State of the Art Gyrotron Simulations and Required Software Features

Jonathan Smith[1], David Smithe[2], Ming-Chieh Lin[3]

[1] Tech-X UK Ltd, Daresbury, Warrington, WA4 4FS
[2] Tech-X Corporation, Boulder, CO 80303 USA
[3] Hangyang University, Korea (prev of Tech-X Corp)

Abstract

Computation has long played a role in the design of vacuum electronic devices due to the need to handle arbitrary geometry and the complicated particle/surface interactions that are often critical to their performance. Here, we present a powerful multidimensional code applicable to a wide range of vacuum electronic applications. We explore critical algorithmic advances from the last 10 years that enable state of the art simulation studies, and place these in the context of magnetrons, klystrons, gyrotrons and travelling wave tubes and passive cavities. We show the new techniques to understand the dynamics of particles in the presence of high power RF fields, their interactions with walls and the ability to handle electrically very large problems.

We show how "hot test" simulation results of the high order modes found in fusion gyrotrons[1] increase understanding of operational showstoppers.

Introduction

Gyrotrons are used for the generation of high-power millimetre, submillimetre and THz radiation. The principle of operation is as follows: An annular electron beam is emitted from a magnetron injection gun (MIG), and is magnetically focussed into a cavity surrounded by a strong (often superconducting) magnet. See Fig 1. The cavity is typically a smooth-walled waveguide, though some variants have a corrugated rather than simple cylindrical cross-section. The strong magnetic field causes orbit with significant transverse velocity component as well as a component along the axis of the device. There is bunching of phase within the gyro-orbits, which is amplified as the particles travel through the device. The mode of operation is generally selected to be very close to cut-off in the waveguide and can be a very high mode number. The magnetic field confines the beam and selects the frequency of operation, as $\omega = \Omega + k_\parallel v_\parallel$ with $\Omega = eB/m_e$, where ω is the operating frequency, e is the electron charge, B is the magnetic field and m_e is the electron mass, $k_\parallel$ and $v_\parallel$ are the axial wavenumber and velocity respectively.
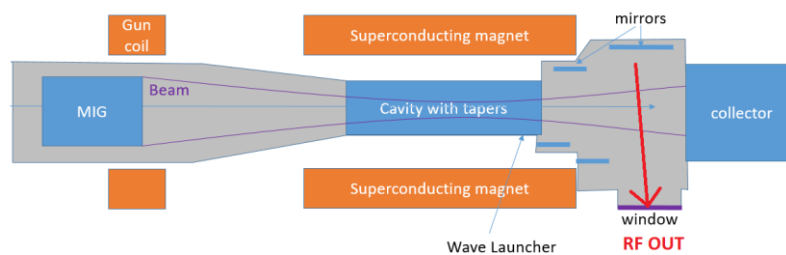

Fig. 1: Schematic of a gyrotron

Typically calculations are performed separately for the cold-test (no electrons) electromagnetic mode patterns as a function of the frequencies in the structure. Low power

gyrotrons may be modelled using a desktop computer, and are characterized by low mode number. They are typically used for research purposes by universities. Medium power gyrotrons[2,3] typically operate using medium mode number (eg 7,3), and are typically used for defence applications, and the cavity interaction has been amenable to computation for around 10 years on a powerful workstation. High order mode gyrotrons[4] are used for applications such as electron cyclotron resonance heating (ECRH) in fusion tokomaks; they currently require high performance computation. The high performance computing requirement demands software which has been designed with scalability in mind, such as the VSim software [5,6].

Simulation requirements for "hot test"

There are a number of considerations for the simulation of a gyrotron. The high mode number requires that the simulation domain is discretized into many cells, the size of the beams requires that these cells be small to resolve the changes in the field. The large number of computational cells requires highly scalable software; the finite difference time domain technique [7,8] has been shown to provide ideal scaling onto $>10^5$ processor cores (Fig. 2). The thin annular beam can have very high charge density, which in order to ensure plasma oscillations are captured, requires $\omega\delta t < 2$ which leads to a very small time-step. One must handle numerical Cherenkov radiation as the device is mildly relativistic through a filtering technique. One must ensure the radiation escapes from the simulation domain without numerical reflection, and as the gyro orbits generate the radiation from noise, sufficient particles must be present in the simulation to adequately resolve the statistical fluctuations. Finally, as we are very close to cut-off, we must take care to be sensitive to any difference between the numerical dispersion curve and the dispersion in free space.
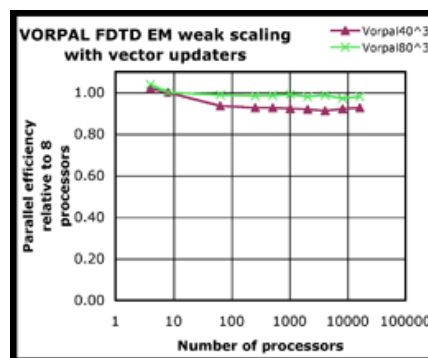

Fig. 2: VSim was shown to utilize tens of thousands of CPU cores with near ideal scaling

In effect the physical field must be accurately sampled by the particles, so on the rectangular mesh 12-16 cells per wavelength should be the minimum used. This places significant demands computer memory, so distributed processing on a compute cluster is normally required to maintain the necessary resolution. Consequently, any software approach should make use of distributed processing, and the domain decomposition approach is a natural fit.
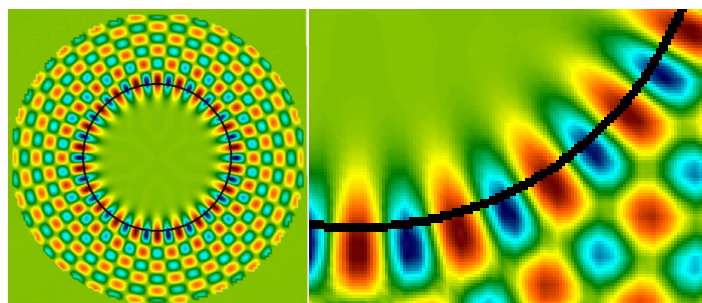

Fig. 3: Mode pattern in a transverse slice and close up showing beam-field interaction region

The geometry to be simulated typically includes a ~3˚ taper at the entrance and output of the cavity, as shown in Fig. 4. This geometry must be accurately represented. To ensure complete confidence about resolving the geometry, the Dey-Mittra method [9-11] may be used to represent the interface between the metal and the vacuum, and allows for the correct compromise to be made between simulation speed and geometric accuracy. Inaccuracies will lead to an incorrect quality factor (Q) being computed for the cavity, and the correct Q is essential to correctly calculate the gain in the cavity. [12]
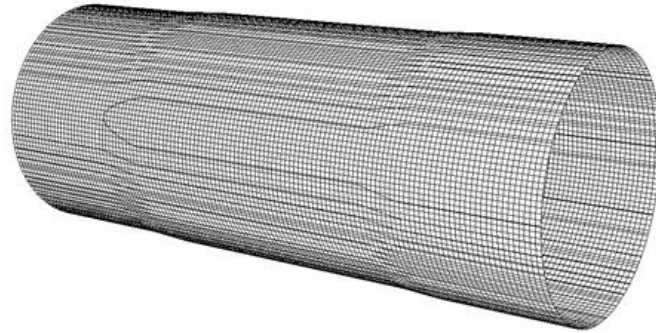

Fig. 4: Geometric 'conformal' representation of cavity showing slight tapering

As the physical device is very close to the waveguide cut-off frequency, the significant quantity is the frequency above cut-off, sometimes called the 'delta-frequency' $\delta\omega = \omega - \omega_{cutoff}$. This is the same in the simulation, but the cut-off frequency may be slightly different. Consequently we need to determine $\delta\omega_{FDTD} = \omega - \omega_{cutoff,FDTD}$. The delta-frequency may be found by varying the frequency above cut-off, and producing a dispersion plot, also known as an 'omega-beta diagram'. See Fig 5.
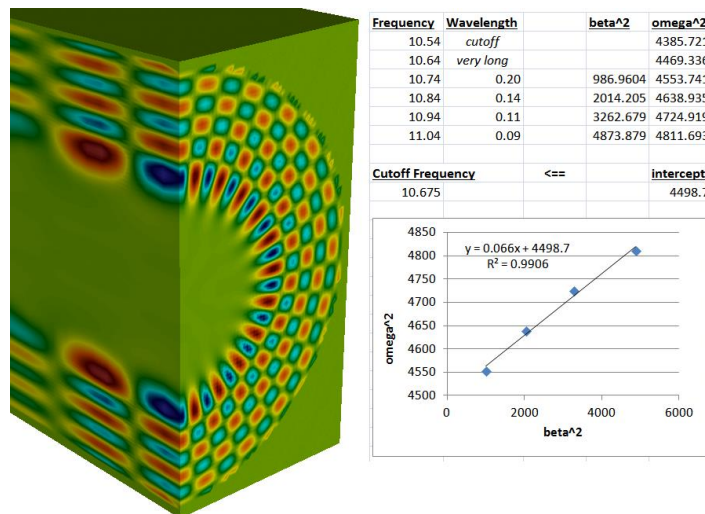

Frequency	Wavelength	beta^2	omega^2
10.54	cutoff		4385.721
10.64	very long		4469.336
10.74	0.20	986.9604	4553.741
10.84	0.14	2014.205	4638.935
10.94	0.11	3262.679	4724.919
11.04	0.09	4873.879	4811.693
Cutoff Frequency		<==	intercept
10.675			4498.7

$y = 0.066x + 4498.7$
$R^2 = 0.9906$

Fig. 5: A dispersion diagram enables computation of the $\delta\omega_{FDTD}$ parameter

Many challenges in operating gyrotrons must also be considered during simulation, such as the sensitivity to magnetic field and non-uniformity, beam alpha (alpha is the ratio of parallel to perpendicular velocity as set by the gun magnetic field), up and down tapers, post-cavity interaction, space charge effects, external circuit non-linearity, the operating mode landscape and occurrence of low frequency oscillations. The mode landscape is complicated by mode competition at various frequencies [13]. VSim has simulated the complete set of forward and backward interactions.

Full scale simulations

Full scale gyrotron simulations should handle the self-consistent interaction between the MIG gun, the damping structures, the cavity, the output coupler and the collector. It is important to be able to record both the time history of the field in various location and to record the power (measured as a Poynting vector) as a function of time. Operation at power levels of >1MW are observed as expected [14] . See Fig. 6.
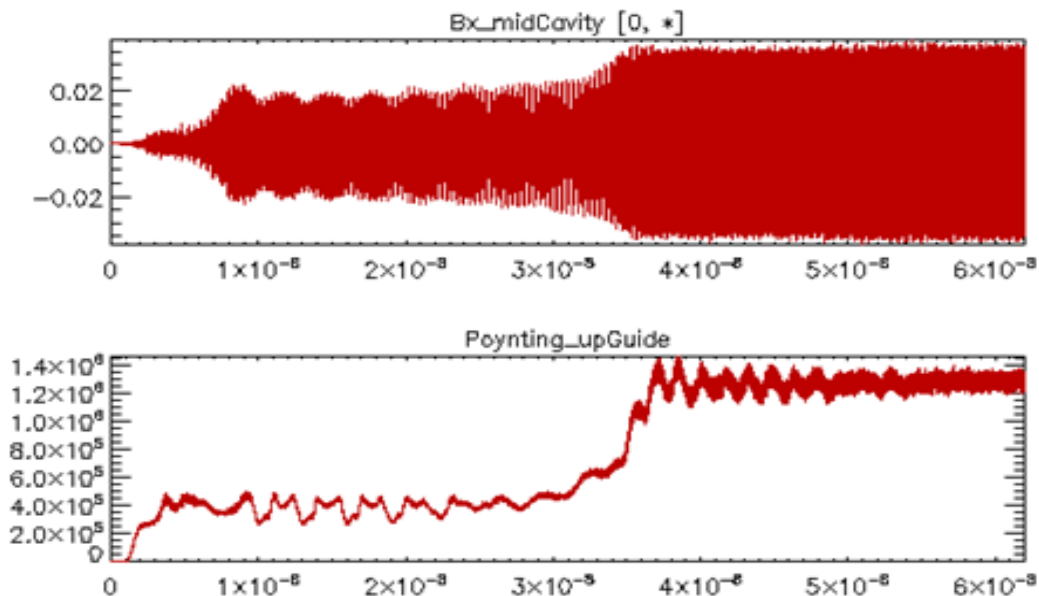

Fig 6. Oscillating microwave magnetic field in the cavity and output power, over time.

A mode is chosen by the magnetic field, *B*. The field in the gun region sets azimuthal beam velocity, which affects the mode excited. The parameters for a simulated device are scanned in the same way as for an experimental prototype. Good qualitative agreement is seen in terms of both the mode excited and stable operation bands, and the regions of this parameter space where the beam would be either reflected or would intercept the walls of the cavity.

Cause of low frequency oscillations

VSim has been used increase understanding of low frequency oscillations through to occur near the magnetron injection gun. It is hypothesized that these are caused by recirculating electron populations in this region, giving rise to a low frequency (~100MHz) signal in this region[15]. See Fig. 7.
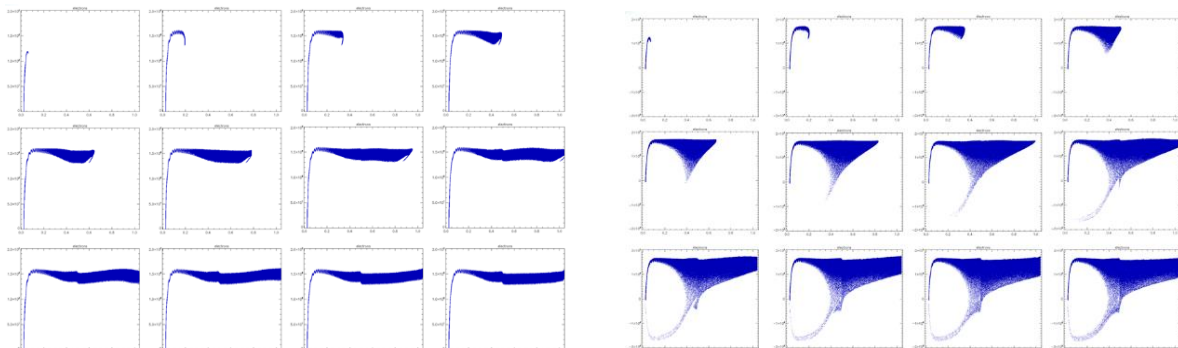

Fig 7: Two groups of 12 plots showing time evolution of z vs p_z.
Read 4 plots left to right then 3 plots down for each group.
Left: no recirculation of electrons, Right: recirculation of electrons

Alternative explanations, such as space charge effects in the collector up-radius have also been assessed. The aximuthal symmetry must be correctly represented by the simulation software, and an improved implementation of Jensen's Globalized Thermal Field (GTF) model[16,17] was developed to accurately calculate the electron phase-space. This advanced modelling enables us the low frequency oscillations to be understood.

Conclusion

Modern computing facilities lend themselves to simulating large gyrotron devices operating at very high mode number. VSim has been successfully helped understand the behaviour of a fusion gyrotron, enabling MIT researchers diagnose the cause of low frequency oscillations. The advanced, scalable, algorithms in VSim that were critical in making this breakthrough may be applied to klystrons, magnetrons, TWTs and other vacuum electronic devices.

References

[1] D S Tax, O V Sinitsyn, W C Guss, G S Nusinovich, M A Shapiro and R J Temkin, "Experimental Study of the Start-Up Scenario of a 1.5-MW, 110-GHz Gyrotron" IEEE Trans. Plasma Sci. Special Issue (2014).

[2] F Li, W He, A W Cross, C R Donaldson, L Zhang, A D R Phelps, and K Ronald "Design and Simulation of a 390 GHz 7th Harmonic Gyrotron using a large orbit electron beam", Journal of Physics D: Applied Physics **43**, 15 (2010) 155204

[3] Ashutosh, B. Ravi Chandra, and P. K. Jain "Multimode behavior of a 42 GHz, 200kW Gyrotron" Progress In Electromagnetics Research B, **42**, pp75-91, (2012)

[4] J Neudorfer, A Stock, R Schneider, S Roller and Claus-Dieter Munz, "Efficient Parallelization of a Three-Dimensional High-Order Particle-in-Cell Method for the Simulation of a 170 GHz Gyrotron Resonator", IEEE Trans Plasma Sci., **41**, **1**, (2013)

[5] C Nieter, J Cary "VORPAL, a versatile plasma simulation code" J. Comp. Phys. **196** (2004) pp448–473

[6] VSim is at https://www.txcorp.com/vsim (link correct on 4th October 2016)

[7] Yee, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media" IEEE Trans. Antennas and Propagation **14** (3) (1966) 302–307

[8] Taflove & Hagness: "Computational Electrodynamics: The Finite-Difference Time-Domain Method", Third Edition, Artech House

[9] S. Dey, R. Mittra, "A Locally Conformal Finite Difference Time Domain (FDTD) Algorithm for Modeling Three-Dimensional Perfectly Conducting Objects" IEEE Microwave Guided Wave Lett. 7 (1997) 273

[10] C. Nieter et al. "Application of Dey–Mittra conformal boundary algorithm to 3D electromagnetic modeling" J. Comp. Phys **228** (2009) 7902–7916

[11] Lin et al. "Accurately and Efficiently Studying the RF Structures Using a Conformal Finite-Difference Time-Domain Particle-in-Cell Method" Open Plasma Physics Journal, **3** (2010), pp 48-52

[12] M-C Lin and D N Smithe "Modelling a gyrotron cavity using a 3D CFDTD PIC Method" Proc IVEC 2013

[13] M-C Lin, D N Smithe, E Choi, K Chu, W C Guss and R J Temkin "Cold test of gyrotron cavity modes using a 3D CFDTD PIC Method" Proc IVEC 2014

[14] M-C Lin, D N Smithe, W C Guss and R J Temkin "Hot test of a gyrotron cavity interaction using a 3D CFDTD PIC Method" Proc IVEC 2014

[15] M-C Lin, D N Smithe "Study on Low-Frequency Oscillations in a Gyrotron using a 3D FDTD PIC method" Proc IVEC 2011

[16] K L Jensen and M Cahay "A General Thermal-Field Emission Equation" Proc. IVEC 2006

[17] M-C Lin, J Loverich, P H Stoltz and C Nieter "Improved Field Emission Algorithms for Modelling Field Emission Devices Using a Conformal Finite-Difference Time-Domain Particle-In-Cell Method" Proc IVEC 2013