A High-Order Discontinuous Galerkin-Approach-Based Particle-In-Cell Method for the Simulation of Large Scale Plasma Devices

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Growing computational capabilities and simulation tools based on high-order methods allow for complex shaped plasma devices to simulate the entire nonlinear dynamics of the Vlasov-Maxwell system modelling the particle-field-interactions of a non-neutral plasma without significant simplifications [4]. Thereby, new insights into physics on a level of detail that has never been available before provides new design implications and a better understanding of the overall physics.

In the field of gyrotron design state-of-the-art fast codes play a crucial role [2, 6]. While procuring their rapidity by making strong physical simplifications and approximations, the correctness of these assumptions is not known to be valid for all considered variations of the geometry and operation setup. Solving the nonlinear Vlasov-Maxwell system without significant physical reductions, the self-consistent transient 3D electromagnetic Particle-In-Cell (PIC) method [1, 3] can provide better insights into these setups and beyond that can serve as validation tool for a fast design code.

We present a high-order discontinuous Galerkin method based PIC code with high-order coupling techniques on unstructured grids in a parallelization framework allowing for large scale applications on high performance computing clusters [7, 10]. We simulate the geometrically complex gyrotron resonant cavity and the quasi-optical mode converter of the 170 GHz gyrotron aimed for plasma resonance heating of the fusion reactor ITER [5, 9]. A result of our high-order transient resonator simulations is shown in Figure 1.

Currently we enhance the range of applications of our PIC-code to rarefied plasma flows in which particles interaction has to be taken into account, i.e. collisional phenomena of the Boltzmann integral. According to the nature of these interactions, the Boltzmann collision integral has to be approximated with different appropriate approaches which require their own numerical model and method. The Direct Simulation Monte Carlo (DSMC) method which has been adopted and coded is the state-of-the-art approach for the numerical modeling of short-range elastic electron neutral collisions and binary inelastic reactions like excitation, ionization, dissociation, recombination, etc. .

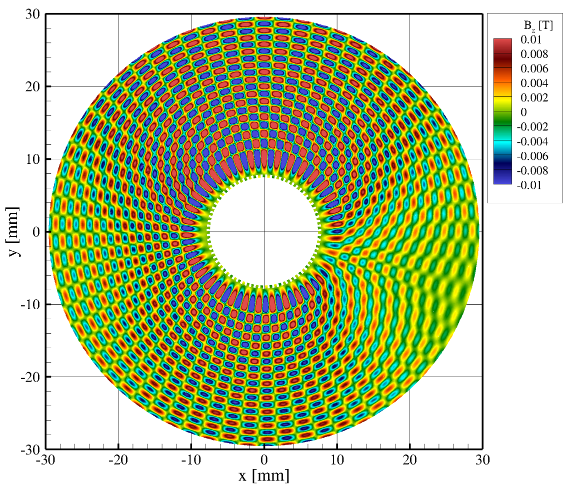

Fig. 1. B_z-field of a 170 GHz gyrotron resonator simulated with the PIC method on 512 processes.

The coupling of the DSMC module with the DG-PIC solver has been carried out and the coupled code is applied to a variety of discharge problems for validation purposes. Besides collective phenomena from computations in gyrotrons, we will here further present and discuss results from plasma streamer simulations (see Fig. 2). Especially, we will focus our attention to the avalanche-streamer transition, the streamer formation and the subsequent streamer evolution which are key mechanisms in the early stage of the discharge phenomenology.

So far, scientific demonstration calculations for gyrotron devices and streamers have been performed [7, 10]. We expect that the growing potential of the code will enable us to simulate a broad range of applications also on industrial scale. Besides streamers and micro and millimeter wave sources, also applications with electromagnetic vulnerability background, such as the impact of space weather on satellites, and new space propulsion concepts such as the *Mini Magnetospheric Plasma Propulsion* can be considered [8].

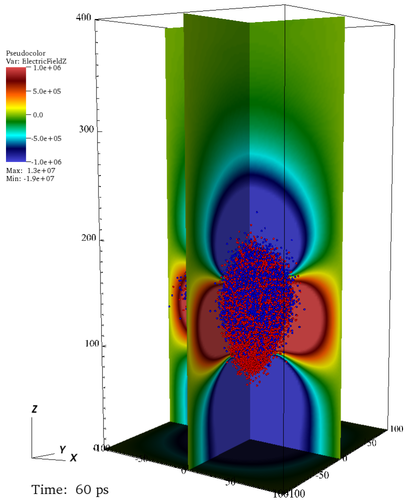

Fig. 2. Field and particle distribution from the streamer simulation on 500 MPI processes with the DG-PIC solver coupled with the DSMC module.

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References

1. C.K. Birdsall and A.B. Langdon. Plasma Physics via Computer Simulation. Adam Hilger, Bristol, Philadelphia, New York, 1991.
2. M. Botton, T. M. Antonsen, B. Levush, K. T. Nguyen, and A. N. Vlasov. MAGY: a time-dependent code for simulation of slow and fast microwave sources. IEEE Transactions on Plasma Science, 26:882–892, June 1998.
3. R. Hockney and J. Eastwood. Computer Simulation using Particles. McGraw-Hill, New York, 1981.
4. G.B. Jacobs and J.S. Hesthaven. High-order nodal discontinuous Galerkin particle-in-cell method on unstructured grids. J. Comput. Phys., 214:96 – 121, 2006.
5. J. Jin, M. Thumm, B. Piosczyk, and T. Rzesnicki. Theoretical Investigation of an Advanced Launcher for a 2-MW 170-GHz $TE_{34,19}$ Coaxial Cavity Gyrotron. IEEE Transactions on Microwave Theory and Techniques, 54(3):1139–1145, 2006.
6. S. Kern. Numerische Simulation der Gyrotron-Wechselwirkung in koaxialen Resonatoren. PhD thesis, Forschungszentrum Karlsruhe GmbH, FZKA 5837, 1996.
7. J. Neudorfer, A. Stock, J. Flamm, F. Hindenlang, G. Gassner, C.-D. Munz, R. Schneider, and S. Roller. Numerical investigation of high-order gyrotron mode propagation in launchers at 170 GHz. accepted for publication in: IEEE Transaction on Plasma Science, XX:yyy–yyy, 2012.
8. M. Pfeiffer, D. Petkow, G. Herdrich, and S. Fasoulas. Assessment of a numerical approach suitable for the m2p2 problem. The Open Plasma Physics Journal, 4:24–33, 2011.
9. B. Piosczyk, G. Dammertz, O. Dumbrajs, O. Drumm, S. Illy, J. Jin, and M. Thumm. A 2-MW, 170-GHz coaxial cavity gyrotron. IEEE Transactions on Plasma Science, 32(2):413– 417, April 2004.
10. A. Stock, J. Neudorfer, M. Riedlinger, G. Pirrung, G. Gassner, R. Schneider, S. Roller, and C.-D. Munz. Three-dimensional numerical simulation of a 30 GHz gyrotron resonator with an explicit high-order discontinuous galerkin based particle-in-cell method. accepted for publication in: IEEE Transaction on Plasma Science, XX:yyy–yyy, 2012.