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Uncertainties in power plant design point evaluations

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HIGHLIGHTS

- New large experimental devices require far extrapolations from current physics and technology.
- Their design therefore has significant uncertainties.
- We conduct an uncertainty quantification analysis for the European DEMO design.
- We find encouraging results.

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ABSTRACT

When designing a new large experimental device, extrapolation from current knowledge and scaling laws into unexplored design space is unavoidable, and predicting the behaviour of a new device is therefore subject to significant uncertainties. This makes it difficult to determine an optimal design. For conceptual fusion power plants, a further concern is whether the expected performance will yield any net electricity and for pulsed power plants a reasonable pulse length.

In this work, we focus on evaluating the effects of selected uncertainties regarding the general plasma physics performance in the current European pulsed DEMO design (nominally 500 MW net electrical power, 2 h pulse length). This is meant as a first step towards uncertainty quantification for DEMO. We use a Monte-Carlo method in combination with the systems modelling code PROCESS to map out the probable machine performance. The results show that assuming only these specific uncertainties it is a reasonable assumption that the current design is capable of providing 400 MW of net electricity while maintaining a pulse length of 1 h or more.

1. Introduction

In the European roadmap towards the 'Realisation of Fusion Energy' [1] the demonstration of electricity production from fusion is a major priority. Currently different design concepts for such a demonstration power plant (DEMO) are being evaluated to find an optimal design point, where the main focus is on the baseline design of a pulsed power plant [2]. In this evaluation process, many uncertainties in both the extrapolation of current plasma physics experiments and understanding as well as technologically achievable efficiencies have to be taken into account.

To achieve the ambitious goal of early electricity production from fusion, the pre-conceptual design phase of DEMO is already ongoing. However, DEMO scenarios also rely on ITER results that will only be achieved at a later time. Therefore, it is crucial not only to extrapolate to an optimal design point for DEMO based on our current knowledge, but to understand the performance margins of such a machine. Together with the assessment of high impact areas this should allow to rule out show stoppers early on. Due to the constraints of this conference proceeding, we will focus our evaluations on the effect of a limited number of uncertainties in the DEMO physics basis only.

Conceptual design activities typically use systems codes (e.g. [3–5]) to evaluate optimal design points for power plants. Uncertainty quantification (UQ) for these design evaluations can be treated in several ways. In this work, we present an approach based on a multi-parameter Monte-Carlo method in combination with our systems code PROCESS. We describe our method in Section 2, the expected physics uncertainties in our input parameters in Section 3 and the implications of our studies on DEMO design point

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evaluation in Section 4. We discuss our results and conclude in Section 5.

2. Method

Our UQ method is based on a Monte-Carlo sampling technique that has been described extensively in [6]. Here we only give a short overview of its key aspects.

There is a range of distribution functions available to describe the uncertainties in the input parameters. The currently implemented options are: Gaussian profile, lower half Gaussian profile, upper half Gaussian profile, flat top profile with relative errors, flat top profile with upper and lower bounds. For the Gaussian profiles the user needs to specify the mean and standard deviation of the distribution, for the flat top profiles either a mean and an error percentage or a lower and upper bound have to be specified. While sampling the input parameters from the user defined distributions, no correlations between the different uncertainties are assumed. Uncertainties can only be specified for input parameters that are not also iteration variables for the constrained optimisation solver. Then the PROCESS systems code [3,4] is run on each input point to find an optimised design point. The final result is a distribution of optimised design points reflecting the assumed uncertainties in the input parameters.

3. Uncertainties

The uncertainties that affect a design point evaluation are dependent both on the specific models implemented and the relevant constraints used in the optimisation of the design point. In the following, we describe a selection of plasma physics uncertainties that have been identified for the pulsed European DEMO plant [2] as derived using the PROCESS code.

Ad hoc multiplication factor for the density limit lower half Gaussian profile (mean 1.2 and standard deviation 0.1).

In the PROCESS runs for the European DEMO baseline the line averaged density is limited to the Greenwald limit [7] multiplied by an ad hoc factor. The ad hoc factor has been introduced as recent work suggests that the Greenwald limit really applies to the pedestal top density instead of the line averaged density and higher values than the Greenwald limit are therefore allowed for the line averaged density due to favourable density peaking. As a result we allow the line averaged density to reach values as high as 1.2 times the Greenwald density (e.g. [8–10] and references therein).

Upper bound on *H*-factor lower half Gaussian (mean 1.2 and standard deviation 0.1).

Please note, that in PROCESS this is the radiation corrected H98-factor [11,12] where a certain amount of radiation from the core region of the plasma is considered as instantaneous losses and are therefore subtracted from the heating power before the loss power is calculated for the confinement scaling. Experience shows that radiation corrected *H*-factors between 1.0 and 1.2 roughly correspond to non-radiation corrected H98-factors of 0.9–1.1 for typical DEMO scenarios. This range should capture all uncertainties in the current confinement time scaling including statistical errors on the exponents and uncertainties due to operating in DEMO relevant regimes that are not covered by IPB98(y,2) [13] database (c.f. [10]).

Core radius in radiation corrected τ_E scaling Gaussian distribution (mean 0.6 and standard deviation 0.15).

This quantity is defined in [11,12] where also expected values for it are discussed. It is treated separately from the uncertainties on the *H*-factor to capture the correlations of expected corrections for high radiation scenarios. Please note, that in this work, we are only varying the radius inside of which the radiation is considered an instantaneous losses to the heating power. The fraction of the radiation that is subtracted from within the core region is fixed at 100% as the uncertainty in this value is correlated with the uncertainties in the radius and this does not need to be captured twice.

Thermal He-4 fraction Gaussian distribution (mean 0.1 and std 0.025).

While the production rate of helium ash in the plasma is well understood, the fraction of thermal He-4 particles with respect to the electron density in the confined plasma is relatively uncertain due to its dependence on particle transport, pumping in the main chamber, ELM behaviour etc. Ikeda [14] suggests that a lower limit for the ratio of He confinement time accounting for wall recycling and energy confinement time τ^*_{He}/τ_E of 6. A reduction of the divertor neutral gas influx [15] or reduced ELM behavior leads to an increase of this value up to an order of magnitude. The He concentration in EU DEMO1 2015 of 10% corresponds to $\tau^*_{He}/\tau_E = 6.5$. Increasing τ^*_{He}/τ_E to 12.6 would correspond to a He concentration of 16%. For numerical stability reasons τ^*_{He}/τ_E is not used as an input to PROCESS: instead the He concentration is given and the confinement time ratio is calculated as an output. Therefore the uncertainties have been applied to this input quantity instead.

***W* number density fraction relative to n_e** Gaussian distribution (mean 10^{-4} and std 5×10^{-5}).

Pütterich et al. [16] have investigated the effect of varying *W* concentrations on the minimum value of fusion triple product $nT\tau_E$ for which a thermonuclear burn is possible. This places certain limits on allowed *W* concentrations in a DEMO reactor. However, predicting expected W concentrations in DEMO is still highly uncertain as it is unclear how much of the impurity will be screened, flushed outwards or drawn inwards (e.g. [17]).

Maximum ratio of P_{sep}/R Gaussian distribution (mean 15 MW/m and std 2 MW/m).

Due to the lack of a robust model predicting the power flow and temperature on the divertor plates in PROCESS, we adopt P_{sep}/R as a divertor measure of similarity [18]. There are many uncertainties associated with allowed maximum values of P_{sep}/R and the chosen distribution reflects the best guess based on current experiments [19,20].

Lower bound on *L*–*H*-threshold limit Gaussian distribution (mean 1.0 and std 0.25).

The European DEMO baseline design uses the well recognised Martin-scaling [21] for the determination of the *L*–*H* threshold. While more recent results suggest that the *L*–*H*-threshold in metal wall machines is in fact lower [22], it is desirable to have a certain margin above the *L*–*H* threshold to achieve reasonable performance [23]. As a result, the distribution of the lower limit for *H*-mode performance has been centred on 1.0 times the *L*–*H*-threshold as given by the Martin-scaling. The standard deviation should cover both statistical errors suggested by Martin et al. [21] and uncertainties concerning how high you need to be above the *LH*-threshold to achieve good *H*-mode performance. Therefore, the standard deviation chosen in this work is larger than the one suggested by Martin et al. for typical average electron densities in DEMO. However, it does not include uncertainties due to extrapolating this scaling to high radiation reactor relevant scenarios, that have not been included in the original data set.

Bootstrap current fraction multiplier Gaussian distribution (mean 1.0 and std 0.1).

This parameter is a multiplication-factor for the Sauter-Angioni bootstrap current [24] implemented in PROCESS for the DEMO design. Its range should capture both the model limitations as well as uncertainties in the prediction of the achievable plasma profiles and the resulting expected bootstrap current.

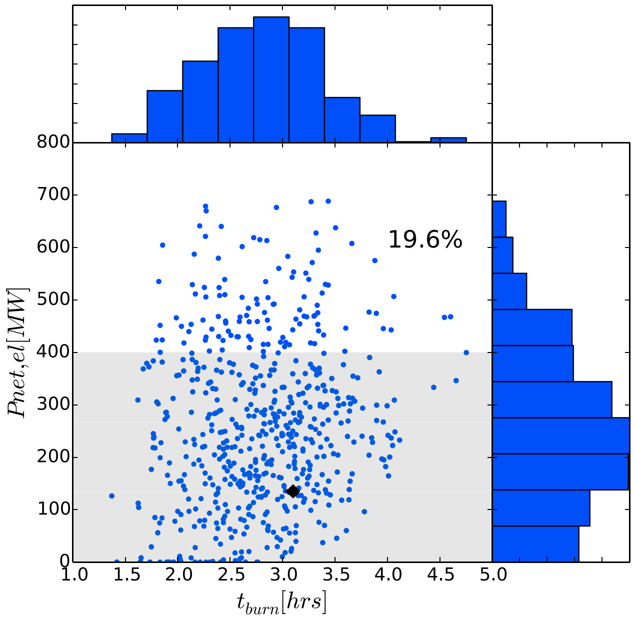

Fig. 1. Showing the predicted machine performance of a pulsed European DEMO, if the pulse length of the machine is optimised. Only about 20% of the scenarios yield acceptable performance (see Section 4). The black diamond indicates the performance with nominal baseline physics assumptions.

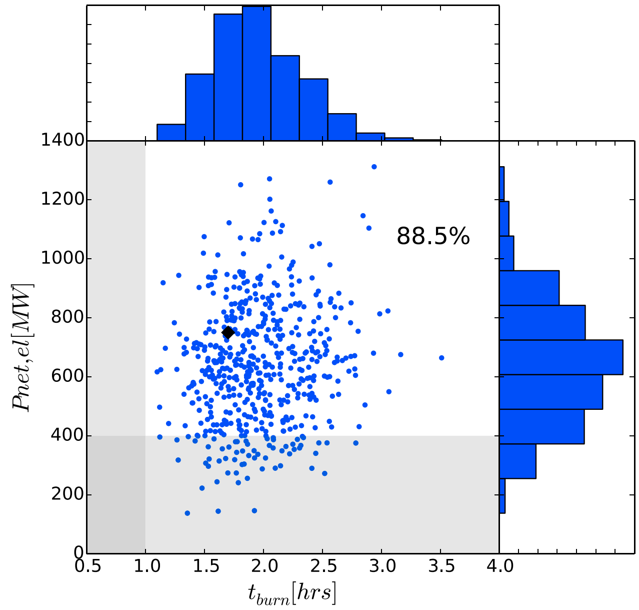

Fig. 2. Same as Fig. 1, but for optimised fusion gain (Q). Nearly 90% of cases yield acceptable performance (see Section 4).

4. Implications for DEMO designs

There are many options in assessing the effect of uncertainties on a given design. In this work, we have decided to fix the radial build and the magnetic field configuration (size/shape of coils and magnitude of coil currents) of the European pulsed DEMO baseline design [2] and have asked the question what kind of performance can we expect from such a machine in the best and worst cases given the current uncertainties in the DEMO physics basis. The original baseline design was optimised to be the smallest machine given the input requirements. However, with the machine build fixed, we can now focus on optimising the plasma scenario. Here we have chosen to investigate optimised pulse lengths as well as optimised performance ($Q = P_{fus}/P_{inj}$) scenarios. Assuming the same physics basis as for the baseline design without uncertainties, this already results in scenarios with up to 750 MW of net electric power, if the burn time is reduced to 1.7 h or up to 3.1 h of burn time, if the net electric output is reduced to 135 MW (see red squares in Figs. 1 and 2). However, the balance of plant (BoP) is likely to only tolerate net electric output variations of +5%/−20% from the baseline value (500 MW).[1] This assumes a steam cycle is used for electricity production independent of whether a typical low temperature nuclear water or a high temperature helium steam cycle will be in operation. This should be taken into account in the further analysis.

Fig. 1 shows the resulting distribution in both burn time and net electric output, if the pulse length of the machine is optimised. Assuming the BoP allows net electric output as low as 400 MW and any performance higher than 525 MW can be reduced, only about 20% of the final distribution would yield an acceptable plant performance. A further assumption is that the energy storage systems is designed to cope with 1 h as well as the nominal 2 h pulse length. Fig. 2 shows the same results as in Fig. 1, but for scenarios with optimised machine performance (maximum Q). Under these assumptions nearly 90% of the cases yield acceptable performance in both net electric output and burn time.

[1] C. Harrington, private communication.

5. Conclusions and discussion

In this work, we have conducted an initial evaluation of the effects of selected uncertainties in the DEMO physics basis on the expected performance of the European pulsed DEMO baseline design [2]. If the machine would be build as currently assumed, the uncertainty quantification shows that it would most likely still lead to reasonable overall machine performance ($P_{net,el} > 400$ MW, $t_{burn} > 1$ h). There is a clear trade off between pulse length and fusion gain Q, depending on chosen operating scenario. Within PROCESS, we are currently only optimising for one of those parameters at the time, but a real operating scenario would likely optimise both. This work is a first step towards a more complete analysis of the effects of currently known uncertainties on the DEMO baseline design. Further work will include evaluating uncertainties in the technology parameters as well as variations in some of the assumed scaling laws and parametrisations.

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