

SELF-SEEDING SCHEME WITH GAS MONOCHROMATOR FOR NARROW-BANDWIDTH SOFT X-RAY FELS

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Abstract

We propose an extension of our single-crystal self-seeding scheme to the soft X-ray range using a cell filled with resonantly absorbing gas as monochromator. The transmittance spectrum in the gas exhibits an absorbing resonance with narrow bandwidth. Then, similarly to the hard X-ray case, the temporal waveform of the transmitted radiation pulse is characterized by a long monochromatic wake, whose power is much larger than the equivalent shot noise power in the electron bunch. The monochromatic wake of the radiation pulse is combined with the delayed electron bunch and amplified in the second undulator. The proposed setup is extremely simple, and composed of as few as two simple elements: a gas cell, to be filled with noble gas, and a short magnetic chicane. The installation of the magnetic chicane does not perturb the undulator focusing system and does not interfere with the baseline mode of operation. **These proceedings are based on the article [1], to which we address the interested reader for further information and references.**

INTRODUCTION

Self-seeding schemes have been studied to reduce the bandwidth of SASE X-ray FEL. In general, a self-seeded FEL consists of two undulators with a monochromator located between them. The first undulator operates in the high gain linear regime starting from the shot noise in the electron beam. After the first undulator, the output radiation passes through the 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 microbunching 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 radiation pulse is recombined with the electron beam, and amplified up to saturation. The radiation power at the entrance of the second undulator is dominant over the equivalent shot noise power, so that the bandwidth of the input signal is smaller than the bandwidth of the FEL amplifier.

Self-seeding schemes proposed for the VUV and soft X-ray region makes use of a grating monochromator. This introduces a path delay with respect to the straight path, which has to be compensated with the introduction of a bypass of the length of about 30 m for the case of the LCLS-II. We recently proposed a new method of monochroma-

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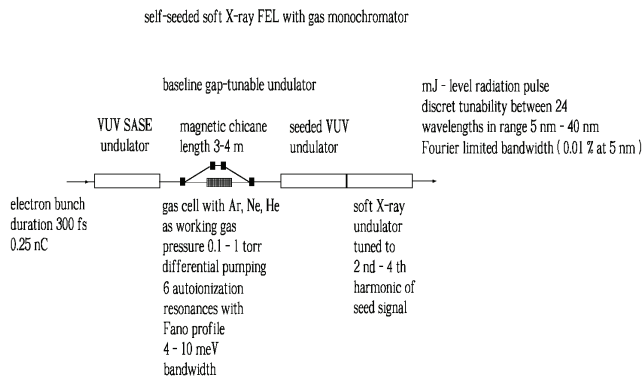


Figure 1: Design of the VUV - soft X-ray FEL undulator system for the narrow bandwidth mode of operation.

tization exploiting a single crystal in Bragg-transmission geometry for self-seeding in the hard X-ray range. A great advantage of such transmission geometry method is that it introduces no path-delay of X-rays in the monochromator, thus avoiding the need for a long electron beam bypass.

Here we propose a new method of monochromatization for soft X-rays based on the use of a cell containing resonantly absorbing gas in the transmission direction. Such cell works, in analogy with the single-crystal monochromator method for hard X-rays, as a bandstop filter. Problems as extra path-delay of radiation pulse, heat loading and monochromator alignment are solved. The proposed setup is extremely simple, and composed of two simple elements: a gas cell and a short magnetic chicane, Fig. 1. As for the hard X-ray case, the magnetic chicane accomplishes three tasks. It creates an offset for gas cell installation, it removes the electron microbunching produced in the first undulator, and it acts as a delay line for the electron bunch. Thus, using a cell with rare gas installed within a short magnetic chicane in the baseline soft X-ray undulator as a bandstop filter, it is possible to decrease the bandwidth of the VUV radiation down to the Fourier limit.

One can implement the proposed scheme in the soft X-ray region, exploiting the tunable-gap soft X-ray baseline undulator. One can first perform monochromatization at 20 - 40 nm with the help of the gas-cell monochromator, and subsequently amplify the radiation in the first part of the output undulator. The amplification process can be stopped at some position well before the FEL reaches saturation, where the electron beam gets considerable bunching at the 2nd, 3rd and 4th harmonic of the coherent radiation. The undulator downstream that position can then be tuned to a given harmonic frequency to amplify the radiation fur-

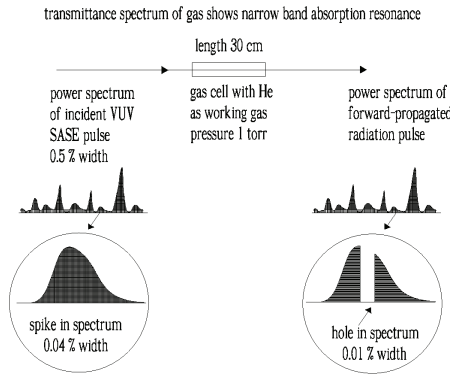


Figure 2: Gas cell with He, Ne and Ar as working gas, will work as a bandstop filter for the transmitted VUV SASE radiation pulse.

ther to saturation, Fig. 1.

We present a feasibility study for applying the self-seeding scheme with gas monochromator to the LCLS-II setup, in order to generate narrow bandwidth, soft X-ray radiation in the proposed soft X-ray beam line. The tentative design for the proposed technique at LCLS-II allows to generate fully coherent radiation at a wavelength of about 5 nm.

SELF-SEEDING WITH A GAS MONOCHROMATOR

Our novel method of monochromatization is based on the use of a cell containing resonantly absorbing gas. It takes advantage of the transmission geometry, where no extra path-delay for the radiation pulse is present. The principle is very simple and is illustrated in Fig. 2. An incident SASE pulse coming from the first undulator impinges on the gas cell. When the spectral contents of the incoming SASE beam satisfies the photo-absorption resonance condition of the gas, the gas cell operates as a bandstop filter for the transmitted VUV SASE radiation pulse. Obviously, if we use a bandstop filter there is no monochromatization in the frequency domain. However, 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. It is then possible to reach a bandwidth limited seed signal by exploiting a temporal windowing technique. Since we deal with a high-gain parametric amplifier where the properties of the active medium, i.e. electron beam, depend on time, 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 pulse experiences a strong temporal separation. In other words, the magnetic chicane in Fig. 1 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. The concept is similar to that developed elsewhere (see [1] for references) for the hard X-ray case. However, in the proposed scheme no optical elements are used, and problems with alignment or heat loading do not exist at all. While the radiation is sent through the gas cell, the electron beam passes through the magnetic chicane, which accomplishes three tasks by itself: it creates an offset for the gas cell installation, it removes the electron micro bunching produced in the first (SASE) undulator and, as already said, it acts as a delay line for the implementation of the temporal windowing.

For the VUV wavelength range, a momentum compaction factor R_{56} in the order of 100 μm is sufficient to remove the microbunching in the electron beam. As a result, the choice of the strength of the magnetic chicane only depends on the delay that we need to introduce between electrons and radiation. In our case, this amounts to 100 μm , see Fig. 1. Such delay is small enough to be generated by a short 3 – 4 m long chicane to be installed in place of a single undulator module at a facility like the LCLS-II. Such chicane is, however, strong enough to create a sufficiently large transverse offset of 1 – 2 cm for installing the gas cell.

The monochromator will take advantage of autoionizing resonances in rare gases. Several gases He, Ne and Ar can be considered [1]. However, here we will limit ourselves to Helium. Autoionizing resonances result from the decay of doubly excited Rydberg states of He^* into the continuum, i.e. $He^* \rightarrow He^+ + e^-$. Since the continuum can also be reached by direct photoionization, both paths add coherently, giving rise to an interference. This interference is related to the typical Fano line shape for the cross-section as a function of energy. The cross section for these series can be modeled by

$$\sigma(\lambda, q, \Gamma) = \sigma_b(\lambda) \left(\frac{(\sum_{n=2}^{\infty} (q_n/\mathcal{E}_n) + 1)^2}{\sum_{n=2}^{\infty} (1/\mathcal{E}_n)^2 + 1} \right), \quad (1)$$

where the energy-dependent background cross-section expressed in Megabarn ($1Mb = 10^{-18}cm^2$) is given by

$$\sigma_b(\lambda) = -0.05504 - 1.3624 \cdot 10^{-4}\lambda + 3.3822 \cdot 10^{-5}\lambda^2 \quad (2)$$

with λ the radiation wavelength in Angstrom units, while the reduced energy \mathcal{E}_n is defined as

$$\mathcal{E}_n = \frac{2(E_{R_n} - hc/\lambda)}{\Gamma_n}. \quad (3)$$

The asymmetry index q_n , the energy of the n th resonance E_{R_n} , the resonance width Γ_n , have been the subject of several calculations (see references in [1]).

The modulus of the transmissivity is given by

$$|T| = \exp[-n_0\sigma/2], \quad (4)$$

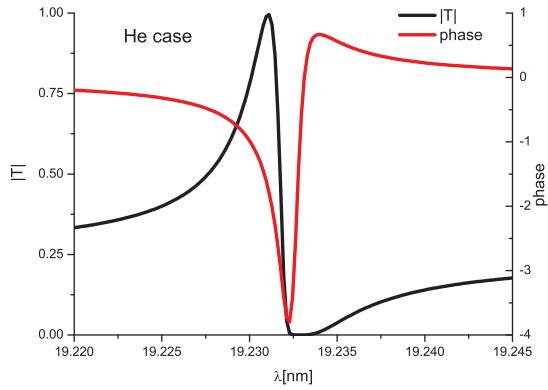


Figure 3: Modulus and phase of the transmissivity of He for the $n = 4$ line of the $(sp, 2n+) ^1P_0$ Rydberg series.

self-seeding scheme with gas monochromator for the LCLS-II baseline soft X-ray undulator

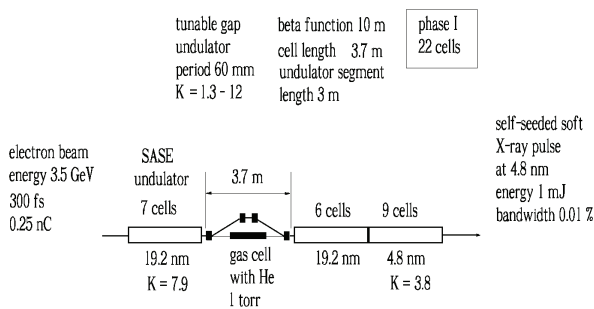


Figure 4: Design of the LCLS-II baseline undulator system.

Considering a column-density equal to $n_0 l = 10^{18} \text{cm}^{-2}$, and restricting ourselves to the third ($n = 4$) resonant line of the $(sp, 2n+) ^1P_0$ Rydberg series for Helium, we recover the phase of T from the knowledge of $|T|$. The transmissivity T (modulus and phase) is shown in Fig. 3.

A FEASIBILITY STUDY

The autoionizing resonance that we consider here as an example is in the 20 nm-range. In order to generate shorter wavelengths we need to go to higher harmonic numbers. A possible way of doing so is to use a two-stage output undulator, with the second stage resonant to one of the harmonics of the first one, Fig. 4. The magnetic chicane dimensions are sketched in Fig. 5. In our feasibility study we will consider, for exemplification purposes, the LCLS-II setup equipped with a 80 m long gap-tunable undulator, which can be operated within the photon energy range between 30 eV to 1100 eV at 3.5 GeV electron beam energy. Due to specific of Front End Enclosure (FEE) system of LCLS-II will be possible direct the radiation into experimental stations only starting around the 200 eV photon energy range. With the chosen parameters (see Table 1 and [1]), the amplitude of the 4th harmonic of the density

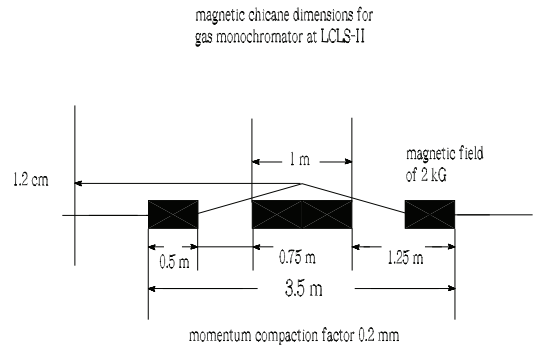


Figure 5: Magnetic chicane dimensions for gas monochromator installation at LCLS-II

Table 1: Parameters for the nominal pulse mode of operation used in this paper.

	Units	
Undulator period	mm	60
K parameter	-	1.3-12
Wavelength (fundamental)	nm	19.2
Energy	GeV	3.5
Charge	nC	0.25

modulation at the exit of first stage of the output undulator is high enough and dominates significantly over the amplitude of shot noise harmonic. This modulation density serves as an input signal for the second part of output undulator, which is indeed resonant with the 4th harmonic. An important feature of our design is that no dispersion section is introduced between the two stages in the output undulator. The advantage of this method of harmonic generation in self-seeded FELs is in the simple hardware required (only a short magnetic chicane for the gas cell installation). However, a gap-tunable baseline undulator is needed.

Here we focus on the implementation of our self-seeding scheme exploiting a wake monochromator to generate fully coherent soft X-rays for LCLS-II. The tentative design for the gas monochromator self-seeding technique at the LCLS-II aims at generating fully coherent radiation at about 5 nm. The main parameters for the nominal 5 nm case are listed in Table 1 in the next Section. Full 3D have been performed in order to confirm the scheme feasibility. The simulations is performed with the code GENESIS 1.3 code, which uses as input the beam parameters obtained in start to end simulations (see [1] for references and details). In all simulations we assumed that the gas used in the monochromator is Helium, and that the energy of the VUV FEL photons is 64.4 eV, or 19.2 nm, corresponding to the $n = 4$ autoionization profiles for the $(sp, 2n+)$ autoionizing series of Helium, considered above.

While the photon beam passes through the gas cell, the electron crosses the chicane, where the microbunching is removed. In fact, in our case, parameters of interest are the

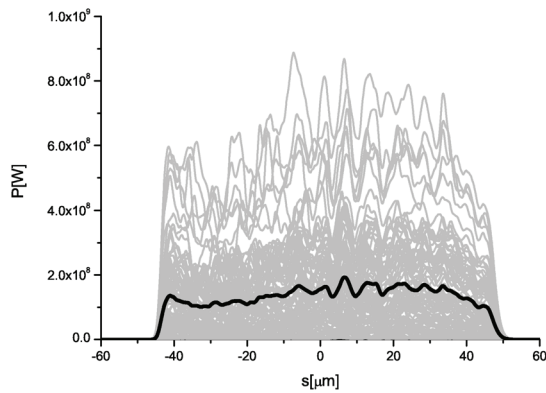
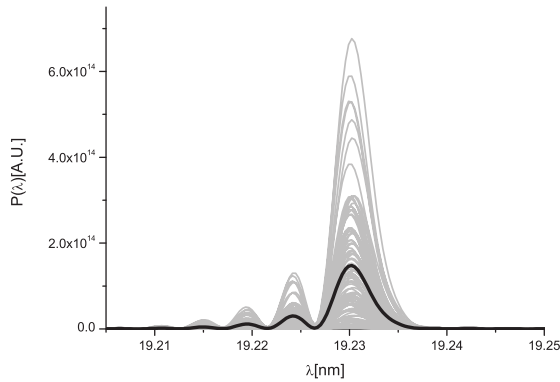


Figure 6: Spectrum (upper plot) and power (lower plot). Grey lines refer to single shot realizations, the black line refers to an average over 100 realizations. The second undulator is tuned at the fundamental.

dispersion $R_{56} = L_w \theta^2 \sim 0.2$ mm (insuring a delay equal to 0.1 mm), and the relative energy spread $\Delta\gamma/\gamma \sim 0.03\%$, corresponding to an energy spread of about 1.5 MeV at an energy of 3.5 GeV. For a wavelength of 19 nm, these parameters lead to the suppression of the beam modulation by a factor of about $\exp(-200)$ for Gaussian local energy spread. Following the chicane, the electron beam is recombined with the photon beam at the entrance of the output undulator. The first stage of the output undulator, consisting of the first 6 cells, is tuned at the fundamental, while the second stage, consisting of 9 cells, is tuned at the fourth harmonic, Fig. 4. The output characteristics in terms of power and spectra at the exit of the first stage are shown in Fig. 6. The final output at the fourth harmonic is shown in Fig. 7, showing power and spectrum. A mJ, fully coherent pulse with a bandwidth in the order of the 0.01% is produced at a wavelength of 4.8 nm.

CONCLUSIONS

We proposed a scheme for controlling the line width of VUV and soft X-ray SASE FELs that offers simplicity and

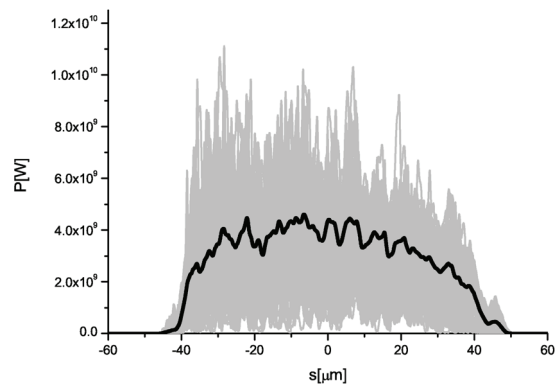
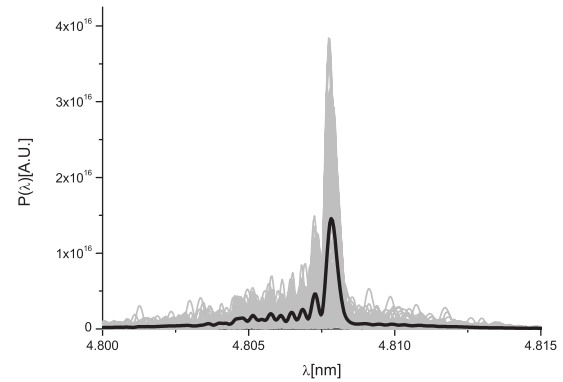


Figure 7: Spectrum (upper plot) and power (lower plot). Grey lines refer to single shot realizations, the black line refers to an average over 100 realizations. The second undulator tuned at the fourth harmonic.

flexibility, and can be added to the baseline undulators of many facilities without significant cost or design changes. Monochromatization down to the Fourier transform limit of the radiation pulse can be performed by exploiting an almost trivial setup composed of as few as two components. The key components of such scheme include only a cell containing dilute noble gas, and short magnetic chicane. A great advantage of our method is that it includes no path delay of the radiation pulse in the monochromator. Implementation of our technique in the baseline undulator will not perturb the baseline mode of operation. We presented an illustration of the scheme for the LCLS-II soft X-ray beam line, although other facilities like FLASH-II, Swiss-FEL, FERMI and SPARC may also benefit from it.

REFERENCES

- [1] G. Geloni, V. Kocharyan and E. Saldin, "Self-seeding scheme with gas monochromator for narrow-bandwidth soft X-ray FELs", DESY 11-049 (2011), <http://arxiv.org/abs/1103.5012>.