SCHEME FOR FEMTOSECOND-RESOLUTION PUMP-PROBE EXPERIMENTS AT XFELS WITH TWO-COLOR TEN GW-LEVEL X-RAY PULSES

G. Geloni, European XFEL GmbH, Hamburg, Germany
V. Kocharyan and E. Saldin, DESY, Hamburg, Germany

Abstract

This paper describes a scheme for pump-probe experiments that can be performed at LCLS and at the European XFEL and determines what additional hardware development will be required to bring these experiments to fruition. It is proposed to derive both pump and probe pulses from the same electron bunch, but from different parts of the tunable-gap baseline undulator. This eliminates the need for synchronization and cancels jitter problems. The method has the further advantage to make a wide frequency range accessible at high peak-power and high repetition-rate. An important feature of the proposed scheme is that the hardware requirement is minimal. Our technique is based in essence on the "fresh" bunch technique. For its implementation it is sufficient to substitute a single undulator module with short magnetic delay line, i.e. a weak magnetic chicane, which delays the electron bunch with respect to the SASE pulse of half of the bunch length in the linear stage of amplification. This installation does not perturb the baseline mode of operation. We present a feasibility study and we make exemplifications with the parameters of 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

The production of short pulses of high-power, coherent x-ray radiation are of great importance when it comes to time-resolved experiments, which are used to monitor time-dependent phenomena. In a typical pump-probe experiment, a short probe pulse follows a short pump pulse at some specified delay. Femtosecond capabilities have been available for some years at visible wavelengths. However, there is a strong interest in extending pump-probe techniques to X-ray wavelengths because they allow to probe directly structural changes with atomic resolution. One of the main technical problems for building pump-probe capabilities is the synchronization between pump and probe pulses, which should have different colors.

Here we propose a method to get around this obstacle by using a two step FEL process, in which two different frequencies (colors) are generated by the same femtosecond electron bunch. It has the further advantage to make a wide frequency range accessible at high peak power and high repetition rate. Our technique is based in essence on the fresh bunch technique, and exploits the short saturation length experimentally demonstrated at LCLS. We consider in particular the case for the low charge, short-pulse mode of operation. Such mode of operation can be successfully taken advantage of at the European XFEL as well. In our analysis we consider baseline parameters similar to those of the SASE2 line at the European XFEL, so that our scheme can be implemented at the very first stage of operation of this facility. Table 1 reports these parameters. It should be remarked that the applicability of our method is obviously not restricted to the European XFEL setup. Other facilities e.g. LCLS may benefit from this work as well.

As we will discuss later, our method can also be used in the case of long-pulse mode of operation. In fact, there is no principle difference between long-pulse and short-pulse

Table 1: Parameters for the short pulse mode used in this paper. The undulator parameters are the same of those for the European XFEL, SASE2, at 17.5 GeV electron energy.

	Units	Short pulse mode
Undulator period	mm	47.9
Undulator length	m	256.2
Length of undulator segment	m	5.0
Length of intersection	m	1.1
Total number of undulator cells	-	42
K parameter (rms)	-	2.513
β	m	17
Wavelength	nm	0.15
Energy	GeV	17.5
Charge	nC	0.025
Bunch length (rms)	μm	1.0
Normalized emittance	mm mrad	0.4
Energy spread	MeV	1.5

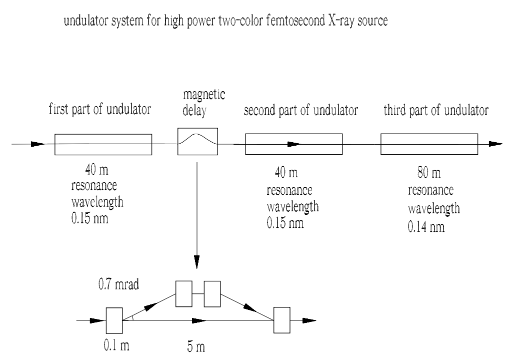

Figure 1: Design of the undulator system for two-color femtosecond X-ray source.

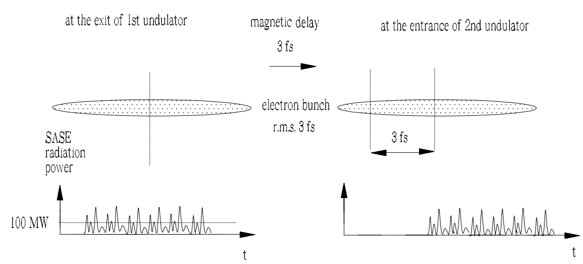

Figure 2: Sketch of principle of "fresh bunch" technique for short (6 fs) pulse mode operation.

modes of operation concerning our pump-probe technique. However, in the case of short-pulse mode of operation the hardware requirement is minimal, and through this paper we will mainly focus on this case. For its implementation it is sufficient to substitute a single undulator segment with a short magnetic chicane, Fig. 1, whose function is both, to wash out the electron bunch microbunching, and to delay the electron bunch with respect to the x-ray pulse produced, in the linear regime, in the first part of the undulator. In this way, half of the electron bunch is seeded, and saturates in the second part of the undulator. Finally, the second half of the electron bunch, which remains unspoiled, lases in the third part of the undulator at a different wavelength.

FEASIBILITY STUDY

With a baseline gap-tunable undulator design (like in the SASE2 case) the pump-probe option in the short-pulse mode of operation only requires the installation of a magnetic delay. Thus, the hardware required for the implementation of our scheme is minimal, and consists in the substitution of one of the undulator segments with a magnetic chicane, as shown in Fig. 1. The quadrupole separation of the undulator FODO lattice (6.1 m) is large enough so that a relatively short (5 m) magnetic chicane can be installed. The electron beam first goes through the first undulator as in the baseline design, producing SASE radiation in the linear regime. After the first undulator the electron beam is guided through the magnetic chicane. The trajectory of the electron beam in the chicane has the shape of an isosceles triangle with the base equal to the undulator segment length, L_w. The angle adjacent to the base, θ, is considered to be small. The magnetic delay needed for the generation of two color x-ray pulses should satisfy three requirements.

First, the radiation pulse must overlap only half of the electron bunch at the chicane exit, i.e. the electron beam extra path length must be of the order of the rms of electron bunch length, as shown in Fig. 2. Second, collective effects, namely coherent synchrotron radiation (CSR) should be avoided in order to preserve transverse emittance. In the present case, simple estimations show that CSR should not be a serious limitation in our case. Third, the electron beam modulation introduced in the first undulator due to FEL interaction must be washed out. The presence of a local energy spread in the electron beam naturally solves the problem. In fact, for Gaussian local energy spread, and neglecting collective effects, the amplitude of the density modulation a at the chicane exit is given by

$$a = a_0 \exp\left[-\frac{1}{2}\frac{\left\langle(\delta\gamma)^2\right\rangle}{\gamma^2}\frac{R_{56}^2}{(\lambda/(2\pi))^2}\right] \qquad (1)$$

where a_0 is the amplitude of the density modulation at the entrance of the chicane, R_{56} is the momentum compaction factor and $\lambda/(2\pi)$ is the reduced wavelength. In our case, parameters of interest are the undulator segment length $L_w = 5$ m, the deflection angle $\theta = 0.7$ mrad, the dispersion $R_{56} = L_w\theta^2 \sim 2.5\mu$m, and the relative energy spread $\Delta\gamma/\gamma \sim 0.01\%$, corresponding to an energy spread of about 1.5 MeV. This leads to the suppression of the beam modulation by a factor of about $\exp(-20)$. Here we assume that an uncorrelated relative energy spread of 1.5 MeV is already present at the entrance of the SASE undulator.

One may also account for the linear energy chirp in the electron beam by introducing a resonance frequency-shift in the second undulator. Thus, we can neglect the linear energy chirp and account for the non-linear energy chirp only. We further require that the non-linear energy chirp be sufficiently small, and that the energy deviation across the lasing part of the bunch be smaller than the FEL ρ parameter. In our case study $\rho \sim 0.1\%$, and simple estimations show that the energy chirp should not be a serious limitation.

After the chicane, the relative positions of radiation and electrons at the entrance of the second undulator part looks like on the right of Fig. 2. The left half of the bunch will start the usual SASE process form shot noise. The right half, instead, is seeded by the radiation produced in the first part of the undulator, and will reach saturation much sooner. Finally, a third undulator part, tuned at a slightly different frequency, will allow two-color operation: the right half of the bunch is spoiled by the SASE process and cannot radiate anymore, while the left half emits usual SASE radiation up to saturation. Low-charge bunch simulations are not time expensive, and we found it convenient to use the Genesis code, i.e. the same code used for simulations at LCLS. Detailed results from the first, second and third stage are given in [1].

The overall result of our simulations is shown in Fig. 3. The output pulses from the second and the third part of the undulator are shown, together with the current profile of the electron bunch. Two femtosecond, ten GW level pulses of coherent x-rays with two different colors can be easily generated with this method.

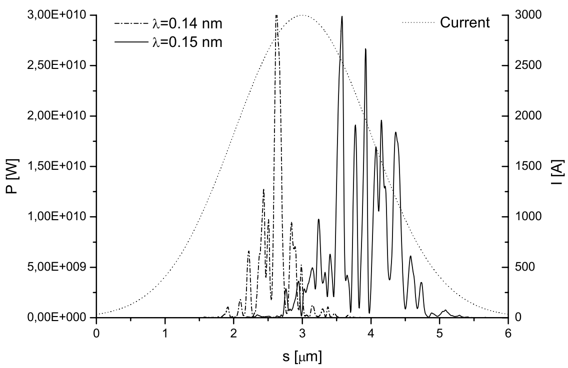

Figure 3: Superimposed radiation pulses at $1.4\,\AA$ and $1.5\,\AA$. The bunch current is also shown.

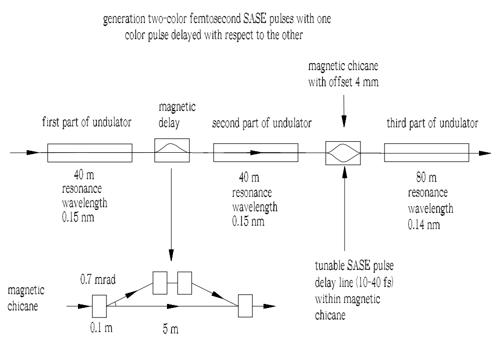

Figure 4: Design of undulator system for short pulse (6 fs) mode operation employing two color femtosecond pulses that are delayed one with respect to the other

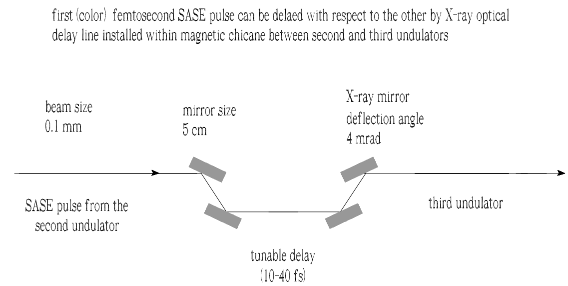

Figure 5: Scheme for delaying the first (color) femtosecond SASE pulse with respect to the other within undulator system. X-ray optical system can be installed within magnetic chicane between second and third undulator

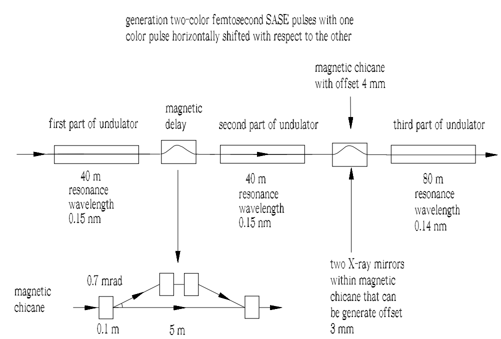

Figure 6: Sketch of an undulator system for short-pulse mode of operation employing two color femtosecond pulses that are horizontally shifted one with respect to the other.

PHOTON BEAM MANIPULATION

Once the result shown in Fig. 3 is established, one faces the task of transport and utilization of the two radiation pulses to the experimental station. While transport can be performed with the same optics without problems, utilization for pump-probe experiments implies the capability of separating and delaying the two pulses of a given temporal amount at the experimental station. Investigating this capability goes beyond the scope of this paper.

A possible alternative is to include a tunable delay already at the level of the SASE undulator setup. This can be done with usual grazing-incidence optics. The idea is to install a mirror chicane between the second and the third part of the undulator, as shown in Fig. 4 and Fig. 5. The function of the mirror chicane is to delay the 0.15 nm-radiation relatively to the bunch and, therefore, also relatively to the 0.14 nm-pulse. The glancing angle of x-ray mirrors is as small as 2 mrad. Inside the photon-beam transport tunnel, the transverse size of the radiation requires long mirrors, in the meter size. In contrast to this, at the undulator location, the transverse size of the photon beam is smaller than $100\ \mu$m, meaning that the mirror length would be just about 5 cm. Moreover, the short-pulse mode will relax the heat-loading issues.

Of course, in order to install the mirror chicane one needs to first create an offset for the electron trajectory, meaning that a magnetic chicane should be inserted at the position of the mirror-chicane. The mirror chicane can be built in such a way to obtain a delay of the SASE pulse of about 40 fs. This is enough to compensate a bunch delay of about 10 fs from the magnetic chicane, and to provide any desired temporal shift in the range $0 - 30$ fs, as shown in Fig. 4.

It should be noted that the main difficulty concerning the manipulation of the two-color photon beam consists in the separation of the two colors. Once this task is performed, the delay problem can be easily solved in the experimental hall with the help of mirrors. Of course, the two colors can be separated in the experimental hall as well with the help of crystals. However, this would lead to a loss of photons due to narrow bandwidth of the crystals.

As an alternative to the tunable relative delay considered above, here we propose to separate the two colors already in the undulator with the help of x-ray mirrors. The idea is sketched in Fig. 6 and Fig. 7. The two colors can be

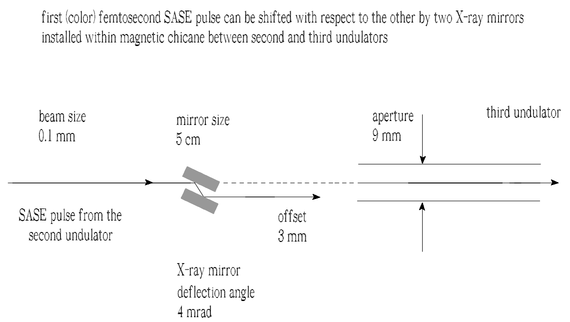

Figure 7: Scheme for horizontally shifting the first femtosecond SASE pulse with respect to the other within the undulator system. Two X-ray mirrors can be installed within the magnetic chicane between the second and the third undulator.

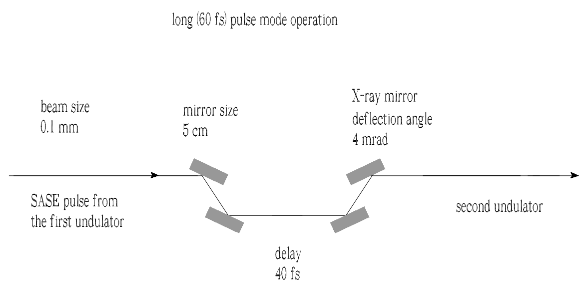

Figure 8: X-ray optical system for delaying the SASE pulse in the case of long (60 fs) pulse mode operation

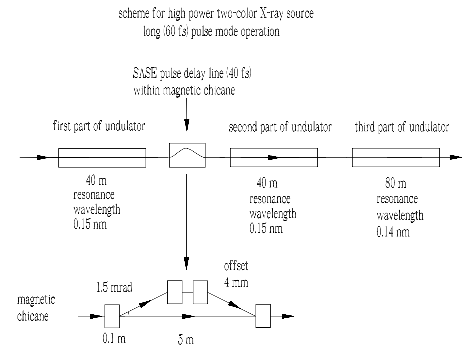

Figure 9: Design of undulator system for long (60 fs) pulse mode operation.

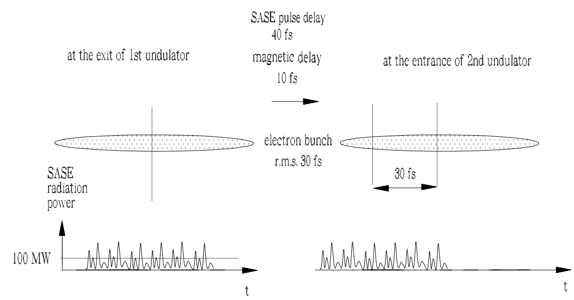

Figure 10: Sketch of principle of ”fresh bunch” technique for long (60 fs) pulse mode operation.

separated horizontally by two mirrors installed within the chicane after the second undulator. The horizontal offset can be about 3 mm, which is enough for separating the two-color pulses, because at the position of the optical station the FWHM beam size is less than a millimeter. Additionally, mirrors can also be used to generate a few μrad deflection-angle, which is not important within the undulator but will create further separation of a few millimeters at the position of the experimental station.

LONG-PULSE OPERATION MODE

As mentioned in the introduction, our method is also suitable for the long-pulse operation mode. A straightforward way of application consists in increasing the magnetic chicane angle up to about 2.5 mrad, thus providing a relative delay of the electron beam with respect to the electron pulse of 30 fs.

Alternatively, one may use an optical delay line which would, however, require extra-hardware. A mirror chicane would delay the radiation relatively to the bunch (see Fig. 8). The difference with respect to the optical chicane for obtaining a tunable delay, considered above, is that now the optical delay line should be installed between the first and the second undulator. As before, the combination optical delay-magnetic chicane can be built in such a way to obtain a delay of the SASE pulse relative to the electron beam of about 30 fs, as shown in Fig. 10. In this way, the strength of the magnetic chicane can be reduced, and the deflection angle of the electron beam can be set to 1.5 mrad. Also note that heat-loading problems would be strongly mitigated by the fact that the photon pulse is still in the linear regime, at low power (100 MW).

REFERENCES

[1] G. Geloni, V. Kocharyan and E. Saldin, ”Scheme for femtosecond-resolution pump-probe experiments at XFELs with two-color ten GW-level X-ray pulses”, DESY 10-004 (2010), http://arxiv.org/abs/1001.3510