Fusion-born alpha particles and the role of full gyro-orbit simulation in the Gauss GIGA stellarator: a study with ASCOT5

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Abstract

One of the optimisation criteria for stellarators is the confinement of the fusion-born 3.5 MeV alpha particles. In this work, the slowing-down process and wall loads of fusion-born alpha particles have been simulated for the conceptual design equilibria of the GIGA stellarator using the orbit-following Monte Carlo code ASCOT5. GIGA is a stellarator currently under development by Gauss Fusion GmbH. It is a four-field-period device with 3 GWs of fusion power and a major radius of approximately 20 meters. In the slowing-down simulations, the lost power varied between 12 % and 23 % with higher plasma densities corresponding to lower losses. The results were obtained using four million guiding centre (GC) markers. The *full power* scenario was also repeated as a full gyro-orbit (FO) simulation. Switching from GC to FO increased the power loss from 16 % to 20 %. The effect of a radial electric field on the confinement was studied in the full power scenario. Neglecting the electric field increased the power losses from 16 % to 20 %, a trend which was expected. The wall loads were investigated in the full power scenario. This simulation with 120 million markers was carried out using the new GPU porting of ASCOT5. Largest wall loads were observed near the toroidal angle of 45 degrees on the outboard divertors and on the wall between these divertors. A portion of the pre-conceptual divertor reached loads above 20 MW/m^2, with a peak load of 66 MW/m^2. The results of this work provide feedback to the further optimisation and development of the GIGA stellarator equilibrium design.

1. Introduction

The stellarator magnetic field leaves a lot of room for optimisation. One of the optimisation criteria is the confinement of the fusion-born 3.5 MeV alpha particles. Firstly, they must deposit the majority of their energy into the plasma so that the plasma stays sufficiently hot for the fusion burn to continue. Secondly, the alpha particles should not produce intolerable heat fluxes on the device inner wall. Both the slowing-down process and wall loads of fusion-born alpha particles have been simulated in the GIGA stellarator and are reported here. The simulations have been performed using the orbit-following Monte Carlo code ASCOT5 [1, 2].

GIGA is a stellarator currently under development by Gauss Fusion GmbH. It is a four-field-period device concept with 3 GWs of fusion power and a major radius of approximately 20 meters [3]. In this work, the slowing down of fusion-born alpha particles has been studied in four different plasma scenarios, see Figure 1. The scenarios have different densities and temperatures, leading to a fusion power ranging between 0.5 GW and 3 GW. These correspond to an alpha power of 100 MW and 600 MW, respectively. After their birth, the population of alpha particles starts to lose energy by colliding with the background plasma. We refer to this as *power deposition*. Some of the energy will also be lost from the plasma, resulting in *fast-ion wall loads*. These are additional wall loads to the power load due to the bulk DT plasma (and radiation). The bulk plasma nor radiation power loads are not considered in this work. Assuming similar material limits than ITER [4], at the very most, a total heat flux of 20 MW/m^2 on the wall could be tolerated but on most wall areas the safe operation limit is considerably lower. Here, the wall loads have been studied in the *full power* scenario since it has the highest alpha power and it is the scenario relevant for steady-state power production.

2. Simulating fast ions with ASCOT5

ASCOT5 follows an ensemble of markers in a 3D magnetic field, subject to collisions and drifts. The background magnetic field and profiles are generated by the BEAMS3D [5] code which makes use of magnetic field from VMEC [6], profiles based on 0.5D power balance modeling, and radial electric fields produced by the PENTA [7] code. ASCOT5 simulations allow the construction of the slowing-down distribution of the alpha particles and the investigation of the wall loads induced by them. For practical reasons, the simulations are carried out in two parts.

1. *Slowing-down simulation:* The alpha particles are followed from their birth location until they thermalise[1] or reach the last closed flux surface (LCFS).
2. *Wall load simulation:* The particles that reached LCFS are further simulated until they hit the device wall.

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[1] Here, the particles are counted as thermalised if either their energy falls below $2T_e$ or below 2 keV.

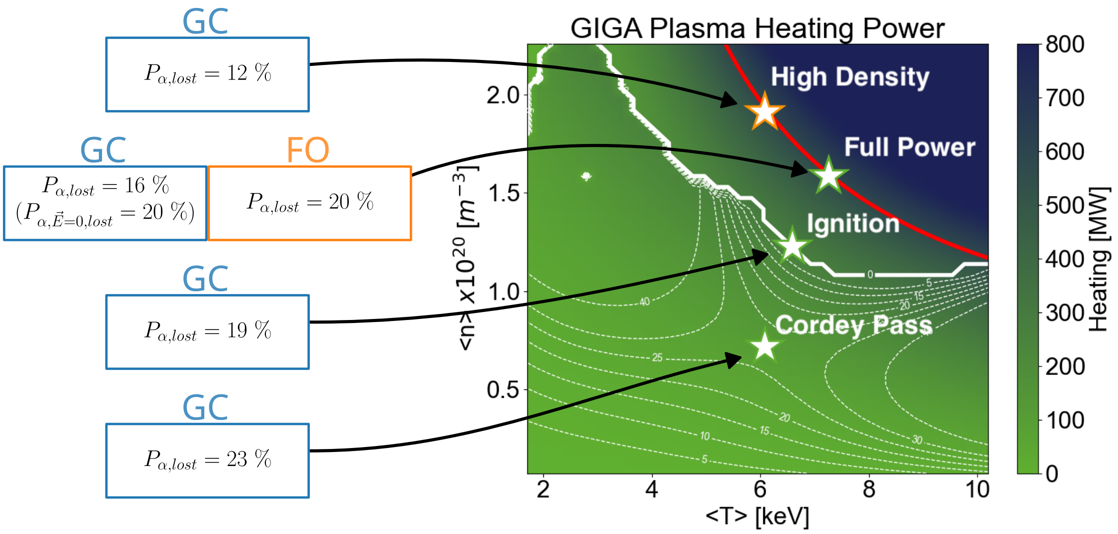

Figure 1: Plasma operating contours (POPCON) plot indicating the four scenarios which were studied in this work. White lines indicate auxiliary power contours, while the red line defines 3 GW fusion power. Alpha power loss percentages are depicted for each scenario.

The first part of the simulation produces the slowing down distribution inside the LCFS. This allows, in particular, the evaluation of the power deposition profile. Another key result of this first part is the amount of power deposited and the amount of power that reaches the LCFS. The latter is referred to here as the *lost power*. This first part of the simulation is typically carried out by following the orbits of guiding centres (GC) as this saves computational resources. In the present study, GC simulations were performed in all of the four scenarios. Additionally, the *full power* slowing down scenario was repeated by following the full gyro-orbit (FO) of the alpha particles.

The second part of the simulation, termed the *wall load simulation*, reveals the possible hot spots caused by the alpha particles. The gyroradius of an alpha particle can be as high as ~ 5 cm, meaning, it is not negligible compared to the device dimensions. Consequently, the wall load simulations must always be performed using the FO following to obtain sensible results.

It is now possible to construct two workflows for simulating alpha particles: a *hybrid workflow* and a *full gyro-orbit workflow*. In the former, we first follow GC markers until the LCFS and then continue the simulation in FO mode until they reach the wall. In the full gyro-orbit workflow, we use FO markers both in the slowing down part and in the wall load part. Lastly, we note that both workflows allow sampling of more markers for the wall load simulation. This was utilised in one of the simulations where first 8×10^6 FO markers were followed until LCFS and then 120×10^6 FO markers were followed until the device wall. The latter part was carried out using the new GPU port of ASCOT5.

3. Results and discussion

3.1 Slowing down

In all four cases, the particle losses happen on two different time scales as illustrated in Figure 2. We refer to the first batch as *collisionless losses* and the second as *collisional losses*. The fraction of lost power varied between 12 % and 23 % with higher plasma densities corresponding to lower losses, see Figure 1. There may be several reasons for this. Density affects the confinement through collisionality. Having a higher collisionality leads, on the one hand, into faster power deposition, and on the other hand, to modified radial transport. In addition to collisionality, the changes in density also influence the magnetic field through diamagnetic effects. Thus, it is also possible that the changes in confinement with varying densities are due to changes in the magnetic field topology. The reasons for the improved confinement were not studied further.

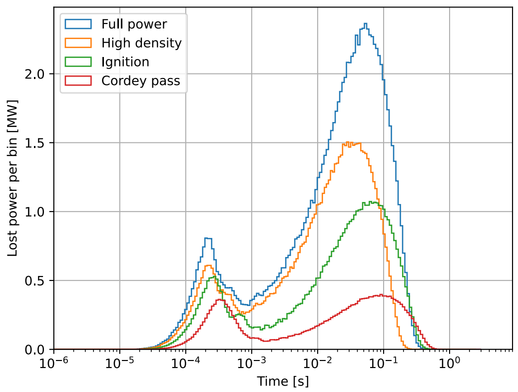

Figure 2: Lost fusion alpha power during the slowing down process in different scenarios.

A radial electric field can improve the confinement of fast ions by inducing a poloidal drift that helps to cancel the radial transport. The effect of a radial electric field on the confinement was studied in the full power scenario using GCs and it was found that neglecting the electric field increased the power losses from 16 % to 20 %.

Following the four GC studies, the *full power* scenario was also simulated using FO markers. Switching from GC to FO increased both collisionless and collisional losses, see Figure 3. Due to this, the total power loss rose from 16

% to 20 %. The result is particularly interesting since typically the alpha-particle slowing-down simulations in stellarators are carried out with GC markers to save computational resources. There is no particular reason to believe that the phenomenon would be limited to the *full power* scenario but the computational resources of the project did not allow to study the rest of the scenarios with FO.

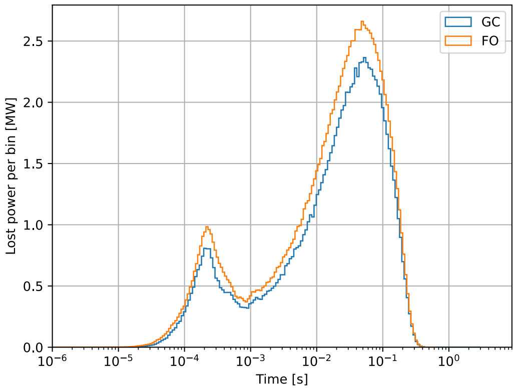

Figure 3: Lost fusion alpha power during the slowing down process: GC vs FO.

It has been noted that nested flux surfaces in a stellarator do not imply nested drift surfaces [8, 9]. In the *full power* scenario, it was found that, while the flux surfaces are nested, the drift surfaces exhibit islands as shown in figure 4. The guiding centre density is decreased at the ρ corresponding to the islands. However, the particle density is hardly affected since, due to their gyromotion, the full gyro-orbit markers in essence "filter out" this feature. The density decrease at $\rho \approx 0.1$ overlaps with drift islands for counter-passing 3.5 MeV alphas (not shown).

3.2 Fast ion wall loads

The alpha particle wall loads were studied in the full power scenario by following 120×10^6 markers from LCFS until they hit the wall. These were generated from the end states of the previous slowing down simulation. The simulation was carried out using the new GPU port of ASCOT5 [10], running on the CSC LUMI supercomputer. It was found that the highest alpha particle wall loads occur on the outer side of the device at around toroidal angle of 45° (in the middle of the four periods). The areas with highest alpha particle wall loads are shown in Figure 5.

Following this project, Gauss Fusion has utilised the wall load results to further develop their divertor design from the pre-conceptual divertor that was used in the simulations reported here. The developed divertor version can be seen in Figure 6 where the Poincaré plane corresponds to 45°.

3.3 Computational times

ASCOT5 is able to simulate test particles on CPU and on GPU hardware. Already the CPU version is efficiently parallelised through hybrid parallelisation and with vector instructions. Since this work was one of the first applications of the GPU porting, we present the computational resources used for the slowing down and wall load simulations in table 1. The run times relevant for the hybrid workflow are shown above the dashed line whereas the run times for the completely full gyro-orbit simulations are shown below the dashed line.

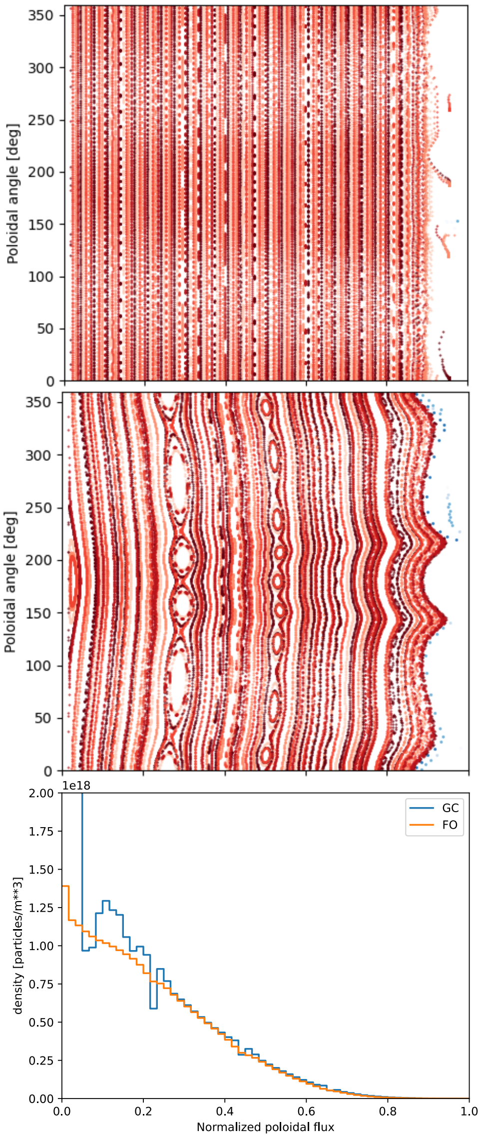

Figure 4: Top: Field line Poincaré plot at $\phi = 45°$. Middle: GC Poincaré plot for co-passing 3.5 MeV alpha particles at $\phi = 45°$. Bottom: FO and GC alpha particle slowing down profiles.

4. Conclusions

The most interesting slowing-down scenarios are the full power and high density since they correspond to the targeted 3 GW fusion power. Gauss Fusion is using these results as they continue optimising the device. We also note that based on the discrepancy between FO and GC simulations, GC simulation results should be used with caution.

The study regarding the electric field confirmed that the electric field indeed has a noticeable effect and, therefore, the electric field should be modelled properly. In the current version of ASCOT5, the electric field implementation does not properly take into account that the distance be-

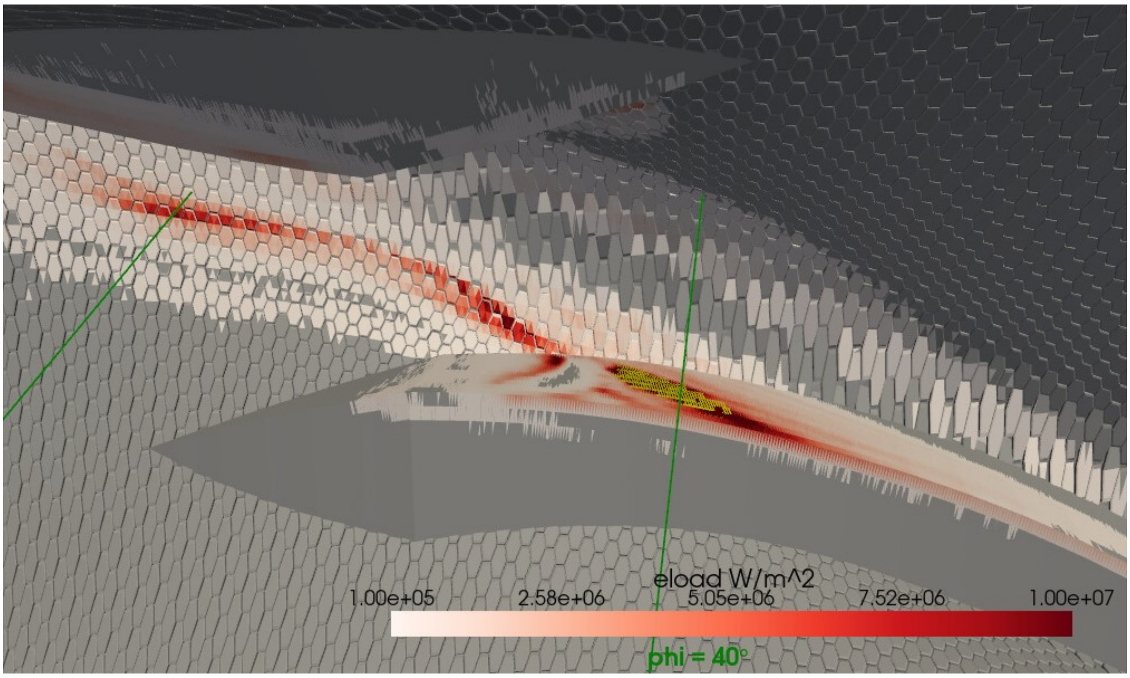

Figure 5: Alpha particle wall loads solved using 120×10^6 FO markers. Green lines indicate toroidal angles of 40° and 50°. The yellow areas have a heat flux above 20 $\mathrm{MW/m^2}$. The colourbar has been capped; the true maximum is 66 $\mathrm{MW/m^2}$

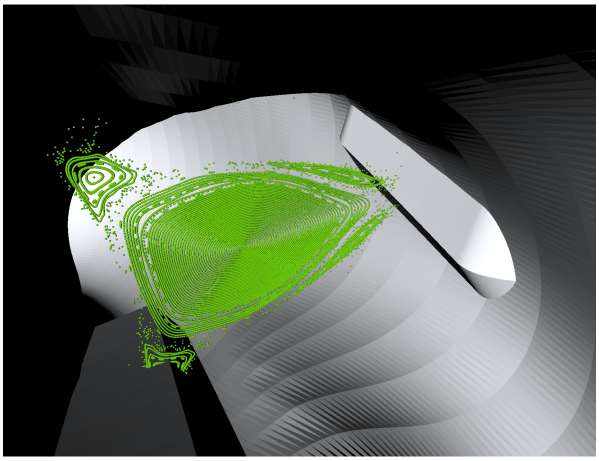

Figure 6: Improved divertor design that was influenced by the results of this study. The Poincaré plane corresponds to 45°.

tween two flux surfaces can vary significantly as a function of the poloidal angle. Since the confinement of low collisionality particles is rather sensitive to the electric field magnitude [11], this part of the model should be improved before any subsequent simulations. Finally, we also note that the effect of the plasma outside the LCFS is completely neglected while in reality it could have an effect on the hot spot location and their spread [12].

Acknowledgements

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Table 1: Run time comparison. First two rows showcase hybrid workflow, last two rows full gyro-orbit workflow.

Simulation	#markers	run time
GC slowing down to LCFS	4×10^6	$60 - 130$ kcoreh[a]
FO markers from LCFS to wall	$\sim 2 \times 10^6$	1 kcoreh[a]
FO slowing down to LCFS	8×10^6	1600 kcoreh[a]
FO markers from LCFS to wall	120×10^6	2200 GPUh[b]

[a] AMD Rome 7h12 CPU, CSC Mahti
[b] AMD MI250x GPU, CSC LUMI

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