Recent Advances in the Theory and Simulation of Pellet Ablation and Fast Fuel Relocation in Tokamaks*

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High-density access, most readily produced by depositing fuel in the central regions of the tokamak by pellet injection, is crucial for meeting fusion power performance requirements in next step devices such as ITER and FIRE. Pellet injection from the high-field-side (HFS) of present tokamaks has been found to promote deeper fuel penetration well beyond the pellet burnout point. The effect is attributed to the inhomogeniety of the toroidal magnetic field. This paper presents new theory and simulations of pellet ablation, and the rapid cross-field redistribution of the ablated and ionized pellet substance following HFS pellet injection in tokamaks. A new time-dependent 2-D Eulerian code CAP, presently the most advanced pellet ablation code [1], models 2-D pressure-driven pellet deformations resulting from non-uniform "illumination" by the hot parallel electron heat flux. The code can establish the 2-D structure of the high-pressure cigar-shaped ionized cloud near the pellet. The near-pellet cloud parameters are critical inputs for codes modeling the subsequent fast mass redistribution. For the mass redistribution we present new results from the Pellet Relaxation Lagrangian Code (PRL). The PRL code is based on an analytical model of ∇B induced polarization and $E\times B$ drift [2]. We present important new extensions of the theory that incorporate the effects of toroidicity and magnetic shear. Development has started on an Adaptive Mesh Refinement (AMR) code, a first of a kind 3-D MHD simulation with full toroidal geometry capability [3]. AMR also provides the required fine-scale mesh for accurate modeling of small-scale pellet clouds featuring huge gradients for the temperature and density perpendicular to the magnetic field.

The CAP code solves the multi-phase hydrodynamic equations, including dissociation and ionization, in the cylindrical axi-symmetric coordinate system (r, z) with z parallel to B, the source of the non-uniform heat flux illumination. Angular variations of the pellet surface pressure p_{sur} (rocket effect), attributed to this non-uniformity, will "fluidize" the pellet when the pressure variations exceed the shear strength of the solid, $S \sim 0.5$ MPa. Such conditions will prevail in the high heat flux regime ($T_{e\infty} > 2-3$ keV, $n_{e\infty} > 10^{14}$ cm^{-3}) expected in the edge pedestal of ITER. Consequently, the solid pellet will experience strong deformation. Figure 1 shows the temporal progression of the pellet shape from initially spherical to

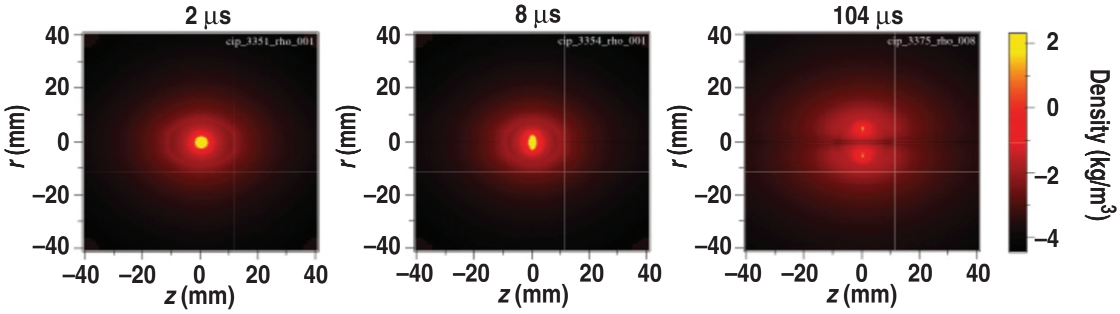

Fig. 1. Density contours showing pellet flattening by non-uniform heat flux illumination

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pancake, and near burnout it eventually becomes ring-shaped. Flattening increases the cross-sectional area intercepting the heat flux, which enhances the ablation rate. For time-stationary (in pellet frame) plasma parameters, the lifetime of “soft” pellets is 2-3x less than that of “rigid” pellets. In actuality, whether the pellet is soft or rigid at any moment depends on the temporal history of the pellet along its trajectory through plasma with realistic profiles. Penetration results with experimental plasma profiles will be presented and compared with the experimental database. The surrounding ablation cloud adjacent to the pellet is inertially dominated. Driven by the intense pressure gradients $\sim p_{sur}/r_p$, the cloud expands almost isotropically $v_{\parallel} \sim v_{\perp} \sim c_s$. Farther away the pressure decays, so at some point the $J\times B$ force dominates and limits the perperdicular velocity component to the small resistivity-driven value $v_{\perp} \sim \eta p_0/r_{\perp}B^2 << v_{\parallel} \sim c_s$. The cloud is then mainly confined within a magnetic tube of force, and forms an elongated ‘cigar-shaped’ structure observed experimentally. Improving on an earlier non-rigorous numerical scheme [4], we shall present the first rigorous 2D simulation of the continuous transition between the inertially dominated region and the fully ionized field-aligned flow region. Our approach would accurately quantify how much the ablation rate is reduced by the enhanced $\int ndz$ offered by the field-aligned flow region. The parameters of this region are also important initial conditions for the longer time scale mass relocation and deposition problem simulated by PRL and AMR codes.

The PRL Code solves the vorticity equation describing the cross-field incompressible flows $\nabla\cdot(\vec{v}_{\perp}/R^2)$ associated with the coherent $E\times B$ drift motion of the cigar-shaped cloudlet while it continues to expand parallel to B. The cloud pressure reaches equilibrium with the background pressure after a few sound times $\sim 5L_c/c_s$ where $L_c = (r_{\perp}R)^{1/2}$ is the cloud half-length. The additional curvature drift induced by parallel flow in the curved B-field maintains $E\times B$ drift, even after the pressure equilibrates, and thus significantly enhances the penetration depth. This effect can be compensated by (1) drifting of cloudlet *up* the tokamak plasma pressure gradient, and (2) mass shedding: magnetic shear causes the two end parts of the cloudlet to sequentially drift to flux tubes outside the electrostatic region of influence, whereupon they are cast aside one by one. Figure 2(a) shows a comparison between the measured Δn deposition profile following HFS pellet injection on the DIII-D tokamak and the PRL code result. The agreement is reasonably good, considering that the pellet was actually injected from 30 cm above the midplane. A preliminary simulation for ITER shows deep fueling is possible [Fig. 2(b)]. A previous cloud relocation model [5] is manifestly inaccurate because the inertial term was not considered in the cross-field dynamics.

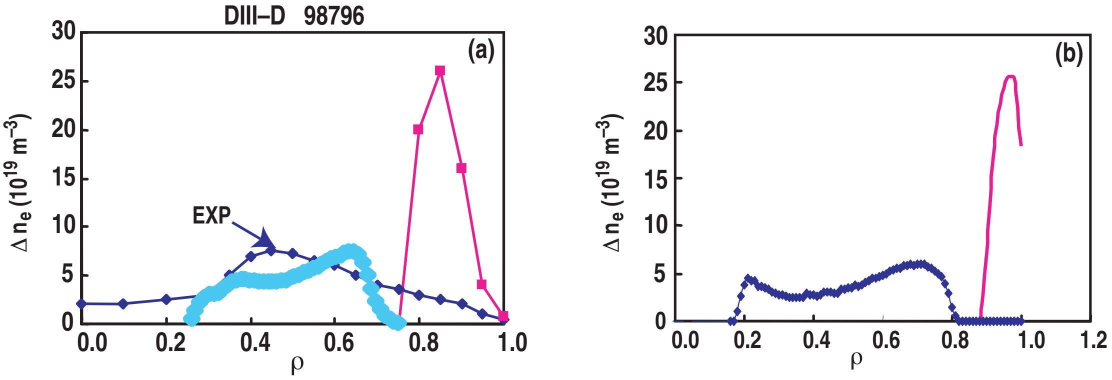

Fig. 2. Fuel deposition increment Δn. (a) Comparison between experiment in DIII-D and PRL model. (b) Prediction for ITER. Note the shallowness of the pellet source profiles (magenta) in both cases.

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