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A VERSATILE THz SOURCE FOR HIGH-REPTITION RATE XFELS

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Abstract

The development of high-repetition rate XFELs brings an exciting time for novel fundamental science exploration via pump-probe interactions. Laser-based pump sources can provide a wide range of wavelengths (200-10000 nm) via various gain media. These sources can also be extended with optical parametric amplifiers to cover a largely versatile spectral and bandwidth range. However beyond 10 μm, toward the THz regime, there exists no suitable gain media, and optical-to-THz efficiencies are limited below 1%. In this paper we discuss the use of Cherenkov-based radiators with conventional electron bunches to generate high-power THz radiation over a wide range of parameters for existing and future XFEL facilities.

INTRODUCTION

The last decades of accelerator physics flourished, the development of superconducting radio frequency (SRF) machines has provided a surge toward unparalleled efficiencies, leading to incredible beam powers $O(1\ MW)$ at MHz repetition rates for a plethora of applications. These machines are very suitable candidates for colliders as in the proposal of the International Linear Collider (ILC), but the limited (but increasing) accelerating gradients of SRF cavities has limited such TeV-frontier facilities to 10s of kilometers.

Other fundamental sciences desire X-rays to explore life sciences, chemistry and more, which require more modest beam energies $O(10\ GeV)$ to provide X-ray energies $O(10\ keV)$ using conventional undulators. While a large portion of users are interested in direct-imaging of their samples, pump-probe spectroscopy has gained significant interest, where generally a pump-laser of specific wavelength and bandwidth is shone onto the sample to e.g. excite it, subsequently an X-ray pulse then measures the developing effects. This technique provides a way to diagnose electromagnetic responses of samples of interest.

Unfortunately the limited optical-to-THz conversion efficiencies below 1% has left an electromagnetic hole of research opportunities in various sciences [1]. Alternatively electron beam based THz sources can in principle cope with the high power, repetition rate, and frequency requirements. The freely available spent beam after a SASE undulator is an attractive option for this purpose, as it still has a high beam power. Moreover it is naturally synchronized to the X-ray pulses and can fulfill all repetition rate requirements. (For a detailed discussion on the compensation of path length differences between THz and X-ray pulses see [2])

At the XUV FEL FLASH, for example, a 9 period electromagnetic undulator with 40 cm period length is installed behind the SASE undulator [3,4]. The generated THz radiation in the range of 1.5 – 30 THz is transported through a 65 m long evacuated beam line to the experimental chamber where it meets the XUV pulse on the sample [5,6]. Six refocusing mirrors in combination with planar mirrors keep the beam size under control and direct the beam to the experiment. A variable delay line allows for adjusting the relative timing of pump and probe beam.

Following the design ideas of FLASH the installation of a special undulator for the generation of THz radiation behind a SASE undulator at XFEL-facilities is discussed in [7]. However, the high beam energy of XFEL facilities (>10 GeV) requires a total undulator length of 10 m with peak fields of up to 7.3 T and a period length of 1 m to comply with the requested THz parameters. While such an undulator appears to be technically feasibly with state-of-the-art superconducting technology the cost and complexity of such a device is unattractive. Another conceivable option is the installation of a separate accelerator near the experimental hutch, because THz radiation can be generated with conventional undulator parameters already at modest ~10 MeV beam energies. While the SASE process in the THz range is possible at these low electron beam energies [8,9], this option is complex and expensive. Finally, compact accelerators based on advanced concepts like e.g. plasma acceleration are not yet able to deal with the beam quality, charge and repetition rate requirements.

In this paper we consider an alternative method which has not yet been proposed in the context of pump-probe sources at XFEL user facilities: the usage of Cherenkov-type waveguides to produce high-power, superradiant THz radiation in a wide range of desired parameters [10–13]. There are various types of radiating structures which include dielectric-lined waveguides (DLW), corrugated structures, and bimetallic waveguides [14, 15]. We provide a brief introduction to various suitable radiation waveguides before discussing the wakefield generation process in arbitrary waveguides. This is followed by a section on radiation extraction and finally, a case for the European XFEL is presented.

SUITABLE RADIATORS

There are many existing candidate structures which have come forward for e.g. beam-driven acceleration and radiation generation with phase velocites of the speed of light. Of these there exists the dielectric-lined waveguide (DLW), the corrugated waveguide, a bimetallic waveguide, and others e.g. photonic bandgap structures, see Fig 1. We give a

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brief introduction to each structure and provide a summary discussion on their relations below.

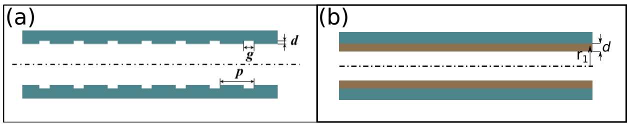

Figure 1: A corrugated structure is shown in (a), in (b) a bimetal or dielectric-lined waveguide is shown, where the thin layer with thickness d is interchanged; generally dielectric-lined waveguides have much larger layers than bimetal structures.

The DLW consists of a dielectric capillary with the outside surface coated with an appropriately thick conductor to cover the skin depth of the particular frequency. The DLW is very easy to manufacture, generally capillaries can be drawn and the coating process is rather trivial, using an e.g. sputtering machine. However, dielectrics do have drawbacks including charging, multipacting, and limited heat conduction.

The corrugated structure consists of periodic grooves along the longitudinal length of the structure. The groove periods are generally much shorter than the wavelength which avoids spatial harmonics. Corrugated structures can be manufactured with high precision CNC machines, for the case of a cylindrical corrugated pipe, generally two hemispheres are manufactured and attached together. The corrugated pipe can be represented as a DLW with the relation, $\frac{\epsilon'}{\epsilon'-1} = \frac{p}{g}$.

Recently, bimetallic structures have been proposed and developed [14, 15]. Here a thin-layer of conducting material is deposited upon another conductor. The properties of bimetallic structures are very similar to DLWs, exhibiting a large range of possible operation parameters.

The various structures have been compared in detail in [16] and exhibit a very similar range of characteristics along the properly scaled dimensions. The following section discusses the generalized radiation characteristics of these structures.

SUPERRADIANT WAKEFIELD GENERATION IN ARBITRARY WAVEGUIDES

For a lossless single-mode structure, a charged particle traveling through the structure will produce a wakefield potential, which is equivalent to the Green's function,

$$G(z) = \kappa \cos(kz), \tag{1}$$

where κ is the loss factor For a charged bunch, the wakefield is given by the convolution of the Green's function and the current profile of the bunch $I(z)$,

$$W(z) = \kappa \int_{-\infty}^{z} dz' G(z') I(z - z'). \tag{2}$$

Equivalently we can express this equation as,

$$W(z) = qF\kappa \cos(kz), \tag{3}$$

where q is the charge, and F is the usual bunch form factor. The total possible extraction energy is then given by

$$\mathcal{E} = q^2F^2\kappa L = q^2F^2L\frac{Z_0c}{\pi r_1^2}, \tag{4}$$

where L is the structure length, r_1 is the inner radius of the structure, and Z_0 is the impedance of free space, and we have used the identity $\kappa = \frac{Z_0c}{\pi r_1^2}$. Now, specifying to a dielectric-lined waveguide, it can be shown that the resonance condition is given by [17],

$$k_0^2 = \frac{2}{r_1d_1}\frac{\epsilon'}{\epsilon'-1}, \tag{5}$$

where the dielectric permittivity is given by $\epsilon_1 = \epsilon_0(\epsilon' + i\epsilon'')$, and here we assume $\epsilon'' << \epsilon'$.

The pulse length of the radiation is related to the group velocity via

$$\tau = \frac{L}{c}(1-\beta_g) = L\frac{\epsilon'-1}{\epsilon'}\frac{4d_1}{r_1c} = \frac{8}{(k_0f_1)^2}\frac{L}{c} \tag{6}$$

By taking the ratio between the energy and the pulse length, the radiated power is given by,

$$P = (qFk_0)^2\frac{Z_0c}{8\pi} \propto \frac{q^2F^2}{r_1d_1}. \tag{7}$$

There are practical considerations to the range of applicable waveguides, generally determined by the Twiss parameters of the driving beam since we should avoid beam losses on the structure, therefore one may impose a condition on the beam sizes at the structure edges e.g. $N\sigma_r < r_1$. We can then find the limitations on the Twiss parameters, beginning with the envelope equation,

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}, \tag{8}$$

where β^* is the minimum betatron value at $s = 0$ corresponding to the center of the waveguide, and from the beam size relation,

$$\sigma = \sqrt{\frac{\beta(L/2)\epsilon^*}{\gamma}} \tag{9}$$

where ϵ^* is the normalized emittance and γ is the Lorentz factor. We can reexpress the condition as

$$r_1 > N\sqrt{\frac{\epsilon^*}{\gamma}\beta^* + \frac{L^2}{4\beta^*}}. \tag{10}$$

Then if we are interested in maximizing the energy extracted from a drive beam through such a waveguide, following Eq. 4 above, $V \propto L/r_1^2$, then

$$V \propto \frac{4\gamma\beta^*}{N^2\epsilon^*}\frac{L}{4\beta^{*2} + L^2}. \tag{11}$$

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Maximizing this equality,

$$\frac{\partial V}{\partial L} = 0 = \frac{4\beta^{*2} - L^2}{(4\beta^{*2} + L^2)^2} \frac{4\gamma\beta^*}{N^2\epsilon^*}, \quad (12)$$

and rearranging terms for minimum rms beam size σ_0 corresponding to β^*,

$$a > N\sqrt{2}\sigma_0, \quad (13)$$

which in correspondence to,

$$L = \frac{2\sigma_0^2\gamma}{\epsilon^*}, \quad (14)$$

gives the optimum structure length to the inner radius,

$$\frac{L}{r_1} = \frac{\sqrt{2}\sigma_0\gamma}{N\epsilon^*}. \quad (15)$$

For the sub-ultrarelativistic regime, these conditions should be considered and optimized for specific applications. However in the ultrarelativistic regime which is the case at XFELs, these conditions are significantly relaxed, allowing for structures with larger aspect ratios, i.e. toward high-frequency structures.

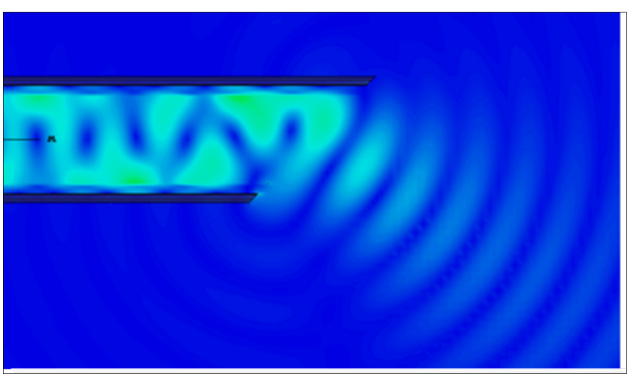

Figure 2: A CST simulation result is shown for the absolute longitudinal component of the electric field for a launched TM mode at 300 GHz. The cut is at 45 degree.

EXTRACTION

It is worthwhile to briefly discuss power extraction. In a conventional undulator, radiation travels with the radiating bunch and a bending magnet is used to separate the two. Alternatively a significant advantage of radiating waveguides is the opportunity to configure the waveguide as a Vlasov antenna [18]. In such a configuration the end of the waveguide is usually cut at an angle which allows the radiation to exit at a similar angle to the cut. A simulation was carried out in CST and is shown in Fig. 2. The simulations show that output coupling efficiencies above 90% can be achieved with various angle cuts.

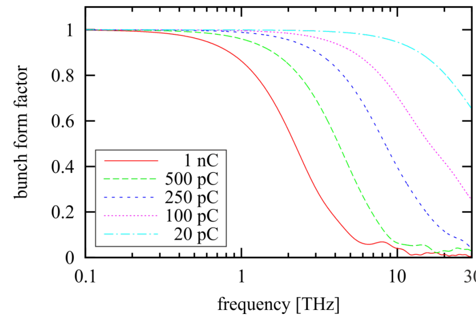

Figure 3: Bunch form factor as a function of frequency for various charge modes of the EuXFEL.

EXAMPLE FOR EUROPEAN XFEL

The European XFEL is designed to operate in a wide range of modes with various bunch charges which covers different user applications. The bunch form factor for the different modes of the Eu-XFEL is shown in Fig. 3. Below 1 THz the bunch form factor is close to 1 even for a high bunch charge of 1 nC. To generate an energy of 3 mJ at 0.1 THz would require for example a structure of only 33 cm length when the structure radius is 2 mm and the bunch charge is 1 nC. The temporal length of the radiation pulse would be 500 ps (50 cycles). And the power reached in this case is 6 MW.

At higher frequencies the bunch form factor shrinks considerably. Lower bunch charges achieve higher form factors so that it can become advantageous to reduce the bunch charge when radiation above 3 THz shall be generated. On the other hand the higher bunch charge of 1 nC is preferable for the lower frequency range but it is not mandatory as longer structures and/or smaller radii are not excluded.

The reduced energy requirements still allow generating sufficient amounts of energy also at higher frequencies. At 6.6 THz only 0.7 μJ radiation energy are requested which requires less than a centimeter structure length (1 mm radius) at charges between 1 nC and 100 pC. Beyond 10 THz, the 20 pC operational mode of XFEL is appealing; however, the usage of bimetallic and corrugated structures becomes challenging due to manufacturing constraints. Fortunately, drawing procedures for e.g. hollowcore optic fibers can produce DLW capillaries to with radii below 1 μm and wall thickness of ~100 nm [19].

CONCLUSION

We have presented a versatile THz source for high-repetition rate XFELs. Our beam-based approach uses radiating or Cherenkov waveguides and can cover a wide range of parameters which are desired by users. The waveguide approach is significantly easier and less expensive than undulator-based approaches which have been previously proposed. Moreover, the flexibility to outcouple radiation without disrupting the beam path is largely appealing to reduce required modifications to beamlines and for its capability to generate multiple THz beamlines with different parameters.

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REFERENCES

[1] P. Zalden, R. Carley, T. Tschentscher, C. Bressler, S. Molodtsov, G. Geloni, A. Scherz, A. Perucchi, S. Bonetti, A. Cavalieri, K. Holldack, D. Turchinovich, A. Lindenberg, K. Nelson, L. DiMauro, M. Lederer, M. Hoffmann, F. Kärtner, A. Cavalleri, M. Krasilnikov, M. Gensch, N. Stojanovic, C. Hauri, A. Savilov, Z. Huang, "Terahertz Science at European XFEL", European XFEL Report XFEL.EU TN-2018-001-01.0, 2018. https://xfel.tind.io/record/1564

[2] Tanikawa, T., Karabekyan, S., Kovalev, S., Casalbuoni, S., Asgekar, V., Gensch, M., Geloni, G., "Superradiant Undulator Radiation for Selective THz Control Experiments at XFELs", European XFEL Report XFEL.EU TN-2018-002, 2018. https://xfel.tind.io/record/1563

[3] E. Syresin *et al.*, "Simulations of Electromagnetic Undulator for Far Infrared Coherent Source of TTF at DESY", in *Proc. 10th European Particle Accelerator Conf. (EPAC'06)*, Edinburgh, UK, Jun. 2006, paper THPLS133.

[4] A. Chesnov *et al.*, "Magnetic Measurements of the FLASH Infrared Undulator", in *Proc. 29th Int. Free Electron Laser Conf. (FEL'07)*, Novosibirsk, Russia, Aug. 2007, paper WEPPH003, pp. 318–321.

[5] M. Gensch *et al.*, "New Infrared Undulator Beamline at FLASH", Infrared Physics & Technology, 51, 5 (2008). doi:10.1016/j.infrared.2007.12.032

[6] A. Willner, "Investigations into the FLASH Infrared Undulator as an Electron Beam Diagnostic Tool", Diploma Thesis, TESLA-FEL 2008-04, (2008). https://flash.desy.de/sites2009/site_vuvfel/content/e403/e1642/e2308/e2310/infoboxContent2

[7] T. Tanikawa *et al.*, "Superradiant Undulator Radiation for Selective THz Control Experiments at XFELs", submitted to Struct. Dyn. 2018. https://arxiv.org/abs/1803.05323

[8] M. Krasilnikov, F. Stephan, E. Schneidmiller, and M. V. Yurkov, "Tunable IR/THz Source for Pump Probe Experiments at the European XFEL", in *Proc. 34th Int. Free Electron Laser Conf. (FEL'12)*, Nara, Japan, Aug. 2012, paper WEPD55, pp. 503–506.

[9] T. L. Vardanyan *et al.*, "ALPHA – The THz Radiation Source based on AREAL", in *Proc. 36th Int. Free Electron Laser Conf. (FEL'14)*, Basel, Switzerland, Aug. 2014, paper TUP083, pp. 561–563.

[10] B. M. Bolotovski, "Theory of Cherenkov Radiation (III)", *Soviet Physics Uspekhi* 4, 781 (1962). doi:10.1070/PU1962v004n05ABEH003380

[11] K.-Y. Ng, "Wake fields in a dielectric-lined waveguide", *Physical Review D* 42, 5, (1990) doi:10.1103/PhysRevD.42.1819

[12] M. Hüning, H. Schlarb, P. Schmüser, M. Timm, "Measurements of Harmonic Wake Fields Excited by Rough Surfaces", *Phys. Rev. Lett.* 88, 074802 (2002). doi:10.1103/PhysRevLett.88.074802

[13] A. M. Cook *et al.*, "Observation of Narrow-Band Terahertz Coherent Cherenkov Radiation from a Cylindrical Dielectric-Lined Waveguide", *Physical Review Letters* 103, 095003 (2009). doi:10.1103/PhysRevLett.103.095003

[14] M. Ivanyan, V. Tsakanov, "Longitudinal impedance of two-layer tube", *Phys. Rev. ST Accel. Beams* 7, 114402 (2004). doi:10.1103/PhysRevSTAB.7.114402

[15] M. Ivanyan, E. Laziev, V. Tsakanov, A. Vardanyan, S. Heifets, A. Tsakanian, "Multilayer tube impedance and external radiation", *Phys. Rev. ST Accel. Beams* 11, 084001 (2008). doi:10.1103/PhysRevSTAB.11.084001

[16] Paper in preparation.

[17] M. Hüning, "Analysis of Surface Roughness Wake Fields and Longitudinal Phase Space in a Linear Electron Accelerator", DESY-Thesis-2002-029 (2002). http://www-library.desy.de/cgi-bin/showprep.pl?desy-thesis-02-029

[18] Vlasov, S.N. & Orlova, "Quasioptical transformer which transforms the waves in a waveguide having a circular cross section into a highly directional wave beam", *I.M. Radiophys Quantum Electron* (1974) 17: 115. doi:10.1007/BF01037072

[19] RF Cregan, BJ Mangan, JC Knight, TA Birks, P St J Russell, PJ Roberts, DC Allan, "Single-mode photonic band gap guidance of light in air", *Science* **285**, 5433 (1537-1539), 1999. https://pdfs.semanticscholar.org/9f51/bfedab35926d03fdd3e7c13013a0600a4394.pdf