TIME DEPENDENCE OF PERSISTENT-CURRENT FIELD DISTORTIONS IN THE SUPERCONDUCTING HERA MAGNETS

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Abstract: The time dependence of the persistent-current sextupole and dipole components has been measured in more than 250 HERA dipoles. The drift of these two multipole components is correlated and almost logarithmic in time. The initial current cycle of the magnet has a surprisingly strong influence on the decay rates. By introducing a break in this cycle the time drift at the HERA injection energy can be greatly reduced, thereby relieving the requirements on time-dependent sextupole corrections considerably. Reference dipoles with diagnostic equipment will be used to determine and correct the time and field dependent dipole and sextupole errors in the HERA proton ring.

Introduction

A well-known feature of superconducting accelerator magnets are the field distortions at low excitation which are caused by persistent magnetization currents in the superconductor filaments. A detailed description of the resulting multipole fields and a comparison with model calculations have been presented elsewhere [1]. Also measurements of the time dependence of the persistent current effects in the HERA magnets have already been published [2]. In this paper we want to present data from a much larger sample of dipole magnets and study in particular the influence of various parameters on the decay rates. Most of the data have been collected at a magnet current of 250 A on the "up-ramp" branch of the hysteresis curve, corresponding to the 40 GeV injection energy of the HERA proton storage ring.

Measurements and Discussion

The sextupole and dipole components as a function of time are routinely measured at a magnet current of 250 A. To establish well-defined initial conditions the majority of the magnets measured so far have been subjected to the following initialization procedure:

a) A quench is triggered by heaters strips
b) The coil current is cycled:
0 A - 6000 A (at 20 A/s)
6000 A - 50 A (10 A/s) (1)
50 A - 250 A (1 A/s)

A minimum current of 50 A has been chosen to ensure a proper power supply regulation which is essential to obtain reproducible results. The injection current of 250 A is approached with a small ramp speed to minimize current overshoots.

The sextupole component is determined with a rotating pickup-coil, the dipole component with an NMR probe. Of great interest for the operation of HERA is the change of the persistent current fields during the 30 minute long accumulation time of proton bunches which starts a few minutes after the magnet current has been stabilized. In the time interval from 200 s to 2000 s the drift of the field components is well represented by the form A-R log(t) (see Fig. 1), so this change is identical with the logarithmic decay rate R.

The persistent-current contribution $\tilde{B}_1$ to the dipole field itself (about 10 Gauss at 250 A) shows a rather similar time dependence (Fig. 2). The decay rates of the sextupole and the dipole components are in fact strongly correlated (Fig.3), suggestive of a common origin for both decays.

It is tempting to attribute the decrease of the multipole fields to flux creep in the superconductor, which is known [3] to lead to a logarithmic time decrease of the critical current density. There are, however, a number of observations which indicate that the drift phenomena in superconducting magnets are of a more complicated nature than those in small superconductor samples. The first observation is that the decay rates vary considerably from magnet to magnet (see Fig. 3) and are significantly different for magnets made from different superconducting cables, as shown in Table 1.

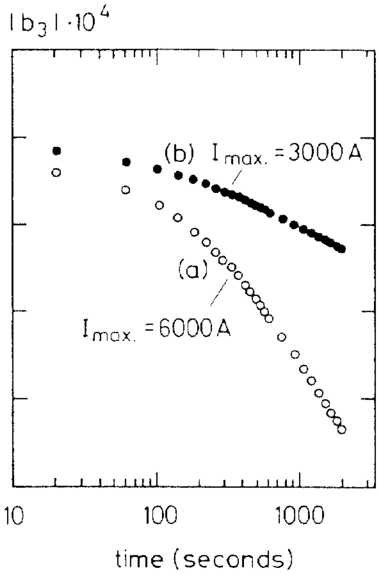

Fig. 1: Time dependence of the absolute value of the sextupole coefficient at a dipole current of 250 A.
Curve (a): Imax = 6000 A
curve (b): Imax = 3000 A

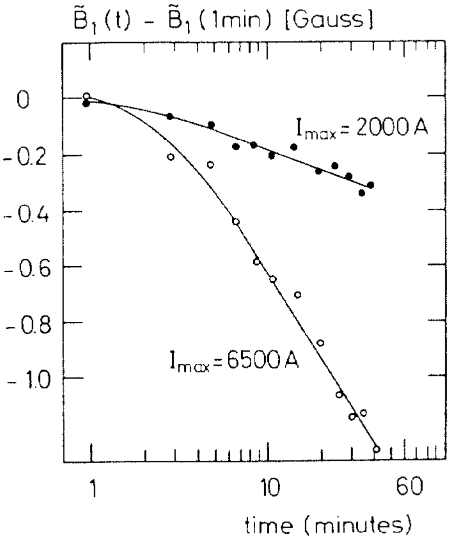

Fig. 2: Influence of the maximum current in the initial cycle on the decay of the persistent-current dipole field $\tilde{B}_1$ in a coil without iron yoke (IGC superconductor)

Table 1: Change of dipole and sextupole components in 106 dipoles with ABB conductor and 122 dipoles with LMI conductor. Initialization procedure (1) with a single cycle and Imax = 6000 A was used

Average change 200 s -> 2000 s	$<\delta\tilde{B}_1>$ (Gauss)	$\delta b_3 \cdot 10^4$
ABB cable	0.68 ± 0.18	1.77 ± 0.48
LMI cable	1.15 ± 0.23	3.22 ± 0.58

Secondly, measurements with a different maximum current in the initial cycle reveal a drastically different decay rate. Curve (b) in Fig. 1 differs from curve (a) only in the value of the maximum current in the initial cycle (Imax = 3000 A instead of Imax = 6000 A) but the decay of the sextupole at 250 A is reduced by almost a factor of 2.5. The strong influence of Imax on the decay is a surprising and unexpected phenomenon because the sextupole hysteresis curve at low currents is hardly influenced by Imax. This phenomenon is observed both in the magnets with ABB and with LMI superconductor and in coils without iron yoke.

Fig. 2 shows that the decay of the persistent-current contribution $\tilde{B}_1$ to the dipole field is also strongly influenced by Imax.

In Fig. 4 we plot the time dependence of the sextupole for increasing maximum currents in the initial cycle. At Imax = 750 A, a very flat behaviour with little decay is found but with increasing Imax the curves become progressively steeper. The first two curves (Imax = 750 A resp. 1500 A, corresponding to dipole fields of 0.7 T resp. 1.4 T) can be directly compared to measurements on the time dependence of the magnetization in superconducting cable samples [4]. In these experiments, the samples are subjected to initial field cycles with maximum fields of up to 1.6 T. The decay rate, measured with a SQUID magnetometer, amounts to 1 - 2 % per decade of time and is thus about the same as in the 750 A and 1500 A curves of Fig. 4. At present it is not known whether cables samples would also show a stronger magnetization decay if they were subjected to a larger initical field sweep.

A proper choice of the maximum current in the initial cycle appears to be the right way to reduce the undesirable time variations in the multipole components of the magnets. From a practical point of view, however, the methods used for a single magnet on a test stand are not always applicable at an accelerator with more than 600 superconducting magnets. An initial quench is obviously excluded. Moreover, when a new injection is needed, the magnets have been excited to high fields from the previously stored beam at 800 GeV. So another way has to be found to reduce the decay rates. One obvious idea would be to ramp the magnets down from the high field and then perform a current cycle with a small maximum current before approaching the injection field. To simulate this procedure on the test stand, we have studied the response of a magnet to an initialization with two current cycles

a) quench
b) first cycle 0 A - 6000 A - 50 A
c) second cycle 50 A - Imax - 50 A - 250 A
(with Imax = 750 A, 2000 A, 3000 A, 4000 A)

The result has been disappointing since all curves show almost the same steep decay irrespective of the value of Imax in the second cycle. Apparently the coil has a long-term memory for the highest field or current applied to it.

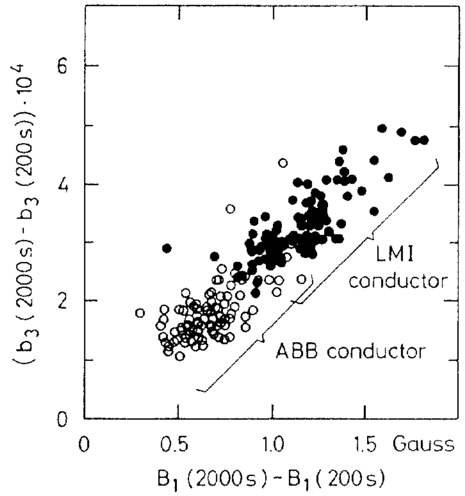

Fig. 3: Correlation between the logarithmic decay rates of the sextupole and dipole components in the HERA dipole magnets (one initial cycle with Imax = 6000 A)

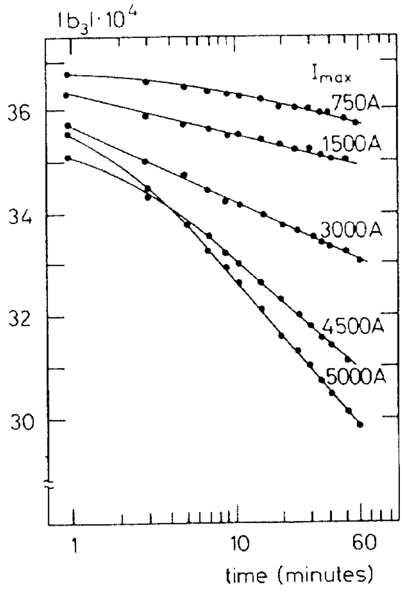

Fig. 4: Sextupole decay for increasing values of Imax in the initial cycle

The next attempt has been to introduce a break in the down-ramp part of the second cycle. While a break at high currents had no effect, a 30 minute long waiting period at low currents (250 A or 50 A) turned out to be quite effective in reducing the sextupole decay rate (Fig. 5). For this reason the initialization procedure for the routine measurements has recently been modified and is now as follows:

a) first cycle 50 A - 5500 A - 50 A
b) second cycle 50 A - 2000 A - 250 A (2)
c) 30 minute break at 250 A
d) 250 A - 50 A - 250 A

The initial quench has been omitted since it cannot be used in the accelerator either.

In all dipole magnets measured since much smaller decay rates have been observed than those shown in Fig. 3. The results from these measurements are summarized in Table 2.

Table 2: Change of dipole and sextupole components in 33 dipoles with ABB conductor and 30 dipoles with LMI conductor. Initialization procedure (2) with a 30 minute break was used.

Average change 200 s -> 2000 s	$<\delta\tilde{B}_1>$ (Gauss)	$\delta b_3 \cdot 10^4$
ABB cable	0.24 ± 0.08	0.80 ± 0.18
LMI cable	0.40 ± 0.10	1.27 ± 0.33

A number of magnets have been studied with both the old and the new initalization procedure. In Fig. 6 we have plotted the respective sextupole decay rates against each other. A clear correlation is observed showing that the waiting period is effective in reducing the decay rate but not the relative spread between different magnets nor the difference between the magnets with ABB and LMI superconductor.

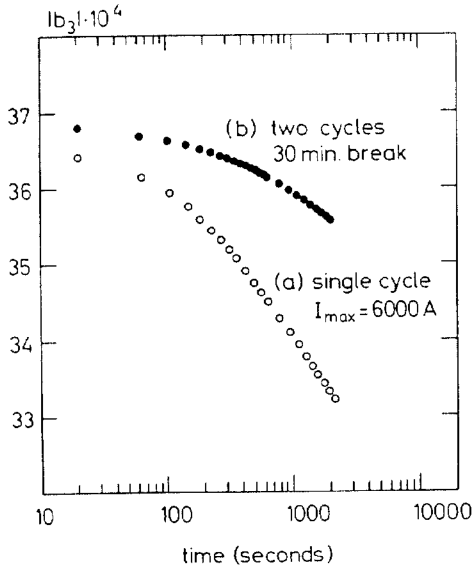

Fig. 5: Sextupole decay after single cycle (a) and after double cycle with 30 minutes break (b)

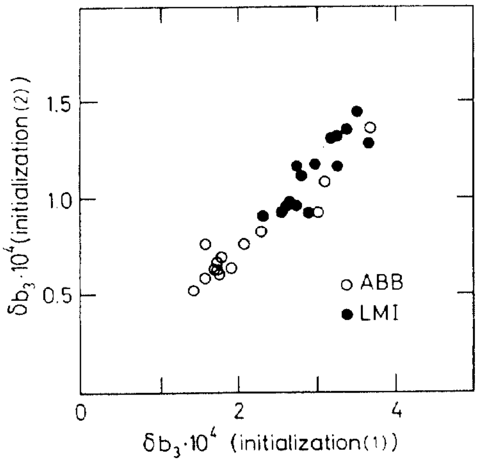

Fig. 6: Correlation between the sextupole decay rates observed after the two different initialization procedures (1) and (2)

When the proton injection is finished, the ramping of the dipole field during acceleration induces new eddy currents in the superconductor filaments. As a consequence, the sextupole reapproaches its original hysteresis curve. Fig. 7 demonstrates that the new initialization reduces not only the time drift during injection but has the additional advantage that the hysteresis curve is reached faster than with the old initialization (1). The overall correction requirements during injection and acceleration are therefore relieved.

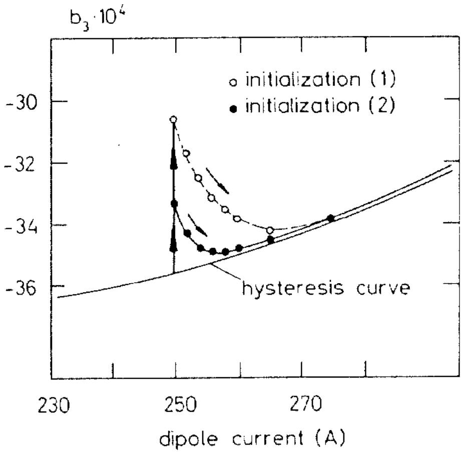

Fig. 7: Time variation of the sextupole coefficient b_3 during the 30 minute long injection period at 250 A and re-approach of the hysteresis curve during ramping of the dipole current. Measurements are shown for the two initialization procedures (1) and (2)

In HERA, the actual status of the dipole field and its sextupole component will be derived from two reference dipoles (one with ABB, the other with LMI conductor) which are equipped with NMR probes, pickup-coils and sextupole sensors and which are excited by the same current as the ring magnets. The measured field values will be used to control the correction coil currents.

Conclusions

Measurements on many HERA magnets have shown that a small maximum current in the initial current cycle leads to a much weaker time dependence of the persistent-current dipole and sextupole components in dipole magnets and of the 12-pole components in quadrupoles. A 30 minute long break in the cycle has a similar effect. The physical reasons for these phenomenona are not yet known and additional investigations on cable samples and on complete magnets are needed. The observations, however, open a practical way to reduce the undesirable time drift during the proton injection period considerably.

References

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