# SCHEME FOR GENERATING AND TRANSPORTING THZ RADIATION TO THE X-RAY EXPERIMENTAL HALL AT THE EUROPEAN XFEL

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## *Abstract*

We consider generation of THz radiation from the spent electron beam downstream of the SASE2 undulator in the electron beam dump area. The THz output must propagate at least for 250 meters through the photon beam tunnel to the experimental hall to reach the SASE2 X-ray hutches. We propose to use an open beam waveguide such as an iris guide as transmission line. In order to efficiently couple radiation into the iris transmission line, generation of the THz radiation pulse can be performed directly within the iris guide. The line transporting the THz radiation to the SASE2 X-ray hutches introduces a path delay of about 20 m. Since THz pump/X-ray probe experiments should be enabled, we propose to exploit the European XFEL baseline multi-bunch mode of operation, with 222 ns electron bunch separation, in order to cope with the delay between THz and X-ray pulses. We present start-to-end simulations for 1 nC bunch operation-parameters, optimized for THz pump/X-ray probe experiments. Detailed characterization of the THz and SASE X-ray radiation pulses is performed. Highly focused THz beams will approach the high field limit of 1 V/atomic size.

## INTRODUCTION

The exploitation of a high power coherent THz source as a part of the LCLS-II user facility has been proposed in the LCLS-II CDR [1]. THz radiation pulses can be generated by the spent electron beam downstream of the X-ray undulator. In this way, intrinsic synchronization with the X-ray pulses can be achieved. A first, natural application of this kind of photon beams is for the pump-probe experiments. Through the combination of THz pump and X-ray probe, XFELs would offer unique opportunities for studies of ultrafast surface chemistry and catalysis [1]. Also, the LCLS team started an $R\&D$ project on THz radiation production from the spent electron beam downstream of the LCLS baseline undulator [2]-[4]. In that case, THz pulses are generated by inserting a thin Beryllium foil into the electron beam. In this paper we describe a scheme for integrating such kind of radiation source at the European XFEL facility [5].

We begin our considerations with the generation of THz radiation from the spent electron beam downstream of the SASE2 undulator in the electron beam-dump area. We then move to consider the transport of THz radiation pulses from the XFEL beam dump-area to the experimental hall. This constitutes a challenge, because the THz output must propagate at least 250 meters in the photon beam tunnel and in the experimental hall to reach the SASE2 X-ray hutches. Since THz beams are prone to significant diffraction, a suitable beam transport system must be provided to guide the beam along large distances maintaining it, at the same time, within a reasonable size. Moreover, the THz beamline should be designed to obtain a large transmission efficiency for the radiation over a wide wavelength range. Transmission of the THz beam can only be accomplished with quasi-optical techniques. In this paper, similarly as in [6], which focused on the LCLS baseline, we propose to use an open beam waveguide such as an iris guide, that is made of periodically spaced metallic screens with holes, for transporting the THz beam at the European XFEL. The eigenmodes of the iris guide have been calculated numerically for the first time by Fox and Li [7] and later obtained analytically by Vainstein [8, 9]. In [6] we already presented a complete iris guide theory. In particular, the requirements on the accuracy of the iris alignment were studied. In order to efficiently couple radiation into the transmission line, it is desirable to match the spatial pattern of the source radiation to the mode of the transmission line. To this end, it is advisable to generate radiation from the spent electron beam directly in the iris line with the same parameters used in transmission line. In this way, the source generates THz radiation pulses with a transverse mode that automatically matches the mode of the transmission line. The theory described in [6] supports this choice of THz source.

In the present work we present a conceptual design for a THz edge radiation source at the European XFEL. It includes an 80 m-long electron beam vacuum chamber equipped with an iris line, and a 250 m-long transmission line with the same parameters. The transmission line, which develops through the XTD7 distribution tunnel and field 5 of the experimental hall, includes at least ten 90-degrees turns with plane mirrors at 45 degrees as functional components. It is possible to match incident and outgoing radiation without extra losses in these irregularities. The transport line introduces a path delay of about 20 m between THz and X-ray pulses generated from the same electron bunch. Since THz pump/X-ray probe experiments should be enabled, in order to cope with this delay we propose to exploit the unique bunch structure foreseen as baseline mode of operation at the European XFEL, with 222 ns electron bunch separation, together with an additional delay line in experimental hall. More details can be found in [10].

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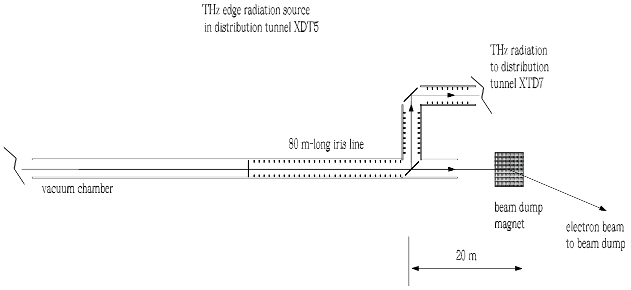

Figure 1: Installation of the setup at the European XFEL.

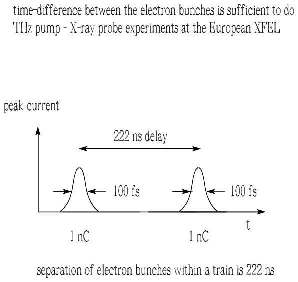

Figure 2: Bunch structure in a macropulse for the baseline multi-bunch operation mode at the European XFEL.

## SCHEME FOR GENERATING THZ EDGE RADIATION AT THE EUROPEAN XFEL

In this section we discuss a scheme for THz generation at the European XFEL. A more detailed description of the principle of THz generation in the iris guide can be found in [10]. The THz edge radiation source proposed in this paper can be realized with little efforts and minimal modifications to the European XFEL baseline setup. The vacuum chamber equipped with iris line and outcoupling system can be installed in the unoccupied straight vacuum line upstream of the first electron beam dump, Fig. 1.

The transport of the THz beam to the experimental hall can be performed exploiting the use of the tunnel XTD7, as reproduced schematically in Fig. 1. The THz transmission line transporting the THz radiation introduces a path-delay of about 20 m with respect to the path of X-ray pulse from the SASE2 undulator. Since THz pump/X-ray probe experiments should be enabled, we propose to exploit the natural bunch spacing within a train, Fig. 2. The THz and X-ray pulses should be synchronized by a THz delay line installed in experimental hall, Fig. 3.

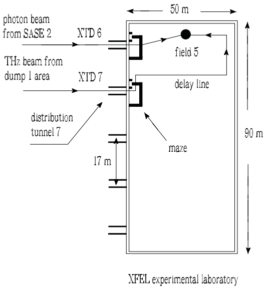

Figure 3: Sketch of a possible arrangement for a THz delay line in the experimental hall.

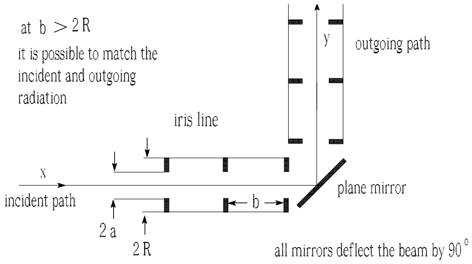

Figure 4: Geometry of a transmission-line turn.

The THz transmission line includes at least ten 90-degrees turns, and will exploit plane mirrors as functional components. If the pipe of the transmission line has a diameter smaller than the distance between the irises it is possible to match incident and outgoing radiation without extra losses in these irregularities, Fig. 4.

It is possible to calculate the energy spectral density at the sample position. The bunch form factor considered here is given in Fig. 5. We set a total length of the transport iris line of 250 m. The energy losses in the line are accounted for. The energy spectral density at the exit of transport iris line as a function of the frequency $\nu = \omega/(2\pi)$ is shown in Fig. 6. Partial contributions of individual modes of the circular iris guide are illustrated. The sample is set at $L_s =$ 250 meters away from the extracting mirror. The curves are calculated with analytical formulas in [10]. Here $N_e = 6.4 \cdot 10^9$ (1 nC), $L = 80$ m, $b = 30$ cm, $2a = 15$ cm. The bunch form factor used is shown on the lower plot of Fig. 5.

The maximum value of the energy spectral density is achieved at $\lambda \simeq 150\ \mu$m. When the bandpass filter is tuned to this value of $\lambda$, the expression for the total edge radiation pulse energy at the sample can be written in the form

$$W[\mathrm{mJ}] \simeq 0.35 \frac{\Delta\omega}{\omega} . \qquad (1)$$

The energy spectral density as a function of frequency exhibits a low frequency cutoff due to losses in the transport line and a high frequency cutoff due to electron bunch form factor suppression.

We studied the influence of the edge radiation setup length $L$ and of the iris hole radius $a$ on the operation of the THz source. Fig. 7 and Fig. 8 show the dependence of the THz pulse energy spectral density on the frequency for different values of these two parameters. In Fig. 7, $N_e = 6.4 \cdot 10^9$ (1 nC), $b = 30$ cm, $2a = 15$ cm. The bunch form factor used is shown on the right plot of Fig. 5. The curves indicated with numbers from 1 to 20 refer to different values of $L$ starting from $L = 20$ m and ending with

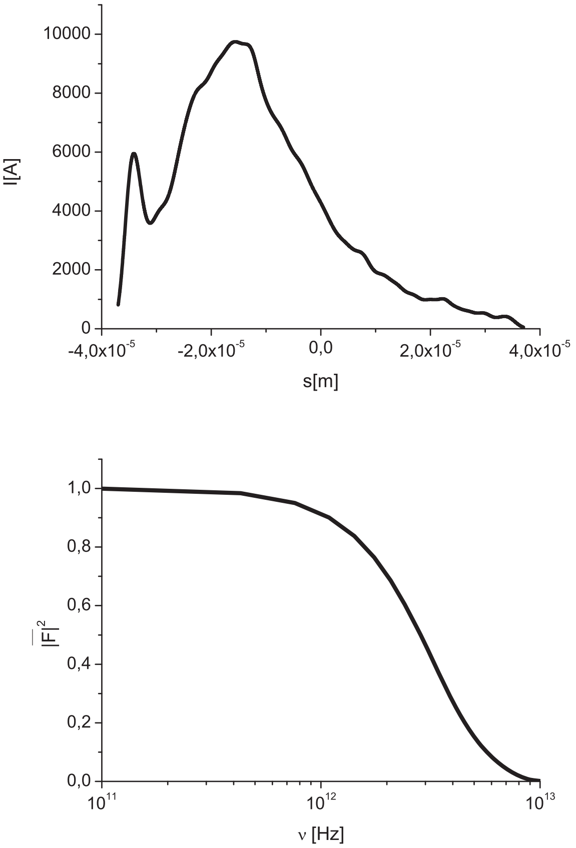

Figure 5: Upper plot: Electron beam current profile at the European XFEL, optimized for THz pump/X-ray probe experiments. Lower plot: Squared modulus of the electron beam form factor, $|\bar{F}|^2$, corresponding to the current profile on the upper plot.

$L = 210$ m, with a step of 10 m. In Fig. 8 $N_e = 6.4 \cdot 10^9$ (1 nC), $b = 30$ cm, $L = 80$ m. The bunch form factor used is shown on the right plot of Fig. 5. The curves indicated with numbers from 1 to 20 refer to different values of $a$ starting from $2a = 6$ cm and ending with $2a = 25$ cm, with a step of 1 cm.

Finally, we note that according to our calculations in Fig. 6, one obtains about 0.12 mJ total THz radiation pulse energy at the sample position at a wavelength around 0.075 mm with a filter bandwidth $\Delta\omega/\omega \sim 0.5$. For one cycle in a pulse, corresponding to 50% spectral bandwidth, one obtains about 0.5 GW peak power level. By highly focusing this THz beam, one will approach the high field limit of 1 V/atomic size.

## EUROPEAN XFEL RADIATION PARAMETERS FOR THZ PUMP/X-RAY PROBE EXPERIMENTS

The electron beam formation system of the European XFEL accelerator complex operates with nominal charge of 1 nC. The initially 2 mm (rms) long bunch is compressed in three magnetic chicanes by a factor of 4, 8 and 4 respectively, to achieve a peak current of 5 kA.

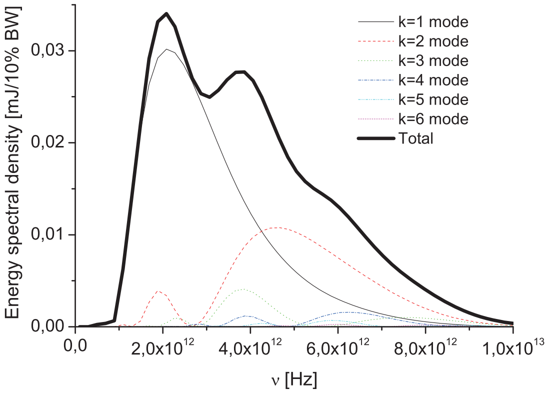

Figure 6: Edge radiation pulse energy spectral density as a function of frequency transported at the sample position.

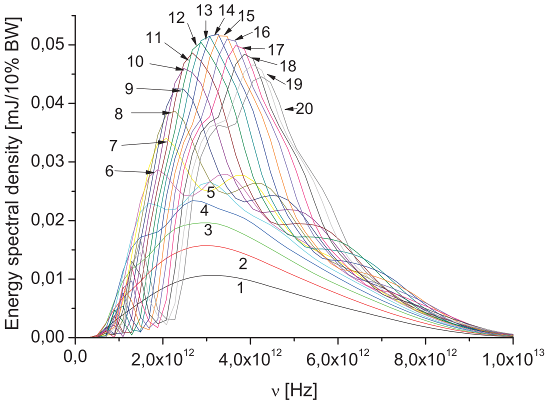

Figure 7: Scan of the dependence on $L$ of the edge radiation pulse energy spectral density transported at the sample position ($L_s = 250$ m downstream of the mirror) as a function of frequency.

The design of our THz source is also based on the exploitation of electron bunches with nominal charge of 1 nC. However, in order to optimize the THz source performance, the electron bunch should be made about two times shorter than in the nominal mode of operation. In this case, the peak current increases by a factor two. Operation beyond the design parameters leads to some degradation of the electron beam quality. The operation of the proposed THz source is insensitive to the emittance and energy spread of the electron bunch. However, one should examine the performance of the electron bunches in terms of X-ray SASE pulses generation, since THz pump/X-ray probe experiments are based on such pulses.

First, we ran start-to-end simulations for the beam formation system [11]. Subsequently, we studied the perfor-

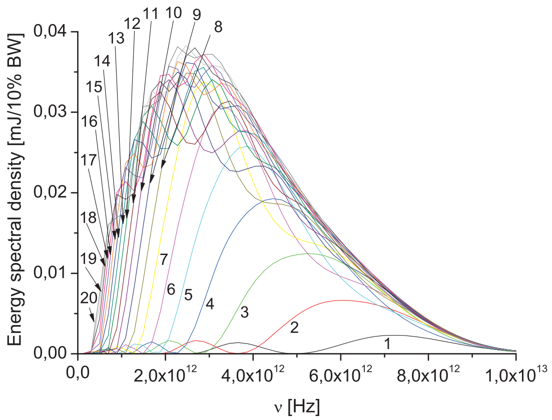

Figure 8: Scan of the dependence on $a$ of the edge radiation pulse energy spectral density transported at the sample position ($L_s = 250$ m downstream of the mirror) as a function of frequency.

mance of the electron bunch with the help of the FEL code GENESIS 1.3 [12] running on a parallel machine.

The SASE2 undulator is composed of 35 cells. The SASE output after the first 10 undulator cells is shown in Fig. 9. On the upper plot we show the output power, while on the lower plot one can see the spectrum around the the fundamental at 1.5 Angstrom. Grey lines refer to single shot realizations, the black line refers to the average over a hundred realizations. The output characteristics are in line with the expected baseline performance, demonstrating an average power of several tens of GW, and a relative bandwidth in the $10^{-3}$ range.

Simulations presented in this Section show that the operation of SASE2 with a 1 nC bunch and a peak-current increase of a factor two compared to the nominal mode of operation (also with a 1 nC bunch but with design parameters), leads practically to the same peak power of the X-ray pulse that is in the order of 20 GW. In other words, the two times shorter bunch duration in our case study has the simple consequence of a decrease in the X-ray pulse energy of about a factor two, from around 2 mJ in the design case to around 1 mJ in our case.

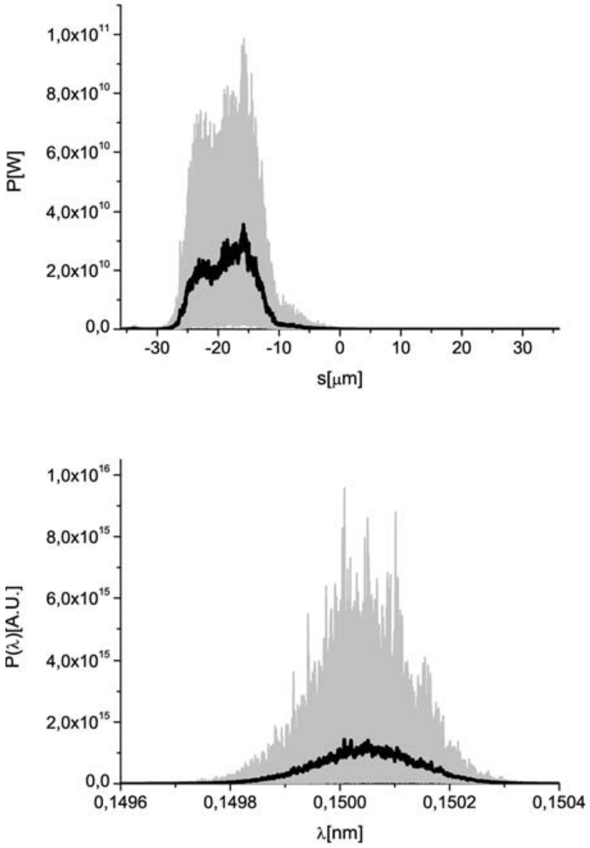

Figure 9: Upper plot: SASE power at the exit of the first 10 FEL undulator cells. Lower plot: SASE spectrum at the exit of the first 10 FEL undulator cells.

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