

# EMITTANCE GROWTH DUE TO THE FIELD ASYMMETRY IN THE TTF RF GUN

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## Abstract

This paper reports the effect on the transverse emittance of the multi-pole field components due to the input coupler of the TTF RF gun. ASTRA simulations with 3D fields from CST MicroWave Studio (MWS) are presented for a typical operation of the Fermilab photo-injector at 1 nC.

## INTRODUCTION

The Tesla Test Facility (TTF) RF gun has been developed by Fermilab as a contribution to the TTF collaboration. The gun consists in a 1.625 cells cavity resonating in the  $TM_{010,\pi}$  mode at a frequency of 1.3 GHz. It is feed through a waveguide connected to the full cell by a coupling slot. Previous studies [1], [2] reported that this side coupling into the full cell induces a field asymmetry which deteriorates significantly the transverse emittance.

In the studies presented in this paper, we used the new implementation of the ASTRA code ([3], [4]) which allows 3D electric fields to be read instead of the usual 2D fields. In this case, the 6 components of the electric field are taken every millimeter around and along the longitudinal axis ( $\pm 10$  mm in X and Y, and 250 mm in Z). In order to cross-check this new implementation, we compared first, for a symmetric RF gun (without coupler), the ASTRA beam dynamics using 2D fields from Superfish [5] and 3D fields from CST MicroWave Studio (MWS) [6]. Then, we developed a MWS version of the RF gun including the coupler and the waveguide and exported the 3D fields into ASTRA. As a benchmark, we considered a typical FNPL photo-injector operation at 1 nC. This photo-injector is a duplicate of the one that was installed at DESY Hamburg for the phase I of TTF.

## SYMMETRIC RF GUN

A symmetric model of the RF gun has been first built using Superfish and is represented in Figure 1(a). Several iterations have been necessary in order to determine the diameters of the hall and full cells (resp.  $\Theta^{HC}$  and  $\Theta^{FC}$ ) which lead to a frequency of the  $\pi$ -mode ( $f^\pi$ ) close to 1.3 GHz with a field flatness ( $\alpha = E_z^{HC}/E_z^{FC}$ ) near unity. In the model showed in Figure 1(a),  $\Theta^{HC} = 178.387$  mm and  $\Theta^{FC} = 178.47$  mm were used leading to  $f^\pi = 1300.009$  MHz and  $\alpha = 0.99$ . The cavity internal quality factor was  $Q_0 = 23665$ .

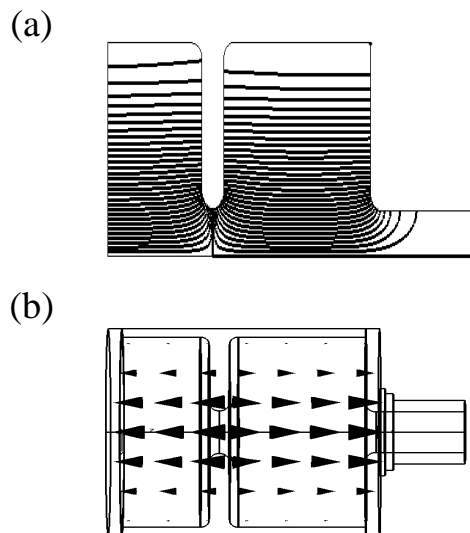


Figure 1: Symmetric model of the RF gun using (a) Superfish and (b) MicroWave Studio.

In order to compare the MWS fields with the ones produced by Superfish, a MWS model of the symmetric RF gun has been built (Figure 1(b)) using the same dimensions than those used with Superfish. The comparison is shown in Figure 2. As we will discuss in Figure 6, the fields and electrical characteristics of the cavity ( $f^\pi$ ,  $\alpha$ ,  $Q_0$ ) produced by MWS were found to be strongly dependant with the size of the quadratic mesh used for the runs. Here a fine mesh has been used in MWS ( $\Delta_x = \Delta_z \cong 4$  mm,  $\Delta_y \cong 2$  mm), leading to  $f^\pi = 1299.82$  MHz,  $\alpha = 0.99$  and  $Q_0 = 22082$ , close to the Superfish results.

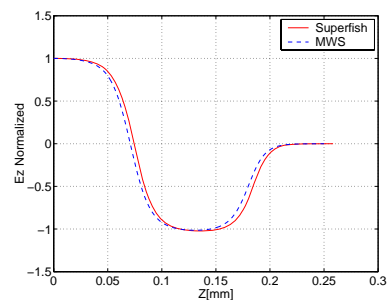


Figure 2: Comparison between Superfish and MWS of the longitudinal electric field on axis for the symmetric model of the RF gun

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## RF GUN WITH COUPLER

A layout of the MWS model of the RF gun with the coupler and waveguide is shown in Figure 3. A description of the coupler is presented in [7].

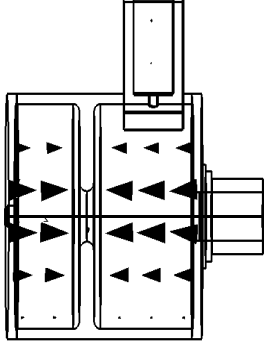


Figure 3: MWS model of the TTF RF gun with coupler.

### Computation of the external $Q$

We tuned the asymmetric RF gun by slightly decreasing the diameter of the cells with MWS in order to obtain a resonant frequency of 1.3 GHz, with a field flatness  $\alpha = 1$  and a coupling  $\beta = Q_0/Q_{ext} = 1$ . The internal quality factor  $Q_0$  was computed directly by MWS and we used the Kroll-Yu method [8] to compute the  $Q$  external ( $Q_{ext}$ ) of the cavity. In this method, a resonant curve of the phase shift along the waveguide vs. the frequency of the  $\pi$ -mode is mapped out, as shown in Figure 4. The slope of the curve multiplied by one half of the resonant frequency results in  $Q_{ext}$ . After several iterations, we obtained:  $f_\pi = 1300.054$  MHz,  $\alpha = 1.03$  and  $\beta = 1.7$  for a fine mesh ( $\Delta_x = \Delta_z \cong 4$  mm,  $\Delta_y \cong 2$  mm), the RF gun being slightly overcoupled.

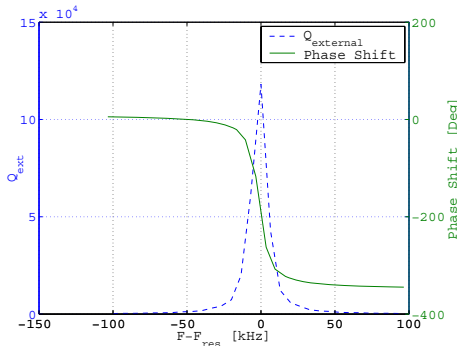


Figure 4: Phase shift vs. frequency ( $F_{res}=1.3$  GHz).

Figure 5 compares the longitudinal component of the electric field  $E_z$  taken along the Y axis (axis of the coupler), at  $z = 138.5$  mm and  $x = 0$  (middle of the coupler) for the case of a symmetric and asymmetric RF gun. Both

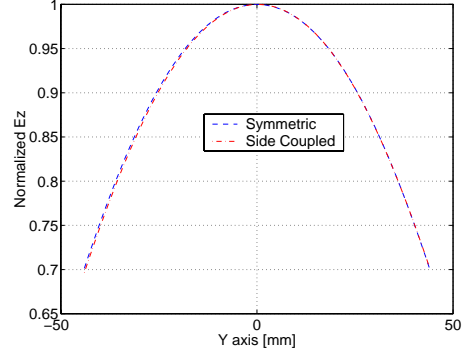


Figure 5: Longitudinal electric field on the coupler axis.

simulations were done with a fine mesh. From these simulations, we can see that the coupler does not induce a shift of the electric field  $E_z$ .

## IMPACT ON BEAM DYNAMICS

In the FNPL photo-injector setup, the RF gun is surrounded by 3 solenoids (a primary, a secondary and a bucking to zero the magnetic field on the cathode) and is followed by a 9-cell superconducting cavity. We stopped our simulations at  $z = 3.8$  m, i.e at the exit of the 9-cell. A description of the entire FNPL beam line is presented in [9]. In the ASTRA simulations presented here, we considered a typical operation of the FNPL photo-injector at 1 nC. We used a uniform transverse and longitudinal distribution of the laser beam of 5000 macro-particles with respectively a diameter of 3 mm diameter and a length of 11 ps. The three solenoids were set at 260 A, implying a peak magnetic field of  $\sim 1321$  Gauss and a residual magnetic field on the photo-cathode of  $\sim 62$  Gauss. In the case of a symmetric RF gun using the Superfish electric fields (ASTRA-2D), the peak field at the cathode was 40 MV/m resulting in a kinetic energy of the beam at the exit of the booster of  $E_k = 17.27$  MeV for a launch phase of  $40^\circ$ . The accelerating field on the 9-cell cavity was 12 MV/m with a phase of  $\sim 10^\circ$  off-crest to minimize the energy spread ( $\sim 26$  keV). In the case of ASTRA-3D simulations using the 3D electric fields from MWS, the peak field on the cathode was lowered ( $E_0 = 38.7$  MV/m for the symmetric RF gun and  $E_0 = 39.0$  MV/m for the RF gun with coupler) in order to match the energy given by ASTRA-2D.

### Case symmetric RF Gun

Figure 6 shows that in the case of a symmetric RF gun using the 2D electric fields from Superfish (Figure 1(a)), the transverse emittance of the beam at  $z = 3.8$  m is symmetric at  $\epsilon_x = \epsilon_y = 2.3$  mm-mrad. It is interesting to notice that when using the 3D fields from MWS, the emittance converges with the size of the mesh used for the MWS simulations to reach a very good agreement with the ASTRA-2D simulation. In fact, for the same geome-

try (Figure 1(b)), the emittance lowers from  $\epsilon_x = \epsilon_y \cong 18$  mm-mrad to  $\epsilon_x = \epsilon_y = 2.3$  for a mesh size in MWS of resp.  $\Delta_x = \Delta_z \cong 10$  mm,  $\Delta_y \cong 5$  mm and  $\Delta_x = \Delta_z \cong 4$  mm,  $\Delta_y \cong 2$  mm. A smaller mesh size in MWS leads to a better accuracy of the electric field but at a price of a much longer simulation run.

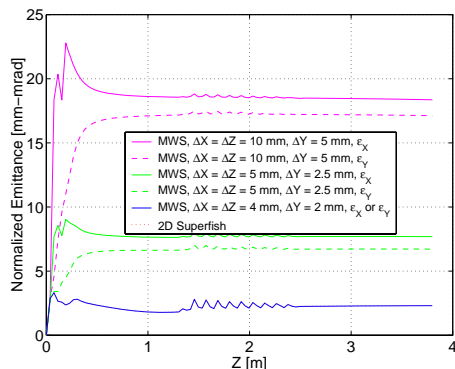


Figure 6: ASTRA simulation for a typical 1 nC operation of the FNPL photo-injector with a symmetric RF gun using 2D electric fields from Superfish and 3D electric fields from MWS (for different mesh sizes).

### Case RF Gun with coupler

In the case of an RF gun with coupler, we had no time to do a convergence study of the emittance with respect to the mesh size in the MWS runs. We used a mesh size of  $\Delta_x = \Delta_z \cong 4$  mm,  $\Delta_y \cong 2$  mm in the same order of the one that showed a good convergence in the case of the symmetric RF gun. In this case, Figure 7 reports an emittance  $\epsilon_x = 2.5$  mm-mrad and  $\epsilon_y = 2.45$  mm-mrad when using 3D fields from MWS. For comparison, we reported also in Figure 7 the ASTRA-2D simulation using the symmetric RF gun. These simulations show an increase of the emittance in the case of an RF gun with coupler compared to the symmetric RF gun of  $\Delta\epsilon_x = 0.2$  mm-mrad and  $\Delta\epsilon_y = 0.15$  mm-mrad. We suspect this increase of the emittance to be due either from the coupler kick or from the mesh used in the MWS runs. A study of the convergence of the emittance for finer mesh size in MWS runs in the case of an RF gun with coupler is necessary to solve this dilemma.

### CONCLUSION

ASTRA simulations showed an increase of the emittance of  $\sim 10\%$  for a typical operation of the FNPL photo-injector at 1 nC in the case of an RF gun with coupler compared to a symmetric RF gun. These simulations have been done using the new feature of the ASTRA simulation code that allows the use of 3D electric fields. These fields were obtained using MicroWave Studio and it has been shown

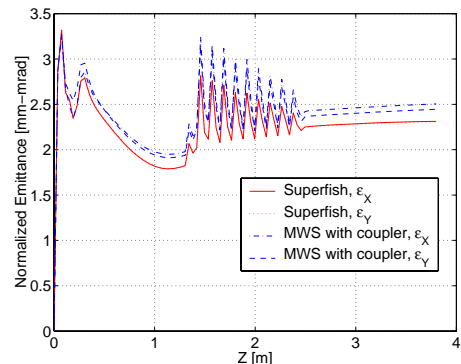


Figure 7: ASTRA simulation for a typical 1 nC operation of the FNPL photo-injector using 2D electric fields from Superfish (symmetric RF gun) and 3D electric fields from MWS (RF gun with coupler).

that the higher the accuracy (i.e the finer mesh) on the electric field the smaller the emittance.

More work needs to be done to determine if this increase of 10% comes from the coupler kick or from the accuracy of MWS on the electric field. If it comes from the coupler kick, then this increase will be 5 times smaller than the one presented in reference [2].

### ACKNOWLEDGMENT

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