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S.C. CORRECTION COILS AND MAGNETS FOR THE HERA PROTON RING

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ABSTRACT:

The quadrupole and sextupole correction coils of the HERA proton ring are mounted on the cold beam pipe inside the main dipole magnets. Superferric dipole magnets for orbit correction are located adjacent to the main quadrupole magnets in a common cryostat which also contains the beam monitor.

The design, manufacture and performance of both types of correction elements will be described.

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Abstract. - The quadrupole and sextupole correction coils of the HERA proton ring are mounted on the cold beam pipe inside the main dipole magnets. Superferric dipole magnets for orbit correction are located adjacent to the main quadrupole magnets in a common cryostat which also contains the beam monitor.

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INTRODUCTION

Figure 1 shows the layout of a HERA proton cell. It consists of a focusing and a defocusing 1.9 m long quadrupole and four 9 m long dipole magnets. The main dipole and quadrupole magnets are connected in series, so it is impossible to change the working point. A ΔQ shift of ±2 seems rather desirable to allow for different optics during injection and colliding beam operation and to compensate for differences between measured and calculated optics. This requires $\int B_2 ds = 0.47$ T·m (at $r = 2.5$ cm and $E = 820$ GeV) per cell for both horizontal focusing and defocusing quadrupoles [1]. (A suggestion has recently been made to provide additional excitation of the main quadrupoles in a "piggy back" scheme, thereby relieving the requirements on the correction quadrupoles).

Chromaticity correction requires sextupole correction coils of $\int B_3 ds = 0.35$ T·m (at $r = 2.5$ cm and at $E = 820$ GeV) for both sextupole polarities per cell [2]. The persistent current sextupole at injection energy (40 GeV) requires a correction $\int B_3 ds = 0.015$ T·m (at $r = 2.5$ cm) per cell using the same correction coils.

Quadrupole and sextupole correction coils of this strength are generated by two single layer coils on the beam pipe in the main dipole magnets. Two correction coil layers of 6 m length each are placed as closely as possible to the corresponding main quadrupole magnets (see Fig. 1).

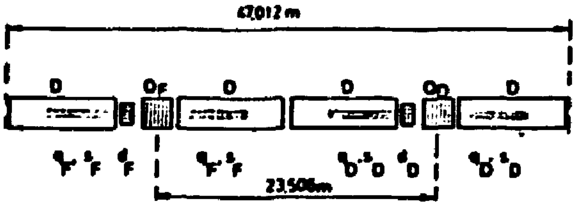

Fig. 1 Corrections coils of the HERA proton ring. D main dipole; Q_F horizontally focusing main quadrupole, Q_D horizontally defocusing main quadrupole; d_F, q_F, s_F correction dipoles, quadrupoles and sextupoles for correction in the horizontal plane; d_D, q_D, s_D correction coils for corrections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

Misalignment of the main quadrupoles and a tilt of the main dipoles (≤ 1 mrad) will be the major source of closed orbit distortions. One horizontally and one vertically deflecting correction dipole per cell with $\int B_1 ds = 0.68$ Tm (at $E = 820$ GeV) are needed for orbit correction. The dipole is a window frame superferric magnet mounted in a common cryostat with the main quadrupole.

In total 208 dipole correction magnets and 416 quadrupole/sextupole correction coils are needed for the arcs of the HERA proton ring. Additional dipole correction magnets will be placed in the straight sections. Separate superferric quadrupole correction magnets for the straight sections are being developed at DESY.

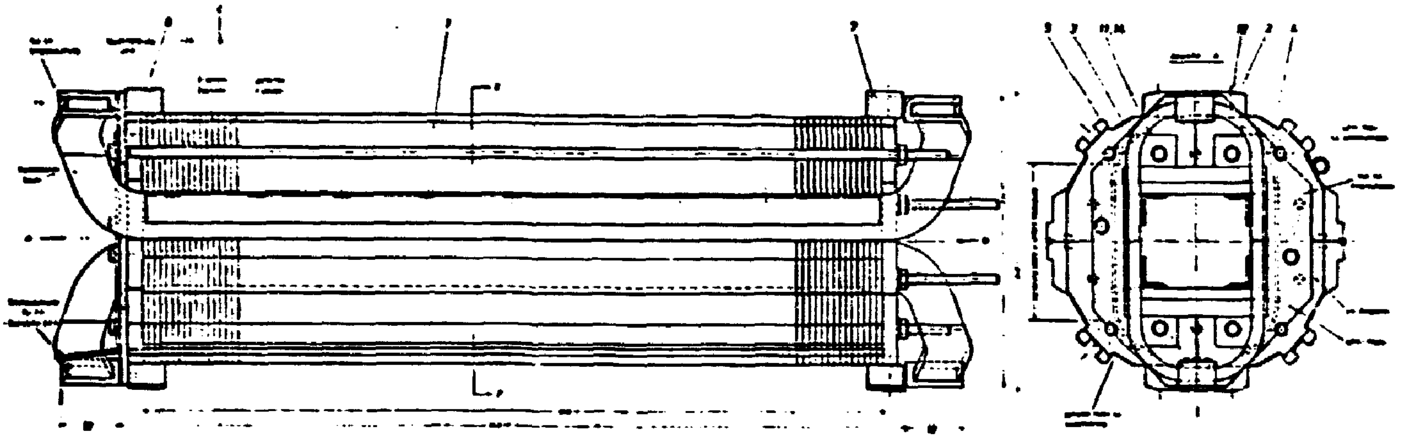

Fig. 2 Layout of the superferric dipole correction magnet.

DIPOLE CORRECTION MAGNET

Figure 2 shows the layout of the superferric dipole magnet. It consists of two saddle coils in an iron yoke of 610 mm length and a gap of 75 mm. The coils are wound from 0.6 mm diameter superconducting wire coated with a polyesterimide varnish insulation. The nominal field of 1.4 T is reached at a current of 45 A. The iron yoke is split in two halves, which are assembled from 5 mm thick precision stamped soft steel laminations. The laminations are held together by 8 mm thick stainless steel rods. These rods determine the longitudinal shrinkage during cooldown from room temperature to liquid helium temperature. When cooled down the soft steel shrinks by 0.2% whereas the stainless steel rods and the superconducting coils contract by 0.3%. The stacking of the laminations is sufficiently loose to allow for a 0.3% shrinkage of the magnet.

The field quality requires a straightness of the yokes of better than 0.2 mm, a twist angle of less than 3 mrad, and a parallelism of the pole faces of better than 0.5 mm. The coils have a height and width tolerance of 0.03 mm and 0.1 mm, respectively. These requirements are achieved using precision tooling.

The two superconducting coils have 1000 turns each and are wound in a flat, race track-like winding mould. They are impregnated with an epoxy (Epikote 215 and Versamid 140, ratio 1:1) which remains flexible at cryogenic temperatures. The long straight sections and the bends of the coil are constrained by compression bars to the required dimensions. The centre of the short straight sections is clamped in a fibre-glass bracket which at one side also contains slots for the fixation of the current leads. The unconstrained part of the short straight sections on each side of the fibre-glass brackets allow a natural bending of the coil into the required saddle shape before curing of the epoxy. This novel technique of producing saddle shape coils of thin wire, down to 0.6 mm diameter, has shown to be very reliable. After bending the coil is baked in an oven at 150°C.

The coils are insulated by a 125 μm Kapton foil and clamped in the yoke by means of bronze angles. Between the insulated coil and the yoke a 0.15 mm stainless steel foil is placed to avoid friction between the coil and the laminated yoke during cooldown.

The first prototype correction dipole magnet has been made with a solid iron yoke to test the performances of the coils before the steel laminations and the stacking fixture were available.

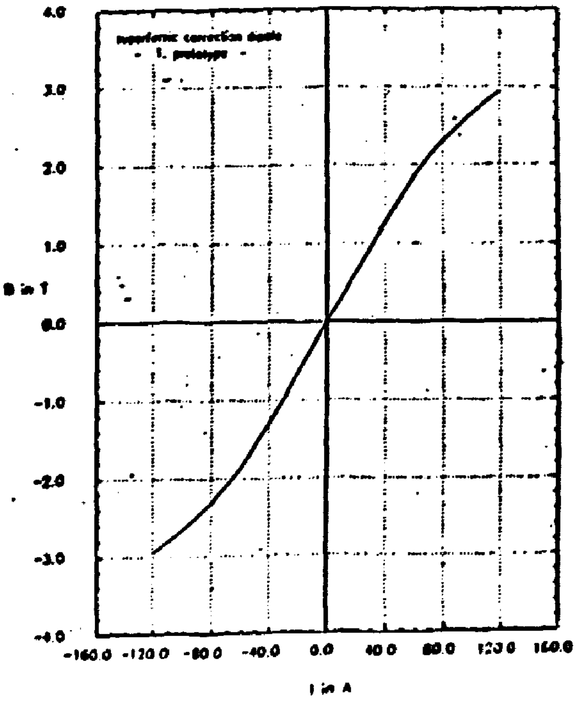

Fig. 3 Excitation curve of the dipole correction magnet.

Figure 3 shows the excitation curve of the magnet. The nominal field of 1.15 T is obtained at 37 A. The magnet reached a field of 3 T at 140 A after four quenches which were probably due to motion of the coils in the yoke. Polarity changes from +140 A to -140 A caused no additional training. The ramp rate was 40 A/min. The remanent field is $3.6\cdot10^{-4}$T.

By far the largest higher multipole is the normal sextupole. Up to 50 A the coefficient b_5 is less than $2 \cdot 10^{-3}$. Above 50 A a steep rise in b_5 is observed caused by saturation of the iron. However, compared to the field integral of the main dipoles over a HERA cell ($\int B_1 ds$ = 163 Tm), all multipole coefficients are far below the allowed tolerances for fields up to 2.5 T.

The orbit correction requires individual excitation of the correction dipoles. A low operating current seems favourable to reduce the power consumption in the copper cables in the ring tunnel between the power supplies and the magnets and to minimise the helium consumption in the current leads. A compromise had to be made, however, with the inductivity of the coils and the viability of the winding method. A wire diameter of 0.6 mm was found to be a safe lower limit for the production of the saddle coils.

QUADRUPOLE/SEXTUPOLE CORRECTION COILS

The main characteristics of these coils are described in ref.[3]. Figure 4 shows the cross-section and an unwrapped view of the quadrupole/sextupole correction coils which are mounted on the 9582 mm long beam pipe with outer (inner) diameter of 60.3 (55.3) mm of the main dipole magnet. They cover a length of about 6 m and are placed as close as possible to the corresponding quadrupole magnet (see Fig. 1).

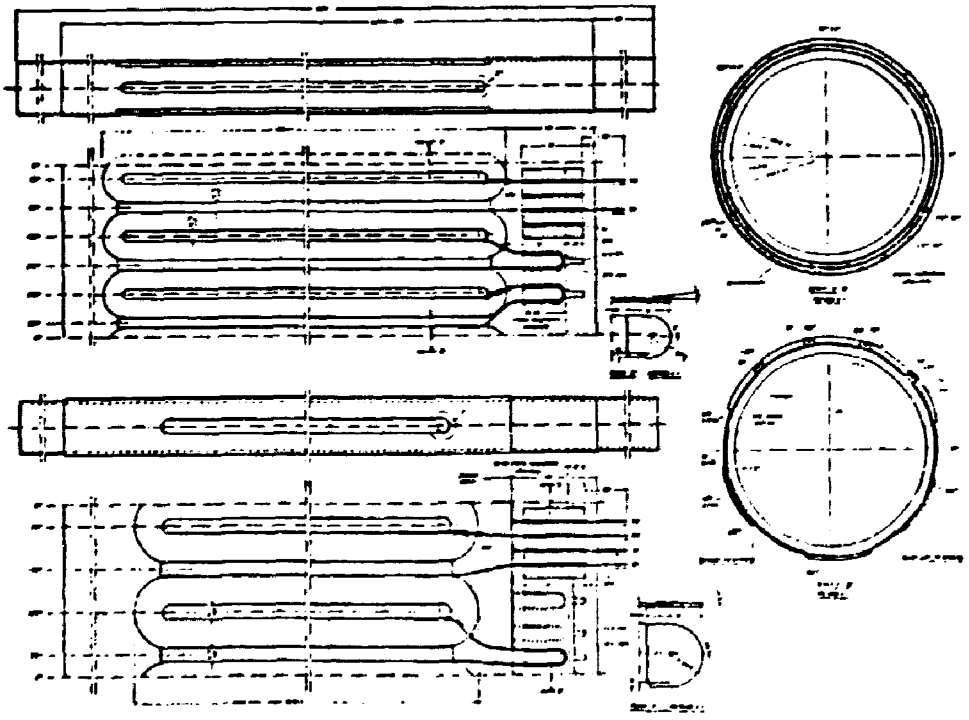

Fig. 4 Layout of the quadrupole/sextupole correction coils.

The beam pipe is insulated with two layers of glass-Kapton-glass tapes (25 mm wide, 0.15 mm thick). The sextupole coils form the first correction layer. It consists of three subcoils, which are precisely positioned by G-11 cores and spacers. Each subcoil has a length of 5900 mm and subtends an azimuthal angle of 100°, cores and spacers cover angles of 20° each. The three subcoils are electrically connected in series. This has the advantage that in case of a quench of the main dipole magnet the inducted voltage cancels over the terminals. The largest inducted voltage in any subcoil is less than 75 V and does not create an insulation problem.

The coils are wound from a single strand conductor with Cu/SC ratio 1.8:1 and NbTi filament diameter of 15 μm. The specified critical current is 250 A at 5.5 T and 4.6°K. The superconductor is insulated with a 50 μm Kapton layer and a 0.1 mm glass silk insulation impregnated with B-stage epoxy. After compression in the baking mould, the insulated wire diameter is 1.03 mm. The sextupole subcoils have 21 windings each.

The sextupole layer is covered by two layers of glass fibre and one layer of glass tape for electrical insulation between the sextupole and quadrupole layer. The quadrupole coils constitute the second correction layer. They consist of two subcoils of 33 windings each of the same superconducting wire as for the sextupole coils. Each subcoil has a length of 5830 mm and subtends 150°, core and spacers cover 30° each. The two subcoils are connected in series electrically. Again the inducted voltage cancels over the terminals if the main dipole magnet quenches. The induced voltage per subcoil will be less than 100 V.

Finally the quadrupole layer is surrounded by a compression wrapping which prevents motion of the coils and slippage of the layers on the beam pipe. An annular slit of about 4 mm is left for the single phase helium flow between the outside of the correction coil assembly and the inside of the main dipole coils.

The nominal sextupole field of 0.030 T at r = 2.5 mm is reached for a current of 65 A, and the nominal quadrupole field of 0.045 T at r = 2.5 mm is reached for a current of 85 A.

The field quality requires a precision in azimuthal angular width of the coils of ±0.3° and an accuracy in positioning of the coils on the beam pipe of ±0.2° over the total length.

The three sextupole and the two quadrupole subcoils are wound on a cylindrical mandrel of about 6 m length. A precise steel key at the top of the mandrel serves as a core for the subcoil during winding and baking. After finishing the winding of a subcoil (21 turns in the sextupole, 33 in the quadrupole) the wires are fixed each half meter with Kapton tape and wetted with epoxy (Epikote 215 and Versamid 140 in the ratio 1:1). Then the mandrel is covered with a top mould. In the gap between the top mould and the mandrel the long sides of the subcoil are compressed by rulers which determine the lateral dimension. The compression is maintained during the bake-out at 150°C.

The 9.6 m long beam pipe is put into a rotating fixture on a machined table which is used as reference for the subsequent operations.

Two layers of glass-Kapton-glass tape are glued over 9.2 m onto the beam pipe for electrical insulation using the rotating mechanism. By means of precise alignment the G11 spacers for the sextupole coils are accurately glued onto the surface of the insulation. The three sextupole subcoils are put into position between the spacers and the G11-cores between the subcoils are inserted. The coils are fixed temporarily with Kapton tape until a glass fibre of 800 tex (800 g per 1000 m length) is wrapped over the coils with a force of about 250 N and a pitch of 25 mm using the rotating feature. This wrapping fixes the subcoils temporarily and still allows an adjustment of the azimuthal position of the coils. The exposed surface is again wetted with epoxy and a continuous layer of fibre is wound on with a force of 250 N and a pitch of 2.5 mm followed by one layer of glass tape and thermoshrinking mylar tape. The entire assembly is cured at 150°C after which the mylar is removed and the surface is roughened for putting on the quadrupole layer. Special attention is given that the coil heads are tightly glued.

The G11-spacers of the quadrupole layer and the quadrupole subcoils are now glued accurately into position with respect to the sextupole coils following the same procedure. The quadrupole layer is covered with a wrapping of 2 layers of glass fibre (pitch 2.5 mm, force 250 N) and a final layer of glass tape for protection of the fibres. A thermoshrinking mylar tape, which is removed after curing at 150°C, finishes the procedure.

A first 1 m prototype with a different coil configuration performed well as reported in ref.[4]. The coils showed no training effects. The observed quench current depended almost linearly on the external magnetic field and on the temperature indicating that the coils probably reached the short sample current. This showed that the basic design was correct.

This prototype and a number of others were made with an aramide fibre compression wrapping. In laboratory tests it was shown, however, that aramide fibres like Kevlar and Twaron exhibit creep effects under load and expand slightly during cooldown whereas the stainless steel beam pipe shrinks by $3\cdot10^{-3}$. In addition the elastic modulus of the aramide fibre almost doubles after cooldown. Thereby most prestress is lost. Fibres of R-glass shrink, though much less than stainless steel, and keep most of the prestress.

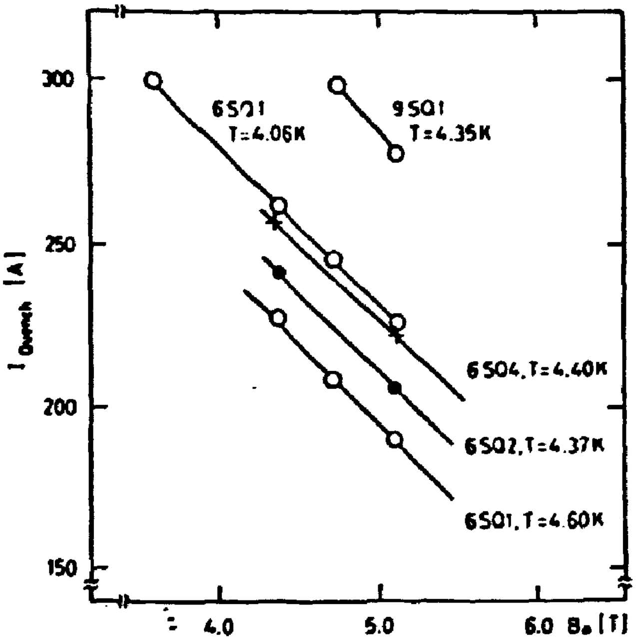

Fig. 5 Quench current vs strength of external dipole field at various temperatures for the 6 m quadrupole/sextupole correction coils.

Figure 5 shows the quench current as function of the external dipole field at various temperatures for a number of the full size prototypes which were wound from superconductors with lower critical current than quoted above. The coils show essentially no training and reach the critical current of the wire used. The coils labeled "6SQ1" to "6SQ4" have been wound on 6 m long beam pipes with 2 mm wall thickness and have an aramide fibre compression wrapping. In these coils we discovered quenches at lower current values when both sextupole and quadrupole coils were excited simultaneously. This can be attributed to a mechanical deformation of the beam pipe due to the Lorentz forces. The first "development" magnet "9SQ1" on a 9.6 m long pipe with 2.5 mm wall thickness and glass fibre compression wrapping has shown a great improvement. The observed quench current in one coil layer is unaffected by the current in the other layer.

A potential source for quenches is continuous or sudden heating of the coils due to image currents in the beam pipe or proton beam losses. By means of a radiation heater placed in the centre of the evacuated beam pipe it was established that the coils could be operated at a continuous heat loss of up to 0.5 W/m. This is a factor of 10 higher than the ohmic heat produced by image currents of the bunched beam in the copper-plated beam pipe. The effect of a sudden localized beam loss is still under investigation.

Table I
Field Harmonics of the Quadrupole/Sextupole Correction Coils of 6SQ2 at 0.5 A Excitation

n	C_n(quadrupole)	C_n(sextupole)
1	$1.89 \cdot 10^{-2}$	$5.14 \cdot 10^{-3}$
2	1.0	$5.83 \cdot 10^{-2}$
3	$4.35 \cdot 10^{-3}$	1.0
4	$5.72 \cdot 10^{-3}$	$1.47 \cdot 10^{-2}$
5	$3.11 \cdot 10^{-3}$	$8.37 \cdot 10^{-3}$
6	$5.05 \cdot 10^{-3}$	$6.97 \cdot 10^{-3}$
7	$1.05 \cdot 10^{-3}$	$2.65 \cdot 10^{-2}$
8	$3.81 \cdot 10^{-3}$	$2.06 \cdot 10^{-3}$
9	$5.17 \cdot 10^{-3}$	$2.65 \cdot 10^{-3}$
10	$2.66 \cdot 10^{-2}$	$2.24 \cdot 10^{-3}$
11	$7.02 \cdot 10^{-4}$	$1.11 \cdot 10^{-3}$
12	$6.03 \cdot 10^{-4}$	$1.39 \cdot 10^{-3}$
13	$3.16 \cdot 10^{-3}$	$3.25 \cdot 10^{-3}$
14	$3.72 \cdot 10^{-3}$	$4.69 \cdot 10^{-3}$
15	$3.21 \cdot 10^{-3}$	$1.56 \cdot 10^{-2}$
16	$1.16 \cdot 10^{-3}$	$2.98 \cdot 10^{-3}$

A warm field measurement was made to determine the field harmonics. Table I shows the result for the coils "6SQ2" at an excitation of 0.5 A. All unwanted multipoles (at $r = 2.5$ cm) are less than $2 \cdot 10^{-4}$ of the field integral of the main dipole field over a full HERA cell.

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