STUDY ON LOW-FREQUENCY OSCILLATIONS IN A GYROTRON USING A 3D CFDTD PIC METHOD*

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Abstract

Low-frequency oscillations (LFOs) have been observed in a high average power gyrotron and the trapped electron population contributing to the oscillation has been measured. As high average power gyrotrons are the most promising millimeter wave source for thermonuclear fusion research, it is important to get a better understanding of this parasitic phenomenon to avoid any deterioration of the electron beam quality thus reducing the gyrotron efficiency. 2D Particle-in-cell (PIC) simulations quasi-statically model the development of oscillations of the space charge in the adiabatic trap, but the physics of the electron dynamics in the adiabatic trap is only partially understood. Therefore, understanding of the LFOs remains incomplete and a full picture of this parasitic phenomenon has not been seen yet. In this work, we use a 3D conformal finite-difference time-domain (CFDTD) PIC method to accurately and efficiently study the LFOs in a high average power gyrotron. Complicated structures, such as a magnetron injection gun, can be well described. Employing a highly parallelized computation, the model can be simulated in time domain more realistically.

INTRODUCTION

Fusion experiments such as the international thermonuclear experimental reactor (ITER) depend on high power continuous wave (CW) gyrotrons to deliver power to the plasma at ECR frequencies. It is estimated that microwave power of up to 48 MW, CW at 170 GHz will be needed for ITER. In the US, the General Atomics DIII-D experiment utilizes six 1 MW 110 GHz CPI gyrotrons, and the US sponsors significant R&D effort at locations such as the gyrotron lab at Massachusetts Institute of Technology (MIT). The supply of these gyrotrons to DIII-D and other plasma experiments nationally and internationally represents an investment of many millions of dollars. However, gyrotrons can suffer from undesirable low frequency oscillations which are known to interfere with the gun-region diagnostics and data collection systems, and are also expected to produce energy and velocity spread in the beam. It is not well known or understood what contribution these spreads may have in terms of efficiency reduction, especially in higher power regimes where there is little experimental data. Furthermore, the origins and processes leading to these oscillations are not fully understood. Existing gyrotron R&D tools, such as static gun solvers and interaction region models, are not designed to look at this type of time-dependant oscillatory behaviour, and thus it has been difficult to research this phenomenon, and to test theoretical concepts and suggest ameliorations. In this work, we propose to use a 3D CFDTD PIC method to accurately and efficiently study the LFOs in a high average power gyrotron.

VALIDATION OF CFDTD PIC SIMULATION OF A MIG GUN MODEL

A 3D model of a magnetron injection gun (MIG) employed in an MIT gyrotron has been built in the VORPAL simulation, as shown in Fig. 1(a). The cathode and the anode are indicated in a cross-sectional view of the MIG, as in Fig. 1(b). A time-dependent voltage has been applied to the MIG electron gun as shown in Fig. 2(a) and an emission current is slowly turned-on, reaching a steady-state value of 40 A at 96 kV, according to the operation condition of the MIT design. Figure 3 shows the on-axis magnetic field profile correlates to 99.96% of the original MIT data. The corresponding off-axis components are described using the following formulas:

$$B_r(x,r) = -\frac{1}{2} r B'_{x0}(x) \text{ and } B_x(x,r) = B_{x0}(x) - \frac{1}{4} r^2 B''_{x0}(x)$$

With the beam parameters and the magnetic profile assigned in VORPAL, we have successfully launched an electron beam in the MIG gun, as shown in Fig. 4. The corresponding behaviours in real and phase spaces are shown in Fig. 5(a). This is the case without suffering an LFO and the steady-steady beam operation is similar to that predicted by a static simulation code such as EGUN.

CFDTD PIC SIMULATIONS OF AN LFO IN A MIG GUN

It was suggested that the trapped electron population contributing to the oscillations is caused by a magnetic mirror effect, as shown in Fig. 6, when an electron beam is strongly focused in the magnetic field compression region. As the magnetic momentum of moving electrons in a static magnetic field needs to be conserved, the increase in transverse momentum of the downstream electrons is compensated by the decrease of their longitudinal counterpart, so that the total energy is conserved. Therefore, electrons retaining a larger transverse velocity or velocity ratio will be reflected and only those with lower velocity ratio will be transported downstream through the throat of the mirror into the interaction cavity. In other words, electrons lying outside

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*Work supported by the U.S. Department of Energy under Grant No. DE-SC0004436.

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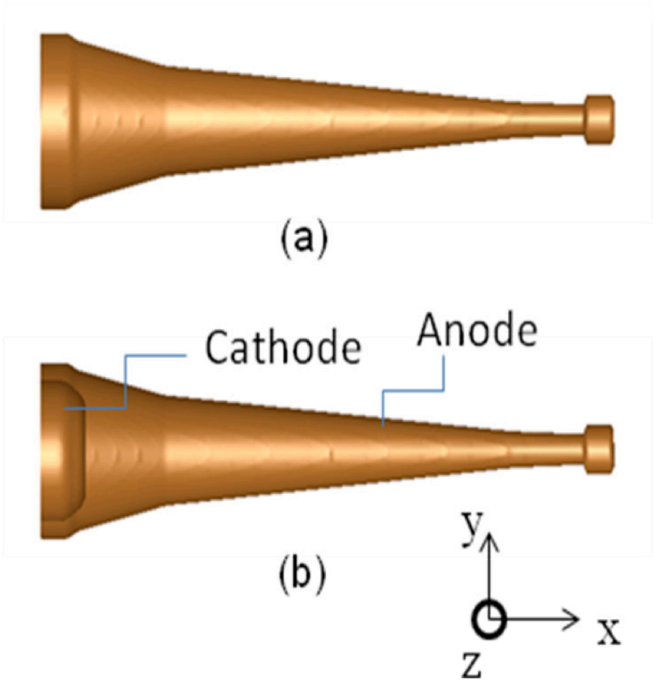

Figure 1: (a) A MIG diode electron gun simulation model constructed in VORPAL and (b) a cross-sectional view of the MIG model showing the cathode and the anode.

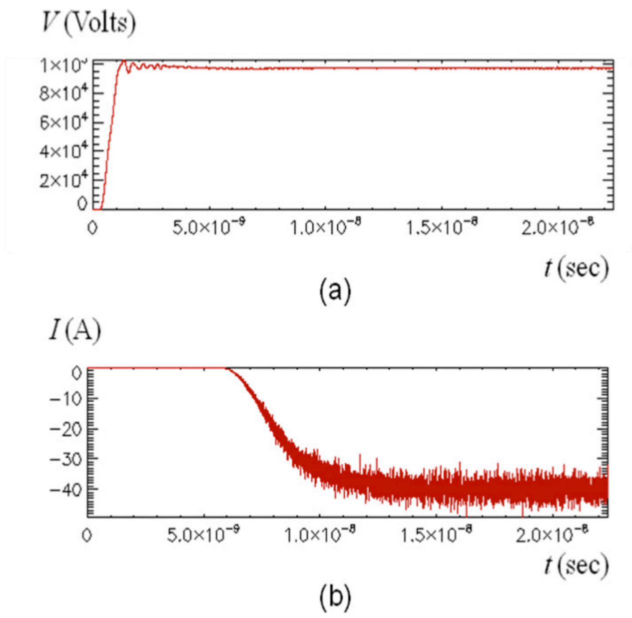

Figure 2: (a) Applied time dependent potential voltage profile between the anode and the cathode of a MIG gun at a voltage of 96 kV and (b) a slowly turned-on emission current reaching a steady-state value of 40 A, as following the MIT design.

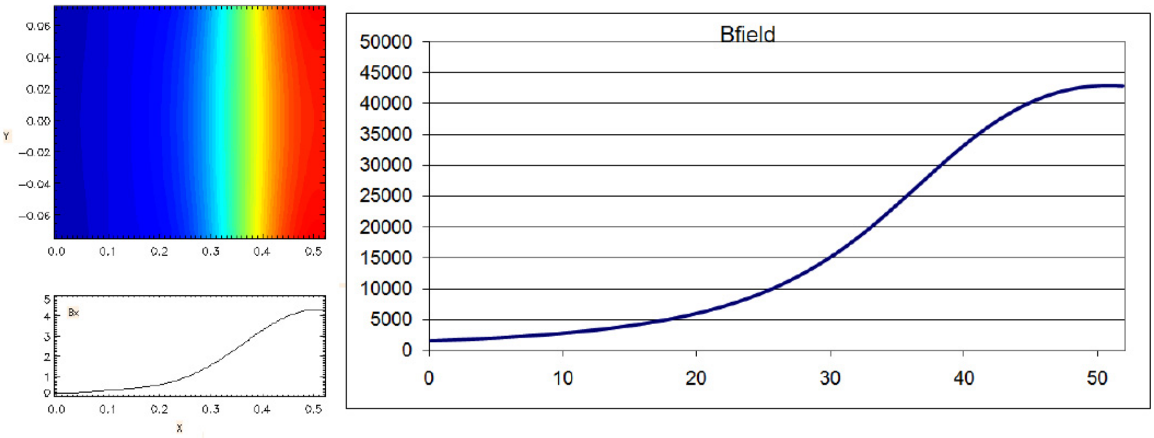

Figure 3: Magnetic field fit used in the VORPAL simulation (left) compared to the on-axis profile provided by MIT (right). The simulation fit correlates to 99.96% of the original data, on axis.

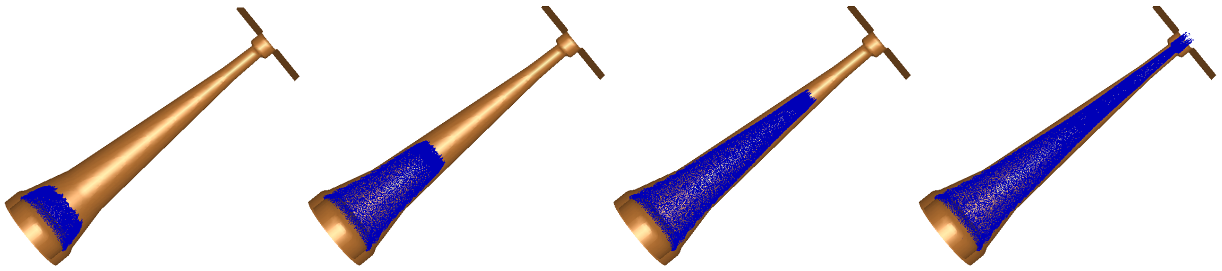

Figure 4: Successfully launching of an electron beam with a voltage of 96kV and a current of 40A in the VORPAL model of the MIT MIG electron gun.

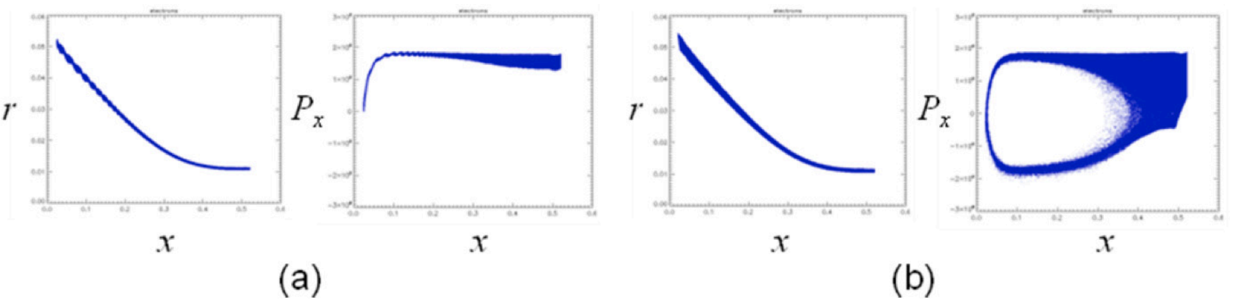

Figure 5: (a) Real space (left) and phase space (right) of launched electron beams in a MIG gun without an LFO and (b) real space (left) and phase space (right) of launched electron beams in a MIG gun with an LFO.

a transmission cone, as shown in Fig. 6(b), will get reflected and be trapped between the magnetic mirror and the cathode. The leading hypothesis is that LFOs are caused by these trapped electrons. However, there is no definitive understanding of how a small minority of electrons capable of being trapped might arise in the first place. There are however, several hypotheses, including thermal spread or effective thermal spread due to surface roughness for example, of the beam at the emission surface. With given some initial transverse velocity to the injected electrons on the cathode surface, the LFOs have been formed and observed in our 3D CFDTD PIC simulations, as shown in Fig. 5(b). As one can see clearly in the phase space, the trapped electrons are in periodic motions. Low frequency oscillations have been simulated in 3D and time domain for the first time.

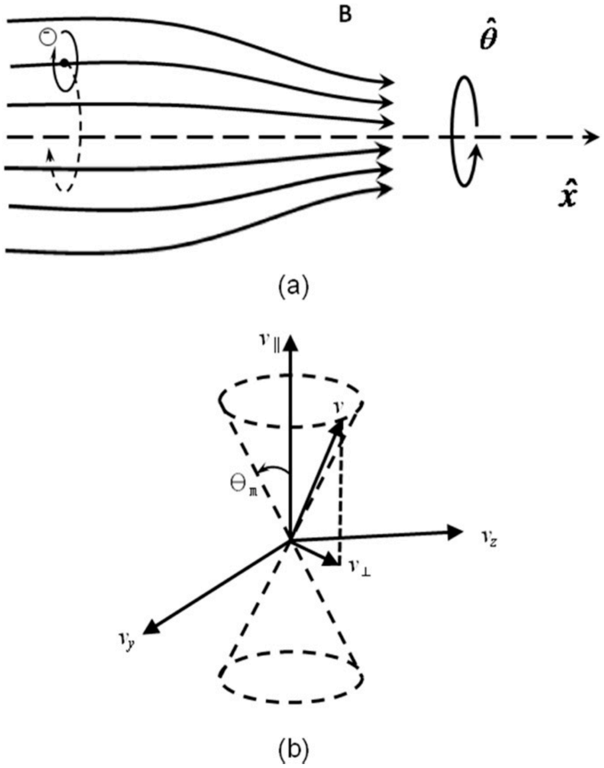

Figure 6: Magnetic mirror. (a) Drift a particle in a magnetic compression field and (b) a transmission cone.

SUMMARY

In this work, we have demonstrated that one can use the 3D CFDTD PIC method as implemented in the VORPAL code to model a MIG electron gun. The electron reflection dynamics, also known as LFOs, at high velocity ratio in the compression region has been simulated and studied numerically. One of the advantages of the CFDTD method is the electromagnetic boundaries are more accurately described than a conventional FDTD method. From our preliminary simulation studies, it is found that not only magnetic compression profile but initial transverse velocity or energy play an important role in the operation of a MIG electron gun. The frequency range of LFOs has been estimated by a periodic asymmetric oscillator model, close to the experimental values.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of DOE and thank Prof. R. J. Temkin for providing the detailed experimental information and helpful discussions and encouragement.

REFERENCES

[1] A. J. Cerfon, E. Choi, C. D. Marchewka, I. Mastovsky, M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, “Observation and Study of Low-Frequency Oscillations in a 1.5-MW 110-GHz Gyrotron”, IEEE Trans. Plasma Sci. **37**, No. 7, 1219-1224, (2009).

[2] C. Nieter and J. R. Cary, “VORPAL: a versatile plasma simulation code”, J. Comput. Phys. **196**, 448-473 (2004).

[3] S. Dey, R. Mittra, and S. Chebolu, “A technique for implementing the FDTD algorithm on a nonorthogonal grid”, Microwave and Opt. Technol. Lett. **14**, 213-215 (1997).

[4] S. Dey and R. Mittra, “A locally conformal finite-difference time-domain (FDTD) algorithm for modeling three-dimensional perfectly conducting objects”, IEEE Microwave and Guided Wave Lett. **7**, 273-275 (1997).

[5] F. F. Chen, “Introduction to Plasma Physics and Controlled Fusion”, 2nd ed. (Springer 1984).