FIELD MEASUREMENTS AND EDDY CURRENT EFFECTS COMPENSATION OF A HIGH-FIELD INJECTION SEPTUM MAGNET FOR JPARC

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Abstract

The injection system of the JPARC 50GeV main ring includes two pulse septum magnets. The high-field septum magnet generates magnetic field as high as 1.46T. However, the flatness of the field that is needed for beam injection is degraded due to the eddy current effects. Overshot current has to be used to compensate the degradation. Field measurements have been performed by both Hall probe and long search coil. The results show that both gap field and leakage field satisfy the requirements after compensation.

INTRODUCTION

JPARC is a multipurpose proton accelerator facility. Protons are accelerated, via a Linac and a 3GeV-25Hz RCS, then injected into the 50GeV main ring (MR). Two septum magnets, a high-field septum and a medium-field septum, are employed to deflect a proton beam from the beam transfer line into the MR. The high-field septum is required to generate magnetic field as high as 1.46T, and pulsed operation is adopted to avoid a serious thermal problem in septum coil. Consequently, eddy currents can be induced in the vacuum chamber walls and the magnet ends by the time variation of magnet field. Even if the ramping rate of magnetic field is not high and the induced eddy current is expected very low compared with the main excitation current, however, field measurements show that the eddy current effects can deteriorate the gap field flatness to an unacceptable level. Thus, eddy current effects compensation has to be employed.

MAGNET GEOMETRY AND FIELD REQUIREMENTS

Figure 1 shows the two-dimensional view of the high-field injection septum. Due to the large beam separation, the magnet is divided into two ½ magnets with a title angle of 15° to improve the efficiency. In the DAY-1 operation, the RCS provides one proton bunches with 25Hz and most of them are delivered to the muon/neutron production targets. Every 3.6s four bunches are extracted to the MR. Because the MR can accept two bunches at one time only, the septum magnet is required to have a sufficient flattop width to accept the succeeding four bunches. The basic parameters of the septum are presented in table 1.

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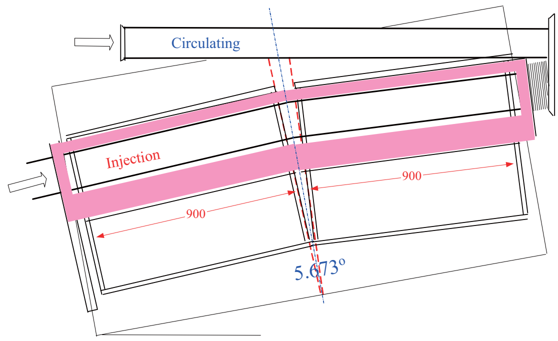

Figure 1: 2D view of injection septum

Table 1: Basic parameters of high-field septum

Parameter	Value
Magnet length	900*2 (mm)
Magnet aperture	87*84, H*V (mm*mm)
Septum thickness	50 (mm)
Gap field	1.46 (Tesla)
Gap field uniformity	0.01
Flattop	>0.2
Leakage field	By: <0.1% of gap field dBy/dx<0.015T/m

EDDY CURRENT EFFECTS

The septum is excited by a series of ladder shaped current pulse with rise time 0f 0.25s and flattop of 0.2s.

Eddy current generation

The septum has a very large aperture to accommodate the high intensity large size injection beam, which leads to a significant end fringe field. Since there is no narrow cut at magnet ends, considerable eddy current can be generated. Moreover, the using of stainless vacuum chamber, instead of a ceramic chamber to save cost, can induce eddy current also. Figure 2 shows the eddy current distribution.

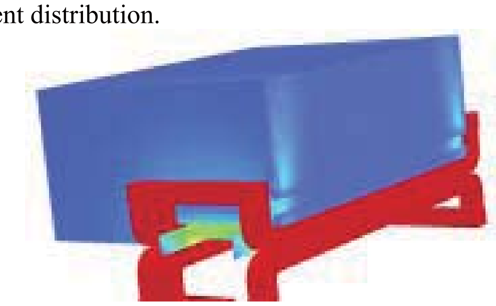

Figure 2: Eddy current distribution (Flange not shown)

Eddy current decay

The eddy current decreases greatly when the excitation current reaches maximum and becomes constant. It does not disappear immediately but decays exponentially. The decay time constant depends on the magnet ends materials property, geometry, size and so on, which cannot be exact determined analytically. It can be resolved by using the OPERA-3D [1] transient function. In addition, the eddy current has a phase delay due to the reactance components in its circuit [2]. Figure 3 illustrates the phenomenon.

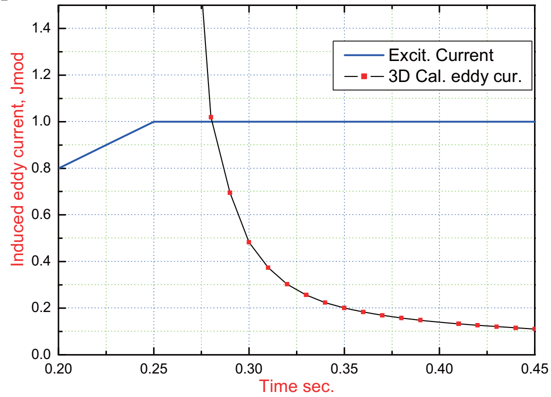

Figure 3: Induced eddy current decay with time

Gap field flatness degradation

The eddy currents generated on the vacuum chamber and magnet ends take energy from the main excitation current, which will decrease the gap field accordingly. During the period of flattop, the eddy current decays exponentially. As a result, the main field increases exponentially. Figure 4 shows the exponential rising gap field during the period of flattop.

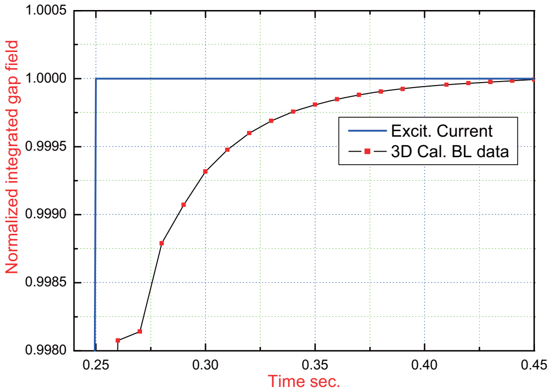

Figure 4: Gap field flatness degradation

EDDY CURRENT COMPENSATION

Flatness requirement

Since the injection system delivers 4 bunches to the main ring at one working cycle, the septum field must be stable during the injection period to ensure the succeeding 4 bunches follow the same orbit. Theoretically, if the flattop of excitation current is wide enough, the eddy current will decay to a negligible level and the gap field can be nearly constant. However, due to the power supply constraints, the current flattop width is limited within 0.2s. Thus, the flatness must be corrected to satisfy the requirement. Taking into account of the margin, the required flatness period is 160ms, which is explained in Figure 5.

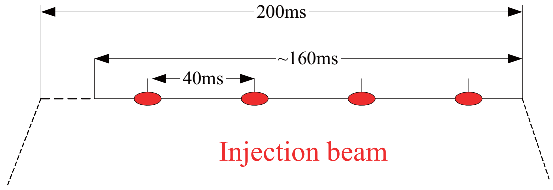

Figure 5: Flatness width of gap field

Overshot current compensation

One straightforward way to compensate the flatness is introduce an exponentially decreasing magnetic field that match the exponentially increasing gap field exactly during the period of flattop. This can be realized by adding an overshot compensation current on the main excitation current. In principle, the compensation current should decay exponentially as the eddy current. In practice, it is simplified, which has 3 adjustable parameters I_0, T_1 and T_2. Figure 6 shows the principle.

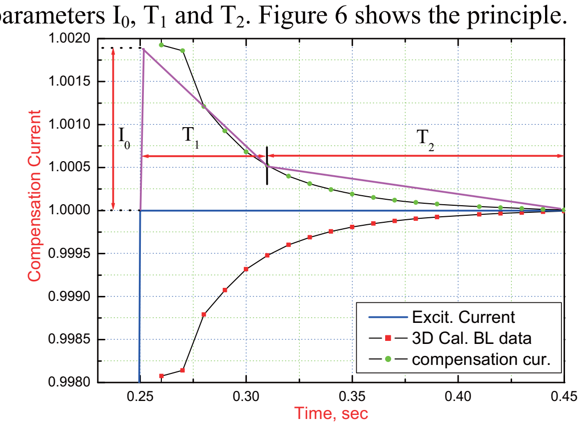

Figure 6: Overshot compensation current

FIELD MEASUREMENT

A conventional long search coil is used to measure the integrated field. Due to the lower ramping rate, the turn number of the coil winding must be large enough to obtain a sufficient SNR. The search coil is 1.5m long and 46mm in width. The turn number is about 300. A 16-bit oscilloscope is used to obtain very high precision.

Flatness without compensation

Without compensation, the flatness is ruined as predicted in 3D calculation. Figure 7 compares the flatness between the measured data and the calculation data. The agreement is very good.

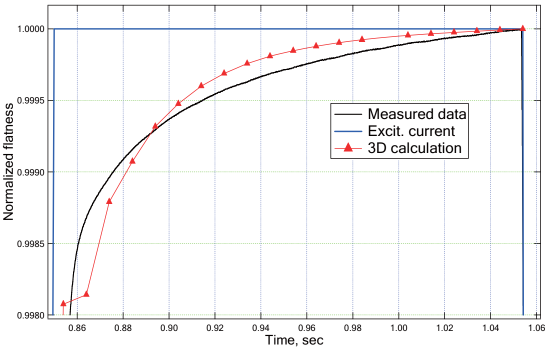

Figure 7: Measured flatness and calculation

Flatness improvement

Without compensation, the flatness within 0.16ms is about 0.08%, which does not meet the requirement. After compensation the flatness can be improved to 0.02% (0.16ms). Actually, many shape of the overshot current can produce the required flatness. Figure 8 shows the compensated flatness with different overshot current.

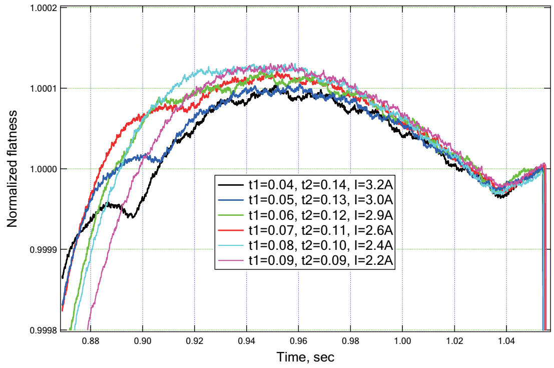

Figure 8: Compensated flatness with different overshot current shape (3 parameters indicated in Fig.6: t1, t2, I)

Gap field uniformity

Since the gap field uniformity is changing during the injection period because of the eddy current decaying. The field uniformity at the middle point of the injection period is taken as the mean value. The measured uniformity is better than $\pm 4*10^{-4}$, which agrees with the 3D calculation. Figure 9 shows the measured results.

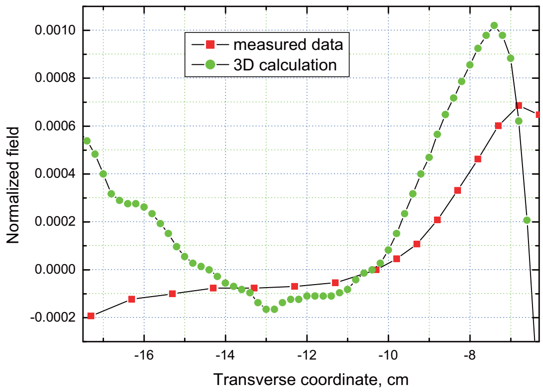

Figure 9: Gap field uniformity comparison

Leakage field

Very strict requirements are imposed on the leakage field in case of the deterioration of the circulating beam. Fortunately, the beam separation is very large except at the downstream ½ magnet as shown in Figure 1. There is sufficient space for magnetic shield installation, thus the leakage field is expected very low. Beam optics require that the integrated leakage dipole must less than 0.0005T*1.8m and the integrated Q component dBy/dx*L<0.015T/m*1.8m.

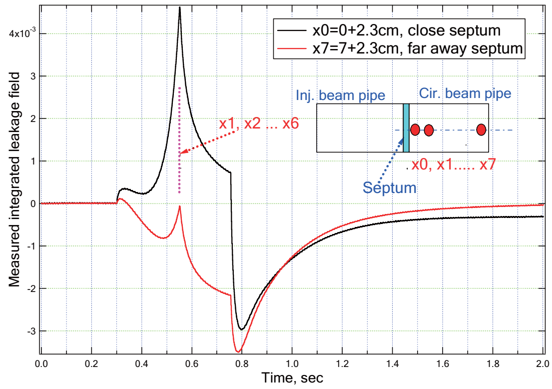

Figure 10: Measured integrated leakage field waveform

The integrated leakage field has two peaks as shown in Figure 10. The first appears at the end of rise time and the second appears at the end of excitation. Consequently, two maximum leakage field distribution can be obtained, which is shown in figure 11.

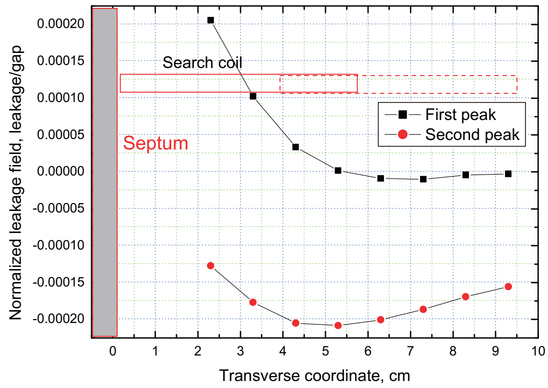

Figure 11: Measured integrated leakage field distribution

SUMMARY

Eddy currents in a pulsed magnet, even if the ramping rate is low, may affect the magnet performance to an unacceptable level. Thus, eddy current effects should be predicted and the consequent precaution process should be applied in the design phase. Reparation methods are also needed in practice to cope with unexpected results.

REFERENCES

[1] OPERA-3D user guide, Vector fields Limited

[2] K. Koseki, M. Tawada et al, pulsed bending magnet of the J-PARC MR, EPAC2006