BENCHMARKING MULTIPACTING SIMULATIONS FOR FEL COMPONENTS

P. H. Stoltz*, C. Nieter, C. Roark, Tech-X Corp., Boulder, CO 80303, USA
J. D. A. Smith, Tech-X UK Ltd., Daresbury, Chesire WA4 4FS, UK

Abstract

Multipacting is a potential limit on the power one can deliver to different components of a free electron laser source. Simulation is a main tool in helping to understand and mitigate multipacting. We present recent work on benchmarking multipacting simulations, including comparison with theory, with other codes and with rectangular waveguide experiments. In particular, we show quantitative agreement between simulation results and theory for the ponderomotive drift of electrons to the edges of the waveguide, and we show qualitative agreement with previous simulation and experiment for multipacting levels as a function of power in the range of a few hundred kilowatts for a 500 MHz waveguide.

MOTIVATION

Multipacting is recognized as a potential limit on different components of an electron accelerator such as is needed as a free electron laser source. For example, two components important to electron accelerators that are known to exhibit multipacting including waveguide power couplers [1] and cathode support stalks [2]. Simulation can help researchers understand and mitigate multipacting, but to give confidence in results, one would like to benchmark the simulation tools. Consequently we present recent work on benchmarking multipacting simulations using the VORPAL code [3], including comparison with theory, with other codes and with rectangular waveguide experiments.

COMPARISON WITH PONDEROMOTIVE THEORY

As a first comparison, we compare VORPAL simulations with a theory for the rate at which electrons will drift from the center of the waveguide to the edge while multipacting (see Fig. 1). The work of Semenov, et. al., [4] showed that the ponderomotive force produces a net drift transversely to the walls. The ponderomotive force due to a non-uniform electromagnetic wave is

$$F_p = -\frac{e^2}{4m\omega^2}\nabla E^2. \tag{1}$$

Using this, one can estimate the time it will take an electron a given distance from the waveguide center to reach the waveguide edge. We show in Fig. 2 this time (in terms of the rf period) as a function of position from the waveguide center (in terms of waveguide width) for three different starting energies. Different curves correspond to different starting energies (blue is 0 eV, green is 1 eV, and red is 3 eV). For these calculations, the frequency is 500 MHz, meaning the period is T_0=2.0 ns, the power is 500 kW in a traveling wave mode, and the waveguide width is L=0.433m. The expression for ponderomotive force in Eq. 1 assumes a time averaging, and so these estimates are only accurate for times much larger than the wave period.

We compare VORPAL simulations with estimates using the ponderomotive force in Fig. 3. This figure shows the time for a particle to reach the edge of the waveguide as calculated by ponderomotive theory (blue solid line) and by VORPAL simulation (red dots). The largest difference between theory and simulation is less than two percent. For these comparisons, we initialize the particle roughly one percent off the center of the waveguide and with zero initial energy.

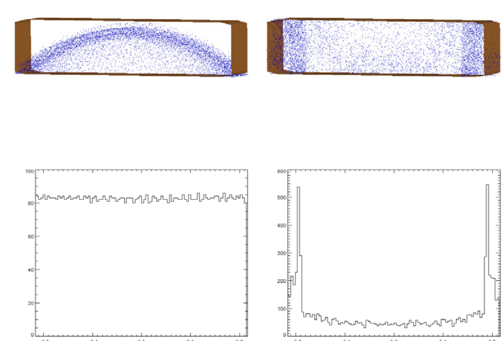

Figure 1: Distribution of the particles within the waveguide early (left) and late (right) in time. The top row shows a three dimensional view, and the bottom row shows a histogram of the transverse position. We benchmark the rate of drift of the particles from the center to the edge of the waveguide by comparing simulation with ponderomotive theory.

COMPARISON WITH EXPERIMENT AND OTHER SIMULATION

Researchers at Cornell University and Lancaster University performed experiments to study multipacting in a 500MHz rectangular waveguide [1]. Burt and co-

* pstoltz@txcorp.com

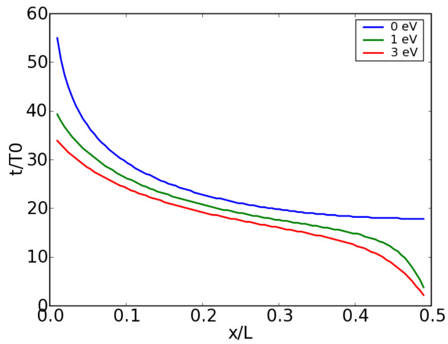

Figure 2: The time required for a particle to drift to the edge of the waveguide as a function of initial distance from the center, as calculated by ponderomotive theory. Different curves correspond to different starting energies (blue is 0 eV, green is 1 eV, and red is 3 eV). For these calculations, the period is T_0=2.0 ns, the power is 500 kW in traveling wave mode, and the waveguide width is L=0.433m.

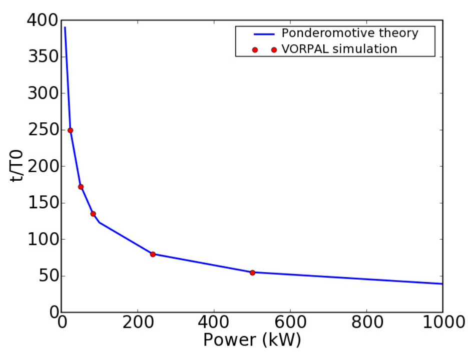

Figure 3: The time for a particle to reach the edge of the waveguide as calculated by ponderomotive theory (blue solid line) and by VORPAL simulation (red dots). The largest difference between theory and simulation is less than two percent. We initialize the particle roughly one percent off the center of the waveguide and with zero initial energy.

workers [5] compared simulations using CST-Particle Studio with those experimental results. As a further benchmark of the VORPAL code as a multipacting tool, we reproduced the simulations of Burt, et. al., and compared with both the previous simulations and the experimental results.

We made the following assumptions and simplifications in doing these comparisons: i) we restricted the simulations to 2D, ii) we assumed zero emission energy for each secondary electron, and iii) we neglected space charge. To reduce the computational time, we did not increase or decrease the number of simulation particles as a result of impact with the walls. Instead, we tracked the change by recording the secondary electron yield (SEY) in a separate variable called the particle weight. All particles start with a weight of one, and at each impact with the wall, the weight is multiplied by the SEY for that energy. We assumed a Vaughan model for the SEY as a function of energy, with a peak of 2.0 at an energy of 250.0 eV. As a result of these assumptions, we consider these comparisons qualitative rather than quantitative.

A standard technique for quantifying multipacting is to follow particles for twenty impacts and then measure the increase or decrease in the number of particles. We use this twenty-impact rule and then calculate an average secondary electron yield per impact, SEY, according to

$$SEY = \frac{log\left(\frac{N_f}{N_i}\right)}{20}, \tag{2}$$

where N_f is the number of electrons after 20 impacts, and N_i is the number of electrons initially. In Fig. 4, we plot this quantity for different power levels (solid blue curve). The VORPAL result at a given power is the maximum with respect to rf phase and is a smoothed result, averaged over ten nearby power levels. Also shown in Fig. 4 is the experimental curve (red), representing the current in a Faraday cup detector, and the CST results (green), representing the number of electrons after twenty crossings (what we call N_f in Eq. 2). The experimental curve and the CST curve are both normalized to the VORPAL result at 400 kW. The results all show qualitative agreement, including a peak near 400 kW. The VORPAL results and the experimental results also show an increase near 550 kW. The VORPAL results are uniformly higher than both the experiment and the CST results below 400 kW. One explanation is that one should not compare directly the simulated SEY and the Faraday cup current. The Faraday current may have a threshold behavior, where if multipacting is not occurring, the Faraday current will read zero. In fact, the threshold of the experimental curve does occur roughly where the VORPAL SEY curve crosses unity. Finally, the CST results and the VORPAL results are comparing different quantities (the CST results are for the final number of electrons, but the SEY varies as the log of this quantity). This discrepancy requires further investigation.

Secondary electron yield is known to vary with the strength of the electric field at the emission surface [6]. For example, researchers have measured the change in SEY as a function of DC electric field for insulators bombarded by ions [7]. To investigate the effect this might have on waveguide multipacting, we repeated the above simulations while suppressing electron yield for various field strengths during the phase of the rf for which the applied field accelerates the electrons back into the surface. We express the strength of the field above which emission is suppressed in terms of the rf phase at 300 kW power level (300kW is roughly the middle of the range of powers considered). We show in Fig. 5 the calculated SEY with no suppression (repeated from above), and for suppression at phases of 15 and 45 degrees (133 kV/m and 97.3 kV/m). For high power, this effect does act to depress the multipacting for small enough suppression field threshold.

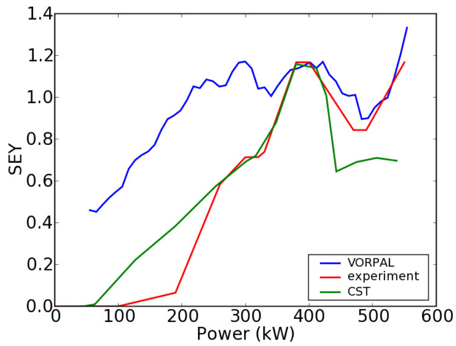

Figure 4: The average SEY after 20 impacts as a function of power as calculated by VORPAL (solid blue curve). The result is the maximum with respect to rf phase and is averaged over ten nearby power levels. The experimental curve (red) is the current in a Faraday cup detector, and the CST results (green) are the number of electrons after twenty crossings. The experimental curve and the CST curve are both normalized to the VORPAL result near 400kW.

Finally, we show in Fig. 6 the result for a different assumption about the suppression effect. Here we assume the suppression is at a fixed phase, independent of field strength. This means the secondary emission is suppressed at different field strength for different power levels. It is less clear how to justify this assumption physically as opposed to the previous assumption of fixed field strength, but the agreement between simulation and experiment under this assumption is worth noting.

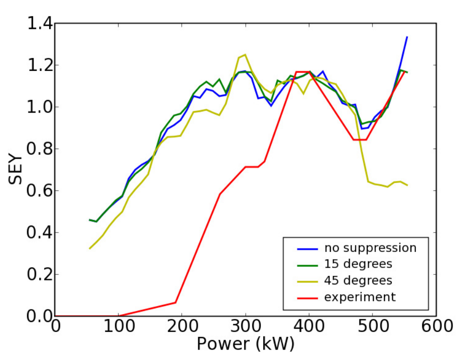

Figure 5: The average SEY after 20 impacts as a function of power for varying levels of SEY suppression as calculated by VORPAL. The experimental curve is normalized to the VORPAL result at 400kW with no suppression.

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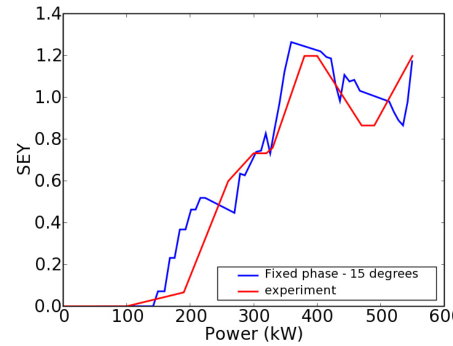

Figure 6: The average SEY after 20 impacts as a function of power with the SEY suppressed for fixed phase as calculated by VORPAL. The experimental curve is normalized to the VORPAL result near 400kW.

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