REDUCTION OF THE DYNAMIC FIELD DEVIATION IN SERIES-CONNECTED SUPERCONDUCTING MAGNETS FOR COMPACT STORAGE RING

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Abstract

Superconducting magnets generally have large individual differences in their dynamic magnetic characteristics caused by eddy current. In series-connected magnets, these individual differences produce magnetic field deviations. In this work, we propose a simple method of connecting the impedance on the magnets in parallel to reduce field deviations. By applying this method to the compact electron ring Super-ALIS at NTT, acceleration was successfully accomplished.

Introduction

Compact storage rings for X-ray lithography with superconducting bending magnets are now being developed at a number of laboratories[1-4]. Their magnet configurations are various. A circular type has only one bending magnet, so that the field quality is better than a racetrack type. However, storage rings have many additional equipments such as an RF cavity and some focusing magnets, so that the bending magnet may be separated as the racetrack type. In this type, especially using a low-energy injection scheme, the magnetic field of each magnet has to precisely keep pace with the field of the other magnet during the ramping period. The dynamic field characteristics thus become very significant. However, the eddy current may be generated in the thermal shields or in unknown closed circuits of the cryostat systems. Especially in superconducting magnets, resistances of these closed circuits are very small and the inductances of the coils are very large. If these characters are quite different, different field dynamic characteristics are produced in each magnet even in the low-frequency region. In series-connected magnets, large magnetic-field deviations are produced even at a slow ramping rate, and therefore, the beams cannot be accelerated. One solution would be to supply current to each magnet with its own power supply. This approach, however, would be expensive, complex and difficult to control. In this work, we propose an alternative method of reducing this field deviation and show how the method has worked in application to NTT's superconducting storage ring Super-ALIS.

Table 1. Super-ALIS Ring Parameters.

	Designed	Achieved
Beam Energy	600 MeV	600 MeV
Injection Energy	15 MeV	15 MeV
Maximum Bending Field	3 T	3 T
Betatron Number ν_x	1.55~1.70	1.565
ν_y	0.20~0.70	0.530
RF Frequency	125 MHz	124.855 MHz
Critical Wavelength	17.3 Å	-----
Vacuum Pressure (static)	5×10^{-10} Torr	2×10^{-10} Torr
Circumference	16.8 m	-----
Beam current	500 mA (limited by RF)	~150 mA

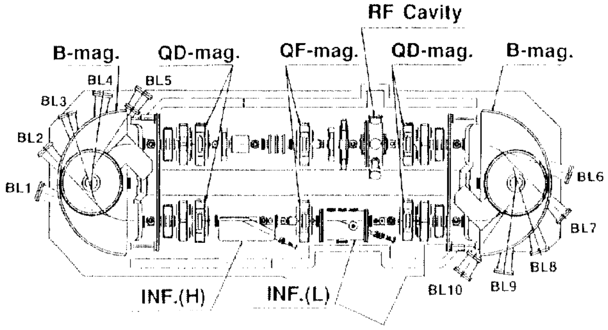

Fig. 1. Schematic of Super-ALIS.

Outline of Super-ALIS

We have been developing a racetrack type compact storage ring called Super-ALIS[5], which has two superconducting bending magnets. A schematic and parameters of Super-ALIS are shown in Fig. 1 and Table 1, respectively. It has the maximum energy of 600 MeV and the maximum bending field of 3 T. A key feature of Super-ALIS is the low-energy (15 MeV) injection which diminishes the size of the injection system. This small injection system is suitable for the industrial use.

Characteristics of the superconducting magnets

Super-ALIS's two superconducting bending magnets--BM1 and BM2-- are connected in series so that the same current can be supplied to both magnets. To observe the dynamic characteristics, we measured the magnetic field using high-precision hall probes during the ramping. The current supplied to the magnets was the same as in the practical acceleration. Initially,

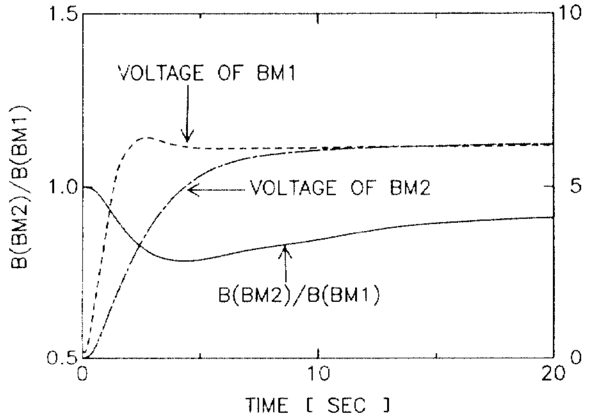

Fig. 2. Measurements of the magnetic field and voltage without Z_P.

the supplied current is for the injection level of ~ 0.08 T. In this static situation, the magnetic field of the magnets are quite equal. Then we increase the current at a constant rate. The measurement results are shown in Fig. 2. The solid line represents the ratio of the field of BM2 to BM1. The voltages of the two magnets are also shown in the figure. The left edge of this figure corresponds to the injection point. The maximum field deviation is more than 20%. In such a situation, the beams could never be accelerated. The voltage difference of course means that there is an impedance difference between the two magnets. We measured the frequency dependence of the magnet impedances. The amplitude of the impedances and their phases are shown by the dashed lines in Figs. 3(a) and (b), respectively. If the magnet consisted of only the main coil, the two curves would agree with each other. Considering the structure of these magnets, we have devised the eddy current equivalent circuits, shown in Fig. 4. The main coil (primary circuit) has N turns, and the secondary circuit should have one turn. The impedance Z_P is the correction impedance later described and ,therefore, is not be considered here. Each magnet has its own secondary circuit in the form of the thermal shields of the cryostat system. Both circuits are almost fully coupled because the secondary circuit is located very close to the main coil. Fitting the equivalent circuit of each magnets to the measured impedances by the least square method, we found that the inductances of the primary circuits L_{11},L_{21}, the secondary circuits L_{12},L_{22}, and the coupling constants k_1,k_2 are equal between each magnets and that the only the resistances of the secondary circuits R_{11},R_{22} are different. These results are reasonable because they have the same geometrical structures. Therefore, we conclude that the difference in dynamic characteristics can be attributed to the difference in resistance of the secondary circuit. This resistance difference probably stems from such factors as temperature differences, and structural deformations due to quenching. Because of the reasons described above, the notations can be replaced to

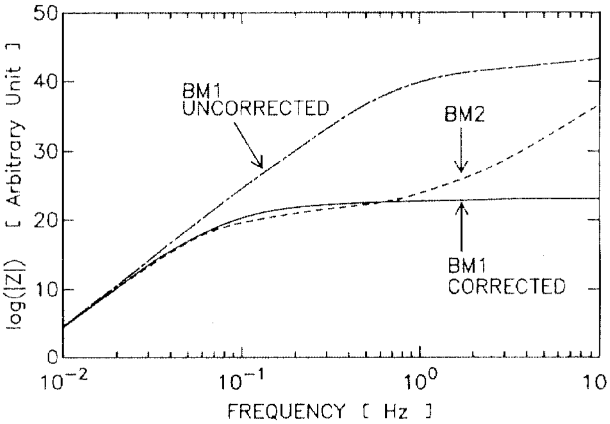

Fig. 3(a). Frequency dependence of impedance amplitude of the magnets.

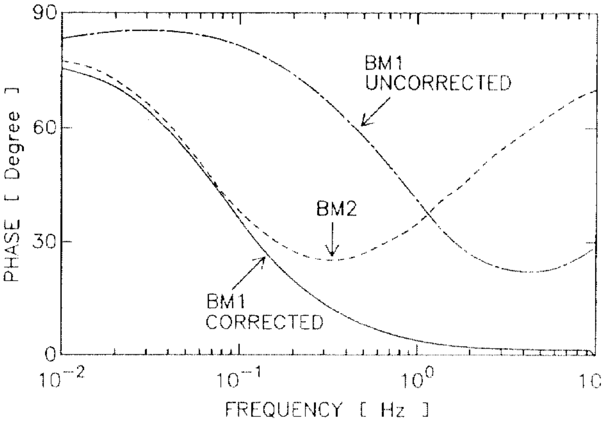

Fig. 3(b). Frequency dependence of impedance phase of the magnets.

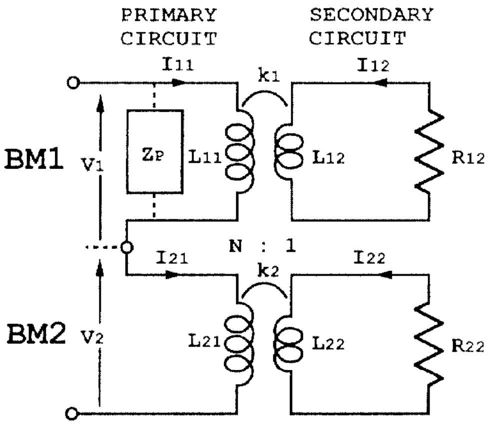

Fig. 4. Equivalent circuits of the magnets.

$$L_{11} = L_{21} = L_1 ,\quad L_{12} = L_{22} = L_2 ,\quad k_1 = k_2 = k . \tag{1}$$

We will consider just one magnet, BM1. The magnetic field B of the full coupling magnet can be expressed approximately by the following equation.

$$B = \alpha (NI_{11} + I_{12}) , \tag{2}$$

where α is the constant depending on the position, and I_{11} and I_{12} are the currents of the primary and secondary circuits of the BM1, respectively. We assume here a magnetic field that is sufficiently below the saturation point. In this equation, I_{12} is a function of R_{12}. Therefore, as far as supplying the same current, the difference in resistance of the secondary circuit produces dynamic field deviation.

Reduction of the field deviation

Now, we rewrite Eq. 2 substituting the supplied voltage V_1 and obtain the following simple equation.

$$B = \frac{\alpha}{\sqrt{L_1L_2}} \frac{V_1}{j\omega} . \tag{3}$$

This equation means that the dynamic magnetic field depends only on the supplied voltage. Even employing two magnets with different dynamic characteristics caused by the eddy current as we described above, the magnetic-field deviations can be eliminated by supplying the same voltage to each magnet. In order to supply the same voltage to each magnet, we introduced parallel impedance Z_P to BM1 which had a larger impedance than BM2, and equalized the impedances of the magnets. Z_P of course is given by

$$\begin{aligned} Z_P &= \left(\frac{1}{Z_2} - \frac{1}{Z_1} \right)^{-1} \\ &= \frac{L_1}{k^2L_2(R_{12}-R_{22})} \{ R_{12}R_{22} + \omega^2(1-k^2)^2L_2^2 \\ &\quad + j\omega (1-k^2)(R_{12}+R_{22})L_2 \} , \end{aligned} \tag{4}$$

where Z_1 and Z_2 are the original impedances of the magnets. Z_P becomes a rather complex function of the frequency, and one would assume that it might be difficult to accomplish the equalization. Fortunately, the rising speed of superconducting magnets is relatively slow, so that we only have to equalize the impedances in the low-frequency region required by the rising speed. If the frequency is small enough and $k \sim 1$ (almost full coupling), the second and the third terms of Eq.4 are negligible. We only really require the first resistance term in the low-frequency region. This result is very important because it makes the parallel impedance much more simple. Applying this method to Super-ALIS, we used only a resistance of 0.88 Ω as the parallel impedance, and equalized the impedances of the magnets in the frequency region up to ~0.1 Hz. This frequency region is enough for the practical rising speed. The impedance of BM1 corrected by Z_P are shown in Figs. 3(a) and (b) by solid lines. Impedances of the corrected BM1 and BM2 agree with each other in the low-frequency region. The results of the field deviation with Z_P are presented in Fig. 5. The supplied current is the same as in our previous measurement, yet the field deviation is less than 1.0%. The voltages of the two magnets are also in very close agreement as can be seen in the same figure.

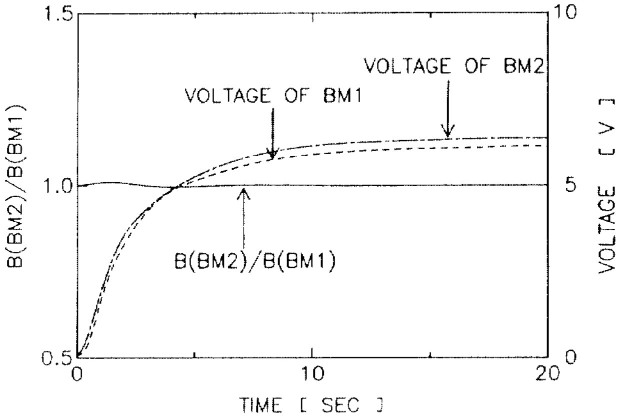

Fig. 5. Measurements of the magnetic field and voltage with Z_P.

The acceleration has thus been accomplished, and the stored current now becomes about 150mA.

Conclusion

A simple method of reducing the dynamic characteristic differences of superconducting magnets due to eddy currents is proposed. Applying this method to Super-ALIS, acceleration was successfully accomplished.

This method permits magnets to be connected series despite differences in dynamic characteristics, thus greatly simplifying the power supply and control systems. This method should make superconducting storage rings much more economical and practical.

Reference

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