SUPERCONDUCTING MAGNETS FOR HERA

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Abstract

The Hadron-Electron-Ring Accelerator (HERA) presently under construction at DESY, Hamburg, consists of an electron storage ring of 30 GeV and a proton storage ring of 820 GeV. Superconducting magnets are used for the proton ring. There are 416 superconducting bending magnets of 4.68 T central field and 8.824 m magnetic length, 224 superconducting quadrupoles of 91.2 T/m central gradient and many superconducting correction dipoles, quadrupoles and sextupoles. The main dipoles and quadrupoles consist of two-layer coils of 75 mm inner diameter clamped with aluminum (for the dipoles) or stainless steel laminations (for the quadrupoles). The collared coils are surrounded by a laminated cold iron yoke and supported inside a low loss cryostat. The protection system uses cold diodes to bypass the current around a quenching magnet. The magnets are cooled with one phase helium supplied by a 3 block central refrigeration system of 20 kW refrigeration power at 4.3 K. Two phase helium is returned through the magnets in good thermal contact with the one phase helium in the dipoles for temperature control. This paper describes the magnet system and gives the results obtained for prototype magnets.

Introduction

The Hadron-Electron-Ring Accelerator (HERA) consists of an electron ring of 30 GeV and a proton ring of 820 GeV. The rings, with a circumference of 6.336 km, are equipped with many bending magnets, focusing magnets and correction magnets. For the proton ring, most of these magnets are superconducting. Prototype magnets designed for series production in industry have been fabricated and tested. In the following chapters the magnet system is described. Details of the magnets and test results are also presented.

Superconducting magnet system

With the exception of some magnets close to the interaction regions, all magnets of the proton ring of HERA are superconducting. There are 416 bending magnets (dipoles), 6 dipoles for vertical deflection, 224 quadrupoles and a large number of dipole correction magnets, quadrupole correction magnets and sextupole and quadrupole correction coils [1, 2].

In the arcs of the proton ring the magnets form a regular cell structure with 2 bending magnets and a quadrupole in each half cell. Sextupole and quadrupole correction coils are placed around the beam tube inside the bending magnets. Dipole correction magnets are housed in the quadrupole cryostats. Quadrupoles in the straight sections close to the interaction region have special cryostats which in addition to the correction dipoles also contain quadrupole correction magnets of the superferric type. All main dipoles and main quadrupoles are connected in series electrically. The nominal current for 820 GeV is 5027 A leading to a central field of 4.682 T with 8.824 m magnetic length in the dipoles and to a central gradient of 91.19 T/m with 1.861 m magnetic length in the quadrupoles.

Bending magnets

The bending magnets are 9.766 m long cryostats with a superconducting cold yoke, cold bore dipole magnet inside (Fig. 1). They consist of a two-layer superconducting coil clamped with laminated collars made from aluminum alloy, a laminated iron yoke around the collared coil, a helium vessel closed with end plates, a beam tube surrounded with 6 m long superconducting sextupole and quadrupole correction coils, an insulating vacuum with superinsulation, an aluminum thermal shield cooled with 50 K helium and a soft steel vacuum vessel. The coil is cooled with one phase (4.4 K, 2.5 bar) helium passing through a string of 52 dipoles. After expansion in a Joule Thomson (JT) valve, the helium returns through the magnets in two phase condition (1.1 bar) passing through a tube in good thermal contact with the one phase helium in the magnet. A safety tube with a check valve and a relief valve protects the helium vessel against overpressure. The cold parts of the cryostat are suspended inside the vacuum vessel at three locations along the magnet using glass fiber straps. Stainless steel tubes with bellows connect neighbouring magnets. The cold connections, with the exception of those for the beam tube, are welded.

The coil is wound from a keystoned 24-strand Rutherford type cable insulated with Kapton tape and with epoxy impregnated glass tape for curing purposes. The protection of each half coil during a quench is done by switching the current around the coil through a cold diode and by firing quench heaters to distribute the quench. The load line of the dipole is shown in Fig. 2. More details of the magnet are given in a separate paper [3].

Four prototype magnets have been built in collaboration with industry. Coils were wound, cured and collared at DESY. Yokes and cryostats were built at BBC, Mannheim. Three of these magnets have been tested at DESY.

Magnet No. 1 with its coil made from Vaccuumschmelze cable and equipped with a beam tube without correction coils was cooled down within 42 hours using a helium gas flow between 4 and 6 g/s. Harmonics measured at 5000 A were excellent. Quenches introduced artificially by quench heaters at this current showed a reasonable pressure rise of 4 bar in the magnet around the beam tube. At 5890 A a fast shut off of the power supply occurred and was accompanied by a breakdown of the insulating vacuum. As was found later, an arc discharge developed in the coil and between the coil and the beam tube. This burned a hole into the beam tube at about 7 cm from the end. It could not be determined whether this accident occurred due to bad turn-to-turn insulation or due to an overload of the coil as the result of inadequate quench detection. During the cold tests this magnet was cooled with two phase helium and the threshold for the quench detection was set to 1 V. For magnets produced later, the electrical testing procedures during coil fabrication and the protection during quenching were improved.

Magnet No. 2 with its coil made from Vacuumschmelze cable also was cooled down within 50 hours using a gas flow of 4 g/s. Heat load measurements resulted in 33 W - 40 W in the 4.6 K region and 45 W at the shield [4]. In the one phase cooling mode and with the quench detection threshold set to 70 mV the magnet was ramped to 5500 A without quench. Quenches were introduced only artificially. The maximum pressure in the magnet center around the correction coil was

18.2 bar. Harmonics were excellent [5]. The stray field was reasonable. Vertical field orientation measurements along the magnet axis showed a variation of 4 mrad [6].

Magnet No. 3 was fabricated from Furukawa cable from an earlier specification with lower critical current (6318 A instead of 8000 A at 5.5 T, 4.6 K). The thermal insulation was improved in this magnet. Cool down was achieved within 6.5 hours with up to 35 g/s of helium gas flow. The heat load was 11 ± 1 W in the 4.6 K region and 40 ± 5 W on the shield [4]. The measured field was excellent (Table 1). Vertical field orientation measurements showed a rotation of 7 mrad. Artificial quench tests were made with the protection diode inverted so all energy was dumped into the magnet. The $\int i^2 dt$ behaviour showed that the magnet could be operated safely as long as the quench heaters were fired. The magnet was ramped to quench at several temperatures reaching 6535 A at 4.28 K at maximum. No training was observed. The quench currents were the same as for tests of a 1 m magnet made earlier from the same cable.

Sextupole/quadrupole correction coils

The correction coil package[7] consists of a sextupole (5.9 m long, 65 A nominal current) and a quadrupole coil (5.83 m long, 85 A nominal current) each wound in a single layer from a 0.7 mm diameter superconducting wire insulated with Kapton tape and B-stage impregnated glass fiber. The coils are glued on the Kapton glass insulated beam tube and surrounded by a glass fiber compression wrapping. Glass fiber spacers are used to support the coil package against the inner surface of the main dipole coil.

The correction coil covers only 2/3 of the length of the dipole beam tube at the end adjacent to the neighbouring quadrupole. This leads to two types of dipole cryostats - those with the correction coils on the left or on the right side.

The correction coils were developed in collaboration with NIKHEF, Amsterdam, following a concept of Brookhaven National Laboratory (BNL). Four "development magnets" and two preseries coils have been delivered by HOLEC, Netherlands. This company will also build the series coils. For the development magnets, wire from Vacuumschmelze was used. The series magnets will be built with wire from SLE, Netherlands, with the exception of the coils for the first octant where wire from BBC, Zürich, will be used.

Several correction coil sets have been tested in a vertical bath cryostat in an external field of 5 Tesla [8]. Recent coils show very high quench currents (above 250 A at 4.35 K, 5.08 T) with no training and small dependence on polarity. Close to 100% quoted short sample current is reached. The field quality was measured at room temperature only. The harmonics are as specified except for one magnet where some higher harmonics in the sextupole coil were about a factor of 1.6 higher than expected. In this case the alignment error between the coils was about a factor 2 larger (15.3 mrad locally) than allowed (± 7 mrad).

Quadrupoles

The standard quadrupoles are 3.978 m long cryostats with a superconducting cold yoke quadrupole magnet, a superferric dipole correction magnet and a beam position monitor inside (Fig. 3). There is a two-layer superconducting quadrupole coil clamped with laminated stainless steel collars [9], a laminated iron yoke around the collared coil, a stiff stainless steel support tube also housing the dipole correction magnet, a helium vessel closed with end plates, a beam tube, a beam position monitor and an insulating vacuum containing superinsulation, a thermal shield cooled with 50 K helium, two 2-phase helium tubes and a vacuum barrier. All are housed in a stainless steel vacuum vessel. The magnets are properly aligned by keys inside the stiff support tube. The coils are cooled with one phase helium. Two phase helium returning through the dipoles passes through two tubes running through the insulating vacuum. These tubes must pass also through the vacuum barrier. For the prototype quadrupoles the inner parts of the cryostat are suspended at two locations along the magnet inside the vacuum vessel using similar glass fiber straps as for the dipoles. The series magnets will have only one plane of suspension straps as the vacuum barrier already acts as a suspension. The connections to the neighbouring dipoles are the same as for the dipoles. The helium vessel and the two phase tubes are protected with check valves and relief valves against overpressure.

As in the dipoles, the coil is wound from Rutherford type cable with 23 strands and slightly different dimensions from the dipole cable (for historical reasons). The cable insulation is similar. A cold diode is used to bypass the current around the coil in case of a quench. The cryostat also houses current leads for the dipole correction magnet (50 A) and buses for the sextupole/quadrupole correction coils sitting in the dipoles.

In addition to the standard quadrupoles, some quadrupoles are necessary with shorter magnetic length (housed in the same cryostat); others have an additional superferric quadrupole correction magnet and therefore longer cryostat (5.09 m). The quadrupole cryostats in the middle of the arcs are only 2.684 m long and contain a quadrupole magnet only.

The quadrupoles were designed at SACLAY. Two prototypes of the standard magnet have been built there. One of them (Fig. 4) has been tested at DESY.

The magnet was cooled down in about 7 hours. The measured heat leaks are 17 W at the 4.6 K area and 33 W at the shield, operated at 89 K. Quench tests of the quadrupole were made at different temperatures. No training was observed. The maximum quench current was 6940 A at 4.6 K. Harmonic measurements show good field quality.

Dipole correction magnets

Dipole correction magnets for orbit correction are housed in the cryostat of the main quadrupole. The 1.5 Tesla magnet is of the window frame type with superconducting saddle shaped coils of 45 A nominal current in a laminated yoke of 610 mm length [10].

Prototype magnets have been developed in collaboration with NIKHEF and HOLEC, Netherlands. A few "development magnets" and preseries magnets have been built by HOLEC. Four magnets have been successfully tested at DESY with the quench current exceeding the specified value of 75 A. One magnet was rejected due to an internal short. In good magnets quench currents between 100 A and 140 A (at 4.3 K) were achieved after some training steps. Magnetic measurements showed good field quality with higher order harmonics less than 2×10^{-3} of the dipole amplitude (at r = 2.5 cm) up to 40 A. The sextupole component rises steeply above 60 A where expected iron saturation begins.

Quadrupole correction magnets

About 30 quadrupole correction magnets are needed in the straight sections of HERA close to the interaction regions. They are housed in main quadrupole cryostats extended to 5.09 m length for this purpose. The magnets are of the superferric type with superconducting coils around classically shaped laminated iron poles. The coils are wound from a varnish insulated wire of rectangular cross section. The nominal current is 42 A giving 22 T/m at a magnetic length of 0.95 m [11].

A prototype with reduced yoke length (50 cm) for this magnet was built and tested at DESY. After a few training steps currents exceeding 200 A for both polarities were reached at 4.35 K. The field quality was good. Higher harmonics are about 10^{-3} of the quadrupole amplitude at 2.5 cm radius.

Electrical circuit

All main bending magnets, vertical bending magnets and main quadrupoles will be connected in series. At nominal current of 5027 A the stored energy in this loop of 26.4 Hy is 333.6 MJ. For the up-ramp, a rise time of 300 s (16.8 A/s) is planned. In order to reduce the number of different magnet types, the previously chosen circuit was changed. The current now will flow first through all dipoles all around the HERA tunnel, bypassing all quadrupoles, and then will return through all quadrupoles bypassing all dipoles. The bypass current (Fig. 5) will flow around the magnet yokes in the cold area inside the magnet cryostats. These bypasses, as well as the electrical magnet connections, are made from ordinary superconducting cable reinforced with 70 mm^2 copper.

In case of a quench, the magnets are protected[12] by cold diodes which bypass the current around the coils if enough resistive voltage (4 V) develops in the magnets. Once the quench is detected switches are opened at each octant of the dipole ring and at the quadrupole ring thus driving the current through dump resistors. In this way the main current is switched off with a time constant of 18 s. If all switches can be opened with a jitter of about 1 ms, the voltage in the magnet ring stays within ± 440 V to ground and below 880 V between buses. Quench heaters are fired in the dipoles in case of a quench in order to distribute and propagate the normal conducting zone in the magnets.

Cryogenic circuit

The superconducting magnets are cooled from a three unit central refrigeration system[13] now being installed close to Hall West on the DESY site. The capacity of each individual unit is 6775 W and 20.5 g/s at 4.4 K and 20 kW between 40 K and 80 K (for shield cooling). For steady state operation two units are sufficient. The third unit is used for cooldown or serves as backup. A transfer line going all around the tunnel distributes the helium to the individual sections.

At each octant the helium enters the magnet string through a feed box at 4.4 K and 2.5 bar. After flowing through the magnets, the helium is expanded in a JT valve at the end of the octant to about 1.1 bar and then returns through the magnets back to the feed box and to the refrigerator. For cool down the full compressor capacity of 1 kg/s from one compressor line can be used. For warm up warm helium gas of 18 bar is pushed through the magnets. The whole cryogenic system including magnet cryostats is designed for 20 bar. Therefore, the volumes in the magnets can be used also for temporary storage of cold gas in case of a compressor failure.

The refrigerators are now being fabricated and installed by SULZER (Switzerland).

Fabrication at industry and time schedule

All major components for HERA will be built by industry.

About one half of all dipoles (242) will be fabricated at Italian firms (Italian contribution to HERA: cable at LMI, collared coil with yoke at ANSALDO, cryostat at ZANON). Significant progress has been made by LMI in reaching and exceeding the required critical current. Winding of the first coil is now starting at ANSALDO. A preseries of 10 magnets is expected to be finished by June 1987. The series production will be completed in October 1988.

A Swiss Superconductor Consortium under the leadership of BBC, Zürich, is fabricating the cable for the other half of the dipoles. The critical current is excellent. Firms for fabricating magnets from this cable will be chosen by the end of this year.

All cable for the quadrupole is being fabricated by Vacuumschmelze, Hanau. The critical current is excellent. A fraction of the quadrupoles may be fabricated by French firms. Bids for the quadrupoles will be available by the middle of September 1986. Nine preseries quadrupoles will be completed by October 1987.

Wire for the sextupole/quadrupole correction coils (with the exception of the first octant) and for the dipole correction magnets is being fabricated by SLE, Netherlands. The achieved critical currents are excellent. The series coils and magnets are being fabricated by HOLEC and will be finished by the end of 1987.

All magnets fabricated by industry will be measured at DESY at liquid helium temperatures before being installed in the tunnel. For this purpose a special magnet measurement facility is being installed at DESY.

Acknowledgements

I would like to thank all colleagues at DESY who have participated in the design, construction and tests of magnets and systems.

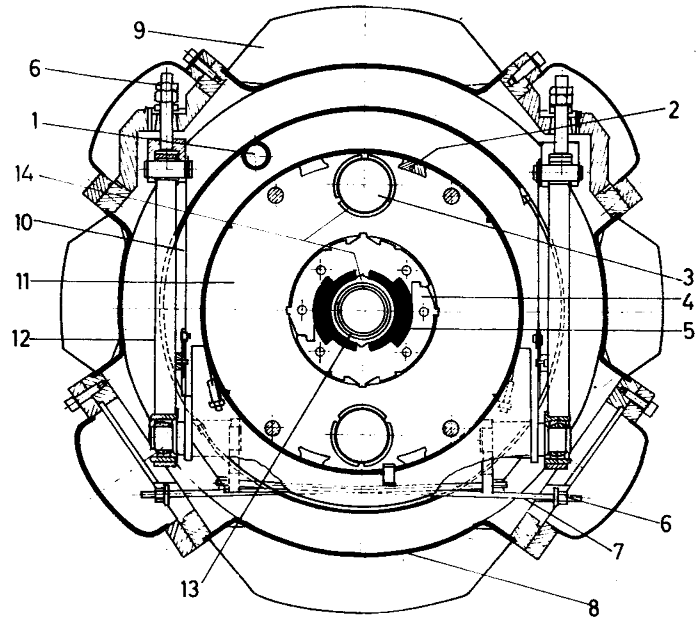

Fig. 1 - Dipole cross section (support region)
1 shield cooling tube; 2 forward and return bus; 3 two phase helium; 4 collars; 5 coils; 6 adjustment; 7 glass fiber rod; 8 vacuum container; 9 reinforcement; 10 support of radiation shield; 11 yoke; 12 glass fiber strap; 13 beam tube with correction coils; 14 one phase helium

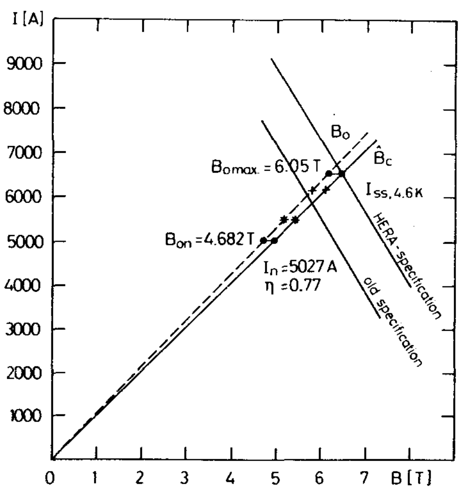

Fig. 2 - Dipole load line
B_0 central field, B_c maximum field at conductor, $I_{ss,4.6K}$ short sample current; B_{on}, I_n nominal values, * magnet no. 2 (no quenches), + magnet no. 3 (cable according to old specification, quench at 4.6 K)

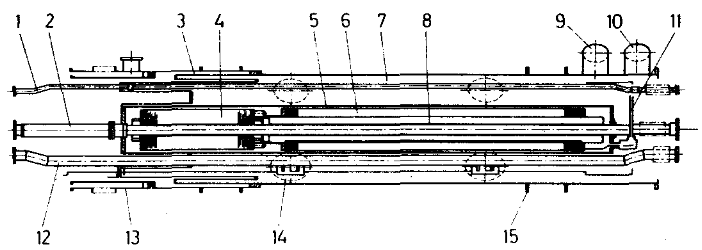

Fig. 3 - Longitudinal cut of quadrupole cryostat
1 shield cooling tube; 2 beam monitor; 3 vacuum barrier; 4 correction dipole; 5 helium container with cold support tube inside; 6 quadrupole; 7 insulating vacuum; 8 beam tube; 9 two phase safety tube; 10 one phase safety tube; 11 current leads for correction dipole; 12 helium tube; 13 sleeve for connecting magnets; 14 internal supports; 15 reinforcing rings

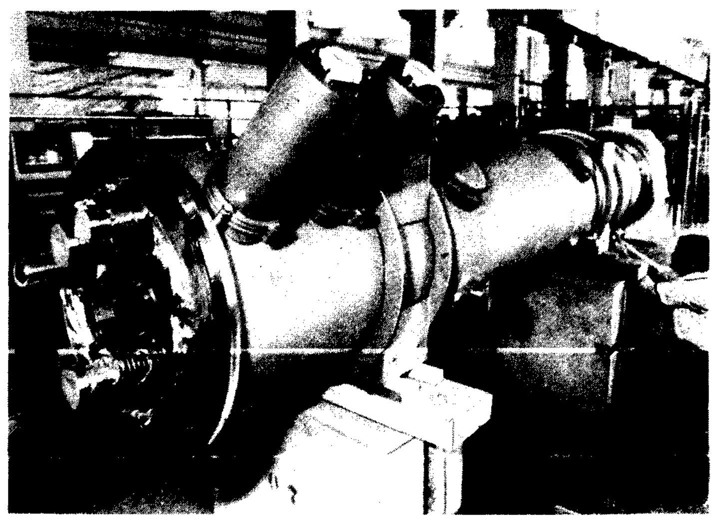

Fig. 4 - First HERA quadrupole cryostat with quadrupole coil and superferric correction dipole inside

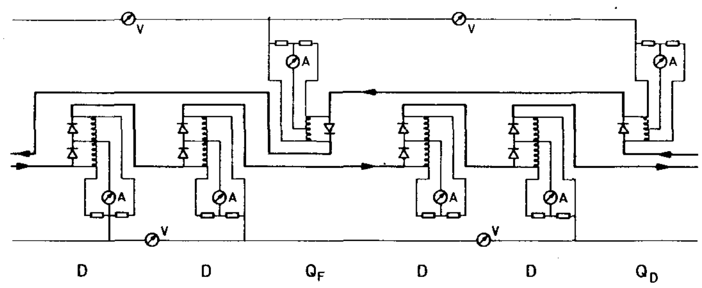

Fig. 5 - Current flow in a magnet cell
D = dipoles, Q_F, Q_D: horizontally focusing and defocusing quadrupoles

Table 1 - Integral harmonics* of dipoles at 5000 A

magnet no.	1**		2		3		allowed values	
n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	b_n
1	0.0	10000.	0.0	10000.	0	10000.		
2	-0.2	0.2	-3.6	0.3	-0.7	-1.4	±4.0	±4.0
3	-0.9	-4.7	-0.4	-1.0	-1.3	-1.6	±3.0	±10.0
4	0.1	0.2	-0.6	-0.1	0.2	0.0	±6.0	±3.0
5	0.5	-0.8	-0.5	-0.4	-0.2	-0.7	±2.0	0.9±5.0
6	0.5	-0.1	0.0	-0.3	-0.5	0.4	±2.0	±2.0
7	-0.2	0.6	-0.1	1.0	0.4	0.8	±2.0	0.3±2.0
8	-0.1	0.1	-0.6	-0.1	0.1	-0.6	±2.0	±2.0
9	0.2	-0.8	-0.1	-0.4	-0.6	-0.7	±2.0	-0.6±2.0

* ratio between harmonic and dipole field at r = 2.5 cm

** central harmonics only

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Discussion

K.P.Myznikov. You have reserve of the flux in your magnet field. Will you use it?

S.Wolff. Certainly, if it turns out that all of our magnets can be powered to higher currents, say, to 6000 A we certainly will use it.

E.Willen. How did you measure the pressure rise during the quench?

S.Wolff. We had a small tube going to the centre of the magnet just at the outside of the beam tube. We measured the pressure rise using this small tube.

Yu.P.Filippov. What are the cross-section magnitudes of He passages in your dipole magnets?

S.Wolff. You see, the one phase helium is flown around the beam tube and the correction coils and there are some channels which can be closed but presently about 1/3 of one phase He is flown here. The diameter of the tube is 63 mm.

К.П.Мызников. Вы бы не могли привести результаты измерений статических теплопритоков в длинных магнитах?

S.Wolff. The static heat loss of a 9 m magnet is 11 watts.