CONFERENCE PRE-PRINT

FAST ION TRANSPORT SIMULATIONS FOR THE SPHERICAL TOKAMAK FOR ENERGY PRODUCTION

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Abstract

This contribution presents simulations to model the transport of fusion-born alpha particles in the spherical tokamak for energy production (STEP). The work is carried out by two Monte Carlo codes ASCOT and LOCUST. In this contribution, ASCOT results are compared against earlier LOCUST simulation results for toroidal field (TF) ripple and resonant magnetic perturbations (RMPs). Furthermore, simulation results are shown for inclusion of resistive wall modes (RWM) in the simulations. In the effort of producing quantitative estimate of the effect of fast ions to the tungsten sourcing, fast ion losses are recorded as a function of the incidence angle and energy for the sputtering yield calculations. These results show that the current design point of the STEP is stable in terms of basic fast ion transport calculations, and no major showstoppers have been identified during the work.

1. INTRODUCTION

Thermonuclear fusion research is entering an era where burning plasmas will be a reality. While many of the properties of these plasmas can be explored in current day experiments, fusion-born alpha particles will constitute a population of particles that is difficult to reproduce in experiments. Therefore, it is important to employ numerical tools to study the effects of these alpha particles. In particular, the standard design activity for any burning plasma experiment should satisfy the following conditions: 1) the confinement of alpha particles is high such that Q>5 can be reached, when the plasma will be dominantly heated by alpha particles, 2) the losses of alpha particles do not endanger the integrity of the first wall. These questions can be answered for various plasma configurations, ranging from axisymmetric approximation to accounting for 3D magnetic field configurations and possible internal magnetohydrodynamic (MHD) modes causing redistribution of the alpha particle ensemble. In this contribution, such numerical assessment is carried out for the spherical tokamak for energy production (STEP).

STEP is a spherical tokamak prototype power plant with a design point [1] (SPP-001, Rgeo=3.6m) producing roughly 1.5GW fusion energy and 100MW net energy. This translates to a significant alpha particle population. To achieve Q>1, alpha particles need to be well confined. Furthermore, alpha particle losses can pose a threshold for safe machine operation. Therefore, it is vital to understand how fast particle losses scale as a function of main design parameters. Last, but not least, the effect of lost alphas on the tungsten first wall can be detrimental in terms of erosion and associated core plasma radiation. While this contribution presents the alpha particle induced tungsten source rate, the transport calculations of tungsten are left outside of this contribution (the work is still ongoing). To increase the confidence of the numerical simulations, two codes, ASCOT [2] and LOCUST [3] will be used for the analysis.

2. NUMERICAL MODELS

Both ASCOT and LOCUST are Monte Carlo codes tracing particle orbits in the given plasma and magnetic field configuration. However, the codes have distinct features: LOCUST relies solely on full-orbit tracing while ASCOT can be used with a guiding centre approximation as well. It is well-known [4] that fast ions in spherical tokamaks cannot be modelled with guiding centre approximation, hence both codes are run using gyro motion tracking. Another difference between the codes is the numerical interpolation of the magnetic field data. ASCOT relies on a 3D spatial grid given in the cylindrical (R,phi,z) coordinate system, while LOCUST can also utilize Fourier decomposed fields. This becomes important when MHD perturbations are modelled.

The magnetic field studied in this work has a dominant contribution from the axisymmetric equilibrium. In both codes, this will be modelled using a common EQDSK file. In addition, a cylindrical perturbation like that shown in [5] will be implemented to model the toroidal field ripple. Lastly, external coils used for ELM mitigation will further perturb the equilibrium field. To model this, the vacuum perturbation is calculated using the Biot-Savart law and plasma response is calculated using the MARS-F model [6] as in [5]. The only MHD perturbation considered in this work is the resistive wall mode (RWM). This perturbation will be implemented using the MARS-F calculation, similarly as was done for the plasma response to ELM coils. In the ASCOT simulations, 100 000 markers are used to calculate the slowing down ensemble of alpha particles and to estimate the losses in the first wall.

3. RESULTS

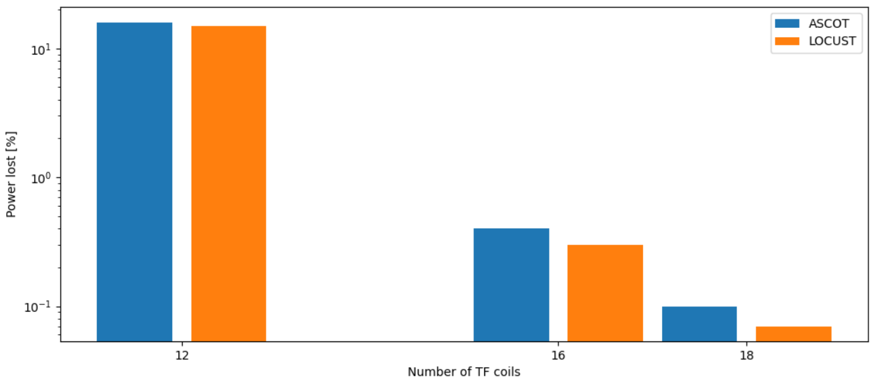

FIG. 1. Comparison of ASCOT and LOCUST for the TF ripple with different number of TF coils (right).

Depending on the size, geometry, and the purpose of the device, the number of toroidal field (TF) coils can generally range anything between 12 and 30. The exact number will be a compromise between spatial requirements and price, with the need to reduce the non-axisymmetry of the magnetic field caused by the finite number of TF coils, dubbed TF ripple. For alpha particles, the general trend is such that more coils will reduce to a smaller TF ripple and, thus, smaller losses.

To study the impact of the number of TF coils for confinement of alpha particles in STEP, ASCOT was used to repeat the earlier LOCUST simulations to gain further confidence on these simulations, see Fig. 1. For a wide range of coil parameters, ASCOT results were found to be consistently above LOCUST results. The absolute error decreased with increasing losses, being less than 5% for losses of around 3.5%. The reason for the discrepancy is unknown, but the impact of input files has been ruled out as a possible explanation. Despite the discrepancy, both codes give losses that are acceptable when the number of TF coils was taken to be 16 or 18. For this STEP design, the nominal number of TF coils was selected to be 16.

Tokamak experiments are typically operated in so called H-mode. This applies to STEP as well. While the performance of the plasma is increased in H-mode, the negative effect will be the so-called Edge Localised Modes (ELMs) that will flush part of the plasma to the first wall. To mitigate the effect of ELMs, resonant magnetic perturbations can be applied using individually wired coil sets. This is planned for STEP as well. However, the non-axisymmetric magnetic field caused by these ELM coils could potentially cause additional losses of alpha particles.

To study the effect of ELM coils on alpha particles, ASCOT repeated the earlier finding of the resonant magnetic perturbation field calculations. ASCOT and LOCUST codes were found to have a similar trend also here in terms of discrepancy as for TF coil study mentioned above. Despite ASCOT being consistently above LOCUST, the two produced a similar scaling with the main design parameters such as number of TF coils, radial location of the TF coil leg and parameters of the RMP perturbation, thereby building trust in the numerical analysis. Two RMP cases, together with an axisymmetric scenario, are shown in Figure 2. The figure confirms the hypothesis that RMP cases show increased alpha particle losses. However, the losses are well below the design threshold for safe and performing operation.

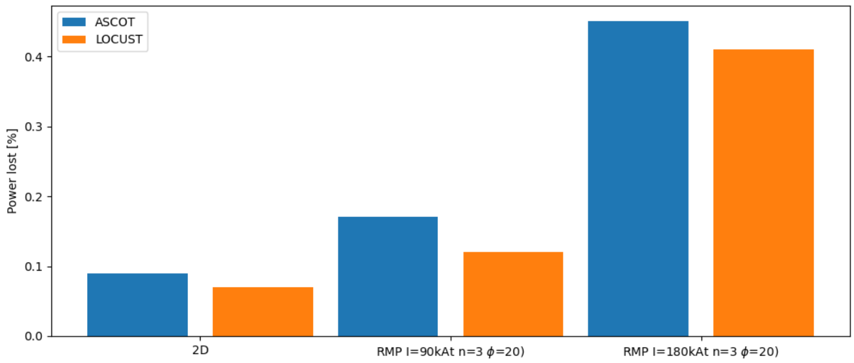

FIG. 2. Comparison of ASCOT and LOCUST for an axisymmetric magnetic field and for two RMP cases with 90 kAt current and for 180 kAt current In each case there is a phase difference of 20 degrees between the upper and lower coil sets.

Many modern tokamak devices operate with so-called advanced scenarios. The idea behind these is to increase the normalized plasma pressure, so called plasma beta parameter. However, the plasma beta is limited by external kink modes. This is especially true because of the finite resistivity of the limiting wall. Such kink modes introduced by the limited resistivity are referred to as resistive wall modes (RWM). There exist ways to limit the amplitude of RWMs. While crucial for plasma stability, controlled RWMs could potentially also cause a magnetic field perturbation sacrificing the confinement of alpha particles.

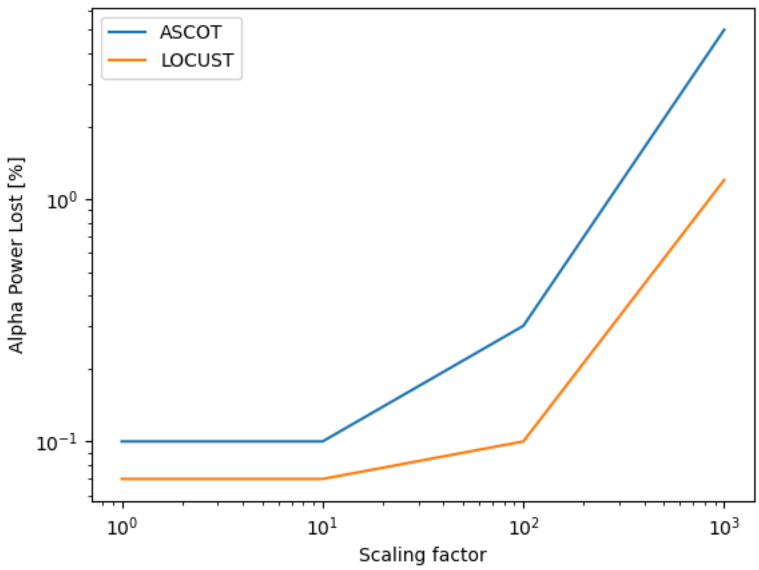

FIG. 3. Scaling of the losses calculated using the ASCOT and LOCUST codes as a function of the RWM saturation amplitude.

In Figure 3, alpha particle losses caused by a resistive wall mode are illustrated. Here ASCOT is again above LOCUST consistently. A scaling factor was used to scan the amplitude of the RWM perturbation, as the saturation amplitude was not modelled with the linear MARS-F simulations. Interestingly, here the relative error is not converging with increased losses as was the case for number of TF coils above. Further analysis shows that the magnetic field with the higher scaling factors have a significant divergence, making these cases vulnerable to numerical diffusion. In a later stage, our plan is to include the additional perturbation caused by the coils used to mitigate the RWMs. These could potentially cause further alpha particle losses, especially as the perturbation will be time dependent.

Lately, some concern has been raised on the possibility for fast particles to cause sputtering of the first wall material. This is especially topical since many modern tokamaks are designed to operate with full tungsten first wall. It was found in the ASDEX Upgrade tokamak that fast ions from neutral beam ion heating can contribute to the total sputtering [7]. To study this effect, the source of sputtered ions needs to be assessed. The standard procedure for this is to use the sputtering yield, the ratio of sputtered particles to incident particles (here, only alphas on tungsten are considered). The sputtering yield is a known to be a function of the incident alpha particle energy and incidence angle (defined as the angle between the velocity of the alpha-particle at the point of impact and the normal to the surface). The sputtering yield can be calculated using, e.g., the SDTrimSP code [8].

ASCOT was used to record the exact loss location of all lost alphas. In addition to the location, the incidence energy and incidence angle were recorded. These quantities are needed to further calculate the spatial tungsten sputtering yield thus enabling calculation of the source of tungsten atoms due to alpha particle impact on the first wall. Figure 4 illustrates the typical alpha particle energy and incidence angle spectrum for a selected STEP SPP-001 RMP scenario. As can be seen, a wide energy range up to 3.5 MeV with mainly incidence angles around 70-80 degrees are recorded. Sputtering yield calculations using SDTrimSP code show, see Fig. 5, that the tungsten sputtering yield is of the order of 0.1, much higher than it would be for hydrogenic species. Integrating over the full first wall for all alpha particle losses, this results in a tungsten source rate of roughly 1e18 tungsten/s. Next, these simulation results will be fed to impurity transport simulations to estimate the amount of tungsten making its way to the core STEP plasma and to assess their impact on plasma performance. Further analysis of the tungsten transport is outside the scope of this contribution.

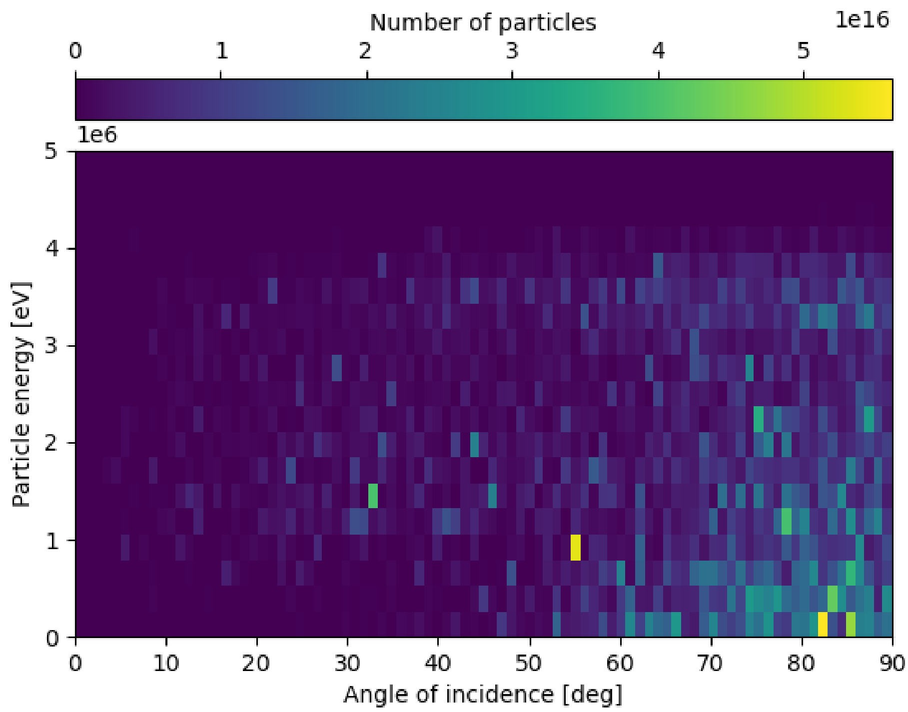

FIG. 4. Alpha particle energy and angle of incidence when alphas are lost to the first wall. The simulation is shown for the RMP scenario with 180 kAt, n=3 and phase shift of 20 degrees.

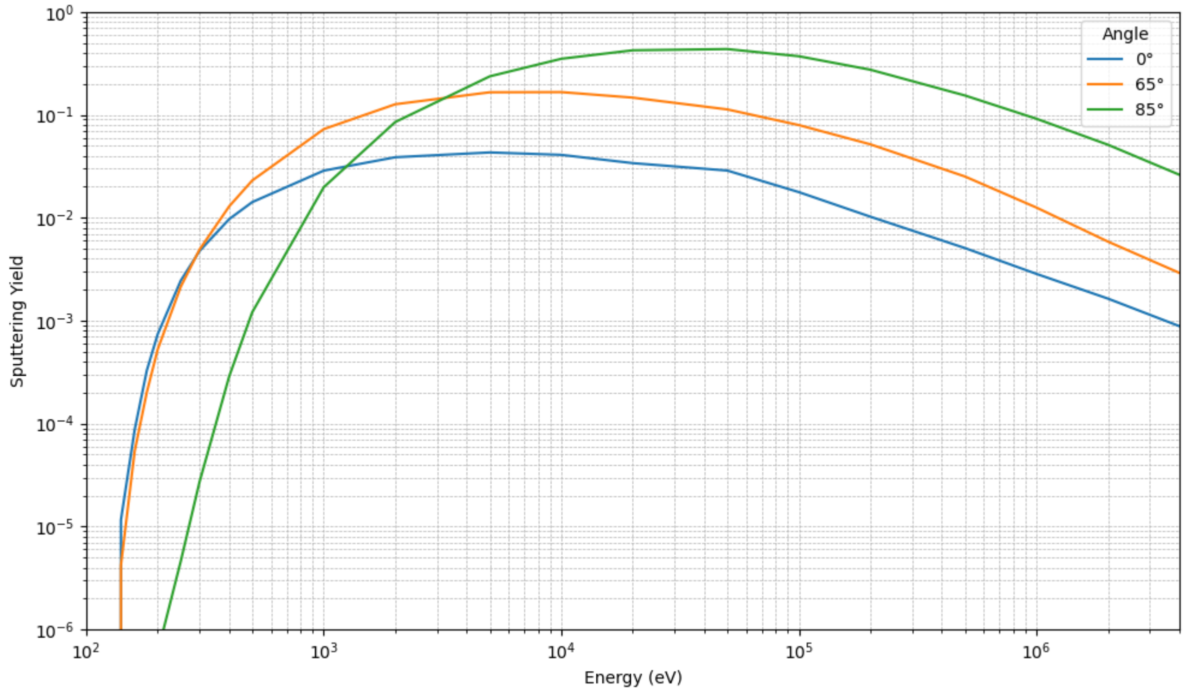

Figure 5: Sputtering yield of tungsten with a incident alpha particles of given energy (x-axis) and incidence angle (different curves).

4. SUMMARY, CONCLUSIONS AND OUTLOOK

To conclude, ASCOT and LOCUST have been used to study alpha particle physics in STEP. The two codes agreed well for losses due to TF ripple, RMP and RWM perturbations. For both the TF and RMP cases, ASCOT losses were higher than those of LOCUST, with relative error decreasing with increasing losses. However, this decreasing trend was not observed for the RWM case possibly due to numerical issues caused by the large RWM perturbation field. All in all, these two Monte Carlo codes produce similar scaling as a function of the main design parameters, building confidence in the numerical results.

Besides the comparison study, ASCOT was used to record basic properties of the lost alpha particles to use this information for the sputtering calculations of the first wall tungsten atoms. Further work is needed to quantitatively analyse the tungsten transport due to alpha particles and compare the effect of alphas to the thermal sources.

While the work described above is concentrated on single configuration (SPP-001), further work is currently being carried out for the next iteration of the STEP design parameters.

ACKNOWLEDGEMENTS

This work has been funded by STEP, a UKAEA programme to design and build a prototype fusion energy plant and a path to commercial fusion.

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