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DESIGN OF A TERAHERTZ RADIATION SOURCE FOR PUMP-PROBE EXPERIMENTS

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Abstract

Narrow-band, tuneable, high-power terahertz radiation is highly demanded for pump-probe experiments at light source facilities. Since the requested radiation properties are not well covered by current terahertz radiation sources, an accelerator-based terahertz source employing the slotted-foil technique in combination with transverse deflecting cavities is proposed in this work. A detailed design has been worked out, and the behaviour of the electron beam and the created terahertz radiation is studied via numerical simulations. The results show that the proposed source produces tuneable terahertz radiation that can meet most of the demanded specifications.

INTRODUCTION

Material scientists need terahertz radiation with power levels of several MW to excite and study their samples. The community has expressed an interest in a terahertz source for pump-probe experiments with the following demanding parameters:

- Tuneable frequency: 1-20 THz,
- Bandwidth <10%,
- Pulse energy >100 µJ,
- Fixed phase from pulse to pulse with respect to external timing reference.

The only type of radiation source than can currently achieve these specifications are supra-conducing, and hence costly, FEL oscillators [1,2]. Since the radiation in these oscillators is build up from the shot noise of the electron beam, the phase of the terahertz radiation is also random (with respect to an external timing reference). A possibility to overcome this limitation is to pre-bunch the electron beam at the correct wavelength. In this case, a normal-conducting linac with a single-pass FEL can be used, which reduces the complexity and the cost of the facility.

The big challenge for this class of terahertz sources is the creation of an electron bunch with the correct pre-bunching. Several scheme have been proposed and tested [3–5] and pre-bunching up to about 1 THz could be created. In this paper, a scheme is presented that produces pre-bunching in the range between 1 THz and 4 THz. It is based on the slotted-foil technique [6] in combination with transverse deflecting cavities (TDC).

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CONCEPT AND FACILITY PARAMETERS

The proposed scheme is illustrated in Fig. 1. A transverse deflecting cavity that is operated at zero crossing applies a transverse kick to an electron beam. The kick is positive for the head of the bunch and decreases linearly along the bunch length. In a subsequent drift space of length L_D, this kick causes the beam to tilt in the horizontal direction. When the beam is sufficiently tilted the beam is sent through a metal foil with slits in it. The electrons that hit the foil are not stopped by the interaction with the material, but are strongly scattered and collimated with tungsten plates located a few centimetres downstream of the foil. Contrary, the electrons that are passing through the slits in the foil are not affected. The resulting longitudinal current distribution is pre-bunched. After the pre-bunching the beam tilt has to be removed again before it can be send to the single-pass undulator, where the radiation is created.

In contrast to earlier schemes that employ the slotted-foil technique [7], the TDC scheme doesn't rely on a large beam energy chirp and dispersion. Also, no dipole magnets are necessary, which reduces the longitudinal beam smearing and energy spread increase via coherent synchrotron radiation (CSR) effects. Due to this simplification of the beam transport, pre-bunching at higher frequencies than before can be produced and transported.

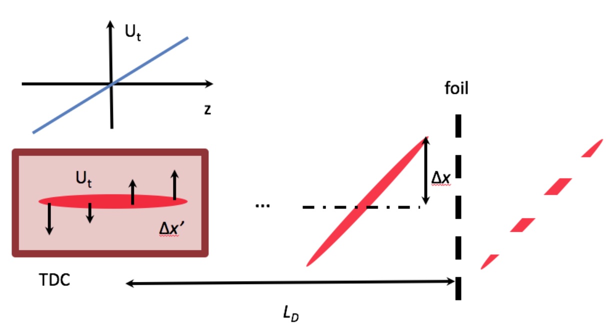

Figure 1: Pre-bunching scheme using a slotted-foil in combination with a transverse deflecting cavity.

The wavelength of the pre-bunching depends on the strength of the beam tilt and can be varied by the voltage of the transverse deflecting cavity. To vary the bunching wavelength from 300 µm (1 THz) to 75 µm (4 THz), the voltage of the transverse deflecting cavities is varied form 0.84 MV to 3.36 MV. The length of the TDC has been chosen to be only 0.3 m in order to minimise the thick lens effect and the associated correlated energy spread. To achieve a BW < 10%, the

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Table 1: Most relevant design parameters.

Micro-bunch (MB) spacing	Δs_B	300 - 75 µm
Min. numb. of MBs	N_B	10
Full bunch length	L_B	3 mm
Bunch charge (injector)	Q_B	2.0 nC
Beam energy	E_B	27 MeV
Undulator period	λ_u	6 cm
Undulator parameter	K_u	5.20 - 2.44
Hor./vert. norm. emittance	$\epsilon_{x/y}$	2 µm
Repetition rate	f_R	100 Hz
Hor./vert. β^* at foil	$\beta_{x/y}$	0.5/3.1 m
Drift length	L_d	1.5 m
Foil gap	g	0.5 mm
Foil gap period	d	1 mm
Facility length	L_t	8.5 m

pre-bunching has to contain at least 10 micro-bunches. Considering the longest targeted wavelength of 300 µm (1 THz), the minimum bunch length from the injector is 3 mm.

An important design constraint for this scheme comes from the fact that the strength of the pre-bunching (quantified by the bunching factor $b = \left|1/N \sum_j^N e^{i2\pi/\lambda z_j}\right|$, where N is the number of particles) also depends on the (slice) beam size σ_x at the foil location. In order to create significant bunching the beam size has to be small compared to the slit gap as was pointed out in [6]. Therefore, a small beta function at the foil location allows to keep the transverse dimensions of the setup small, which ultimately allows to reach higher pre-bunching frequencies. In the current design, the beta function at the foil location is 0.5 m. A reduction of this value in future designs could further increase the reachable pre-bunching frequency. The most important parameters of the facility are collected in Table 1.

The challenge for the design of the FEL section is to reach a resonant wavelength as long as of 300 µm. Therefore, a long undulator period, a low beam energy and a high undulator parameter have been chosen (see Table 1). Higher resonant wavelengths can be easily achieved by lowering the magnetic field of the undulator. Due to its symmetric strong natural focusing, a helical undulator is employed.

PRE-BUNCHING SIMULATIONS

To verify this concept a simulation setup was created that includes an injector with photo-cathode gun and S-band linac, the pre-bunching section and matching sections. The injector is based on the design of the SwissFEL electron gun test stand [8] with adaptations to allow for a higher bunch charge. The simulations of this section have been carried out with the space charge code ASTRA [9]. For the rest of the beamline, the code ELEGANT [10] is used, where 300000 particles have been tracked. In the following, only 4 THz results are discussed, since they are the most challenging.

Figure 2 shows the transverse beam profile. After the injector, the beam is well focused (black), apart from the head and the tail where focusing errors are visible. This is

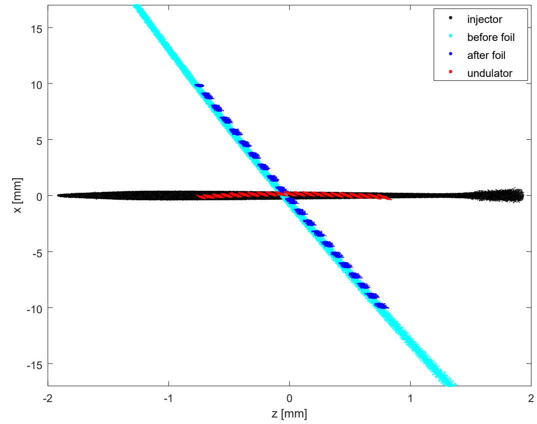

Figure 2: Transverse profile of the electron beam as a function of the longitudinal coordinate with a 4 THz pre-bunching at different locations along the terahertz facility.

due to the space charge induced energy errors created already at the gun. At the foil, the beam is tilted due to the upstream kick from the transverse deflecting cavity. Figure 2 shows the strongest used beam tilt before (cyan) and after (blue) the foil, which creates a pre-bunching for 4 THz. After the foil, the created micro-bunches, the bunching factor reducing effect of the beam size, and the cut of the wrongly focused head and taik are clearly visible. The beam is cut by the foil at an offset of ±1 cm, which limits the necessary beam pipe aperture. A drawback of this beam aperture limitation is that the total bunch length and the total charge are reduced.

In the downstream beamline, the tilt is taken out and the beam is focused strongly to the entrance of the undulator (red). This focusing is necessary to match the beam to the natural beta function of the undulator. The longitudinal overlap of the individual micro-bunches is clearly visible. Still the bunching is largely sufficient to overcome the SASE process. The corresponding current profile is shown in Fig. 3, which corresponds to a bunching factor b of 0.34. For 1 THz, the bunching factor is even as high as 0.44.

UNDULATOR SIMULATIONS

The beams tracked by the ASTRA/ELEGANT setup have been used as an input for GENESIS [11] simulations. With this code the FEL process can be modelled. The number of used particles varied from 150000 for 1 THz to 72000 for 4 THz (due to the bunch shortening), which corresponds to a charge from 1.0 nC to 0.48 nC. Earlier studies [12] have shown that a round metallic waveguide of 1 cm radius inside the undulator is beneficial for the FEL process. The waveguide reflects the diffracted radiation, which is especially beneficial at lower frequencies. In the simulations, the waveguide has been included in an approximate fashion, by adding boundary conditions on the EM field grid. Still, diffraction and space charge are the dominating effects.

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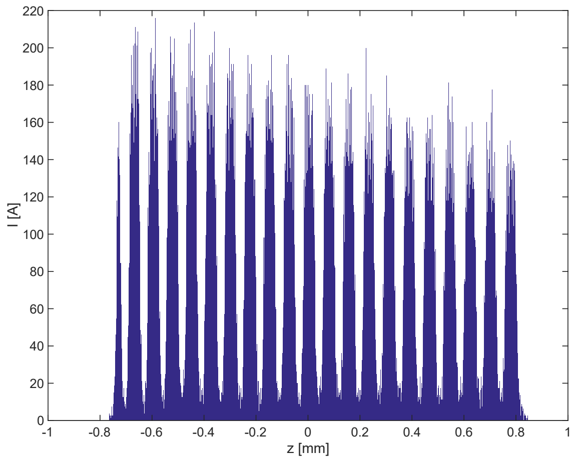

Figure 3: Current profile of the electron beam at the entrance of the undulator with a 4 THz pre-bunching.

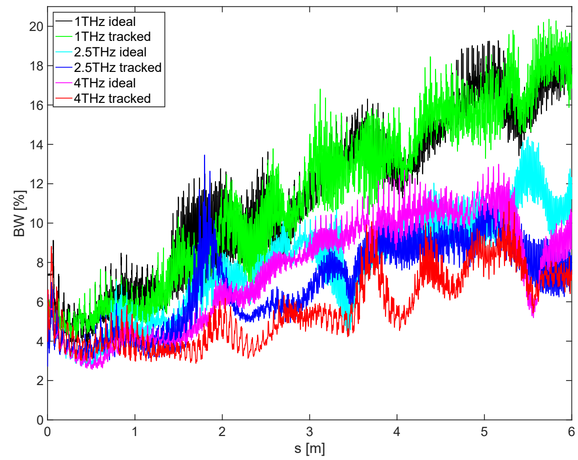

Figure 5: Bandwidth of the created radiation along the undulator for different wavelengths.

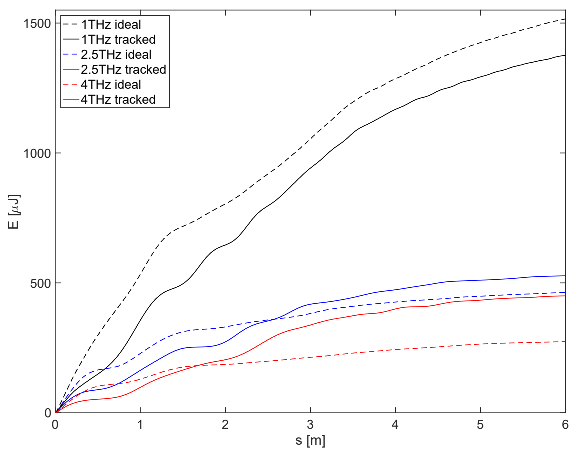

Figure 4: Energy of the the created radiation along the undulator for different wavelengths.

Figure 4 shows the pulse energy of the created terahertz radiation for three different tuning frequencies. The pulse energy is the highest for 1 THz and reduced with increasing frequency. This is expected, since the FEL output power scales linearly with the FEL parameter, which decreases for higher frequencies. Additionally, the total charge injected into the undulator is reduced for higher frequency due to the beam length shortening by the foil. Still, even for the 4 THz case the requested specification of a pulse energy of >100 μJ can be met if the undulator is at least 1.5 m long. For lower frequencies the produced pulse energy is significantly higher, e.g. 500 μJ for 1 THz at 1.5 m.

Additionally to the simulations with the tracked beams, also ideally pre-bunched and perfectly matched beams have been tested as a benchmark (dashed lines). In contrast to the beam shown in Fig. 3, the ideally pre-bunched beam consists of a sequence of equally spaced rectangular pulsed of equal height. Figure 4 shows that the ideally pre-bunched beams perform only slightly better than the tracked beams or even worse for some undulator lengths. This shows that the undulator process is not very sensitive to matching errors (which are always present for tracked beams) and slight distortions in the transverse beam profile. The facility is therefore likely to behave robustly in practice.

The bandwidth of the created radiation is shown in Fig. 5. For the 2.5 THz and the 4 THz case, the bandwidth specification of <10% can be met basically for all undulator lengths. On the other hand, for the 1 THz case the bandwidth exceeds the 10% limitation if the undulator is longer than 1.5 m. This wider bandwidth is due to the fact that the number of micro-bunches is smaller for the 1 THz case. As for the pulse energy, the bandwidth results for the tracked beams and the ideally bunched beams are very similar. Concluding, an undulator length of 1.5 m seems to be the optimum for the proposed facility, since it allows to meet the pulse energy and bandwidth requirement over the full frequency range. With this short undulator the overall facility length is 8.5 m.

CONCLUSIONS

In this paper, a scheme is presented that is capable of producing a tuneable pre-bunching between 1 THz and 4 THz in an electron beam. This pre-bunched beam can be used to create terahertz radiation in an undulator. The concept utilises the slotted-foil technique in combination with transverse deflecting cavities. The advantage of this scheme is that it does not require a large beam energy spread and large dispersion to create the pre-bunching. Also, no dipole magnets are necessary, which avoids the associated longitudinal beam smearing and CSR effects. In simulation studies it was verified that the scheme can produce a pre-bunching with bunching factors of 0.44 at 1 THz and 0.34 at 4 THz (entrance of an undulator). These beams produce in a helical undulator of 1.5 m length terahertz radiation with a pulse energy between 100 μJ and 500 μJ, with a bandwidth between 10% and 4%. The specifications of the material science community for a terahertz source for pump-probe experiments can therefore be met between 1 THz and 4 THz. Future work will aim to extent the tuning range to even higher frequencies.

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