COHERENT X-RAY SEEDING SOURCE FOR DRIVING FELS*

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Abstract

The success of the hard X-ray self-seeding experiment (HXRSS) at the LCLS is very important in that it provided narrow, nearly transform-limited bandwidth from the FEL, fulfilling a beam quality requirement for experimental applications requiring highly monochromatic X-rays. Yet, because the HXRSS signal is generated from random spikes of noise, it is not a truly continuous monochromatic seed signal and even higher FEL performance would be achieved using a continuous seed source. We propose developing such a source using a low-Q X-ray cavity to achieve a continuous, narrowband X-ray seed signal. The low-Q cavity works like a return path for the fields, produced in the undulator situated within an X-ray cavity. We do not assume that X-ray fields can be coherently stored in the cavity because of the high tolerances on the cavity length. But we assume that the undulator works as a very high gain amplifier, which compensates amplitude loss due to X-ray reflections in the cavity. The cavity may consist of several elements, which can reflect X-rays by several degrees to make a total of 360 degrees. For example, the elements could be four crystals with a corresponding Bragg angle of about 45 degrees each with additional small angle correcting elements. In this case, the amplitude loss is due to the small bandwidth of the reflected fields. The frequency spectrum of the final X-ray signal will be determined by the bandwidth of the reflected elements. This is not a very new idea. A regenerative-amplifier FEL (RAFEL) has been even demonstrated in the infrared wavelength region [1] and discussed in the angstrom wavelength region [2, 3]. In this study we analyze the interaction of X-rays and electron beams with this cavity. The electron beam source in this proposal uses a train of electron bunches initially accelerated in a linear accelerator which then pass through a radiator element situated within an X-ray cavity.

A CONCEPT

The basic schematic is shown in Fig. 1. We suggest using several LCLS undulators [4] as the radiator element inside the X-ray cavity. We may use the same type of crystals that are currently in use in the XCS experiment (The X-ray Split Pulse Experiment) at the LCLS. Two chicanes provide a path for the electron beam around the X-ray cavity crystal mirrors. The electron beam goes through the first chicane avoiding the X-ray cavity mirrors, then passes through the cavity undulator making the X-ray beam for the cavity and then goes through the second chicane again avoiding the X-ray cavity mirrors. Then the beam enters the main part of the LCLS undulators (output undulators). SASE radiation from the leading electron bunch in a bunch train is spectrally filtered by the Bragg reflectors and is brought back to the beginning of the cavity undulator to interact with the second beam bunch. The X-ray pulse that circulates in the cavity repeatedly interacts with consecutive electron bunches in the train, forming a regenerative amplifier FEL. This process yields a growing laser field in the x-ray cavity if the amplification of the field in the cavity undulator is more than the reflection losses. The FEL interaction with these short bunches regeneratively amplifies the radiation intensity because the crystal reflectors filter the radiation, making the frequency bandwidth smaller. The last bunch of a train (or all bunches) after becoming highly monochromatic goes into the main part of the undulators and produces high power monochromatic radiation. Compared to a SASE X-ray FEL, this approach should need a shorter main undulator length. A small number of electron bunches may generate multi-GW x-ray pulses with excellent temporal coherence. The resulting spectral brightness of these x-ray pulses can be another 2 to 3 orders of magnitude higher. It is important to mention that we do use the X-ray cavity in a fundamental way, as a cavity with resonator eigenmodes. We use only the last return X-ray pulse, which modulates the next coming bunch. Due to the large single-pass gain in the X-ray cavity, the output intensity at the cavity exit is orders of magnitude above the input.

As with classical FEL, the beam energy (a few GeV) corresponds to the radiation wavelength. The beam energy spread and beam emittance must not be above the usual FEL requirement. The electron bunch pattern may consist of an initial train of relatively low current bunches followed by a high current bunch. The bunch spacing depends upon the total length of the undulators inside the cavity. However there is no strong requirement on the arrival time because the reflected X-ray pulse length is increased (~ps) due to the frequency filtering (because of the multiple reflections inside the crystal).

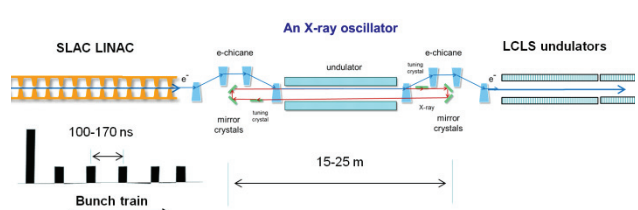

Figure 1: A proposed layout of an X-ray oscillator using high-energy electron beam.

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ISBN 978-3-95450-126-7

COMPUTER SIMULATIONS

To demonstrate the advantage of our concept we have made a simulation comparison with the LCLS FEL [4]. We take approximately the same parameters for the undulators and the beam used the modified code, developed by Z. Huang [5] for a 1D FEL model.

Results for LCLS FEL Simulation

We consider the X-ray wavelength to be around 0.15 nm, the FEL beam parameter to be $5\cdot10^{-4}$, total undulator length of 56 m. These parameters provide the following results: output averaged power of $1.6\cdot10^{10}$ W and relative R.M.S. bandwidth of $5\text{-}6\cdot10^{-4}$. Figures 2-4 show power gain along the undulators, the X-ray pulse and its frequency spectrum.

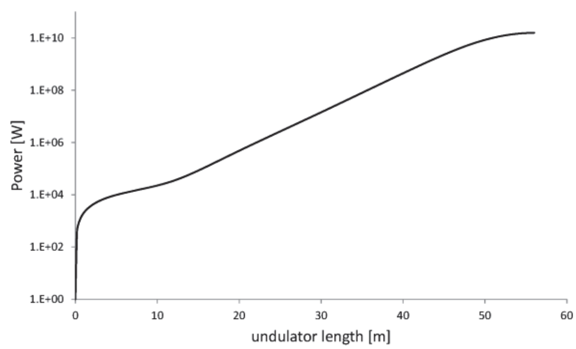

Figure 2: Power gain along undulators.

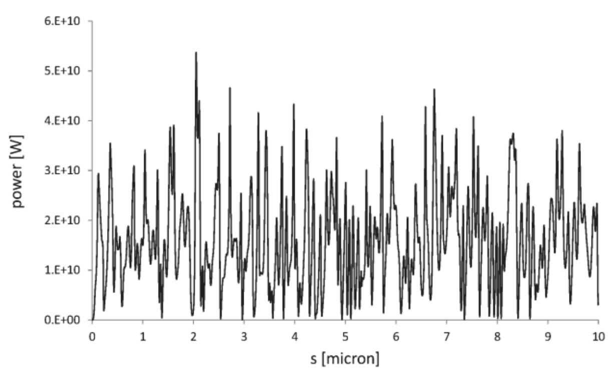

Figure 3: Time structure of the radiation power.

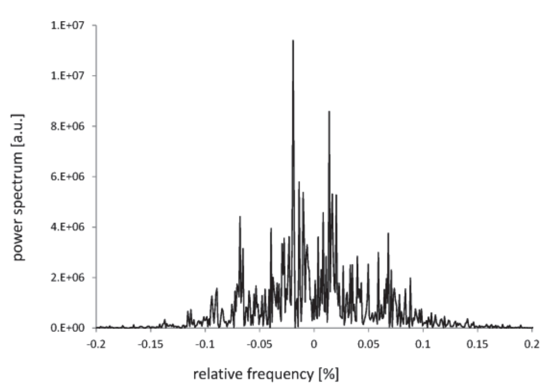

Figure 4: Spectrum of the output signal.

Bandwidth and Reflection Loss

The use of crystals as X-ray mirrors brings frequency filtering that in some sense means power loss not only for out band frequencies but also for the main frequency due to lengthening of the pulse. We use a convolution method to calculate the reflected X-ray signal:

$$E(t) = e^{-i\Delta\omega t} \int_{-\infty}^{\infty} E(t-\tau)\, W(\tau,\sigma_\omega) d\tau \qquad (1)$$

together with a Gaussian filter:

$$W(\tau,\sigma_\omega) = \frac{\sigma_\omega}{\sqrt{2\pi}} e^{-\frac{(\sigma_\omega \tau)^2}{2}} \qquad (2)$$

or a rectangular filter:

$$W(\tau,\sigma_\omega) = \frac{sin\left(\frac{\sigma_\omega \tau}{2}\right)}{\pi\frac{\tau}{2}} \qquad (3)$$

Δω is the difference between a frequency of undulator radiation and the central frequency of the filter. We show the results of Gaussian filtering for the output signal (Fig. 3) at Fig. 5.

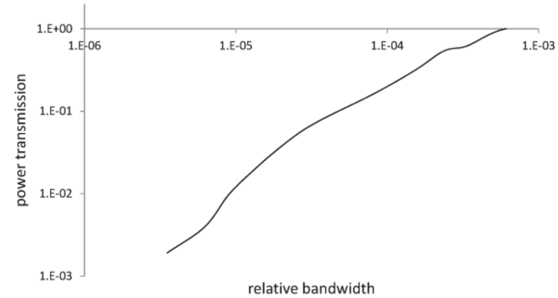

Figure 5: Power transmission as a function of the reflection filtering.

As can be seen in Figure 6, we can make an X-ray bandwidth that is less than 10^{-5}, if we can compensate for the power loss of 20-30 db and make the reflected X-ray signal dominate the field due to the stochastic beam structure. To do this, according to Fig. 2, we will need at least 2-3 SLAC undulators (8-12 m).

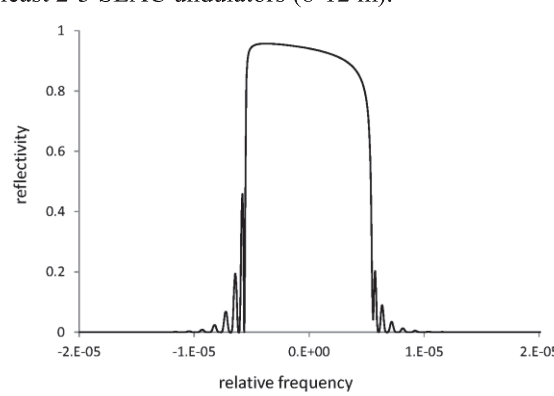

Figure 6: Spectrum reflectivity of four diamond (311) crystals.

ISBN 978-3-95450-126-7

Concerning the mirrors, we can choose 100μ thick diamond crystals. Bragg's angle of 45 degrees can be found at Miller indices of 311 for the wavelength of 0.152 nm. The reflectivity curve of p-polarized radiation from four crystals is shown in Fig. 6. We use code XOP [6] for these calculations. The reflectivity shape is not very far from rectangular, having a small (10%) slope. Transmission power is not high, but enough to make the Q-value of X-cavity itself less than 10. The total bandwidth is around $1.0\cdot10^{-5}$ and the R.M.S. bandwidth is $3.0\cdot10^{-6}$.

Simulations for Three SLAC Undulators

We checked how many undulators inside an X-ray cavity we would need and how many electron bunches are needed to come to saturation, which depends upon the number of undulators after the X-ray cavity. We found that the minimum number of undulators must be three (12m). If we keep same total length of undulators including undulators inside X-ray cavity we will need only 3 electron bunches to come to saturation. In this case we will achieve the same output power, but with only two times smaller bandwidth in compared to the "classical" LCLS FEL regime. If we continue to increase the number of bunches we can get a much smaller bandwidth for less total undulator length (fewer undulators after the X-ray cavity). The number of bunches, total undulator length, output power and bandwidth are shown in Table 1.

Table 1: Achievable Bandwidth

Number of bunches	Total pulse length[μs]	Undulator length [m]	Output power [W]	Bandwidth
1 (LCLS)	-	56	$1.58\cdot10^{10}$	$6.1\cdot10^{-4}$
3	0.3	56	$1.67\cdot10^{10}$	$3.3\cdot10^{-4}$
6	0.6	40	$1.74\cdot10^{10}$	$3.5\cdot10^{-5}$
8	0.8	28	$1.77\cdot10^{10}$	$1.3\cdot10^{-5}$

Figure 7 shows power gain in undulators including X-ray cavity undulators for the case of 6 bunches and 40 m of undulators. We reach the same power (you may compare this plot with Fig.2).

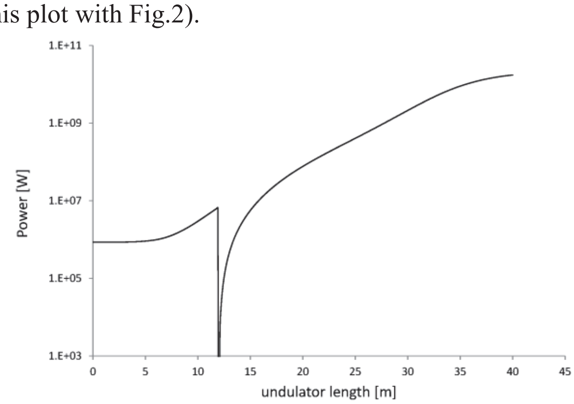

Figure 7: Power gain in X-ray cavity and output undulators.

The time signal or power distribution along the last bunch is shown at Fig. 8.

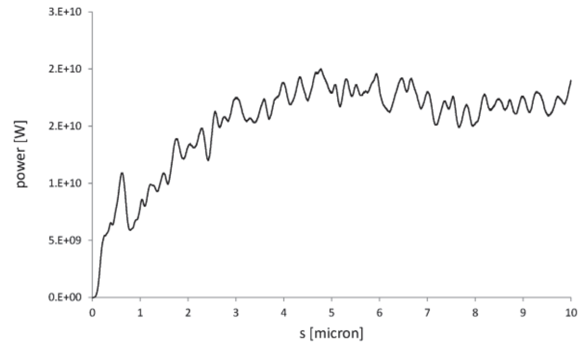

Figure 8: Power distribution along the last (6) bunch.

If you compare this plot with Fig. 3 you may see that the distribution becomes much smoother. We show the spectrum of the output power in Fig. 9.

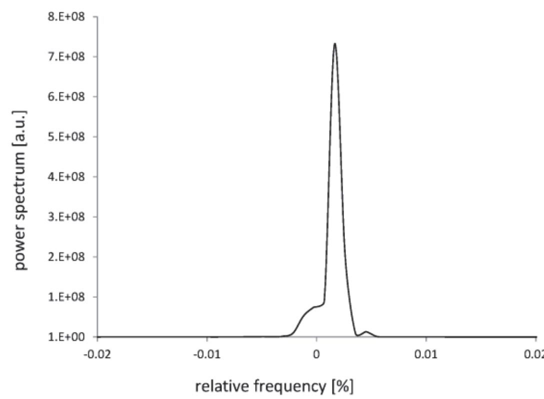

Figure 9: Spectrum of the output signal. Frequency scale is ten times smaller than at Fig.4.

CONCLUSION

In simulations we have achieved very efficient lasing with the regenerative amplifier free-electron laser. The results demonstrate the utility of an X-ray cavity to achieve high-monochromatic X-rays. Work is in progress to understand more details of this proposal.

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ISBN 978-3-95450-126-7