VORPAL AS A TOOL FOR THREE-DIMENSIONAL SIMULATIONS OF MULTIPACTING IN SUPERCONDUCTING RF CAVITIES*

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Abstract

Considerable resources are required to run three dimensional simulations of multipacting in superconducting radio frequency cavities. Three dimensional simulations are needed to understand the possible roles of non-axisymmetric features such as the power couplers. Such simulations require the ability to run in parallel. We consider the versatile plasma simulation code VORPAL as a possible platform to study such effects. VORPAL has a general 3D domain decomposition and can run in any physical dimension. VORPAL uses the CMEE library to model the secondary emission of electrons from metal surfaces. We present a three dimensional simulation of a simple pillbox RF cavity to demonstrate the potential of VORPAL to be a major simulation tool for superconducting radio frequency (SRF) cavities.

VORPAL

VORPAL [1] is a simulation code that began as an electromagnetic particle-in-cell code for studying beam-plasma and laser-plasma interactions. VORPAL is a multidimensional code capable of simulating one, two, or three dimensions, with the unique property that the same code base supports any choice of dimensionality (most codes use *case-switch* statements to execute different lines of code depending on the dimensionality). The authors of VORPAL accomplished this dimension-free coding through meta-template programming techniques. Another feature of VORPAL is that it has general three dimensional domain decomposition, which allows VORPAL to scale well on large supercomputers as well as Linux clusters. Any collection of bricks that add up to the simulation domain is a valid domain decomposition. This allows static load balancing to be done to improve performance. Communication and computation are overlapped at two different levels in the VORPAL update. This limits the time the processors are idle and improves scaling on parallel machines. Fig. 1 shows the speed up of a scaling test done on the IBM SP3 at the NERSC supercomputer center. The circles are the speed up (ratio of the time taken by N processors to the time taken by a serial run) for a laser-plasma simulation. The solid line is a line of slope one going through the 256 processor data point.

VORPAL supports a variety of computational models for electrodynamics, plasma dynamics, neutral gas dynamics, and ionization processes. Electromagnetics can be modeled explicitly with a standard Yee finite difference or with an implicit solver based on work by Bowers [2]. Several boundary conditions for the electromagnetic solver exist, including wave-launching boundaries and open boundaries using Perfectly Matched Layers [3]. An electrostatic solver that uses the parallel matrix mathematics library, Aztec [4] is also available. Models for both field and impact ionization are available through the IONPACK library [5]. Routines for secondary electron emission from metallic surfaces are provided by the CMEE library described below.

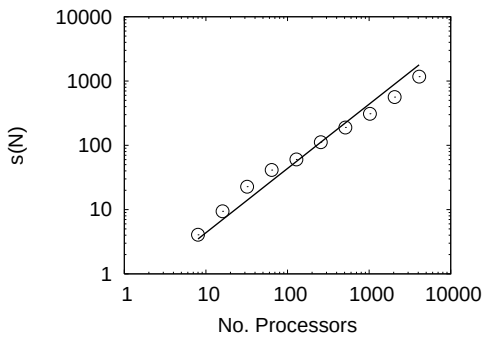

Figure 1: Scaling test of VORPAL on the IBM SP3.

CMEE

For modeling secondary electron emission VORPAL incorporates the CMEE (Computation Modules for Electron Effects) library [6]. This suite of routines was developed by researchers at Tech-X corporation along with collaborators at LBNL and LLNL. The feature of CMEE most relevant to SRF modeling is the secondary emission model from the POSINST code [7]. The POSINST routines divide the emitted secondary energy spectrum into three parts: true secondaries, rediffused, and elastic electrons. POSINST fits each of these three parts of the emitted spectrum with an empirical function that has a few adjustable parameters, including the relative amounts of each that will be emitted. For instance, in POSINST, the relative amounts of each part of the spectrum for copper are 78% true secondaries, 20% rediffused, and 2% elastic. Other parameters describe the shape of the emitted energy distribution. For the elastic part of the spectrum, POSINST has a Gaussian fit to the energy distribution. For the rediffused part, POSINST has a power law fit. For the true secondaries, POSINST has a combination of a power law and an exponential decay.

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The routines also have a model of the angular dependence:

$$\delta(\theta) = \delta(0)\left(1 + e_1(1 - cos\left(\theta^{e_2}\right)\right), \qquad (1)$$

where $\delta\left(0\right)$ is total secondary electron yield (SEY) at normal incidence, and e_1 and e_2 are adjustable parameters (typical values are $e_1 = 0.25$ and $e_2 = 2.0$). The angles from the surface at which the electrons are emitted are distributed uniformly. While the POSINST routines are among the best in the field for modeling secondary electron emission, a current limitation to POSINST (especially as it applies to SRF simulations) is that the SEY models are for copper and stainless steel only.

SIMULATIONS OF RESONANT CAVITY

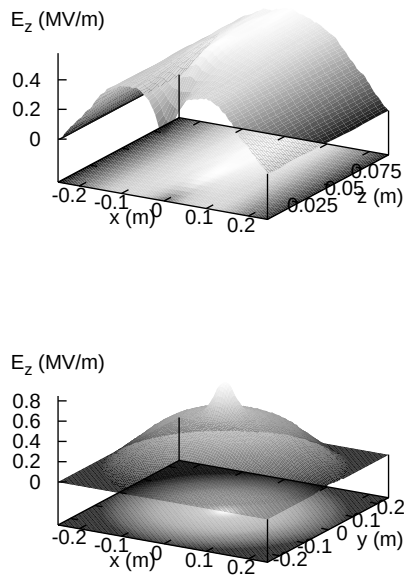

Figure 2: The electric field on axis in the resonant cavity.

To demonstrate VORPAL's potential to model 3D structures similar to the ones involved in SRF cavities, we have run a 3D simulation of a resonant cylindrical cavity. We consider a simple closed cylindrical cavity with a radius of 0.5 m and a length of 0.1 m. The cavity axis is in the z-direction and we place the origin of our coordinate system in center of the front circular face. All the cavity surfaces are assumed to be perfect conductors. The cylindrical surfaces are modeled with stair step boundaries. To excite the TM010 resonant mode we apply an oscillating current in the center of one of cylindrical faces of the cavity at the resonant frequency of the cavity. The simulation is run for several resonant periods of the cavity. Fig. 2 shows surface plots of the electric field in the cavity axis direction for a cross section in the middle of the cavity and a cross section just off axis. The fields show the expected TM010 mode structure with some distortions from the fields directly generated by the driving current.

To understand how an electron would behave in the resonant fields of the cavity, we inject a single electron into the simulation at $x = -0.125$ m and $y = -0.125$ m just above the front face of the cavity. The electron is given an initial energy of 10 eV which corresponds to the typical energy of a multipacting electron produced by another electron colliding with the cavity wall. The electron's trajectory in the x-z and y-z planes is shown in Fig. 3. The electron is accelerated by the resonant field and moves into the cavity, until the field changes sign. The particle is then decelerated and its trajectory is reversed. It impacts the cavity wall close to the location where it was emitted. Depending on the energy of the electron at impact it may create additional secondary electrons.

Multipacting can occur if the electron's trajectory is in resonance with the resonant fields in the cavity. When the electron returns to the cavity wall close to where it was emitted, secondary electrons can be produced that will follow a similar trajectory. If the electron's energy is in the 10 to 100 eV range, multiple secondary electrons can be produced. This leads to a build up of electrons in the cavity which can limit the accelerating field.

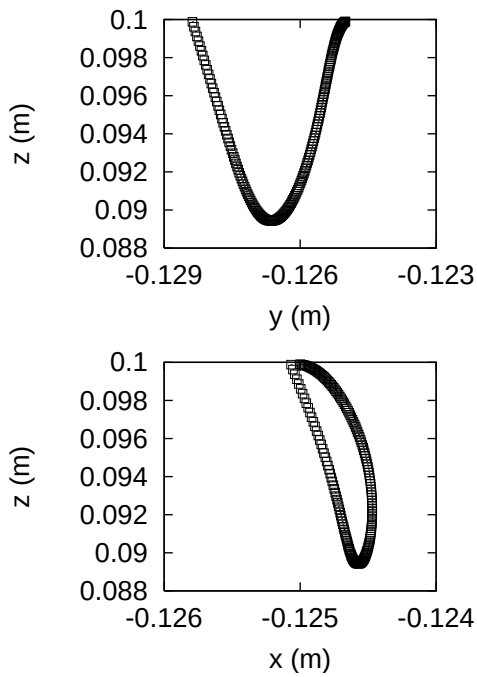

Figure 3: Trajectory of a multipacting electron in the resonant cavity.

SUMMARY

VORPAL's flexibility and capacity to run large problems makes it an excellent tool for the study of multipacting in

SRF cavities. It can simulate 3D structures and run in parallel with a general domain decomposition. It has computational models to deal with electron production from ionization and secondary emission processes. With some simple modifications, such as improved boundary conditions to handle couplers and elliptical cavities and the addition of new materials to the secondary electron emission models, VORPAL will be able to self-consistently model multipacting in current SRF cavity designs.

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