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DISCUSSION ON CSR INSTABILITY IN EEHG SIMULATION

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Abstract

Echo-Enabled Harmonic Generation (EEHG) is an external seeding technique for XUV and soft X-ray Free Electron Lasers (FEL). It has recently been experimentally demonstrated and currently many facilities worldwide intend to incorporate it in user operation. The EEHG process relies on very accurate and complex transformations of electron beam phase space by means of a series of undulators coupled to lasers and dispersive chicanes. As a result of the phase space manipulation, electrons are bunched at a high harmonic of the seed laser wavelength allowing coherent emission at few nm wavelength. Dispersion occurring in strong chicanes is imperative for implementation of this scheme and effective electron bunching generation. However, strong chicanes at the same time can be source of beam instability effects, such as Coherent Synchrotron Radiation (CSR), that can significantly grow in these conditions and suppress the bunching process. Therefore, there is a common need to investigate such effects in detail. Here, we discuss their treatment with simulation codes applied to a typical EEHG setup.

INTRODUCTION

Classical high-gain Free Electrons Lasers (FEL), where the FEL radiation generation is initiated by the electron beam shot noise, suffer from pulse-to-pulse fluctuations and lack of longitudinal coherence. This makes it impossible to use FELs for a number of applications, for instance in spectroscopy where high spectral flux is needed to allow high statistics, and well defined photon energies to measure accurately. External seeding schemes, such as Echo-Enabled Harmonic Generation (EEHG) [1], eliminate these drawbacks and have allowed interesting and novel experiments such as coherent control [2], two pulses experiments [3] and attosecond trains [4]. EEHG is also more efficient than other seeding schemes in generating high harmonics of the seed laser wavelength typically lying in the ultraviolet (UV) regime, which means short output wavelengths down to few nm, with 2.6 nm being the shortest wavelength measured as a coherent signal at FERMI [5].

A schematic setup for realization of EEHG is shown in Fig. 1. Modulators are undulators coupled to a laser, and together they create a sinusoidal energy modulation along the electron bunch. Chicanes are dispersive elements that delay lower energy electrons with respect to higher energy electrons and thus, can take advantage of the already induced energy modulation and alter the longitudinal phase space of the electron bunch. The first chicane is quite strong, typically of a longitudinal dispersion R_{56} of mm and creates filamentation in phase space, as shown in Fig. 1. The second one is weaker, in the order of several tens to hundreds of µm, and enhances the bunching at a harmonic of the seed laser wavelength. The fine phase space manipulation depicted in Fig. 1 is crucial for the performance of EEHG. At the same time, the process is quite sensitive to electron beam instabilities, such as ones induced by Coherent Synchrotron Radiation (CSR) [6, 7]. The effect of CSR is the most pronounced in chicanes as already known from the experience of operating with bunch compressors [8], and is especially important for the stronger chicane 1 in Fig. 1. In order to investigate how CSR affects the performance of EEHG, we employ numerical simulations. We focus on the most decisive quantity for EEHG – bunching at the target harmonic of the seed laser wavelength before the radiator. We want to find out how CSR influences this quantity and if the influence can be controlled by internal geometry of the strong chicane 1.

METHODS

For the investigation we use a typical EEHG lattice. The most relevant parameters are given in Table 1. The simulations are performed with the particle-tracking code `ELEGANT` [9]. As one can see from the table, we vary the length of bending dipoles L_b of the first chicane while keeping its full length and R_{56} constant. Chicane 1 is the only element, for which the simulations include CSR, using built-in options of `ELEGANT`. The bunching spectrum is calculated as Fourier transform of the particle distribution along the bunch, as illustrated in Fig. 1. Beside the bunching spectrum after chicane 2, we also track the energy profile of the electron bunch after the CSR-affected chicane 1.

Table 1: Parameters of the Sample Lattice. The Electron Beam is Gaussian. The Seed Laser Pulses are Infinitely Long with Constant Power throughout the Pulse

Electron beam energy	1.35 GeV
Initial energy spread	150 keV
Normalized emittance	0.5 mm · mrad
Electron bunch length rms	50 µm
Charge	0.1 nC
Seed lasers wavelength	300 nm
Target harmonic	75 (4 nm)
R_{56} of chicane 1	7.05 mm
Chicane 1 full length	6.1 m
Chicane 1 dipole length L_b	0.21 – 0.63 m
R_{56} of chicane 2	81.25 µm

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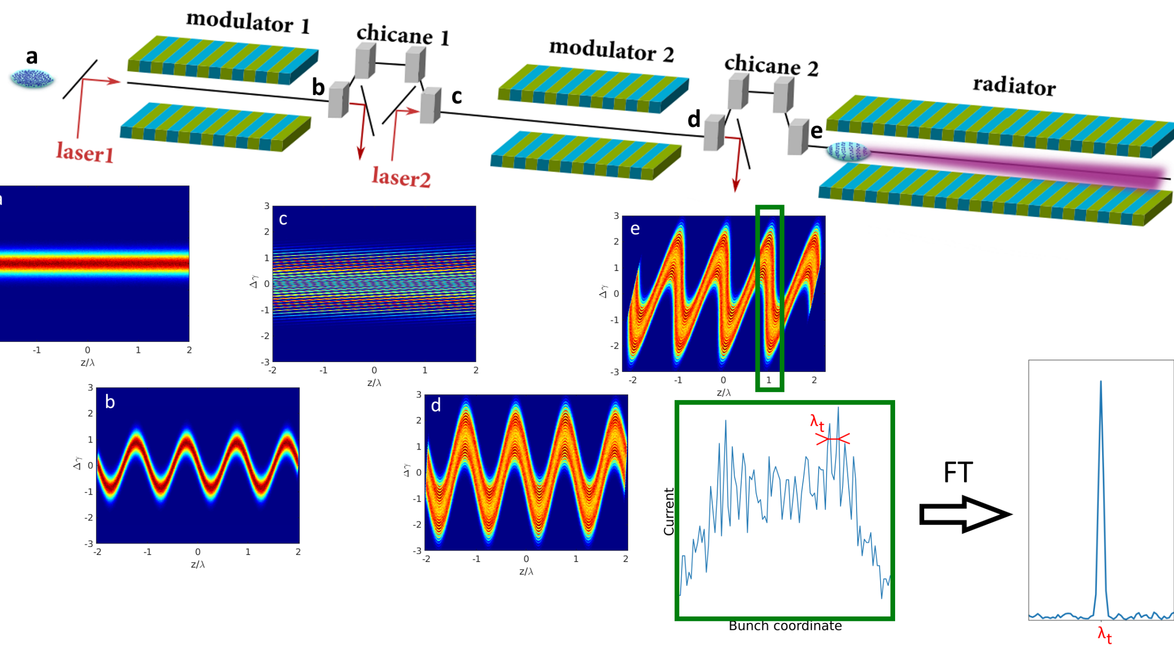

Figure 1: The electron bunch travels through 2 modulators and 2 chicanes before the radiator (top), the heat map plots of the longitudinal phase space of the electron bunch at positions a-e (middle), the current profile of a bunch slice and its Fourier transform around the target wavelength λ_t (bottom-right).

RESULTS AND DISCUSSION

In Fig. 2 we see the energy profile of the bunch in 4 different cases: 1) CSR in chicane 1 is disabled and its L_b does not play a role; 2-4) CSR is enabled and L_b is set to three different values. From the figure one can see, that CSR induces an energy modulation along the bunch and the shape of this modulation depends on L_b.

The energy modulation can be considered as a varying chirp, induced in between the two chicanes. The effect of energy chirp of the electron bunch on EEHG has already been extensively studied [10–13] and is associated with a wavelength shift. In Fig. 3 we see that with CSR the bunching spectrum acquires a wide and complex shape. We attribute this change to the fact, that different regions of the bunch have different value of the chirp and, hence, contribute to the bunching at slightly different wavelengths.

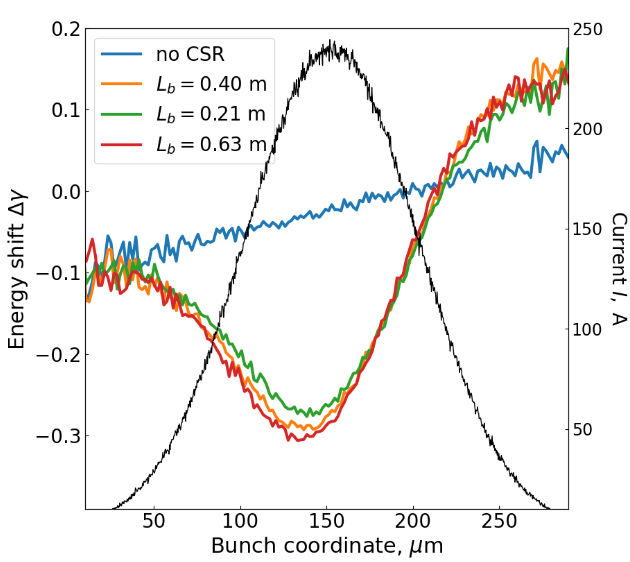

Figure 2: The energy profile of the electron bunch with CSR disabled (blue), the CSR-induced energy modulation for different dipole lengths and the current profile (black) along the bunch after chicane 1. The energy shift is calculated with respect to the nominal beam energy.

To investigate this matter further, we consider only one

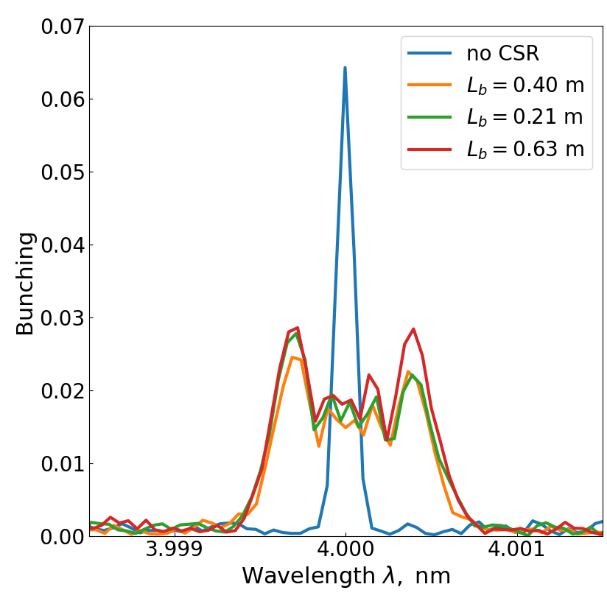

Figure 3: The bunching spectrum around the target wavelength.

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dipole length (the medium $L_b = 0.4\,\mathrm{m}$) and choose two regions, where the chirp has a dominant linear component, as depicted in Fig. 4. We calculate the bunching spectrum with CSR enabled for those regions only and compare it to the case with disabled CSR for the full bunch.

In Fig. 5 one can see, that the chirp of different signs shifts

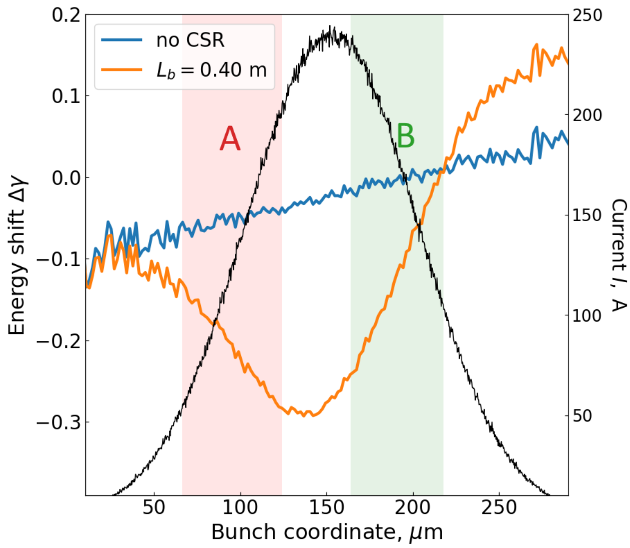

Figure 4: The energy profile of the electron bunch with CSR disabled (blue), the CSR-induced energy modulation for $L_b = 0.4\,\mathrm{m}$ with two selected regions and the current profile (black) along the bunch after chicane 1. The energy shift is calculated with respect to the nominal beam energy.

the bunching spectrum in opposite directions, as expected from the theory. One can also notice that the heights of the peaks in the spectra are slightly different, which can not be addressed solely to the value of the linear chirp. We speculate that this could be the consequence of non-linear components in the energy modulation in the given regions. The reduction of the bunching amplitude requires additional investigation.

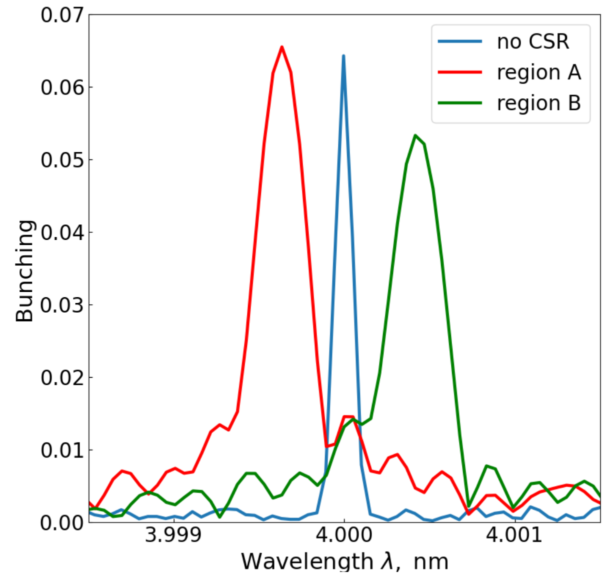

Figure 5: The bunching spectrum around the target wavelength. For regions A and B the bunching is normalized to the number of particles inside the corresponding region.

CONCLUSIONS

We investigated the effect of CSR on the bunching achieved in a typical EEHG setup using numerical simulations. We found that CSR in the stronger chicane 1 induces an energy modulation along the electron bunch. The profile of this modulation can be to certain extent controlled by the internal geometry of the chicane. We confirmed that the linear component of the CSR-induced electron beam energy modulation is responsible for the wavelength shift in the bunching spectrum. At the same time, the linear component can not be directly related to the change in the bunching amplitude, observed in simulations with CSR. Further work will focus on unraveling the mechanism of the CSR-induced bunching reduction.

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