Properties and Practical Performance of SC Magnets in Accelerators

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Abstract

A report is given on the properties and performance of superconducting accelerator magnets in the 5-6 Tesla regime. Most of the information stems from the industrially produced HERA magnets which were thoroughly tested both at industry and at DESY; data from prototype magnets for RHIC and SSC are also included. All magnets exceed the specified nominal field by a safe margin and can generally be excited to the critical current of the superconductor. The field integrals of the HERA magnets were determined with a precision of 0.02-0.03%, the field orientation to within 0.15 mrad and higher harmonics with a relative accuracy of 0.002%. Persistent current effects were studied in detail. During the commissioning of the proton-electron collider HERA the superconducting magnets worked with high reliability and their properties were exactly as predicted from the magnetic measurements. Not a single real quench was encountered in four months of continuous operation but just a few false alarms in the protection system.

1 INTRODUCTION

The hadron storage rings in the TeV range are all based on superconducting magnet technology providing significantly higher fields than normal magnets at much reduced operating costs. The requirements imposed on these magnets with respect to operational safety and field quality are demanding. The coils must be fabricated with a precision of 10-20 μm and confined by sturdy clamps of comparable accuracy, both to prevent the magnets from quenching under the influence of the enormous Lorentz forces and to keep the field distortions in the 0.01% range or below. All recent designs draw heavily on the principles of the pioneering Tevatron magnets. An important modification, devised at DESY, is the "cold-iron" yoke which surrounds the non-magnetic clamps and provides a substantial gain in central field without sacrificing the good field quality at high excitation.

For the HERA project, 449 dipoles, 247 quadrupoles and more than 1500 sc correction coils were manufactured by various firms in France, Germany, Italy and Holland. Prior to their installation in the cryostats, the harmonics of the coils were determined at room temperature. For quite a number of dipoles a re-opening of the clamps and shimming turned out to be necessary to keep the sextupole and skew quadrupole components within the specified limits. Upon their arrival at DESY, all magnets were subjected to an extensive test program comprising mechanical, optical and electrical measurements but above all thorough cryogenic investigations. All dipoles and quadrupoles were driven to a spontaneous quench at least 3-5 times; field integral, field orientation with respect to an external reference system and quadrupole axis were determined; higher harmonics were measured at various field levels with particular emphasis on persistent current effects and their time dependence. The results of these investigations are presented in Sections 2-5. The experience gained during the commissioning of HERA is reported in Sect. 6.

2 QUENCH PERFORMANCE, FORCES

The nominal HERA proton energy of 820 GeV corresponds to a field of 4.68 T and a gradient of 91.2 T/m which are achieved at a coil current of 5025 A. All magnets were driven to spontaneous quenches until a plateau in quench current was established. With the exception of 5 dipoles suffering from winding shorts or bad spots in the superconductor, every dipole passed the 5025 A level without any quench and 93% exceeded 6000 A at the first attempt. For the majority, zero or one training step sufficed to arrive at the plateau. The plateau quench current was 6373±98 A for the Ansaldo-Zanon dipoles and 6536±75 A for the ABB dipoles at a helium temperature of 4.75 K. These numbers are compatible with the critical currents of the LMI resp. ABB cables. The temperature in HERA is lower (4.4 K) resulting in a peak field of 6.3-6.4 T.

The HERA quadrupoles exhibit a similar, almost negligible training, achieving higher quench currents of 7384±154 A owing to the smaller field at the position of the superconducting windings.

Two HERA coils were used in a twin aperture dipole, which was built by ABB Mannheim for the LHC project at CERN. In a recent test [1] the magnet reached 8.3 T in superfluid helium of 1.8 K. This is a proof that coil structure and insulation are able to sustain considerably higher forces than occurring at HERA.

The HERA magnets feature an ample safety margin between operating and peak field. The magnets of the Relativistic Heavy Ion Collider RHIC possess the same reassuring property as was demonstrated in a recent FODO cell test [2]. The new SSC dipoles with 50 mm bore can be excited to 7.5 T with hardly any training [3] thereby exceeding the nominal 6.6 T by 13%.

A prerequisite for such a good performance is sufficient clamping of the superconducting windings. The recent SSC dipoles, built at Fermilab, feature stiff collars with additional support by the iron yoke. The deflections under excitation are below 0.02 mm. Fig. 1 shows the measured prestress; it remains positive up to a field of 8 T. The coil ends are preloaded axially to sustain the longitudinal forces.

Considerable effort has gone into improving the epoxy-fibreglass spacers in the coil head region where many quenches occurred in previous SSC prototypes.
The quench currents in the SSC magnets show a strong decrease at high ramp rates (dI/dt>100A/s), caused by eddy-current heating of the coil.

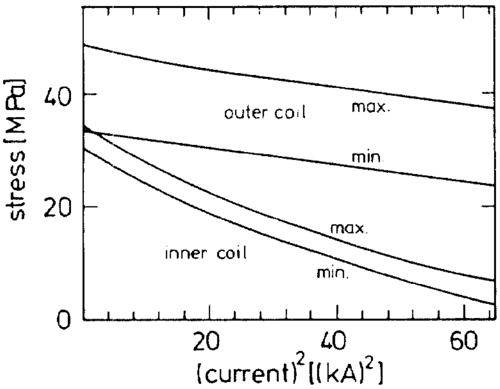

Fig. 1: Prestress in an SSC dipole as function of the square of the coil current [3].

3 FIELD INTEGRAL AND FIELD ORIENTATION

The field integral of the HERA dipoles is determined with a precision of 0.02%, using a nuclear magnetic resonance (NMR) and two Hall probes [4], and its angle relative to gravity to within 0.15 mrad. There is a 0.19% systematic difference between the Italian and the German made dipoles. This is compensated by means of correction dipoles.

The quadrupole field is analyzed with a 100 μm copper-beryllium wire that is stretched through the magnet parallel to its axis [5]. The magnetic flux swept in various horizontal and vertical motions is used to calculate the integrated gradient with a precision of 0.03%, the field orientation to within 0.15 mrad and the position of the axis to within 0.2 mm. The French (Alsthom) and German (Interatom/Noell) quadrupoles differ by 0.12% in the integrated gradient.

The coils were prealigned inside their cryostats at the companies. The magnetically determined field orientation differs from the prealignment by 1.5±1.1 mrad, the vertical axis position by Δy=-0.38±0.33 mm. The reason may be non-uniform contraction of the internal support elements during cooldown. Horizontally, no shift is observed, Δx=-0.03±0.33 mm. The magnetic data were used as a basis for the survey in the accelerator.

4 HIGHER MULTIPOLES

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

$$B_\theta(r,\theta)=B_{main} \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} [b_n\cos(n\theta)+a_n\sin(n\theta)]$$

Here r_0 is the reference radius and B_{main} is the magnitude of the main field at $r = r_0$.

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

Quadrupole: $B_{main} = g \cdot r_0$, $b_2 = 1$.

The multipole indices used in the USA are lower by one, so a normal sextupole is denoted by b_2 instead of b_3. In the following, the multipole coefficients are quoted in "units" of 0.0001.

The multipoles in the HERA magnets are measured with rotating pick-up coil systems with internal compensation of the large main field to achieve a resolution of 0.2 units for higher order poles. The average values of the skew and normal multipole coefficients of the HERA dipoles at the nominal field are depicted in Fig. 2.

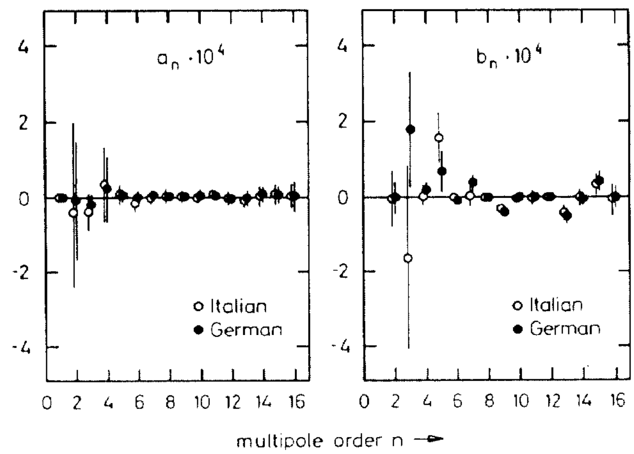

Fig. 2: The average multipoles with rms errors of the HERA dipoles at 5000 A. The data are averaged over the full length of the magnets, including the end fields.

Most of the coefficients are very small and have an rms spread well below 0.5 unit. There are a few exceptions: (1) the normal sextupole b_3 and decapole b_5 which are extremely sensitive to slight changes in the limiting angles of the coil shells and, (2), the skew quadrupole a_2 and octupole a_4. The measured rms variations of the b_3 and a_2 terms in the Tevatron [6], HERA, RHIC [2] and SSC [2,3] 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 is also true for RHIC magnets. The recent SSC dipoles feature a smaller skew quadrupole due to very precise moulding of the coils. It remains to be seen whether the narrow spread can be maintained in a large scale production. 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.

Table 1: Spread of the skew quadrupole and the normal sextupole in units of 0.0001

	$\sigma(a_2)$	$\sigma(b_3)$	
Tevatron	0.50	3.12	r_0 = 25 mm
ABB	1.55	1.56	
Ansaldo	1.97	2.45	
RHIC	4.3	4.6	
SSC	0.43	0.30	r_0 = 10 mm

The skew quadrupole is probably caused by a shift of the mid-plane between the top and bottom half coil during the collaring process. At the manufacturing plants, the HERA dipole coils were measured at room temperature before their installation in the yoke and cryostat, using an 11 Hz ac current and a lock-in analyzer. Fig. 3 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 decapole and in the skew quadrupole and octupole terms. This proves the geometric origin of these poles. From the room-temperature data one can predict the coefficients at 4 K with an rms precision of 0.2 - 0.9 units, which is well within the specified limits.

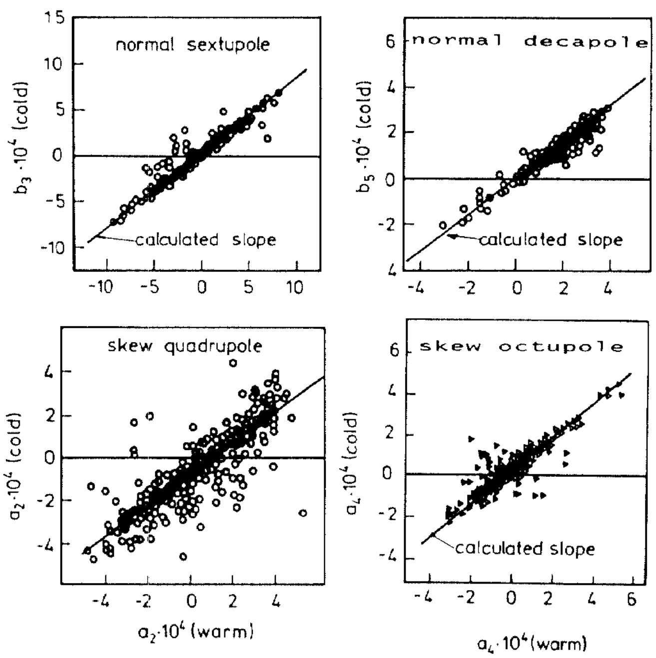

FIG. 3: Correlation between the "warm" multipoles data from collared coils (horizontal axis) and the "cold" data from complete magnets (vertical axis).

In the coil heads, the ideal dipole coil geometry is distorted and strong multipoles appear. By inserting suitable epoxy-fibreglass spacers in between the windings one can achieve end-field sextupoles and decapoles that integrate to zero. The coil head regions are included in the integrated multipole data of Fig. 2.

The multipole coefficients of the HERA quadrupoles are well below 0.5 units when related to the integrated dipole field.

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.

5 PERSISTENT-CURRENT EFFECTS AND YOKE SATURATION

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 NbTi filaments (14-16 μm diameter), considerable effort has been spent to analyze the effects. At the proton injection energy of 40 GeV the dipole field is reduced by 0.5% and the quadrupole gradient by 0.2-0.3%. The sextupole hysteresis curve, averaged over all dipoles, is plotted in Fig. 4a (sextupoles caused by geometric errors were subtracted).

The data are in excellent agreement with model calculations [7]. At 0.23 T, the sextupole is -32 units with an rms spread of 1.4 units and a difference between the ABB and Ansaldo magnets of 1 unit. It is compensated using the beam pipe sextupole 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.

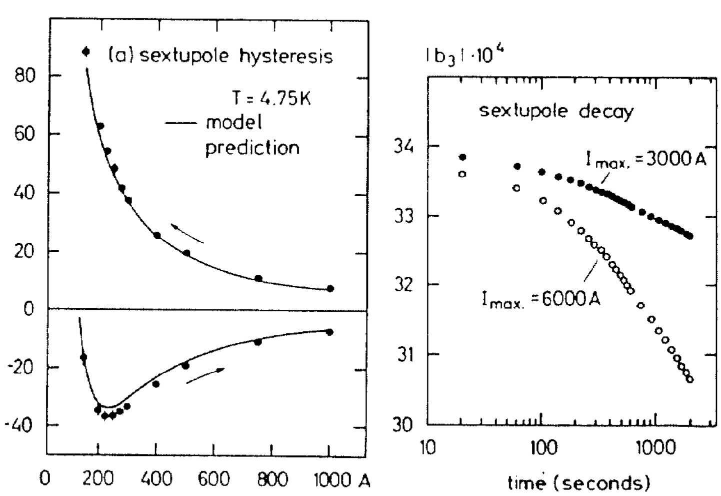

Fig. 4 (a) The sextupole in the HERA dipoles for increasing and decreasing main field. (b) Time dependence at I=250 A for 3000 A resp. 6000 A in the preceding cycle.

The persistent-current fields exhibit an approximately logarithmic time dependence (see Fig. 4b). The phenomenon is partly due to flux creep [8] in the superconductor, however the decay rates measured in magnets are usually much larger than those in short cable samples [9]. Surprisingly, the rates are strongly influenced by the strength and duration of the maximum field in the preceding cycle (Fig. 4b).

Another surprising property of the persistent-current fields is their periodicity along the magnet axis [10]. The explanation is probably a non-uniform distribution of the transport current among the strands in the cable. Because of its short wavelength of 95 mm, the oscillation has no impact on the dynamic aperture.

The influence of iron yoke saturation on main field and gradient is shown in Fig. 5a. The quadrupoles saturate earlier since the minimum yoke thickness is only 32 mm . In the SSC dipoles, a very small sextupole variation with excitation has been achieved (Fig. 5b) by punching suitable holes into the iron.

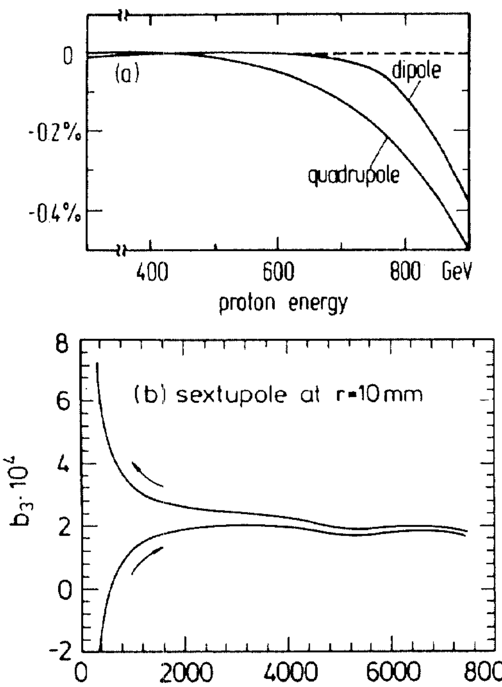

Fig. 5: Effect of yoke saturation on (a) field and gradient of HERA magnets and (b) sextupole in SSC dipole [3].

6 EXPERIENCE DURING THE COMMISSIONING OF HERA

In the 1991 commissioning phase the quench and overvoltage protection system was not yet fully implemented and the s.c. magnet current had to be limited to 3000 A. The proton beam intensity was far lower than eventually needed, only 1-10 of the 210 proton bunches were injected. With these conditions not a single genuine quench was encountered but only a few false alarms in the protection and interlock system. A number of potential wires needed repair because some high voltage breakdowns occurred during fast discharge of the magnet current.

The high voltage integrity of coils, current leads and potential wires is an extremely critical issue, particularly in helium gas atmosphere.

The first beam test of the HERA proton ring was made with positrons of only 7 GeV, the reason being that these were available with a high repetition rate of 1-2 Hz which eased the calibration of the beam position monitors and the steering around the ring. At a field of only 0.04 T the sc magnets would normally suffer from intolerable persistent-current field distortions. To eliminate these, a special initialization was performed which was first tried out on a single magnet in the test hall. The entire ring was heated to 15 K to extinguish any persistent currents from previous tests and, after cooldown to 4.4 K, the current was raised to 112 A and then lowered to the value of 42.5 A needed for 7 GeV/c. Fig. 6 shows that the sextupole in the test magnet in fact vanished and this turned out to be representative for the whole ring. From the measured chromaticity a sextupole suppression factor of 100 was inferred. The same procedure was used in the 40 GeV proton run in April with a current cycle 42.5 A $\rightarrow$ 314 A $\rightarrow$ 244.5 A, again with very satisfactory results.

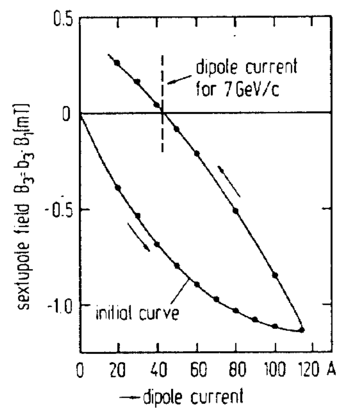

Fig. 6: Current cycle in sc magnets for 7 GeV/c positron injection and resulting sextupole field.

The special initialization is of course not applicable in routine operation. If one wants to accelerate protons the magnets have to be on the "up-ramp" branch of the persistent-current hysteresis loop. From August 1991 on, the following procedure was used before any new injection. The current was lowered to 50 A and then a cycle was performed

$$50\text{ A} \rightarrow 1000\text{ A} \rightarrow 50\text{ A} \rightarrow 244.5\text{ A}$$

It was verified that this cycle guarantees highly reproducible initial conditions for injection.

In the beginning there was a mismatch between HERA and the pre-accelerator PETRA. The magnet current in HERA had to be set 1 A lower than computed from the field measurements and the known influence of the persistent currents. The HERA calibration turned out to be correct, PETRA delivering protons of 39.76 instead of 40 GeV/c.

The proton ring is augmented with two "reference" dipoles which are electrically in series with the ring magnets. Their main purpose is to provide a continuous monitoring of the persistent-current effects and their dependence on the previous excitation and on time. In the stationary case the dipole field is measured by NMR and these data are indispensable for matching the energy to PETRA. During a ramp, the induced voltage in a stationary pick-up coil is converted into a train of pulses which steer the currents in the more than 400 normal magnets and sc correction coil circuits of HERA. This way it has been possible to precisely synchronize the field ramps of the sc main magnets and the other magnets in spite of vastly different time constants. The persistent-current sextupole is determined with a triple coil system rotating at a frequency f = 5 Hz whose signal is processed by a lock-in analyzer synchronized to the third harmonic 3f.

The chromaticity compensation at 40 GeV turned out to be stable from injection to injection. The sextupole correction currents depend in a non-linear fashion on the particle energy. In the past period only linear current programs were available. As a consequence, severe shifts in chromaticity were observed during the acceleration from 40 to 70 GeV, as shown in Fig. 7. The expected chromaticity shifts were calculated from the non-linear energy dependence of the sextupole fields in the reference magnets. They are in perfect agreement with the data. A non-linear correction of the sextupole currents removed the chromaticity variations (curves (c) in Fig. 7).

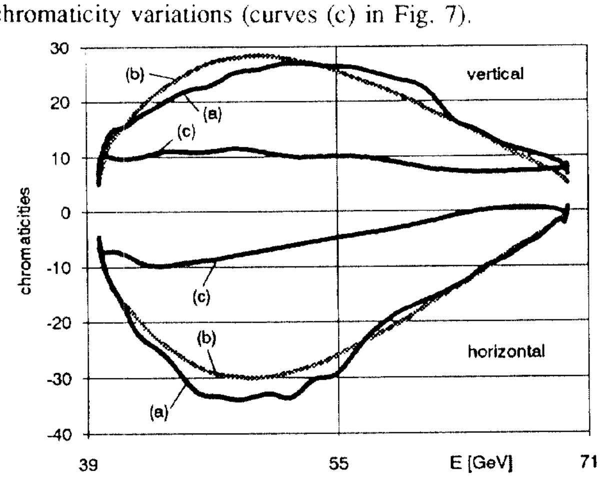

Fig. 7: Excursion of horizontal and vertical chromaticities during acceleration from 40 to 70 GeV. Curves a: measured chromaticities; curves b: predicted behaviour; curves c: measurement with non-linear sextupole correction [11].

When the beam is kept at 40 GeV for a longer period, the chromaticities exhibit a nearly logarithmic time dependence which is again in accordance with the reference magnet data (Fig.8). These results imply that the persistent-current sextupoles and their time dependence can be accurately compensated using the reference magnet system.

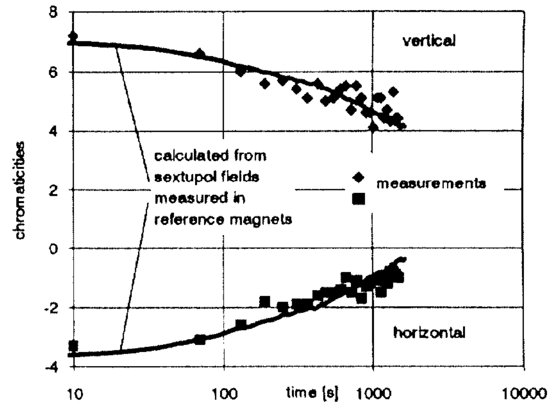

Fig. 8: Time dependence of chromaticities at 40 GeV in comparison with prediction from reference magnet sextupole.

The currents in the 10-pole and 12-pole coils were set to their theoretical values. The observed beam life time of 3 hours at 40 GeV and more than 70 hours at 480 GeV is a proof that non-linear fields are sufficiently suppressed. Two skew quadrupole correctors have been successfully used in HERA to eliminate the betatron coupling caused by the skew quadrupole terms in the dipoles and by misaligned quadrupoles. The best beam life time is in fact obtained with a working point close to the coupling resonance $Q_y=Q_x+1$.

Summarizing one can say that the superconducting proton ring so far has proven a very forgiving machine and that the magnets behaved in a predictable way.

I want to thank R. Meinke and the magnet measurement group at DESY for a most enjoyable collaboration and J. Strait and P. Wanderer for kindly providing me with data on the RHIC and SSC magnets.

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