Orbit-following fusion alpha wall load simulations with full orbit wall collisions

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Introduction. Fusion alpha particle losses from tokamaks with magnetic field ripple are of great concern because they may lead to highly localised power peaks on the first wall components. In axisymmetric or weak-magnetic-ripple cases and in devices of low or moderate aspect ratio, guiding centre simulation is often assumed accurate enough to produce realistic wall and divertor loads. In the case of hot ions, however, transport mechanisms related to the finite Larmor radius [1] may play a significant role and affect alpha loss rate and wall load results especially in large-aspect-ratio or strongly non-axisymmetric configurations.

In collisionless inductive-mode ITER simulations, guiding centre and full orbit estimates of alpha loss rates have been found to be broadly consistent [2]. In a recent comparison of guiding centre and full orbit simulations [3], however, a notable difference was observed in the power loss rates for ITER Scenario 4 without ripple mitigation. These simulations were made on a few-millisecond time scale, just long enough to see orbit losses and prompt collisionless losses caused by ripple. As the simulations were limited to inside the separatrix, wall loads were estimated at the last closed flux surface, omitting possible re-entry.

In the present work, both guiding centre (GC) and full orbit (FO) simulations are made using the orbit-following Monte Carlo code ASCOT, modelling both unmitigated and ripple-optimized cases for ITER Scenario 4. Load profiles on the wall are obtained by following an ensemble of fusion alphas until they slow down past 100 keV or collide with the wall. Alpha losses from pure GC simulations on the slowing-down time scale are compared to results refined by near-wall full orbit simulation as well as pure full orbit simulations.

The ASCOT code. ASCOT [4] is an orbit-following Monte Carlo code capable of using fully 3D magnetic backgrounds of real tokamaks and 3D wall data including non-periodic and protruding elements such as limiters. It can follow escaping particles all the way to the vessel wall. Recently, full Larmor orbit capability using the leapfrog Boris method has been added.

The 3D wall collision model, used for both GC and full orbit collisions, is based on a fast ray-polygon collision algorithm [5]. As the finite Larmor radii of energetic ions can significantly affect the wall hit location as compared to GC simulation, an improved wall collision model has been added to ASCOT. The GC distance from the nearest wall element is now monitored, and when it becomes less than or equal to the local Larmor radius, ASCOT can optionally switch from GC to FO simulation. This GC+FO scheme simply refines the wall hit locations. The GC equations of motion are solved alongside the full orbit solution. If no wall collision occurs and the GC distance to the wall again exceeds the Larmor radius, GC simulation is resumed from the exact location given by the GC equations of motion. This is done because switching between the GC and FO location accurately enough for orbit-following purposes (with the related changes in velocity components and constants of motion) is not trivial.

Simulations. In order to simulate fusion alpha wall loads in a realistic ITER background, the 3D magnetic field for ITER Scenario 4 was used. This is a steady-state scenario with a weakly reversed central shear and a relatively low plasma current of 9 MA. Without modelling of the ferritic inserts for ripple mitigation, the maximum ripple amplitude at the separatrix is 1.1%. As the low plasma current makes Scenario 4 especially vulnerable to ripple losses, and as the fusion power is concentrated near the magnetic axis, this was selected as the high ripple case. When the effect of optimized ferritic inserts is modelled, the maximum ripple amplitude at the separatrix is 0.25%. This was used as the ripple-optimized case.

Scenario 4 plasma profiles (D, T, He, 3He, Be, Ar) with core T_e = 24 keV and core n_e = 0.72×10^{20} 1/m^3 were imported for creating the appropriate alpha test particle ensemble and for modelling Coulomb collisions of test alphas with a Maxwellian background. A 3D ITER wall with poloidal limiters at each toroidal period was used for recording alpha wall collisions. About 50000–100000 3.5 MeV alphas were initialized on a poloidal 2cm×2cm grid at random toroidal angle and a weight factor calculated from the local fusion rate and volume element.

Pure guiding centre simulations (GC), guiding centre simulations with near-wall full orbit modelling (GC+FO) and pure full orbit simulations (FO) spanning almost the whole fusion alpha slowing-down period (down to 100 keV energy) were made for both the high ripple and the optimized scenarios in order to evaluate the full orbit effects on the wall load profiles.

The load distribution on the 3D wall is shown in Fig. 1 for the GC+FO simulations in the high

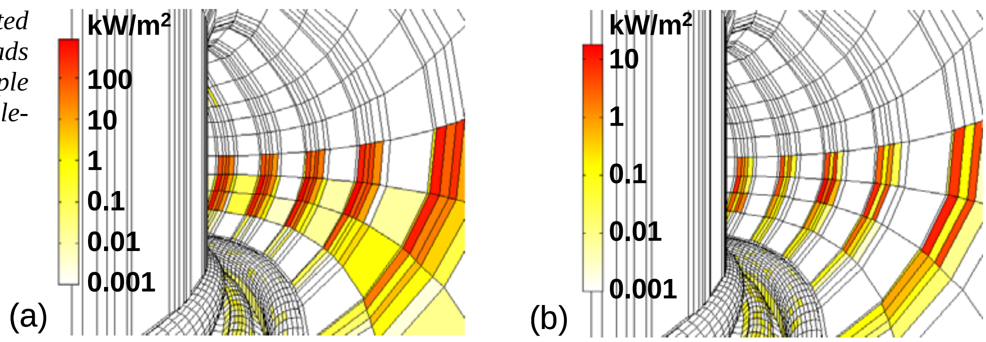

Figure 1. Simulated fusion alpha wall loads for (a) the high ripple case and (b) the ripple-optimized case.

ripple case and the optimized case. In the high ripple case, the "hot spot" peak loads for the GC, GC+FO and FO cases were 1.32, 1.20 and 1.97 MW/m^2, respectively. In the optimized case, the "hot spot" peak loads were (in the same order) 26.7, 45.3 and 144.2 kW/m^2.

Figure 2 shows the toroidally averaged wall load profiles vs. the poloidal angle θ. Compared to pure GC simulation, GC+FO simulation emphasizes the peak just below the outboard equator. The peak is caused mostly by energetic ripple-transported alphas with a large Larmor radius (several cm) not accounted for in pure GC simulation. The peaks on the lower outboard wall (θ = –80°...–40°) are mostly caused by orbit losses and neoclassical diffusive losses.

In slowing-down simulations, switching from GC to FO simulation near the wall only adds about 0.1% to the overall CPU time. While FO simulation is about 100 times as CPU-intensive as GC simulation, typically only the last time step needs to be done in FO mode while ~10^5…10^6 GC time steps are taken to follow an alpha particle while it is slowing down.

Pure full orbit simulation increases the toroidally averaged peak load just below the outboard equator even further by taking into account the ripple transport mechanisms that are lost in the guiding centre approximation [1]. Thus more realistic results are obtained, but the CPU requirements are increased by two orders of magnitude. The present two pure full orbit simulations took about 14 000 node-hours each on the HPC-FF supercomputer.

For the high ripple case, with enough alpha losses for good statistics, the pure FO peaks on the lower outboard wall are in good agreement with the GC+FO result, indicating that these peaks arise from other causes than ripple loss (orbit losses and neoclassical diffusion).

In the high ripple case, the alpha loss fraction is increased from 8.7% to 20.2% (including slowing-down alphas), and the toroidally averaged equator peak load is increased by 50% to about 140 kW/m^2. The same effect is particularly pronounced in the ripple-optimized case.

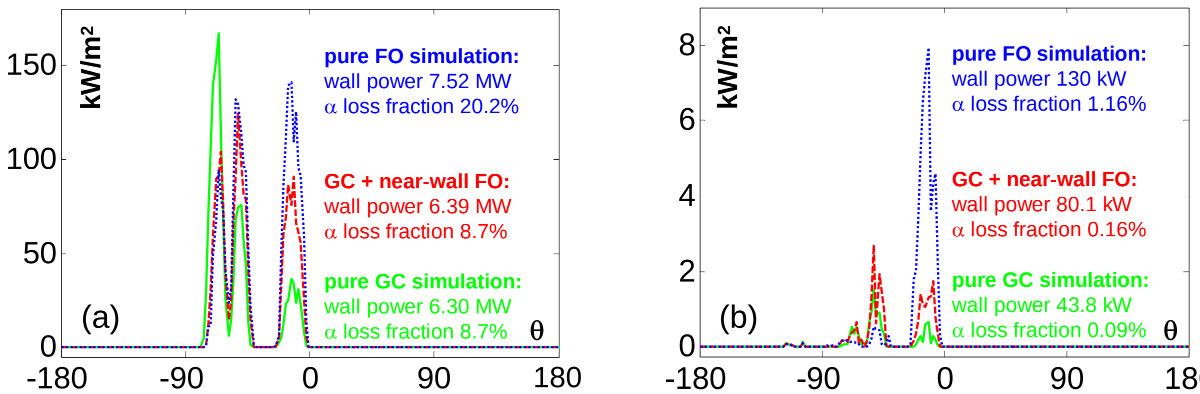

Figure 2. Toroidally averaged alpha wall loads for (a) the high ripple case and (b) the ripple-optimized case. The pure GC result is shown in green, the GC+FO result in red/dashed line and the pure FO result in blue/dotted line.

The reason for this is either the added structure in the toroidal magnetic field, due to the ferritic inserts, or the low overall alpha loss rate (0.16% for the GC+FO case and 1.16% for the pure FO case) which emphasizes the ripple-transported energetic alpha contribution. Even so, the toroidally averaged peak loads remain below 10 kW/m^2 for the ripple-optimized case.

Summary and conclusions. The effect of finite Larmor radii on fusion alpha wall load simulation results has been studied for ITER Scenario 4 with and without ripple mitigation. It was found that alpha wall load profiles from pure guiding centre simulation are significantly changed when full orbits are followed near the wall. The CPU cost was found to be negligible in slowing-down simulations. Pure full orbit simulation takes into account ripple transport mechanisms lost in the guiding centre approximation and thus further refines wall load estimates, but at a severe cost in CPU time. A hybrid guiding centre and full orbit algorithm, capable of accurately switching back and forth between the two formalisms (e.g. near banana orbit tips), would facilitate large scale simulations of alpha wall loads for large aspect ratio tokamaks, stellarators etc. and for cases where the magnetic field structure is perturbed by, e.g., test blanket modules (TBM). Work is in progress to develop such an algorithm.

Alpha losses caused by other mechanisms, e.g. MHD phenomena, are omitted in the present work. They may redistribute the radial alpha birth profile and thus increase the hot alpha population in the edge region where the ripple mechanisms may significantly affect alpha containment. The present wall load results should thus be considered as a low limit estimate. For future work, a model for certain MHD modes has recently been added to ASCOT [6].

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