AN OSCILLATOR CONFIGURATION OF AN X-RAY FREE-ELECTRON LASER FOR EXCEPTIONAL SPECTRAL PURITY AND STABILITY*

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Abstract

A hard x-ray free-electron laser in oscillator configuration—an FEL oscillator (XFELO)—will produce highly stable x-ray beams of ultra-high spectral purity and high average brightness, offering unique scientific opportunities. An XFELO is well suited for an energy recovery linac (ERL) facility. If combined with a high-gain amplifier, possibly with harmonic generation, an XFELO would constitute an ultimate x-ray machine.

XFELO—AN X-RAY FEL IN AN OSCILLATOR CONFIGURATION

The recently successful LCLS [1] is the first x-ray free-electron laser operating in a self-amplified spontaneous emission (SASE) mode, in which the initial spontaneous emission is amplified to intense, quasi-coherent radiation in a single pass. High-gain XFELs are currently under vigorous development; several additional facilities are being constructed, the self-seeding scheme is being developed to improve the temporal coherence of a hard x-ray SASE [2], and seeded high-gain devices for soft x-rays have also been proposed [3].

An x-ray FEL oscillator (XFELO) is a qualitatively different device that will further enrich the era of x-ray FELs. In an XFELO, x-ray pulses are trapped in a high-Q optical cavity for repeated low-gain amplification, giving rise to highly stable, ultra-high spectral purity x-ray pulses. Oscillators were the first FELs built: they have been operated for many years for UV and lower photon energy regions where both low-loss, normal-incidence reflectors and accelerators producing the required beam qualities were readily available [4]. The concept for an XFELO that uses crystals as low-loss reflectors was first proposed in 1983 [5], at the same time that the x-ray SASE was proposed [6]. However, the concept did not receive its due attention until a recent, detailed study showed that an XFELO would be feasible with low-intensity, ultra-low-emittance electron bunches [7].

In the basic configuration shown in Fig. 1, an x-ray pulse is stored in an optical cavity consisting of two crystal reflectors and a grazing-incidence, curved mirror. Each time a pulse arrives at the undulator entrance it meets an electron bunch, and the pulse intensity becomes amplified as they travel together through the undulator. If the gain per pass is higher than the total loss, the pulse intensity increases steadily and the spectral shape narrows from pass to pass. Eventually, the gain decreases due to nonlinear effects, and the FEL reaches a steady state when the gain balances the loss. One of the crystals is made thin so that a fraction of the intra-cavity power is coupled out for users.

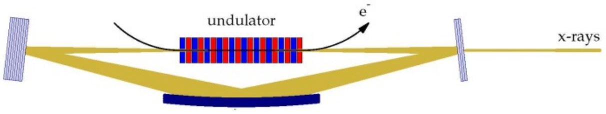

Figure 1: A basic scheme for optical cavities for XFELO which is not tuneable.

The tuning range of the basic scheme is severely limited because the curved mirror (necessary to control the transverse mode profile) efficiently reflects x-rays only when the grazing angle of incidence is less than a few mrad. Tuning can be achieved with the four-crystal scheme shown in Fig. 2 [8]. For this, the four crystals' Bragg angles are changed in unison while keeping a constant round-trip path length by a coordinated translation of the crystals. The four-crystal scheme also allows the use of one crystal material for all spectral regions of interest—an important advantage since we can then choose diamond, taking advantage of its excellent thermo-mechanical properties, as will be explained later.

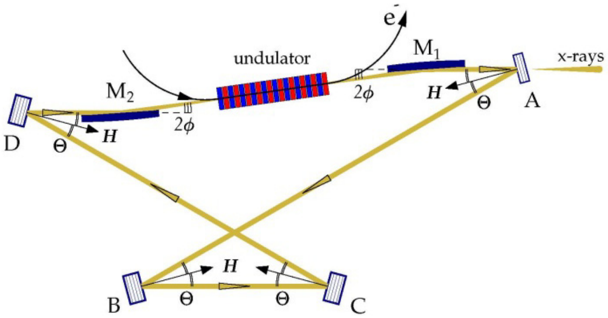

Figure 2: A tuneable cavity configuration in terms of four crystals.

The major parameters of an example XFELO are listed in Table 1. The electron beam parameters considered here are relatively conservative, as discussed below. XFELO parameters with higher beam qualities, lower bunch charge, and lower electron beam energy may also be feasible [9].

UNIQUE CHARACTERISTICS

The distinguishing properties of an XFELO output are the exceptionally narrow bandwidth and the high pulse-to-pulse stability of the output. The narrow bandwidth is due to the repeated gain narrowing by the crystal reflectors. An XFELO is inherently stable since the pulse-to-pulse fluctuation is averaged out.

Although the output number of photons per pulse is three orders of magnitude less than the LCLS, the peak spectral brightness is similar due to the narrow bandwidth. Most importantly, the average brightness is higher due to the high repetition rate.

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*Work supported by U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

ISBN 978-3-95450-145-8

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Table 1: Major Parameters

Electron Beam	
Energy	5 – 7 GeV
Bunch charge	25 – 50 pC
Bunch length (rms)	0.1 – 1 ps
Normalized rms emittance	0.2– 0.3 mm-mrad
Energy spread (rms)	2×10^{-4}
Bunch repetition rate	~ 1 MHz (constant)
Undulator	
Period length	~ 2 cm
Deflection parameter K	1.0 – 1.5
Total length	30 – 60 m
Optical Cavity	
Configuration	2 – 4 diamond crystals and focusing mirrors
Total roundtrip reflectivity	> 85% (50% for 100A peak current)
XFELO Output	
Photon energy coverage	5 – 25 keV (plus the third harmonic)
Spectral purity	1 – 10 meV (10^{-6} –10^{-7} in relative BW)
Coherence	Fully transverse and temporal
X-ray pulse length	0.1 – 1.0 ps
Tuning range	2 – 6 %
Number of photons/pulse	~ 10^{9}
Pulse repetition rate	~ 1 MHz
Peak spectral brightness	10^{32} – 10^{34} ph/[s*mm^2*mrad^2*(0.1% BW)]
Average spectral brightness	10^{26} – 10^{28} ph/[s*mm^2*mrad^2*(0.1% BW)]

The XFELO operation with Bragg reflectors will be difficult below 5 keV by enhanced photo-absorption in the crystal and above 20 keV by the small crystal bandwidth. Although the four-crystal configuration is tunable to any Bragg angle in the range from 90 to 45 degrees, the practical tuning range for a specific Bragg plane is limited to 2 – 6% because the angular acceptance can become smaller than the x-ray beam divergence at lower Bragg angles. We note that a few % is in fact rather broad when compared to its ~10^{-7} bandwidth.

An example of the radiation output from a tuneable, 4-mirror XFELO near the energy of 14.4 keV is shown in Fig. 3 [10]. In panel (a) the output radiation power as a function of time is indicated in red, with the electron beam current profile in green for reference. This power profile is obtained after 1000 passes, after which time it has saturated at approximately 2 MW. In panel (b) we plot the corresponding output spectrum with a red line, showing that the spectral FWHM is approximately 1.8 meV, corresponding to a relative FWHM of ~1.3×10^{-7}. Note that this bandwidth is much narrower than the reflectivity width of the Bragg crystals (the blue line) and approaches the Fourier transform of the electron bunch length.

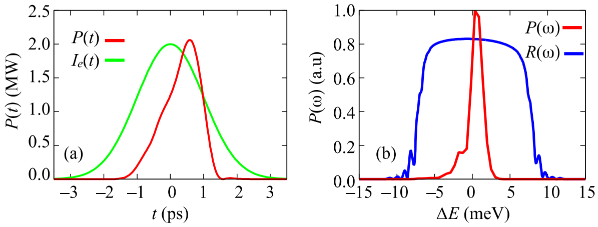

Figure 3: (a) The red line plots the temporal power profile of the XFELO output at 14.4 keV, showing peak powers ~ 2MW; the electron beam current is shown as a green line. (b) Spectrum of the XFELO output as a red line. The FWHM ~1.8 meV is much narrower than that of the crystal reflectivity, shown in blue.

The number of passes to reach the steady state spectral shape, about 1000 passes, is relatively modest due to the small bandwidth of diamond reflection. If the bandwidth of the reflector were broad, say a few eV, it would take a much greater number of passes, > 10^{11}, to reach the transform-limited bandwidth, probably causing the FEL operation to be unstable.

An XFELO may be regarded to be a more natural extension of the third-generation sources. Currently the APS, one of the brightest sources in the hard x-ray range, produces 10^{9} photons per second in the meV bandwidth, which will be increased a million-fold by an XFELO. Inelastic x-ray scattering and nuclear resonance scattering techniques, which are currently limited by the available flux in the desired bandwidth, can be revolutionized by an XFELO. Hard x-ray imaging will be feasible with nanometer resolution using multilayer Laue lenses that require x-ray bandwidth of less than 10^{-5}. The intensity of an XFELO will also enable hard x-ray photoemission spectroscopy for time-resolved study of Fermi surfaces in bulk material. The temporally coherent photons at an average rate of 10^{15} photons per second will be a game changer for x-ray photon correlation spectroscopy.

ACCELERATOR SYSTEM

At the level of an individual bunch, the electron beam characteristics required for an XFELO (Table 1) have already been demonstrated, for example, by the LCLS accelerator system in its low-charge mode [11]. Producing ultra-low emittance bunches at a constant and high repetition rate is a challenge currently being actively addressed by several research groups, in particular those pursuing an ERL-based light source. These studies indicate that an injector with the bunch characteristics of Table 1 and a repetition rate in the MHz to GHz range is feasible. A variety of approaches based on laser-driven photocathodes, but employing either a DC voltage [12,

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13] or a low-frequency radio frequency (rf) cavity [14] are in various stages of development.

The main accelerator for an XFELO should be of a cw superconducting type to accommodate a constant bunch repetition rate, with one or more recirculation paths to save cost. An XFELO is therefore a natural fit for a multi-GeV ERL-based light source facility. Various technical issues on ERL accelerator systems are being addressed in these proceedings, including the design of high-current, low-emittance injectors; beam mergers for the recirculation loop; cw superconducting linacs; and recirculation optics that preserve the electron beam quality [15]. The KEK-JAEA collaboration plans to construct a one-loop ERL with a 3-GeV superconducting linac in the first step. An XFELO operation is envisaged in the second step by adjusting the rf phase of the recirculation path to double the final energy to 6-7 GeV, as shown in Fig. 4 [16]. Note that energy recovery is not necessary for an XFELO due to its low average current.

A pulsed superconducting linac such as that being used for the European XFEL [17] can operate an XFELO in a pulsed mode. The macro-pulses in this linac are 1–2-ms long, accommodating 1000–2000 micropulses at a 1-MHz repetition rate, which is sufficient to drive an XFELO to saturation level.

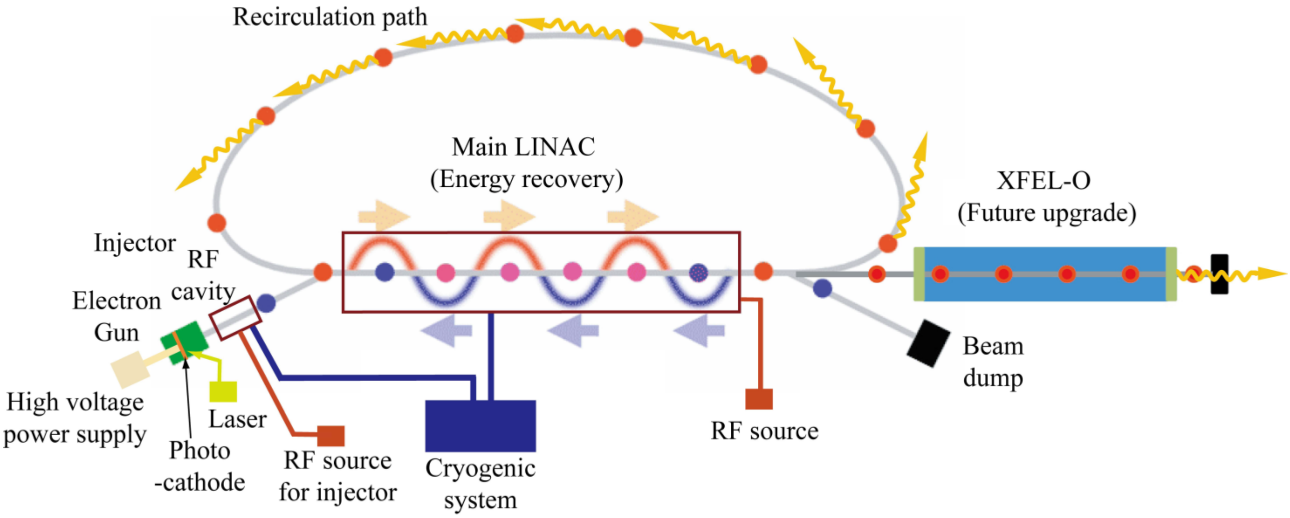

Figure 4: XFELO plan for the future KEK-JAEA 3-GeV ERL (courtesy of S. Sakanaka).

X-RAY OPTICS

Diamond is a material whose superb physical qualities are well suited for an XFELO cavity: high mechanical hardness, high thermal conductivity, high radiation hardness, low thermal expansion, and chemical inertness. An exceptionally high ≥ 99% reflectivity is predicted in x-ray Bragg diffraction, higher than that from any other crystal due to the uniquely small ratio of the extinction length to the absorption length. The issue is then whether synthetic diamond crystals of sufficient size (active volume ~1 mm^3) and crystalline perfection required for high reflectivity can be manufactured. Working with several crystal growers, 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 [18, 19].

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 $T \leq 100$K. 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 $T < 100$K as measured recently [20].

High radiation hardness is another desirable feature of diamond. The power density incident on diamond crystals in the XFELO cavity is ~ 4 kW/mm^2, which is about 30 times higher than that of the undulator radiation used to test the first crystal at the APS. While it is encouraging that the APS crystals have survived one year of operation without an apparent decrease in performance, additional studies should be performed to understand the degree of irreversible radiation damage in diamond and how this damage affects its reflectivity.

Deviations of the crystal and focusing mirror surface from its ideal will disturb the x-ray wave-front, producing mode distortions and large-angle scattering. For diamond crystals, the surface error height δh should be a fraction of the x-ray wavelength times the difference of the index of refraction from unity δn. Since δn for hard x-rays is of the order of 10^{-6}, the tolerance on δh is about a micron, which should be achievable. The tolerance of the grazing incidence mirror on the height error (contributing to diffusion) is about $\delta h \leq 1$ nm, while the tolerance on figure error (contributing to mode distortion) is about 0.1 μr. These tolerances are tight but are current state-of-the art.

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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) [21]. We will need to improve the scheme to meet the XFELO requirements—a multiple-axis system with better than 10-nrad stability.

CONCLUSIONS

The accelerator technology for an XFELO is essentially available in view of the active R&D program of the ERL projects. Several important advances have been made for the x-ray optics, such as the demonstration of near-perfect diamond reflectivity, the discovery of its low thermal expansion coefficient, and the success of a single-axis feedback for optical elements' mechanical stability. Issues that require further R&D include quantifying the radiation damage and preserving the wave-front after reflection from optical elements. However, we believe that there are good indications that these issues can be overcome.

An x-ray XFELO will provide capabilities outside the realm covered by high-gain x-ray FELs. After some development, it may be feasible to construct a low-power, compact XFELO providing seed radiation for a high-gain amplifier and producing very stable x-ray pulses with ultra-high spectral purity together with high intensity. With harmonic generation, the combination could produce "ultimate" x-ray beams up to 100 keV or higher.

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ISBN 978-3-95450-145-8