FEMTOSECOND X-RAY PULSE GENERATION WITH AN ENERGY CHIRPED ELECTRON BEAM

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Abstract

We study the generation of short (sub 10 fs) pulses in the X-ray spectral region using an energy chirped electron beam in a Self Amplified Spontaneous Emission Free Electron Laser (SASE FEL) and a self-seeding monochromator [1-4]. The monochromator filters a small bandwidth, short duration pulse from the frequency chirped SASE spectrum. This pulse is used to seed a small fraction of the long chirped beam, hence a short pulse with narrow bandwidth is amplified in the following undulators. We present start-to-end simulation results for LCLS operating in the soft X-ray self-seeded mode with an energy chirp of 1% over 30 fs and a bunch charge of 150 pC. We show the possibility to generate 5 fs pulses with a bandwidth 0.3 eV. We also assess the possibility of further shortening the pulse by utilizing one more chicane after the self-seeding stage and shifting the radiation pulse to a "fresh" part of the electron beam. Experimental study on this short pulse seeding mode has been planned at the LCLS.

INTRODUCTION

Ultrashort x-ray pulses of femtosecond to sub-femtosecond duration are important for time-resolved ultrafast studies in chemistry, biology, and material science. Operating in the self-amplied spontaneous radiation (SASE) mode [1], different schemes have been proposed in the past years to shorten the x-ray pulses. One such method, using a configuration similar to the selfseeding setup, was first proposed by Schroeder et al. [2]. In this mode, the electron beam has a time-energy correlation and a monochromator selects a narrow-bandwidth seed to interact wiith a small fraction of the chirped bunch. The central wavelength is determined by the monochromator hence the output central wavelength would be stable against beam energy jitter. In this paper we study the generation of femtosecond level pulses in start-to-end simulations for the LCLS beam.

A time-energy chirped beam can be generated in an over-compression mode in the second chicane compressor at LCLS. In this mode, the bunch head has higher beam energy than the tail. This chirped beam generates wide-bandwidth SASE radiation before the Soft X-ray Self Seeding (SXRSS) chicane. We choose the appropriate number of undulator sections to reach a radiation power on the 10MW level before the SXRSS monochromator. After the monochromator grating, we achieve a narrow-bandwidth seed determined by the monochromator resolving power. For a resolving power R the rms bandwidth is σ_m=1/(2.355*R). After the monochromator the pulse duration is given by [4]:

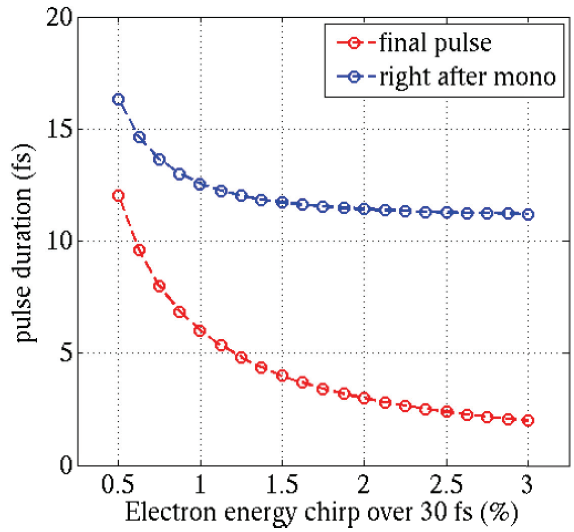

Figure 1: Theoretical expected pulse duration given by Eq. 1 right after the mono and at the end of the undulator. Prediction is in excellent agreement with simulation results for a beam with a 1 % chirp over 30 fs.

$$\sigma_{t,m}^2 = \frac{\sigma_\omega^2 + \sigma_m^2}{u^2} + \frac{1}{4\sigma_m^2} \quad (1)$$

where σ_ω is the SASE bandwidth, σ_m is the monochromator bandwidth and $u = \Delta\omega/\Delta t$ is the energy chirp on the beam. After the amplification process the pulse duration shortens and is dominated by the SASE bandwidth and the energy chirp $\sigma_{t,f} \approx \sigma_\omega/u$. The pulse length expected as a function of the electron beam chirp is shown in Fig. 1. Slippage of the radiation spike along the chirped beam requires reverse tapering of the undulator field in order to preserve the resonance condition and amplify a short pulse [5, 6]. In the amplifying section after the SXR monochromator only a small fraction of the chirped bunch is on resonance with the seed and will undergo microbunching at the radiation wavelength. To increase the gain and further shorten the pulse duration we consider using a second chicane as an additional delay to shift the radiation pulse to a "fresh" part of the beam downstream of the SXR monochromator. This ensures that the radiation will be continually amplified by a fresh bunch. The delay can be optimized to achieve shorter pulses and superradiant effects may also further shorten the pulse duration.

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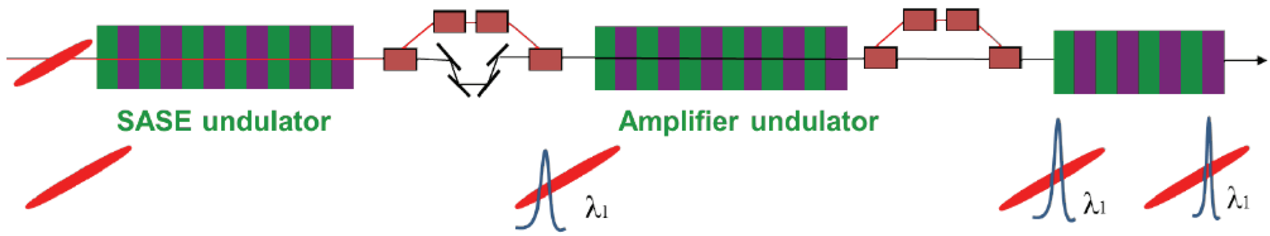

Figure 2: Schematic of the operation mode for soft x-ray self seeding with a chirped electron beam. The second chicane is used as an additional delay to shift the radiation to a “fresh" part of the electron bunch and shorten the pulse duration.

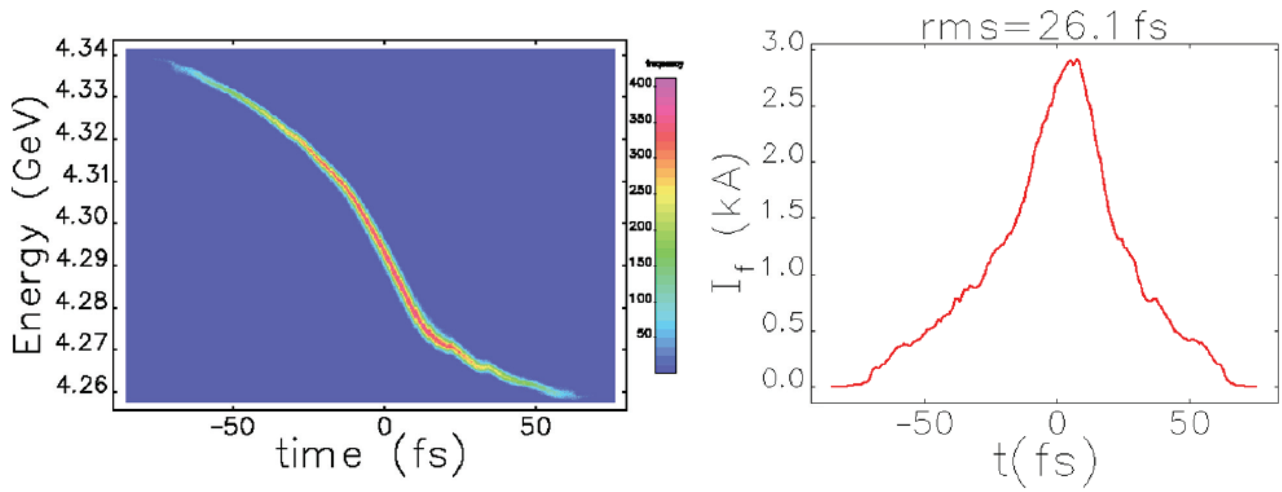

Figure 3: Longitudinal phase space and current profile for the LCLS beam with 150 pC charge and a chirp of 1 % over 30 fs in the core.

Table 1: GENESIS Simulation Parameters

Parameter Name	**Parameter Value**
Undulator:	
Undulator Period λ_w	30 mm
Undulator Parameter aw_0	2.4749
Electron Beam:	
Beam Energy E_0	4.3 GeV
Beam Peak Current I_{pk}	2.8 kA
Normalized Emittances $\epsilon_{x,n}/\epsilon_{y,n}$	0.4/0.4 μ m
Radiation:	
Radiation Wavelength λ_r	1.523 nm
(Before/after SXRSS chicane)	
Peak radiation power P_{in}	1.2GW/ 0.2MW
Pulse Duration FWHM σ_τ	17 fs→ 7 fs

START TO END SIMULATION STUDY FOR LCLS

Soft X-ray Self Seeding

We study the chirped seeding method in start to end simulations of the LCLS electron beam with a bunch charge of 150 pC and an energy chirp of 1% over 30 fs in the core part. The electron beam longitudinal phase space and current profile are shown in Fig. 3, the GENESIS simulation parameters are given in Table 1 [3] and a schematic of the undulator configuration is shown in Fig. 2. The first SASE section is 5 undulators long (20 m) and the SASE bandwidth generated is larger than 1% for this chirped beam. After the SXRSS monochromator with a resolving power of 5000 the bandwidth of the seed spike is 0.14 eV FWHM and the pulse length is approximately 13 fs consistent with the expected vaules from Eq. 1. We align the seed to the core part of the bunch and allow the bunch to amplify the radiation for 5 undulators between the SXRSS chicane and the second chicane. We find empirically that peak power is maximized for the shortest pulse duration with no tapering of the undulator K in the section between the two chicanes. This is due to the combined effects of radiation slippage towards the high energy part of the beam and electron beam energy loss due to the FEL process. The time domain and spectral evolution of the radiation between the SXRSS monochromator and the second chicane delay are shown in Fig. 4. At the second chicane after 20 m of amplification a peak power of 20 GW is achieved with a narrow bandwith of 0.3 eV and a pulse duration of 7 fs, also in excellent agreement with the theoretical prediction shown in Fig. 1.

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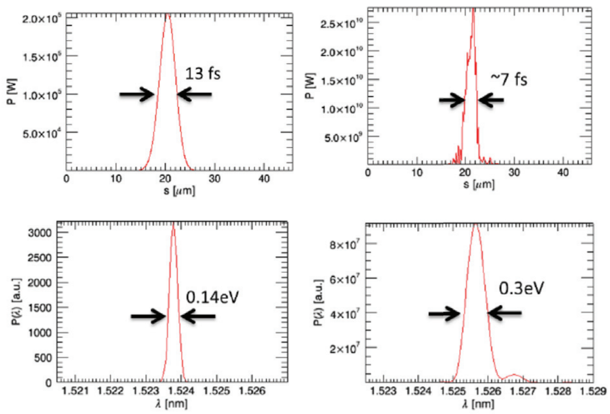

Figure 4: Evolution of the FEL pulse in the time and frequency domain for a chirped beam in the self-seeded operation mode. The left column is after the SXRSS monochromator and the right column is after 20 m of amplification before the second chicane.

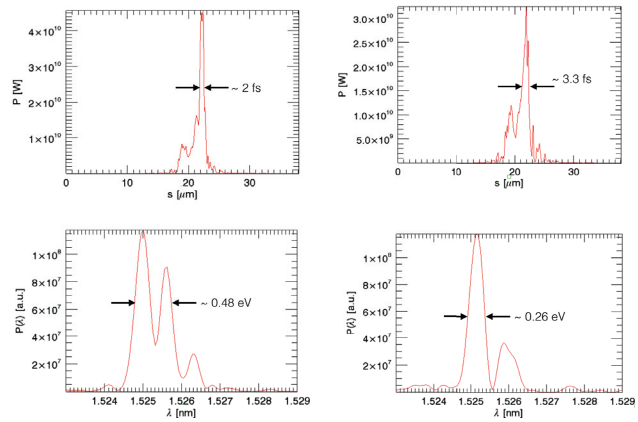

Figure 5: Time and frequency domain for a chirped beam in the self-seeded operation mode 4m downstream of the second chicane delay. The left column is for a 1 μm chicane delay and the right column is for 0.5 μm delay.

Fresh Bunch Technique

We then optimize the delay in the second chicane to further shorten the pulse and amplify using a fresh part of the electron beam. The time domain and spectrum 4 m downstream of the second chicane for two separate delays of 0.5 and 1 μm are shown in Fig. 5. Examining the spectral and time-domain evolution of the pulse we find that the shortest pulse ~ 2 fs, a FWHM bandwidth of 0.48 eV and a peak power of 45 GW is generated with a chicane delay of 1 μm. This delay corresponds to roughly half the pulse overlapped with fresh electrons. In this case the gain for the head of the radiation pulse is larger than for the tail and as a result the radiation pulse compresses in the time domain. For a larger delay of 2 μm the peak power of the radiation pulse increases but the pulse is longer in time ~ 6 fs. A smaller delay of 0.5 μm produces ~ 3.3 fs pulse with a cleaner spectrum and a peak power of 30 GW. The spectrum will ultimately become polluted if we amplify for more than two undulators after the second chicane due to the growth of the SASE from the chirped beam.

Experimental study of the chirp seeded mode are in progress at LCLS. Preliminary results show that pulses of ~ 10 fs time duration can be produced without using the second chicane delay. Data analysis for these experiments is ongoing.

CONCLUSION

We performed start to end simulations of femtosecond X-ray pulse generation using an energy chirped electron beam and a self-seeding monochromator at the LCLS. We consider a shceme originally proposed in Ref [2] in which a time-energy chirped electron beam is used to produce frequency chirped SASE, the frequency chirped SASE is filtered by a monochromator and recombined with the electron beam. A downstream undulator section is then used to amplify a narrow spike of radiation in both the time and frequency domain.

Using the LCLS start to end electron beam with 150 pC of charge and an energy chirp of 1 % over 30 fs in the core part we produce 12 GW of SASE power with >1 % bandwidth using 5 undulators before the SXRSS chicane. The large bandwidth improves wavelength stability after the monochromator against electron beam energy jitter coming from the linac. The monochromator selects a narrow bandwidth signal which is amplified in the following undulators by preserving the resonance condition over a short section of the chirped electron beam. The pulse duration after the monochromator is 17 fs and following 20 m of amplification, the pulse narrows to a FHWM duration of 7 fs and 20 GW peak power before the second chicane delay.

We then make use of the second chicane to introduce an additional delay and shift the radiation pulse to a “fresh" part of the electron beam. This increases the gain and with a 1 μ m delay reduces the pulse duration to ~ 2 fs, 4m downstream of the second delay. The peak power reaches 45 GW at this location. Smaller and larger delays are investigated, with larger delays producing higher peak powers but longer pulses. A shorter delay of 0.5 μ m reduces the peak power but produces a cleaner spectrum with a pulse duration ~ 3.3 fs. The main factor limiting further amplification is the growth of SASE from the chirped electron beam. Increasing the signal to noise ratio after the SXRSS monochromator will act to suppress this effect. Experimental investigations are ongoing at LCLS with initial results suggesting that ~ 10 fs pulses can be generated using the chirp-seeded configuration.

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