POSITIONING OF THE CERN INTERSECTING STORAGE RINGS:

THE GEODETIC APPROACH

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1. INTRODUCTION

Present-day research in the field of particle physics is now centred mainly around accelerators. The scale on which research is being conducted has become increasingly small, ranging from $10^{-8}$ cm for the atom, $10^{-12}$ cm for the nucleus to $10^{-13}$ cm for the particle. To break into an atom requires only a few tens of electronvolts (eV) -- the equivalent of, say, striking a match. To split a nucleus, however, several million electronvolts are needed (MeV), and to break open a particle this figure rises to thousands of millions of electronvolts (GeV).

For this research to prove fruitful, it is necessary to build accelerators which have increasingly large nominal energies. In the present state of the art, however, there is no known method of increasing the energy of an accelerator without also increasing its over-all dimensions. As a result, accelerators have soared to gigantic proportions. With the energy levels thus achieved, a whole new world of phenomena has been opened up, shattering earlier concepts about matter: previously unknown particle states have been discovered, new forces controlling the mutual behaviour of particles have been revealed and certain intuitive ideas about symmetry in nature have been overthrown.

The work carried out at the large proton synchrotrons, namely those at CERN (28 GeV), Brookhaven, USA (33 GeV), and Serpukhov, USSR (78 GeV), has resulted in the discovery of 160 particles, apparently all elementary. Physicists are now working on the relationships between these particles and attempting to classify them. For this, however, more information is needed about the properties of each particle, in order to explain their internal relationships. To do so, even higher energies are needed. This explains why a 200 GeV proton synchrotron is now being built at Batavia, USA, and Europe is planning to build a 300 GeV machine.

One way of getting a glimpse of what occurs at much higher energies is by making two particle beams collide head-on. In an accelerator, when particles reach the desired energy they are directed onto a target and collide with its stationary nuclei. To conserve momentum, most of the energy given to the accelerated particles is used to project, in a forward direction, the particles which originate from the collision. Only a modest fraction of the acceleration energy is used for the transformation and creation of new particles. The useful energy of the CERN 28 GeV Proton Synchrotron (PS) is only about 7 GeV. The approximate formula used to calculate the useful energy from the nominal energy is:

$$E_U = \sqrt{2E_A}$$

where

$E_U =$ useful energy, in GeV

$E_A =$ acceleration energy, in GeV.

Thus a 300 GeV machine only provides about 24 GeV of useful energy. If, however, particles of the same energy are made to collide head-on, the useful energy is double the acceleration energy. To reach a useful energy of 56 GeV it was decided to construct the intersecting storage rings, using the CERN PS as the injector. To achieve this energy level would normally have required a machine with an energy of about 1700 GeV. Colliding beams do,
however, present the disadvantage that they restrict the field of research to proton-proton interactions.

Construction of the CERN Intersecting Storage Rings was approved by the CERN Council in December 1965. Work started in 1966 on a site made available by France, next to the CERN laboratory which was set up in Switzerland in 1954 (Fig. 1). The Intersecting Storage Rings (ISR) consist of two concentric rings of magnets, 300 m in diameter, in which protons travel in opposite directions. The magnets are housed in a circular underground tunnel some 500 m away from the 28 GeV PS; they are interlaced so as to intersect at eight points, called interaction regions, where the beams can be made to collide.

Protons accelerated in the CERN PS to energies of between 8 and 28 GeV are directed by a fast ejection system into a transfer channel which guides them to the storage rings. They are then directed to one or other of the rings, depending on whether a bending magnet at the fork is switched on or not.

If only one pulse were to be taken from the PS, containing say $10^{12}$ protons, and sent into the ISR, the number of collisions per second occurring where the beams meet in the interaction regions would be unacceptably small. Experimenters are used to several hundred thousand collisions per second with hydrogen targets. To increase the intensity of the orbiting beams so that they each contain $4 \times 10^{16}$ protons, a large number of successive pulses from the PS can be stacked by means of a radio-frequency system. This moves the particles from their injection orbit along the inner wall of the vacuum chamber to an orbit nearer to the outside; the injection orbit is then free to receive the next pulse which, in turn, is accelerated and moved to an orbit only a fraction of a millimetre from where the first pulse was before. This process is repeated until a beam 70 mm wide is obtained. About an hour is needed to fill each ring. The protons can circulate in the rings for a whole day before the latter need refilling.

![Fig. 1 Aerial view of CERN, May 1970.](image-url)
The need to build up intense proton beams and keep them orbiting in their rings for many hours poses very different problems from those met with in classical accelerators, where the beam is in and out of the machine in about a second.

The magnet system has to provide a very precise field configuration to guide and focus the beams; consequently, its positioning must be very accurate. The requirements placed on the vacuum system are particularly severe; the aim is to retain the beams in the rings for many millions of turns at a speed near that of light without a serious loss in intensity, i.e. in the number of orbiting protons. Not only must the guide fields be very precise in themselves and accurately positioned, but also the number of residual gas molecules that the beams meet must be very small to avoid scattering protons out of the beams. In the CERN PS, pressures of about $10^{-6}$ torr are adequate; in the ISR this figure has to be lowered to $10^{-3}$ torr and locally, in the interaction regions, to $10^{-11}$ torr.

It is expected that the ISR project, which was begun in 1966, will be completed by the scheduled date of 1971.

2. GEOMETRY OF THE ISR

Altogether, the 800 MeV booster, the 28 GeV PS, the transfer tunnels and the two rings of the ISR comprise about 4 km of tunnelling, in which some two thousand components have to be positioned in relation to each other with an accuracy of a tenth of a millimetre. It is easier to find the methods and design the instruments to overcome the problems that arise than to think of a name for this new technique, which is somewhere between metrology and geodesy. The terms 'microgeodesy' and 'macrometrology' may sound romantic but the expression "accelerator metrology", used at CERN, combines the idea of extreme precision and the exceptional sizes of these machines.

Although four different solutions were used for aligning the magnets in the booster, 28 GeV PS, transfer tunnels and storage rings, the objective was the same, namely to enable accelerated particles to orbit in a magnetic field with minimum losses, so that the "intensity" of the beam in the accelerator and "luminosity" (number of particle interactions per second in the storage rings) are maintained.

Most of the present paper is devoted to the geodetic approach to the problem of positioning the ISR components. In the conclusion, a comparison is made with the solutions used for the 28 GeV PS and 800 MeV booster, and an approach is made to the problems which will be posed by the future 300 GeV machine.

It should be stressed that the advent of computers has profoundly altered the methods used. Recent discoveries in optics, however, have proved to be of very little help for the positioning of accelerator components. For example, the laser beam has to travel through an evacuated pipe if accuracy is to be maintained; similarly, inertia guidance techniques have proved difficult to apply and adapt for this purpose. Although desirable, highly precise measurements over very large distances are not absolutely essential. The relative position of two points located 3 km apart on the same diameter of a 300 GeV synchrotron is not critical, but the relative position of adjacent components such as magnets or lenses determines how well the accelerator will operate. Although these components weigh several tons, the relative accuracy in locating a magnet in relation to the adjacent ones must be
at least $10^{-7}$ of the distance between the sockets mounted at each end of the magnets. These tolerances are determined by the characteristics of the closed orbit.

The survey network of the 28 GeV PS consists of nine monuments, one in the centre of the ring and eight around the perimeter. The over-all stability of the monuments has been very good: accurate measurements of the distances and angles have shown that the movement does not exceed two tenths of a millimetre a year. This stability was confirmed by measurements on the centre monument by means of Marussi-type horizontal pendulums over the period 24 August 1965 to 13 February 1968, independently of any triangulation (Fig. 2).

Fig. 2 Movement detected in the monument at the centre of the PS, according to measurements with horizontal pendulums over the period 24 August 1965 to 13 February 1968.
Measurements, made each year during the long shut-down of the accelerator to check the position of the synchrotron magnets, showed vectors of radial and vertical movement of over 2 mm. This proves that the stability of the survey monuments is at least one order of magnitude better than that of the accelerator's components.

As the accelerator diameters increase, the more necessary it becomes to divide the circumference into a large number of elementary figures, so that the synchrotron components can be positioned and checked inside the basic figure selected without the need for a completely new survey. Inside each figure it is not difficult to meet the required accuracy of 1 in 10^6 to 1 in 10^7, provided the measurements are made over short distances and numerous checks are made. The difficulty lies in choosing the elementary figures, triangles and braced quadrilaterals as well as their dimensions, in order to maintain the required accuracy and at the same time carry out overall positioning of the accelerator in a reasonably short time. Once this overall survey has been completed, all of the accelerator components can be positioned in relation to the elementary figures. Repositioning of the components has been carried out only twice in the whole of the ten years' existence of the 28 GeV PS. This method also gives the operating staff the chance to juggle with the orbits knowing that the measurements can always indicate the limits within which such gymnastics are possible.

3. LAYING OUT THE ISR. LINKING UP WITH THE 28 GEV ACCELERATOR

The problems raised by the construction of the storage rings were different from those of conventional accelerators in that the former were to be an extension to an already existing accelerator. In the PS system of coordinates, the location of the ISR depended on the position of the PS itself. In addition, survey work was made difficult by the narrowness of the site. A ring with an outside diameter of 316 m had to be located on a site barely 400 m wide; furthermore, sufficient space had to be left for a road on each side of the ring and, on the south side, for excavations to a depth of 25 m.

These deep excavations caused a change in the natural stability of the ground and the movements induced by the disruption of the mechanical equilibrium were further increased by disturbances in the hydro-geological equilibrium. A primary triangulation (Fig. 3) was made starting from reference points P0, P5 and P6, which belong to the survey system of the 28 GeV PS. This isosceles triangle, which is 530 m away from the centre of the ISR, is small in comparison with the overall triangulation. To make the extension of this triangle and minimize the scale error of the new triangulation, a 450 m long base was measured. To enable the base measurements to be made as often as required, 10 thermally insulated concrete survey monuments were deeply embedded in the molasse along the northern boundary of the site in a position where they would not be interfered with during construction work. An automatic distinvar was used for measuring the 450 m distance between pillars B_2 and B_3, with an accuracy of 0.02 x √5 = 0.06 mm. As the distances P5P6 and P6P0 were also measured with the same accuracy, homogeneity of the length measurements was respected over the whole triangulation. The azimuth of the whole figure is related to the bearing of P0P5 and P0P6. All the angles of the primary triangulation with 16 sets were measured with a Wild T3 theodolite. The adjustment of the triangulation was processed by least squares on the CDC 6600 CERN computer, using the variation of coordinates method.
From the main framework, detailed survey points were established, as required, terminating in the marks on the axis of the tunnel (Fig. 4) and in the foundation of the walls of the rings, and in those of the transfer tunnels -- a total of about 160 triangulated points. The triangulation was re-made as often as required to ensure self-consistency of the measurements. For example, points close to excavations, such as $S_1$ and $S_2$, were subjected to a horizontal displacement of the order of 2 cm during civil engineering work. Each subsequent measurement of the main framework gave slightly different coordinates, so complete sets of measurements and calculations had to be made for the detailed survey points. As a result of the numerous re-surveys, the self-consistency of the coordinates of the markers was kept within $\pm 1.5$ mm throughout the entire perimeter of the ring. The precision levelling was done with Wild N3 levels.

When construction of the ring tunnel starting from Hall I$_4$ reached Hall I$_1$, the survey monuments built in this Hall for the accelerator metrology were connected with the main
Fig. 5 Mekometer. CERN prototype.

Fig. 6 Mekometer. Seen from above.

Fig. 7 Mekometer. Variable light path.
framework in coordinates as well as in azimuth. To do this, the first quadrilateral 11.12.87.88 of the internal system of the tunnel was included in the main framework. This measurement was made in May 1969.

The Survey Group Instrument Workshop had set itself the task of completing the first prototype mekometer (Figs. 5, 6 and 7) by the above date, in order to be able to measure directly all the lengths already obtained by triangulation and thus make a trilateration to check them. The mekometer is an instrument designed to measure distances. The measuring process consists of determining the phase of modulated light returned from a reflector (placed at one end of the line to be measured) back to the instrument. Elliptical polarization modulation is used, so that linear electro-optic crystals of the KDP type may be used for both modulation and demodulation. A modulating cavity is excited into strong oscillations at frequencies near to 500 MHz for a duration of 40 μsec by pulsing the ceramic disc seal of a triode valve. It develops several thousand volts of modulating field across each crystal. This instrument was designed and developed by Froome and Bradsell at the National Physical Laboratory, Teddington. (See Fig. 8.) The prototype built at CERN was ready to be used in May 1969. It had been tested on the 600 m long base, the tops of the monuments being situated in a horizontal plane. All the distances were measured many times by increments of 50 m up to 600 m with the CERN mekometer, in varying atmospheric conditions. The results were compared with the values obtained with the distinvar. The accuracy proved to be independent of the measured length, in the 50 m to 600 m range. The mean-square error was 0.3 mm.

On 16 May 1969, the Metrology Group's specialist for the electronics of the mekometer was killed in a helicopter crash. Froome and Bradsell were therefore asked to come to CERN.
to make the planned trilateration measurements, using their own mekometer: the CERN prototype had to be readjusted and circumstances prevented us from doing this. Measurements were completed in one day, in sunny weather, only once in each direction and without any return measurements. Figure 9 shows the deviation between the lengths as given by the mekometer and the same lengths obtained from the triangulation. It will be seen that the horizontal distance $B_4B_7$ (100 m) was still within the limits previously obtained. The other values did not, however, confirm this accuracy, and the more the measurements were made out of the horizontal, the more the error appeared to increase. The discrepancies were due not to the mekometer itself, but probably to its support.

Triangulation measurements were therefore used to determine the coordinates of monuments 11, 12, 87, 88, which served as the start for the ISR metrology. The estimated accuracy of these coordinates is ±1.5 mm. Checks were made in spring 1970, when it was a straightforward operation to connect the 28 GeV PS directly with the reference points in the ISR through the transfer tunnels TT1 and TT2.

In tunnel TT1, the deviation between the theoretical value and the measurement is only 1 mm and, in tunnel TT2 it is 3 mm. These are the results of the preliminary measurements, and the deviations should be even less once the final adjustments have been made. Although such an accuracy in connecting the ISR to the 28 GeV PS is not really essential for correct operation, an effort was made to get as close as possible to the theoretical coordinates to ensure that the corrections to the transfer beams would be as small as possible.

![Diagram](image)

**Fig. 9** Comparison between the results obtained by triangulation and those obtained by mekometer measurements (in mm).
4. ACCELERATOR METROLOGY

Although this triangulation, a combined set of angular and distance measurements, gave an accuracy of 1.5 mm for the purpose of the civil engineering work, the accuracy required for positioning the scientific equipment is of the order of a tenth of a millimetre. This means that the individual measurements have to be made to within ten or twenty microns.

The entire metrology of the ISR is based solely on distance measurements, the method of which has gradually improved over the last ten years, due to a general increase in the size of engineering structures and scientific equipment, but the accuracy requirements have not changed; if anything, they have become more stringent.

A 4 m invar rule is the basic standard against which all length measurements are referred. The calibration bench, which was installed in 1958 in one of the radial tunnels of the 28 GeV PS, cannot be reached when the synchrotron is in use. To make the bench completely independent, it is now being transferred to a new tunnel specially designed to accommodate it. The ambient temperature will be controlled to within one degree and the whole equipment, with the exception of the 4 m rule and read-off microscopes, will be entirely modified so that it is quicker to use, but without any alteration in its accuracy. A distance of 50 m can be calibrated with an accuracy of 2 μ.

The automatic distinvar is used to transport the length calibrated on the base to the points to be measured. Over a 50 m distance the distinvar's accuracy is 14.7 μ -- the r.m.s. value of 1000 measurements made on the bench. The time required for one measurement is about 2 minutes. The result can be read from a counter, a digital voltmeter, recorded on tape or fed directly into a computer.

The distinvar has been described in an article in the December 1965 issue of "Géomètre". The principle of the instrument is still the same, but it has been substantially modified to make it fully automatic, more accurate and quicker to operate (see Figs. 10 and 11).

Fig. 10 Automatic distinvar. Measurement equipment and fixed point.
ISR metrology is based on a chain of braced quadrilaterals, at the corners of which survey monuments have been deeply embedded in the molasse. As the tension exerted by the wire of the distinvar is applied directly to the pillars, the latter have been designed to keep distortion below 0.01 mm. In the top of each monument there is a socket, with a high-precision 30 mm bore, located in a pair of eccentrics in such a manner that it can occupy any position within a radius of 20 mm (Fig. 12). The centre of the bore can be located with an accuracy of 0.02 mm by means of a single device, which can be fitted to any of the sockets (Figs. 13 and 14). This is obviously a cheaper solution than to have an adjustable system on each of the 64 monuments. Figure 15 shows all the monuments used for the metrology of the transfer tunnels and the ISR. In the latter, the chain is formed of 32 braced quadrilaterals.

The six lengths of each braced quadrilateral are measured with the distinvar (Fig. 16). The wires are calibrated on the bench before and after each measurement. All the monuments are now erected.

Whenever a triangulation is made, the sum of the three angles must be compared with the correct value, 180° plus the spherical error; during trilateration it is necessary to ensure that the relation between the six lengths of a braced quadri-
lateral is satisfied. More than 100 braced quadrilaterals have been measured and the relation between the six lengths is satisfied with an error less than 0.06 mm ± 0.05.

Adjustment of the 32 braced quadrilateral chain is by least squares using the coordinate variation method. As the figure is a repetition of the same quadrilateral 32 times, a system of polar coordinates was chosen using the imaginary centre of the rings as the origin of the coordinates. In this case, we used as coordinates for the approximate network the theoretical coordinates computed from the values given by the physicists. The unknowns are, for each point, two rectangular vectors, one of which is radial and the other transverse. The vectors fix the position of the computed point in relation to its theoretical position. There are 160 observation equations, one for each measured length, and 128 unknowns. The observation equation is as follows:

\[ d_{lu2} = (dr_2 \sin \theta_2 + dt_2 \cos \theta_2) - (dr_1 \sin \theta_1 + dt_1 \cos \theta_1) \]

where

\[ d_{lu2} = \text{measured length minus theoretical length between 1 and 2.} \]
\[ dr_1, dr_2 = \text{radial deviation at points 1 and 2.} \]
\[ dt_1, dt_2 = \text{transverse deviation at points 1 and 2.} \]
\[ \theta_1, \theta_2 = \text{angle between the straight line 12 and the direction of \( dt \) at point 1 and point 2 (Fig. 17).} \]

The solution of the least squares is achieved by making

\[ \sum_{i=1}^{160} \left( d_{lu2} - \left[ (dr_2 \sin \theta_2 + dt_2 \cos \theta_2) - (dr_1 \sin \theta_1 + dt_1 \cos \theta_1) \right] \right)^2 \]

minimum.

The result of the adjustment gives directly the values by which the bores must be displaced to bring them into their theoretical position, thus enabling the "theoretical machine" to be constructed.
Fig. 16 Reference braced quadrilaterals in octant 5.

Fig. 17 Observation equation.

Fig. 18 Positioning of magnets in a braced quadrilateral.
The use of polar coordinates implies that the matrix of the coefficients is the exact replica of a single sub-matrix repeated 32 times along the diagonal. Since the theoretical network has been chosen as the approximate network, the position of any pillar can be calculated before the measurement of the chain has been completed. Consequently, installation and alignment of the magnets in the completed parts of the tunnel could be done a long time before the latter was finished. This obviously assisted over-all planning. The ISR tunnel has now been completed and the 64 monuments erected and equipped; all the 160 length measurements have been carried out and the first general adjustment is in progress.

The magnets, in the top of which are two reference sockets, are positioned inside a braced quadrilateral (Fig. 18). Each magnet is supported by three jacks, which provide radial, tangential and vertical movements. As each magnet is brought into the tunnel it is placed within a few millimetres of its final position, and is then levelled to its theoretical height. The socket which is situated above the two jacks is positioned by measuring, with the distinvar, the distances from two monuments of the reference braced quadrilateral (Figs. 19, 20, 21 and 22). It is possible to make two additional checks from the other corners of the quadrilateral. One reference socket per magnet is thus positioned inside the same quadrilateral. A nylon wire is then stretched between the sockets, already positioned with the invar wire, of two adjacent magnets, and a graduated plate is placed on the socket of the magnet. This extremity of the magnet, which rests on the single jack, is moved radially until the nylon wire bisects the target on the plate to give the desired curvature (Fig. 23).

This pointing provides an accuracy of ±0.05 mm; the measurement can be done very quickly, in a matter of seconds. If the displacement to be given to a magnet is greater than 1 mm, the first reference socket has to be repositioned and a new alignment made for

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Fig. 19 ISR tunnel. Alignment of a magnet from two survey monuments.
Fig. 20  Alignment of a magnet from survey monuments.

Fig. 21  Distinvar on the adjustable reference socket of a survey monument.
the second. Generally, only two adjustments are needed to obtain the desired accuracy. This method of aligning the magnets is not only quick, but also provides the possibility of making a very smooth magnet orbit. Inside a braced quadrilateral, the sockets of each magnet are located by referring to the monuments, using the same processes and with the same accuracy; the intermediate sockets are aligned within the adjacent ones, which enables a smooth curve to be obtained. As can be seen from Fig. 8, the additional measurements made on the magnets in the middle of the quadrilateral were taken from the four corners, and they ensure that the system is uniform throughout.

A very large number of components, including accelerator cavities, pick-up electrodes, lenses, etc., have to be installed between the magnets. These components are aligned with the magnet sockets situated on each side of the straight section where the component is to be installed.
Fig. 24 Basic survey configuration in curved section TTL.
The problems of positioning are different in the transfer tunnels (TT1, TT2, TT2a, TT3) connecting the 28 GeV PS with the ISR. Accelerated particles pass through only once per pulse; therefore, if one of the components is misaligned, there can be no cumulative effect. Moreover, adjustments can be made by varying the magnetic field intensity of one or several of the 125 bending magnets to correct any positioning error. The same tolerances as in the rest of the machine are sought in order to give the beam transfer system maximum flexibility.

The geometry of the transfer tunnels is no different from that required for the beams in the experimental halls. It consists of long straight sections followed by curved ones, occasionally combined with variations in slope, which means that certain delicate three-dimensional operations must be carried out (Fig. 24).

The cross-section of the transfer tunnels is much smaller than that of the rings; in particular, the width is only a third of that of the ISR; this gives rise to problems in the curved sections, where the radius of curvature is the same as that of the rings themselves.

The braced quadrilateral has been retained as the elementary reference figure, but as the tunnel is narrow, it is physically impossible to measure the side of the quadrilateral facing the centre of curvature. Consequently a search was made for a figure which would enable three sockets to be aligned. This alignment gives an additional observation equation for each quadrilateral and thus enables the figure to be adjusted by least squares. One of the difficulties lay in connecting the straight sections with the curved sections. To maintain uniformity and accuracy, the angles were constructed solely by measuring lengths.

In view of the size of the tunnel it was impossible to erect a double row of monuments. There is consequently only one row, and it has been placed in the beam axis. The monuments are embedded in the tunnel's foundations. The other reference sockets are mounted on brackets set into the inner wall of the tunnel. The dimensions of the figures were calculated on the basis of the geometry (i.e. the need to have three holes aligned) and were determined by the apparatus to be installed between the monuments. The reference sockets are mounted in the same system of eccentrics as that used for the ISR.

To position the scientific equipment in the straight sections of the transfer tunnels, only the centre row of monuments need be used. In tunnel TT2, the straight alignment is 300 m long and a monument was erected every 27.69 m. The first monument in the alignment was coordinated directly from the reference points on the magnets of the synchrotron. Three hundred metres from that point, at the entrance to the ISR, the last pillar was triangulated from the survey monuments of the rings. The preliminary positioning of the reference sockets was done with the help of a theodolite, for measuring the angles, and the distinvar for measuring the distances.

Various methods were used to ensure that the alignment was within the required tolerances. To maintain an accuracy of a tenth of a millimetre it was decided to abandon the use of a theodolite or a laser beam; in view of the temperature gradients in the tunnel and air turbulence, a measurement accuracy greater than 1 mm is not possible over distances of this magnitude. A test was made over 55.38 m, the distance between three monuments,
with a helium-neon laser beam focused by a lens at the exit of the laser to obtain a virtually parallel beam. The beam was received on a target consisting of four photoelectric cells mounted in a Taylor and Hobson sphere; two of the cells are horizontal and the remaining two vertical. They act as a differential cell. The laser beam travelled through an evacuated pipe. The vacuum was between $10^{-2}$ and $10^{-3}$ torr. The pointing on the target situated 55.58 m away from the laser stayed within ±0.02 mm, and the intermediate target at 27.69 m could be aligned with the same accuracy.

Although the accuracy was remarkable, this method of measurement was very soon found to be most inconvenient, and it was impossible to install and align the magnets and lenses under the vacuum tube.

At the same time, another method was being tried out, by modifying the equipment used for aligning the intermediate sockets of the magnets in the rings. A nylon wire is stretched between three monuments practically to breaking point in order to obtain a straight line. The reference socket of the centre monument is moved until it is situated under the wire. The equipment constructed for this purpose is of very simple design, but the measurements can be made quickly and pointing accuracy is 0.05 mm. To construct the straight line, one has first to choose the direction and then proceed step by step, three pillars at a time. A large number of measurements were made to check that the deviations from the straight line were less than a tenth of a millimetre. Once the sockets have been aligned it is easy to position the magnets and lenses between the monuments by this method.

The level of the ISR floor was set 12 m above that of the 28 GeV synchrotron to avoid excessive excavation work owing to the topography of the site. The difference in level had to be recovered at certain points; this was done partly at the synchrotron exit, but mainly at the ISR entrance. Not only did this lead to problems of levelling, but a solution had to be found for measuring distances in non-horizontal planes; hitherto, in accelerator metrology, lengths had been measured only in a horizontal plane. It even proved necessary to measure the corrections which had to be made to the lengths. The measurements were made in a test area where the height of one of the sockets could be adjusted, whilst the other remained fixed. This empirical method had to be used, since the influence of the sagging of the wire on the length could not be determined with sufficient accuracy; furthermore, it was impossible to calculate the corrections to the length due to the effect of the sagging of the wire on the behaviour of the equipment.

5. COMPARISON OF THE DIFFERENT GEOMETRIES USED IN THE CERN COMPLEX

Before making a comparative analysis of the geometry of the 28 GeV PS and that of the ISR it will be interesting to describe briefly the method to be used for aligning the 800 MeV booster synchrotron.

As part of the 28 GeV PS improvements programme, it was decided in 1964 to increase the number of cycles during which the protons would be accelerated, as well as the number of protons accelerated during each cycle. To do this, it was decided to construct an 800 MeV booster between the 50 MeV linac and the 28 GeV PS. The booster would be made of four superimposed rings; the protons would first be accelerated and then injected into the PS. The aim is to accelerate $3 \times 10^{12}$ protons per second in the initial stage, and
eventually increase this figure to $10^{13}$ protons per second. This increase in synchrotron intensity will improve the luminosity and shorten the ring filling time.

The radius chosen for the booster was 25 m, the inside width of the tunnel being 4 m. There are 32 magnets and 16 quadrupole lens triplets which have to be aligned with a greater tolerance than that laid down for the components of the ISR (Fig. 25).

A novel solution was found for the metrology of the booster, which was still based on the principle of measuring only the lengths. As the radius of the orbit was set at 25 m it was felt unnecessary to break down the 157 m of circumference into elementary figures; the addition of errors due to the cumulative nature of the operations stayed within the tolerances, or at least could be brought within these limits after adjustment and correction.

Only one monument was erected in the injection hall, which is also the beam ejection hall. The monument is positioned by measuring distances and angles in relation to the P₁ and P₄ pillars of the synchrotron. Furthermore, a reference bore is mounted on the inside wall of the hall to provide a bearing when the shielding walls preclude measurement from P₁ and P₄. The length measured by the distinvar from the bore on the monument to the one on the wall acts as a base for the construction of the figure.

The two magnets on each side of this line will be positioned by measuring the lengths; they will serve as the starting points for a double traverse which will be made directly on the reference sockets of the magnets.

The adjustment will indicate the displacements to be applied to the magnets to locate them in their theoretical position. Levelling will be made from magnet to magnet with the hall monument as a reference.

The above method is akin to the solutions used for the transfer tunnels and storage rings, and is an example of the versatility and varied nature of the equipment used. In each case, it was adapted to the structure and dimensions of the accelerators.

In the case of the 28 GeV PS, the reference figure chosen in 1954 was a regular octagon with a central point (Fig. 26). Eight radial tunnels were used to measure the radii. Measurements were also made of the angles at the centre and at all the vertices. The figure was a difficult one to measure, eight radii of 105.85 m, eight sides 81 m long, and 24 angles; on the other hand, the adjustment was very simple. The magnets were positioned from the pillar of the octagon by measuring the distance with an invar wire equipped with two scales for effecting the pointing under the microscope, and the angles were measured with a Wild T3 theodolite. These measurements were very satisfactory, as was proved by the fact that the synchrotron was able to operate for the first time on 24 November 1959, and no orbital defect gave grounds for suspecting any misalignment.

However, as soon as the first check measurements were made, a number of difficulties came to light; these had been predicted when the metrology was being carried out but they became critical on account of the short time available for the measurements during the shut-down. They were as follows:

i) the difficulty of handling the 105.85 m invar wires in the radial tunnels;

ii) the difficulty (and subsequent impossibility) of measuring in one stretch the 81 m between each octagon pillar;
Fig. 25  Basic survey configuration for the 800 MeV booster.
Fig. 26 Basic survey configuration for the 28 GeV Proton Synchrotron.
iii) the unduly long time required to measure the lengths using refined but nevertheless conventional equipment such as knife-edge pulleys and microscope readings of the scales;

iv) the fact that, in spite of all precautions, the theodolite could not measure angles with an accuracy better than one sexagesimal second, owing to the temperature gradients and air turbulence in the tunnels.

One of the merits of the distinvar was that, right from the start, the time taken to measure lengths was cut by a factor of 10; measurement accuracy remained unaffected. It now takes just one day to measure the distances from the pillars to the 100 magnets of the synchrotron.

As the octagon cannot be altered and the tunnel is gradually becoming more encumbered with equipment, angular measurements are an absolute necessity, and it is still necessary to spend a whole week on theodolite measurements. It can readily be seen how very much longer it takes to measure the angles than the distances. Furthermore, the distance measurements are absolutely reliable because the wires can be calibrated as frequently as desired. The accuracy obtained in the measurements with a 50 m wire is 14.7 μ. This test, based on a thousand measurements, was carried out on the calibration bench, under microscopes, using an automatic distinvar. Fifty metres proved to be the maximum operating length for the invar wire with normal reliability and rapidity.

These were, therefore, the reasons for using length measurements throughout the accelerator metrology. In each case the best reference figure should be sought which enables the angles to be constructed with distance measurements. A correct balance must also be found between the dimensions of the elementary figures and their number, to avoid the accumulation of errors when a series of cumulative operations has to be carried out.

At its computer centre, CERN has a CDC 6600 and a CDC 6400. These computers provide directly the corrections to the measurements in order to obtain the theoretical figures.

There are, however, matters which must be left to the imagination, namely the choice of the shape of the figures and the breakdown of the over-all figure into fractional elements, within which it will be easy to install the accelerator components.

6. CONCLUSION: SOME THOUGHTS ON THE METROLOGY TO USE FOR A 300 GeV SYNCHROTRON

The 300 GeV synchrotron will have a radius of 1456 m, i.e. a circumference of nearly 10 km (Fig. 27). The cross-section of the tunnel in which the accelerator components will be installed is about 4.30 m.

Two sockets will be located at intervals of 95 m on the same radius, on brackets embedded in the rock, one on the inner wall and the other on the outer wall of the tunnel. The figure is chosen in such a way as to respect the synchrotron's periodicity of six, and to enable a straight alignment to be made between three successive sockets: two on the outside wall and the intermediate one on the inner wall (Fig. 28). In this way, there will be distances of 95 m and 190 m which will need to be measured with the mekometer. A second prototype is at present being designed at CERN, the desired accuracy of which is ±0.15 mm for a length of 200 m. According to the results obtained with the first prototype built at CERN the improvement appears to be approximately twofold, which seems quite
feasible. The over-all geometrical figure thus determined will then be adjusted. The components of the accelerator can then be installed inside the pseudo-quadrilaterals. This can be done by making measurements with the invar wire for the distances, using a nylon wire for smoothing the curvature, by steps, from one magnet to the next (we call this the "little train method") and by closure every 95 m on the sockets.

The principle used is simply an extrapolation of the measurement method developed for the curved sections of the transfer tunnels connecting the 28 GeV PS to the ISR. Hence our special interest in this particular part of the geometry, which is at present being carried out.

The wealth of equipment which is now available for accelerator metrology will have probably been still further increased before the 300 GeV PS has finally been aligned. Even at the present time, the methods already developed by the CERN Metrology Group enable the tolerances to be met.
A large number of parameters affect the calculation of the half apertures of the magnet components. Two of these parameters are dependent on accelerator metrology. One is a static parameter, depending on the stability of the foundation, and therefore on the rock mechanics. It is, however, difficult to calculate in advance the vertical and horizontal displacement resulting from slight ground movements. The other parameter is dynamic and depends on the method of measurement and the degree of accuracy achieved. By a quadratic combination of these two values we obtain the one used for the calculations.

In the 28 GeV PS the static element has been provided by a continuous concrete beam, 628 m long, resting on elastic supports borne by 80 pillars embedded in the molasse. The dynamics of the measurements are based on an octagon with a central point, and on distance and angle measurement, which is also used for positioning of the magnet.

In the storage rings, the static element is composed of a discontinuous concrete beam bearing on the molasse through special supports, in order to smooth out any possible deformation of the molasse. The dynamics are provided by a chain of braced quadrilaterals which, by adjustment, must coincide with the theoretical figure. For this, only distance measurement is used, and the curvature is smoothed by means of a nylon wire.

As for the booster, the static element is formed by the tunnel which itself rests on the molasse. The dynamic element is simply a monument and a reference mark anchored in the wall. The distance measurements and alignments are performed step by step.

In the transfer tunnels the static element is provided by the tunnels themselves; the molasse in which they have been drilled is generally sound. The dynamics are: either an alignment for the straight sections or a chain of pseudo-quadrilaterals for the curved sections; distance measurements; and the alignment of three points.

The 300 GeV project will incorporate many novel aspects, one of which is the need to select a site whose foundation rock appears to be most uniform and likely to provide the necessary stability for the accelerator. Experience with the 28 GeV PS has shown that, over a period of two to three years, the magnets installed on the concrete beam are ten times less stable than the survey marks of the reference figure.

As far as the 300 GeV accelerator is concerned, any attempt to disregard the advantages of the natural stability of the rock or miss the opportunity to use a varied but unsophisticated geometry would be a serious error of judgement. Increasing the number of correcting elements, certain of which might be used to correct alignment defects, is a costly solution which might limit the freedom to juggle with the closed orbits and could give rise to difficulties when the accelerator is operated.
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