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The Ramp Rate Dependence of the Sextupole Field in Superconducting Dipoles*

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Abstract -- Sextupole components are induced in the magnetic field of superconducting dipoles when the current is changed. The magnitude of this effect depends on the rate of change of field, the strand-to-strand resistance in the superconducting cable, and the twist pitch of the wire. Ramp rate measurements have been made on a number of SSC dipoles wound from conductors with different interstrand resistances. The technique employed uses an array of Hall probes sensitive to the sextupole field and can measure the difference for field increasing or decreasing as a function of axial position. Magnets with very low interstrand resistance exhibit a large axial oscillation in the sextupole field between up and down ramps which is rate dependent. When the strand resistance is high the amplitude of this oscillation is almost independent of ramp rate.

I. INTRODUCTION

Variations in the magnitude of the harmonic coefficients along the axis of superconducting accelerator magnets made from cabled conductor have been studied under dc conditions for several years [1-3]. Dynamic measurements of the same phenomenon are more difficult to perform since, in general, the field must be determined in a point-by-point fashion with each axial position representing a cycle of the magnet at the ramp rate of interest. Strand-to-strand currents induced by the changing field produce harmonics that exist only when the main magnet current is ramping and decay rapidly when the ramp stops. If the interstrand resistance, R_i , is uniform throughout the coil, the effect of these interstrand currents can be calculated [4,5]. The induced currents vary with the azimuthal position of the turns in the magnets due to the changing angle between the driving field and the width of the conductor. If the interstrand resistance is not uniform due to variations in the conductor or the molding pressure during magnet fabrication, then unallowed harmonic fields are generated, which is the case for some SSC magnets [6]. When the ramp rate is sufficiently high the effect of interfilament eddy currents may become observable since most accelerator magnets are made from conductors with a twist pitch of only 15 mm. This effect can be characterized by an interfilament eddy current time constant, τ , for the strand in the cable [7].

II. EXPERIMENTAL TECHNIQUE

The measuring apparatus previously used to map out the variation along the axis under dc conditions [2-3] has been adapted for dynamic measurements using software developed for energy loss measurements. Two synchronized computer controlled DVM's read the sextupole field and the current over a complete magnet cycle. The data are fit to a polynomial curve near the current of interest and the difference between the up and down branches is computed. This is then repeated for another identical cycle at a different axial position to obtain a plot of the variations along part of the magnet. Fig. 1 illustrates a typical measurement for SSC magnet DCA 213 near the injection current (650A). Fitting the individual field-current readings allows accurate determination of the up-down difference at a specific current and the fact that the sextupole field is determined at the same value of the dipole field on the up and down ramps compensate for the non linear nature of the Hall probes. Fixed field scans of the axial variation are obtained in the usual way by mechanically moving the field probe and recording the sextupole field. Fig. 2 is a typical dc scan along the axis of an SSC dipole at high field. Because the dynamic measurements are made point-by-point it is only practical to measure one or two oscillation wave lengths at each ramp rate. Extrapolating to zero ramp rate allows comparison with dc measurements.

Figure 1. Signal from the three-Hall probe assembly, the difference in the up and down ramps is the sextupole field due to filament magnetization plus rate dependent effects.

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Figure 2. Oscillation in the sextupole field along the axis of an SSC 5 cm magnet at 7 T.

III. EXPERIMENTAL RESULTS

The difference in the sextupole field for the up and down ramps at 650A is shown for dipole DCA213 in Fig. 3a. This magnet has an intermediate value of interstrand resistance (see Table I) and the oscillation pattern is seen to move as a unit with little or no change in amplitude. The width of the up-down field as measured by conventional techniques corresponds to the average value over an oscillation cycle and this is plotted against ramp rate in Fig. 3b. Note that this average value increases with rate which is consistent with filament-to-filament coupling and a larger effective strand magnetization. Extrapolating the up-down difference to zero rate gives the curves of Fig. 4. For this magnet the extrapolated value agrees reasonable well with the dc value (Fig. 4a) and the ramp dependance with position is small indicating no significant effect on the oscillation amplitude (Fig. 4b).

Similar measurements were made on DCA312 a dipole fabricated with conductor of low interstrand resistance. In this case there is a dramatic change in the amplitude of the oscillations in the up-down sextupole as shown in Fig. 5a. The average value of the differences now decreases with ramp rate (Fig. 5b) and is consistent with the effect of interstrand currents on the sextupole field [5,6]. Fig. 6a compares the dc measurements with the extrapolated zero rate values and the axial variation of the rate dependance (Fig. 6b) is almost fifty times as large as in the higher interstrand resistance magnet DCA213.

Dipoles with even higher values of the strand-to-strand resistance have been examined and give results consistent with their interstrand impedance. Interstrand resistance can be measured directly on conductor samples but great care

must be exercised to ensure that the conditions of temperature and pressure exactly duplicate those used in magnet fabrication. Loss measurements on magnets [8] can also be used to estimate the effective value of the strand-to-strand resistance [9]. Table I summarizes the parameters for the magnets measured including the effective interstrand resistance deduced from loss measurements [10] taking into account the effects of intrastrand coupling. Estimated R_i and τ values are based on calculations by T. Ogitsu of the loss and B_z changes due to interstrand eddy currents and interfilament coupling for the 5cm SSC dipole design [11].

Table I.

	$\Delta B_z \text{ slope}^1$ G/(A/s)	Loss/cycle ² Joules/(A/s)	R_i $\mu\Omega$	τ msec
DCA211	-0.009	2.8	250	6
DCA213	-0.020	7.9	79	16
DCA312	0.081	60.4	6	24
DCA317	-0.0016	3.7	158	7
DCA318	-0.005	3.9	130	6

¹ Data normalized to a radius of 1cm

² Magnet cycle 500A-5000A-500A

Figure 3. (a) $B_z(\text{up})-B_z(\text{dn})$ as a function of axial position for DCA213; (b) axial average of $B_z(\text{up})-B_z(\text{dn})$ as a function of ramp rate.

Figure 4. (a) $B_2^{(up)} - B_2^{(dn)}$ extrapolated to zero B vs. axial position and comparison with DC value; (b) slope of rate dependent B_2 vs. axial position.

Figure 6. (a) $B_2^{(up)} - B_2^{(dn)}$ extrapolated to zero B vs. axial position; (b) slope of rate dependent B_2 vs. axial position.

Figure 5. (a) $B_2^{(up)} - B_2^{(dn)}$ as a function of axial position for DCA312; (b) axial average of $B_2^{(up)} - B_2^{(dn)}$ as a function of ramp rate.

IV. DISCUSSION AND CONCLUSIONS

The effect of changing current on the harmonic coefficients at a given position in the magnet is made up of at least three parts. The first and most obvious ramp-rate effect is due to induced currents between the strands in the cable which can be substantial for conductors with very low interstrand resistance. Such induced harmonics will have the opposite sign to those produced by filament-to-filament (intrastrand) coupling which increases the effective magnetization. A further complication is added by the oscillations that occur along the axis of the magnet and which are thought to arise from a non-uniform distribution of the transport current among the strands. For very low resistance conductor the strand-to-strand currents dominate and the field oscillations are considerably enhanced during ramping. If the interstrand resistance is high there will be little strand-to-strand coupling and the oscillations amplitude will not change but merely be superimposed on any changes in the average value caused by intrastrand coupling. Intermediate values of the interstrand resistance can cause a balancing between the two mechanisms so that the magnet would exhibit less B_2 change with ramp-rate than expected from loss measurements. Future experiments should make it possible to quantify this complex situation.

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REFERENCES

- 1) H. Brück et al., "Observation of a periodic pattern in the persistent-current fields of the superconducting HERA dipole magnets", DESY report HERA 91-01, 1991.
- 2) A.K. Ghosh et al., "Time dependent magnetization effects in superconducting accelerator magnets", Int. J. of Mod. Phys. A (Suppl.) 2B, 1993. p. 665.
- 3) A.K. Ghosh et al., "Axial variations in the magnetic fields of superconducting dipoles and quadrupoles", Proceedings of the '93 Particle Accl. Conf. Washington, DC, 1993 (in press).
- 4) G.H. Morgan, "Eddy currents in flat metal-filled superconducting braids", J. Appl. Phys. vol. 44, 1973, p. 3319.
- 5) E.D. Courant, "Eddy currents in superconducting braid", ISA Tech. Note 168, BNL, 1980 (unpublished).
- 6) T. Ogitsu et al., "AC loss measurements of SSC dipole magnets", Proceedings of ICFA Workshop on AC Superconductivity, KEK Report 92-14, 1992, p. 23.
- 7) M.M. Wilson, Superconducting Magnets, Clarendon Press Oxford, 1983, p. 176.
- 8) J. Strait et al., "Quench performance of Fermilab - General Dynamics built full-length SSC Collider dipole magnets", in Supercollider 4, (ed. J. Nonte) Plenum Press, NY 1992, p. 365.
- 9) T. Ogitsu, "Dependence of AC loss and multipole coefficients on cable eddy currents", MD-TA-240-SSCL, 1993 (unpublished).
- 10) R. A. Thomas, "Loss measurements in SSC and RHIC dipoles", MD note, BNL, (unpublished).
- 11) T. Ogitsu, SSCL (private communication).

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