Status of Divertor/Scrape-Off Layer Modelling in PROCESS

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Summary

Systems codes, such as PROCESS, model all systems of a power plant to investigate large numbers of design points. They are used for scoping studies and to identify areas of feasible design points. Multi-dimensional modelling of the plasma Scrape-Off Layer (SOL), divertor and seeded impurities is too computationally intensive to be incorporated directly into a systems code. Divertor protection parameters such as P_{sep}/R_0 and $P_{sep}B_T/q_{95}AR_0$ have been used as a constraint for capturing the divertor problem in previous studies instead. A 1D SOL/divertor model has been implemented in PROCESS to try and produce more accurate information regarding the divertor conditions. The aim of the 1D model is to determine if the divertor is detached, whether the power crossing the separatrix is consistent with required conditions at the target, and to model the loss of power and momentum along the 1D flux tube. The following physical processes are included: convected heat flux; thermal conduction; momentum conservation; radiation by deuterium, tritium and impurities; charge exchange; electron impact ionisation; and surface recombination. Pumping is not included – all particles striking the target are recycled. The strong shearing of the flux tube near the X-point is not taken into account. As the seeded impurity concentration is increased a discontinuous transition is observed between an attached state, where the plasma temperature at the target is 50 eV, and a state where the temperature at the target hits the lower bound of the simulation, 1.1 eV. We interpret this as a detached state, within the limitations of the model. The 1D model has been compared to 2D models (e.g. the Japanese code SONIC) for DEMO-like machines. However, a large database of DEMO-like runs using the detailed codes is not readily available, so benchmarking the 1D model against detailed codes is an ongoing process. PROCESS now also allows a double-null divertor configuration as an alternative to the single-null considered standard for conventional aspect ratio tokamaks, but to achieve worthwhile power sharing between the upper and lower divertors would seem to require a high degree of control of the plasma position.

PROCESS – 0D

- Simple constraints can be be implemented for divertor protection.
- One common approach is to limit the ratio of the power crossing the separatrix (P_{sep}) over the major radius (R_0).
- Another limit is based on the scaling of the power decay length at the midplane outside (λ_q) with the poloidal gyroradius (Eich et al. 2011, Physical Review Letters, 107, 215001) and is given by including the ratio of the toroidal field on-axis (B_T) over the aspect ratio (A) and safety factor (q_{95}) .
- The limits typically applied in PROCESS are given in the table below:

Diagnostic	Limit
P_{sep}/R_0	17 MW m^{-1}
$P_{sep}B_T/q_{95}AR_0$	9.2 MW T m^{-1}

PROCESS – 1D

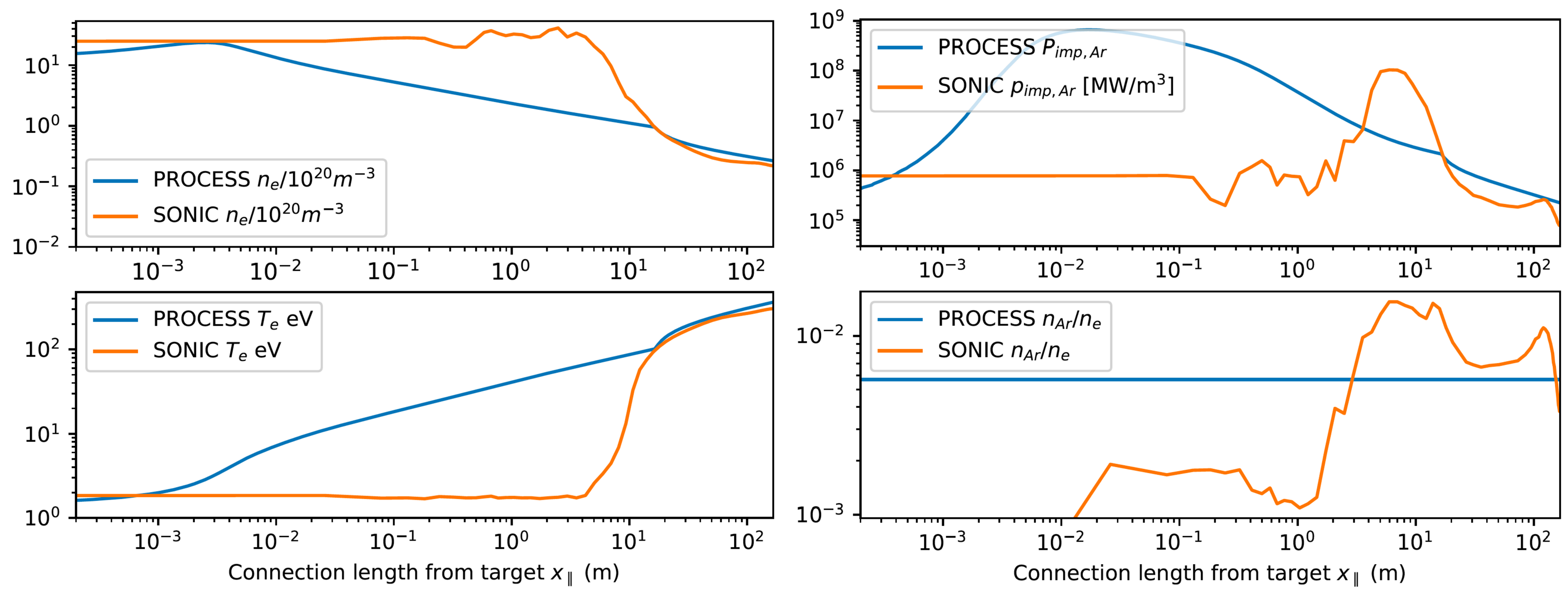
A 1D model based on Kallenbach et al. (2016; Plasma Physics and Controlled Fusion, 58, 045013) has been implemented to model the outer divertor leg. PROCESS contains a set of ordinary differential equations to describe the physical processes in the SOL. The processes modelled include:

- Convected heat flux
- Thermal conduction
- Momentum conservation
- Radiation by D, T and impurities
- Charge exchange
- Electron impact ionisation
- Surface recombination
- Assumes all particles striking the target are recycled (i.e. there is no pumping)

Comparison of the 1D model with SONIC

SONIC (Shimizu et al. 2009, Nuclear Fusion, 49, 065028) is a 2D divertor simulation code that combines IMPMC (a Monte-Carlo impurity code), SOLDOR (a 2D plasma fluid code) and NEUT2D (a 2D Monte-Carlo neutral transport code). Using a 2D geometry, SONIC calculates over multiple flux tubes. For this comparison a single flux tube that is the same radial distance from the separatrix at the outboard midplane as PROCESS is used (2 mm).

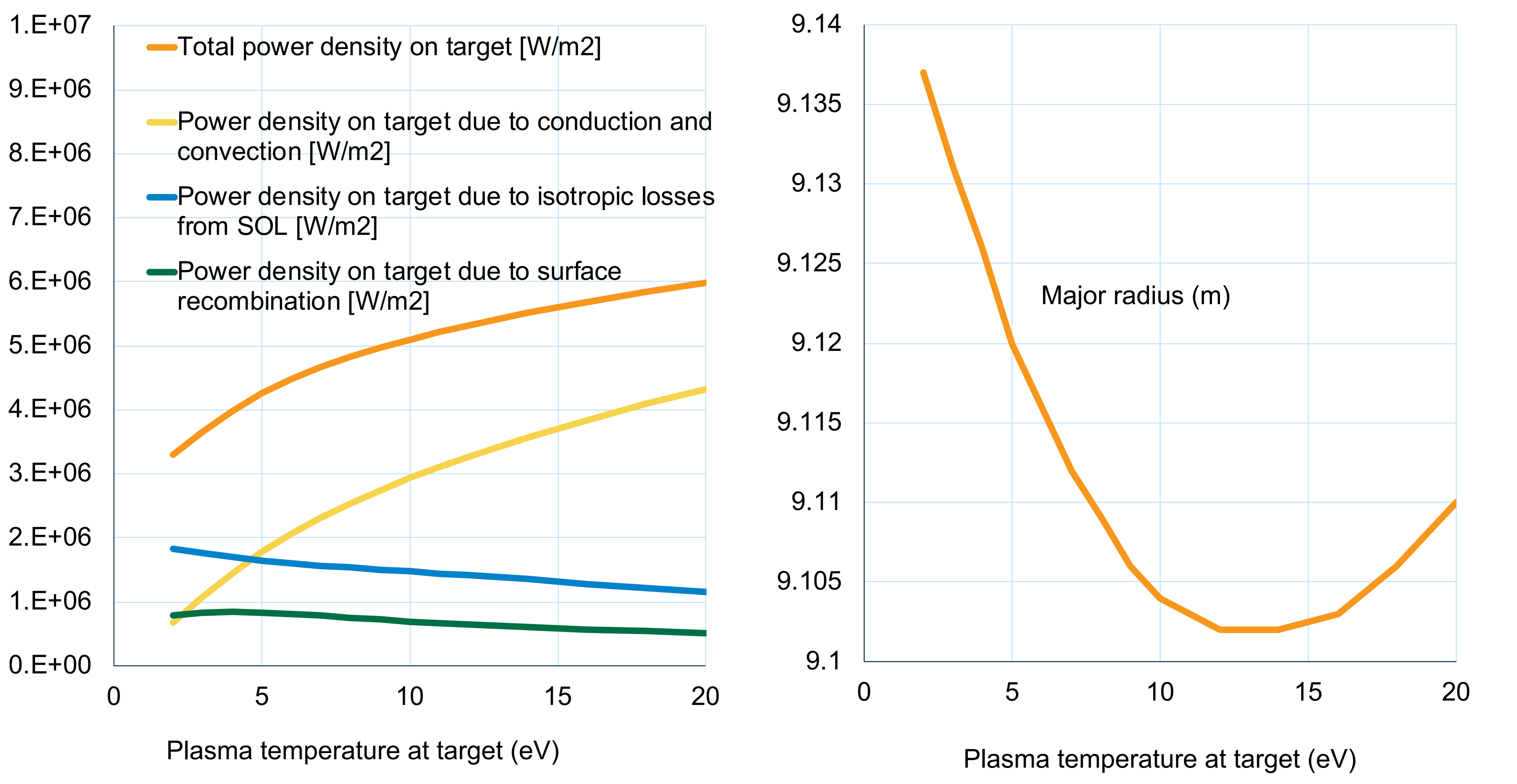
Output	PROCESS	SONIC	Units
Total power crossing separatrix	241	258	MW
Electron density at outboard target	122	195	10^{19} m^{-3}
Electron temp. at outboard midplane	364	303	eV
Electron density at outboard midplane	2.6	2.2	10^{19} m^{-3}
Argon impurity radiation (outer divertor)	73	79	MW



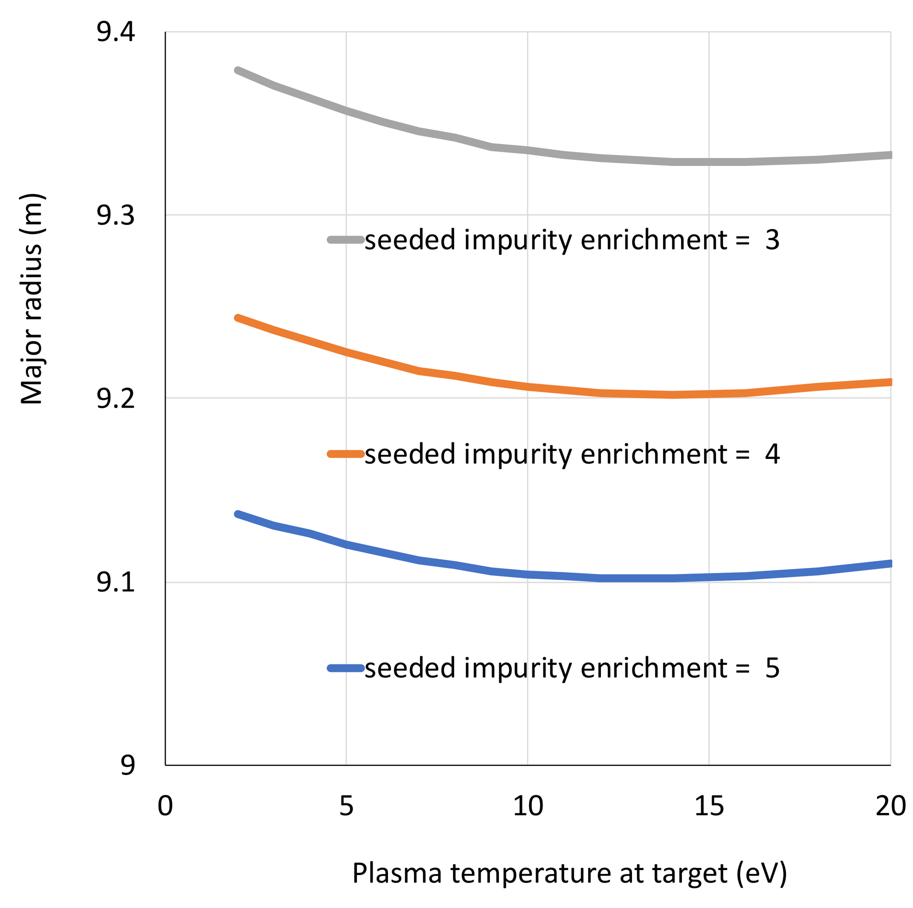
The calculated power crossing the separatrix is in good agreement, as well as the boundary conditions at the target and the midplane. SOL behaviour near the target is not accurately captured in the 1D code because of uncaptured physical processes, such as radial transport near the target, and a fixed argon density, however the purpose of the 1D code is to accurately model detachment conditions and estimate P_{sep}.

Consequences for Optimised Reactor Scenarios

The benefit of implementing the SOL model in PROCESS is that many parameters can be varied independently. Below is a scan as the target temperature is reduced from 20 eV to 2 eV.



- PROCESS increases the argon concentration to lower the target temperature.
- Below 5 eV isotropic emission of fast neutrals due to charge exchange dominates.
- Reducing the target temperature from 20 eV to 2 eV only increases the major radius by 27 mm.
- Reducing the enrichment factor (the ratio of the impurity in the SOL to the confined plasma) increases the core plasma impurity leading to greater fuel dilution and a slightly larger device.



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