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The eddy current induced in the pulsed bump magnet for the CSNS/RCS injection

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Abstract: The injecton pulsed bending bump magnets of Rapid Cycling Synchrotron (RCS) in China Spallation Neutron Source (CSNS) consist of four horizontal bending (BH) magnets and four vertical bending (BV) magnets. The BH magnets are operated at a repetition rate of 25 Hz and are excited with a trapezoid rectangle waveform with about 1.6 milliseconds duration. The eddy current is induced in BH magnets and in the end plates it is expected to be large, so the heat generation is of our great concern. In this paper, the eddy current loss of the BH magnet has been investigated and calculated by using a coupling method of 3D electromagnetic and thermal analysis. The accuracy of the analysis is confirmed by testing the prototype BH magnet. The end plate temperature of the BH magnet provided with slit cuts has been decreased obviously and met the requirements.

Key words: eddy current, BH magnet, injection, CSNS/RCS

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1 Introduction

The CSNS accelerator consists of an 80 MeV H^-linac and a rapid cycling synchrotron (RCS) of 1.6 GeV. It will be operated at a 25 Hz rate. The RCS accumulates protons via H^- stripping injection. The injection of the RCS takes place in a 9 m long straight section, which contains four shift magnets (BC) to form a horizontal orbit bump, eight symmetrically placed dynamic bump magnets (BH&BV) for the phase space painting in both the horizontal and the vertical planes, two septum magnets and two strippers as shown in Fig. 1.

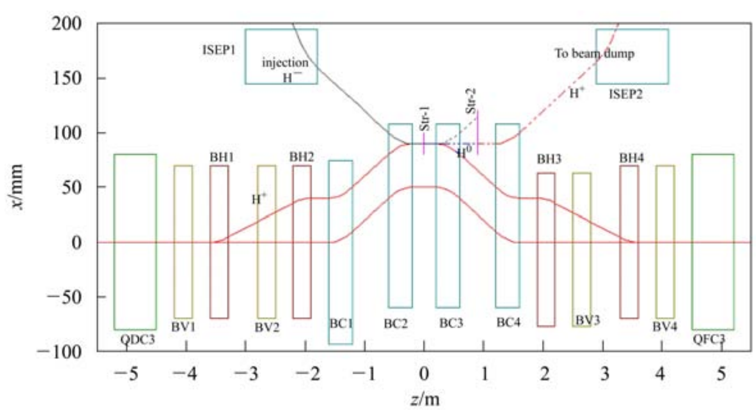

Fig. 1. The component layout of the injection.

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In order to create a dynamic orbit bump in the injection process, the BH magnet should shift the circulating beam horizontally for the painting injection. So the BH magnets must form a magnetic field in 1 millisecond, keep the top of field 50 microseconds and drop the field between 500 microseconds and 700 microseconds. In addition, the synchrotron is operated with a rapid cycle of 25 Hz and it is expected that the pulsed field will induce eddy currents in the magnet components, such as the iron core, the end plate and the coil conductor and the heat generation is of our great concern. This paper will deal with eddy current effects in the end plates of the BH magnet. The assembly of the prototype BH magnet is show in Fig. 2.

The prototype BH magnet has used silicon steel laminations with each being 0.15 mm in thickness for the iron core to reduce the amount of eddy current [1] and to cut the path of the eddy current in the end plates of the BH magnet. The slit cuts are made as shown in Fig. 3. The eddy current loss and temperature distribution have been calculated by using 3D OPERA electromagnetic analysis and thermal analysis. The results are checked with experimental measurement of the prototype BH magnet. Parameters of the prototype BH magnet are shown in Table 1.

Fig. 2. The assembly of the prototype BH magnet.

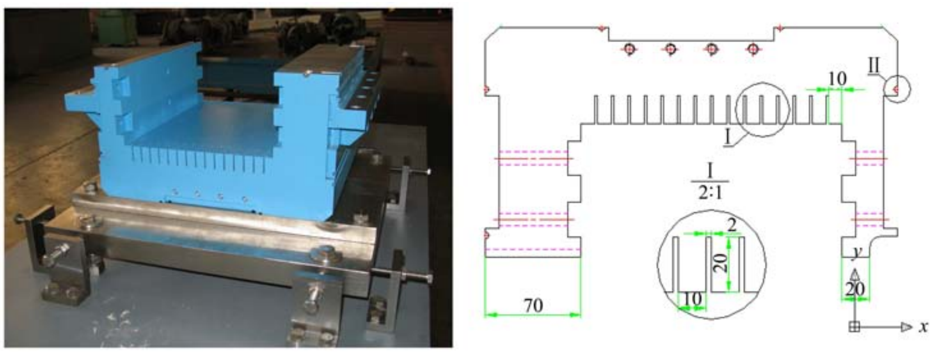

Fig. 3. The slit cuts in the end plates of the lower half core.

Table 1. The parameters of the prototype BH magnet.

Max. field/T	0.2313
structure	W-frame
effective length of magnet/m	0.3
beam aperture(H/V)/mm	140/170
peak current/A	18000
peak voltage/kV	3
turns of the coil	2
rise time of field/ms	1
top time of field/μs	50
drop time of field/μs	Prog. 500–700
lamination thickness/mm	0.15

2 Analysis

According to the Maxwell equations, the variational $\vec{B}$ can induce variational $\vec{E}$ and $\vec{j}=\sigma\vec{E}$, so there is an eddy current induced in the BH magnet components, such as the iron core, the end plate and the coil conductor. The eddy current is expected to be large, so heat generation is of our great concern. In order to reduce the eddy current in the core, the prototype BH magnet core has used silicon steel laminations with each being 0.15 mm in thickness. As the thickness of a piece of silicon steel is so small and the resistance of the loop of eddy current in the z-direction of the core is very large, the eddy current loss of the core is reduced and meets the requirments [2]. The eddy current effect of the coil conductor can make the magnet not work normally and destroy the distribution of the magnetic field. To reduce the temperature caused by the eddy current in the coil, according to the international experiment [3], water cooling is the best method for the coil. The prototype BH magnet copper coil uses special water-cooled configuration, according to which the coil is perfor-

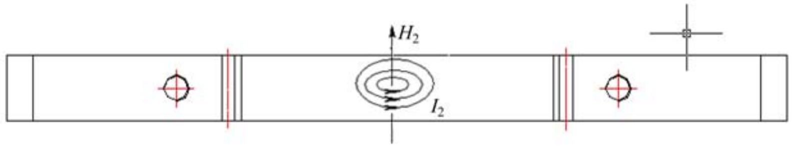

Fig. 4. The path of eddy current in the planform of the end plate.

ated in the middle of the copper plate to form the water-cooled channels. The temperature rise of the coil is low. To reduce the eddy current loss in the end plates, the slit cuts are made to cut the path of the eddy current. The path of eddy current in the planform of the end plate is shown in Fig. 4. In this paper, it emphasizes the analysis of the eddy current in the end plates.

3 Computational method and results

3.1 Two-dimensional model

To analyze the eddy current loss at the end plates of the magnet, the two-dimensional model [4] has been used, which assumes that the time dependent external field is expressed by:

$$\vec{H}_{\rm ext}=\vec{\hat{H}}_{\rm ext}{\rm e}^{{\rm i}\omega t}.$$

When the magnetic field perpendicular to a plate, say the y-componet, is dominant, an eddy current field can be treated two-dimensionally. The fundamental equations describing eddy currents are as follows:

$$\begin{aligned}\nabla\times\vec{E}&=-\frac{\partial\vec{B}}{\partial t},\\ \nabla\times\vec{H}&=\vec{j},\\ \vec{j}&=\sigma\vec{E},\end{aligned}$$

where $\vec{H}$ and $\vec{E}$ are the magnetic and electric field strength, respectively. $\vec{B}$ is the magnetic flux density and $\vec{j}$ is the current density, μ and σ are the magnetic permeability and electric conductivity, respectively. Supposing the eddy current field is sufficiently smaller than the external field $\vec{\hat{H}}_{\rm ext}$, we can obtain an equation in the plate:

$$\frac{\partial^2 \upsilon}{\partial x^2}+\frac{\partial^2 \upsilon}{\partial y^2}=k\hat{H}_{\rm ext}.$$

Here the $k={\rm i}\omega\sigma\mu$. Then the above equation is solved numerically in terms of an equivalent difference equation. The $H_{\rm ext}$ is calculated at each mesh point by using the ELEKTRA results, the eddy current is:

$$\vec{j}_{\rm eddy}=\nabla\times\vec{\upsilon}.$$

The eddy current loss in the end plates of BH magnet can be computed with the eddy current density $j_{\rm eddy}$.

3.2 3D electromagnetic and thermal analyses

The heat generation was calculated by 3D-OPERA analysis. We used flexible mesh generation and symmetric conditions to carry out the analysis effectively. The mesh sizes varied according to the electromagnetic characteristics. By using symmetric conditions, the 1/4 model of BH magnet was constructed and simulated as shown in Fig. 5. The end plate thermal conductivity was 14.6 W/mK and no current in laminated direction in the cores was assumed. Heat generation in each finite element calculated by 3D-OPEAR ELEKTRA [5] analysing $j_{\rm eddy}$ was input into the OPERA thermal analysis. Using the conductivity, thermal analysis has been done. Fig. 6 shows the calculation result of the losses calculated by the electromagnetic field analysis code of OPERA\ELEKTRA and the eddy currents in the end plates with and without slit cuts are compared. It can be seen that the eddy current loss in the end plates with slit cuts has decreased obviously. The distribution of the temperature in the end plates is shown in Fig. 7. The max temperature in the end plates with slit cuts is 35 ℃, while without the slit

Table 2. The eddy current loss and temperature of the end plate of BH model.

	mean eddy current loss/W	Max. temperature/℃
with no slit cut	196	65
with slit cuts	76.25	35

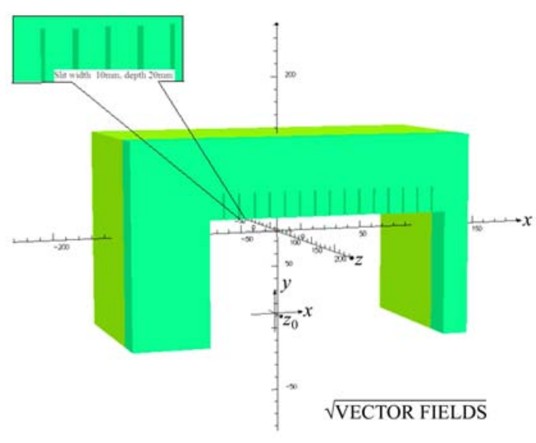

Fig. 5. The 1/4 BH magnet finite element model.

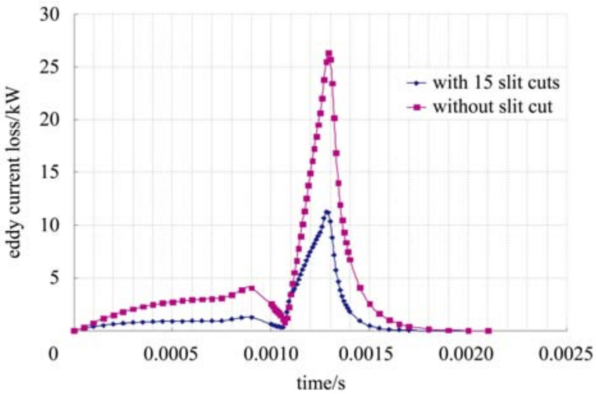

Fig. 6. The calculated results of the eddy current losses.

cuts, the max temperature is 65 ℃. The results of the thermal analysis are shown in Table 2.

3.3 The distribution of the temperature in the end plate with slit cuts

According to Table 2, it can be seen that the eddy current loss in the end plates with slit cuts has decreased obviously. Using the same method of 3D-OPERA analysis, the end plate distribution of the temperature with different slit cuts has been calculated.

The distribution of the temperature in the end plates is shown in Fig. 8. The max temperature in the end plates with 15 slit cuts is 35 ℃, the slit width is 10 mm and the silt depth is 20 mm. When there are 9 slit cuts, each of the slit width is 20 mm and its slit depth is 20 mm and the max temperature is 53 ℃. In Fig. 9, it is the distribution of the temperature in the end plates with the same sized slit cuts, the slit width is 10 mm and the slit depth is 20 mm, but the number of slit cuts is different. The max temperature with 14 slit cuts is 42 ℃, while the max temperature with 15 slit cuts is 35 ℃.

In conclusion, the distribution of the temperature in the end plates involves the size and number of slit cuts in the end plate. The larger the size and the less the number of the slit cuts, the higher the max temperature in the end plate.

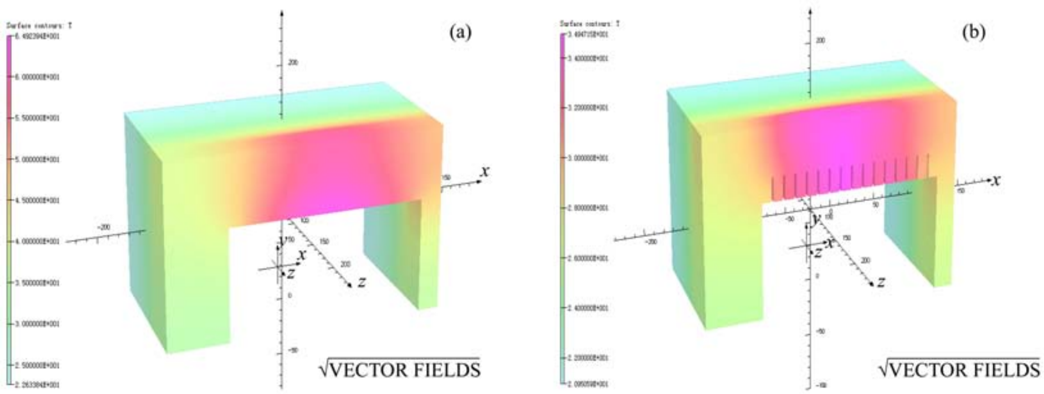

Fig. 7. The distribution of the temperature in the end plates. (a) The end plate without slit cut; (b) The end plate with 15 slit cuts.

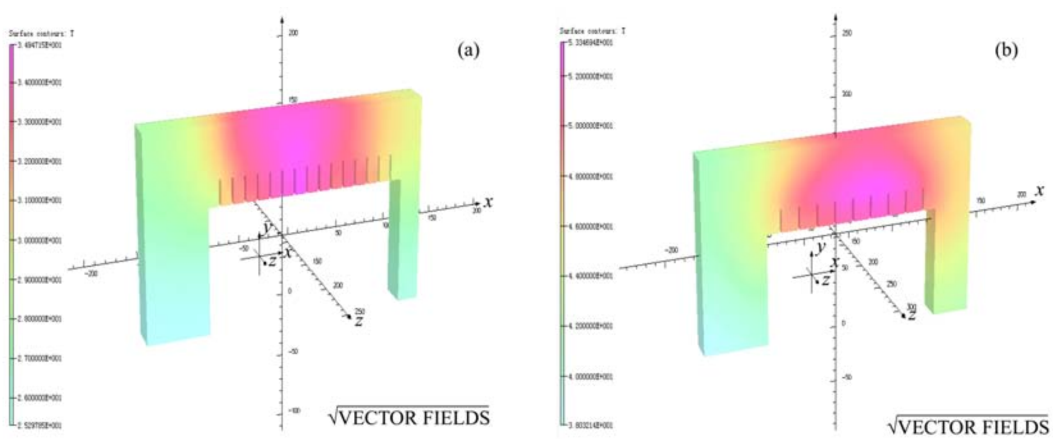

Fig. 8. The distribution of the temperature in the end plates. (a) The end plate with thin slit cuts; (b) The end plate with wide slit cuts.

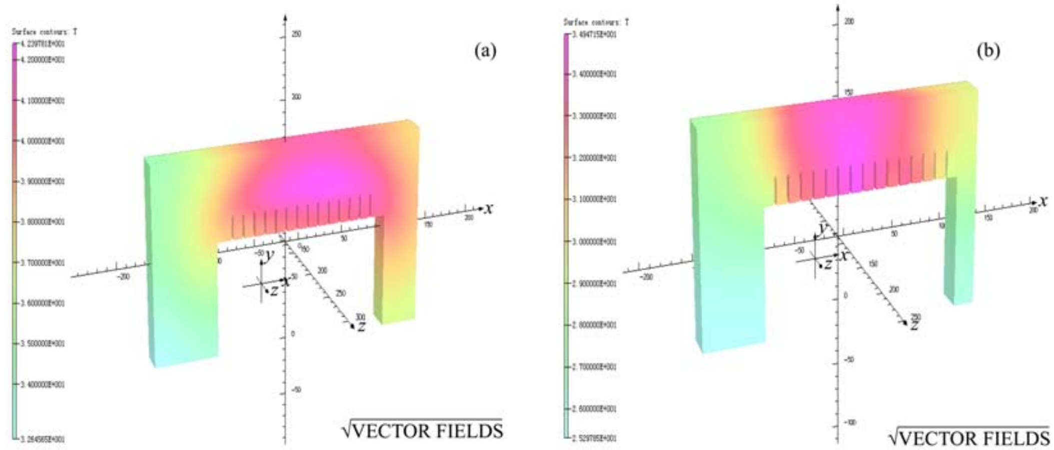

Fig. 9. The distribution of the temperature in the end plates. (a) The end plate with 14 slit cuts; (b) The end plate with 15 slit cuts.

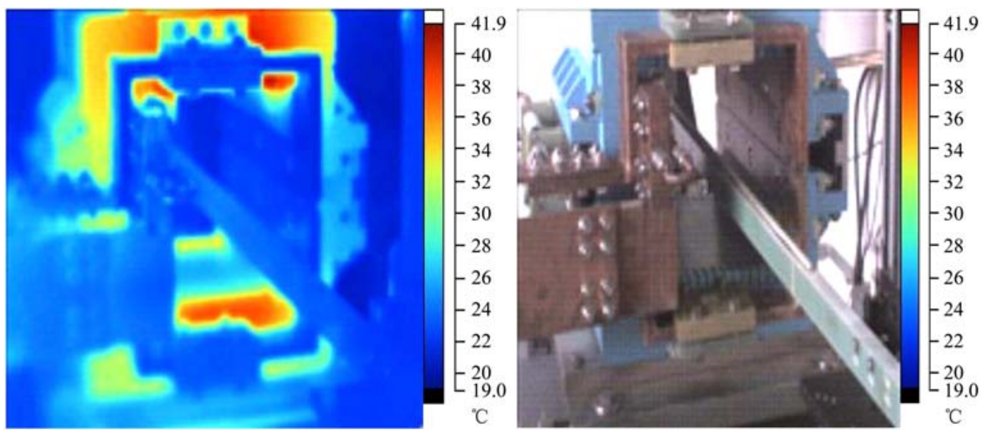

Fig. 10. The measurement of temperature in the end plates.

4 Experimental results and discussion

4.1 Test analyses of the BH magnet

After the assembly of the prototype BH magnet was finished, the temperature distribution in the end plates was measured with a Thermal Imager. The magnet was excited with the pulsed current of 25 Hz, which has a trapezoid rectangle waveform of 1.6 milliseconds duration and 1.8 kA peak current. After 8 hours' testing, the max temperature in the end plates was 41.9 ℃. The distribution of the temperature in the end plates is shown in Fig. 10.

4.2 The differences between the computational analysis and the prototype magnet measurement

The temperature distribution is almost consistent with the prediction of the computational analysis. The calculated max temperature is slightly smaller than the measurement. The possible reason is that the boundary condition and the assumable condition of the model are different from the actual ones. However, this method gives a good calculation for the eddy current effect investigation.

5 The optimize structure of the BH magnet end plate

After the assembly of the prototype BH magnet, the important experiments have been done. The relative magnetic field of the BH magnet was measured using the long search coil (Fig. 11). The long search coil needs the center point of the magnetic field to demarcate the position, so there must be a center point in the end plate which can be found easily. In the middle of the end plate in y-direcion, there is no slit cut. The optimized structure of end plate is shown in Fig. 12. And the size of the slit cuts are 10 mm in width and 20 mm in depth. The number of slit cuts is 14. The max temperature of the end plate, which is calculated by OPERA code, is 42 ℃, and the result meets the requirement too. So in the next prototype

BH magnet, the optimized structure of the end plate will be used. The distribution of the temperature in the end plate is shown in Fig. 13.

Fig. 11. The experiment of search coil measuring magnetic field.

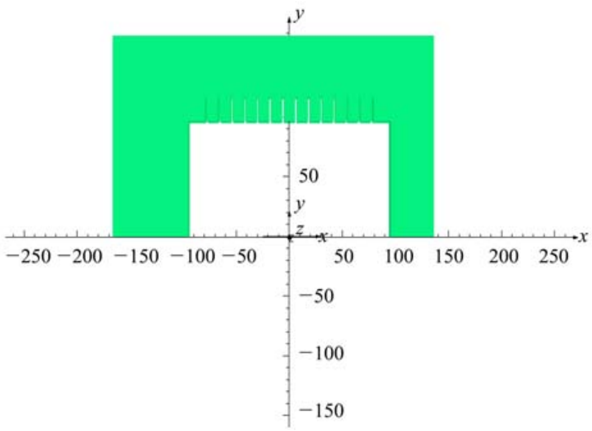

Fig. 12. The optimized structure of the end plate.

6 Conclusions

The BH magnet operates at 25 Hz and the heat generation are of our great concern in the magnet design. Investigating the eddy current effects and evaluating the temperature rise of pulsed magnet are developed using OPEAR ELEKTRA and THERMAL analyses. The method first calculates the losses due to the eddy currents and iron loss, then puts the values into thermal analyses with the same finite element size model.

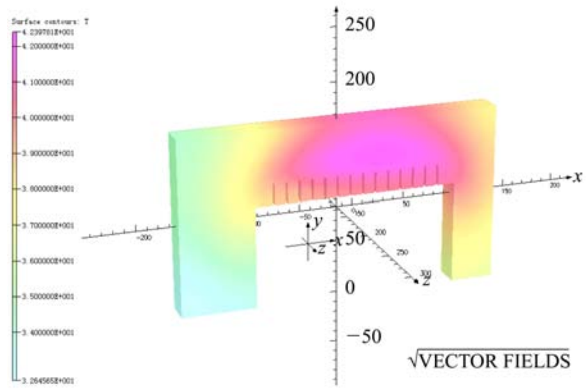

Fig. 13. The distribution of the temperature in the end plate.

From the temperature measurement of prototype BH magnet the validity of the method analyses is confirmed. The test data show that a proper slit cut configuration for the magnet end plates could reduce the temperature rise drastically. Reduction of the eddy current loss is important for energy saving of the power supply. In the future, the optimized design of the BH magnet end plate can be used.

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