HERA STATUS

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Abstract: The electron-proton collider HERA consists of two independent accelerators designed to store respectively 820 GeV protons and 30 GeV electrons and to collide the counter rotating beams head on in four interactions regions spaced uniformly around its 6.3 km circumference. In addition to HERA several booster accelerators must either be constructed or modified.

The status of the project can be summarized as follows:

The civil engineering work has been completed.

Electrons were stored for the first time in the HERA electron ring in August 1988.

Commissioning of the first two accelerators in the proton injection chain - the 50 MeV H^- linear accelerator and the 7.5 GeV DESY III synchrotron has started. The central helium refrigerators have been running routinely for nearly two years. Production of superconducting magnets is well underway in industry and the first magnets have already been installed in the tunnel.

1. Introduction

HERA[1)] has two distinct features. It is the first electron proton collider ever to be built and it is being realized within the framework of a novel form of international collaboration, where institutions in Canada, China, France, Netherlands, Israel, Italy, Poland, United Kingdom and the USA are contributing either technical components built at home or skilled manpower.

The main parameters of the HERA rings are listed in Table 1.

The HERA project was authorized in April 1984 and will be completed in 1990. The construction of the 6336 m long tunnel and the large subterranean buildings providing space for detectors, control rooms and various utilities has been completed. The electron/positron booster accelerators are operational. Electrons were stored for the first time in the HERA electron ring in August 1988. Commissioning of the H^- linac and DESY III is underway and the first protons are scheduled to be injected into the first octant of the HERA proton ring towards the end of the year. The central Helium plant has run for more than 70000 hrs without an unscheduled shutdown and the helium distribution system will be ready for commissioning in July 1989. Series production of superconducting magnets is well underway in industry and the first superconducting magnets have been installed.

In this talk I'll review the status of HERA with emphasis on the proton ring and the superconducting magnet programme.

Table 1

	p-ring	e-ring
Energy (GeV)	820	30
Polarization time (min)		28
Luminosity ($cm^{-2}s^{-1}$)	$1.5x10^{31}$	
Space between IR Quad (m)	15	
Crossing angle (mrad)	0	
Circumference (m)	6336	
Magnetic field (T)	4.68	0.165
Number of particles (10^{13})	2.1	0.8
Number of bunches	210	
Injection energy (GeV)	40	14
Filling time (min)	20	15
σ_x/σ_y at I.P. (mm)	0.29/0.07	0.26/0.02
σ_z at I.P. (mm)	110	8.0
Energy loss/turn (MeV)	$1.4x10^{-10}$	127
Circumferential RF-voltage (MV)	0.2/2.4	165
RF-power (MW)	1	13.2
Refrigerator	21.0 kW (isothermal at 4.3 K) 60 g/s liq.He 60 kW (40 K - 80 K)	

2. The Injection Complex

The HERA injection complex is shown in Fig. 1. The beam transfer channels linking PETRA with HERA have been completed and successfully tested with electrons and positrons.

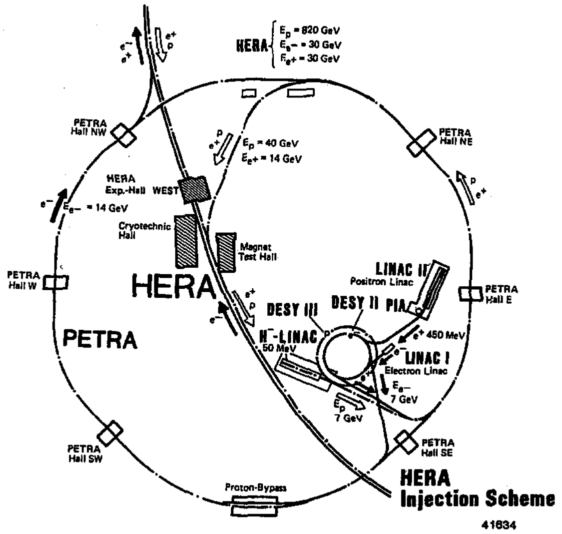

Fig. 1 - The HERA injection complex

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The electron (positron) injection complex is based on available accelerators and is operational. However, in order to handle the high multibunch current PETRA II will be equipped with transverse and longitudinal broadband feedback systems.

The first element in the proton preaccelerator chain is a 50 MeV H^- linear accelerator. H^- ions of 18 keV from a Cesium loaded magnetron[2] type ion source, focussed by a pair of solenoid magnets, are accelerated to 750 keV in a RFQ[3], injected into a conventional drift tube Alvarez structure and accelerated to 50 MeV. The linac has been in routine operation since December 1988 and now delivers a 5 mA H^- beam in a normalized transverse emittance of 6π mm mrad and an energy spread of $1\text{-}2 \times 10^{-3}$. Note that the intensity is being kept below the design intensity of 10 mA in order to minimize the induced radioactivity in DESY III during the commissioning phase and that two of the early drift tube quadrupoles are not powered.

The H^- ions are stripped by a thin (30 $\mu g/cm^2$) Al_2O_3 foil and injected into the synchrotron DESY III. The first beam was stored at the injection energy in December 1988 and accelerated to the design energy of 7.5 GeV in February 1989. Note that the DESY III transition energy is 8.5 GeV. The intensity on the flat top was 10^{10} protons or roughly 1% of the design intensity. The beam was extracted and passed half way along the beam line linking DESY III with PETRA II in March 1989.

The bending magnets in PETRA II limit the maximum proton energy to 40-45 GeV. The quadrupoles are rather weakly focussing resulting in a large dispersion and a transition energy of 6.5 GeV, which is below the DESY III maximum energy of 7.5 GeV. Thus the protons never cross transition during the whole injection cycle. PETRA II is now in the midst of its upgrading programme; the 52 MHz proton RF-system has been installed and tested, the magnets of the 110 m long arc which allow the protons to bypass the high impedance electron cavities have been installed, the injection-kicker and septum have been rebuilt, the power supply for 40 GeV operation has been commissioned and a new movable ejection kicker has been built. It is estimated that PETRA II will be ready for proton injection by early June.

3. The Electron Ring

For a recent technical description of the HERA electron ring see the report by G.A.Voss in reference 1.

At the start up of the first commissioning run in August 1988 several components were not yet installed or not operational

- only one out of six 1.2-1.5 MW RF transmitters and 14 out of 80 cavities were operational
- the spin rotators were not installed
- the vacuum system in the straight sections was not final
- the magnet water cooling was not connected limiting the energy to 14 GeV
- no feed-back system existed.

Despite this, the first 6 weeks commissioning run went remarkably well and brought a wealth of information:

- single bunch currents up to 0.3 mA could be stored consistent with the proposal value
- the maximum average current was 0.3 mA compared to the design value of 60 mA
- electrons were accelerated from 7 GeV to 14 GeV
- the β-functions agreed with the calculations
- the lifetime was 1.5 hr, presumably pressure limited.

The next electron ring run is scheduled for August and September 1989. It is hoped that the average current can be increased by using a broad band feed-back system. Positrons will also be injected in order to investigate potential ion-driven instabilities.

The RF system will be improved in two stages. In the first stage, 7/8 of the PETRA RF system are transferred to HERA leaving just enough RF in PETRA for its role as a 14 GeV electron/positron injector. With this system, which will be ready for the next run, it will be possible to reach 26 GeV at the design current or 29 GeV with a stored beam of 10 mA.

To reach - or surpass - the design energy of 30 GeV, the present RF system will be augmented by a superconducting RF system[4] to be installed in straight section West. A prototype of the foreseen 500 MHz cavity, made of two 4 cells structures in a single 4.2 m long cryostat, has been successfully tested at PETRA. The cavity reached an accelerating gradient of 5 MV/m with a Q value of 5×10^9. Eight cavities with a total active length of 19.2 m have been ordered. Delivery will start in spring 1989 and the system should be operational one year later.

An energy of 29 GeV with 60 mA of stored beam or 33 GeV with 20 mA can be reached with the superconducting RF system running in parallel with the normal conducting system. If straight section West was to be completely filled with superconducting cavities then the corresponding maximum energies would be 31 GeV respectively 38 GeV. The main reason for pushing the electron energy, besides the obvious gain in c.m. energy, is the reduction in polarization time. At the nominal energy of 30 GeV the time constant for the build-up of transverse polarization is 28 min, decreasing as E^{-5} to 17 min at 33 GeV and 8 min at 38 GeV.

4. The HERA Proton Ring

The conventional components of the proton ring, i.e. the two RF systems, beam diagnostic equipment, injection system, vacuum system and beam abort system are under construction and should be installed by the end of 1989.

Normal magnets are used to guide the protons in the plane of the electron ring in order to avoid that cold magnets are hit by the primary synchrotron radiation and to ease the problems with injection and beam abort. The accumulated distance equipped with normal-conducting magnets amounts to 1 km. All the warm magnets have been delivered, measured and installed. The all metal vacuum system has been baked out at CERN at 1050° C and provision has been made for in situ bake out at 300° C. The components are now being installed.

4.1 The refrigeration system

The helium refrigerator plant is located on the DESY site. It is subdivided in three identical plants each providing 6.6 kW isothermally at 4.3 K, 20.4 g liquid helium per second and 20 kW at 40 K to 80 K. The liquid helium and the 40 K helium gas are supplied by a fourfold transferline to the feed boxes which are installed at the ends of each octant. The same transferline is needed to return helium gas of 4.6 K and of 80 K to the refrigerator.

The performance of the helium plants meets or exceeds the specified values listed above. The plant efficiency is very high, 287 Watt of electrical power are needed to produce 1 Watt of cooling power at 4.2 K.

Two 23.5 m long modules of the transferline have been produced by industry and extensively tested at DESY. The measured heat load was less than 0.1 Watt/m and at the 4.2 K level and 1.1 Watt/m at the shield temperature level. All the transferline elements have been installed in the HERA tunnel. A 22 bar pressure test and the vacuum test of the process tubes and the cryostats are nearly complete for the transferline in the West half ring and have just been started for transferline in the East half ring.

The production of the 23 helium feed boxes are well advanced in industry and the first 6 boxes have been delivered and installed in the tunnel.

The cold test of the complete helium distribution system will start in May 1989.

In the case of a quench the quenched magnet is bypassed by a set of cold diodes. The quench is detected by a balanced bridge circuit using the dipole half coils as part of the bridge. Heaters in the coils of the quenched dipole are fired, the power supply is disconnected from the magnets and the stored energy is dumped in external resistors. The warm gas from the quenched magnets is fed through a safety valve to a ring line which returns the gas to storage vessels at a pressure of up to 20 bar. The quench gas return line has been installed all around the ring and tested. Also the warm ring lines required for magnet cooldown and warmup, for the return of current lead gas, and for the control of the safety valves have been installed.

4.2 The superconducting magnets

The superconducting magnets in the arcs are arranged in 104 cells and the ordering within one such cell is shown in Fig. 2.

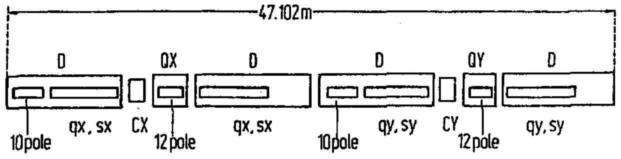

Fig. 2 - A unit cell of the HERA proton ring. D main dipole; QX (QY) main quadrupole with horinzontal (vertical) focusing; qx (qy) quadrupole correction coils; sx (sy) sextupole correction coils; cx, cy correction dipoles. In addition there are 10-pole and 12-pole correction coils

The main dipoles and quadrupoles are powered in series with the forward current flowing through the dipoles and the return current through the quadrupoles. A small, auxilliary supply in the quadrupole circuit makes it possible to simoultanously change the horizontal and vertical betatron tunes.

The quadrupole and sextupole correction coils are realized as 6 m long coils wound directly on the dipole beam pipe at the end adjacent to main quadrupoles.

Errors in the proton orbit are corrected by superferric dipole magnets installed in the quadrupole cryostats. For matching purposes, and also in order to facilitate a change between injection and collision optics, individually controlled superferric quadrupoles are installed in the main quadrupole cryostats at the end of the arc.

The sextupole coils are used for the chromaticity correction but also for the compensation of the persistent current sextupoles in the main dipoles. In addition, 10-pole and 12-pole coils are needed to compensate higher persistent current multipoles. These coils are mounted on the beam pipe inside the main dipoles or quadrupoles.

Dipole magnets: A new type of dipole magnet[5] based on earlier designs at Fermilab and Brookhaven, has been developed at DESY. A vertical cut through the dipole magnet is shown in Fig. 3.

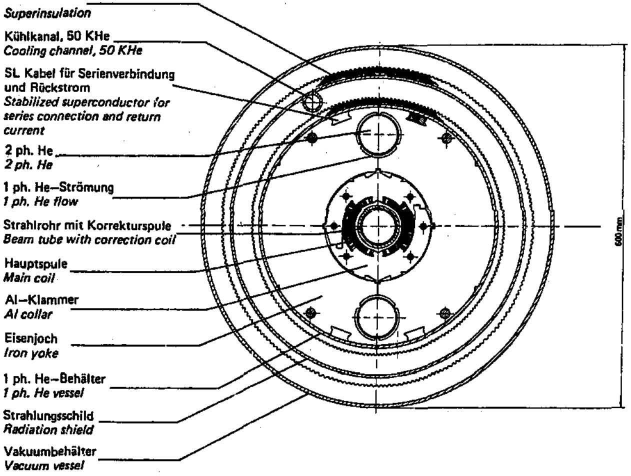

Fig. 3 - Vertical cut through a dipole magnet

The two layer coils are wound using a 24 strand Rutherford type cable. Each strand, with a diameter of 0.84 mm, is made of 1230 NbTi filaments of 14 μm diameter, imbedded in a copper matrix. The copper to superconductor ratio is 1.8 to 1. The specified current is 8000 A in an external field of 5.5 T at 4.6 K.

The two half coils are clamped using 4 mm thick aluminum laminations, which are locked by two 9 m long tie rods. This method avoids any welds of the collars and leads to a highly reproducible collar geometry. The collars can easily be opened to correct for field errors. The coil is centered inside a laminated cold iron yoke by 4 nose cones which fit into notches in the iron. The magnets are curved with a radius of 588 m. The radius of curvature and the twist are defined by the one phase stainless steel tube which surrounds the cold mass. The radiation shield consists of a circular aluminum vessel cooled by gaseous helium flowing in a single extruded channel. The magnet is suspended inside the cryostat at three positions using unidirectional epoxy-fibreglass bands.

The superinsulation of the 4 K part of the cryostat consists of 10 layers of aluminum coated (2x400A) mylar foils interleaved with glas net spacers. The 40 K shield is wrapped with 30 layers.

416 superconducting dipoles of 8.824 m length and 6 vertically deflecting dipoles of 3.356 m length are needed to complete the HERA ring. The nominal field of 4.682 T, corresponding to 820 GeV, is reached at an excitation current of 5027 A.

Istituto Nazionale di Fisica Nucleare in Italy contributes half of the dipole magnets to the HERA project and these magnets are being manufactured by a group of Italian firms. The remaining part of the dipole magnets is being built in Germany.

The preseries production of 30 magnets has been completed. Three of the magnets went through the accelerator life test consisting of 30 temperature cycles between 40 K and 300 K, 2000 current excitation cycles and about 100 spontaneous quenches at currents some 25% above the nominal operating current. These magnets were then disassembled and inspected. After the correction of some minor faults the series production of collared coils was released in the spring of 1988 and the production of the whole magnet at the end of 1988.

The present status can be summarized as follows:

- 865 km of the 937 km cable ordered has been delivered. The average short sample critical current, measured at BNL, is 8800 A in an external field of 5.5 T and 4.6 K and thus well above the specified value of 8000 A.
- A total of 370 dipole coils out of 416 has been wound and cured and 290 dipole coils have been collared.
- 30 preseries magnets have been delivered and the first series magnet is expected towards the end of March 1989. The total series production rate is 10 magnets per week.

Quadrupole magnets: The quadrupoles6) have been developed by CEA Saclay. 224 quadrupole magnets with lengths between 1.861 m and 1.514 m are needed. The nominal gradient at 820 GeV is 90.18 T/m. The series production of the quadrupoles is divided between a French company which produces the quadrupoles contributed by France to the HERA project and two German firms.

The salient design features are a two layer coil clamped with 1.5 mm thick stainless steel laminations nestled inside the laminated iron yoke. The quadrupole cable is similar to that used in the dipole except that it consists of 23 strands instead of 24. A stiff support tube surrounded by the 1 phase helium container is used to define the azimuthal position of the quadrupole. The one phase helium container is fixed by a vacuum barrier on one end and by unidirectional glass tapes on the other. The 4 K part of the magnet is surrounded by an aluminum radiation shield cooled with 40-80 K helium gas. The superinsulation is similar to that used for the dipoles.

The series production of collared coils was released in early 1988 and the production of the complete magnets in mid 1988. One quadrupole went through the accelerator life test without damage.

The status of the project is as follows:

- The cable (115 km) has been delivered by Vacuumschmelze. The short sample critical current, measured at BNL, is (8039 ± 87)A in an external field of 5.5 T at 4.6 K compared to the specified value of 7000 A.
- All the collared quadrupole coils have been produced, tested and accepted.
- A total of 150 magnets out of 224 has been delivered. The series production rate is 8 magnets/week.

Correction magnets: The sextupole/quadrupole correction coils and the superferric dipole magnets have been designed7) in collaboration between DESY and NIKHEF.

These magnets (440 S/Q-coils and 250 dipoles) have been financed by the Netherlands and produced by Dutch companies. All the correction magnets have been produced, tested and accepted. The quench current distribution exceeds the operating current by a factor of 2 to 3. The field quality is also a factor of 3 better than required.

Some 40 superferric quadrupoles8) have been designed and produced at DESY. The measured quench current exceeds the operating current by a comfortable margin.

The 10-pole and 12-pole compensation coils have also been built and tested.

4.3 Cold test of dipole and quadrupole magnets

All superconducting magnets are tested at liquid helium temperatures. Eight measurement stands are available. The turn around time is 80 hrs per magnet.

So far 27 dipole magnets and 67 quadrupole magnets have been measured. The results can be summarized as follows:

- None of the magnets quenched below the nominal operating current of 5027 A. 95% of all the magnets reached the short sample critical current on the first or second quench. The mean value of the quench currents at 4.6 K are: (6453 ± 110) A for the dipoles and (7350 ± 190) A for the quadrupoles.
- The integrated dipole field length has an rms fluctuation of $3\text{x}10^{-4}$ for the magnets from one vendor. The field lengths of the magnets produced in Italy and Germany differ by $1\text{x}10^{-3}$.
- The integrated quadrupole gradient has an rms variation of 10^{-3}. The position of the axes at 4 K agrees horizontally to (0.07 ± 0.32) mm and vertically to (0.43 ± 0.32) mm with the position as determined by the manufacturer at room temperature.
- The field quality of both the dipole and the quadrupole magnets is excellent.

In Fig. 4 the skew (a_n) and normal multipole coefficients (b_n) are shown for the quadrupole magnet at full field, normalized to the quadrupole field at a radius of 25 mm. In Fig. 5 the skew and normal dipole multipole coefficients are plotted. The field quality at full excitation is excellent and much better than specified.

At low excitation, particularly at the injection energy, persistent eddy current in the NbTi filaments lead to large sextupole and decapole fields in the dipole and dodecapole fields in the quadrupole.

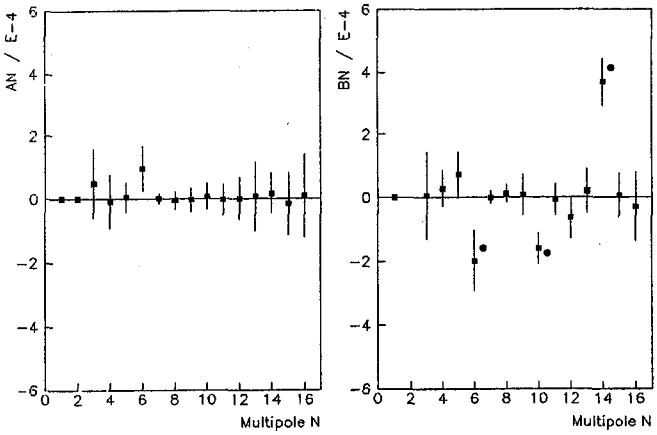

Fig. 4 - The average value of the multipole coefficients for 67 quadrupole magnets measured at full field. The dots indicate the expected values of the coefficients, all other coefficients should disappear

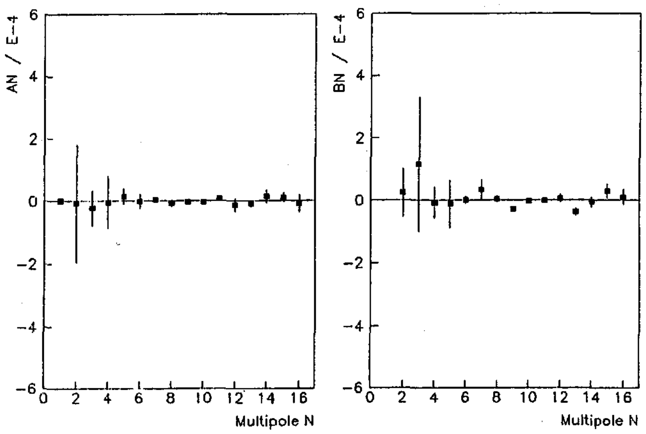

Fig. 5 - The average value of the multipole coefficients for 27 dipole magnets measured at full field

The hysteresis curve for b_3 (sextupole) and for b_5 (10-pole) are plotted in Fig. 6 as a function of magnet current. Data are shown for an individual dipole and the average of 19 dipoles. The sextupole and decapole coefficients have been corrected for geometric effects. The solid line is an absolute prediction[9] made by Müller and Schmüser. Note that this prediction depends crucially on the critical current of the conductor at low field. Although the absolute values of b_3 and b_5 are large at the injection they vary little from magnet to magnet and can hence be compensated by a constant excitation current in the sextupole and decapole coils.

Presumably caused by flux creep in the superconductor, the magnetization varies as a function of time. For example the main dipole field at injection varies between 100 s and 2000 s by 2.2 Gauss or about 10^{-3} for magnets produced in Italy and by 1.1 Gauss for magnets produced in Germany. The corresponding values for the sextupole coefficient are 6.3×10^{-4} respectively 2.7×10^{-4} in the same time interval. The 12-pole field in the quadrupole varies by 1.1×10^{-4}. However, note that the magnetizition will approach its old value when the excitation cycle is resumed.

In order to control the fields at injection it is planned to measure the field continuously in cold magnets powered in parallel with the ring magnets.

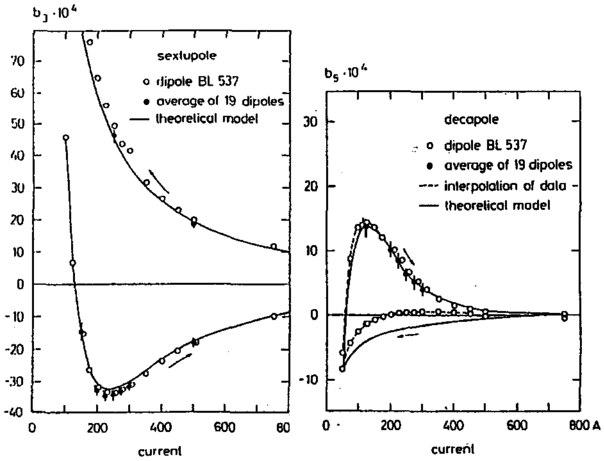

Fig. 6 - The values of b_3 and b_5 as observed for the dipole magnets as a function of current

4.4 System Test

A string of two quadrupole magnets and three dipole magnets was assembled with an inclination of 10 mrad and thoroughly tested over a period of 10 months. The system behaved as predicted.

The magnet string was cycled 10 times between room temperature and liquid helium temperature without problems. The heat load of the string was in good agreement with the sum of the measured heat loads of the individual magnets and also in agreement with the proposal value.

The quench protection system, after some modifications, worked very reliably. It was demonstrated for currents up to the nominal value that a quench induced in one magnet does not propagate to its neighbours.

Summary

It still seems possible to meet the original aim of observing the first electron-proton collision in HERA in 1990.

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