FIELD QUALITY ISSUES IN SUPERCONDUCTING MAGNETS

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Abstract:

The extensive measurements, made on all magnets of the proton-electron collider HERA, yield a wealth of information on the field quality that can be achieved in a large-scale industrial production of superconducting magnets. The field integrals of the dipoles and quadrupoles have been determined with a precision of 0.02 to 0.03%, the field orientation to within 0.15 mrad and the position of the quadrupole axis to within 0.2 mm. Higher harmonics have been measured at various excitations of the magnets and also in collared coils at room temperature. The persistent-current contributions to the main field of the magnets and to the higher multipoles as well as their time dependence have been studied in detail.

I. INTRODUCTION

The quality requirements imposed on the superconducting magnets of large, high intensity hadron storage rings are quite demanding. The recently completed proton-electron collider HERA comprises 422 dipoles, 224 quadrupoles and more than 1000 correction coils, all superconducting. The magnets were produced in various industrial firms and were thoroughly tested in industry and at DESY. Additional data exist from prototype magnets of the Relativistic Heavy Ion Collider RHIC at Brookhaven and of the Superconducting Super Collider SSC.

My first topic is not related to field quality but is of prime importance for the accelerator, namely the quench performance and reliability of the magnets. The quantities characterizing the precision of the magnets are presented in Sections III, IV and V: field integral and field orientation; higher multipole components; effect of persistent magnetization currents and their time dependence.

II. QUENCH PERFORMANCE

The nominal proton energy in HERA is 820 GeV, corresponding to a dipole field of 4.68 T and a quadrupole gradient of 91.2 T/m at a coil current of 5025 A. All 449 dipoles (including spares) and 246 quadrupoles were cryogenically tested and driven to a spontaneous quench at least 3-5 times.

The average quench current of the Ansaldo/Zanon dipoles, made in Italy from LMI cable, is 6373±98 A at a helium temperature of 4.75 K. The ABB magnets, produced in Germany from the slightly superior ABB conductor, achieved 6536±75 A. The measured quench current is close to the critical current of the conductor. The helium temperature in the HERA ring is 4.4 K, resulting in a peak field of 6.3 - 6.4 T.

Except for four magnets with shorted windings and one with a bad spot in the superconductor, which were sent back to the companies for repair, no magnet quenched below the nominal current of 5025 A and 93% exceeded 6000 A in the first attempt. For the majority zero or one training step sufficed to reach a plateau in the quench current. The quadrupole quench currents peak at higher values (7384±154 A) owing to the smaller local field in the coil. No significant difference was observed between the French (Alsthom) and German (Interatom/Noell) production lines which used both Vacuumschmelze superconductor. The plateau was again reached at the first or second excitation.

The HERA magnets have a large margin between the operating and the peak field. The same applies for the RHIC magnets [1]. The data from eight 9.7 m long dipoles show a bit of training but the magnets appear to be totally safe at the operating field of 3.5 T. The situation has been much more critical with the early 4 cm-bore SSC magnets in which the operating field of 6.6 T and the peak field were almost identical. In the new 5 cm-design, sufficient superconductor cross section is foreseen to allow for a 10% safety margin. Nevertheless, a quench test of every single magnet is necessary in my opinion to ensure safe operation of the collider.

III. FIELD INTEGRAL AND FIELD ORIENTATION OF DIPOLES AND QUADRUPOLES

The dipole field is determined with a detector [2] containing a nuclear magnetic resonance and two orthogonal Hall probes, coupled to a gravitational sensor. The detector is moved through the dipole with a positional accuracy of better than 1 mm. The field integral is determined with a precision of 0.02%. The field direction along the dipole axis is obtained from the readings

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of the two orthogonal Hall probes and of the gravitational sensor with an accuracy of 0.15 mrad.

The distributions of the field integrals for more than 440 dipoles are plotted in Fig. 1a.

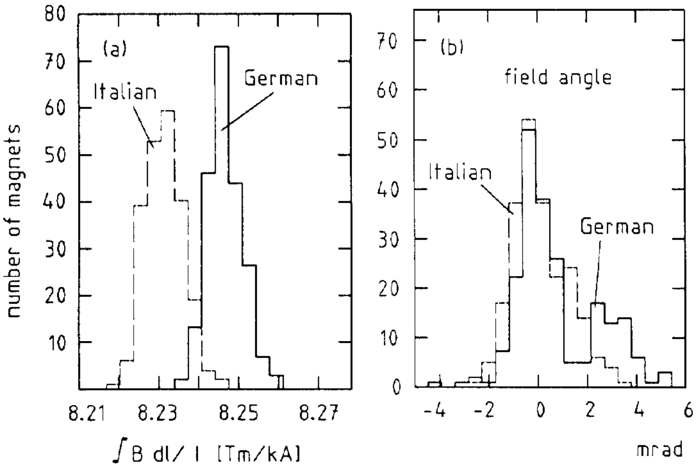

Fig. 1 (a) The integrated dipole field, normalized to the current, for all HERA dipoles. (b) The field orientation with respect to gravity, averaged over the full magnet length.

A systematic difference of 0.19% is observed between the dipoles from the Italian and the German production, which is caused by differences in the magnetic length as well as in the central field:

	ABB	Ansaldo/Zanon
l_{mag}	8.8335±0.0020	8.8257±0.0017 m
B/I	0.9336±0.0005	0.9328±0.0005 T/kA

In the HERA ring, this is compensated by means of correction dipoles. The iron yoke saturation amounts to 0.14% at 5000 A. The field angle with respect to gravity is shown in Fig. 1b. The average twist is 0.00±0.25 mrad/m.

In the quadrupoles, the gradient and the field direction are determined by a "stretched-wire" system [3]. A 100 μm thick copper-beryllium wire, stretched through the magnet parallel to its axis, is moved horizontally or vertically with micrometer precision. The magnetic flux swept by the motion is recorded. Suitable combinations of various motions yield the integrated gradient $\int g\,dl$, the angular orientation of the field and the position of the quadrupole axis.

The integrated gradient (Fig. 2a) differs by 0.12% between the quadrupoles made in France and in Germany.

The field direction with respect to gravity (Fig.2b) is 1.5±1.1 mrad for both production lines. The nonvanishing average value may be caused by slightly different contractions of the internal support elements during the cooldown of the

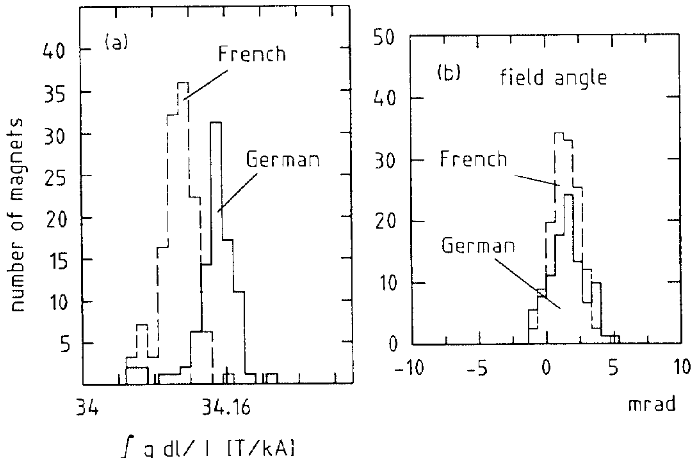

Fig. 2 (a) Integrated gradient in the HERA quadrupoles, normalized to the coil current. (b) Field orientation with respect to gravity.

magnet. A systematic shift is also seen in the vertical position of the quadrupole axis whereas the horizontal prealignment agrees quite well with the magnetic measurement:

	Alsthom	Noell
Δx =	-0.18±0.32	+0.13±0.35 mm
Δy =	-0.41±0.28	-0.36±0.37 mm

Similar data were obtained for the Tevatron quadrupoles [4]. The magnetically determined field orientation and axis were used for the survey of the dipoles and quadrupoles in the HERA accelerator.

IV. HIGHER MULTIPOLES

The normal resp. skew multipole coefficients b_n resp. a_n are defined by the multipole expansion of the azimuthal field component B_θ:

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

Here r_o is the reference radius, chosen to be 25 mm in the Tevatron, HERA and RHIC magnets and 10 mm in the prototype SSC dipoles with 40 m inner bore. B_{main} is the magnitude of the main field at $r = r_o$.

Dipole: $B_{main} = B_1$, $b_1 = 1$

Quadrupole: $B_{main} = g\cdot r_o$, $b_2 = 1$.

In the USA it is customary to expand the Cartesian field components in a power series. The multipole indices are then lower by one unit, so a normal sextupole is denoted by b_2 instead of b_3. In the following, the multipole coefficients are quoted in units of 10^{-4}.

The multipole coefficients in the HERA magnets are measured with rotating pick-up coil systems with several subcoils which internally compensate the main field to achieve a resolution of 0.2 units for higher order poles. The quadrupole system compensates also a dipole component which arises when the pick-up coil is not centered on the magnet axis.

The average values of the skew and normal multipole coefficients of the HERA dipoles at the nominal field are depicted in Fig. 3. The error bars represent the rms spread of the distribution.

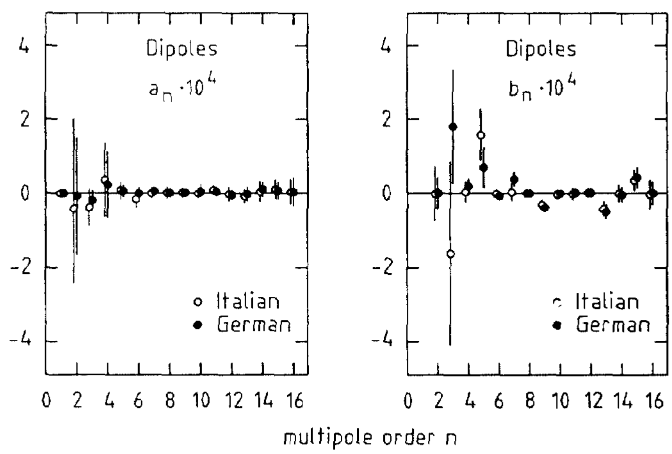

Fig.3 The average multipoles with rms errors of the HERA dipoles at 5000 A. The data are averaged over the full length of the magnets, including the end fields.

Most of the coefficients are very small and have standard deviations well below 0.5 units, the value used in the tracking program to determine the dynamic aperture of HERA. There are, however, a few exceptions: (1) the normal sextupole b_3 which is extremely sensitive to slight changes in the limiting angles of the coil shells and, (2), the skew quadrupole term a_2. The measured rms variations of these terms in the Tevatron [5], HERA, RHIC [1] and SSC [1] magnets are compared in Table 1.

While the HERA (especially the ABB) magnets have a smaller sextupole variation than the Tevatron magnets, their skew quadrupoles show a significantly larger scattering. This latter term is also large in the RHIC and SSC prototypes.

The Tevatron dipoles are the only magnets that allow a minimization of the quadrupole term by adjusting the coil with respect to the "warm-iron" yoke. The skew quadrupole is probably caused by a shift of the mid-plane between the top and bottom half coil during the collaring process. Although the half coils were matched with respect to their measured elastic moduli and many dipole coils were reopened and shimmed, it turned out to be very difficult to keep this coefficient within the specified limits. The a_2 term has an impact on the dynamic aperture of the HERA proton ring [6] and requires the installation of skew quadrupole correctors to reduce the coupling of horizontal and vertical betatron oscillations. At present no good method is known to me of how to ensure significantly smaller skew quadrupoles in future dipole magnets since the mid-plane is not constrained in any of the present dipole designs.

Table 1 Spread of the skew quadrupole and normal sextupole in units of 1E-4

	$\sigma(a_2)$	$\sigma(b_3)$	
Tevatron	0.50	3.12	$r_o = 25$ mm
ABB	1.55	1.56	
Ansaldo	1.97	2.45	
RHIC	4.3	4.6	
SSC	1.45	1.44	$r_o = 10$ mm

The sextupoles in the ABB and Ansaldo dipoles differ by 3 units. The sextupole correctors are used to compensate this systematic effect.

At the manufacturing plants, the dipole coils were measured at room temperature before their installation in the yoke and cryostat, using an ac current and a lock-in analyzer. Fig. 4 demonstrates a very clear correlation between the room-temperature data from collared coils and the cryogenic data from complete magnets, both in the normal sextupole and in the skew quadrupole terms. This proves the geometric origin of these poles. Similar correlations are observed for other coefficients. From the room-temperature data one can predict the $b_3(a_2)$ coefficients at 4 K with an rms precision of 0.6 (0.9) units, which is well within the specified limits. At SSCL it is in fact planned to measure only 10% of the magnets at 4 K and to derive the multipoles of the other magnets from "warm" measurements.

In the coil heads, the ideal dipole coil geometry is no more possible and strong multipoles appear. By inserting suitable epoxy-fibre-glass spacers in between the windings one can achieve end-field sextupoles and decapoles that integrate to zero. Fig. 5 shows the end-field sextupole and dipole in a HERA magnet, measured with a triple Hall-probe detector. The coil head regions are included in the integrated multipole data of Fig. 3.

The average multipoles of the HERA quadrupoles are shown in Fig. 6. The "allowed" coefficients b_6, b_{10} and b_{14} have non-vanishing theoretical values, indicated by open squares, which agree very well with the measured data. Concerning their effect on the beam, the multipole

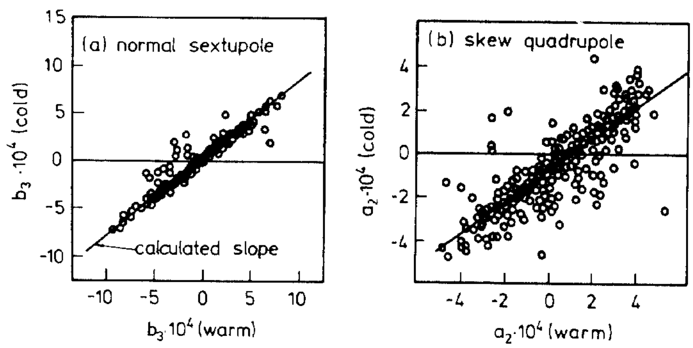

Fig. 4 Correlation between "warm" multipole data from collared coils and "cold" data from complete magnets. (a) normal sextupole (b) skew quadrupole

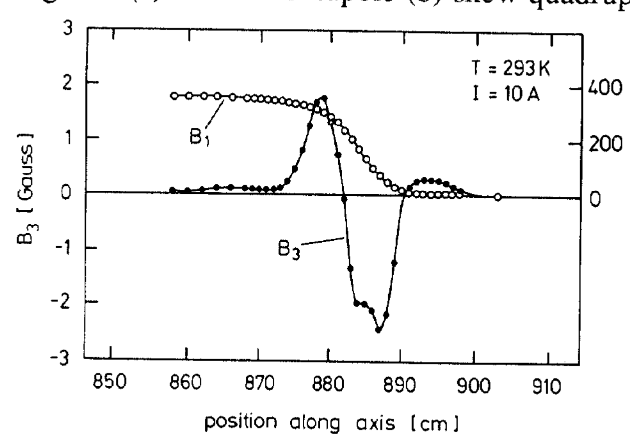

Fig. 5 The sextupole and dipole field in the coil head of a HERA dipole, excited to I=10A at room temperature.

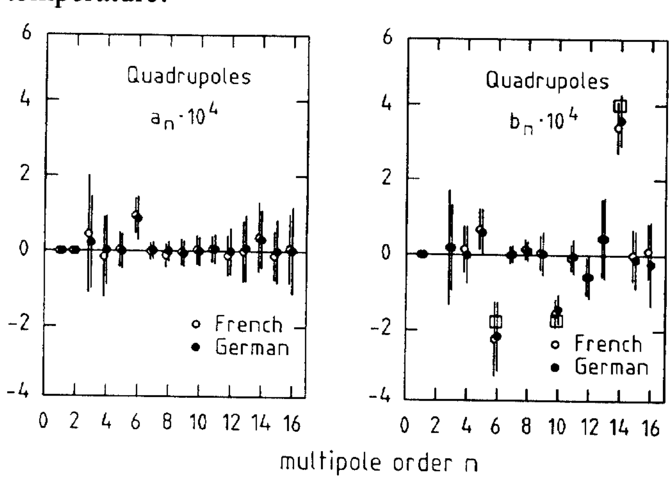

Fig. 6 The multipoles of the HERA quadrupoles at 5000 A, averaged over the full magnet length.

fields have to be related to the much longer integrated dipole field (one 1.9 m quadrupole per two 8.9 m dipoles). Then all quadrupole coefficients are below 0.5 units. Comparable multipoles were measured in the Tevatron quadrupoles [4].

The general conclusion is that a remarkable field quality has been achieved in a large-scale industrial production of superconducting magnets. All multipole coefficients are within the specified limits given to industry but most of them fulfill much tighter criteria.

V. PERSISTENT-CURRENT EFFECTS

At low excitation the field quality of superconducting magnets is seriously impaired by persistent currents in the niobium-titanium filaments, generating all multipoles allowed by coil symmetry: n = 1,3,5.. in a dipole, n = 2,6,10.. in a quadrupole. Since the field distortions are particularly large in HERA, owing to the low injection field of 0.23 T and the fairly thick filaments (14-16 μm diameter), considerable effort has been spent to analyze the effects. Fig. 7 shows the persistent-current contributions to the main dipole field and quadrupole gradient. At the proton injection energy of 40 GeV the main fields are reduced by 0.5% resp. 0.3% requiring a careful adjustment of the coil current to match HERA to

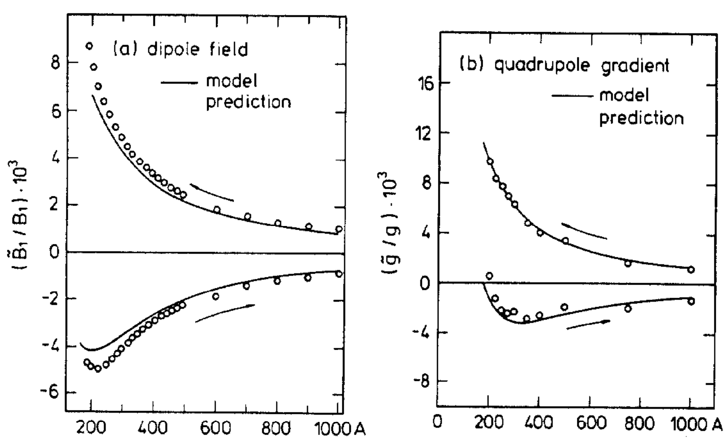

Fig 7 Persistent current contribution to (a) the main dipole field and (b) the quadrupole gradient.

the energy of the booster. The average sextupoles of all dipoles are plotted in Fig. 8a (the geometry sextupole was subtracted). The data are in excellent agreement with model calculations [7]. At 0.23 T, the rms spread is 1.4 units and the difference between the ABB and Ansaldo magnets is 1 unit. The sextupole component is compensated using the distributed sextupole correction coils. In addition, the 10-pole field in the dipoles and the

12-pole field in the quadrupoles require compensation, which is unnecessary in the Tevatron with its larger injection energy of 150 GeV. The precise field measurements have enabled to inject a positron beam of only 7 GeV into HERA. In the past weeks, 40 GeV protons were successfully stored.

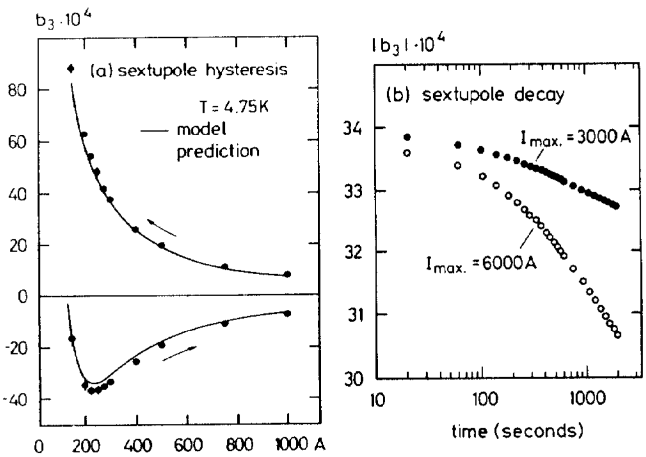

Fig. 8 (a) The sextupole in the HERA dipoles for increasing and decreasing main field (b) Time dependence of the sextupole at I = 250 A for 6000 A resp. 3000 A in the preceding current cycle.

A time dependence of the persistent-current sextupole was first observed at the Tevatron [8]. The drift is almost logarithmic in time (see Fig. 8b) and is observed in all multipole components. The phenomenon can be partly explained by flux creep [9] in the superconductor, however the decay rates measured in magnets are usually much larger than those in short cable samples [10].

Surprisingly, the decay rates are strongly influenced by the value and duration of the maximum field in the preceding field cycle (Fig.8b). Recently, another surprising phenomenon has been

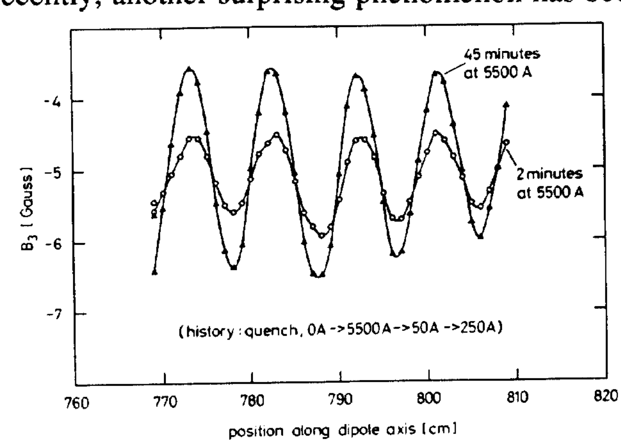

Fig. 9 Persistent-current sextupole at I = 250 A, measured along the dipole axis. The magnet was previously excited to 5500 A for 2 resp. 45 minutes.

detected [11]: when measured along the dipole axis, the persistent current fields exhibit an almost perfect harmonic oscillation with a wavelength close to the cable transposition length (see Fig 9). The explanation is probably a non-uniform distribution of the transport current among the strands in the cable. Like the decay rates, the oscillation amplitude measured at low field depends strongly on the magnitude and duration of the maximum field in the preceding cycle. Both effects are probably related. Because of its short wavelength, the oscillation has no influence on the dynamic aperture.

VI. CONCLUSIONS

In the intermediate field range of 4-6 Tesla, mass-produced superconducting accelerator magnets have gained a high degree of reliability and field quality. Using fine filaments (6 μm or less in the SSC) and a relatively high injection energy, the persistent-current field distortions can be kept at a very moderate level. For magnets in the 9-10 Tesla region, as needed in Large Hadron Collider LHC , the quench performance and field quality are still issues that require considerable R & D work.

I want to thank R.Meinke and the magnet measurement group at DESY for a most enjoyable collaboration. I am grateful to P.Wanderer for kindly providing me with information on the RHIC and SSC magnets and to S.Wolff for helpful comments.

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