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THERMAL AND MECHANICAL ANALYSES ON A VACUUM CHAMBER IN A COMPACT SUPERCONDUCTING UNDULATOR WITH HTS TAPES

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Abstract

Superconducting (SC) undulators composed of high temperature superconducting (HTS) tapes, which can be applied to compact light sources such as a table-top free-electron laser, are a part of research and development projects at Karlsruhe Institute of Technology (KIT). In order to minimize the beam heat loads in a cryostat including the compact SC planar undulator, a vacuum chamber (liner) positioned in the undulator gap is considered. In this study, we discuss the preliminary cryostat design based on a simple cooling concept with a cryocooler and report thermal and mechanical simulation results with the liner at cryogenic temperature.

INTRODUCTION

Based on the development of high-temperature superconducting (HTS) tapes, promising concepts and designs of superconducting (SC) insertion devices for compact light sources such as a table-top free-electron laser (FEL) have been proposed [1, 2]. An example is the development of an SC undulator (SCU) with second-generation HTS tapes for improving the critical current density and resultant magnetic field strength, which has been done at Karlsruhe Institute of Technology (KIT) [3, 4]. In comparison to typical type-II superconductors, the HTS tapes can allow relatively higher beam heat loads. Nevertheless, it would be beneficial to minimize the possible heat-load sources in a cryostat, like geometrical impedances and resistive wall heating (RWH), from the viewpoints of operation stability and cost efficiency. For this reason, we consider a vacuum chamber in the undulator gap, instead of an in-vacuum undulator scheme with technical challenges.

In this investigation, we introduce a conceptual design of the vacuum chamber (liner) and a cooling scheme with a cryogen-free cryocooler. A cryostat with a structure similar to the COLDDIAG (cold vacuum chamber for beam heat load diagnostics, which was also developed at KIT) having a cryocooler and thermal shields is considered for installation and assembly of the SCU with the liner [5-8]. Simulation results for optimal temperatures and mechanical properties at the liner are also reported.

CONCEPTUAL DESIGN OF A VACUUM CHAMBER

Figure 1 shows the quarter schematic of a cryostat having a cryocooler (in the COLDDIAG case, two-stage Gifford-McMahon type, model: SRDK-415D-F50H, manufacturer: Sumitomo Heavy Industries, Ltd.) and thermal radiation

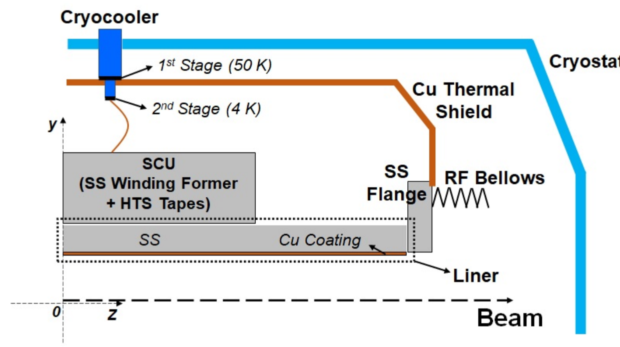

Figure 1: Schematic of a vacuum chamber (liner) positioned at the SC undulator gap in a cryostat.

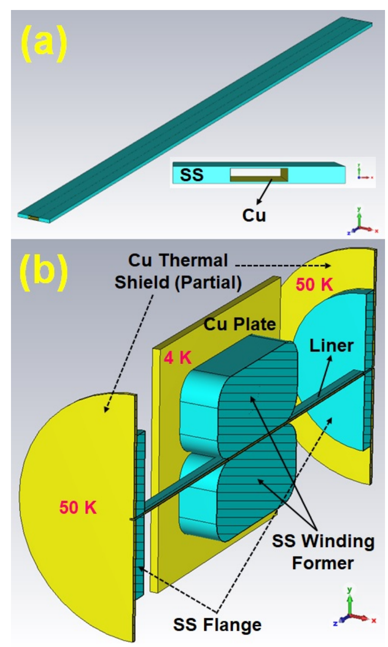

Figure 2: Modeling of (a) the liner and (b) its peripheral components for thermal and mechanical analyses.

shields made of copper (Cu). The SCU has a pair of stainless-steel (SS) winding formers with meander-structured HTS tapes, which has been tested at a liquid-helium (LHe) environment at KIT [9, 10]. As shown in Fig. 2(a), the SS liner has a simple rectangular structure based on the planar undulator, where Cu deposition at the inner surfaces is considered to reduce the image current from RWH. The Cu thickness of 10 μm is enough for low conductive heat intake (described in the following section), which is also longer than the skin depth of 3 μm at a typical RF frequency of 500 MHz. For the fabrication of the liner, the welding processes

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after each Cu coating in the upper and lower SS parts can be considered. Figure 2(b) shows a modeling of the liner and its peripheral components for simulations in the following section, which is also symmetric at the *y*-*z* plane (two Cu plates). The flanges and winding formers are thermally conducted from the shields and Cu plates connecting the 1^{st} stage (50 K) and 2^{nd} one (4 K) of the cryocooler, respectively. Especially, the two Cu plates are required for compensation of opposite thermal gradients in the SS winding formers. Furthermore, the formers should be contacted with the liner (directly or using straps) for more efficient cooling of the liner. Each flange and RF bellows (Fig. 1) at both ends of the liner should be designed to have identical apertures with the liner for keeping the beam vacuum space and minimizing the geometrical impedances like a step.

SIMULATION RESULTS

The CST Studio Suite® was used to estimate the thermal distribution and mechanical characteristics in the liner at cryogenic temperatures. The thermal simulations in a steady state were performed and then the results were imported for the mechanical analyses.

Thermal Analyses

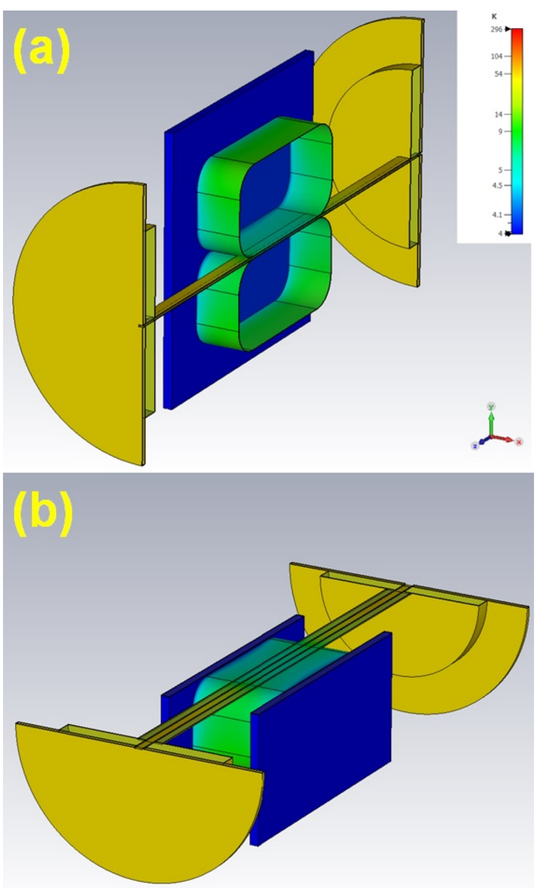

Figure 3: Temperature distributions in the liner and its peripheral components shown with cutting planes of (a) *y*-*z* and (b) *z*-*x*, respectively.

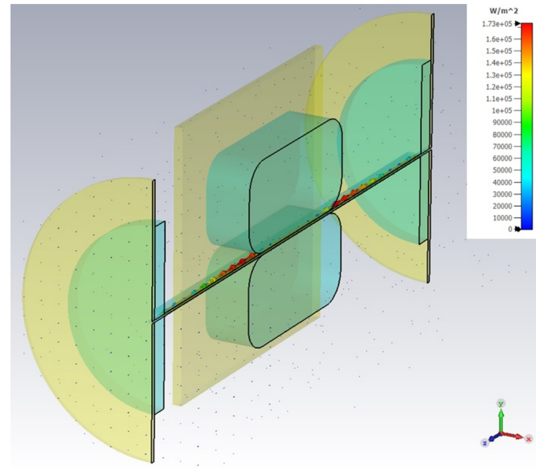

Figure 4: Distribution of heat flow density at the liner.

Figure 3 shows the temperature distribution in the liner and its peripheral components when 4 K and 50 K were applied to the Cu plates and the thermal shields, respectively. The temperatures at the winding former around the beam axis were maintained at approximately 5.5 K to 7.5 K. These values are sufficient for acceptable temperatures below 10 K for maximizing the critical currents of the HTS tapes with the outermost high-conductive silver (Ag) layers [4]. The temperature range of the liner was foreseen from ~5.5 K to 55 K for both SS component and 10 µm-thick Cu layer. From the temperature difference, the total heat intake by conduction in the liner with a length of 554 mm was analytically calculated to ~0.2 W. The distribution of heat flow density at the liner is also shown in Fig. 4.

Mechanical Analyses

Figure 5 shows the simulation results with a boundary condition of the fixed flanges (green color in the inset) without the bellows. The Von Mises stresses at the liner were almost uniform as ~1.2 GPa, which far exceeds the yield strength of around 575 MPa at 5 K for annealed SS and thus can lead to severe mechanical deformation [11]. The displacements at the liner in *z*-direction, which means thermal contraction in beam direction, were predicted to be within approximately ±300 µm.

Figure 6 shows the simulation results with a boundary condition of the free flanges with the bellows (Fig. 1). The maximum Von Mises stress at the liner was ~10 MPa, which are negligible, compared to the yield strength of SS. Even though the thermal contraction of the liner in beam direction is estimated to be within ±1.4 mm, it is acceptable with the use of the bellows.

SUMMARY AND OUTLOOK

We proposed a vacuum chamber (liner) in the SCU with HTS tapes in order to minimize the beam heat loads in the cryostat. A cryostat with a cryogen-free cryocooler and thermal raidation shields, like the COLDDIAG, can be a candidate for testing the SCU with the liner. The thermal

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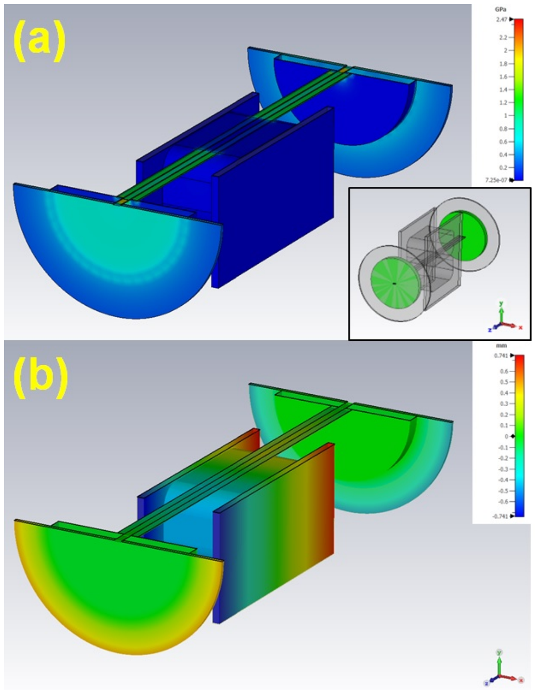

Figure 5: Distributions of (a) Von Mises stress and (b) displacement in z-direction with a boundary condition of the fixed liner ends, shown as the green color in the inset.

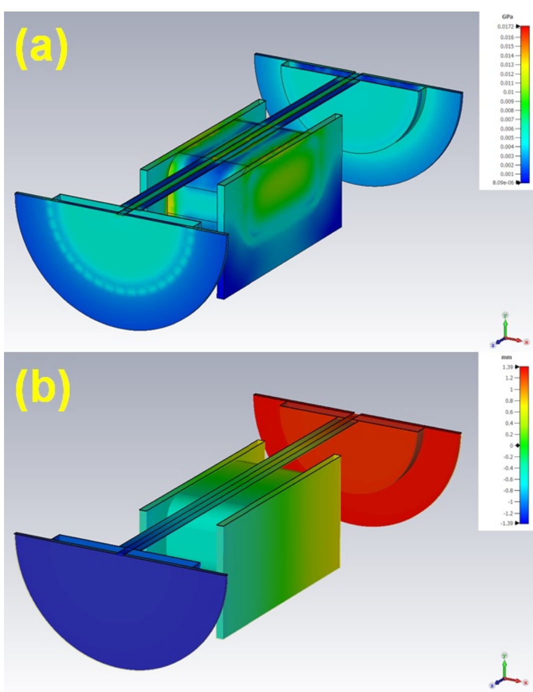

Figure 6: Distributions of (a) Von Mises stress and (b) displacement in z-direction with a boundary condition of the free liner ends.

simulation results indicate that the key technologies are simultaneous cooling with two Cu plates on both sides of the SCU winding former and another cooling of the liner center with the SS former for reducing the respect thermal gradient. These configurations are suitable for both the increase of critical current density at the SCU and the decrease of conductive heat intake at the liner. The utilization of bellows is essential for stable operation of the liner at cryogenic temperature, which was also proven through the estimation of mechanical stresses and thermal contraction in the cryostat.

The liner can be manufactured with machining of two near-nonmagnetic SS parts, conventional electroplating for micron-thick Cu deposition, and final welding. After fixing the design of all components including mechanical supports, possible diagnostic devices and so on, it will be able to calculate a total static-heat load in the cryostat. Such an estimation can affect the thermal budget from the heat capacity of the cryocooler and if required, the temperature rise at each stage of the cryocooler may be considered for cooling power margin against the static- and beam-heat loads.

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