# The Alignment of the DESY-Accelerators An Overview

F. Löffler, Hamburg

**Abstract**

To run the HERA-collider three pre-accelerators are necessary: DESY II, DESY III and PETRA. Each of them has to be aligned with a relative accuracy of better than 0.2 mm similar to that of HERA. In spite of the extremely different sizes of the accelerators, similar surveying schemes and evaluation techniques have been found to achieve this accuracy.

## 1 Introduction

The DESY laboratory was founded in 1958. It's first synchrotron DESY began to work in 1964. In 1974 the Electron Positron Collider DORIS and in 1978 the Storage Ring PETRA were ready for running.

At present only DORIS runs an Experiment for High Energy Physics (ARGUS) and is additionally used as a Source for Synchrotron Radiation.

DESY and PETRA were modified in the last years to pre-accelerators for the new project, HERA (Fig. 1). In the DESY-tunnel now two accelerators are mounted: DESY II for electrons and positrons, which come from the Linear Accelerators Linac I and II with an energy of 200 MeV and 450 MeV respectively. The other synchrotron DESY III gets protons from the H-accelerator Linac III with an energy of 50 MeV. Both synchrotrons accelerate their particles up to 7 GeV and finally send them to the storage ring PETRA.

At PETRA the particle energy is increased to 14 GeV for the electrons and positrons, which are circulating clockwise and counterclockwise respectively around the circumference. On the other hand protons, also travelling counterclockwise, are accelerated up to 40 GeV.

Finally electrons and protons are injected into HERA, an Electron Proton Collider with a design energy of 30 GeV and 820 GeV respectively. The beams collide head on in two interaction regions in Hall South and Hall North where the detectors ZEUS and H1 are located. On both sides of the interaction regions electrons and protons are separated and guided within their own vacuum and magnet systems. While the electron magnets are normal conducting, the proton magnets in the arcs are superconducting and located above the electron machine.

This collider has been under construction since June 1984. The tunnel was completed in August 1987. The mounting of the electron accelerator was started immediately after the first. tunnel-quadrant, was accessible. The first, bunches were stored in August 1988.

In the meantime the mounting of the proton accelerator began and will hopefully be finished towards the end of 1990. At present the last quadrant is equipped with superconducting magnets. A first cold test for the HERA-octant, behind the injection area, was successful.

## 2 The DESY-Synchrotrons

The original synchrotron from 1964 was replaced by the electron- positron synchrotron DESY II in 1985, which has a separated function lattice. It's 48 dipole,. 48 quadrupoles and 16 sextupoles are mounted on the inner side of the ring tunnel (Fig. 2 ).

For the proton synchrotron DESY III the 48 combined function magnets of DESY I were overhauled and mounted again on their old concrete support structure in 1987. The lattice was slightly changed. To gain space for 32 additional quadrupoles the larger magnets were moved azimuthally so that longer straight sections were created (Fig. 3).

For the alignment of these two accelerators a **reference network** is available. It consists of 8 concrete pillars, which form a regular octagon. with an additional pillar in the center (Fig. 4). The coordinates of these pillars were determined for years by invar-tape measurements /1/. At present however the distances between adjacent and opposite pillars are measured with the Kern ME5000. By a free least square adjustment of the redundant observations, by coordinate variation with respect to the nominal values, we can derive the adjusted coordinates x and y of the pillars within 0.1 mm. Since the Kern centering plates on top of the pillars are equipped with reference points for height measurements they also define our reference system for the vertical alignment. Height differences between the pillars can be measured by precision levelling and easily transformed to elevations above beam level z.

The height measurements for the **magnets** can also be achieved by precision levelling between the magnets along the circumference with connections to the pillar system. For this small levelling rods are used, which are set directly on top of the magnet iron.

For the position measurements of the magnets each can be equipped with two Kern centering plates. To obtain the necessary accuracy for the radial positioning we use angle measurements and choose so-called "mainpoints" where the theodolite is mounted. From each mainpoint the directions to the two preceding and the two following mainpoints are measured (Fig. 5). Then the accuracy of the angle measurements defines that of the radial position of the standpoint with respect to the neighbouring points. If one assumes a standard deviation of one direction of 0.3 m grades and a distance between the mainpoints of 20 m one gets a standard deviation for the calculated offset $P_1$ of 0.07 mm /2/,/8/. For $P_2$ it is 0.13 mm.

This method is used in all of our accelerators. Depending upon the lattice the distances of the mainpoints vary but are always kept below 20 m. If possible the measurements from the mainpoints are made in one sequence of operation for the whole circumference of the accelerator to minimize systematic influences. Additional centering plates on the magnets between the mainpoints are included by polar measurements.

For the azimuthal positioning of the magnets we use distance measurements with the ME5000 between selected mainpoints and to the intermediate centering plates on the magnets.

The mainpoints of the two synchrotrons are given by one plate on every dipole (Fig. 3). So we have 48 standpoints for the angle measurements. From 24 of them the directions to the adjacent pillars of the DESY octagon are observed additionally to obtain a connection to the reference system.

A free least square adjustment of the angle and distance measurements with datum definition by the nominal coordinates of the centering plates once more leads to reliable x and y coordinates for all plates. One only has to take care, that the residuals, which are obtained by the adjustment for the distances, are as small as possible in order to avoid distortions of the actual circumference of the accelerator /2/. This can be accomplished by a reasonable choice of the weights for directions and distances.

The results up to now have shown that the survey around the synchrotrons and the free adjustment provide coordinates of the octagon pillars which correspond with those from the ME5000 measurements of the octagon it self within some tenth of a millimeter /2/. Under normal conditions it therefore will not be necessary to observe the reference network at all.

The adjusted coordinates of the centering plates are compared with their nominal values. The differences are converted in radial and tangential components. Depending upon the height of the plates above the magnetic axis. the measured radial deviations may have to be corrected because of the roll of the magnet.

The obtained results are still influenced by systematic deformations. They can be evaluated by a smoothing function for the whole circumference. For DESY II and DESY III we usually choose a Fourier Analysis up to the second order. The remaining offsets from the calculated curve then give the actual radial deviations of the magnets, which have to be removed by an alignment.

## 3 The PETRA accelerator

PETRA was designed as an electron-positron-storage-ring. In 1987 it was changed to a pre-accelerator for electrons and protons for HERA. Therefore the detectors had to be removed and additional quadrupoles be mounted in the straight sections. A proton bypass in the South region and some new cavities had also to be installed.

In the original version an unbroken survey around the PETRA magnets was not possible /3/. This was prevented by the four detectors in the shorter straight sections. To allow the connection of the adjacent octants a survey **network on the surface** was installed (Fig.6). Eleven concrete pillars were erected in the neighbourhood of the PETRA halls and four additional points on top of high buildings on the DESY site.

In addition vertical steelpipes were inserted in the tunnel-ceiling of PETRA near the end of the eight straight sections. They lead to the surface, where they can be equipped with an auxiliary pipe of aluminum. This allows one to center a Kern centering plate with respect to a reference point in the tunnel-floor of PETRA by optical plumbing.

The coordinates of the plates on top of the pillars and the survey pipes were determined at the beginning by distance measurements with the ME3000 as shown in Fig.6, combined with height measurements by precise levelling. All positional measurements within the eight arcs of PETRA then were referenced to the two points in the floor at each end. The magnets in the long straight sections could be aligned between the first and the last magnets respectively of the adjacent arcs. The magnets in the short straight sections on both sides of the detectors had to be controlled from the corresponding arcs.

With the new lattice we now can carry out a complete survey around PETRA. That means one can start the angle measurement on a mainpoint with pointing to the two backward and forward mainpoints and additionally taking the directions to the intermediate centering plates as described for DESY II and III. Then proceed continuously to the following mainpoints along the circumference of PETRA until one returns to the starting point. Additionally distances have to be measured so that every magnet point is defined azimuthally on the circumference.

By using the precision theodolite Kern E2 and the Kern ME5000 we can achieve the necessary accuracy for the relative radial position of the magnets and the actual length of the accelerator circumference. Connecting measurements to the reference points in the tunnel floor are helpful, if their positions have been recently determined by precision measurements from the surface network. If they are introduced as datum points in the calculation of the least square adjustment of the observations the systematic influences on the derived radial positions of the magnets between the reference points are minimized.

Under normal conditions it is not necessary to connect the traverse measurements on top of the magnets with the reference points in the tunnel-floor, once the fundamental alignment has been achieved with respect to them. If the least square adjustment then uses the nominal coordinates of the magnet points for datum definition, one no doubt gets bigger radial deviations. because there is only one constraint by the closure of the loop traverse. The systematic parts of these deviations have to be determined by calculating a best fitting curve. The choice of a Fourier Analysis up to the 8th order is usually sufficient to define the actual deviations.

Such a smoothing procedure has to be carried out even if the reference points are used as datum points. Both methods should provide similar results however.

Originally all PETRA magnets could be equipped with two Kern centering plates for the position measurement. The height and roll measurements were directly referenced to the magnet surface as known from DESY /3/.

In the meantime the survey platforms for the dipoles and the quadrupoles have been changed according to our system which is used in HERA. They are equipped with a conical base, which defines the height as well as the position of the magnet by the center of a spherical Taylor-Hobson target which rests in the cone. A special tribach also allows one to center a theodolite or the ME5000 on this base with an exactly defined height of the axis of tilt /4/. So it is possible to measure the horizontal direction and the vertical angle with one pointing to the spherical target. The slope distances can be measured to a reflector, which is inserted in a target sphere.

As the **dipole platform** rests with two feet in a groove and with a third foot directly on the surface of the magnet it additionally allows one to measure the roll of the magnet. Two small reference spheres on top of the platform define the base for an inclinometer (Fig. 7).

The **quadrupole platform** can be fixed on top of the magnet by screwclamps, so that the height of the target sphere with respect to the magnet is also well defined (Fig. 8).

With these survey platforms we can choose every second quadrupole as main points for the magnet survey as shown in Fig. 9. The platform is mounted in the middle of the magnet which gives the advantage, that the most important point of the magnet is directly included in the loop traverse. Additionally the height differences between the mainpoints can be derived by redundant measurements of the vertical angles without additional levelling. Only the pointings to at least two scale divisions of a levelling rod on reference points are necessary at certain equal intervals to provide the height references to the beam level. Quadrupoles between the mainpoints are pointed at from both neighbouring standpoints for control.

The dipoles are not included in the traverse measurements anymore. If an alignment is necessary they are referenced directly to the adjacent quadrupoles. Only the roll of these magnets is controlled regularly.

## 4 The electron-proton-collider HERA

### 4.1 The surface network

For the construction of the HERA tunnel and the mounting of the two accelerators a geodetic network on the surface was installed (Fig. 10). It is based upon the PETRA network, which was enlarged by three additional points, a survey tower near hall North, another smaller one on top of the staircase of the "Vollsparkstadion" near hall East and a steelpillar on the roof of a high building near hall South /5/.

On top of each hall additional concrete pillars are mounted with integral vertical steelpipes /6/.

The coordinates of the centering plates on top of the network pillars are determined by distance measurements with the ME5000, precise levelling and a free least square adjustment of the observations with respect to the coordinates from previous network surveys. Results are shown in Fig. 11. Although the network includes distances between 32 and 2000 m the maximum observed changes of position between 1986 and 1989 were smaller than 3 mm, which shows the high accuracy of the ME5000 and the stability of the survey monuments.

The pillars on top of the halls have to be connected to the network by polar measurements for hall North, East and South. For hall West a coordinate determination by distance measurements only is possible.

## 4.2 The underground reference system

Vertically below the reference pillars on the halls. machined steel plates are mounted on concrete platforms. They allow one to attach aluminum pillars with a forced centering precision for the Kern centering plates on top within 0.2 mm. Their coordinates can be easily derived from those of the surface monuments by optical plumbing /6/. In spite of the angle measurements on the surface and the transfer to the tunnel level the reproducibility of the coordinates until now has proved to be better than 2 mm after one year.

The survey plates below the surface monuments define the fundamental points for the reference system in the tunnel. They are located in one corner of each hall. Similar plates are mounted on concrete platforms in the three other corners and in the floor of the HERA tunnel (Fig. 12). Overall we have 44 survey plates in every quarter of the tunnel pitched at 35.2 m intervals (Fig. 13). Two auxiliary points in front of the tunnel mouths. between the corner points, allow the coordinate determination of the plates in the tunnel by running connecting traverses between the fundamental points, which are used as datum points.

The traverse measurements in the tunnel are similar to those described for the magnet survey in the smaller accelerators. Directions are measured to the two preceding and the two following aluminum pillars from every traverse point with the Kern E2 (Fig. 14). The distances are observed from every second pillar with the Kern ME5000 (Fig. 15) to the two preceding and the one following points. In addition all necessary observations which connect the tunnel traverse with the datum points in the halls are made.

The coordinates of the traverse points can be obtained by a least square adjustment of the observations by coordinate variation. Again the choice of the weights for angle and distance measurements has to guarantee that the residuals of the distance measurements then are as small as possible. Regular systematic influences on the angle measurements are then compensated for and deformations of the traverse kept within some mm.

The reproducibility of the position determination of the traverse points is sufficient. Independent measurements after one year gave differences in radial position of 3 mm maximum. After subtraction of systematic deformations the actual changes proved to be smaller than 1 mm.

The reference points for the height measurements are defined by spherical steel pegs, which are inserted in the tunnel floor beside the steel plates for the position survey. Their heights are determined by precise loop levelling on the HERA circumference and can be transferred to the neighbouring steelplates so defining also the height of the centering plates on top of the aluminum pillars.

## 4.3 The surveying procedure for the HERA-magnets

Since the HERA-machine plane has an inclination of 1% the coordinates of the fiducial points of the magnets have to be determined in a three- dimensional system. For both accelerators special survey platforms have been developed. which can be attached to the sides of the magnets. They define the reference point by the center of a sphere, which rests in a conical base. Additionally they are equipped with a polished steel bar or two small reference spheres, which define the base for roll measurements.

For the **electronmachine** a module construction was chosen in the tunnel arcs. Quadrupoles, sextupoles and dipoles are connected as one unit. The guide rods and height screws for the alignment are located beneath the quadrupole on the lefthand side of the module. The righthand side rests on the quadrupole girder of the next module and moves together with the corresponding quadrupole /6/.

The survey platform for the electron ring can be directly referenced to the geometry of the quadrupole. It rests with two feet in a precision groove on the inner side of the magnet which defines the radial position of the reference sphere. A third foot touches the laminated iron on the underside of the quadrupole, so defining roll and height. The azimuthal position is fixed with respect to the end of the magnet by a distance piece (Fig.16).

Each module is equipped with only one survey platform in the middle of the quadrupole. Single quadrupoles and dipoles in the straight sections have two conical bases on top (Fig.17).

The first alignment was carried out from the reference traverse by polar measurements with simultaneous correction of the roll and height (Fig. 18). The control measurements took place from the platforms of the quadrupoles themselves by using our normal observation scheme. In this case only the directions to the two forward and backward magnets were measured along the whole HERA-circumference.

The free adjustment by coordinate variation was done with these directions and the nominal distances between adjacent quadrupoles. As reference coordinates the nominal values of all the survey platforms used were taken into account. From the differences between the adjusted and the nominal coordinates radial deviations were derived. Their systematic parts could be evaluated by a cubic Spline function /2/, so that finally the actual correction values for the radial alignment were at hand.

The figures for the first relative vertical alignment of the electron accelerator were achieved by precision levelling between the survey platforms. In the future we will use the method of determining height differences by vertical angle measurements simultaneously with the position survey as described for PETRA.

This method has been applied to the superconducting magnets of the **proton accelerator** of HERA from the very beginning of their alignment. Originally developed for this accelerator, where every magnet has to be equipped with two survey platforms /7/, it provides a notable decrease in the overall survey time. A short description of the survey and alignment procedure was given in /6/. Fig. 19 shows a-sketch-of the surveying scheme. More details are described in /4/ and /9/.

## 5 Conclusion

Our results for the proton accelerator HERA show, that horizontal and vertical angle measurements combined with distance measurements give a fast and precise means to determine the three-dimensional coordinates of the reference spheres on top of the survey platforms. Therefore it makes sense to extend this method to all the other machines at DESY. This step already has been done for PETRA. DESY II and DESY III will follow.

For DESY II the survey scheme will be changed similar to PETRA, so that only the quadrupoles will be standpoints for the instruments. Therefore the new PETRA survey platforms can be used, because the geometry of the DESY II quadrupoles is the same as that of the

PETRA quadrupoles. Polar measurements to the dipoles are possible, if they are necessary. however here only roll measurements are really important.

For DESY III the dipoles further on will give the position of the instrument standpoints, since these magnets are combined function magnets and therefore have to be aligned with the same accuracy as normal quadrupoles. For the moment we can measure with the Taylor-Hobson spheres and the corresponding theodolite support by using an adapter, which connects the Kern centering plate on top of the dipole with the necessary conical base. For the quadrupoles once more the PETRA survey platforms can be used. For the future it is planned to exchange the Kern centering plate by a newly constructed conical base, which can he directly mounted on the dipole.

The only accelerator on the DESY site, which has no connection to HERA is the storage-ring DORIS. It‘s magnets are equipped with fixed Kern centering plates similar to those of DESY III. Since this machine is now being changed in its lattice to get more sources for synchrotron radiation, we of course will equip the new magnets with conical bases for our reference spheres. For the other magnets we will temporarily use the adapter. until new plates have been constructed.

## 6 References

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/2/ **Schwarz, W.:** Die Justierung von Teilchenbeschleunigern, Allgemeine Vermessungs Nachrichten 97 (1990) 1, S. 3-19.

/3/ **Löffler, F.:** Geodätische Präisionsvermessung des Groß-Speicherringes PETRA, Allge meine Vermessungs-Nachrichten 86 (1979) 8/9, S. 301-305.

/4/ **Schwarz, W. / Neubauer, G.:** Threedimensional Alignment. Methods for the HERA-Superconducting Magnets. Second International Workshop on Accelerator Alignment. Hamburg, 1990.

/5/ **Löffler, F.:** Vermessungsarbeiten beim Bau des Beschleunigertunnels für HERA. Ingenieurvermessung 88. Beiträge zum X. Internationalen Kurs für Ingenieurvermessung, Beitrag D5, Dümmlerbuch 7808, Bonn 1988, ISBN 3-427-78081-3.

/6/ **Löffler, F. / Schwarz, W.:** The Geodetic Approach for HERA. First International Workshop on Accelerator Alignment, Stanford 1989.

/7/ **Löffler, F.:** Referencing the Magnet Axis for HERA’s Superconducting Magnets. First International Workshop on Accelerator Alignment, Stanford 1989.

/8/ **Schwarz, W.:** Some Considerations on the Alignment Accuracy for Accelerators. Second International Workshop on Accelerator Alignment, Hamburg 1990.

/9/ **Schwarz, W.:** Hochgenaue dreidimensionale Punktbestimmung zur Justierung von Teilchenbeschleunigern. Zeitschrift für Vermessungswesen 115 (1990) 7/8, S. 333-345.

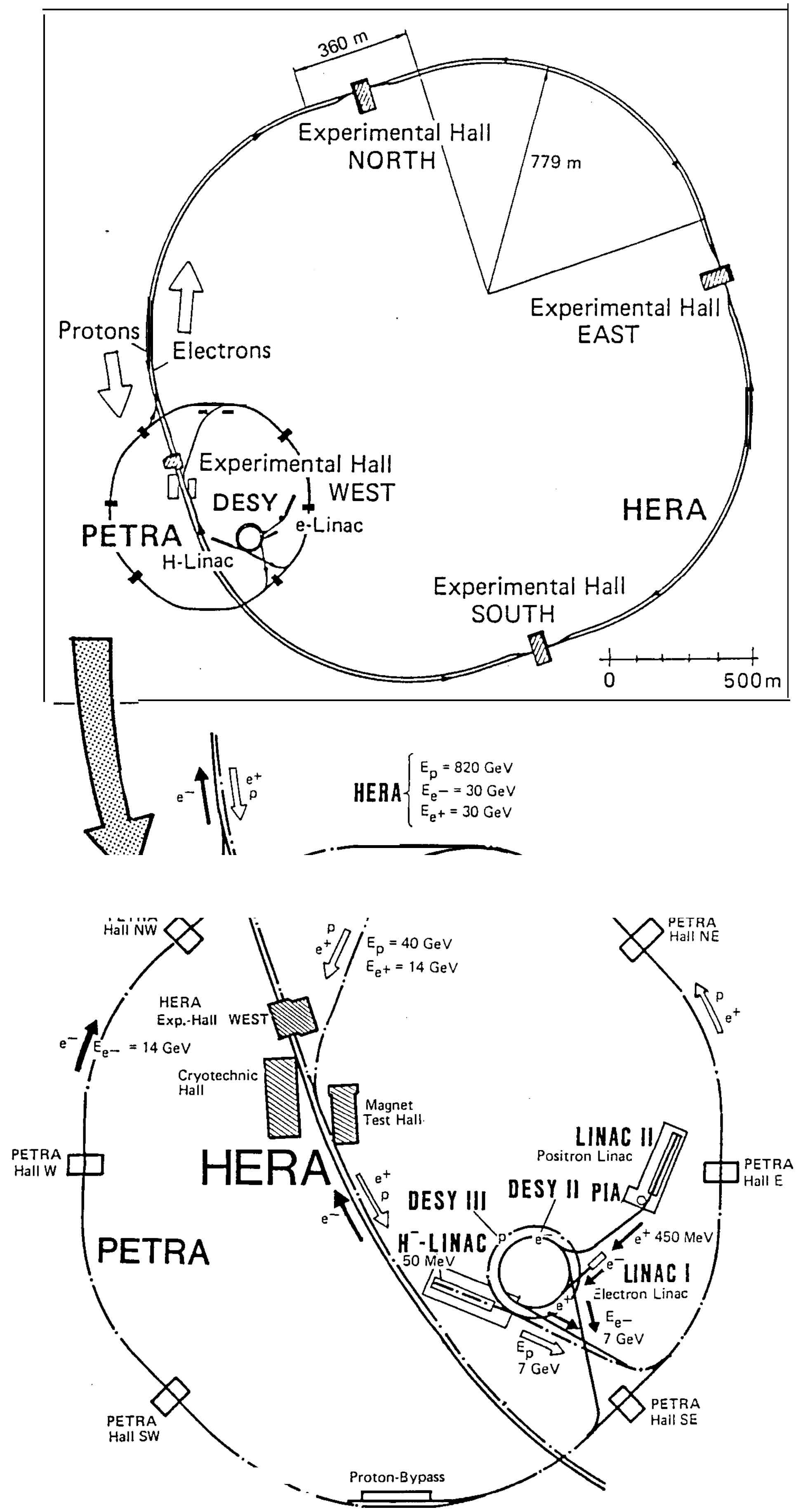



Figure 1: Injection scheme DESY - PETRA - HERA

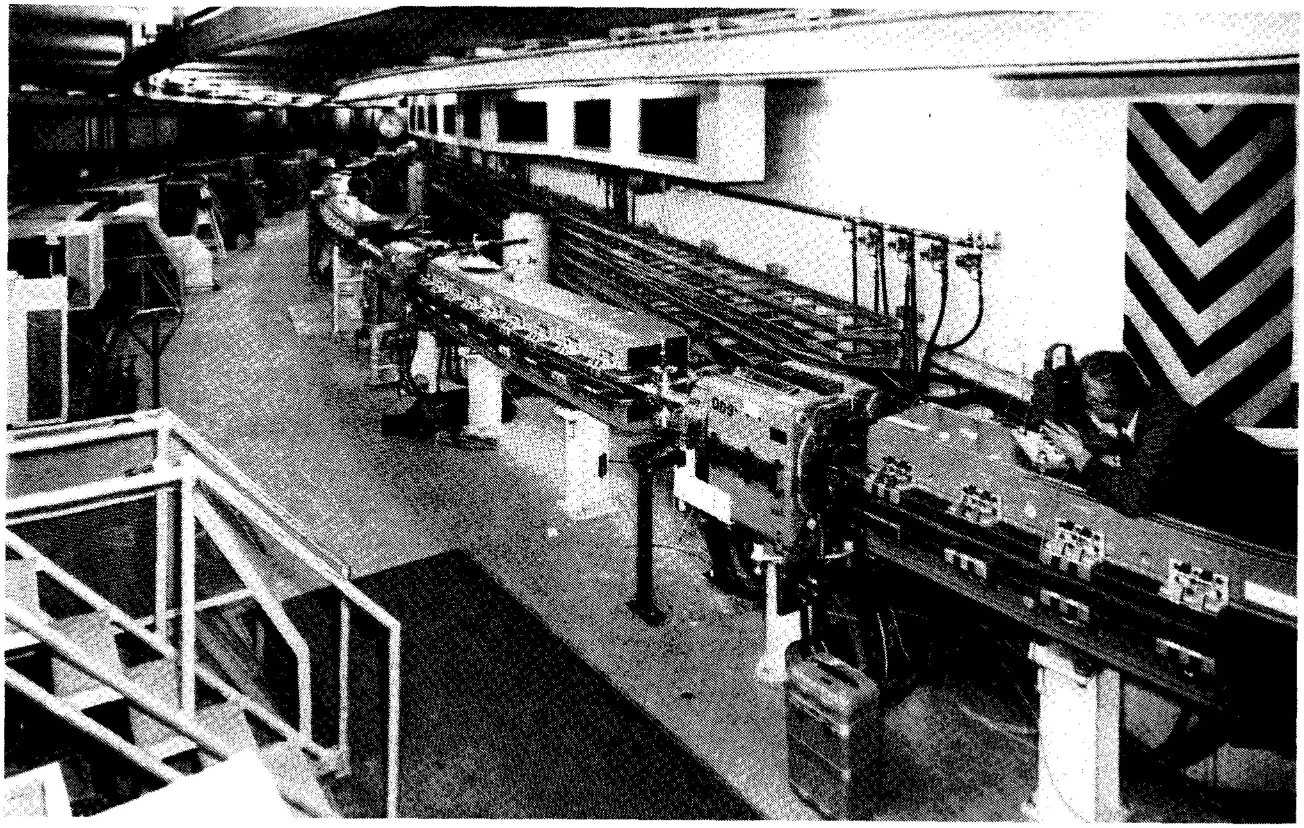


Figure 2: Ring tunnel DESY

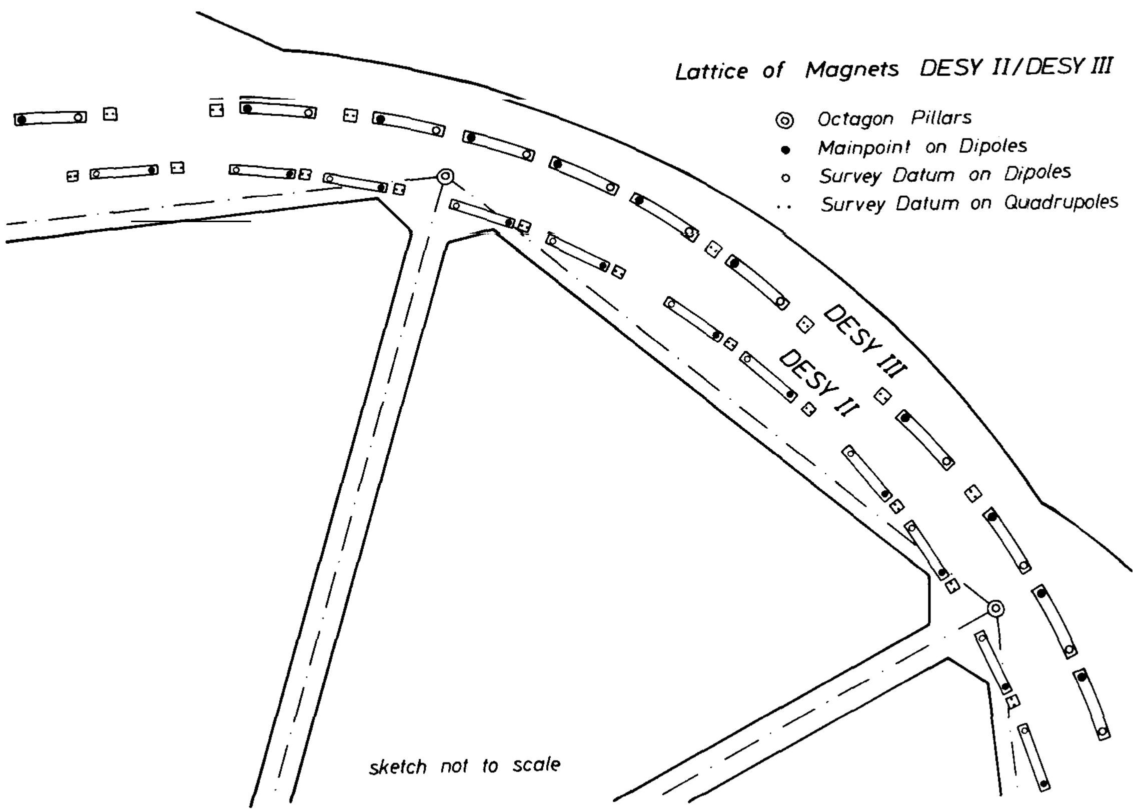



Figure 3: Magnet lattice DESY II / DESY III fore one octant

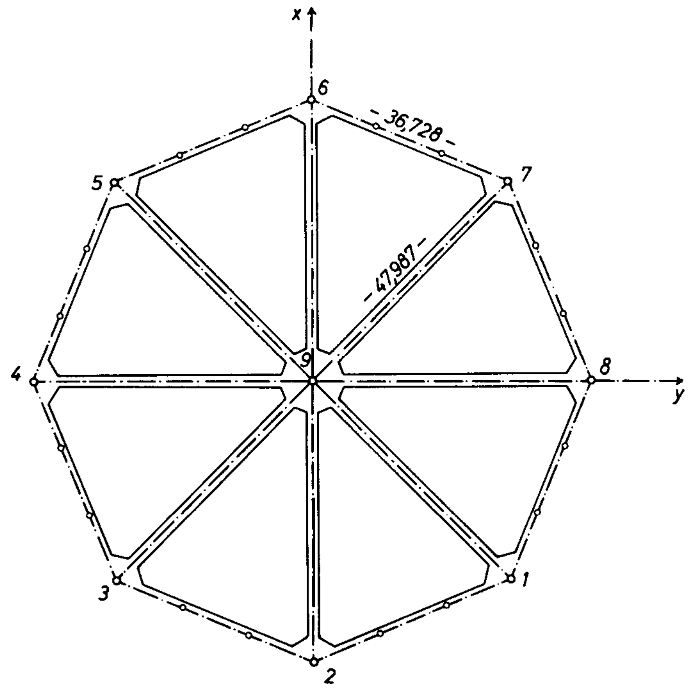



Figure 4: Pillar octagon DESY

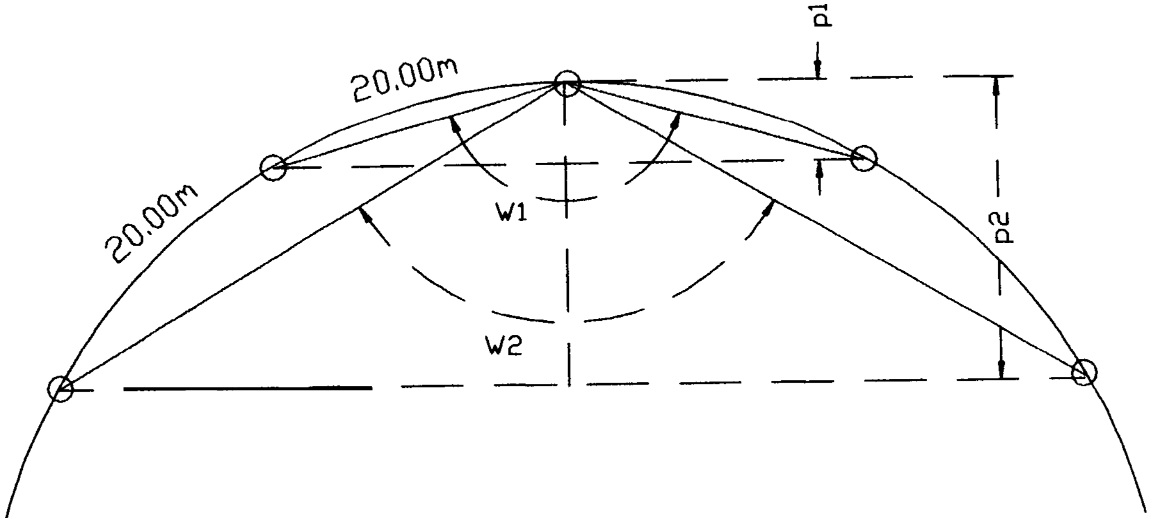



Figure 5: Offset determination by angle measurement

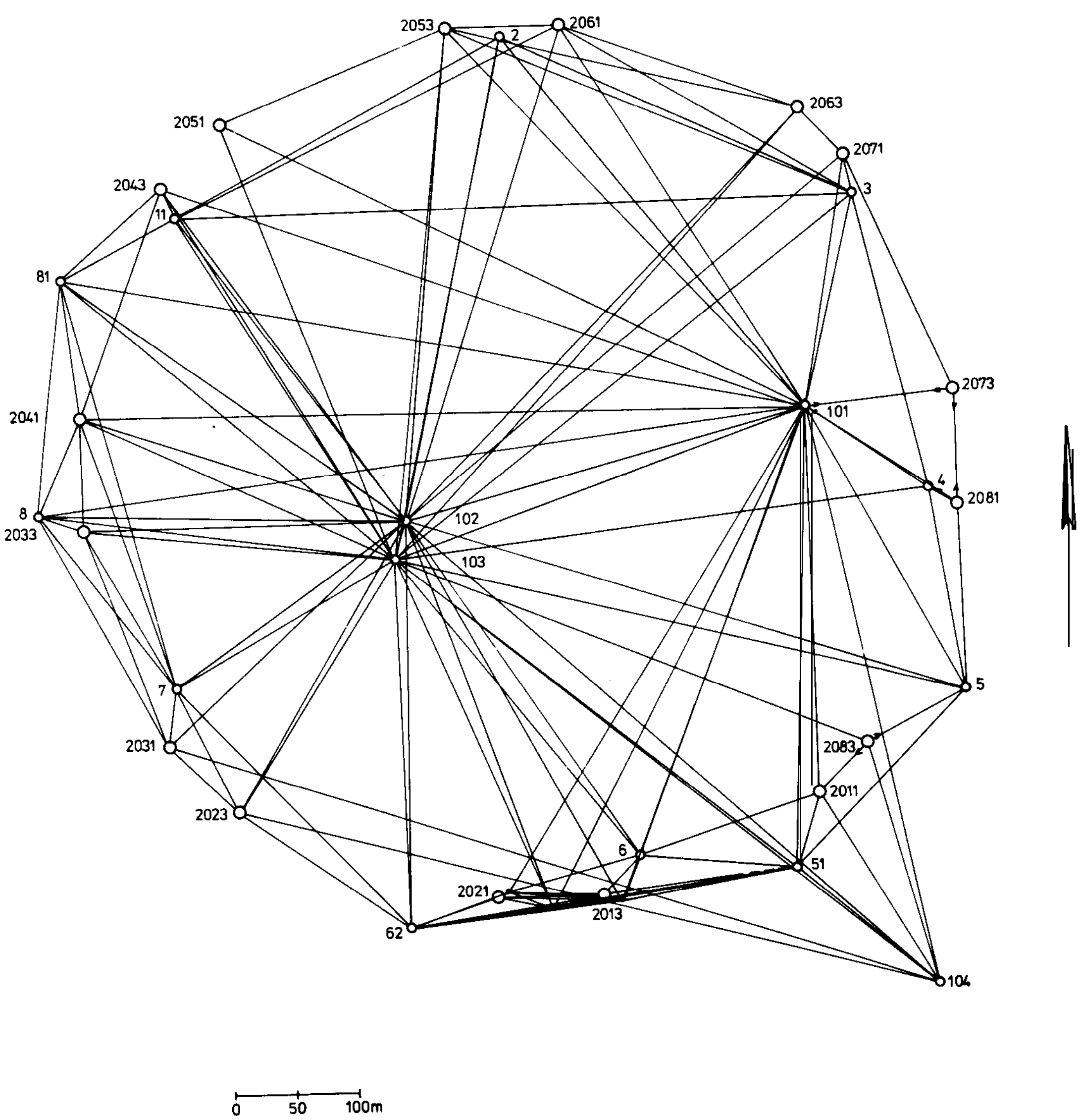



Figure 6: Surface network for PETRA

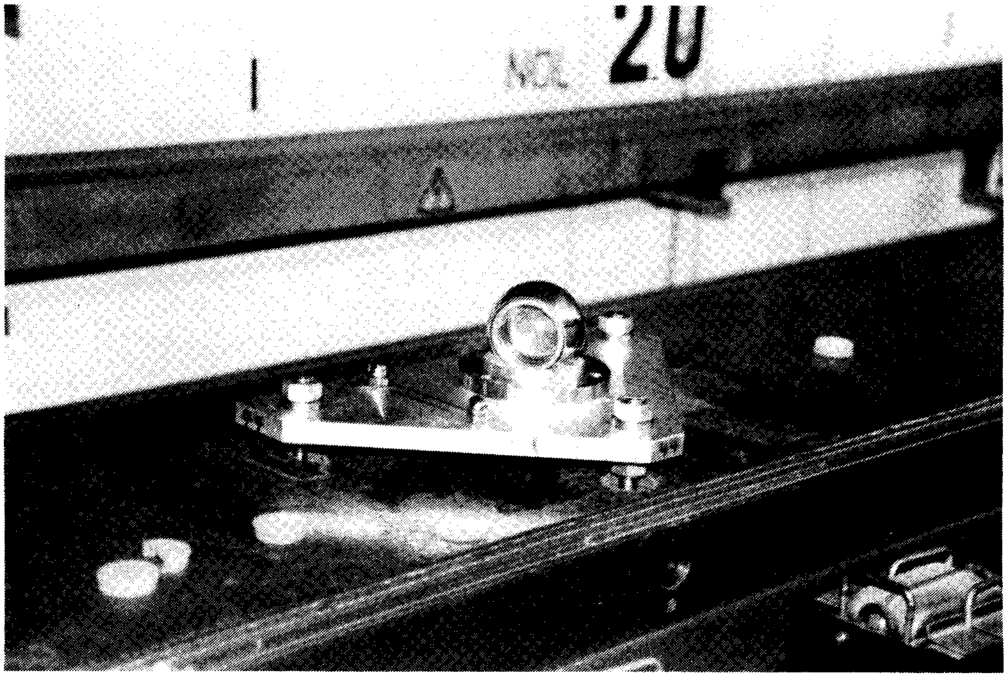



Figure 7: Dipole platform PETRA

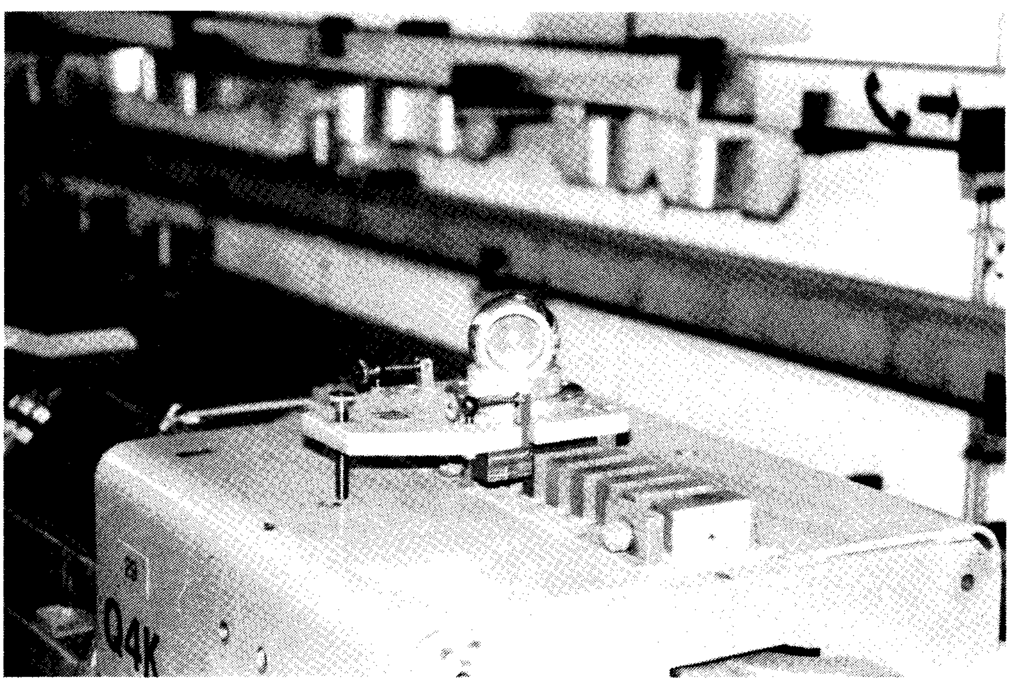



Figure 8: Quadrupole platform PETRA

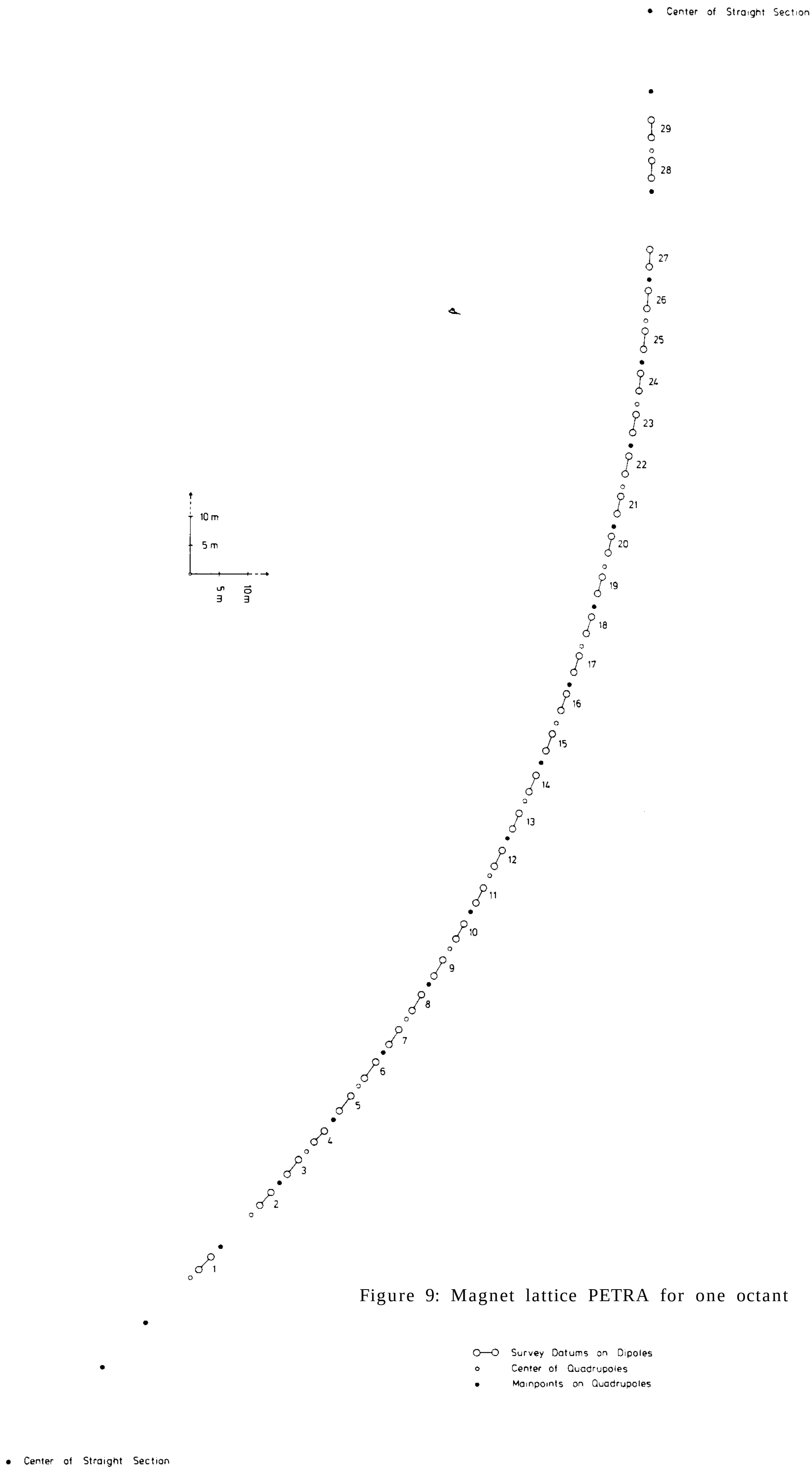



Figure 9: Magnet lattice PETRA for one octant

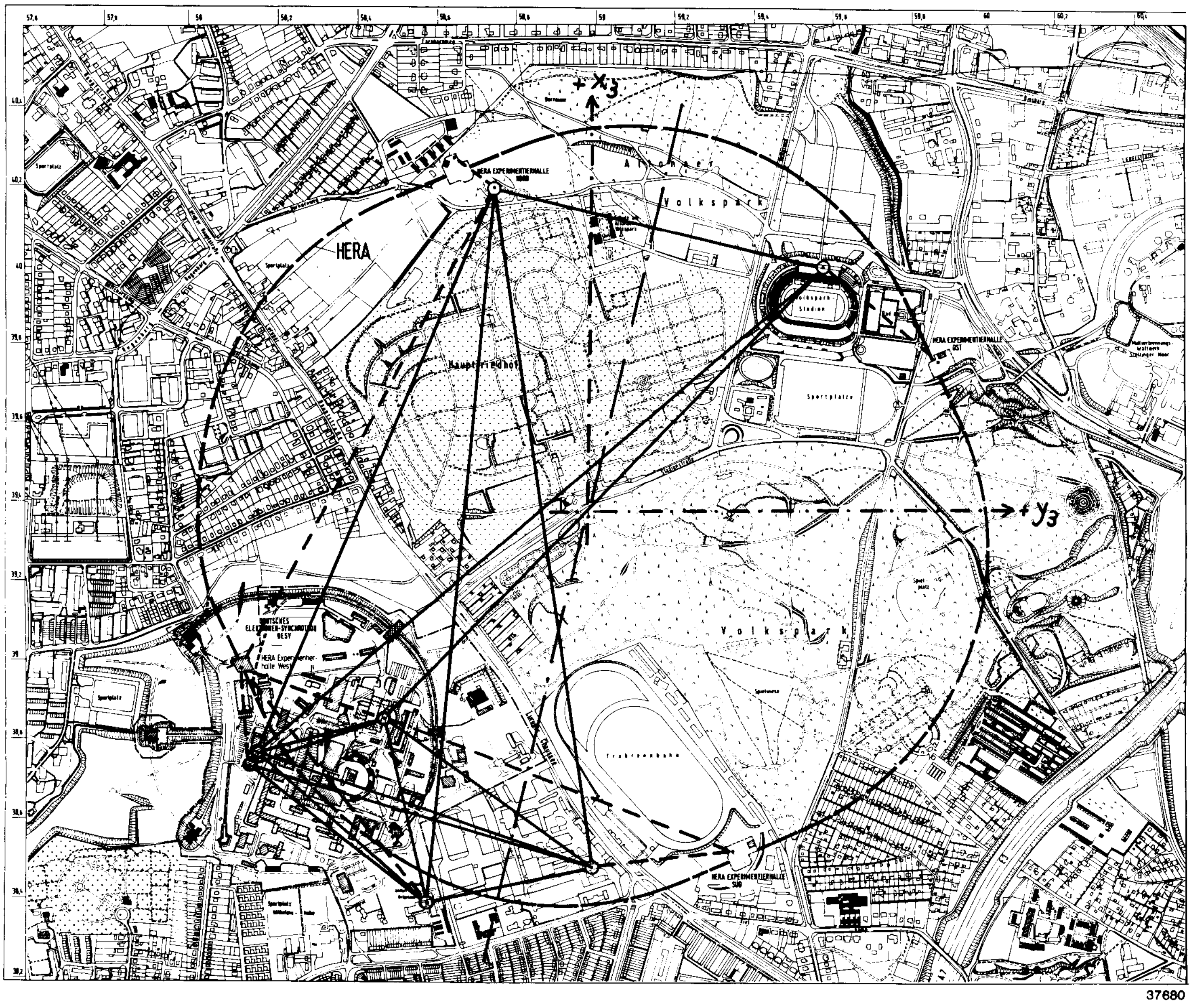



Figure 10: Surface network HERA

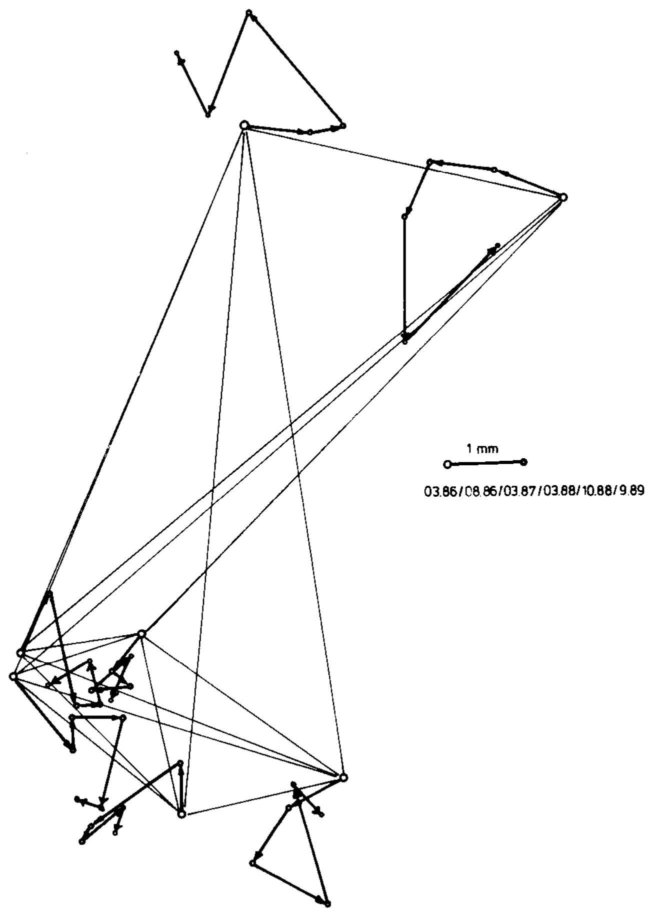



Figure 11: HERA network - Changes of position since 1986

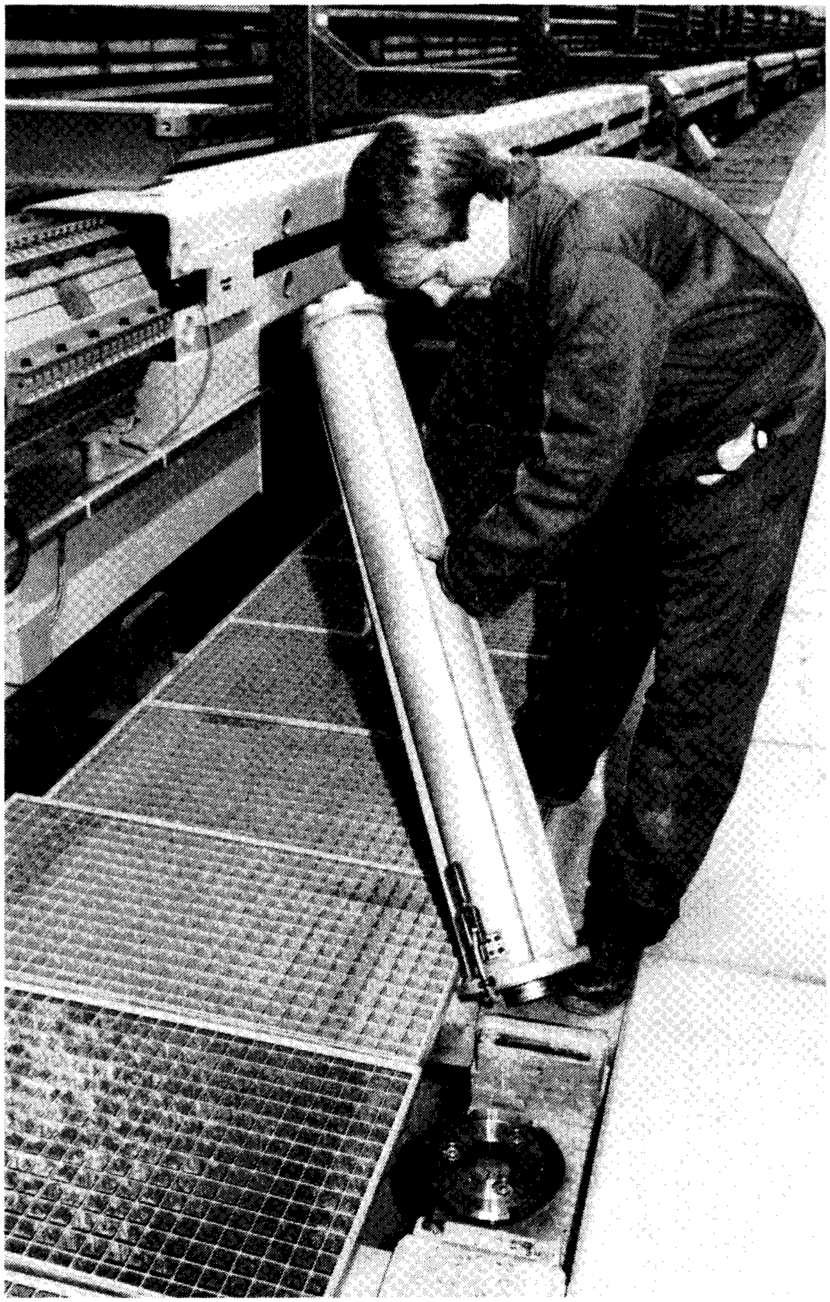


Figure 12: Survey plate and auxiliary pillar HERA

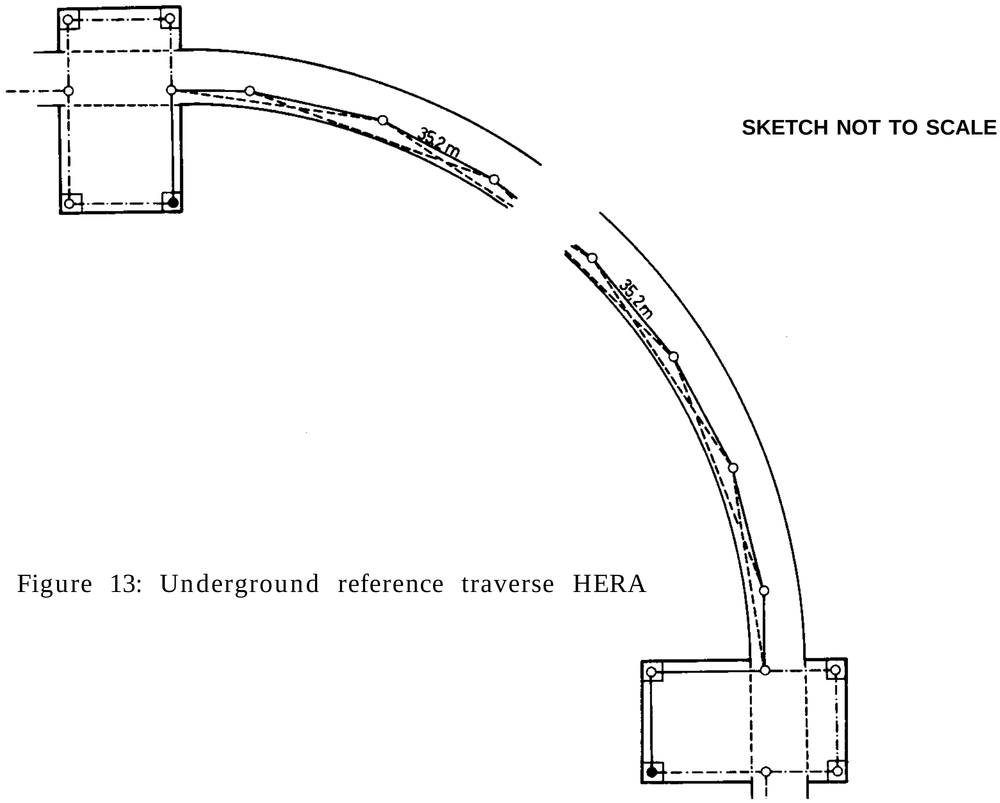
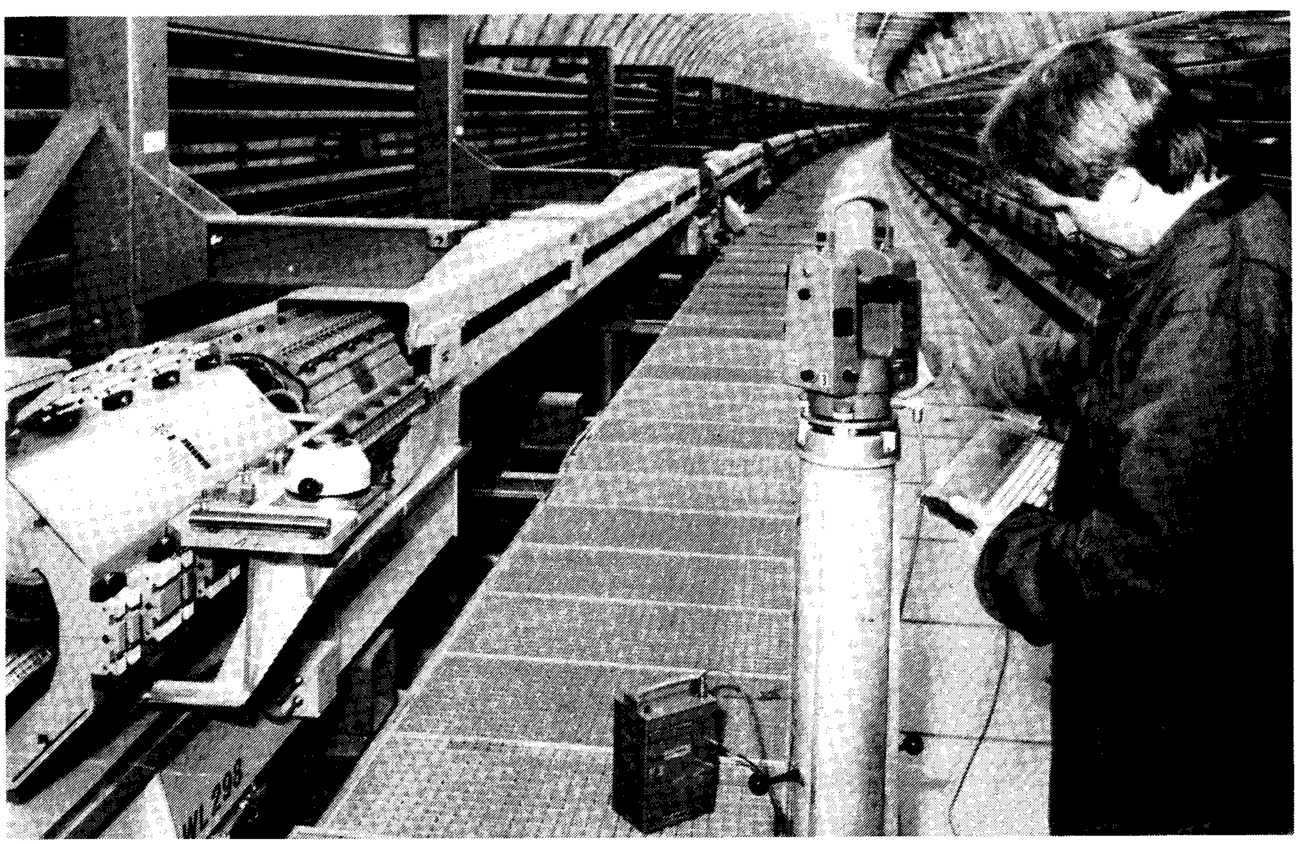



Figure 13: Underground reference traverse HERA

Figure 14: Auxiliary pillar with theodolite



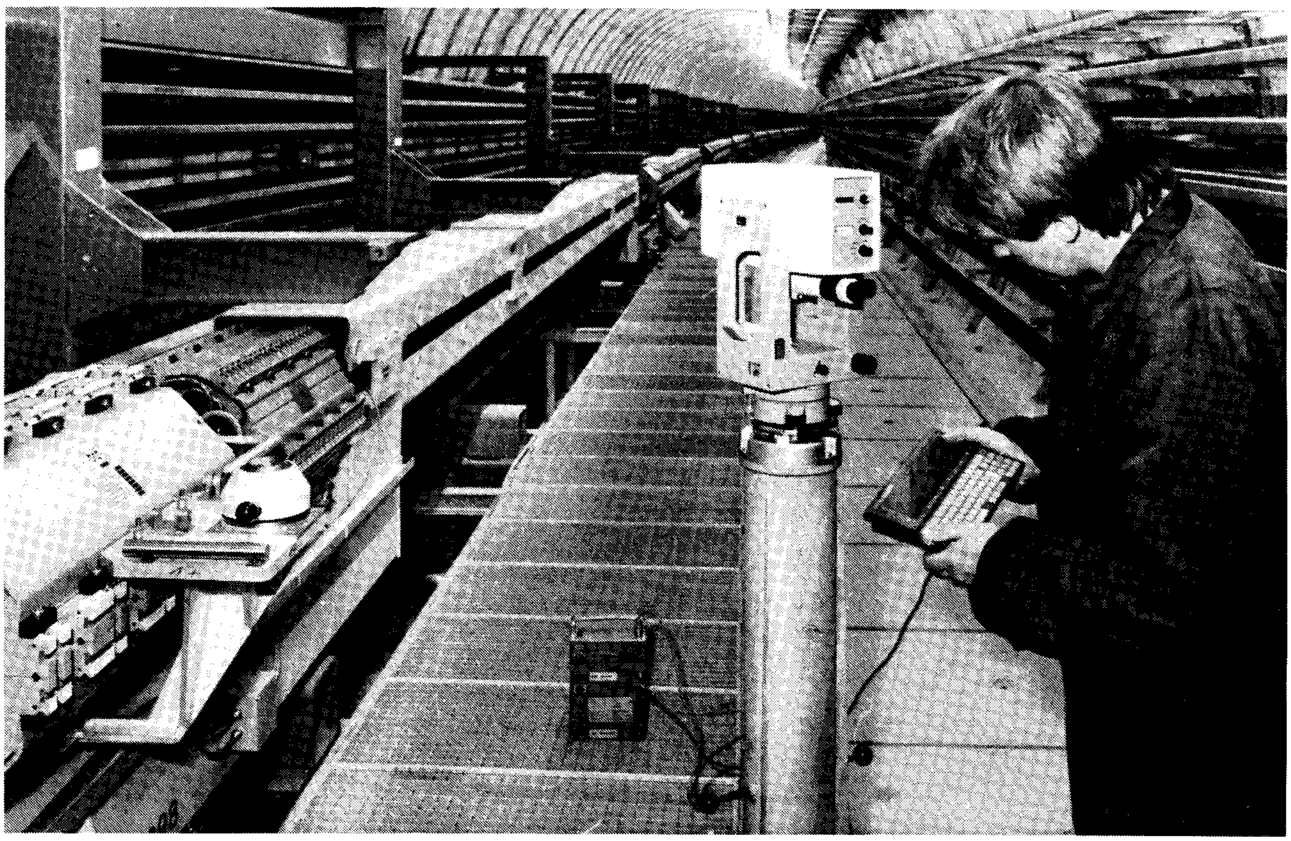


Figure 15: Auxiliary pillar with ME5000

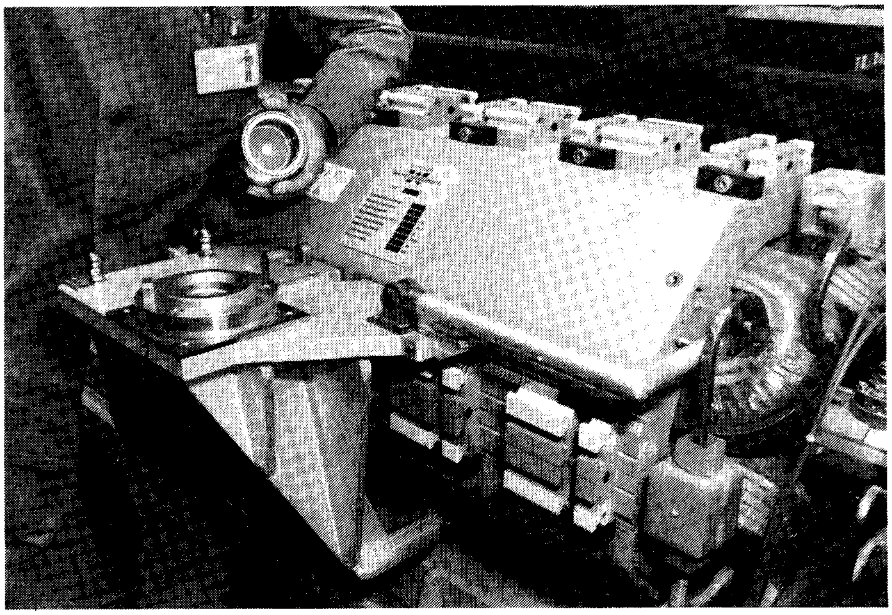


Figure 16: Survey platform HERA e-

Figure 17: Surveyplatforms HERA (straight section)

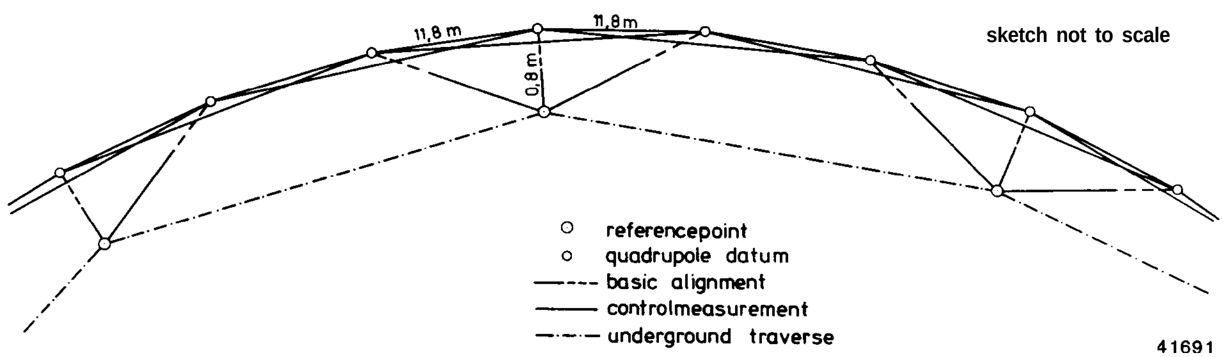



Figure 18: Survey scheme HERA e-

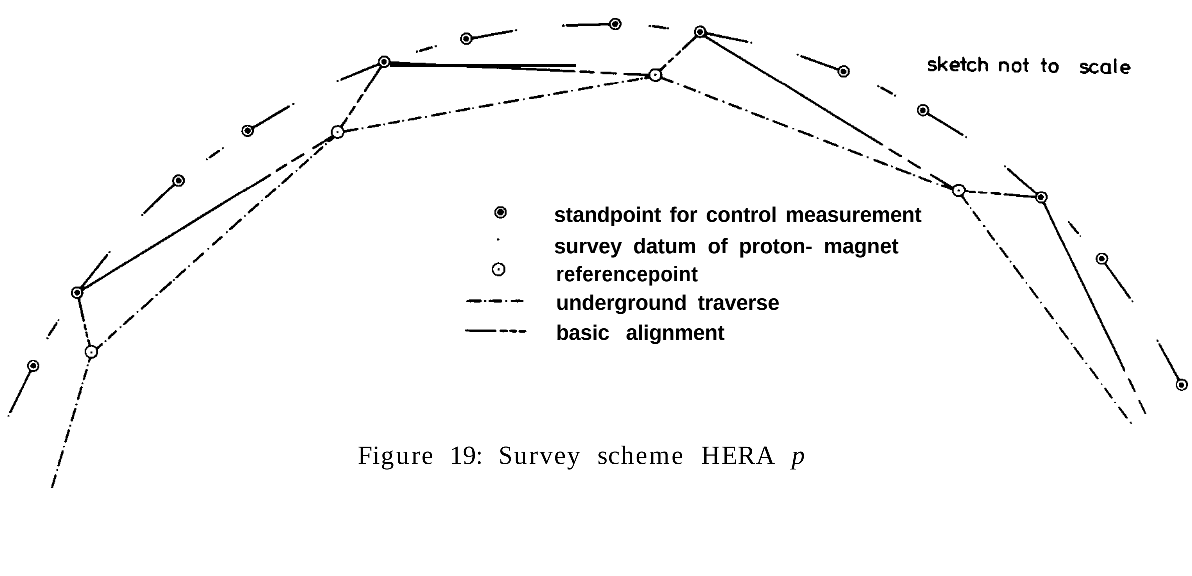



Figure 19: Survey scheme HERA *p*