SIMULATIONS OF ELECTRON EFFECTS IN SUPERCONDUCTING CAVITIES WITH THE VORPAL CODE

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Abstract

Modeling the complex boundaries of superconducting radio frequency (SRF) accelerating cavities on a Cartesian grid is a challenge for many Finite Difference Time Domain (FDTD) electromagnetic PIC codes. The simulation of such cavities requires conformal (curve fitting) boundaries. Modeling the full cavity including couplers and ports is fundamentally a three dimensional problem requiring the capability to run in parallel on large numbers of processors.

We have recently added conformal boundaries using the method of Dey and Mittra to the plasma simulation code VORPAL. Using this higher order boundary algorithm and the surface physics package TxPhysics, we have begun studies of self-consistent electron effects in SRF cavities. We have modeled the beam excitation of cavity modes and the effects of electron multipacting. Results from these studies will be presented using the new user-friendly visualization tool developed specifically for VORPAL.

VORPAL

VORPAL is a proven electromagnetic Particle-in-Cell code (EM-PIC) [1]. It was originally developed to model problems in Laser Wakefield Acceleration (LWFA) and was recently used to provide simulation support for experiments conducted at Lawerence Berkeley National Laboratory which created one of the first mono-energetic electron beams from LWFA [2]. VORPAL is a multidimensional code capable of simulating one, two, or three dimensions. By using template specialization and recursive updates, VORPAL supports the different dimensionalities with the same code base (most codes use *case-switch* statements to execute different lines of code depending on the dimensionality). VORPAL is highly portable, running under multiple operating systems and running on a variety of different hardware from desktop computers to high performance supercomputers. The code has been optimized for use of parallel machines allowing it to scale to 1000s of processors. Figure 1 shows the results of scaling tests done on the IBM SP3 at the NERSC supercomputing center.

VORPAL can be used with the Tech-X corporation library TxPhysics [3], 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 TxPhysics secondary electron emission model have tunable parameters allowing fits to specific experimental data sets. In Figure 2 we see results for the secondary electron yield of niobium for a heated and unheated surface. The data points are results from a fit of the TxPhysics model to experimental results [4]. VORPAL also has field-induced electron emission from solids. These models allow VORPAL to simulate multipacting behavior in cavities.

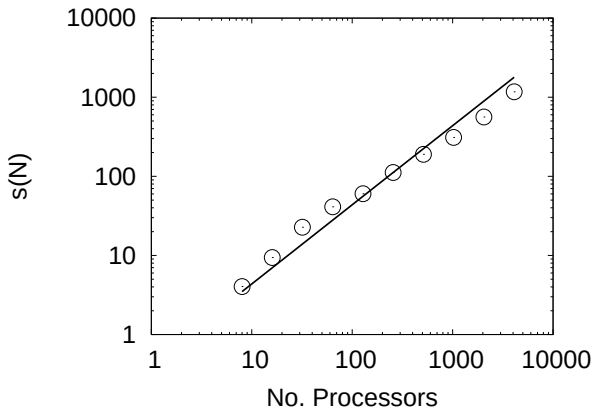

Figure 1: The speed up (ratio of the time for a single processor run to the time for a N processor run) as a function of number of processors used for a series of LWFA simulations of fixed size at the NERSC supercomputing center.

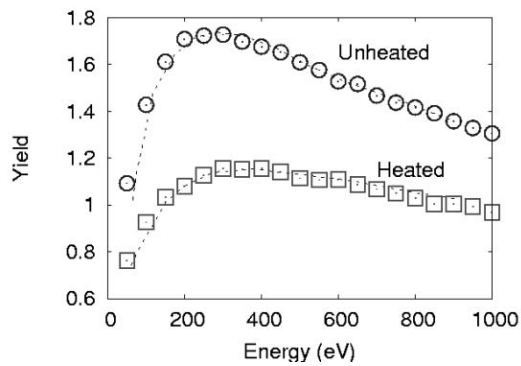

Figure 2: The secondary electron yields given by TxPhysics secondary electron model fitted to experimental data.

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CUT CELL CONFORMAL BOUNDARIES

Modeling multipacting phenomenon requires an accurate knowledge of the fields at the multipacting surface. This is a challenge for finite-difference electromagnetic codes since curved boundaries are often modeled with stair step boundaries which are known to only be first order accurate in space. To over come this limitation we have implemented the Dey-Mittra [5] cut-cell boundary algorithm which is known to be second order accurate in space.

The Dey-Mittra algorithm works by considering the Faraday update of the magnetic field on a standard Yee mesh as a loop integral along the edges of the cell face where the magnetic field lives. If the cell is cut by the boundary the loop integral is limited to the edges that are fully or partially inside the boundary. The edges that are partially cut have their lengths reduced by the appropriate amount. The area used in the integral is also reduced by how much area is inside the boundary. In Figure 3 results for scaling tests done on the VORPAL implementation of the Dey-Mittra algorithm are shown. In these simulations a spherical conducting cavity is excited by driving a current at the physical frequency of the lowest mode of the cavity. The current has a gaussian envelope in time and has the same approximate spatial profile as the cavity mode. A series of simulations where the physical dimensions were held fixed while the number grid cells was increased was done for both stair step and Dey-Mittra boundaries.

The crosses represent the data for the stair runs and the squares represent the data for the Dey-Mittra runs. The straight lines represent scaling that is first and second order accurate. Not only does the Dey-Mittra give an error that is lower than the stair step, it gives second order scaling where stair step has only first order scaling. The line representing first order accuracy has been extended past the data to show what grid resolution would be needed to achieve an error under 10^{-4} with stair step boundaries. Over a 1000 grid points per radii would be required to achieve such an error where less than 100 are needed using Dey-Mittra.

One disadvantage of the Dey-Mittra boundaries is the time step must obey the Courant condition for the smallest cut cell on the boundary to maintain stability. To keep the time step at a reasonable value we introduce an input parameter which gives the fraction of the Courant step that we will allow. The code then checks all the cut cells to see if they would be stable for this time step. If they are not stable then they are rejected and are not used. In practice this only changes the coefficient of the scaling, not the exponent. The data shown in Figure 3 is for a quarter of a Courant time step and we still see second order accuracy for the Dey-Mittra boundaries.

We have begun work on so called 'area borrowing' techniques which give second order accuracy while allowing the full Courant time step. This is achieved by adding contributions from neighboring cells for the field update. In effect, area is borrowed from neighboring cells to maintain stability. The various 'area borrowing' methods differ in the amount of area that is borrowed and whether the small cut cells receive or donate this area. One of the algorithms that we have begun to implement is the Zagorodnov [6] method which borrows area from neighboring cell if the cell is cut by more than half. Figure 4 gives an example of the area borrowing done in this method.

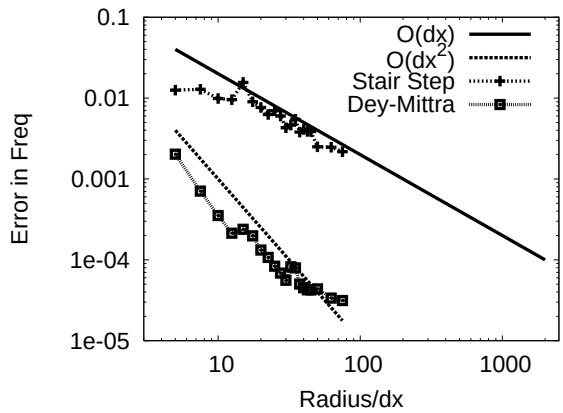

Figure 3: The error in the simulated frequency for the lowest mode in a spherical cavity. The crosses are data from simulations using stair step boundaries and the squares are from simulations using Dey-Mittra boundaries.

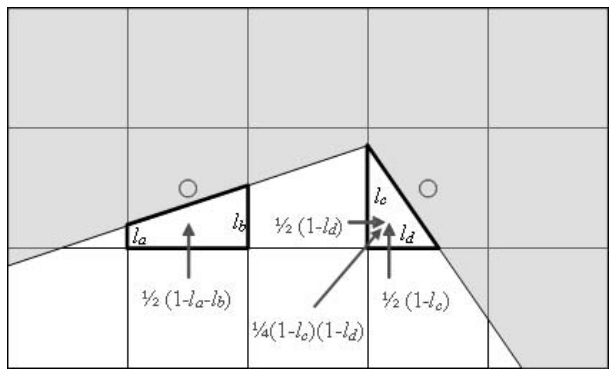

Figure 4: Area fractions borrowed by cut cells in the Zagorodnov boundary algorithm.

CAVITY SIMULATIONS OF ELECTROMAGNETIC AND ELECTRON EFFECTS

For many research problems in SRF cavity modeling, self-consistent electron dynamics are needed to capture the relevant physics. For example, as multiple beams pass through an accelerating cavity they will produce wakefields in the cavity that can interfere with the accelerating mode of the cavity. In Figure 5 we see a visualization of the wake fields produced by an electron beam passing through a SRF cavity from a VORPAL simulation.

Accelerating cavities are typically driven at a specific cavity mode during operation. We use a well known tech-

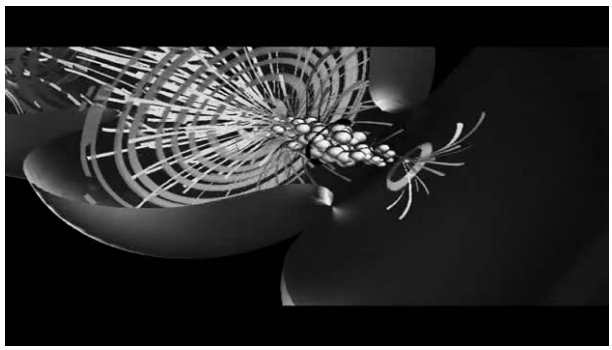

Figure 5: Visualization [7] of electron beam and associated wakefields in cavity from VORPAL simulation of beam wakefield generation.

nique to drive a specific cavity frequency by introducing an initial current source into our simulations. An oscillating current pulse with a gaussian envelope and a spatial profile that roughly matches the mode profile is driven in the cavity. The length of the gaussian envelope can be adjusted so the pulse's footprint in frequency space is sharply peaked about the desired mode frequency. This prevents any excitation of neighboring cavity modes. Once the current pulse is shut off the cavity will continue to ring with the desired mode. An electron beam can now be introduced or electron emission can be turned on to study electron effects on the cavity modes and vis versa. We have begun preliminary studies of multipacting behavior in SRF cavities. We have developed simulations where we can release electron bunches at the wall and observe the trajectories as they are accelerated by the cavity fields. By varying the phase that the particles are released at we can study the possible multipacting trajectories that can occur.

Work has been begun on integrating the various emission algorithms mentioned earlier with the conformal boundaries. We can currently remove particles that cross the curved boundaries. We are working on methods to correct for the unphysical image charge build up that occurs when a particle is deleted in the middle of a grid cell. We are also developing field and secondary emission models for the conformal boundaries that will make use of the Tx-Physics routines. Once these models are ready we will be able to dynamically model multipacting in SRF cavities.

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