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Informal Report

A CORRECTION COIL FOR RANDOM MAGNETIC FIELD ERRORS
IN A SUPERCONDUCTING STORAGE ACCELERATOR

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Abstract

Some considerations are given on the relative size of the random nonlinear field errors in the magnets of a superconducting storage accelerator and of a conventional warm accelerator. A possible correction coil is presented for the random field errors in the magnets of a superconducting storage accelerator. This correction coil consists of 24 conductors spaced equally around a circle, 12 of which can be independently excited. Each conductor can carry a maximum current of 1000 A, and has the dimensions of 0.32×0.008 in. for a 40-kG magnet with a 4-in. aperture.

I. Introduction

This report is primarily directed towards designing a set of correction coils which will correct for nonlinear fields introduced by the random error multipoles in the magnets of a superconducting accelerator. The need for such correction coils arises partly from the fact that the random field errors in superconducting magnets tend to be larger than in conventional warm magnets.¹

Reported measurements² of the nonlinear fields present in the ISR indicate that the random error multipoles present in superconducting magnets are roughly ten times larger than the random error multipoles present in warm magnets, where the number 10 is to be taken as an order of magnitude estimate only. It may be pointed out that some other factors, which determine the strength of nonlinear resonances, tend to favor ISABELLE over the ISR. These factors are the emittance of the beam and the β -factor in the magnets. Since the mechanism whereby the nonlinear fields affect beams which have long lifetimes is not known, it is difficult to make exact comparisons between the ISR and ISABELLE.

It was pointed out by Keil³ that the beam-beam interaction in storage rings is also an important source of nonlinearities acting on the beam. The ISR beam-beam interaction produces a linear ν -shift of $\Delta\nu \simeq 6 \times 10^{-4}$, while in ISABELLE the beam-beam interaction is intended to cause a $\Delta\nu$ -shift of

$\Delta v = 5 \times 10^{-3}$. Thus a comparison of the linear v-shift due to the beam-beam interaction indicates that the nonlinearities generated by the beam-beam interaction may be roughly 10 times larger in ISABELLE than in the ISR. Again, there are other factors present such as the emittance of the beam and the relevant β -factors that tend to favor ISABELLE and would reduce this factor of 10.

A comparison of the nonlinearities introduced by the random error multipoles in the magnets, and by the beam-beam interaction, is made complicated by the fact that the imperfection resonances, which are near the working line of the beam in v_x and v_y , depend on the random differences among the beam-beam interaction regions, which are not known. A reasonable kind of guess suggests that the nonlinearities due to the beam-beam interaction may be at least as large and more probably larger than the nonlinearities due to random errors in the magnets. One should not conclude that one can therefore forget about the nonlinearities due to random errors in the magnets, but rather that one has to deal with both sources of the nonlinearities.

The role of the structure nonlinear resonances driven by the beam-beam interaction, which are present even if all interaction regions are identical, is affected by the choice of the number of superperiods which is 4 for the ISR, since the larger the number of superperiods the further the working line can be from the structure resonances. The possibility of large nonlinearities from the beam-beam interaction may be regarded as a reason for choosing 4 superperiods rather than 2 for ISABELLE.

A possible set of nonlinear correction coils is shown in Fig. 1. This correction coil consists of 24 conductors spaced equally around a circle, 12 of which can be independently excited. Each conductor contains forty 8-mil superconducting wires, where each wire carries a maximum current of 25 A. The conductor dimensions are 0.32×0.008 in. This correction coil could be placed in each dipole, and, as suggested by G.K. Green, each such correction coil can be separately excited. This set of correction coils can correct for all nonlinear resonances up to and including those of fifth order.

Figure 1

II. Theory of the Correction Coil

The following assumptions were made in the study of the correction coil:

1. The magnitude of the random error multipoles to be corrected is that due to random errors in the magnet coil positions of 0.002 in. in a magnet having a 4-in. aperture. These random multipoles⁴⁻⁶ are listed in Table I.

2. The correction coils will be capable of correcting all resonances up to and including those of fifth order, whether generated by errors in the vertical median-plane field, B_z , or by errors in the radial median-plane field, B_r . If the multipoles are defined by expanding the error fields ΔB_z , ΔB_r in the median plane as

$$\Delta B_z = B_0 \sum_{m=0} \Delta b_m r^m ,$$

$$\Delta B_r = B_0 \sum_{m=0} \Delta a_m r^m ,$$

where B_0 is the unperturbed dipole field, then the correction coil will be capable of correcting the 10 error multipoles, Δb_m , Δa_m , $m=0$ to 4.

3. The conductors making up the coils will be wound out of 8-mil superconducting wires which carry a maximum current of 25 A.

4. Correction coils will be placed in each of the dipole magnets, each such correction coil being independently excitable as suggested by G.K. Green. This allows considerable freedom in exciting the desired azimuthal harmonic around the accelerator.

First, let us consider the approach of correcting each of the error multipoles listed in Table I by a separate pure multipole winding and let us find the current distribution required in each such multipole winding. A pure multipole $\cos(m+1)\theta$ winding will produce a multipole field according to⁵

$$B_m = - \frac{\mu}{4} \frac{m+1}{R^{m+1}} I_t^{(m)} r^m , \quad (2.1)$$

TABLE I. Δb_m are the rms values of the multipoles that are assumed to need correction. $\Delta I_t^{(m)}$ is the total current required in a pure $\cos(m+1)\theta$ multipole winding to correct for Δb_m , and $\bar{c}_m$ gives the corresponding current distribution as $\bar{c}_m \cos(m+1)\theta_n$ where the multipole winding is assumed to be made of 24 conductors spaced equally around a circle at the angles $\theta_n = 2\pi/24$.

m	$\Delta b_m/10^{-3}$ (A)	$\Delta I_t^{(m)}$ (A)	$\bar{c}_m$ (A)
0	0.302	160.0	20.9
1	0.195	104.0	27.2
2	0.122	87.0	34.2
3	0.070	74.6	39.1
4	0.039	66.5	43.5
5	0.020	56.9	44.7
6	0.011	53.6	49.1

where $I_t^{(m)}$ is the total current of the multipole winding, $\mu = 4\pi/10$ in cgs units, and R is the radius of the coil. Thus the current required to correct an error multipole Δb_m is given by

$$\frac{\Delta I_t^{(m)}}{I_t^{(0)}} = \frac{R^m}{m+1} \Delta b_m, \quad (2.2)$$

where $I_t^{(0)}$ is the current in the main coils of the dipole magnet and $I_t^{(0)} = 533,000$ A at 40 kG for a 4-in.-aperture magnet.

If the multipole winding is generated by N conductors around a circle spaced equally at the angles θ_n , and given by the current distribution

$$\Delta I_t^{(m)}(\theta_n) = c_m \cos(m+1)\theta_n, \quad (2.3)$$

then the c_m and $\Delta I_t^{(m)}$ are related by

$$c_m = \frac{\pi}{2} \frac{2(m+1)}{N} \Delta I_t^{(m)}. \quad (2.4)$$

Formulas (2.1) to (2.4) are for the error multipoles in the B_z field which require $\cos(m+1)\theta$ correction windings. A similar set of formulas apply to the error multipoles in the B_r field which require $\sin(m+1)\theta$ correction windings.

Table I lists the correction currents required, $\Delta I_r^{(m)}$, and the corresponding current distributions as given by $\bar{c}_m$. For the case of the cosine magnet, the error multipoles in the radial B_r field, Δa_m , are equal to the error multipoles in the vertical B_z field, Δb_m , and the results in Table I also give the currents and current distributions for the $\sin(m+1)\theta$ windings.

One could now use the results in Table I to construct a correction coil having 10 different pure multipole windings having the current distributions $\cos(m+1)\theta$ and $\sin(m+1)\theta$, $m = 0$ to 4, which would be able to correct up to and including fifth order nonlinear resonances. However it appears simpler, and probably requires less correction current, to combine the ten windings into the one winding shown in Fig. 1, where one has 24 conductors spaced equally around a circle, 12 of which are independently excited and are labeled I_n , $\bar{I}_n$, $n = 1$ to 6. One could use 20 conductors, 10 of which are independently excited, to control up to fifth order resonances. Twenty-four conductors are used because 24, being divisible by 2, 4, 6, 12, allows the possibility of exciting relatively pure multipoles for b_2, b_3, b_4, b_6 in the vertical B_z field and for a_2, a_3, a_4, a_6 in the radial B_r field.

One needs now to compute how much current each of the 24 conductors shown in Fig. 1 need to carry to correct for random error multipoles of the magnitude given in Table I. For a given set of random errors, the correction current required in N independent conductors with $N = 12$ is

$$I(\theta_n) = \sum_{m=0}^4 \left(c_m \cos(m+1)\theta_n + d_m \sin(m+1)\theta_n \right), \quad n = 1, 12, \quad (2.5)$$

where θ_n gives the location of the conductors and the rms values of c_m and d_m are given by the $\bar{c}_m$ listed in Table I. Now let us compute the rms of $I(\theta_n)$, $\bar{I}$, and we find

$$\bar{I} = \sqrt{2 \sum_{m=0}^4 \bar{c}_m^2} , \quad (2.6)$$

where we have assumed that $\bar{c}_m = \bar{d}_m$, the bar indicating rms values, and that different error multipoles are not correlated.

Using the results of Table I for the $\bar{c}_m$, we find

$$\bar{I} = 105 \text{ A} .$$

On the average, each of the 24 conductors will carry 105 A in order to correct for error multipoles introduced by an assumed random error of 0.002 in. in the position of the current blocks in a cosine magnet with a 4-in. aperture. This is a statistical result, and in order to allow for possible large fluctuations, we assume a safety factor of 10, and assume that the required current for each of the 24 conductors is

$$\bar{I} = 1000 \text{ A} .$$

If we assume that each conductor and its return conductor are wound out of an 8-mil superconducting wire which carries a maximum of 25 A, then each conductor requires 40 turns of this 8-mil wire. The dimensions of the conductor are then 0.32 by 0.008 in.

In the above calculations, the presence of the iron shield was neglected. The effect of this is that the currents required have been overestimated by about 25%.

Changing the Location of the Correction Coil

In the above, it was assumed that the correction coil would be put in each dipole around the accelerator. If it is desired to put the correction coil in a smaller number of magnets, then the currents required in the correction coils are increased by a factor which is inversely proportional to the total azimuthal length of all the magnets having the correction coil. One needs to have sufficient correction coils around the accelerator to control the azimuthal harmonics generating the resonances.

Window Frame Magnets

The above results were computed assuming the random error multipoles expected in cosine magnets. The random error multipoles expected for window frame magnets are about the same, or somewhat smaller, as those for the cosine magnets.⁷ Thus the same correction coil should be acceptable for the window frame magnet.

Linear Random Field Errors

The correction coil presented above can correct for not only the random nonlinear multipoles but also the linear random multipoles, b_0 , b_1 in the vertical B_z field, and a_0 , a_1 in the radial B_r field. The linear field errors give rise to displacements of the equilibrium orbit and possible coupling between the vertical and horizontal betatron oscillations. However, another source of the linear field errors is the misalignment of the magnets, particularly the quadrupoles. If this source of the linear field errors is much stronger than the random errors in the magnet coil positions, then some extra current capacity has to be put into the correction coils to allow for this.

Correcting to a High Order Nonlinear Resonance

The 24 conductors assumed here, having 12 independent currents, can correct for up to sixth order resonances by increasing the current capacity somewhat, since the above result was obtained for correcting up to fifth order resonances. If higher order resonances are to be controlled, then the number of conductors needs to be increased.

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