The next step in systems modelling: The integration of a simple 1D transport and equilibrium solver

K.V. Ellis* [1], H. Lux[1], E. Fable[2], R. Kembleton[1,3], M. Siccinio[2, 4]
[1] CCFE, UKAEA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[2] Max-Planck Institute for Plasma Physics, Garching, Germany
[3] EUROfusion PMU, Culham Science Centre, Abingdon, OX14 3DB, UK
[4] EUROfusion PMU, Garching, Germany
*Corresponding author. Tel.: +44 (0)1235-46-6993. E-mail address: katy.ellis@ukaea.uk

Introduction Systems codes are used in the conceptual phases of fusion reactor design. They employ a multitude of simplified models to simulate an entire power plant and ensure that designs are self-consistent, viable and optimised with respect to a given figure of merit. Their strength is the fast determination of an overall, consistent design. This cannot replace a detailed study, but aids decision making given complex model interactions.

The **PROCESS** systems code [1] [2] is the leading European systems code, and as such, is being used to design the European demonstration fusion power plant DEMO. It is under continuous development to improve its capabilities. In this paper, we describe the integration of a simple, 1D transport and equilibrium model known as PLASMOD [3] into PROCESS. This represents a significant step up in physical realism with the creation of self-consistent radial profiles including electron density and temperature. Better quantification in this key area give the system design studies for DEMO and other tokamak/power plants higher validity. This supersedes work done in [4].

PLASMOD is a time-independent energy and particle transport model combined with the equilibrium solver also used in ASTRA [5]. Testing has been carried out to ensure a good match with results from ASTRA, which is used routinely in DEMO scenario modelling for EUROfusion. We present initial results from PLASMOD integrated with PROCESS, highlighting the impact on the calculated power plant design, and performance of the newly implemented transport model. This work is novel, as no other systems code fully integrates a transport solver, to our best knowledge. The goal is to increase the turn-around speed when iterating with more detailed physics simulations and lower the risk in the DEMO design procedure.

Code structure The models implemented in PROCESS represent many aspects of a fusion power plant design, including plasma physics, magnet characteristics and structural properties. The inputs can be fixed values, or 'iteration variables' which are varied by the solver to find an optimal result, in combination with a set of 'constraint equations' which must be satisfied for a feasible solution. For each iteration, a set of variables relating to the geometry, physics and engineering are fed to the VMCON [6] solver which determines whether the constraints are satisfied, and if an optimised solution is found. If not, the iteration variables are altered, and another attempt is made.

PLASMOD replaces much of the ‘physics’ functionality, as specified in the following sections. It is called from within the physics subroutine of PROCESS and performs its own iterative process to solve 1D transport equations in the plasma core, including for power and particle balance ensuring the plasma is above the LH-threshold. The 2D plasma equilibrium is determined for a specified plasma shape, via the EMEQ Grad-Shafranov solver. Future developments include fulfilling divertor protection constraints by modelling the scrape-off layer transport and divertor heat loads.

A simple gyro-Bohm transport model, with the output H-factor scaled to replicate the input, is the only one currently available in PLASMOD. Work is on-going to test the validity of H-factor as a genuine output from the model. In the longer term it is planned to add more transport models, such as the trapped gyro landau fluid (TGLF) model.

Integration procedure The PLASMOD code was initially written to run standalone and tested independently of PROCESS using results from ASTRA. Lessons learned from a previous attempt to integrate a similar code into PROCESS drove the requirement for a clear interface between the two codes, and internal loops in PLASMOD which assure that PROCESS does not easily push PLASMOD into unphysical regimes while searching for a constrained, optimised solution. PLASMOD takes already existing PROCESS inputs as well as a number specific to its own solver. New subroutines in PROCESS link the inputs and outputs of PLASMOD to the appropriate variables which then feed back to PROCESS in a fully-coupled system. To help the user switch to the 1D model and get some guidance on how much results might change, PLASMOD can also be triggered just once after a successful PROCESS run.

Physics models PLASMOD supersedes much of the 0D plasma physics modelling, with a more sophisticated and detailed approach. More realistic and precise calculations of fusion power, currents, etc. may be obtained via radial profiles of plasma temperature, density, current and so on. The fusion power is integrated over the core for D-T, D-D and D-He interactions using cross-sections computed by PROCESS. Plasma currents, including bootstrap, and bremsstrahlung radiation are determined by PLASMOD.

While PLASMOD replaces many PROCESS physics models, others are currently maintained, for example the L-H threshold scaling, fusion reaction cross section calculations, EPED pedestal scaling [7], and synchrotron/line radiation loss functions.

Test models An example model with some DEMO-like features was adapted so as to be appropriate for running in PROCESS 1D, ASTRA and PROCESS 0D. In all three cases the 'build' has been fixed, i.e. engineering properties relating to the size and shape of components, including the toroidal field magnets and central solenoid, are not permitted to vary. Net electric power is required to be 450 MW and the H-factor is set at 1.0. Therefore, a direct comparison can be made with respect to the physics models which are being replaced. An alternative approach might be to create models producing the same fusion output and monitor changes in the build, for example the major radius.

Results show that the radial profiles calculated by PROCESS 1D and ASTRA are in excellent agreement, see examples in figure 1. Significant differences are only seen in the total current density core profile (not shown here). This is thought to be due to the simplification of the sawtooth modelling in PLASMOD.

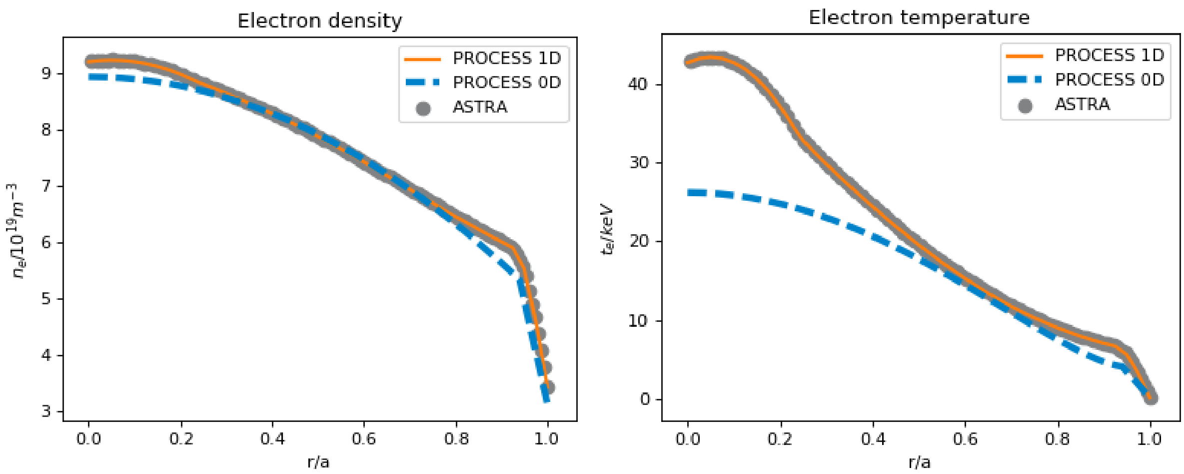

Figure 1: Electron density and temperature radial profiles output from PROCESS 0D and 1D, and ASTRA

PROCESS 0D uses a simple parametrisation from core to pedestal for the electron density and temperature radial profiles. Figure 1 shows that in this case, the electron density profile is a good approximation for the more complex model, but electron temperature is significantly underestimated in the core. For simplicity, PROCESS optimises only one parameter per profile, i.e. the density and temperature at the 'core' and therefore does not output physically consistent profiles. Hence the argument for a 1D model.

Differences in the q profile (figure 2) suggest that the 0D model is unrealistic, and the plasma current required to produce the desired fusion output is being underestimated. The 1D model reports a lower bootstrap current fraction, which in turn lowers the overall efficiency of the machine.

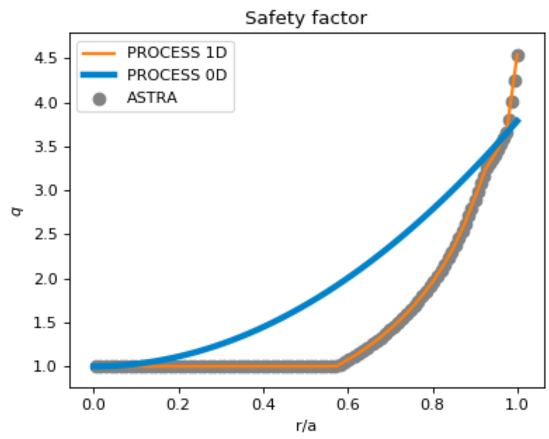

Figure 2: Safety factor, or q profile output from PROCESS 0D and 1D, and ASTRA

CPU time One concern related to the integration of PLASMOD into PROCESS was the expected increase in computing time. PROCESS typically makes a single run in a matter of a few seconds, and this is one of its selling points. The PROCESS 1D results shown here took approximately three minutes to run, albeit from an already well-behaved starting point. Other runs have taken up to 30 minutes. This increase is not considered too costly, and the user still has the option to revert to the original 0D behaviour.

Summary and future work Excellent progress is made in the integration of PLASMOD into PROCESS. The next steps will be to improve the transport model using state-of-the-art theoretical and experimental knowledge, and couple to more sophisticated divertor models, e.g. [8]. Following validation against ASTRA, and comparisons with PROCESS 0D, the usage of 1D transport models is considered a worthwhile step forward which will increase model consistency and hence confidence in PROCESS results, leading to quicker turn-around in tokamak design time.

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