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PROSPECTS FOR PHOTON SCIENCE AND BEAM DYNAMICS STUDIES OF A THZ UNDULATOR AT FLUTE

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Abstract

In recent years, the interest in high intensity, short-pulse coherent THz radiation for non-linear experimental research and applications grew with upcoming high intensity lasers. In contrast to lasers, accelerators provide free electrons for which emission properties can be tailored to the demand at typically much higher repetition rates than high-intensity lasers can provide. Efforts are ongoing to augment short-bunch accelerators such as the European XFEL with THz radiation sources such as undulators.

At the far-infrared linac and test experiment (FLUTE) at Karlsruhe Institute of Technology (KIT), we can facilitate experiments to investigate coherent THz radiation from different sources and provide short electron bunches. As an additional THz radiation source, a superconducting undulator can be inserted and investigated.

In this contribution, we evaluate the opportunities of this THz undulator at FLUTE for linear accelerators and free-electron lasers (FELs).

MOTIVATION

THz radiation sources are of increasing importance in various fields of research. The non-destructive properties for biological tissue are of significant value in imaging techniques in medical application [1]. The characteristics of a THz radiation pulse are determined from the generation process. At FLUTE, the laser-based method using a Ti:Sa laser at 800 nm generates THz radiation in the range from 0.14 THz to 0.80 THz with the tilted-pulse-front pumping in a non-linear crystal [2]. In contrast to the laser setup, the electron bunches can generate a broad band of frequencies by emitting synchrotron radiation. Though the intensity of synchrotron radiation is higher compared to a typical laser, the intensity in the THz range is still low for some applications of THz radiation. For short-pulse electron bunches the total radiation power $P(\omega)$ increases according to

$$P(\omega) \propto p(\omega)N[1 + (N-1)\mathscr{F}^2(l,\lambda)], \quad (1)$$

where $p(\omega)$ is the radiation power of a single electron, N the number of electrons in a bunch and the form factor is described by $\mathscr{F}$. Therefore, the light intensity for particle accelerators increases quadratically instead of linearly with the number of particles N, when generating short-pulse coherent THz radiation which requires short electron bunches in the fs-range. The setup of FLUTE as a test experiment provides a unique opportunity to study different sources and possible applications of THz radiation.

FLUTE CONCEPT

At the linac-based test experiment FLUTE electrons are generated in a photo-injector. The Ti:Sa main laser pulses at 800 nm are converted in a non-linear process to 266 nm. The resulting fs-short laser pulses are stretched in a dispersive medium to 2.5 ps and used to generate the electron bunch from a copper cathode. The electron source is followed by a 5.2 m long accelerator using a travelling wave structure. With a maximum energy of 41 MeV the electron bunch enters the bunch compressor. This dispersive chicane with four bending magnets shortens the bunch length to the fs-scale. With the inner magnets installed on movable stages, the compression can be adjusted by the magnet position and bending strength. In addition, the available bunch charge from the electron source can be increased from <1 pC up to 1 nC. This enables a wide range in bunch parameters at the end of the accelerator to investigate the THz generation process and useful applications. The beam parameters at the exit of the bunch compressor are summarised in Table 1. FLUTE is conceptualised as a modular experiment, which enables the integration of temporary experimental setups. In Figure 1 the diagnostic elements for bunch charge and bunch size are shown, including the split-ring resonator experiment. As a bunch length diagnostics it utilises laser-based THz radiation in a electron streaking setup [3, 4].

Table 1: FLUTE Electron Beam Parameters from [5].

Quantity	Value	Unit
Electron energy (E_e)	~ 41	MeV
Electron bunch length (σ_z)	1 – 300	fs
	0.3 – 90	µm
Bunch charge (Q)	<1 – 1000	pC
Horizontal emittance (ε_x)	1	mm mrad
Vertical emittance (ε_y)	1	mm mrad
Horizontal beta function (β_x)	1.1	m
Vertical beta function (β_y)	1.1	m
Pulse repetition rate	10	Hz

THz Radiation of Different Sources

At FLUTE, three different sources of THz radiation are foreseen downstream of the chicane. Firstly, there is the effect of coherent synchrotron radiation (CSR) emitted by the last bending magnet of the chicane. Implementing Eq. 1

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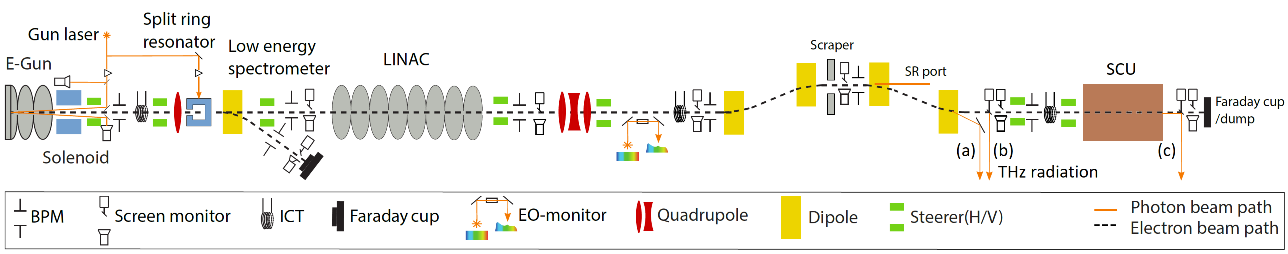

Figure 1: Schematic layout including beam diagnostics and proposed position of superconducting undulator (SCU), not to scale. (a) CSR/CER, (b) CTR, (c) radiation from SCU.

for the FLUTE electron parameters, the coherent radiation in the THz range is up to 10 orders of magnitudes higher than the incoherent radiation emitted by a longer electron bunch. In addition to CSR, coherent edge radiation (CER) occurs at the magnet exit [6]. The extraction of this THz radiation is indicated in Figure 1 at the position (a). Secondly, the electron bunch will be able to pass through a retractable thin metal foil generating coherent transition radiation (CTR). The position of this setup next to the chicane exit is indicated as (b) in Fig. 1. Lastly, in addition to the unavoidable CSR and CER the modular setup of FLUTE allows the investigation of a short-pulse electron bunch in conjunction with a THz undulator. In Figure 1 such an insertion device is located at position (c).

This setup allows to study the different sources of THz radiation at the same time.

UNDULATOR CONCEPT

Parameter

The design of such an insertion device was directed to a superconducting undulator (SCU). Together with experiences in existing SCU devices, the limited available space at the experimental setup strengthen the design choice. In comparison to larger permanent magnet undulators, the SCU, with a total length of 1.8 m, can fit into existing infrastructure and might be interesting for larger facilities such as the EuXFEL. In this regard, FLUTE can also serve as a test-bed for superconducting insertion devices in linear accelerators. The parameter set of the THz undulator found to be suitable for FLUTE are listed in Table 2. This THz SCU is under construction and further details of the parametrisation, design and status of the actual THz SCU can be found in [7].

Table 2: FLUTE SCU Specifications

Quantity	**Value**	**Unit**
Period length (λ_U)	65	mm
Number of full periods	15	
Maximum magnetic field (B_{max})	>0.88	T
K-value	>5.34	
Magnetic gap (g_{mag})	40	mm
Nominal magnetic length (l)	1600	mm
Radiation frequency λ_r	3.9	THz

Comparison with European XFEL

Though FLUTE includes a linear accelerator with a chicane and undulators like the European XFEL (EuXFEL), the purposes of these machines are different. As FLUTE operates at relatively low energies the photon intensity is not going to be as high as in high energy FELs, such as the EuXFEL. In Figure 2 one can see the flux density at 1 m after the source simulated 0.1 nC bunch charge and the superconducting undulators designed to serve as a THz radiation source for FLUTE. A comparison with an THz SCU optimised for the EuXFEL shows differences in the order of magnitudes in intensity. Also, for a high energy machine the period length must be very large and the fields very strong [8], such that the undulator behaves like a wiggler for higher photon energies. In contrast, at low-energy machines such as FLUTE, one can go to smaller period lengths and magnetic fields, and see the undulator-like behaviour dominating over the entire range of photon energies.

Whereas EuXFEL is an FEL, FLUTE is not designed as one. However, the undulator's radiated light has got a larger wavelength than the bunch length. The bunch length can be as small as 1 fs or 300 nm. The undulator's first harmonic is at

$$\lambda_R = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \approx 77\,\mu\text{m}$$

with the relativistic Lorentz factor $\gamma = E_{kinetic}/E_{rest\,mass}$, the undulator period length λ_U, the undulator parameter K and

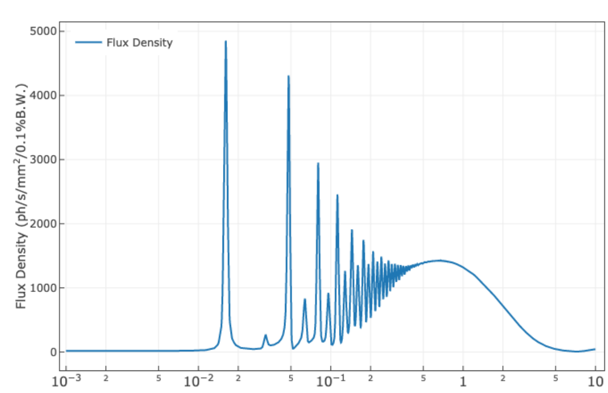

Figure 2: Spectrum of the spacial flux density produced by the ideal THz undulator at FLUTE with SPECTRA [9] on-axis at 1 m distance with 0.1 nC bunch charge.

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the radiation wavelength λ_R. Therefore, it is possible to tune the bunch length and the frequency of the undulator radiation to match each other. It is possible to have a detailed look at the transition from incoherent synchrotron radiation to coherent synchrotron radiation in the THz range.

Ideas for cSTART

In case one would locate the undulator in a proposed version of the Compact STorage ring for Accelerator Research and Technology (cSTART) [10] with RF and 50 MeV beam energy, it could also serve different purposes. One use would be to obtain information on the length of the bunches from the radiation spectrum, in order to verify their shortness.

As it would have its first harmonic at $\lambda_R = 51.8\,\mu m$ or $f = 6\,THz$, it would shift the measurable light relative to the bending magnets with a critical frequency in the UV spectrum $\omega_{crit} = 3 \cdot 10^{15}$ Hz. Furthermore, it increases the photon flux at the peak frequency to enable the bunch length measurement at cSTART.

Another use case could be to serve as an insertion device for optical stochastic cooling [11] and thus be able to benchmark measurements done at [12]. The feasibility of these and other applications is currently investigated.

SUMMARY

In this paper we provided an overview of the different THz radiation sources at FLUTE including a new proposed THz SCU. The opportunities of such a superconducting device as diagnostic for very short electron pulses were mentioned. Possible applications at FLUTE and also perspectivly at cSTART were discussed. A SCU can be parametrised to provide coherent radiation in the range of 4 THz to 20 THz.

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REFERENCES

[1] Amini T *et al.*, "A Review of Feasible Applications of THz Waves in Medical Diagnostics and Treatments", *J. Lasers Med. Sci.*, vol. 12, e92, 2021. doi:10.34172/jlms.2021.92

[2] M. Nabinger, M. Nasse, C. Widmann, Z. Ollmann, E. Bründermann, and A.-S. Mueller, "Characterization and optimization of laser-generated THz beam for THz based streaking", presented at the IPAC'23, Venice, Italy, May 2023, paper THPA079, this conference.

[3] T. Schmelzer *et al.*, "Diagnostics and First Beam Measurements at FLUTE", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2484–2486. doi:10.18429/JACoW-IPAC2019-WEPGW010

[4] J. Schaefer *et al.*, "Split-ring resonator experiments and data analysis at FLUTE", presented at the IPAC'23, Venice, Italy, May 2023, paper THPL122, this conference.

[5] A. Malygin *et al.*, "Commissioning Status of FLUTE", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4229–4231. doi:10.18429/JACoW-IPAC2018-THPMF068

[6] M. J. Nasse *et al.*, "FLUTE: A Versatile Linac-based THz Source Generating Ultra-short Pulses", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPWA010, pp. 2147–2149.

[7] A. Grau *et al.*, "A THz Superconducting Undulator for FLUTE – Design Parameters and Layout", presented at the IPAC'23, Venice, Italy, May 2023, paper MOPM108, this conference.

[8] J. Gethmann *et al.*, "Progress of the Development of a Superconducting Undulator as a THz Source for FELs", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2933–2935. doi:10.18429/JACoW-IPAC2021-WEPAB135

[9] T. Tanaka *et al.*, "SPECTRA: a synchrotron radiation calculation code", *J. Synch. Rad.*, vol. 8, no. 6, pp. 1221-1228, Nov. 2001. doi:10.1107/S090904950101425X

[10] A. I. Papash *et al.*, "Flexible Features of the Compact Storage Ring in the cSTART Project at Karlsruhe Institute of Technology", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2620–2623. doi:10.18429/JACoW-IPAC2022-THPOPT023

[11] A. A. Mikhailichenko and M. S. Zolotorev, "Optical Stochastic Cooling", *Phys. Rev. Lett.*, vol. 71, no. 25, p. 4146, Dec. 1993. doi:10.1103/PhysRevLett.71.4146

[12] J. Jarvis *et al.*, "Experimental demonstration of optical stochastic cooling", *Nature*, vol. 608, pp. 287–292, 2022. doi:10.1038/s41586-022-04969-7