Geodetic Survey and Component Alignment of the Combined Heavy Ion Synchrotron SIS and the Experimental Storage Cooler Ring ESR

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Abstract

On Monday, April 23, 1990, the extention of the existing GSI accelerator in Darmstadt was officially put into scientific service by the German Science Minister Riesenhuber.
For maximum efficiency, the alignment precision of the setup has to lay within some tenth of a millimeter. This paper describes the measurement techniques and instrumentation that enables this accuracy to be reached.

1. Introduction

GSI works on fundamental research in the domain of atom and nuclear physics. It seeks applications of fast heavy ions. These ions are atoms of heavy elements that are electrically charged because one or more of their electrons have been stripped off. The ions of nearly all elements can be accelerated up to 20 % of the speed of light in the 120 m long UNILAC accelerator (UNIversal Linear ACcelerator). This means a kinetic energy of about 20 MeV/u.
The following modules have been added lo the setup (fig. 1):

- Heavy Ion Synchrotron (SIS) (circumference 216 m)
- Experimental Storage Ring ESR (circumference 108 m)
- Experimental Setups and target stations (90 x 50 m)

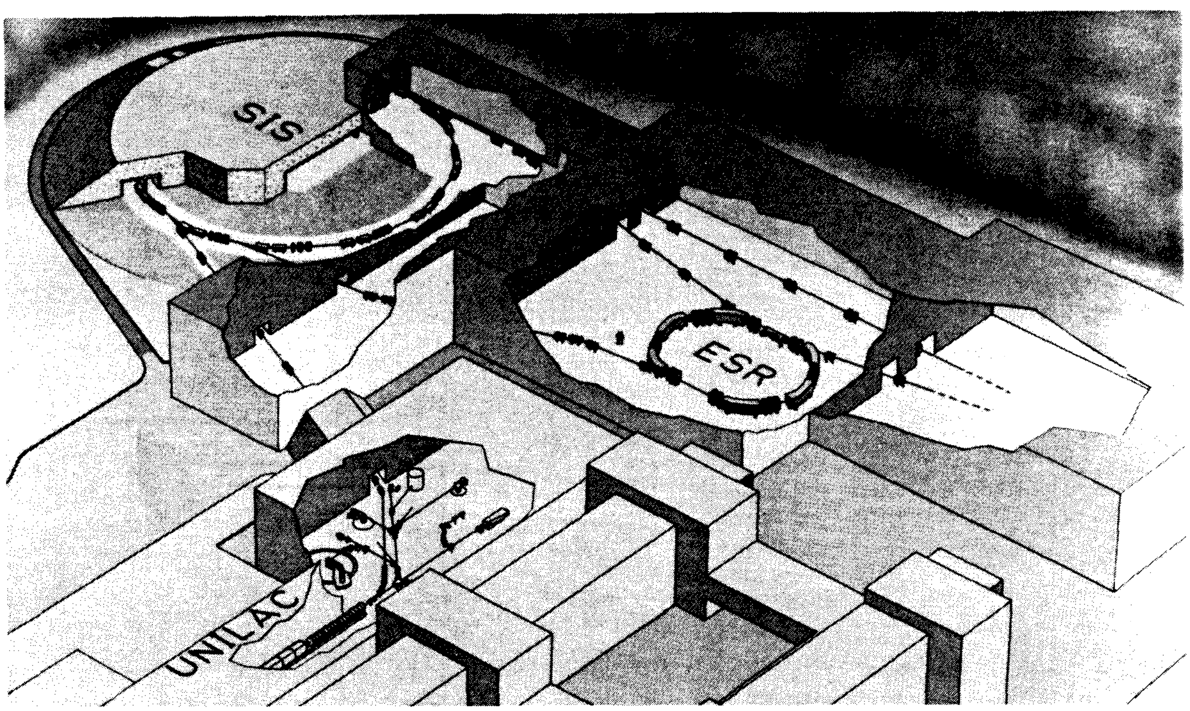

Fig. 1: Break-open view of the GSI complex

Due to SIS the reachable energies of heavy ions are enhanced by 100 times i.e. up to a maximum of approx. 2000 MeV per nucleon, The strongly charged ion beam can be stored in the experimental ring ESR where it will be cooled down, ready for experimental use. For each model a special geodetic network was established with corresponding accuracy: SIS network, ESR network, Experimental hall network, see fig. 2.

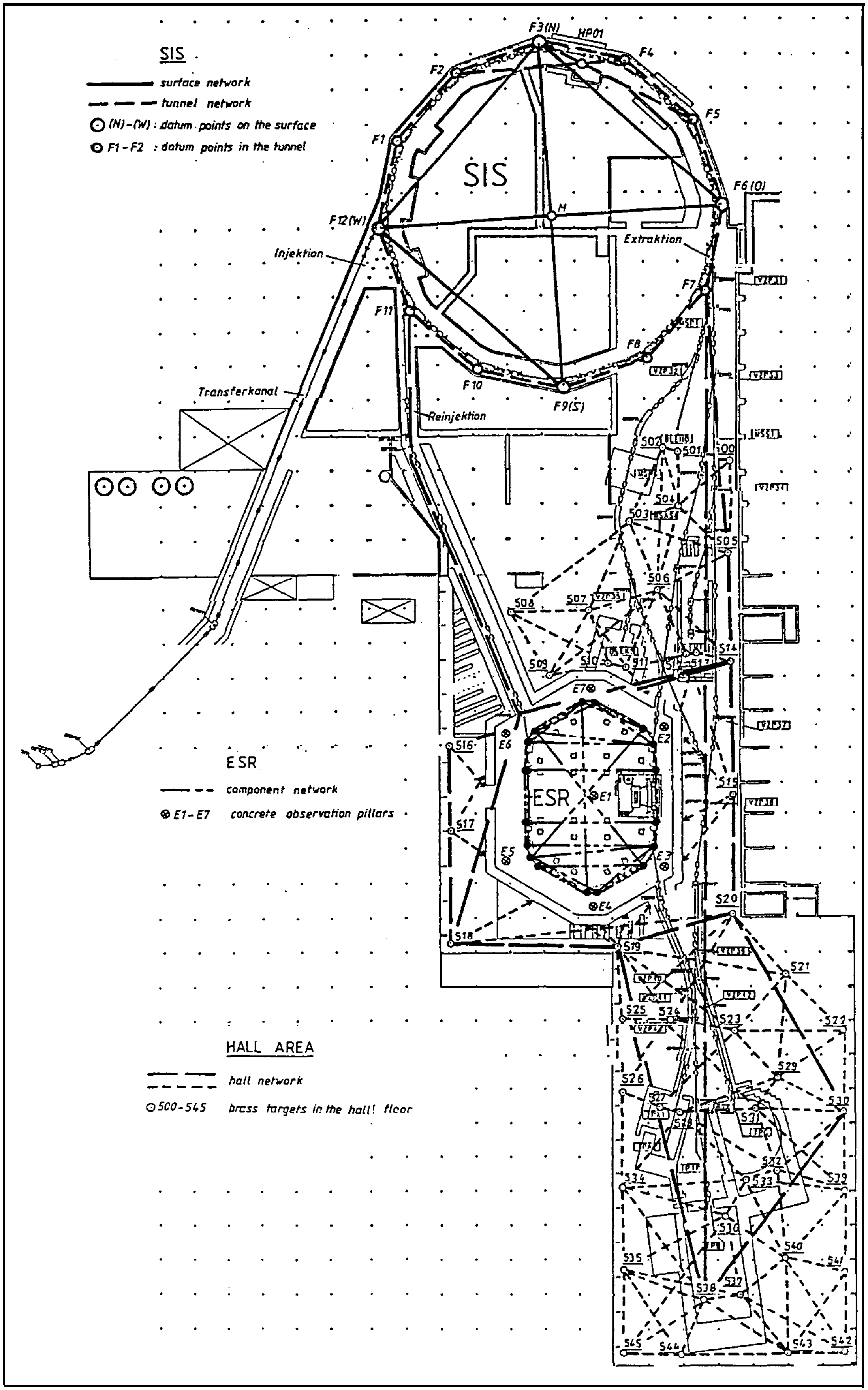

Fig. 2: Geodetic network systems of the new accelerator complex

2. Geodetic Networks of SIS

The synchrotron has a dodecagonal shape. Each corner contains a pair of dipolar beam deflector magnets. The synchrotron building was originally erected at ground level and subsequently covered with high earth shielding, against radiation (neutrons), with a height of 5.6 meters. The tunnel is made out of several concrete segments without separate foundation for each beam relevant component.

These initial conditions together with financial limitations led to a concept of dynamic measurements. The measurement basis is a stable pentagonal field of fixpoints at the ground surface and a tunnel network with its reference pillars located peripherically around the SIS dodecagon (fig. 3). Direct sight between points (0) and (S) is interrupted by the transfer hall in the surface network. Both systems are coupled with vertical sightpipes. The height difference is 8 meters.

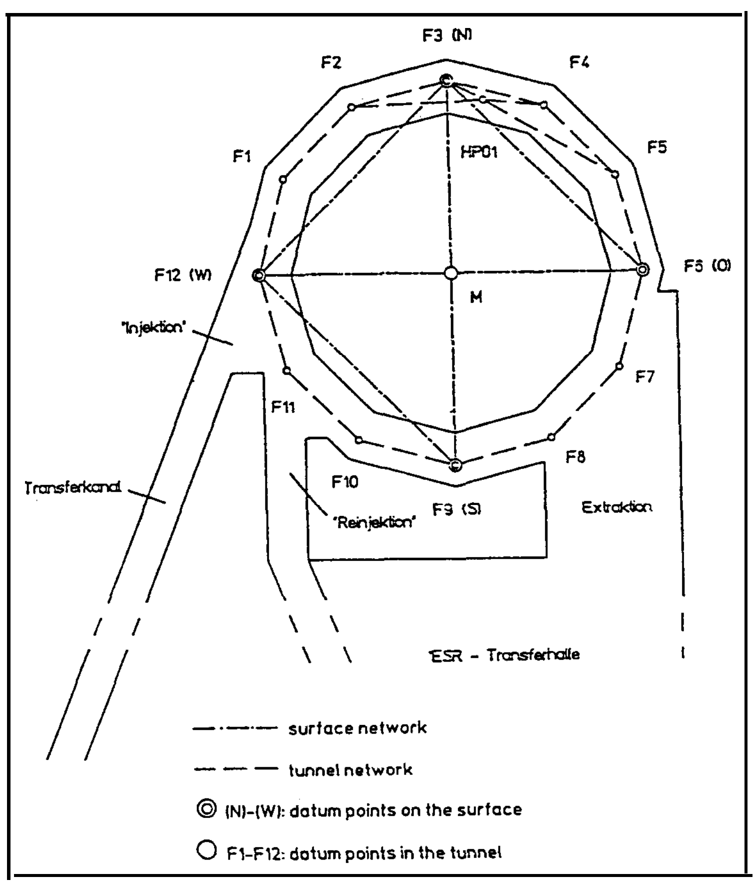

Fig. 3: Overview of surface and underground reference networks

Surface network:
18 directions and 9 distances can be measured directly in the surface network. The centers of the pillars can be defined very accurately because of the nearly equal distances and the even atmospheric conditions in the field of datum points.

The standard deviations of the compensated coordinates in the horizontal plane s_x and s_y lay between 0.01 mm and 0.02 mm (fig. 4). The a priori standard deviations of 0.1 mgon for angular measurements and 0.05 mm for range measurements are confirmed by the compensation calculus and are low as compared to usual values. This fact is an indication for low discrepancy within the network and for the intrinsic accuracy of the measuring instrumentation.

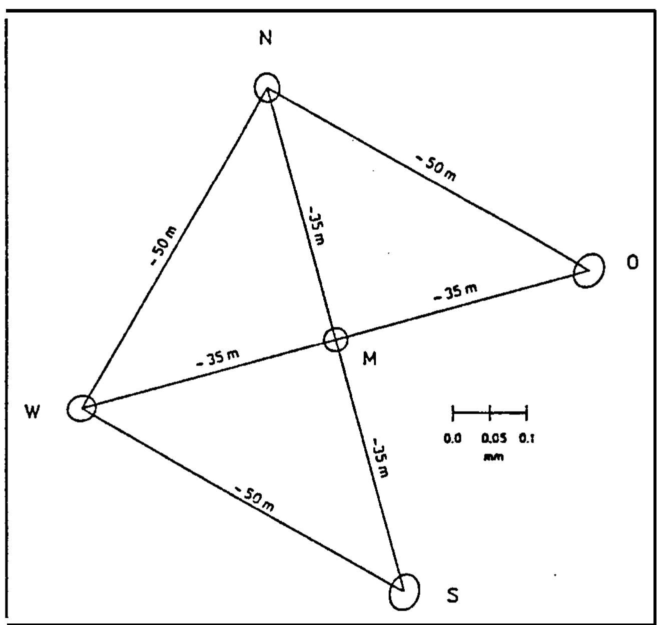

Fig. 4: 95 % confidence ellipses for a typical measurement in the surface network. The scale of the ellipses is strongly magnified for visibility.

Underground network:
The underground or tunnel network is measured as a dodecagonal loop travers (fig. 3). The first batch of angular measurements in the tunnel was disturbed by an accumulation of lateral refractions, which lead to strong angular closure errors (up to 1 cgon). These refractions came from temperature dependent density inhomogenities, mainly in the areas of extraction, injection and reinjection. Temperature gradients of up to 0.6°C/m could be measured in these zones. Periodic forced ventilation of the tunnel during the measurements reduced the closure error from originally 4 - 9 mgon to less than 1.5 mgon. Another source of angular errors could have been optical diffraction occuring because the measuring direction is in a line of sight close to power supply cables.

Optical plumbing

Both networks are coupled by optical plumbing with theodolite. From fig. 5 it can be seen that zenith angle measurements are made from the corresponding pillar centers in the tunnel to the pillar centers of the surface network marked by glass targets. The measuring stations are carefully precentered and levelled. The working conditions allow typical standard deviations of 0.02 mm in optical plumbing on two faces, peak values being 0.07 mm.

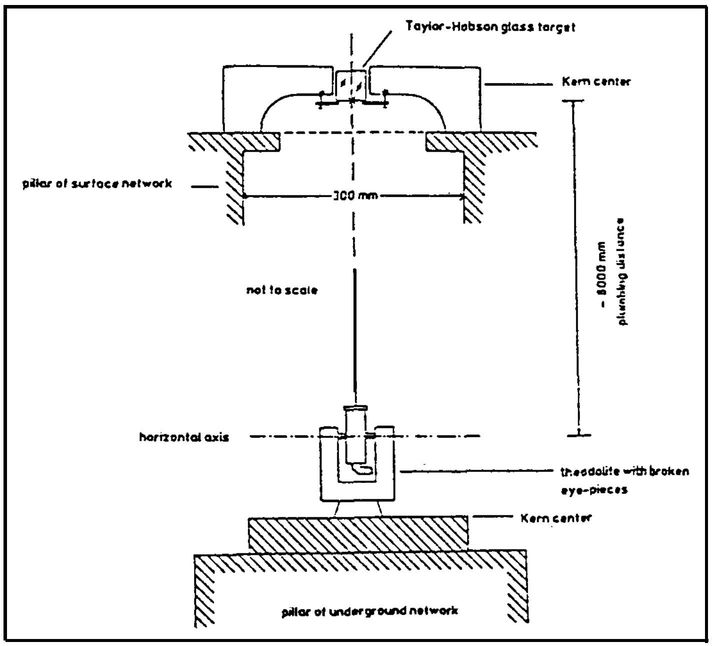

Fig. 5: Optical plumbing scheme

Each of the networks is computed in a separated 3-dimensional compensating calculation. All measured informations:

- surface network (stabilization)
- underground network (relation to SIS)
- optical plumbing (systems coupling)

can be introduced after reduction to the tunnel level in a common 3-dimensional free compensating calculation if one assumes an arbitrary height difference at one of the optical plumbing points. The height differences at the remaining plumbing points are computed from the single network calculations and input into the system as error free data. This method completes the underground measurements with the high precision horizontal data from the surface network. The height reference is taken from the underground network because of its precise levelling connection to UNILAC beamline.

The main use of the connection to the surface network is a horizontal stabilization. In the tunnel network the confidence ellipses have their main axes in the radial direction (fig. 6), where as in the common compensating system the main axes are tangential to the SIS beam line. This is a favorised situation because of the needed high radial precision of the setup (fig. 7).

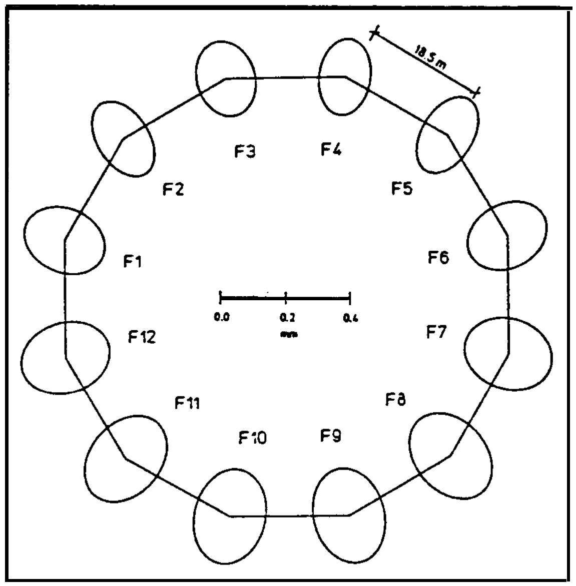

Fig. 6: 95 % confidence ellipses of the tunnel network

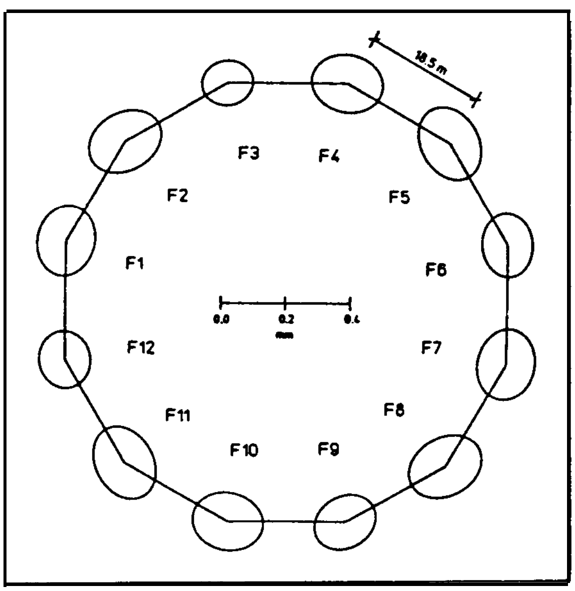

Fig. 7: 95 % confidence ellipses of the combined system, i.e. surface and tunnel network

Because of the established large settlements within parts of the SIS (fig. 8), the network measurements were periodically repeated within 3 months. At the moment not any of the reference points can be regarded as fixed, but their fluctuations measured against the zero measurement can be determined by the calculation of similarity transformations, so one achieves an overview of the variations of the point positions. This is necessary to estimate how long the reference points of the network could be seen as fixed during the adjustment phase and to know about the time that necessitates a repeat of the measurements based on already adjusted points of the SIS.

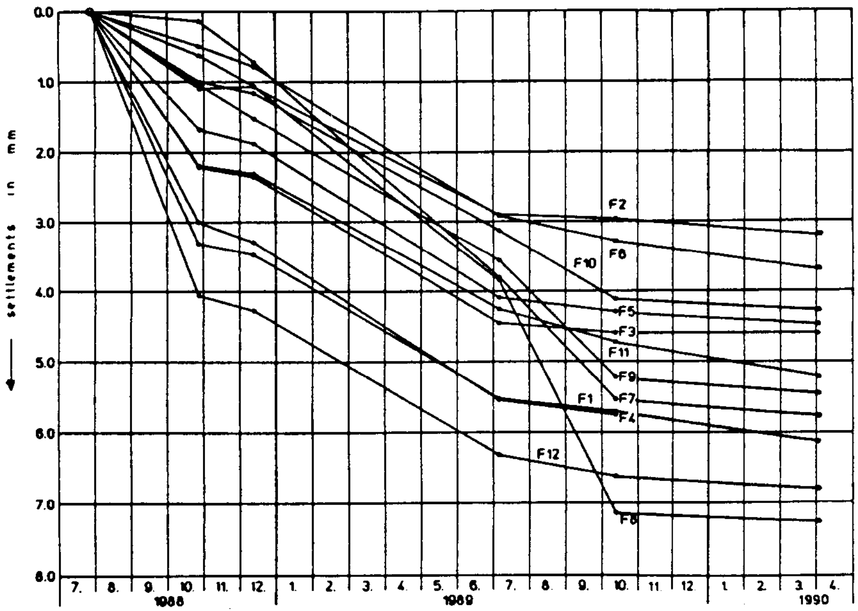

Fig. 8: Time progressing settlement diagram of the SIS loop traverse

3. Alignment of the SIS Components

As measurement principle for the determination of the single SIS component positions the intersection in space with a constant base was chosen. This base is built out of the very precisely determinated coordinates of the fixpoints in the loop traverse. Future adjustments will be made with an on-line 3-dimensional measuring system.
A provisory test of the accuracy of this method has been carried out during the network measurements. Angular observations of the machine reference points following the spatial intersection method have been tested in the overall surface and tunnel network compensating calculation. The resulting standard deviations are 0.05 - 0.20 mm in the radial and vertical direction and up to 0.5 mm longitudinally.
At the moment the real position of the machine does not exceed the zero approximation. The difference between the required absolute and actual positions lie between 1 and 3 mm in the 3 dimensions. The vertical divergencies primarily result from settlements and deformations during the corresponding time period. Differences in the horizontal plane are due to the alignment techniques used conventionally in large scale metrology, e.g. surface cracks, angular- and distance-measurements without self-centering, mechanical plumbing methods for the positioning of the machine components.
The quadrupoles are premounted, adjusted and fixed as triplets on one mount. In the tunnel the dipoles and quadrupole - mounts are standing on 4 adjustment feet each. There is one screw in the center of the feet for vertical correction and for the radial and longitudinal positioning 4 horizontal counter screws can be moved. On every entry and exit point of a magnet 6 ballpoint setscrews and 2 cotterpins are centering a platform with a target sphere on top of it. This construction is overdetermined but can be handled within the mechanical magnet tolerances with certain reservations. The platform centering screws had been optically aligned and fixed with respect to the geometrical axis and the magnetic field measurements.
In April 1989 the first beam had been transfered through SIS without fine adjustment of the components. The results show, that a more precise adjustment is needed. In September 1990 we will begin the geodetical alignment as previously described.

4. Assembling of the ESR

The height and horizontal control measurements being necessary for the basic adjustment of ESR, foundate from a system of measuring pillars, that encloses the ESR as a sextagon. One survey pillar is standing in the center of the ESR (fig. 9). Due to this network a fast and accurate orientation of a 3-D measuring system for the adjustment of the dipoles can be derived. Each dipole is made out of four single blocks. These blocks have to be adjusted within 0.1 mm relative to one another to allow the critical assembly of the dipole chambers and coils.
The ESR network was coupled by polar measurement to axis points of the reinjection and extraction of the SIS beam line (fig. 2).

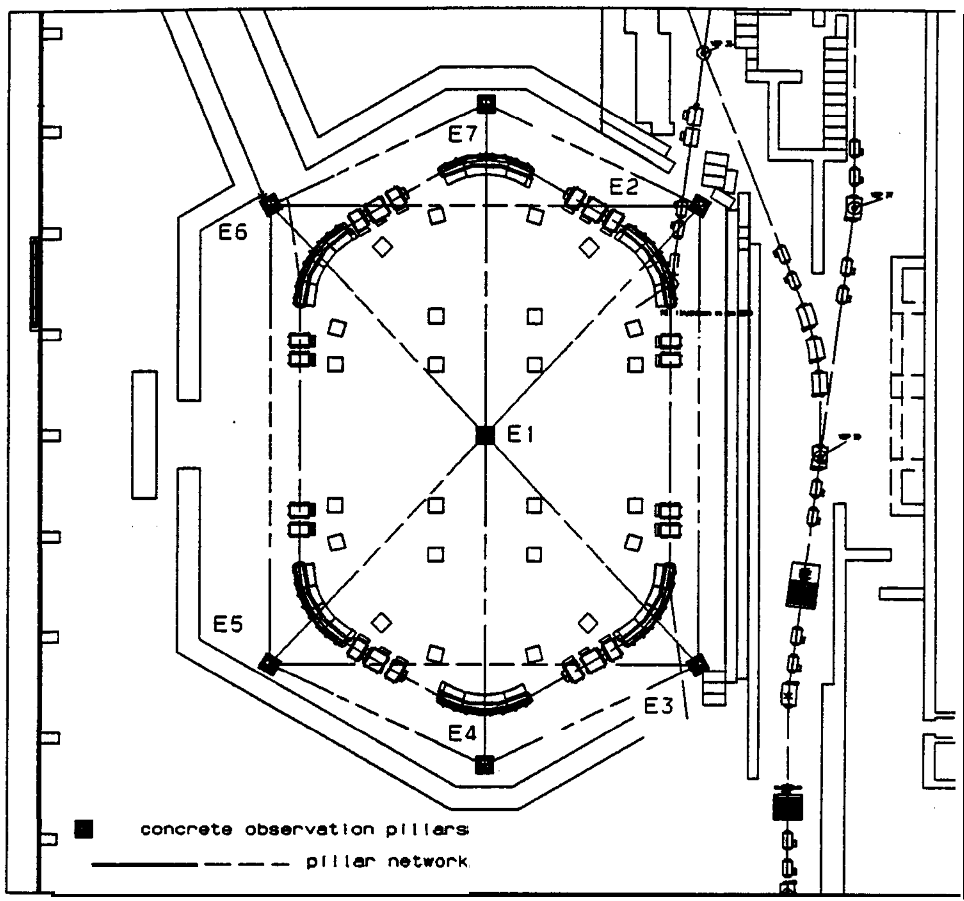

Fig. 9: Concrete pillar network of ESR

The ESR reference points are massive concrete pillars. They provide plenty of room to stand on, allowing for comfortable working conditions during the adjustments at a height of about 3 meters above ground. The ESR itself is installed on a separated foundation while the pillars are erected directly on the flooring plaster. The position of the pillars is expected to drift even over short periods of time because of their weight and temperature effects. This obliged us to provide the pillars with an illuminated hollow pipe allowing plumbing on brass target marks located on the hall floor. This was made with the plumbing telescope, the setting screws of the theodolite's tribac as well as with its high precision 2-axis compensator. This technique allows you to compensate possible excentricities at the pillar tops within a few 0.01 mm.

The network measurement is carried out in the same way as the SIS system, i.e. measuring horizontal and zenith angles as well as slope distances. The coordinates of the reference points result from a 3-dimensional free compensating calculation. The standard deviation of these points in the horizontal plane is 0.04 mm and 0.08 mm vertically. The orientation of the 3-dimensional measuring system for each dipole is determined from a fixed concrete pillar and a set of auxiliary points on metal tripods (fig. 10).

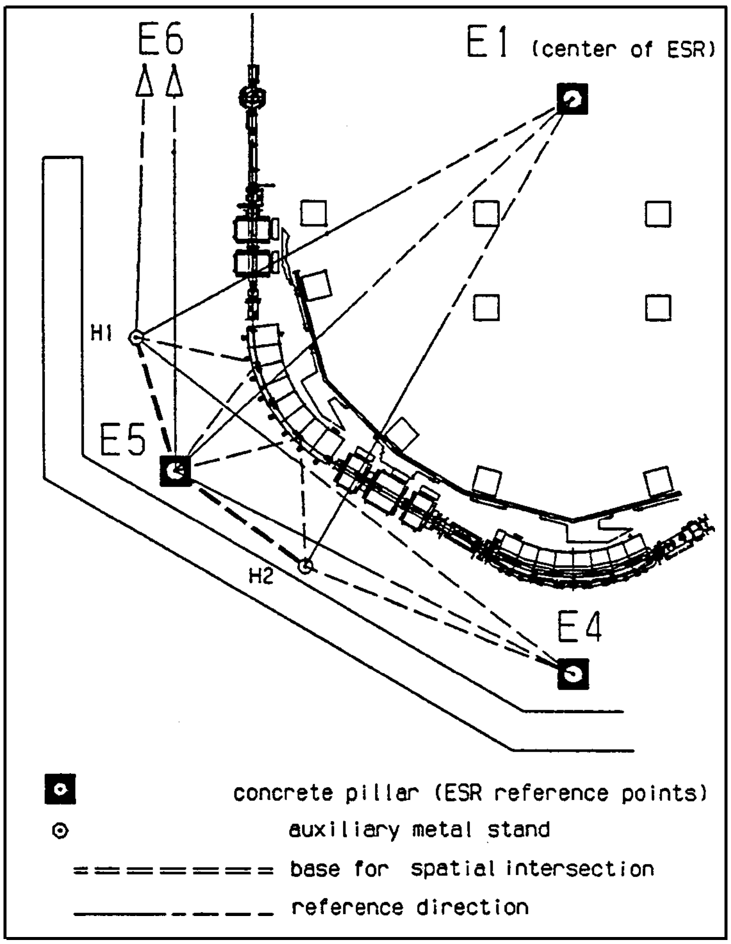

Fig. 10: 3-dimensional measuring system for a single dipole

The adjustment of one complete dipole block took 1.5 day. The tangential orientation of the dipole feet respective to the dipole bow resulted in time consuming coordinate transformations. The quadrupoles are finally aligned between the dipoles through angular and scale bar measurement.

5. Control Network for the ESR Alignment

An immediate ESR machine network has been designed in order to control the accuracy of the indirect spatial intersection method (pillar network) for the adjustment of the ESR (fig. 11).

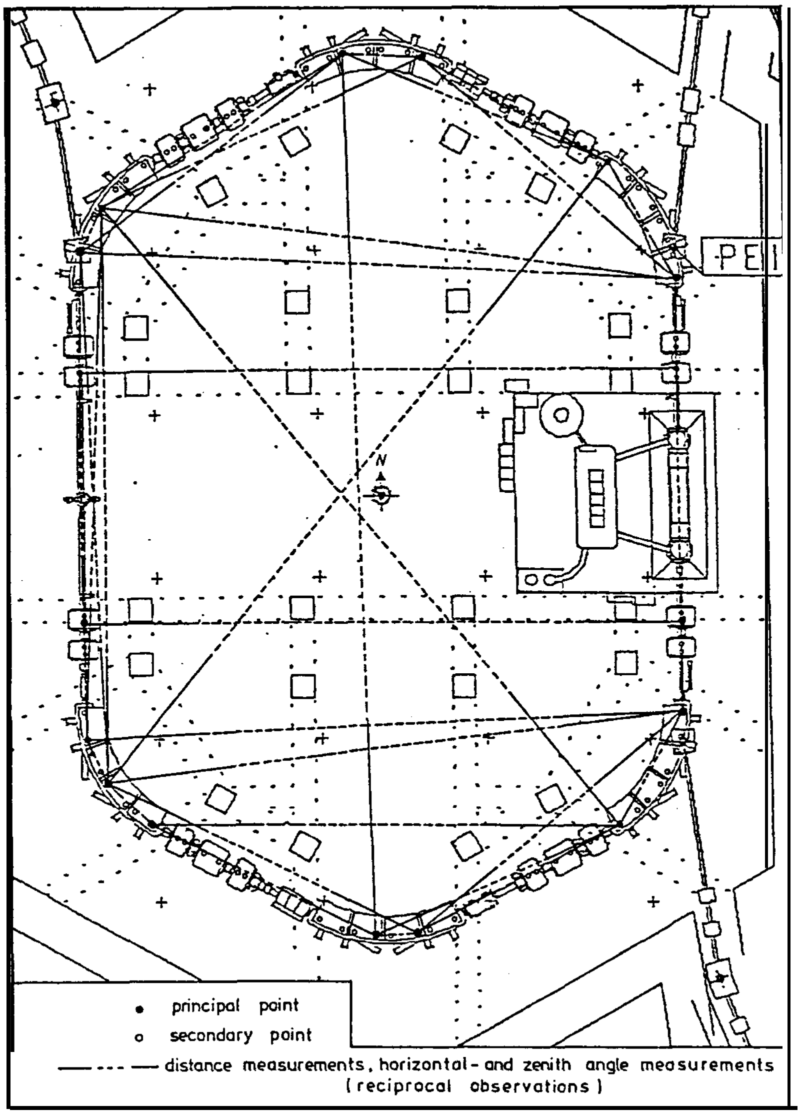

Fig. 11: Machine network of the ESR

In the machine network the reference points are identical with the points to be adjusted. These points have a good stability because of the separate foundation under the ESR. The observer has to climb on the magnets for his measurements. These accurate measurements won't be feasible anymore if, as the physicists are expecting, these magnets become permanently highly radioactive. The network is made out of principal and secondary points. Machine points that remain observable over long distances are defined as principal points. The main optical obstacles are cable bundles and supports for the movable concrete shields. The secondary points are two fold polarity coupled to each two principal points. A free 3-dimensional compensating calculation delivers confidence ellipsoids for the principal points, the standard deviations being longitudinally and radially 0.15 mm and vertically 0.1 mm. The deviations of the secondary points are twice as big. These unsatisfactory results were the reason for new studies of the centering and securing accessories for the swapping of targets and measuring instruments on the GSI platforms.

These studies revealed that the position reproducibility with the standard accessories could be as bad as 0.3 mm. Hence these accessories will be redesigned (fig. 12 to 15).

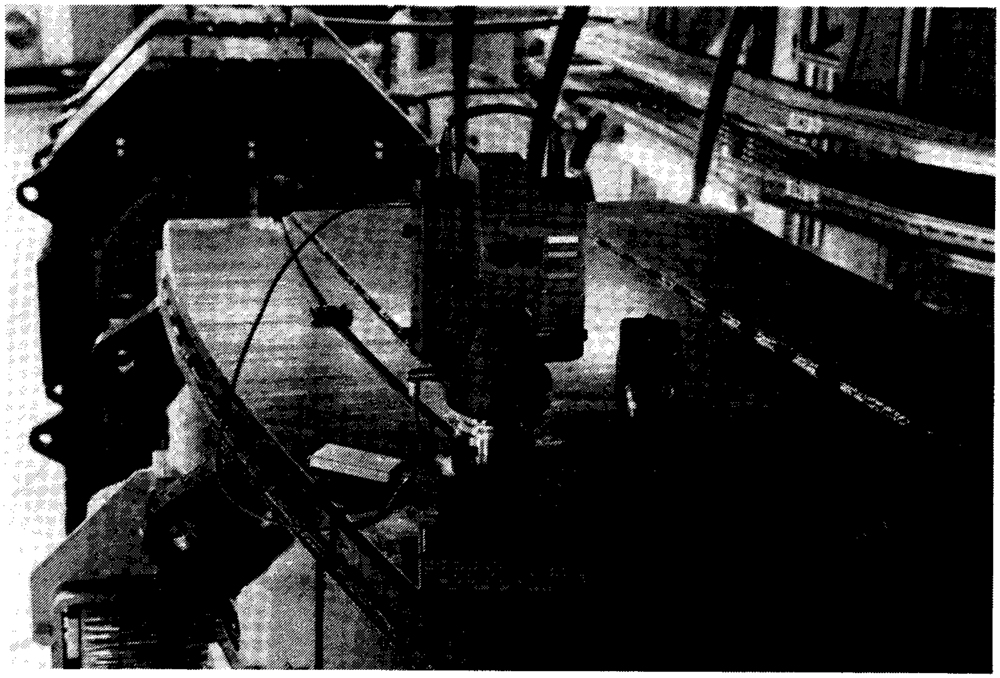

Fig. 12: KERN theodolite on ESR dipole-survey platform

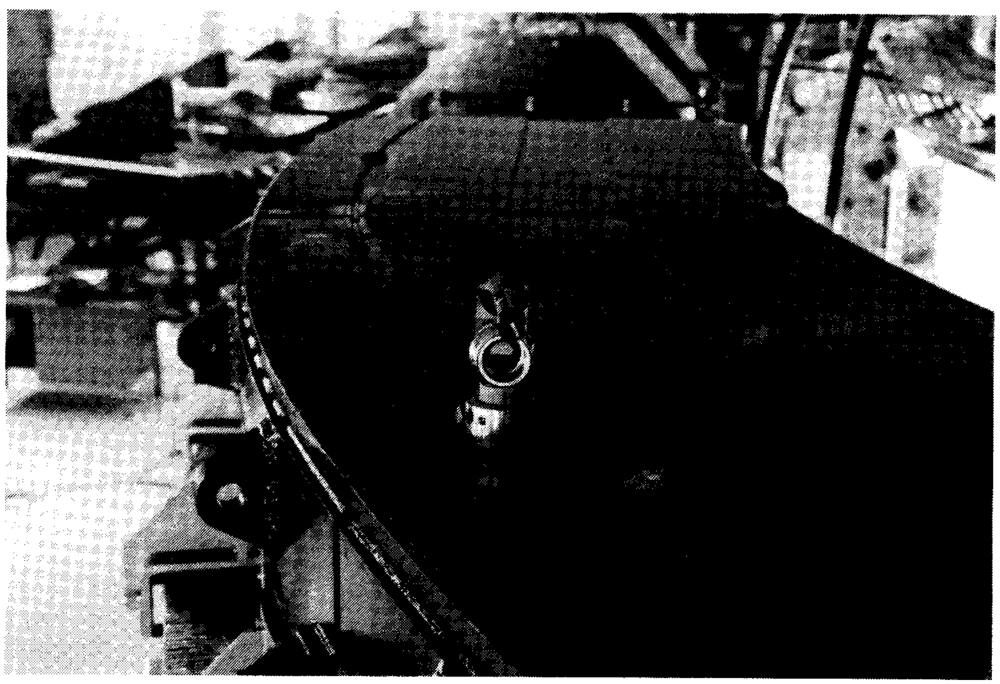

Fig. 13 TAYLOR-HOBSON sphere on ESR dipole-survey platform

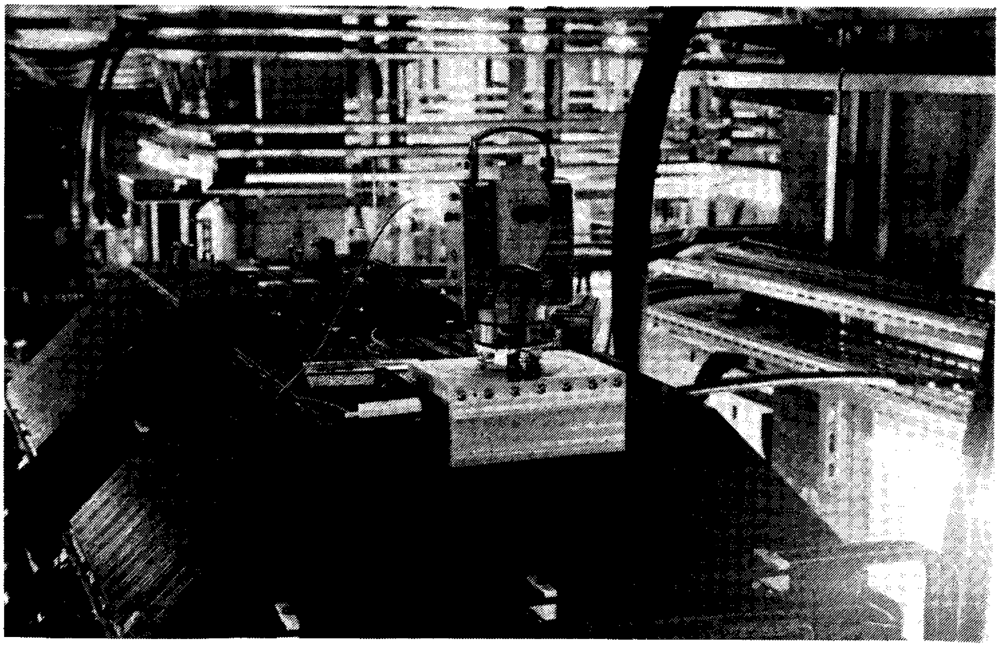

Fig. 14 KERN theodolite on ESR quadrupole-survey platform

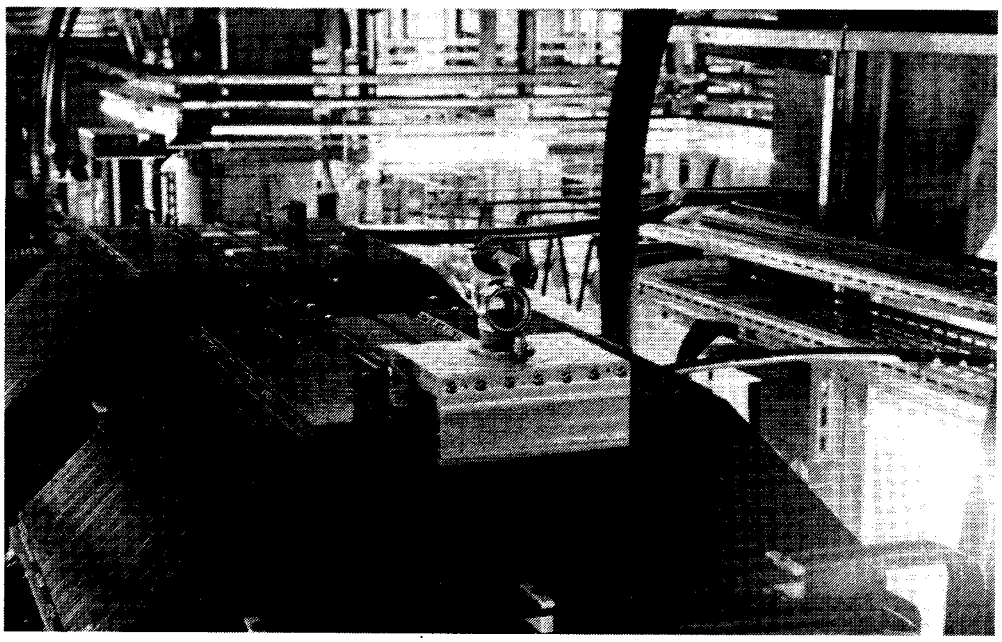

Fig. 15 TAYLOR-HOBSON sphere on ESR quadrupole-survey platform

Results of the control measurements:
The difference between the points as measured over the pillar network and the same points in the machine network lays in the range of 1 mm. Within one dipole block the discrepancy lays by 0.1 - 0.2 mm for the relative distance between subunits. This accuracy is good enough for the installation of the dipole chambers and coils. Two independent sources could be responsible for the high absolute discrepancies:

1. Each dipole block has been determined in the pillar network with its own measuring bases without any direct reference to the other dipoles. Furthermore the orientation measurements contain unavoidable unfavorable angles.

2. A long time, up to 1 year, elapsed between the measurements in the pillar network and the control on the machine network. This may have left time for building settlement.

6. Geodetic Network in the New Hall Area

The achievement of the hall building (1988) was a favorable opportunity to design a new measurement network in the area including transfer-, ESR- and target halls. The coordinates of this network are coupled to the SIS system. This network is a necessity in order to cope flexibly and fast with modifications and new constructions of experimental setups and shielding elements. The network is also useful for settlement measurements. Its single reference points are chosen in positions that will remain accessible as long as possible. They are located in access ways and within already existing experimental fields. The fixed points are plates embedded in the concrete of the hall floor and protected with plastic caps. The plates are self constructed and can be used for various purposes. The following can be centered on the cylindrical pivot of the brass plates:

a) target for optical/mechanical plumbing
b) target for horizontal determining of direction
c) reading mark for steel tape
d) sphere for vertical measurements (settlement measurements).

A minimum of 25 µ centering accuracy is guaranteed by the quality of fit of all splits. The standard deviation of the single plumbing with an electronic high precision theodolite in a height of about 1.8 m is calculated as 0.03 mm, that of the horizontal determining of direction as about 0.01 mm. By using a specially developed levelling device the brass plates could be secured in the ground with not more than 20' angle of tilt. In the case the difference in height of about 20 mm between the plumbing center and the horizontal direction target center would give less than 0.1 mm in accuracy in the x - y plane. A conical support in the upper part of the cylindrical centering pivot guarantees the vertical self - centering in the z-plane by putting a steel sphere in it (as used in ball bearings). The angles are measured with high precision electronic theodolite, the distances with steel tape by correction with respect to temperature and tension and with high precision laser range finder. A least square fit is carried out as a 2-dimensional compensating calculation. By couple measurements to three well known SIS pillar centers we obtain the orientation of the SIS coordinate system. The semi-major axis of the confidence ellipses of the compensated coordinates amount to an average value of 0.2 mm. It is remarkable that the steel tape measurements correspond to the far more precise laser range finder results to within 0.2 mm. The controllability of the compensating calculation of the distances is between 80 % - 90 % and over, that means their influence on the point positions is insignificant. It is not possible to orientate the network to SIS with economic expenditure. We have to take in account the possibility of a twist. But the decisive factor for the range of use is that the high inner accuracy of the network is not touched by the twist. The absolute accuracy of the system in SIS coordinates amounts to about 1 - 2 mm.

7. Instrumentation

Horizontal and vertical angles are measured with high precision electronic theodolite KERN E2 or E2-I. The measured data is automatically registered with the KERN ECDS 2 software or with the portable PC HUSKY HAWK 8/6 (1.1 MB/MS DOS-CPM version). A lot of the HUSKY registration software we obtained with the friendly help of the DESY survey unit.
For distance measurements we are using the KERN laser range finder ME 5000, the KERN 1 m-scale-bar and precision steel tapes.
In addition to the usually centerings we have job order scheduled self-constructions. As reference points on top of the adjustment devices we prefer the spherical target system of TAYLOR HOBSON.
Preadjustments were carried out with the support of large scale metrology such as optical alignment telescopes, collimation and autocollimation methods, electronic tilt measurements. Therefore we have sufficient mechanical laboratory equipment. The comprehensive and various tasks make it very important to have an access to an efficient mechanical laboratory.
Height measurements are levelled with ZEISS NI 1, WILD N 3 or trigonometrically defined. Up to now the trigonometric levelling results can be seen as a comparable to that of the geometric levellings.
For 3-D evaluation we use the ECDS software. The 3-D network adjustments were calculated with the PAN 3-D program system from the firm GEOTEC and our own supplementary software. The remarkable features of the PAN software are its various options, statistical tests and its speed.
All software is installed on a TANDON IBM compatible PC with Intel 80286 processor and 80 MB hard disk.

8. Strategies and Remarks

When one looks at the matter critically one will notice that too little attention is paid to the necessary work of the surveying engineer during the design phase of the project. The design of the large scale metrology components and the building complex has taken place at a time, when the measurement and adjustment works were not properly taken into account. It’s up to the surveying engineer than to try on very hard conditions to meet challenging demands. Therefore often only the second best technique can be realized. But for such a project accurate geodetic survey and component alignment are so important, that the engineer in charge should be consulted right from the start. Especially when additional changes are applied to the machine, as it happened in our case.

9. Man Power

The surveying works of such a project require a lot of time, energy and money. Therefore you usually have a survey unit with several qualified engineers, technicians and mechanics. GSI took a different way. It’s the task of a single engineer to carry through all the surveying work. He has to plan and to coordinate all measurements and even to carry them through with changing additional staff. If you can’t cope with all the work, some of it is delegated to other engineering offices. It is obvious that these paid services are of very different quality. In these conditions it is not possible to make the necessary and comprehensive tests of measurement methods and own instrumental developments. They can only be carried out with the assistance of other institutions e.g. technical universities, because special laboratories for measurement tests and metrology are not part of this conception. In spite of the successful work to date I think it would be better to have a special GSI survey unit at an accelerator complex of that size, especially considering the complicated measuring necessary and the demands placed on it and on the flexibility of the measurement service during the GSI experimental running phase.

10. References

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