magneto-hydrodynamic (MHD) pressure drops. Thanks to the MMS design, the PbLi velocity has been considerably reduced inside the modules (2-3 cm/s) resulting in relatively low MHD pressure losses (about 2.5 bar according to a preliminary assessment).

The design of the auxiliary system used for the T extraction from the blankets has also progressed. The preliminary P&ID of Pb-16Li loops (for HCLL, WCLL, and DCLL) were carried out together with the selection of the main components. The design of the PbLi loop has to take into account several interdependent aspects, such as: corrosion of structural materials, development of permeation and corrosion coating, design of the purification and chemistry control systems, evaluation of helium generated in the BB, design of the expansion tank, evaluation of pressure drop due to MHD effects and impact of MHD effects on corrosion rate, selection of pumping system, etc. The computation of 3D MHD effects with thermal coupling, as well as tritium transport, have been performed for different benchmark problems that consider fully developed MHD flows in rectangular channels with various electrical boundary conditions. The developed codes are under validation by means of MHD experiments at low and high velocity in the MEKKA laboratory at KIT. The different tritium extraction/removal technologies have been assessed: cryogenic trapping and permeation against vacuum have been preselected as baseline methods for solid and liquid blankets respectively, whereas membrane/membrane reactors and vacuum-sieved trays have been kept as back-up solutions for further consideration. This choice was largely motivated by the technology readiness levels (TRLs) of the different processes that might evolve during the R&D phase [29].

5.2 Balance of Plant (WPBOP)

The primary objectives of this project are to develop a feasible and integrated conceptual design for the PHTS and BoP systems that meet the overall DEMO plant requirements and the system requirements for the in-vessel components, interfacing with the BoP. The conceptual design shall be substantiated for a plant-level conceptual design review, by activities such as modelling, engineering, cost, RAMI and safety analyses.

Classification (e.g. seismic, safety, QA) of the BoP systems and components is foreseen together with the definition of associated design rules. The PHTS and BoP are being modelled, taking into account both helium and water as primary coolants, in order to investigate the dynamic behaviour of the plant. In particular, attention is being paid to the impact of pulsed operation that may lead to unacceptable fatigue stress on essential components. The BoP may require stable thermal operating conditions throughout the plasma operational phases (pulse and dwell) and this, in turn, would invoke the need for an energy storage system (ESS). Preliminary sizing of the main components to meet the system requirements is being done with the direct involvement of industry. A technology assessment is necessary to establish the TRL of identified components to identify feasibility and performance risks of the various options. A specific task is devoted to the preliminary design of the layout, including the ESS, for both helium and water as primary coolants, to investigate space and cost requirements. Finally, design, manufacture, and testing of prototype Li-Pb heat exchanger components will support the evaluation of a DCLL breeding blanket technology.

5.3 Diagnostics and Control (WPDC)

The main objective of the diagnostics and control project is to develop a conceptual design of a control system that ensures machine operation in compliance with nuclear safety requirements, avoids machine damage, and achieves high plant availability and an optimized fusion performance. Essential quantities to be measured and controlled are: plasma current, position and shape, plasma density, plasma pressure, fusion power, plasma radiation, local wall loads and wall temperatures, and finally plasma instabilities (MHD). Practically all of these control quantities are closely related to operational limits which should not be exceeded due to the risk of machine damage. A low disruption rate (key to achieving high plant availability) can only be obtained if the operational point is chosen with sufficient margins against any of the operational limits. These margins have, however, to be properly balanced with the associated reduction in overall fusion performance [30].

Design work has started in 2015 to develop a control system concept with high availability over extended periods of operation, relying on an enhanced long-term stability of individual diagnostic systems and actuators, as well as on a reasonable level of redundancy in terms of numbers of methods and channels. In addition, plasma modelling and integrated data analysis together with in-situ calibration and consistency checking methods have to be developed and incorporated into the DEMO control system. Some of the issues to be solved for DEMO diagnostic and control overlap with problems being addressed on ITER. 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.

5.4 Divertor (WPDIV)

In the divertor project, engineering work focusses on: (i) the design of the divertor cassette body, considering a number of variant layouts; and (ii) the development of a number of candidate target concepts including fabrication trials and high-heat flux tests. Currently, seven different divertor target concepts are being developed for water-cooled plasma-facing targets and one for helium-cooling. The target concepts are mostly based on tungsten monoblock type designs. The eight concepts differ from the choice of their heat sink (structural) or interlayer materials. In addition, novel concepts have been devised, including composites tube (W wire-reinforced Cu composite, W/Cu and W/V laminate), thermal break interlayer (Cu felt), functionally graded interlayer (W/Cu), and Cr monoblock with flat W tiles [31]. The crucial design requirements for the target are to ensure sufficient margins to slow thermal transient events, and to accommodate the relatively high neutron irradiation dose expected for a DEMO divertor. Progress on the ongoing physics work including investigation of innovative divertors is described elsewhere (see. [32]).

5.5 Heating and Current Drive (WPHCD)

Feasible technology options for neutral beams, ECH and ICH systems for DEMO are being explored. System efficiencies and potential launch positions for these technologies have been investigated, together with the impact arising from integrating these systems in the plant. The status of design integration of H&CD Systems is described elsewhere (see for example [33] and references therein). The work focuses on: (i) the system engineering aspects of each method (definition of the various loads and RAMI); (ii) the development of the systems compatible with operation of DEMO (sources, transmission system and antennas) and the assessment of their impact on DEMO requirements (in particular, tritium self-sufficiency); and (iii) the development of advanced technologies to match the constraints of a DEMO machine producing net electricity (increase of system efficiency in view of minimizing the recirculating power).

For ECW, the main R&D activities encompass the development of a high frequency gyrotron at high power and a high efficiency, and a multi frequency gyrotron. For IC, the concept of a distributed antenna is being investigated. For NBI, R&D is concentrated on non-caesiated negative ion sources, and the development of photo-neutralization as a means to improve the NBI efficiency. All the R&D will make use of the experience gained by ITER.

5.6 Magnets (WPMAG)

The magnets project has been considering basic coil and winding pack layouts, fabrication methods, and possibilities for using high temperature superconductors [34].Most of the work to date has concentrated on the design of the TF conductors and coils. Three options for the TF winding pack were proposed, encompassing a broad technological domain – ranging from ITER-like concepts to more technologically distant ones. The three options all use cable-in-conduit conductors, but with aspect ratios ranging from one to three, react & wind or wind & react approaches, and central or asymmetric cooling channels. The winding approach between concepts also differs, with layer and pancake approaches being considered, although issues relating to electrical and hydraulic connections are still to be assessed. Two full-size TF conductor samples were fabricated, building on the ITER experience, and will be tested in the EDIPO facility at EPFL/PSI in 2015 [35]. Similarly, samples of high-temperature superconductor were fabricated and tested, and associated studies were conducted to model their behaviour.

Thermo-hydraulic and mechanical analyses carried out on the three designs indicated that all options show deviations from usual magnet design criteria within the allocated space, which are more or less numerous and pronounced depending on the concept. This outcome constitutes useful feedback to be taken into account for the future overall DEMO reactor baseline updates, which will need to allocate more space to the TF coil to host additional material (stainless steel, copper, superconductor). Generic studies on the cryoplant and quench protection systems were also carried out.

5.7 Materials (WPMAT)

Work has continued to consolidate a materials database and material processing trials have been performed to improve the performance of key structural material candidates for use in-vessel [36]. A major part of the Advanced Steels program is dedicated to the extension or shift of the operating temperature window of EUROFER-type steels [37]. Studies on EUROFER97-2 plates have shown that the upper temperature limit (determined by tensile and creep strength) might be increased from 550°C to 650°C by specific non-standard heat-treatments. A draw-back of the hardening process is the shift of the ductile-brittle transition temperature from about -120°C to -20°C (measured by Charpy tests). However, this shift could still be tolerable for the European helium-cooled DEMO breeding blanket concepts. More than 20 new experimental heats based on thermo-dynamical simulations have been produced recently in cooperation with different industrial partners, in particular, two 80 kg batches of low temperature optimised EUROFER material, alongside nine 80 kg batches of high temperature optimised material.

An important divertor materials issue is the loss of strength of CuCrZr above 300°C under irradiation. The High Heat Flux Materials program follows several reinforcement strategies to extend ITER-type divertor concepts for the more demanding DEMO operating conditions [38]. In this context, a very promising fabrication route for fibre-reinforced CuCrZr pipes has been established. In cooperation with textile industries, multilayer tungsten wire frameworks can now be braided, which will be embedded in CuCrZr pipes by melt infiltration.

For the code qualification of the current baseline materials (EUROFER, CuCrZr and tungsten), various irradiation campaigns in-fission material test reactors need to be executed over the next decade. A first set of campaigns will be launched in 2016, where data for component design (up to end of component life dose) and materials development (down-selecting options, low/medium fluence) as well as basic material behaviour and validation (very low fluence) are addressed.

5.8 Remote Maintenance (WPRM)

Technical work is progressing in the definition and development of the RM system, including a comprehensive requirements capture exercise, in-vessel and ex-vessel maintenance equipment concept and strategy development, and the development of service joining techniques [39].

A complete set of system requirements for the RM system has been developed. As failure modes are critical to the RM system achieving the availability and safety requirements, FMECAs have been updated to match the latest RM design strategy and they show how the designs have improved or show the consequence of changes to the requirements. A technical risk analysis has also been conducted to identify the areas where development work is required to maximise the feasibility of the resulting concept design.

The technical risk analysis has identified that end-effectors capable of handling the blankets or divertor cassettes may not fit into the space available in the port. A layout of the end-effectors has been proposed and work is starting to validate these layouts by specifying motors and bearings and analysing the stress and stiffness in the resulting structure. A cassette handling assessment has been conducted to compare a range of divertor port arrangement options using an Analytic Hierarchy Process. A new cask deployment strategy has also been proposed for the upper port in which horizontal transfer casks deliver and remove remote maintenance equipment or items of plant to and from a vertical transport cask, which is deployed over the port and is used to deploy the tools and extract and replace the plant items. This has the advantage of reducing the contamination and radiation dose to which the remote handling equipment is exposed.

A double lidded door system has been proposed to contain the contamination within the ports and within the casks when they are not connected to each other. It minimises the spread of contamination and the production of secondary waste. A cask transport system has been proposed in which autonomous trolleys are used to lift the casks and move them between the tokamak ports and the Active Maintenance Facility. The trollies only add a small height to the cask, allow the cask to be highly manoeuvrable, and have excellent rescue options in the event of unrecoverable failure. The Active Maintenance Facility concept was developed in 2012 and updated in 2013 and further work is underway in 2015 to update it in order to match the developing maintenance strategy and to improve the process flow through the facility.

Another area identified by the technical risk analysis as requiring development is the service joining systems that must be capable of rapidly achieving reliable joints that can be demonstrated to meet the requirements of the safety regulator. Laser welding has been identified as an ideal technology due to its speed if it can be demonstrated to work reliably. To this end, trials have been conducted at Cranfield University using P91 as a substitute for EUROFER. An excellent weld form was created once the correct shield gas mix had been identified but the weld affected zone had unacceptable hardness that would require a long heat treatment process to resolve. A hybrid laser and MIG arc set-up was tested along with a reduced cooling rate achieved by applying a defocused laser to the joint after welding. Hardness levels were reduced but not to an acceptable level. Further trials will be carried out using other materials. Investigations into available industrial technology to provide mechanical connections were undertaken. A full set of requirements for the NDT needed to validate the joints was compiled, and a number of suitable technologies were investigated, resulting in a proposal for a concept for applying a vacuum near the welded joint for He leak testing.

5.9 Safety and Environment (WPSAE)

From the very beginning of conceptual design, safety and environmental (S&E) considerations are at the heart of the project. The favourable characteristics of fusion power in terms of low accident potential, good operational safety and minimal environmental impact provide a potential for excellent S&E performance. But to fully realise this potential the design must incorporate safety provisions to minimize hazards and to ameliorate the consequences of any abnormal operation or system failure. In the EU DEMO project a safety approach has been adopted based on principles such as Defence in Depth, and with a view to the possible requirements that may arise from licensing by a European nuclear regulator. A first draft of a Project Safety Requirements Document has been produced that will evolve as the design process continues and in response to the outcome of safety analyses. These safety analyses are based on computer modelling of postulated accident scenarios, and an important part of the activity so far has been the development of the models and discerning the needs for their verification and validation. These tasks also help to identify the fundamental design choices that may have an impact on the S&E performance.

The main safety function to be fulfilled in the safety design is the confinement of radioactive material, principally tritium and neutron activation products. Each radioactive inventory is to be protected by two independent confinement systems, each comprising one or several barriers. The selection of these barriers and the arrangement of confinement systems in all parts of the plant in all operational phases (including accident conditions) is the subject of the confinement strategy. Several alternative proposals for this strategy are currently being evaluated.

Looking to the future, and the minimization of the waste burden from DEMO and future fusion power plants, studies are also being carried out on key aspects of radioactive waste management. In particular, techniques are being evaluated for the detritiation of solid waste prior to recycling or disposal. This is typically structural material containing tritium that has permeated into the bulk of the material. A comprehensive survey of potential detritiation methods has been carried out in order to select candidates to be the focus of R&D efforts.

5.10 Tritium Fuelling and Vacuum (WPTFV)

One important milestone achieved in early 2015 was the establishment of a novel architecture of the inner fuel cycle to avoid an excessively large tritium inventory in the system that would result from a simple scale-up of the ITER technologies for pumping and isotope separation [40]. The large inventory would result in long DT cycle times and a correspondingly slow-acting control characteristic of the whole fuel cycle. This is why a novel concept is being proposed now, which replaces batch processes by continuous processes wherever possible [41]. The 2015 DEMO inner fuel cycle architecture is based on the following three major guidelines: (i) full application of the Direct Internal Recycling concept leading to two continuous re-cycle loops in addition to an outer loop with classical isotope separation and tritium plant exhaust detritiation technologies; (ii) tritium inventory minimisation, requiring the continual recirculation of gases without storage, avoiding hold-ups of tritium in each process stage, and immediate use of tritium released from tritium breeder blankets (without intermediate storage); and (iii) environmental protection and dose minimisation under normal operating and accident conditions.

The first continuous re-cycle loop is realised within the DEMO vacuum system which features novel metal foil vacuum pumps making sure that DT fuel is not unnecessarily separated into constituent isotopes whilst circulating in the primary tritium plant loop from tokamak exhaust to matter introduction, followed by continuously working liquid metal based and non-cryogenic backing pumps. The second continuous re-cycle loop is provided as first stage within the tritium plant which features a dedicated processing system, potentially based on membrane reactors to remove impurities and plasma enhancement gases, and thermal cycling adsorption technology (TCAP) to remove protium. It generates purified mixed DT gas that will, after passing an isotope re-balancing step, be returned to the gas distribution system for immediate reinjection into the tokamak.

In the meantime, as the next step in the TFV programme, supporting R&D has started to build up models and demonstrate the viability of the chosen technologies for DEMO scales. In parallel, tailored experiments are under definition in the field of tritium accountancy and TCAP technology for isotope separation and rebalancing.

5.10 Early Neutron Source (WPENS)

Finally, although not a direct DEMO project, to finalize the DEMO design and licensing an appropriate neutron source is proposed to characterise the materials to be used [1]. Work has started in 2015 in strong coordination with F4E and building on the knowledge acquired with the IFMIF/EVEDA project, carried out in the framework of the Broader Approach Agreement between EU and JA [42]. Based on the recommendations of the Ad Hoc Group on "Options towards IFMIF Accelerator-driven Sources for materials irradiation", (October 2014), both F4E and EUROfusion have agreed the selected configuration for the Early Neutron Source (ENS) is the IFMIF-DONES approach, based on a IFMIF-type neutron source with reduced specifications. The primary objectives of WPENS are to: (i) perform the engineering design of the plant with a focus on design integration to enable start of the ENS construction around 2020; (ii) develop the engineering design of all systems which are not on the critical path but have interfaces to the systems described in (i); (iii) support the R&D activities required to finalize the engineering design of the IFMIF-DONES plant.

6. Concluding remarks

The demonstration of production of electricity before 2050 in a Demonstration Fusion Power Reactor (DEMO) that produces its own fuel represents the primary objective of the fusion development program in Europe. The approach followed to achieve this goal is outlined in this paper, together with a preliminary description of the design solutions being considered, and the R&D strategy required to tackle the considerable challenges that lie ahead. ITER is the key facility in this strategy and the DEMO design is expected to benefit largely from the experience that is being gained with the ITER construction. Nevertheless, there are still outstanding gaps that need to be overcome requiring a pragmatic approach, in particular to evaluate and improve the readiness of the foreseen technical solutions through dedicated physics and technology R&D. A systems engineering approach is needed and industry must be involved early in the DEMO definition and design. Availability of sufficient resources and an adequate implementing organization are prerequisite to success.

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