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INVESTIGATION OF BEAM IMPEDANCE AND HEAT LOAD IN A HIGH TEMPERATURE SUPERCONDUCTING UNDULATOR

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Abstract

The use of high temperature superconducting (HTS) materials can enhance the performance of superconducting undulators (SCU), which can later be implemented in free electron laser facilities, synchrotron storage rings and light sources. In particular, the short period < 10 mm undulators with narrow magnetic gap < 4 mm are relevant. One of the promising approaches considers a 10 cm meander-structured HTS tapes stacked one above the other. Then, the HTS tape is wound on the SCU. The idea of this jointless undulator has been proposed by, and is being further developed at KIT. Since minimizing the different sources of heat load is a critical issue for all SCUs, a detailed analysis of the impedance and heat load is required to meet the cryogenic system design. The dominant heat source is anticipated to be the resistive surface loss, which is one of the subjects of this study. Considering the complexity of the HTS tape, the impedance model includes the geometrical structure of the HTS tapes as well as the anomalous skin effect. The results of the numerical investigation performed by the help of the CST PS solver will be presented and discussed.

INTRODUCTION

Nowadays, the majority of the undulators installed in free electron laser facilities and synchrotron storage rings are based on permanent magnet technology. An important step was made towards superconducting undulators (SCUs) allowing for higher brilliance and wider spectral ranges [1]. One of the approaches considers meander-structured high-temperature superconducting (HTS) tapes stacked on top of each other [2, 3]. The new idea has been introduced and is being further developed at KIT (Karlsruhe, Germany): a jointless undulator that is wound from a single laser-scribed HTS tape [1, 4]. This concept is particularly advantageous for undulators with a short period < 10 mm and a narrow magnetic gap < 4 mm.

To increase the current density of the winding, the HTS tape contains no copper layers [1]. Instead, there is a thin silver layer on top of the HTS that interacts with the beam. To maximize the critical current the working temperature should be around 4 − 10 K.

HTS-SCU MODELS

The full model of the HTS SCU made of stainless steel and wound with a long HTS tape is shown in Fig. 1. This model is used to estimate the geometrical coupling impedance due to the entrance and exit sections of the undulator. The undulator model is 10 cm long, 6 cm wide, and 10 cm high. The gap between the magnets is 8 mm.

Each of the HTS tapes has a meander structure made by laser scribing and has a period length of ≈ 8 mm [1]. The current design considers that the laser-scribed sections are not seen by the beam, but in this study we will analyze both cases.

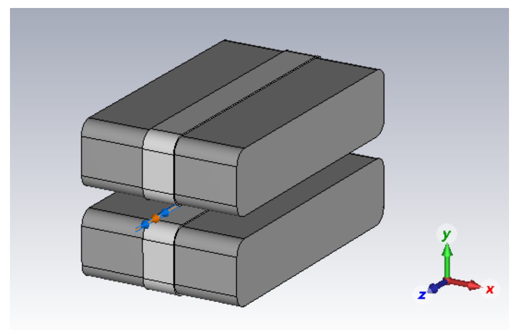

Figure 1: Full model of the HTS-SCU for CST PS simulations.

In this study, the nominal bunch length is 15 mm and the single charge $Q_{\text{bunch}} = 0.1$ nC. The bunch spectrum will cover a GHz-frequency region, so that the skin effect has to be considered. Because of the combination of high frequency and low operating temperature, the anomalous skin effect (ASE) plays an important role.

Figure 2 (left) shows a simplified model of the SCU which is based on two parallel plates and is used in the CST Particle Studio (CST PS) simulations to investigate the resistive wall (RW) impedance and heat load. On the right, the model of the laser-scribed HTS tape is shown. The various conductivities of stainless steel and silver used in CST PS simulations are given in Table 1, where $\sigma = 2.01 \times 10^9$ S/m is used as a nominal conductivity for the silver layer. In a first step, the model considers a single-layer HTS tape. In a second step, simulations are performed with a 30-layer HTS tape with a total thickness of 1.65 mm (multi-HTS model). Thus, the gap between the plates reduces to ≈ 5 mm.

Table 1: Material Conductivities Used in the Simulations

Material	**Conductivity, σ [S/m]**
Stainless steel 304	$2.06{\times}10^6$
Silver RRR = 30 - 200	$2.01{\times}10^9$ - $1.3{\times}10^{10}$

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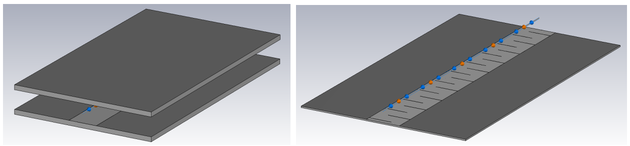

Figure 2: Left: Simplified parallel plate model of the HTS-SCU for resistive wake simulations. Right: Model of the laser-scribed HTS tape on top of the stainless steel core.

BEAM IMPEDANCE

The longitudinal geometrical and RW impedances for the 10 cm structure are shown in Fig. 3. The geometrical impedance at low frequencies is comparable to the one due to the resistive wall. However, the effect of geometrical impedance increases sharply at higher frequencies.

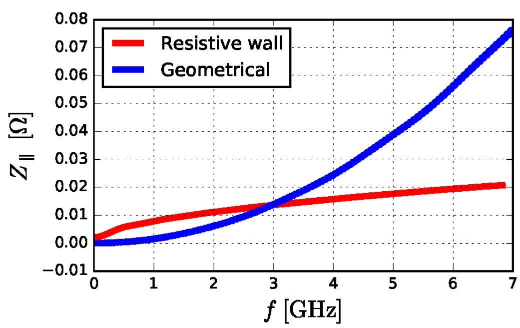

Figure 3: Longitudinal geometrical and resistive wall impedance computed with the models in Figs. 1 and 2, respectively. In the simulations, a smooth silver layer with nominal conductivity is considered.

Figure 4 shows the longitudinal RW impedance obtained for the smooth single silver layer in comparison to the model including the laser-scribed sections. The effect of the laser-scribed sections is negligible. For the multi-HTS model, the impedance increases due to the smaller vertical aperture. Overall, the effect of the scribing structure and multi-layered HTS is small and can be neglected for further investigations.

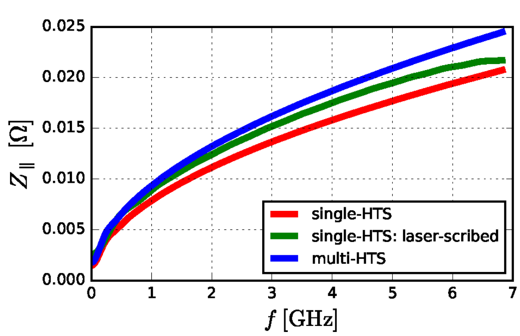

Figure 4: Longitudinal resistive wall impedance with and without laser-scribed sections and for a multi-layered HTS.

Figure 5 shows the resistive impedance when the anomalous skin effect and the magnetoresistive effect are considered for the silver layer. The magnetoresistance data of silver are taken from [5]. Furthermore, the following interpolation formula for the resistance in the case of ASE is used [6]:

$$R_s(\omega) = R_\infty (1 + 1.157\alpha^{-0.276}) \quad \text{for } \alpha \geqslant 3,$$

where $\alpha = 3\lambda^2/2\delta^2$ with the electron mean free path in silver λ, skin depth $\delta(\omega) = \sqrt{2/(\mu_r \mu_0 \sigma \omega)}$, vacuum permeability μ_0, relative magnetic permeability μ_r, angular frequency ω. The surface resistance in the limit of $\lambda \gg \delta(\omega)$, $\lambda \to \infty$ is given by

$$R_\infty(\omega) = \left(\frac{\sqrt{3}}{16\pi} \frac{\lambda}{\sigma} (\omega \mu_0)^2 \right)^{1/3}.$$

The magnetoresistance is an important effect, but it can be neglected with respect to ASE. The ASE tends to increase the RW impedance, especially at higher frequencies. The magnetic field strength assumed in the simulations is in the range 2.5 – 5 T, which corresponds to the anticipated field levels in the undulator. The electrical conductivity of the stainless steel (grade 304) is non-magnetic and is assumed to be temperature independent.

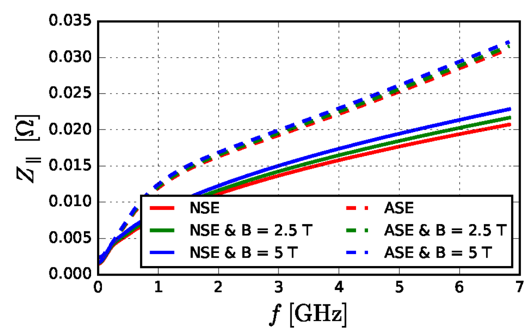

Figure 5: Longitudinal resistive wall impedance including ASE and magnetoresistance. NSE stands for normal skin effect.

HEAT LOAD RESULTS

The heat load due to resistive wall losses can be calculated as $P = N_\mathrm{b} f_\mathrm{rep} W_\mathrm{d}$, with the number of bunches in a train N_b, the repetition rate f_rep, and the deposited energy W_d on the undulator walls by a single electron bunch.

Figure 6 shows the loss power for one bunch due to the resistive losses. Since the silver layer is closer to the beam, the heat load in silver is higher than the one in stainless steel. The laser-scribed sections on the silver layer lead to the smaller effective surface, thus the losses are slightly smaller.

For the characterization of the material purity the residual-resistance ratio (RRR) = $\rho(300\mathrm{K})/\rho(4\mathrm{K})$ is used. Table 1 shows the corresponding silver conductivities for RRR = 30, 100, and 200. A lower RRR (or lower conductivity) results in a higher RW impedance and therefore a higher heat load.

Figure 7 shows the total bunch energy loss for the normal skin effect in comparison to ASE and magnetoresistance.

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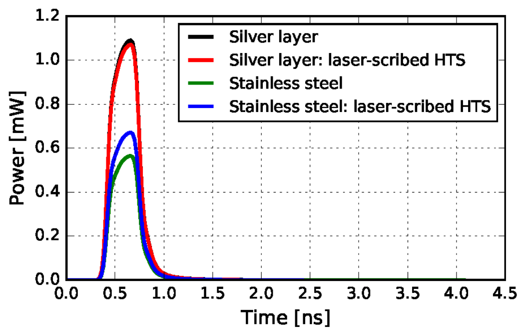

Figure 6: Resistive loss power in the silver layer and stainless steel for a single bunch excitation.

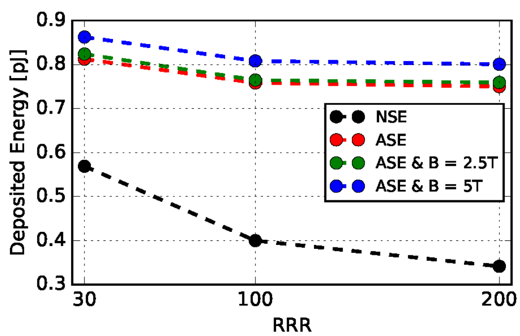

Figure 7: Total deposited thermal energy for a single bunch as a function of RRR taking into account the ASE and magnetoresistance.

The deposited energy due to ASE is 1.5 − 2 times higher, while the external magnetic field leads to additional few percents increase of the heat load.

Figure 8 shows the deposited thermal energy for the single-layer HTS tape in comparison to the 30 layers of HTS tape. As previously mentioned, the multi-HTS model results in a smaller vertical aperture, thus, leading to a higher heat load compared to the corresponding single-HTS case.

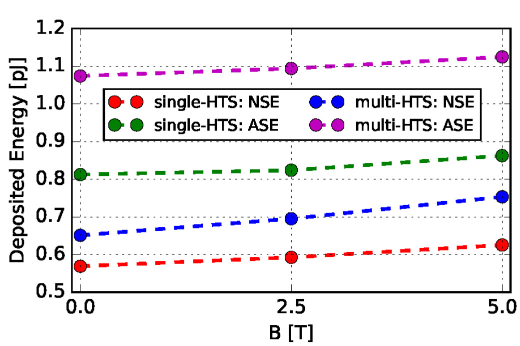

Figure 8: Thermal energy deposited by a single bunch as a function of the external magnetic field in the case of single and multiple HTS tapes.

Heat Load Estimation for Beam Operation

So far, the nominal electron bunch on the undulator axis was considered. Figure 9 shows the deposited energy in the case of the bunch offset in both x and y direction. The bunch shift is attributed to the wiggling. The simulations show that the heat load is highly sensitive to bunch parameters. Thus, the heat load can increase up to 5 times if the bunch is shifted by 4 mm in the x-direction.

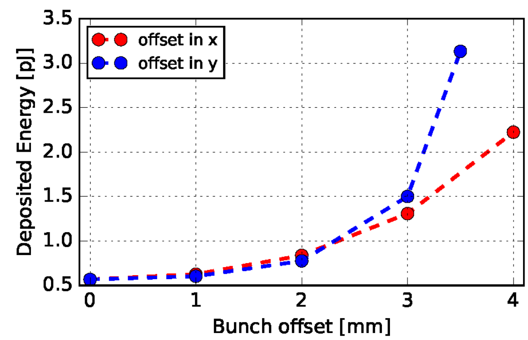

Figure 9: Total deposited energy in the case of a bunch offset.

Using the above results and considering a beam repetition rate f_{rep} = 2.7 MHz, the average heat load for a train of 184 bunches is in the range of less than 1 mW for the 10 cm undulator. This is rather small and can be handled easily by a standard cryogenic system. In the extreme case of 30 layers of HTS tape including ASE in the silver layer with RRR = 30 and 5 T magnetic field, for a bunch length of 5 mm, bunch charge of 0.3 nC, and a beam offset of 4 mm, the average power loss increases to 67 mW.

CONCLUSION

The heat load due to resistive wall losses has been numerically investigated with CST PS solver. The anomalous skin effect is found to be significant, while the magnetoresistance effect is less important for the purpose of heat load estimations. The effect of the laser-scribed pattern on the HTS tape can be neglected, while the application of multiple HTS tapes effectively narrows the gap, thus leading to a higher heat load. The beam current and its offset from the axis can significantly affect the heat load. Power losses can be reduced by using a higher RRR of silver inside the HTS tape. Nevertheless, the overall heat load of the device for the nominal operation parameters is quite small and remains in the range of a few mW.

ACKNOWLEDGEMENTS

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