ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST034

MAGNETIC CHARACTERIZATION OF A SUPERCONDUCTING TRANSVERSE GRADIENT UNDULATOR FOR COMPACT LASER WAKEFIELD ACCELERATOR-DRIVEN FELs*

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Abstract

A transverse gradient undulator (TGU) is a key component compensating for the relatively large energy spread of Laser Wakefield Accelerator (LWFA)-generated electron beams for realizing a compact Free Electron Laser (FEL). A superconducting TGU with 40 periods has been fabricated at the Karlsruhe Institute of Technology (KIT). In this contribution, we report that the superconducting TGU has been commissioned with nominal operational parameters at an off-line test bench. An experimental set-up for mapping the magnetic field on a two-dimensional grid in the TGU gap has been employed for the magnetic characterization. We show the first preliminary results of these measurements showing the longitudinal quality, the transverse gradient and the transient behaviour of the superconducting TGU field.

INTRODUCTION

A superconducting transverse gradient undulator (TGU) demonstrator with 40 periods has been designed and constructed at the Karlsruhe Institute of Technology (KIT) [1] with the purpose of proving the technical feasibility of short-period and high-transverse gradient undulators as well as experimentally demonstrating the TGU's capability to generate narrow-bandwidth radiation in spite of a large energy spread of the electron beam. The TGU scheme has been discussed as a viable solution to enable Free Electron Lasers (FEL) driven by laser wakefield accelerators (LWFA) [2]. A schematic layout of a LWFA-driven TGU radiation source or FEL is shown in Fig. 1. It consists of a LWFA-based electron source, a dispersive beam transport line, for example a dogleg chicane, and the TGU. The design parameters of the superconducting TGU demonstrator under investigation here are listed in Table 1.

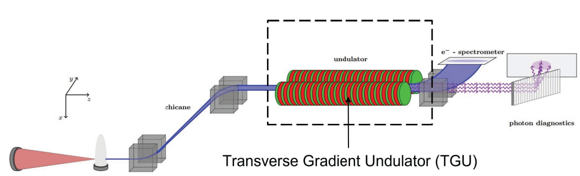

Figure 1: Schematic layout of a LWFA-based Transverse Gradient Undulator radiation source [3].

Table 1: Design parameters of the superconducting TGU demonstrator [4, 5]. E_0 denotes the nominal beam energy.

Parameter	Value	Unit
Relative energy acceptance ($\Delta E/E_0$)	±10	%
Period number (N_u)	40	
Period length	10.5	mm
Gap width (at $x(E_0)$)	2.40	mm
Magnetic flux density on axis $x(E_0)$	1.1	T
Undulator parameter (at $x(E_0)$)	1.10	
Transverse K gradient	150	m^{-1}
SC wire material	Nb-Ti	
Operating current	750	A

The TGU has been commissioned and investigated using its own cryostat, designed and manufactured by the company CRYOVAC, Germany. The cold mass is conduction-cooled employing a liquid-Helium thermosiphon scheme. The cooldown of the TGU to operating temperature (4.3 – 4.4 K) takes about 9 days [6].

MAGNETIC POWERING TEST

For the magnetic powering tests the two superconducting coils constituting the TGU were connected in series and powered through two pairs of high temperature superconductor (HTS) current feedthroughs with an ampacity of 600 A each, as schematically depicted in Fig. 2. Example TGU coil temperature recordings during the powering test are shown in Fig. 3.

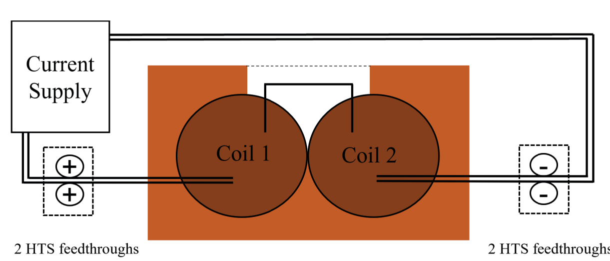

Figure 2: Circuit diagram of the TGU during the powering tests and magnetic measurements. The undulator coils are connected in series which allows to power the undulator coils through two parallel-connected pairs of 600 A-HTS feedthroughs up to the quench limit at 850 A.

In this example, the current is ramped with a ramping speed of 0.2 A s^{-1} from 0 to 700 A, leading to a temperature

* This work is supported by the Development and Promotion of Science and Technology Talents Project (DPST), Thailand) and by the Federal Ministry of Education and Research (BMBF), Germany, under grant No. 05K19VKA.
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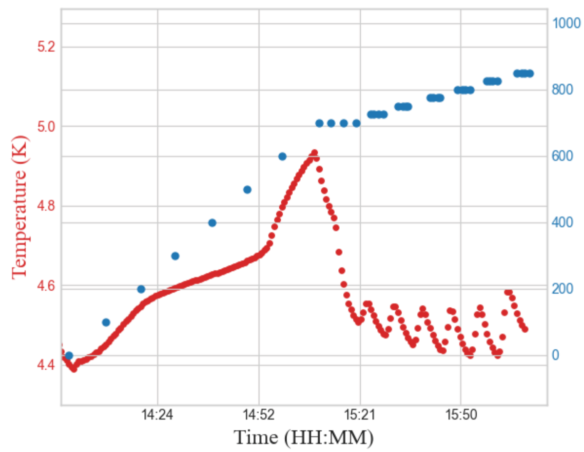

Figure 3: Current ramp and temperature recorded at the TGU coil formers during a powering test with a ramp rate of 0.2 A/s. The temperature curve shows the eddy current heating during ramping and the slow eddy current [7, 8] decay at constant operating current

increase from 4 39 to 4.94 K due to eddy current heating in the coil former. Then, the current was further ramped in steps of 25 A in order to avoid reaching critical conditions in terms of temperature and flux density at the conductor. In this way, the TGU safely reached its nominal operating current of 750 A and could be powered up to a maximum stable current of 850 A, which is consistent with earlier powering tests in a liquid Helium bath [1] and demonstrates the reliability of the cooling design.

MAGNETIC CHARACTERIZATION

The magnetic field measurement system consists of longitudinal sliding system attached to the cold mass. The slide, carrying an array of seven Hall probes placed at equidistant transverse positions, is moved by a magnetically coupled linear translation unit operating at ambient temperature. This setup allows recording a 2-D field map by scanning the seven Probes in longitudinal direction. A diagram explaining the cryogenic-temperature part of the measurement system, a photo of the 7-Hall probe array and a 2-D sectional view in the transversal plane are shown in Fig. 4 and Fig. 5, respectively.

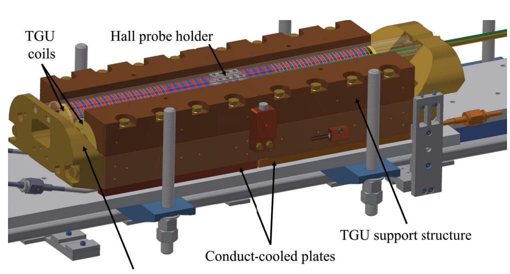

Figure 4: Magnetic field measurement system installed with the TGU [9].

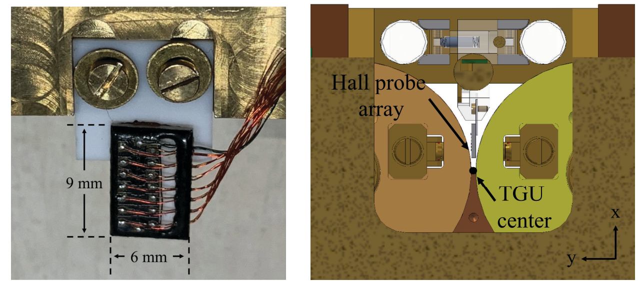

Figure 5: Photo of the 7-Hall probe array attached on a MACOR ceramic plate for electrical isolation from the TGU and the measurement system (left) and 2-D cross-sectional view in the transversal plane (right) [9].

The 7-Hall probe array shown in Fig. 5 (left) was manufactured by AREPOC s.r.o, Slovakia. The sensitivities of the seven Hall probes are around 52 mV/T at 4.2 K with an operating current of 10 mA applied. The transverse positions of the Hall probe centers with respect to the center of the TGU are 9.30 , 6.75 and 4.20 mm for probes No. 1 , 4 and 7 [1], respectively.

In this configuration, the magnetic field measurements were performed at coil temperatures ranging from 5.8 to 6.3 K due to a considerable heat load through the magnetic measurement system, therefore using rather small applied current values between 10 and 50 A. In addition, the measurement could only be performed for 31 out of the 40 periods of the TGU due to mechanical restrictions of the sliding system. An example measured magnetic field map is presented in Fig. 6.

A preliminary evaluation of the transverse flux density slope at the longitudinal position of a flux density maximum is shown in Fig. 7. The displayed error bars account for the statistical and the a priori known systematic errors of the measurement. A comparison with the also displayed expected flux density values calculated from an OPERA-3D model of the TGU shows a fair agreement The relative transverse magnetic field gradient is given by:

$$\alpha\ [1/\mathrm{m}] = \frac{\Delta B}{B \Delta x} \frac{[\mathrm{mT}]}{[\mathrm{mTm}]}. \qquad (1)$$

The relative transverse flux density gradient at the transverse position of the beam center, at 30 A, is estimated to be $-162\,\mathrm{m}^{-1}$.

Figure 8 shows the temporal behaviour of measured magnetic fields. The full field is not reached immediately after the current ramp, but shows an exponential asymptotic drift due to the presence of inter-turn and coil-to-former short circuits. The time constant of the exponential is $\tau = 1400$ s. The reported field measurements and scans were performed after a transient time of $5\tau = 7000$ s. I should be noted that the flux density measurements shown here are very sensitive to misalignments of the Hall probe array due to the large flux density gradients present in the TGU gap. A detailed analysis of the systematic measurement errors in line with a development of correction schemes for those errors which

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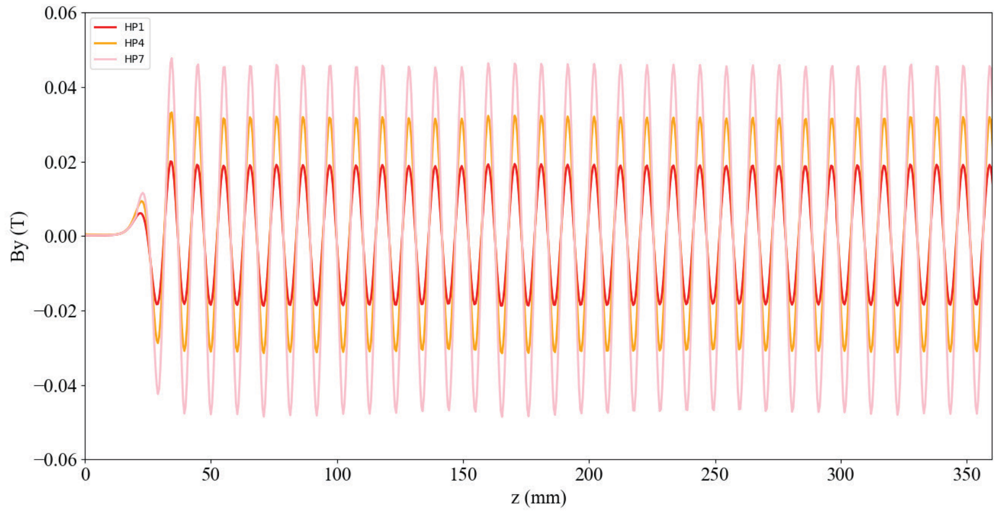

Figure 6: Example result of the magnetic field distribution along parallel axes at the transverse positions of Hall probes 1, 4 and 7 at a TGU operating current of 30 A. The longitudinal resolution is 0.5 mm.

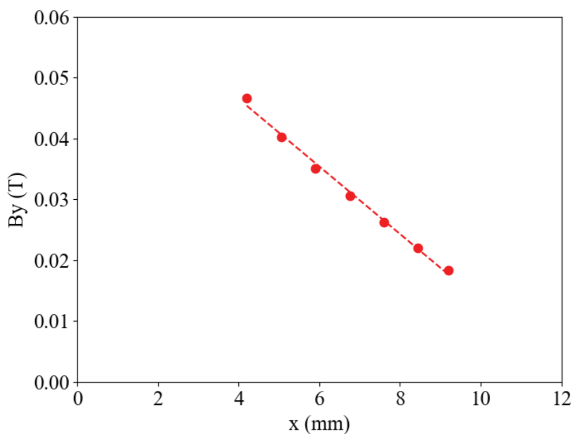

Figure 7: Transverse magnetic fields measured form 7-Hall probe array and the field generated from the ideal position of the Hall probes dependent on distances from the TGU center at a TGU operating current of 30 A.

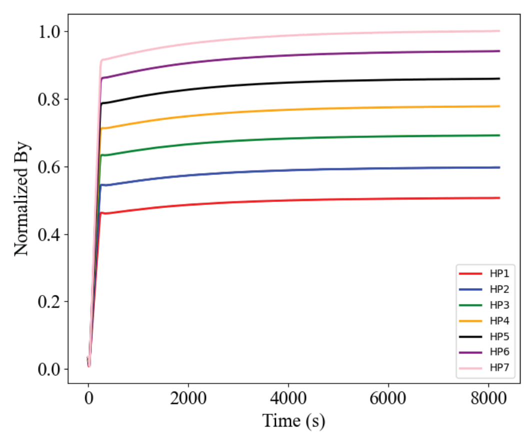

Figure 8: Normalized magnetic flux density amplitude measured by 7-Hall probe array as a function of time. Field values were normalized to the maximum field value measured by Hall probe number 7.

can be directly determined from the measured data is ongoing. In the following step, an updated OPERA-3D model will be created which reproduces the observed real field properties and which will then be employed for particle tracking and radiation field calculations in order to reveal the effect of the measured field properties on the TGU performance.

SUMMARY AND OUTLOOK

The superconducting TGU has been stably operated at up to 850 A in its own, conduction cooling-based cryostat. The magnetic flux density was mapped along seven equidistant, parallel longitudinal axes spanning 31 out of the 40 periods of the TGU. Due to the elevated heat load introduced by the measurement system, the field measurements were performed at around 5-6 K and accordingly low applied current values between 10 and 50 A (1.3 to 6.7 % of the nominal operating current). Because the system is iron-free, however, the flux density scales proportional to the applied current, and the measured field maps are fully representative. Therefore, in the following steps, reliable conclusions on the TGU field quality and the expected radiation and FEL performance will be drawn.

ACKNOWLEDGEMENTS

The research team would like to acknowledge Stefan Uhlemann, Daniel Ritz, Ralf Lang, Bennet Krasch, and Nicole Glamann, who strongly supported the experimental work.

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