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CHARACTERIZATION OF AN SRF GUN: A 3D FULL WAVE SIMULATION

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Abstract - We characterized a BNL 1.3GHz half-cell SRF gun is tested for GaAs photocathode. The gun already was simulated several years ago via two-dimensional (2D) numerical codes (i.e., Superfish and Parmela) with and without the beam. In this paper, we discuss our investigation of its characteristics using a three dimensional (3D) full-wave code (CST STUDIO SUITE™). The input/pickup couplers are sited symmetrically on the same side of the gun at an angle of 180°. In particular, the inner conductor of the pickup coupler is considerably shorter than that of the input coupler. We evaluated the cross-talk between the beam (trajectory) and the signal on the input coupler compared our findings with published results based on analytical models. The CST STUDIO SUITE™ also was used to predict the field within the cavity; particularly, a combination of transient/eigenmode solvers was employed to accurately construct the RF field for the particles, which also includes the effects of the couplers. Finally, we explored the beam's dynamics with a particle in cell (PIC) simulation, validated the results and compare them with 2D code result.

INTRODUCTION

The photocathode RF gun is one of the key enabling technologies for the low-emittance high-brightness beams required in facilities such as Free Electron Lasers (FELs) and high-energy colliders. Typically, simulations are used in designing the RF gun to optimize its emittance, energy spread, and bunch length.

A traditional 2D particle program (e.g., Parmela) is employed to delineate the beam's dynamics. However, it is widely accepted that to represent non-symmetrical structures, a 3D numerical simulation of the EM field is essential to the success of the accelerator-cavity's design. Earlier, the suitability was tested of BNL's 1.3GHz half-cell SRF gun for the Nb photocathode [1]; now is used for the polarized electron-source base on the GaAs photocathode.

The 2D RF field-simulation program, Superfish, and the 2D particle simulation program, Parmela, were used in that simulation. Particle simulations also demonstrate phenomena such as ion- back bombardment, and the multipacting effect arising from electron back-

bombardment. These simulations help to avoid the dangerous RF phase-range in electron emission, and to assure the survival of sensitive photocathodes, like GaAs [2].

Figure 1 illustrates the structure of the SRF gun. The input and pickup couplers are symmetrically placed on the gun's beam pipe at an angle of 180°. The GaAs photocathode is placed on a plug, inserted opposite the beam pipe.

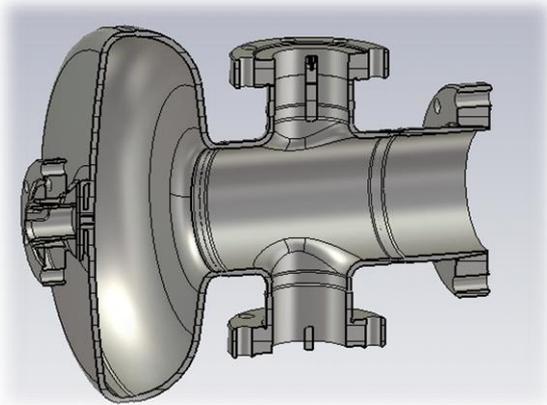


Figure 1 - Structure of BNL's 1.3GHz SRF gun

The CST PARTICLE STUDIO™ (CST PS) is a specialist tool used for designing and analyzing the electromagnetic components for accelerating and guiding a charged-particle beam [3]. It specialized for 3D simulation of electromagnetic fields interacting with charged particles. This paper demonstrates the results of our 3D simulation and compares them with those from the 2D code.

RF FIELD SIMULATION

A full 3D RF simulation of the gun with couplers first is carried out with an Eigen solver. The frequency predicted by earlier calculations with the Superfish 2D code is 1.297969GHz, in agreement to within 0.3% of the Eigen solver. The gun model used in CST includes the input port and the pickup port, whereas the model used in the Superfish code was considered symmetric. Figure 2 shows the electric-field pattern of the primary mode on the central axis. The maximum peak electron is normalized to 15MV/m.

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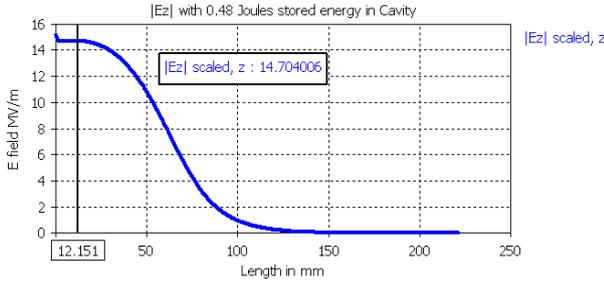


Figure 2. The electric field of the primary mode obtained from Eigen solver.

We note that the Eigen solver simulation does not consider coupling. The frequency solver and transient solver do encompass the coupling effect, and so the S parameter of the coupler port can be obtained. To study the cross-talk that affects the beam, either one of these solvers can be used. However, in our experience, the transient solver takes more than 1000 days of simulation to reach a steady-state due to the high Q of the SRF gun.

The frequency solver has some advantages, such as offering an easy way to model fields with excitation, and a faster resolution of the high Q problem. Its disadvantage is that the frequency must be known accurately before running the simulation. For the high-Q SRF cavity, an accurate resonant-frequency (typically within few Hz) is hard to obtain.

The Q factor of the BNL gun with photocathode is 2×10^8 , so the bandwidth is about 6.5Hz and the resonance frequency is 1.3GHz. To assess an accurate field at the resonant frequency in the SRF gun, we used an optimizer available in the CST Frequency solver, and employed the Trust Region Framework [4]. The probed E field at the center of the cavity was a goal function. We optimized the frequency near the resonance calculated from the Eigen solver. The precise resonance frequency was found as the probed E field is at the maximum value. After obtaining the resonance frequency, we undertook a frequency sweep to measure the bandwidth.

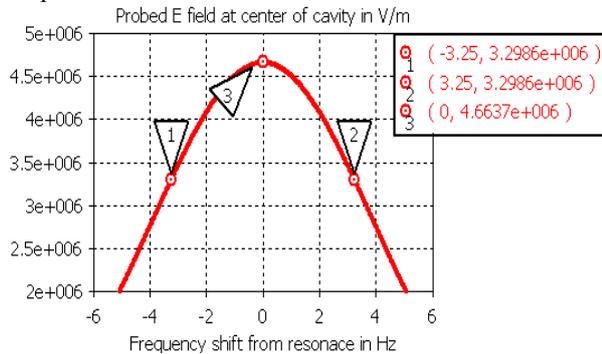


Figure 3 The frequency scan follows the amplitude of the electric field

Figure 3 shows the results of our optimization. We obtained a resonance frequency for the gun of 1.2977261373467GHz that differs from the the Superfish code result by 200 kHz. Figure 3 shows the bandwidth at about 6.5Hz. The Q value is $1.3\text{GHz}/6.5\text{Hz} = 2 \times 10^8$, agreeing well with the result from the Eigen solver result.

The Q factor of the gun with the GaAs photocathode is 1.3×10^8 tested at 2K. The new structure of the plug's design improves this Q factor. To match the beam load, the GaAs wafers absorb energy and the surface energy dissipates; therefore, the external Q of the input coupler is set to 2×10^8 . The length of the coupler probe is 1.4inches in the test structure used for the simulation.

PS SIMULATION

In the particle simulation, the RF field is imported from the frequency-domain solver and from the Eigen solver. Table 1 lists the parameters for the simulation, corresponding to the requirements of the polarized electron-gun test. The longitudinal- and transverse-distribution of the bunch is uniform.

Table 1 - The simulation parameters for the PS simulation

Nominal parameter	
Repetitive frequency	81.5MHz
Laser spot size	2mm diameter
Bunch length	10ps
Charge per bunch	10pC
Initial phase	20°
Freq.	1297.97 MHz
Particle number	36000
E _{cathode}	15MV/m

Tracking-solver simulation

The tracking-solver simulation derives the beam's dynamics without the space-charge effect. The electron energy evolves in the gun; we compared the electron phase-shift via Particle Studio(PS) and the 2D-code Parmela. The phase shift is defined by the shift between the phase of the center electron and the RF field. The RF field used in Parmela is imported from the Superfish code. As we show in Figure 4, the results of the single-particle simulation from the two programs match well. Under the same initial conditions, the difference in the electron bunch's energy at the gun's exit is less than 2%, whilst the difference in phase shift at the gun's exit is less than 3%.

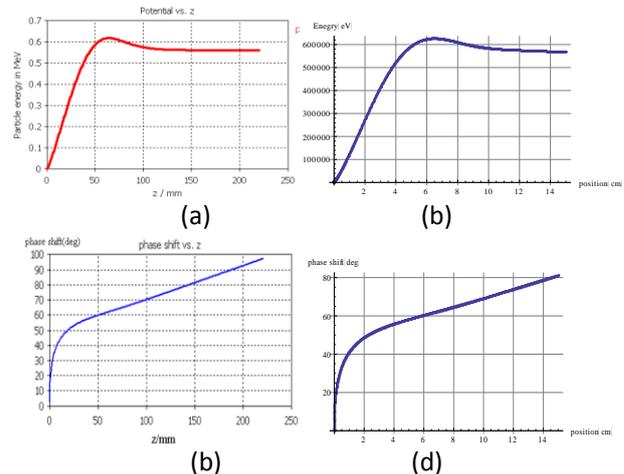


Figure 4 - Electron energy in the gun simulated by the coded CST (a), and Parmela (b). The phase shift in the gun simulated by the codes CST (c) and Parmela (d).

The calculated phase-shift follows its different positions in the gun simulated by the CST(c) and by Parmela (d). The small transverse-emittance is the key feature of the RF gun. Electrons with a low space-charge are emitted from the photocathode's surface with a very strong RF field. The growth in emittance due to the effects of the RF and space charge occurs within the RF gun. It is important to understand the formation of emittance in the photocathode RF gun. To investigate the evolution of normalized emittance in the gun we used the PS tracking solver and Parmela. The former does not support the consideration of the space-charge effect. At the gun's exit port, the transverse normalized emittance is 0.315mm-mrad (Figure 5). With the same parameters, the Parmela code yielded a transverse normalized emittance of 0.28mm-mrad at the gun's exit port. With the cross talk study, we didn't find any emittance different from with or without the couplers at the beam pipe according to the CST tracking solver result,. This can be explained by the high Q of the SRF gun.

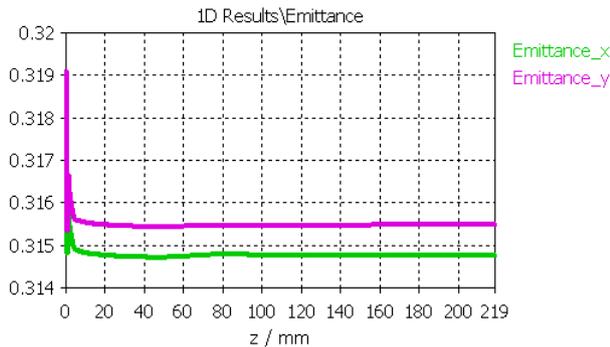


Figure 5 - The transverse emittance evolution in the RF gun simulated (CST tracking solver).

PIC solver simulation

In contrast to the tracking solver, the PIC solver simulates particles in self-consistent fields using a time-integration scheme for both the particles and the electromagnetic fields; the interdependency of fields and charges is taken into account [5]. With the PIC solver, a bunch in phase space can be read in steps, and we used a value of 25ps to step through the frames. Figure 6 shows the phase-space evolution of the y direction in the gun. The phase space ellipses corresponding to the various phases can be explained by the emittance compensation technique. Since the slices are all born aligned at the cathode and are very close in time, that they have a regular and correlated relationship. It is the understanding and control of this correlated relationship allows us to compensate for projected emittance growth due to linear space charge force [6]. The normalized emittance reaches ~0.3 mm-mrad; a value is comparable to the result from the 2D simulation.

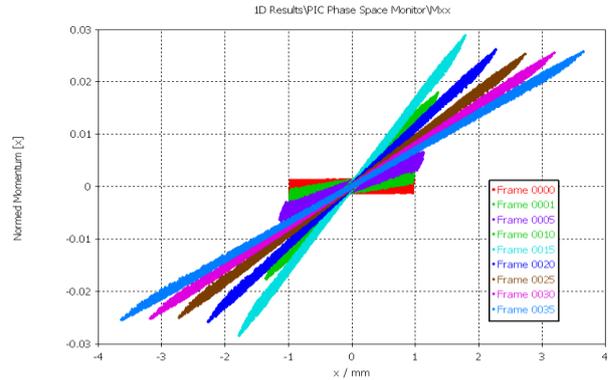


Figure 6 - The bunch evolution in the phase space when passing through the gun

CONCLUSIONS

We characterized by simulation a 1.3GHz half-cell SRF gun used at BNL for GaAs photocathode using a 3D full wave code (CST STUDIO SUITE™). The asymmetries of the input/pickup points are taken into account fully; we compared the results from the Eigen solver, the frequency solvers, and the PIC solver with the data from 2D code simulation (Parmela and Superfish). The result of simulation account into 3D effect is comparable to the 2D result due to this highly cylindrical symmetric gun and the trust region optimizer algorithm allows capturing with excellent accuracy the resonance frequency as compared to the other 2D codes.

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