COMPARISON OF PARMELA AND MAFIA SIMULATIONS OF BEAM DYNAMICS IN HIGH CURRENT PHOTOINJECTOR

Sergey S. Kurennoy, LANL, Los Alamos, NM 87545, USA

Abstract

A high-current RF photoinjector producing low-emittance electron beam is an important technology for high power CW FEL. LANL-AES team designed a 2.5-cell π-mode 700-MHz normal-conducting RF photo-injector [1] with magnetic emittance compensation. Using the electric field gradients of 7, 7, and 5 MV/m in the three subsequent cells, the photoinjector will produce a 2.5-MeV electron beam with 3-nC charge per bunch and 7-mm-mrad transverse rms emittance. Beam dynamics in the photoinjector has been modeled in detail. In addition to the usual approach, with fields calculated by Superfish-Poisson and beam simulations performed by Parmela, we also used MAFIA group of codes, both to calculate cavity fields and to model beam dynamics with its particle-in-cell module TS. The second way naturally includes wake-field effects into consideration. Results of simulations and comparison between two approaches are presented.

INTRODUCTION

The normal-conducting RF cavity of the high-current CW photoinjector (PI) for high-power free-electron lasers consists of 2.5 cells plus a vacuum plenum [1]. The cells have an on-axis electric coupling through large beam apertures. The PI has an emittance-compensating solenoid with a bucking coil. After the first half-length cell, where a photocathode will be housed, there are two full-length cells, followed by a vacuum plenum with vacuum-pump ports. Two ridge-loaded tapered waveguides for RF input are connected to the third cell. The vacuum-plenum cell has its resonance at about 650 MHz, well below the frequency 700 MHz of the working π-mode in the cavity.

The photoinjector RF cavity is practically axisymmetric except for the RF couplers and vacuum pump ports. These discontinuities create only small perturbations of the cavity RF fields, even though the coupler irises are the locations of the highest power density of the wall ohmic losses, see [1, 2]. Therefore, field calculations and beam dynamics study in the cavity can be performed with good accuracy using 2-D codes. The 2-D design of the cavity and magnets was performed using the Poisson / Superfish (SF) codes [3] for field computations and Parmela [4] for beam dynamics simulations.

CAVITY FIELDS

The layout used for field computations in MAFIA [5] and the electric field of the working RF mode are shown in Fig. 1. Unlike the case of SF/Parmela, where the fields calculated by SF are interpolated for Parmela, here we want to use exactly the same mesh for both field computations and PIC simulations.

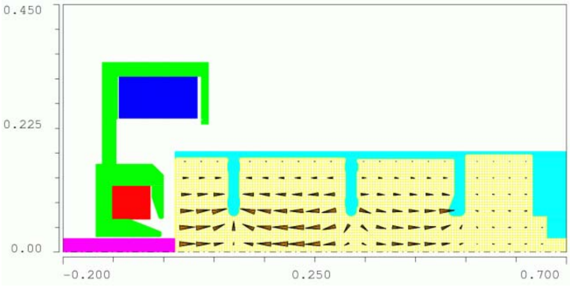

Figure 1: 2.5-cell PI RF cavity layout used in MAFIA. Dimensions are in m. The main solenoid (dark blue) and bucking coil (red) are surrounded by steel (green).

The emittance-compensating magnetic field in MAFIA is calculated by the static solver S. Near the photocathode this field vanishes due to properly adjusted currents in the main solenoid and the bucking coil. The comparison of the fields computed by Poisson/SF and MAFIA is presented in Fig. 2. The left graph shows the profile of the longitudinal electric field on the cavity axis. The electric field alternates its direction from one cell to the next, as it should be in a π-mode. The fields in the third cell are designed to be lower than in the first two cells to reduce the power density on the coupler irises in that cell. The fields in the vacuum plenum are low. The right picture shows the longitudinal component of the emittance-compensating magnetic field on the cavity axis. In addition to vanishing near the photocathode, the field decreases again far from it, where the beam is already relativistic and more rigid, so that the solenoidal focusing is no more needed. Both the electric and magnetic fields found by two different codes agree perfectly.

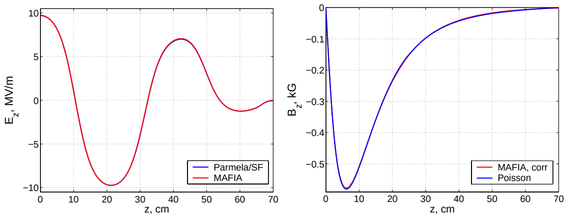

Figure 2: Longitudinal electric field (left) and longitudinal static magnetic field (right) on the cavity axis.

WAKE FIELDS

Wake field effects can be, in principle, included into Parmela beam dynamics simulations [4]. However, Parmela does not compute the wakes: they must be calculated externally, by another code. Here is the main difficulty of this particular problem: one has to calculate wake fields in the photoinjector cavity, where the beam is accelerated from a non-relativistic, almost zero speed to the speed of light, becoming relativistic only by the second cell. A standard numerical approach with ABCI or MAFIA T-module, where a rigid bunch travels through the structure at the speed of light and the wakes behind it are calculated, does not work in this case. In fact, there is no other way to calculate wake fields in such a problem except using a self-consistent numerical solution of the Maxwell equations with account of particle motion, e.g., a particle-in-cell (PIC) simulation. This is exactly what TS-codes (TS2 for 2-D and TS3 for 3-D problems) in the MAFIA suite do. Unlike that approach, Parmela applies particle-push method using the RF and static fields extracted from SF and Poisson, respectively, in the region where the beam travels. It takes into account the beam space-charge, as well as the image currents in the photocathode plane, but does not calculate fields created due to the beam charge interaction with the cavity walls, i.e. the wake fields.

BEAM DYNAMICS SIMULATIONS

TS2 PIC Simulations

An example of beam dynamics modeling with the MAFIA TS2 PIC code is illustrated in Fig. 3. Snapshots of the electric field (arrows) and particles (red dots) show the bunch evolution during its acceleration in the cavity. The injected 3-nC bunch has a uniform charge density with a longitudinal flat-top pulse shape of the total length of 6° RF, and its center is injected at the RF phase equal to 15°. In TS2 the number of injected particles in the bunch is defined by the code, unlike the case of Parmela, and depends on the number of mesh points. The particles can have different charges. For a typical TS2 run with 1.45 M mesh points in the whole 2-D region of Fig. 1, including magnets and outside the cavity, the number of particles in the bunch of 1-cm radius is 6360 (only 10% of particles are plotted in Fig. 3). The mesh has the step sizes inside the cavity $\Delta z \approx \Delta r \approx 0.5$ mm (it should be homogeneous in z inside the cavity for TS). The TS2 run with this 1.45-M mesh takes 1.4 hours on a 3.2-GHz PC, with a significant fraction of this time spent preparing the output file. For a finer mesh of 4.41 M points, with $\Delta z \approx \Delta r \approx 0.3$ mm in the cavity, the same bunch consisted of 8040 particles, and the TS2 run took 3.6 hours.

For each frame in Fig. 3 (numbered in its lower left corner), Table 1 gives the physical time and the value for a maximal arrow of the electric field in that frame. The fields in the frames are scaled independently; enforcing one global scale would not be useful here since the field values differ by almost two orders of magnitude. A few frames in Fig. 3 show the RF field near its minima (RF phases are close to 0° or 180°), to emphasize the bunch self-fields (space charge) and wake fields. In particular, in the frames 3, 5, and 6, there are noticeable field arrows near the bunch, which deviate from the RF field pattern and correspond to the bunch self-fields. In the frame 8 one can clearly see the fields left after the bunch (wakes) near the cavity exit.

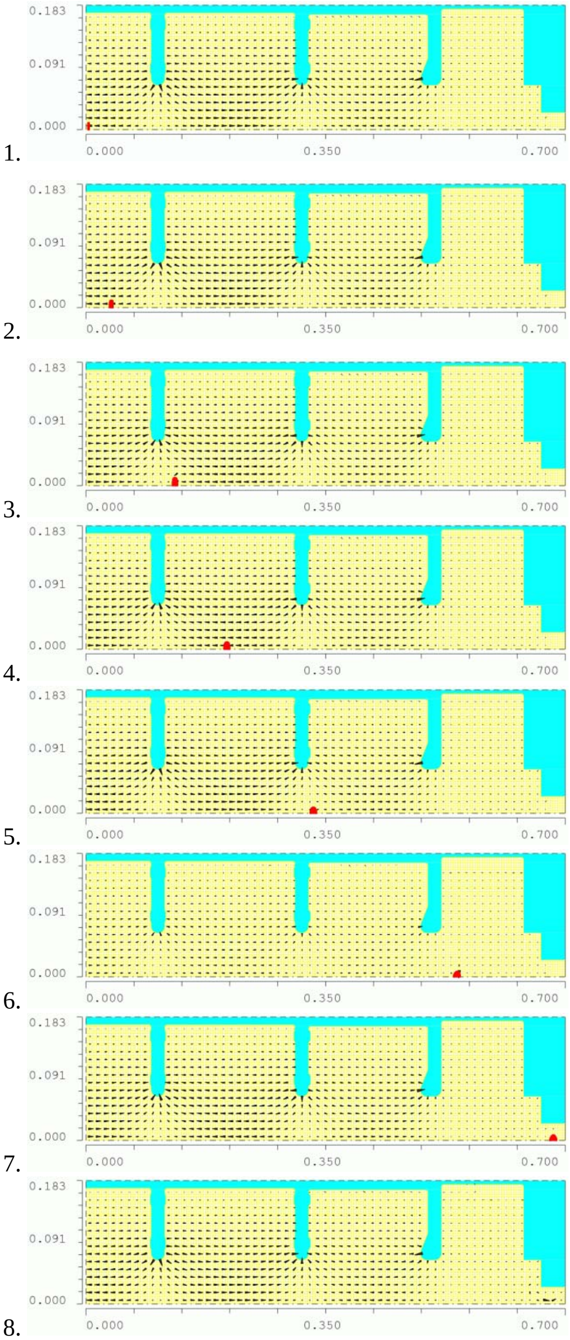

Figure 3: Electric field and bunch evolution in the cavity.

Table 1: Time (ns) and max arrows (MV/m) in Fig. 3

Frame	1	2	3	4	5	6	7	8
Time	.12	.32	.67	.95	1.4	2.1	2.6	2.8
E_{max}	10	15	.53	14	.53	.53	13	.52

Figure 4 shows two snapshots of the electron bunch shortly after injection. The bunch is very short and shaped like a pancake. Its size rapidly increases due to space-charge forces until it moves away from the photocathode where the magnetic field is getting stronger to prevent the bunch radial expansion. The bunch shape near the cavity exit and the wakes are shown in Fig. 5 in detail, cf. Fig. 3 (note different scales in Figs. 4-5; dimensions are in m).

Figure 4: Electron bunch near the photocathode (*a*. *t*=0.08 ns, E_{max}=5.3 MV/m; *b*. *t*=0.24 ns, E_{max}=9.4 MV/m).

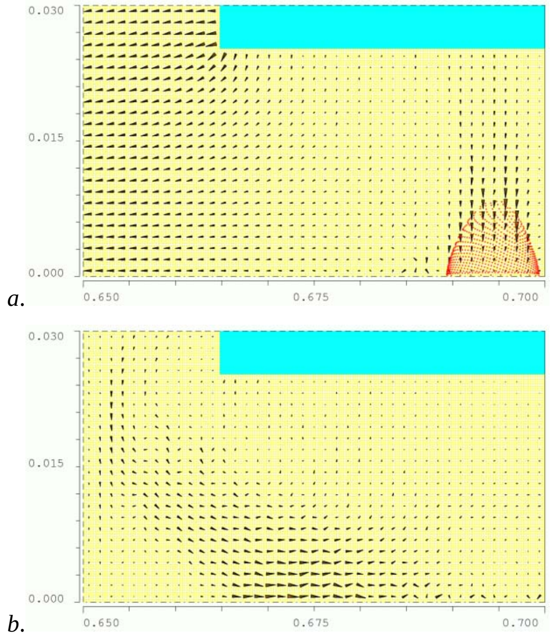

Figure 5: Bunch and fields near the cavity exit (*a*. *t*=2.62 ns, E_{max}=1.1 MV/m; *b*. *t*=2.82 ns, E_{max}=0.63 MV/m).

From Figs. 3-5 we see that the 3-nC bunch is focused well by the external magnetic field and remains compact. Its maximal transverse size at the cavity exit is below 7 mm, smaller than the initial size of 1 cm. The bunch length increases, of course, but remains below 1 cm.

Analyzing Figs. 3-5 and similar field snapshots, one can conclude that the beam space-charge electric fields are below 1 MV/m, while the wake fields do not exceed 0.7 MV/m. These values are small compared to the maximal RF field values of 10-15 MV/m.

We performed TS2 runs with a few (up to four) identical 3-nC bunches separated in time by two RF periods, which corresponds to 350-MHz bunch repetition rate. Simulations show identical bunch parameters during the passage and at the cavity exit. This confirms that even at a very high bunch repetition rate no noticeable wake influence is observed.

Comparison of TS2 and Parmela results

We now will compare results of TS2 and Parmela beam dynamics simulations of the photoinjector RF cavity. Figures 6 show the beam transverse rms size, the beam transverse rms emittance in the lab frame, and kinetic energy as the function of the beam position in the cavity for 3-nC charge per bunch.

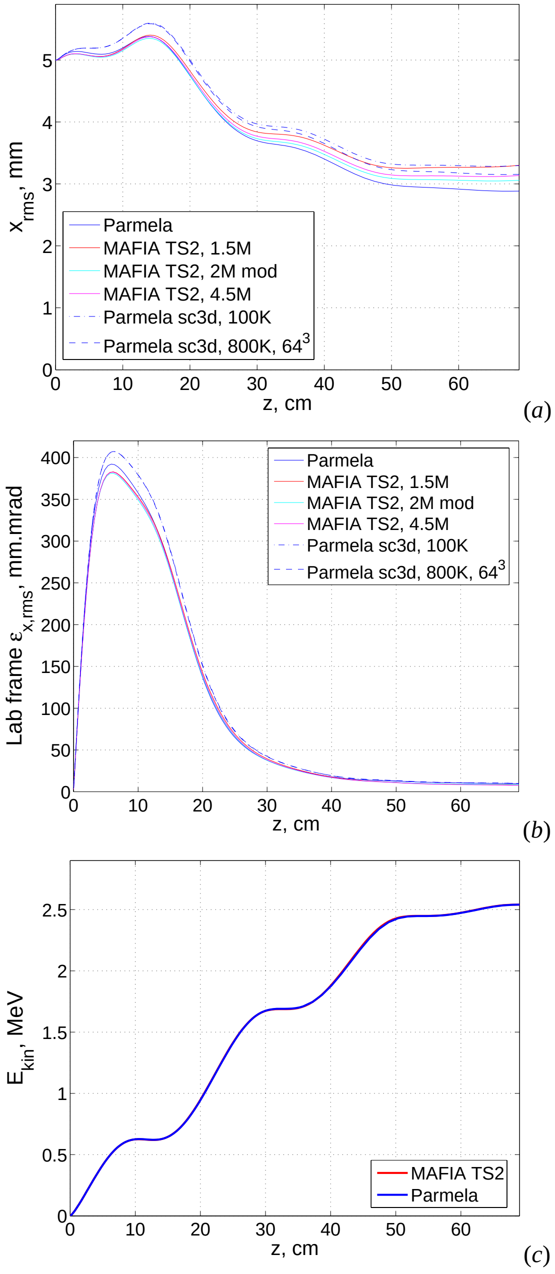

Figure 6: Beam transverse rms size (*a*), emittance (*b*), and kinetic energy (*c*) versus beam position for a 3-nC bunch.

According to Figs. 6, TS2 and Parmela results agree well. The kinetic energy curves from both codes just overlap. The rms beam size predictions agree in general, but there are some differences accumulated by the cavity end. The transverse emittance was calculated in the lab frame, so the apparent emittance blow-up in the first cell is simply due to the bunch rotation in the solenoidal field. In Fig. 6*b* we see differences between two codes near the point where the rotational part of the emittance reaches its maximum. Investigating the reasons, we performed a few code runs with modified parameters. In MAFIA, finer meshes were used. In Parmela, we used optional 3-D space-charge computations with *spch3d* instead of the standard axisymmetric 2-D space-charge routine *scheff* [4]. These results are also plotted in Figs. 6. One can say that the results obtained using 3-D and 2-D routines in Parmela differ more than those of Parmela and TS2.

It is interesting to see how the results depend on the bunch charge. For that purpose, a few runs with bunch charges of 10 nC and 1 nC have been performed, without changing other parameters. Obviously, when the bunch charge is varied without changing the magnetic field that was tuned for 3 nC, the bunch focusing is no longer optimal. As one can expect, the beam is under focused for 10-nC bunch (Fig. 7), and over focused for 1-nC one. For 1-nC, the bunch becomes so tiny near the cavity exit (below 2 mm transversely) that its self-field is getting high, about 2.3 MV/m. The wake fields remain rather weak. For the 10-nC case, the bunch is much larger both transversely (more than 1.5 cm) and longitudinally (about 2.5 cm) than for 3 nC. The self-field of 10-nC bunches is not large because the charge density is reduced due to the bunch blow-up. There was also no noticeable wake-field increase. More details can be found in [6].

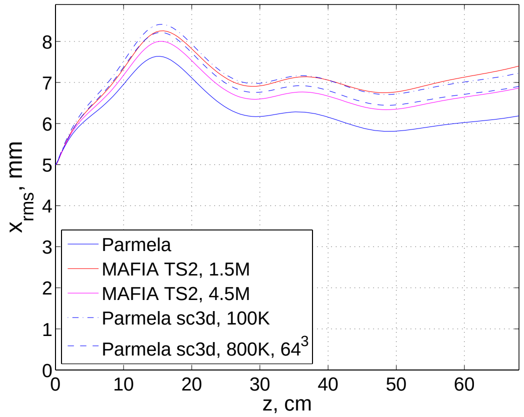

Figure 7: Transverse beam size versus beam position in the cavity for a 10-nC bunch.

For all bunch charges, the kinetic energy plots are very similar to that in Fig. 6*c*. As for other parameters, for 1-nC bunches the agreement between the codes is excellent, but for 10 nC the differences are more noticeable than in the 3-nC case. The reason is most likely in the strong effects of the space charge at the initial stage of simulations, where both Parmela and TS2 have difficulty computing space-charge fields of the thin pancake-like bunches accurately.

The transverse emittance values at the exit of the PI RF cavity are between 7 and 10 mm·mrad. The bunch slices in the phase space are not completely aligned yet after the PI cavity. The design goal was to provide the lowest beam emittance at the wiggler. If we allow a 3-nC bunch to drift after the PI cavity, its transverse emittance will reach about 6 mm·mrad that corresponds to the best possible alignment of the bunch slices. The design requirement for the photoinjector was to have the beam transverse rms emittance below 10 mm·mrad for 3-nC charge per bunch.

SUMMARY

The beam dynamics simulations of the high-current photoinjector for high-power FEL using the MAFIA PIC code TS2 are described. Results obtained from TS2 and Parmela simulations agree well. Since the wake fields are not taken into account in Parmela computations, this agreement confirms that the wake-field effects in the photoinjector RF cavity are negligible. The wakes are weak not only for the design bunch charge of 3 nC, but even for the higher bunch charge of 10 nC. The main reason for that is the large size of the beam apertures in the photoinjector RF cavity. The only noticeable wake fields are observed near the RF cavity exit, where the aperture radius is reduced to its smallest value of 2.5 cm. However, the wakes die out before the next bunch arrival, even at the very high bunch repetition rate, 350 MHz, as was confirmed by TS2 simulations with a few bunches. For the design beam current of 100 mA, the bunch repetition rate is 35 MHz.

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REFERENCES

[1] S.S. Kurennoy, D.L. Schrage, R.L. Wood, et al. “Normal-conducting RF cavity of high current photoinjector for high power CW FEL”, these proc.

[2] S.S. Kurennoy, D.L. Schrage, R.L. Wood, et al. “Development of photoinjector RF cavity for high-power CW FEL”, NIM A528 (2004) 392.

[3] J.H. Billen and L.M. Young. “SUPERFISH/Poisson Group of Codes”, report LA-UR-96-1834, Los Alamos, 1996 (rev. 2003).

[4] L.M. Young (documentation by J.H. Billen). “PARMELA”, report LA-UR-96-1835, Los Alamos, 1996 (rev. 2004).

[5] MAFIA, v.4.107, CST GmbH (Darmstadt, Germany), 2002; www.cst.de

[6] S.S. Kurennoy. “Simulation of beam dynamics in high-power CW photoinjector cavity with MAFIA PIC code TS2”, tech note LANSCE-1: 04-012 (TN), Los Alamos, 2004.