HIGH-ORDER PIC SIMULATION OF HIGH POWER MILLIMETER WAVE SOURCES COMPONENTS

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Introduction

Geometrically and physically complex plasma devices require the complete solution of the Maxwell-Vlasov equations without approximations that could restrict the results of the simulations to particular situations. Gyrotron oscillators provide an example of this category of radiation sources: they are successfully applied as high power micro- and millimetre wave sources for electron cyclotron current drive, electron cyclotron resonance heating, stability control and diagnostics of magnetically confined plasmas for generation of energy by controlled thermonuclear fusion. The Institute for Pulsed Power and Microwave Technology has been leading gyrotron designs for more than twenty years by means also of in-house codes like SELFT and ESRAY which provided excellent results but still included those geometrical and physical approximations, e.g. reduced, one-dimensional physical modelling as well as rotational symmetry, that prevented an exact description of the plasma. On the contrary, the HALO-PIC code is a novel, highly flexible, high-order tool developed at the IAG for the numerical solution of the Maxwell-Vlasov equations (MVE) in six-dimensional phase space [8, 5]. It is expected that this simulation code will serve for the assessment of a variety of engineering tools that rely on physical approximations. A co-operation between these two institutes has been established for the simulation of high energetic microwave source for fusion plasma heating, without the use of any physical approximations to the MVE.

Numerical Approach

An attractive and powerful method to solve numerically the MVE in six dimensional phase-space is the Particle- In-Cell (PIC) approach [1, 9]. The basic ideas of this technique can be summarized as follows (see Fig. 1): the plasma inside the device is represented by a

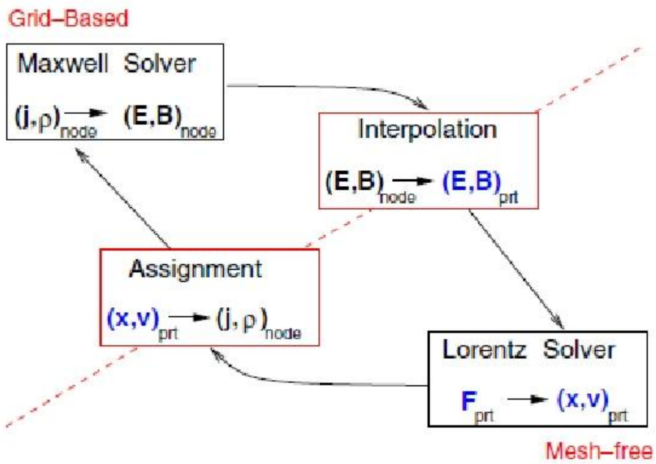

Figure 1: Standard PIC cycle

sample of charged particles; at each time step the electromagnetic fields are evaluated by numerical solution of the Maxwell equations. In the present context, the Maxwell solver is based on discontinuous Galerkin (DG) methods which allows for polymorphic grid cell arrangements [2] and for, in principle, arbitrary high-order accuracy in both space and time. Additionally, divergence cleaning techniques are applied [3] to avoid discrete charge conservation violation. Afterwards, the electromagnetic fields are interpolated to the actual locations of the charged simulation particles [5]. According to the Lorentz force the charges are advanced and the new phase-space coordinates are determined by solving numerically the law of the relativistic dynamics, where a low-storage explicit Runge-Kutta method [7] or space-time expansion [8] time integrator is used. In order to close the chain of self-consistent interplay the particles have to be located with respect to the computational mesh in order to compute the contribution of each charged particle to the changed charge and current density [5] being the source terms for the Maxwell equations in the subsequent

Results

The above described fully relativistic, self-consistent PIC method has been applied to simulate two of the components of different gyrotrons, namely the $TE_{0,3}$ mode resonator and the $TE_{22,6}$ mode launcher. In the first case, the Maxwell solver is coupled with the particles, so that the whole PIC cycle depicted in Fig. 1) is operating, while in the second example the capability of the Maxwell solver is examinated.

The $TE_{0,3}$ mode resonator: The resonator is that gyrotron component where the emission radiation takes place. Microwaves are excited by the bunching of electrons with cyclotron motion in strong magnetic field and taking advantage of the relativistic electron cyclotron resonance maser instability. The benchmark is a standard test case presented in [4] and

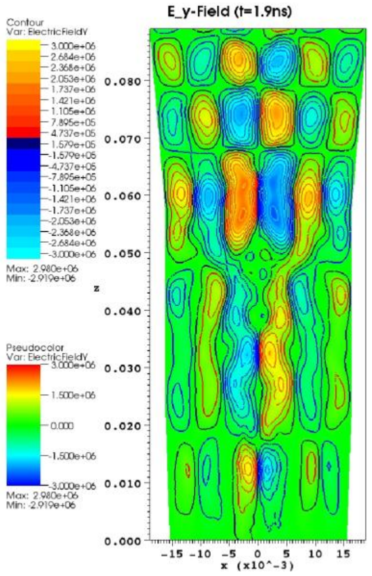

Figure 2a: The $TE_{0,3}$ mode resonator

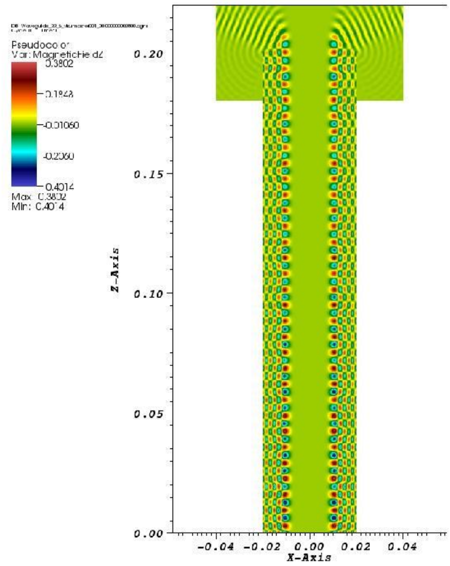

Figure 2b: The $TE_{22,6}$ mode cylindrical launcher

reproduced in [5] and here with a ~ 9000 fourth-order tetrahedral elements and 10^6 macro-particles. The simulation results, recorded at t = 1.9ns, were obtained on 128 cores of the 'Nehalem' cluster (Intel Xeon X5560, 2.80 GHz, 8MB Cache, FSB 1333 MHz) at the High Performance Computing Center Stuttgart (HLRS). The result obtained by the third-order B-splines (see Fig. 2a) is in very good agreement with the comparative simulation. [4]. The time sequence shows at the very beginning when several modes compete, an unstructured field pattern; an incoming wave is established for some time, before the desired $TE_{0,3}$ mode finally arises and the stationary wave travels in the expected outward direction.

The $TE_{22,6}$ mode launcher: The second gyrotron component which was successfully simulated with HALO-PIC at IAG is the complete $TE_{34,19}$ mode launcher and a paper is on preparation. Here we present a simplified cylindrical shape of the $TE_{22,6}$ mode. This simulation required 512 processors of the 'Nehalem' cluster at the HLRS for about 10 CPU hr. In this experiment (see Fig. 2b) we initialize an analytical electromagnetic wave at the entrance of the cylindrical wave guide which we surrounded with some external space at the exit where it can freely propagate. The whole computational domain was discretized with ~2.6 x 10^6 tetrahedrons with a characteristic discretization length of ~10^{-3} (about 0.5λ , the wavelength) and the fields where approximated up to the fourth order. The picture is recorded at t = 2.8ns and clearly shows that as expected the wave travels the cylinder undisturbed; 'Perfect conducting' boundary condition are prescribed here. Outside of the cylinder, on the contrary the wave is free to propagate and it tends to assume the characteristics of a plane wave, with an angle of ~ 30 ° with respect to axis of the cylinder.

Conclusions and Outlook

We have shown that HALO-PIC can simulate highly complex plasma devices like the resonator of a $TE_{0,3}$ and the launcher of a $TE_{22,6}$ mode. Indeed, demanding three dimensional PIC simulations of complex large scale engineering applications are possible and yield accurate results. More challenging simulations of higher modes resonators and launchers, e.g. the $TE_{34,19}$ are currently under study (a more detailed paper will be published soon) together with post-processing tools for the frequency analysis of the resulting field pattern.

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