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CONSIDERATIONS ON IMPLEMENTING EEHG WITH A STRONG LINEAR CHIRP

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ABSTRACT

Due to the stochastic nature of SASE radiation its longitudinal coherence is limited to a small fraction of the electron bunch. By pre-bunching the electrons before entering a radiator, the FEL radiation is ensured to have the same initial phase all through the bunch. Echo enabled harmonic generation (EEHG) is a technique that, by cleverly using two modulators and two dispersive sections, creates microbunches of electrons at a high harmonic of the seed laser used in the modulators. 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

In a recent experiment [1], EEHG has been shown to be suitable as a high harmonic generation scheme with evidence of coherent radiation up to the 100th harmonic of a 260 nm UV laser.

The motivation for this work partly emerges in the wake of a bigger project to build a soft X-Ray FEL laser at MAX-IV the design would have account a large energy chirp of the electron beam at the Linac exit.

The scope of this paper is to have a better understanding of the effects of a strong linear chirp on the EEHG concept, not to give a definitive answer on using EEHG as a seeding method for SXL. For starters it is worth going through the classic EEHG process as proposed in [2].

The electron beam is modulated by having it co-propagate with a high intensity laser (Seed 1), in what is usually a strong insertion device Figure 1 Modulator 1. For long undulators with narrow gain bandwidth it is possible to have different modulation levels for different parts of the electron beam as electrons get off-resonance energies.

A strong dispersive section(in our case Chicane 1) folds the energy modulation of the electron bunch creating a fine structure of equally spaced energy slices. If the electron beam has a chirp, this element will either compress or de-compress the electron bunch depending on the combination of the chirp and dispersion sign.

To convert the fine energy separation into longitudinal bunching, a classic scheme involving a modulator (Figure 1 Modulator 2) and a weak dispersive section is used (Figure 1 Chicane 2).

In our analysis we use scaled notations as in [3] to have a feeling for the general phenomena rather than particular cases.

- **Scaled chirp** $Ch = \frac{\lambda_{mod1} Chirp[eV/m]}{2\pi\sigma_e}$. We can think of it as how many σ_e will the energy increase in one wavelength along the bunch.
- **Scaled Amplitude** $A_i = \frac{E-E_0}{\sigma_e}$. This parameter may be understood as the beam energy modulation amplitude in units of energy spread.
- **Scaled dispersion strength** $B_i = \frac{2\pi R56_i \cdot \sigma_e}{\lambda_{mod1} E_0}$. where $R56[m]$, is the normal momentum compaction factor. 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.

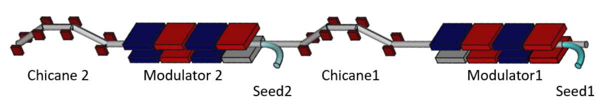

Figure 1: Layout of the EEHG scheme depicting the first modulator Modulator 1, the first dispersive section , in our case a chicane (Chicane 1), the second modulator Modulator 2, the second dispersive section, Chicane 2.

FEL SIMULATIONS

Common Settings

Simulations were carried out on LUNARC [4] using the FEL simulation code Genesis1.3 V4.3.1 with the *one4one* control parameter on, meaning that each electron is simulated as an individual particle. The layout used in simulations is similar to the one depicted in Figure 1. And it comprises of two identical modulators and two chicanes with positive momentum compaction $R_{56} > 0$. A summary of the electron beam and lattice parameters is show in Table 1.

All the simulations are based on the matching presented in Figure 2. The radiator is tuned to 5 nm and for the EEHG simulations the seed has the wavelength of 260 nm or 248 eV. As a test case we use a SASE run with 0.23 scaled (0.5 MeV/fs) energy chirp using the same radiator.

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Table 1: Lattice and Beam Parameters

Beam parameters			
γ	5871		
σ_E/E	1e-4		
$\Delta_l bunch$	80 μm		
Modulators	Period [m]	Length [m]	A_i
Modulator 1	0.25	2	3
Modulator 2	0.25	2	3
Chicanes	Length [m]	B_i	R_{56} [mm]
Chicane 1	3	18.15	24
Chicane 2	1	0.35	0.1
Radiator	period [m]	Length [m]	
Rad	0.04	4	

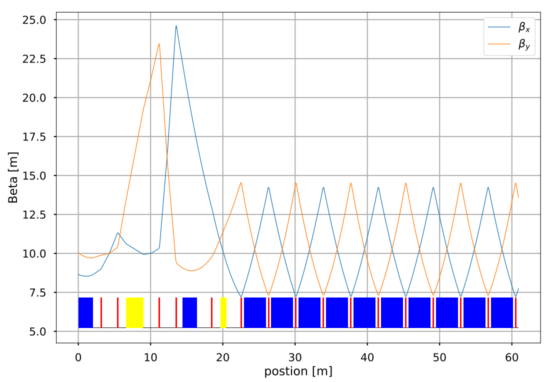

Figure 2: Beta function matching.

Chirp Sign Effects on Bunching

As discussed in the introduction, certain combinations of chirp and dispersive section sign lead either to a compression or a de-compression of the bunch. We used a series of chirps ±0.23 ±0.1 ±0.05 and 0, in scaled units, to highlight how the FEL radiation quality depends on the chirp. Among these, the -0.05 and -0.1 chirp are the only ones that get compressed (the final bunch length is shorter than the initial). Even though -0.23 has negative chirp it is over-compressed to over 3 times its initial size. This can be easily checked using $\frac{\Delta l}{l} = Ch(B1 + B2)$ bunch lengthening formula in [3]. The -0.05 case has a more extreme compression of about 3 times, which will have effects on the gain curve and the spectrum.

In Figure 3 the phase space of three different types of chirp is plotted. We highlight three phenomena that occur due to the chirp in the electron beam as it passes through the ECHO scheme.

1. In Figure 3 d), the peak current value is 25 % higher for the negative chirp than for the positive one.

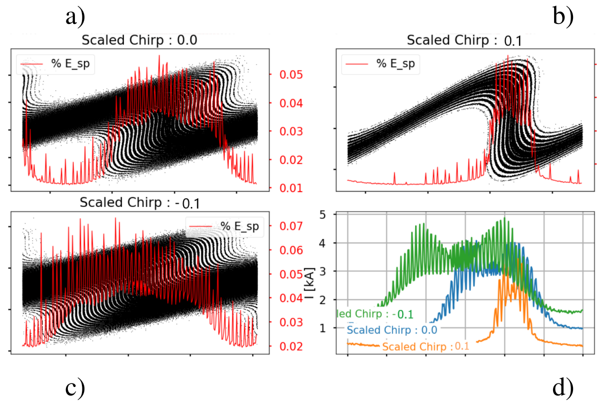

Figure 3: Figure plotting the electron beam phase space, slice energy spread and current profile at the entrance of the radiator. Phase space and slice energy spread for a) No chirp, b) scaled chirp of 0.1, c) scaled chirp of -0.1. d) current profile for the three chirp cases.

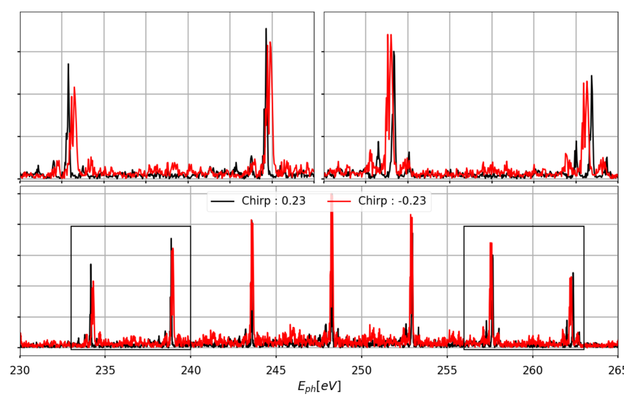

Figure 4: Spectra after 2 undulator periods (bottom). Zoom in left square (upper left), zoom in right square (upper right) for chirped beams with 0.23 (black) and -0.23 (red) scaled chirps.

2. The slice energy spread is almost two times higher for negative than for positive chirp, as one would expect from a compression scheme. Comparing to the initial 0.01% energy spread we see that all EEHG cases have a number of times higher values for this parameter.

3. Within one period of the seed laser Figure 3 a), b) and c), and by extension in the entirety of the bunch, the proportion of the beam that is modulated is 4 times as high for the negative as for the positive chirp. This effect is largely due to the energy spread relative to the modulation amplitude in Modulator 2.

A more subtle effect is related to the side-bands in the EEHG spectrum. We can use the spontaneous radiation generated by the particles a few periods into the radiator to get some information about electron bunching at various wavelengths. In Figure 4 we look at the spectrum of this radiation to observe the effect of the chirp on the spacing between high peak current regions, manifesting in the

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spectrum. A larger distance in time domain will translate to a smaller separation in the frequency domain. After Chicane 1 the -0.23 chirp case will have a stronger chirp than the 0.23 case therefore the modulations induced in modulator 2 will be spread out more by Chicane 2 and hence the side-bands separation will be smaller. Indeed analyzing the top left and top right plots of Figure 4 we see that the side-bands of 0.23 chirp are always further apart from the central peak.

Power Output

Looking at the Gain curves in Figure 5 it is plain to see that the FEL process favors the negatively chirped cases with the shortest saturation length of 11 m for -0.05 scaled chirp, which also has the highest pulse energy of 1.5 mJ. We attribute these values to its high compression and thus peak current. The saturation length of chirps 0.23 and -0.23 is longer than SASE indicating that the current profile has been stretched to the point that it doubled the initial gain length.

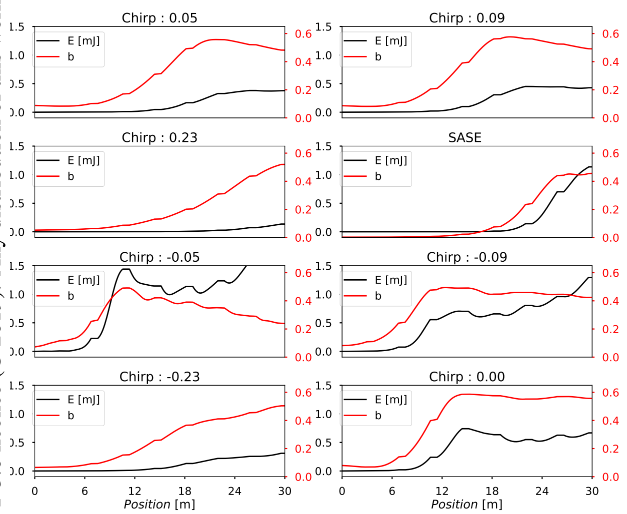

Figure 5: Pulse energy (black plot line) and bunching (red plot line) for different chirps in the electron beam along the radiator.

Spectra

We begin our spectral analysis looking at Figure 6 where the spectra of different chirp cases are plotted. As a first observation we find that the spectra of all the EEHG have a FWHM bellow 0.05% except the -0.05 case which is 0.2%, five times as wide. By looking at the phase space at the exit of Chicane 1 for this specific chirp, Figure 7 , We can see that the there are different chirps along the beam detail that does not appear in the other cases. We suspect this generates bunching at slightly different wavelengths that creates this broadening but further investigation is needed.

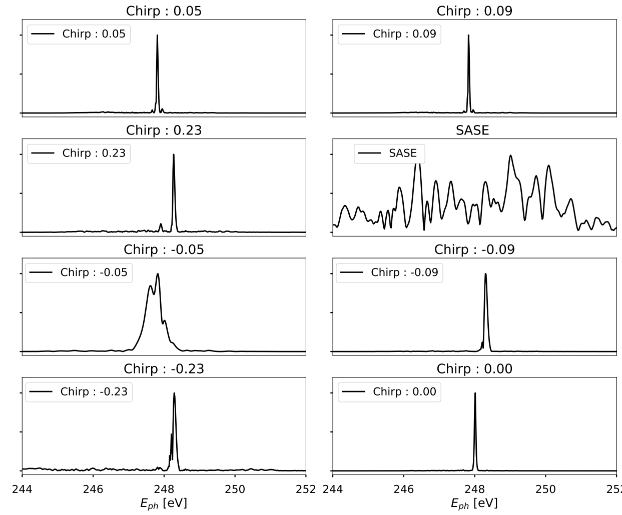

Figure 6: Spectra for different chirps and SASE at saturation (black) and after two undulator periods (red).

Negatively chirped shots have, in general, broader spectra, this may be due to the the fact that in Chicane 1 the they pass through a phase of over bunching that increases the energy spread, and the -0.05 is an extreme case of that. Out of the EEHG shots the 0 chirp has the narrowest spectra.

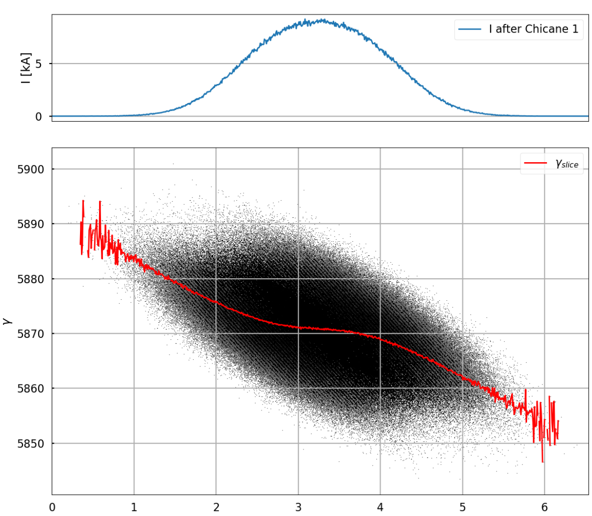

Figure 7: Phase space for -0.05 scaled chirp with slice energy along the bunch at the exit of chicane 1.

CONCLUSIONS

We have studied the chirp influence on EEHG FEL and shown that there is a strong dependency of the FEL radiation quality with the chirp for a given EEHG configuration. In our simulations we still found that 0 chirp is preferable but there are also advantages of certain combinations of chirp and chicane strength. Further work is needed to properly evaluate the over-compressing cases or possibly integrate the bunch compression as part of the EEHG scheme.

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