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Thermal analysis of UHV beam tube of SIS100 for FAIR

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We have studied the effect of eddy current joule loss on the beam tube of SIS100 superconducting magnet. In order to keep the ultra high vacuum (UHV) in the range of 10^{-12} mbar inside beam tube, we design beam tube as an extended cryopump. The design optimization procedures enable us to reduce the loss down to 11.2 % of total dynamic loss of SIS100 superconducting magnet. Appropriate cooling pipe position is also simulated to find optimal temperature profile which satisfies our design criterion. Design activities and related numerical simulation results are presented.

INTRODUCTION

Among the many components in superconducting magnet for accelerator, the beam tube is located in the region of highest magnetic field. During the operation of the magnet, we expect induced current on the beam tube which can be a cause of additional mechanical forces, joule heating and stray magnetic field. These phenomena disturb field quality inside beam tube and initiate instability during magnet operation. In order to maintain the high performance of the SIS100 magnet, extensive studies have been conducted on the mechanical stability of the superconducting cables, eddy current loss on beam tube and the effect of iron yoke as well as magnetic permeability of materials at low temperature [1-4].

The major role of beam tube for FAIR SIS100 is a boundary as a cryo-cooled UHV chamber. The beam tube for FAIR is designed to work as an extended cryopump and expected to have the vacuum range of 10^{-12} mbar. To maintain such high vacuum, lowest temperature on the surface of the beam tube should be lower than 5 K and highest temperature should be lower than ~ 15 K. The beam tube needs mechanical stability against pressure differences, low thermal contraction and electromagnetic forces due to induced current. The joule heating can disturb temperature and quality of vacuum inside beam tube. The present paper deals mainly with the thermal effect on the beam tube due to eddy current.

As can be seen figure 1, the beam tube is designed elliptic shape and the cooling pipe is mounted on it. The ribs also will be installed for reinforcement of mechanical strength. The cooling pipe itself is designed to have zero net magnet flux to avoid electrical closed loop. However after attaching on the beam tube, it may increase effective conductivity along the possible eddy current path. Although the ribs have only 3 mm thickness, it is expected to be effective to increase eddy current especially at the both

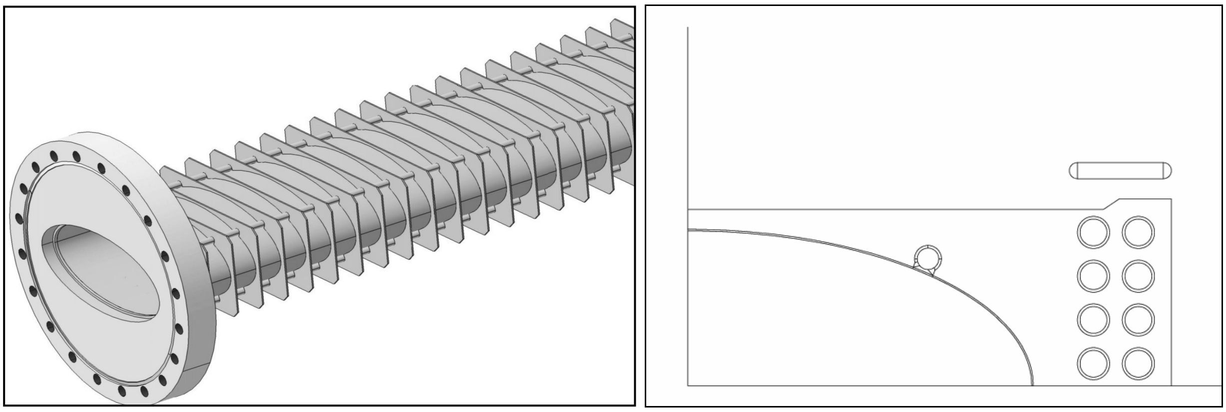

Figure 1 The beam tube for SIS100 magnet. The length is 2976 mm and wall thickness 0.3 mm, aperture 128 mm × 58 mm, rib thickness 3 mm.

end aperture of beam tube. We report the design of beam tube with optimized cooling pipe position and thermal effect during magnet operation. The effort to reduce electrical link between each three components with insulation layer of Al_2O_3 is also discussed.

ANALYSIS MODEL AND MAGNET OPERATION CONDITION

The major axis length of beam tube is 128.6 mm, minor axis 58.6 mm. And full length is 2976 mm with thickness 0.3 mm. The stainless steel P506 produced by company Böhler is considered for the beam tube and its resistivity for this calculation is 5.0×10^{-7} Ωm.

The calculation condition is based on the SIS100 operation scenario [5]. We choose the scenario, 2C, of magnet operation which generate magnetic field shown in figure2. It is expected highest joule loss. With given current excitation based on scenario 2C, we can generate corresponding magnetic field in figure 2. And this periodic operation of field is applied into beam tube to simulate induce joule heating.

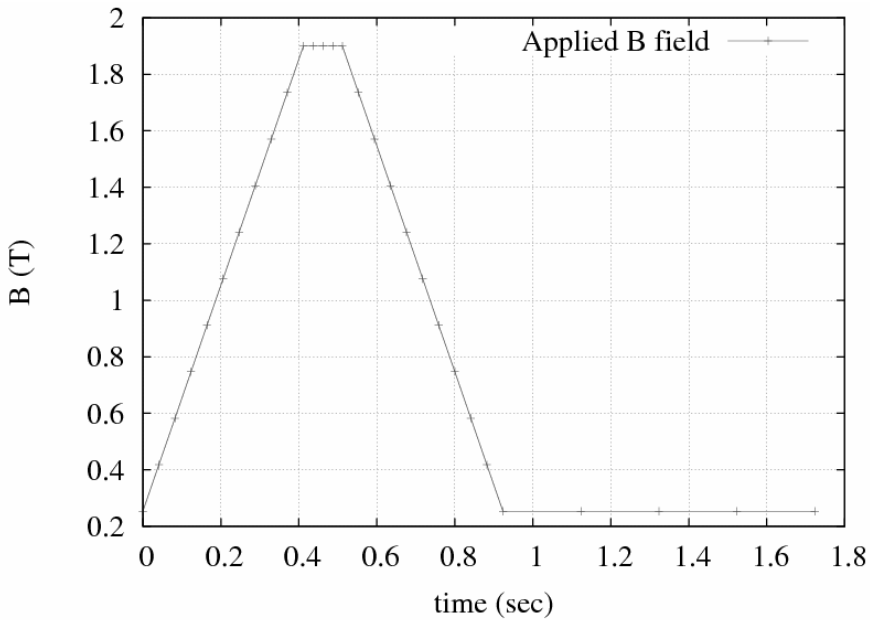

Figure 2. SIS100 operation condition for this analysis. Maximum field reach 1.9 T and minimum 0.25 T at the center. The ramping rate is 4 T/sec.

Figure 2 shows designed magnetic induction |B| at the center of the magnet as a function of time which has to reach maximum 1.9 T, minimum 0.253 T with ramping rate 4 T/sec and high field flat top duration 0.1 sec, low field flat bottom duration 0.8 sec.

We choose commercial code, ANSYS, for finite element (FE) analysis. The simulation is carried out on electro-magnetic behavior with thermal effect so called coupled analysis. In order to find temperature profile on beam tube, we designed firstly 2D finite element model of SIS100 contained beam tube, coils and iron with corresponding physical values. The time dependent magnetic field based on the scenario *2C* was generated through controlling excitation current on coils. The eddy current due to the magnetic field variation is a cause of joule heating and the heat also can be a cause of temperature rising on beam tube. All this simulation was performed simultaneously with controlling the current at the coils.

$$\vec{B}(\vec{r},t) = \nabla \times \vec{A}(\vec{r},t) \tag{1}$$

In order to calculate the effect of eddy current around the end of beam tube, we need to build 3D FE model for the analysis. Instead of using iron inside model we generate artificial magnetic field directory with vector potential. It allows us of ease to build FE model of beam tube and surrounded vacuum space instead of using magnetic edge element and avoid making full model of magnet system into ANSYS. Using the relation Eq. (1), we could calculate appropriate vector potential and distributed on the outer surface of the FE model as a boundary condition.

INDUCED JOULE HEATING AND TEMPERATURE PROFILE

We excite coil of FE model based on the operation scenario above up to the cycle number of ~ 60th. The generated magnetic field is applied on the beam tube. The eddy current density and induced joule heat was calculated as a function of time. The figure 3 shows heat generation due to the induced current at the first stage of ramping period. The maximum loss reaches to 8.3 watt/m.

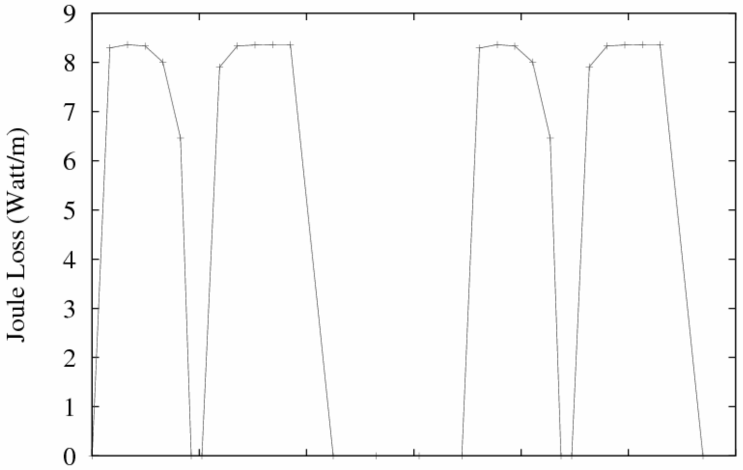

Figure 3. Joule loss due to the induced current on the beam tube at the first ramping. The continues cycle increase temperature gradually and start to saturate around 50th of cycle.

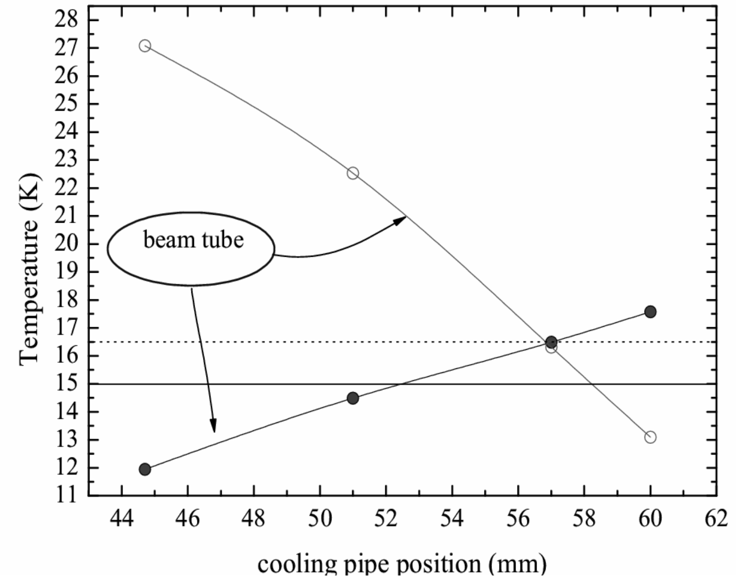

Figure 4. The temperature on the top and lateral side of the beam tube as a function of cooling pipe position. The optimal position close to our criterion is bound at x = 57 mm.

The direct contact between beam tube and cooling pipe enables us to secure the 4.5 K region where the temperature is lower than our criterion on the surface of beam tube. However on the top and bottom side of the beam tube is expected to have highest temperature as well as lateral end side of beam tube. Therefore, we calculate temperature profile along the elliptic circumference of the beam tube and check maximum temperature with respect to 4 different cooling pipe positions in order to find optimal position of cooling pipe. The maximum temperature is summarized in figure 4. The solid circles show temperature at the lateral side of beam tube and the open circles are top and bottom of it. As the distance of cooling pipe from center of beam tube is increased, the temperature of the lateral side is decreased while that of top and bottom surface is increased. We expect optimal temperature profile at two curve crossing point of 57 mm from the center of the beam tube. The maximum and minimum temperatures are found to be 16.4 K and 4.5 K and it is marginally close to our design criterion.

With the cooling pipe position, 57 mm, the temperature profile of the beam tube is examined as a function of ramping cycles shown in figure 5. The region of cooling pipe has 4.5 K due to the forced flow of supercritical He. After ~50th, the highest temperature starts to saturate to 16.4 K and shows same value at top and lateral side of beam tube. There is rapid temperature increase as a function of cycle around lateral side, > 57 mm, because of highest eddy current density induced at that region. The maximum eddy current density of the top side is 2580 A/m^2 and corresponding joule heat is 4.47 watt/m^3. The lateral side has 5.8×10^5 A/m and loss of 1.7×10^5 watt/m^3.

The ribs for mechanical reinforcement also affect electrical resistance on longitudinal and transversal direction of current path on beam tube. The entire beam tube with cooling pipe shows the peak power loss of 8.12 watt/m during ramping up the magnetic field. After including the ribs into our calculation model, the joule loss is increased about 10 % higher than that of without ribs. Longitudinal direction of the eddy current is major current flow in the middle of beam tube. Therefore the ribs may not generate considerable loss in that region. However, the ribs at the end-aperture of beam tube region are good conductor to transversal direction current. We found that the joule loss of the ribs at the beam-aperture were much higher than that of ribs located the other part of beam tube.

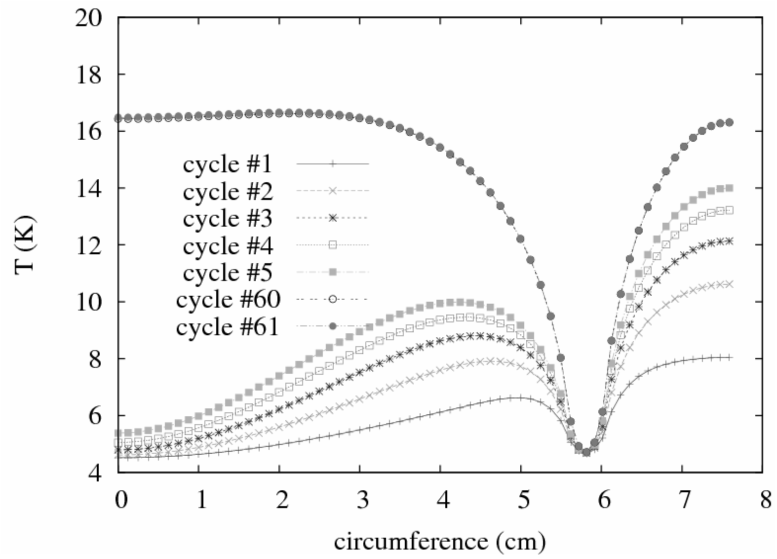

Figure 5. Temperature profile of beam tube up to 61th cycle of 2C scenario operation with cooling pipe position at x = 57 mm from the center of beam tube.

Figure 6 shows the calculation result with alternative model of new cooling pipe which has Al_2O_3 electrical insulation layer. The purpose of the insulation layer is to reduce the electric conduction between beam tube and cooling pipe. The Al_2O_3 coated cooling pipe is placed on two different positions for simulation; one is located at the same as on the beam tube shown in figure 1 and another is attached at the edge of the ribs. The insulation layer reduces the joule loss effectively down to 25 % lower than without insulation layer. Even we calculate the loss with triangular cycles which considered extreme operation scenario; the maximum temperature is lower than our design criterion. In addition, in the case of the cooling pipe located at the edge of the ribs also shows lower joule loss than without insulation layer. And highest temperature is lower than our criterion. However, the lowest temperature is higher than 10 K after several numbers of cycles. And the profile is shown in figure 6 (b). This result shows that the direct contact between beam tube and cooling pipe with insulation layer is one of the most effective cooling schemes for SIS100 beam tube.

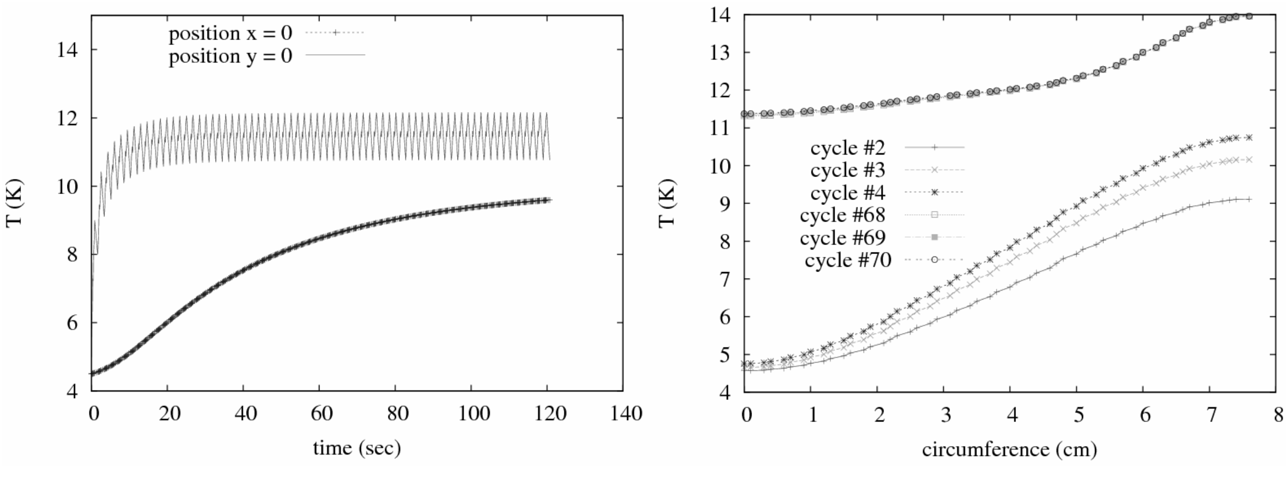

Figure 6 The cooling pipe is covered by Al_20_3 layer for electric insulation. (a) Temperature increase with respect to the cycling of the magnet. The temperature at y = 0 is converged to 11.5 K with 1.5 K amplitude oscillation due to close cooling and heat source. Cooling pipe is position on the beam tube at x = 57mm from center of beam tube. (b) shows temperature profile on the beam tube with cooling pipe positioned at the edge of the ribs.

SUMMARY

The thermal effect of eddy current on the beam tube has been simulated for cryogenic design study. The appropriate cooling pipe position has been defined through FE calculation under the one of the heaviest scenario of SIS100 magnet operation. We confirmed temperature distribution on the beam tube which is considered critical parameter for keeping the UHV. The highest temperature on the beam tube has been found to be 16 K and lowest 4.5 K due to the direct contact between cooling pipe and beam tube. We can simply estimate total joule loss with the number of whole SIS100 dipole magnet at FIAR, 108 × 12.4 W = 1340 W. It is considered 15 % of the total dynamic heat load of the FAIR. The effect of the electrical insulation layer on the cooling pipe also has been simulated to compare the joule loss. This layer enables us to reduce the loss effectively. Further feasibility study on this insulation layer would clarify convenient cryogenic application for the beam tube cooling. The losses are summarized at table 1.

Table 1. The eddy current loss of beam tube with cooling pipe positioned at 57 mm form the center of the beam tube. The magnet operation condition is based on 2C scenario of SIS100.

	• Beam-Tube	• Beam Tube • Cooling pipe	• Beam Tube • Cooling pipe • Ribs	• Beam-Tube • Cooling pipe with Al_2O_3 coated layer • Ribs
Average Loss	7.21 watt	11.52 watt	12.4 watt	9.26 watt
Average Loss per unit length	2.4 watt/m	3.84 watt/m	4.13 watt/m	3.08 watt/m

REFERENCES

1. Bobrov, E. S., High-Cycle Fatigue and Fracture Mechanics Evaluations of the Conductor for the Fast Cycling SIS100 Synchrotron, GSI Technical Report (2006) 1-76.
2. Gersem, H. D., Koch, S., Weiland, T., Eddy-Current Losses in the Beam Tube of the FAIR SIS-100 Dipole Magnet, GSI Technical Report (2007) 1-18.
3. Gersem, H. D., Koch, S., Weiland, T., Magnetodynamic Formulation Resolving Eddy-current Effects in the Yoke and the Superconductive Cable of the FIAR Dipole Magnets, Proceeding of ICAP, Chamonix, France (2006) 90-95.
4. Nikolay, M., Alexander, K., Sergey, P., Final Design Report On SIS100 curved magnet, Budker Institute of Nuclear Physics (2007).
5. FAIR Technical Design Report, GSI Spring (2008).