MAGNETIZATION EFFECTS IN SUPERCONDUCTING ACCELERATOR MAGNETS

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ABSTRACT

Measurements of the effect of the superconductor magnetization on the field shape of dipole magnets are presented. Such effects are most obvious at low fields where the current capability of the windings is very high and only a small fraction is used to support the transport current which produces the field. In most dipoles the fundamental field component is reduced slightly when the field is increasing and enhanced by an almost equal amount when the field is decreasing. The effect on the higher allowed harmonics such as the sextupole and decapole components is much greater, giving rise to considerable hysteretic behavior at the low field levels where the beam is injected into the accelerator. The measurements summarized in this paper indicate that it is possible to accurately specify the field from current measurements if a "standard" energizing cycle is used and the previous "history" of the magnet is known.

I. INTRODUCTION

The nonreversible nature of the fields produced by superconducting magnets are well known. Trapped fields and nonlinear transfer functions are the most obvious manifestations of the magnetization of the superconductor induced by the changing transport current. While the advent of modern finely divided composite conductors has greatly reduced the magnitude of these effects, they are still large enough to require compensation in magnets for high energy accelerators. Since the exact field shape is a function of the past magnetic history, the harmonic coefficients display a marked hysteretic behavior and have a different value for increasing and decreasing fields. In addition, at high rates of change of field, currents can be induced between the individual wires in a large conductor giving rise to changes in field shape which decay to zero when field ramping is stopped. Detailed measurements have been made on several dipoles built for the ISABELLE¹ Project and they are summarized in this report.

II. TRANSFER FUNCTION

The field distribution in a dipole magnet can be written conveniently as

$$B = B_0 [1 + b_1 x + b_2 x^2 + b_3 x^3 + \dots b_{n-1} x^{n-1} + \dots]$$

where B_0 is the field at the magnetic center, x is the distance along the median plane and b_{n-1} are the harmonic coefficients. In a conventional magnet the field B_0 is directly proportional to the current at least at low fields where there is no iron saturation. The constant of proportionality B/I is termed the "transfer function". In Fig. 1 the transfer function of the MK-VI dipole is shown vs magnetic field. The curve coming up from the lower left is for the initial energizing cycle and the arrows indicate the path followed on subsequent cycles. The measurements were made using a NMR field probe and a precision dc current transducer. It can be seen from Fig. 1 that the transfer function is depressed from its nominal value (14.482 gauss/amp) when the field is increasing, and is enhanced by an almost equal amount when the field is decreasing. The difference between the observed and calculated values

becomes smaller and smaller at higher fields because more and more of the super current is used up by the transport current which produces the field.

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Fig. 1. The transfer function for dipole MK-VI as a function of central field.

The reproducibility of the field from cycle to cycle is of considerable importance in accelerator design. In Fig. 2 the field near injection, (3750 gauss), is shown as a function of current for three cycles from zero to maximum current. No measurable difference was observed in the field provided that each cycle started at the same current value and increased uniformly. Decreasing currents give a parallel curve approximately 15 gauss higher. The sensitivity of the instrumentation implies that the reproducibility from cycle to cycle is considerably better than 1 part in 10^4 . At higher temperatures the deviation from the classical value is reduced as indicated by the dashed lines for 6.1 K, where the separation between up and down is only 10 G. If very small excursions are made about a nominal current value, simulating power supply noise, the central field reproduces exactly following the lower curve up and down. This is not true for the high allowed harmonics. Current changes greater than a few A, however, will cause hysteretic behavior in the fundamental.

III. HIGHER HARMONICS

Since the magnetization is a bulk effect which occurs throughout the volume of the windings, it can only effect the harmonics allowed by the symmetry of the magnet. In a dipole this means that it will be most noticeable for the sextupole and decapole components. The sextupole component of the MK-VI magnet is shown in Fig. 3 as a function of current. The lower curve is for the initial magnetization cycle and the arrows show the path followed after the first cycle.

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Since this curve is for a full current cycle, it represents the envelope of the hysteretic behavior at that temperature and any point inside can be reached by following a suitable current path. The field change required to saturate the filaments is approximately 3.5 kG so that any change greater than this will result in the sextupole coefficient following the curve of Fig. 3. Again the up and down curves become closer and closer together as the field increases and the excess supercurrent is used up producing the main field. In the sextupole case the deviation decreases as the square of the field rather than linearly as occurs with the dipole component. A similar curve for the decapole (5^{th}) component would show the magnetization effect decreasing very rapidly (as the fourth power of the field).

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Fig. 2. The dipole field near injection as a function of current.

Because of the much greater hysteresis in the higher harmonics, the effect of small current changes is more dramatic. This is shown in Fig. 4 for the first two allowed terms. The loops swept out by the field changes are dependent on the amount of current change; following the normal curve for increasing current and following a diamagnetic one when the current is decreased. This means that the change in sextupole component for power supply ripple at injection is much larger than the change in the dipole field. It is, however, still quite reasonable at $5 \times 10^{-7} \text{ cm}^{-2} \text{ gauss}^{-1}$ for the sextupole and $10^{-8} \text{ cm}^{-4} \text{ gauss}^{-1}$ for the decapole.

IV. TEMPERATURE DEPENDENCE

The magnetization dipole and sextupole components were measured at different temperatures and the results are shown in Fig. 5 where the deviation from the classical value is plotted against temperature. Both components extrapolate to zero in the vicinity of 10 K which is in good agreement with the critical temperature of NbTi at 4 K.

Fig. 3. The effect of superconductor magnetization on the sextupole coefficient of MK-VI at low fields.

Fig. 4. The effect of small current excursions on the sextupole and decapole components of MK-VII near the injection field.

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Fig. 5. The temperature dependence of the magnetization induced dipole and sextupole fields in MK-VI.

V. DYNAMIC EFFECTS

Rapidly changing fields can induce currents between the wires in the braided conductor used in these magnets. This has an effect similar to that arising from the magnetization except that such currents decay rapidly when the field stops changing. In Fig. 6 the sextupole field generated by the changing dipole field is plotted against the rate of change of field for two dipoles MK-VI and MK-VII. The MK-VII magnet has a conductor which employs a special high resistivity interwire filler to reduce the induced coupling. Since the dipoles are fitted with a sextupole trim coil, this "dynamic" effect can be controlled by offsetting the normal current program by a fixed amount which is proportional to the rate of change of field.

VI. CONCLUSIONS

The following conclusions can be drawn from these measurements: i) The field shape can be accurately specified from the current provided a specific cycle is followed and the current does not reverse direction during the energizing, ii) Power supply ripple will produce a ripple in the central field which is directly proportional to the current, iii) Power supply ripple will produce a magnified ripple in the higher harmonics but still well within the bounds needed for successful machine operation.

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REFERENCES

1. ISABELLE, A Proton-Proton Colliding Beam Facility, BNL 50718, January 1978.

Fig. 6. The rate induced sextupole field in MK-VI and MK-VII as a function of the rate of change of field.