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SIMULATION OF COUPLED SPACE CHARGE AND WAKEFIELD EFFECTS FOR A PROTOTYPE TW-GUN AT SwissFEL*

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Abstract

We have developed a novel computational method for beam dynamics simulations which takes into account space charge and wakefield effects self-consistently. This approach enables us to simulate the evolution of wakefields throughout the emission and acceleration in the injector section. We present extensive studies of the coupled wakefield and space charge effects in a traveling wave electron gun which is under development at the SwissFEL. This allows to quantify the impact of geometric wakefields on the beam dynamics at very low energies for the new multi-cell design of the gun.

INTRODUCTION

To optimize the performance of FEL light sources, detailed knowledge of the beam dynamics in the injector section is required. Simulations of the electron gun typically focus on internal space charge forces and externally applied fields, while neglecting transient electromagnetic wakefields arising from the interaction with the walls. Recently, we developed a computational method to account for both space charge and wakefield effects self-consistently [1]. In this work, we present extensive simulation studies using this approach for the planned upgrade of the traveling wave (TW) gun of the SwissFEL [2]. The gun prototype consist of a 12-cell cavity, where electron bunches are accelerated up to ≈ 13 MeV. However, the multicell design has raised concerns about the impact of wakefields on the low energy beam within the gun cavity. The simulation studies presented in the paper allow to quantify this impact over the full injector line.

SIMULATION METHOD

A detailed description of our simulation method is given in Ref. [1]. In the following, we present a sketch of the procedure for the reader's convenience. The core idea is to couple a space charge solver in the rest frame of the bunch with a wakefield solver by means of a scattered field formulation. The total field $\mathbf{E}_\mathrm{t}$ is decomposed into the incident or self-field $\mathbf{E}_\mathrm{i}$ and the scattered or wakefield $\mathbf{E}_\mathrm{s}$,

$$\mathbf{E}_\mathrm{t} = \mathbf{E}_\mathrm{i} + \mathbf{E}_\mathrm{s}. \quad (1)$$

We apply a Green's function Fast Fourier Transform (FFT) solver for the space charge contribution in the near field and a Finite Integration Technique (FIT) solver for the wakefield computation [3, 4]. Hereby, the free-space solution for the space charge field at the cavity walls is used as an equivalent excitation for the wakefield problem [1]. The evaluation of the space charge field at the PEC boundaries is done with the Fast Multipole Method (FMM) [5, 6]. An illustration of the coupling scheme is given in Fig. 1. We stress that the approach is fully 3D and can be applied to arbitrary bunch shapes, velocities and chamber geometries.

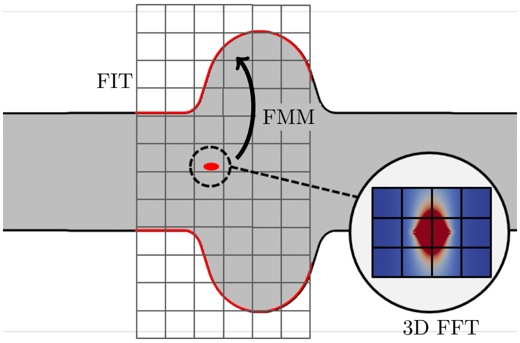

Figure 1: Illustration of the coupling scheme. The space charge solver (FFT) uses a local mesh around the bunch. The wakefield solver (FIT) uses a global mesh with a moving window approach. The far-field of the bunch is evaluated at PEC boundaries with the Fast Multipole Method (FMM).

TW ELECTRON GUN

The TW electron gun proposed in Refs. [2, 7] features a 12-cell design with a cathode field of up to 200 MV/m and a gun exit energy of 12.6 MeV. An outline of the gun geometry is in Fig. 2. Throughout this work, we study a uniform bunch of 0.2 nC charge and 1.25 ps pulse length. After emission, the bunch quickly expands into a pancake-like shape with a maximum transverse size of ≈ 1 mm, before being compressed by a 0.43 T solenoid. This size poses a significant portion of the 5 mm iris radius compared to conventional, 1.5 cell RF guns. As the RF wave propagates alongside with the bunch, acceleration is continuous over the ≈ 22 cm gun length, leading to the comparably high exit energy. Subsequently, the beam drifts through a pipe of 6 mm radius, succeeded by two S-band accelerating cavities and accompanying solenoids, until the beam leaves the injector section with around 130 MeV. In the gun, the narrow cell design and the long, elaborated geometry raise the question on the impact of geometric wakefields.

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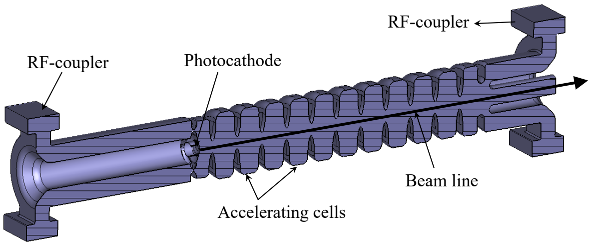

Figure 2: Cross-section of the vacuum domain in the TW gun [2]. The gun consists of 12 cells with an acceleration length of ≈ 22 cm.

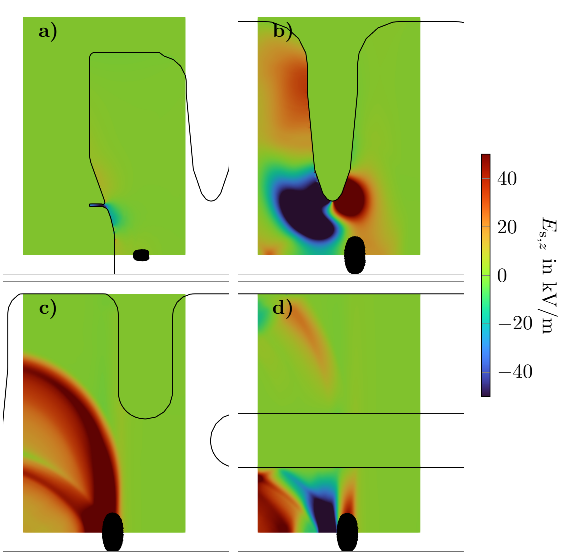

Figure 3: Longitudinal component of the scattered electric field in the gun at four different time instants: a) right after emission b) during acceleration c) close to the gun exit and d) in the beam pipe. The black spot depicts the position and shape of the particle bunch.

RESULTS

Beam Dynamics in the Gun

To quantify the wakefield effect, we compare simulations that include space charge fields only, with those that include both space charge and wakefields using our coupled scheme. The evolution of the wakefields and the dynamics of the bunch as it traverses the gun is shown in Fig. 3.

Figure 4 shows the evolution of the RMS energy spread of the bunch. It can be seen that the relative reduction in energy spread due to the wakefields is about 10 % at the gun exit. To better understand the effect, we look at the slice energy distribution at $z = 22$ cm in Fig. 5. The overall impact of the wakefields on the particle's energy is marginal. However, the tail of the bunch is affected stronger than its head. This effect is such that it counteracts the energy chirp induced by the RF field, thus leading to an effective RMS energy spread reduction. In contrast, relative deviations of less than 5 % are found for the uncorrelated energy spread and core transverse emittance.

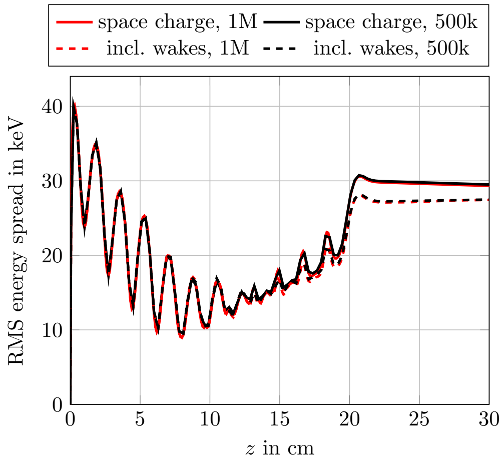

Figure 4: RMS energy spread in the gun. The results for both the space charge only and including wakefield effects are shown. For verification purposes, two different macroparticle numbers of 5×10^5 and 10^6 were used in the simulations.

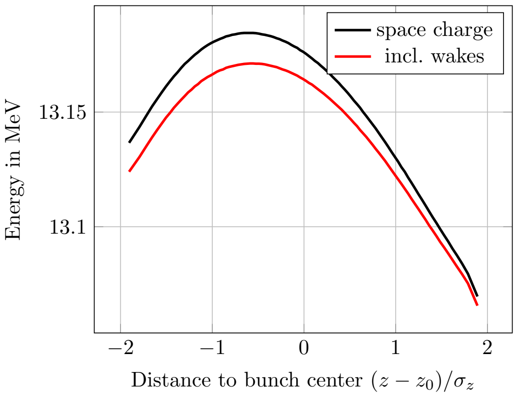

Figure 5: Slice energy distribution at $z = 22$ cm. The results of two calculations, including space charge fields only and with combined space charge and wakefields, respectively, are shown.

To estimate the influence of wakefields under non-ideal operation conditions, we simulate a bunch with an initial transverse offset of 0.5 mm at the photocathode. Figure 6 shows the evolution of the slice energy spread in the bunch core along the beam line. For reference, the results for the on-axis case are shown as well. It can be seen that transverse wakefields can be significant. The laser misalignment of 0.5 mm assumed in the simulation is, however, quite large and unlikely to occur under normal operation conditions.

Full Injector Line Simulation

So far, we have considered the beam dynamics in the gun only. The impact of wakefields in the downstream injector is expected to be less relevant due to larger geometry dimensions and higher beam energy, as long as wakefields from the gun do not propagate into the beam pipe and attached cavities. The steady-state electromagnetic field in a uniform pipe of circular cross-section can be estimated analytically.

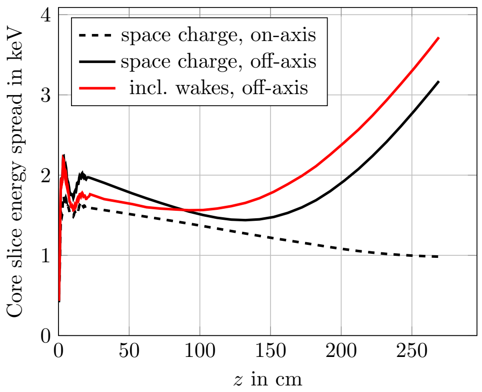

Figure 6: Core slice energy spread along the beam line of the SwissFEL injector. A laser spot misalignment of 0.5 mm at the photocathode is assumed. The results including space charge only (with and without offset) as well as with combined space charge and wakefield effects are shown.

We assume a disk-shaped bunch of radius a, total charge Q, longitudinal particle density distribution $\lambda(z)$ and Lorentz factor γ inside a cylindrical beam pipe with radius R. Then, the longitudinal electric field on the axis reads (see Ref. [8])

$$E_z(z) = -\frac{Q}{2\pi\varepsilon_0\gamma^2}\left(\ln\frac{R}{a}+\frac{1}{2}\right)\frac{\mathrm{d}\lambda}{\mathrm{d}z}. \qquad (2)$$

In the beam pipe behind the gun, $\gamma = 25.8$ and $a = 0.8$ mm on average. Figure 7 depicts E_z at three different positions inside the beam pipe. Hereby, we compare the results of our self-consistent simulation with the analytical estimation Eq. 2. With increasing distance up to ≈ 2.5 m from the cathode, the simulated field in the bunch closely approaches the analytical result. This indicates that the wakefields generated in the gun do not significantly couple into the beam pipe.

As a result, the full injector line simulation can be performed efficiently by considering the gun section separately. In the gun section, we employ the self-consistent tracking approach described previously. For the remaining part of the injector, we use space charge fields only. As illustrated in Fig. 8, we find a reduction in the energy spread of 5.5 keV at the end of the injector compared to the case when the geometry of the chamber if fully ignored. This effect is only partially due to the geometrical wakefields in the gun as part of the contribution stems from the impedance of the beam pipe. However, neglecting the transient wakes in the gun and using instead the steady-state pipe impedance for the full injector line would lead to incorrect results. For comparison, using the analytical field Eq. 2 would predict a reduction in energy spread of 7.1 keV.

CONCLUSION

The wakefields were shown to influence the RMS energy spread of the bunch in the electron gun. Essentially, this effect consists in a compensation of the energy chirp induced by the RF field. Thus, there is no beam quality deterioration due to the wakefields in the gun. Contrary, RMS energy spread is lower than predicted by conventional beam dynamics simulations. The total reduction of the RMS energy spread at the gun exit for nominal bunch parameters amounts to about 10 %. Even though the net effect on bunch dynamics appears small, we have shown that in unfavorable conditions, such as an off-axis bunch, the wakefields can have a significant impact.

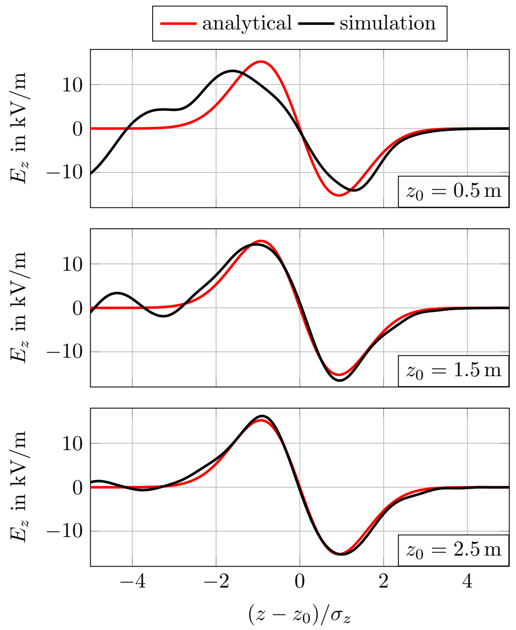

Figure 7: Longitudinal electric field of the bunch at three different positions inside the beam pipe. The red curve corresponds to the space charge impedance field in a uniform cylindrical pipe.

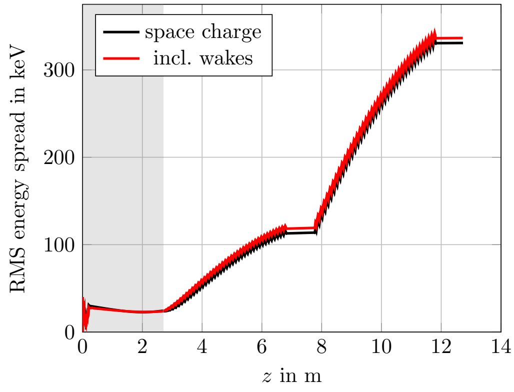

Figure 8: RMS energy spread of the bunch along the full injector line. The coupled simulation is carried out until the beginning of the first S-band accelerating cavity at 2.7 m (gray), the remaining part of the injector is simulated with space charge fields only.

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