INITIAL 3D VORPAL SIMULATIONS FOR RF ELECTRON GUN MODELING*

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Abstract

The Relativistic Heavy Ion Collider (RHIC) contributes fundamental advances to nuclear physics by colliding a wide range of ions. A novel electron cooling section requires the acceleration of high-charge electron bunches with low emittance and energy spread. A radio frequency (RF) electron gun is a key component of the RHIC-II upgrade that is designed for the emission of such bunches. Accurate, fully electromagnetic modeling of electron beams in RF electron guns with complex geometries is needed. Development of new 3D algorithms and computational capabilities in the VORPAL particle-in-cell code are promising to address this problem. Initial results from 3D VORPAL simulations on a specific RF gun considered for the RHIC-II upgrade will be presented and discussed.

INTRODUCTION

To address the need for high average-current, high brightness electron beams for the RHIC-II upgrade, an RF electron gun that meets specific operational parameters (e.g. for beam size and low emittance) has to be designed and developed [1, 2, 3]. Simulations provide valuable insight during the design of RF electron guns. There are a number of codes [5, 8, 9] (and the references therein) that are currently in use for RF gun simulations. Different algorithms [6, 10, 8] have been implemented to compute space charge and beam propagation often using approximations that can accurately predict only some of the physical properties of interest.

Codes that use reduced/approximate theoretical models usually predict RF gun performance parameters that significantly exceed experimentally measured quantities [7]. While this discrepancy potentially involves measurement uncertainty, there are known simulation issues [7] when using approximate theoretical models. The main simulation inaccuracies come from using electrostatics for space charge forces, not taking into account wakefield effects, not modeling the physics of electron emission, and not including 3D effects (often the codes are restricted to 2D axisymmetric simulation cases).

The VORPAL [4] particle-in-cell (PIC) framework has been extended with new capabilities [12, 13] to address these simulation issues and to enable more accurate modeling of RF electron guns.

Here, we report on our initial work to simulate a specific RF gun with VORPAL. This gun is designed for operation at RHIC. In the next section, we describe the problem and relevant parameters. Then, we present results from VORPAL simulations and how they compare with results from PARMELA code [5]. PARMELA simulations are extensively used in the process of designing RF electron guns. Finally, we summarize and mention future work on VORPAL RF gun code development and simulations.

PROBLEM DESCRIPTION

The RF gun we simulate consists of $1\frac{1}{2}$ cells followed by a pipe. The beam is emitted from a recessed photocathode. The pipe length is 23.5 cm. The distance from the photocathode emitting surface to the beginning of the pipe (including the $1\frac{1}{2}$ RF cells) is 36.7 cm. We show a representation of a cross section of the RF gun in Fig. 1. From the simulation data, we can analyze beam evolution in the gun (two consecutive beams are shown in Fig. 1) and development of wakefields. We consider these in greater detail in the next section.

For the RF field in VORPAL, we used data on this gun from the SUPERFISH code in order to compare with results from PARMELA (since PARMELA represents the RF field using values from SUPERFISH). However, in these initial VORPAL simulations, our treatment of the RF field from the SUPERFISH data is less accurate than in PARMELA. We developed a piece-wise fit to an off-axis SUPERFISH data (for a fixed transverse coordinate value) and scaled it to different transverse coordinates. This approximate treatment of the RF field allowed us to start simulating this gun with VORPAL in a short period of time. Moreover, as shown in the next section, the produced electron energies are in very good agreement with the values from PARMELA. In a future code development, we will implement a much more accurate computation of the RF field in VORPAL that directly imports SUPERFISH data based on the approach in Ref. [14].

The RF field frequency is 703.75 MHz. The longitudinal RF electric field on axis at the surface of the photocathode is -8.28 MV/m. Its amplitude is 30 MV/m.

Although we have implemented [15] in VORPAL two models that take into account physics of the photoemission process, the simulations presented here are with an ideal-

* The work at Tech-X Corp. is supported by the U. S. Department of Energy under a Phase I SBIR grant.

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ized, “beer can”, beam shape. This shape is considered as one of the best candidates in terms of electron beam performance and laser beam shaping ability. Moreover, this beam shape can be simulated by both VORPAL and PARMELA which facilitates better comparison between the codes. The

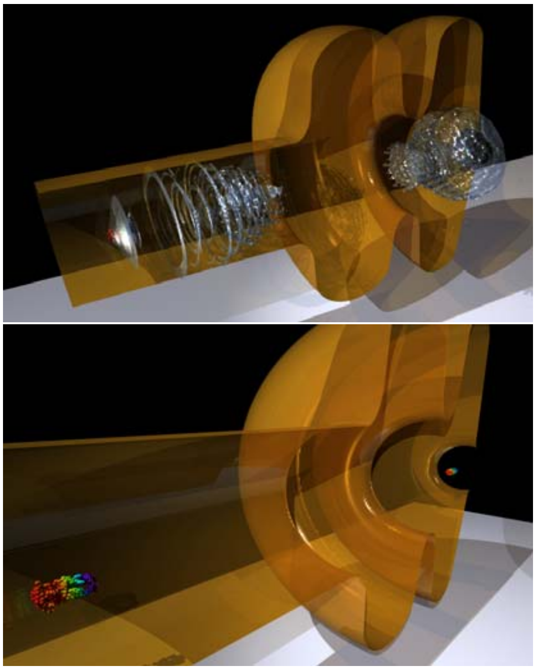

Figure 1: The top image shows a visualization of half of the $1\frac{1}{2}$ cell electron gun. Electron beams are emitted from a domain on the right side of the gun and propagate to the left. The beam shown in this image is close to the exit from the gun. Isosurfaces of the wakefields that develop are shown as well. The bottom image displays two particle beams from the multi bunch simulations. The beam on the left side is close to exiting the gun while the beam on the right is close to the emitting surface. The color coding of the particles, easier to see in the front beam, show their speed from highest (red) to lowest (blue).

emitted beams have a total charge of approximately 5 nC, beam radius of 4 mm, and length of 80 ps. To explore the ability to simulate multiple bunches with VORPAL, we also did several multi bunch runs. Due to the exploratory nature of the multi bunch runs and their high computational resource requirements, only the lowest grid resolution was used. A bunch was emitted every RF period. This leads to an average current of about 3.5 A. This RF gun is being designed [1, 2] for operation with an average current of 50 mA.

To better understand how VORPAL results depend on grid resolution and number of macro particles used, we ran a number of cases varying these parameters. We considered here varying only the longitudinal grid cell size. The transverse cell sizes were set equal to approximately 2.1 mm. The longitudinal cell size was varied from about 3 mm down to 75 μm. The number of macro particles used to represent the 5 nC beams was varied from 5000 to 500000.

SIMULATION RESULTS

To evaluate how results from VORPAL compare to output from PARMELA, we calculated four quantities: average kinetic energy, rms beam sizes (both longitudinal and transverse), and rms emittance as a function of the average beam position along the symmetry axis (direction of beam propagation) of the RF gun.

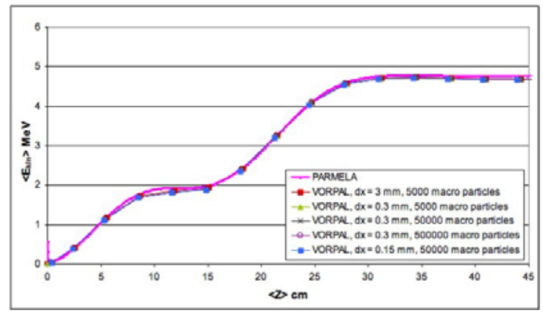

Figure 2: The data from VORPAL on average kinetic energy vs average beam position for different simulation resolutions are in good agreement with results from PARMELA. Thus, the current representation of RF fields in VORPAL is sufficiently close to the one in PARMELA for simulating beam particle kinetic energies.

In Fig. 2, we have plotted the average kinetic energy from a PARMELA run (the solid curve with no symbols: the same style is used for all PARMELA results presented) and from several VORPAL runs with different cell sizes and number of macro particles. The symbols are at the average beam positions when processing VORPAL data while the lines connecting the symbols are guides for the eye only. The average kinetic energy from the VORPAL runs is in very good agreement with the PARMELA result. Furthermore, the VORPAL results from the different simulations cases are essentially the same indicating that the average kinetic energy does not change significantly when varying the cell size resolution and the number of macro particles.

More importantly, the close agreement between VORPAL and PARMELA, implies that our current, approximate treatment of the RF field in VORPAL is sufficiently close to the more accurate representation in PARMELA, at least to obtain the average kinetic energy.

The multi bunch simulations, from data on 11 bunches emitted in consecutive RF periods, show that the average kinetic energy at the exit from the gun (at the end of the pipe) varies within 1 % of the value from the first beam. Thus, the wakefields that develop in the gun over the 11 RF periods of this simulation do not appear to significantly affect the acceleration of the bunches.

Next, we consider the rms beam sizes. The evolution of the transverse rms beam size is shown in Fig. 3 and for the longitudinal rms size in Fig. 4. The transverse rms beam size from the PARMELA simulations is larger than from VORPAL, although the qualitative behavior from both codes is similar. Moreover, the difference between PARMELA and VORPAL increases in magnitude when the beam moves towards the exit of the gun. The beam in VORPAL is smaller radially than in PARMELA. The transverse rms size does not change significantly for the different resolutions simulated. This is not unexpected since we did not increase the transverse cell size resolution. We will investigate the effect of the transverse cell size on this quantity in future simulations.

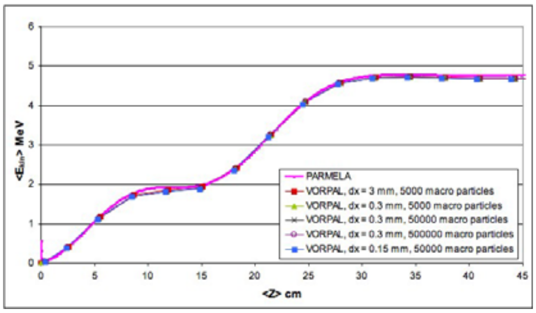

Figure 3: For the resolutions used in the VORPAL simulations, the values of the transverse rms beam size are smaller than in PARMELA indicating a narrower beam in VORPAL.

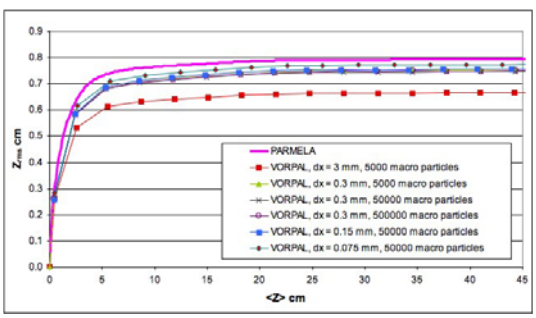

Figure 4: The longitudinal rms size of beams in the VORPAL simulations are shorter than in PARMELA. However, when reducing the longitudinal cell size in VORPAL, the rms size approaches the values from PARMELA.

The multi bunch simulations show transverse rms variation at the exit of the gun within 3 % of the value of for the first beam. However, all values are higher than the value of the initial beam. Thus, it is of considerable interest to investigate the wakefield effects when we study multiple bunches over their designed repetition rate. This rate will lead to development of higher order modes that could significantly affect the propagation of multiple beams.

As expected, the longitudinal rms beam size does change when increasing the VORPAL grid cell resolution along this direction. The rms beam size from VORPAL approaches the values from PARMELA from below. The beam size in VORPAL is shorter than in PARMELA. Note that changing the number of macro particles does not significantly affect this rms size. However runs with finer resolutions will be needed [8, 11] to reach convergence for the rms results with VORPAL.

In the multi bunch simulations, the longitudinal rms size varies within the interval from -1 to 4 % relative to the value from the first beam measured at the exit from the gun.

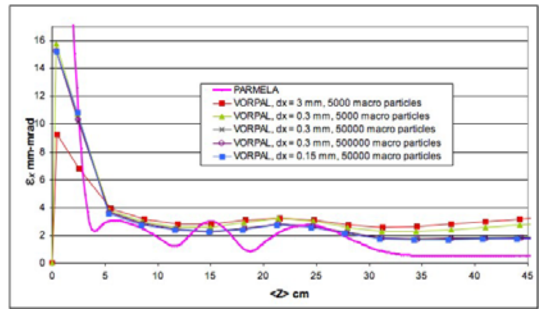

Figure 5: The transverse rms emittance from VORPAL is higher close to the exit of the gun compared to the PARMELA result. The emittance from VORPAL decreases when decreasing the longitudinal cell size but at the end of the gun it still remains approximately three times larger than in PARMELA.

We also calculated the transverse rms emittance for several resolutions. These results and the values from PARMELA are shown in Fig. 5. There are regions where the emittance from VORPAL is smaller than the corresponding PARMELA values. However, for most of the propagation in the gun, the emittance values from VORPAL are larger. Moreover, at the exit of the gun for the runs with the highest resolution simulated, the emittance from VORPAL is about three times larger than the observed in PARMELA. We are planning further simulations to investigate the reason for this difference. Finally, the multi bunch VORPAL simulations showed small emittance variation, from -2 to 4 %, at the exit of the gun relative to the value from the first beam.

SUMMARY

The results from the initial 3D parallel PIC simulations with VORPAL are in qualitative to quantitative agreement with PARMELA results on an RF gun designed for the RHIC-II upgrade. The average kinetic energy from VORPAL agrees quantitatively with PARMELA. The transverse and longitudinal rms sizes in VORPAL are smaller than in PARMELA. Increasing the longitudinal grid cell size resolution in VORPAL improves the agreement with PARMELA. The emittance from VORPAL is about three times larger at the exit from the gun than from PARMELA. Multi bunch simulations, up to 11 beams in consecutive RF periods, do not show large variations in the considered beam diagnostics.

These initial VORPAL results on RF gun modeling demonstrate that the code is uniquely suited for such studies since it takes into account wakefield, 3D, and electrodynamic effects. It also has two models implemented that incorporate physics of the photoemission process.

There are, however, several important limitations in the current study. The RF field was treated in an approximate way. A more accurate algorithm is currently being considered for implementation.

The geometry of the gun was represented with a stair-step boundary (first order accuracy). Thus, a very fine grid is required to accurately model the surface of the gun with a stair-step boundary. VORPAL now has a second-order accurate, cut-cell boundary algorithm implemented [12].

Another limitation of the current simulation comes from using particle sinks to remove beam particles at the end of the gun. These boundary conditions lead to generation of coherent transition radiation (CTR) propagating backwards into the body of the gun. This strong backward wake is present only in the simulations due to these boundary conditions. To minimize and practically remove this effect, we have now the capability to use perfectly matched layer (PML) boundaries that can absorb reflected electromagnetic waves.

Extended parameters runs with VORPAL using PMLs, cut-cell boundaries, more accurate treatment of the RF field, and higher resolution grids are planned to be investigated in a forthcoming study.

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