DESIGN STUDY OF A VERY LARGE APERTURE EDDY CURRENT SEPTUM FOR J-PARC

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Abstract

An eddy current septum has been studied for the 50GeV main ring injection in the JPARC. Due to the high beam intensity, very large aperture is required to accommodate the large size injected beam. A large aperture magnet leads to significant end field and considerable eddy current losses, which degrades magnet performance and creates thermal problems. This paper discusses the eddy current effects on the field distribution and studies the methods for the eddy current effects compensation.

INTRODUCTION

The JPARC comprises a Linac, a 3GeV RCS and a 50GeV main ring. The main ring injection system employs two pulsed septum magnets to deflect the injected 3GeV proton beam. An eddy current septum, which has the merits of thin septum, mechanical simple and less thermal difficulties, is selected as the downstream thin septum magnet. Eddy current septum magnets have been designed and operated successfully in many institutes for e^-/e^+ beam injection and extraction [1,2]. Usually, these existed eddy current septum magnets have very narrow aperture because of the tiny e^-/e^+ beam size. However, In the case of JPARC 50GeV injection, the injected beam has large transverse size because of the high beam intensity and the significant space charge effects. Thus, a very large aperture is required, which leads to significant end field and considerable eddy current losses. OPERA 2D/3D codes are used to study the eddy current effects. The basic parameters are summarized in table 1.

Table 1: Basic parameters of eddy current septum

Parameter	Value
Magnet length	1.5 (m)
Magnet aperture	87*80, H*V (mm*mm)
Septum thickness	<8 (mm)
Gap field	0.34 (Tesla)
Uniformity	0.01
Leakage field	0.1% of gap field

LEAKAGE FIELD SUPPRESSION

In order to suppress the leakage field, different parameters effects on the leakage field are studied carefully.

Septum Thickness Effects

Since eddy current only flows near the surface of conductor (skin depth, Fig.1), in principle it is possible to make a very thin septum. However, to suppress the leakage field effectively, usually the thickness of septum is 3~4 times larger than the skin depth.

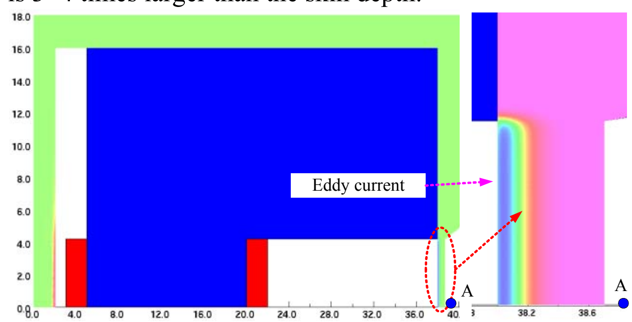

Figure1: Cross section of septum and eddy current distribution

Assume excited by a half-sine current pulse with pulse width of 150μs, the effects of septum thickness on the leakage field (at point A, in Fig.1) are studied, which are shown in Fig.2. The thinner septum, the earlier the leakage field appears and the longer the decay time constant. Thicker septum can decrease the leakage field and reduce the decay time, however it is not so effective. For example, the septum thickness doubles from 3mm to 6mm, the corresponding maximum leakage field decreases nearly to half, from 24Gs to 11Gs

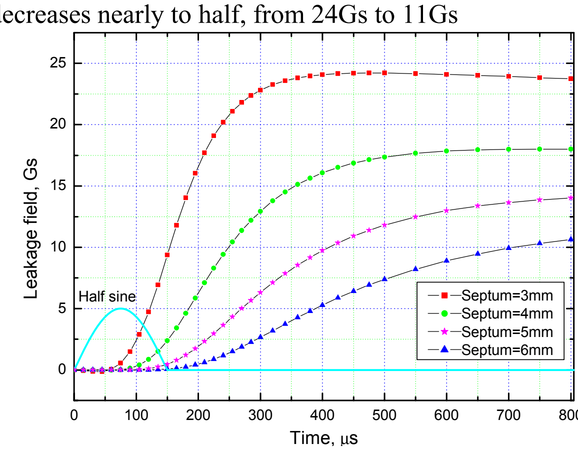

Figure 2: Leakage field varies with time (point A)

Pulse Waveform Effects

To decrease the leakage field more, a full-sine waveform excitation current can be used. Assume the septum thickness is 5 mm, Fig.3 compares the leakage field with a half/full sine excitation current. A full sine current pulse not only decreases the leakage field to almost half, but also makes the decay time constant shorter, due to the generation of a reverse eddy current on the same septum.

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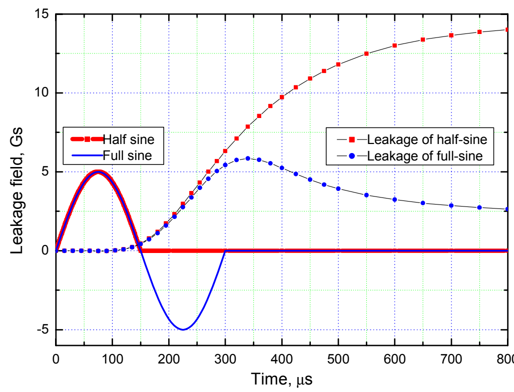

Figure 3: Leakage field with different excitation (Septum thickness is 5 mm)

Magnetic Shield Effects

The previous methods, increasing septum thickness and using a full-sine current pulse, cannot suppress leakage field effectively. Fortunately, a magnetic shield can be used to screen the leakage field, which is not allowed in a directive drive septum. Because the iron shield can be isolated from the eddy current due to the skin depth during the excitation period, as shown in Fig.4. Calculation shows that with 2 mm magnetic shield, the leakage field can be reduced about 80 times.

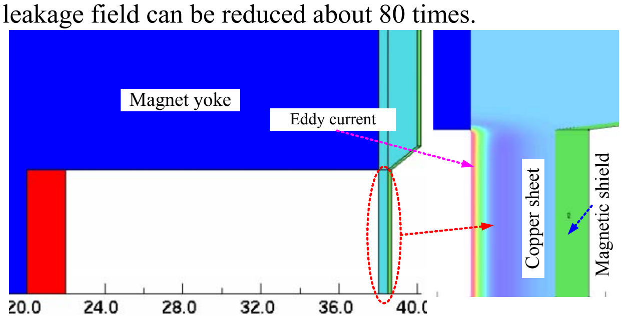

Figure 4: Septum magnet with magnetic shield

Pulse Width Effects

To shield the leakage effectively, shorter current pulse is preferable. However, the maximum voltage across the magnet increases greatly with the shortening of pulse width, which creates difficulties for power supply design and impair the operation reliability.

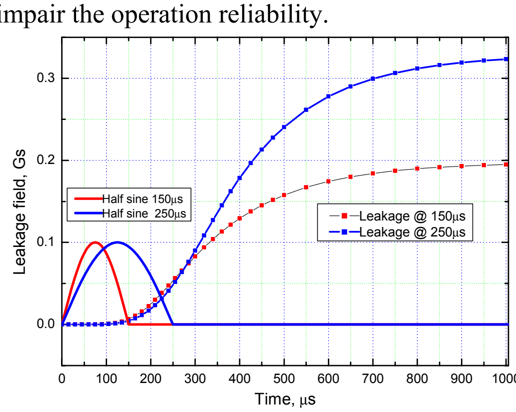

Figure 5: Leakage field with different pulse width (2 mm magnetic shield)

If a magnetic shield is employed, the current pulse width can be longer to reduce the voltage across the magnet, which improves the operation reliability. Fig.5 compares the leakage field with different current pulse width.

EDDY CURRENT LOSSESES

In an ideal laminated iron magnet, the return magnetic flux only stays inside one lamination and never intersects the neighbouring lamination, so the induced eddy current is negligible. However, at magnet ends, especially for a large aperture magnet, significant magnetic field components perpendicular to the lamination and considerable eddy current losses are unavoidable.

Eddy Current Losses Simulation

Fig.6 shows the eddy current distribution. To reduce the eddy current losses, narrow slits are fabricated at the magnet ends.

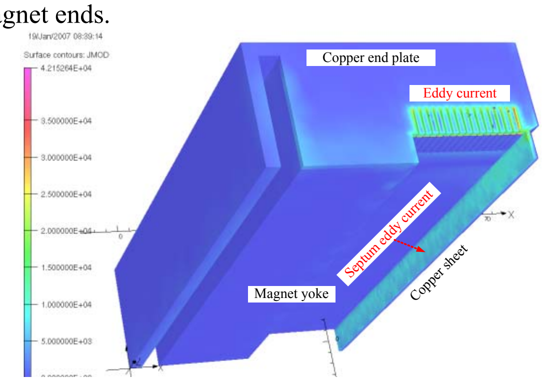

Figure 6: Eddy current distribution

Due to the eddy current losses, gap field decreases at magnet center, however increases at magnet ends, which is shown in Fig. 7.

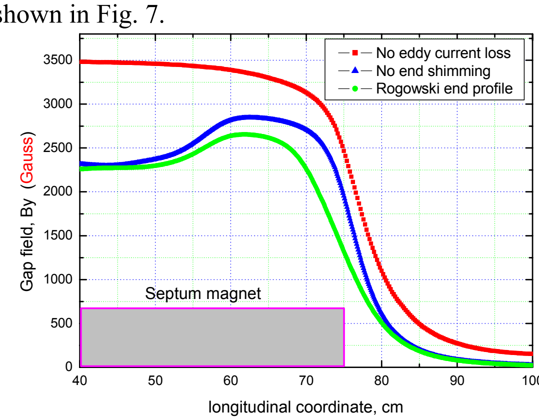

Figure 7: Longitudinal field distribution at magnet end

Gap Field Uniformity Degradation

Since the gap field uniformity of an eddy current septum heavily depends on the "passive" eddy current generated on the septum. Eddy current losses, which occurs at magnet ends mainly, take much power, as a result the eddy current generated at septum sheet decreases, which can degrade the gap field quality greatly. Increase the pulse width can reduce the effects but not effective. Fig.8 compares the degradation of transverse field uniformity.

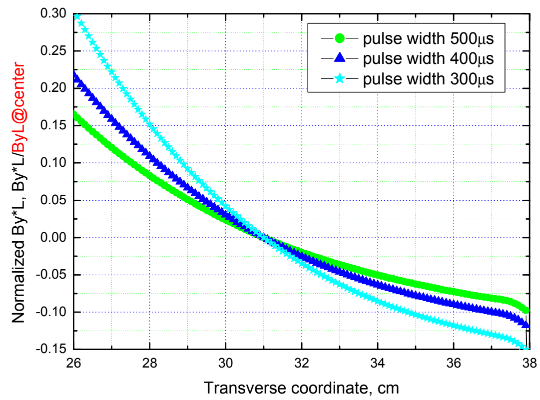

Figure.8: Integrated gap field uniformity degradation

GAP FIELD COMPENSATION

Local Compensation

Naturally, the most directly way to reduce the eddy current losses is to alter locally the end field by properly shimming the magnet ends. Such as end profile optimization, increasing narrow slits…. Fig.9 shows a magnet ends with ROGOWSKI profile together with many narrow slits. The eddy current losses occurred at magnet ends can be suppressed. Fig. 7 compares the gap field with/out end profile shimming.

However, this correction method needs rather elaborate end shapes that are difficult and costly to fabricate especially in the case of laminated core. Moreover, end pole shimming also reduces the effective magnet length.

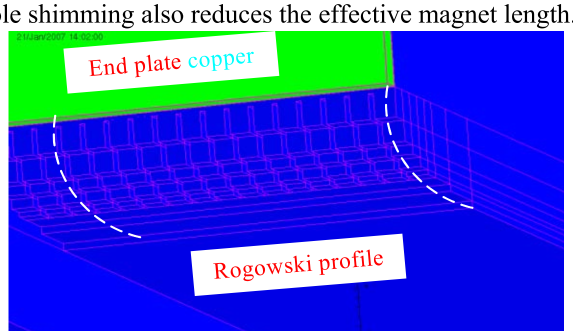

Figure 9: End profile modification

Pole Profile Modification

The other way of solving the problems of field degradation is not reduce the end field and eddy current losses on the spot, but rather compensate the field errors by modifying the magnetic field inside magnet. In this way, the magnet pole shape can be modified like Fig.10.

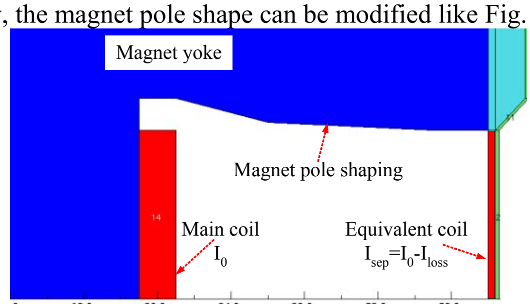

Figure 10: Magnet pole shaping

The eddy-current septum can be simulated as an equivalent coil with an excite current of I_0-I_{loss}. The pole shaping depends on the eddy current losses predication. Thus, the exact predication of current loss I_{loss} is crucial.

Flexible self-induced Current Compensation

However, not all eddy current losses can be predicted exactly. Thus, flexible compensation method is needed to cope with unexpected factors. Fig. 11 shows the principle.

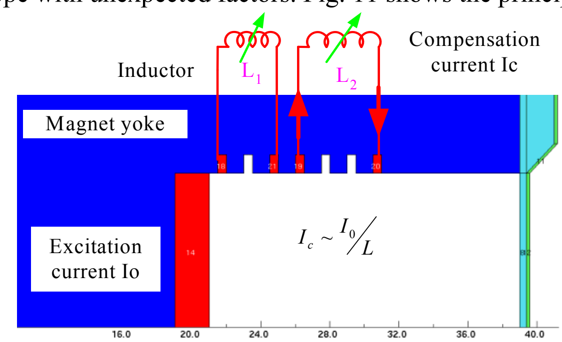

Figure 11: Self-induced compensation

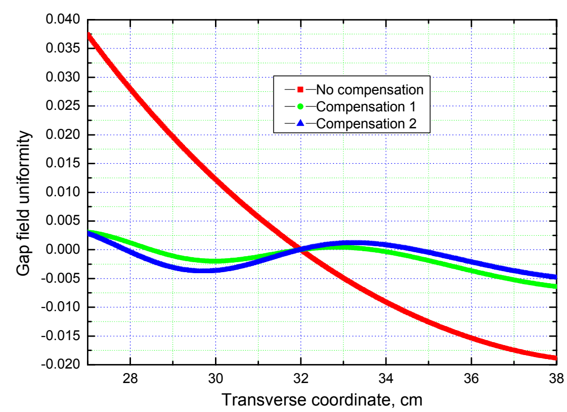

Figure 12: Gap field comparison

The self-induced compensation current can be adjusted by changing the inductance based on the actual measurement results. Fig.12 compares the gag field uniformity with/out compensation.

SUMMARY

Predication of eddy current effects, and afterwards optimization and compensation are crucial for a large aperture eddy current septum design. The magnet fabrication will be finished soon. If success, it will be the largest aperture eddy current septum in the world.

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[2] M. Kikuchi, T. Honda, N. Iida et al, Beam-transport system of KEKB, NIM-A 499 (2003) 8-23