PERSISTENT CURRENT EFFECTS IN THE SUPERCONDUCTING HERA MAGNETS AND CORRECTION COILS

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Abstract

Measurements are presented on the sextupole and decapole components in 315 HERA dipoles and on the 12-pole and 20-pole components in 236 quadrupoles. The data agree very well with model calculations based on magnetization currents in the niobium-titanium filaments of the superconducting cable. The influence of the helium temperature on the sextupole component has been studied. The dipole magnets are equipped with superconducting quadrupole, sextupole and decapole correction coils mounted on the beam pipe. The mutual influence of the nested superconducting coils has been studied. The effect is found to be uncritical for the operation of the HERA storage ring.

Introduction

The proton storage ring of the HERA collider [1] is equipped with 422 superconducting dipole [2] and 224 quadrupole [3] magnets. For the nominal proton energy of 820 GeV dipole fields of 4.68 T and quadrupole gradients of 90.2 T/m are required which are achieved with a current of 5027 A. The magnetic length is 8.8 m for the dipoles and 1.9 m for the quadrupoles.

The dipole magnets contain 6 m long superconducting quadrupole and sextupole coils which are mounted in two layers on the beam pipe. Decapole correctors of 2.9 m length cover the remaining part of the beam pipe. The concept of distributed beam pipe coils was chosen since it appeared difficult to incorporate sufficiently strong quadrupole correctors in short spool pieces together with the necessary dipole and sextupole correctors; secondly, an extended sextupole seemed superior to a short lens in compensating the persistent current effects. A clear disadvantage of this scheme is the mutual influence of the nested superconducting coils: a current ramp in the main coil leads to magnetization currents in the correction coils and vice versa.

The effect of persistent currents in the superconducting filaments is most pronounced at the low injection energy of 40 GeV. The resulting field distortions from the complete set of superconducting coils have been carefully analyzed under different conditions relevant for the operation of the HERA storage ring. If not explicitly stated all measurements are made at a helium temperature of 4.7± 0.05 K.

Effects of Magnetization Currents

The multipole components of the magnets are defined by the expansion

$$B_\theta\ (r,\theta) = B_{ref} \sum_{n=1}^{\infty} \left(\frac{r}{r_o}\right)^{n-1} (b_n \cos(n\theta) + a_n \sin(n\theta))$$

and B_r correspondingly. The reference radius is r_o = 25 mm, i.e. 2/3 of the inner coil radius. B_{ref} is the amplitude of the main field (dipole resp. quadrupole) at $r = r_o$.

Any change of the magnet current induces magnetization currents in the niobium-titanium filaments which generate multipole fields of all orders allowed by the coil symmetry: n=1, 3, 5,.. for dipoles, and n =2, 6, 10,.. for quadrupoles. These closed-loop currents have opposite direction for increasing and decreasing main fields, resulting in the well known hysteresis effects of the 6- and 10-pole coefficients of dipoles and the 12-pole and 20-pole coefficients of quadrupoles. In Figs. 1 and 2 we show the averaged multipole components of about 300 dipoles and 225 quadrupoles with their rms variations. Before performing the measurements the magnets are quenched and the current is cycled 0 A -> 6000 A -> 50 A to establish well defined initial conditions. For the dipole magnets the measurements are done in the 3m long section outside the quadrupole and sextupole correction coils and are therefore not affected by magnetization currents in these coils. Magnetization currents in the decapole coil generate only multipoles of very high order (n = 9, 19, ..) which are in addition quite small since the coil is implemented as a single wire loop. Similarly, the magnetization of the 12-pole coil in the quadrupoles has no influence on the multipoles in Fig. 2.

It should be noted that the time dependence of the persistent currents [4] introduces a systematic error in the multipole coefficients. The measurements presented here are made with rotating pick-up coils and start about 1 minute after a preselected current has been reached. The measurement itself takes 5 seconds. We estimate that the multipole coefficients are shifted systematically by a few percent due to these delays.

The predictions of a magnetization current model[5], shown as continuous curves in Figs. 1 and 2, are in excellent agreement with the data. The persistent current contribution to the main field in the dipole and quadrupole magnets is discussed elsewhere [6]. In the model long lasting eddy currents are assumed to occur within single filaments, but not between different filaments of a strand or between different strands of a transposed cable. The persistent eddy currents are calculated according to the experimentally verified "critical state" model [7] and are therefore governed by the critical current density $J_c(B,T)$ at the given local field and temperature. To determine J_c at low fields, we have used recent measurements by A. Ghosh [8] on the magnetization of ABB cable samples. The uncertainty in J_c is estimated to be about 10 %.

The Meissner phase has not been taken into account in the model, although its influence can be clearly seen when a virgin magnet is excited to fields below $B_{c1}(T)$. After a large field sweep, however, fluxoids remain trapped in the superconductor and the Meissner phase is strongly suppressed except in a limited region of the coil where the local field is sufficiently low. This region is too small to contribute significantly to the multipole fields.

The HERA dipoles from the two vendors ABB (Germany) and Ansaldo/Zanon (Italy) have only slightly different persistent current multipoles, although they are made from different superconductors. In the German magnets, ABB conductor with filaments of 14 μm diameter is used and the average sextupole at injection energy is b_3 = (-35.7±1.2) E-4. In the Italian magnets, made from LMI conductor with 16 μm filaments, b_3 = (-36.7±1.6) E-4. The product of filament diameter and critical current density is nearly the same for both conductors and so are the magnetization effects.

To investigate the influence of temperature on the magnetization currents, a dipole magnet was cooled with two-phase forced-flow helium in the temperature range of 4.4 K to 6.4 K. As can be seen in Fig. 3, a clear temperature dependence of the sextupole hysteresis is observed. In the HERA accelerator the temperature around the ring is expected to vary by at most 0.2 K.

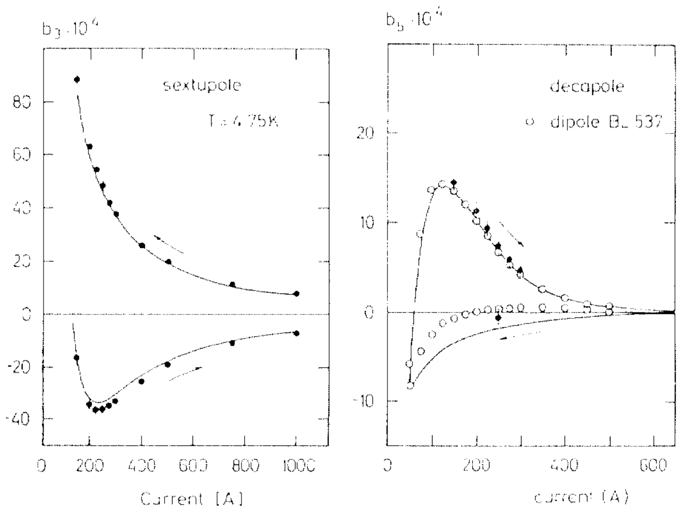

Fig.1:
The averaged sextupole and decapole coefficients with rms variations from 315 HERA dipoles as a function of the coil current. Open points are measurements of a single magnet. The curves are model [5] calculations. The ramp direction of the current is indicated by arrows.

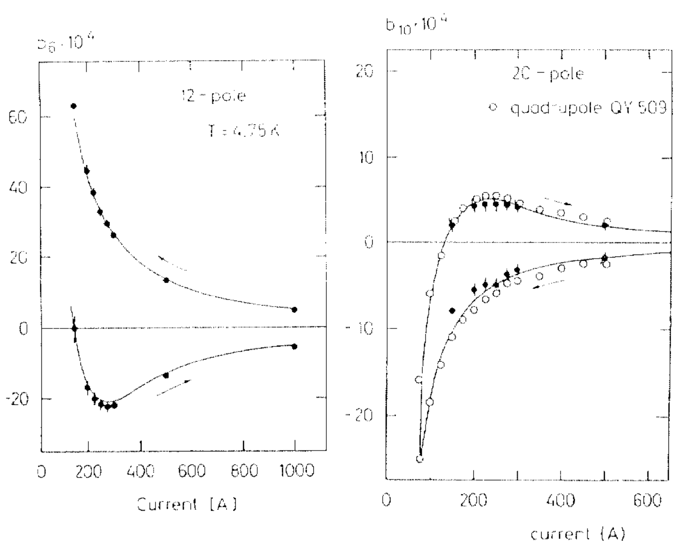

Fig. 2:
The averaged 12-pole and 20-pole coefficients from 236 quadrupoles.

The resulting sextupole variations are therefore about 0.5 E-4 at the injection energy.

Magnetization Effects of Correction Coils

The beam pipe correction coils nested inside the main dipole coil generate persistent current effects in two ways. Firstly, they act as passive superconductors, i.e. any change in the main dipole field induces eddy currents in the filaments which influence the field at the proton beam. Secondly, when the correction coils are excited their outer field induces magnetization currents in the filaments of the main dipole coil which have to compete with the already existing persistent currents in these filaments.

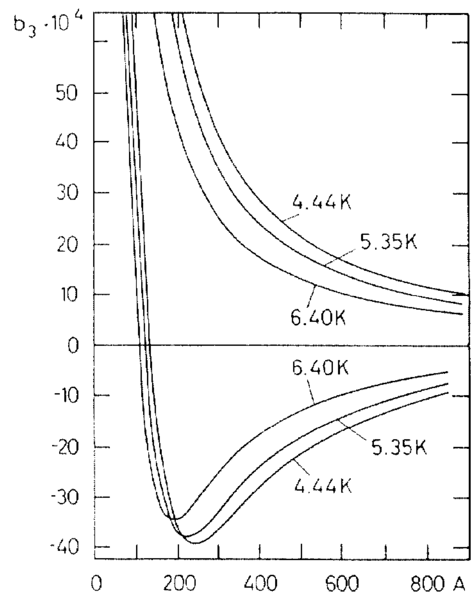

Fig. 3:
Sextupole hysteresis in a HERA dipole magnet with LMI conductor for different temperatures. The curves are eyeball fits to the measured data points.

The "passive superconductor" aspect can be studied experimentally since the quadrupole and sextupole correction coils cover only two thirds of the main dipole coil. In Fig. 4 we have plotted the difference of the sextupole components measured inside and outside the correction coils (at zero correction coil current) and similarily for the decapole. Good agreement is observed between the data and model calculations. It is interesting to note that the quadrupole windings contribute to the sextupole field and the sextupole windings to the decapole.

More complicated are the persistent currents in the main dipole coil which are induced by current changes in the quadrupole or sextupole correction coils. Large field distortions at the injection energy may result if the current in the correction elements is raised to unreasonably high values. The quadrupole correctors shift the tune of the machine at 800 GeV by 2 units with a correction coil current of 80 A. The chromaticity correction at this energy requires a sextupole current of 46 A. At the injection energy of 40 GeV the currents needed in the correction coils are below 4 A. The multipole components resulting from a correction current variation of 4 A have been measured and are all below 1. E-4 and thus rather modest.

Moreover, it should be noted that during the proton beam injection much smaller variations of the correction coil currents are needed to control the working point and the chromaticity of the machine and to accomodate for the time dependence of the persistent current effects. When the protons are accelerated the correction currents are raised in proportion to the main current, but the multipole coefficients induced by the increasing correction fields remain small since the main dipole field is also increasing. At large fields they become totally negligible since the critical current density is dropping rapidly there.

Unacceptable field distortions may result, however, if accidentally the correction coils should have been

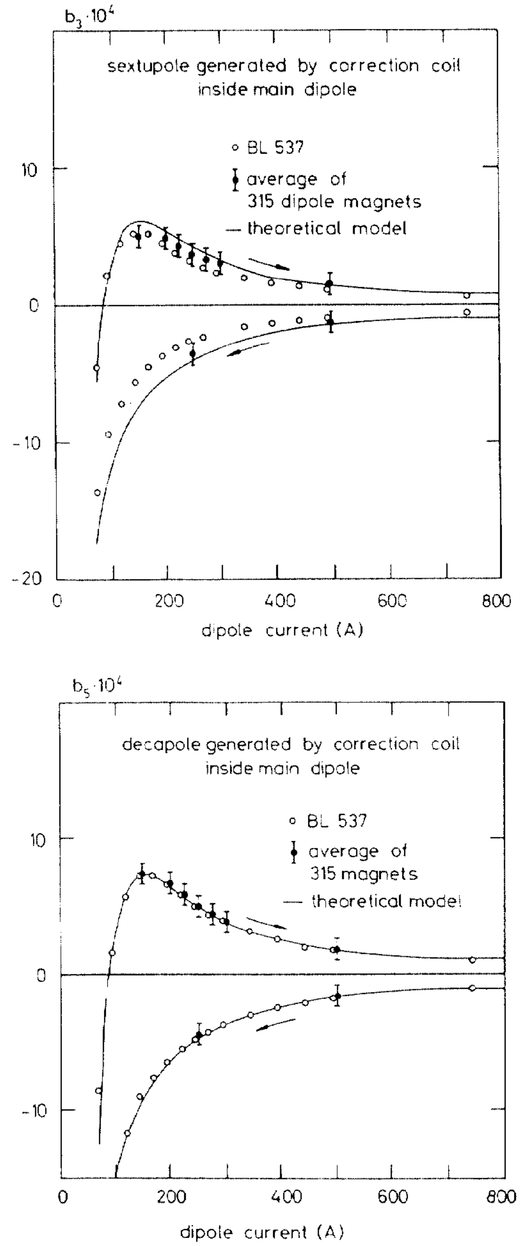

Fig. 4:
Sextupole and decapole components generated by persistent currents in the beam pipe correction coils as a function of the dipole current. Shown are data from a single magnet (BL 537) and the average values with rms variations from 315 dipoles. The ramp direction of the main dipole current is indicated by arrows. (The correction coil current is zero in these measurements).

excited to currents much larger than 4 A while the main magnets are close to the injection field or if, after a luminosity run at 800 GeV, the main current and the correction coil currents are not ramped down simultaneously.

Fortunately, these field distortions can be completely extinguished by performing an extra current cycle 250 A -> 2000 A -> 50 A -> 250 A in the main magnets as has been verified experimentally.

Conclusions

The field distortions from magnetization currents have been measured for the majority of the HERA magnets and are found to be in excellent agreement with model calculations. The correction coils inside the main dipole coil modify the sextupole and decapole components. Current changes in these coils have only a small effect on the magnetization of the main dipole coil provided the correction currents are limited to the allowed range. Stronger persistent currents, which may be induced by large accidental excitations of the correction coils, can be eliminated by an extra current cycle in the main coil. The HERA control system will include energy dependent limits for the correction coil currents to prevent such excitations.

Acknowledgement

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References

[1] B.H. Wiik, "HERA Status", Invited talk given at this conference.

[2] For a description of the magnets see: H. Kaiser, "Design of Superconducting Dipoles for HERA", 13th Inter. Conf. on High Energy Accelerators; Novosibirsk, USSR, Aug. 1986. S. Wolff, "Superconducting HERA Magnets", IEEE Trans. Mag.24, No. 2, 719 (1988).

[3] R. Auzolle, P. Le Marrec, A. Patoux, J. Perot, J.M. Rifflet, "Superconducting Quadrupoles for HERA", ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven 1986, BNL 52006.

[4] H.Brück, D.Gall, G.Kries, J.Krzywinski, R.Lange, R. Meinke, H. Preißner, P. Schmüser, Y. Zhao, "Time Dependence of Persistent-Current Field Distortions in the Superconducting HERA Magnets", this conference.

[5] H. Brück, R. Meinke, F. Müller, P. Schmüser, Z. Phys. C 44, 385 (1989).

[6] H. R. Barton et al., "Performance of the Superconducting Magnets for the HERA Accelerator", MT-11, Tsukuba, Japan 1989.

[7] C.P. Bean, Phys. Rev. Letters 8 (1962), 250.

[8] A. K. Ghosh, private communication.