3D Electromagnetic Particle-in-Cell Simulation of EMP Generated by Pulsed X-rays

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***Abstract*—Pulsed X-rays could cause significant cavity system-generated electromagnetic pulse (SGEMP) interference. A 3D electromagnetic particle-in-cell simulation approach is developed to calculate EMP generated inside a cylindrical cavity after X-ray illumination. The waveform, spatial distributions and resonant frequencies of cavity SGEMP are demonstrated by the computations. The peak value of cavity SGEMP main pulse is 72.88 kV/m. When farther away from the charge emitting face, the field strength decreases quickly and its polarity reverses; when the distance from symmetry axis increases, the field strength declines relatively slower. The cavity SGEMP would form a stable resonance and its frequency is dominated by the radius and length of cavity. The simulation method is verified and can be applied to the X-ray radiation hardness.**

Keywords*—*Cavity SGEMP, charge conservation, conformal mesh, PIC, X-rays.

I. INTRODUCTION

After X-rays penetrate metal surface, numerous electrons would be emitted to the internal vacuum region, forming transient current and emerging strong cavity system-generated electromagnetic pulse (SGEMP) in electronic equipment [1]. Previous studies have developed the 2D calculation ability under X-rays generated by nuclear explosion, like the ABORC code [2]. The influence of input parameters and geometry are also well discussed [3-4]. However, systematic research on the frequency and spatial characteristics and three-dimensional simulation of cavity SGEMP are still insufficient.

II. CALCULATION METHOD

A. Discrete Charge Conservation Theorem

The source term for Maxwell's equations is the current density $\boldsymbol{J}$ from emitting electrons:

$$\boldsymbol{J} = \sum Q_M \boldsymbol{v} N_S \,. \tag{1}$$

Where Q_M and $\boldsymbol{v}$ is charge and velocity of a macroparticle, while N_S is the assignment factor.

Conventional volume-based weight assignment method might not satisfy the Maxwell's divergence equations and require a very complex Poisson correction, which performs fairly complex iterations by SOR or other algorithms and cost a lot of memory resources and calculation time [5]. Chen et al. [6] proposed the discrete charge conservation by ensuring the continuity equation to automatically satisfy the Maxwell divergence equation. For example, the charge-conserving assignment for x component of the current density J_x is:

$$\begin{aligned} &J_x^{n+1/2}(i+\frac{1}{2},j,k)+J_x^{n+1/2}(i+\frac{1}{2},j+1,k)+J_x^{n+1/2}(i+\frac{1}{2},j,k+1) \\ &+J_x^{n+1/2}(i+\frac{1}{2},j+1,k+1)=\rho_M\cdot\frac{x_M^{n+1}-x_M^{n}}{dt}. \end{aligned} \tag{2}$$

Where ρ_M and x_M is charge density and position of a macroparticle.

B. Conformal Mesh Technique

Modelling irregular structures is an inevitable problem for three-dimensional simulation. "Staircased" approximation is broadly adopted to represent the curve with a polyline in conventional FDTD, inevitably generating some errors for complex structures. To accurately model the cylinder in three dimensions, conformal mesh is adopted, which is the internal part of conventional mesh at the boundary [7]. In this case, the magnetic field $\boldsymbol{B}$ is calculated by integrating the electric field $\boldsymbol{E}$ along the boundary of conformal mesh:

$$\oint_{C_l} \boldsymbol{E}\cdot d\boldsymbol{l} = -\frac{\partial}{\partial t}\iint_{S_l} \boldsymbol{B}\cdot d\boldsymbol{S}\,. \tag{3}$$

Where C_l and S_l is the edge and area of conformal mesh.

III. COMPUTATION RESULTS

A vacuum cylindrical cavity, with a diameter of 50 cm and a length of 50 cm, is considered here to represent the typical metal shell of electronic device, as shown in Fig. 1. It is assumed that 10-keV-energy, 1-J/cm^2-fluence and 1-ns-duration X-rays illuminate one end of the cylinder uniformly along the direction of the symmetry axis. Therefore, the total number of electrons is calculated to be $N_0 = 2.38\times10^{12}$ by a Monte Carlo software. The waveform, frequency and spatial characteristics are calculated by the self-developed code 3Dcavitysgemp V1.0.

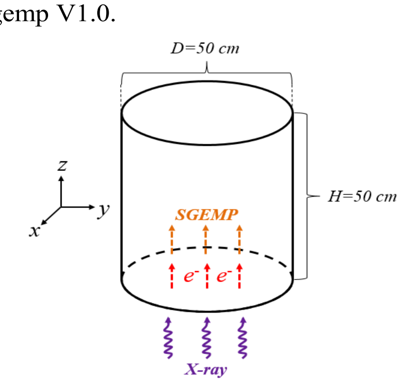

Fig. 1. Computation model of cylindrical cavity.

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A. Waveform of EMP

There are four output positions which are 9 cm away from the axis of symmetry and 9 cm away from the emitting end, as well as 90 degrees apart from each other. They are marked as point A, B, C and D. The 10 ns waveforms of four output positions are illustrated in Fig. 2. Theoretically, they should be exactly the same for the geometric symmetry of cylindrical model. Numerically, these four waveforms do overlap each other qualitatively, with only slight distinctive caused by randomness of macroparticles' initial locations. The largest relative errors for Peak 1, Peak 2, Peak3 are 2.94%, 4.71%, 4.38% respectively. Therefore, it can be quantitatively concluded that simulation results have good hoop symmetry and agree well with the calculation model.

By averaging the data at four output positions, the peak value of cavity SGEMP main pulse is 72.88 kV/m.

B. Spacial Distributions of Cavity SGEMP

Fig. 3 depicts electric fields at locations 9 cm away from the axis of symmetry and leaving the emitting end with various distances from 1 cm to 40 cm. The space charge limited phenomenon at high X-ray fluence is clearly observed. Positive charges left on emitting end and emitting electrons excite a strong positive electric field that modifies the trajectories of electrons and returns majority of them back. A small amount of electrons can move beyond this lay, generating a relatively lower negative electric field. As a result, the field strength becomes smaller quickly when farther away from the emitting end and its polarity reverses when the distance is larger than 9 cm.

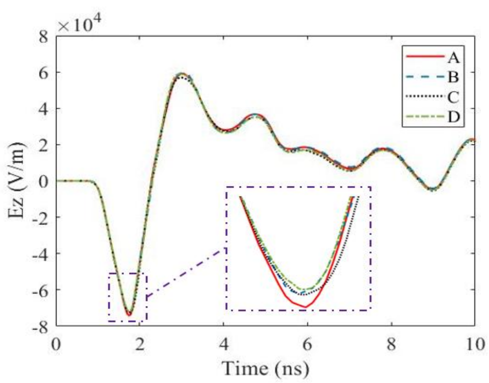

Fig. 2. Waveforms of four output positions.

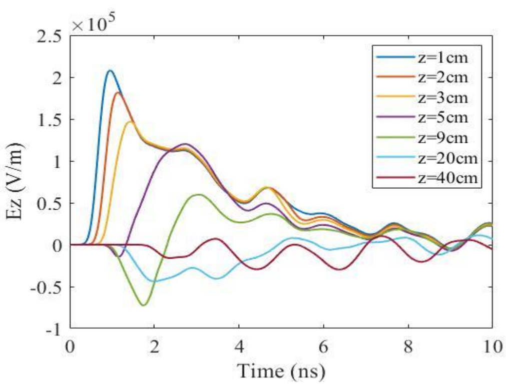

Fig. 3. Axial distribution of electric fields.

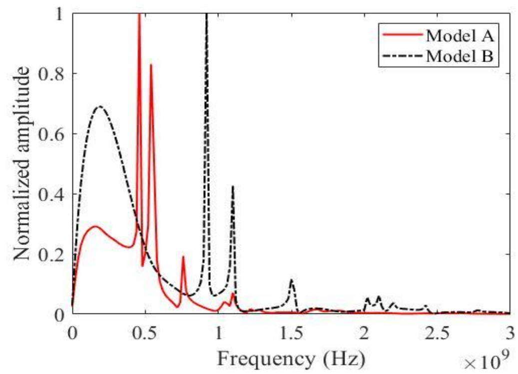

Fig. 4. Normalized spectrum under model A and B.

C. Resonant Frequency

To test the frequency characteristics of cavity SGEMP, two models of different size are established. The model used in above simulations are named as model A. Model B is a smaller cylindrical cavity with a diameter of 25 cm and a length of 25 cm. Fig. 4 demonstrates the normalized spectrum. Theoretically, resonant frequencies of a cylindrical waveguide are dominated by the radius and length. Numerically, discrete frequency centers under model A and B differ from each other as a factor of 2, exactly the same as prediction. Overall, the cavity SGEMP does form a stable resonance after reflections of the main pulse by metal walls.

IV. CONCLUSION

The 3D novel simulation approach is verified to be accurate within the error tolerance. The peak value, spatial distributions and resonant frequencies of cavity SGEMP are all demonstrated through 3D computations. These work could provide great help for solving the EMC problems in pulsed X-ray related physical experiments and applications.

REFERENCES

[1] C. L. Longmire, "State of the art in IEMP and SGEMP calculations," IEEE Transactions on Nuclear Science, vol. NS-22, no. 6, pp. 2340-2344, Dec. 1975.

[2] R. Keyser and D. Swift, "Analysis and tests of a right circular cylinder in a photon environment," IEEE Transactions on Nuclear Science, vol. NS-24, no. 6, pp. 2445-2448, Dec. 1977.

[3] E. P. Wenaas, S. Rogers and A. J. Woods, "Sensitivity of SGEMP response to input parameters," IEEE Transactions on Nuclear Science, vol. NS-22, no. 6, pp. 2362-2367, Dec. 1975.

[4] A. J. Woods and E. P. Wenaas, "SGEMP geometry effects," IEEE Transactions on Nuclear Science, vol. NS-22, no. 6, pp. 2374-2380, Dec. 1975.

[5] Y. Dong, Z. Dong, H. Zhou, and W. Yang, "Application of a novel charge-conservation method used in large-scale parallel computation for fully electromagnetic Particle-In-Cell simulation," Journal of Terahertz Science and Electronic Information Technology, vol. 14, no. 4, pp. 574-580, Aug. 2016.

[6] L. Chacón and G. Chen, "A curvilinear, fully implicit, conservative electromagnetic PIC algorithm in multiple dimensions," Journal of Computational Physics, vol. 316, pp. 578-597, July 2016.

[7] M. R. Cabello, L. D. Angulo, J. Alvarez, A. R. Bretones, G. G. Gutierrez, and S. G. Garcia, "A new efficient and stable 3D conformal FDTD," IEEE Microwave and Wireless Components Letters, vol. 26, no. 8, pp. 553-555, Aug. 2016.