# AN OSCILLATOR CONFIGURATION FOR FULL REALIZATION OF HARD X-RAY FREE ELECTRON LASER*

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*Abstract*

An X-ray free electron laser oscillator (XFELO) is feasible by employing an X-ray cavity with Bragg mirrors such as diamond crystals. An XFELO at the 5th harmonic frequency may be implemented at the LCLS II using its 4 GeV superconducting linac, producing stable, fully coherent, high-spectral-purity hard x-rays. In addition, its output can be a coherent seed to the LCLS amplifier for stable, high-power, femto second x-ray pulses. We summarize the recent progress in various R&D efforts addressing critical issues for realizing an XFELO at LCLS II.

## INTRODUCTION

The basic configuration of an XFELO is illustrated in Fig. 1, in which an x-ray pulse is trapped in an x-ray cavity. The pulse will then be repeatedly amplified in an undulator located in one of the straight path in the cavity, and the pulse intensity starts to increase exponentially if the gain is larger than the roundtrip loss. For hard x-rays, large-angle, low-loss reflection can be accomplished by Bragg crystals as first proposed in 1983 [1]. It took more than two decades, after having witnessed the realization of a single pass x-ray amplifier, to theoretically demonstrate that an XFELO will be feasible with achievable parameters of electron beam, undulator, and Bragg crystal parameters [2]. With the zig-zag path shown in Fig. 1, the Bragg angle, and therefore the photon energy is arbitrarily adjustable [3,4]. Another important advantage of the zig-zag path is that the choice of the Bragg crystal can be made from considerations other than the photon energy coverage. We choose diamond as having the most optimal optical and thermos-mechanical properties.

### *An LCLS II-based XFELO*

The XFELO performance based on a 7 GeV superconducting electron linac in the range of 5 to 25 keV using fundamental harmonics has been studied and shown to be well-suited for hard x-ray photon sciences in areas complementary to self-amplified spontaneous emission [5]. It was then pointed out that an XFELO can be run at harmonic frequencies. The electron energy can then be reduced, reducing the cost of the accelerator [6]. We have therefore studied a 5th harmonic XFELO based on the 4 GeV superconducting linac that will be built for the LCLS-II project [7]. A preliminary study found the XFELO performance satisfactory and also identified the ESA building to be a possible site at SLAC [8,9].

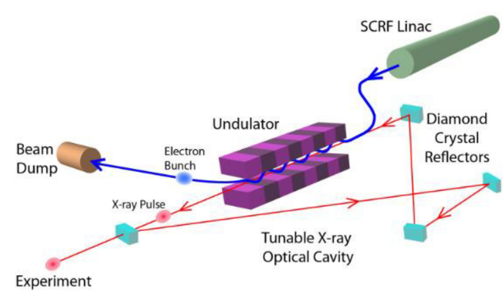


Figure 1: Layout of an XFELO facility.

## XFELO PERFORMANCE

An XFELO requires a low-emittance, small-energy-spread electron bunch. The bunch length should be sufficiently long to have a good overlap with narrow-band x-ray pulse. Optimization of LCLS II injector and accelerator parameters has been performed, the main challenge being to maintain the flatness of the electron energy over the length of the electron bunch [10]. The result is shown in Fig.2.

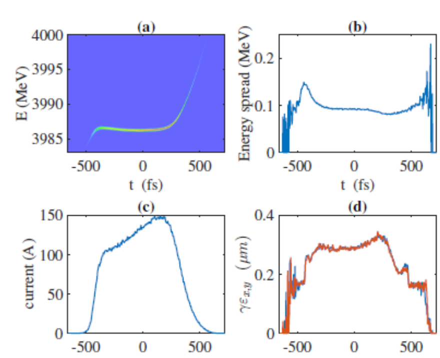


Figure 2: Electron beam optimized for flat energy distribution [10] .

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The XFELO performance at 14.4 keV using the electron beam distribution obtained in the above was simulated with GINGER, and the resulting spectral and temporal pulse shapes of output are shown in Fig. 3. A summary of the major parameters of an XFELO at LCLS-II are summarized in Table 1.

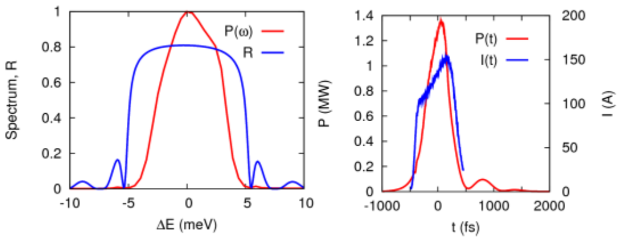


Figure 3: XFELO performance, spectral (left) and power (right) distribution.

Table 1: Major Parameters of an LCLS-II Based XFELO

| Parameter | Value | Units |
|---|---|---|
| Electron energy | 4 | GeV |
| Peak current | 100-140 | A |
| Bunch charge | 100 | pC |
| Bunch length | 400 | fs |
| Energy spread | 0.1 | MeV |
| Norm. emittance | 0.3 | μm |
| Photon energy@5$^{th}$ harm. | 14.4 | keV |
| Round trip loss | 15 | % |
| Undulator period | 2.6 | cm |
| Undulator K | 1.43 | |
| # of undulator periods | 1250 | |
| # of photons/pulse | 3 | $10^8$ |
| Spectral BW (FWHM) | 5 | meV |

## X-RAY OPTICS

### *Previous Results*

Working with several crystal manufacturers, we found that modern techniques can grow high-quality diamonds containing defect-free regions suitable for an XFELO. Experiments with 13.9-keV and 23.7-keV x-ray photons have established that the predicted reflectivity greater than 99% at near normal incidence is feasible [11, 12].

Temperature gradients that lead to gradients in the crystal lattice spacing can diminish the reflectivity. The simulation shows that the radiation heat load produced by an XFELO requires that the diamond crystal be cryogenically cooled to a temperature $T \leq 100K$. In this case, the diamond has sufficient time to conduct away the heat, so that the crystal temperature becomes homogeneous before the subsequent radiation pulse arrives. Low temperatures are favorable because diamond has an unmatched thermal diffusivity and an extremely small coefficient of thermal expansion for $T < 100K$ [13].

The requirements to stabilize the crystals and the mirrors in the cavity are stringent—better than 10-nrad (rms) angular stability and 3-μm (rms) positional stability. The null-detection feedback technique employed at the Laser Interferometer Gravitational-Wave Observatory (LIGO) can stabilize several optical axes with a single detector, and therefore appears to be a promising approach. A pilot experiment with a high-resolution, six-crystal x-ray monochromator at the APS Sector 30 beamline succeeded in achieving an angular stability of 13 nrad (rms) [14]. We will need to improve the scheme to meet the XFELO requirements—a multiple-axis system with better than 10-nrad stability.

### *Diamond Resilience Under High Power Exposure*

The power density incident on diamond crystals in the XFELO cavity is 1-10 kW/mm$^2$, which is by one to two orders of magnitudes higher than that of the power density on the first crystals at undulator beamlines of third generation synchrotron radiation facilities. It is therefore of paramount importance to determine whether a diamond crystal can survive as an x-ray mirror for an XFELO. Theoretical estimates of various processes under intense x-ray exposure indicate that the damage threshold for the x-ray power density is several orders of magnitude higher than 10 kW/mm$^2$[15].

A systematic experimental study of diamond resilience is in progress at the APS beamlines. The 35-ID beamline was used to produce a focused spot of 8 keV x- rays, roughly comparable in size and power density anticipated for an XFELO, 120×30 μm$^2$ and 8 kW/mm$^2$, respectively. The a well-characterized, 100-μm thick diamond sample was irradiated at ten different positions for different duration--1/64, 1/32, 1/16, .., 4, and 8 hours, as shown in Fig. 4 (left). The colour represents the rocking curve FWHM map of the irradiated crystal measured with 8 keV x-rays at the APS beamline 1BM-B, recording the FWHM of rocking curve peaks at each point on the surface. The fact that it is uniformly green implies that there is apparently no discernible change in the spectral responses when the diamond sample was exposed up to 4 hours (we disregard the 8-hour spot since there were some uncertainties for this exposure) within the relative accuracy of $10^{-6}$ of the topography set-up for this experiment. However, the image of the optical microscope revealed a darkening of the irradiated spots, indicating adsorption of impurity material, most probably carbon.

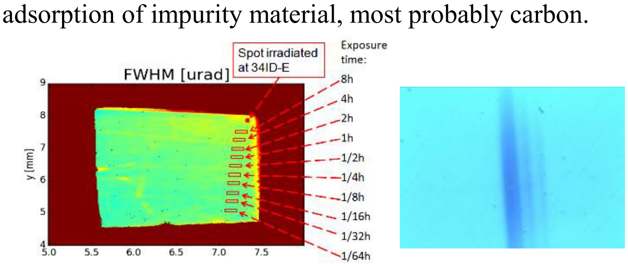


Fig. 4: The rocking curve FWHM map of the irradiated diamond surface where the exposure times of irradiated rectangles are indicated with the exposure times (left) and the image of the optical microscope of the spot with 4-hr exposure (right).

Subsequent measurement with a high resolution ($10^{-8}$) indicated possible shifts in the position of spectral peaks of the order of 1 meV in the irradiated area. Although this is a small effect that is probably correctable during an XFELO operation, we are planning a more detailed study about the physics behind the spectrum shift—is it possibly related to the impurity deposition on the surface, etc—by another round of x-ray exposure and precision topography.

### *XFELO Focusing Optics*

In addition to high-reflectivity mirrors, an XFELO cavity requires focusing elements so that the transverse mode profiles can be controlled [5]. Grazing-incidence, curved mirrors, in particular those being perfected at JTEC [16] are an option. However, being large and heavy, these are challenging to operate, especially if the photon energy, and thus the incidence angle to the curved mirror, need to be tuned.

Another option is the compound refractive lens (CRL) made from Be with parabolic surface profile [17]. One unit of a compound lens consists of two opposing parabolic faces. At synchrotron radiation beamlines, sets of more than ten units are used to create a sub-micron spots.

The loss due to small angle scattering could be rather high, 40% or more. As a focusing element for an XFELO with 100-300 m roundtrip length, the focal length could be longer than 20-m [5]. A Be CRL composed of one or at most two compound units is then an attractive, compact option. The loss is small for IF-1 grade material. However, questions have been raised whether the surface of a parabolic Be CRL can be shaped sufficiently accurately and its roughness sufficiently controlled.

We purchased Be CRLs of radius of curvature R= 100 μm and 50 μm from RXOPTICS. The surface profile measured at the APS metrology laboratory is shown in Fig. 5. The deviation of the surface from the ideal shape is less

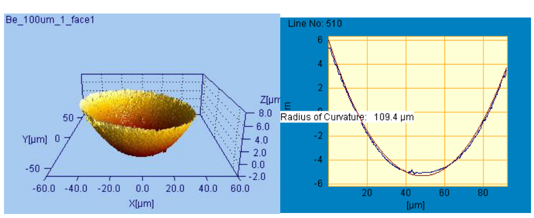


Figure 5: Surface metrology of a parabolic Be CRL.

Figure 6 shows the phase and phase error of image of the source formed by the CRL. The rms phase error measured to be 0.16 rad, from which the rms thickness error of 0.75 μm can be deduced, consistent with the metrology data. Thus, Be CRLs are an attractive candidate for XFELO focusing.

During the high-power irradiation of diamond, a 25-μm Be window was exposed to 3 kW/mm$^2$ of x-ray power density up to 8 hours without any apparent damage. Thus, the resilience of Be CRL is also demonstrated.

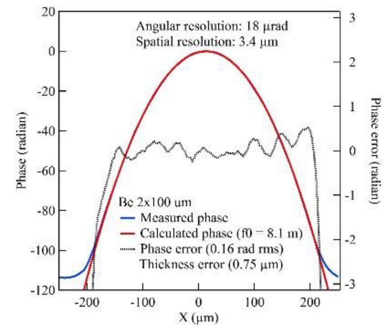


Figure 6: Phase and phase error of CRL imaging.

## CONCLUDING REMARKS

The results of the x-ray optics experiments on diamond resilience and Be-CRL performance are encouraging information for the feasibility of an XFELO. We have also demonstrated that the LCLS-II accelerator parameters can be optimized to implement a 5-th harmonic XFELO, widening the scientific reach of LCLS II to areas that require intense, fully coherent, ultra-fine spectral resolution x-rays.

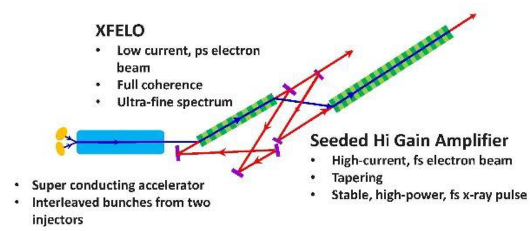


Figure 7: Concept for an ultimate XFEL Facility.

We may further envision an ultimate XFEL facility consisting of both an XFELO and high-gain amplifiers. The XFELO output can serve as the seed for the amplifier. If the amplifier employs fs electron bunches, then only the fs portion of the seed will be amplified to provide a stable, fully coherent, fs x-ray pulses. With full coherence an efficient tapering section can be attached beyond saturation point, thus increasing the fs pulses to TW regime.

Harmonic generation starting from 10 keV coherent input could be a promising route to higher energy XFEL, perhaps to 50 keV or higher.




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