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ANALYSIS OF THE EFFECT OF ENERGY CHIRP IN IMPLEMENTING EEHG AT SXL

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Abstract

As a part of the efforts to improve the longitudinal coherence in the design of the Soft X-ray FEL (the SXL) at MAX IV, we present a possible implementation of the EEHG harmonic seeding scheme partly integrated into the second bunch compressor of the existing LINAC. A special focus is given to the effect of CSR on the resulting EEHG bunching and on how this unwanted effect might be controlled.

INTRODUCTION

The SXL project [1] is a user driven initiative to build a soft X-ray FEL at the MAX IV laboratory, taking advantage of the existing LINAC infrastructure. It is designed to produce radiation in the 1-5 nm wavelength range with a 3 GeV electron beam. We propose improving the longitudinal coherence of SXL by a harmonic seeding technique called Echo Enabled Harmonic Generation (EEHG) [2]. In this technique the electron pulse is modulated twice in two undulators by an external seed-laser. After each modulation a magnetic section transforms the longitudinal phase of the electrons, such that bunching occurs at a high harmonic. Typically these magnetic sections are chicanes, of which the first is comparatively strong with an R_{56} in the order of millimeters. The specific compression scheme currently employed at the MAX IV LINAC offers the opportunity to use a part of the last bunch compressor as the strong dispersive section in the EEHG scheme.

The Electron Beam and the MAX IV LINAC

The LINAC at MAX IV (Fig. 1 (a)) consists of the injector and two groups of accelerating structures (L1 and L2) and two bunch compressors, aptly named BC1 and BC2. Due to the fact that BC2 compresses the electron beam at full energy, 3 GeV, there is a strong linear chirp in the beam at the exit of the LINAC (Fig. 1 (b)). The radiator line follows either BC2 for the layout without the EEHG module (Fig. 1 (a)) or Chicane 2 for the layout with the EEHG module in place (Fig. 1 (c)).

Early work discussing the effect of energy chirp on implementing EEHG [3] has shown that it can be advantageous to use a strong dispersive section that in combination with the chirp compresses the beam. We have therefore used a part of the second bunch compressor as the strong dispersive section needed in the EEHG scheme.

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In Fig. 1 (c) we sketch the changes needed to the layout. Our proposal for implementing EEHG seeding will use the existing achromat 2 of BC2 as the strong dispersive section. We introduce a modulator in the straight middle section of BC2, and after BC2 we add an identical modulator and a relatively weak chicane to complete the ECHO scheme. We note that the in-coupling of the seed laser to the first modulator needs a small chicane. The extra hardware requirements are listed in Table 1.

Table 1: Ardware Requirements for EEHG with BC2

Incoupling Chicane and Chicane 2	
Bending Magnet length	0.25 m
Bending angle	125 mrad
Total length	3.00 m
R_{56}	0.15-0.2 mm
Modulators	
Resonant wavelength	260 nm
Total length	2.00 m
Undulator period	0.25 m
K parameter	11.9

METHOD

The study was carried out using the particle accelerator code ELEGANT [4]. We used a start-to-end beam, tracked from the electron gun, and the lattice presented in [1] with the modifications discussed in Fig. 1 (c). Our main figure of merit in analyzing the effectiveness of the EEHG scheme was to evaluate the harmonic content of the electron density distribution, at the end of Chicane 2, in the form of bunching vs. wavelength. A final confirmation of the quality of the bunching involved running GENESIS1.3 [5] simulations.

A particular challenge for the present work was the fact that the design of the BC2 achromats was done previously [6] and we thus aimed at keeping the R_{56} in the achromat fixed. We therefore did not follow the exact optimization for selecting the bunching wavelength as in the original EEHG paper [2], instead choosing to have the modulation amplitudes, in the two modulators, and the second R_{56} as free tuning parameters. We optimized the setup to produce bunching at harmonic 52 of a 260 nm seed laser. The modulation amplitude in the first modulator was $A_1 = 3.5 * E_{sp}$ the R_{56} of the second achromat was $R^1_{56} = 12$ mm, the second modulator was set to modulate with an amplitude of

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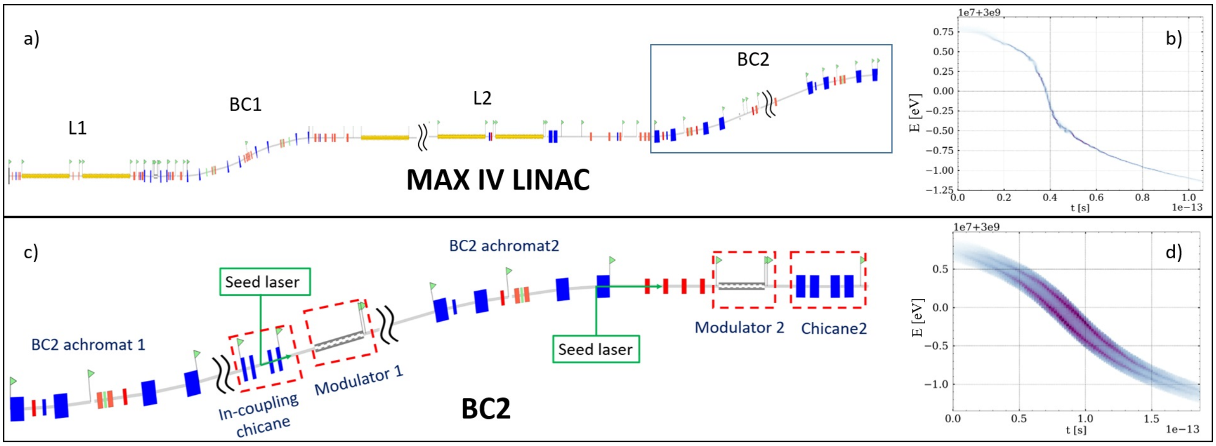

Figure 1: Layout of the MAX IV LINAC a) and a zoom in of the final bunch compressor BC2 c). The red dashed squares mark the extra hardware, not currently available, needed for implementing EEHG. The longitudinal phase space of electrons exiting BC2 with the existing lattice b) and with the extra EEHG hardware included d).

$A_2 = 3 * E_{sp}$ and the final chicane was set to $R^2_{56} = 35\,\mu\text{m}$. Where $E_{sp} = 300\,\text{keV}$ is the uncorrelated energy spread at the entrance to the in-coupling chicane.

RESULTS

Effect of CSR

The compression scheme used in SASE simulations is described in [1] and it is the starting point for our studies as well. Even though Coherent synchrotron radiation (CSR) does not significantly influence the FEL radiation properties in SASE operation, the thin phase space stripes, crucial to the EEHG harmonic conversion, are severely affected by CSR.

To study the effect that CSR has on bunching we took advantage of the capabilities of ELEGANT to enable and disable the CSR effect and compare the outputs in terms of bunching level. In Fig. 2 we show the phase spaces at the end of the Chicane 2 with and without CSR, and the corresponding bunching as a function of wavelength. The relevant effect of CSR on the phase space is only visible when zooming in to see the characteristic EEHG stripes. In the Fig. 2 (c) (CSR on) we see a clear deterioration of the visibility of the fine structures in comparison with b) (CSR off). Our visual intuition is confirmed by Fig. 2 (d) and (e) which shows a reduction of more than 50 % in the bunching between the two cases.

Mitigating CSR Effects

These initial simulations showed that the effect of CSR will reduce the microbunching created with EEHG at high harmonics. To mitigate the CSR effect we employed two steps: 1. changing the chirp of the electron beam by changing the RF-phase of one of the LINAC structures by 1% and 2. reducing the total charge of the bunch from 100 pC to 80 pC in order to reduce the chirp induced by the wake-field in the LINAC cavities.

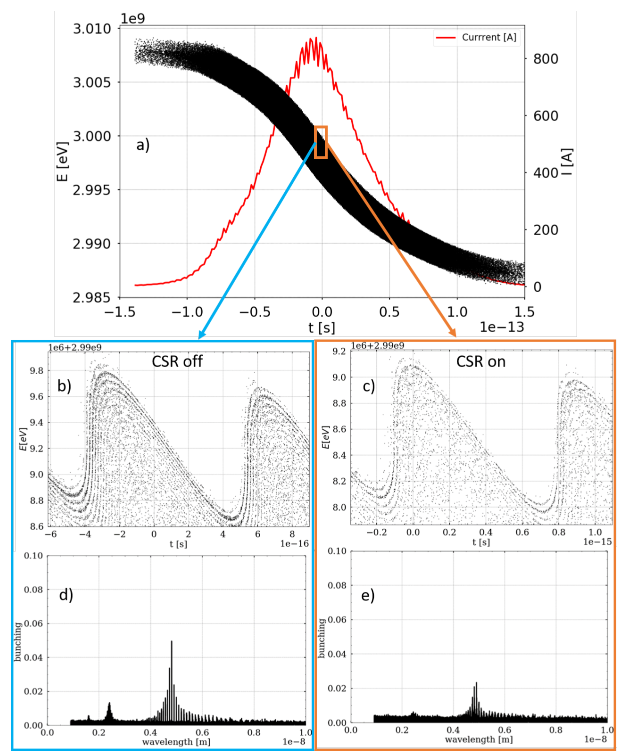

Figure 2: Coarse longitudinal phase space a) at the exit of Chicane 2 with EEHG engaged. b) a zoomed in longitudinal phase space for CSR off (disabled). c) a zoomed in longitudinal phase space for CSR on (enabled). d) Bunching vs wavelength for CSR off. e) Bunching vs. wavelength for CSR on.

Using the beam described in the previous paragraph and keeping CSR on, we were able to recover the bunching level (Fig. 3) from the CSR off case. Comparing the electron bunches exiting the EEHG module (and entering the radiators) for the mitigated and original beams, Figs. 2 (a) and 3 (a)

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respectively, one can see that the mitigated beam is 30 % longer and has a 25 % smaller peak current.

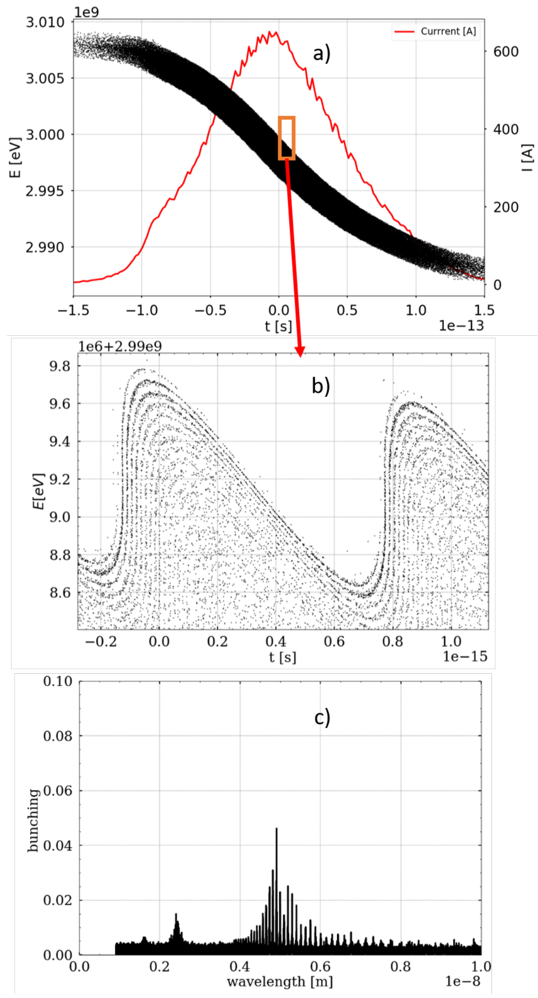

Figure 3: a) Longitudinal phase space (black) and current (red). b) Zoomed in phase space after Chicane 2 with CSR on and with the mitigated beam.c) Bunching vs. wavelength for the mitigated beam with CSR on at the end of Chicane 2.

FEL Simulations

To simulate the FEL we used the code GENESIS1.3 with a lattice that had the same undulator parameters as described in [1] and Table 1, namely 2 m sections with 40 mm period and intersection length of 1 m. We tuned the K parameter to match the exact harmonic we have in the bunching (h = 52). Due to the fact that EEHG creates a complex distribution of the electron beam it was necessary to import the macroparticles from the ELEGANT simulation into GENESIS1.3 as such, without any particle number up-scaling. We carried out a modified version of "one4one" simulations in which we increased the charge of the directly imported macroparticles to match the charge they had in ELEGANT.

The FEL simulation results, Fig. 4, show that the process reaches saturation after 20 m with 130 µJ pulse energy. The spectrum confirms that the bunching induced by the EEHG

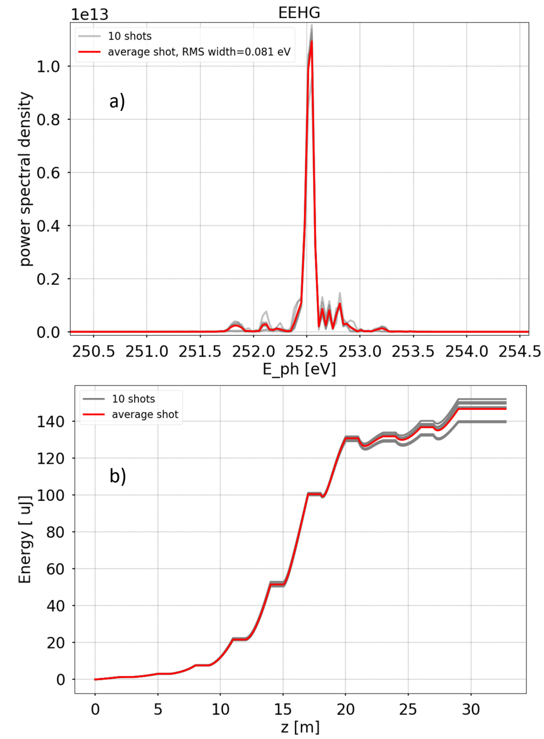

Figure 4: FEL radiation properties. a) 10 shots (gray) and average (red) of spectrum and b) gain length.

is sufficient to overcome the spontaneous emission noise and produce narrow band radiation.

CONCLUSIONS

We have studied, through simulations, a compact design of a EEHG seeding option for SXL. The CSR effect may significantly reduce the bunching in the EEHG scheme, but we show that it is possible to control and to reduce this effect by changing the chirp and total charge of the electron beam. FEL simulations showed that the resulting beam has a clear seeded signal and saturates as early as 20 m into the undulator line.

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