ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP056

FEASIBILITY STUDIES OF THE 100 keV UNDULATOR LINE OF THE EUROPEAN XFEL

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Abstract

The European XFEL is a multi-user X-ray FEL facility based on superconducting linear accelerator. Presently, three undulators (SASE1, SASE2, SASE3) deliver high-brightness soft- and hard- X-ray beams for users. There are two empty undulator tunnels that were originally designed to operate with spontaneous radiators. We consider instead a possible installation of two FEL undulators. One of them (SASE4) is proposed for the operation in ultrahard X-ray regime, up to the photon energy of 100 keV. In this contribution we present the results of the first feasibility studies of this option.

INTRODUCTION

The European XFEL is a X-ray FEL user facility, based on superconducting accelerator [1]. It provides ultimately bright photon beams for user experiments since 2017. Two hard X-ray undulators (SASE1 and SASE2) and one soft X-ray undulator (SASE3) are presently in operation [2], see Fig. 1. There are two empty undulator tunnels that were originally designed [3] to host the undulators U1 and U2 (see Fig. 1) to be used for generation of spontaneous undulator radiation in the range 20-90 keV.

Recently, design studies have been initiated aiming at conceptual and technical designs of FEL undulator lines instead of spontaneous radiators in the empty tunnels. One of the options, requested by the user community, is an undulator capable of generation of powerful X-ray radiation in the ultrahard photon energy range, up to 100 keV. Realization of such an option would rely on the unique features of the European XFEL among other facilities of such kind, namely the highest electron energy (17.5 GeV) and the longest tunnels. Note that the idea of using a SASE undulator for lasing up to 90 keV instead of spontaneous radiators in one of the empty tunnels was suggested and illustrated with numerical simulations in [4]. In this paper we perform extended considerations of this option.

UNDULATOR LENGTH AND LOCATION

The hard and ultrahard X-ray undulator can be located in the tunnel XTD3 (place for U1 in Fig. 1) or in XTD5 (place for U2). The planned lengths for the installation of the spontaneous radiators is 120 m in XTD3 and 140 m in XTD5. It would be desirable to have a larger length for

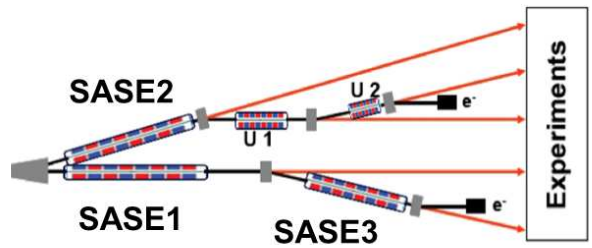

Figure 1: Layout of undulator tunnels of the European XFEL

SASE4 if it is supposed to lase up to 100 keV, and one can consider alterations to the tunnel infrastructure and electron lattice. In particular, a more aggressive bending can be considered at the end of XTD3, thus making about 200 m in this tunnel available for the installation of the SASE4 undulator. Also, we discuss an installation of a bypass line (as an alternative to the fresh bunch technique [4]) to avoid beam quality deterioration in SASE2 undulator (see below).

EXPECTED PROPERTIES OF THE ELECTRON BEAM

Electron beams with a high peak current, low emittance and energy spread are required for operation of short-wavelength FELs. This is especially important when we discuss a challenging range of photon energies, up to 100 keV. We performed start-to-end simulations of the beam dynamics in the European XFEL accelerator (tools and methods are described in [5]), and present here the results for 100 pC bunches, accelerated to 17.5 GeV and transported to the SASE2 undulator. The current, emittance, uncorrelated energy spread are presented in Fig. 2 as functions of a position along the bunch length. One can see that slice parameters in the bunch core are good: peak current is 5 kA, slice emittance is below 0.3 mm mrad, and uncorrelated energy spread is below 1 MeV. The latter parameter can degrade if the bunches are transported through SASE2 undulator, it can increase up to 3 MeV due to the quantum diffusion [6] if SASE2 operates with fully closed gap. To fully decouple operation of SASE2 and SASE4, it would be desirable to consider a bypass line (also wakefield effects would be strongly reduced then).

We also consider an advanced compression, namely eSASE [7]. In that case, we compress the beam relatively weakly in bunch compressors (to 1-2 kA) thus avoiding strong CSR effects during compression and transport. Then

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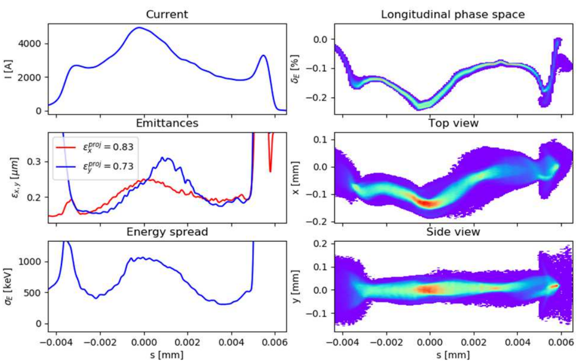

Figure 2: The results of start-to-end simulations for the bunch charge of 100 pC. Left column: current, slice emittance (horizontal in red, vertical in blue) and uncorrelated energy spread versus the position along the bunch length. Left column: longitudinal phase space, top view and side view of the bunch.

we can obtain a high peak current in front of SASE4 as follows: we modulate the beam by a laser in a wiggler and get high-current spikes in a compact chicane. First simulation results are encouraging [8].

LIMITATION ON THE PHOTON ENERGY

A fundamental limit on a shortest wavelength of a SASE FEL is given by the growth of uncorrelated energy spread due to quantum fluctuations of the undulator radiation [6, 9]. The shortest wavelength can be estimated as [10]:

$$\lambda^{\mathrm{q}}_{\mathrm{min}}[] \simeq \frac{4\,\epsilon_n[\mu\mathrm{m}]}{I^{3/5}[\mathrm{kA}]\,L_{\mathrm{w}}^{2/5}[\mathrm{m}]} \qquad (1)$$

Here I is the peak current,ϵ_n is the rms normalized emittance, L_{w} is the undulator length. It is assumed that electron energy and undulator parameters can be freely chosen and are optimized. Let us estimate the limit for the following parameters: $I = 5$ kA, $\epsilon_n = 0.3$ mm mrad, $L_{\mathrm{w}} = 175$ m. According to (1) we get $\lambda^{\mathrm{q}}_{\mathrm{min}} \simeq 0.06$, and the corresponding photon energy is about 200 keV.

UNDULATOR TECHNOLOGY

To be specific, we will assume that the magnetic length of SASE4 undulator can be as large as that of SASE1 and SASE2 undulators [11], namely 175 m. All the calculations below are done for the beam energy of 17.5 GeV, include quantum diffusion in SASE4 undulator, and assume the following slice parameters of the lasing core of electron bunch at the entrance of SASE4: peak current 5 kA, normalized slice emittance 0.3 mm mrad, and uncorrelated energy spread 1 MeV. It follows from formulas of ref. [10] that the shortest achievable FEL wavelength is simply proportional to an undulator period for these parameters. Thus, it is worth considering short-period undulators such as in-vacuum or superconducting ones. On the other hand, we should not exclude from consideration the standard out-of-vacuum undulators with longer periods and advanced lasing options. Apart from giving a possibility to reach high photon energy, SASE4 undulator should have a significant tunability range because it will be one of the five undulators simultaneously providing X-ray beams for users. Let us briefly consider three different scenarios using the properties of undulators summarized in [12].

In-Vacuum Undulator

The technology of in-vacuum (IV) undulators is relatively well developed and used at other XFEL facilities (SACLA, Swiss FEL). Let us consider as an example the undulator period of 22 mm and the gap of 5 mm. For the above mentioned parameter set we find that the tunability range would be 40 - 100 keV.

Superconducting Undulator

A few meters long superconducting (SC) undulators are installed and successfully operated at storage ring based light sources, but substantial R&D is required towards building a long string of undulators of an excellent quality for X-ray FELs. The main advantage of SC undulators is a possibility to combine a short period and a strong magnetic field, resulting in a large K-value. For example, for a period of 25 mm and the pole gap of 7 mm (beam stay-clear gap is 5 mm), the maximum K-value is about 5.5. Then, for our parameter set, the tunability range of such an undulator would be 7 - 90 keV. An interesting technical option could be the period doubling that would allow to further reduce the period length while increasing the tunability. More details on SASE4 performance with a superconducting undulator can be found in [13].

Standard out-of-Vacuum Undulator

This is the most cheap and reliable technology. Let us consider an undulator with the period of 35 mm and the gap of 7.5 mm. The tunability range would be 8 - 60 keV on the fundamental, and the upper limit can be extended to 85 keV with harmonic lasing [14]. In case of a higher quality of the electron beam, the highest photon energy can be above 100 keV.

As an option, one can consider a combination of two undulators with different periods in the same way as it was proposed for FLASH upgrade [15]. For example, an undulator with a period of 40 mm and magnetic length of 100 m can be followed by a 75 m long section with the period of 30 mm. With the gap of 10 mm, this configuration would provide the same tunability range as the undulator with the period of 35 mm and the gap of 7.5 mm, considered before. Note that the gap might be a critical issue for an XFEL based on the superconducting accelerator with a high average beam power.

Let us finally note that the large tunability in case of the last two options is a very attractive feature. It supports the operation of multi-user facility with the same electron energy most of the time and may let serve two user stations operating at 7 - 25 keV and 25 - 100 keV with a possible day/night switching.

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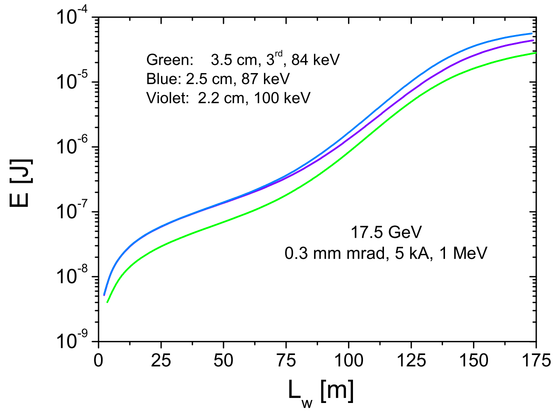

Figure 3: FEL pulse energies versus undulator length for the three undulator cases: superconducting (blue), in-vacuum (violet), and standard out-of-vacuum with the 3rd harmonic lasing (green).

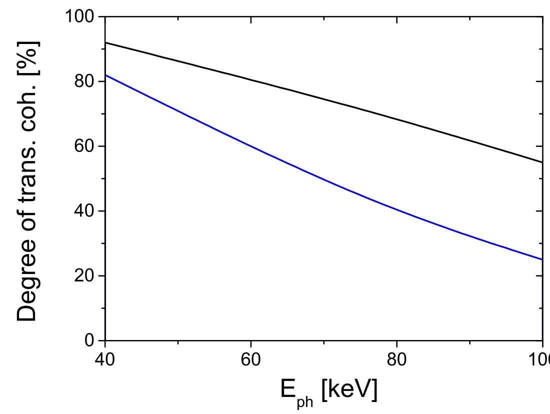

Figure 4: Expected degree of transverse coherence (see the definition in [17]) of SASE FEL radiation as a function of photon energy. Blue line: normalized emittance is 0.3 mm mrad. Black line: normalized emittance is 0.2 mm mrad. Electron beam energy is 17.5 GeV. Estimates were done using the results of Ref. [17].

EXPECTED PROPERTIES OF THE RADIATION

We performed numerical simulations with the code FAST [16] for three sets of undulator parameters from the previous Section and photon energies approaching 100 keV. Pulse energies versus undulator length are shown in Fig. 3, they are in the range of several tens of microjoules what corresponds to about 10^9 photons per pulse. Divergence of the FEL radiation for these photon energies is about 0.3 μrad (FWHM), and the intrinsic bandwidth ranges between 10^{-4} and 3×10^{-4} (FWHM). Actual bandwidth might be influenced by an energy chirp (but an installation of a dechirper can help keep it small).

The transverse coherence depends on the ratio of a geometric emittance to the wavelength [17] and is expected to be relatively poor for photon energies about 100 keV. If the normalized emittance is 0.3 mm mrad, the degree of transverse coherence (see the definition in [17]) can be estimated at the level of 20% using the results of ref. [17] (see Fig. 4).

Radiation properties can be improved in case of using eSASE based compression scheme that might allow for compression to a higher peak current while preserving slice emittance of the lasing spikes. In this case the number of photons per pulse can be increased to the level of 10^{10} for the photon energies about 100 keV, and the transverse coherence can be also improved.

ADVANCED LASING CONCEPTS

High energy photons can be produced by nonlinear harmonic generation mechanism but with low intensity, large fluctuations and a strong background on the fundamental. One can consider, instead some advanced schemes eliminating these problems. Harmonic lasing was already mentioned as an opportunity to extend the photon energy range of SASE4, it can provide high-brightness photon beams [14]. Recent experimental developments [18–20] confirm a validity of this concept in X-ray regime. Another option is the reverse tapering of the main undulator plus an afterburner [21] where an efficient background-free generation of harmonics is possible as it was shown in recent experiments [22]. One can also consider cascaded frequency multiplication [23,24] that might be especially efficient when several compact chicanes are installed as parts of the undulator system. The operation of the single-stage multiplication scheme, the frequency doubler, was demonstrated experimentally [25, 26]. One or more of these methods could complement standard SASE FEL operation on the fundamental, and this would be especially desirable in the case of using the standard undulator technology.

SUMMARY AND OUTLOOK

We can conclude that 100 keV lasing at the European XFEL seems to be feasible. Final choice of the photon energy range, possible length and location of the undulator, choice of the undulator technology will be a result of an iterative process that includes in particular user requirements, financial and technological aspects.

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