TRANSIENT ELECTROMAGNETIC ANALYSIS AND THERMAL DESIGN ON THE MAGNET OF 3-GeV SYNCHROTRON

M. Abe, S. Tounosu, Power & Industrial Systems R&D Lab., Hitachi Ltd., Hitachi-shi, 319-1221,
Y. Chida, K. Nakamura, T. Watanabe, Hitachi works, Hitachi Ltd., Hitachi-shi, 317-8511, Japan
N. Tani, T. Takayanagi, JAEA, Tokai-mura, Ibaraki 319-1195, Japan
T. Adachi, KEK, Tsukuba-shi, 305-0801, Japan

Abstract

We used a coupling method of 3D electromagnetic and thermal analysis for 3-GeV synchrotron magnets. The accuracy of the analysis was confirmed by tests on the R&D magnets. The magnets were designed to operate at 25 Hz and heat generations were of great concerns. We calculated the losses due to eddy currents and iron losses, and they were included in thermal analyses. The eddy current losses were the major heating up sources and slits were effective to reduce them. In the magnet designs, the slit arrangements were optimized to decrease temperature rises.

INTRODUCTION

Japan Proton Accelerator Research Complex is composed of 400-MeV linac, 3-GeV synchrotron and 50-GeV synchrotron [1]. Its construction is almost finishing, under collaboration between JAEA and KEK. The 3-GeV synchrotron is operated at frequency of 25Hz. In designs, the heat-up of the magnet was of great concern. Magnets are made from coils, laminated electric steel sheets (iron core), insulation material between the sheets and stainless steel (SS) end plates. Excess temperature rise (over 150 degree) would damage the adhesive resin at the core end area. In order to mitigate the temperature rise, we optimised slits arrangements on the core and conductor cooling method, using a design method consist of 3D electromagnetic (EM) analysis and thermal analysis.

Heat generations due to AC operation occur in 4 reasons. They are due to following four causes,

(1) eddy currents in the sheets flowing along the sheet surfaces,
(2) eddy currents on the SS end plates,
(3) iron losses due to hysteresis and eddy currents in the sheets flowing in the thin cross sections,
(4) Joule losses on the conductors.

The causes (1) to (3) were taken into accounts in all magnet designs and the last one was only on bump magnet designs [2], because of Cu bar conductors. The causes (1) and (2) were found to be major causes of the temperature rise. The iron cores of the magnets are made of 0.5mm thick electrical steel sheets. As far as the magnetic force lines are along the sheets, little eddy current can flow. On the end areas, the force lines flow through the sheets and generate intense eddy currents.

3D EM dynamic analysis and thermal analysis were necessary to calculate the losses and temperature distribution. The former was done by EMSolution [4] and the latter was done by ANSYS with basic material constants. Our method was confirmed with experimental tests of R&D magnets [3].

The following describes the method of the analyses and practical applications of the magnet designs.

COMPUTATIONAL METHOD

The heat generations were calculated in 3D dynamic EM analysis. The hysteresis loss is determined using experimentally obtained table, which describes the iron losses as a function of the time averaged magnetic field strength and the amplitude of magnetic field oscillation in the core. The method is based on finite element (FE) method of EM analysis by EMSolution and thermal analysis by ANSYS.

Finite Element Model

Schematic description of quadrupole magnet (QM) and bending magnet (BM) are shown in Fig. 1. First of all, we applied the method on the R&D magnets. In order to carry out the analysis effectively, we used flexible mesh generation and symmetric conditions. The mesh sizes were varied according to electromagnetic characteristics. The symmetric conditions reduced FE size by 1/16 (QM) and 1/8 (BM). Fig. 2 shows the model of QM. Large size meshes were produced in air region. The same FE models were used in both EM and thermal analyses.

Material constants of the iron cores are listed in Table 1. No current in laminated direction in the cores (insulating in beam direction) was assumed. Heat generation in each FE calculated by the EM analysis was input into the thermal analysis.

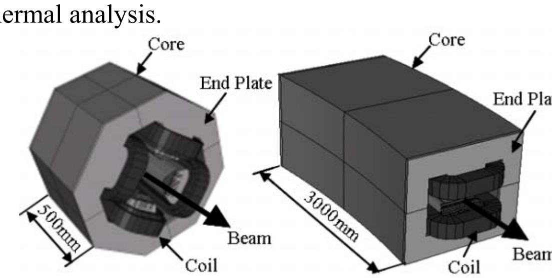


Figure 1: Rough sketches of quadrupole (left) and bending magnet (right)

The thermal conductivities are determined from those of air, insulating resin and the steel sheets with packing factor of 98%. To the laminated direction, the heat conducts through the sheets and the resin or air. On the end area, the sheets are pasted with the resin and the conductivity is 5.4W/mK, but it is 1.26W/mK without resin on the other core area.

Heat dissipates from surfaces of the magnet. Heat transfer was calculated assuming natural convection on vertical plate [5] and emissivity 0.9 on a painted magnetic surface [6]. Total heat transfer coefficient was calculated as 14W/Km^{2}., which is valid as far as the surface temperature rise is less than 100K. Using these constants, thermal analyses were done.

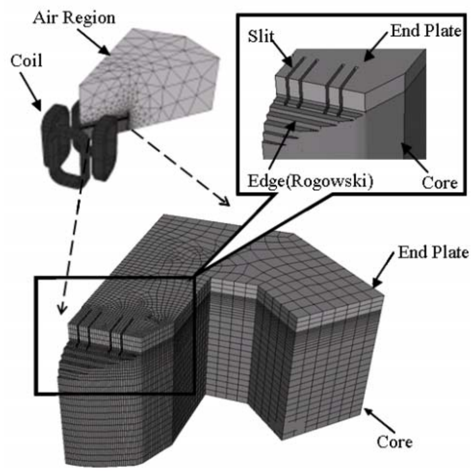


Figure 2: Finite element 1/16 model for EM analysis of QM magnet including air & coils region (top left), Magnet core (bottom), Detail of end area (top right).

Table 1: Material constants

Parts		Resistivity (Ωm)	Thermal conductivity (W/mK)
Core	Laminate direction	Infinite	5.4 or 1.26
	Other direction	2.8×10^{-7}	36.8
End plate		7.0×10^{-7}	14.6

TEST ANALYSES ON R&D MAGNETS

Coil currents were DC biased AC, or sum of currents I_{DC} and I_{AC}. Test conditions are as Table 2.

Fig. 3 shows the centre magnetic field strength of the BM and eddy current heat generation in the 1/8 model. Rapid magnetic field response was calculated. However, it took 0.7 s for heat generation to reach steady state level. Applied current frequency was 26.8 Hz, while the heat generation varied with 53.6 Hz.

Our concerns were steady state temperature rises. We averaged the last 2 cycles (4 peaks) as for steady state heat generation. Other than the eddy current heat generations as listed (1) and (2) in introduction, there were iron losses in the core. We referred the experimentally obtained iron loss for each mesh. The loss was experimentally obtained at 25 Hz, so the loss was extrapolated to the experimental frequency assuming proportional to frequency.

Table 2: Current on R&D Magnets

Magnet	Turn	IDC(A)	IAC(A)	Frequency (Hz)
QM	32	900	520	28.1
BM	36	1200	520	26.8

The calculated heat generations in test conditions are summarized in Table 3. Roughly 50 to 75% heat is due to eddy currents. Since the currents are localized around end region, the ratio between eddy current to iron losses density reaches 1000 to 1. i

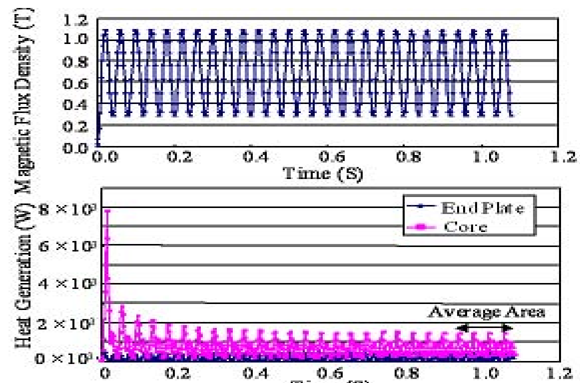


Figure 3: Magnetic field and eddy current heat generation

Table 3: Heat generations (kW) in R&D magnets

Magnet	Frequency (Hz)	Eddy current	Iron loss	Total
QM	28.1	3.49	1.12	4.61
BM	26.8	1.30	1.20	2.50

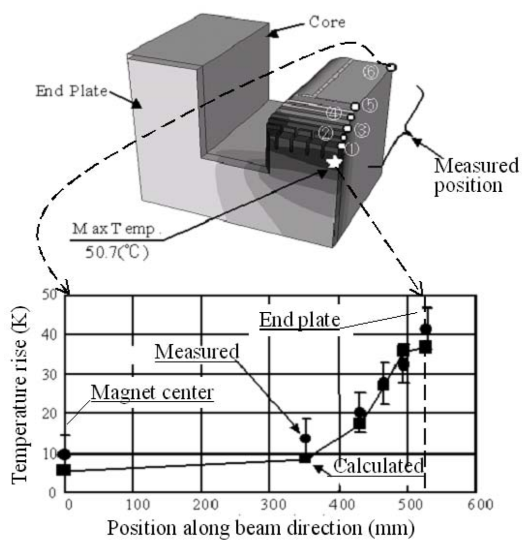


Figure 4: Calculated and measured temperature distributions of the BM. Top shows the distribution in grey scale and bottom shows it along centre l ne

Fig.4 shows calculated temperature distribution and a comparison between the calculated and the measured temperature rises for BM. The room temperature was 7.7 degrees and coil was 30 degrees, to which temperatures, heat dissipated from iron core surface. Maximum measured temperature was 50.7degrees at foot of the end plate centre slit (No. 1 point). At top of the end plate (No. 2 point), it was 41.7 degrees. Points No. 3 to 6 were on the iron core and the temperature went down from end to the centre (No. 6 point). The eddy currents became dense at the end region including the end plate. This was a reason why end region had high temperature rise.

The test calculation was also carried out on the QM, which had higher temperature rise than the BM. The highest temperature measured was 100.3 degrees, and calculated one was 96.2 degrees at the same point.

The calculated temperature rises were well agreed with measured ones. We decided to apply the method on the magnet designs to evaluate the temperature rises.

APPLICATION ON MAGNET DESIGNS

The EM analyses and thermal designs of the magnets on 3-GeV synchrotron were done. The slits arrangements were optimized. Fig. 5 compares the temperature distributions before and after slits optimization. Additional slits were designed to lower the temperature from 147 down to 101 degrees. This arrangement was necessary because calculated eddy current was dense not only on the end-top area but also at end-corner area.

Fig. 6 shows the reduction of heat generation due to the slit optimization at 25 Hz (I_{DC}=858.5, I_{AC}=515.5A) operation. Each figure has two plots. They are for end plate and iron core. Eddy currents are induced by dI/dt, and the heat generations have 50 Hz component. Optimization of the slits arrangements clearly decreased the heat generation.

The large permeability makes eddy currents duration long in the core. They build-up in dI/dt>0 phase and vanish rapidly in dI/dt<0 phase. This is the reason why heat generation of core dI/dt<0 phase is small

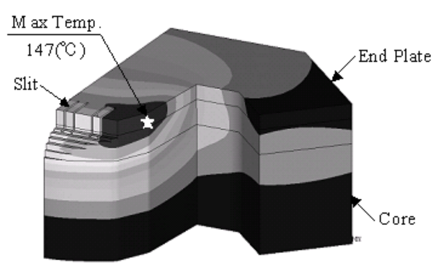


Figure 5-1: Before optimization

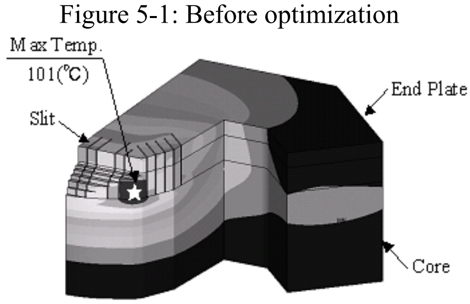
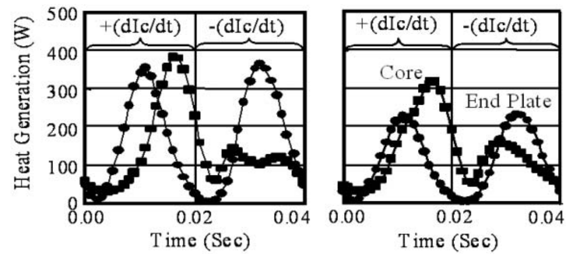


Figure 5-2: After optimization

Figure 5: QM magnet temperature distributions in steady state 25 Hz operation.

Fig. 7 plots transient temperature rises measured in BM at points on end plate and iron core. The lines are calculated steady state temperatures. The measured temperatures rose in a day and reached roughly the calculated temperatures. We concluded that thermal designs were successfully completed.



Before optimization After optimization

Figure 6: Comparison the eddy current heat generations between those before and after optimization.

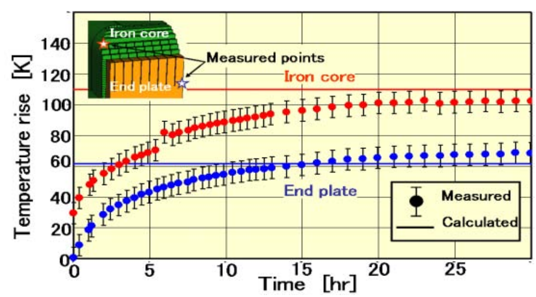


Figure 7: Transient temperature rises of BM at 25Hz

CONCLUSION

The J-PARC 3-GeV synchrotron operates at 25Hz repetition and heat-up of magnets were of great concern in magnet designs. A method to evaluate temperature rises of magnets was developed using 3D transient EM and thermal analyses. We calculated the losses due to eddy currents and iron losses, and they were input into thermal analyses, for magnet designs to avoid the heat-ups.

The validity of the analyses was confirmed by R&D magnets test data that the temperature rises were well calculated. The eddy current losses were the major heat sources and slits were effective to reduce them. In the magnet designs, the slit arrangements were optimized to lower temperature rises. The magnets are now under operation.

ACKNOWLEDHEMENTS

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