Radial Displacement of Pellet Ablation Material in Tokamaks Due to the grad-B Effect*

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An apparent displacement of deposited pellet ablation substance towards the low-field or large-R side of the tokamak is often detected during pellet injection from the low-field side [1], and it has been attributed to uncompensated ∇B and curvature drifts induced by the 1/R toroidal field [2]. The effect was recently exploited in ASDEX-U during pellet injection from the high-field side in order to promote deeper fuel penetration [3]. This paper presents for the first time a simple and fairly comprehensive model that predicts the large-R transport distance. The particle source from an ablating pellet presents a significant disturbance to the plasma. Initially, an ablated "cloudlet" just separated from the pellet shadow is a toroidally localized, high-pressure ($\beta_\mathrm{c} \sim 1$) resistive plasmoid, which will polarize and $E \times B$ drift towards the low-field side of the tokamak. The cloudlet is assumed to have a long thin cylindrical shape with a diffuse $\mathrm{sech}(\alpha z)$ density profile with initial half-length $L(0)$ ~ 10–20 cm in the parallel z-direction, and a sharp-boundary density and pressure profile in the radial direction. The cloudlet is allowed to expand along the field lines against the ambient backpressure p_∞, while it undergoes center-of-mass rigid body motion in the large-R direction. This model applies under the condition that transverse particle diffusion is classical, $D_\perp = \beta_\mathrm{c} D_\mathrm{mag}$, and thus much slower than parallel expansion, as experiments suggest. The rigid body motion is obtained from $\vec{\mathrm{B}} \cdot \nabla \times$ of the momentum equation, while a combination of the parallel component of the momentum equation and the energy balance equation, in one-dimensional Lagrangian coordinates, expresses the parallel dynamics. Heating comes mainly from partial absorption of the parallel heat flux which is carried by ambient electrons in passing through the cloudlet. The grad-B drift drive enters into in the large-R motion in the form of a toroidal drive integral

$$\Psi(t) = \int_0^{L(t)} [p(z,t) - p_\infty] dz \ ,$$

and results in a closed form expression for the center-of-mass cloud drift velocity

$$\frac{dV_\perp}{dt} = -\frac{2B^2 V_\perp}{\mu_0 \Sigma_\mathrm{c} V_{A\infty}} + \frac{2\Psi(t)}{R\Sigma_\mathrm{c}} \ .$$

where Σ_c is the non-varying column density of the cloudlet. The ends of the cloudlet in effect act like a thin parallel current source that excites longer-wavelength shear Alfvén waves, as represented by a damping term that is somewhat analogous to the restoring force in the ballooning mode equation. It turns out that parallel pressure relaxation cutsoff the toroidal drive after the cloudlet has expanded to a half-length that is about 10 times its original length, or about 2 m, which is still much smaller than the connection length $2\pi qR$ in current tokamaks. Comparisons will be made with upcoming high-field-side pellet injection experiments on DIII–D, and previous low-field-side results on TFTR and JET. The model suggests favorable prospects for fueling the central regions of an ITER-RC-class device by high-field-side moderate-velocity pellet injection.

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