Spin effects in plasmas

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Dense plasmas, with number densities approaching or exceeding 10^{28} electrons/m^3, are routinely encountered in metallic nanostructures, compact astrophysical objects such as neutron stars, and high-intensity laser-plasma experiments. At those densities, quantum effects are expected to play some important role, for the statistical (Fermi-Dirac distribution) as well as the dynamical properties (e.g., interference effects) of the plasma.

To investigate the quantum plasma dynamics, recent works [1, 2] have made use of the Wigner representation of quantum mechanics, whereby the electron population is represented by a pseudo-probability density that evolves in the phase space according to the nonlocal Wigner equation, which bears some similarity with the classical Vlasov equation.

However, these works only considered the charge dynamics, and disregarded the spin degrees of freedom of the electron. It is well known that spin effects (particularly the Zeeman effect and the spin-orbit coupling) play an important role in ferromagnetic nano-objects [3]. The coupling between the spin degrees of freedom and the electron orbital motion is of the utmost importance in many experimental studies involving magnetic nanostructures, such as the ultrafast demagnetization induced by a femtosecond laser pulse in ferromagnetic thin films [4].

Although several theoretical works have been devoted to the modelling of spin effects in plasmas [5–9], no concrete simulation results have been put forward to date. Simulations of spin plasmas are computationally complex, as the corresponding Wigner distribution is not a scalar quantity (as in the spinless case) but rather a 2×2 matrix [6, 7]. It is also possible to define an equivalent scalar probability distribution that evolves in an extended 8D phase space [5], where the spin is treated as a classical two-component variable (related to the two angles on a unit sphere).

From a computational point of view, the extended phase space method is more apt to be simulated using particle-in-cell (PIC) codes, because the corresponding distribution function is transported along classical trajectories in the extended 8D phase space. In contrast, the matrix Wigner function methods is more naturally amenable to grid-based Vlasov codes, because the corresponding distribution function only depends on the six variables of the ordinary phase space.

We have derived a semiclassical Vlasov equation with spin effects by expanding the full quantum model (Wigner equation) to first order in the Planck constant. This "spin-Vlasov" equation is coupled to the Maxwell equations to form a self-consistent mean-field model.

We have used the extended-phase-space formalism to construct a PIC code that solves the coupled nonlinear spin-Vlasov-Maxwell equations. The numerical scheme is based on a Hamiltonian representation of the full system of equations [10, 11]. Thanks to a finite-element PIC discretization of the extended phase space [12], we derive a semi-discrete Poisson bracket that satisfies the usual properties (anti-symmetry, Jacobi identity, conservation of Casimir invariants). A Hamiltonian time-splitting integrator [12, 13] enables us to get a fully discrete Poisson integrator, which preserves both the divergence of the magnetic field and Gauss's law.

As an example of application, we have studied the impact of spin effects on the interaction of an intense laser source with a dense plasma, focusing in particular on stimulated Raman scattering (SRS). SRS is a parametric instability where the incident electromagnetic wave drives two waves inside the plasma: a scattered electromagnetic wave (propagating either forward or backward) and a forward electron longitudinal plasma wave. The three waves must obey matching conditions on their frequencies and wave numbers.

Here, we use the spin-Vlasov-Maxwell PIC code described above to study forward Raman scattering for spin-polarized electrons. We investigate how the SRS instability is modified by spin effects and how the spin coherence is progressively destroyed by the instability. We also explore the possibility to induce a spin polarization using appropriately tailored laser pulses.

References

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