# DESIGN, TRAINING AND MAGNETIC FIELD CHARACTERIZATION OF THE SUPERCONDUCTING THz-UNDULATOR COILS FOR FLUTE

A. Grau†, N. Glamann, B. Krasch, D. Saez de Jauregui
Karlsruhe Institute of Technology, Karlsruhe, Germany
T. Gerhard, A. Hobl, H. Wu, W. Walter
Bilfinger Nuclear & Energy Transition GmbH, Würzburg, Germany

## *Abstract*

FLUTE (**F**erninfrarot **L**inac **U**nd **T**est **E**xperiment – far-infrared linac- and test-experiment), a short-pulse linac and short-bunch THz test facility at the Institute for Beam Physics and Technology (IBPT) at the Karlsruhe Institute of Technology (KIT), serves as an accelerator test setup for a variety of accelerator physics studies. In its final stage of expansion, it is foreseen to provide coherent radiation in ultra-short, very intense light pulses in the terahertz and far-infrared spectral range. A superconducting undulator (SCU) at the end of the accelerator structure offers the possibility to generate photon radiation between 4 THz and 12 THz (energies between 16.5 meV and 50 meV) with a high pulse energy. This energy range, for instance, is of interest for studies of water-soluble interactions. The final undulator design was carried out by Bilfinger Nuclear & Energy Transition GmbH (BNET) in close collaboration with the IBPT.

Before assembling the final undulator device, the superconducting coils were trained and magnetically characterized in CASPER II, a magnetic measurement setup which is part of the Magnet and Cryogenics Facilities (MCF) at the IBPT. In this contribution we describe the general SCU layout, present the results of the coil training, the local magnetic field characterization and field integral minimization of the THz-undulator coils.

## INTRODUCTION

Solid state physics and biological applications demand an analysis within a wide spectral range from terahertz (THz) to infra-red (IR) whereas 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. 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 built at the Institute of Beam Physics and Technology (IBPT) at KIT [1]. In the final state the FLUTE linear accelerator is supposed to serve as an injector for the **C**ompact **ST**orage Ring for **A**ccelerator **R**esearch and **T**echnology (cSTART) [2].

In addition to the production of coherent photons in the THz regime at the end of the bunch compressor, an insertion device is foreseen to be installed in an accelerator straight section.

Based on our extensive know-how in magnetic design, magnetic characterization, cryogenics, and to build, in collaboration with our industrial partner BNET, reliable LTS SCUs, we decided to design and built a compact and superconducting THz undulator.

## FLUTE ACCELERATOR

The electrons are produced in a photo-injector system, driven by a Ti:Sa laser with 1 kHz repetition rate. The laser pulses are converted at a reduced repetition rate of 10 Hz to 266 nm, to be able to generate electrons from the copper cathode. The 5 MeV electron bunch is focused by a solenoid at the gun exit and subsequently accelerated to 41 MeV by the following linac structure of about 5.2 m length. After additional focussing by quadrupoles, the electrons enter the bunch compressing section, where the chirped pulses are compressed to the bunch length of fs. The accelerated and compressed bunches enter then 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 insertion device is shown and described in detail in [3] and the main beam parameters of the FLUTE accelerator are given in Table 1.

Table 1: Flute Electron Beam Parameters

| Quantity | Value | Unit |
|---|---|---|
| Electron energy ($E_e$) | ~41 | MeV |
| Average beam current ($I_{AVG}$) | $10^{-6}$ | mA |
| Electron bunch length ($\sigma_Z$) | 1 – 300 | fs |
| | 0.3 – 90 | µm |
| Horizontal emittance ($\varepsilon_x$) | 1 | mm mrad |
| Vertical emittance ($\varepsilon_y$) | 1 | mm mrad |
| Horizontal beta function ($\beta_x$) | 1.1 | m |
| Vertical beta function ($\beta_y$) | 1.1 | m |
| Pulse repetition rate | 50 | Hz |

## THz-UNDULATOR PARAMETERS

The general goal of the undulator for FLUTE 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 lengths from 75 µm to 2 µm, respectively. The on-axis photon radiation wavelength $\lambda_R$ emitted by an insertion device such as an undulator

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†andreas.grau@kit.edu

depends on the magnetic field $B$ of the device, and is given for the $n^{th}$ odd harmonic by the following equation [4]

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

where $\lambda_U$ 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, $m_{0e}$ and $e$ the electron mass and charge, and $c$ the speed of light. Solving the equation for the FLUTE Lorentz factor $\gamma = E_{kin}/m_{0e}\,c^2 = 80$ and $\lambda_U = 65$ mm, and with

$$f_R = \frac{c}{\lambda_R}$$

it is found that the photon frequencies aimed for can be reached with a reasonable field as shown in Fig. 1.

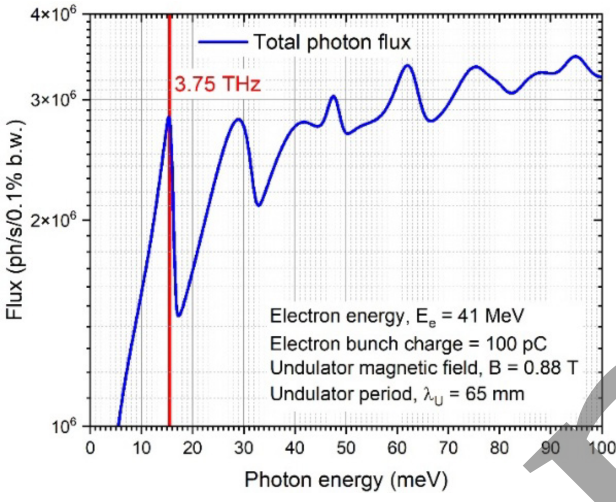

Figure 1: SPECTRA [5] calculation of the total photon flux to illustrate the photon emission line just below 4 THz with stated machine and insertion device parameters.

The comparatively small energy of the electron beam yields to a large spatial distribution of the emitted photons. Therefore, the vacuum gap was set to 38 mm and the magnetic gap to 40 mm. Due to the maximum available space of 1.8 m for the final device, the number of full periods was chosen to 14.5 plus 1.5 end field periods with 7/8, 1/2 and 1/8 full windings leading to a magnet length of 1040 mm plus end plates. After setting further basic parameters and clarifying if the resulting current needed for 0.88 T is suitable, the coils were manufactured and wound by our collaborating company BNET.

## CASPER II MEASUREMENT SETUP

After manufacturing the coils and before installation in the final cryostat they had to be trained and magnetically characterized. This was done in the magnetic measurement setup CASPER II as part of the MCF facilities at the IBPT (see Fig. 2).

In CASPER II coils are tested in a conduction cooled environment such as in the final device. Coil training can be performed as well as local magnetic field measurements and field integral evaluation, including field integral minimization within the same cooldown [6].

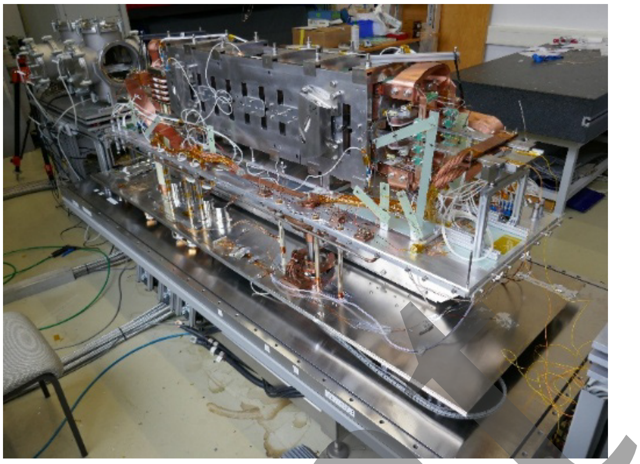

Figure 2: SCUF coils assembled in CASPER II, ready for magnetic training and characterization.

## TRAINING OF THE COILS

Following up the design of the magnetic structure of the SCUF with a period length of 65 mm and 40 mm magnetic gap the operating current to reach 0.88 T should be 358 A. The first step was to train the coils to at least this current and the trend is shown in Fig. 3. Afterwards it was successfully tested to power the coils stable at 360 A for 65 hours.

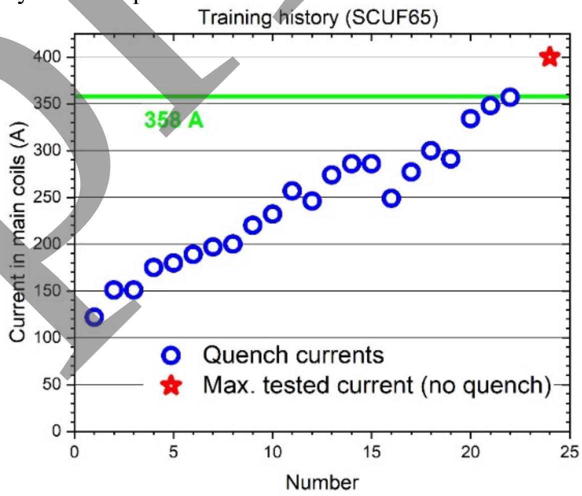

Figure 3: Results of the training of the SCUF coils up to 360 A (corresponding to 0.88 T).

Each SCUF magnet half (top and bottom magnet) is electrically divided in 4 sections, and a quench is detected if the difference between the voltage drop along the upper and lower coil exceeds 100 mV for 10 ms. Figure 3 shows the training behaviour for the SCUF coils, and 22 quenches were needed to reach the nominal operating current of 358 A. To ensure a stable operation at 360 A, this current was exceeded to 400 A without any further quenching. A stability test for 65 h was performed at 360 A.

Figure 4 shows the temperatures of each coil after selected quenches. The maximum coil temperature reached 24 K and it took ~5 h before the next ramp which was started as the temperature reached less than 5 K. This time span is expected to be shorter once the coils are in the final cryostat because of the more sophisticated cooling design.

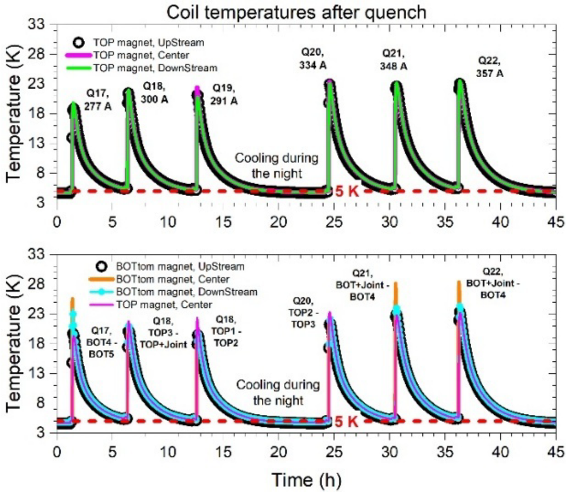

Figure 4: Temperature evolution of top and bottom coil during selected quenches.

## FIELD INTEGRAL MEASUREMENTS

The field integrals of insertion devices can potentially have a strong impact on the electron on its path through the accelerator. Vertical field integrals lead to a distortion in the horizontal plane and horizontal field integrals in the vertical plane, respectively. Field integrals can be measured by means of the moving stretched wire method where in this case a tensioned CuBe wire with 125 µm diameter is moved for 1 mm horizontally or vertically in the gap to measure the vertical and horizontal field integral, respectively.

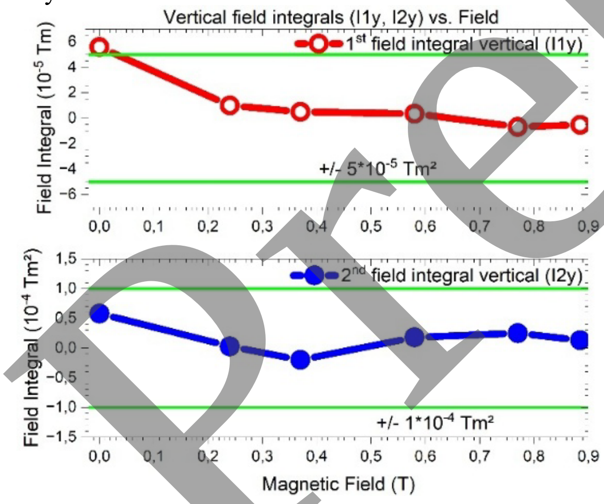

Figure 5: Minimized first and second vertical field integral for selected field values.

By applying field in the correction coils upstream and/or downstream (Helmholtz arrangement), which are manufactured out of superconducting wire, these field integrals are minimized at the moving wire position X = 0 mm and Y = 0 mm (beam path), and the results are shown in Fig. 5 for selected current steps. The currents to be applied to stay within the limits, range up to 0.6 A for the Helmholtz coil upstream and 0.7 A for the Helmholtz coil downstream.

To correct for the horizontal field integrals there are no correctors installed at the final device but the values to be corrected for can be easily corrected by normal steerer coils which will be mounted before and after the insertion device.

## LOCAL FIELD MEASUREMENTS

Following up the field integral minimization, local field measurements with Hall samples were performed at 5 different field values and the roll-off was evaluated. The roll-off is defined as the peak field value difference between the Hall sample measurements in middle position and the value at ± 10 mm left/right of the middle in percent.

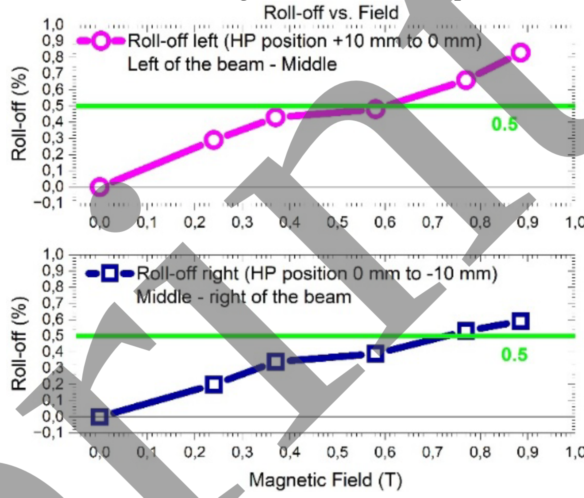

Figure 6: Evaluated roll-off as a function of the magnetic field for selected field values.

Figure 6 shows the progression of the roll-off as the field increases. The roll-off for the left side is slightly larger than for the right side and, as the field rises above 0.77 T (300 A) it exceeds 0.5 % but stays still below 1 % which is satisfactory for an insertion device with 40 mm magnetic gap.

## CONCLUSION

In this contribution the results of the training, field integral minimization and local field measurements of ~1.1 m long superconducting undulator coils with 65 mm period length, 40 mm magnetic gap and a maximum operating field of 0.88 T are presented. The device is to be installed in the linear accelerator FLUTE to produce photons in the energy region between 4 THz and 12 THz and enables accelerator physics studies, investigations on coherent synchrotron radiation and the comparison of different radiation sources. The coils were characterized in CASPER II, a measurement setup as a part of the magnet and cryogenics facilities at IBPT, fulfil the given limits, and the final superconducting THz-undulator is ready to be installed in the accelerator.

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