STAGED SELF-SEEDING SCHEME FOR NARROW BANDWIDTH, ULTRA-SHORT X-RAY HARMONIC GENERATION FREE ELECTRON LASER AT LINAC COHERENT LIGHT SOURCE*

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Abstract

Success of the world's first x-ray (0.15-1.5 nm) free electron laser (FEL) - LINAC Coherent Light Source (LCLS) opens the gate for new science. In this paper, we study the FEL performance for a two stage self-seeding scheme by introducing a photon monochromator and an electron by-pass in the undulator system. The FEL generated in the first part of the undulator system is purified in spectrum, recombines with the electron bunch, and is amplified in the second part of the undulator system to saturation. Such modifications will improve the FEL longitudinal coherence, reducing the FEL band-width by orders of magnitude, but with similar peak power; hence improving the peak spectrum brightness by orders of magnitude. Such a self-seeding scheme is studied for both soft x-ray (200 eV to 2 keV) and hard x-ray (800 eV to 8 keV) cases. The photon monochromator system is configurated as variable line spacing gratings for soft x-ray and crystals for hard x-ray. Harmonic Generation and Chirped FEL are also considered aiming at reaching even shorter wavelength x-ray photons and at generating FEL pulse with even shorter temporal duration, respectively.

Introduction

The success of the LINAC Coherent Light Source (LCLS) [1] motivates an extension of the capacity, capabilities, and quality of this revolutionary new light source. Here, we study the possibility of generating narrow bandwidth FEL at LCLS via self-seeding scheme which was originally proposed some time ago [2] and is shown schematically in Fig. 1 . In such a self-seeding scheme, a photon monochromator is introduced between two undulator systems. The monochromator system will purify the FEL generated from the first undulator. The spectrally purified FEL pulse then servers as the highly coherent seed into the second undulator system to interact with the electron bunch again to configurate a seeded FEL amplifier. The first undulator system is configurated into a conventional Self-Amplified Spontaneous Emission (SASE) FEL, but works in the linear exponential regime (well) before saturation. This is important, since the same electron bunch will be used for the second undulator system, the FEL induced energy spread has to be small enough to support the exponential growth in the second undulator. This is very much like High Gain Harmonic Generation FEL [3], the first undulator, the modulator only induces small amount of energy modulation. Through out the paper, detailed FEL numerical simulation is performed with GENESIS [4] code.

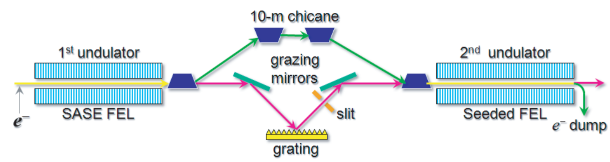

Figure 1: Schematics of the two-stage self-seeding scheme.

According to the LCLS upgrade plan, there will be both soft x-ray FEL beam line and hard x-ray FEL beam line, hence self-seeding is considered for both soft x-ray and hard x-ray. The monochromator for the soft x-ray FEL is considered to be a rotational planar variable-line-spacing (VLS) gratings [5]. A preliminary design of the gratings adopts constant focal-point mode, so that we have fixed slit location. The optical delay varies within 10 $\%$ with a nominal value of 5 ps, when tuning the FEL energy. The electron by-pass chicane will provide R_{56} of about 3 mm to smear out the microbunching generated in the first undulator, but will still be weak enough not to degrade the electron bunch. The excursion of the chicane is about 10 cm. Hence, the electron bypass chicane and the photon optics may have to be in two orthogonal planes, one in the x- and the other in the y-plane. For hard x-ray self-seeding, we plan to use crystals. In a conventional 4-crystal monochromator, it is difficult to make the optical delay to be smaller than 2 to 3 mm, hence the electron by-pass chicane has to provide R_{56} on order of 5 mm, which will make the chicane quite long in size. Hence, using the seed generated from one electron bunch, but interacts with the next coming electron bunch becomes interesting [6]. A yet more interesting proposal is to use monochromatized wakefield for self-seeding with single electron bunch [7]. Shown in Fig. 1, as an example, the monochromator part is a gratings for the soft x-ray case.

Soft X-ray Self-Seeding FEL Performance

In our study and simulation, we use the same parameters for the electron bunch as the existing LCLS measured electron bunch parameters. For example, based on the start-to-end simulation, when the electron bunch is being under-compressed, the electron current profile $I_{pk}(s)$ exhibits double-horn structure along the internal coordinate s as shown in Fig. 2. Besides the peak current, in general there is local structure and non-uniformity in all the 6-D

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phase space distribution. We carry out FEL simulations with the start-to-end simulated electron bunch 6-D distribution including high-order optics, and known collective effects, like the space charge, the coherent synchrotron radiation, the wakefields, etc. to make the FEL simulation as close to reality as possible.

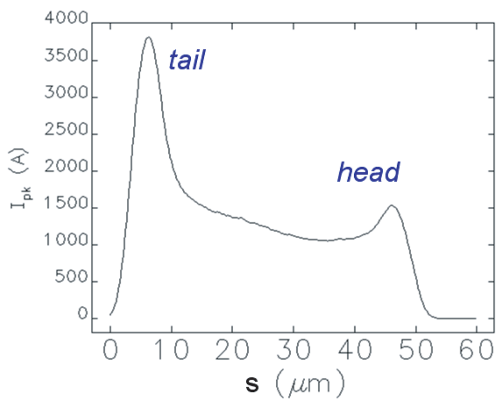

Figure 2: Typical current profile when the electron bunch is under-compressed.

In the following, we show two extreme cases: the FEL of 200 eV, *i.e.*, wavelength of 6 nm, and the high extreme of 2 keV FEL at 6 Å wavelength. The simulation is for the nominal charge of 250 pC. The slice emittance is about 0.6 μm. For the 6 nm FEL, we set the peak current at 1 kA, while for the 6 Å FEL, the peak current is 3 kA. Other parameters and FEL performance are given in Table 1.

Table 1: Soft X-ray FEL Beam Line Self-Seeding Summary at 6 nm and 6 Å

Parameter	6 nm	6 Å	units
Slice Emittance	0.6	0.6	μm
Peak Current	1	3	kA
Pulse Length rms	35	12	fs
Bandwidth FWHM	24	5.2	10^{-5}
Limited bandwidth	15	4.4	10^{-5}
Seed Power	100	100	kW
Power on Mono	50	2000	MW
Mono Efficiency	10	0.2	%
Overall Efficiency	20	0.5	10^{-4}
Saturation Power	5	10	GW
Saturation Length	30	35	m
Brightness Increment	50	150	

It is worthwhile to point out that in Table 1, besides the monochromator efficiency, we also show the overall efficiency, because we have to consider the phase space area conservation. With the monochromator decreasing the bandwidth by 1 to 2-orders of magnitude, the effective power within this smaller bandwidth is smaller by the same order of magnitude, if compared to the overall FEL power shedding onto the monochromator. In other words, it is because this overall FEL has a much larger bandwidth. Hence, the reduction of the FEL power due to phase space area consideration and the monochromator efficiency is substantial. On the other hand, we know the purified seed into the second undulator has to be significantly larger than the shot noise to avoid coherence degradation [8]. For example, in the second undulator for the 6 nm FEL, the startup noise is estimated to be less than kW [9, 10], while after the monochromator, the purified seed is about 100 kW for this particular case, so the seed well dominate the noise. With this amount of seed power, the final FEL at saturation is close to a transform limited pulse with the spectrum shown in Fig. 3.

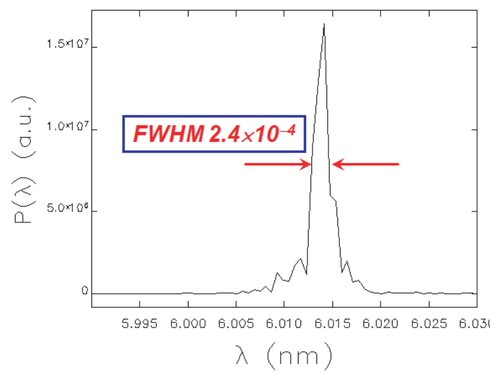

Figure 3: The 6 nm FEL final spectrum indicates a FWHM bandwidth of about 2.4 $\times 10^{-4}$.

Due to the overall low efficiency of the monochromatization process in getting the coherent seed for the 6 Å, we show in Fig. 4 the FEL pulse spectrum bandwidth for the case when the seed power is only 100 kW into the second undulator. The simulation shows that 100 kW seed power is sufficient to generate close to transform limited FEL pulse, even though it is shown in Fig. 4, that bandwidth increment is about to be noticeable. Due to the uncertainty of the monochromator overall efficiency, we performed simulation for even lower seed power into the second undulator, for example, if the seed power is down to 20 kW, the final FEL bandwidth can still be within 2 times of the transform limited bandwidth. On the other hand, if we increase the seed power to 1 MW, not only the FEL bandwidth is close to transform limited, the temporal profile is also more close to uniform as shown in Fig. 5, where the black curve is for the seed power of 1 MW, while the red curve is for seed power of 100 kW. By introducing multi-layer design for the gratings, it is possible to increase the overall efficiency, so that 1 MW seed into the second undulator can be possible.

It is worthwhile to point out that the definition of a transform limited pulse depends on the temporal profile. For example, for a Gaussian pulse, a transform limited pulse means that $\Delta\omega_{\rm FWHM}\sigma_t = \sqrt{2\ln(2)} \approx 1.18$, where σ_t is the rms temporal duration of the pulse intensity, and the pulse intensity full-width-half-maximum (FWHM) bandwidth $\Delta\omega_{\rm FWHM}$ is related to the pulse intensity rms bandwidth σ_ω by $\Delta\omega_{\rm FWHM} = 2\sqrt{2\ln(2)}\sigma_\omega$. On the other

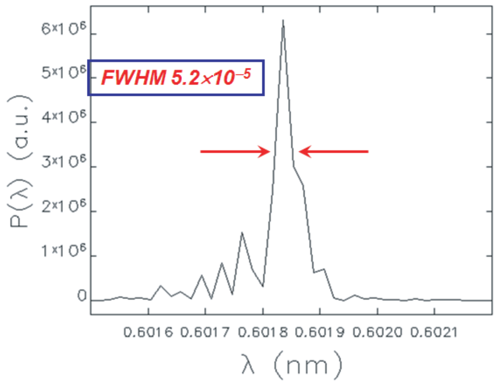

Figure 4: The 6 Å FEL final spectrum indicates a FWHM of about 5.2 $\times 10^{-5}$.

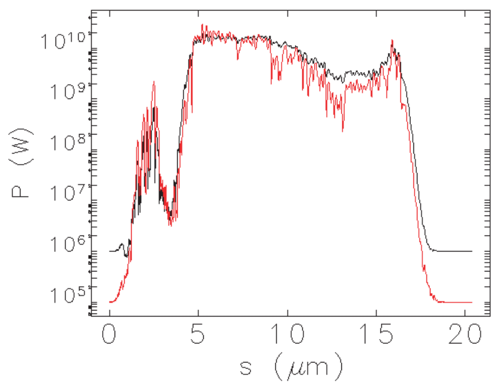

Figure 5: Temporal profile of the 6 Å FEL pulse for cases of 1 MW seed (black) and 100 kW seed (red) power.

hand, if the pulse intensity is temporally uniform, the longitudinal phase space area for a transform limited is $\Delta\omega_{\mathrm{FWHM}}\sigma_t \approx 1.61$. One might compare the equation for the temporal uniform distribution to the equation for the Gaussian pulse, and comments that for a temporal uniform distribution pulse, even if it is fully coherent, transform limited pulse, the bandwidth is larger than that of a Gaussian pulse by a factor of about 36.5 %.

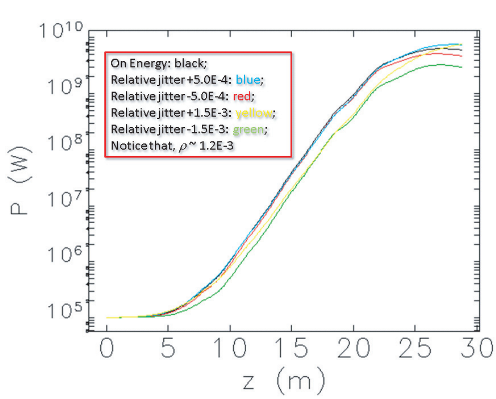

Figure 6: The FEL power evolution along the second undulator for electron bunch having different energy jitter.

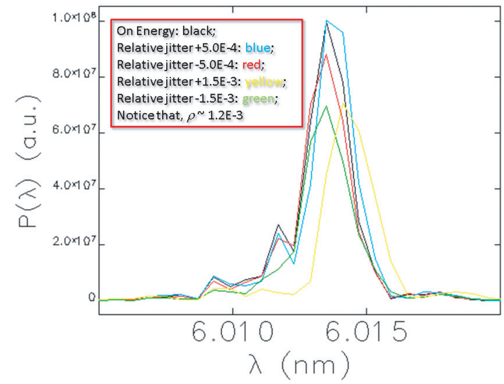

Figure 7: The FEL spectrum profile near saturation point for electron bunch having different centroid energy jitter.

Energy jitter and detuning The electron bunch centroid energy jitter in the self-seeding scheme is translated into a detuning effect in the second undulator FEL amplifier. Here we show a detailed example to capture general features of the detuning effect [11].

We take the 6 nm FEL case, whose FEL parameter is about $\rho \approx 1.2 \times 10^{-3}$. According to LCLS performance [1], the relative centroid energy jitter is about 1.2×10^{-3} for a 4.3 GeV electron bunch, *i.e.*, the jitter is about the same as the FEL parameter ρ. We perform simulation for electron centroid energy having relative jitter of $\pm 5.0 \times 10^{-4}$ and $\pm 1.5 \times 10^{-3}$. The FEL power evolution along the undulator is shown in Fig. 6 for these cases. The black curve is for the case of the relative jitter to be zero, the blue curve for the relative jitter of $+5.0 \times 10^{-4}$, the red curve for -5.0×10^{-4}, the yellow curve for $+1.5 \times 10^{-3}$, and the green curve for -1.5×10^{-3}. The results agree with the general detuning theory. For a positive detuning (the blue and yellow curves), even though the gain length can be longer than that of zero detuning case, the final power at saturation can be even larger; while for a negative detuning (the red and green curves), even the saturation power is smaller. Even though there is noticeable power fluctuation with the energy jitter, the spectrum bandwidth is relatively stable as shown in Fig. 7. The color convention for the five different curves in Fig. 7 is the same as that for the curves in Fig. 6. Due to the details in the 6-D phase space distribution, for the largest positive detuning of 1.5×10^{-3}, there is a small shift for the FEL centroid frequency.

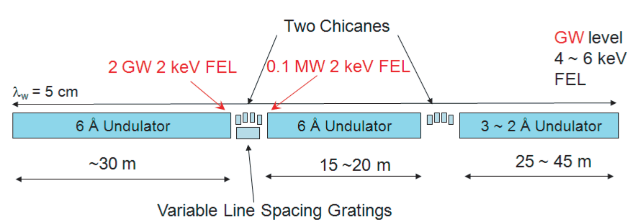

Figure 8: Schematics of a Harmonic Generation FEL in a Self-Seeding FEL configuration.

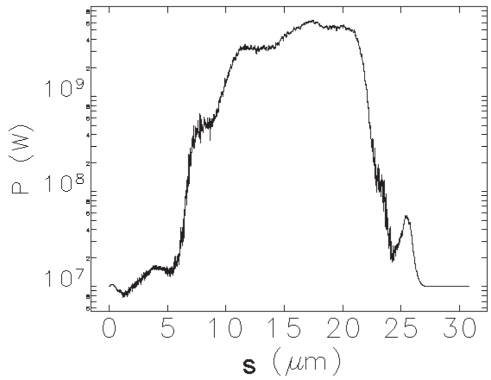

Figure 9: Hard x-ray self-seeding final FEL profile.

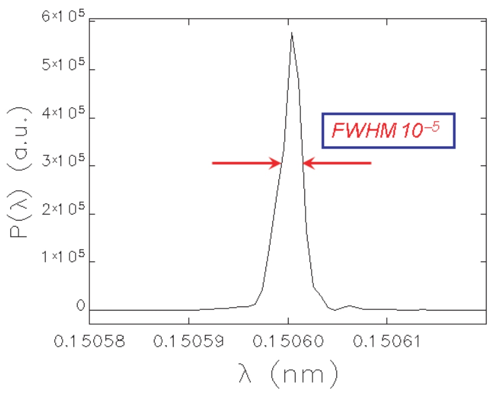

Figure 10: Hard x-ray self-seeding final FEL spectrum.

Harmonic Generation With a self-seeding scheme cleaning up the 6 Å (2 keV) FEL, one can further configure the second undulator system to have Harmonic Generation FEL. Shown in Fig. 8, if a small chicane is introduced into the second undulator system, so that total there will be three undulator systems, then a Harmonic Generation FEL can be configurated in this Self-Seeding FEL scheme. For this particular simulation, the undulator period is set to be $\lambda_w = 5$ cm through out the three stages. In the first two stages the FEL resonant wavelength is $\lambda_r = 6$ Å. The first undulator is about 30 m long to generate SASE FEL of about 2 GW, through the VLS gratings, there is about 0.1 MW seed into the second undulator. The second undulator is about 15 to 20 m long to support the FEL process to generate significant relative energy modulation at 6 Å with amplitude δ_m. Through a small chicane with small R_{56}, so that $\delta_m R_{56} \sim \lambda_r/4$, substantial density modulation at 6 Å and its harmonics is built up at the entrance of the third undulator. If the third undulator is configurated to have resonant wavelength of 3 Å, *i.e.*, the second harmonic, simulation shows that within about 25 m, the 3 Å FEL can saturate. If on the other hand, the third undulator is designed to be resonant at 2 Å, *i.e.*, the third harmonic, then 2 Å FEL can saturate at around 45 m into the third undulator. Further optimization of the system can make the total undulator length shorter. Furthermore, we can choose $\lambda_w = 4.1$ cm as the current thinking for upgrade, then the total undulator length will also be much shorter than that shown in Fig. 8.

Hard X-ray Self-Seeding FEL Performance

In the upgrade plan, we also consider self-seeding for the hard x-ray FEL beam line. As mentioned above, it can be two-bunch scheme with two electron bunches [6], or a single-bunch scheme [7]. These different schemes call for different monochromator design with either 4 crystals or single crystal. Here we show a simulation for the FEL after monochromator. To avoid the monochromator damage issue, here we assume that there is only 10 MW seed at 1.5 Å into the second undulator. The electron peak current is set to be 3 kA, other parameters are the same as the LCLS measured values. The 10 MW seed is amplified to saturation at about 40 m into the second undulator. The temporal profile of this FEL is shown in Fig. 9, while the spectrum is shown in Fig. 10. The simulation shows that a FWHM bandwidth of 10^{-5} is possible, which should be compared to the SASE FEL having a FWHM bandwidth on the order of 10^{-3}. Since the FEL reaches saturation with similar saturation power in the self-seeding scheme, the final FEL spectral brightness is increased by two-order of magnitude.

Discussion In this paper, we discuss the self-seeding scheme for the LCLS upgrade. Studies are conducted for both the soft x-ray FEL beam line and the hard x-ray beam line. If an energy chirped electron bunch is introduced into the system, only part of the electron bunch will radiate in the second undulator, hence, the final FEL pulse can be much shorter than the entire electron bunch length. Due to the limited article length, here we will not present details of such a scheme to generate short FEL pulse.

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