Effect of Toroidicity on Fast Fuel Relocation in Tokamaks[*]

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Abstract

Pellet injection from the inner midplane region, or high-field-side (HFS) of a tokamak promotes a deeper fuel deposition profile, well beyond the pellet penetration depth. The effect stems from the inhomogeniety of the toroidal magnetic field, which causes an inward $E\times B$ advection of the high-pressure ablation plasmoid, polarized by the magnetic drift currents. Three important new mechanism have been identified, which extend the previous analytical theory of the advection process: 1) *Mach Number Effect*. The parallel expansion velocity of the plasmoid ranges from subsonic to supersonic, with respect to the sound speed of the plasmoid, and it is thus the only near-sonic flow in a tokamak. This unusual result, means that the centrifugal force arising from $M \sim 1$ parallel flows, coupled with the curvature of the (largely) toroidal magnetic field, will drive a significant *additional magnetic curvature drift current* inside the plasmoid. Since the parallel flows persist long after the plasmoid pressure has relaxed towards the background plasma pressure, the curvature effect still continues to power the $E\times B$ drift, and consequently it significantly *lengthens the fuel penetration depth*. 2) *Toroidicity* This geometrical effect results from the expansion of the plasmoid along a helical magnetic flux tube, while it drifts inward. At any moment, the electrostatic potential $\Phi\,(x,y)$ in the plasmoid is assumed to be uniform along a given field line defined by a point in the orthogonal field line following (FLF) coordinate system (x,y), with x pointing in magnetic flux direction. Consequently, the internal electric field E must rotate with respect to the fixed vertical grad-B drift direction with increasing distance z along the field lines inside the plasmoid. *This reduces the drift velocity and penetration*. 3) *Mass Shedding* Magnetic shear makes the cloud and flux-tube cross section threading the cloud become more elliptical with increasing distance z along the field lines, while preserving the cross-sectional area. After the cloud has expanded to a distance of order of the magnetic shear length $L_S = qR/\hat{s}$, where $\hat{s} = (r/q)q'$ is shear parameter, elliptical compression and rotation in the FLF coordinates orients the polarization charge layers in different directions as z increases. This result in a differential drift of the cloud segments: the end parts of the cloudlet can drift to flux tubes out of the electrostatic region of influence and "peel off" one by one. This dispersal effect *spreads out the fuel deposition profile*. The new theory was incorporated in the Pressure Relaxation Lagrangian Code (PRL), which solves for the 1-D parallel expansion dynamics and couples it to the analytic solution of the parallel vorticity equation describing the cross-field incompressible flows $\nabla \cdot (\vec{\mathrm{v}}_\perp / R^2)$ associated with the coherent $E\times B$ drift motion. The cloud pressure reaches equilibrium after a several sound times $\sim 5L_c/c_s$ where $L_c = (r_\perp R)^{1/2}$ is the initial cloud half-length, at which point the plasmoid temperature is only ~20–40 eV which agrees with experimental measurements. A comparison between the measured Δn deposition profile following HFS pellet injection on the DIII-D tokamak and the PRL code result show reasonably good agreement, considering that the pellet was actually injected from 30 cm above the midplane. A preliminary simulation for ITER shows deep fueling is possible.

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