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Uncertainties in power plant design point evaluations

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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 500MW net electrical power, 2 hour pulse length). This is meant a 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 1hr or more.

Keywords: Fusion Reactor, DEMO, Uncertainty Quantification, Systems Studies

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, 4, 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 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,

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lower half Gaussian profile, upper half Gaussian profile, flat top profile with relative errors, flat top profile with upper and lower bounds. While sampling the input parameters from the user specified distributions, no correlations between the different uncertainties are assumed. 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.

Upper bound on density limit lower half Gaussian profile (mean 1.2 and standard deviation 0.1).
The value is the factor by which the density limit suggested by Greenwald [7] is multiplied with when limiting the line averaged density in PROCESS. As recent work suggests that the density limit in a confined plasma really applies to the pedestal top density instead of the line averaged density due to density peaking, an upper allowed value of 1.2 is chosen (e.g. [8, 9, 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 1.0-1.2 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 α-particle fraction Gaussian distribution (mean 0.1 and std 0.025)
The thermal He-4 fraction is dependent on the ratio of particle confinement time to energy confinement time tau^*_{He}/tau_E, which is highly variable in current transport simulations and hence very uncertain. However, for numerical stability reasons this ratio 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. [14] 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. [15]).

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 [16]. 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 [17, 18].

Lower bound on L-H-threshold limit Gaussian distribution (mean 1.0 and std 0.25)
The DEMO baseline design uses the Martin-scaling [19] for the determination of the L-H

threshold. As more recent results suggest that the threshold is in fact lower in metal wall machines [20], but we need a certain margin above the L-H threshold to achieve reasonable performance [21], the fraction of the L-H-threshold power is chosen to be centred one 1.0. The uncertainties distribution should cover both statistical errors suggested by Martin et al. [19] and uncertainties concerning how high you need to be above the LH-threshold to get good performance. 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 [22] 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.

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 and magnetic build 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 hrs or up to 3.1 hrs of burn time, if the net electric output is reduced to 135 MW (see red squares in Figures 1 and 2). However, the balance of plant (BoP) is likely to only tolerate net electric output variations of $+10\%/-20\%$ from the baseline value (500 MW). This should be taken into account in the further analysis.

Figure 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

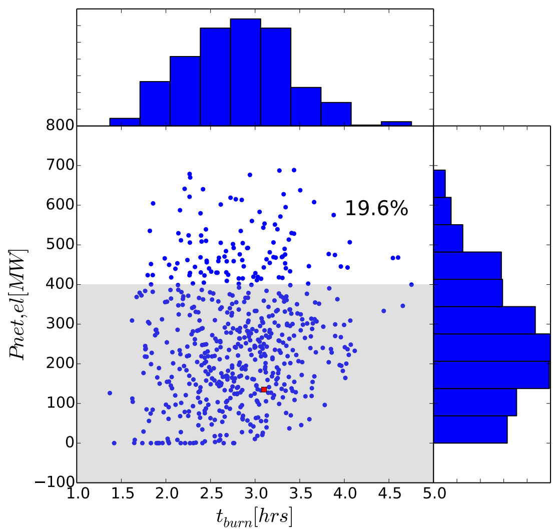

Figure 1: Showing the predicted uncertainty distribution for the pulse length and net electric power of a pulsed European DEMO, if the pulse length of the machine is optimised. While the majority of scenarios have a significant pulse length, the net electric output is often unacceptably now. Only about 20% of the scenarios yield both acceptable performance for the BoP $P_{net,el} > 400$ MW and a pulse length of $t_{burn} > 1$hr. The red square indicates the performance with nominal baseline physics assumptions.

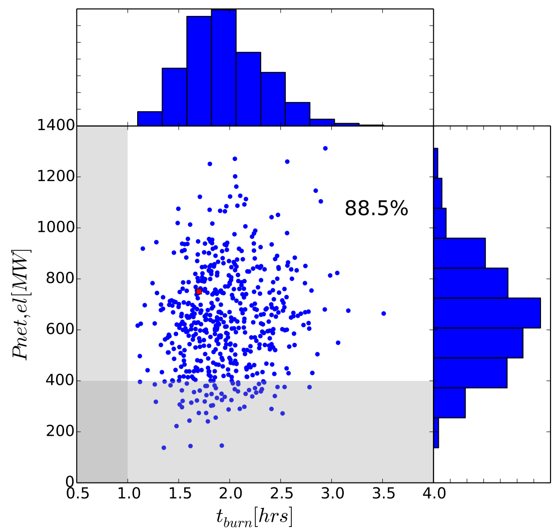

Figure 2: Same as Figure 1, but for optimised machine performance (Q). While few cases have less than 400 MW of net electric output, still all scenarios have a pulse length > 1hr, leading to nearly 90% of cases with acceptable performance.

higher than 550 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 1hr as well as the nominal 2hr pulse length. Figure 2 shows the same results as in Figure 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.

5. Conclusions and Discussion

In this work we have evaluated 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, $t_{burn} > 1$ hr). 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.

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