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PROPERTIES OF SUPERRADIANT SPONTANEOUS THz UNDULATOR RADIATION BY AN RF COMPRESSED ELECTRON BEAM

W.K. Lau, W.Y. Chiang, M.C. Chou, H.P. Hsueh, A.P. Lee, NSRRC, Hsinchu, Taiwan
S.Y. Teng, S.H. Chen, Department of Physics, NCU, Taoyuan, Taiwan
J. Qiang, LBNL, Berkeley, USA

Abstract

Rectilinear rf bunch compression in photoinjector linac is a convenient technique to generate few tens MeV short electron bunches. The compressed beam of sub-picosecond bunch duration is especially suitable for generation of superradiant spontaneous radiation from undulator in THz range. Longitudinal multi-particle dynamics in photoinjector have crucial effects on temporal and spectral distributions of the radiation power. The situation is further complicated by space charge effect in the photoinjector during rf bunch compression and longitudinal dispersion of the correlated energy spread beam in undulator. In this study, we perform beam dynamics simulation for NSRRC photoinjector with a fully three dimensional space charge tracking code – IMPACT-T. Since the duration of the output beam is shorter than the radiation wavelength in our case of consideration, calculation of beam-radiation interaction in a 10-cm period planar undulator is done by the broadband three dimensional unaveraged FEL code – PUFFIN. The simulation results revealed that, as the rf compressed beam with non-negligible correlated energy spread from the photoinjector traverses along the undulator, significant elongation of bunch length due to undulator R_{56} is clearly seen. As a result, a strong reduction of instantaneous coherent radiation power that leads to an uneven temporal field profile as well as spectral broadening is observed.

INTRODUCTION

Accelerator-based superradiant THz undulator sources are a special kind of high power devices that draw much attention in recent years [1, 2]. TELBE at Helmholtz-Zentrum Dresden-Rossendorf (HZDR), THz beamline at FLASH, and Israeli THz FEL [3-5] are good examples of such facilities that are either in operation or under development. In NSRRC, a coherent THz facility has been developed to produce intense emission from an 18-periods variable gap planar undulator of 10-cm period length [6]. In this setup, electron beam is generated from a 1.6-cell 2998 MHz photocathode rf gun and a 5.2-m long constant gradient traveling-wave rf linac for beam acceleration. Bunch compression is possible by setting rf linac phase near zero-crossing [7]. Solenoid magnets are installed right after the gun cavity and at the first 2 meters of the linac for compensation of transverse emittance growth in the photoinjector due to linear space charge forces. In an initial experiment, a 0.6 THz radiation of ~20 μJ pulse energy from the undulator has been obtained from a 280 pC, 17.7 MeV drive beam at 490 fs bunch duration. However, it has been observed that instantaneous power of the superradiant undulator radiation decreases gradually with time. It therefore leads to a broadening of radiation spectral bandwidth. To understand this phenomenon, we perform beam dynamics simulation of NSRRC photoinjector with a full 3D space charge tracking code – IMPACT-T [8] when it is operated in velocity bunching mode in which space charge effect is considered to be serious. Since the length of the photoinjector output beam can be shorter than the radiation wavelength for cases with high compression ratio, self-consistent calculation of beam-radiation interaction in a 10-cm period planar undulator is required and can be done by the broadband three dimensional unaveraged FEL code – PUFFIN [9, 10] because most of the commonly used multi-dimensional FEL simulation codes such as GENESIS [11], MEDUSSA [12], etc. are not adequate because these codes are based on averaged slowly varying envelop approximation (SVEA) on the radiation field. For SVEA FEL codes, simulation for processes that require sub-resonant wavelength resolution are not possible.

RF BUNCH COMPRESSION

In this section, we describe the IMPACT-T simulation we have done in case of velocity bunching at high compression ratio. Throughout this preliminary simulation study, we use an initial beam of 100,000 maroparticles with parameters listed in Table 1.

Table 1: Initial Beam Parameters of the NSRRC Photoinjector Being Used in IMPACT-T Simulation

Beam Parameter	Value
Bunch charge [nC]	0.25
Long. particle distribution [μm]	4.35 flat-top
Long. momentum spread	0.0
Trans. particle distribution	uniform
Beam size (x and y) [mm]	0.577 RMS
Trans. particle momentum	Gaussian
Normalized emittance [mm-mrad]	0.5 RMS

Peak field of the 1.6-cell, 2998 MHz photo-cathode rf gun is set at 60 MV/m. The peak accelerating field of the 5.2-m rf linac is set at 18 MV/m to obtain a maximum energy gain of ~60 MeV. Gun phase and gun solenoid field are adjusted to minimize transverse emittance at the injector exit for an on-crest beam. Fig. 1 shows how bunch length and relative energy spread of the NSRRC photoinjector output beam change with linac phase when linac solenoid magnet has been turned off despite the fact that transverse beam size may become too large during bunch

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compression. Total beam energy spread (including correlated and uncorrelated beam energy spread) varies from 0.6 to 7.4% when linac phase scans from -30° to 84°. A beam with 16 5 µm bunch length can be achieved under this operation parameters at zero linac phase.

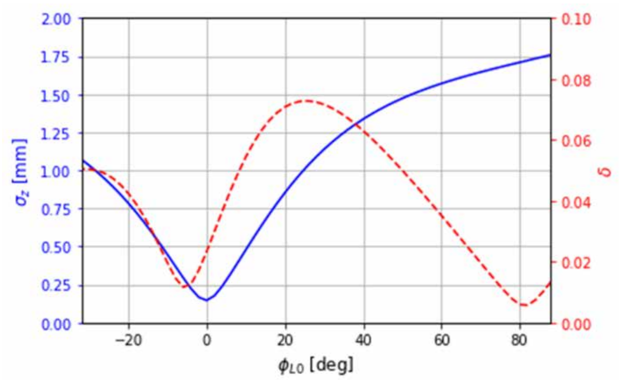

Figure 1: Bunch length (blue solid line) and relative energy spread (red dotted line) of the photoinjector output beam as a function of linac phase calculated by IMPACT-T.

For a case study of superradiant undulator radiation calculation, we choose to operate the linac at a slightly positive phase above zero-crossing because most of the electron trajectories in longitudinal phase space do not cross one and another throughout the whole bunch compression process. Fig. 2 depicts the evolution of bunch length in NSRRC photoinjector with linac phase at 3°. The RMS bunch length decreases monotonically as the beam accelerates in the rf linac to higher energy. In this case, final energy of the beam at photoinjector exit is 35.5 MeV and have a final RMS bunch length of 250 µm which corresponds to a bunch peak current of ~300 A. Compression ratio of velocity bunching in rf linac is about 10 in this case.

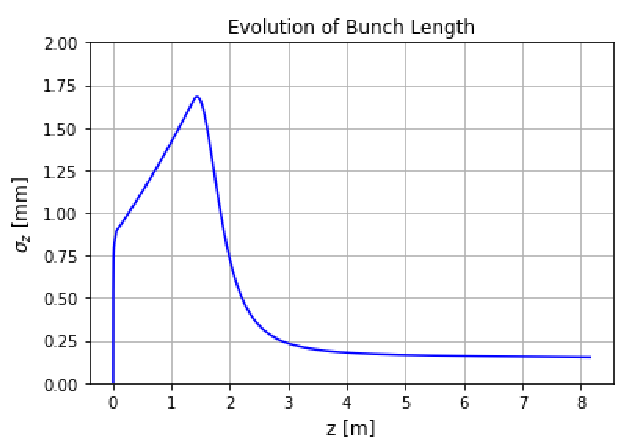

Figure 2: Evolution of bunch length in NSRRC photoinjector with booster rf linac phase ϕ_{L0} is operated at 3°.

It is worth noting that growth of beam size and transverse emittance can be controlled by the linac solenoid field strength. Normalized beam transverse emittance of the photoinjector output beam is limited to 3 mm-mrad when linac solenoid field is adjusted to 0.45 kG. Figure 3 shows the electron distribution in three dimensional phase spaces and longitudinal beam profile. The beam is slightly focused in horizontal direction in this example. As the electrons are concentrated at the bunch head, bifurcation of electron distribution in longitudinal phase space is clearly seen. It leaves a relatively long tail in longitudinal beam profile as shown in the bottom right diagram of Fig. 3. The tail may have significant contributions to both RMS transverse and longitudinal emittances. Parameters of the compressed beam are listed in Table 2 for PUFFIN simulation.

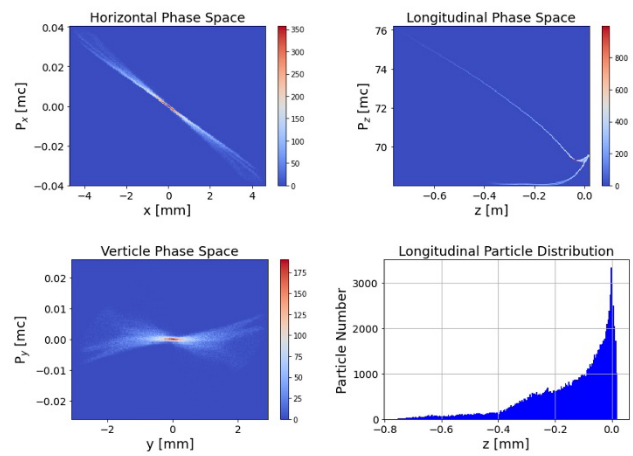

Figure 3: Electron distributions in horizontal (top left), vertical (top right), longitudinal (bottom left) phase spaces and longitudinal particle distribution (bottom right) at NSRRC photoinjector undulator entrance when booster rf linac phase ϕ_{L0} is set at 3°.

Table 2: Parameters of the Drive Beam Calculated by IMPACT-T

Drive Beam Parameter	Unit
Beam energy [MeV]	35.5
Bunch charge [nC]	0.25
Bunch length [µm]	250
Peak current [A]	300
Transverse emittance [mm-mrad]	3.0
Beam sizes [mm]	1.9/1.2
Energy spread [%]	3.5

SUPERRADIANT THZ UNDULATOR RADIATION

With the drive beam discussed in the last section, we use PUFFIN to calculate the superradiant THz undulator emission from the short bunch. It is a broadband three dimensional unaveraged FEL code developed by Campbell and McNeil [9, 10]. Fig. 4 depicts the evolution of superradiant radiation power emitted from the bunch under the action of magnetic field of a U100 undulator which is an 18-periods undulator with 10 cm period length. The radiation is immediately established in the undulator and quickly achieves to its maximum value (i.e. 1 MW) as we expected for superradiant emission from a bunch with its bunch length shorter or comparable to the radiation wavelength. In this simulation, the parameter K of the U100 undulator is set at 4.6 and the radiation frequency is 2.6 THz.

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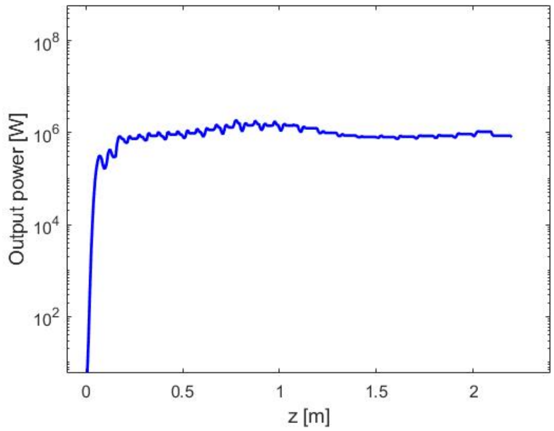

Figure 4: Evolution of the 2.6 THz superradiant spontaneous undulator radiation power in the 18-periods U100 undulator with K=4.6.

If we take a snapshot of the output radiation field at the end of U100, we noticed that the amplitude of the radiation field decay gradually from its initial value for the leading half of the pulse (on right hand side of Fig. 5). This can be explained by the bunch lengthening effect due to the longitudinal dispersion of an energy spread beam in the undulator. As the bunch traverses across the undulator field, the increase of bunch length implies a reduction of bunch form factor and there hence a reduction of instantaneous coherent undulator radiation power. However, it needs further investigation for the tailing part of the radiation pulse in which the field amplitude does not have significant change.

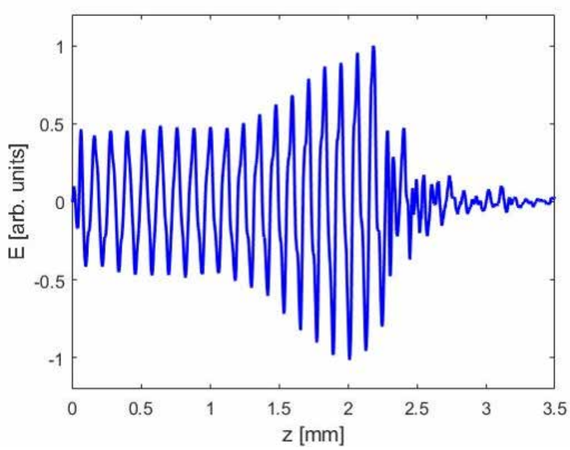

Figure 5: Snapshot of the superradiant undulator radiation field calculated by PUFFIN.

As can be seen in Fig. 6, bunch duration has been increased by a factor of ~4.5 in the undulator. One might suspect that if 3D space charge force within the compressed beam responsible for the bunch lengthening. In order to clarify this, we perform IMPACT-T calculation by replacing the undulator with a 2-m drift section and check whether bunch lengthening due to space charge is significant in this drift section. It turns out that the change of bunch length due space charge force is not noticeable as the beam travels along the drift.

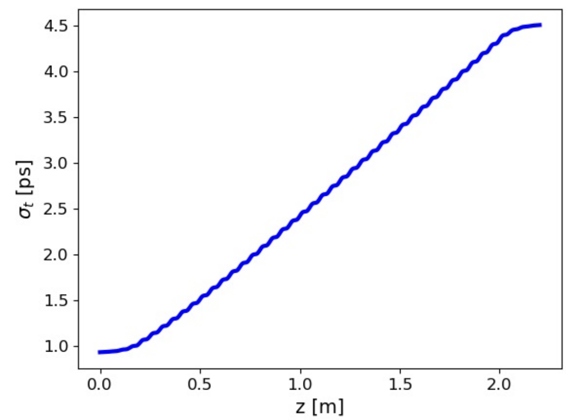

Figure 6: Evolution of bunch length in the U100 undulator in PUFFIN simulation.

Figure 7 shows the distribution of the 2.6 THz superradiant spontaneous undulation radiation from the 250 μm electron bunch in transverse space scaled with cooperative length L_c which is defined as $1/2\rho k_r$, the phase slippage per unit gain length [9, 10]. ρ is the FEL parameter and k_r is the radiation wave number. The centre part of the distribution resemble the first harmonic σ-mode undulator radiation [13] as expected.

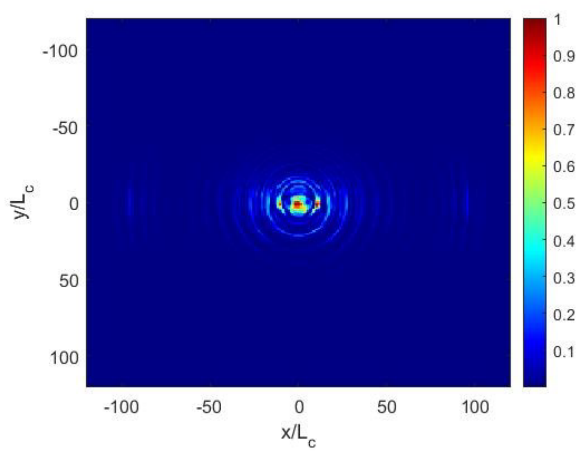

Figure 7: Distribution of the superradiant spontaneous undulation radiation from a 250 μm electron bunch.

CONCLUSIONS

We performed start-to-end simulation of the NSRRC coherent THz facility by using IMPACT-T for space charge tracking of photoinjector in velocity bunching mode for generation of sub-picosecond electron beam and PUFFIN for beam-wave interaction in the U100 planar undulator. The simulation results show that an rf compressed beam with non-negligible correlated energy spread traverses along the undulator experiences significant elongation of bunch length due to undulator R_{56}. Such bunch lengthening effect leads to a significant decrease of coherent radiation field with time. Spatial distribution of the superradiant spontaneous undulation radiation from the compressed beam is also obtained.

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