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Rotation driven by fast ions in tokamaks

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Abstract

Two aspects of momentum drive by a fast ion population in tokamak plasmas are investigated numerically. Firstly the collisionless deposition of momentum by injected fast ions in a neutral beam injected discharge is described, and it is demonstrated in a proof-of-principle Monte-Carlo simulation in MAST that saturation of the electric field, or equivalently of plasma flows, can occur through a purely electrodynamic, collisionless mechanism. Secondly, the fast ion current carried by α-particles in a burning plasma is considered with fusion reaction rates relevant to ITER. Order of magnitude estimates of toroidal flows are given, and it is shown that the torque induced by α-particles on the plasma cannot be neglected when establishing the rotation velocity of fusion plasmas.

Rotation driven by fast ions

Fast ions born in a fusion plasma have an intrinsic ability to drive plasma flows when born on trapped orbits : in the absence of collisions, they describe periodic banana orbits, and their time-averaged radial location generally differs from their birth position. Under the assumption that the associated electrons remain on their birth flux surface owing to their smaller mobility, an instantaneous current j_f is generated by the fast ion motion and a net polarisation appears which remains finite when a statistical average over a complete distribution of iso-energetic particles is performed. The fast ion current is non-ambipolar and plasma particles respond to it in the form of a "return current" j_r which has nearly equal amplitude but opposite direction. It is this current which, crossed on the equilibrium magnetic field, produces the toroidal Lorentz force that drives the plasma flow.

Electric field saturation in MAST

In the following, the fast ion current is computed using test particle simulations of Neutral Beam Injection against the plasma current in MAST in an axisymmetric magnetic field with poloidal flux function corresponding to a Solov'ev equilibrium. In the case of neutral injection against the plasma current, the fast ion displacements are all towards the edge of the plasma as a result of conservation of the canonical angular momentum and losses of fast ions beyond the

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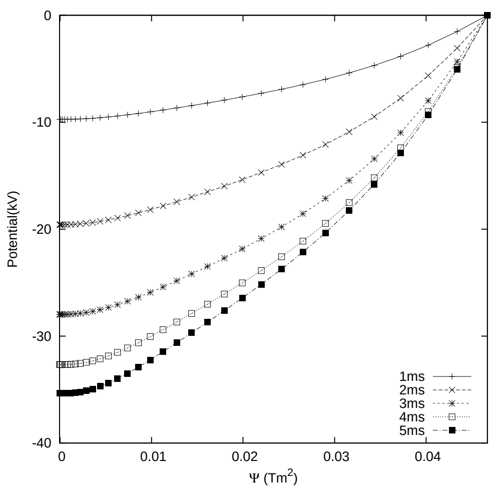
last closed flux surface can occur through collisions with the wall or charge exchange reactions. The outgoing current and consequently the torque on the plasma are thus enhanced, and have been observed to drive supersonic toroidal flows in MAST [1].

Saturation of the flow can then occur either as a result of collisional drag or via an alternative mechanism of purely electrodynamic nature [2], and we investigate the latter here. This mechanism relies on a feedback loop between the fast ion trajectories and the radial electric field: as the positive fast ions are injected and subsequently move towards the edge on a time of order of the bounce-period, a negative charge is generated at their birth position. A radial electric field pointing from the edge towards the birth position builds up and the fast ions are increasingly trapped in a potential well whose depth increases with time. The effect of the electric field becomes noticeable when the difference in potential energy between the inner and outer legs of the banana orbits becomes comparable with the particles' kinetic energy. Approximate conservation of the particles' total energy on the bounce timescale then implies that the banana orbits are squeezed so that the fast ion current decreases, the growth of the electric field is slowed down and eventually a steady state can be reached.

In the simulation presented, deuterons are injected against the plasma current in a MAST-like equilibrium with a velocity of $2 \times 10^6 \mathrm{ms}^{-1}$, corresponding to an energy of 40keV, at a steady rate simulating a neutral beam with injection rate of $3 \times 10^{20} \mathrm{s}^{-1}$. Their trajectories are advanced in time and their spatial distribution then used to solve a flux-averaged Poisson equation, under the assumptions that electrons remain at all times on the flux surface where the corresponding fast ions are injected and that ions crossing the last closed flux-surface are lost [3]. The near cancellation of the fast ion current by the return current is included by using the effective plasma permittivity $\varepsilon = j_f/E_r = \varepsilon_0(1 + c^2/c_A^2(\Psi))$ (c_A is the Alfvén speed, c the speed of light and ε_0 the permittivity of a vacuum) which reaches $3 \times 10^3 \varepsilon_0$ in the simulated plasma, so that the evolution of the electric field is considerably slower than in a vacuum.

The fast ion current in this configuration is mostly a result of prompt losses outside the last closed surface which affect more than 90% of the injected ions. Following their loss, the plasma becomes negatively charged and the potential difference between the injection point and the separatrix increases (Figure 1 left). Over the first 2ms, the loss rate is steady and the electric potential decreases linearly, after which it becomes large enough to yield improved confinement of the deuterons. The loss rate subsequently drops (Figure 1 right) and after 5ms, the potential reaches -35kV. The difference in potential energy of the particles is then comparable to the deuterons' birth kinetic energy so that no further losses are allowed and the electric field saturates, as discussed in [2]. The potential drop is however much larger than the value of -12kV



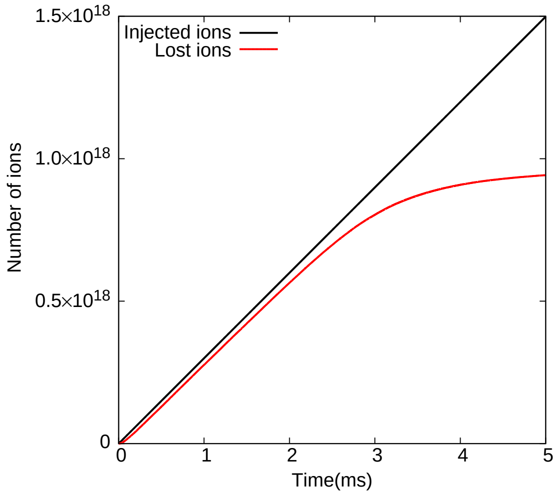


Figure 1: Evolution of the electrostatic potential in a test-particle simulation of neutral-beam injection with a self-consistent electric field in MAST (left). Number of particles injected and lost in the same simulation (right).

observed in the discharges with the largest toroidal velocities in MAST [1], and saturation must therefore generally occur as a result of collisions.

Momentum driven by α particles in ITER

Given its role in the stabilization of MHD modes [5], plasma rotation driven by fast ions is also of considerable interest in burning plasmas where intrinsic rotation can occur through the motion of α-particles: these particles have large energy (3.5MeV) as well as inertia with four proton masses and can therefore travel over large radial distances along their banana orbits. They are born in an isotropic distribution in velocity space, and therefore drift in equal proportion inwards or outwards. Nevertheless, the radial inhomogeneity of their birth profile implies that the inwards and outwards currents do not cancel, and owing to the decrease of plasma density and temperature (of which the fusion reaction rate is an increasing function) with minor radius, the current carried by α-particles is directed outwards and a torque driving the plasma in the counter-direction is expected.

Here we estimate numerically the current carried by the fusion particles with birth profiles relevant to an ITER plasma [4] from which we compute the corresponding fusion reaction rate (Figure 2 left), with plasma currents of 10MA (steady-state scenario), 15MA (inductive scenario) and 20MA. Figure 2 (right) shows that the fast ion current is generally maximum in the plasma core. It is a decreasing function of plasma current as a result of the increase in orbit width as the current is decreased. Computation of the final toroidal velocity would require a full transport analysis, and we limit ourselves to an order of magnitude estimate assuming that the toroidal momentum confinement time τ_φ and the energy confinement time are comparable.

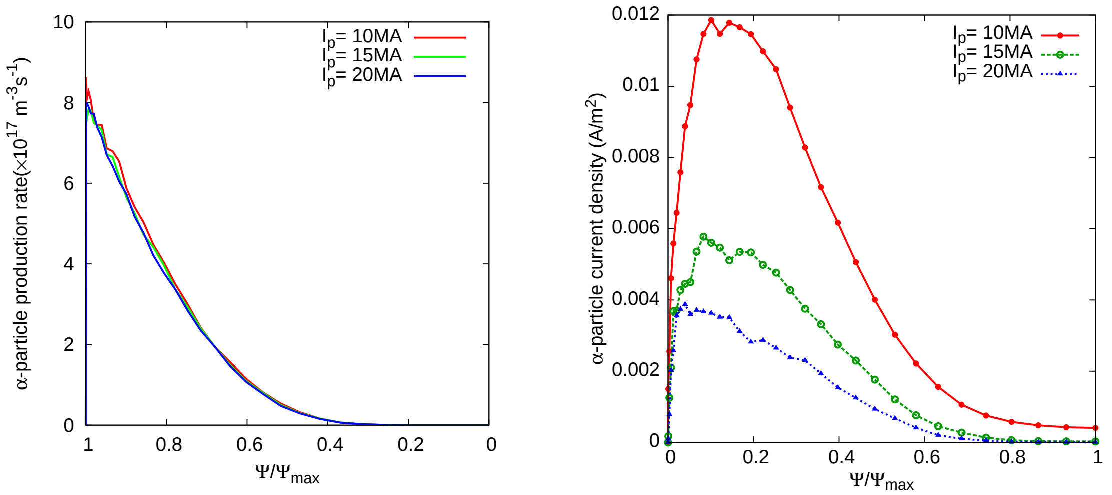


Figure 2: α-particle birth profile (left) and α-particle current density as a function of minor radius in ITER (right) for plasma currents of 10, 15 and 20MA.

The toroidal velocity is then of order $v_\varphi = -(j_f B_\theta \tau_\varphi)/\rho_m$, where B_θ is poloidal field and ρ_m is mass density, which yields counter-plasma rotation values of -25km/s and -50km/s in the steady state and inductive scenarios respectively, i.e. non-negligible modifications to the 140km/s co-rotation driven collisionally by neutral beams in the steady state scenario [6]. The present simulations therefore indicate that omission of the torque provided by α-particles in a burning plasma could yield notable effects on the predicted rotation rate and on the expected MHD stability properties of an ITER plasma [7].

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