SPOT: a New Monte Carlo Solver for Fast Alpha Particles

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Abstract

The predictive transport code CRONOS [?] has been augmented by an orbit following Monte Carlo code, SPOT (Simulation of Particle Orbits in a Tokamak). The SPOT code simulates the dynamics of non-thermal particles, and takes into account effects of finite orbit width and collisional transport of fast ions. Recent developments indicate that it might be difficult to avoid, at least transiently, current holes in a reactor. They occur already on existing tokamaks during advanced tokamak scenarios. The SPOT code has been used to study the alpha particle behaviour in the presence of current holes for both JET and ITER relevant parameters.

1 Introduction

The orbit width of a 3.5MeV alpha particle in an ITER plasma is typically of the order 40-50 cm for monotonic current profiles, i.e. around 20% of the plasma radius. Thus, accurate simulations of the alpha particle heating should take into account finite orbit width effects. Moreover, it has recently been realised that current holes, i.e. a central plasma region with virtually zero current density, are likely to appear at least transiently in reactor plasmas. For this reason, it has become essential to consider fast ion orbit effects and their impact on the dynamics of such ions in fusion plasmas. To address this problem the SPOT code (Simulation of Particle Orbits in a Tokamak) has been developed. The main aim with this development was to integrate SPOT with the transport code CRONOS [**?**]. The combined package should allow for self-consistent simulations of the thermal plasma evolution and the alpha particle dynamics.

SPOT is an orbit following Monte Carlo code that calculates guiding centre orbits of fast ions in arbitrary toroidally axi-symmetric equilibria. Collisions between the fast ions and the bulk plasma are taken into account by periodically applying Monte Carlo operators, see e.g. [**?**], along the simulated orbits. Accelerated collisions, a procedure whereby a simulated poloidal orbit represents many orbits in reality, as well as a weighting scheme is employed to reduce the computing time and improve the statistics. The SPOT code uses the output from CRONOS (2D-equilibrium, temperature, density profiles etc.) to evolve the fast ion distribution for a time step. The output from SPOT, in terms of heating, fast ion pressure and driven current profiles, is in its turn used in CRONOS to integrate the thermal plasma transport equations and the equilibrium to the next time step. The procedure is repeated until the end of the calculation.

Finite orbit width effects lead, in addition to a general broadening of the heating and pressure profiles, to anisotropies in the fast ion pressure and to finite currents driven by the energetic ions. This is the case even when the fast ion source is isotropic. These effects are particularly pronounced in plasmas with current holes. In this paper, we present the first results from SPOT on the impact of current holes on the alpha particle behaviour. Most recent work on current holes and alpha particles has concentrated on the confinement of the latter [**?**]. In this paper we also consider the fast ion pressure and driven current profiles, and present results for both JET and ITER equilibria.

2 Topology of alpha orbits for current holes

Typical orbits of 3.5 MeV alpha particles intersecting a current hole are illustrated in Fig.**??** for an ITER configuration. Owing to the absence of a current density, and thus a poloidal magnetic field, only the grad-B and curvature drifts play a role for the poloidal projection of the orbit in a current hole. Consequently, the particle follows an iso-B line during its drift through the current less region. This has several consequences. First, particles that are born in the current hole with toroidal velocities in the co-current direction are always on co-current passing orbits. This is a simple consequence of the conservation of the toroidal angular momentum $P_\phi = -mRv_\phi + ze\psi/2\pi$, where v_ϕ is defined such that it is positive in the co-current direction and the poloidal flux, ψ, is taken to be zero in the current hole, but otherwise positive. Thus, a particle starting with a positive v_ϕ in the current hole can only increase its v_ϕ as it enters the region of a finite current, i.e. it can never be trapped. Another important property is that particles born in the current hole at the same point on passing orbits but with v_ϕ in opposite directions will follow each other in the poloidal plane until they encounter the region with finite current density; at that point the orbit with $v_\phi < 0$ turns towards the high field side while the other continues towards the low field side. Thus, significant asymmetries in velocity space can be expected for any given point in or near the current hole.

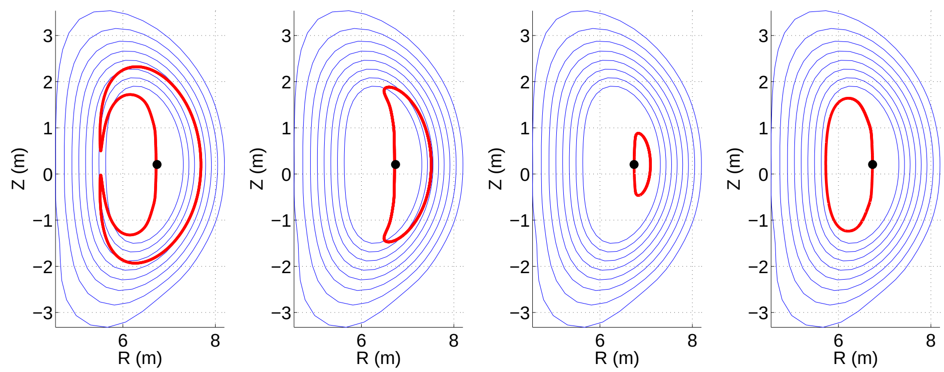

Figure 1: Orbit topology of 3.5 MeV alpha particles inside an ITER current hole. From left to right: barely trapped, trapped, co-passing and counter-passing orbits.

3 Alpha particle losses in the presence of JET current holes

The influence of current holes on alpha particle confinement has been simulated for a typical JET configuration. This investigation is mainly motivated by recent experiments on JET with trace tritium. The fraction of lost alpha power as a function of the current hole width, as well as the individual contributions from first orbit and collisional losses have been studied.

Several current profiles have been imposed, corresponding to the safety factor profiles shown in Fig.**??**. The total plasma current has been kept constant at 2.2 MA in all cases. The resulting losses are shown in Fig.**??** (the current hole size is here defined as the width of the zero-current density region). The power losses due to the reduced confinement can reach around 30 % for a current hole width of about 50 % in the JET tokamak. The losses are dominated by first orbit losses. The collisional losses, evaluated by considering particles lost after the completion of their first full poloidal orbit, amount to around 10% of the total lost power for a current hole width of around 60 %.

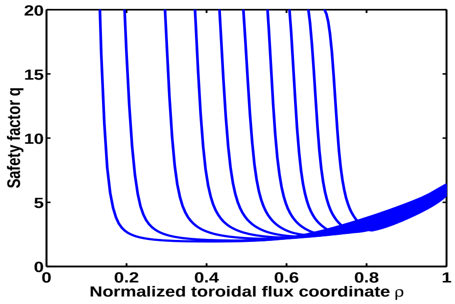

Figure 2: Safety factor profiles obtained for current holes of a typical JET configuration.

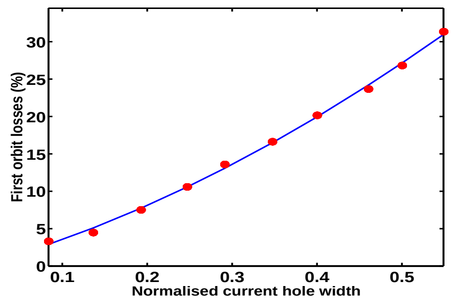

Figure 3: Power losses versus the current hole size for JET equilibria.

4 Anisotropy and alpha particle current generation for ITER equilibria with current holes

Simulations for ITER equlibria show that alpha particle losses are small even in the presence of a wide current hole. The losses are of the order of 0.5 % for current holes at around 60 % of the plasma radius. Thus, direct alpha losses in ITER should be a minor issue. For this reason we here concentrate on possible anisotropies in the alpha particle pressure and the currents driven by the alpha particles. As explained in the section **??**, there is reason to believe that non-negligible anisotropies can occur.

We first consider the alpha particle pressure for ITER parameters yielding a fusion power of about 130 MW. The parallel and perpendicular pressures in 2D as well as the pressures as a function of the major radius through the midplane are shown in Fig.**??**. The 1D plot of the pressure shows that the anisotropy is weak for a small current hole whereas it is around 10-20% over a significant part of the plasma cross-section for a 60% hole. The most striking feature is the strong poloidal variation of the pressure in the case of a large current hole.

Any velocity space anisotropy is expected to have a more significant effect on the driven current, which is also born out by the simulations. Figure **??** shows a 2D plot of the current density profiles of fast alpha particles

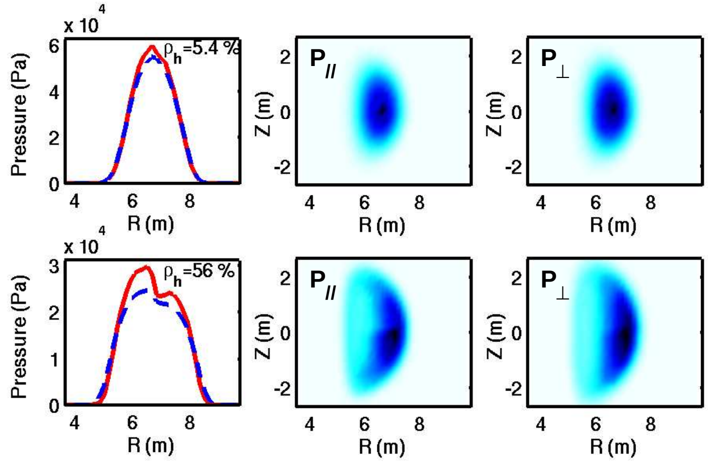

Figure 4: 1D parallel (solid line) and perpendicular (dashed line) and 2D pressure profiles of fast alpha particles for a small (top figures) and a large (bottom figures) current hole in ITER.

for different current hole sizes. The influence of the topology of the orbits typical of the current hole is very clearly seen. Counter-current passing alpha particles provide a negative current density towards the high field region whereas the co-passing ones give rise to a positive current shifted towards the low field side, leading again to very significant poloidal variations. Owing to several factors, e.g. the fact that no particle born with $v_\phi > 0$ in the current hole is on a trapped orbit, the number of co-passing orbits dominates and the total current driven by the alpha particles is positive. This is illustrated in Fig.**??**, where the contributions to the current from particles with different orbits are displayed together with the total current. For small current holes the asymmetry is small and the current density remains modest. The driven current density increases with the current hole size, and reaches 60kA/m^2 for 56% hole. This can be compared to the maximum current density in the plasma which is about 700kA/m^2. Thus, the current is not negligible, especially in view of the fact that it is driven in the current hole region.

5 Summary

The effect of a current hole on fusion born alpha particles has been investigated. The confinement of those alpha particles can be significantly degraded in JET plasmas, with losses up to 30% for a current hole of 50% of the minor radius. On the other hand, the losses of alpha particles in ITER are small even for such a large current hole. For ITER the role of the current

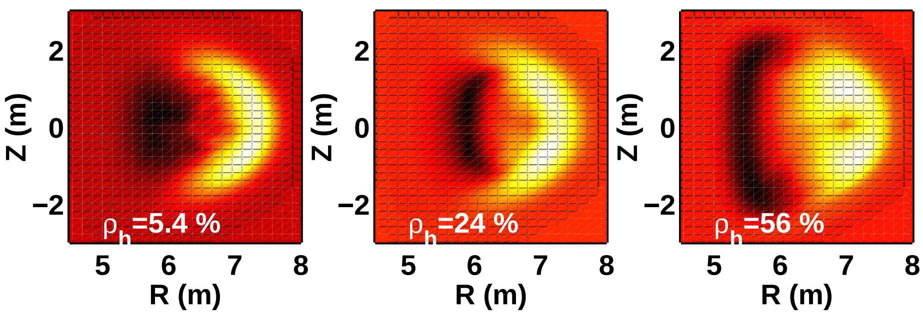

Figure 5: Fast alpha particle driven current density profiles for three ITER current holes. The dark (bright) region corresponds to a negative (positive) current.

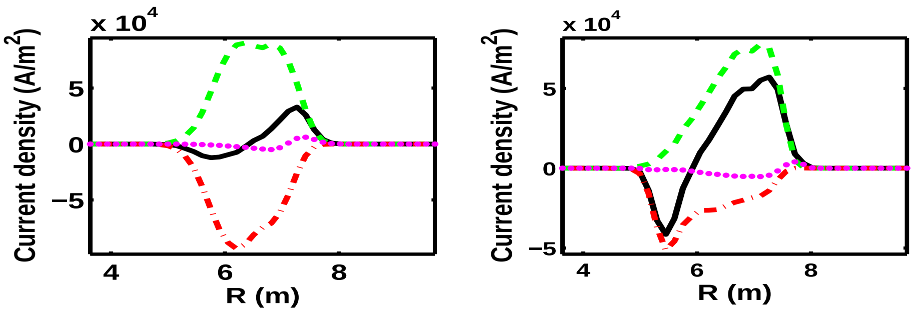

Figure 6: Total alpha particle driven current density profile (solid line) for a small (left figure) and a wide (right figure) current hole in ITER. The individual contributions from alpha particles on co-passing (dashed), counter-passing (dot-dashed) and trapped (dotted) orbits are also displayed.

hole is more to create asymmetries in the velocity space of the alpha particles. These lead to anisotropies in the pressure profile and to a significantly enhanced alpha particle driven current in and around the current hole area.

References

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