Asynchronous 3D HYPERS simulations of compact toroids and magnetoplasmas: spheromak merging, FRC formation, magnetized shocks, laser-produced plasmas and turbulence

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HYPERS (Hybrid Parallel Event-Resolved Simulator) is a dimension-independent (compile-time-configurable) quasineutral hybrid (fully kinetic ions and inertialess electrons) massively parallel code that scales to hundreds of thousands of processes and advances electromagnetic fields and particles asynchronously on time scales determined by local physical laws and mesh properties. To achieve high computational accuracy in complex device geometries, HYPERS employs high-fidelity Cartesian grids with masked (conductive) cells. The HYPERS model includes multiple ion species, energy and momentum conserving ion-ion collisions, and provides a number of approximations for plasma resistivity and vacuum regions. Both local and periodic boundary conditions are allowed. The HYPERS solver preserves zero divergence of magnetic field and utilizes the EMAPS (Event-driven Multiscale Asynchronous Parallel Simulation) technology that replaces time stepping with self-adaptive update events. As a result, local calculations are carried out only on an "as needed basis". EMAPS (i) guarantees accurate and stable processing of physical variables in time accurate simulations, and (ii) eliminates unnecessary computation. This makes HYPERS a robust tool for modeling inhomogeneous plasmas with ion kinetic and Hall effects. The current capabilities of HYPERS are demonstrated on a number of applications of interest to fusion, space and astrophysical plasma physics. Future extensions to the asynchronous hybrid model are also discussed.

1. Spheromak merging

3D hybrid simulations of merging spheromaks indicate that a tilt-stable field-reversed configuration (FRC) can be achieved via fast merging and magnetic reconnection of spheromaks with opposite helicities. The simulations show that initially produced spheromaks must be delivered quickly enough to the collision point in order to avoid relaxation to the m=1 Taylor helix mode, which may lead to a severe loss of symmetry and ultimate disruption of the final FRC.

2. Theta-pinch formation of FRCs

The formation, spontaneous spin-up, and stability of theta-pinch formed field-reversed configurations have been studied self-consistently in 3D. The end-to-end hybrid simulations reveal poloidal profiles of implosion-driven fast toroidal plasma rotation and demonstrate three discharge regimes as a function of experimental parameters: the decaying stable configuration, the tilt unstable configuration, and the nonlinear evolution of a fast growing tearing mode.

3. FRC collisions with magnetic mirrors

Interactions of fast plasma streams and objects with magnetic obstacles (dipoles, mirrors, etc) lie at the core of many space and laboratory plasma phenomena ranging from magnetoshells and solar wind interactions with planetary magnetospheres to compact fusion plasmas. HYPERS simulations are compared with data from the MSX experiment (LANL) that focuses on the physics of magnetized collisionless shocks through the acceleration and subsequent stagnation of FRC plasmoids against a strong magnetic mirrors and flux-conserving boundaries.

4. Exploding magnetoplasmas

Results from hybrid simulations of two experiments at the LAPD and Nevada Terawatt Facility are discussed where short-pulse lasers are used to ablate solid targets to produce plasmas that expand across external magnetic fields. The first simulation recreates flutelike density striations observed at the leading edge of a carbon plasma and predicts an early destruction of the magnetic cavity in agreement with experimental evidence. In the second simulation a polyethylene target is ablated into a mixture of protons and carbon ions. A mechanism is demonstrated that allows protons to penetrate the magnetic field in the form of a collimated flow. The results are compared to experimental data and single-fluid MHD simulations.

5. Plasma turbulence

HYPERS simulations of externally driven plasma turbulence demonstrate the formation and evolution of coherent structures (current sheets) that play an important role in the dissipation of cascading energy. In the inertial range of scales magnetic spectra derived from hybrid simulations compare favorably with those from fully kinetic simulations. This match validates the hybrid model as a promising approximation for studying kinetic properties of large-scale (hundreds of ion inertial lengths) plasma turbulence.