ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB071

CONSIDERATIONS ON IMPLEMENTING EEHG WITH A STRONG LINEAR CHIRP

Mihai Pop*, Sverker Werin
Physics Department, Lund University

Abstract

In the pursuit for a more coherent FEL radiation there have been ingenious schemes proposed in order for the FEL process start not from noise but from an initial bunching. Echo enabled harmonic generation (EEHG) is one such technique used to improve coherence in FELs by manipulating the electron phase space prior to entering a radiator. It uses two modulators and two chicanes to create microbunches of electrons with the periodicity of a few nm. In this paper we will present some of the challenges of using this technique in combination with a strongly chirped beam and indicate a few ways to overcome said challenges.

INTRODUCTION

The EEHG is now a well established method for generating coherent FEL pulses with good experimental results shown in [1]. By pre-bunching at short wavelengths the FEL radiation is ensured to have the same initial phase all through the bunch. Analytical work on chirped beam in combination with the Echo scheme has been carried out in [2] and it was shown to be less sensitive to chirp than other harmonic generation schemes.

The motivation for this work lies in the idea of using EEHG to enhance the coherence of the perspective MAXIV soft X-Ray FEL (SXL). Working on the basis that the new FEL will be using the MAXIV Linac as driver, we have to take into account a large energy chirp of the electron beam at the Linac exit, which is where the new FEL is envisioned to start.

To have a better understanding of the effects we will study, it is worth going through the classic EEHG process as proposed in [3]. The electron beam is modulated in a wiggler by having it co-propagate with a high intensity laser of wavelength λ_{mod1}, Fig. 1 M1. A strong dispersive section(DS1), with either positive or negative $R56$, overcompresses the electron bunch creating fine structure of equally spaced energy slices as in Fig. 1 b). To convert this energy modulation into a longitudinal modulation, a second modulator with λ_{mod2} (Fig. 1 M2) and weak second dispersive section (Fig. 1 DS2) is used. The result is a current profile with fine periodic modulations at the desired harmonic and another modulation with the periodicity of the second modulator wavelength as shown in Fig. 1 f).

In the following we will look at the effects of a strong linear chirp on the EEHG process highlighting the effects it has on the bunching intensity at different harmonics. To visualize the bunching we Fourier transform the particle distribution to generate the spectrum of the bunching or harmonic content. As the bunching gives the initial radiation time structure so does the bunching harmonic content give the spectrum of the initial radiation. Therefore, we use the equivalent photon energy for bunching at a certain spatial distance. As an example, if we have a periodic bunching of 1 nm it will coherently radiate at this wavelength and the equivalent energy of one of these photons is 1240 eV.

To make the analysis more general we use scaled units in terms of energy spread σ_e and initial modulation wavelength λ_{mod1} for the electron energy modulation amplitude, the dispersion introduced by the two dispersive sections and for the electron beam chirp. These notations are done following [2]

- We refer to a beam as having positive chirp when the head of the beam has higher energy than the tail. If the electron beam is characterized by a chirp in terms of $[eV/m]$ the scaled chirp would be $Ch = \frac{\lambda_{mod1} Chirp[eV/m]}{2\pi\sigma_e}$. We can think of it as how many σ_e will the energy increase in a wavelength along the bunch.

- The scaled parameters for modulation amplitude are defined as $A_i = \frac{E-E_0}{\sigma_e}$. This parameter may be understood as the beam energy modulation amplitude in units of energy spread.

- If the normal momentum compaction factor is $R56[m]$, the scaled dispersion strength, for each section is $B_i = \frac{2\pi R56_i \cdot \sigma_e}{\lambda_{mod1} E_0}$. It is useful to think about B_i as the number of λ_{mod1} a particle with energy deviation of 1 σ_e is shifted w.r.t. a particle with reference energy.

GENERAL DISCUSSION ABOUT CHIRP

To study the electron beam phase space and bunching, we simulate the electrons passing through a scheme presented in Fig. 1.

Chirp Sign Effects

We analyze the quality of a certain configuration by the intensity of the bunching harmonic content. To show the importance of choosing the right dispersion sign for a specific energy chirp (Ch), we simulate two types of energy chirp equal in amplitude but with opposite signs. The first dispersive section DS1 is also changed so that we have 4 combinations of chirp and DS1 signs (positive Ch positive DS1, negative Ch positive DS1 , negative Ch negative DS1 and positive Ch and negative DS1). Each run is optimized for the same harmonic. Depending on the sign of DS1 there is a preferential sign for the chirp in the electron beam. As

* mihai.pop@maxiv.lu.se

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB071

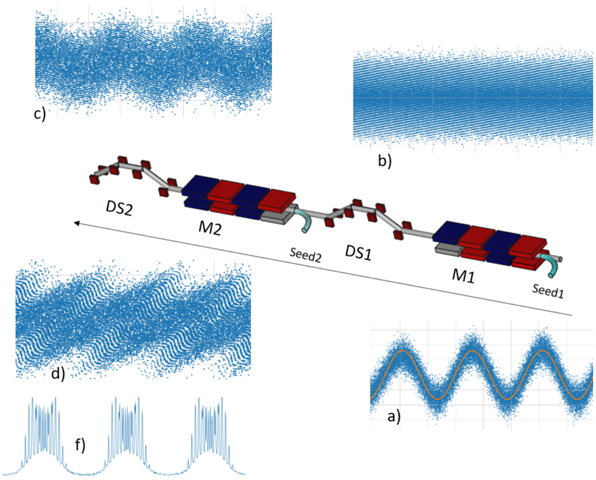

Figure 1: Layout of the EEHG scheme before the radiator with illustrations of how the electron beam phase space looks at each stage. After the first modulator M1 a), after the first dispersive section DS1 b), after the second modulator M2 c), after the second dispersive section DS2 d). Picture f) shows the current profile at the exit of DS2.

seen in Fig. 2 bunching is enhanced for harmonic 52 (248 eV) in the case with positive chirp and negative DS1 and in the case of negative chirp and positive DS1 while almost disappearing for the other combinations.

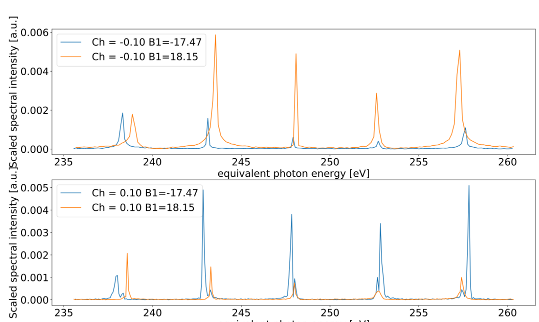

Figure 2: Harmonic content of bunching for positive (top) negative (bottom) chirp having the first dispersive section with different signs. Simulations are optimized for harmonic 52 of a seed laser $\lambda_{mod1} = 260nm$ for a non chirped beam.

Harmonic Content of Bunching

For an unchirped beam the harmonic content (the harmonics at which bunching is significant) is given by a few equally spaced frequency components. In Fig. 3 we plot the current profile and the harmonic content for two different modulator 2 (M2) wavelengths. The modulation wavelength determines the spacing between consecutive peaks in the frequency domain $\Delta\nu = \frac{c}{\lambda_{mod2}}$. Adding a chirp will slightly change the spacing between the larger current spikes but no significantly. Carefully looking at Fig. 2 we can find that the change in separation is given by $\Delta L = \frac{\lambda_{mod1}}{2\pi} B2 \cdot Ch$.

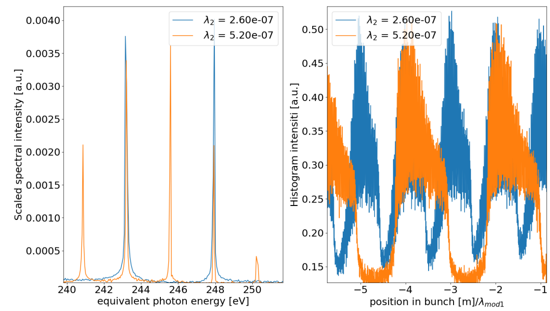

Figure 3: Figure presenting the harmonic content of bunching (left) and beam distribution histogram (right)for two second modulator wavelengths $\lambda_{mod2} = 260nm$ and $\lambda_{mod2} = 520nm$.

Pulse Narrowing

If the energy of an electron is sufficiently different from the resonance energy, the efficiency of the modulation drops, therefore the maximum amplitude modulation is reduced. A chirped electron beam means that there is a correlation between position and energy, implying that different parts of the electron beam will be modulated with different amplitudes. In Fig. 4 we plot the modulation amplitudes and the bunching level along an electron beam with scaled chirp Ch=0.23 (close to what is expected to come from the MAXIV Linac). Each of the two modulators has been tuned to be resonant to the middle part of the electron bunch. The values of B1 and B2 were optimized for harmonic 52 for given modulation levels A1=3 and A2=3. We can observe that the bunching quality has a maximum where the modulation A2 was closest to the design value of 3.

Although this is normally an unwanted effect one can use it to keep the head and the tail of the bunch, which normally have higher emittance and slice energy spread, from developing bunching. Another useful feature of this effect is that it restricts the width of the electron beam that radiates effectively, thus producing shorter pulses.

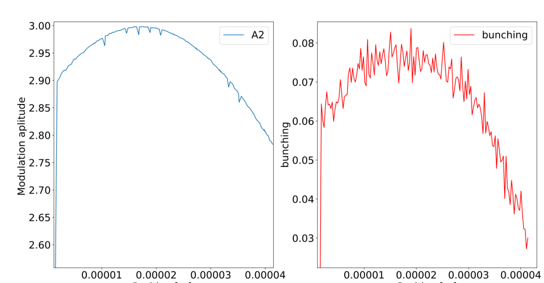

Figure 4: Figure comparing the amplitude modulation (left) after MOD2 to bunching level along the electron pulse at entrance to the radiator (right) of a chirped beam going through the layout in Fig. 1.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB071

EEHG FOR SXL

The soft X-Ray FEL being considered for MAXIV would be fed by the Linac that is currently in operation, powering the two rings. Therefore the changes to it should be kept to a minimum. Currently the chirp produced in the Linac is positive and so the bunch compressors in the Linac have negative dispersion to be able compress the beam. Our estimates place the chirp coming from the Linac at Ch=0.3 in scaled units.

As a first try in implementing the EEHG scheme to the MAXIV Linac we use the scheme in Fig. 1. Confirming the conclusions relating to the sign of the chirp and sign of the chicane, we observed that even though the bunching level was acceptable for harmonics 52 and 104 (8 and 4 % respectively), the peak current was deteriorated. Starting from a beam as described in table 1 we obtained, after the EEHG setup a beam with peak current of 200 A and 350 fs length. We concluded that it is difficult to have any significant lasing in this configuration.

SXL Constraints and Desired Operation Range

Table 1: SXL Main Parameters

Parameter	**Value**
Fixed electron energy	3 GeV
Energy chirp	500 keV/fs
Current	2.5 kA
Bunch length after last compressor	50 fs
Slice energy spread	300 keV

One option is to take advantage of the last bunch compressor in the Linac and incorporate it in the EEHG setup. It would thus play the role of DS1 in the layout in Fig. 1. This layout gives a big advantage because the sign and magnitude of the dispersion is the correct one for our chirp. In regular use, choosing the right wiggler and second dispersive section, the ECHO stage could be made transparent for the electron beam.

This idea also imposes some challenges on the design such as keeping the parameters in the bunch compressor unchanged as it is also set up to compensate some non linear effects in the beam. To keep the dispersive strength within $+-4\%$ when going from harmonic 52 (5 nm) to 260 (1 nm) calculations show that one needs to change the modulation in the second modulator by a factor of 5. The parameters we have chosen to cover the 1-5 nm range are presented in table 2.

Table 2: Echo Parameters for Harmonics 52 and 260

harmonic=260		
Modulator 1	3	450 keV
Dispersive section 1	58	2.4 cm
Modulator 2	5	700 keV
Dispersive section 2	0.23	0.01 cm
harmonic=52		
Modulator 1	3	450 keV
Dispersive section 1	55	2.3 cm
Modulator 2	1	150 keV
Dispersive section 2	1	0.04 cm

CONCLUSIONS

We have presented a way to use the EEHG scheme with an electron beam that has a strong linear chirp. An obvious conclusion to draw from this work is that it is preferable to have the ECHO dispersive sections the opposite sign of the chirp to avoid stretching the beam but also reducing the bunching. We have shown that a chirped in combination with EEHG offers the possibility to generate shorter pulses by limiting the region of the beam that is pre-bunched going in to the radiator. Extensive simulations still have to be done for the option of including the final bunch compressor of the MAXI Linac in an ECHO scheme but initial calculations are promising.

REFERENCES

[1] Primož Rebernik Ribič *et al.*, “Coherent soft x-ray pulses from an echo-enabled harmonic generation free-electron laser”, *Nature Photonics* pp. 1-8, 2019, doi: 10.1038/s41566-019-0427-1.

[2] Z. Huang *et al.*, “Echo microbunching in presence of a linear chirp”, 2009.

[3] D. Xiang and G. Stupakov, “Echo-enabled harmonic generation free electron laser”, *Physical Review Special Topics - Accelerators and Beams*, vol. 12, no. 3, pp. 1-10, 2009.