THE POTENTIAL FOR THE DEVELOPMENT OF THE X-RAY FREE ELECTRON LASER: MULTI-USER PHOTON DISTRIBUTION SYSTEM FOR XFEL LABORATORY

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Abstract

X-ray photon beam from a SASE FEL undulator is in principle a single user tool, just like an optical laser. Therefore, the operation and amortization cost cannot be easily spread over many simultaneous experiments. To avoid prohibitive cost for each experiment, a new XFEL laboratory scheme is proposed. A photon beam distribution system based on movable multilayer X-ray mirrors can provide an efficient way to generate a multi-user facility. Distribution of photons is achieved on the basis of pulse trains and it is possible to partition the photon beam among a few tens independent beamlines thereby obtaining many users working in parallel. The second way to increase the number of simultaneous experiments is based on the working with a series of perfect crystals in transmission (Laue) geometry. The later concept is the basic idea of the Troika beamline at ESRF. In principle, a hundred of photon beamlines with different experiments can be served by a single XFEL source.

INTRODUCTION

The preferred layout of a SASE FEL is a linear arrangement in which the injector, accelerator, bunch compressors and undulators are nearly collinear, and in which the electron beam does not change the direction between accelerator and undulators. On the other hand, a X-ray FEL laboratory should serve several tens, may be up to a hundred experimental stations which should operate independently according to the needs of the user community. The present paper describes a beam distribution system which allows to switch the FEL beam quickly between many experiments in order to make efficient use of the source. Many applications require only very high peak brilliance. Such experiments for which average brilliance and wavelength are not critical, could operate simultaneously at the same radiation wavelength.

Each FEL source emits only one photon beam. Therefore, the operation and amortization costs cannot be easily spread over many simultaneous experiments. To avoid prohibitive cost for each experiment, new photon beam distribution scheme is proposed. It would specifically partition the photon beam among a few tens independent beamlines thereby obtaining many users working in parallel. Our analysis shows that proposed mult-user photon distribution schemes may be implemented at future upgrades of XFEL facilities [1, 2, 3].

MULTI-USER DISTRIBUTION SYSTEM BASED ON MULTILAYERS

The technical approach adopted in this variant of XFEL laboratory design makes use of movable multilayer X-ray mirrors. Layered synthetic materials – multilayers – are layered structures with usually two alternating materials: a low and high density materials. They play an important role in synchrotron X-ray optics [4, 5, 6, 7]. They provide less energy resolution but correspondingly more flux and keep the angular beam divergence constant (in the ideal case). Typical multilayers used as optical elements at third generation synchrotrons provide a spectral bandwidth of 1 to 5%. Typical glancing angles are of the order of a degree and thus lie between the mrad wide angles of X-ray mirrors and the much bigger 10 degree wide Bragg angles of single crystals. The angular acceptance of X-ray multilayer mirror is of the order of one mrad (for a bandwidth 1%). As a rule, from 100 to 400 periods participate in effective reflection in such mirrors. About 90% peak reflectivity was achieved for wavelengths around 0.1 nm. Computer simulations are in very good agreement with experimental results in all cases so that efficiencies can be safely predicted.

The concept of photon beam distribution system is very simple. Figure 1 shows relevant photon beamline configuration. The distribution of pulse trains among the different user stations can be done by movable deflectors. A schematic diagram of a movable deflector is shown in Fig. 2. Its key components include rotating multilayers and multifacet reflector. The advantages of multilayer as movable photon beam deflector are based on two factors: the larger deflection angle compared to X-ray mirrors; and the larger angular acceptance compared to crystals. The multilayer mirror angular acceptance is of the order of one mrad, and is well matched to the natural opening angle, (from one to a few μrad), of an XFEL source. In order to achieve stable photon beam deflection the alignment accuracy of multilayer deflectors must be less than 0.1 mrad. It is believed that technology, presently in advanced development for applications other than XFEL, will enable rotating multilayers to satisfy these requirements. The initial photon beam is transformed into 5 beams. The switching mirrors need to rotate at a frequency of 1 Hz such that each user actually receives one train of pulses with a full duration of

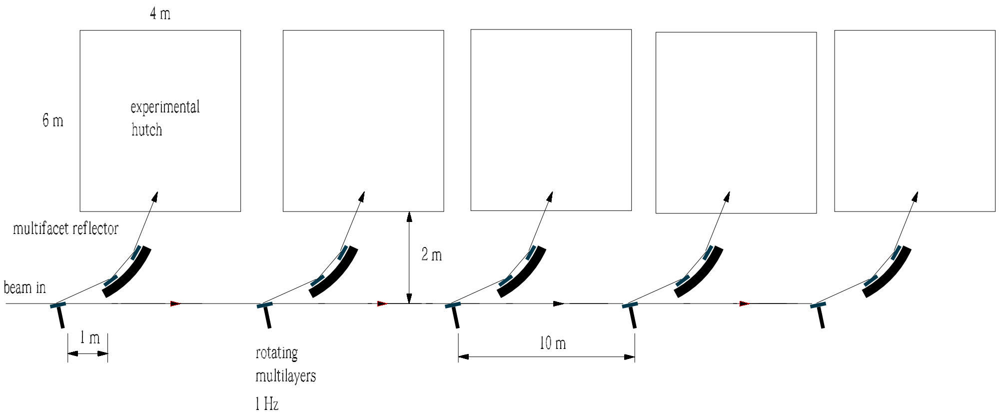

Figure 1: Proposed SASE undulator beamline for studies with maximum X-ray flux. The distribution of photons is achieved on the basis of pulse trains and it is possible to serve 5 user stations with repetition rate 1 Hz.

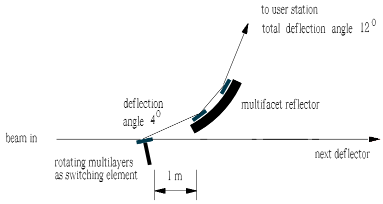

Figure 2: Concept of the photon beam deflector based on multilayer X-ray mirror. Using rotating multilayer mirrors as switching elements between the multifacet reflectors makes it possible to provide X-ray radiation for many user stations.

1 ms per second. Note that even if the photon beam is distributed among many users, the peak flux per user remains untouched (apart from the losses in the deflector system). Such a scheme, which adopts multilayer deflector concept, allows one to increase the total number of user stations by using standardized X-ray optical components.

An attractive feature of the distribution system based on movable multilayers is the absence of no apparent limitations which would prevent operation at even hundred user stations (per SASE undulator) simultaneously. All users will receive the photon beam of identical (and high) quality. Every time deflection process happens only once during one pass of the photon beam through the deflector unit with only three multilayers, and the problem of the absorption of the radiation in the distribution system does not exist at all. Another advantage comes from small (one to a few μrad) angular divergence of the FEL radiation. As a result, in an extended sequence of deflectors (say, a few tens of meters), photon beam properties (spot size) remain unchanged. The larger number of beamlines, the smaller is the macropulse repetition rate per user station. Note also that even if the beam is distributed among 50 users, the macropulse repetition rate per user will still be 0.1 Hz. It is important to note that for many experiments this may not be a difficulty and the macropulse (4000 pulses) per 10 seconds is more than sufficient. Photon intensity integrated over macropulse is equivalent to an intensity integrated per an hour at synchrotron radiation sources today. Another attractive feature of the proposed photon system is a high degree of flexibility: if some user will request a full photon flux for a while, this can be done simply by means of ”freezing” motion of the multilayers for a while such that full photon flux is directed to dedicated user station.

MULTI-USER DISTRIBUTION SYSTEM BASED ON CRYSTAL DEFLECTORS

Photon beam distribution system based on movable multilayers is one of the alternatives under consideration to extend the XFEL capability to a few tens users working in parallel. The second potential candidate for the XFEL laboratory to progress into multi-user facility class is that distribution system based on (fixed) crystal deflectors. Figure 3 shows a schematic layout of the photon distribution

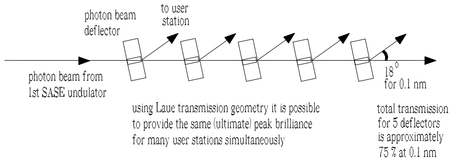

Figure 3: Photon beam distribution system setup based on crystal deflectors for simultaneous multi-user mode of operation at 0.1 nm

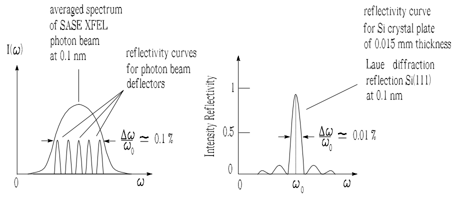

Figure 4: Basic principle of the XFEL multi-user distribution system. Using Laue diffraction in Si crystals as a method of photon beam deflection it is possible to provide X-ray radiation for many user-station simultaneously.

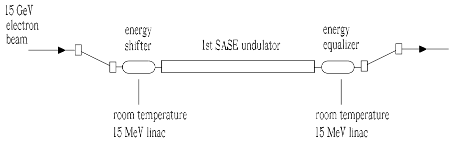

Figure 5: Electron (photon) energy shifter as a switching element between 3 beamline clusters. Conceptual layout.

system. This is a farm of multi-station SASE undulator beamlines, working with a series of transmission crystal deflectors. Advantage of this scheme is the possibility of using not only the diffracted photon beam, but also the transmitted "broadband" SASE beam for downstream experimental stations operating at different photon energies (see Fig. 4). The latter concept is the basic idea of the Troika beamline at ESRF [8, 9, 10]. Note that even if the photon beam is distributed among a few tens of users, the peak brilliance per user remains untouched (apart from the losses in the deflector system). In the case of end stations the direct photon beam is used.

The relative spectral bandwidth for Laue reflection is independent of the wavelength or glancing angle of X-rays and is given merely by properties of the crystal and the reflecting atomic planes. In particular, it implies that the choice of a crystal and reflecting atomic planes determines the spectral resolution. For example, one can consider Si(111) crystals, which have FWHM bandwidth of $\Delta\lambda/\lambda \simeq 1.2 \times 10^{-4}$ in Laue transmission geometry. Deflectors at photon beam lines are fabricated from silicon. The main advantage of the silicon is the availability of almost perfect synthetic monocrystals, with high transparency. The reason is that semiconductor industry has created a huge demand for defect-free, perfect single crystal. In order to maintain a high transmission through the deflectors for the downstream stations, it is necessary to limit the absorption in the 10 deflectors to about 50% at 0.1 nm. The thickness of the one crystal must therefore not exceed 15 μm. The angular acceptance of silicon deflector is of the order of 20 μrad for a wavelength of 0.1 nm, and is well matched to the natural opening angle, (one μrad), of an XFEL source.

The use of a Laue deflector can be extremely advantageous in the case of high thermal loads, because the beam is almost entirely transmitted, and only a small part is absorbed. At 0.1 nm an average power of 40 W (2 mJ$\times$ 5 trains/s $\times$ 4000 pulse/train) at the 1st SASE undulator exit corresponds to a normal incidence power density of 50 W/mm^2 at the distance of 1000 m from the undulator for a beamsize (FWHM) of 1 mm. The absorbed power per one deflector is about 2 W.

Silicon has the advantage of a high heat conductivity and high damage threshold, thus achieving good performance at high power load. It is well known that when crystal plate is cooled, the thermal deformation results in a slope error composed of a bending and bump component. Briefly, the thermal deformation of the crystal induced by heat load depends on the ratio α/k, where α and k are the thermal expansion coefficient and the thermal conductivity of the crystal, respectively. This ratio is strongly temperature dependent for silicon. The ratio α/k is zero at 125 K, and about 50 times smaller at liquid-nitrogen temperature (77 K) than at room temperature.

The time-averaged power and power density at large distance from the SASE undulator are comparable to those of the third generation synchrotron radiation sources. For example, the brightest X-ray beams at ESRF facility are produced by in-vacuum undulators. These undulators emit about 0.5 kW of X-ray power in the central cone and the power density, at the position of the silicon monochromator 30 m from the source, is about 200 W/mm^2. Cooling techniques such as cryogenic cooling of Si have become standard at the third generation sources. The thermal deformation of the silicon crystal, which is indirectly cooled by liquid nitrogen, was studied experimentally and by finite-element analysis. Excellent agreement between the experimental measurements and theoretical results was observed. There is the best high-power working point for the crystal, when the power is raised to the point where the maximum temperature reaches 125 K. At this temperature the ratio between the thermal expansion and the thermal conductivity is zero [11].

The advantage of operating single-crystal-silicon deflector at cryogenic temperatures is obvious. Lowering the temperature of silicon from room temperature to liquid-nitrogen temperatures improves the so-called figure of merit, k/α, by 50-fold. A thin crystal is desired so that a large fraction of the incident beam would be transmitted, hence reducing the absorbed power in the deflector that has to be removed by the liquid nitrogen.

Although XFEL sources are designed primarily to generate brilliant X-rays with moderate energy 5-15 keV, high-energy X-rays are of great usefulness. In particular, high-energy focused beam is quite attractive for structural studies of amorphous solids and liquids and for diffraction studies of crystalline materials because of its extinction-free nature. The analysis shows that strong harmonic growth can

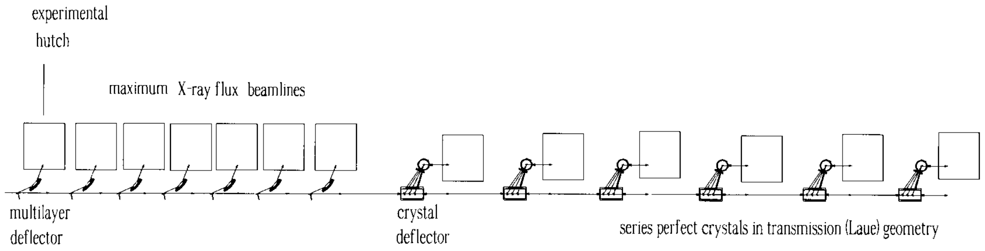

Figure 6: 1st SASE undulator beamline. A photon beam distribution system based on combination movable multilayers and crystals in transmission (Laue) geometry can provide efficient way to generate a multi-user facility.

be expected in SASE XFELs. When a beam is strongly bunched in the sinusoidal ponderomotive potential formed by the undulator field and the radiation field of fundamental frequency, the electron beam density spectrum develops rich harmonic contents. Coherent radiation at the odd harmonics can be generated in a planar undulator and significant power levels for the third harmonic can be reached before the FEL is saturated. Explicit calculations show that the power of the transversely coherent third-harmonic radiation can approach a fraction of a per cent of the fundamental power level.

In this paper we propose to utilize the third harmonic radiation from the XFEL. Four upstream transparent deflectors, which adopt so-called "Laue transmission geometry" concept, enable us to perform five different experiments simultaneously. High-energy X-rays are associated with a large penetration power, which makes it possible to use relatively "thick" silicon deflectors. The thickness of one crystal is 0.1 mm. The other main difference between diffraction at high energies and at conventional energies is the smaller Bragg angles. In particular for the 1st order Si(111) reflection at 0.03 nm the deflection angle is about 0.1 rad.

The distribution of pulse trains among the different beamline clusters can be done by a photon (electron) energy shifter pulsed at 5 Hz. It directs every other photon pulse train into a second cluster of photon beamlines. This method of pulse train distribution is based on the accelerator technique. In this case the SASE undulator beamline consists of an input energy shifter, SASE undulator, and output energy equalizer (see Fig. 5). Using photon energy shifter as switching element between 3 clusters of photon beamlines makes it possible to provide simultaneously X-ray radiation for $5 \times 3 = 15$ user station. Distribution of photons is achieved on the basis of pulse trains. Each user station actually receives one, two, or three pulse trains of full length at 1 Hz repetition rate.

It should be noted that crystal deflector performances are complementary to those of multilayer deflectors, whose bandwidth is much wider but whose photon flux is much higher. Crystal deflectors have a band-pass of the order of 10^{-4}, which is unnecessary narrow in many experiments. On the other hand, the fundamental SASE radiation has an energy peak-width of 10^{-3} and thus, using the whole SASE radiation peak, the flux is more than 10 times higher than that obtained with crystal deflector.

Both types of deflectors are important, their roles are complementary, and one type cannot replace the other. Figure 6 shows the optimal beamline configuration. The first 20 beamlines are planned to be multi-purpose beamlines for experiments with maximum X-ray flux. In this case 21st ... end-stations use the photon beam distribution system working with transmission crystal deflectors.

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