H E R A

B.H.Wiik
II.Institut für Experimentalphysik, Univ. Hamburg, and
Deutsches Elektronen-Synchrotron DESY, Hamburg.

Introduction

In this report I discuss the electron-proton colliding beam facility HERA, now under construction at DESY in Hamburg,and give an update of the status and the machine parameters.

In 1979 a detailed feasibility study[1)] of the project was organized by the European Committee on Future Accelerators (ECFA) and this was followed by a technical design report[2)] prepared by DESY in collaboration with other institutions. This work resulted in a formal proposal to the German authorities to construct a large electron-proton colliding beam facility designed to collide 820 GeV protons with 30 GeV electrons in four interaction regions. These studies have also been the basis for several[3,4] workshops. The project was authorized by the German authorities in April of 1984 and actual construction started a month later.

Besides Germany, institutions in Canada, France, Netherlands, Israel, Italy and the United Kingdom have expressed interest in joining the HERA project. The collaboration is modeled after the construction of large experimental facilities; the collaborating institutions contribute machine components to be built in the home countries and manpower.

Site and Buildings

The layout of HERA is shown schematically in Fig. 1 and the main parameters are listed in Table 1.

The machine has a fourfold symmetry; four 360 m long straight sections are joined by four arcs with a geometric radius of 779.2 m yielding a total circumference of 6336 m. The tunnel containing the two rings is located some 10 - 30 m below the surface resulting in a negligible radiation level on the surface. The tunnel intersects the PETRA ring at a depth of 20 m and only short injection paths are needed to connect the two accelerators.

The installations to provide power, cooling and refrigeration for the accelerator will be located at the DESY site and the distribution to the four experimental halls will be either in trenches on the surface or through the tunnel.

A tunnel diameter of 5.2 m is required in the straight sections and the bids revealed that it is cheaper to make the complete tunnel with an uniform diameter of 5.2 m rather than to reduce the diameter in the arcs to 3.2 m as proposed. Fig. 2 shows a cut through the tunnel in the arc with the proton accelerator mounted on top of the electron machine and with utilities installed.

The counter rotating beams are brought to collision in the middle of the four long straight sections by making them cross at an angle of 20 mrad. At each of these locations there will be a large 7 stories deep subterranean building containing the detector, control rooms for experiment and machine and all auxilliary equipment. These buildings provide the only access to the tunnel and components weighing up to 40 to can be brought directly into the experimental hall through a loading shaft 9 m x 6 m. The experimental halls are 25 m along the beam direction and 43 m wide (except hall West which is 35 m wide). The crossing point is 4.6 m above the floor and the halls are served by a 40 to crane.

Bids for the tunnel and for the subterranean buildings were received on February 28 and the contract signed on April 24. The tunnel will be drilled in clockwise direction starting from hall South. Hall South is now being excavated such that the drilling can start early 1985. Installation of machine components can start in April 1986 in the tunnel section linking hall West and hall South. The civil engineering will be completed towards the end of 1977 according to the present schedule.

Design Parameters

The general parameters are listed in Table 1. The maximum energy of the electron beam is determined by the available RF power and the lower energy by the damping time. The electrons will be transversely polarized due to the Sokolov-Ternov effect[5]. The buildup time for the polarization is

20 min at 30 GeV electron energy and it scales as E^{-5}.

The maximum proton energy of 820 GeV is reached using superconducting magnets with an induction of 4.53 T. The proton orbit must be shortened with respect to the electron orbit in order for electrons and protons to remain in phase. The necessity of moving the proton orbit limits the lowest collision energy to about 300 GeV. The lower limit on the proton injection energy is determined by persistant currents in the superconducting coils. The relative importance of these currents decreases with energy as they cause constant higher multipole fields disturbing the dipole field. We plan to compensate for the average persistent current effects using correction coils wound directly on to the beam pipe. In this case tracking calculations[6)] show that a lifetime of several hours can be expected at the injection energy of 40 GeV.

In a crossing angle geometry the luminosity is proportional to the proton line density and this favour a high proton RF frequency. The proton RF frequency has been raised from 208 MHz in the proposal to 500 MHz, the frequency used for the DESY electron machine and also forseen for the electron ring in HERA. The proton RF system is presently designed to produce a circumferential voltage of 20 MV. The maximum proton current of 163 mA is divided into 210 bunches spaced 28.8 m apart each containing $1 \cdot 10^{13}$ protons.

The electron ring of HERA will - as a first stage - make use of the large RF system installed at PETRA. Sufficient RF will be left in PETRA to enable the accelerator to reach 14 GeV. The remaining system installed in HERA will enable a current of 16 mA (50 mA) at 30 GeV (27.5 GeV). The maximum forseen current of 58 mA in 210 bunches may be reached by either expanding the present system or by installing superconducting cavities. The latter option would lead to substantial saving in power cost.

The first stages of booster accelerators are shown in Fig. 3. PETRA suitable modified serves as the final stage both for electrons (positrons) and protons.

The RF system remaining at PETRA limits the electron (positron) energy to 14 GeV. A special beam optic with rather weak focusing will permit acceleration of protons in PETRA up to 40 GeV. The filling time of about 20 min for positrons and protons are mainly determined by the estimated 70 s cycle time of PETRA.

Interaction Regions and Spin Rotators

A possible collision geometry is shown in Fig. 4. The beams cross in the horizontal plane at an angle of 20 mrad leaving a distance of $\pm$ 7.5 m around the interaction point free for the detectors. A horizontal crossing was chosen since the horizontal beam size is much larger than the vertical. A finite crossing angle makes it possible to design the two HERA rings without common elements such that the electron and the proton energy might be chosen independently and the synchrotron radiation is minimized by locating bending magnets far away from the interaction region. However, the allowable tune shift has been found to be reduced in a crossing geometry due to synchrotron-betatron resonances[7]. At DORIS the crossing angle leads to a ΔQ-reduction by about a factor of 3. For a proton beam the reduction factor is expected to be even larger[8] since the protons are not damped by synchrotron radiation. An alternative layout permitting head on collissions is presently being studied.

The ability to collide electrons (positrons) of well defined helicity with protons provides a very important tool in the investigation of neutral and charged current interactions. This requires that the electron (positron) beam is transversely polarized in the arcs and that the transverse polarization is turned into a state of defined helicity before the collision and that its transverse polarization is restored upon entering the next arc. By emperically compensating[9,10] those harmonics of the vertical orbit distortions which are close to the number of spin precessions per revolution transverse polarizations close to the theoretical limit of 92.4% has been achieved[11] routinely with PETRA. High transverse polarizations are therefore expected at HERA since the machines only differ by a factor 1.5 in energy. Furthermore, the depolarization due to beam-beam interactions have been found to be small for the ΔQ values listed above. The spin rotators will also produce depolarizing effects.

An optics solution for a spin rotator[12] employing horizontal and vertical bends has been worked out in detail. About 80% polarization can be reached with this design. To change helicity, magnets must be physically moved and the rotator only work for a limited energy band. An alternative rotator[13] consisting of a large superconducting solenoid and a horizontal bending magnet is also being investigated. This rotator seems in principle capable of yielding a high polarization, however, the details still remains to be worked out.

Injection

The layout of DESY II, the proton linac and DESY III is shown in Fig.3.

DESY II[14] - which will be used to accelerate single electron (positron) bunches, is a new 9 GeV electron synchrotron under construction in the same tunnel which also houses the present DESY I Synchrotron. DESY II will be completed in March 1985 and will become fully operational in March of 1986.

H^- ions from a new 50 MeV linac[15] are stripped and injected for 10 revolutions into DESY III where they are captured into 11 RF buckets with the final bunch spacing of 28.8 m. The protons are accelerated to 7.5 GeV and transferred in one go to PETRA. The procedure is repeated and the 22 bunches in PETRA are accelerared to 40 GeV. At this energy the protons in PETRA are rotated by 90° in longitudinal phase space and injected into the 500 MHz RF buckets in HERA. During the injection cycle the protons never cross transition.

The 50 MeV proton linac is based on the CERN design but with some important changes. The CERN duoplasmatron is replaced by a magnetron source capable of delivering up to 35 mA of negative Hydrogen ions at 18 kV. The ions, focused by a system of solenoids, are injected directly into a Radio Frequency Quadrupol (RFQ) where they are longitudinally bunched and accelerated up to the 750 kV. The linac is under construction and will become operational in spring of 1987.

The rebuilding of DESY I into DESY III[16] includes a new all metal vacuum chamber, replacing the present electron cavities with a proton RF system, a new magnet powering system which will take protons up to 8 GeV in a 2s long savetooth cycle and a new monitoring and control system. The combined function magnets will be rearranged and augmented by 16 quadrupols such that the transition energy of the machine can be varied from 7.4 GeV at injection to 10.4 GeV at injection.

For proton acceleration in PETRA[17)] the focusing will be rather weak corresponding to a transition energy of 5.9 GeV. The protons will pass through a special straight section arrangement in PETRA which by passes the remaining electron cavities.

Electron ring components

The dipole, quadrupole and sextupole magnets of the HERA electron ring will be mounted and aligned on a common strong back before being brought into the tunnel Compared to the proposal the electron half cell length has been increased to 11.769 m. The dipole has a length of 9.199 m and is excited by a single Cu conductor. Prototypes of the various magnets are now under construction.

The critical energy and the power density of the synchrotron radiative are similar to the values now occuring in PETRA. It has been proposed to use a Cu-vacuum chamber which would contain most of the synchrotron radiation.

Proton ring components

For the proton ring superconducting dipole, quadrupole and correction magnets must be developed.

The properties of the bending magnet (warm iron) and the quadrupoles are listed in Table 2. The vertical and horizontal correction magnets are designed for $\int Bdl = 0.7$ Tm. The quadrupole and sextupole correction magnets have an integrated induction of 0.54 Tm respectively 0.35 Tm at a radius of 2.5 cm.

Two types of bending magnets have so far been investigated, a warm iron magnet built at DESY and a cold iron magnet built at Brown-Boveri, Mannheim, in collaboration with DESY. Both magnets are of the cold bore type. A cross section of the two magnet types is shown in Fig. 5.

The coils are wound using a helium transparent Rutherford type cable with the niobium titanium imbedded in a copper matrix in the ratio 1 to 1.8. The cable is wound using 24 strands of 0.83 mm diameter and each strand consists of 2340 superconducting filaments 10 μm in diameter. The critical strand current before cabling is 265 A at 4.6 K in a field of 5.5 Tesla.

The precision stamped collars, used to fix the coils, are made out of an aluminium alloy. Contrary to the behaviour of stainless steel, aluminum contracts more than the coil during cooldown such that the maximum clamp pressure occurs at liquid helium temperatures where it is needed, and where the tensil strength of the materials are higher. Collars made out of aluminum have been put through more than 5000 excitation cycles at liquid helium temperature and then inspected for micro cracks. None were observed. These collars are fixed azimuthally using 6 m long stainless steel tie rods leading to a reproducible coil geometry without welds. It is also possible to disassemble the collared coil without destroing the collars.

In the two shell structure higher multipoles up to and including the decapole can be made to vanish within fabrication tolerances. By introducing spacers in the inner and the outer coil the remaining 14 and 18 pole were reduced from $14.9 \cdot 10^{-4}$ and $-13.9 \cdot 10^{-4}$ to respectively $-1 \cdot 10^{-1}$ and $0.2 \cdot 10^{-4}$ measured at a radius of 2.5 cm with respect to the dipole field.

So far a total of 6 x 1 m long coils, 3 x 6 m long full size magnets and 7 x 8 m long coils have been built and partly tested.

The results[18] can be summarized as follows:

- the tooling is well suited for mass production
- the magnets reach the short sample limit in few training steps
- the field quality is acceptable
- the critical field is about 15% above its nominal value.

Three full size cold iron magnets have been ordered from BBC, Mannheim, and the first magnet of this type is presently being tested.

The magnets are cooled by one phase helium. At the end of each octant the one phase helium is expanded strough a Joule-Thompson value and the ensuing two phase helium is returned through the magnets in good thermal contact with the one phase helium. The temperature of the magnets is determined by the pressure in the two phase line. The heat shield is maintained between 40 K and 60 K by passing cold helium gas through the outer cryostat.

The cryostat is supported inside the warm iron yoke by a set of four spring loaded bolts in seven planes. The bolts are made of fibre glass expoy tubes and stainless steel tubes.

Based on the present experience, we propose to combine some of the advantages of the cold and warm iron magnets into a hybrid magnet[19)]. A cross section of the hybrid magnet is shown in Fig. 6. It uses the collared coil developed for the warm iron magnet. The collared coil is nestled directly inside the cold iron. The hybrid magnet has the following characteristic design features:

- passive quench protection using diodes (cold or warm)
- the iron contributes 22% to the magnetic induction (4.5 T → 5.2 T)
- a simple cryostat with a low heat loss
- the induction increase nearly linearly with the current up to 6.5 T. Multipoles due to iron saturation are small.

We also propose to increase the magnetic length from 6.08 m to 9.18 m. - i.e. a half cell consists of two instead of three bending magnets. The number of magnet interfaces is thus reduced.

The first full size prototypes will be ready early 1985. The decision whether to use the warm iron magnet or the hybrid magnet will be taken in July 1985.

Two fullsize quadrupole[20)] magnets have been built and tested at Saclay. They reached the design gradient without quenching and the field quality is acceptable. Two hybrid quadrupoles are now under construction.

The quadrupole and sextupole correction magnets[21] are wound directly on the cold dipole beam pipe. Two 1 m long coils made by NIKHEF and by Holec, a Dutch company, have been successfully tested at DESY. The first 6 m long coil is presently being prepared for testing at DESY. A 0.7 m long superferric magnet installed into the quadrupole cryostat, will be used for beam steering. The first prototype of such a magnet has been built by NIKHEF and successfully tested at DESY.

The refrigeration system must provide 13 kW at 4.6 K, 40 g/s of liquid Helium for cooling the leads and 40 kW at 50 K. In the proposal refrigerators were installed in each experimental hall cooling adjacent octants, with a centrally located compressor station. We now propose[22] to also locate the refrigerators centrally and to pipe liquid helium to the four experimental halls were it is distributed to the octants. The refrigeration load listed above is divided on two refrigerators each providing 50% of the load. Full redundancy can be achieved by installing a third refrigerator.

Time Schedule

Some of the most important milestones for the HERA project are listed in Table 3.

References

1) Proceedings of the Study of an ep-facility for Europe, U.Amaldi (Editor) DESY 79/48 (1979)

2) HERA - Proposal DESY HERA 81/10 (1981)

3) Résumé of the Discussion Meeting "Physics with ep colliders in view of HERA" in Wuppertal, DESY HERA 81/18 (1981)

4) Proceedings of the Workshop Experimentation at HERA NIKHEF Amsterdam, June 9-11, 1983, DESY HERA 83/20 (1983)

5) A.A.Sokolov and J.M.Ternov, Sov.Phys. Dokl., 8, 1203 (1964)

6) A.Wrulich, DESY HERA 84/07 (1984) and references therein

7) A.Piwinski, DESY 77/18 (1972)

8) A.Piwinski, private communication

9) R.Schmidt, DESY M 82-22 (1982)

10) Résumé of the Workshop "Polarized Electron Acceleration and Storage", Hamburg, March 1982 - DESY M 82-09 (1982)

11) D.P.Barber, "Polarisation Measurements and Future Plans" DESY M 83-29 (1983)
D.P.Barber et al., "Progress in Measurement and Understanding of Beam Polarisation in Electron Positron storage Rings" DESY 83-065 (1983)

12) K.Steffen, DESY HERA 83/16 (1983) and references therein

13) P.C.Barber, J.Kewisch and R.Rosmanith, private communication

14) G.Hemmie, DESY M 82-18 (1982)

15) Proposal for the HERA Proton Linac, DESY HERA 84/12 (1984)

16) J.R.Maidment, DESY HERA 84/08 (1984)

17) J.R.Maidment, DESY HERA 83/12 (1983)

18) G.Horlitz, H.Kaiser, G.Knust, K.H.Mess, P.Schmüser, B.H.Wiik, S.Wolff DESY HERA 83/21 (1983)

19) K.Balewski, H.Kaiser and P.Schmüser, private communication

20) R.Auzalle, A.Patoux, J.Perot, J.M.Rifflet, DESY HERA 83/27 (1983)

21) C.Daum and P.Schmüser, DESY HERA 83/02 and 83/07 (1983)

22) G.Horlitz, DESY HERA 84/02 (1984)

Figure Captions

Fig. 1 - Schematic Layout of HERA

Fig. 2 - Cut through the tunnel in the arc

Fig. 3 - The new 50 MeV proton linac is shown together with DESY III, the rebuilt DESY I. DESY II, a new 9 GeV electron synchrotron, is installed in the same tunnel

Fig. 4 - HERA straight section design with the spin rotators located at the ends

Fig. 5a - Cross section of the warm iron magnet

5b - Cross section of the cold iron magnet

Fig. 6 - Cross section of the hybrid magnet

Table Captions

Table 1 - General Parameters

Table 2 - Superconducting Magnet Parameters

Table 3 - Milestones

Table 1 - General parameters

	p.ring	e-ring	units
Energy range	820 - 300	30 - 10	GeV
Circumference	6336		m
Number of interaction points	4		
Length of each straight section	360		m
Free space for experiments	15		m
Polarization time (30 GeV)	20		min
Magnetic bending field	4.53	0.1849	T
Injection energy	40	14	GeV
RF frequency	499.667	499.667	MHz
Max. circumferential volts	20	290	MV
Circulating current	163	58	m
Number of bunches	210		
Beta functions at interaction points β_x/β_z	3.0/0.3	3.0/0.15	m
Beam size at interaction points	0.12(0.41)/0.027	0.22 / 0.013	mm
Tune shift $\Delta Q_x/\Delta Q_z$	0.0006/0.0009	0.008/0.014	
Luminosity	0.4×10^{32}		$cm^{-2}s^{-1}$
Required refrigeration power at 4.3 K	13 / 40		kW/(g/s)
Required refrigeration power at 40-60 K	40		kW

Table 2 - Superconducting Magnet Parameters

Parameters	Dipole	Quadrupole	Units
Number of magnets	656	304	
Magnetic length	6.08	1.90	m
Induction	4.53		T
Gradient		91.2	T/m
Bore	56	56	mm
Nominal current	5582	5582	A
Load factor (4.6 K)	0.89	0.86	
Stored energy	560	76	kJ
Mass	5750	448	kg

Table 3 - Milestones

Authorization	April 1984
Start of civil engineering	May 1985
Start installation of machine components	April 1986
DESY II operational	April 1986
Superconducting Magnets, start of series production	July 1986
Electron injection: first quadrant	February 1987
Start commissioning of Proton Linac	April 1987
Delivery of the last magnet for e ring	October 1987
Civil engineering complete	December 1987
Start commissioning of DESY III	December 1987
Refrigeration plant operational	January 1988
Start commisioning of electron ring	March 1988
Proton injection: first quadrant	April 1988
Delivery of last superconducting magnet	October 1988
Start commissioning of proton ring	June 1989
Electron-Proton Physics	early 1990

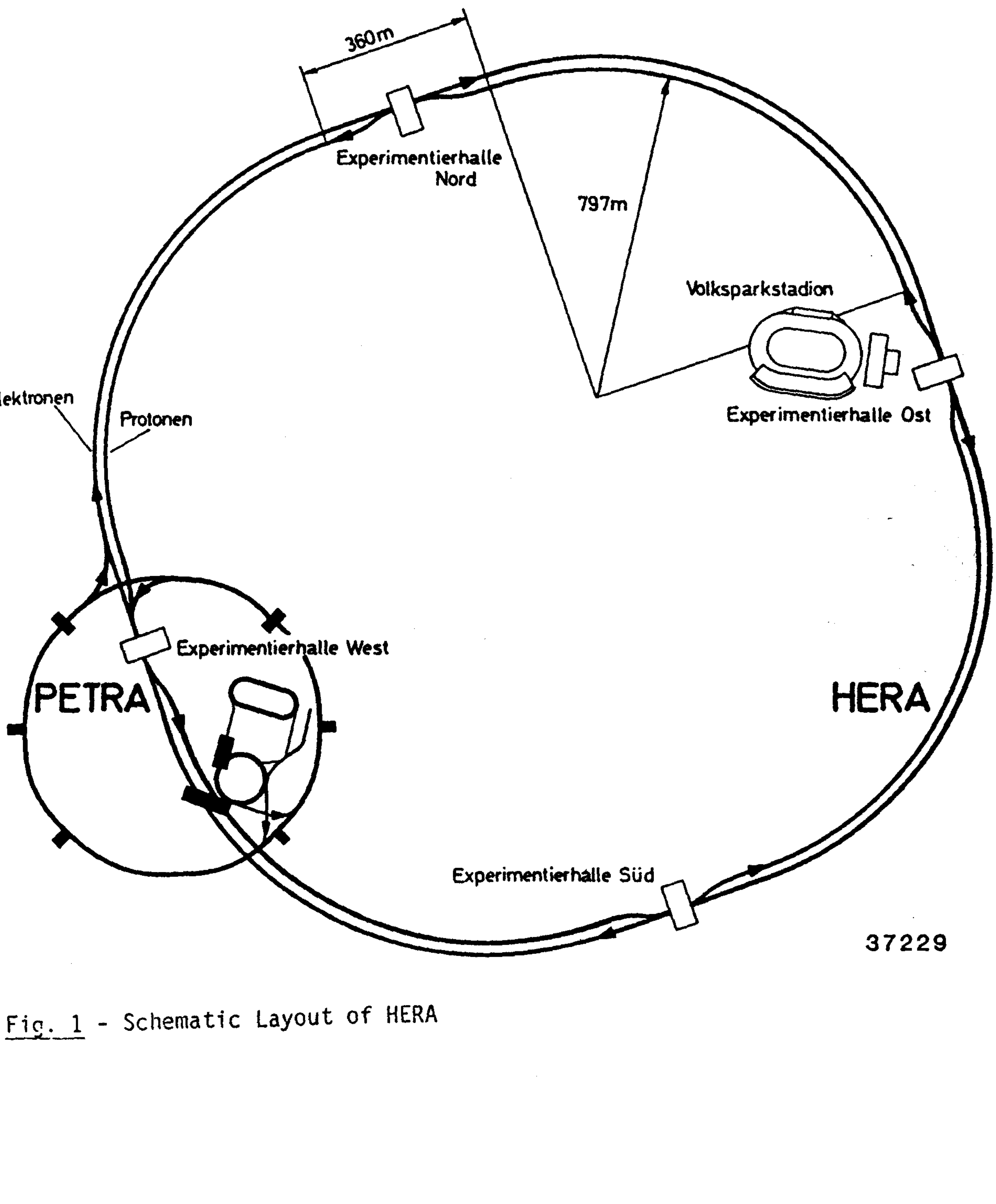
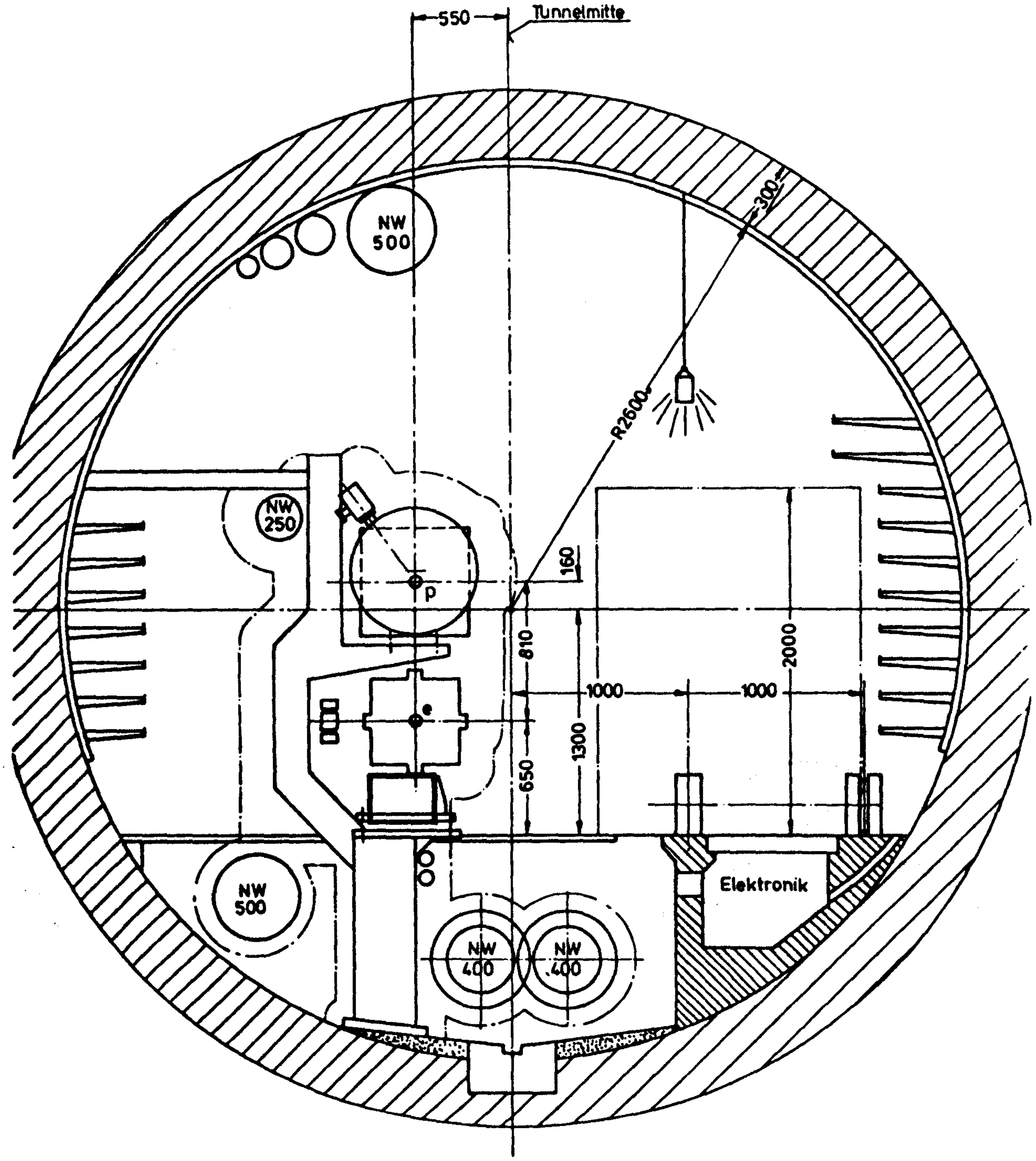


Fig. 1 - Schematic Layout of HERA



H E R A

Bogenbereich

37410

Fig. 2 - Cut through the tunnel in the arc

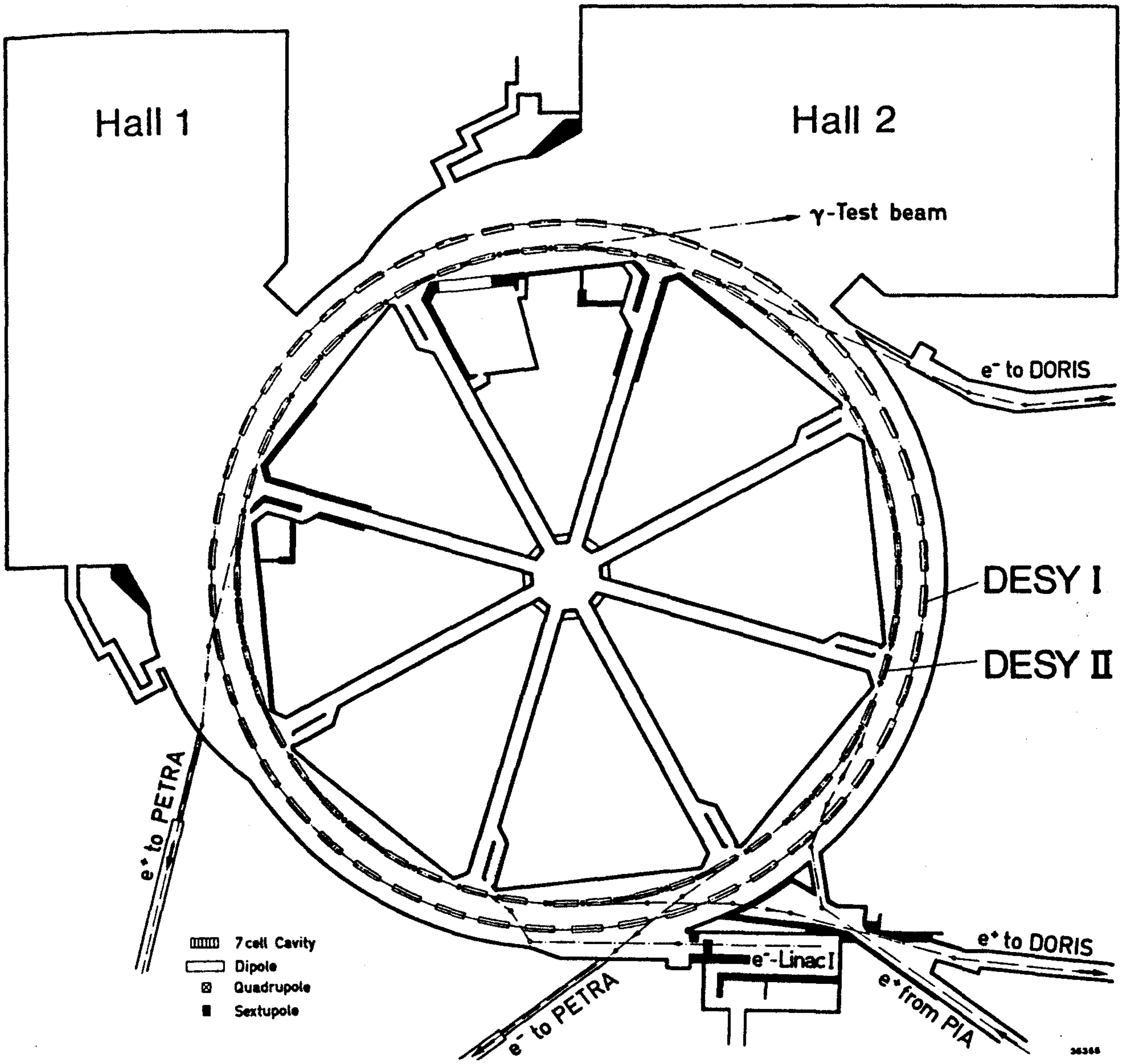


Fig. 3 - The new 50 MeV proton linac is shown together with DESY III, the rebuilt DESY I. DESY II, a new 9 GeV electron synchrotron, is installed in the same tunnel

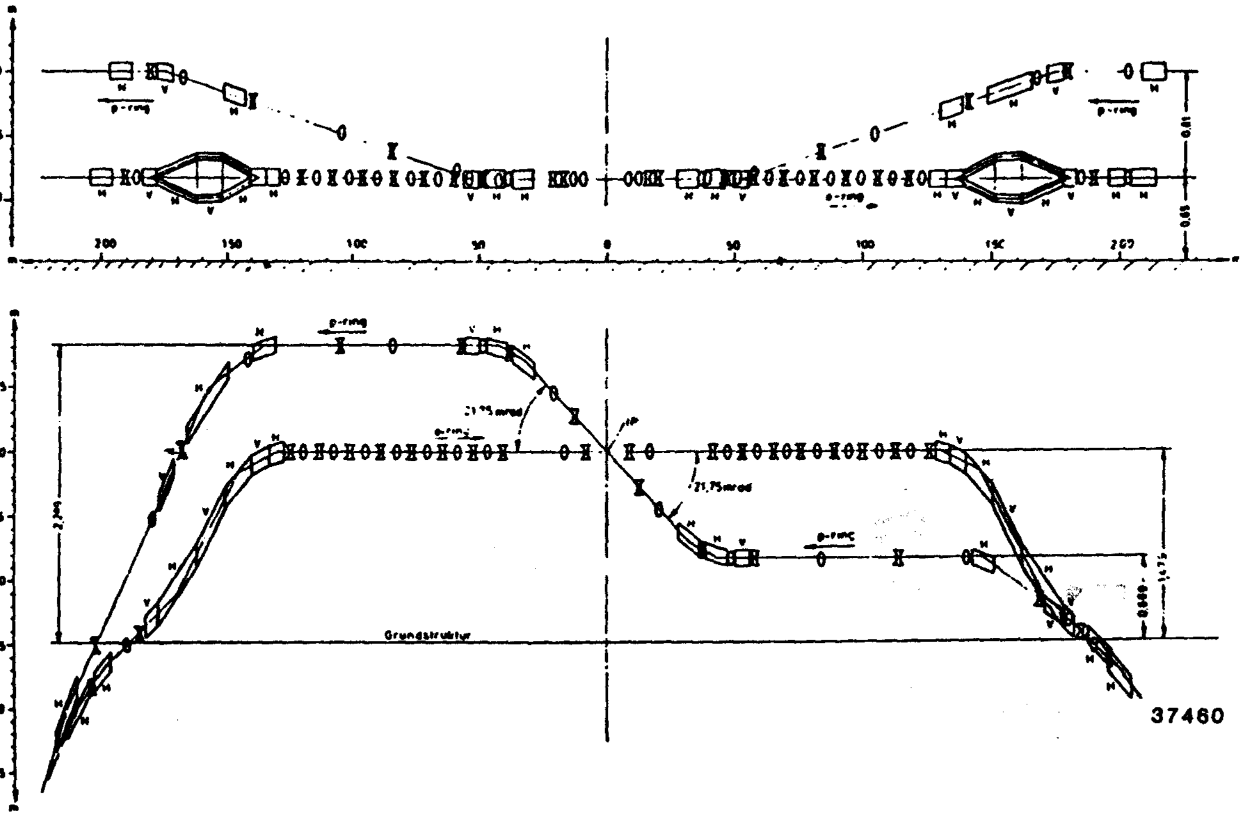


Fig. 4 - HERA straight section design with the spin rotator located at the ends

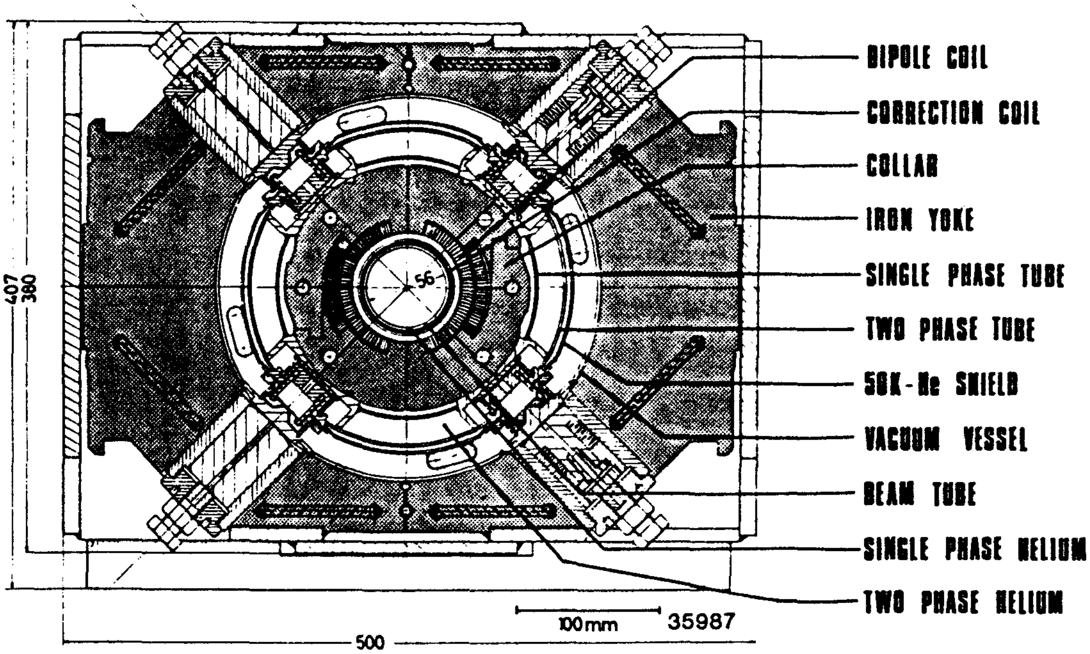


Fig. 5a - Cross section of the warm iron magnet

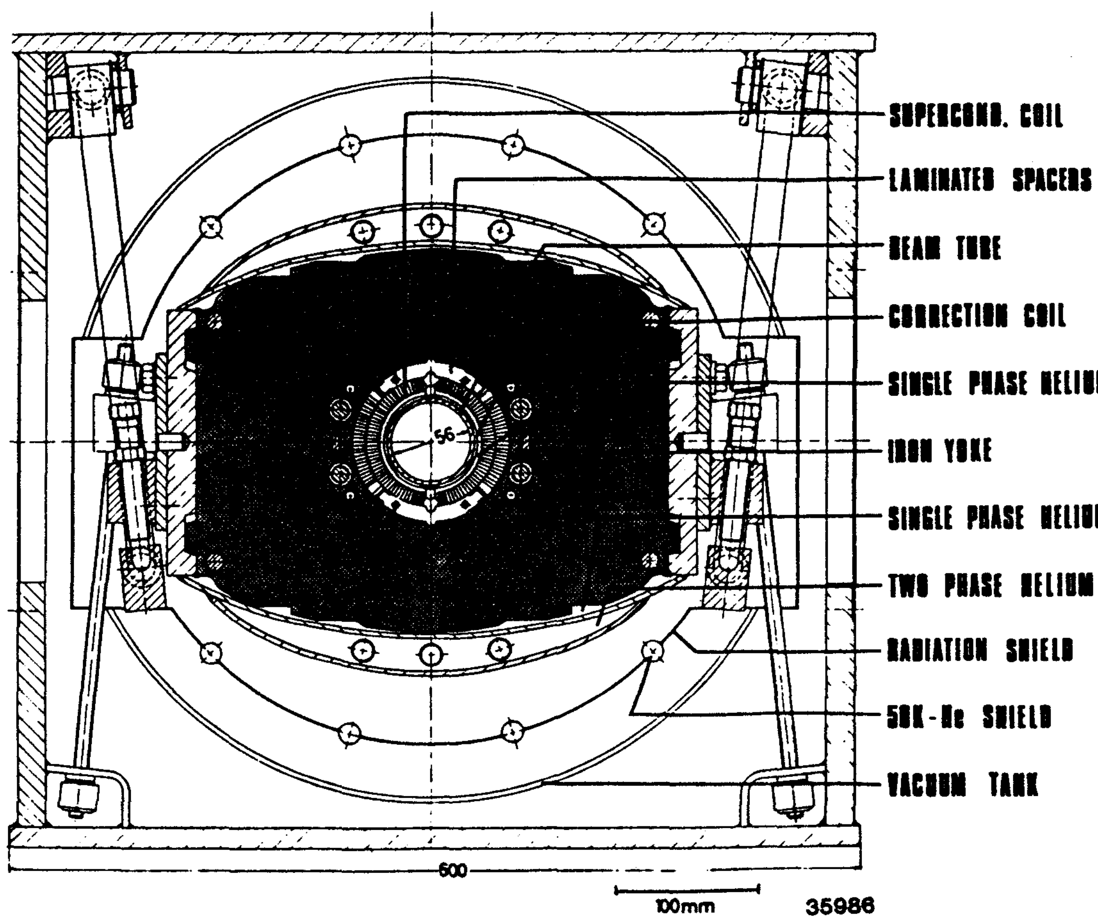


Fig. 5b - Cross section of the cold iron magnet

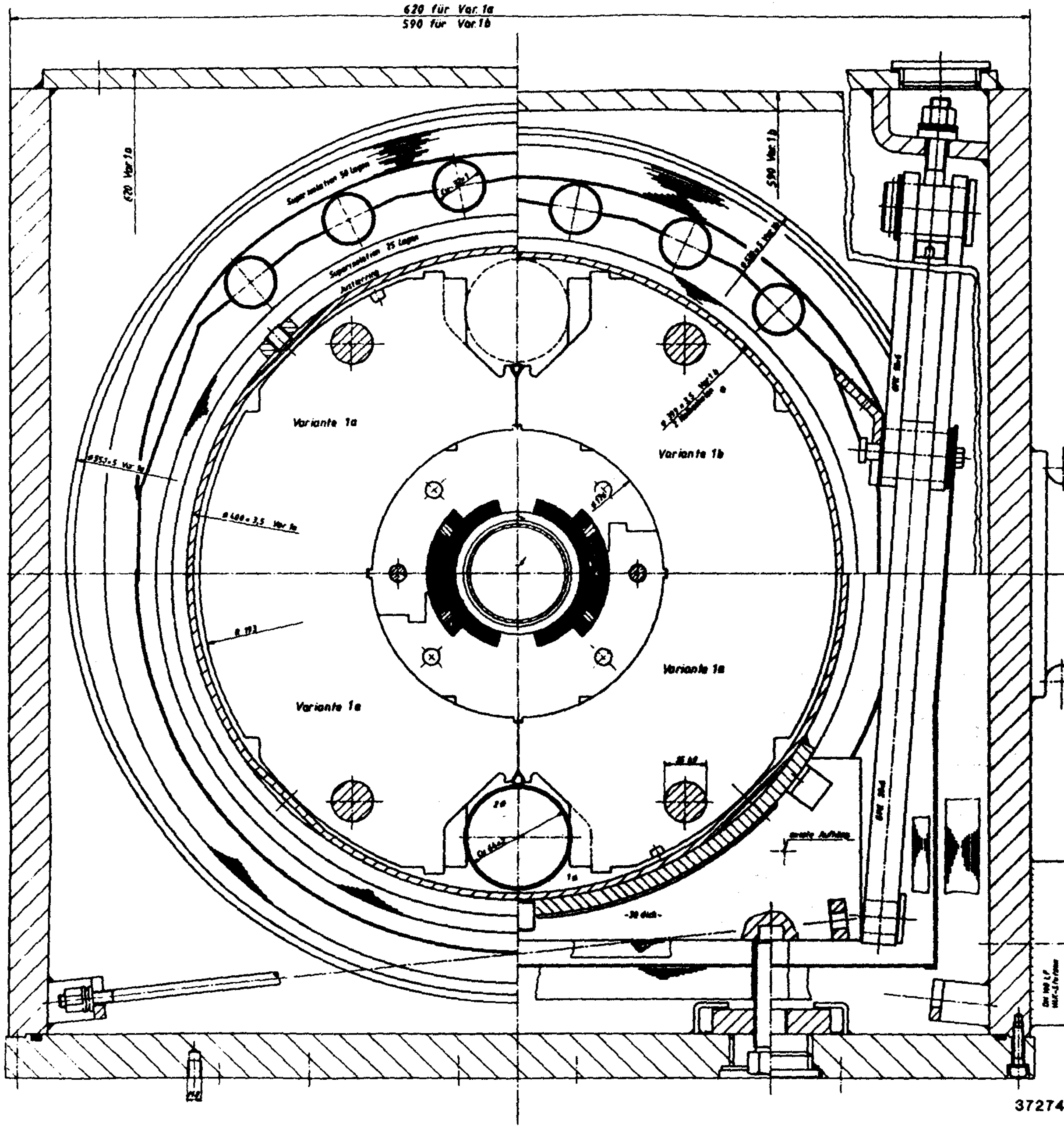


Fig. 6 - Cross section of the hybrid magnet