Comprehensive benchmark studies of ASCOT and TRANSP-NUBEAM fast particle simulations

P. Sirén[1,2], E. Tholerus[3], Y. Baranov[3], F. Casson[3], J. Varje[2], Z. Stancar[4] and JET Contributors[*]

[1] VTT Technical Research Centre of Finland, P.O Box 1000, 02044 VTT, Finland

[2] Aalto University, Department of Applied Physics, P.O. Box 11000, FI-00076 Aalto, Finland

[3] CCFE, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, UK

[d] Jožef Stefan Institute, Jamova cesta 39, Ljubljana, Slovenia

*See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)

Introduction

After changing then wall material from carbon to beryllium at JET, significant differences in neutron rate between measurements and calculations have been observed. Typically, neutron rates have been overestimated compared values measured by fission chambers and additionally, similar differences have been seen also between fusion product codes. [1]

ASCOT-AFSI [2,3] and TRANSP-NUBEAM [4] are the most used fast particle and fusion product calculation tools and they have been used systematically in the analysis of different types of discharges at JET. Differences in the results given by ASCOT (coupled to JINTRAC) and TRANSP-NUMBEAM have been mentioned in [1], which concentrated on mainly looking at thermal-fast fusion rate and neutron production rate.

This contribution concludes the most significant observations in the comprehensive benchmark studies where the simulation set up, inputs and implementation of the physics models have been matched as well as is reasonably possible between those codes. Differences in the code implementation have been analysed and discussed in chapter 2 and the code modifications in chapter 3. For the analysis, two widely analysed plasmas (with the neutron rate record) were selected and the main results based on the modified simulation have been reported in chapter 4. The importance of the benchmark exercise and the additional remarks based on the benchmarks between ASCOT and PENCIL [5] and, also comparison with the experimental neutron rates utilising fast and automated execution of ASCOT via JETPEAK database connection [5,6] have been discussed in the conclusion part in the chapter 5.

ASCOT & TRANSP basis

The code implementation and the calculation process in TRANSP and ASCOT differ significantly in some parts. TRANSP is used mainly plasma scenario modelling whereas ASCOT is designed mainly for fast particle following in specific conditions.

Recently, the development of ASCOT, especially at JET has been focused on the system integration (as a part of coupled modelling environment such as JINTRAC and ETS) and in the view of physics, the fusion product analysis. In this contribution, the ASCOT results have been based on the simulation with the ASCOT-JINTRAC version, which enables similar work flow as a part of scenario modelling chain as TRANSP. In addition, in the larger scale benchmarks mentioned in the chapter 5, the automated standalone version was used.

Benchmark set up

There are two significant differences in the beam source physics model in ASCOT and TRANSP. Though, both ASCOT and TRANSP use a similar beamlet model for generating the NBI source, there are small differences in the implementation: in TRANSP, a factor of $\sqrt{2}$ wider Gaussian divergence for the beams is used. For the ionisation cross section, the ADAS beam stopping data is used in ASCOT, while TRANSP uses by default a combination of PREACT and Janev-Boley-Post data.

One of the most fundamental differences which is difficult to eliminate is the equilibrium calculation. An experimental-based reconstruction (EFIT) of equilibrium or a self-consistent ESCO equilibrium solved in JINTRAC. In TRANSP, a dynamic equilibrium, which is internally calculated by TEQ equilibrium solver, is used by default. The NBI ion losses in both codes are calculated using a 2D contour representing the first wall geometry. However, the magnetic field outside the LCFS in TRANSP is extrapolated from the TEQ equilibrium, whereas ASCOT uses the EFIT equilibrium that extends to the wall. There may also be small differences in the wall geometry itself.

Finally, plasma rotation enters the calculation at multiple points: In beam stopping, in the Coulomb collisions during slowing-down and in the beam-thermal fusion cross sections. In ASCOT, each flux surface is assumed to rotate as a rigid body, and a toroidal angular velocity profile is used to calculate the rotation velocity.

Benchmark cases

Two different scenarios from the latest DD campaign (2016) were selected as representative cases for plasma inputs for the benchmark studies: reference baseline plasma #92436 (time interval 47.5-49s) and AT/hybrid plasma #92416 (time interval 44.8-45.6s) with higher fast particle density.

The most interesting physical phenomenon, which affects especially fast-thermal fusion rate is the fast particle fraction. Instead, the ion temperature is the most important parameter to vary thermal fusion rate. In this benchmark fast-thermal fusion rates and production rate profiles were focused on the comparison. Thermal fusion rate is implemented based on the same Bosch-Hale cross section model in the both codes. The effect on beam divergence, Coulomb logarithm and ionisation cross section was studied by modifying ASCOT implementation. However, the total effect coming from those different implementations was not significant (typically around 5% but systematically lower than 10%). Even though some differences were found in the beam source models between TRANSP and ASCOT, these do not cause a remarkable difference in the NBI source profiles. The cross-sections in ionisation are likely very similar, and the beam is probably narrow enough that the difference in the divergence does not significantly affect the beam penetration.

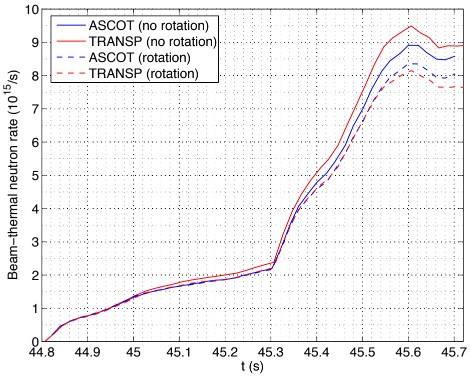
The baseline case has been performed by using time-independent EFIT equilibrium for ASCOT and time-dependent TEQ equilibrium for TRANSP without modifications. Instead in the hybrid case, the both codes were set to used time-independent EFIT equilibrium due to eliminating the effect of the equilibrium especially in the 1.5D output profiles. All simulations have been performed with and without the option of the plasma rotation.

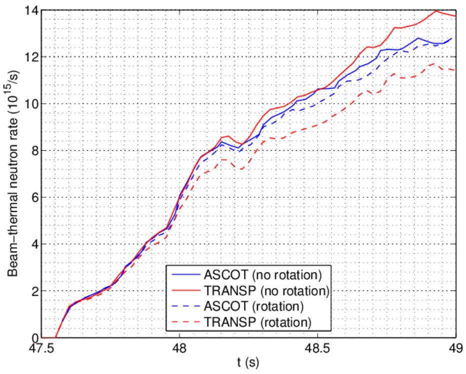
Differences between several output variables, including time traces and the profiles have been analysed and the largest differences have been presented in Table1 between TRANSP-TRANSP, TRANSP-ASCOT and ASCOT-ASCOT (with and without rotation) simulations.

Table 1: Maximum differences (%) between baseline and hybrid plasma benchmark simulations performed based on the fixed input and conditions with TRANSP and ASCOT

	TRANSP-TRANSP		TRANSP-ASCOT		ASCOT-ASCOT	
	Baseline	Hybrid	Baseline	Hybrid	Baseline	Hybrid
Neutron rate	15-17	17-19	10-15	5-7	<6	<8
Neutron profile	17-28	15	<15	<15	<10	<10
Power dep. (max of el/ion)	15	<10	<14	20	12	<6

The largest differences were observed in the effect of plasma rotation. Both test cases have a quite high rotation frequency, which is up to 100 krad/s for #92436 and 80 krad/s for #92416. TRANSP produces significantly larger differences compared to ASCOT, when plasma rotation is enabled. The difference is most apparent in neutron rate (Figure 2), where the difference is up to 17 % in the baseline case in TRANSP, while ASCOT predicts less than 6% difference between rotation and no-rotation cases. The differences in electron and ion heating are more similar between ASCOT and TRANSP in both cases. Largest differences in the comparison between TRANSP and ASCOT can be observed in the neutron production profile (both cases around 15%) and electron power density in hybrid case (20%).





Neutron rate given by ASCOT (blue) and TRANSP (red) with modified settings #92416 and #92436

Conclusions

The comprehensive benchmark studies between TRANSP-NUBEAM and ASCOT-AFSI with the modified simulation set-up where the settings and physics models were modified to match as well as reasonably possible have been presented in this contribution.

In the analysis of JET baseline and hybrid/AT plasmas, the largest differences in neutron rate can be observed between TRANSP simulations with and without rotation and differences in the neutron production profile were larger in baseline plasma simulations, where the different plasma equilibrium has been used but the significant differences in power deposition profile were observed especially in the hybrid case. The effect of rotation is significant, so the implementation of rotation in both codes should be look through more carefully. In the future, the large-scale comparison and benchmark between ASCOT and TRANSP will be done by using JETPEAK database interface for the simulation execution.

References

[1] H. Weisen et al 2017 Nuclear Fusion 57 076029
[2] E. Hirvijoki et al. 2014 Comput. Phys. Commun. 185 1310-1321
[3] P. Sirén et al. 2018 Nucl. Fusion 58 016023
[4] A. Pankin et al. 2004 Comput. Phys. Commun. 159 157-184
[5] P. Siren et al 2019 Role of JETPEAK database in validation of synthetic neutron camera diagnostics and ASCOT- AFSI fast particle and fusion product calculation chain in JET, submitted to Journal of Instrumentation
[6] P. Sirén et al. 2019. Improvements in physics models of AFSI-ASCOT-based synthetic neutron diagnostics at JET. In Press in Fusion Eng. Des.