SUPERCONDUCTING CORRECTION MAGNETS FOR THE HERA PROTON STORAGE RING

C. Daum and J. Geerinck, NIKHEF-H, Amsterdam, The Netherlands
R. Heller, Deutsches Elektronen-Synchrotron DESY, Hamburg, West Germany
P. Schmüser, II. Inst. f. Experimentalphysik, Universität Hamburg, West Germany
P.A.M. Bracké, HOLEC B.V., Ridderkerk, The Netherlands

Abstract: The HERA proton ring is equipped with superconducting dipole and quadrupole magnets. The adjustment of the working point and the chromaticity correction are provided by quadrupole and sextupole correction coils which are mounted on the cold beam pipe inside the main dipole magnets. The coils are fixed on the pipe by epoxy and a strong glass fiber wrapping.

The orbit correction in the proton ring is made by means of superferric correction dipoles which are mounted in common cryostats with the main quadrupoles and beam position monitors.

The layout of both types of correction magnets will be described and experimental results on quench behaviour and field quality will be presented.

Introduction

A regular cell of the HERA proton storage ring has the usual FODO structure with a focusing (Q_F) and a defocusing quadrupole (Q_D), both 1.9 m long, and four 9 m long dipole magnets (see Fig. 1). The main

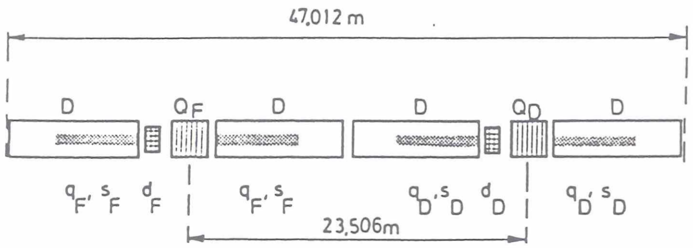

Fig. 1 A regular cell of the HERA proton ring lattice. D main dipole; Q_F horizontally focusing main quadrupole, Q_D horizontally defocusing main quadrupole; d_F, q_F, s_F correction dipoles, quadrupoles and sextupoles for corrections in the horizontal plane; d_D, q_D, s_D correction coils for corrections in the vertical plane

quadrupoles are excited by the same current, so quadrupole correction coils (q_F, q_D) are needed to adjust the horizontal and vertical betatron tunes independently. Their focusing strengths have been chosen such that Q_x and Q_z can be varied by ± 2 units, allowing to change the machine optics from injection to colliding beam operation.

The chromaticity of the lattice and the persistent current sextupole fields in the main dipoles are compensated by two families of sextupole lenses (s_F, s_D).

Finally, each cell contains a pair of correction dipoles (d_F, d_D) to correct horizontal and vertical closed orbit distortions.

The maximum field integrals of the correction elements, referred to the nominal proton energy of 820 GeV and a reference radius r_o = 25 mm, are as follows[1]

quadrupoles $\int B_2 ds$ = 0.47 Tm (both q_F, q_D)

sextupoles $\int B_3 ds$ = 0.35 Tm (s_F, s_D)

dipoles $\int B_1 ds$ = 0.68 Tm (d_F, d_D).

The quadrupole and sextupole coils are mounted on the cold beam pipe inside the main dipole magnets. Two 5.9 m long coil sets belong to each main quadrupole (Q_F or Q_D) and are positioned as close as possible to this magnet (see Fig. 1). The correction dipole is a superferric window frame magnet. It is mounted in a common cryostat with the main quadrupole and a beam position monitor.

A total of 440 quadrupole/sextupole coils and 250 correction dipoles are being built by Dutch industry. They constitute the Dutch contribution to the HERA project. At present, about 30% of the magnets have been completed and tested.

Quadrupole/Sextupole Correction Coils

The layout of the correction coils[2] follows the "beam pipe coil" concept developed at Brookhaven National Laboratory. The coil package consists of an inner sextupole layer of 5900 mm length and an outer quadrupole layer of 5830 mm length. The coils are glued on the 9582 mm long beam pipe of the main dipole magnet with the current connections as close as possible to the adjacent main quadrupole. A cross section is shown in Fig. 2. The beam pipe (stainless steel DIN 1.4429,

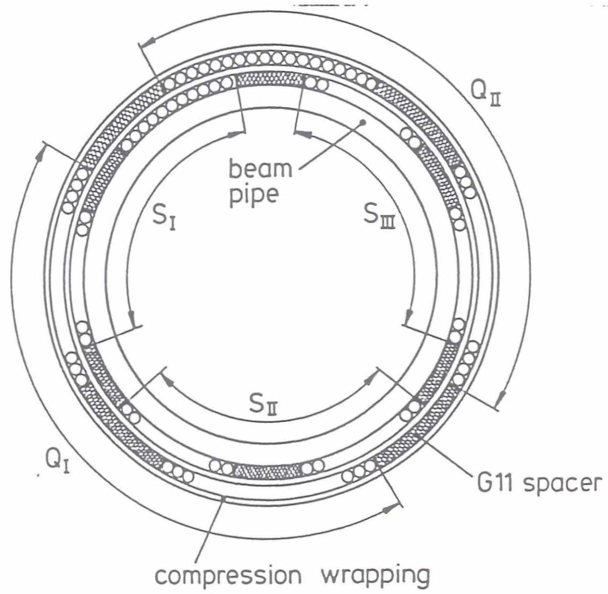

Fig. 2 Cross section of the beam pipe with the correction coils. S_I, S_{II}, S_{III} subcoils of the sextupole; Q_I, Q_{II} subcoils of the quadrupole.

equivalent to 316 LN) has an inner (outer) diameter of 55.3 mm (60.3 mm) and is insulated by a double layer of 0.15 mm thick glass-Kapton-glass tape.

The sextupole comprises three subcoils. Each subcoil contains 21 turns and covers an azimuthal angle of 100° with a central G11 core 20° wide. The coils are glued on the insulated beam pipe between precisely oriented G11 spacers of 20° width. The sextupole coil is insulated by a glass epoxy layer and then the quadrupole coil is mounted. It consists of two subcoils each containing 33 turns and covering an angle of 150° . The G11 cores and spacers are 30° wide. Both correction coils are mounted on the beam pipe with an angular accuracy of ± 0.2° over the whole length. The subcoils are made from a Kapton and glass insulated superconductor using a cylindrical winding mandrel and a precise baking mould. The insulation layers and coils are glued on the beam pipe with an

epoxy (Epikote 215 and Versamid 140 in a ratio of 1:1, baking temperature 150°C) which is suitable for cryogenic temperatures and radiation resistant. The main mechanical strength, however, is provided by a glass fiber compression wrapping. The sextupole is covered by a single layer and the quadrupole by a double layer wound from a very strong glass fiber (0.31 mm^2 VETROTEX R glass, tensile strength 3600 N/mm^2) with a tension of 800 N/mm^2 and a pitch of 2.5 mm. The compression wrapping provides a high radial pressure on the windings (about 6 N/mm^2 at T = 4 K) which together with the glue joints inhibits conductor motion under the influence of Lorentz forces.

Between the correction coil package and the main dipole coil remains a 4 mm wide annular slit for forced-flow cooling by single phase helium of 4.35 to 4.60 K. The correction coil is centered in the dipole with an accuracy of ±0.3 mm by sets of G11 spacers glued on the beam pipe every 1.1 m.

For the nominal proton energy of 820 GeV the main dipole field is 4.69 T and the maximum currents in the correction coils are 85 A in the quadrupole and 65 A in the sextupole.

The superconductor has a significantly higher current capacity in order to increase the quench safety in the case of beam-induced heating of the coils (image currents or proton beam losses). The specified critical current is 250 A at 4.60 K and 5.5 T.

The superconductor is a single strand wire of 0.70 mm diameter, a copper to NbTi ratio of 1.8:1 and a filament diameter of about 15 μm. Conductors from various manufacturers (BBC, SLE, VAC) have been used. The wire is insulated by 25 μm Kapton tape with 50% overlap and two glass fiber layers with a B-stage epoxy coating.

The quadrupole or sextupole fields at the reference radius r_o = 25 mm are more than two orders of magnitude smaller than the main dipole field. Therefore it is possible to choose a single current shell arrangement for these coils without internal spacers which greatly simplifies the production. Of course, higher normal multipoles are present because of the simple design (see Fig. 2): in the quadrupole $b_{10}/b_2 = -0.0241$, $b_{14}/b_2 = 0.0063$; in the sextupole $b_{15}/b_3 = -0.0148$. In comparison with the large field of the main dipole these higher multipole components can be neglected. The specified limits for all other normal (b_n) and skew (a_n) multipole coefficients are ±0.010. The field measurement is done at room temperature. The quadrupole or sextupole coil is excited with an alternating current of 0.7 A and 11 Hz and the signal induced in a 2.05 m long pickup coil is registered by a lock-in amplifier and digitized. A full rotation of the pickup coil is divided into 100 steps. A microcomputer controls the measurements and performs a Fourier transformation to compute the multipole coefficients. The procedure is repeated for both coil layers in three longitudinal positions of the pickup coil to cover the entire length of 5.9 m. Field measurement data are available for 134 quadrupole sextupole coils. Averaged over all coils and all positions, the results for the expected multipole coefficients are:

$$\text{quadrupole:} \quad b_{10}/b_2 = (-2.35 \pm 0.08)\cdot 10^{-2}$$

$$b_{14}/b_2 = (0.61 \pm 0.05)\cdot 10^{-2}$$

$$\text{sextupole:} \quad b_{15}/b_3 = (-1.37 \pm 0.08)\cdot 10^{-2}.$$

These values agree very well with the computed numbers. In Fig. 3 we plot the difference between the measured and expected normal multipole coefficients. The values are compatible with zero; the statistical errors are much below the qualification limit of 0.01. For the skew multipole coefficients a_n a similar distribution is obtained.

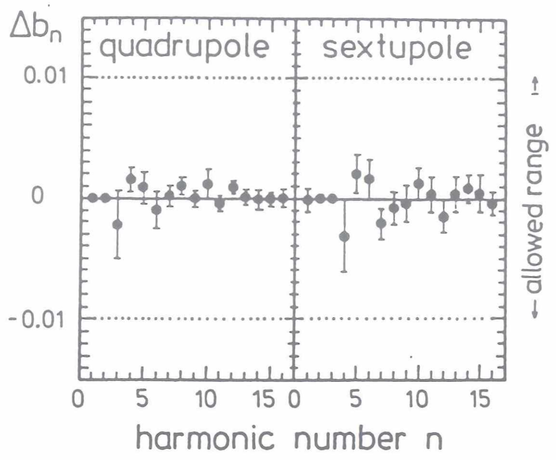

Fig. 3 The averaged normal multipole coefficients for 134 quadrupole/sextupole coils having passed the cryogenic test. The main coefficient (b_2 in the quadrupole, b_3 in the sextupole) is normalized to 1. For b_{10} and b_{14} in the quadrupole and b_{15} in the sextupole the computed values have been subtracted from the measured values (see text). Specified limits: ± 0.01.

The field measurement allows also to determine the misalignment angle between the quadrupole and sextupole coil. The average value is 1.42 ± 2.59 mrad, which again is well below the specified tolerance of 2·0.2° = 7 mrad.

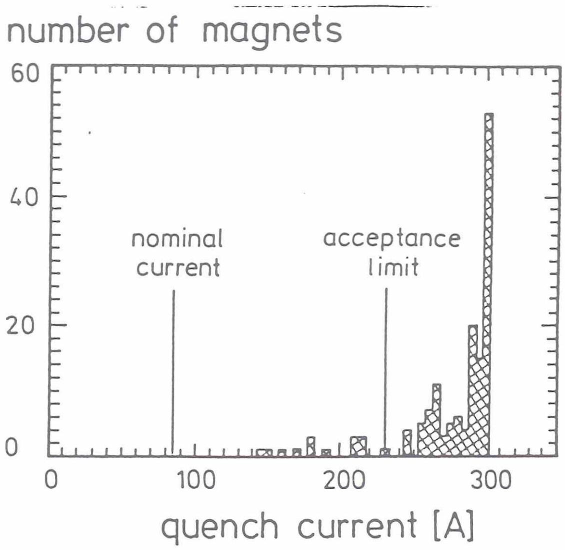

Fig. 4 Distribution of quench currents for 148 quadrupole/sextupole coils. Plotted is the minimum of the quench currents achieved in either the quadrupole or the sextupole in an external field of 5.08 T.

A cryogenic test of the correction coils is performed in a vertical bath cryostat containing a dipole magnet with a maximum field of 5.08 T. The test results of the first part of the series production were excellent: among 61 coils only one was below the qualification level of 230 A (at 5.08 T and a helium temperature of 4.40 K) and the remaining 60 reached the short sample current of the conductor. In the following production a larger failure rate occurred. For all coils with low quench currents it could be demonstrated that the failures were not caused by insufficient fixation of the windings but by weak spots in the superconductor. For this purpose the quench cur-

rent was measured as a function of the helium temperature and the external field [3]. Eddy current tests were performed with large lengths of uninsulated superconductor and in fact a few spots were found where filaments had been damaged by small inclusions. A significantly lower critical current was measured at these locations. However, some damage of the conductor might also have occurred during the insulation or coil production process.

In Fig. 4 we plot the observed quench current distribution of the correction coils produced so far. The large majority reaches values close to the short sample current, but about 10% are below the qualification level of 230 A (which, however, is much higher than the operating current). In the future production only eddy-current tested superconductor will be used.

Correction Dipole

The correction dipole is a window frame magnet with an iron yoke of 610 mm length and 75 mm gap and two superconducting saddle coils. A cross section is shown in Fig. 5.

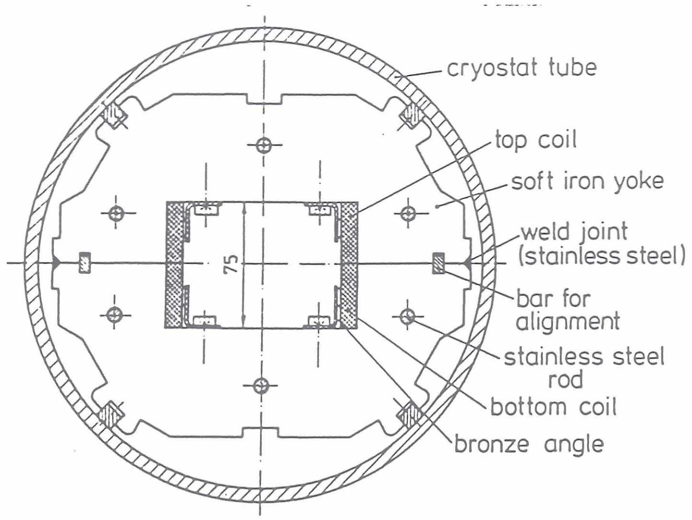

Fig. 5 Cross section of correction dipole, mounted in the cryostat

Since every dipole has to be powered individually, a low operating current (35 A for the nominal field of 1.17 T) and a correspondingly large number of turns (1000 per coil) are essential.

The superconductor has a diameter of 0.56 mm, a copper to NbTi ratio of 3.7:1 and contains 36 filaments of 45 μm diameter. The specified critical current is 250 A at 1.5 T. The wire is insulated by a polyesterimid varnish. The coils are wound in a flat, racetrack-like winding mould with the wire passing through epoxy. When the winding is finished, the long straight sections and the arcs of the coil are constrained by precise compression bars. The center of the short straight section is clamped in a fiber glass bracket. Then the long straight sections are folded up, allowing a natural bending of the unconstrained short sections into the saddle shape. After bending the coil is baked in an oven at 150°C. This novel technique of producing saddle-shaped coils with many turns of thin conductor has proven to be quite reliable. The epoxy used for impregnation is a mixture of Epikote 215 and Versamid 140 in a ratio of 1:1. In the preseries and early series production the epoxy was used without filling material. Since in a number of magnets excessive training was observed, it was decided to add Al_2O_3 powder (40% by volume) to the epoxy, thereby reducing the differential shrinkage between the superconductor and the impregnation during cooldown. The magnets with Al_2O_3 filled epoxy show in fact a considerable reduction in training steps.

The iron yoke is split into two halves which are assembled from 5 mm thick precision-stamped laminations. The coils are insulated with 125 μm Kapton and fixed in the half yokes by means of bronze angles. Then the half yokes are put together and joined by two weld joints in the horizontal plane. The welding material is stainless steel which has almost the same thermal contraction as the coils.

The cryogenic test of the correction dipoles comprises measurements of the quench current and the central field, using a Hall probe. A multipole measurement with a rotating pickup coil is performed only for sample magnets since the field quality is largely determined by the accurate iron yoke and very reproducible from magnet to magnet.

The observed distribution of quench currents is shown in Fig. 6. The specified qualification level is 75 A. (At this current, the Lorentz forces acting on the windings are a factor of 4 larger than at the nominal current of 35 A). The majority of the magnets achieves quench currents above 100 A but some have failed the qualification level. These magnets will be

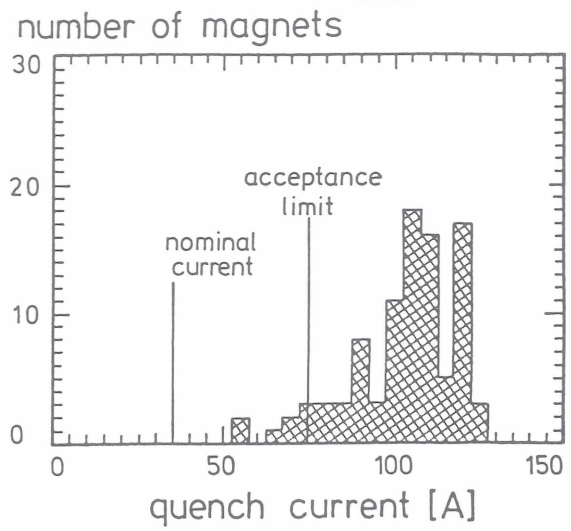

Fig. 6 Distribution of quench currents for 95 correction dipoles

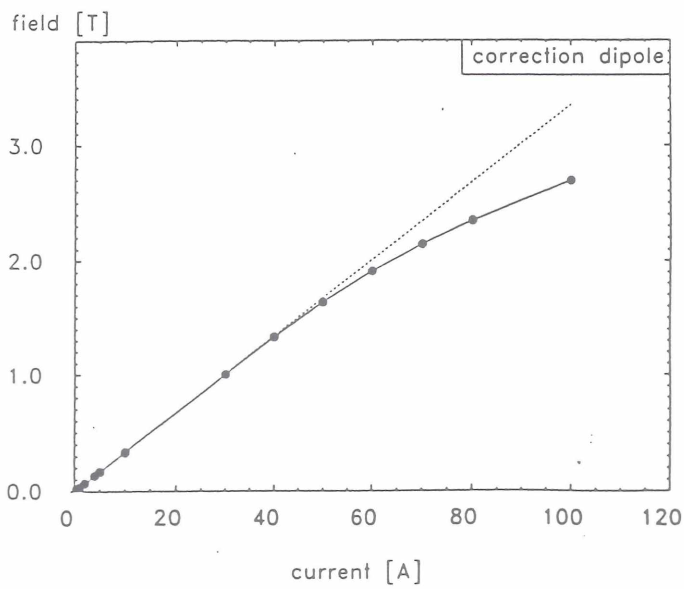

Fig. 7a Central field as a function of the current

recuperated by replacing one coil. In normal accelerator operation the magnets have a large safety margin because the operating current at 1.5 T is less than 20% of the critical current.

In Fig. 7a and 7b we summarize the field measurements done on a recent series magnet. The field increases almost linearly with the current up to 2 T.

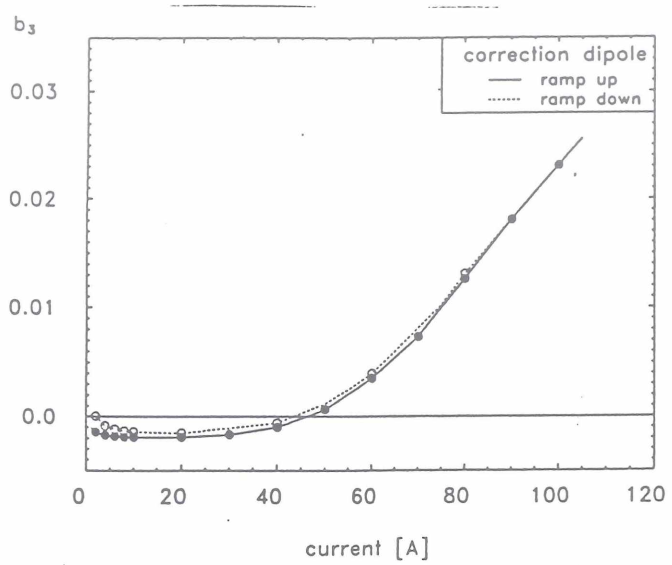

Fig. 7b Sextupole coefficient b_3 as a function of the current

The only significant higher multipole is the normal sextupole. The coefficient b_3 is slightly negative for small currents, but rises steeply for currents above 50 A, where the iron yoke starts to saturate. The remanent field in the iron has been measured to be 5 Gauss.

Acknowledgements

We want to thank the cryogenic and magnet measurement groups at DESY for their support in the test of the correction magnets.

References

1 J. Roßbach, DESY HERA 85-04 (1985),
R. Brinkmann, A. Wrulich, private communication

2 C. Daum, P. Schmüser, DESY HERA 83-01 (1983)

3 H. ten Kate, H. Boschman, University of Twente, internal report (1987)