ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB135

# PROGRESS OF THE DEVELOPMENT OF A SUPERCONDUCTING UNDULATOR AS A THz SOURCE FOR FELs

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*Abstract*

To produce radiation in the THz frequency range at X-ray Free Electron Lasers, undulators with large period length, high fields, and large gaps are required. These demands can be fulfilled by superconducting undulators. In this contribution, the actual requirements on the main parameters of such a superconducting undulator will be discussed and the progress of the design will be presented. In addition, beam impedance and heat load estimations obtained analytically will be presented.

## MOTIVATION

Pump-probe experiments using radiation in the THz regime for pumping and X-rays for probing are demanded for e. g. electronic phases in strongly correlated materials [1, 2]. X-ray Free-Electron-Lasers (XFELs) do offer X-rays, but currently do not offer THz radiation for pump-probe experiments, yet. If they could offer both coherently, they would be an excellence utility for aforementioned experiments. First experiments demonstrated that undulators can be used to provide THz radiation in addition to the FEL's main radiation [3, 4]. However, much of the radiation was absorbed [5]. Also at LCLS II this use case was tackled [6] as well as at the European XFEL (EuXFEL) where superconducting undulators (SCUs) were taken into consideration [1]. In this paper the progress of the development of a SCU for 3 THz to 30 THz with 10 full periods is presented.

## PARAMETER OPTIMISATION

A model of the undulator including its matching coils was developed and optimised. The undulator was based on the parameters presented in [1] for the EuXFEL. The minimum reasonable gap height was calculated to be $g = 40$ mm and thus selected for the model. The influence of the gap height on the field strength is much stronger than that of the period length. Thus the latter was chosen to be $\lambda_u = 1$ m in order to meet the accessible magnetic field. This results in a minimal required magnetic field $B(\lambda_r = 3\,\mathrm{THz}) = 7.34$ T for the EuXFEL at its maximum energy $E = 17.5$ GeV. One coil pair of the horizontal racetrack undulator with an outer and an inner coil is depicted in Fig. 1. The figure includes further labels of the coil's geometry.

* This work is supported by the BMBF project 05K19VK2 SCUXFEL (Federal Ministry of Education and Research). J. Gethmann acknowledges the support by the DFG-funded Doctoral School “Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology”

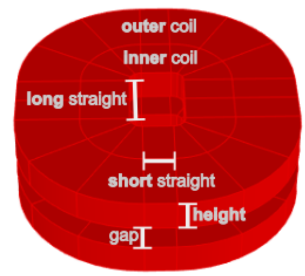


Figure 1: One racetrack coil pair of the horizontal undulator with the labels referenced in the text.

A horizontal racetrack scheme is chosen for easier manufacturing at such large dimensions. Two nested coils can produce higher on-axis fields as the outer coil's current is not limited by the inner coil's maximum current. Therefore, the outer coil can be operated at higher current.

The inner radii of the inner coil $r_1$ and of the outer coil $r_2$ were optimised for maximum on-axis field, keeping the outer radius of the outer coil to fill the geometry to half of the period length. The radii are listed in Table 1. Furthermore, the ratio of the currents of the inner and outer coils were optimised. The fraction between the inner and outer coil of 1:3 was found to be the optimal choice being close to the top of a rising slope of the magnetic field depending on the fraction, but far enough away from the steeper falling slope.

Table 1: Undulator parameters

| Parameter | Value | Unit |
|---|---|---|
| Period length $\lambda_u$ | 1 000 | mm |
| Periods | 10 | |
| Magnetic gap $g$ | 40 | mm |
| Field strength $B$ | 7.6 | T |
| Inner coil radius $r_1$ | 9 | mm |
| Outer coil radius $r_2$ | 80 | mm |
| Outer coil's outer radius $r_3$ | 235 | mm |
| Short straight $a$ | 30 | mm |
| Long straight $b$ | 40 | mm |
| Coil height $h$ | 50 | mm |

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Also the length of the short and long straight sections, respectively, and the height of the coil were optimised for maximum on-axis field and small dimensions.

## HEAT LOAD BY SYNCHROTRON RADIATION BY UPSTREAM UNDULATORS AND BENDING MAGNETS

As a further step in designing a superconducting undulator, the heat impact on the device has to be considered, e.g., by synchrotron radiation [7].

As a first step the radiation cone $1/\gamma$ with the Lorentz factor $\gamma$ was considered, as most of the radiation is within this cone for high energies.

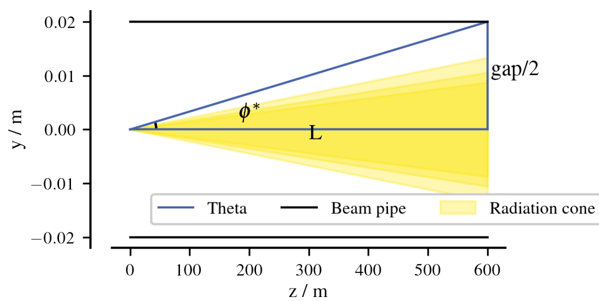


Figure 2: Radiation cone of the undulator for different energies. The beam pipe (black lines) is not hit by the synchrotron radiation cones (yellow). The integration angle $\tan\phi^* = \frac{g/2}{L}$ for a length $L$ and the half gap of the beam pipe $g/2$ are depicted, too.

As can be seen in Fig. 2 the radiation of the undulator itself does not hit the beam pipe even if several such undulators would be placed in a row, because the opening angle $\phi \propto \frac{1}{\gamma} = 0.044\,\text{mrad} \ll \phi^* = \tan^{-1}(\frac{g/2}{L}) = 0.067\,\text{mrad})$ for all common energies of EuXFEL 11.5 GeV, 14.5 GeV, and 17.5 GeV are too small. Only if more than 7 undulators were placed in LCLS II (4 GeV) radiation would hit the beam pipe.

If the undulator is installed immediately after the upstream undulators of EuXFEL's SASE 3 beamline, the radiation impact would not be an issue either for the same reason. The opening angle would be $1/\gamma = 0.036$ mrad in that case, resulting in 4.37 mm diameter of the base of the cone at the position of the end of one of the THz SCUs and thus 36 mm smaller than the gap.

Though the main radiation cone does not show any impact, the radiation at lower photon energies outside of this cone will be taken into consideration in the near future.

Another possible configuration might be a shifted undulator to create a spatially separated THz beam. This requires a chicane which also radiates onto the undulator as shown in Fig. 3. A scraper or absorber can screen off some of the radiation.

Here we assumed a chicane with electromagnets and a bending radius of $\rho = 38.92$ m producing a horizontal offset of 1 m located 2 m upstream of the undulator coils. The radiated power of a dipole can be integrated for the different cases

$$P = \frac{2eI\gamma^4}{6\pi\varepsilon_0\rho}\frac{21}{32}\times \int_{\phi=0.008}^{5.333} \frac{\gamma}{(1+\gamma^2\psi^2)^{5/2}}\left[1+\frac{5}{7}\frac{\gamma^2\psi^2}{1+\gamma^2\psi^2}\right]\mathrm{d}\psi$$

with the average beam current $I$, vacuum permittivity $\varepsilon_0$, and the elementary charge $e$. The radiation hitting a flat hexagonal beam pipe is in the range of 0.2 µW without any scraper and for a beam pipe that is as large as in the main SASE undulators ($g = 8$ mm). With 10 mm as the diameter of the main beam pipe as well as of the scraper, the radiated power hitting the undulator's beam pipe is in the order of 0.4 µW. As a consequence, using a small beam pipe outside the undulator and a heat absorber outside the cryostat reduces the heat impact inside the undulator's cryostat to less than a µW.

## HEAT LOAD DUE TO RESISTIVE WALL IMPEDANCE

For the investigation of resistive wall losses, an elliptical beam pipe made of stainless steel with a 30 µm thin copper coating can be considered as a bulk copper pipe, because of the extremely small slin depth at THz frequencies.

The EuXFEL beam consists of 27000 bunches which are grouped into 600 µs trains a repetition rate of 10 Hz. Each train consists of 2700 bunches with a repetition rate of 4.5 MHz. In this study bunches with rms bunch length $\sigma_z = 40$ µm and charge $q = 1$ nC and $\sigma_z = 10$ µm and $q = 0.25$ nC are considered.

At cryogenic temperatures it is necessary to consider the anomalous skin effect (ASE). In particular, such very short bunches, which correspond to the THz-frequency range, result in the extreme ASE. At low temperatures, the material conductivity is defined by the residual-resistivity ratio (RRR) [8]. For the electroplated copper this value is usually between 10 and 100 [9]. For RRR > 5 and such short bunches, the energy loss $E = -k_{\text{loss}}q^2$ can be calculated using the loss factor from Ref. [10]:

$$k_{\text{loss}}/L = \frac{BZ_0c\Gamma(\frac{5}{6})}{4a\pi^2\sigma_z^{5/3}}, \tag{1}$$

where $L$ is the length, $Z_0$ is the free space impedance, $c$ is the speed of light, $a$ is the beam pipe radius and $\Gamma(...)$ is the Gamma function. The constant $B$ is

$$B^3 = \frac{\sqrt{3}}{16\pi Z_0}l/\sigma_c,$$

where $l$ is the mean free path of electrons, $\sigma_c$ is the material conductivity. $l/\sigma_c = 6.6\times10^{-16}$ Ωm$^2$ and $B = 3.9\times10^{-7}$ m$^{2/3}$ for copper.

The results of the energy loss calculations for different bunch lengths including the ASE are shown in Table 2. The

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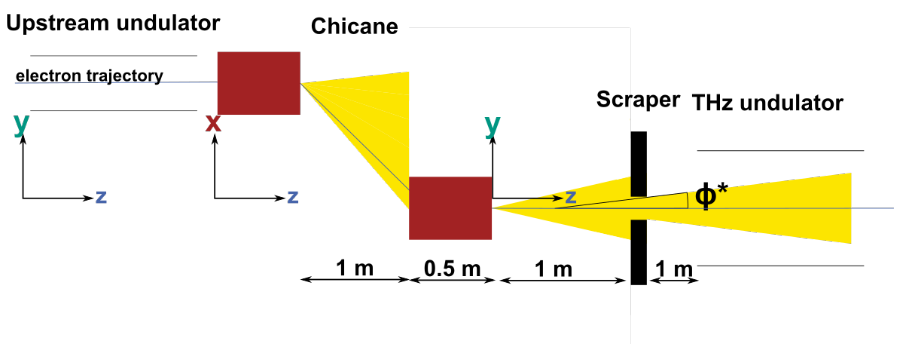


Figure 3: Scheme of the radiation from a bending magnet of a chicane between the SASE line and the THz undulator. The beam pipe of the undulators is shown as black lines, the chicane bends as red blocks, a scraper in black and the radiation cones in yellow. Mind the coordinate change for the chicane.

magnetoresistance effect due to the undulator magnetic field is negligible compared to the ASE.

Table 2: Energy loss per bunch in the undulator pipe taking into account the ASE

| **Bunch length, $\sigma_z$ / µm** | **Bunch charge, $Q$ /nC** | **Energy loss / µJ/m** |
|---|---|---|
| 10 | 0.25 | 8.5 |
| 40 | 1 | 13.5 |

The average loss power $P_{\text{av}}$ can be written as

$$P_{\text{av}} = Q^2 N_{\text{b}} f_{\text{rep}} k_{\text{loss}},$$

with $Q$ the bunch charge and $N_{\text{b}}$ the number of bunches.

Thus, the average loss power of the beam for short electron bunches with $\sigma_z = 10$ µm is $\approx 0.23$ W/m, whereas for $\sigma_z = 40$ µm the heat load reduces to $\approx 0.36$ W/m.

## OUTLOOK

Besides further detailed heat impact studies also for the radiation of the undulator itself, magnetic field error studies have to be carried out and the beam pipe design has to be finalised next.

## CONCLUSION

The geometry of a superconducting undulator designed to serve as a THz light source for the EuXFEL has been optimised. Heat load contributions from the synchrotron radiation of the upstream undulators, bendings have been found to be not significant. For 10 m EuXFEL undulator, the heat load due to the resistive wall impedance for $Q = 250$ pC is 2.3 W and for $Q = 1$ nC is 3.6 W.

## ACKNOWLEDGEMENTS

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