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A SUPERRADIANT THz UNDULATOR SOURCE FOR XFELS

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Abstract

The European XFEL has successfully achieved first lasing in 2017 and meanwhile three SASE FEL beamlines are in operation. An increasing number of users has great interest in a specific type of two-color pump-probe experiments in which high-field THz pulses are employed to drive nonlinear processes and dynamics in matter selectively. Here, we propose to use a 10-period superconducting THz undulator to provide intense, narrowband light pulses tunable in wide range between 3 and 100 THz. The exploitation of superconducting technology allows us to meet the challenge of generating such low photon energy radiation despite the very high electron beam energy at the European XFEL. In this paper, we will present the latest developments concerning THz undulator design and the expected THz pulse properties for the case of the European XFEL.

CONCEPT AND MOTIVATIONS

X-ray Free-Electron Lasers are currently the extremely bright and tunable sources of ultrashort X-ray pulses available for basic scientific research. Among many possible uses, the ultrahigh brightness and the ultrashort duration of these pulses can be exploited in a "pump-probe" configuration, to probe non-equilibrium states of a matter sample that can be excited by previous interaction with terahertz radiation. Since the latest generation XFELs under early operation stages or construction, such as the European XFEL [1] and the LCLS-II [2] are based on superconducting technology, THz pulses are also required in CW or burst mode with repetition rates of between 100 kHz and 4.5 MHz. The generation of high-field THz pulses at such high duty-cycle by means of femtosecond lasers does not allow achieving the required parameters in terms of pulse energy and narrow-bandwidth; therefore, a superradiant THz undulator emerges as one promising solution. In this paper, we describe the technological feasibility for implementing a few-period superradiant THz undulator that fits the particular case of the electron linac of the European XFEL.

THz UNDULATOR PARAMETERS

The main challenge in the construction of a THz undulator for the production of superradiant THz pulses at the European XFEL is the very high-energy of the electron beam, nominally in the range from 8.5 to 17.5 GeV. In fact, the resonance condition on-axis for the first harmonic reads:

$$\lambda = \lambda_U \frac{1 + K^2/2}{2\gamma^2}\,, \tag{1}$$

and

$$K = 93.66 B[T] \lambda_U[m] \tag{2}$$

with λ the fundamental wavelength, λ_U the undulator period, γ the Lorentz factor, K the undulator parameter, and B the magnetic field. We will limit our considerations to fundamental frequencies higher than 3 THz, corresponding to about $\lambda = 100$ µm, and assuming an electron beam energy fixed throughout the paper of 17.5 GeV. If we now fix $\lambda_U =$ 1 m, we find that in order to reach a minimal frequency of about 3 THz a value K = 685 is needed, corresponding to a maximum field on axis B ≈ 7.3 T, which is feasible to reach using a well-proven NbTi technology.

The total pulse energy generated by a single electron bunch W_{bunch} while passing through any kind of radiator depends on the bunch length and follows the relation

$$W_{bunch} = N_e[1 + (N_e - 1)|\bar{F}(\nu)|^2]W_0 \tag{3}$$

where Ne is the number of electrons in the bunch, W_0 the pulse energy emitted by a single electron and $\bar{F}(\nu)$ the bunch form factor. In order to sustain FEL lasing at X-ray wavelengths, very high peak currents must be achieved (in the order of several kilo amperes for the European XFEL), and hence it is needed to strongly compress the electron bunch in the first place. Therefore, it makes sense to exploit the spent XFEL electron beam for generating superradiant THz pulses, because the form factor until high THz frequency is available. The level of compression depends on the charge, with bunches of lower charge being compressed more to obtain the same peak-current level. In Fig. 1, the nominal electron current profiles, calculated using start-to-end simulation for the European XFEL with different charges [3], are reported. In Fig. 2 we show the pulse energy that can be obtained at different fundamental frequencies (by changing the K parameter of the THz undulator) for several nominal electron bunch charges using 10 % bandpass filter with boxcar line function. From Fig. 2 we can see a competition between the N_e^2 dependence of the pulse energy, which favors high charges, and the form factor dependence on the frequency, which favors low charges (at the same peak current, needed to sustain the previous FEL process). As expected, the highest electron charge considered here, 500 pC, yields the best

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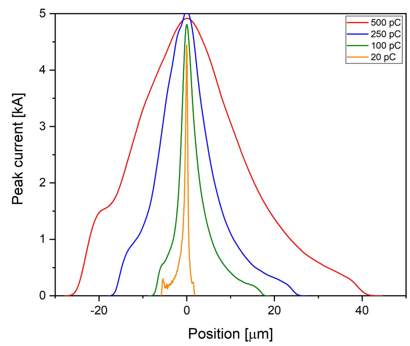

Figure 1: S2E simulated electron current profiles for different charges at the European XFEL.

results, in terms of energy per pulse, in the lowest frequency range, between 3 and 6 THz with expected energies above 100 µJ. A charge of 250 pC appears optimal in the range between 6 and 15 THz, with energies above 30 µJ. Finally, the lower charge of 100 pC is suitable for frequencies starting from 15 THz. Our proposed undulator is expected to obtain energies above 10 µJ up to frequencies of about 30 THz. For frequencies higher than that value, the yield remains around the 10 µJ level up to frequencies of about 50 THz. Finally, note that the yield of the lowest nominal charge of 20 pC always falls below that of the 100 pC. We note that the choice of charges is forcefully linked to the operation mode of the considered XFEL, so that operational restrictions might apply. It should also be remarked that angular filtering can be used, instead of spectral filtering.

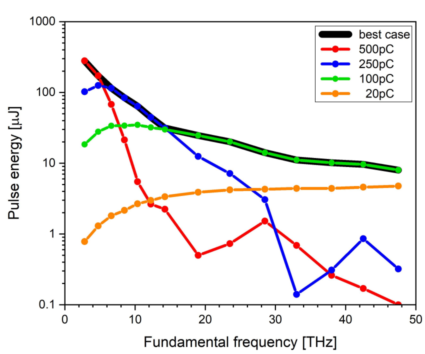

Figure 2: Tunability of the THz undulator fundamental: pulse energy at different fundamental frequencies for several electron bunch charges using a 10 % bandpass filter.

As just mentioned, it is important to look at the expected beam size at the fundamental frequency inside the undulator. This is critical to understand the minimum gap acceptable in the undulator design, under the assumption that we accept the full transverse size at the longest fundamental wavelength. We will consider the case for the fundamental at 3 THz at electron energy of 17.5 GeV. In order to study the transverse size of the THz source we used two approaches, analytical and numerical. Analytical formulas are available for the field of the radiation source at resonance, in the middle of the undulator, and at any position in free space, after the undulator, even in the near zone [4]. The numerical computations are done using wave-front propagation codes [5]. The results of back-propagation at different distances and the calculation of the FWHM are shown in Fig. 3 left where we also plot a comparison with the analytical expressions, and in Fig. 3 right the result of back-propagation at the virtual source.

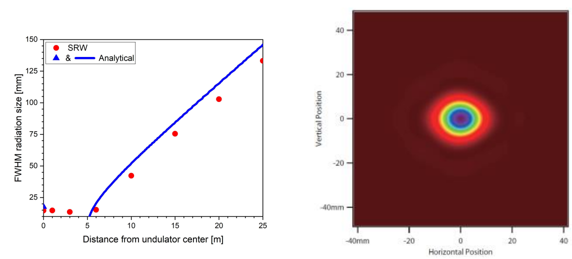

Figure 3: Radiation beam size evolution from the undulator center for a fundamental of 3 THz with an electron beam energy of 17.5 GeV. Blue triangles: analytical expectations in the undulator center, at z = 0 and after the undulator exit at 3 THz. Red circles: results from wave-front propagation simulations at 3 THz. SRW back propagation at the source for a fundamental of 3 THz.

In Fig. 4 we report the frequency in THz of the first harmonic on axis produced by an undulator with different period lengths, ranging from 0.6 to 1.5 m, as a function of the peak field on axis B, for 17.5 GeV, the maximum nominal electron beam energy of the European XFEL.

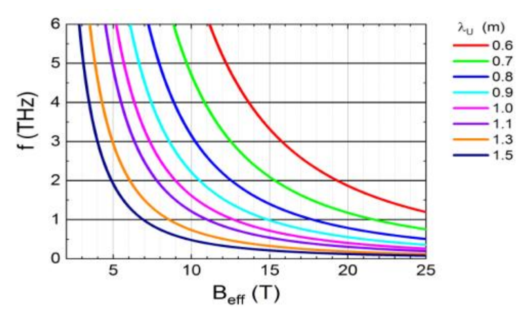

Figure 4: Frequency of the first harmonic on axis produced by an undulator with different period lengths, as a function of the effective field on axis B, for 17.5 GeV electron beam energy.

In order to reach 3 THz as the minimum value for the frequency of the first harmonic, for magnetic peak fields below 10 T the period length of the undulator should be longer than 0.9 m. To have some margin, and to keep the period length as short as possible we focus on a period length of 1 m.

Undulators are realized with different technologies [6]. The most widely used is the permanent magnet technology. Alternatively, it is possible to use electromagnets wound with

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copper conductors or with superconductors. If the engineering current density needed to produce the desired magnetic peak field on axis is below 10 A/mm^2, electromagnets using copper as a conductor can be used.

Above this limit of the engineering current density, the ohmic losses become untreatable. For the same period length and vacuum gap, especially for long period lengths, superconducting undulators can produce higher magnetic peak fields on axis than the permanent magnet ones [7]. We consider a NbTi based THz superconducting undulator working at liquid helium temperature (4 K), feasible for the European XFEL. NbTi operates up to magnetic fields on the conductor of about 10 T [8]. The simulation for the magnetic field profile of a 10 periods undulator model from Fig. 5 with the code Radia [9] has been performed using the engineering current densities of 115 A/mm^2 in the outer coils, and 55 A/mm^2 in the inner coils. The on-axis effective magnetic field of 7.3 T allows reaching the minimum value of 3 THz for the frequency of the first harmonic.

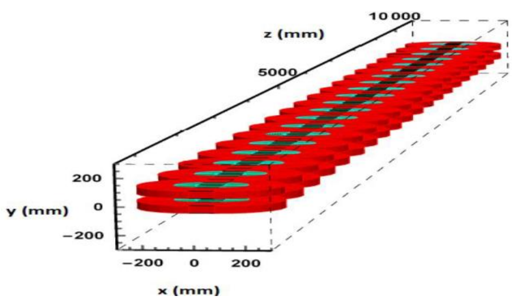

Figure 5: Ten periods of the THz undulator model simulated with the code Radia. Green parts show the inner coils and red parts show the outer coils.

THz TRANSPORT LINE

As concerns the feasibility of the transport of the generated THz pulses to the experimental end stations, we assume that the THz undulator would be positioned just in front of the electron beam dump as is the case at the prototype device at the XUV FEL FLASH. Experience at FLASH shows that Kepler telescopes of a length of 12 m allow transport and refocusing without diffraction losses [10] down to frequencies of 3 THz. A distance of 290 m, as needed in the case of the XTD4 tunnel at the European XFEL, would then require 24 Kepler-telescopes and a total of 48 mirrors (of which 32 would be focusing optics and 16 would be planar mirrors). The main loss will be due to the actual reflectivity. At FLASH and TELBE gold-coated aluminum or copper optics are employed, with the gold coating being a layer of about 200 nm, substantially thicker than the skin depth at these frequencies. Then the reflectivity of the optics can be as high as 99 % resulting in a reflectivity loss of 36 % for the mere transport to the experimental end stations. Additionally, there potentially will be losses in the window separating the accelerator vacuum from the experiment vacuum, which are in the few 10 % range, depending on the choice of material. Therefore roughly 50 % of the generated pulse energies are received at the experiments.

CONCLUSION

In this paper, we explored the possibility of using the spent electron beam at the European XFEL to produce high-field THz pulses by means of a superconducting undulator. We show that current superconducting technology allows for the construction of such device with 10-periods with fundamental frequency starting from 3 THz using a 17.5 GeV electron beam. Lower frequencies can be obtained by using lower nominal electron energy points. Owing to the quality of XFEL electron beams, one can generate narrow-band, frequency-tunable THz pulses with the frequency range of 30 down to 3 THz and corresponding pulse energies range of 10 to 280 μJ (see Table 1). Furthermore, mJ-level pulse energies are achievable when the full bandwidth between 1 and 100 THz is utilized. The repetition rate naturally follows that of the European XFEL. Moreover, the THz transport line, albeit several hundred meters long, is feasible and can be hosted in the tunnels designed for the X-ray transport. For more details regarding this study, see [11].

Table 1: Maximum pulse energy (total, up to 100 THz and around the fundamental frequency with 10 % bandpass filter) at different values of the fundamental and corresponding electron charge (see Fig. 3).

Fundamental frequency [THz]	Tot. pulse energy [μJ]	Fund. pulse energy [μJ]	Electron charge [pC]
3	3450	279	500
5	2600	172	500
7	1540	115	250
9	1340	84	250
10	1180	64	250
12	1050	45	250
14	955	31	250
19	441	25	100
24	388	20	100
29	345	14	100
33	311	11	100
38	285	10	100
43	263	10	100
48	245	8	100

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