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VIII Microscopic particle-in-cell approach

A broad spectrum of scenarios resulting from the exposure of dense material to strong laser fields takes place in the realm of intense but nonrelativistic light-matter interactions. The quest for a microscopic understanding of the underlying processes is driven by both fundamental interest and various striking applications, ranging from industry-driven technologies like laser micromachining [13] and laser modification of metals and dielectric materials [48, 52] over the development of devices based on ultrafast strong-field nanoplasmonics [25, 35, 44, 54] to attosecond dynamics in solids [30, 49]. For intensities close to the ionization threshold where material is transformed from a solid into a plasma, the dynamics is particularly complicated as it is dominated by transient effects, proceeds far from equilibrium, and is strongly coupled [33, 42]. The latter aspect makes a physical understanding challenging, as the description of strong coupling is intimately connected to a correlated description of the physical many-body processes.

Modeling the interaction of laser light with strongly coupled plasmas is a challenging task even in the nondegenerate regime,[1] as the classical trajectories of all electrons and ions have to be propagated explicitly, and microscopic processes such as collisions have to be fully resolved. For small systems, where the dipole approximation is justified and field propagation effects can be neglected, this can be done efficiently with electrostatic molecular dynamics (MD) calculations [16, 43]. However, to describe macroscopic plasma volumes, an electromagnetic treatment is required that fully accounts for field propagation effects like field attenuation.

A widely used numerical method to study the interaction of light with macroscopic plasma volumes including field propagation effects is the electromagnetic particle-in-cell (PIC) approach [7, 11, 51]. In PIC, Maxwell's equations are solved on a grid along with the relativistic equations of motion for all PIC particles. Typically, these PIC particles represent an average over many physical particles and are sampled

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1 For thermal energies, $k_B T$, smaller or equal to the Fermi energy, E_F, quantum effects (e.g., Pauli-blocking) become important, i.e., the plasma is degenerate, and a classical description is in general not longer justified. In terms of the degeneracy parameter, $\Theta = k_\mathrm{B} T/E_F \lesssim 1$, the classical approximation is valid for $\Theta > 1$.

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