SELF-CONSISTENT SIMULATIONS OF MULTIPACTING IN SUPERCONDUCTING RADIO FREQUENCIES *

C. Nieter†, S. Ovtchinnikov, D.N. Smithe,
P.H. Stoltz, P.J. Mullowney, Tech-X Corporation, Boulder, CO 80026, USA

Abstract

Multipacting continues to be an important issue in Superconducting Radio Frequency (SRF) cavities, particularly near waveguide couplers. Most modern simulations of multipacting are not self-consistent, using the fields from a purely electromagnetic simulation to drive the motion of multipacting electrons. This approach works well for the onset on multipacting but as the electron density increases in the cavity it can have an effect on the cavity mode.

Recently VORPAL has demonstrated its ability to mode the electrodynamics of SRF cavities using finite difference time domain (FDTD) algorithms coupled with cut-cell treatments of the cavity boundaries based on the Dey-Mittra method. The FDTD approach allows us to easily incorporate multipacting electrons as PIC particles in the simulations.

To allow multipacting simulations to be done with EM-PIC we have been developing particle boundaries for the cut-cells. Recently we have added particle removal boundaries at the particle sinks which will correct the unphysical build up of image charge at the boundaries. We have also modified the secondary electron routines in VORPAL so they are now aware of the cut-cell boundaries and use the normal to the boundary surface when emitting secondaries. Using these new particle boundary conditions we have started preliminary simulations of multipacting electrons in a SRF cavity.

VORPAL

VORPAL is a proven electromagnetic Particle-in-Cell code (EM-PIC) [1]. VORPAL is a multidimensional code capable of simulating one, two, or three dimensions. VORPAL can be used with the Tech-X corporation library TxPhysics [2], giving VORPAL access to models for charged particle effects including various ionization models and electron emission from solids by ion and electron impacts. Of particular interest is the secondary electron emission model which separates the secondary electrons into reflected, diffusely reflected and true secondary electrons. The electromagnetic solver in VORPAL can handle complex conducting boundaries such as those found in SRF cavities using the Dey-Mittra [3] cut cell method.

Our recent efforts have focused on introducing charged particles modeled using the Particle-In-Cell (PIC) model into our cavity simulations. This has required several modifications to VORPAL, included a new treatment of particle removal at the cut cell boundaries to prevent image charge build up and modifying the secondary electron routines to handle emission from complex boundaries.

PARTICLE REMOVAL AT CUT CELL BOUNDARIES

To insure charge conservation when charged particles are removed at non-grid line positions in a cut cell corrections need to be made to the standard Buneman current deposition. If no corrections are made ghost charges will build up on the grid and adversely affect fields and particle dynamics. This can be understand by considering how the particle's charge is distributed on the grid. The charge is distributed to the four corners of the cell by weighting the fraction of the charge to the volume occupied by the box formed by the particle's position and the location of the cell corner opposite the one in question. If the particle is removed immediately after crossing the boundary surface, its charge will remain on all four corners of the cell. Since at least one of those corners is still inside the vacuum region we now have a ghost charge at that position which will result in a unphysical static electric field. As more and more charges are removed more and more ghost charge will build up causing the static electric field to build up quickly.

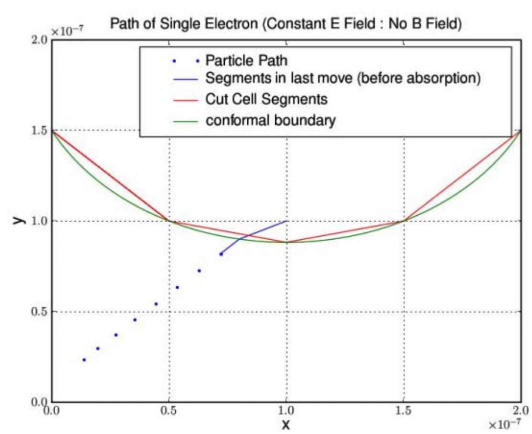

Figure 1: Trajectory of a particle being removed at at cut cell boundary

A simple method to correct this is to continue the particle motion after it passes the boundary surface to a corner which is inside the metal. This puts all of the particle charge outside the vacuum region so no image charge will build up. VORPAL's particle move is done as a series of segments to allow particles to interact with more compli-

* Work supported by DOE grant DE-FG02-05ER84172 and DOD grant FA9451-06-M-0095
† nieter@txcorp.com

1-4244-0917-9/07/$25.00

cated boundaries such as reflections off corners. After a particle crosses the boundary surface the remaining segments of its move are recalculated so the particle is moved to a corner which is inside the conducting boundary. The currents deposited by this new move are precisely the currents needed to correct the charge distribution on the cell corners. Figure 1 shows a typical particle trajectory and how the move segments are altered to remove the particle.

SECONDARY ELECTRON EMISSION FROM CUT CELL BOUNDARIES

The secondary electron emission routines in VORPAL where originally designed with the assumption that the emission surface was flat and in line with the computational grid. To allow secondary electron emission from the cut-cell boundaries these routines had to be modified so data such as the location of the boundary crossing and the normal to the boundary were available. The secondary electron emitter was given access the needed data structures that described the boundary surface, in particular the normal to the boundary in each cell was made available. A flag was also added to force the secondary electron emitter to only admit a single secondary. This was to done so simulations of a single particle could be done to track individual multipacting trajectories. Figure 2 shows a time series of plots of an electron beam striking a metal plane which is at an angle with respect to the grid axis. The third and fourth frames show secondary electrons which have been emitted from the surface.

Figure 2: Time series of an electron beam impacting a conductor producing secondary electrons

PRELIMINARY MULTIPACTING SIMULATIONS

As an initial test of VORPAL's new multipacting capabilities we ran a series of simulations to explore different possible multipacting trajectories in a SRF cavity. We emit a single electron from the surface of a single cell of the TESLA cavity [4] after the primary accelerating mode of the cavity has been excited to a peak field of 22.5 MeV/m. The entire cavity surface is set up as a secondary electron emitter which is only allowed to emit a single secondary. The resulting multipacting trajectories depend on where along the cavity surface the electron is emitted and at what phase of the cavity mode the emission occurs.

In Figure 3 we see an example of a multipacting trajectory where the electron continues to across the cavity by being accelerated back and forth by the caviy field in a series of absorption and emission events. In this case the electron remains in the cavity cell for over five cavity mode periods. In Figure 4 we see an example of a multipacting trajectory that exits the cavity after only one cavity mode period. The electron is pulled to the other side of the cavity where it is absorbed and emits a secondary electron which is then pulled out of the cavity cell into the beam pipe by the cavity field. The only difference between these two simulations was for the exiting trajectory the initial electron was emitted approximately a tenth of a mode period later in time.

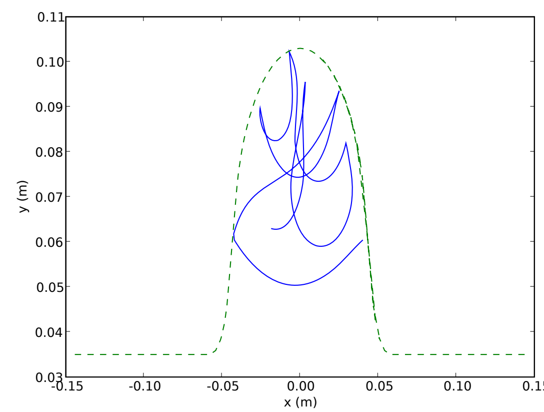

Figure 3: Multipacting trajectory of electron on a plane parallel to the cavity axis. This trajectory remains inside the cavity cell. The cavity wall is shown as a dashed line.

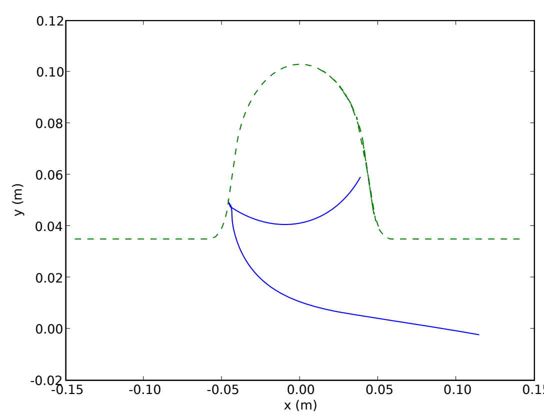

Figure 4: Multipacting trajectory of electron on a plane parallel to the cavity axis. This trajectory exits out the beam pipe. The cavity wall is shown as a dashed line.

CONCLUSIONS

VORPAL can now model electron multipacting in SRF cavities from first principles. Specific cavity mode can be excited by driving the cavity with a current source at a known frequency. Electrons can then be introduced at arbitrary times and locations in the cavity and their dynamics can be observed as well as the dynamics of any secondary produced by impacts with the cavity walls. Single multipacting trajectories can be studied as well as possible multipacting cascades. Further improvements are planned for VORPAL, including an eignemode solver for the electromagnetics as well as field emission models for the particles.

REFERENCES

[1] C. Nieter and J. R. Cary, "VORPAL: a versatile plasma simulation code," J. Comput. Phys 196 (2004) 448.

[2] P. H. Stoltz, J. P. Verboncoeur, R. H. Cohen, A. W. Molvik, J.-L. Vay, and S. A. Veitzer, Phys. Plasmas 13, (2006) 056702.

[3] S. Dey and R. Mittra, "A locally conformal finite-difference time-domain (FDTD) algorithm modeling three-dimensional perfectly conducting objects", IEEE Microwave and Guided Wave Letters 7 (1997) 273.

[4] Aune, B. and Bandelmann, R. and Bloess, D. and Bonin, B. and Bosotti, A. and Champion, M. and Crawford, C. and Deppe, G. and Dwersteg, B. and Edwards, D. A. and Edwards, H. T. and Ferrario, M. and Fouaidy, M. and Gall, P.-D. and Gamp, A. and Gössel, A. and Graber, J. and Hubert, D. and Hüning, M. and Juillard, M. and Junquera, T. and Kaiser, H. and Kreps, G. and Kuchnir, M. and Lange, R. and Leenen, M. and Liepe, M., Phys. Rev. ST Accel. Beams 3 (2000) 092001.

