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CONSTRUCTION AND FIRST MAGNETIC FIELD TEST OF A SUPERCONDUCTING TRANSVERSAL GRADIENT UNDULATOR FOR THE LASER WAKEFIELD ACCELERATOR IN JENA *

V. Afonso Rodriguez†, A. Bernhard, A. Grau, P. Peiffer, R. Rossmanith, M. Weber, C. Widmann, A. Will, Karlsruhe Institute of Technology (KIT)
M. C. Kaluza, M. Nicolai, A. Sävert, Friedrich Schiller University Jena
M. Reuter, Helmholtz Institute Jena

Abstract

A superconducting transversal gradient undulator (TGU), tailored to the particular beam properties of the laser wakefield accelerator (LWFA) at the University of Jena, has been designed and constructed at KIT. This undulator in combination with a specialized beam transport line will be employed to produce undulator radiation with natural bandwidth despite the relatively large energy spread of the electrons ($\Delta E/E_0 \sim 10\,\%$) produced by the LWFA. The fabrication of this undulator and first results of the magnetic field measurement are discussed in this paper.

INTRODUCTION

The experimental proof of a TGU source concept was proposed in [1], overcoming the limitations of LWFA-driven radiation sources imposed by the energy spread of laser wakefield-accelerated electron bunches. The basic setup is sketched in Fig. 1. The electron bunch is energetically dispersed in xz-plane by a magnetic chicane and sent into a TGU with a x-dependent flux density amplitude $\tilde{B}_y(x)$. The dispersive beam transport line is currently under development [2].

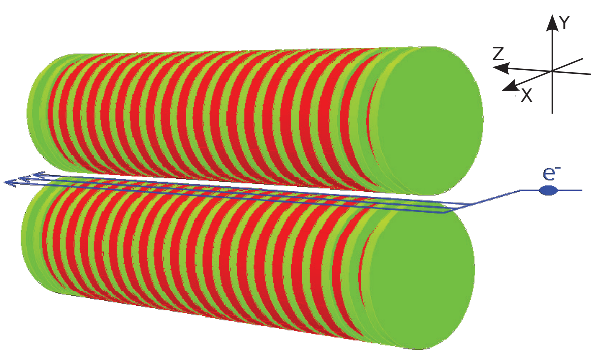

Figure 1: Sketch of the electron beam dispersion in the xz-plane through the TGU.

Design Optimization

For the design optimization of the undulator we assumed a reference electron energy of $E_0 = 120\,\mathrm{MeV}$ with an energy spread of $\Delta E/E_0 = \pm 10\,\%$. The flux density amplitude is matched to the dispersion of the electrons (see Fig. 2) in such a way that particles with different energies oscillate at the same amplitude and frequency.

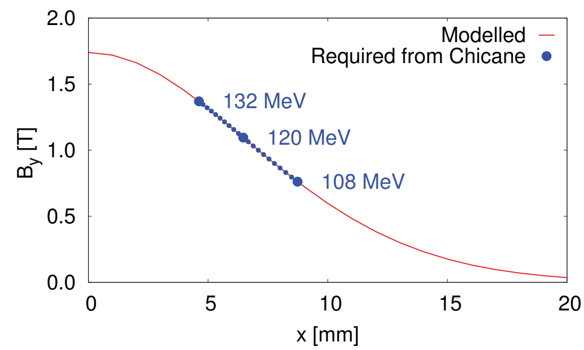

Figure 2: Simulated Magnetic Field B_y along the transverse position x for the TGU.

This matching is achieved if the modified undulator equation

$$\lambda(x) = \frac{\lambda_u}{2\gamma^2(x)}\left(1 + \frac{K^2(x)}{2}\right) = const. \qquad (1)$$

is satisfied, where $\lambda(x)$ is the wavelength of the emitted radiation, λ_u the period length of the undulator, $\gamma(x) = E(x)/m_e c^2$ the x-dependent Lorentz-factor of the electrons, and $K(x) = (2\pi e/m_e c)\lambda_u \tilde{B}_y(x)$ the x-dependent undulator parameter. The resulting emitted wavelength as a function of x-position after the optimization is shown in Fig. 3.

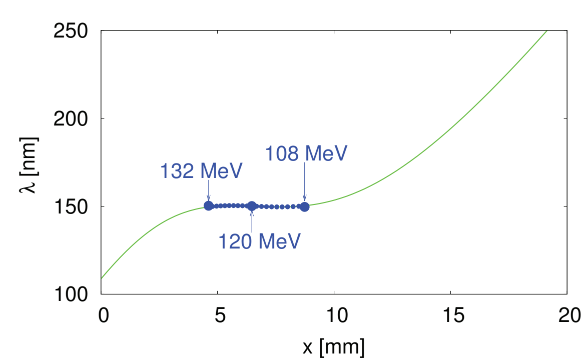

Figure 3: Resulting emitted wavelength along the transverse position x for the TGU.

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† veronica.rodriguez@kit.edu

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The design goal for the cylindrically shaped undulator was to achieve a bandwidth of the undulator radiation wavelength $\lambda(x)$ described by Eq. 1 in the order of the natural bandwidth for $N_u = 100$ periods

$$(\lambda_{max} - \lambda_{min})/\lambda_{E_0} \leq 1/N_u = 1\%, \qquad (2)$$

at a gap width on symmetry axis not falling below $1.1\,\mathrm{mm}$, an undulator parameter for the central electron energy $K_{E_0} \geq 1$ and a period length as short as possible. The main parameters of the TGU resulting from the optimization is given in Table 1.

Table 1: Undulator and Superconducting Wire Parameters

Period Number, N_u	40	
Period Length, λ_u	10.50	mm
Pole Radius	30.00	mm
Gap on Axis	1.10	mm
Peak Field on Axis	1.74	T
K_{E_0}	1.10	
SC Wire Material	NbTi	
SC Wire Dimensions (bare)	1.00 x 0.60	mm
Cu:SC Ratio	1.35:1	
Turns per Layer	4	
Number of Layers	6	
Eng. current density	1020	$\mathrm{A/mm^2}$
Magnet Operating Temperature	4.20	K

The transverse gradient of the magnetic flux density amplitude causes a ponderomotive drift of the electrons in x towards lower flux density. This drift can be corrected by superposition of a weak combined sextupole-dipole field as discussed in [1] and [3] and is generated by two long narrow coils placed inside the TGU coil former. Therefore it has to be ensured that the correction field source is not screened by unsaturated soft magnetic material. Thus all soft magnetic parts of the undulator are required to be completely saturated or, as an alternative, the undulator has to be iron-free. We chose the latter option.

CONSTRUCTION

Although the design optimization described above was performed for a 100 period undulator, the full-scale prototype actually built at KIT for the proof-of-principle experiment has 40 periods. Both the TGU and the correction coils were wound from standard commercial NbTi wires on a winding machine in our laboratory at KIT as shown in Fig. 4. The properties of the wire used are summarized in Table 1.

The winding packages consist of 6 layers x 4 turns of solenoid and racetrack coils. It is required to lay out every second winding package as an upright racetrack coil, because the space between two adjacent winding packages is smaller than the dimension of the superconducting wire. To bring the field integrals to zero the number of Ampère-turns in the first two grooves are reduced to $1/4$ and $3/4$ of those in the full periods.

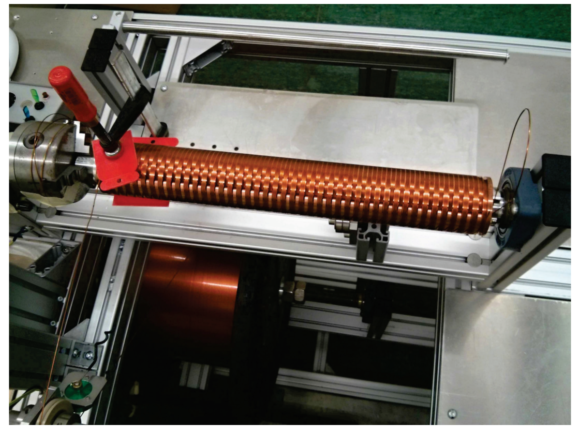

Figure 4: Winding of the second undulator coil in our semi-automatic winding machine.

Each coil former is composed of 3 modules (see Fig. 5 left), which are assembled before winding the superconducting coils. This assembly is in principle extendable to 100 periods by four times repeating the inner coils modules. This coil assembly is supported by a bolted clamping structure. The support structure defines the magnetic gap of the undulator, applies compressive prestress to the outer parts of the racetrack coils and takes up the magnetic forces acting on the undulator coils as a whole. More details are given in [3].

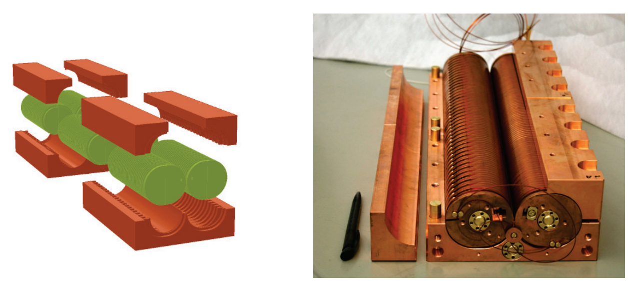

Figure 5: Schematic mechanical layout of the TGU (left): coil former (green) and coil support structure (brown). The assembled TGU (right).

The superconducting coils are wound on a copper former in order to ensure good heat conduction and to minimize thermally induced mechanical stress. The support structure is made of copper for the same reasons. Fig. 5 right shows the full-scale TGU after the assembly.

The superconducting undulator coils will be conduction-cooled. A schematic view of the cryostat is shown in Fig. 6. A plate heat exchanger will be bolted to the bottom of the support structure. The cooling channels of the heat exchanger will be connected to a 50 liter liquid helium reservoir placed above the coils, constituting a thermosiphon cooling scheme. To precisely measure the temperature DT-670 silicon diode sensors will be mounted at several positions on the undulator and the $4.2\,\mathrm{K}$ shield. Additional PT100 sensors will be placed in the external shields. The operation temper-

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ature in this cryostat is expected not to exceed 5 K at the superconducting wires.

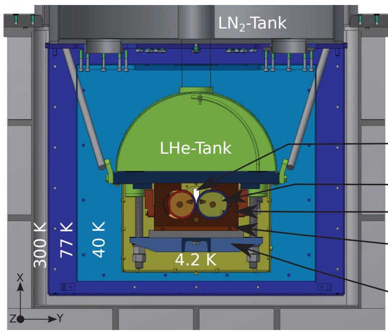

Figure 6: TGU horizontal cryostat assembly.

MEASUREMENTS

Short Prototypes

The main purpose of the manufacture and testing of short prototypes was to prove the undulator geometry and the winding technique that could be scaled up for the longer TGU. The first magnetic field test of a two periods short model was performed at KIT in the cryostat CASPER [4] at 4.2 K .

The magnetic field was measured with a Hall-Probe-Array (Arepoc s.r.o.) of 7 Hall-probes arranged along the x-axis to measure at 7 discrete x-positions. The size of the entire array is 9 x 6 x 1 (mm). The spacing between the individual probes is 0.85 mm.

The beam positions are within the area of x between 4 mm and 10 mm, therefore the measuring range was correspondingly adapted. The support structure used is the same as for the full-scale TGU scaled down to two periods (See Fig. 7).

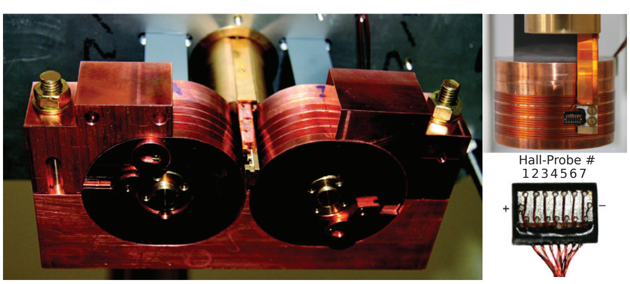

Figure 7: Test measurement system and Hall probe array for the short model.

First a quench test was performed. The quench currents reached 88 % of the short sample limit for the first, 100 % for the second coil with an improved design. The operating current will be at 77 % of the measured quench current, providing a sufficient safety margin.

Fig. 8 shows the first measured data of the magnetic field B_y with the the Hall probe (HP) 1, 4 and 7 along the longitudinal position z compared with the simulated field [5]. The measurement shows an excellent agreement with the theoretical expectations.

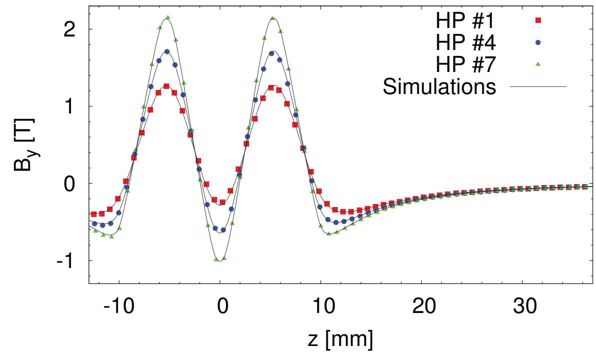

Figure 8: Test Magnetic Field Measurement B_y along the longitudinal position z for the short model TGU.

Full-Scale Undulator

The magnetic field of the full-scale TGU will be measured by the Hall probe array described in the previous section. The measurement will be performed within the horizontal cryostat, at liquid Helium temperature and in high vacuum. This Hall probe array will be fixed to the shaft of a transfer rod (VACOM), which will allow a translation of the Hall probe along the z-axis (See Fig. 9) without rotation. The maximal z-stroke of the linear movement is 609 mm. The movement of the probe will be controlled with a side mounted stepper motor with a resolution of the probe position of 2 μm.

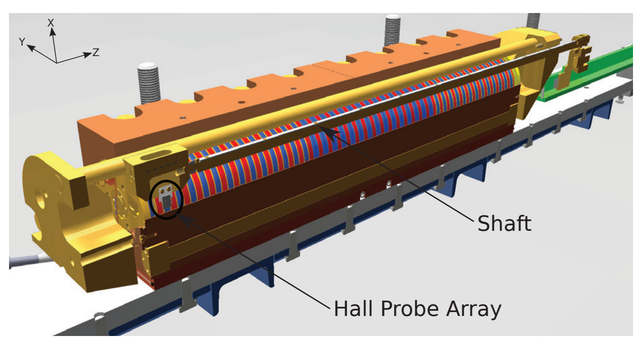

Figure 9: Measurement system assembly.

CONCLUSION

A full-scale 40 periods TGU has been designed and built at KIT. The aim of this TGU in combination with a dispersive chicane is to produce radiation with natural bandwidth even assuming ±10% energy spread of the electrons. The first magnetic field measurements of the short model show a good agreement with the predictions. The full-scale TGU and a custom horizontal cryogenic system will be tested in the coming months at KIT. The current plan assumes a proof-of-principle experiment at the LWFA in Jena with the whole setup at the end of 2014.

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