HIGH EFFICIENCY, HIGH BRIGHTNESS X-RAY FREE ELECTRON LASERS VIA FRESH BUNCH SELF-SEEDING*

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Abstract

High efficiency, terawatt peak power X-ray Free Electron Lasers (XFELs) are a promising tool for enabling 3D atomic resolution single molecule imaging and nonlinear science using X-ray beams. Increasing the efficiency of XFELs while maintaining good longitudinal coherence can be achieved via self-seeding and tapering the undulator magnetic field. The efficiency of tapered self seeded XFELs is limited by two factors: the ratio of seed power to beam energy spread and the ratio of seed power to electron beam shot noise. We present a method to overcome these limitations by producing a strong X-ray seed and amplifying it with a small energy spread electron bunch. This can be achieved by selectively suppressing lasing for part of the electron beam in the SASE section and using the rest of the bunch to generate the seed radiation. In this manner one can reach saturation with the seeding electrons and the strong seed pulse can be overlapped with the "fresh" electrons downstream of the self-seeding monochromator. Simulations of this scenario demonstrating an increased efficiency are presented for two systems, an optimal superconducting undulator design and the Linac Coherent Light Source. In the case of the LCLS we examine how the betatron oscillations leading to selective suppression can be induced by using the transverse wakefield of a parallel plate corrugated structure, a dechirper.

INTRODUCTION

Increasing the extraction efficiency of short wavelength Free Electron Lasers (FELs) by tapering the undulator field has been the subject of several recent studies [1] [2] [3] [4] [5]. At hard X-ray wavelengths the motivation for higher peak power and larger phtoon yield comes primarily from the single molecule imaging and nonlinear science communities where X-ray pulses in the TW power scale would open the door for new experimental opportunities. Achieving good longitudinal and transverse coherence as well as high peak power requires careful optimization of the undulator taper profile. As has been shown recently in [5] for a seeded XFEL, this optimization is critically limited by time dependent effects which cause electron detrapping due to oscillations in the electric field amplitude and phase along the electron bunch. These limitations can be overcome by operating the XFEL in a quasi "time independent" regime in which the input seed power is sufficiently large such that it greatly exceeds the electron beam shot noise power. This mitigates detrapping from effects due to slippage, electron beam energy spread and the synchrotron sideband instability.

In a self-seeded XFEL having a large input seed comes at the expense of the electron beam energy spread at the start of the seeded section. This trade-off means that self-seeded XFELs typically operate far from quasi "time independent" conditions and as a result of this their extraction efficiency is limited even after post-saturation tapering. In this work we explore a method to overcome this trade-off by separating the lasing electrons in the first SASE section with the (fresh) electrons amplfying the seed pulse in the seeded section of the XFEL. The SASE radiation is passed through a self-seeding monochromator and an adjustable chicane delay gives control of the temporal overlap between the seed pulse and the fresh electrons downstream of the monochromator. We note that this allows one to control which part of the beam lases in the seeding section (head or core) and adjust the temporal duration of the amplified seed pulse in order to generate short (sub 10 fs) high peak power seeded pulses which is not possible in regular self-seeded operation. In the following section we explain the Fresh Bunch Seeding (FBS) technique in greater detail.

FRESH BUNCH SELF-SEEDING

Fresh Bunch Seeding Schemes

Self seeding a fresh bunch of electrons with a high power, narrow bandwidth hard X-ray seed can be accomplished with a number of schemes:

1. A single bunch set-up in which only the tail of the bunch lases in the first SASE section. The SASE radiation is passed through a monochromator and the seed pulse is moved to the head of the bunch which amplifies the narrow bandwidth signal.
2. A twin bunch set-up in which two bunches occupy the same RF accelerating bucket, the trailing bunch lases in the SASE section and the leading bunch amplifies the seed pulse in the seeding section.
3. A two-bunch set-up in which the two bunches occupy successive RF buckets, the trailing bunch lases in the first SASE section and the leading bunch is used to amplify the seed signal downstream of the monochromator. The advantage of this set-up is the possibility of using a transverse RF deflecting cavity to induce betatron oscillations in the leading bunch in the SASE section and for the trailing bunch in the seeding section.

In this paper we will focus predominantly on the first method which is illustrated schematically in Fig. 1. In the first section we will present the theoretical framework for selective lasing suppression in part of the electron beam.

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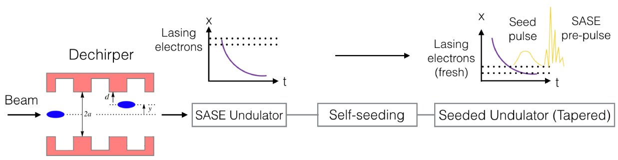

Figure 1: Schematic of the fresh bunch self-seeding experimental set-up with the geometry of the dechirper for the LCLS with a beam on and off axis. The experimental values for the gap and offset are: 2a=4.5 mm, y=1.7 mm

This is accomplished by using the transverse wakefields of a dechirper as a fast passive kicker. We will then present start-to-end simulation results of the first fresh bunch seeding method as applied to the LCLS. We will also discuss the application of the third method to an optimized undulator design [5] in which the fresh bunch seeding method produces multi-TW XFEL pulses and the extraction efficiency is not significantly affected by time dependent effects.

Dechirper as a Passive Transverse Kicker

Using a corrugated structure, or "dechirper", to remove the energy chirp from an electron beam in an XFEL was first proposed in Ref. [6]. As was suggested in Ref. [7] [8] the dechirper can also be used as a passive deflector for example to measure the bunch distribution of very short bunches. As a passive deflector the transverse wakefield of the dechirper generates a correlation between transverse and longitudinal position along the bunch. This effect can be used to deliberately induce large betatron oscillations on part of the electron beam thereby selectively suppress lasing for parts of the bunch. The fresh bunch seeding scheme relies on selectively suppressing lasing for different parts of the electron beam in different parts on the undulator. The tail of the beam lases in the first (SASE) section, and the seed pulse is overlapped with the head of the bunch in the second seeding section. The orbit of the head electrons is corrected and the head of the bunch amplifies the seed radiation beam downstream of the monochromator. Following work done in Ref. [9] we calculate the transverse kick induced by the dechirper and estimate the FEL power gain degradation as a function of the intra-bunch position.

Assuming the beam has a uniform current distribution of small transverse extent and its length is much shorter than the dominant wavelength of the wakefield we can write the bunch wake from Ref. [9]:

$$W_{\lambda y}(y,s) \approx w'_{y0}(y)\frac{s^2}{2l} \tag{1}$$

where l is the bunch length and s is the intra-bunch coordinate. A simple expression for the slope of the bunch wake is given by $w'_{y0} = \pi/(8a^3) * \sec^2\left(\frac{\pi y}{2a}\right)\tan\left(\frac{\pi y}{2a}\right)$ from which we can deterimne the transverse impulse $\delta p_y = eW_{\lambda y}(y,s)/c$ and the angular kick $\delta y' = \delta p_y/p_z$. The angular kick as a function of position is then given by:

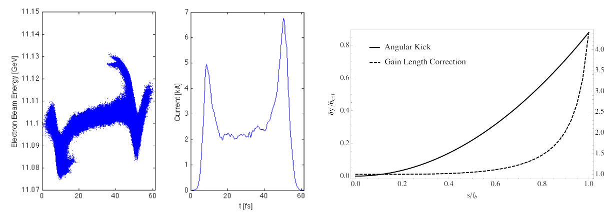

Figure 2: (left) Longitudinal phase space and current profile at the entrance of the undulator for the LCLS start-to-end beam from the particle tracking code ELEGANT. (right) Angular kick and gain length correction factor as a function of intra-bunch coordinate for the LCLS simulation case parameters (see Table 1). Note: head of the beam is at s = 0.

$$\delta y'(s) = \frac{Z_0 c}{4\pi}\frac{eQL}{E}\frac{s^2}{2l}w'_{y0} \tag{2}$$

Where Q is the bunch charge, L is the length of the dechirper and E is the electron beam energy in MKS units. The effect of an angular kick on the FEL gain length has been studied in detail in Ref. [10]. From eq. 42 we have an estimate of the gain length degradation as a function of angular kick $L_g/L_{g0} = 1/\left(1 - \delta y'(s)^2/\theta_c^2\right)$ where $\theta_c = \sqrt{\lambda/L_{g0}}$ is the critical angle beyond which lasing is completely suppressed (see Fig. 2).

Start to End Simulations for the LCLS

Start to end simulations of the LCLS linac and undulator are performed using the simulation codes ELEGANT and GENESIS respectively. The longitudinal phase space at the undulator entrance for a core current of 2.2 kA and an 11.1 GeV beam are shown in Fig. 2. The electron beam is given a quadratic transverse kick consistent with the calculation shown in the previous section and the matching is done such that a 8-10 fs part in the tail end the beam lies on-axis during the first SASE undulator section. As is shown in Fig. 3 the SASE power at the location of the monochromator is 32 GW with a pulse energy of 250 uJ. Assuming the transmission efficiency of the monochromator is 0.5 % this gives 160 MW seed power at the entrance of the seeded undulator, a factor of 15-20 larger than typical values in the 5-8 keV photon energy range at LCLS. The self-seeding section includes an electron beam bypass chicane with a 20 fs temporal delay after which the short seed pulse is overlapped with the head of the beam which travels on-axis downstream.

The post-saturation taper profile in the seeded section takes the form $a_w(z) = a_{w0} \times (1 - c \times (z - z_0)^2)$ and is optimized with respect to the taper start location z_0 and the quadratic tapering amplitude c. The results show the peak power increase to 102 GW at the undulator exit, a gain of over a factor of 6 compared to the SASE saturation power in the absence of undulator tapering. The total FEL intensity at the undulator exit is 1.5 mJ corresponding to 1.7×10^{12} photons. The monochromator bandwidth at

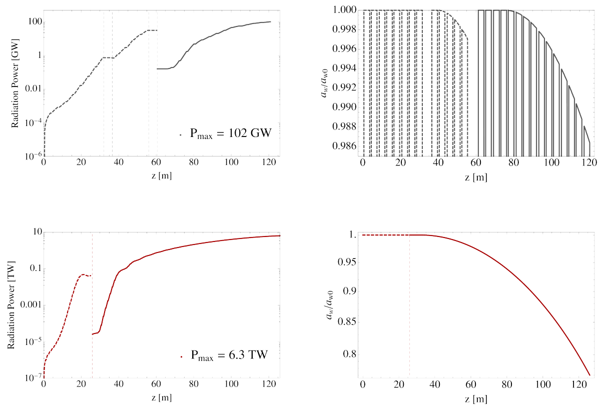

Figure 3: (top) Radiation power and RMS undulator parameter in start-to-end simulations of fresh bunch self-seeding at the LCLS and (bottom) for an optimized superconducting undulator design. The extraction efficiency is over 6 times the SASE saturation level in the LCLS case and in the superconducting undulator case reaches 12 %.

LCLS is on the order 10^{-4}, about a factor of 10 narrower than the SASE bandwidth at saturation. We define the photon beam brightness as $B = N_{ph}/(2\pi\Sigma\sigma_t\sigma_\omega/\omega)$ where $\Sigma = \sqrt{\sigma_x^2+\sigma_r^2}\sqrt{\sigma_{x'}^2+\sigma_{r'}^2}\sqrt{\sigma_y^2+\sigma_r^2}\sqrt{\sigma_{y'}^2+\sigma_{r'}^2}$ is the transverse phase space area, $N_{ph} = \eta N_e$ is the number of photons and η is the extraction efficiency after post-saturation tapering. Assuming a 10 fs seeded pulse and a 50 fs SASE pulse we can write the brightness ratio between SASE and Fresh Bunch Seeded (FBS) photons $B_{FBS}/B_{SASE} = (\eta_{SASE}\Delta t_{SASE}\Delta\omega_{FBS})/(\eta_{FBS}\Delta t_{FBS}\Delta\omega_{SASE}) \sim 5\eta_{FBS}/\eta_{SASE}$

The tapering efficiency for the FBS case is expected to be larger than the SASE due to the absence of large fluctuations in the electric field profile. The above estimates simulation results will be compared to forthcoming experiments at LCLS.

Simulations for an Optimized Undulator Design

We now consider applying the third fresh bunch self-seeding scheme to an undulator designed to achieve TW level pulses in the shortest possible distance: superconducting (K=3), short period ($\lambda_w = 2cm$), with short breaks and built in strong focusing. A detailed analysis of the tapering optimization for this kind of undulator design is given in Ref. [5]. The analysis of Ref. [5] shows that the input seed power is critical to the tapering optimization and extraction efficiency. In the simulation case presented we use a seed power of 25 MW which corresponds to approximately 5 GW incident on the monochromator assuming an efficiency similar to the LCLS. We note that the power reaches this value in the SASE section before exponential saturation around 15 m and that it is possible to generate a ~ 8 times larger seed by taking the SASE section to saturation. In contrast with the LCLS case, here we consider overlapping the seed pulse with a completely fresh beam with all electrons on axis and matched to the lattice. The evolution of the radiation power in the post-saturation tapering region shows a constant power growth with little sign of taper saturation. Spectral analysis shows that the integrated sideband power remains below 10 % of the total power for the entire undulator. This results in a reduced sensitivity to electron detrapping due to the synchrotron sideband instability and is a result of the large ratio between input seed power and electron beam shot noise at the start of the seeding section. The final power at the undulator exit is 6.3 TW, a 12 % extraction efficiency and 11.8×10^{13} photons.

CONCLUSION

In this work we have presented a novel method to increase the extraction efficiency of a self seeded tapered hard X-ray FEL. The scheme consists in separating the lasing portions of the electron beam in the SASE and seeding section so as to avoid the trade off between seed power and energy spread downstream of the self-seeding monochromator. We have proposed achieving this selective suppression by using the transverse wakefield of a parallel plate dechirper to induce a spatial chirp along the electron bunch. The spatial chirp, coupled with appropriate orbit correction allows for separate lasing in the head and tail of the beam before/after the self-seeding chicane. We have performed start to end simulations of this scheme for the LCLS operating at 5.5 keV photon energy. The results show that the peak power at the undulator exit is around 100 GW, the FEL pulse intensity is 1.5 mJ and the extraction efficiency is 0.45% a factor of 6 larger that the SASE saturation value and a factor of 2.3 larger than the SASE power after post-saturation tapering. The photon beam brightness is also expected to increase by at least a factor of 5 compared to SASE. Experimental confirmation of simulation results at the LCLS is currently under investigation.

We have also analysed the fresh bunch seeding technique as applied to an optimized undulator design tailored to achieve TW peak power levels in the shortest possible distance. In this case the scheme uses two bunches separated by one RF bucket, the betatron oscillations are induced by a transverse deflecting cavity and a photon beam delay is used to move the seed radiation from one pulse to the next. As described in Ref. [5] the tapering optimization in this case does not suffer significantly from time dependent effects and the extraction efficiency is similar in single frequency and time dependent simulations. With a seed power of 25 MW and a seeding undulator section of 100 m the final power at the undulator exit is 6.3 TW, an extraction efficiency of 12 % sufficient for enabling 3D atomic resolution single molecule imaging and nonlinear science.

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