THE GEODETIC APPROACH FOR HERA

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Abstract

At DESY in Hamburg the electron-proton-collider HERA is under construction. The demanded relative accuracy of some tenths of a millimeter can be achieved by specific alignment techniques and survey equipment. Methods and first results are described.

1. Introduction

HERA is a high energy accelerator, which is presently under construction at DESY in Hamburg. It consists of two independent storage rings designed for 30 GeV electrons and 820 GeV protons (Fig. 1). The counter-circulating beams collide head on in interaction regions, which are located in three of the long straight sections. In the regions close to the interaction points protons and electrons are within the same vacuumpipe. Then they are separated. While the electrons are kept in the e^-plane, the protons are brought to a higher level. At the end of the straight sections the height difference between electron and proton beam reaches 0.81 m and is then kept constant in the arcs of HERA, so defining the plane of the proton machine. The circumference of HERA is 6.335 km. All magnets for the e^- ring are normalconducting. The magnets of the proton ring are normalconducting in the straight sections, but superconducting in the arcs.

For the operation of HERA the other DESY-machines are used as preaccelerators. Electrons as well as protons are generated in linear accelerators (Linac I, Linac III). Then they are preaccelerated in the synchrotrons DESY II and DESY III respectively up to 7 GeV and transferred to the storage ring PETRA for further acceleration, the electrons up to 14 GeV and the protons up to 40 GeV. With these energies the particles are injected into HERA, the electrons clockwise, the protons anticlockwise.

Fig. 2 gives an overview of the area of Hamburg, where HERA is located. In the foreground the DESY-laboratory is shown surrounded by the PETRA-ring and private residential areas. In the center the HERA-ring is outlined with its four experimental halls. Only one is located within the DESY-site. The others were constructed on public ground. The HERA-tunnel lies in the western and southern regions beneath the DESY-laboratory and the residential areas. The rest of the ring is located predominantly under a large city park.

The HERA-machine-planes are not horizontal, but have an inclination of 1%. Therefore it was necessary to introduce a three-dimensional coordinate system to define the position of the accelerator components. These coordinates have to be projected to a reference sphere before they can be used for geodetic measurements.

Fig. 3 shows the dimensions of HERA with respect to the surrounding area and the orientation of the coordinate system. The sketched diameter gives the direction of the maximum inclination.

2. The Geodetic Network on the Surface

For the construction of the tunnel/2/ and the alignment of the machine a geodetic network on the surface was installed as shown in Fig. 3. Four points of this network were already given by the PETRA-system/1/. Three more had to be built especially for HERA. Near hall North a survey tower more than 20 m high was constructed. Another point was installed on the staircase-building of the "Volkspark-Stadion." The third is situated on a building near hall South.

All distances between the monuments are measured by the high precision electronic distance measuring instrument KERN ME 5000/3/, the height differences by precision leveling. The coordinates of the survey points then result from a least square fit of the observations.

Fig. 4 gives the results of several measurements of the combined PETRA-and HERA-network. The changes in position are not more than 1.5 mm. Since they include the actual movements of the monuments the achieved accuracy is sufficient for the alignment of the accelerators. Fig. 5 shows one of the PETRA-monuments, Fig. 6 the survey tower near hall North.

Additional survey monuments were built on top of the HERA-halls. Vertical steel pipes (diameter 0.4 m) were inserted in the ceilings and protected by concrete jackets. On top self-centering KERN-datums were mounted, as used for the other survey points at DESY/1/. In this case the datums are equipped on the underside with a target, which can be illuminated and seen from below. Each hall has one point. Its coordinates can be derived from distance and angle measurements from the neighboring monuments of the HERA-network (see Fig. 3). Fig. 7 shows the concrete pillar on top of hall South.

3. The Reference Traverse in the Tunnel

Special survey datums were developed for the tunnel. As Fig. 8 shows we chose steel plates with a well-machined surface and a centering bore. They are inserted in the concrete wall of the tunnel, which is used as a trail for the transport vehicle. Auxiliary pillars of aluminum can be mounted onto these plates. A pivot, which fits into the bore, gives the centering, a machined baseplate defines the vertical adjustment of the pillar, which can be attached by clamps onto the survey plate. On top of the pillar we again find the proved self-centering KERN-datum. It defines the actual survey point, so that reductions with respect to the baseplate are not necessary.

Over all we have 44 survey datums in each quarter of HERA, which have a distance of 35.2 m from each other. The underground system is completed by four plates, which are mounted on concrete platforms in the corners of each hall, and two auxiliary points in front of the tunnel mouths. The line of sight from these points to the adjacent corners of the hall pass through openings of the shielding wall, so that the connection of adjacent tunnel arcs is possible even when the experiment is in its final position (Fig. 9).

One of the four survey plates in the corners of each hall is located vertically below the pillar on the surface. A steel shaft is led through all floors, so that the illuminated target on top of the hall can be pointed at from below. By measuring zenith angles from the aluminum pillar in the hall to the surface point it is possible to determine the difference in x and y between the two points, once the height difference between theodolite and target has also been determined. The angle measurements have to be performed in two vertical planes, which are perpendicular to each other and orientated toward one of the adjacent survey points. The obtained accuracy for this coordinate-transfer from the surface to the tunnel level is better than 0.8 mm for height differences up to 32 m. We can use these points as reference points for the survey on one tunnel quadrant.

We have a basic traverse with distances of about 35 m and overlapping lines of about 70 m length. From each pillar the directions to the two preceding and the two following points are measured. The corresponding distances are determined from every second standpoint to minimize the observation time. In addition all necessary observations are done, which give the connection of the traverse with the reference points in the hall. For the angle measurements, we use precision theodolites KERN E2 (Fig. 10). The observation data is directly registered and analyzed by a handheld computer HUSKY-HAWK. The targets for the angle measurements have been used for many years in our other accelerators (Fig. 11). The distance measurements are carried out with the KERN ME 5000 (Fig. 12).

The complete position survey of one quadrant is performed in about 7 hours, when angle and distance measurements are made by two separate survey-teams. The standard deviation of the direction measurement is 0.1 to 0.2 mgon, that of the distance measurement better than 0.1 mm. The coordinates of the traverse points are obtained by a least square fit of our redundant measurements, where the reference points are used as fixed points.

4. Alignment of the Electron-Accelerator

In the arcs of the e^- ring the bending magnets and the preceding quadrupoles and sextupoles are fixed as one unit. The focusing magnets are mounted on a girder, which is connected with the dipole. They are aligned in the workshop with respect to the dipole.

In the tunnel the module rests on a support, which is arranged underneath the quadrupole, The dipole-end is placed on two screws of the following clockwise module for vertical adjustment. One of these screws fits in a groove, which allows an azimuthal movement of the dipole, while the radial position with respect to the following module is fixed. The height and inclination of the quadrupole side can be adjusted by two screws of the girder, which rest on hardened steelplates on top of the support. Radial and tangential corrections can be done by guide rods, which connect the girder and the support. Fig. 13 shows in side view the principle of the e^- configuration and also the protonmagnets above the electron machine. Fig. 14 gives details of the alignment mechanism.

For the positioning of the modules only one survey datum is necessary. Because of the inclined machine plane it has to define the position as well as the height. That was achieved by using the center of a sphere resting on a conical base, which is mounted on an aluminum platform. This then has to be attached to the side of the quadrupole and is centered by feet, which fit into grooves of the laminated iron. Additionally it carries a polished steel bar, which defines the radial inclination of the module. Fig. 15 shows this platform with a coincidence level.

The sphere used is of the CERN-type. The axis of its precision bore can be adjusted vertically with the help of a precision level at any position of the ring. Then it has to be locked in order to keep the vertical position during the subsequent measurements. Therefore a bearing cage has been developed, which in conjunction with a screwcap provides a fast lock and unlock procedure. In the precision bore of the sphere, with the use of an adapter, targets for angle measurements can be inserted as well as index marks for distance measurements or leveling rules for height measurements (Fig. 16).

With this equipment the alignment of the e^- modules was performed in two steps. First was a basic alignment of the magnets by polar measurements with respect to the reference traverse in the tunnel (Fig. 17). Since the survey points of the traverse are located directly opposite the reference sphere of each third quadrupole the azimuthal position of these spheres was achieved first by angle measurements with a very high precision. Simultaneously the radial position was corrected by reading a precision rule. Then the two adjacent quadrupoles were aligned by the given directions with respect to the reference traverse and the distances, which were measured with a tape from the magnet next to the traverse point. Necessary corrections of the inclinations and heights of the magnets were performed during the position alignment, using coincidence levels and precision leveling instruments. The reference points for the leveling procedure are inserted in the concrete wall beside the traverse plates. Their height was derived from precision levelings of the HERA-circumference.

Parallel to the adjustment of the quadrupole the dipole-end of the module had to be set to the correct value for height and inclination. Thus we used another platform which refers to the surface of the laminated iron of the dipole. Like that for the quadrupole it carries a steel bar for the inclination measurement. For the height control a special sphere is used.

Since the dipole-end of the module rests on the girder of the following clockwise module, the alignment procedure had to follow the ring counterclockwise. So there was no influence on the magnets, which has been adjusted before.

The accuracy of this basic alignment was about 2 mm. Since the final value in radial position and in height should be within some tenths of a millimeter, a second alignment procedure had to follow. Thus we performed a continuous position survey directly from the survey-spheres of the quadrupoles with respect to the neighboring magnets. By measuring the directions from one reference sphere to the two preceding and the two following ones (Fig. 17) one gets a high relative accuracy for the radial offset of the quadrupoles, whereas it is not necessary to take care of the traverse points in the concrete wall anymore.

To achieve these measurements we copied an adapter of CERN, which allows the combination of a CERN-reference-sphere with the self-centering datum of KERN. Thus the use of the KERN-targets and theodolites for the horizontal-angle measurements was possible (Fig. 18). As for the measurements of the reference traverse the observation data was directly transferred to the computer, so that the complete survey of one arc of HERA (100 modules) could be accomplished in one day.

The calculation of the least square fit of the direction-measurements was done with the nominal values of the distances between adjacent quadrupoles. As reference coordinates the nominal coordinates of all quadrupole-spheres were used. From the differences between calculated and nominal coordinates finally the radial deviations were derived.

Fig. 19 shows the results of such a survey of an arc. The calculated deviations are liable to a systematic deformation, which might be caused by horizontal refraction during the angle measurements as well as by inaccuracies of the self-centering of the theodolites and targets. Since it is not important for the machine that the magnets are on their nominal position, but that they are aligned on a smooth line, it is possible to calculate a best fit curve and to define the radial deviations with respect to this curve. The necessary alignment was performed using dial gauges. Then a complete control survey was carried out. In our example (Fig. 20) the results of the alignment were sufficient: the deviations from the calculated function are within some tenths of a millimeter.

The procedure for the vertical alignment of the magnets is very similar to that of the radial component. To obtain the necessary accuracy until now the height differences between adjacent quadrupoles were measured directly by precision leveling and the corrections were made with respect to the best fit curve. In the future it will be possible to measure both components at the same time. By the development of a theodolite-support, which rests directly in the conical base of the survey-platform the CERN-reference-spheres with the complicated adjusting and locking procedure will then no longer be necessary. The support centers itself by the lower part of a reference sphere. The vertical axis of the theodolite can be adjusted by two screws of the support, while that of the theodolite are locked in a medium position. So the height of the line of sight of the E2-theodolite is well defined and constant. As targets Taylor-Hobson spheres will be used, which can be inserted directly in the conical bases as well. By one pointing to the target the horizontal direction and the zenith angle are available and can be read out by the computer. The height differences then can be derived from the zenith angle measurements. Fig. 21 shows the underside of the new support and the conical base on top of the survey platform for the proton magnets.

5. Mounting of the Proton-Machine

The electron-machine is complete and made its first successful test run in

August/September 1988. In the meantime began the mounting of the superconducting magnets for the proton ring. As shown in Fig. 13 the proton cell has two dipoles and one quadrupole. Each magnet rests on the jibs of two supports, which overhang the e^- machine (Fig. 10). The height adjustment of the dipoles is performed by four independent screws: two on each jib. From the four feet of the quadrupoles two are coupled by a brace with a central pivot point, so creating a three-point support. Radial and tangential corrections can be carried out by similar guide rods as used for the e^- machine.

Each magnet can be equipped with two survey platforms, which are simlar to those of the e^-ring (Fig. 21). They are attached to the side of the magnet by a tension-screw with respect to a plane, which is defined by the ends of three radial screws. The position in height is given by two vertical screws, which the platform rests upon. In azimuthal position a finger from the survey platform is fixed by reference screws respectively. All these screws are adjusted with respect to the geometrical, axis and the main planes of the magnets by the construction companies. After delivering to DESY the position and inclination of the survey platforms are controlled and corrected, if necessary. Then the magnets are cooled down for the magnetic field measurements, which finally provide the position of the two reference spheres and the inclination of the reference bars on top of the survey platforms with respect to the magnetic field. With these values the nominal coordinates of the spheres and the corresponding inclinations for the foreseen location of the magnets in the HERA-tunnel can be calculated.

To perform the magnet alignment we once more have to refer to the tunnel traverse. Because of the height difference between the aluminum pillars and the proton ring and the different azimuthal distribution of the survey platforms a slightly changed procedure compared to the e^-ring is applied. First the position and height of one survey platform of a dipole is determined by angle measurements with the E2-theodolite using the new equipment as described before (Fig. 22, Fig. 23). Spherical targets of Taylor-Hobson are also used for the auxiliary pillars (a special adapter has been constructed on this behalf). Their height is determined by precise leveling. The directions to adjacent traverse points and to the second reference sphere of the standpoint-magnet are read in both the horizontal and vertical plane (Fig. 24) and registered by a computer. At the moment we use a COMPAQ SLT 286. Later on we will change to the MS-DOS-version of the HUSKY-HAWK, which is more compact and has a higher battery capacity. Additionally the horizontal angles to a 1 m-scale-bar on top of the next traverse pillar are measured. From the stored data the computer calculates the three-dimensional deviations of the two magnetpoints from their nominal values as well as the horizontal and vertical directions to the targets on the two preceding and the two following magnets in their nominal position. The theodolite telescope has to be set on these directions, while the corresponding magnets have to be moved horizontal and vertical until the crosshair of the theodolite covers the center of the target. For the azimuthal corrections the use of a steeltape is sufficient, which is fastened at one end to a reference point of the survey platform with the theodolite and read at the other end with an indexmark. The value of the nominal distance is shown by the computer also. Simultaneously the nominal inclinations of the survey platforms have to be achieved. They are measured by two Schaevitz-levels. The deviations with respect to the nominal values are read out continuously by a HUSKY-computer.

When the alignment of the neighboring magnets is finished, that of the standpoint magnet has to follow. Therefore the theodolite is mounted on a nearby survey platform. The radial and vertical deviations are transformed in correction angles and the magnet is moved respectively. The tangential corrections are controlled by tape-measurements.

The final control of the alignment is achieved by angle and distance measurements from the survey platforms similar to the procedure for the e^-ring. On principle certain dipole platforms are chosen as standpoints, as shown in Fig. 24. The magnet traverse is determined by angle measurements between the two preceding and the two following standpoints and the corresponding distance measurements. Additionally all survey datums of the magnets between adjacent standpoints are pointed at with the theodolite, so that these spheres are taken into account at least twice. If necessary connecting measurements to the reference traverse are performed. Then the least square fit of the redundant observations is made with respect to the used reference points.

Up to now a string of seven protonmagnets was mounted completely, so that a first test of the described alignment and control procedure was possible. Fig. 25 shows this part of the HERA-tunnel during the control measurements, Fig. 26 the Schaevitz-level on top of the survey platform and the reading index for the tape measurements. The results of our test alignment were encouraging. The following control measurement showed radial and vertical deviations from the nominal values within ± 0.3 mm. A second control survey reproduced the values of the first one to better than 0.1 mm.

The achieved accuracy is sufficient for the basic alignment of the proton ring. The final alignment will be performed, when all superconducting magnets of one arc are mounted and pre-aligned. The overall control measurement then gives coherent results for the remaining radial and vertical deviations. As for the e^- ring connections to the reference traverse then can be relinquished. The least square fit will then refer to the nominal coordinates of the magnet spheres.

6. References

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7. Figure Captions

Fig. 1: HERA-injection scheme

Fig. 2: Aerial view of the HERA-site

Fig. 3: Layout of HERA with coordinate system, axis of inclination and surface network

Fig. 4: Accuracy of the surface network

Fig. 5: PETRA-monument

Fig. 6: Survey tower near hall North

Fig. 7: Concrete pillar on top of hall South

Fig. 8: Survey plate of the reference traverse with auxiliary pillar

Fig. 9: Survey scheme of the reference traverse

Fig. 10: Precision theodolite KERN E2 on auxiliary pillar

Fig. 11: Conical target for horizontal angle measurement

Fig. 12: Distance measuring instrument KERN ME 5000

Fig. 13: Sideview of the HERA-normal-cell

Fig. 14: Alignment mechanism of the e^-module

Fig. 15: Survey platform of the e^-module

Fig. 16: Leveling rule on top of the CERN-reference-sphere

Fig. 17: Survey scheme for the aligning and control procedure of the modules

Fig. 18: Theodolite on CERN-reference-sphere

Fig. 19: Results of the basic alignment of the e^-modules

Fig. 20: Results of the precision alignment of the e^-modules

Fig. 21: Underside of theodolite support

Fig. 22: Theodolite on proton-survey platform

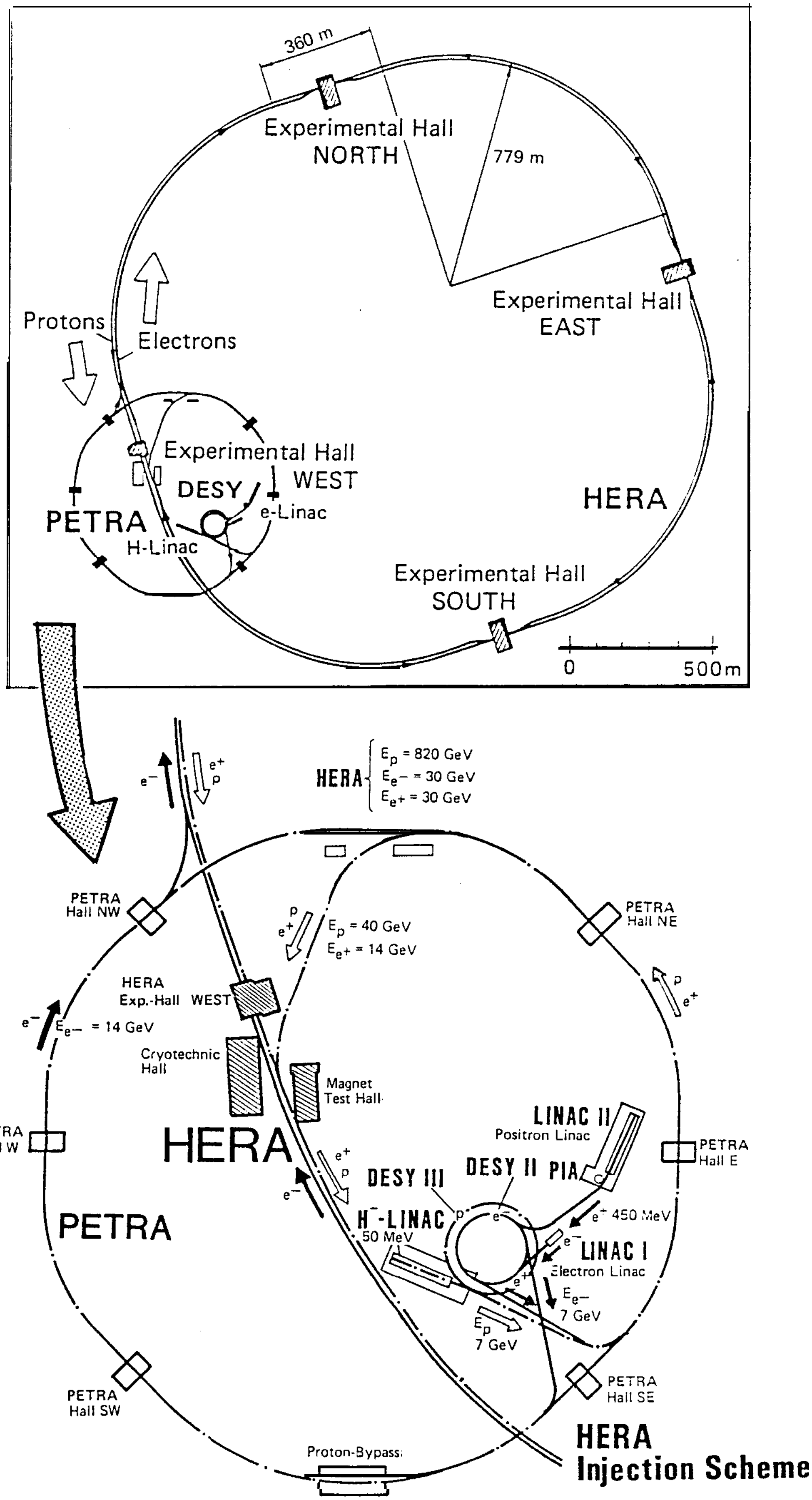
Fig. 23: Taylor-Hobson sphere on proton-survey platform

Fig. 24: Survey scheme for the alignment of the superconducting proton magnets

Fig. 25: Protonmagnets in the tunnel

Fig. 26: Schaevitz-level and tape reading on proton-survey platform

Fig.1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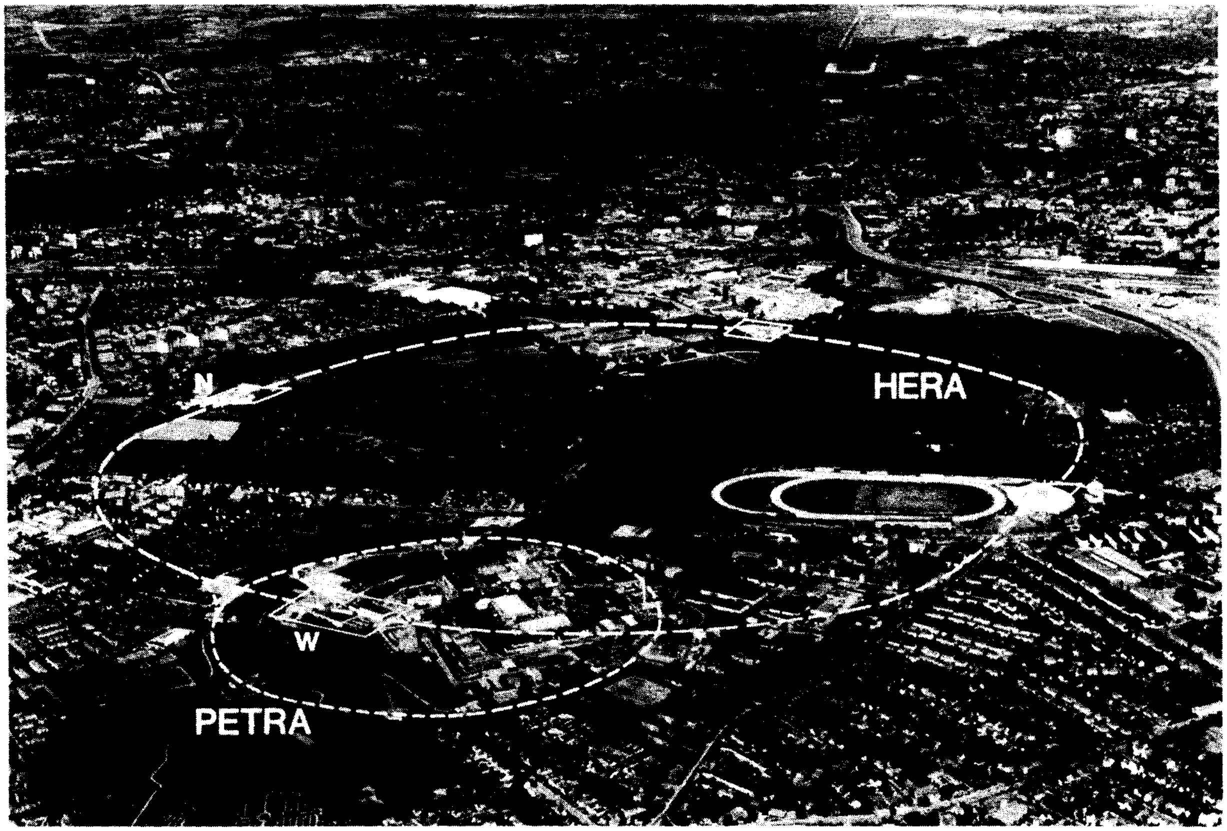

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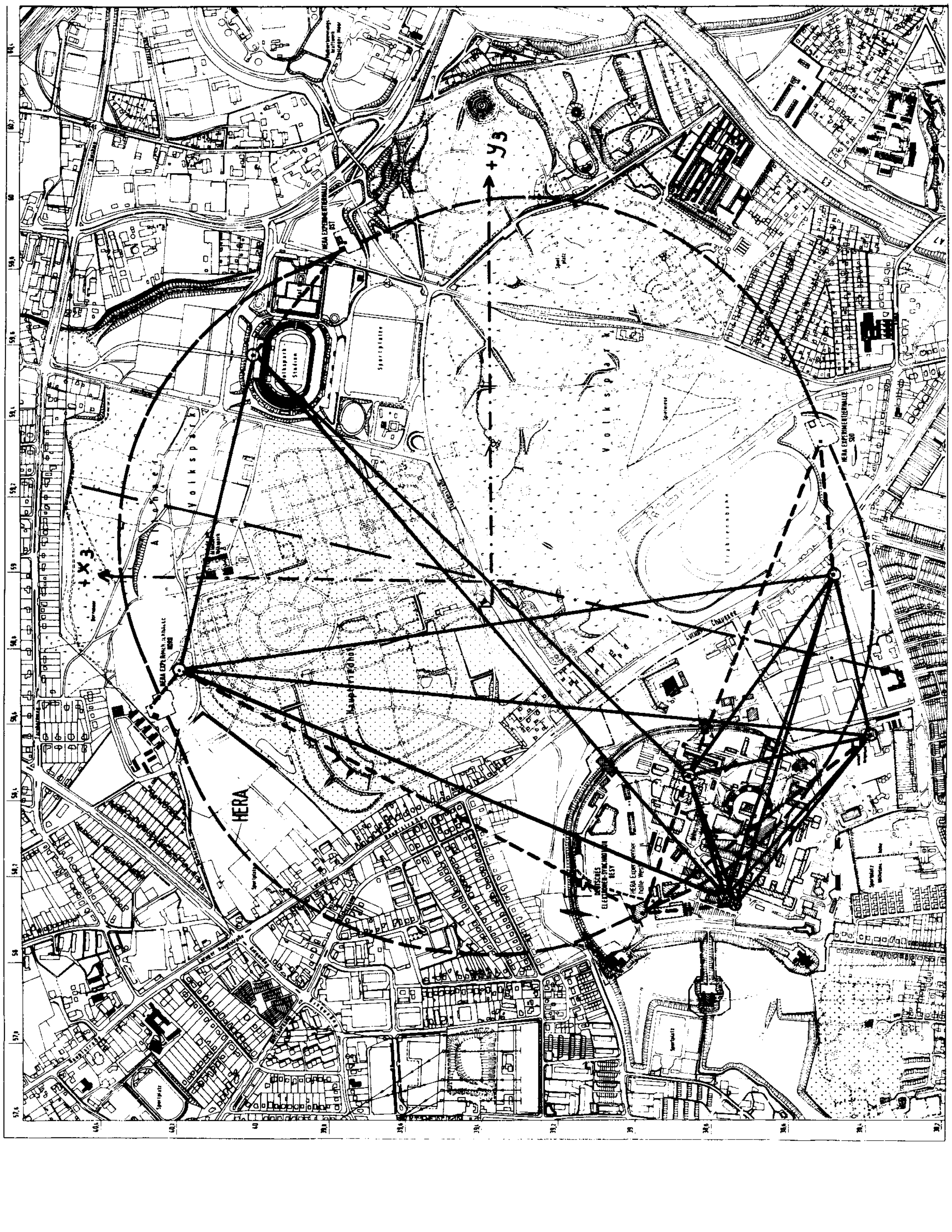

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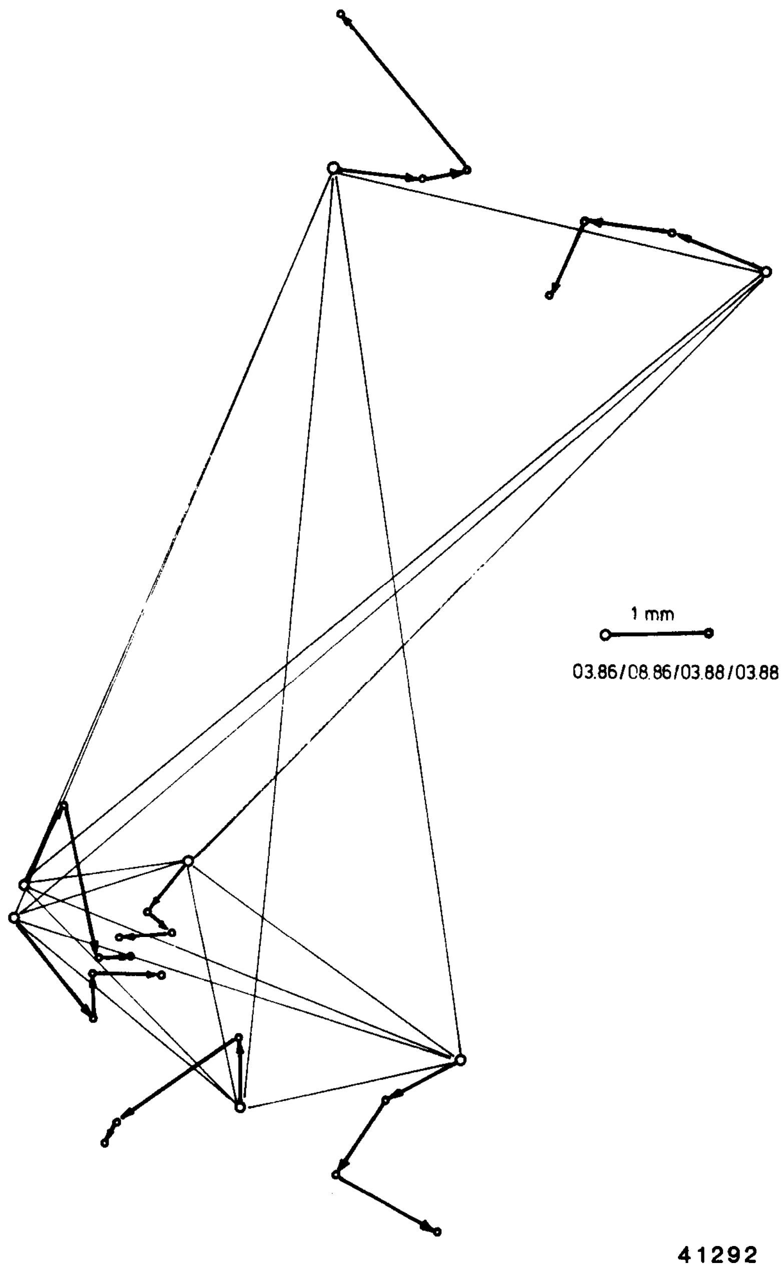

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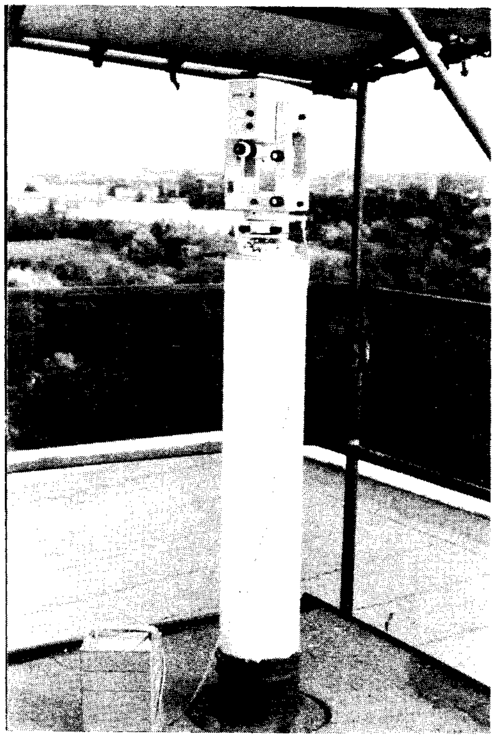

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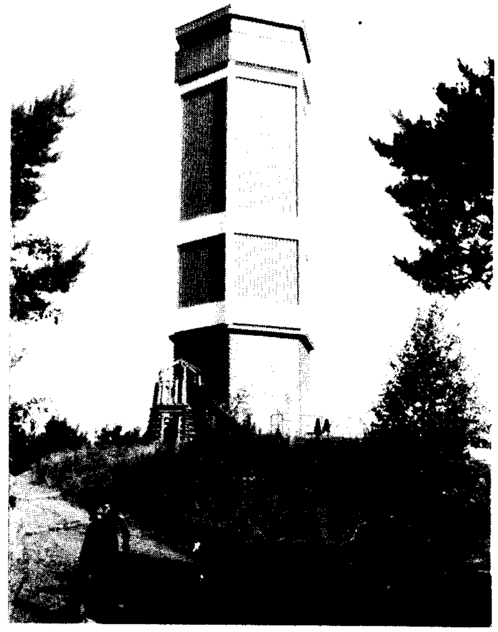

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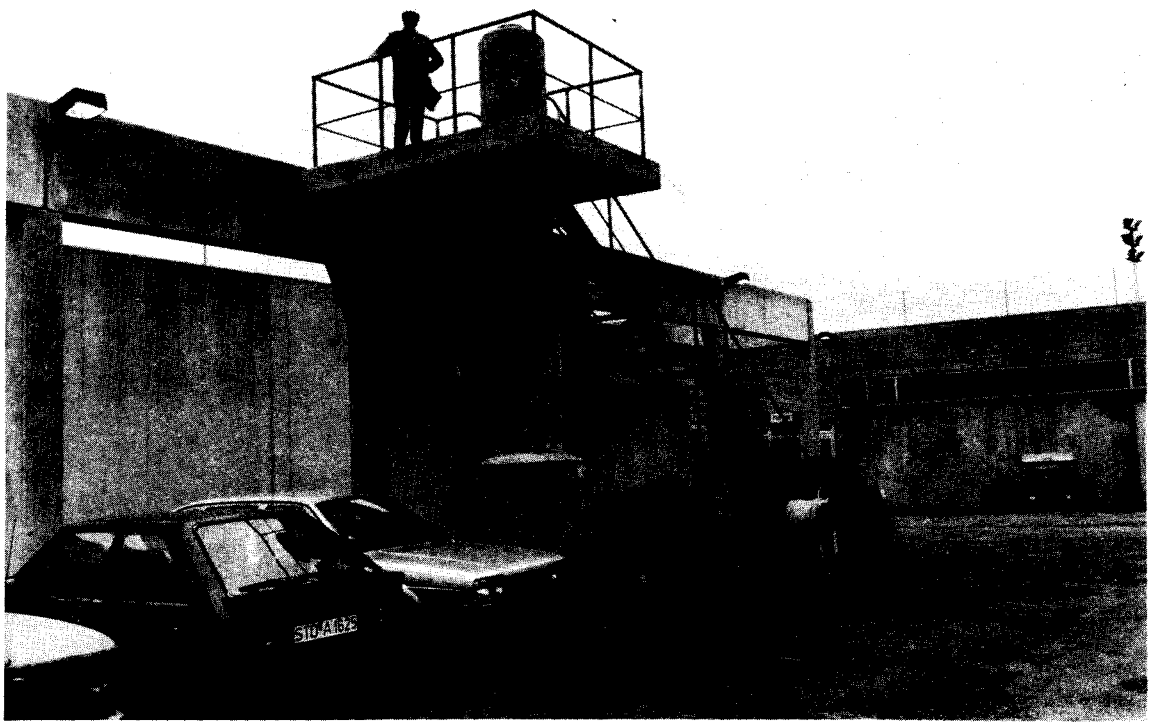

Fig. 7

Fig. 8

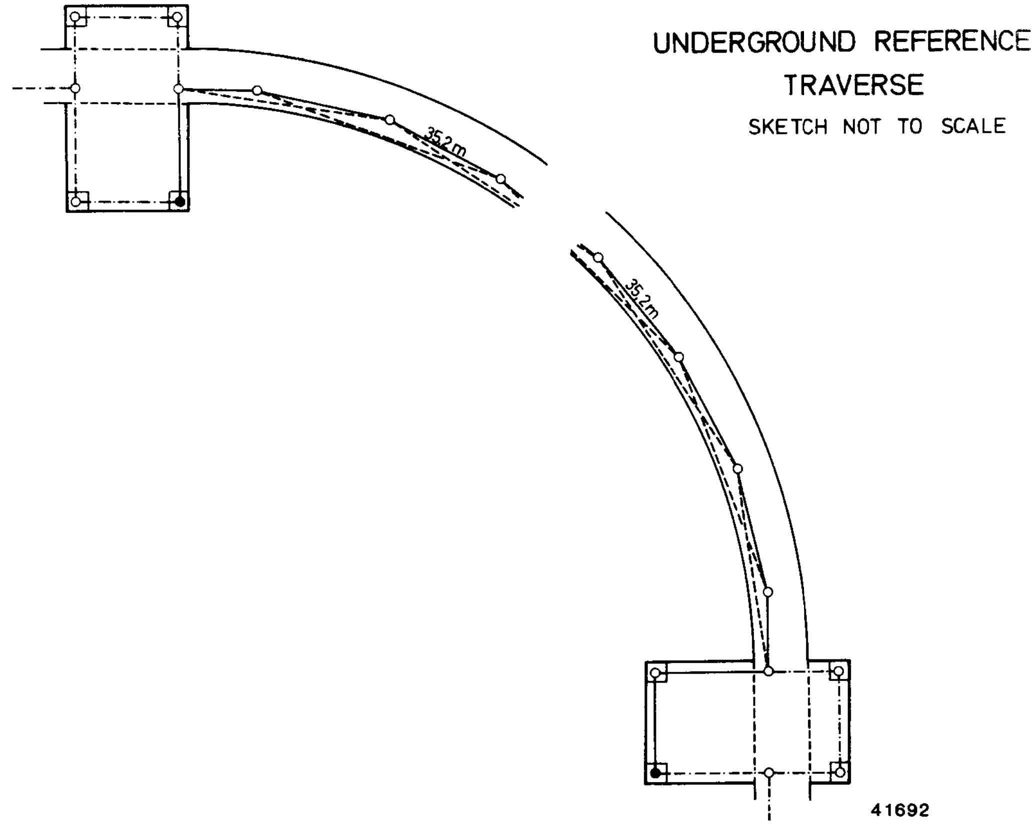
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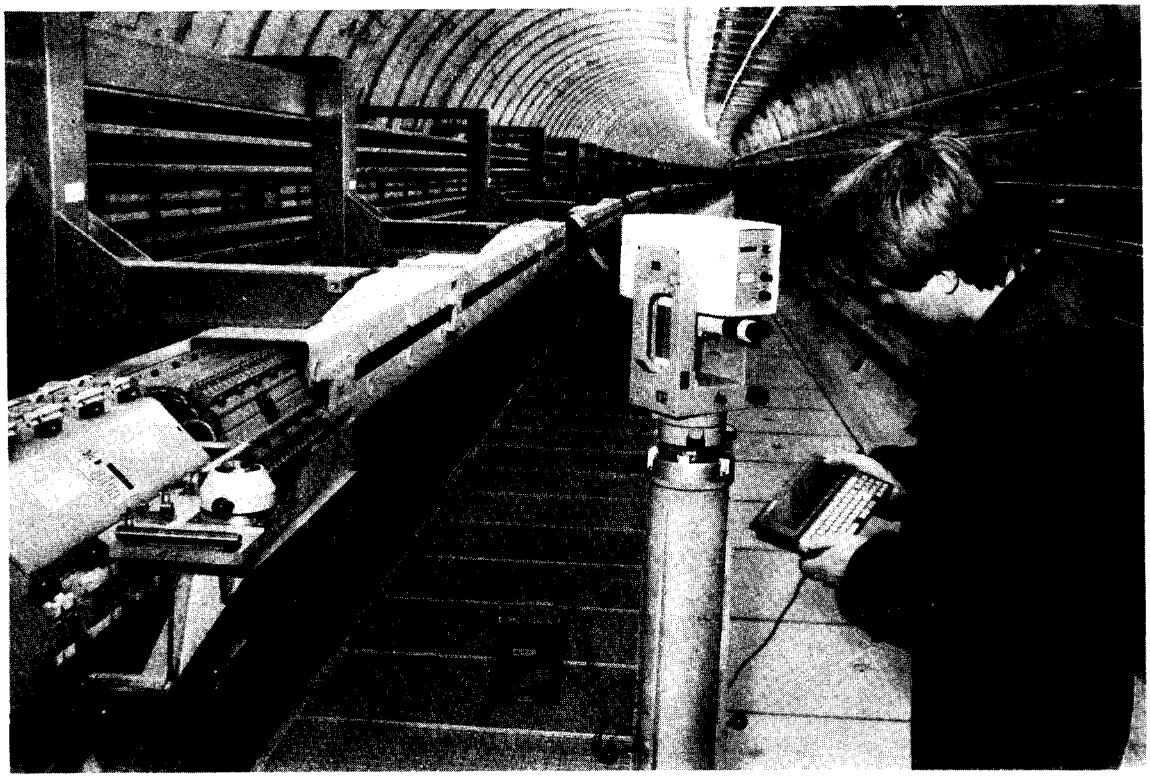
Fig. 9



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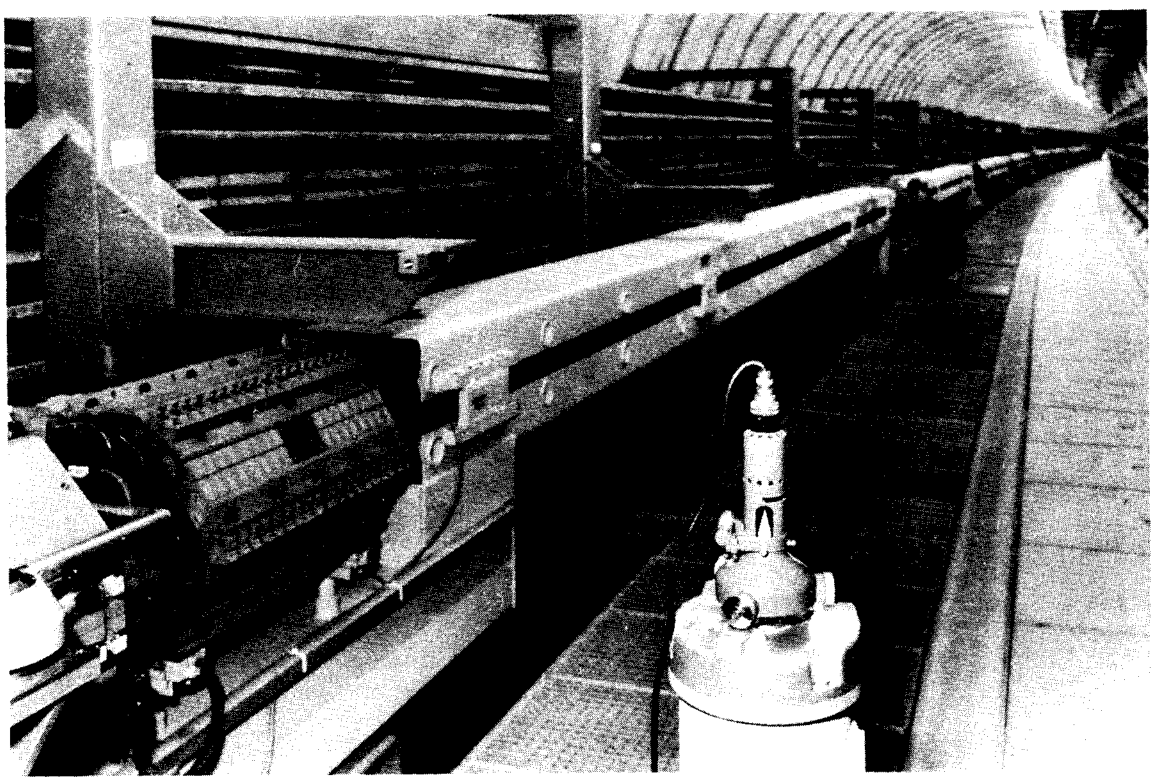

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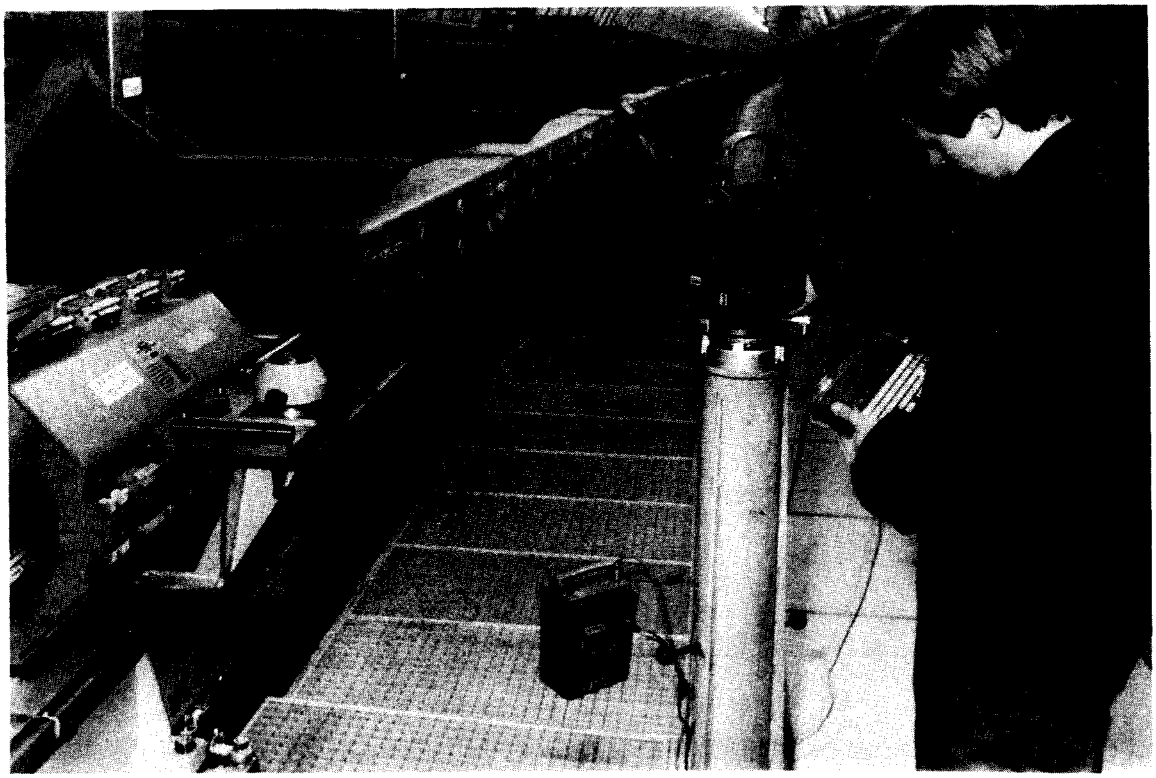

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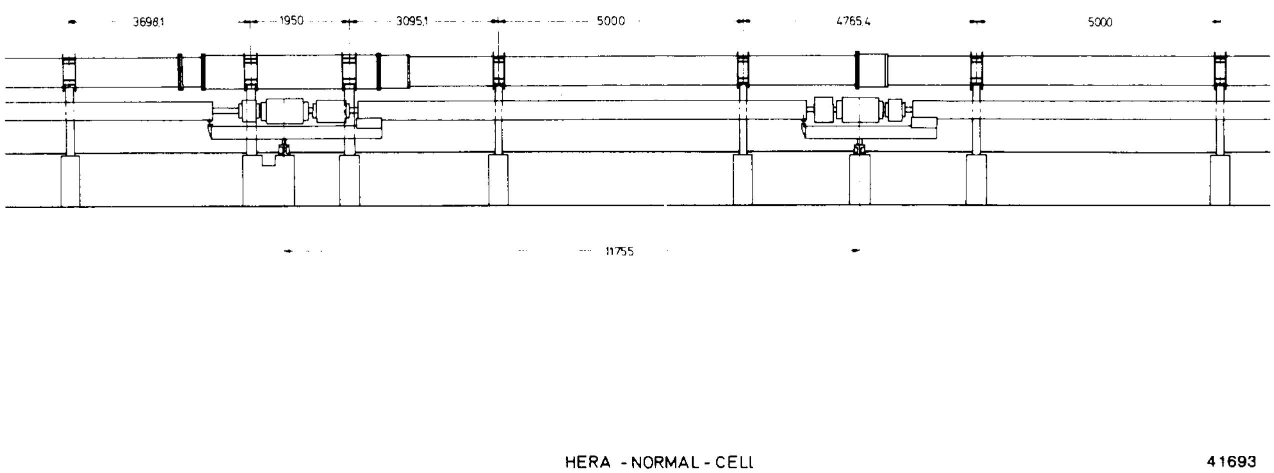
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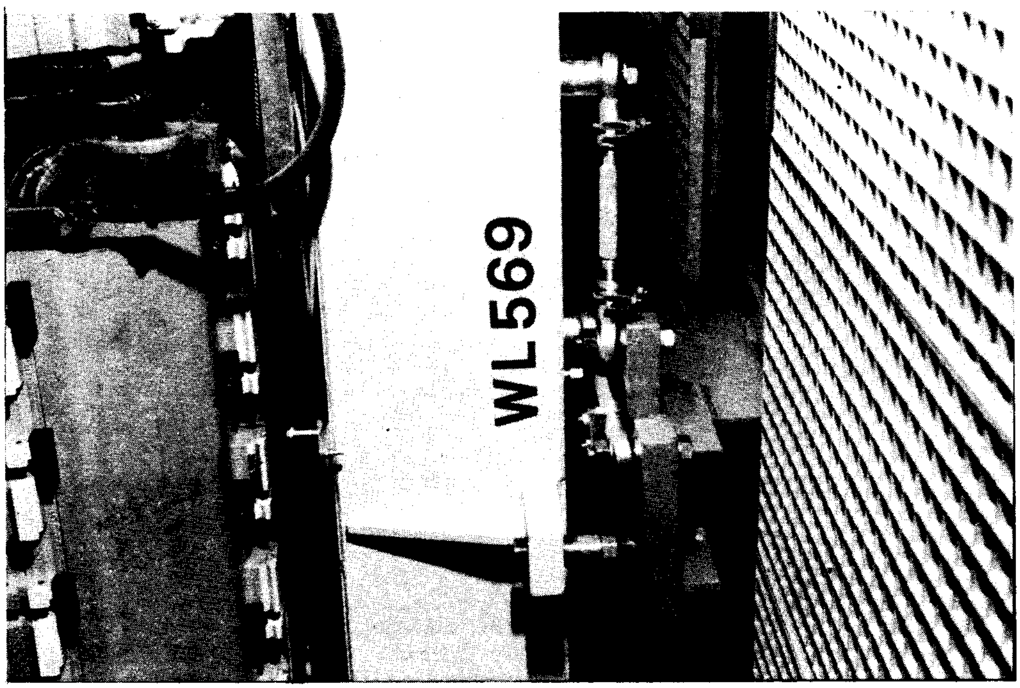
Fig.13



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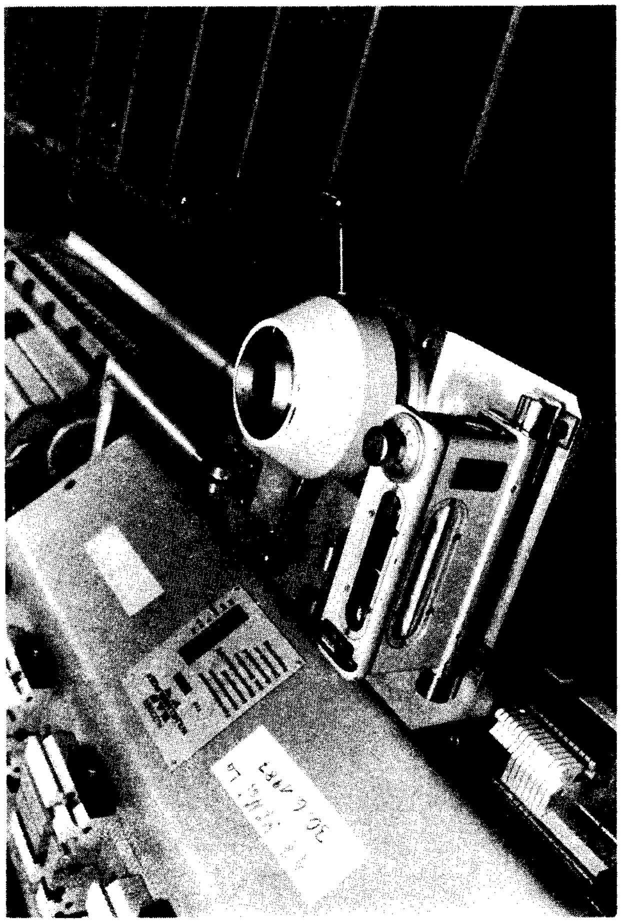

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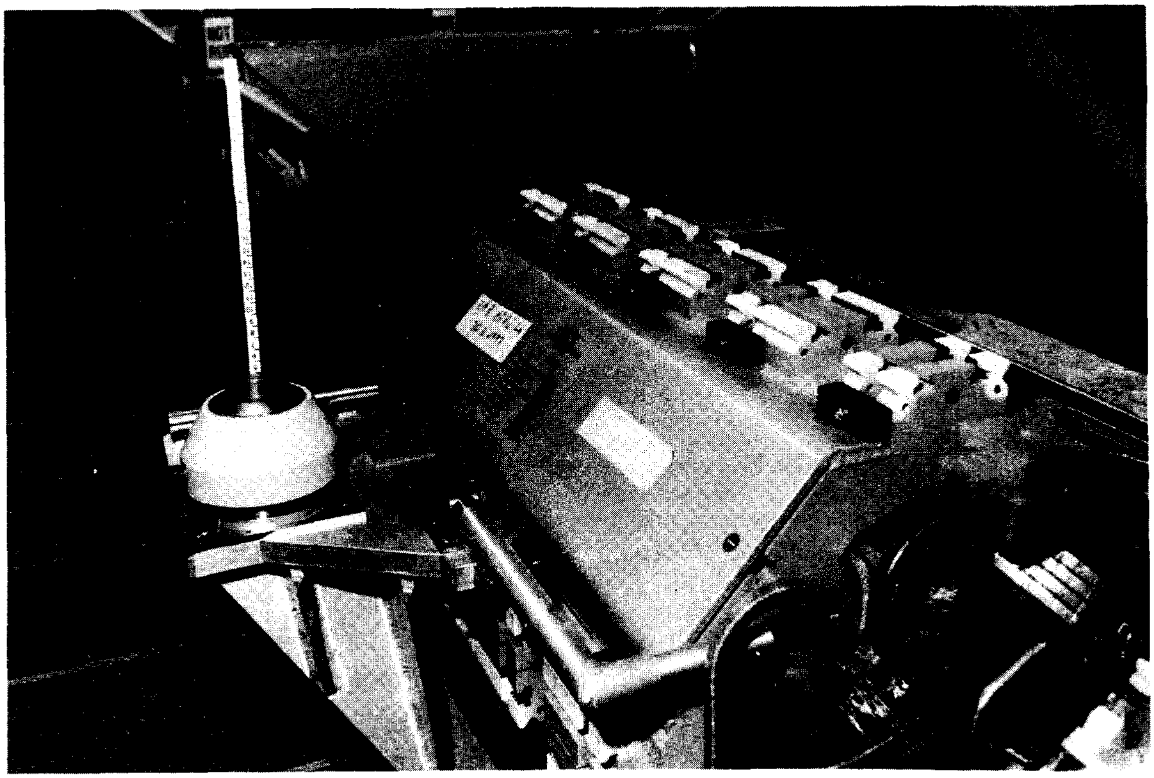

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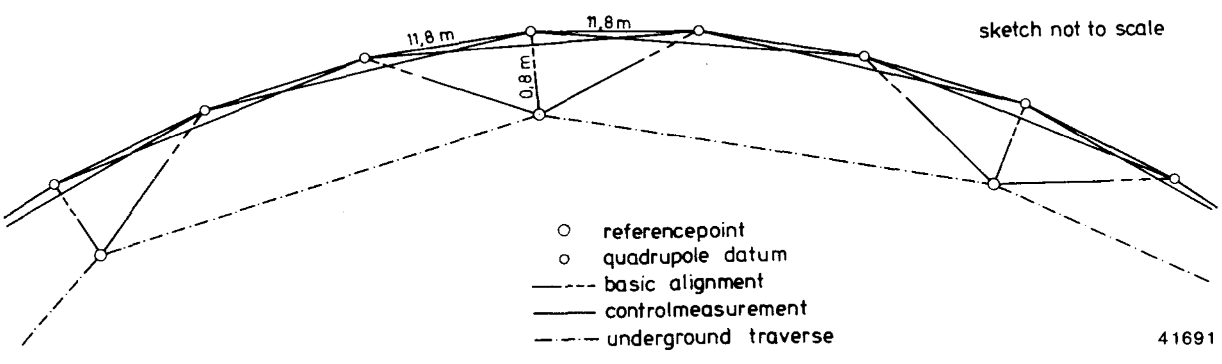
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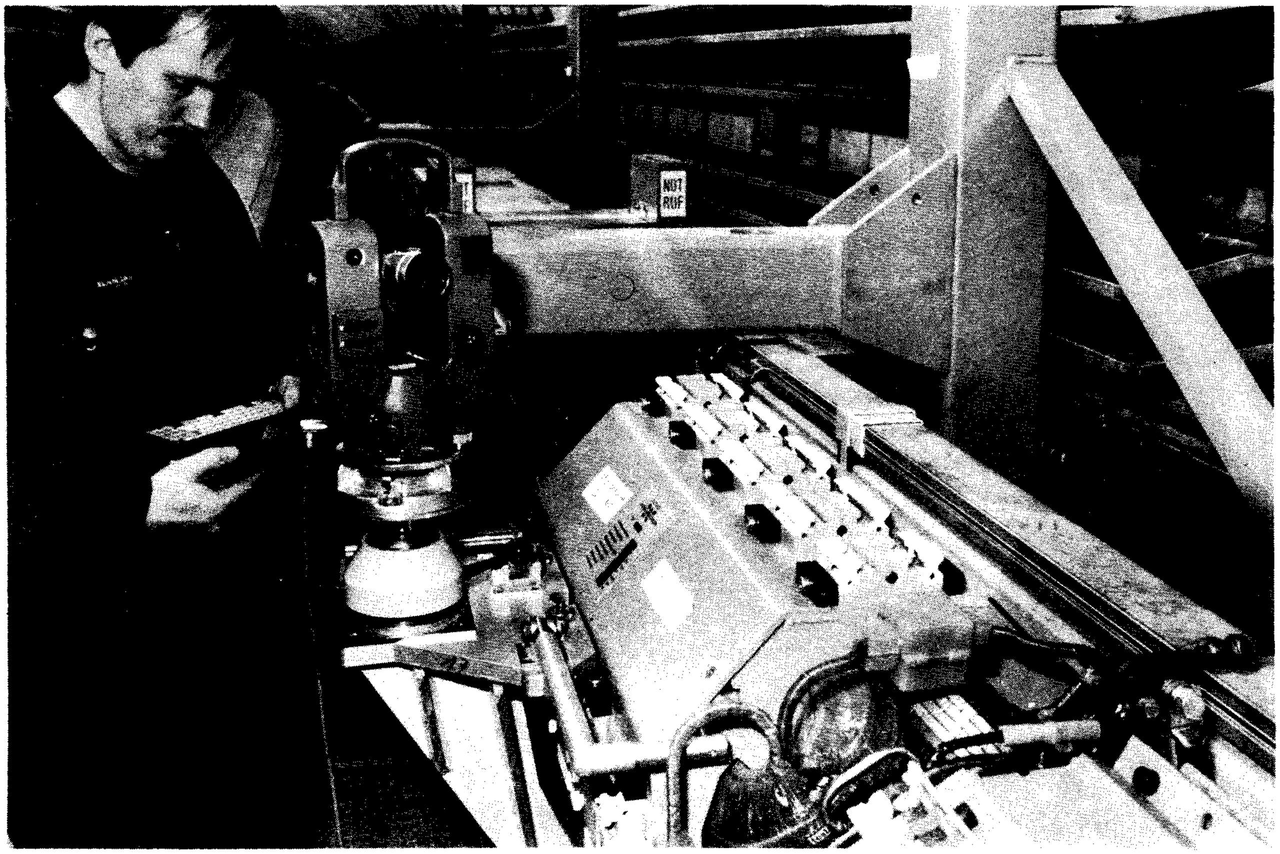
Fig.17



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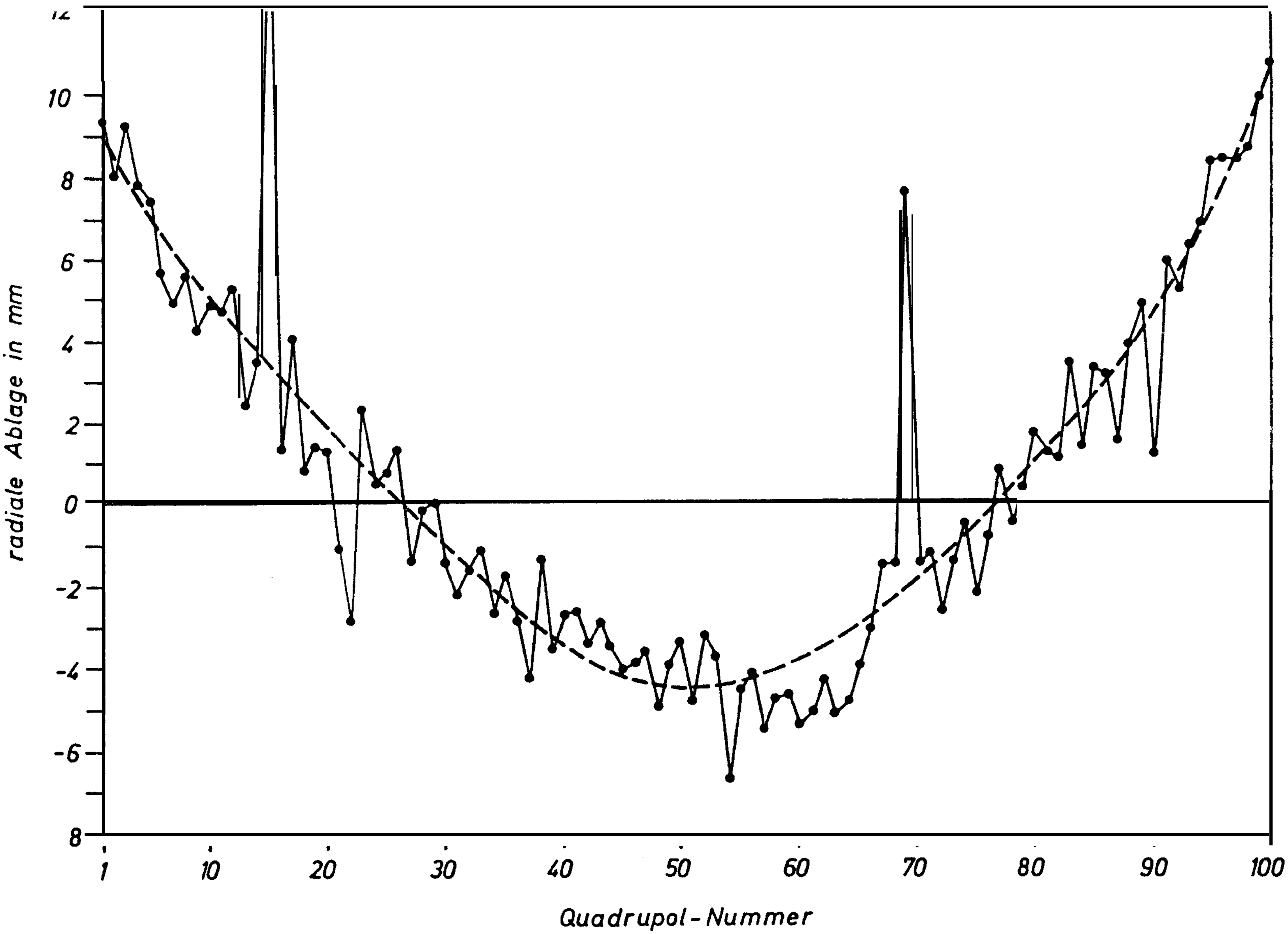
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Fig.19

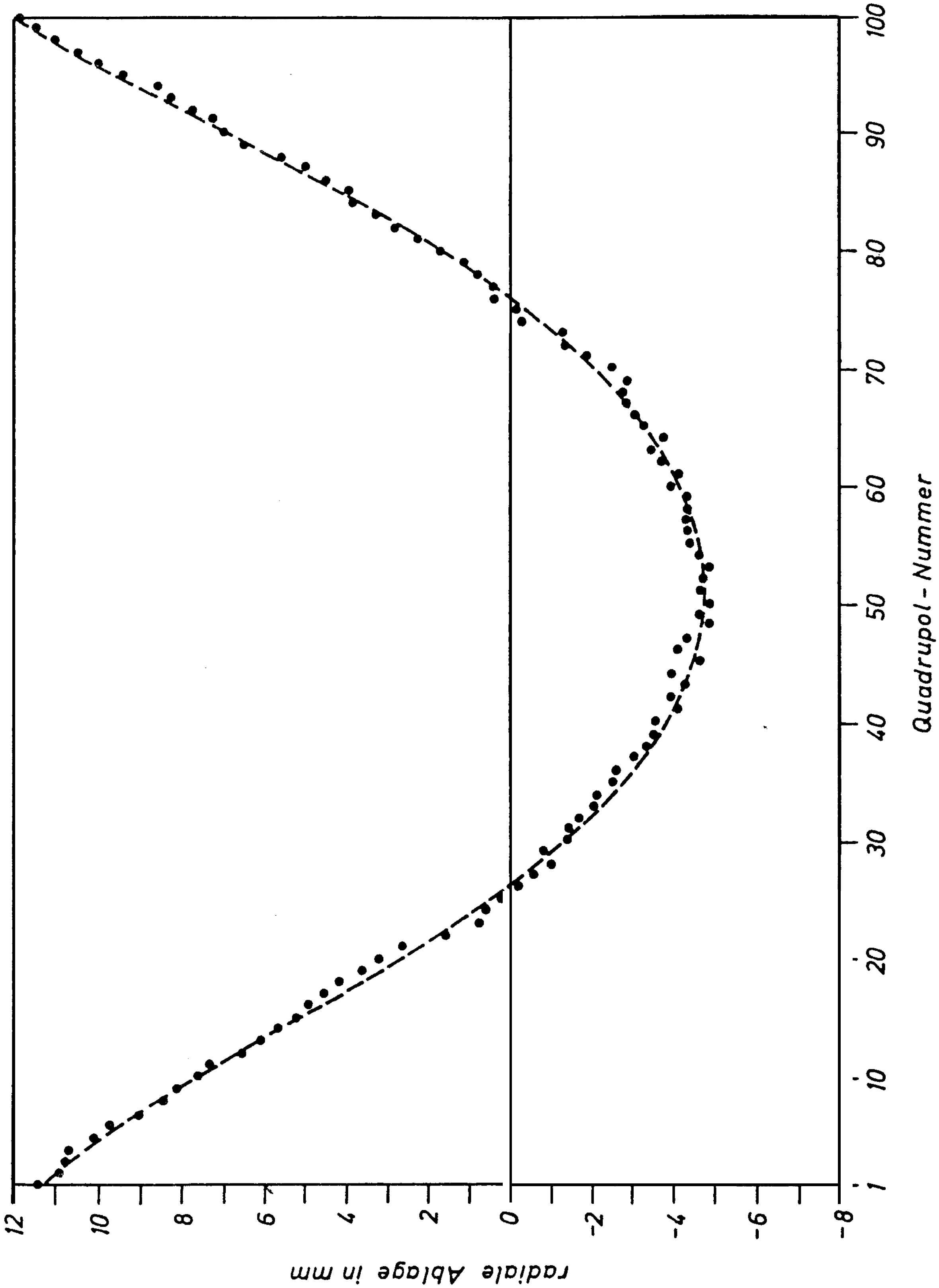
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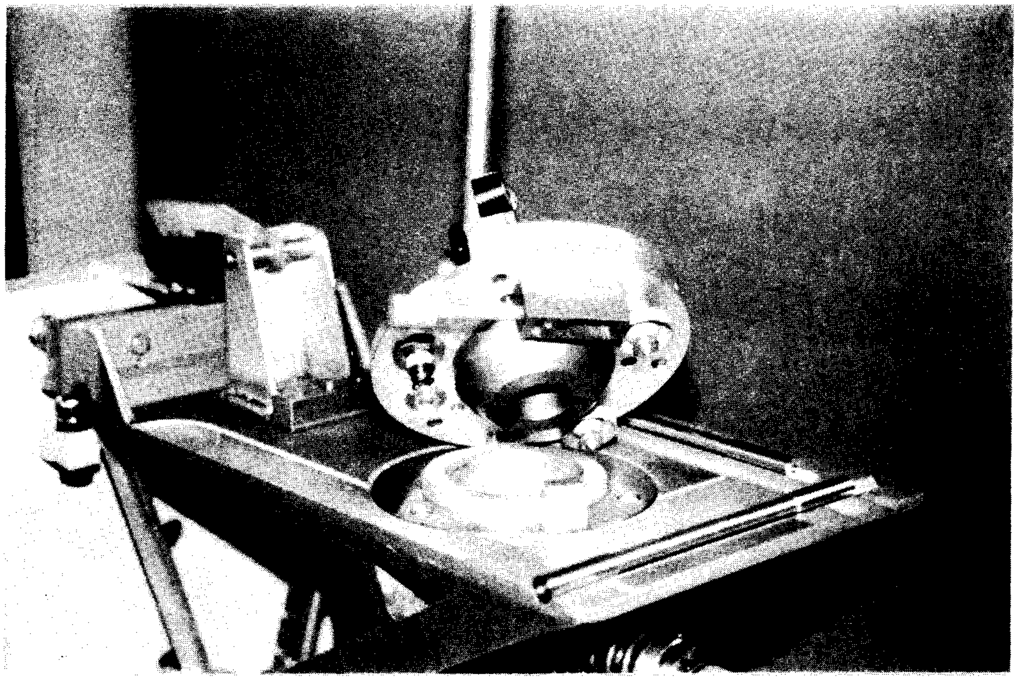
Fig. 20



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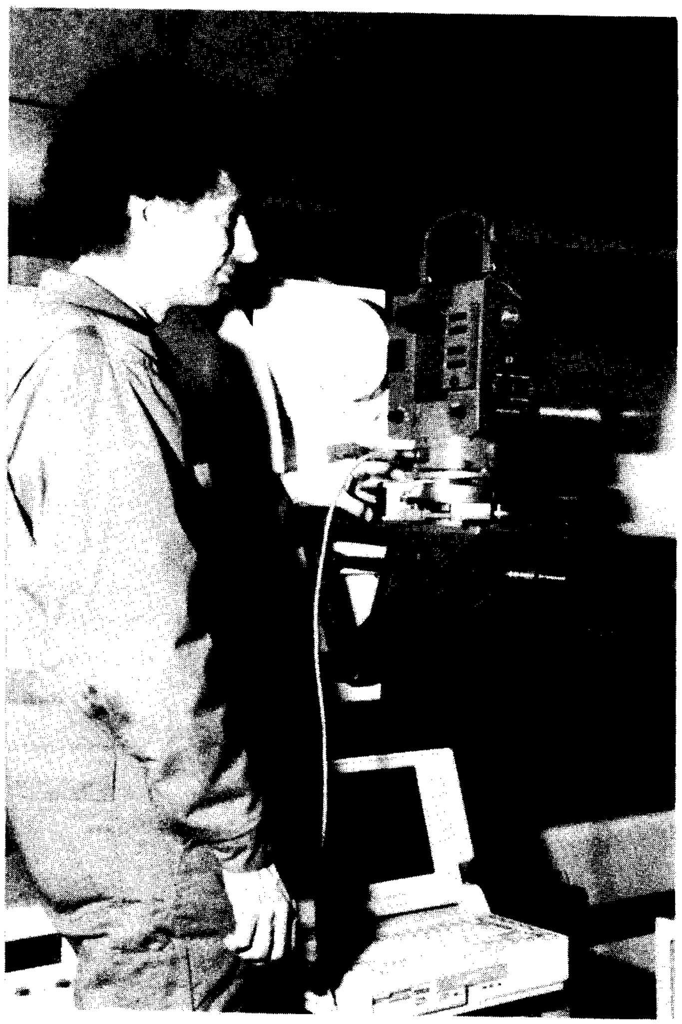

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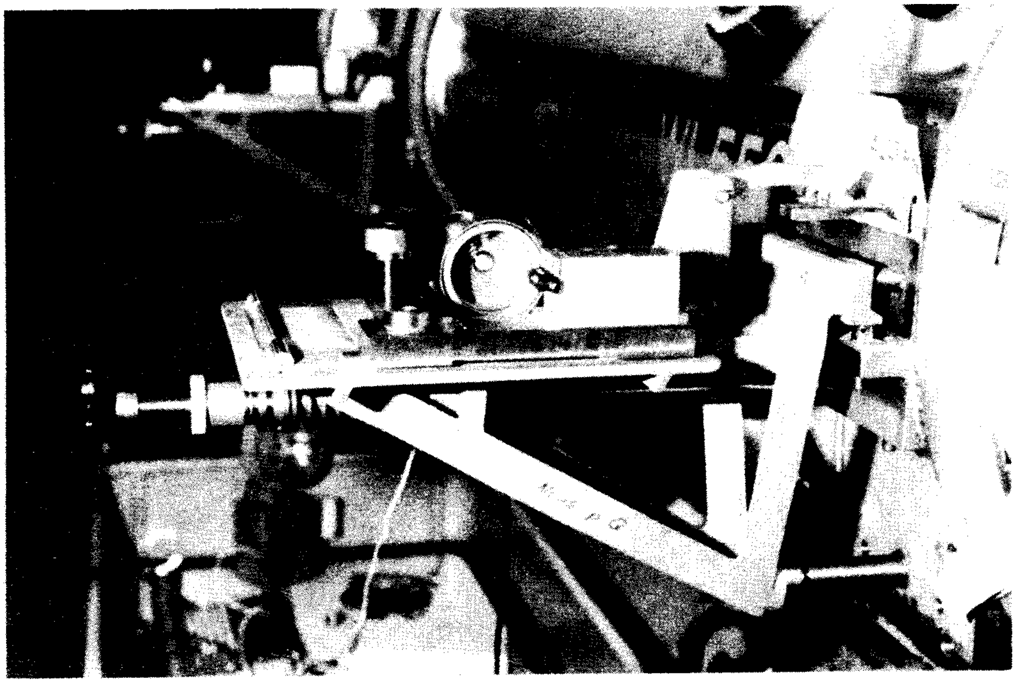

Fig. 23

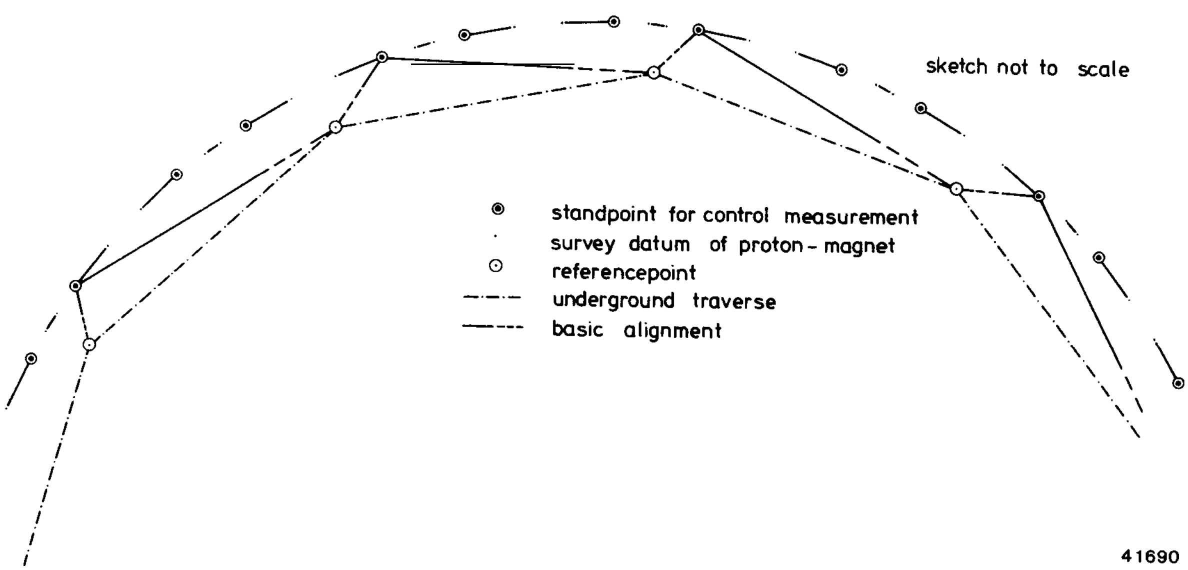
sketch not to scale
standpoint for control measurement
survey datum of proton - magnet
referencepoint
underground traverse
basic alignment
41690

Fig. 24

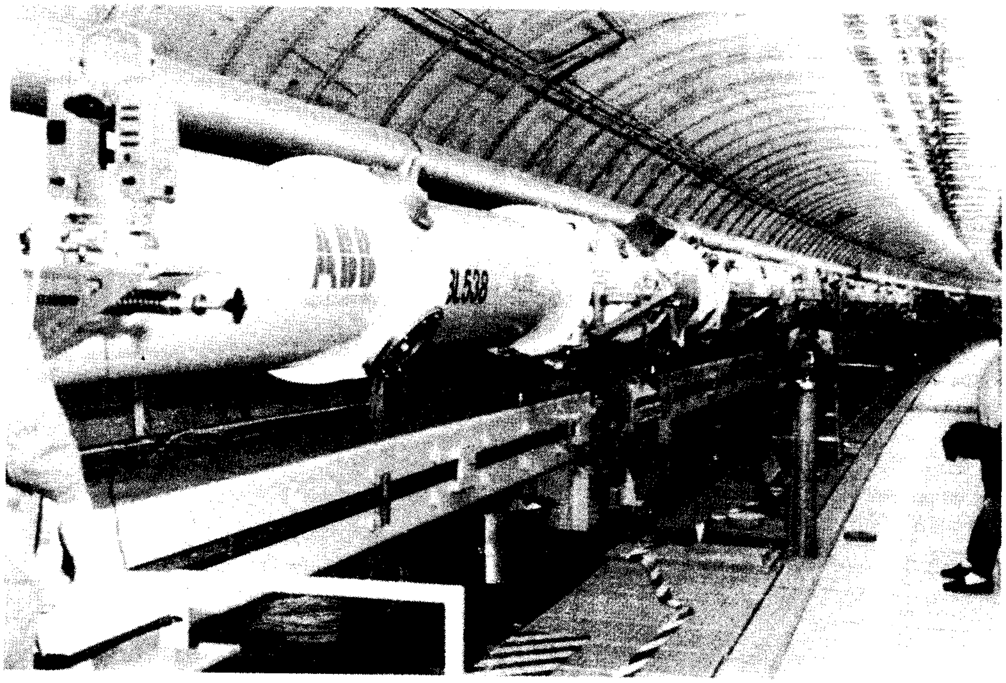

Fig. 25

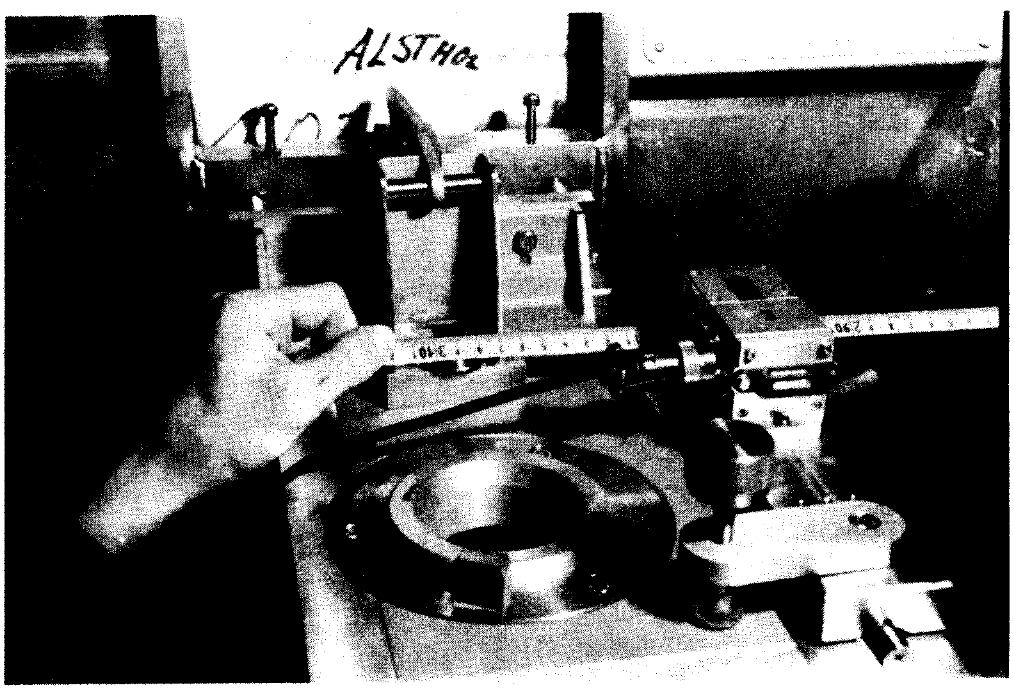

Fig. 26