Lagrangian particle simulation of neon pellet ablation clouds for plasma disruption mitigation in tokamaks

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A leading candidate for the ITER plasma disruption mitigation system is the Shattered Pellet Injection (SPI) [1] that performs fragmentation of a large, frozen, neon-deuterium pellet before its injection into a tokamak, and forms a stream of small fragments into plasma, causing a thermal quench. The pellet ablation problem in tokamaks can be studied on relatively small length scales compared to the tokamak size. By resolving all relevant physics processes such as pellet surface ablation, formation of a dense and cold ablation cloud, deposition of energy of hot electrons in the ablation cloud, heating, ionization and channeling of the ablated material along magnetic field lines by MHD forces, and radiation losses, such local models describe the evolution of the process in great detail and compute pellet ablation rates. Significantly different approximations are used in global pellet ablation models, which study the transport of the ablated material in the entire tokamak. Local studies have been performed using a number of theoretical models with analytical or semi-analytical solutions and one- and two-dimensional numerical simulations [2, 4, 5]. Global studies have been performed using typical MHD codes for tokamak plasmas with the addition of analytic source terms [6, 7]. However, local studies of a single pellet ablation in a spherical or axisymmetric approximation is not sufficient for the study of SPI, when a large number of gas / plasma clouds, created by the ablation of pellet fragments, partially screen each other from the incoming electron heat flux. Our work intends to fill the gap in this area by developing accurate local 3D simulation models suitable for SPI. In the next phase of our work, our local models will be coupled with the well-known tokamak MHD codes NIMROD and M3D-C1.

As the pellet surface is rapidly ablated by the heat flux of hot electrons traveling along magnetic field lines, a dense and highly non-uniform cloud of cold, neutral gas surround the pellet. By absorbing most of the incoming electron energy, this cloud is the major factor defining the pellet ablation rate [2, 5]. An efficient 3D numerical method suitable for the resolution of both the dense neutral cloud and hot ionized plasma in the far-field must be highly adaptive. In addition, a Lagrangian treatment of the ablated material is desirable as it eliminates several numerical difficulties associated with the simulation of the tokamak plasma background in an Eulerian code. Finally, the Lagrangian approach makes it much easier to extract relevant data for a multiscale coupling with tokamak-scale MHD codes. As Lagrangian hydrodynamics codes have achieved most of success only in 1D due to mesh tangling caused by complex flows in 2D and 3D spaces, particle-based Lagrangian approaches present an attractive alternative. All desired features of an efficient pellet ablation simulation are present in our recently developed Lagrangian Particle (LP) method for hydrodynamic equations [8], which has been selected as the basis of our pellet / SPI numerical model. The LP method greatly improves the accuracy and mathematical rigor of the known method of smoothed particle hydrodynamics (SPH). While several approaches have been recently proposed to improve non-convergence issues of the traditional SPH, LP is the only method that proposes consistent particle-based discretization of PDE's based on general principles of numerical approximation, i.e. without the use of artificial smooth kernels of SPH. Particle neighbors in highly non-uniform particle distributions, typical for pellet ablation clouds, are efficiently computed using parallel octree data structure construction and search.

In the pellet ablation numerical model, parcels of the ablated material are represented by Lagrangian particles. Using a local polynomial fit on particle distributions, a method also known as generalized finite differences, MHD equations in the low magnetic Reynolds number approximation [5] are solved. All physics models related to the pellet ablation are similar to those implemented in the axi-symmetric pellet ablation model based on the FronTier code [5]; they are illustrated in Figure 1. Among models that go beyond [5], which dealt with deuterium fueling pellets, are the equation of state with atomic physics transformations for high-Z materials based on the average-ionization Zeldovich model [9] as well as tabular eos based on solutions of the full system of coupled Saha equations, and a non-local-thermodynamic-equilibrium radiation model in optically thin limit.

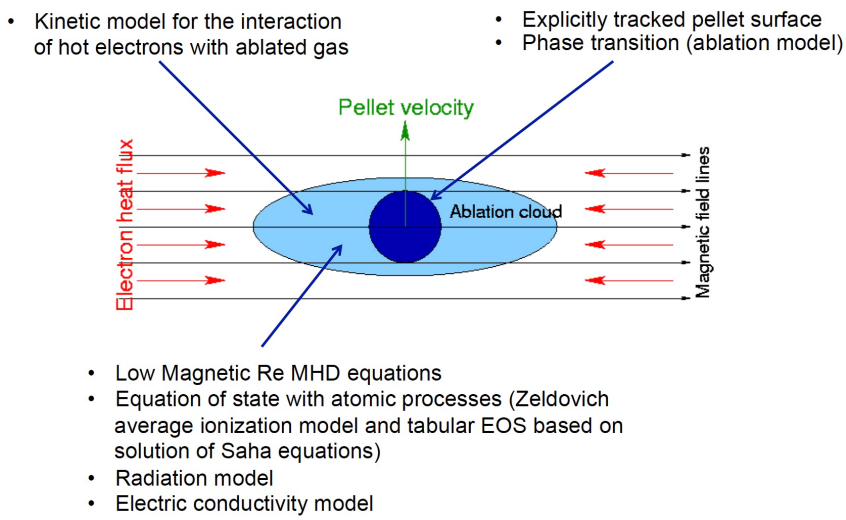

Figure 1: *Schematic of physics models implemented in LP pellet code.*

Unless noted otherwise, we use the following parameters in simulations presented in this paper. We consider neon pellets with the radius of 2 mm, injected in a tokamak plasma with the temperature of 2 keV and electron density of 10^{14} 1/cc. In the kinetic model for the electron heat deposition, the electron density has been reduced by coefficient 9.36 to account for electrostatic shielding in the pellet cloud. Verification studies have been performed by comparing spherically-symmetric LP simulations with a semi-analytic model [3] that improves the Neutral Gas Shielding model [2] and spherically-symmetric simulations using the Frontier-based pellet code [5]. In the spherically-symmetric approximation, the 3D Lagrangian particle simulation gives the ablation rate of 54.5 g/s, which is in a very good agreement with 1D FronTier simulation (54 g/s) as well as with the theoretical prediction (51.7 g/s). Simulations are also in agreement with theory on the scaling laws for the pellet ablation rate G, namely $G \sim T_e^{5/3} r_p^{4/3} n_e^{1/3}$, where r_p is the pellet radius, and T_e and n_e are the temperature and density of the background tokamak plasma.

Figure 2 illustrates results of pure hydrodynamic simulations of the pellet ablation in 3D. In such simulations, the magnetic field only directs the hot plasma elections along magnetic field lines, but $J \times B$ forces in the cloud are ignored. The purpose of such simulations is to quantify the effects of the directional heating on the pellet ablation rate and compare them with spherically symmetric simulations.

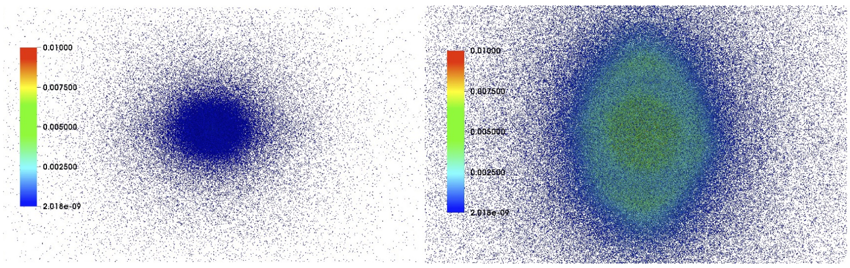

Figure 2: *Hydrodynamic simulation of neon pellet ablation. Left: view from far-field. Right: zoom-in dense ablation cloud near the pellet surface.*

Figure 2 depicts the evolution of the pellet ablation mass flux in 3D hydro simulations with directional heating computed at various distances to the pellet. The ablation rate is reduced to 48 g/s.

In the presence of MHD forces and atomic processes, the dense, cold ablated material gradually ionizes and streams along magnetic lines by the action of $j \times B$ forces, forming a narrow ablation channel (Figure 4). Simulations study

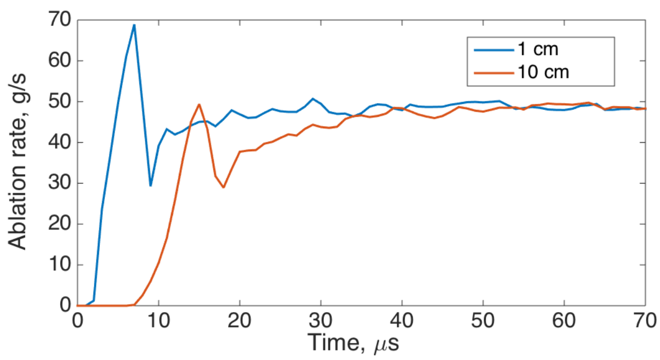

Figure 3: *Evolution of ablation mass flux computed from hydrodynamic simulations data at distances of 1 cm (blue line) and 10 cm (red line) from pellet surface.*

the dependence of ablation channel prop-
erties and pellet ablation rates on the magnetic field strength, and parameters of the background plasma, including the pedestal. The latter is modeled by an artificial parameter called the warm-up time. During the warm-up time, equal to 10 μs in present simulations, the background electron density is linearly ramped-up to its maximum value.

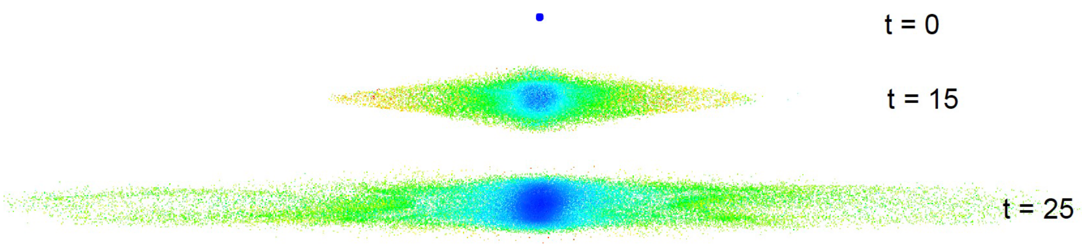

Figure 4: *MHD simulation of formation and evolution of pellet ablation cloud in 6T magnetic field. Distribution of the pellet ablated material are shown at initial time (top image), 15 µs (middle image), and 25 µs (bottom image). Color represents the Mach number distribution.*

In the present paper, we have shown numerical simulations of only single neon pellets. Due to high level of adaptivity, the LP numerical method is capable of simulating the ablation of a large number of pellet fragments or SPI. Preliminary simulations with multiple fragments have already been performed and will be reported in a forthcoming paper.

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