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HIGHER MAGNETIC FIELD MULTIPOLES GENERATED BY SUPERCONDUCTOR MAGNETIZATION WITHIN A SET OF NESTED SUPERCONDUCTING CORRECTION COILS

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Correction elements in colliding beam accelerators such as the SSC can be the source of undesirable higher magnetic field multipoles due to magnetization of the superconductor within the corrector. Quadrupole and sextupole correctors located within the main dipole will produce sextupole and decapole due to magnetization of the superconductor within the correction coils. Lumped nested correction coils can produce a large number of skew and normal magnetization multipoles which may have an adverse effect on a stored beam at injection into a high energy colliding beam machine such as the SSC.

BACKGROUND

Higher multipoles due to the magnetization of superconductor have been observed in superconducting dipole magnets since 1970.[1] The effect of the superconducting persistent currents has been modeled on the computer,[2] and it is a reasonably well understood phenomena. The effects of superconductor magnetizations have been observed in accelerator dipoles and quadrupoles for many years.[3] This paper deals with the effects of superconductor magnetization in accelerator correction elements.

Colliding beam accelerators, such as the Superconducting Super Collider (SSC)[4] near Dallas, Texas and the Large Hadron Collider at CERN in Europe, require very uniform magnetic fields (better than 1 part in 10000) within their dipole magnets. Continuous correction windings have been proposed in the SSC dipoles for correcting sextupole generated by magnetization in the dipole superconductor, for correcting sextupole generated by saturation of the dipole magnet iron, and correcting the tune of the accelerator by providing a continuous quadrupole correction. Studies of these correction windings at LBL and HERA have shown that these windings will generate undesirable higher multipoles within the dipole bore. For example, a quadrupole winding within a dipole will generate a sextupole magnetization field component, and a sextupole within the dipole will generate a decapole magnetization field component.

These field components have been measured within the HERA dipole magnets. Calculations of these components at LBL using the SCMAG04 code, which agree substantially with the measured multipoles, are presented in the report. As a result, in the proposed continuous correction winding for the SSC dipoles have been replaced with lumped correction elements every six dipole magnets (about 120 meters apart).

Nested lumped correction elements will also produce undesirable higher magnetization multipoles. This report shows a method by which the higher multipole generated by nested correction elements can be identified.

THE HERA DIPOLE CORRECTORS

The HERA accelerator dipole magnets have a quadrupole corrector and a sextupole corrector built into them. The skew quadrupole and normal sextupole extend over two-thirds of the length of the dipole magnet. The magnetization multipoles within the dipole are the odd normal multipoles (N1, N3, N5 and so on, where 1 is dipole, 2 is quadrupole, 3 is sextupole, 4 is octupole, 5 is decapole and so on). The presence of the skew quadrupole and normal sextupole will alter the magnetization normal sextupole (N3) and the normal decapole (N5) at injection into the HERA machine. The altered sextupole can be corrected by the sextupole corrector, but the altered decapole cannot be corrected.

The HERA dipole magnet with its correction coils was modeled using the SCMAG04 computer code. The computer model predicts that the correction skew quadrupole will produce a normal dipole and a normal sextupole when it is within a uniform dipole field. The model also predicts that the correction normal sextupole will produce a normal dipole and a normal decapole when it is within a uniform dipole.

The model HERA dipole with normal quadrupole and sextupole correctors is shown in Figure 1. Table 1 shows the predicted sextupole and decapole multipole ratios with and without the correctors as a function of the central dipole induction within the dipole. The multipole ratios are taken at a radius of 25.0 mm. The assumed central induction cycle for the magnet was from 4.5 Tesla to zero to the induction at which the multipole ratio was calculated. Figure 2 shows a plot of the predicted sextupole and decapole multipole ratio as a function of central induction with the HERA dipole corrector installed.

The normal quadrupole corrector within the HERA dipole (see Figure 1) reduces the magnetization sextupole at injection by about 5 units (1 unit equals 1 part in 10000). The normal sextupole corrector increases the magnetization at injection decapole by nearly 7 units. (If a skew quadrupole is used instead of the normal quadrupole, the magnetization sextupole is increased by five units.) The calculated change of the sextupole and decapole compares favorably with the measurements made by DESY.[5] The increase in the decapole is potentially troublesome to the HERA machine when the proton beam is being stacked into the machine. The change in the magnetization dipole due to the skew quadruople and the normal sextupole correctors is predicted to be about 0.44 gauss. The entire change of the dipole term due to the correctors is caused by the images in the iron shell around the dipole.

The effect of the operation of the correctors on the dipole coil has not been measured or calculated. It is expected that effect of the correctors on the dipole is relatively small because the field with the dipole bore (and in the dipole coils) is dominated by the dipole itself. It is predicted that a small amount of quadrupole, sextupole and octupole will be introduced by the powering of the HERA dipole correction coils.

NESTED CORRECTION COILS

It is proposed that the lumped correctors of the SSC machine will be assembled together on a common bore. The higher multipole correction magnets would be mounted inside the lower multipole correction magnets. Unlike the HERA continuous correctors for the dipole, the lumped correctors are not dominated by a particular magnetic flux pattern. As a result, both normal and skew magnetization multipoles can be generated at injection within a lumped corrector set.

Table 2 shows which multipoles are produced by which coils in a nested set of coils. As an example, a powered dipole will cause dipole (N = 1), decapole (N = 5) and 22 pole (N = 11) magnetization components to be formed by sextupole winding within the dipole. In addition, dipole (N = 1), sextupole (N = 3), decapole (N = 5), in pole (N = 7) and so on will be produced by magnetization in the dipole windings. If the sextupole within the dipole is powered instead of the dipole, a different pattern of magnetization multipoles is formed within the dipole, N = 1, 3, 5 and so on is formed and within the powered sextupole, N = 3, 9, 15 and so on is formed. Whether or not the magnetization multipole is skew or normal depends on whether the driving field is skew or normal.

Table 2 applies for nested magnets within an iron shell. If the iron shell is removed, the fundamental multipole (the driving powered multipole) is changed and in some cases completely eliminated. For example, the powered dipole (N = 1) term in the first row in Table 2 all contains an N = 1 term. If the iron shell is removed, this term is no longer present in the field.[6]

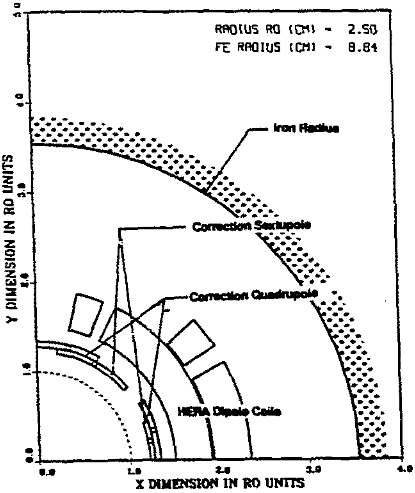

Fig. 1 A quarter cross-section of the HERA dipole showing the dipole coils, the quadrupole corrector and the sextupole corrector.

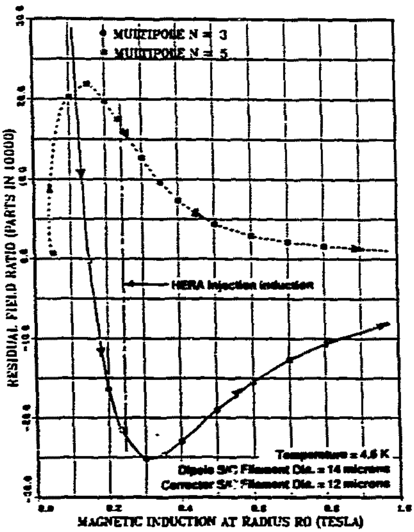

Fig. 2 The magnetization sextupole and decapole ratio at a radius of 25 millimeters as a function of the dipole central induction.

Table 1

CALCULATED MAGNETIZATION SEXTUPOLE AND DECAPOLE RATIO AS A FUNCTION OF CENTRAL INDUCTION IN THE HERA DIPOLE WITH AND WITHOUT THE NORMAL QUADRUPOLE AND SEXTUPOLE CORECTORS

(Central Induction Change 4.5 tesla to 0.0 tesla to Bo)

Dipole Induction Bo going up (T)	Multipole Ratio* (units#)			
	Dipole w/o Correctors		Dipole with Correctors	
	Sextupole	Decapole	Sextupole	Decapole
0.050	183.07	10.08	175.85	0.68
0.100	35.61	14.97	39.62	20.22
0.150	-6.20	14.16	-0.27	21.90
0.200	-22.13	12.25	-16.39	19.74
0.233	-26.71	10.75	-21.52	17.52
0.300	-29.10	7.61	-25.21	12.68
0.350	-27.83	5.55	-24.70	9.63
0.400	-25.59	3.94	-23.00	7.31
0.500	-20.80	2.00	-18.96	4.39
0.600	-16.83	1.06	-15.41	2.91
0.700	-13.80	0.64	-12.67	2.12
0.800	-11.61	0.41	-10.68	1.62
1.000	-8.48	0.15	-7.84	0.99

* At a radius of 25.0 millimeters

\# One unit equals 1 part in 10000 of the central induction

Table 2

MAGNETIZATION MULTIPOLES PRODUCED IN UNPOWERED MAGNET COILS BY POWERING OTHER MULTIPOLE MAGNET COILS

	Unpowered Multipole Magnet				
	N = 1	N = 2	N = 3	N = 4	N = 5
N = 1 POWERED	1, 3, 5, 7, ...	1, 3, 7, 11, ..	1, 5, 11, ...	1, 7, 15, ...	1, 9, 19, ...
N = 2 POWERED	2, 4, 6, 8, ...	2, 6, 10, ...	2, 4, 6, 8, ...	2, 6, 10, ...	2, 4, 6, 8, ...
N = 3 POWERED	1, 3, 5, 7, ...	1, 3, 5, 7, ...	3, 9, 15, ...	1, 3, 5, 7, ...	1, 3, 5, 7, ...
N = 4 POWERED	2, 4, 6, 8, ...	4, 8, 12, ...	2, 4, 6, 8, ...	4, 12, 20, ...	2, 4, 6, 8, ...
N = 5 POWERED	1, 3, 5, 7, ...	1, 3, 5, 7, ...	1, 3, 5, 7, ...	1, 3, 5, 7, ...	5, 15, 25, ...

Note: N = 1 is a dipole; N = 2 is a quadrupole; N = 3 is a sextupole; N = 4 is an octupole; and N = 5 is a decapole. The symetrical higher multipole magnet coils are inside the lower symetrical multipole coils.

Note: If a normal magnet drives the magnetization, the magnetization multipoles are normal. If a skew magnet drives the magnetization,the magnetization multipoles are skew.

Note: The strongest magnetization multipoles are represented by bold multipole numbers.

If one nests skew magnets with normal magnets, one gets magnetization multipoles with both normal and skew terms. If one mixes even types of magnets (N = 2 or 4 quadrupole and octupole) with odd types of magnets (N = 1, N = 3 or N = 5 dipoles, sextupoles and decapole) one will get a field with magnetization multipoles which contain both the odd and even terms. It is clear from Table 2 that it probably is not a good idea to nest even magnets (N = 2 and 4) with odd magnets (N = 1, 3 and 5). It is also clear that the nesting of skew and normal magnets should be avoided.

Table 2 suggests that nested correction magnets will produce a lot of different magnetization multipoles. Whether or not this is a problem in an accelerator depends on a number of factors. These factors include (1) the length of the nested correction elements as compared to the overall length of the dipole string, (2) the amount of superconductor in the correctors, (3) the types of magnets nested on the corrector spools, (4) the tune of the machine and (5) the beam size within the nested lumped corrector relative to the inner most coil radius and (6) the average field in the correction coils during the injection front porch of the machine.

SUMMARY

The nesting of correction elements with a dipole or within other correction elements will produce undesirable higher magnetization multipoles. Whether these multipoles pose a problem in the operation of an accelerator is dependent on which elements are powered. Any magnets which are nested within other magnets can produce undesirable magnetization multipoles. Calculations of the magnetization multipoles within correctors can establish a worst case estimate of the magnetization multipoles. Since the operation of correction elements is not entirely predictable, a worse case analysis is the best that can be expected.

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