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OPERATIONAL EXPERIENCE AND CHARACTERIZATION OF A SUPERCONDUCTING TRANSVERSE GRADIENT UNDULATOR FOR COMPACT LASER WAKEFIELD ACCELERATOR-DRIVEN FEL*

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Abstract

A 40-period superconducting transverse gradient undulator (TGU) has been designed and fabricated at Karlsruhe Institute of Technology (KIT). Combining a TGU with a Laser Wakefield Accelerator (LWFA) is a potential key for realizing an extremely compact Free Electron Laser (FEL) radiation source. The TGU scheme is a viable option to compensate the challenging properties of the LWFA electron beam in terms of beam divergence and energy spread. In this contribution, we report on the operational experience of this TGU inside its own cryostat and show the current status of the TGU and the further plan for experiments. This work is supported by the BMBF project 05K19VKA PlasmaFEL (Federal Ministry of Education and Research).

INTRODUCTION

The application of Laser Wakefield Accelerators (LWFA) is a potential key for realizing extremely compact Free Electron Laser (FEL) [1] due to an unprecedentedly high longitudinal electric field inside the laser-driven plasma wave. LWFA-based electron beams exhibit challenging initial conditions in terms of beam divergence and large energy spread. This project aims at experimentally proving that the TGU scheme is a viable option to enable FEL amplification in spite of a large energy spread of the electron bunch, using the example of a superconducting (sc) TGU designed and built at KIT. The complete set-up for this proof-of-principle experiment consists of the LWFA-based electron source, a beam transport line layed out as dogleg chicane [2, 3] and the scTGU. A schematic layout of the system is shown in Fig. 1, and the design parameters for the electron beam and the scTGU are listed in Table 1.

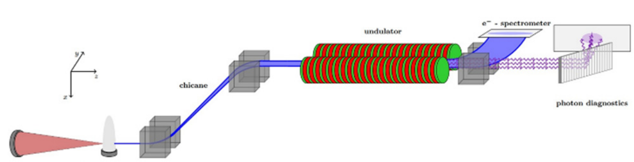

Figure 1: Schematic layout of a LWFA-based scTGU radiation source [2].

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Table 1: Design Parameters for the Electron Beam and the scTGU [4-6]

Parameter	Value	Unit
Relative energy acceptance ($\Delta E/E_0$)	±10	%
Period number (N_u)	40	
Period length	10.50	mm
Gap width @E_0	2.40	mm
Peak field on axis	1.74	T
Undulator parameter @E_0	1.10	
SC wire material	Nb-Ti	
SC wire dimension (bare)	1.00 x 0.60	mm
Critical temperature	9	K
Operating current	750	A

TGU COOL-DOWN PROCEDURE

Cryostat Configuration

The TGU was operated and tested in its own cryostat, specially designed and fabricated by CRYOVAC, Germany. A photo of the scTGU designed and built at KIT and a sectional view of this cryostat are shown in Fig. 2. The TGU is placed in a vacuum and conduction-cooled via LHe-cooled plate heat exchangers. It is surrounded by thermal shields at temperature levels 4 K, 40 K and 77 K, cooled by liquid Helium, Helium vapor and liquid Nitrogen, respectively.

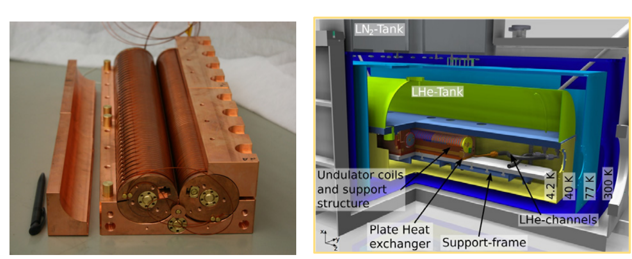

Figure 2: (left) A photo of the scTGU and its own copper support structure and (right) a sectional view of the cryostat assembly with different temperature regions and the TGU is placed in vacuum and conduction-cooled [4].

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Cool-Down Procedure

The cool-down procedure started with filling liquid Nitrogen to the Nitrogen reservoir. When liquid Nitrogen temperature was reached in the Nitrogen reservoir, the temperatures in the Liquid Helium (LHe) region were still in the order of 200 K. At this stage, liquid Nitrogen was repeatedly filled to the liquid Helium tank, keeping the temperature of the bottom of the tank in the range between 100 and 200 K in order to avoid condensation of Nitrogen inside the Helium system. During this process, the TGU temperature decreased with a larger ratio because the bottom of the tank contacts the flat-top surface of the TGU support structure. This process was continued until the TGU temperature was decreased to around 100 K.

After that, warm helium gas was filled into the liquid Helium system to flush the remaining Nitrogen gas. An additional vacuum pump was used to bring the mixture of gases out of the system. This process was repeated several times to ensure there was no remaining Nitrogen gas. Finally, the liquid Helium tank was continuously filled with liquid Helium. The TGU reached its operating temperature of 4.7 K after altogether. The TGU temperature during the cool-down process is shown in Fig. 3.

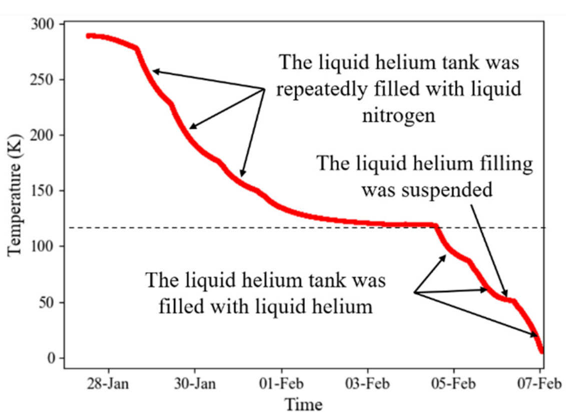

Figure 3: TGU temperature during the cool-down process.

MAGNET POWERING TEST

In this investigation, the TGU was cooled to 4.7 K and magnet powering tests were performed in a parallel circuit configuration. This allows to power each undulator coil individually. In this configuration, the maximum current is limited to 600 A by the HTS current feedthroughs (confer Fig. 7). These tests are to investigate the thermal and quenching behaviour of the TGU and to accumulate significant data for the future experiment.

Improvement of the TGU Set-Up

In a first experiment, the current could not be increased above 400 A due to premature quenches [7, 8]. To overcome this limitation, the support structure and connection method for the superconducting wires have been improved. These improvements are sketched in Fig. 4. In the improved configuration, all SC wires are guided along a new designed support structure to the conduction-cooled points where the SC wires from the TGU and the HTS current feedthroughs are soldered together. Four cylindrical oxygen-free copper cylinders are installed between the bottom of the liquid helium tank and the connection points aiming to allow an efficient heat transfer to the liquid Helium reservoir.

In Fig. 4, red lines refer to the SC wires, the gray part is the support structure and vertical brown parts are copper cylinders. After this improvement, successful powering of each individual coil up to 600 A (limitation of the current feedthroughs) was achieved.

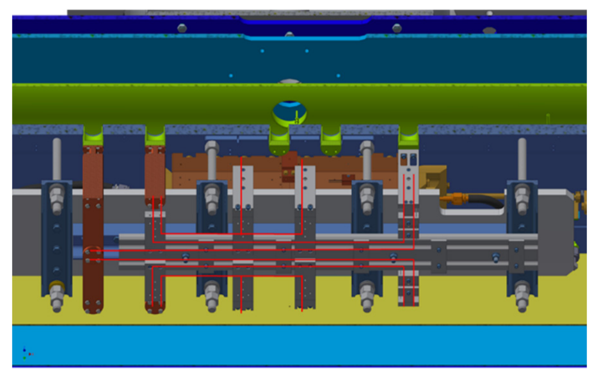

Figure 4: Superconducting wires support structure [9].

Figures 5 and 6 show example results of the powering tests with the improved set-up for the cases of normal current ramps and immediate suspension of the current supply due to the detection of a quench. The observed thermal behaviour can be attributed to eddy current heating: The change in magnetic flux upon ramping the superconducting coils gives rise to induced currents in the copper coil former, which decay rather slowly due to the high conductivity of the material at LHe temperature. The eddy current [10] intensity is given by

$$I_e = -\frac{1}{R}\frac{d\phi_B}{dt} \quad \text{and} \quad \phi_B = \vec{B}\cdot\vec{A}, \tag{1}$$

where R is the resistance of the coil former, $\vec{B}$ is the magnetic flux density and $\vec{A}$ is the area enclosed by the SC wire. The heat generated by the eddy current is given by

$$P = I_e^2 R. \tag{2}$$

To avoid reaching the critical temperature of the superconductor, it is required to ramp the current in steps and to allow for cooling back to 4.7 K in between. Applying currents up to 600 A using ramp rates of 0.5 1.0 and 2.0 A/s were successful. Stable operation at 600 A was achieved for each coil. In case of a quench, significantly more heat than during a ramping step is deposited, however, the coil temperatures do not exceed 15 K due to the low energy stored in the TGU field, and the TGU is back at operation conditions after ~2 hours.

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In the upcoming step, both TGU coils will be connected in series as shown in Fig. 7 (right) and powered together up to the operating current of 750 A.

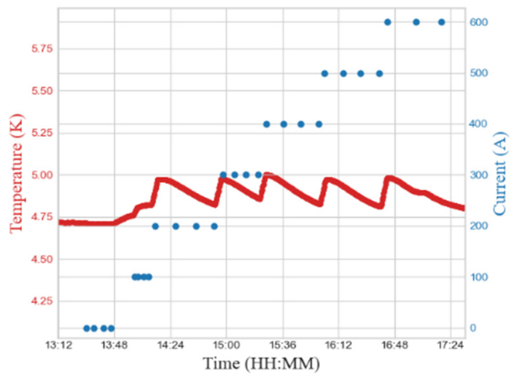

Figure 5: TGU thermal behaviour during powering test using a ramp rate of 0.5 A/s when the applied current was normally increased.

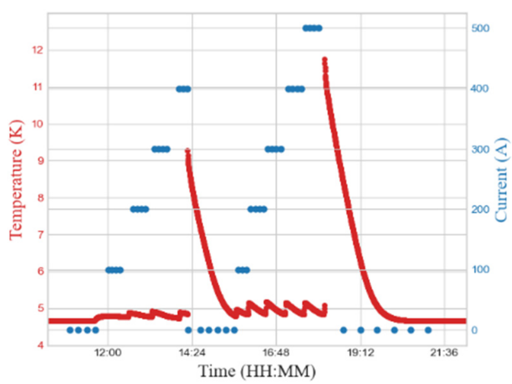

Figure 6: TGU thermal behaviour during powering test using a ramp rate of 2 A/s when the applied current was immediately suspended.

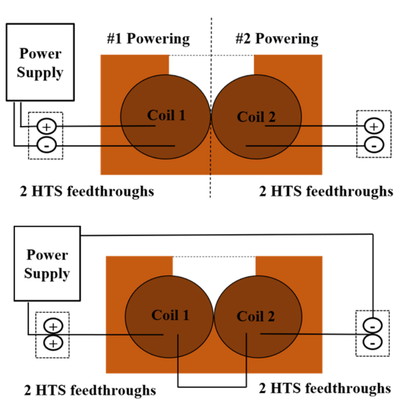

Figure 7: Diagram to explain the magnet powering test conditions for (above) this step and (below) the upcoming experiments.

MAGNETIC CHARACTERIZATION

The measurement system for the magnetic characterization of the TGU consists of an array of seven Hall probes equally spaced in transverse direction, attached to a sliding system for longitudinal scans which is directly mounted to the TGU. The slide with the probes is moved through the TGU gap by an external, magnet-coupled linear stage. The clearance between the Hall probe array and the undulator coils is only in the order of 0.1 mm. The accuracy requirements for the sliding system are accordingly tight. Therefore, the slide's transverse displacements and angular orientations as a function of longitudinal positions were characterized by means of a tactile coordinate measurement system at room temperature. In upcoming steps, the field measurement system will be fully commissioned.

The transverse magnetic field along the TGU longitudinal axis will be characterized by measuring a 2-D field map at operating temperature and current. A side view of the hall probe array installed for the characterization of a 2-period TGU short model and a 2-D cross-sectional view in the transversal plane [6] are shown in Fig. 8.

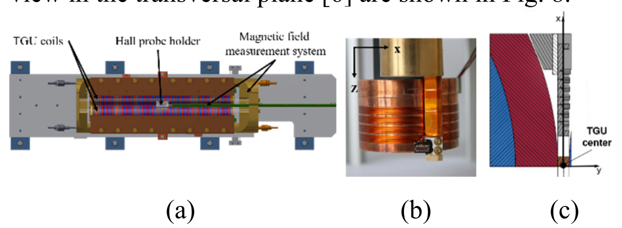

Figure 8: (a) A schematic view of an installation of the magnetic field measurement system attached to the undulator [9], (b) side view of the hall probe array installed for the characterization of a 2 period TGU short model and (c) 2-D cross-sectional view in the transversal plane [6].

CONCLUSION AND OUTLOOK

The cool-down process and operation of the TGU inside its own cryostat were investigated. Both TGU's coils reach the superconducting state. Each coil was powered in preparation for the TGU's magnetic characterization up to 600 A at various ramp rates. The TGU's thermal behaviors during the cool-down process, powering tests and during quenches were investigated. In the upcoming steps the field measurement system will be fully commissioned and the transverse magnetic field shape along the beam axis will be measured.

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