Beam Dynamics of the DESY FEL Photoinjector Simulated with MAFIA and PARMELA

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Abstract– **We present a wake field simulation of the DESY FEL [1] gun by using the MAFIA self-consistent solver TS2. It has been found that the wake field induced emittance degradation is not very significant. Different options of emittance-conserving beam transport using triplets, doublets, or solenoids are discussed. The solenoid option appears to be the best, thanks to the space charge compensation.**

I. Introduction

For low emittance guns the wake field is a big issue. There are already many gun simulations which address the dynamics of the beam in a non-self-consistent way with no physical boundaries included. There is increasing concern about the effects of wake fields on beam emittances. In this context, we present a self-consistent wake field simulation with full gun geometry using the MAFIA Finite Difference Time Domain Particle-In-Cell (FDTD/PIC) solver TS2.

It is important to be able to conserve the emittance of a beam while it is transported over long distances. Several options are discussed using triplets, doublets, or solenoids.

II. MAFIA Wake Field Simulation

The gun geometry is shown in Fig. 1, where the accelerating gradient at the cathode is $E_h = 50\text{MV/m}$, the final beam energy $E = 5\text{MeV}$, the injection phase $\phi_{rf} = 32^o$, the laser FWHM=10ps, and the maximum on-axis $B_z = 2080\text{G}$. Since the initial bunch length was 0.43mm, a mesh with a total number of points equal to 990,000 was employed. A total of 5800 macro particles were generated and the simulation took 53 cpu hours on a SUN workstation. The error numbers for the run are:

$$\eta_t = 10\frac{(\delta t)^2 T}{\tau^3} = 10\times\frac{(9.6\times10^{-14})^2\times1.086\times10^{-9}}{(10^{-11})^3} \approx 0.1$$

$$\eta_r = 10\frac{(\delta r)^2 L_r}{\lambda_r^3} \approx 6$$

$$\eta_z = 10\frac{(\delta z)^2 L_z}{\lambda_z^3}\left\{\begin{array}{ll} 5\rightarrow 0.05 & z=0\rightarrow 2\text{cm} \\ 6 & z=2\rightarrow 25\text{cm}\end{array}\right.$$

If a simulation satisfies $\eta_t < 0.1$ and $\eta_s < 5$, the results will be reasonably accurate.

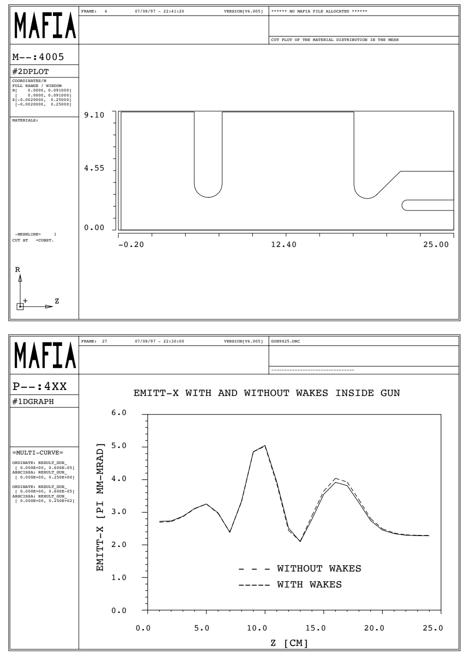

Fig. 1: Upper: DESY FEL Gun with Coaxial RF Input; Lower: Emittance with and without Wakes

Since TS2 is a 2D solver employing $r\phi$ geometry, we use the following relation to evaluate the transverse emittances:

$$(2\epsilon_x)^2 = \epsilon_r{}^2 + \epsilon_\phi{}^2,$$

with

$$\epsilon_r = \sqrt{< r^2 >< p_r^2 > - < rp_r >^2},$$

$$\epsilon_\phi = \sqrt{< r^2 >< p_\phi^2 >}.$$

For the two runs, with and without wake fields, the numerical settings, such as mesh sizes, particle numbers, integration time steps and ultimately, the error numbers were approximately the same. The emittances inside the gun are presented in Fig. 1. It is seen that there is only a very slight difference between the two. What is more interesting is that the one with wake fields is smaller than that without. There are two possible explanations for this. One is numerical, the other physical. The open absorbing boundary condition for the non-wake case is not perfect for all frequency components, causing some reflections from the boundary, which act back on the bunch. If this is ruled out, the following physical explanation will be more convincing. Non-linear contributions of the wake fields behave in a similar "favorable" way to the space charge forces in the emittance compensation process [2].

Due to the results of this simulation, we can now be more confident of the results obtained by non-wake simulations, like those with PARMELA. We can eventually rely on faster space charge based algorithms. However, at high energies, wake field emittance dilutions can be significant, for example, through port step junctions or bunch compressors.

III. Emittance Conserving Beam Transport

In the DESY FEL injector there exists a long beam transport section of 7 meters from the minimum emittance to the first main accelerator (Fig. 2). In order to avoid

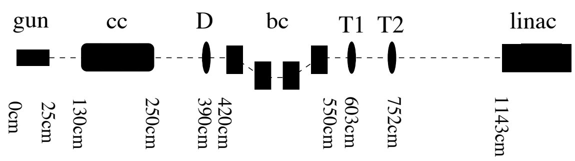

Fig. 2: Beam Line Layout for DESY FEL Injector

emittance increase over this section, one has to apply appropriate focusing elements along the line. Three versions have been investigated with PARMELA: two triplets (T1 and T2), one doublet (at T1), or one solenoid (at T1). Table I lists the emittances measured at 12 m for all the cases. The beam coming from the gun is round and emittance symmetrical. It reaches the minimum emittance of $0.9\,\pi$ mm-mrad at about 5.2 m from the cathode. Without any focusing elements, the emittance would drift gradually up to $2.5\,\pi$ mm-mrad.

TABLE I

Emittance Measured At Linac Entrance

Setup (10K particles)	$\epsilon_x^n/\epsilon_y^n$ (π mm-mrad)
Two triplets (T1 & T2)	2.3/1.9
One doublet at T1	1.4/1.8
Solenoid shielded Neumann	1.3/1.4 No fringe B_z
Solenoid shielded 2cm hole	1.4/1.5 Small fringe B_z
Solenoid shielded 3cm hole	1.4/1.5 Small fringe B_z

Note: BC is switched off.

The version with two thick triplets, each of size DOFOD=8cm-6cm-14cm-6cm-8cm, seems to be the worst. The lowest emittances ($\epsilon_x^n/\epsilon_y^n$) achieved are 2.3/1.9 π mm-mrad. The emittances are not symmetrical and moreover, they are usually hard to control.

A better choice would be a thin doublet. By using a FOD doublet of size 5cm-3cm-5cm with a gradient of 500 G/cm, we are able to reduce the emittances to $1.4/1.8\,\pi$ mm-mrad, although symmetry is still a problem.

With the effectiveness of the solenoid driven space charge compensation in a gun in mind, one automatically turns to solenoids in place of quadrupoles. In addition, solenoid focusing is symmetrical by nature. These two advantages make the solenoid version the best choice. The space charge compensation process along a beam line is exactly the same as that after a gun with respect to the phase space precession (Fig. 3).

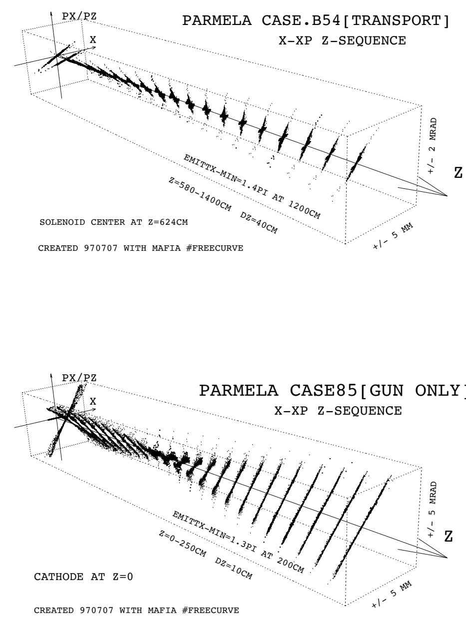

Fig. 3: Upper: 3D $x-x'$ Space Charge Compensation Process along Beam Line; Lower: Emittance Compensation Process after Gun

IV. Conclusion

We have presented a wake field simulation of the DESY FEL low emittance gun by using the MAFIA FDTD-based self-consistent solver TS2. It was found that the wake field induced emittance growth is quite small. Thus space charge codes are usually accurate enough for such gun simulations.

It has been seen that solenoids are best suited for conserving the beam emittances of a symmetric beam along transport lines, when beam emittance is a primary concern. This is, in fact, an extension of the space charge compensation technique to beam lines.

References

[1] "A VUV free electron laser at the TESLA test facility at DESY, Conceptual design report", *DESY Print*, **TESLA-FEL 95-03**, June 1995

[2] Carlsten, B.E., "New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator", *Nucl. Instr. and Meth.*, A285 (1985)