GPU-Accelerated 3D Large-Signal Device Simulation Using the Particle-in-Cell Code ‘Neptune’

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Abstract: *We present large-signal, 3D simulations of vacuum electronic slow-wave amplifier operation using the GPU-accelerated FDTD-PIC simulation code, ‘Neptune’. Neptune implements a self-consistent, charge-conserving, electromagnetic, particle-in-cell algorithm optimized for parallel execution in both multi-core CPU and GPU processors. Significant performance gains achieved using a 512-core Nvidia GTX-580 graphics card are demonstrated.*

Keywords: FDTD-PIC; non-linear; slow-wave amplifier; GPU.

Introduction

The design of modern, high-performance vacuum electron devices relies on the use of advanced numerical simulation tools to achieve high performance operation while reducing development time and cost. For specific classes of slow-wave amplifiers, 1D and 2D large-signal simulation codes, such as CHRISTINE [1] and TESLA [2] developed at NRL, provide accurate predictions of amplifier performance over a wide range of conditions. These are widely used as design tools due to their speed of execution, ranging from a few seconds per simulation point in 1D to typically tens of minutes in 2D. There are, however, many situations when these 1D and 2D codes cannot capture the either the simulation geometry or the essential physics sufficiently well. In these cases, full 3D modeling is possible using well-tested electromagnetic particle-in-cell (PIC) codes such as MAGIC [3]. For these simulations, however, speed of execution is typically measured in hours per simulation point, even using parallel computation across a multiple-CPU cluster, making such codes less effective as design tools.

To address this situation we have developed a new general-purpose 3D electromagnetic PIC simulation code, ‘Neptune’, which accelerates simulations using high-performance Graphics Processing Unit (GPU) hardware. A typical high-end graphics card can contain 512 or more computational cores, combined with fast memory addressing, at the relatively low cost of ~$1/core. In Neptune we take advantage of this parallelism to accelerate electromagnetic simulations by up to 70-80 times compared to a single CPU core. Alternatively, Neptune can perform parallel simulations on multi-core CPUs when a GPU is not available, showing almost linear speed-up for calculation on a 12-core system. Here we report on the application of this new capability to achieve rapid 3D simulation of vacuum electronic amplifiers.

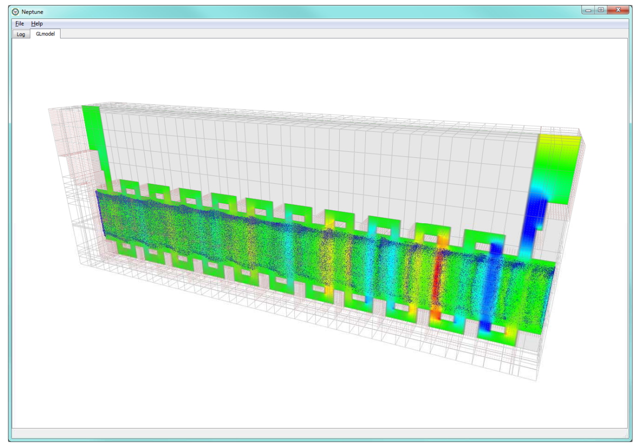

Figure 1. Run-time visualization of a large-signal sheet-beam CCTWT amplifier simulation in Neptune.

3D Electromagnetic PIC Code - Neptune

Neptune provides a collection of algorithms for both electromagnetic FDTD and particle-in-cell (PIC) simulation that are tailored for parallel operation on high-performance CPUs and GPUs. For electromagnetics, these algorithms include conventional FDTD as well as alternating-direction implicit (ADI-FDTD) time-domain solvers. The present particle algorithm is a charge-conserving Boris-push particle-in-cell method, coupled self-consistently to the FDTD fields. Figure 1 shows a running PIC simulation in Neptune.

The Neptune code consists of four parts: (1) a graphical user interface with an embedded scripting language, Lua, using just-in-time compilation for high performance [4]; (2) a library of Lua code providing access to geometry creation, the FDTD time-loop and diagnostic facilities; (3) an interface layer including C++ data structures to handle CPU/GPU communication and visualization; and (4) a set of core computational kernels designed for parallel execution on either the GPU or the CPU, via Nvidia’s CUDA library and Intel’s TBB library. User scripts interact with the first layer, providing a flexible interface.

We present here the results of simulations performed using Neptune.

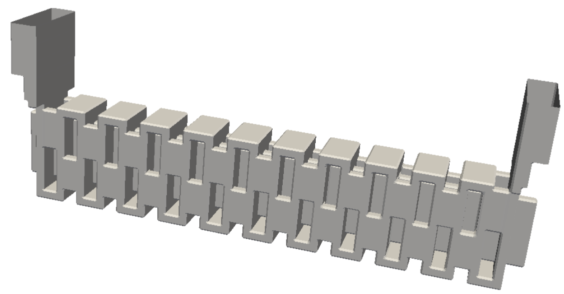

Figure 2. Sheet-beam coupled-cavity TWT structure

Sheet-beam Coupled-Cavity TWT Amplifier

Figure 2 shows the 3D structure of the metal surface of a Ka-band sheet-beam coupled-cavity TWT amplifier under development at NRL [5]. This device consists of 22 cavities connected by sets of three staggered coupling slots arranged around the central rectangular beam tunnel. Input and output ports are connected to the first and last cavities respectively, which are modified to provide broadband matching.

A running simulation of this device using Neptune at the central design frequency of 35GHz is shown in Figure 1, with the simulation region discretized on a 82×220×475 cell grid (8.6M cells total). Non-uniform gridding in Neptune allows each surface in the structure to be meshed conformally, shown as marked grid lines in the figure. The input port is driven in a rectangular TE_{10} mode with 200W average power, ramped over 100 rf cycles (~2.8ns). Matched impedance boundary conditions at the input and output ports absorb outgoing waves, and conductive surface losses of the metal structure are included. The beam is imported from a MICHELLE electron gun simulation. The resulting time history of the power at each port is shown in Figure 3. A direct comparison with results obtained using MAGIC for similar numerical parameters is shown in Figure 4, with good agreement observed across the operating bandwidth. Each Neptune simulation of 80,000 time steps (10ns), with an average particle load of ~350k particles, takes 20 minutes running on an Nvidia GTX-580 graphics card.

Conclusion

Neptune provides a powerful new capability for rapid 3D electromagnetic PIC simulation of vacuum electronic amplifiers. Execution times for a full 3D device simulation are comparable to existing 2D simulation codes, making 3D large-signal simulation effective as a rapid design tool.

Acknowledgements

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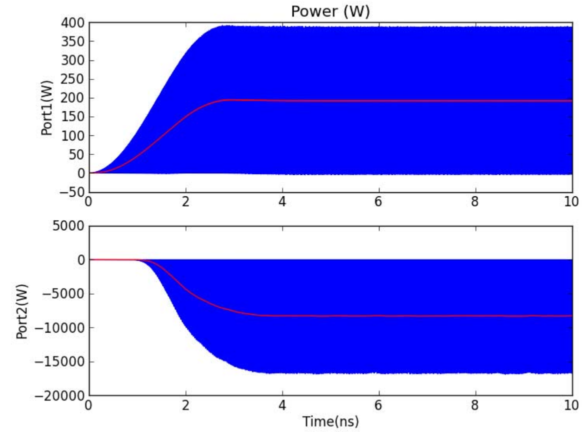

Figure 3. Integrated Poynting flux at the input and output ports, showing instantaneous and time-averaged signals.

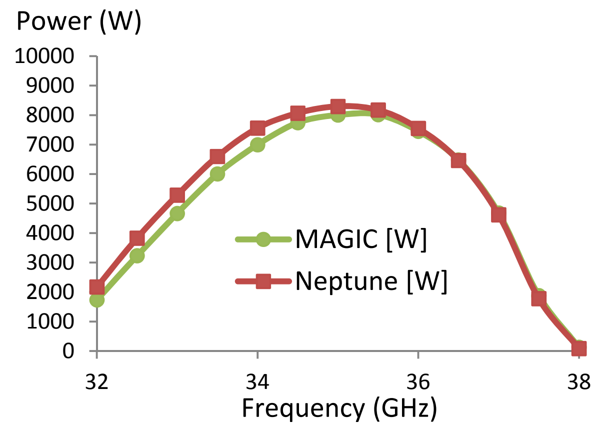

Figure 4. Comparison between MAGIC and Neptune simulations of large-signal CCTWT amplifier operation.

References

1. D. Chernin, T. M. Antonsen, Jr., I. A. Chernyavskiy, A. N. Vlasov, B. Levush, R. Begum, J. R. Legarra, "Large-signal multifrequency simulation of coupled-cavity TWTs," IEEE Trans. on Electron Devices, vol. 58, no. 4, April 2011.
2. I. A. Chernyavskiy, S. J. Cooke, A. N. Vlasov, T. M. Antonsen, Jr., D.K. Abe, B.Levush, and K.T.Nguyen, "Parallel simulation of independent beam-tunnels in multiple-beam klystrons using TESLA," IEEE Trans. on Plasma Science, vol. 36, no. 3, June 2008
3. B. Goplen, L. Ludeking, D. Smithe, and G. Warren, "User-configurable MAGIC for electromagnetic PIC calculations," Comput. Phys. Commun., vol. 87, no. 1, pp. 54–86, May 1995
4. See www.lua.org; www.luajit.org.
5. P. B. Larsen, D. K. Abe, S. J. Cooke, B. Levush, T. M. Antonsen, Jr., and R. E. Myers, "Characterization of a Ka-band sheet-beam coupled-cavity slow-wave structure," IEEE Trans. on Plasma Science, vol. 38, no. 6, June 2010.