

THERMAL SIMULATIONS FOR THE MULTI-LAYER COATING MODEL

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Abstract

Thermal simulations for the multi-layer coating model has been developed based on previous work of a finite difference thermal feedback code. RF field-attenuation formula for the multi-layer coating model has also been included. The temperature distribution along different superconducting layers under applied magnetic fields has been calculated with various superconducting material parameters.

INTRODUCTION

Technology of fabricating superconducting cavity with Nb has been developed for several decades. Recently two 9-cell cavities made from large grain Nb reached 45MV/m at DESY which has increased the high gradient record [1]. The room for further gradient increase is limited by the theoretical boundary of Nb 60MV/m, because the thermodynamic critical field of Nb is about 200mT [2]. An idea to enhance the RF breakdown field of superconducting cavities by multilayered nanoscale coating is proposed by A. Gurevich in 2006 [3]. The simple model consists of an alternating superconducting layer (S) and an insulator layer (I) that both deposited on the Nb bulk. Based on this model, the formulae that describes the RF electromagnetic field attenuation for each layer has been derived from a calculation with the Maxwell equations and the London equation [4].

The thermal feedback code is developed to calculate the thermal performance of Nb bulk with pit-like defect [5]. Different from the traditional Nb bulk, in the multilayer structure the Nb bulk is covered by the insulator layer I and the alternating superconducting layer S . Both of the two layers are thin and have the different thermal conductivity from the Nb. By the modification of the previous code, the new program can be used for multilayer structure. On the other hand, with the help of the electromagnetic field attenuation formulae the magnetic field in each layer is easy to calculate, and then the temperature distribution of the multilayer model in certain magnetic field can be revealed by the new code.

THERMAL FEEDBACK CODE FOR MULTILAYER COATING MODEL

To simplify the calculation, the multilayer coating model in this code is adopted to be a cylinder disk which consists of three layers. From top to bottom, it is alternating superconducting layer, insulator layer and Nb layer as shown in Fig. 1. In this case, this model is an axial symmetry structure. So it is only need to calculate the temperature distribution

on the cross-section, and the problem is reduced to solving 2D finite difference thermal equation. On the top surface of the model, the magnetic field is assumed to be parallel to the layers. Since the magnetic field can penetrate from the top layer to the bottom layer, to neglect the dielectric loss in the middle layer, the heat will generate in both top layer and bottom layer. The 2K liquid He is assumed to surround the bottom and brim of the multilayer disk to export heat from the disk. When the heat export e-

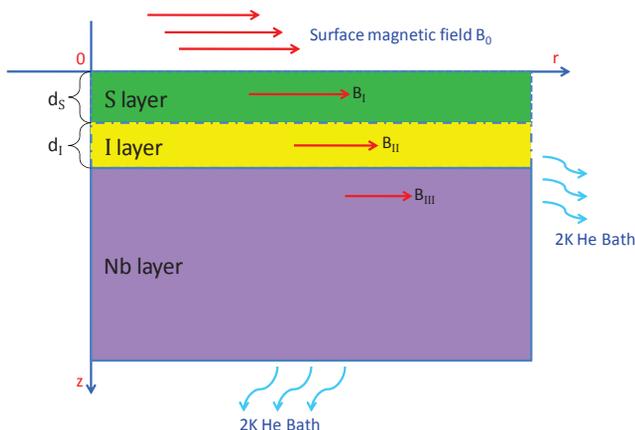


Figure 1: The multilayer model for thermal simulation. Along with positive direction of z axis, it is S layer, I layer and Nb layer successively. It should be emphasized here, that the temperature distribution figures below are plotted as an inversion of this model.

quals to the heat generation, the thermal system will get into a balance state, and then the temperature distribution on the cross-section can be calculated. The thermal conductivity of the Nb layer is temperature dependent. The thermal conductivity of the coating layers is constant in consideration of the nanoscale coating thickness. The heat transport between the disk and the liquid He depends on the Kapitza conductance. The mesh is important in this code, for the two coating layers are much thinner than the Nb layer. The ‘linear increase mesh’ method is used in vertical direction, in that way the vertical dimension of the mesh will increase in constant proportion to reduce the total number of the elements, to make a balance between the calculation accuracy and the running time.

MAGNETIC FIELDS IN THE MODEL

Before the thermal calculation, the magnetic field attenuation relation in each layer should be got, which can be used to calculate the heat generation of the multilayer mod-

el. Thanks to Takayuki Kubo's job, the magnetic field formulae in each layer can be described as bellow [6]

$$B_I = B_0 \frac{\lambda_1 \cosh \frac{d_S - x}{\lambda_1} + (\lambda_2 + d_I) \sinh \frac{d_S - x}{\lambda_1}}{\lambda_1 \cosh \frac{d_S}{\lambda_1} + (\lambda_2 + d_I) \sinh \frac{d_S}{\lambda_1}}, \quad (1)$$

$$B_{II} = B_0 \frac{\lambda_1}{\lambda_1 \cosh \frac{d_S}{\lambda_1} + (\lambda_2 + d_I) \sinh \frac{d_S}{\lambda_1}}, \quad (2)$$

$$B_{III} = B_0 \frac{\lambda_1 e^{-x - d_S - d_I}}{\lambda_1 \cosh \frac{d_S}{\lambda_1} + (\lambda_2 + d_I) \sinh \frac{d_S}{\lambda_1}}. \quad (3)$$

Here, B_0 is magnetic field applied on the surface of the model. B_I , B_{II} , and B_{III} are magnetic fields in layer S , I , and Nb respectively. λ_1 and λ_2 are London penetration depth for S layer and Nb layer. d_S and d_I are thickness of the coating layer S and I . The materials used for S layer is assumed to be Type II superconductor $\lambda_1 \gg \xi_1$, and the S layer thickness is larger than the coherence length $d_S \gg \xi_1$. Note that the S layer of our model is not necessarily a thin film, hence the discussion below can be applied to any S layer with arbitrary thickness $d_S \gg \xi_1$ [6].

As the description above, B_{II} is the magnetic field in the middle layer which is a constant along the depth. At the same time, B_{II} is still the field applied on the surface of the Nb layer that caused the heat generation on the Nb surface. For convenience, B_{II} can be indicated as $B_{II} = \beta \cdot B_0$, here

$$\beta = \frac{B_{II}}{B_0} = \frac{\lambda_1}{\lambda_1 \cosh \frac{d_S}{\lambda_1} + (\lambda_2 + d_I) \sinh \frac{d_S}{\lambda_1}} \quad (4)$$

is defined as magnetic field attenuation factor. Since the heat of the superconductor surface is caused by Ohm loss, the heat generation on the S layer and Nb layer can be described as $Q_s = \frac{1}{2} R_s H_0^2$, $Q_s = \frac{1}{2} R_s (\beta H_0)^2$, where $R_s = R_{BCS} + R_{res}$ (BCS resistance) + R_{res} (residual resistance). It can be found that β is important in our simulation. For different materials, to take their character parameters into the equation (4), β can be computed, and then be inputted into our code for the thermal calculation.

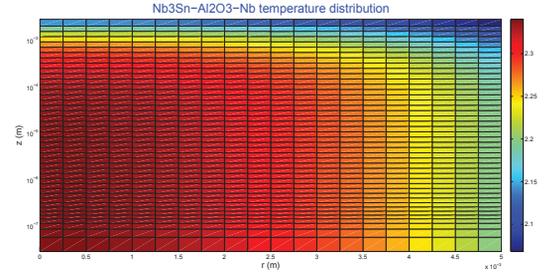
SIMULATION RESULTS FOR THE MODEL

Model with thin Coating Thickness

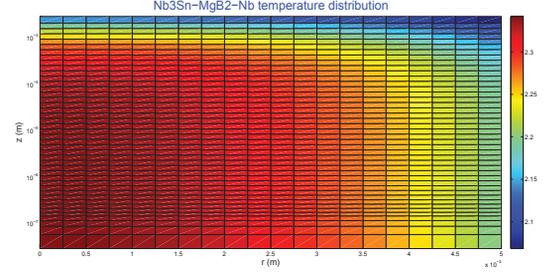
In the simulation, Nb_3Sn is used as the materials for the S layer, hence $\lambda_1 = \lambda_{Nb_3Sn} = 60nm$. The London penetration depth of Nb is 50nm, so $\lambda_2 = \lambda_{Nb} = 50nm$ [6]. To make a comparison, there two kind of materials used for I layer, Al_2O_3 and MgB_2 . The thermal conductivity of Al_2O_3 and MgB_2 are 1W/m-K and 0.07W/m-K respectively [7, 8]. In the first case, the thickness of S layer and I layer is chosen as 60nm and 90nm ($d_S = 60nm$, $d_I = 90nm$). Take λ_1 , λ_2 , d_S and d_I into the equation(4), then we can get $\beta = 0.2334$. The surface magnetic field is used as 150mT. The temperature distribution for this case is shown in Fig. 2. Since the coating thickness is only nanoscale, the vertical axis is plotted in log coordinate for

06 Material studies

J. Basic R&D Other materials (multilayer, MgB2, . . .)



a) temperature distribution of $Nb_3Sn-Al_2O_3-Nb$ model
 $d_S = 60nm$, $d_I = 90nm$, $K_{Al_2O_3} = 1W/m-K$



b) temperature distribution of $Nb_3Sn-MgB_2-Nb$ model
 $d_S = 60nm$, $d_I = 90nm$, $K_{Al_2O_3} = 0.07W/m-K$

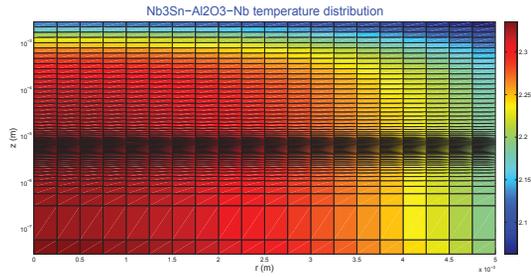
Figure 2: Two temperature distribution with different I layer materials. The highest temperature of two model are same as 2.34K. The thickness of the whole model is 3mm, and the disk radius is 5mm. For a better view, the vertical axis is shown in log coordinate.

a clear view of the distribution. From the comparison of the two results, the highest temperature on the surface is the same as 2.34K in the two pictures, though the thermal conductivity of Al_2O_3 is much larger than the MgB_2 .

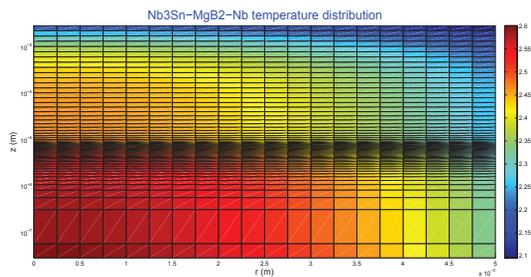
Model with Thick I Layer

In the second case, we can increase the thickness of the coating layer. For the convenience of comparison the thickness of S layer is fixed, and then the thickness of I layer is increased into micronscale, such as 8um. Because of the change of thickness, β will decrease to 0.0063. Fig. 3 shows the new calculation results. The highest temperature of $Nb_3Sn-MgB_2-Nb$ model is 2.6K, which is larger than 2.3K the temperature of the model with Al_2O_3 I layer. Compare to the case one, with the increase of I layer thickness, the temperature of $Nb_3Sn-MgB_2-Nb$ model rises quickly. On the other hand, the temperature of $Nb_3Sn-Al_2O_3-Nb$ model maintains at the same value 2.34K as before, due to the high thermal conductivity of I layer. Here it can be found that, with the increase of I layer thickness, the thermal conductivity of I layer will play a more important part in the temperature rise. In other words, when the thickness is in micronscale the low thermal conductivity will induce a quick temperature rise under the same surface magnetic field. It is easy to understand,

this conclusion is also useful to the \mathcal{S} layer. For the thermal performance, the thinner the coating thickness is, the better the multilayer model will be.



a) temperature distribution of $Nb_3Sn-Al_2O_3-Nb$ model
 $d_S = 60nm$, $d_I = 8um$, $K_{Al_2O_3} = 1W/m-K$



b) temperature distribution of $Nb_3Sn-MgB_2-Nb$ model
 $d_S = 60nm$, $d_I = 8um$, $K_{Al_2O_3} = 0.07W/m-K$

Figure 3: Two temperature distribution with thick \mathcal{I} layer. When the thickness of \mathcal{I} layer is $8um$, due to the low thermal conductivity of MgB_2 , the highest temperature of $Nb_3Sn-MgB_2-Nb$ model reaches $2.6K$, while that of $Nb_3Sn-Al_2O_3-Nb$ model still maintains at $2.34K$.

Model with low Thermal Conductivity

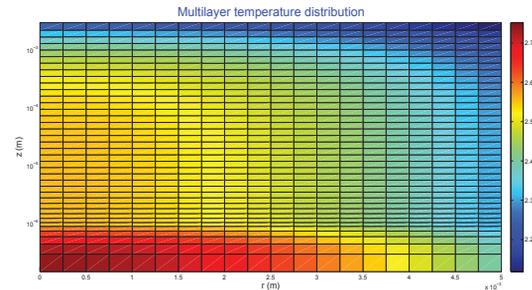
In the third case, we should forget the real material's parameters and just consider this model in theory. The Nb_3Sn s parameters are also used in \mathcal{S} layer, but the thickness is increased to $300nm$. In \mathcal{I} layer, the thickness is $600nm$ and the thermal conductivity is $0.005 W/m-K$. Here β is computed to 0.0011 . As shown in Fig. 4, the temperature on the surface is up to $2.75K$. Further increase the thickness of layer or decrease the thermal conductivity of layer, the top layer will lose superconducting which we called quench. So it should be taken a comprehensive consideration in choosing coating thickness and thermal conductivity.

SUMMARY

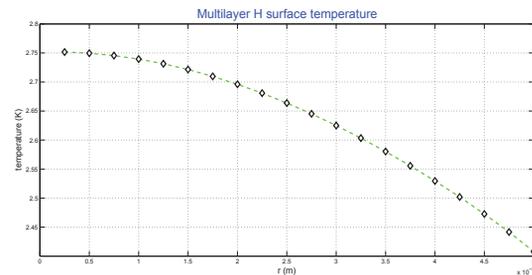
The 2D thermal feedback code introduced in this paper is a tool to analysis the thermal performance of the multilayer coating model. The coating thickness and the thermal conductivity of the coating layer are important parameters in calculating the temperature rise of the model. If the

ISBN 978-3-95450-143-4

coating thickness is near microscale and the thermal conductivity is low, the temperature rise on the \mathcal{S} layer will be a limitation to achieve the high surface magnetic field. For the real multilayer coating structure does not have only one \mathcal{S} layer or \mathcal{I} layer, the thermal simulation for more complex model need to be developed in the future.



a) temperature distribution
 $d_S = 300nm$, $d_I = 600nm$, $K_{I-layer} = 0.005W/m-K$



b) magnetic field temperature distribution

Figure 4: Temperature distribution with low thermal conductivity. The highest temperature reaches to $2.75K$, as a result of low thermal conductivity of \mathcal{I} layer.

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