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Uncertainty Analysis of an SST-2 Fusion Reactor Design

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Abstract

Systems codes asses the viability of fusion reactor designs by using simplified models for the entire reactor system, and allow for the exploration of large areas of parameter space. However, every design will have an associated uncertainty that arises from the accuracy of the models used, the assumptions made and the values of input parameters adopted. For individual codes, the uncertainty on their results can be quantified by investigating the dependence on the combination of input parameters. More generally, different codes can be compared against each other to test the underlying models. In this paper we compare the results of two systems codes, SPECTRE and PROCESS, using a conceptual design for the SST-2 fusion reactor for benchmarking. We find that overall both codes produce similar results, however slightly different plasma temperatures and densities are found due to the treatment of radiation in the loss function differing between the codes. We then apply a Monte-Carlo based uncertainty quantification tool using PROCESS to find that while the design can produce in excess of 100 MW of fusion power, it is unlikely to produce pulses over 400 s. This is in agreement with previous work and suggests a larger aspect ratio is required.

Keywords: Fusion Reactor, SST-2, Uncertainty Quantification, System Studies
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1. Introduction

Systems codes are a powerful tool for designing the next generation of nuclear fusion reactors. By exploring a large design space in a single calculation, they can obtain highly optimised solutions. However, while a single design is informative, it does not give the whole picture. Often new designs will push boundaries, whether that involves scaling to new physical regimes or applying new technologies. All of this will introduce uncertainty which needs to be quantified to give a complete understanding of the performance of a proposed reactor. Uncertainty analysis and sensitivity studies can then inform about high impact areas, critical design aspects or simply confirm the robustness of the design.

For this study we have used two systems codes, SPECTRE [1] and PROCESS [2, 3]. SPECTRE was developed for the Indian DEMO program [1], while PROCESS has been applied to a number of designs, most recently the European DEMO [4]. Both codes solve for the plasma properties and include models for bremsstrahlung, synchrotron and impurity line-radiation. Beyond the plasma properties, PROCESS additionally solves for a number of engineering constraints.

We have chosen to apply the two codes to, and quantify the uncertainty of, a recently published conceptual design for SST-2 (Steady-state Superconducting Tokamak-2)[5]. The SST-2 fusion reactor is a proposed medium sized device with low fusion gain (Q = 5) and capable of producing fusion power from 100 to 300 MW. Tritium breeding will be achieved by having breeding blankets only on the outboard side, while on the inboard side, shielding blankets will be placed due to the limited space available. The magnets will be superconducting in nature to achieve steady state operation.

The rest of the paper is set out as follows. In Section 2 we benchmark the outputs of SPECTRE and PROCESS using the conceptual design of SST-2. In Section 3 we apply the PROCESS Monte-Carlo uncertainty quantification tool to the design to investigate the variation in fusion power and pulse length. In Section 4 we present our conclusions.

2. Benchmarking between SPECTRE and PROCESS

In order to compare results between SPECTRE and PROCESS, we benchmarked the codes using an updated version of a conceptual design for SST-2 presented in Srinivasan et al. [5]. This was originally produced using SPECTRE. PROCESS has an extensive and detailed output, and for brevity we will restrict our comparison to a few core parameters. These are presented in Table 1. The poloidal cross-section from the PROCESS run is shown in Figure 1.

Overall SPECTRE and PROCESS produce similar results. For the same input plasma shape, both produce 100 MW

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Parameter	SPECTRE	PROCESS
R (m)	4.42	4.42(IP)
a (m)	1.47	1.47(IP)
κ_{95}	1.70	1.70(IP)
δ_{95}	0.24	0.24(IP)
P_{aux} (MW)	20.0	20.0
P_{fus} (MW)	100.0	100.0
B_{T} (T)	5.42	5.42
I_{p} (MA)	11.17	11.17
β_{N}	1.22	1.34
$H_{\mathrm{IPB98(y,2)}}$	1.00	1.00
n/n_{GW}	0.65	0.58
$< T_e >_n$ (keV)	6.09	7.72

Table 1: The plasma parameters for SST-2 produced by SPECTRE and PROCESS. PROCESS values marked with IP are given as fixed inputs to match SPECTRE.

of fusion power for 20 MW of auxiliary. Additionally both use exactly the same toroidal field and plasma current. Differences start to appear in the properties of the plasma. Both have the same H-factor, but adopt different values for the temperature and density to achieve the desired fusion power. This difference stems from the way the loss power is calculated in the two codes.

The SST-2 conceptual design is for ELMy H-mode operation and both SPECTRE and PROCESS use the IPB98(y,2) scaling law [6]. Within both systems codes the loss power is calculated and it is imposed that this has to be above a threshold power obtained from a published scaling relation to be in H-mode. By default SPECTRE uses the scaling presented in Snipes et al. [7]. PROCESS has a number of L-H threshold scalings implemented, but by default uses that of Martin et al. [8]. For the purposes of this work, and to aid benchmarking with SPECTRE, we have implemented the Snipes et al. scaling in PROCESS.

The two scaling relations produce very different threshold powers for the same input values. For the PROCESS solution, the L-H threshold power is 24 MW for the Snipes et al. scaling and 34 MW for the Martin et al. scaling. The exact value required is uncertain due to the scatter in the data that the scaling relations are derived from, and the effect of hysteresis. The L-H transition typically occurs at a higher threshold power than the H-L transition, and in actual machines H-mode may be entered under different condition to operation [8]. This is not captured within either code. The L-H threshold is an uncertain parameter that we will investigate in Section 3 and for the purpose of this study we will use the Snipes et al. value as a reference, as it is implemented in both.

The loss power is required to be above the L-H threshold, however PROCESS tends to produce lower values compared with SPECTRE. This is caused by different treatments of the radiation. SPECTRE only subtracts the core line-radiation when calculating the loss power, while PROCESS subtracts all the line-radiation. This leads to PROCESS being closer to the L-H threshold than SPECTRE which requires it to adopt a different density and temperature to stay above the limit.

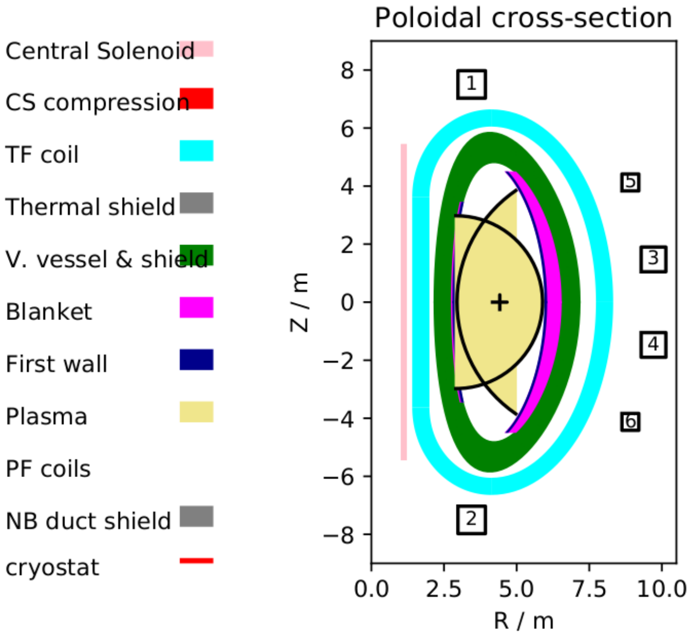

Figure 1: The poloidal cross-section from the PROCESS output.

In summary, SPECTRE and PROCESS produce similar overall designs matching a number of key parameters. However, by default PROCESS uses a higher L-H threshold and has a lower loss power, as it subtracts more radiation. This makes it harder to maintain H-mode using PROCESS than SPECTRE and so leads to different plasma properties.

3. Uncertainty Quantification

PROCESS has a Monte-Carlo based uncertainty quantification tool that has previously been applied to the preconceptual design of the European DEMO [9]. For a given parameter, the user specifies a distribution that describes the uncertainty on that parameter. Currently the distributions available are a Gaussian, a lower or upper half-Gaussian or a uniform distribution. Having specified the centre and width, values for the parameter are drawn at random using the distribution. This is done for all the parameters with uncertainty, which are combined into a single input, and run with PROCESS. Parameters chosen to be used in the uncertainty quantification must have fixed values in the input. The generation of inputs is repeated a user-specified number of times and the variation of outputs between runs is used to quantify the uncertainty.

The following parameters and distributions were used to evaluate the uncertainty on the SST-2 conceptual design we used for benchmarking:

Lower bound on the Greenwald density [10]: The minimum density was limited to produce a solution closer to [5], however PROCESS produces longer pulses for a lower Greenwald fraction. Therefore we apply a lower half-Gaussian

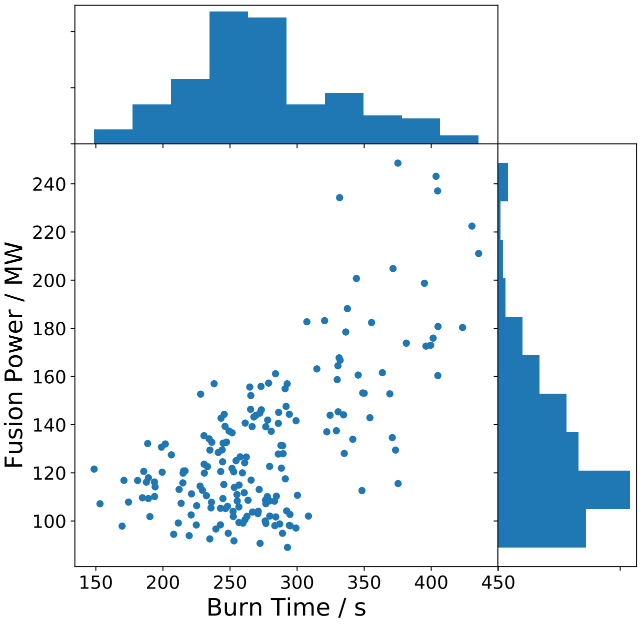

Figure 2: The uncertainty in the fusion power to burn time for no auxiliary current drive. PROCESS optimised on pulse length.

to the limit with a mean of 0.58 and standard deviation of 0.1.

Upper bound on H-factor: While an H-factor of 1.0 was used for benchmarking, it is possible that a future device could achieve an enhancement. Therefore we have taken an upper half-Gaussian with standard deviation 0.1 for an upper bound mean of 1.2.

Core radius in radiation corrected τ_E scaling: PROCESS uses a radiation corrected H-factor where radiation from the core is considered an instantaneous loss. For Section 2 we converted the radiation corrected H-factor to a non-radiation corrected H-factor to compare with SPECTRE. The size of the core will influence the amount of radiation subtracted, so we have taken a Gaussian centred on a normalised radius of 0.75 with a standard deviation of 0.15.

L-H threshold: As discussed in Section 2, the L-H threshold is uncertain. We have applied a uniform distribution between the Snipes et al. value and 1.5 times this, which corresponds to the Martin et al. value from Section 2.

Bootstrap fraction multiplier: PROCESS calculates the bootstrap fraction using the method described in [11]. The uncertainty on this is taken as a Gaussian with standard deviation 0.1.

Current drive efficiency: The current drive is calculated from the NBI and the uncertainty is taken as a Gaussian with fraction standard deviation of 0.05. Note that the run in Section 2 does not have current drive and this is only used in the upcoming case where we explicitly state it.

Ejima coefficient: The Ejima coefficient is used to calculate the flux consumption and influences the pulse length. Here we have taken a Gaussian centred on 0.35 with a standard deviation 0.05.

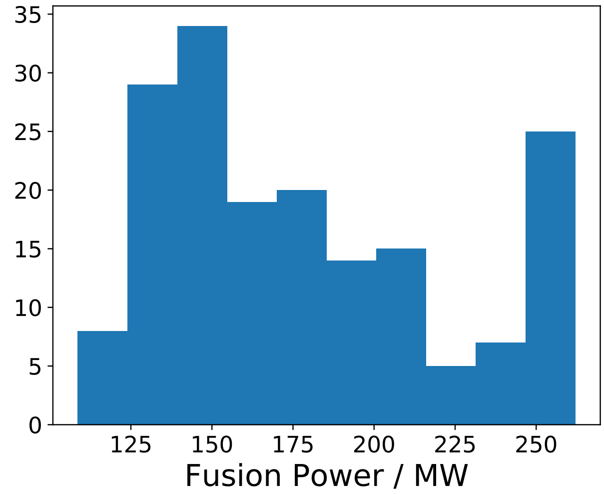

Figure 3: The distribution of fusion power when optimised for fusion gain.

We generated 200 realisations and ran with PROCESS. Initially we allowed for no current drive from the NBI to agree with the original SPECTRE run and increased the upper limit on the fusion power from 100 MW to 300 MW. The radial build was fixed to values obtained in Section 2 so that just performance parameters are being tested.

Figure 2 shows the fusion power against burn time. The majority of solutions are clustered with burn times between 200 and 300 s, and fusion power between 100 and 140 MW. At the extremes of the uncertainty distributions, fusion power as high as 250 MW and burn times approaching 450 s can be achieved. For this run PROCESS is solving for maximum burn time as opposed to maximum fusion power, therefore higher fusion powers are possible.

It was highlighted in [5] that the flux linkage required to sustain a 400 s pulse is not achieved by the present design, and this is confirmed by our PROCESS runs. Only 4 per cent of the solutions have pulses longer than 400 s. One way of increasing the pulse length is to allow current drive from the NBI, reducing the amount needing to be induced by the central solenoid.

For the reference design optimised for pulse length, PROCESS determines that it is optimal for 10 per cent of the plasma current to be generated by current drive from the NBI. A similar scatter to Figure 2 is found with current drive, however the burn times are shifted to higher values. The peak of the distribution is approximately 50 s longer than the case with no current drive.

We can also run PROCESS optimising for fusion gain instead of pulse length. Figure 3 gives a histogram of fusion power for this case. It can be seen that fusion power up to 260 MW is feasible for this design. Higher fusion power could potentially be obtained by adjusting the radial build, which is not done here.

In summary, we have applied uncertainty distributions to a selection of PROCESS input parameters and found that while the fusion power lies in the 100 to 260 MW range, pulse lengths are typically less than 400 s. This supports the suggestion made in [5] that an increased aspect ratio, for fixed minor radius, should be explored. Increasing the aspect ratio would allow for a bigger central solenoid, therefore increasing the flux swing and hence the pulse length. Given that the current design can produce greater than 100 MW of fusion power, increasing the aspect ratio should not take the fusion power below the lower limit.

4. Conclusions

We have benchmarked the outputs of two system codes, SPECTRE and PROCESS, using a conceptual design for the SST-2 fusion reactor. We found that both codes produce broadly similar results, however PROCESS subtracts the total radiation when calculating the loss power, while SPECTRE uses just the core radiation. This leads to PROCESS being closer to the L-H threshold and so adopts a different temperature and density for operation.

We then applied a Monte-Carlo based uncertainty quantification tool using PROCESS to the design. We found that the majority of cases produce in excess of 100 MW of fusion power, with up to 260 MW potentially being possible for this build. However the pulse length is unlikely to be in excess of 400 s agreeing with previous work. This suggests that the aspect ratio needs to be increased to accommodate a larger central solenoid.

Overall, we have shown the robustness of the SST-2 design that can be recovered by different systems codes. In future we will look at the impact of the aspect ratio on pulse length and plasma properties. This can be done in PROCESS which calculates pulse lengths. Additionally, one of the goals of SST-2 is to demonstrate tritium breeding, however neither code currently calculates the tritium breeding ratio. Developing a model to calculate the tritium breeding ratio would be beneficial long term.

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