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Abstract: The 820 GeV HERA proton storage ring, presently under construction at DESY, will be equipped with about 650 superconducting main magnets (dipoles and quadrupoles) and approximately the same number of superconducting correction elements (dipoles, quadrupoles and sextupoles). These magnets will form a continuous cold string through the 6.3 km long HERA tunnel interrupted only by warm sections around the interaction regions.

The superconducting dipoles (4.68 T central field, 8.824 m magnetic length) as well as the superconducting quadrupoles (91.2 T/m central gradient, 1.861 m magnetic length) are of the cold bore, cold yoke type. In case of the dipoles aluminium alloy is used to clamp the coils.

For magnet protection cold diodes are by-passing the main current around the quenching coil. After quench detection heaters will be fired to distribute the quenching zone.

The magnet system is 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 for temperature control.

Prototypes of all types of superconducting magnets have been built and tested at liquid helium temperatures. The tested magnets have good field quality and good quench behaviour, which proves that these magnets are well suited for HERA.

Industrial production of magnets has started with the fabrication of "pre-series" magnets at several firms spread over several countries in Europe.

1. Introduction

The Hadron Electron Ring Accelerator (HERA) in construction at DESY consists of an electron storage ring of 30 GeV and a proton storage ring of 820 GeV nominal energy. The proton ring is mounted on top of the electron ring in a 5.2 m diameter tunnel of 6.3 km circumference 10 m to 20 m underground. Dipole, quadrupole and sextupole magnets are needed for bending, focussing and correcting the beam. Normal-conducting magnets are used for the whole electron ring and for the proton ring in a small area around the interaction regions. For the arcs of the proton ring superconducting magnets are needed.

2. Superconducting Magnet System

In the arcs of the proton ring the superconducting magnets [1] are arranged in a regular cell structure with 2 dipoles (nominal central field 4.682 T at 5027 A, magnetic length 8.824 m) and one quadrupole (nominal central gradient 91.18 T/m, magnetic length 1.861 m) in each half cell. Superconducting sextupole and quadrupole correction coils of 6 m length are wound on the beam tube in the dipoles adjacent to the neighbouring quadrupoles. A correction dipole magnet is mounted with the quadrupole and the beam monitor in a common cryostat.

All superconducting magnets needed for HERA are listed in Table 1.

3. Dipoles

3.1. Design

The main features of the dipoles [1,2,3] (see Figs. 1 and 2) are a 2 layer superconducting coil clamped with 4 mm thick aluminium laminations, a cold laminated yoke surrounding the collared coil, the sextupole/quadrupole correction coils around the beam tube, a superinsulated helium vessel around yoke and coils with one phase helium flowing through it and 2 phase helium returning through a tube through it in good thermal contact with the one phase helium, a vacuum vessel with glass fiber support bands at 3 locations along the magnet length and

Table 1 Superconducting Magnets for HERA

type	L cryost.	field/grad.	L field	number
dipole				
	9.766 m	4.682 T	8.824 m	416
	4.298 m	4.682 T	3.356 m	6
quadrupole				
	3.978 m	91.18 T/m	1.861 m	178
	3.978 m	91.18 T/m	1.679 m	8
	3.978 m	91.18 T/m	1.519 m	4
	5.090 m	91.18 T/m	1.861 m	18
	5.090 m	91.18 T/m	1.679 m	12
	2.648 m	91.18 T/m	1.861 m	4
beam pipe correction coils S/Q	-	46.4 T/m^2 /1.8 T/m	~5.9 m	416
correction dipole	-	1.5 T	0.61 m	220
correction quadrupole	-	22 T/m	0.95 m	30

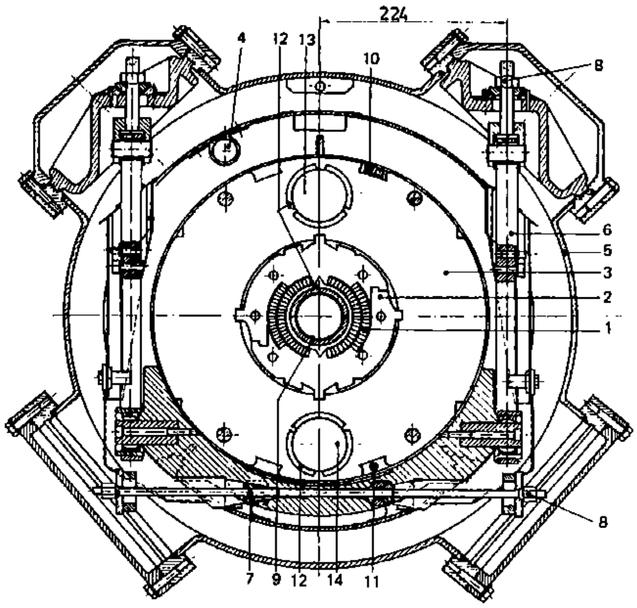

Fig. 1 HERA dipole cross section

(1) two layer coil
(2) laminated aluminium collars
(3) laminated yoke
(4) shield cooling tube
(5) vacuum container
(6) glass fiber band
(7) glass fiber rod
(8) adjustment
(9) beam tube with correction coils
(10) forward and return bus
(11) correction coil bus
(12) one phase helium
(13) two phase helium
(14) aluminium filler

an aluminium thermal shield cooled with 40-80 K helium gas and superinsulation around it.

The coil is wound from a key-stoned Rutherford type cable (1.67/1.28 mm x 10 mm, 24 strands). It contains copper wedges in the straight part and G11 spacers in the coil ends to improve the field quality. Quench heaters on the outside of the outer coil layer serve to propagate quenches.

At 4.6 K the dipole is operated at 77% of the short sample current (along the load line).

The magnet also contains a set of 2 cold diodes inside the helium vessel for protection, bellows at the ends to compensate for the thermal shrinkage and flanges at the cold connection which are welded when the magnets are connected with each other.

This dipole design combines the properties of good field quality even at high currents, safe mechanical support of the magnetic forces, safe quench protection and low heat loss.

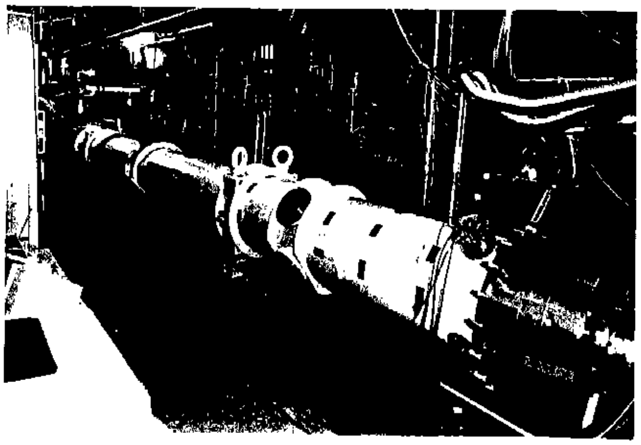

Fig. 2 HERA dipole on measuring stand

3.2. Fabrication and Test of Prototypes

Five dipole prototypes with collared coils built at DESY and yokes and cryostats fabricated at BBC, Mannheim were tested at DESY. With the exception of the first one, which was destroyed in an accident at 5890 A, all magnets were operated successfully. The cryostat was changed slightly during the fabrication of the prototypes in order to improve the heat load to final values of 6.7 W on the 4.2 K region and 27.5 W on the shield (60 K). The field quality was good.

Three magnets were driven to self quenches at different temperatures (maximum 7605 A equivalent to 7.0 Tesla at 3.91 K). There was no training with the exception of one training step at the last magnet.

3.3. Series Production

3.3.1. Italian Production: A total of 242 magnets including 10 preseries magnets are being fabricated in Italy (cable at LMI, Florence, collared coils and yokes at Ansaldo, Genova, cryostats at Zanon, Schio) financed by the Italian government.

More than 50 km of cable have been fabricated at LMI so far with an average short sample current of 8519 A (at 4.6 K, 5.5 T external field, σ = 287 A, see Fig. 3). The cable series production is progressing smoothly.

At Ansaldo 9 preseries coils have been wound and cured, five have been collared. Two of them have been tested cold and reached the acceptance current (7400 A).

The collared coils show good field quality (see Table 2).

One coil-yoke assembly has been completed with all its electrical connections and has been delivered

Table 2 Integral harmonic coefficients* of Ansaldo collared coils without yoke at room temperature

harmonic no.	normal average b_n x 10^4		normal σ_{b_n} x10^4	skew average a_n x 10^4	skew σ_{a_n} x10^4
2	0.70		0.53	0.59	3.11
3	-9.75	**	3.54	-0.48	0.71
4	0.08		0.34	0.33	0.42
5	-2.48	**	0.71	-0.21	0.10
6	0.03		0.08	0.21	0.25
7	0.23	**	0.19	0.04	0.04
8	0.04		0.05	-0.15	0.12
9	-0.38	**	0.11	-0.03	0.04

* fraction of dipole field at 2.5 cm radius

** design values $b_3 = -14.3 \times 10^{-4}$, $b_5 = 1.3 \times 10^{-4}$, $b_7 = 0.4 \times 10^{-4}$, $b_9 \geqq -0.8 \times 10^{-4}$ without yoke

to Zanon.

All tooling for the series production is ready.

At Zanon the fabrication of the first cryostat has started. Tooling suitable for series production at a rate of 5/week is being tested.

Completion of the Italian series production is scheduled for mid 1989.

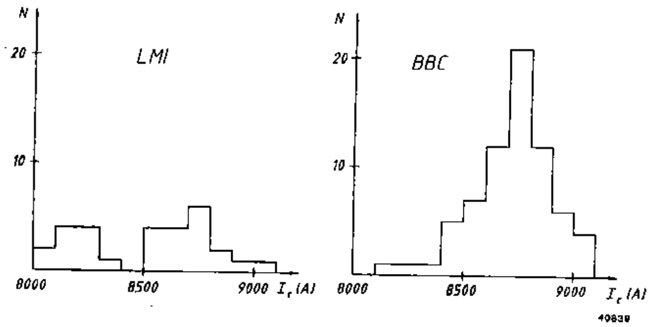

Fig. 3 Short sample critical current (5.5 T external field, 4.6 K) BBC: mean 8721 A, σ = 181 A; LMI: mean 8519 A, σ = 287 A

3.3.2. German Production: A total of 215 standard dipoles and 8 vertically deflecting dipoles of reduced length have been ordered at BBC, Mannheim. The superconducting cable is being produced at the Swiss Superconductor Consortium under the leadership of BBC, Zurich. More than 94 km of cable have been fabricated with an average current of 8721 A (σ = 181 A, at 4.6 K, 5.5 T external field, see Fig. 3). At BBC a "zero" coil has been wound, cured and collared using DESY material and tooling. Winding of the first BBC preseries coils has started. More tooling is being made at BBC for series production at a final rate of 5/week [4].

Completion of the German series production is scheduled for mid 1989, too.

4. Quadrupoles

4.1. Design

Main features of the quadrupoles[5] (see Fig. 4) designed by CEA Saclay are a 2 layer coil clamped with

1.5 mm thick stainless steel laminations, a cold laminated yoke surrounding the collared coil, a stiff support tube for aligning the quadrupole with respect to its neighbouring correction dipole and the beam position monitor, a beam tube, a superinsulated helium vessel around the support tube, a vacuum vessel with a vacuum barrier on one end and glass fiber support bands on the other, a 2 phase helium tube running through the vacuum and an aluminium thermal shield cooled with 40-80 K helium gas and superinsulation around it. The superconducting cable is similar as in the dipoles (however, only 23 strands). At 4.6 K the quadrupole is operated at 72% of short sample current (along the load line).

The cryostat also contains a cold diode for protection.

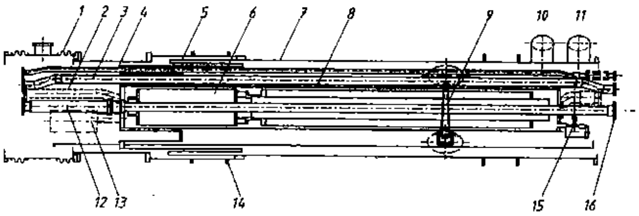

Fig. 4 Longitudinal cut of quadrupole cryostat

(1) vacuum sleeve
(2) one phase tube
(3) two phase tube
(4) shield tube
(5) vacuum barrier
(6) correction dipole
(7) vacuum container
(8) support tube and helium container
(9) glass fiber band
(10) two phase safety tube
(11) one phase safety tube
(12) beam position monitor
(13) cold diode
(14) external support
(15) correction dipole current leads
(16) beam tube

4.2. Fabrication and Test of Prototypes

Two quadrupoles built by CEA Saclay were tested at DESY. The heat loads are 9.0 W (at 5 l/min lead cooling gas rate) on the 4.2 K region and 28 W on the shield. The field quality (measured cold at collared coils) was good. Both quadrupoles were driven to self quenches at several temperatures and showed no training.

4.3. Series Production

4.3.1. French Production: A total of 126 standard quadrupole coils and 120 standard cryostats are being fabricated at Alsthom, Belfort, France, financed by the French government. The cable fabricated at Vacuumschmelze (VAC) is being supplied by DESY. (The average current for all cable from VAC is 8039 A, σ= 87 A, at 4.6 K, 5.5 T external field.)

Thirty preseries pole coils have been wound and cured. Two quadrupoles have been collared.

Fabrication of the first preseries cryostat (out of 6) has started.

The production rate will be 4/week.

The completion of the series production is scheduled for beginning 1989.

4.3.2. German Production: A total of 120 quadrupoles (collared coils) have been ordered at Interatom/KWU, some of them with slightly reduced length for the straight sections at the ends of the arcs of HERA. The cable has been fabricated by Vacuumschmelze, too (see 4.3.1.).

Fourteen preseries pole coils have been wound and cured. Two quadrupoles have been collared and were sent to the cryostat manufacturer.

Cryostats (117) including the special ones needed at the end of the arcs will be fabricated at Noell, Würzburg at a rate of 4/week. The first preseries cryostat (out of 3) is being assembled. The completion of the German quadrupole fabrication is scheduled for early 1989.

5. S/Q Correction Coils

5.1. Design

The sextupôle/quadrupole correction coils [6] wound from a wire of 0.7 mm diameter are placed around the glass-Kapton-glass insulated beam tube with glass fiber wrapping in between and glass fiber wrapped around and cured with epoxy. The nominal gradients are 46.4 T/m^2 for the sextupole and 1.8 T/m for the quadrupole.

5.2. Prototypes and Series Production

A total of 440 correction coil sets are being now fabricated at HOLEC, financed by the Dutch government. More than 160 sets have been completed already using wire from BBC, SLE and Vacuumschmelze. The final production rate is 10/week. The coils are tested cold at DESY in a vertical bath cryostat with an external field of 5 T [7]. Quenches occur generally close to the critical current of the conductor of about 300 A. Only a few coils are below the acceptance current of 230 A. The field quality is good.

6. Correction Dipoles

6.1. Design

The correction dipoles [6] inside the quadrupole cryostats are of the window frame type (laminated yoke) with coils wound from a wire of 0.56 mm diameter. The nominal central field is 1.5 T achieved at 45 A (less than 50% of short sample current on the load line). The magnetic length is 0.61 m.

6.2. Fabrication

After completion of a few prototypes, 250 correction dipoles are now being fabricated at HOLEC, again a contribution of the Dutch government. So far 100 magnets have been built, all of them have been tested at DESY [7]. The production rate is 5/week. Quench currents are around 100 A with some training but above the nominal current. The field quality is good.

7. Correction Quadrupoles

Close to the interaction regions some quadrupole cryostats which are longer than the standard ones also contain a superferric correction quadrupole (laminated yoke) with coils wound from a wire of rectangular cross section. The nominal gradient is 22 T/m achieved at 42 A. The magnetic length is 0.95 m.

The magnets are being fabricated at DESY presently.

8. System Test

A continuous string of prototypes (3 dipoles, 2 quadrupoles, see Fig. 5) representing nearly one full cell was assembled, cooled down and operated. Quenches were introduced by firing the quench heaters. Finally the string was driven to a self quench at 6193 A (4.55 K), which is at the short sample limit of one of the prototype dipoles (due to cable with lower performance in this magnet). At this current the central field is 5.71 T corresponding to 1000 GeV proton energy. The quench protection system [8] in this test proved to work satisfactorily.

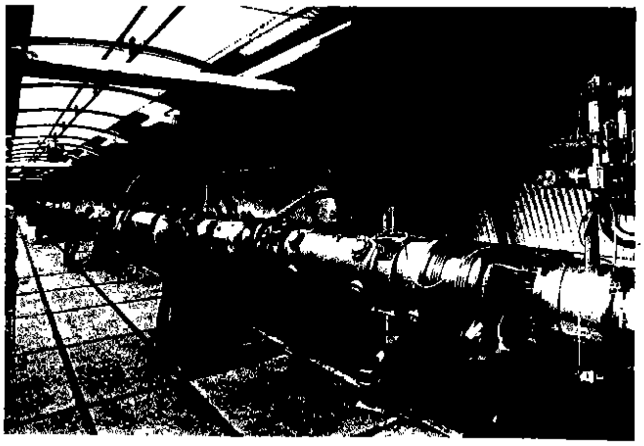

Fig. 5 Magnet string (System test)

9. Magnetic Measurements

All superconducting magnets will be tested cold at DESY. For dipoles and quadrupoles a magnet measuring facility with 6 test stands, supplied by one of the main refrigerator units for HERA has been installed and is being tested [9,10].

10. Electrical System and Protection

All dipoles and quadrupoles are switched in series using one main power supply with the possibility of feeding a small correction current through the quadrupoles alone (for adaptation). In case of a quench the current is by-passed around the quenching magnet via cold diodes [8]. When the quench is detected through voltage taps, the energy of the whole system is dumped into resistors which are switched into the main current line. The time constant for the current decay is 18 s. In the quenching magnet quench heaters are fired in order to propagate the quench.

11. Cryogenic System

The magnets are cooled from a central refrigeration system [11] consisting of 3 refrigerator units, each delivering 6.5 kW at 4.3 K plus 20.5 g/s liquid helium plus 20 kW at 40-80 K for shield cooling. A transfer line is distributing the helium to the individual octants around the tunnel. At each octant one phase helium is fed into the magnet string, it is passed through it and it is expanded at the end of the string to two phase helium, which is then returned through the magnets for temperature control. In case of a quench the evaporated helium is vented into a quench gas line.

Installation of the central refrigeration system by Sulzer-Escher Wyss, Lindau is nearly finished. Acceptance tests for one refrigeration unit have been completed.

12. Summary

Prototypes of all kinds of superconducting magnets and coils for the proton ring of HERA have been tested and have shown to be suitable for HERA. In a string test the magnet connections and the quality of the quench protection was tested. Preseries fabrication is going on for the dipoles and quadrupoles, series production for the correction magnets already. Completion of the magnet production is expected in mid 1989. Test results indicate good quality.

A test facility for testing the main magnets has been set up. The system of electrical connections has been fixed. Installation of the central refrigeration system is nearly completed.

Acknowledgements

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