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基于 PIC 和 MC 方法的同轴虚阴极反射三极管阵列辐射场数值模拟方法

摘要

同轴虚阴极反射三极管是一种辐射转化效率高、结构简单的新型脉冲硬 X 射线负载，串并联为阵列工作时可产生高能注量、大面积、均匀的硬 X 射线场。数值模拟是同轴虚阴极反射三极管阵列辐射场设计调控的重要技术途径，但由于涉及的物理过程多，电磁、粒子及辐射环境复杂，实现辐射场精确模拟较为困难。本文从同轴虚阴极反射三极管的物理过程出发，对阵列负载工作过程进行分段建模，考虑了阴极等离子体扩散对阻抗负载特性的影响，进行了不同模型之间的电子能量损失校核，改进了辐射场空间叠加方法，建立了基于 PIC 和 MC 方法的同轴虚阴极反射三极管阵列辐射场数值模拟方法。与实验结果相比，能注量模拟结果的平均相对误差为 7.0%，辐射场强度的模拟精度与原有模拟方法相比实现了显著提升。该模拟方法为同轴虚阴极反射三极管阵列型负载的设计提供更准确的依据。

关键词

同轴虚阴极反射三极管，等离子体，强流电子束，轫致辐射，硬 X 射线源

Abstract

The Cylindrical Virtual Cathode Reflex Triode (CVCRT) is a new type of pulsed hard X-ray load characterized by high radiation conversion efficiency and a simple structure. When connected in series or parallel as an array, it can generate a high-fluence, large-area, uniform hard X-ray field. Numerical simulation is an important technical approach for the design and regulation of the radiation field of CVCRT arrays. However, it is difficult to achieve an accurate simulation of the radiation field due to the multitude of involved physical processes and the complex electromagnetic, particle, and radiation environments. This study presents modifications to the original simulation method: a phased modeling approach for the array load operation was adopted, incorporating the influence of cathode plasma expansion on the impedance load characteristics. Electron energy loss verification was performed across different models, and the spatial superposition method for the radiation field was refined. Consequently, a numerical simulation methodology for the radiation field of CVCRT arrays based on PIC and MC methods was established. Compared with experimental data, the mean relative error for the simulated photon fluence was 7.0%, and the simulation accuracy of the radiation field intensity was significantly enhanced compared to the original simulation method. This improved simulation method provides a more accurate basis for the design of CVCRT array-type loads.

Keywords

cylindrical virtual cathode reflex triode, plasma, high current electron beam, bremsstrahlung, hard X-ray source

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