14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPM108

A THz SUPERCONDUCTING UNDULATOR FOR FLUTE – DESIGN PARAMETERS AND LAYOUT

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Abstract

During the last years the interest to perform experiments with coherent, short-pulse radiation in the terahertz (THz) energy regime with high intensity, increased. This radiation can be provided by high intense lasers or electron accelerators. The linear accelerator FLUTE (Ferninfrarot Linac Und Test Experiment – far-infrared linac- and test-experiment) at the Karlsruhe Institute of Technology (KIT), serves as an accelerator test facility for a variety of accelerator physics studies. Additionally, FLUTE is foreseen to provide coherent radiation in ultra-short, very intense light pulses in the THz and far-infrared spectral range. A superconducting undulator in the accelerator structure after bunch compression offers the possibility to generate high-energy, pulsed radiation between 4 THz and 12 THz corresponding to photon energies between 16 meV and 50 meV.

In this contribution we describe the specific design parameters and the general layout of the THz superconducting undulator to reach the envisioned goals.

INTRODUCTION

Many important questions from solid state physics to biological applications demand an analysis within a wide spectral range from terahertz (THz) to infra-red (IR). The THz frequency range, for instance, is of high interest for interaction and reaction studies of liquids, especially in water, and thus for biological and medical research. But these wavelengths are difficult to cover with high intensity using ring-based light sources. To satisfy the increasing interest to use THz radiation, from an accelerator physics point of view, it is necessary to study bunch compression effects, coherent synchrotron radiation as well as generation mechanisms in theory and experiment.

Therefore, during the last years the FLUTE accelerator R&D facility was build up at the Institute of Beam Physics and Technology (IBPT) at KIT [1], did undergo a commissioning phase in the electron production section and is now furthermore developed in the accelerator and bunch compression section. In the final state the FLUTE linear accelerator is supposed to serve as an injector for the Compact STorage Ring for Accelerator Research and Technology (cSTART) [2].

The production of coherent photons in the THz regime will take place at the end of the bunch compressor, where the short-pulse electron bunch generates coherent synchrotron radiation. In addition to these THz generation processes an insertion device will be installed at the end of the accelerator. Since the IBPT is in the lead for the know-how in magnetic design, magnetic characterization, and cryogenics, it is foreseen to install a superconducting undulator (SCU), which is currently built by our collaborating company Bilfinger Noell (BNG).

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FLUTE ACCELERATOR

The electrons are produced in a photo-injector system, driven by a Ti:Sa laser with 1 kHz repetition rate. The laser pusles are converted at a reduced repetition rate of 10 Hz to 266 nm, to be able to generate electrons from a copper cathode. The 5 MeV electron bunch, is focused by a solenoid at the gun exit and it compensates transverse blow up due to space charge effects in the electron bunch.

Subsequently, the electrons will enter the linac structure of about 5.2 m length, which will accelerate the electrons to 41 MeV. After exiting the linac and being focussed by quadrupoles, the electrons enter the bunch compressing section consisting of four symmetrically arranged dipole magnets. This dispersive section utilizes the chirped pulse to compress the bunch length to single fs. The accelerated and compressed bunches will then enter the insertion device to produce photons between 4 THz and 12 THz which can be characterized after the device. The FLUTE layout including diagnostics and the new insertion device is shown in Fig.1 and the main beam parameters of the FLUTE accelerator are given in Table 1.

Table 1: FLUTE Electron Beam Parameters from [3]

Quantity	Value	Unit
Electron energy (E_e)	~ 41	MeV
Bunch charge (Q)	< 1 – 1000	pC
Electron bunch length (σ_z)	1 – 300	fs
	0.3 – 90	µm
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

SCU DESIGN PARAMETERS

The general goal of the undulator to be installed in the FLUTE accelerator is to produce photons in the low THz regime, i.e. in the range from 4 THz to 12 THz corresponding to photon energies from 16 meV to 50 meV or wave-

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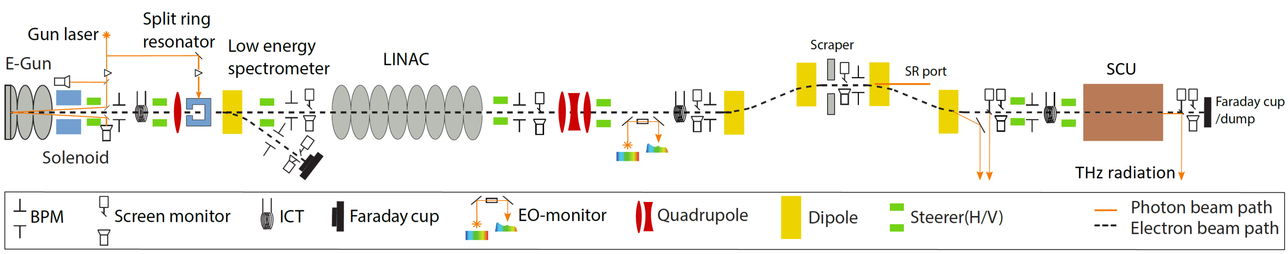

Figure 1: Schematic layout of the FLUTE accelerator with beam diagnostics and new SCU (not to scale).

lengths from 75 µm to 25 µm, respectively. The on axis photon radiation wavelength λ_R emitted by an insertion device such as an undulator depends on the magnetic field B of the device, and is given for the nth odd harmonic by [4]

$$\lambda_R = \frac{\lambda_U}{2\,n\,\gamma^2}\left\{1+\frac{1}{2}\left(\frac{e}{2\,\pi\,m_{0_e}\,c}\lambda_U\,B\right)^2\right\}, \qquad (1)$$

where λ_U is the period length of the undulator, $\gamma = E_{kin}/E_0$ the Lorentz factor resulting from the kinetic energy of the electrons accelerated by the machine, m_{0_e} and e the electron mass and charge, and c the speed of light.

Figure 2 shows the field dependence of the frequency of the produced photons within the observation angle $\theta = 0$ (on axis), for several iterations of λ_U, for a Lorentz factor $\gamma = 80$, calculated from Eq. 1 and $f_R = c/\lambda_R$.

It is found that with the beam parameters of the machine and an undulator period length of $\lambda_U = 65$ mm, the desired photon frequencies aimed for can be reached for reasonable magnetic field values.

It is also possible to reach the required frequencies with other period lengths. Because the flux of the emitted photons depends on the number of periods one strives to smaller periods lengths during the design phase because of the limited device length. Unfortunately, smaller period lengths lead to the prerequisite that a higher magnetic field is required, which might be challenging to reach when having magnetic

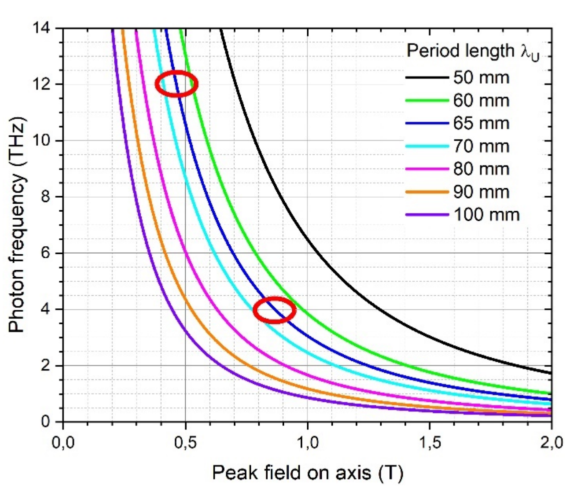

Figure 2: Field dependence of the frequency of the emitted photons for different period lengths.

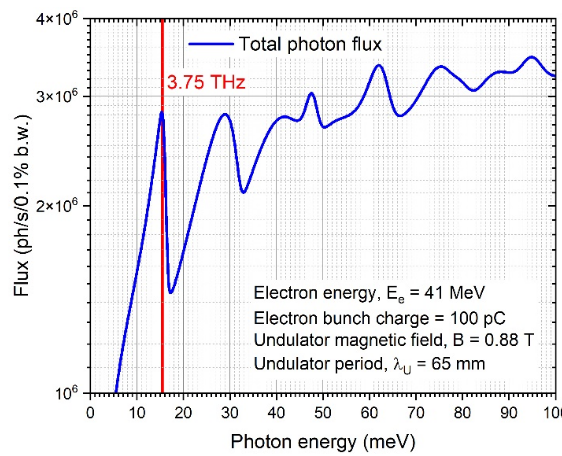

Figure 3: SPECTRA [5] calculation of the total photon flux to illustrate the photon emission line just below 4 THz with stated machine and insertion device parameters.

gap sizes between 30 mm to 40 mm. Therefore, the period length of 65 mm was chosen.

After choosing the period length, SPECTRA [5] calculations were performed to extract the required maximum magnetic field strength to generate photon emission of the first harmonic near 4 THz.

Figure 3 shows the calculation of the total photon flux vs. photon energy for the given parameters, yielding to the result that the energy of the emitted photons at the 1st harmonic reaches 15.5 meV or a frequency of 3.75 THz, respectively.

Although FLUTE is a single pass machine and hence the vacuum conditions in the electron beam region are not as critical as for storage rings, it was decided to separate the beam vacuum from the isolation vacuum where the superconducting coils are mounted. Additionally, this would give the advantage to possibly install the device in a low energy electron storage ring, such as the cSTART project at KIT, where the laser plasma accelerated electrons from FLUTE will be stored and, for example, their beam dynamics can be investigated experimentally.

To separate the vacua, an electron beam chamber, the so-called liner, will be installed. The comparatively small energy of the electron beam yields to a large spatial distribution of the emitted photons and one has to take care that no photons are lost along the insertion device liner because of hitting the beam chamber wall. Calculations performed with

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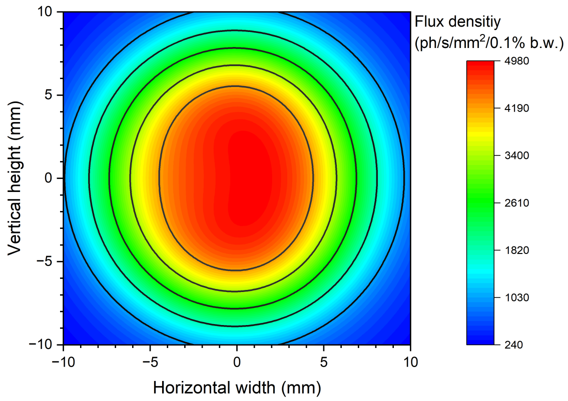

Figure 4: Representation of the spatial flux density of the photons at 1 m from the source calculated with SPECTRA.

SPECTRA [5] show a round spatial flux density distribution of the photon beam, with a size of ~ 20 mm diameter of the 1st harmonic with a photon frequency of 3.86 THz, observation angle $\theta = 0$ (on axis), at 1 m from the source point, as depicted in horizontal and vertical direction in Fig. 4.

Unlike for storage rings, the photon beam has a round shape and according to the photon beam size and the maximum installation space in FLUTE (1.8 m), a tube of minimum inner diameter of 35 mm can be used as liner. The final gap height between the coils results from the required wall thickness of the liner and the distance needed between the liner and the superconducting coils.

Since there is no liquid helium available onsite at FLUTE, it is inevitable to use cryocoolers to cool the device to working temperatures.

A summary with additional main specification parameters for the THz undulator for FLUTE is given in Table 2.

Table 2: Specified General Properties of the Undulator

Quantity	Value	Unit
Period length (λ_U)	65	mm
Magnetic field (B)	> 0.88	T
K-value	> 5.34	
Minimum vacuum gap (g_v)	> 35	mm
Length flange to flange (l)	1800	mm
Maximum ramping time (t_R)	< 300	s
Power supply stability at nominal current	$< \pm 10^{-5}$ for 8 h	
Beam heat load	0.3	W

CONCEPTUAL SCU DESIGN

The specified main parameters of the THz SCU were transferred by BNG to a conceptual design for the device. To keep the overall length of 1800 mm, the superconducting coils consist out of 14.5 fully wound periods in vertical racetrack configuration. For the period length of 65 mm the former will be manufactured with a groove for the winding package widths of 21.7 mm and pole width of 10.8 mm. The groove depth is foreseen to be 10.2 mm excluding a non magnetic ground isolation. To compensate the end fields of the coils a 1/4, 3/4 end field configuration is designed.

Because of integer numbers of windings in the end grooves it does not necessarily mean that a perfect end field configuration can be met. Therefore, auxiliary coils are wound in the first and second, second to last, and last groove of each coil to correct for this. These coil pairs can be powered individually. Additional Helmholtz corrector coil pairs, wound in horizontal racetrack configuration, are placed upstream and downstream of the main coils to correct for the errors of the 1st and 2nd field integral which might result from iron magnetization effects, manufacturing and winding tolerances. During magnetic characterization and operation of the device the correctors have to be tuned during ramp-up and -down to keep the field integrals minimal.

For the main coils a rectangular superconducting wire with a cross section of $(1.08 \times 0.68)\,\mathrm{mm}^2$, including insulation, and a critical current $I_C \geq 1000$ A at 5 T field at the conductor, will be used. The correction coils will be made from a round wire with a diameter of 254 µm, including insulation, and an $I_C \geq 42$ A at 5 T.

The concept envisages a round electron beam chamber out of stainless steel to separate the beam and isolation vacuum. It has an inner diameter of 35 mm, outer diameter of 38 mm and will be coated inside by 30 µm of copper. Resulting from this the magnetic gap is designed to 40 mm and for a current of 355 A in the main coils the field of 0.88 T can be reached.

Considering the heat loads to the three temperature regimes 4.2 K (magnets), 20 K (liner), 50 K (shielding) the usage of only three cryocoolers is necessary. All first stages are connected to the 50 K level, cooling the shield and the intercept between resistive and HTS part of the current leads. The 2nd stages of two cryocoolers with a total cooling power of 2 W @ 4.2 K will be used to cool the coils and the liner will be cooled by the 2nd stage of the third cooler of a different type, with a cooling capacity of 5.4 W @ 10 K to take advantage of the less strict base temperature of the liner.

SUMMARY

A superconducting undulator to be installed in the linear accelerator FLUTE was specified and the conceptual design and layout is developed to produce photons in the region between 4 THz and 12 THz. FLUTE and the emitted photon radiation of the SCU enables accelerator physics studies, investigations on coherent synchrotron radiation and comparison of different sources. The specified design parameters can be met, the technical design report is in preparation and after manufacturing of the coils magnetic characterization will be carried out before installation in the final cryostat.

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