A SIMPLE METHOD FOR CONTROLLING THE LINE WIDTH OF SASE X-RAY FELS

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Abstract

This paper describes a novel single-bunch self-seeding scheme for generating highly monochromatic X-rays from a baseline XFEL undulator. A self-seeded XFEL consists of two undulators with an X-ray monochromator located between them. Previous self-seeding schemes made use of a four-crystal fixed-exit monochromator in Bragg geometry. In such monochromator the X-ray pulse acquires a cm-long path delay, which must be compensated. For a single-bunch self-seeding scheme this requires a long electron beam bypass, implying modifications of the baseline undulator configuration. To avoid this problem, a double bunch self-seeding scheme based on a special photoinjector setup was recently proposed. At variance, here we propose a new time-domain method of monochromatization exploiting a single crystal in the transmission direction, thus avoiding the problem of extra-path delay for the X-ray pulse. The method can be realized using a temporal windowing technique, requiring a magnetic delay for the electron bunch only. When the incident X-ray beam satisfies the Bragg diffraction condition, multiple scattering takes place and the transmittance spectrum in the crystal exhibits an absorption resonance with a narrow linewidth. Then, the temporal waveform of the transmitted radiation pulse is characterized by a long monochromatic wake. The radiation power within this wake is much larger than the shot noise power. At the entrance of the second undulator, the monochromatic wake of the radiation pulse is combined with the delayed electron bunch, and amplified up to saturation level. The proposed setup is extremely simple and composed of as few as two simple elements. These are the crystal and the short magnetic chicane, which accomplishes three tasks by itself. It creates an offset for crystal installation, it removes the electron micro-bunching produced in the first undulator, and it acts as a delay line for temporal windowing. Using a single crystal installed within a short magnetic chicane in the baseline undulator, it is possible to decrease the bandwidth of the radiation well beyond the XFEL design down to 10^{-5}. The installation of the magnetic chicane does not perturb the undulator focusing system and does not interfere with the baseline mode of operation. We present feasibility study and exemplifications for the SASE2 line of the European XFEL. **These proceedings are based on the article [1], to which we address the interested reader for further information and references.**

INTRODUCTION

As a consequence of the start-up from shot noise, the longitudinal coherence of X-ray SASE FELs is rather poor compared to conventional optical lasers. The coherence time is defined by the inverse spectral width. For conventional XFELs this is typically two orders of magnitude shorter than the electron pulse duration. Hence, the typical XFEL pulse bandwidth is about two orders of magnitude larger than the Fourier transform limited value for the total bunch length. Given this physical properties, it is in principle possible to improve the longitudinal coherence and produce X-rays with a bandwidth of about 10^{-5}.

Self-seeding schemes have been studied to reduce the bandwidth of SASE X-ray FELs. A self-seeded FEL consists of two undulators with an X-ray monochromator located between them. The first undulator operates in the linear high-gain regime starting from the shot-noise in the electron beam. After the first undulator, the output radiation passes through the X-ray monochromator, which reduces the bandwidth to the desired value, smaller than the FEL bandwidth. While the radiation is sent through the monochromator, the electron beam passes through a bypass, which removes the electron micro-bunching introduced in the first undulator and compensates for the path delay created during the passage in the monochromator. At the entrance of the second undulator, the monochromatic X-ray beam is then combined with an electron beam and amplified up to the saturation level. The radiation power at the entrance of the second undulator is dominant over the shot noise power, so that the bandwidth of the input signal is smaller than the bandwidth of the FEL amplifier. The realization of this self-seeding scheme for the European XFEL requires two undulators, the first 54 m long (9 cells) and the second 72 m long (12 cells), separated by a four-crystal, fixed-exit monochromator in reflection (Bragg) geometry. In the monochromator, the X-ray pulse acquires a centimeter-long path delay, which must be compensated. For a single bunch self-seeding scheme this requires a long electron beam bypass with a length of about 60 m, implying modifications of the baseline undulator configuration, Fig. 1. As an attempt to go around this obstacle, a double-bunch self-seeding scheme was proposed based on a photoinjector setup using a laser pulse doubler (see references in [1]).

All X-ray crystal monochromators operate in the frequency domain as bandpass filters. In this paper we propose, instead, a new method of monochromatization based on the use of a single crystal in the transmission direction as a bandstop filter. In this way, the problem with the ex-

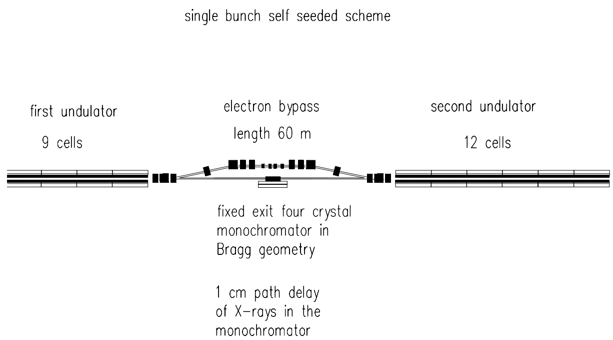

Figure 1: Design of an undulator system for the narrow bandwidth mode of operation. The scheme is based on the use of a single bunch self-seeding scheme with a fixed-exit four-crystal monochromator in Bragg geometry. The presence of the monochromator introduces a path delay of the X-rays, which has to be compensated with the introduction of a long electron beam bypass.

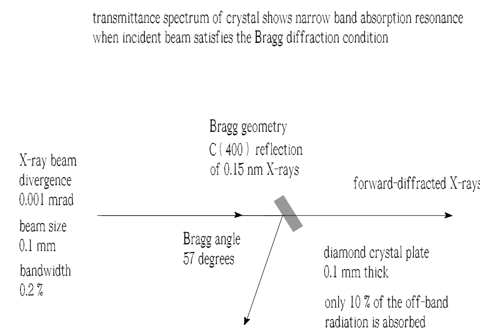

Figure 2: Forward diffraction in a single crystal in Bragg geometry. Due to multiple scattering, the transmittance spectrum in a crystal shows an absorption resonance with a narrow (10^{-5}) linewidth. Resonant wavelength and incident angle of the X-ray beam satisfy the Bragg diffraction condition. When the incident angle and the spectral contents of the incoming beam satisfies the Bragg diffraction condition, the temporal waveform of the transmitted radiation pulse exhibits a long monochromatic wake. The duration of the wake is inversely proportional to the bandwidth of the absorption resonance.

tra path-delay of the X-ray pulse does not exist at all. Our scheme can be realized with the help of a temporal windowing technique. When the incident X-ray beam satisfies the Bragg diffraction condition, multiple scattering takes place in the crystal and the spectrum of the reflectance exhibits a narrow line width. As a consequence, the spectrum of the transmittance exhibits an absorption resonance with a narrow line width, thus behaving as a a bandstop filter. After such bandstop filter, the frequency spectrum of the transmitted X-ray pulse experiences a strong temporal separation. In particular, the temporal waveform of transmitted radiation pulse exhibits a long monochromatic wake. At the entrance of the second undulator, the monochromatic wake of the radiation pulse is combined with the delayed electron bunch, thus exploiting the before-mentioned temporal windowing technique, and it is amplified up to saturation. The wake power is dominant over the shot noise power, so that the bandwidth of the input signal is small, compared to the bandwidth of the FEL amplifier.

The proposed setup is extremely simple, and is composed of two simple elements: a crystal, Fig. 2, and a short magnetic chicane, Fig. 3. The magnetic chicane accomplishes three tasks. It creates an offset for the crystal installation, it removes the electron microbunching produced in the first undulator, and it acts as a delay line for the implementation of the temporal windowing. Thus, using a single crystal installed within a short magnetic chicane in the baseline undulator as a bandstop filter, it is possible to decrease the bandwidth of the radiation well beyond the XFEL design down to 10^{-5}. The installation of the magnetic chicane does not perturb the undulator focusing system and does not interfere with the baseline mode of operation. The scheme can work in combination with a fresh bunch technique both for short (6 fs) and long (60 fs) pulse mode of operation.

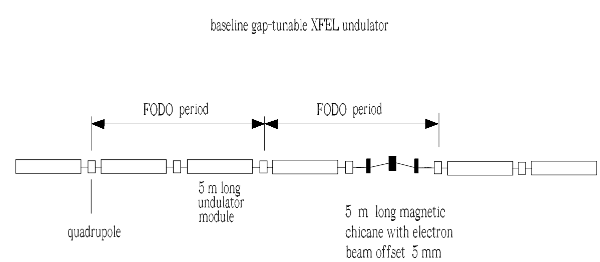

Figure 3: Installation of the magnetic chicane in the baseline XFEL undulator. The magnetic chicane absolves three tasks. First, it suppresses the electron beam modulation. Second, it allows for the installation of the single-crystal filter. Third, it performs a temporal windowing operation by delaying the bunch.

PRINCIPLES OF THE SELF-SEEDING TECHNIQUE BASED ON THE USE OF A WAKE MONOCHROMATOR

In this section we illustrate our novel method of monochromatization, based on the use single crystal monochromator. As already said, this technique takes advantage of the transmission geometry, where no extra path-delay for the X-ray pulse is present. The method consists of a combination of a single bunch self-seeding scheme, based on the use of a single crystal monochromator, and of a temporal windowing technique.

The principle of the new method of monochromatization

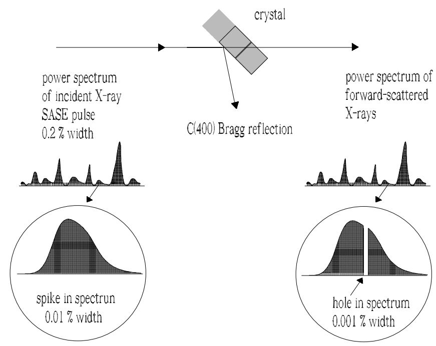

Figure 4: Single crystal in Bragg geometry as a bandstop filter for the transmitted X-ray SASE radiation pulse.

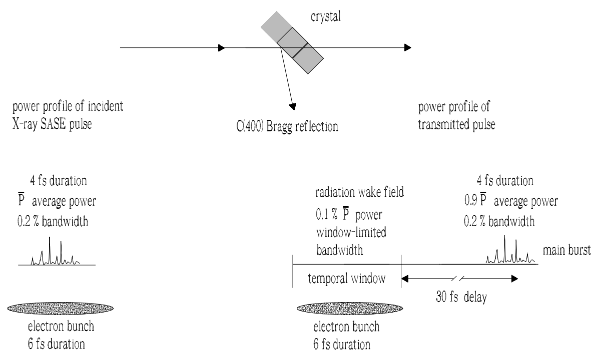

Figure 5: Temporal windowing concept. It is possible to eliminate the spikes in the seed signal by using a temporal window positioned after the bandstop filter as indicated in the figure. This can be practically implemented by delaying the electron bunch at the position where the frequency spectrum of the transmitted X-ray pulse experiences a strong temporal separation.

is very simple and is illustrated in Fig. 4 and Fig. 5. An incident SASE pulse coming from the first undulator impinges on a crystal set for Bragg diffraction. When X-rays impinge upon a crystal, forward-scattered X-rays are produced. The phase shift acquired by the forward-scattered X-rays on the passing through the crystal depends on the refractive index of the crystal. In general, the refractive index is slightly less than unity and complex. The refractive index, however, requires a correction when the incident beam almost satisfies the Bragg diffraction condition and multiple scattering takes place. Usually, X-ray multiple scattering in a perfect crystal is described by the dynamical theory of X-ray diffraction. According to this theory, when the incident angle is near the diffraction condition, the transmittance spectrum of a thick crystal shows an absorption line with a narrow width, which is close to the line width in the reflectance spectrum for the case of small absorption influence. In this paper we will discuss only the case for small absorption: in particular, we will consider the C(400) reflection of 0.15 nm X-ray from a 0.1 mm-thick diamond plate, see Fig. 2. When the incident angle and the spectral contents of the incoming beam satisfies the Bragg diffraction condition, the temporal waveform of the transmitted radiation pulse shows a long monochromatic wake. The duration of this wake is inversely proportional to the bandwidth of the absorption line in the transmittance spectrum. Then, the single crystal in Bragg geometry actually operates as a bandstop filter for the transmitted X-ray SASE radiation pulse, see Fig. 4. Obviously, if we use a bandstop filter there is no monochromatization in the frequency domain. However, it is possible to reach a bandwidth limited seed signal by using a temporal window positioned after the bandstop filter as indicated in Fig. 5. In the XFEL case we deal with a parametric amplifier where the properties of the active medium, i.e. electron beam, depend on time. As a result, the temporal windowing concept can be practically implemented in a simple way by delaying the electron bunch at the position where the frequency spectrum of the transmitted X-ray pulse experiences a strong temporal separation. In other words, the magnetic chicane in Fig. 3 shifts the electron bunch on top of the monochromatic wake created by the bandstop filter. By this, it is possible to seed the electron bunch with a radiation pulse characterized by a bandwidth much narrower than the natural FEL bandwidth. In the proposed scheme, no time dependent elements are used and problems with synchronization and time jitter do not exist at all.

COMBINATION OF SELF-SEEDING AND FRESH BUNCH TECHNIQUES

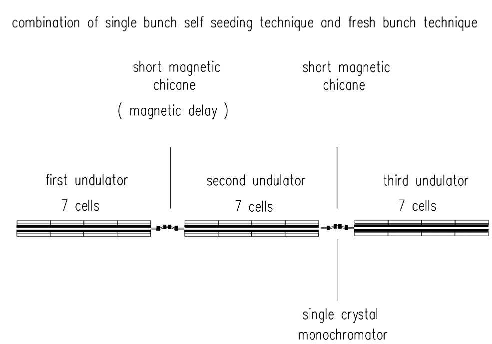

Figure 6: Design of an undulator system for the narrow bandwidth mode of operation. The method exploits a combination of a single bunch self-seeding scheme, based on the use of a single crystal monochromator and of a temporal windowing technique, and of a fresh bunch scheme.

In this section we will discuss how the above-described method may be combined with a fresh bunch technique. The idea is sketched in Fig. 6, Fig. 7, and Fig. 8. The scheme can be practically realized by using three undulator parts, Fig. 6. The first undulator operates in the linear high-gain regime starting from the shot noise in the electron beam. After the first undulator, the electron bunch is sent to a short magnetic chicane, which removes the mi-

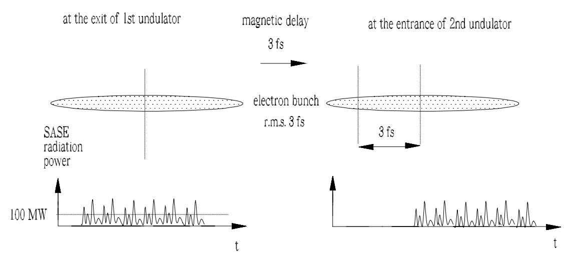

Figure 7: Sketch of principle of the fresh bunch technique for the short (6 fs) pulse mode of operation.

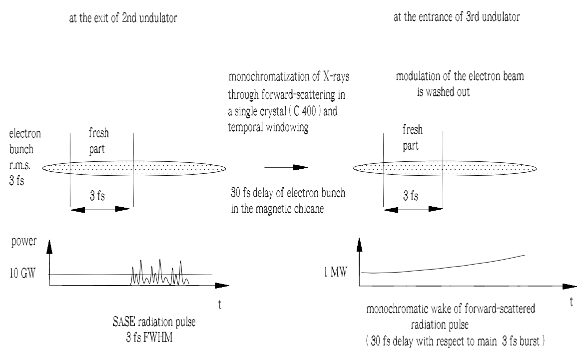

Figure 8: Sketch of the X-ray monochromatization principle from the second to the third undulator. By using a combination of a fresh bunch technique and a single-bunch self-seeding technique, based on the use of a single crystal monochromator and of the temporal windowing operation, a MW-level monochromatic wake of radiation can be produced behind the monochromator.

crobunching and introduces a delay of the electron bunch with respect to the radiation pulse, Fig. 7. In this way, half of the electron bunch is seeded, and saturates in the second part of the undulator. Note that for European XFEL or LCLS parameters, microbunching is washed out already with a small dispersive strength R_{56} in the order of ten microns, allowing for a short 5 m-long chicane to be installed in place of a single undulator module. After the second undulator the electron bunch is sent to a second magnetic chicane, Fig. 8, and the strong radiation pulse impinges on a crystal set for Bragg diffraction. The refracted radiation pulse seeds the remaining fresh part of the delayed electron bunch, thus implementing the temporal windowing technique, and is amplified up to saturation in the third part of the undulator. In this scheme, the mean value of the radiation power after the crystal within the temporal window will be in the few MW level. This is the input radiation power at the entrance of the third undulator, and is much larger than the shot noise power (3 kW).

The combination of self-seeding and fresh bunch techniques is extremely insensitive to noise and non-ideal effects. In fact, the radiation pulse used to produce the monochromatic wake is in the GW level power. This large power can tremendously improve the signal to noise ratio of the self-seeding scheme. It should be remarked that the possibility of combining self-seeding scheme and fresh bunch technique would be especially of great importance during the early experimental stage, when a proof of principle is built. During this stage all non ideal effects can be reduced to a minimum. After this stage, one may implement other self-seeding schemes based on the wake monochromator.

The advantage of our novel self-seeding method is a minimal hardware requirement, consisting in the installation of two short magnetic chicanes as shown in Fig. 6. These chicanes do not perturb the undulator focusing system and do not interfere with the baseline mode of operation. Our three stage self-seeding scheme is therefore compatible with the baseline design of the European XFEL.

CONCLUSIONS

In this paper we propose a novel scheme to produce highly monochromatic X-rays from a baseline SASE XFEL, down to a relative bandwidth of 10^{-5}. The key components of such scheme include only a single crystal and a short magnetic chicane with very small offset. A distinguishing feature of our method is that it uses a single crystal in the transmission direction, instead of a fixed-exit four-crystal monochromator. As a result, the X-ray optics is extremely simple to align: it involves no beam-recombining and no scanning of the delay. The alignment tolerance of the crystal angle is expected to be in the range of a fraction of mrad for fitting the Bragg reflectivity line to the SASE XFEL radiation bandwidth.

Here we illustrated the method. A detailed feasibility study of the proposed technique for both short and long pulse mode of operation, together with theoretical considerations can be found in [1].

A great advantage of our method is that it includes no path delay of X-rays in the monochromator. This fact eliminates the need for a long electron beam bypass, or for the creation of two precisely separated, identical electron bunches, as required in previously proposed self-seeding schemes. The present scheme is therefore inexpensive and compact. Moreover, the proposed combination of single crystal and weak chicane allows for a straightforward installation of the self-seeding setup in the baseline undulator system, already during the commissioning phase of SASE2 at the European XFEL, and can become operational by the end of 2014.

REFERENCES

[1] G. Geloni, V. Kocharyan and E. Saldin, ”A simple method for controlling the line width of SASE X-ray FELs”, DESY 10-053 (2010), http://arxiv.org/abs/1004.4067