NUMERICAL SIMULATIONS OF A SUB-THz COHERENT TRANSITION RADIATION SOURCE AT PITZ

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Abstract

The Photo Injector Test facility at DESY, Zeuthen site (PITZ), develops high brightness electron sources for modern linac-based Free Electron Lasers (FELs). The PITZ accelerator can be considered as a proper machine for the development of an IR/THz source prototype for pump and probe experiments at the European XFEL. For this reason, the radiation generated by high-gain FEL and Coherent Transition Radiation (CTR) produced by the PITZ electron beam has been studied. In this paper, numerical simulations on the generation of CTR based on the PITZ accelerator are presented. The beam dynamics simulations of electron bunches compressed by velocity bunching are performed by using the ASTRA code. The characteristics of CTR are calculated numerically by using the generalized Ginzburg-Frank formula. The details and results of the simulations are described and discussed.

INTRODUCTION

The Photo Injector Test facility at DESY, Zeuthen site (PITZ), has been established to develop, study and optimize high brightness electron sources for modern linac-based short-wavelength Free-Electron Lasers (FELs) like FLASH and the European XFEL. The concept of generating IR/THz radiation by electron bunches from a "PITZ-like" linear accelerator for pump and probe experiments at the European XFEL was presented in Ref. [1]. In order to study and demonstrate the capabilities of IR/THz generation from such an accelerator, PITZ has continued the case study for such a prototype IR/THz source. The main goal of the development is to generate radiation that covers wavelengths from IR (µm) to THz (cm) with a variety of field patterns (from single-cycle to narrow-band), and with a high level of peak and average radiation power from the PITZ accelerator. In addition, developments and studies on radiation based electron bunch diagnostics and photon diagnostics can be done at the same time. The radiation generations using high-gain FELs and Coherent Transition Radiation (CTR) have been studied and preliminary results have been obtained.

The layout for the simulations of radiation generation as shown in Fig. 1 is similar to the current PITZ beamline with some additional radiators. The layout consists of a 1.6-cell L-band photocathode RF gun surrounded by main and bucking solenoids, a cut disk structure (CDS) booster, screen stations, quadrupole magnets and dipole magnets. The CTR station is placed at 16.30 m downstream from the cathode. An APPLE-II type undulator is placed at the end of beamline for the high-gain FEL radiation using Self-Amplification of Spontaneous Emission (SASE) process. Preliminary start-to-end simulations for the SASE FEL using the PITZ accelerator and covering radiation wavelength from 20 µm to 100 µm were studied and presented in Ref. [2].

In principle, the radiation wavelength of the CTR emitted from a relativistic electron bunch is longer than or comparable to the bunch length. Therefore, in order to cover radiation frequencies in the THz region, the electron bunch length must be in the sub-ps scale. The nominal FWHM bunch length of the electron beam at PITZ is about 2 ps to 20 ps, it is obvious then that the beam needs to be compressed in order to fulfill our request.

In this paper, we present methods and results of numerical simulations of the CTR source based on the PITZ accelerator. The paper is organized as follows: the details and results of the bunch compression simulations using the velocity bunching are described in the next section. Then, the characteristics of the CTR obtainable from the compressed bunches are calculated numerically and discussed. Finally, our conclusion and outlook are presented.

SIMULATIONS OF VELOCITY BUNCHING

We would like to maximize the electron bunch charge in order to increase the CTR intensity and to minimize the bunch length in order to broaden the spectral bandwidth. The photocathode laser system at PITZ is able to produce pulses having gaussian temporal pulse shape with minimum FWHM length of 2.43 ps. The electron bunch charge can be varied by adjusting the laser pulse energy. With this laser temporal length and large laser spot size on the cathode (rms size of 1 mm), it is possible to reach about 1 nC bunch charge.

When accelerating on-crest from the gun and the booster with their possible maximum peak electric fields, the beam can be accelerated up to about 22 MeV/c mean momentum. Since the peak electric field at the cathode has to be high enough for extracting the expected bunch charge from the cathode, the RF phase in the gun was fixed to its Maximum Mean Momentum Gain (MMMG) phase and we use only the booster for the velocity bunching. However, the minimum beam momentum is limited to about 15 MeV/c in order to prevent from too strong space-charge domination problems during the beam transport and a too big emission angle from the CTR which is directly proportional to $1/\gamma$ where γ is the Lorentz factor of the electron beam.

The ASTRA code [3] was used for tracking the electron beams from the cathode to the CTR station which is placed 16.30 m downstream from the cathode as shown in

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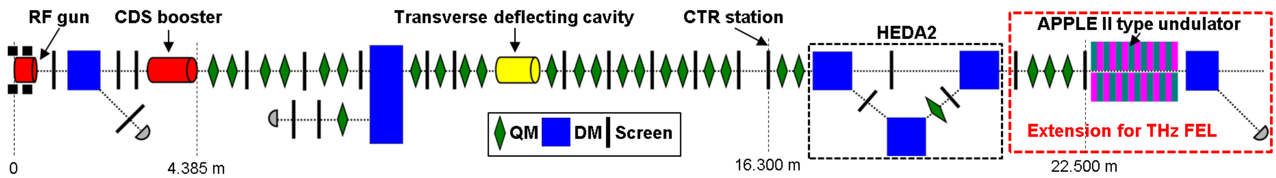

Figure 1: Schematic layout of the PITZ beamline including radiation stations, CTR and SASE FEL, for simulations studies. Here QM and DM represent quadrupole magnets and dipole magnets, respectively.

Fig. 1. A gaussian laser temporal shape with pulse duration of 2.43 ps FWHM and bunch charges of 20 pC, 100 pC, 200 pC, 500 pC and 1 nC were used as input for the simulations. The gun phase was set to its MMMG phase. The booster phase was set to −60° off-crest with respect to (w.r.t.) its MMMG phase in order to obtain the final electron beam momentum of about 15 MeV/c as required. Important input parameters for the ASTRA simulations are listed in Table 1.

Table 1: Input Parameters for ASTRA Simulations

Paramaters	Values
Rms laser spot size at the cathode, [mm]	1
Z_{start} to Z_{end}, [m]	0 to 16.30
Bunch charge [nC]	0.02 to 1
Peak electric field in the Gun, [MV/m]	60
Peak electric field in the booster, [MV/m]	18
Gun phase w.r.t. MMMG phase, [degree]	0
Booster phase w.r.t. MMMG phase, [degree]	−60

The evolution of the simulated rms bunch length from the cathode (0 m) to the CTR station (16.30 m) is shown in Fig. 2. The rms momentum spread and peak current as a function of the bunch charge at the CTR station are shown in Fig. 3 and the corresponding longitudinal phase spaces are shown in Fig. 4. The rms bunch length at the CTR station decreases by about 30 % w.r.t. its value at the booster exit for a 20 pC beam. On the other side, for a 1 nC beam there is only a reduction of about 14 %. The decreasing of the compression efficiency from the velocity bunching for higher bunch charge is due to the stronger longitudinal space-charge force. Furthermore, the rms momentum spread is lower for the higher bunch charge as can be seen from the plot in Fig. 3 and more obviously from the slopes of the longitudinal phase spaces in Fig. 4. This also reduces the compression efficiency.

CALCULATION OF THE CTR

For calculating the CTR produced by an electron bunch, a longitudinal form factor of the electron bunch is introduced as follows:

$$F_{long}(\omega) = \int_{-\infty}^{\infty} \rho_{long}(t) \exp(-i\omega t) dt \qquad (1)$$

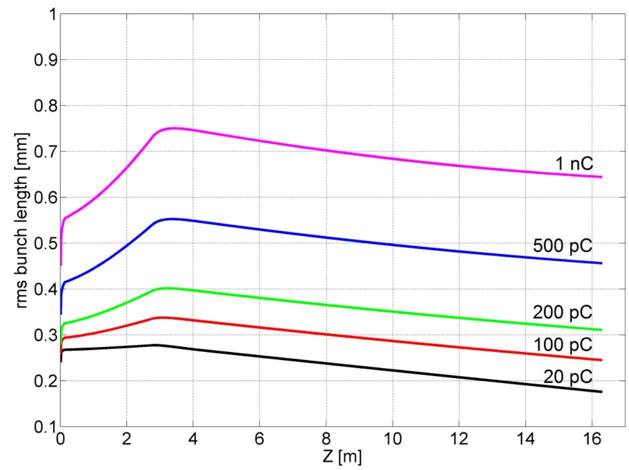

Figure 2: Simulated rms bunch lengths from the cathode (0 m) to the CTR station (16.30 m) for bunch charges of 20 pC to 1 nC.

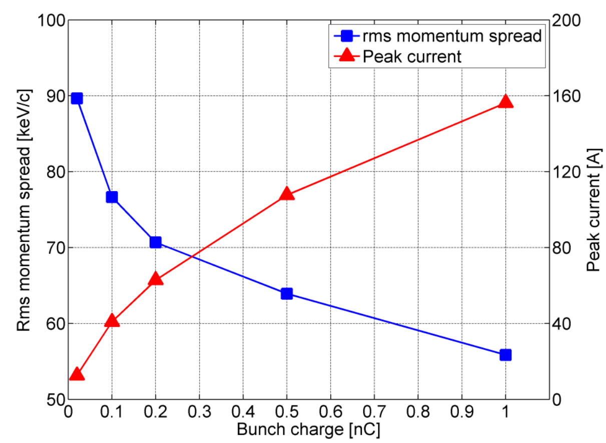

Figure 3: Simulated rms momentum spread and peak current of the compressed bunch as a function of bunch charge at the CTR station.

where $\rho_{long}(t)$ is the function that describes the longitudinal charge profile. The generalized Ginzburg-Frank formula [4] is used for calculating the radiation energy. This formula assumes that the radiator screen is a finite circular metallic screen with the radius a. Furthermore, the electron beam having a transverse radius size r_b and a Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$, where β is the electron speed normalized to the speed of light, impinges normally on the screen. Then the

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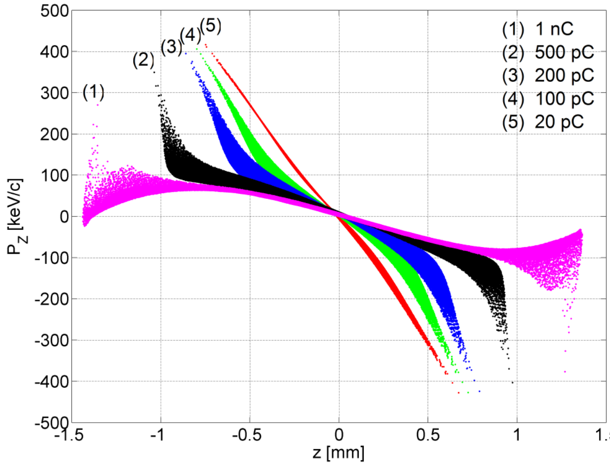

Figure 4: Simulated longitudinal phase spaces of the compressed bunch at the CTR station.

spectral and spatial radiation energy in the far-field regime for backward CTR are given by [4]

$$\frac{d^2U_{bunch}}{d\omega d\Omega} = \frac{e^2}{4\pi^3\varepsilon_0 c}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\cdot N^2\left|F_{long}(\omega)\right|^2 \times\left[\frac{2c}{\omega r_b\sin\theta}J_1\left(\frac{\omega r_b\sin\theta}{c}\right)- \frac{2c\beta\gamma}{\omega r_b}I_1\left(\frac{\omega r_b}{c\beta\gamma}\right)T(\gamma,\theta,\omega)\right]^2, \tag{2}$$

where θ is the angle between an axis normal to the screen plane in backward direction and the emitted radiation direction, J_n is the Bessel function, K_n and I_n are the modified Bessel functions and the term $T(\gamma,\theta,\omega)$ is written as

$$T(\gamma,\theta,\omega) = \frac{\omega a}{\beta\gamma c}J_0\left(\frac{\omega a\sin\theta}{c}\right)K_1\left(\frac{\omega a}{c\beta\gamma}\right)+ \frac{\omega a}{\beta^2\gamma^2 c sin\theta}J_1\left(\frac{\omega a\sin\theta}{c}\right)K_0\left(\frac{\omega a}{c\beta\gamma}\right). \tag{3}$$

The form factors of the simulated electron bunches in the previous section are calculated by Eq. 1 and shown in Fig. 5. The form factor of the bunch with 20 pC charge gives the widest spectrum that covers the frequency up to 0.5 THz but of course delivers only a very low CTR intensity when compared to the radiation from 1 nC bunch charge which will be shown later in this section.

For the calculations of the radiation characteristics, the screen radius is assumed to be 15 mm. Transverse focusing of the beam at the screen can be done by using quadrupole magnets between the booster exit and the CTR station. However, we will address this issue in further dedicated studies while for the moment we assume the transverse radius of the beams to be 0.5 mm for all the bunch charges.

Figure 6 shows contour plots of the radiation energy calculated by Eq. 2 versus radiation frequency and the angle θ for bunch charges of 20 pC and 1 nC. For the case of 20 pC (top plot), the plot shows that the radiation has the highest intensity in the frequency range from 0.1 to 0.25 THz within the measured angle of about 0.15 rad. While for the case of 1 nC (bottom plot), the highest intensity is in the frequency range of 0.05 to 0.1 THz within the measured angle of 0.3 rad.

The total pulse energy of CTR radiation is obtained by integrating Eq. 2 over the frequency band and the backward hemisphere. Figure 7 shows the calculated total pulse energy as a function of bunch charge by integrating the frequency up to 0.5 THz. The total pulse energy for the case of 1 nC reaches about 2 µJ while it reaches about only 4 nJ for the case of 20 pC.

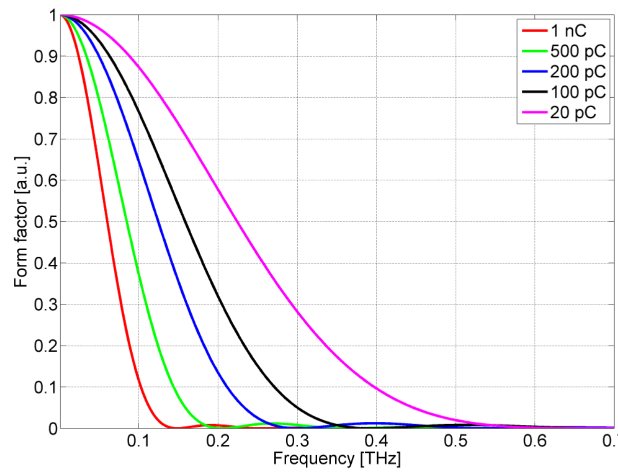

Figure 5: Form factors of the compressed bunch at the CTR station.

CONCLUSION AND OUTLOOK

We have obtained preliminary results for the calculation of CTR characteristics generated by the electron beam from the PITZ accelerator. In this case study the bunch is compressed by the velocity bunching using the booster cavity. These results will be used as a reference for preparing a CTR experiment at PITZ which is foreseen to take place in the beginning of 2016.

More realistic conditions are needed to be implemented in the CTR calculation, such as the radiation from an oblique target screen and calculation in the near-field regime. The calculation of the electric field of the CTR pulse has also been planed.

An other option for bunch compression is to use the HEDA2 section (Fig. 1). Studies on the feasibility of this option need to be done. The use of a modulated electron bunch by employing the flexibility of the PITZ photocathode laser is also an option to a produce CTR spectrum with narrow-band and higher harmonics frequencies as shown in example studies from Ref [5].

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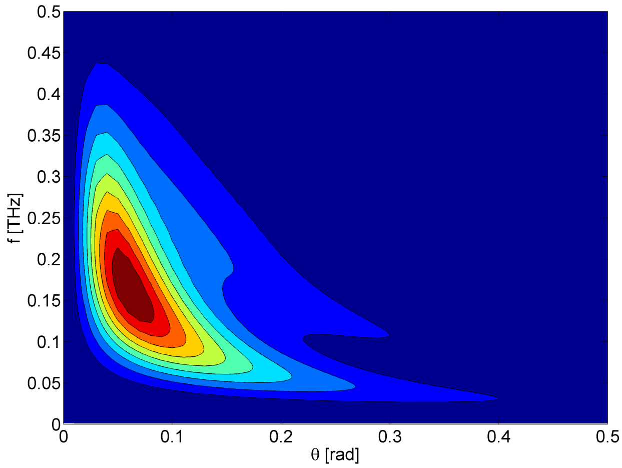

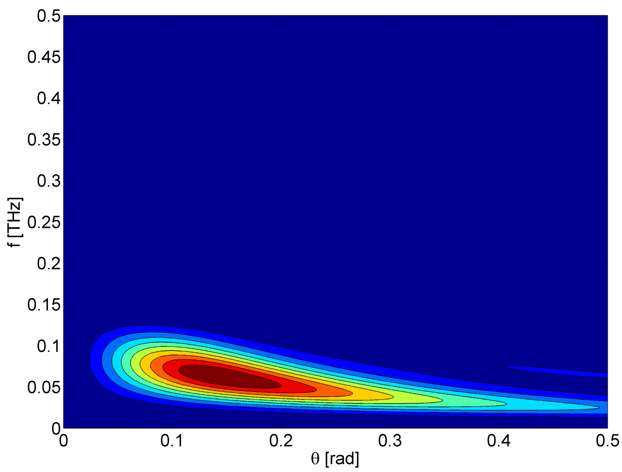

Figure 6: Contour plot of the normalized radiation energy as a function of the radiation frequency and the angle θ for bunch charges of 20 pC (top) and 1 nC (bottom).

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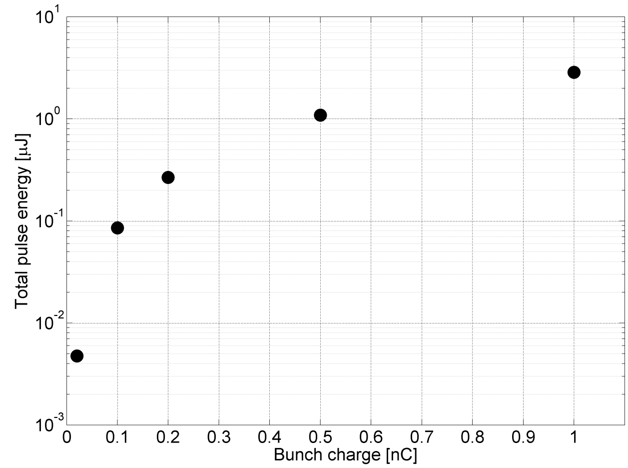

Figure 7: Calculated total radiation energy as a function of the bunch charge.

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