DEMO Design Point Studies

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Abstract:
To allow coherent conceptual design activities for a demonstration fusion power plant (DEMO), a self-consistent design point must first be developed. The DEMO design point is a set of parameters characterising the key features of a DEMO power plant on which evaluation of different systems can be based with confidence that there are no significant conflicts between those systems. 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 purpose of using a systems code is to identify potential solution spaces without having to carry out complex analysis at every point.

The EU DEMO strategy currently considers two possible operating scenarios: a conservative pulsed design, using near-ITER technology and plasma performance, termed DEMO1; and an optimistic, higher-performance, steady-state option (DEMO2). This contribution presents the work being carried out to develop these design points, including development of the systems code models. In each case the variables are subject to change as more DEMO-relevant models and experimental data become available and technological knowledge improves. However, these operating points are intended to provide a well-justified and stable foundation on which to base wider design evaluation work.

1 Introduction

Nuclear fusion holds the promise of abundant, clean energy. However, there are significant technical hurdles to overcome before electricity generated from fusion can be commercialised. In order to target research in the most effective areas it is important to understand where technology or physics limits most affect the performance of a power plant. In addition, for integrated conceptual (and later, engineering) design activities, a self-consistent plant operating point must be developed which incorporates any expected performance limitations and avoids conflicts between the demands of different plant systems. Such operating points are found through the use of systems codes.

The ultimate goal of research into fusion for energy is to supply electricity economically, sustainably, and safely. At some point we must demonstrate that fusion is a credible energy source: this is what DEMO is intended to do. The target of the EU DEMO strategy
FIG. 1: Exploring operating space: the net electrical power (250-1000 MW) and pulse length (1-4 hrs) were varied to explore the consequences for machine design.

is that DEMO should demonstrate significant net electrical power for significant time; tritium self-sufficiency; and functional lifetime demonstration of all relevant supporting technology including divertor, remote handling systems, etc. [1]. A target of 500 MW net electrical power and pulse length of 2 hrs are considered sufficient to provide for the inevitable variation during detailed analyses whilst retaining performance. These choices are explored more fully in reference [2]. While there are many different fusion concepts, the EU DEMO is a tokamak-based system as this is considered the most developed of the concepts. The DEMO design point will build on ITER, which should demonstrate robust burning plasma physics regimes, using a conventional divertor, and the validity of breeding blanket technologies. This allows the design of an “early DEMO” with well-established technology and regimes of operation.

The overall performance of a fusion power plant is the result of the behaviour of a large number of linked sub-systems which interact with one another, requiring the whole plant must be optimised as a system. System codes representing a full fusion power plant capture the interactions between (usually relatively simple) models of all the important plant subsystems and are used to identify design points based on assumptions about the plasma performance and technology. Given the very large potential number of such design points, a single point can be chosen by optimising a figure of merit such as capital cost, major radius, or pulse length. The systems code PROCESS [3] has been used for past conceptual studies such as the European Power Plant Conceptual Study, and is now being used for the development of baseline DEMO designs to underpin EU DEMO design studies. The purpose of using the systems code is to rapidly identify potential solution spaces without having to carry out complex analysis at every point. PROCESS is under continuous development to improve models and incorporate new data. The physics basis of DEMO is also under development to identify and investigate areas of significant uncertainty [4]. Operating space and the consequences of choosing different target global parameters can be quickly explored, as illustrated in figure [1].
FIG. 2: DEMO design point development strategy. The detailed modelling stages include physics and engineering modelling to confirm that the design meets performance requirements and limits.

Since the large number of physics and technology models in a systems code must of necessity be simple enough to rapidly run many times during the optimisation process, the solution must be checked in detail using more complete models before acceptance. This iterative process, using a systems code to find an overall operating point, testing this operating point in detail, and using those results to refine the operating point and the systems code, is intended to lead to an increasingly confident baseline version of DEMO. The process is illustrated in figure 2. This strategy involves a variety of tools, including systems codes and more detailed modelling and engineering analysis, to identify and develop the design points. First, a set of performance targets and physics and technology limits are agreed, then the systems code is used to identify and optimise an operating point meeting those requirements. The operating point is then analysed further by a scenario modelling group who use more sophisticated tools such as transport codes to assess the performance of the plasma and auxiliary systems such as current drive, which may not be well represented in a 0-D systems code model [5]. Their results, and those arising from interactions with fusion technology engineering groups, are fed back into the systems code analysis, either through adjustments of the design parameters or reconsideration of the physics models, and a new operating point identified and optimised. This interaction is repeated until the group is satisfied with the realism of the design point, which can then be circulated as a “stable release” for wider evaluation of both physics and engineering. Of course, this wider evaluation may lead to further adjustments of the operating point in the future. The intention is not to claim a particular “best” solution, as the solution will depend upon the performance requirements and technological assumptions.

The EU DEMO strategy currently considers two possible operating scenarios: a conservative pulsed design, using near-ITER technology and plasma performance, termed DEMO1; and an optimistic, higher-performance, steady-state option termed DEMO2, outside the Roadmap [6] but evaluated for comparison [2] (table 1). In order to allow a
long pulse, DEMO1 is larger to allow more flux swing. DEMO2, on the other hand, requires much higher recirculating power to support the current-drive systems, which tends to exacerbate the divertor heat load challenge, one of the key constraints in these studies. Whilst DEMO1 is intended to be deliverable in the short to medium term (e.g. construction starting ~20 years from now), DEMO2 is based around more optimistic (but “less mature”) physics assumptions – which are at the upper limit of what may be achieved in ITER Phase 2 – and technology assumptions, allowing higher temperatures, heat flows, and neutral beam energies, which change the balance of plant demands. In each case these variables are subject to change as more DEMO-relevant models and experimental data become available and technological knowledge improves. However, these operating points are intended to provide a well-justified and stable foundation on which to base wider design evaluation work.

2 Pulsed versus steady-state

DEMO will be operated as a steady-state electricity source over an extended period of time, although the plasma itself may not be steady state. Studies performed within the European fusion programme indicate that energy storage is not a cost driver and could store large amount of high grade heat compatible with electricity production \[\text{[1]}\]. A steady-state machine eases the issue of mechanical and thermal fatigue of components but places large demands on the plasma facing components, especially the divertor, and the control systems, due to the large additional power which must be injected for current drive. This also has an effect on the recirculating power in the plant and hence the net electrical power (figure 3, right). For these reasons the “near-term” DEMO is pulsed, as this gives the greatest chance of demonstrating net electricity output and allowing the qualification of supporting technologies. However the long-term goal is the development of a steady-state
<table>
<thead>
<tr>
<th>Value</th>
<th>DEMO1</th>
<th>DEMO2</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_N$ limit</td>
<td>3.0</td>
<td>3.5</td>
<td>Total $\beta_N$, performance usually limited by $H$-factor instead</td>
</tr>
<tr>
<td>$H_{98}$-factor limit</td>
<td>1.1</td>
<td>1.3</td>
<td>Radiation-corrected (uncorrected “experimental” value is 0.1 lower);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DEMO2 assumes hybrid mode</td>
</tr>
<tr>
<td>$q_0 / q_{95}$</td>
<td>1.0 / 3.0</td>
<td>1.3 / 3.5</td>
<td>Hybrid mode, higher $f_{bs}$ to reduce $P_{CD}$ in DEMO2</td>
</tr>
<tr>
<td>$\langle n_{\text{line}} \rangle / n_G$</td>
<td>1.2</td>
<td>1.2</td>
<td>Assuming $n_G$ is a pedestal limit; tGLF predictive transport simulations indicate density peaking</td>
</tr>
<tr>
<td>Operation</td>
<td>Pulsed / 2 hr</td>
<td>Steady-state</td>
<td>L-H transition power: $f_{\text{HL}} = (P_{\text{heat}} - P_{\text{rad,edge}})/P_{\text{HL}}$</td>
</tr>
<tr>
<td>$P_{\text{LH}} / f_{\text{LH}}$</td>
<td>155 / 1.0</td>
<td>107 / 1.2</td>
<td></td>
</tr>
</tbody>
</table>

### Heating and current drive

| Power (MW)                  | 50   | $\sim 150$ | DEMO1 power principally for burn control [2]; extra will probably be required to reach burn |
| $E_{\text{beam}}$ (keV)     | 1000 | 1500        | Higher energy gives higher $\gamma_{CD}$                                  |
| $\eta_{\text{WP}}$         | 0.4  | 0.5         | Wallplug efficiency $\eta_{\text{WP}} = P_{\text{inj}}/P_{\text{electrical}}$ |

### Divertor

| $P_{\text{div}}/R$ (MW m$^{-1}$) | 17.0 | 20.0 | DEMO1 based on ITER values, DEMO2 slight upgrade |

### Balance of plant

| $P_{\text{recirc}}$ (MW)      | 300  | 550  | Principally current drive and coolant pumping |
| $\eta_{\text{therm}}$        | 37%  | 40%  | Higher temperatures in coolant and/or heat recovery from divertor assumed for DEMO2 |

**TABLE I: Differences between DEMO1 and DEMO2. In some areas (e.g. magnets) the technology is assumed to be the same. For the “radiation-corrected” $H$-factor values, the core radiation is subtracted from the loss power in both the energy balance and the confinement scaling law.**

solution, for which the principal challenge is finding ways to reduce the auxiliary power required. Methods may include the development of more efficient current-drive systems and high bootstrap current plasma scenarios.

DEMO2 is intended as a steady-state machine and consequently is optimised to reduce current-drive power. This leads to a higher $q_0$ and $q_{95}$, and consequently higher $\beta_P$ to give a higher bootstrap fraction of $\sim 50\%$. The scenario is a development of the ITER hybrid scenario, optimised for DEMO [3]. It is assumed that the blanket is more advanced and can support higher temperatures, allowing greater thermodynamic efficiency in the
FIG. 4: Magnetic field on TF coils as a function of aspect ratio; estimated TF coil costs; and estimated total plant capital costs. Different curves represent different stress limits on the coils and limits on plasma $\beta$. The lower stress is 88% of the higher stress, to represent more conservative assumptions about cyclical stress loading in pulsed operation. Due to the variation in magnet costs, there is a cost trade-off between a large machine volume and high field.

balance of plant. However the high recirculating power required for the current drive limits the overall plant efficiency $P_{\text{net}}/P_{\text{fus}}$ to $\sim 24\%$, much the same as DEMO1 (table I).

3 Choice of aspect ratio

An important global parameter for tokamak physics design is the aspect ratio. Instinctively it may seem that a higher aspect ratio should lead to a longer pulse length since the bore and hence available flux swing should be greater, but for fixed major radius this is not the case (figure 3, left). It is also the case that low aspect ratio, although it may result in a large machine volume, allows lower magnetic fields to achieve the same energy confinement and fusion power. Since the TF coil magnets are a significant contributor to the overall cost of the plant, a lower aspect ratio, lower field device may be cheaper than a smaller, higher-field machine (figure 4).

To investigate the full impact of varying the aspect ratio, beyond the simplified models in the systems code, operating points were developed at aspect ratios of 2.6, 3.1, and 3.6, and these were iterated around the loop illustrated in figure 2. The resulting operating points are illustrated in table II. In these cases, PROCESS was run to minimise the major radius subject to the constraints mentioned in the table caption. Although all three machines have a similar major radius the plasma parameters and costs are quite variable. Currently these designs are being evaluated to check the consistency of the engineering and energy confinement assumptions.

It is interesting to see which constraints limit the sizes of the machines listed in table II. At low aspect-ratio, the principal limitation is pulse length, and eliminating this requirement allows the reduction of machine size by nearly two metres (but zero burn time!). At high aspect-ratio the pulse length is $\sim 2.5$ hours and the size is constrained by the confinement and power density. Here the power across the separatrix is also only slightly above the L-H threshold power. The increase in the threshold is driven by $\langle n_e \rangle$ and $B_T$, which both enter the scaling. At higher aspect ratios the requirement to stay in
TABLE II: Cross-section plots and basic parameters for the aspect-ratio scan cases. All machines had a target net electrical power of 500 MW, with a minimum 2 hour pulse length. Auxiliary power was fixed at 50 MW for burn control [7]. The maximum allowable divertor load, as power over the separatrix divided by major radius, was limited to 17 MW m$^{-1}$, which was set by varying the $Z_{\text{eff}}$ to control plasma radiation. Separatrix power was also checked to ensure it was above the L-H transition power [9]. $H$ factor was 1.1 (radiation corrected), and NBI energy was 1 MeV. $f_{\text{rad}}$ is the fraction of power radiated divided by the total heating power (not including radiation in the divertor). Capital cost estimates are normalised to aspect ratio 2.6 costs.

H-mode while protecting the divertor would prevent further increases in power density.

The cross-section plots in table II show that, particularly in the low aspect-ratio case, the outer limb of the TF coil is a long way from the vacuum vessel. This is due to the requirement to keep the toroidal field ripple at the outer mid-plane of the plasma below 1% and prevent fast-ion losses [11]. An approximation for the ripple is $\delta = \left( \frac{R_0 + a}{R_{\text{TF}}} \right)^N$, where $(R_0 + a)$ is the outer midplane of the plasma, $R_{\text{TF}}$ is the radial position of the TF
limb, and $N$ is the number of TF coils [11]. For a large device, this can become significant unless the coils are appropriately shaped. Alternatively the number of coils (18 in this study) can be increased, meaning that remote handling and other systems would have to be redesigned. Work is underway to assess the impact of $\delta$ on DEMO confinement, to investigate how to further reduce the ripple by measures such as the use of ferritic inserts, and to set an appropriate value; 1% is a greater ripple than is anticipated in ITER.

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References


