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DESIGN AND FABRICATION CONCEPTS OF A COMPACT UNDULATOR WITH LASER-STRUCTURED 2G-HTS TAPES

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Abstract

To produce small-scale high-field undulators for table-top free electron lasers (FELs), compact designs have been proposed using high temperature superconducting (HTS) tapes, which show both large critical current densities and high critical magnetic fields with a total tape thickness of about 50 µm and a width of up to 12 mm. Instead of winding coils, a meander structure can be laser-scribed directly into the superconductor layer, guiding the current path on a quasi-sinusoidal trajectory. Stacking pairs of such scribed tapes allows the generation of the desired sinusoidal magnetic fields above the tape plane, along the tape axis. Two practically feasible designs are presented, which are currently under construction at KIT: A coil concept wound from a single structured tape with a length of 15 m, which has been presented already in the past, as well as a novel stacked and soldered design, made from 25 cm long structured tapes, soldered in a zig-zag-pattern. In this contribution the designs are briefly recapped and the experimental progress is presented.

INTRODUCTION

Charged, relativistic particles passing along an alternating magnetic field with field amplitude B_0 perpendicular to their direction of motion are deflected on a sinusoidal trajectory and emit synchrotron radiation, predominantly in forward direction. The undulator equation describes the emitted wavelength for the first harmonics in case of coherent emission as [1].

$$\lambda = \frac{\lambda_\mathrm{u}}{2\gamma^2}\left(1+\frac{K^2}{2}+(\theta\gamma)^2\right) \quad \text{with} \quad K=\frac{eB_0\lambda_\mathrm{u}}{2\pi m_\mathrm{e}c}. \tag{1}$$

K is referred to as the undulator parameter, where m_e is the electron mass, e the electric elementary charge, c the speed of light and γ is the relativistic Lorentz-factor. The output flux on axis is at around 80% of the maximum flux for values of K around one. A short period length λ_u and a large on-axis magnetic field amplitude B_0 are required to enable both short emitted wavelength and high output flux, which is desired for example in FEL applications. One possibility to achieve this is by using meander structured high-temperature superconductor(HTS)-based tapes [2, 3], which will be presented in the following.

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FIELD GENERATION BY MEANDER-STRUCTURED HTS CONDUCTOR

The concept of meander-structured HTS tapes for undulator field generation was originally proposed by Prestemon *et al.* [2, 3]. We denote z the direction along the tape, equal to the beam axis, x the direction within the tape surface, perpendicular to the beam axis, and y the direction perpendicular to the flat tape surface. A tape with a meander structure, as shown in Fig. 1, ideally imposes a sinusoidal current flow in the x-z plane. An overlap of two tapes with opposing current directions with respect to the z-axis, and with a shift of the meander structure by $\lambda_\mathrm{u}/2$ along z results in small current loops, which generate an alternating magnetic field B_y along the beam axis z, above the tape surface. Two stacks of tapes can be placed, one above another, to create an undulator.

Alternating the current direction from tape to tape within such a stacked tape undulator is the main technical challenge. A joint-less winding concept from a single tape has been proposed [4] and is currently being actively developed at KIT. A second approach, based on individually structured tape pieces, which are stacked and soldered is presented in this contribution, which is also actively being developed at KIT. The meander structures in both designs are laser-scribed into the tapes (see [5]). The tape width is 12 mm and the scribed meander structure covers alternating 8 mm of that width, leaving a current channel width of 4 mm (cf. Fig. 1).

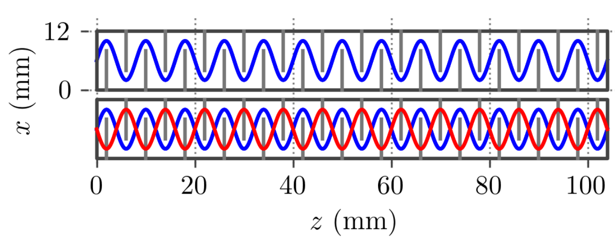

Figure 1: Top: Simplified sinusoidal line current model in the meander-structured tape. Bottom: sinusoidal current in the meander structure (blue line) and a second tape's current with phase shift of $\lambda_\mathrm{u}/2$ and inverse current direction (red line), together forming small current loops in alternating direction.

Magnetic Field Simulation

For the magnetic field simulations of the meander-structured tapes, a simplified line current model was assumed to approximate the current distribution, as shown

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in Fig. 1. The line currents were assumed sinusoidal. To achieve a higher engineering current density in the stack and, hence, a higher magnetic field in the gap, the tapes are assumed to be copper-free. The thickness is approximately 55 µm per tape. Based on calculations in [4], the number of tapes per side was fixed to 30. The gap between the two tape stacks was set to 4 mm. The design parameters for the undulator prototype, as used in the simulations, are shown in Table 1. The magnetic field was simulated with a Biot-Savart solver in Python. The simulated magnetic field component B_y within the center gap plane is shown in Fig. 2. The magnetic field B_y along the nominal beam axis (x = 0, y = 0) is also shown. At nominal operating current of 500 A, a peak field close to 1 T is estimated.

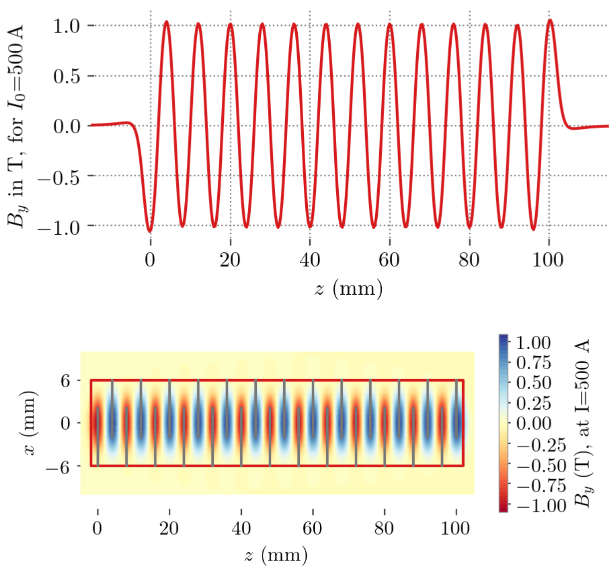

Figure 2: Simulated magnetic field B_y along the nominal beam axis z (top) and in the xz-plane (bottom) in the center of the magnetic gap, i.e. both with a distance of 2 mm to the tape stacks. The parameters used in this simulation are shown in Table 1.

Table 1: Design Parameters for a Stacked-tape Undulator Prototype at KIT

Simulation parameter	**Variable**	**Value**
Operating current	I_0	500 A
Undulator period length	λ_u	8 mm
Tape width	w_T	12 mm
Channel width	w_c	4 mm
Magnetic gap	g	4 mm
Number of tapes per stack	n_t	30
Number of periods per tape	n_p	12

WINDING CONCEPT I - SINGLE WOUND

A design of a joint-less winding scheme for structured tape was proposed by Holubek *et al.* [4]. A single piece of tape is structured, folded in half and wound in this double-layered way, such that the current direction between two layers is opposing. The structured sections are precisely overlapping with the help of alignment pins, for which an alignment hole is laser-cut. A wound prototype winding former for first powering tests is shown in Fig. 3 with the alignment holes visible beneath the polyimide insulation layer on top.

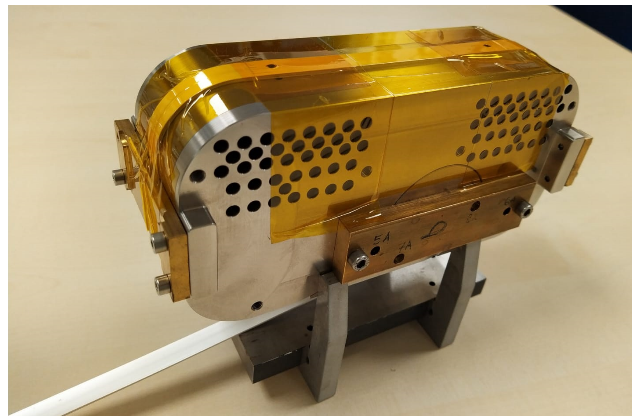

Figure 3: Prototype winding former with structured tape wound according to the jointless winding scheme as described in [4].

Setup for Magnetic Field Measurements at 4.2 K

For this option, a magnetic field measurement system was designed and is being fabricated. A Hall-probe array with ten Hall-probes, in-house calibrated at KIT at 4.2 K and spaced 0.65 mm is pulled through the center gap, such that the field component B_y within the x-z plane can be mapped. The planned setup including the Hall-probe array is shown in Fig. 4.

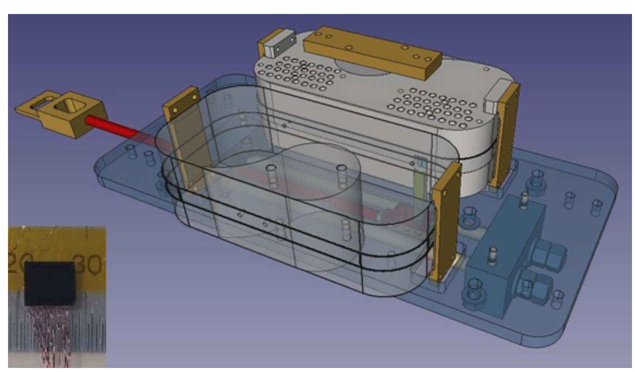

Figure 4: Setup for first field measurements of the single-wound winding formers in the CASPER I liquid helium bath cryostat at KIT. On the bottom left, a Hall-probe array with ten integrated probes is shown.

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WINDING CONCEPT II - SOLDERED TAPE STACK

Another approach is followed in parallel at KIT, where individually structured tape pieces are stacked and soldered alternating at the tape ends. The scheme is shown in Fig. 5. An advantage of this design is the scaling in length, only limited by the maximum individual tape piece length. Manufacturers are capable nowadays to create tape lengths of a few hundred meters, which sets the limit of the undulator length in this design. Furthermore, the amount of unused tape is minimized, which in a single-wound or coil-based design is needed for the current return. The exchange of single tape pieces in case of failure is also possible.

Soldered Joints

The most crucial part in this design are the solder joints. In HTS tapes, the superconductor is usually only deposited on one side of a Hastelloy®-tape, which mainly defines the geometry. For a lowest possible joint resistance the sides with the superconductor should face when forming the solder connection. This is naturally possible on one side of the stack, while on the other, the substrate sides would face each other, as shown in Fig. 5. To overcome this, an interwoven joint is needed, achieved by a small cut-out of half the tape width. The critical current of the original tape is already reduced to one third, due to the channel width of the meander structure, so that this cut-out does not limit it further. The overlapping joint area can be fabricated as large as needed, to achieve a small contact resistance. Furthermore, the tape ends are copper-plated on the joint area. An image of the structured individual tapes with and without copper-plated ends is shown in Fig. 6. A fabricated prototype stack with three tapes, i.e. with both facing joint and interwoven joint is also shown in Fig. 6. The interwoven joint of this stack was characterized in liquid nitrogen, at 77 K. It showed a joint resistance of 68 nΩ. The resistance is expected to improve further, when operated below 10 K as planned. An estimate of the heat load of a full undulator will be given in the following, where a cryostat system will be discussed.

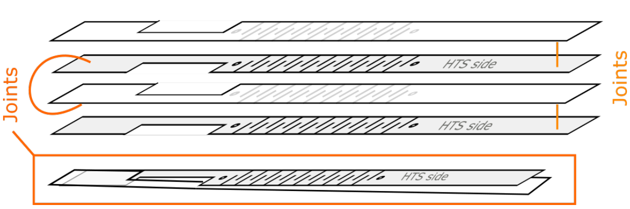

Figure 5: Schematics of the zig-zag soldered tape stack with both facing joints (on the right) and interwoven joints (on the left and bottom sketch).

CRYOSTAT SYSTEM

An advantage of HTS tapes is the relatively small loss in critical current when operated at $\lesssim$10 K compared to 4 K. As the cooling capacity of commercial cryo-coolers strongly increases with temperature, it is highly beneficial to allow the undulator to operate at temperatures above 4 K. The presented undulator design has several sources of heat input, which need to be dealt with and which might lead to an increase of the temperature during operation. Due to the small gap, the beam impedance resistive losses directly to the tape are relevant and are studied (compare [6]). They are expected to be in the order of a few milli-Watts [6] and therefore acceptable. Depending on the winding scheme, resistive losses need to be taken into account as well. An allowable resistive loss of 1 W was set, which is about the cooling capacity at 4 K for commercial cryo-coolers. For 2×30 tape joints in the case of the stacked and soldered design, at an operating current of 500 A, this corresponds to $\approx$ 70 nΩ per joint. In first tests this joint resistance could be achieved in a prototype stack as shown in Fig. 6. The resistance was measured at 77 K and is expected to improve further when cooling to below 10 K, thus, facilitating a cryogenic design using only a single state-of-the-art cryo-cooler.

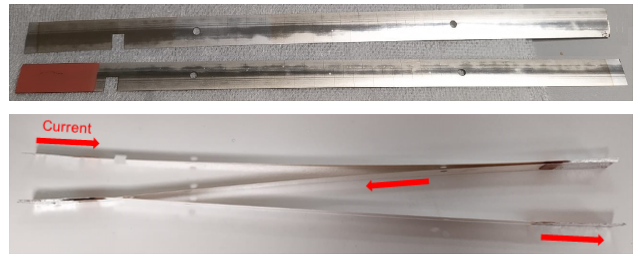

Figure 6: Top: Structured tape piece with a length of 25 cm and the copper-plated tape end. Bottom: tape stack from three HTS tapes, including both types of joints.

SUMMARY AND OUTLOOK

Two designs for laser-scribed meander-structured tapes are actively being developed at KIT. A joint-less single-wound winding former was presented in the past and a first prototype has been fabricated. A stacked design, where single tape pieces are soldered was also presented. First prototype stacks were fabricated and the joint resistance characterized. Both designs are foreseen to result in prototype undulators with 2×30 stacked tapes and a magnetic gap of 4 mm, achieving a nominal magnetic field, approaching 1 T. First operational tests are foreseen in the near future. Furthermore, a magnetic field measurement system was designed and is being fabricated, allowing to map the magnetic gap field B_y in the gap plane. Finally, heat load calculations are on-going to design a cryo-cooler-based cryostat system. Both, the heat input due to joint resistance and due to the beam impedance (see [6]) are being considered.

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