Mesh-free Plasma Simulation with a Parallel Tree Code

Numerical simulation of hot, ionized matter poses a perennial challenge to the theoretical plasma physicist because of the virtually unlimited degrees of freedom, extreme nonlinear behaviour and vast range of length- and timescales characteristic of both natural and man-made plasmas. Traditionally, the intractability of first-principles simulation is overcome by first simplifying the problem in phase space; replacing individual particle trajectories by a smooth velocity distribution and then solving a Vlasov-Boltzmann-type equation. By rigorous application of kinetic theory, many problems can be further reduced to the magnetohydrodynamics picture – the plasma equivalent of the Navier-Stokes equations.

Whether kinetic or fluid, nearly all plasma modelling over the past four decades has relied on a spatial mesh to mediate the interplay between plasma particles and their associated electric and magnetic fields. While these models have proved highly successful, the presence of a grid ultimately places restrictions on the spatial resolution or geometry which can be considered – especially in three dimensions. Recently a new mesh-free plasma simulation paradigm has been developed which overcomes some of these limitations. Inspired by the N-body tree algorithms designed to speed up gravitational problems in astrophysics, this approach reverts to first principles by computing forces on individual particles directly, following their trajectories in a Lagrangian, “molecular dynamics” fashion [1].

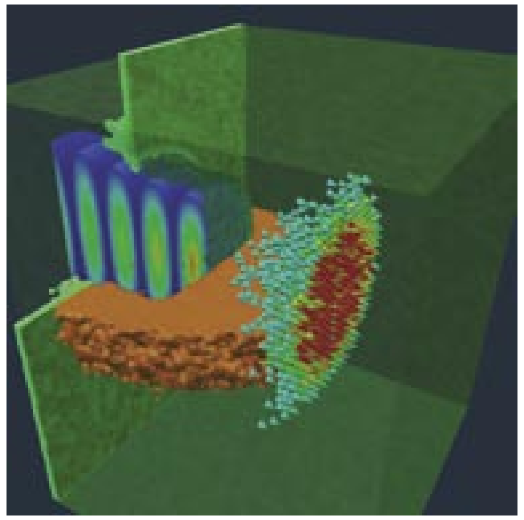

Figure 1: Mesh-free kinetic simulation of proton acceleration by a high intensity, short-pulse laser

At ZAM we have applied this technique to study particle transport in Petawatt laser interactions with solid targets – see Figure 1. In this case the laser (blue discs) is modelled as a simple momentum and heat source, drilling into the target and accelerating a substantial fraction of the plasma electrons to energies of several MeV in the process. In effect, the laser induces a multi-Megaamp current directed into the target, a feat which is only sustainable if a return current can be supplied by the cold background charge. If the target resistivity is high, an imbalance will result, setting up a DC electric field in the range of 10^{12} Vm^{-1}. This field hinders the hot electrons from passing through the target (orange cloud), but on the other hand leads to enhanced acceleration of ions from the front side of the target (arrows). Such laser-based energetic ion sources have many promising applications in areas such as isotope production, tumor therapy and advanced fusion schemes [2].

A typical investigation is set up with a total of 6 million electrons and ions placed in a “foil” with dimensions 12x12x5 µm3. The simulation of this interaction process for a 100 fs laser pulse would consume 5000 hours on a single Power4 CPU, but this reduces to around 100 wall-clock hours when run on 96 processors (3 frames) of the IBM supercomputer “Jump” at the Research Centre Jülich. Further preliminary benchmark tests with several million charges (1-25 million) demonstrate that this code scales up to at least 256 CPUs on Jump and 1024 CPUs on the new BlueGene/L architecture – Figure 2. Although slower than particle-in-cell codes (their mesh-based equivalents) parallel tree codes offer completely new possibilities in plasma simulation, particularly where collisions are important (here they are included automatically); or for modelling complex geometries; or for mass-limited systems in which artificial boundaries would severely compromise the simulation´s validity (for example atomic clusters). The generic nature of this algorithm, combined with good parallel scalability, means that it can be easily adapted to other systems dominated by long-range interactions – currently one of the research priorities at ZAM [3].

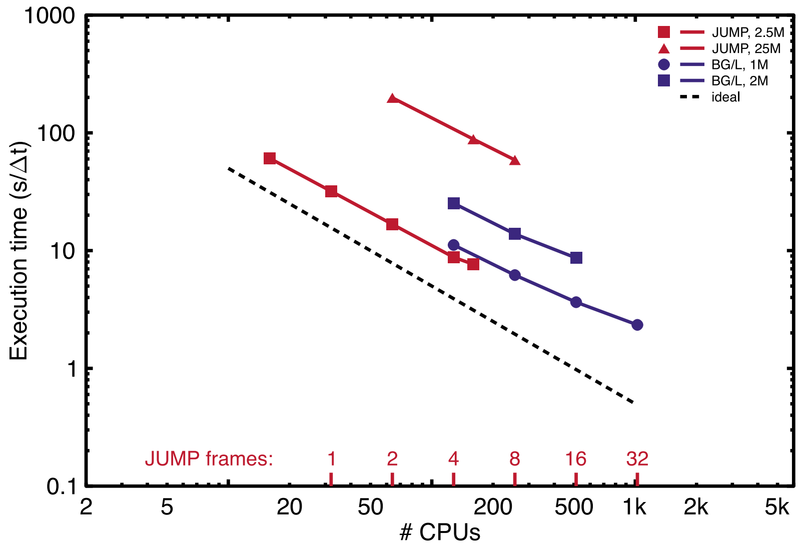

Figure 2: Scaling of the parallel tree code on Jump and BlueGene/L for spheres with various numbers of charges

References

[1] S. Pfalzner, P. Gibbon
Phys. Rev. E 57, 4698 (1998)

[2] P. Gibbon
Short Pulse Laser Interactions with Matter, Imperial College Press, London (2005)

[3] For further information, see:
www.fz-juelich.de/zam/cams

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