BENCHMARKING SIMULATIONS OF MULTIPACTOR IN RECTANGULAR WAVEGUIDES USING CST-PARTICLE STUDIO

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Abstract

Multipactor can be a limiting factor in the design on many SRF cavities, however this is often a difficult phenomena to numerically model. In order to study the reliability of various codes we have undertaken to study the simulation of multipactor in rectangular waveguides and to compare this to experimental results obtained in previous work. In this paper we present the simulation results using CST-Particle Studio.

INTRODUCTION

Multipactor is an electron phenomena where resonant electron trajectories cause an exponential growth in the number of electrons by secondary emission. However the behaviour of multipactor is quite complex as it initially starts with a low number of electrons where space charge forces are negligible and as the number of electrons increase the space charge forces grow. It is impractical to simulate multipactor with enough electrons to correctly predict the behaviour with space charge forces so most simulations tend to use particle tracking with no space charge. Simple assumptions are generally used to establish the presence of multipactor, however it is not immediately clear that the start of an exponential electron growth definitely leads to multipactor. In addition in is important to accurately determine the exact time, position, energy and angle of electron impacts on the surface. This can be difficult to achieve and can cause some codes to disagree with each other.

In order to verify the accuracy of a multipactor simulation it is necessary to benchmark against a multipactor simulation for which we have experimental data. An experimental study has previously been performed by Cornell and Lancaster University of multipactor in a half height rectangular waveguide at 500MHz [1] for the CESR input coupler and this data provides and excellent problem for benchmarking multipactor simulations. The simulation geometry is simple and conformal to the mesh and experimental data on suppression of multipactor with DC magnetic fields provides additional data for benchmarking.

SIMULATION OF MULTIPACTOR IN CST-PS

CST Particle studio (CST-PS) [2] has a PIC solver and a particle tracking solver that allows the simulation of charged particle interaction with electric and magnetic fields [3]. For multipactor due to the large number of particles involved the authors advise the use of tracking simulations which exclude space charge effects and hence are less computationally intensive.

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First we must define the geometry and calculate the electric and magnetic fields of the mode of interest. The implementation of emitting surfaces in particle studio requires the walls as well as the vacuum to be included in the geometric definition. The experiment was performed on half height waveguide with width 457.2 mm, height 102 mm and was constructed of stainless steel. An eigenmode solver is used to calculate the fields utilising periodic boundaries in order to obtain a travelling wave solution. A very dense mesh of around 80 lines per wavelength is required in order to obtain a field map of sufficient accuracy. The transverse electric field is shown in figure 1.



Figure 1: The transverse electric fields in the waveguide from CST-PS.

Next we must open a new simulation with the same geometry and import the electric fields into the simulation. To do so we select define magnetic field, then select "import external field" and select the required input file. We must click "consider the electric fields" to also import the electric field. We also set the phase at this point. This allows the tracking solver to use a denser mesh than the eigenmode solver, which is often limited by memory. A mesh of 100 lines per wavelength was used for the tracking simulations.



Figure 2: Initial seed electron emission points on the top plate of the waveguide.

Having defined the fields we must now set up the initial seed electrons. In our simulations we set the seed

electrons by using a fixed emission. In the solve menu select the "particle emission on a PEC surface" and select the surface where we wish the seed electrons to be emitted from, as can be seen in figure 2. This will bring up the particle emission menu, select a fixed emission and set the initial mean electron energy and energy spread in energy. For our simulations we emit the initial electrons from the top of the cavity with an initial energy of 0-4 eV. The emission area was set to cover 180 degrees in phase so that it was not necessary to sweep the phase over multiple simulations.

After setting up the seed electrons we then need to define the secondary emission properties. This is a tab in the material properties menu. From this menu we can select user defined secondary emission properties, or use the Furman-Pivi [4] secondary emission model for copper or stainless steel. For our simulations we chose the Furman_Pivi Stainless steel model. Also in this tab we can select maximum number of generations and maximum number of secondaries per impact. It is important when modelling multipactor that we generate all possible secondaries at each generation so both values should be set as high as possible. The maximum number of secondaries per impact is 10.

In the particle tracking solver menu we select the fields we wish to use in the simulation. Also at this stage we can alter the field amplitude using the Amp setting. Amp is a linear multiplier to the imported fields (note this is a field amplitude multiplier not a power multiplier). Select the predefined field and set the amplitude to the required level. In the specials menu we can set the number of timesteps required for the run. The length of each time-step is set by the fastest particle in the simulation and hence is not constant. In the simulations we typically run for 200-600ns. Finally we run the simulation.

POST-PROCESSING

Identifying multipactor from simulation results is not a trivial process. As multipactor is not established until a sizeable current is produced this can take a large number of RF periods and unfeasibly large simulations involving space charge effects. We can however instead predict the start of multipactor using tracking simulations for a finite number of RF periods. This is done by observing the increase in the number of electrons with time or particle crossing.



Figure 3: The number of "live" particles in the simulation as a function of time.

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In CST-PS we can obtain these diagnostic values in post processing. The simplest value to find is the increase in the number of electrons with time, as this is automatically given as a post processing plot at the end of the simulation as a 1D Result as "Particles vs Time" as shown in Figure 3.

The 2nd diagnostic is the how the number of electrons increase per particle crossing [5]. This can be obtained from the "collisional information" table. From this table we can extract the total number of electron hits for each component and the secondary electrons emitted, SEE. By dividing the total SEE by the total number of hits we obtain an averaged secondary emission yield per impact, or \langle SEY \rangle . Also on this table we obtain the total impact energy per component. By dividing this number by the number of hits we obtain the average impact energy, \langle E_i \rangle , which is useful for comparing with the SEY curve used in the simulation.

Finally it is incredibly useful to observe the electron trajectories in order to understand and visualise the multipactor. CST-PS allows the visualisation of the electron trajectories as lines, shown in Figure 4. The colour of these lines can be set to show electron energy, velocity, momentum or other related parameters.



Figure 4: The electron trajectories plotted in CST-PS. The line colour denotes the electron energy.

PARAMETER OPTIMISATION

Initially we must optimise the code running parameters in order to simulate a realistic case while keep the simulation runtime to a manageable time. CST-PS has a number of parameters we can specify when running the code, we will investigate the variation of mesh density, maximum number of time-steps, maximum number of secondaries per impact, initial electron energy, the number of initial electrons and the area we launch the initial electrons over.

First we decided to vary the mesh density. In the simulations we import the fields from a previous CST-MWS calculation hence we can independently vary the mesh of the field solver and the tracking solver. Initially we set the field solver mesh to 50 lines per wavelength (LPW) at 600 MHz (the meshing is more complex than this but we will use lines per wavelength at 600 MHz as a basis for comparison). As we vary the mesh in the tracking solver we calculate and record the average secondary emission yield, <SEY>, and the average impact energy, < E_i >. As expected both values converge towards a single value as the mesh increases. It was found for the geometry of interest that a mesh of at least 50 LPW is

required and a mesh of greater than 100 LPW (6.8 M elements over 1270 mm length waveguide) is preferred, as can be seen in Figure 5. It should be noted that CST-PS uses a small gap between where the electrons are emitted and where it defines the surface boundaries. At high retarding electric fields this gap may be large enough for electrons to gain enough energy in the gap to produce true secondaries. This leads to a very rapid unphysical growth in the number of electrons. It is very important therefore to have mesh dense enough to minimise the gap size such that the gap voltage is less than 10 V.



Figure 5: $\langle SEY \rangle$ and $\langle E_i \rangle$ as a function of mesh density at an input power of 158

All other parameters were also carefully studied and optimised, all the simulation parameters used are listed in Table 1 below.

Table 1: Simulation Param	eters
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Eigenmode Mesh / LPW	70
Tracking Mesh / LPW	100
Emission Energy / eV	0-4
Time-steps	40,000
Maximum Secondaries per impact	10
No. of initial electrons	150
Length of emission area / mm	700

SIMULATION RESULTS AND COMPARISON WITH EXPERIMENT

All the different parameters were optimised until the results converged and the simulation was repeated for various different field amplitude, and their corresponding input powers. The *<*SEY*>* is plotted against input power in figure 6.

These results can be compared to the experimental results described in [1]. The experimental results chosen for comparison is the variation in Faraday cup signal with input power. As the results vary with surface conditions the measurements varied with time as the multipactor conditioned the surface. We compare our simulation data with unprocessed and processed results.



Figure 6: The averaged secondary emission yield *<*SEY*>* as a function of input power.

The experiment consisted of an evacuated half-height waveguide section sealed by mylar windows at both ends. Due to the limitations of the mylar windows, vacuum in the waveguide was limited to $\sim 10^{-4}$ Torr, which was sufficient to allow unimpeded electron trajectories but allowed monolayers of gas to form on the surfaces. A high power klystron could provide up to 600kW pulsed power, or about 300kW CW.

The experiment was fitted with a Faraday cup (shown in figure 7) on the broad wall of the waveguide, allowing measurements of electron currents at different energies. For the measurements this paper is concerned with, the retarding potential was negatively biased at 20V. It was also fitted with a number of electron probes, which allowed us to look for localised differences in electron current. All the probes and their locations are shown in figure 8.



Figure 7: Picture of the energy analyser showing the variable retarding potential grid and the Faraday cup.



Figure 8: Schematic of one of the experimental waveguides showing the electron probes (P1-P4) and energy analyser ports (EEA).

Various coatings were applied to one of the broad wall surfaces in one experiment, but the vacuum conditions limited the amount of information we could collect from those experiments. The experiments using a copper or stainless steel plate were the most repeatable and informative.

Effectively, all probes and Faraday cups gave the same signal at any one time, showing that the multipactorinduced electrons spread out throughout the waveguide. The experiments also confirmed, with the aid of a groove in the broad wall, the location of the main stable multipactor trajectories. A coil wrapped around the waveguide allowed us to generate static longitudinal magnetic fields used to bend the electron trajectories and achieve multipactor suppression.

The experimental results show the variation in current on the Faraday cup as a function of power, hence it is not immediately clear how to compare the two results. It is generally considered that a trajectory can be said to be multipactor after 20 crossings [6] hence we choose to compare the Faraday cup signal to the electrons in the simulation after 20 crossings, this is equal to $\langle SEY \rangle^{20}$. As can be seen in figure 9 the simulations correctly predict the input power at which the peak multipactor occurs in a processed waveguide, around 400 kW, and roughly follows the same trend. The simulations do show multipactor starting at a lower power than the processed results however the simulations do agree for starting power with the unprocessed results. As the exact SEY curve for the CESR waveguide is unknown it is understandable that the simulation results fall somewhere in between the two. In addition the experimental results varied with position and with time.



Figure 9: The number of electrons after 20 crossings calculated from the simulations as a function of input power compared to the Faraday cup signal from the experiment for an unprocessed and processed stainless steel sample.

If we instead compare the results to the increase in the number of electron remaining in the simulation over 50 ns (taken between 150-200 ns of the simulation to establish multipactor) to the processed waveguide results we see even better agreement at high power. This is shown in Figure 10. This is to be expected as the high power simulations reveal a lower order multipactor than the lower power results resulting in those results growing faster in time.



Figure 10: The increase in the number of electrons after 50 ns calculated from the simulations as a function of input power compared to the Faraday cup signal from the experiment for a processed stainless steel sample.

Both the simulations and the experiments exhibit a continuous distribution of multipactor as a function of input power. Previous simulations in other codes have found discrete multipactor bands as expected from theory. However the effect of a realistic surface emission model including elastic and inelastic scattering (such as that found in particle studio) can be shown to merge these bands together giving the continuous distribution found in the experiments and in these simulations [7].

CONCLUSIONS

The comparison between the simulations and the experiment show good agreement between the simulation and the processed data, predicting the power level where the peak multipactor occurs. The uncertainty in the SEY curve in the experiment however is a problem for benchmarking.

What is interesting in comparing the simulation results to the experiment is the initiation of multipactor does not occur at $\langle SEY \rangle$ of greater than one, but doesn't seem to be initiated for $\langle SEY \rangle$ less than ~ 1.2 . This could be due to different surface conditions in the experiment, ion adsorption, collision with atoms, or space charge effects which would all lower the growth of multipactor in a real case.

Next we plan to simulate the suppression of multipactor with the grooves and DC magnetic fields as was performed in the experiments. Additionally simulations are underway to study multipactor in cavities, with and without DC magnetic fields. It is currently difficult to import both RF and DC fields simultaneously in CST 2009, however the next iteration, CST 2010, is expected to have better field importing abilities.

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