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SPACE CHARGE FIELD BEAM DYNAMICS SIMULATIONS FOR THE THz SASE FEL AT PITZ*

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Abstract

A proof-of-principle experiment on a THz SASE FEL is under consideration at the Photo Injector Test facility at DESY in Zeuthen (PITZ). One of its options assumes utilization of 4.0 nC bunches at 16.7 MeV [1]. In this operation mode, space charge interaction strongly influences the dynamics of the electron beam inside the undulator. In this contribution, we investigate the beam dynamics in the THz undulator of PITZ using a particle-particle interaction model based on a Liénard-Wiechert approach. We analyze the influence of retardation and radiation fields on the beam dynamics resulting in the microbunching effect. Furthermore, we compute the radiation field and estimate the radiation power at the exit of the undulator. The validity of the underlying numerical models is discussed.

INTRODUCTION

The photoinjector test facility at DESY in Zeuthen (PITZ) is currently developing a high power, tunable THz radiation source for pump and probe experiments at the European XFEL [1]. The source design uses SASE-FEL to generate THz pulses with 100 µm center wavelength and up to ~ 40 MW peak power [1]. Reaching the design specifications requires a 16.7 MeV electron beam with up to 4.0 nC bunch charge. Due to the moderate energy, space charge induced beam divergence along the 3.4 m long FEL undulator is extremely critical. In the following, we use a 3D, fully relativistic Liénard-Wiechert simulation code [2] to analyze the beam dynamics inside the undulator. Furthermore, we evaluate the particle fields at the exit of the undulator and investigate the generation of THz radiation.

MODELING APPROACH

The undulator field is modeled as,

$$\vec{B}(\vec{r}) = -B_0 \cdot \vec{\nabla}\phi(y,z), \qquad (1)$$

$$\phi(y,z) = \sinh(k_u y)\sin(k_u z)/k_u \qquad (2)$$

using a periodic 2D potential of an idealized planar undulator [3]. In addition to the oscillatory motion of the particles in the x-direction, this model allows to reproduce the undulator focusing effect in the y-direction. The parameter values for the field amplitude $B_0 = 1.28$ T and the undulator wavelength $\lambda_u = 2\pi/k_u = 3.0$ cm reflect the experimental setup described in [1]. Figure 1 shows the magnetic field map for a 3.6 m long undulator with 120 periods as used in the simulations. We use a linearly increasing or decreasing amplitude, $B_0 = B_0(z)$, towards the entrance or exit of the undulator, respectively, to guarantee a smooth transition of the particle beam at both undulator ends.

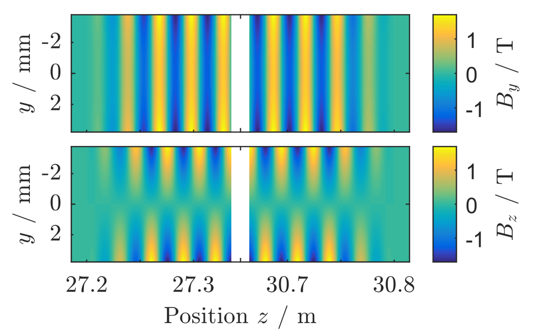

Figure 1: Magnetic field map used in the simulations. Only a small section including the entrance and exit of the 3.6 m long undulator model is shown.

A complete electromagnetic field model for relativistic particles undergoing oscillatory motion has to take retardation and radiation effects into account. Our simulation code [2] models the space charge interaction based on the Liénard-Wiechert (LW) fields of a charged particle moving along a trajectory $r_s = r_s(t)$:

$$\vec{E}(\vec{r},t) = \frac{q_s \left\{ \underbrace{\frac{\left(\vec{n}_s - \vec{\beta}_s\right)}{\gamma_s^2\ |\vec{r} - \vec{r}_s|^2}}_{\text{static}} + \underbrace{\frac{\vec{n}_s \times \left[\left(\vec{n}_s - \vec{\beta}_s\right) \times \dot{\vec{\beta}}_s\right]}{c_0\ |\vec{r} - \vec{r}_s|}}_{\text{radiation}} \right\}}{\left(1 - \vec{n}_s \vec{\beta}_s\right)^3}, \qquad (3)$$

$$\vec{B}(\vec{r},t) = \frac{\vec{n}_s \times \vec{E}(\vec{r},t)}{c_0}, \qquad (4)$$

where q_s is the charge of the particle, c_0 the speed of light, γ_s the Lorentz factor, $\beta_s = \dot{r_s}/c$, and $\vec{n}_s \equiv (\vec{r} - \vec{r}_s)/|\vec{r} - \vec{r}_s|$. All s-indexed expressions in (3) have to be evaluated at the retarded time t_s such that

$$c_0(t - t_s) = |\vec{r} - \vec{r}_s| \qquad (5)$$

holds. Equations (3) and (4) need to be evaluated for every particle pair. This implies, first, that the calculation of space charge forces in this simulation model scales with N^2, where N is the number of particles. Second, the full history of

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particle previous positions and velocities needs to be stored in memory. Therefore, LW simulations are computationally expensive and require parallel cluster computing to achieve a reasonable runtime.

Conventional space charge codes like ASTRA [4] or KRACK [5] use rest frame (RF) approximations. In this approach, a purely electrostatic field is computed in the rest frame of the bunch. Assuming this frame to be inertial, the space charge fields in the laboratory frame are determined by Lorentz transformation. However, for the particle's oscillatory motion in the undulator, the rest frame is clearly non-inertial. Furthermore, synchrotron radiation cannot be modeled properly. In the following section we compare simulation results for both space charge field models.

SIMULATION RESULTS

Figure 2 compares the simulated growth of the transverse rms bunch size σ_x along the undulator for three different space charge field models. The LW model includes both, time retarded static as well as acceleration radiation fields. The Radiation Off (RO) model uses time retardation, but neglects the radiation term (cf. (3)). A comparison of the simulation results for the LW model (dashed line) and the RO model (dotted line) provides an estimation on the relative contribution of radiation fields in the undulator. The RF model (solid line), KRACK (plus), and ASTRA (cross) simulations correspond to different implementations of the rest frame space charge field model. These latter simulations, agree perfectly with each other. Compared to the LW model,

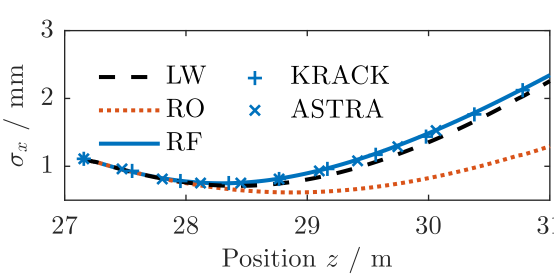

Figure 2: Transversal rms bunch size σ_x inside the undulator computed with three different space charge field models.

the RO model significantly underestimates the transversal space charge effects. This shows that radiation fields are important for the beam dynamics. The RF approximation seemingly provides reasonable values for the bunch rms size σ_x even if it does not include radiation field effects. This behavior is related to the effectively reduced mean longitudinal momentum of a particle bunch undergoing oscillatory motion. This increases the effective space charge field of the bunch artificially and, thus, leads to some sort of compensation for the missing radiation field contribution to the transverse size growth of the bunch. On the other hand, the reference frame EM field model introduces non-negligible errors, especially, in the longitudinal phase space. The energy spread σ_E shown in Fig. 3 demonstrates the significant error induced by the RF approach in the longitudinal beam

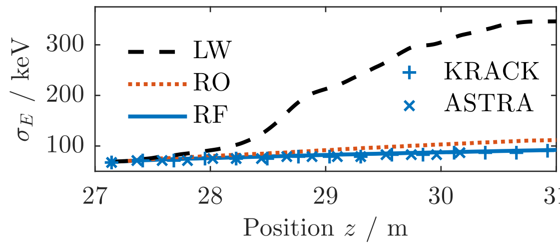

Figure 3: Energy spread σ_E inside the undulator computed with three different space charge field models.

dynamics. Table 1 gives an overview of the beam properties at the undulator exit. For the investigated simulation parameters, the simulated beam dimensions $\sigma_{x,y,z}$ of the RF model are in reasonable agreement with the results of the LW approach. Hence, the RF approximation provides a quick and reasonable estimate for the size of the electron bunch within the undulator for this particular configuration. In the general case, however, the discrepancy induced by the deficiency of the RF space charge field model may be larger for other beam and undulator configurations. The huge deviation between LW and RF resulting for the rest of phase space parameters (cf. Table 1) indicates that the RF model is not appropriate for the simulation of THz SASE radiation effects. Figure 4 compares the longitudinal phase

Table 1: Beam Properties at Undulator Exit

Qty.	LW-model	RF-model	Rel. Dev.
σ_x	3.1 mm	3.1 mm	+0.5%
σ_y	2.6 mm	2.6 mm	−0.9%
σ_z	2.2 mm	2.2 mm	−2.3%
σ_E	347.4 keV	95.7 keV	−72.5%
ε_x	17 π mrad mm	13 π mrad mm	−24.6%
ε_y	10 π mrad mm	7 π mrad mm	−30.5%
ε_z	1366 π mrad mm	282 π mrad mm	−79.4%

spaces at the undulator exit computed by RF and LW simulations, respectively. From FEL theory it is known that shot noise in the particle bunch distribution gives rise to coherent microbunching instability [3]. This effect is present in the simulation results for the LW model. The mean longitudinal periodicity $\Delta \sim 119\,\mu$m fits quite well to the THz radiation wavelength $\lambda_{THz} \sim 107\,\mu$m of the simulated setup. Furthermore, simulating the beam dynamics for different magnetic field amplitudes B_0 consistently reproduces the analytically known correlation $\lambda_{THz} \propto B_0^2$. The phase space profile obtained by RF simulations features a substantially smaller energy spread. Furthermore, microbunching cannot be reproduced. This is expected as this effect is intrinsically due to radiation fields. For the investigation of THz radiation field, we record EM field samples with $\Delta x = 20\,\mu$m, $\Delta y = 200\,\mu$m, $\Delta z = 1\,\mu$m spatial and $\Delta t = 0.02$ ps temporal resolution at the undulator exit, $z_0 = 30.8$ m. Figure 5 shows the THz radiation spectra of four different initial particle bunches consisting of 50 k particles each. At the en-

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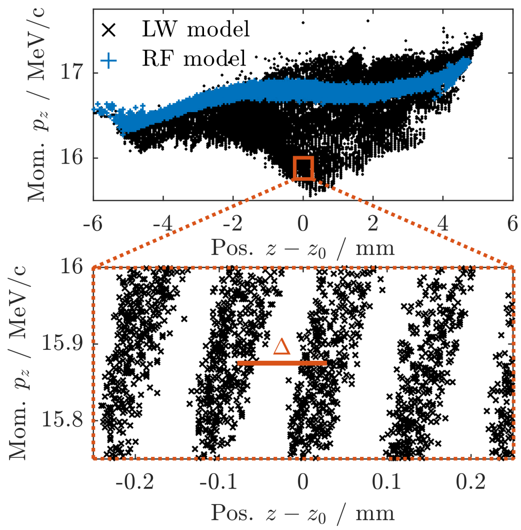

Figure 4: Longitudinal phase space at the undulator exit (top). Magnified view of the microbunching effect simulated by the LW approach (bottom).

trance of the undulator, all four bunches describe the phase space of the beam after passing through the electron gun and booster section. However, each of the four particle distributions correspond to different random realizations. Thus, the simulation results for the THz radiation spectra are slightly different depending on the shot noise characterizing the initial distribution. The averaged spectrum of all samples is centered at $\lambda_{THz} = 108.5\,\mu m$ and has a spectral width of $\delta\lambda_{FWHM} = 4.7\,\mu m$. For comparison, GENESIS 1.3 simulations in [1] based on a non-idealized magnetic field map find $\lambda_{THz} = 106.8\,\mu m$ and $\delta\lambda_{FWHM} = 4.8\,\mu m$. Considering the differences in the field map model, the results agree very well. Figure 6 shows the corresponding intensity profiles of the generated THz radiation pulses at the undulator exit. Beam matching studies have shown that optimum beam transport through the undulator requires a transversally asymmetric particle distribution [1]. This is reflected in the asymmetric radiation pattern generated by this distribution as depicted in Fig. 6. Compared to a real electron beam, the initial shot noise of a 50 k macroparticles bunch is larger. We plan to conduct simulations using larger particle numbers N to investigate the influence of macroparticle shot noise in the LW approach. A more detailed investigation of space charge effects in the paraxial approximation as used, e.g., in GENESIS 1.3 will be presented in future work.

CONCLUSION

We present space charge beam dynamics simulations for the full undulator length of the THz SASE FEL experiment at PITZ. The simulations use a relativistic, three dimensional Liénard-Wiechert field model that takes radiation and retardation effects into account. We show that the conventional rest frame approximation provides reasonable results for the bunch size inside the PITZ undulator, however, it cannot properly reproduce the longitudinal phase space dynamics.

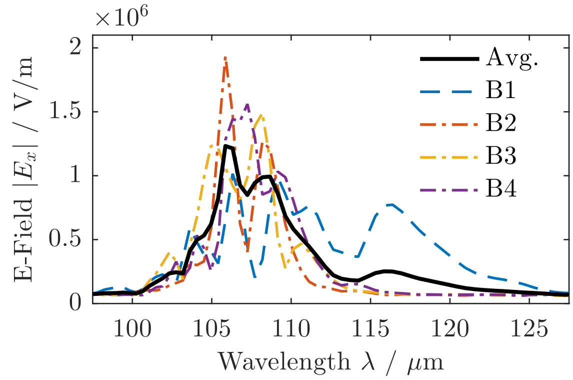

Figure 5: THz radiation spectrum of four different initial particle distributions and their average spectrum as simulated at the undulator exit.

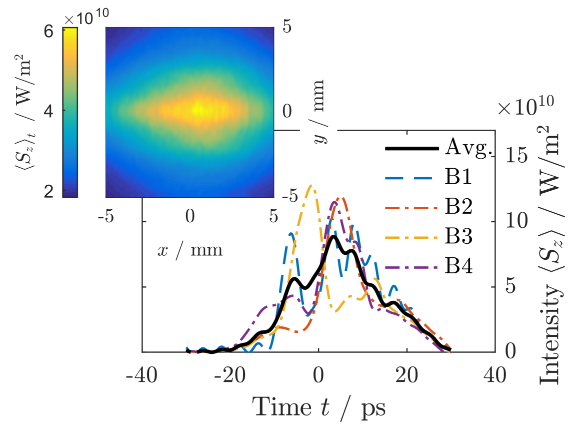

Figure 6: Temporal profile of the THz radiation pulse at the undulator exit. Spatial pattern of radiation intensity at the undulator exit (contour plot).

On the other hand, the LW approach can predict the microbunching effect that is in the core of the SASE process. The simulations clearly show the expected radiation amplification at the undulator exit and the computed THz spectra are in good agreement with previously reported results.

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