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HFSS ENABLES MULTIPACTION ANALYSIS OF HIGH POWER RF/MICROWAVE COMPONENTS*

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Abstract

This paper describes system-level simulations for high-power RF/microwave components from full-wave electromagnetics (EM) to RF breakdown under vacuum for arbitrary 3D structures. Full-wave electromagnetic simulations can be performed in HFSS using the modal or terminal solution; the time-domain simulation then takes over to predict the onset of multipaction breakdown. The entire simulation can be executed in a single run for EM analysis and the prediction of RF breakdown. The accuracy and robustness of the simulation can be guaranteed through the FEM unstructured mesh. Particle-in-cell simulation for tracking multipaction electrons in an unstructured FEM mesh is a key success. A comprehensive visualization user interface helps to explain the detailed physics.

INTRODUCTION

The quest for high energy in exploring the fundamental nature of the universe is of utmost interest for particle accelerators [1]. The radiofrequency (RF) components in particle accelerators operated under a vacuum condition and driven by high-power RF electromagnetic (EM) waves may be prone to electron multipaction [2-4]. The RF-triggered electron resonance ignited by the RF multipaction may cause malfunction, which results in detuning, beam loading, arcing, etc, which, in turn, reduces the target energy for accelerating the beam. Therefore, exploring the design challenges of vacuum RF windows, cavities, and other devices to avoid electron multipaction becomes necessary. Setting up an experiment to mitigate the failure of RF devices is expensive and time-consuming, which may lead to a significant delay in the project. Therefore, a high-fidelity computer simulation modeling the arbitrary geometry and tracking the particles (electrons) in a complex electromagnetic environment is desirable. Ansys HFSS through Finite Element Mesh (FEM) for the full-wave RF simulation combined with the particle-in-cell (PIC) technique for tracking particles in EM fields; enables the engineers/physicist successful prediction of system failure against the electron multipaction. The multipaction analysis feature has been integrated into the Ansys electronics desktop (AEDT); full-wave electromagnetic and multipaction simulations can be set up in the same design. The breakdown threshold predicted by the solver helps users determine the multipaction susceptibility of devices under design. Moreover, the animation of multipaction charge particles helps visual inspection.

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MODEL DESCRIPTION

For purposes of illustration, we have selected an RF cavity, however, the workflow can be directly applied to any other structure. The multipaction simulation in HFSS can be combined with the RF design performed either in the "modal" or "terminal" solution type.

RF Simulation

The cavity geometry illustrated in Fig. 1 has been set up for the "modal" solution type. The RF power has been fed into the cavity using a co-axial feed through the beam pipe and the dual orthogonal modes are excited simultaneously. The RF modeling has been performed for 1 W of input power, which can be simply scaled for any desired power after the execution of the simulation.

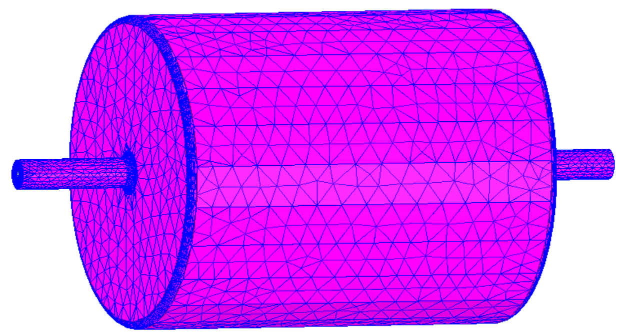

Figure 1: A schematic of the cavity used in the model for operation at 550 MHz.

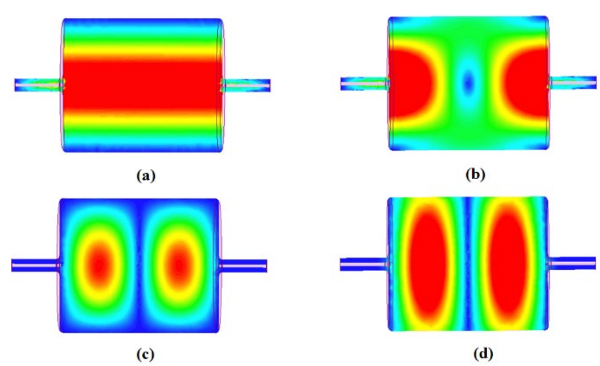

Figure 2: Sub figures (a-d) shows electric field distributions of four modes excited inside the cavity at about 549.82 MHz, 626.7 MHz, 732.44MHz, and 732.47 MHz, respectively.

Figure 2(a-d) shows four eigenmodes excited inside the cavity. The fundamental mode is depicted in Fig. 2a, which represents the accelerating mode. The remaining modes illustrated in Fig. 2(b-d), correspond to the higher-order modes (HOM); the degenerate modes are indeed indicated in Fig. 2(c-d).

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Multipaction Simulation

For multipaction simulation, we need to spray seed electrons in the vacuum region of the cavity, which can be done through a simulation domain as an excitation. In this simulation, we have taken 4000 seed electrons to initiate the multipaction. The multipaction secondary electron emission (SEE) boundaries are added to the surfaces interfacing the vacuum and material. HFSS offers an enhanced Vaughan model [5]. The users can opt to import an experimental or empirical SEE model for their materials. The work function (see Fig. 3) accounts for the energy of the secondary electrons. The HFSS multipaction package supports dielectric or magnetic materials, and the external electric/magnetic bias can be applied for a realistic design. Since the multipaction phenomenon involves electron-electron interaction, the concept of space charge physics accounts for the Coulomb force between the two electrons.

HFSS offers a convenient workflow for the multipaction simulation together with the RF simulation in the same design. This means there is no need to import data from the EM solution to the multipaction model. Once the setup for multipaction analysis is completed, we can analyze all. The multipaction simulation starts automatically as soon as the execution of the RF simulation finishes. The users can start visualizing the simulation output during the run process because the multipaction is performed in the time domain.

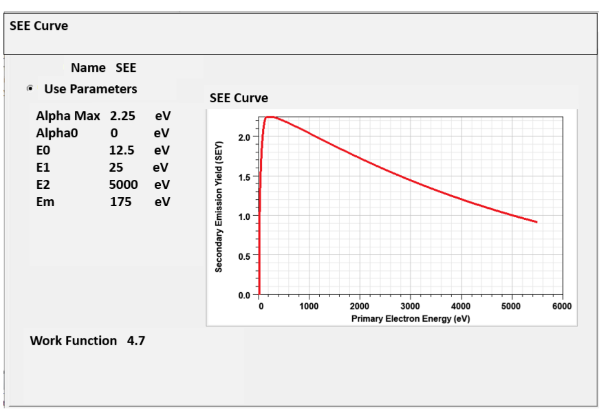

Figure 3: The secondary electron emission (SEE) model for copper as a coated material of cavity.

The growth of multipaction electrons with respect to time is plotted in Fig. 4. The legend shows the power multiplier, which in this case is the actual power because the excitation power is 1 W. The lowest power is 1 kW (blue curve) for the cavity where the exponential growth of electrons is distinctive. The power threshold for the multipaction breakdown is predicted about 683.6 W. Table 1 summarizes the multipaction breakdown onset and offset power levels. Since the power levels are discrete, users must pay attention when the operating power reaches the breakdown onset power (687.5 W). The predicted breakdown threshold is the average of 687.5 W and 679.7 W.

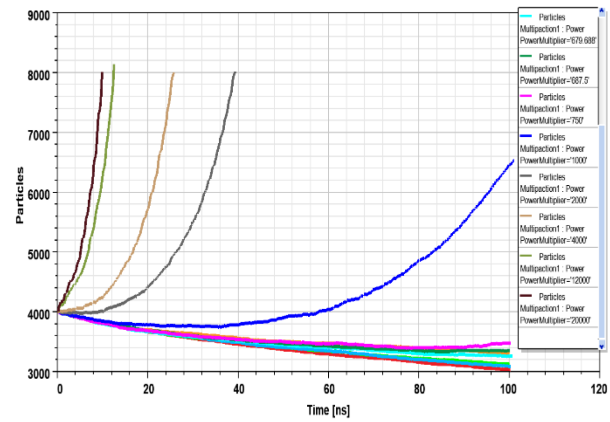

Figure 4: Evolution of multipaction particle (electron) growth.

Table 1: Multipaction Breakdown Prediction

Power (W)	Breakdown
20000.0	Yes
12000.0	Yes
4000.0	Yes
2000.0	Yes
1000.0	Yes
750	Yes
687.5	Yes
679.7	No

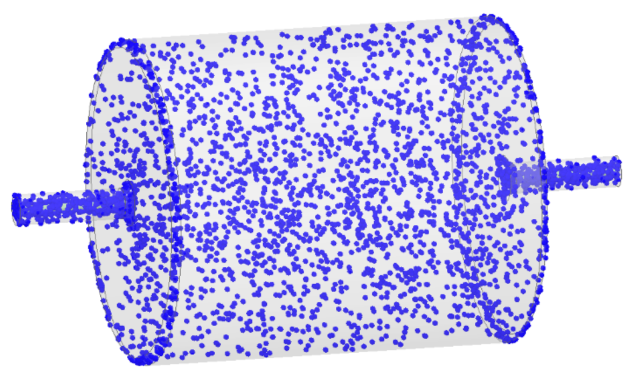

Figure 5: Visual representation of multipaction electrons.

The multipaction phenomenon occurs in real-time. Figure 5 shows the snapshot of multipaction electrons inside the cavity corresponding to the 2-kW power level. The complete evolution of the multipaction phenomenon can be seen by animating the events with time.

CONCLUSION

In this paper, a comprehensive workflow for the successful design of a high-power RF component used in the particle accelerator has been demonstrated. Power handling capability for vacuum operation can be estimated through the multipaction analysis. Having a complete physics module in a single computer code is an advantage. The accuracy and robustness of the simulation can be assessed through the accurate extraction of EM fields in an unstructured mesh and tracking the particle motion using particle-

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in-cell (PIC) simulation technology. Various details will be discussed in the conference presentation.

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