Fast ion transport in presence of magnetic perturbations using full-orbit and guiding-center simulations

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The optimal operation of current and future tokamak reactors relies on the good confinement of fast ions that can occur as fusion products, e.g. alpha-particles, or as the result of auxiliary plasma heating methods like neutral beam injection (NBI) or radiofrequency heating in the ion cyclotron range of frequencies (ICRH). A good confinement of these ions in the plasma ensures that they spend enough time experiencing collisions with the background plasma so that they can effectively heat the bulk plasma. However, the presence of magnetic perturbations may increase the transport and reduce the confinement time which would reduce heating efficiency. The use of magnetic coils to mitigate edge localized modes (ELMs), for instance, has been found to negatively affect fast ion confinement [1] for both NBI ions and fusion-born alpha particles. Magnetic islands due to tearing modes also increase the losses of fast ions, as shown in [2, 3] for alpha particles.

In this work, the transport of fast ions in the energy range of NBI heating in presence of magnetic perturbations is analyzed using two approaches for the particle trajectories, a full orbit description and a guiding center approximation. The specific case of magnetic islands as the perturbations is considered evaluating their effect on transport through the particle flux across the island chain. Both the guiding center (GC) and the full orbit (FO) codes are benchmarked with neoclassical transport as function of plasma collisionality. A model magnetic field representing a mid-sized tokamak with circular magnetic surfaces is considered for all the simulations. By following a population of fast ions released on a magnetic surface internal to a magnetic island chain, the collective transport is analyzed as they cross the island. It is found that the GC fluxes are less sensitive to magnetic perturbations than the equivalent FO predictions. As expected, more collisional plasmas (higher density) have increased radial fluxes across the island since collisions enhance the neoclassical transport across magnetic flux surfaces. In FO simulations, ions of higher energy show a weaker dependence od density since their collisionality is lower, but GC results produce higher ion flux for higher energies because they travel faster along field lines.

When the island is rotating the flux is affected in function of the rotation frequency ω and the rotation direction. However the effect is much less important in GC simulations. The rotation usually produces a reduction of the flux with respect to the non-rotating island and it is larger for counter-rotation than for co-rotation; this is a FO orbit effect since GC simulations do not show a significant dependence on the sign of ω. It is observed that for narrow islands the reduction for counter-rotating islands can yield flows even below the one without island, thus acting as a sort of transport barrier.

As function of the rotation frequency, the ion flux first deceases as soon as $\omega \neq 0$ and then begins increasing with frequency until it reaches a maximum value and after that the flux decreases again; this indicates that there is a resonant process with the island rotation. The resonant frequency is around the frequency range corresponding to the ion bouncing time of barely trapped particles. Therefore, it is likely that ions that get trapped when they are thermalizing are responsible the increased flux.

When the electric field associated with the island is included it increases the rate of ion radial crossing. This is a sheer 3D effect of the E-field since a purely radial E-field would reduce the radial fluxes through the driven poloidal flow. The presence of non-radial components of the electric field is responsible of a radial velocity component.

The bottom line of the research is that finite Larmor radius effects are quite important in determining the transport of fast ions in presence of magnetic islands.

References

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