IMPLEMENTATION AND FIRST RESULTS OF THE SURVEY AND ALIGNMENT OF ACCELERATOR FACILITIES AT GSI USING THE TASA SYSTEM

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1. INTRODUCTION

GSI (Gesellschaft für Schwerionenforschung mbH, Darmstadt) is a heavy ion research center funded by the Federal Government of Germany and the state of Hessen. GSI operates a heavy ion accelerator facility consisting of the linear accelerator UNILAC (energy of 2 - 20 MeV per nucleon), the heavy-ion synchrotron SIS 18 (1 - 2 GeV/u), the storage cooler ring ESR (0.5 - 1 GeV/u) and about 30 experimental setups.

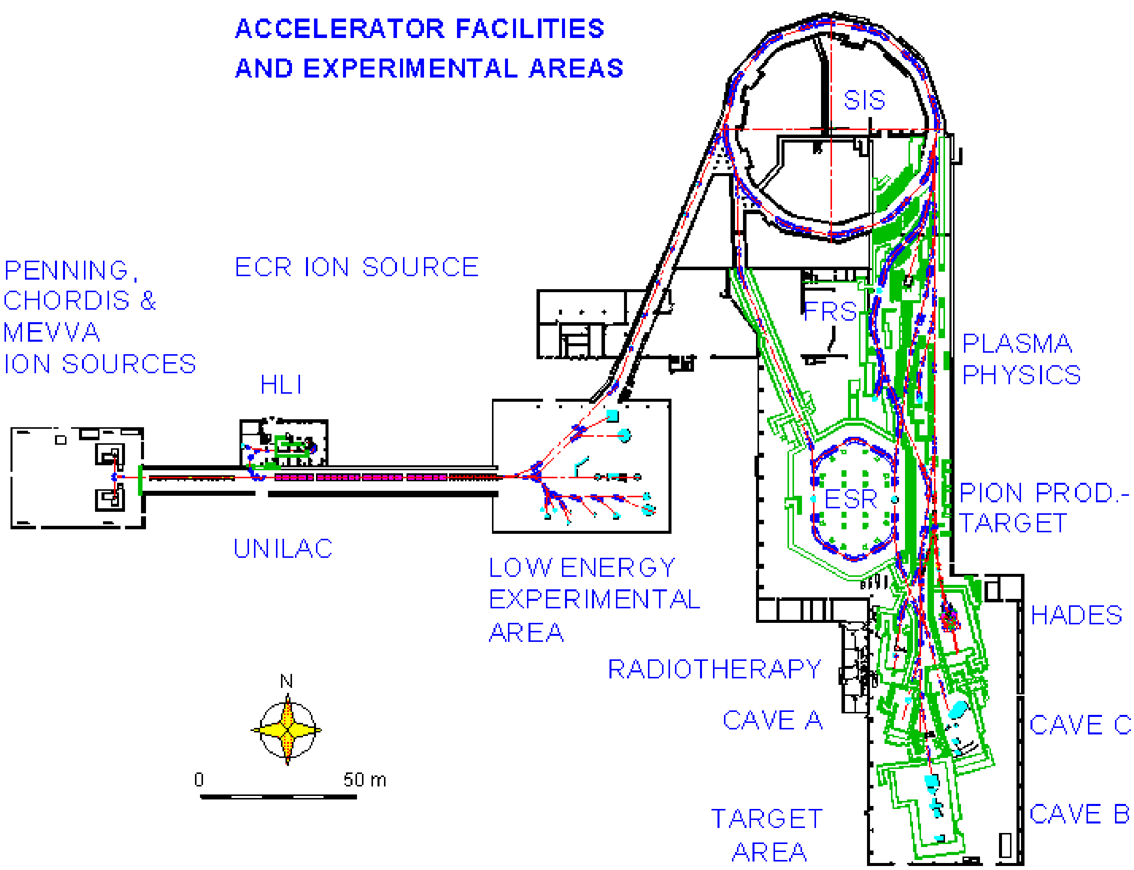

Fig. 1: Accelerator facilities and experimental areas at GSI [4]

The accelerator survey at GSI is done by applying angle- and distance measurements. The latest complete alignment of ESR and the FRS / HEST (Fragment Separator / High energy transportation beamline) based on such measurements was done in August 1996 respectively in three phases in January, March and May of 1997.
Transfer measurements to establish new nominal coordinates for the fiducial points of components, which were necessary for a new alignment system as well as reference network measurements, were carried out before.
This work was done with the new TASA System which has been presented for the first time at KEK (Japan) at the Fourth International Workshop on Accelerator Alignment (IWAA95). TASA replaced an older existing and practiced method at GSI.

2. THE TASA SYSTEM

TASA stands for **T**acheometric **A**ccelerator **S**urveying and **A**lignment. This system was developed by the Metronom GmbH Germany as a new alignment method including hardware and software.
TASA will be used for all alignments of different accelerator subsystems at GSI. All components can be positioned using the same method. The TASA System is based on the systematic use of a high-precision total station and electronic inclinometers for polar measurements and tilt measurements. In addition a complete software package for the different tasks of surveying and alignment is provided and supports the entire procedure.

2.1 Hardware

The polar method for the alignment of accelerators requires the utilization of a high-precision total station with equal accuracy of angle- and distance measurements. The Leica TC2002 which is used at GSI reaches a standard deviation of 0.06 mm for distance measurements [1]. This accuracy assumes a determination of atmospheric parameters like temperature, pressure and humidity, and an employment of high-grade triple prisms, realized at GSI by integrating a Leica standard prism to a Taylor-Hobson sphere. The standard deviation of angle measurement is declared as 0.15mgon (0.5″). Therefore the TC2002 is suited for the accelerator alignment as a stand-alone instrument without paying attention to specific requirements of configurations, which were necessary in the past because of the different precision of angle and distance measurements an instrument could achieve.

For tilt measurements of a single component two LUCAS SCHAEVITZ LSOC - inclinometers with a measuring range of $\pm 1°$ (=17.45 mrad) and a precision of 0.03 mrad are employed.

2.2 Software

The TASA software package is applied to handle the great number of data which is generated during the different procedures of surveying and alignment. It is specifically designed for polar alignments based on the described hardware.
The complete data flow of the collected angles and distances up to the presentation of the displacements of a component related to the beamline is supported.

The TASA software package contains modules for measuring and processing tilt data (program INKLINO) as well as angles and distances (especially for building a reference network / PROLOG). For data reduction and correction etc., the polar point determination and file generation for least square adjustment software the program called REWORK is used. A transformation program for the calculation of the nominal coordinates of new fiducial points - specifically designed for the GSI - is implemented too (CARRY). Within the program ALIGN, which is the software for the online adjustment of components, an orientation measurement - including the possibility of free stationing - could be done at first to be able to determine thereafter the coordinates of the fiducial points by polar measurements. The evaluated actual coordinates of the fiducial points of this component (beam-in, beam-out) are compared with their nominal values. The adjustment offsets are then presented in a graphic.

3. TASA AT ESR AND FRS / HEST

3.1 Machines

The Experimental Storage Ring was the first area of the GSI accelerator that were realigned. Figure 2 shows the characteristics of the ESR. The transfer measurements, reference network and the alignment of this subsystem will especially be illuminated in this paper.

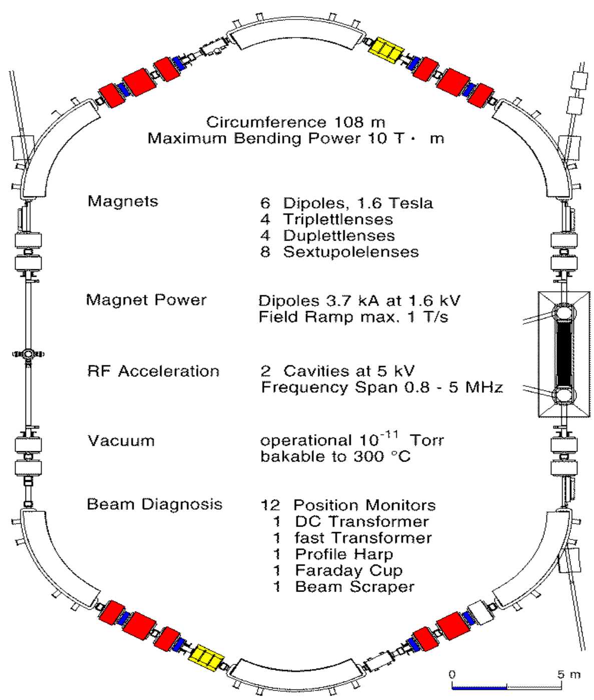

Fig. 2: Main features of the ESR [4]

After we succeeded in aligning the storage ring within the given tolerances the Fragment Separator (FRS) and the High Energy Transport Beamline (HEST) were the next beam line modules to be realigned. The FRS has a length of 70 m and consists of about 50 magnets. Several are mounted on girders so that about 10 girder assemblies, 6 Dipoles and several single placed magnets had to be aligned. The HEST that is the transportation beamline to the Experimental Caves (A, B, C, Medical,...) consists of about 90 different components. They are all installed at single concrete monuments.

3.2 Transfer measurements

The new surveying and alignment system at GSI - TASA - is based on the use of new fixed consoles as fiducial points instead of formerly used mobile plates which had to be put on top of the actual measured component. All magnets are equipped with two new fixed consoles that are welded at various appropriate positions considering lines of sight, heights of stands, configuration etc. They are usually easy to access and improve reliability.
Besides a socket for the Taylor-Hobson sphere every console has a device to put on an electronic inclinometer for the measurement of the transversal tilt of the component. The longitudinal tilt is calculated as the difference in height of the two fiducial marks.

The new fiducial points had to get nominal coordinates used for the alignment of a component by TASA. To determine these nominal values a transfer measurement from the „top-points“ to the new points were carried out. Additionally the transversal tilt of the components in reference to a horizontal coordinate system was observed.

3.2.1 Transfer ESR

For the transfer measurements at the ESR the KERN Electronic Coordinate Determination System ECDS3 was used. Tilts were calculated out of points which were measured at the surface. For the verification of the results a second tilt measurement was done by conventional leveling.
The transfer measurement of a component should be a unique process. Due to the reliability of data each fiducial point („old“ / „new“) was measured several times and taken on an average. After the mobile plates were taken away and fixed again on top of the magnet all measurements were repeated.

The repeatability of transfer measurements for different components carried out with ECDS is established as 0.15 to 0.3 mm for the radial / longitudinal and 0.1 to 0.15 mm for the vertical direction depending on the kind of element.

In the past different components needed different mobile plates and adapter for the visualization of the fiducial points. In order to transfer the known coordinates of points that represent the beam line in a defined height to the new fiducial marks one has to use the mobile plates fitted to the component. Unfortunately there were several components with no existing adapter or even fiducial marks so that it was found necessary to define new points at the top - e.g. bore fits - as „old“ points, to create a fitting adapter and to transfer these points to the new fixed devices. These facts causes uncertainties that have to be taken into account.

3.2.2 Transfer FRS / HEST

During September / October of 1996 transfer measurements for FRS / HEST subsystem took place. Instead of the ECDS-System a SMX Laser Tracker 4000 was employed in order to accelerate this process of transfer measurement. Besides the advantage of time savings as there is no need of long-winded orientation measurements the employment of a laser tracker requires only one person.

In comparison to the number of elements of the ESR and the time we used for only one component the transfer in FRS / HEST was at least twice as fast without a loss of accuracy. On the contrary. The precision of repeated measurements was established as about 1/10 mm. Again, the biggest part of this inaccuracy is caused by the bad conditioned adapter.

Results of these measurements are coordinates of the old and new fiducial points in a local oriented horizontal coordinate system. Exactly as the evaluated data out of ECDS the coordinates received by the laser tracker are - in addition to the measured tilt - transformed: first into a coordinate system related to the component, and second into a global coordinate system within the nominal coordinates are known.

Unlike the tilt measurements in the ESR, where tilt of a component is derived from point-wise measurements on the outside of the magnet, the laser tracker is able to scan the surface and is therefore qualified to detect possible twists of components more precise.

3.3 Reference network measurements

Following the requirement of no use of concrete monuments but mobile pillars, which could be installed for a measuring period and taken away after terminating the adjustment works, a mobile reference network with temporary pillars and consoles was constructed.

3.3.1 ESR network

The network for the Experimental Storage Ring (ESR), that was defined by 14 pillars enclosing the machine, was measured in July 1996 using the Leica TC2002 tachymeter including angle- and distance measurements. Furthermore the actual positions of all Dipols, Quadrupoles etc. were determined by polar measurements related to the reference network. Angle measurements on 6 stands were repeated. These observations were introduced to strengthen the network calculation in order to receive more accurate probable values for the position of the reference points.

There was no orientation for the network of the ESR provided by monuments or similar. Therefore free net adjustment was practiced without fixed points. The resulting absolute error ellipses for all network points were in the range of ± 0.03 mm. In order to get information about the actual condition of the storage ring the reference points had to be known in the ESR coordinate system. For that purpose all measured points were transformed into the ESR system using the magnet points with their nominal coordinates as control points. The residuals show the corrections that have to be attached to achieve the ideal position of the component. The final

datum was set by choosing the most difficult adjustable magnets - the 6 dipoles which consist out of 4 sections - and defining them exclusive as control points to avoid large corrections just there.
In order to fix the elevation datum a leveling was carried out to transfer known heights from points on the floor onto the pillars. The results were introduced into the least square adjustment process. This way the results of the adjustment were referred to the desired height of the beam line that was defined as the average height of the components of the Heavy Ion Synchrotron (German acronym SIS). The height of the floor points are connected with the altitude of the magnets by settlement measurements that are carried out regularly.

Results of the determination of the actual magnet positions before the alignment process was carried out are shown in figure 3.

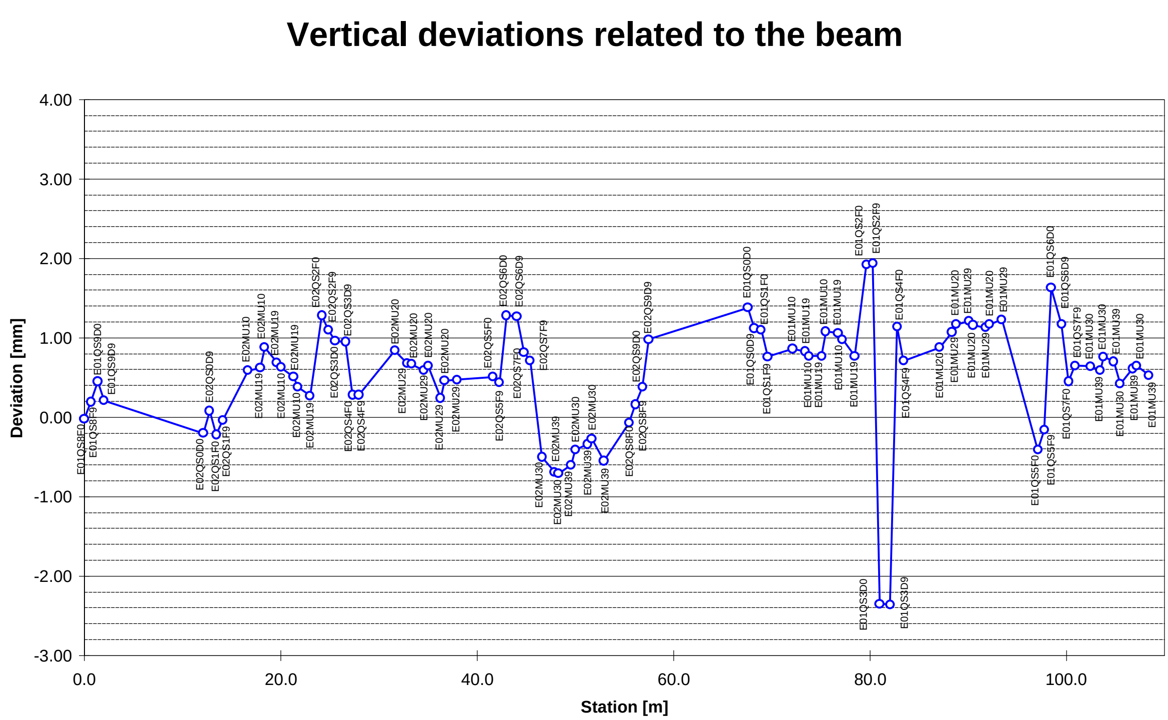

Figure 3.1: Vertical deviations of the ESR components related to the beam line before the alignment process

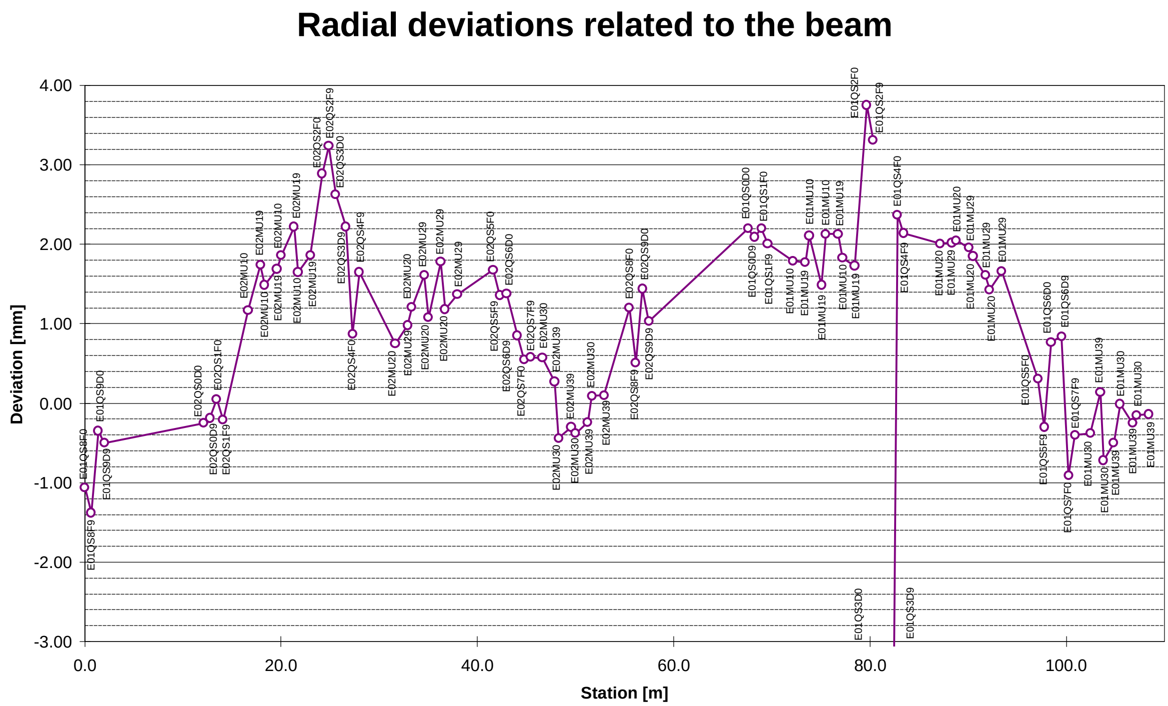

Figure 3.2: Radial deviations of the ESR components related to the beam line before the alignment process

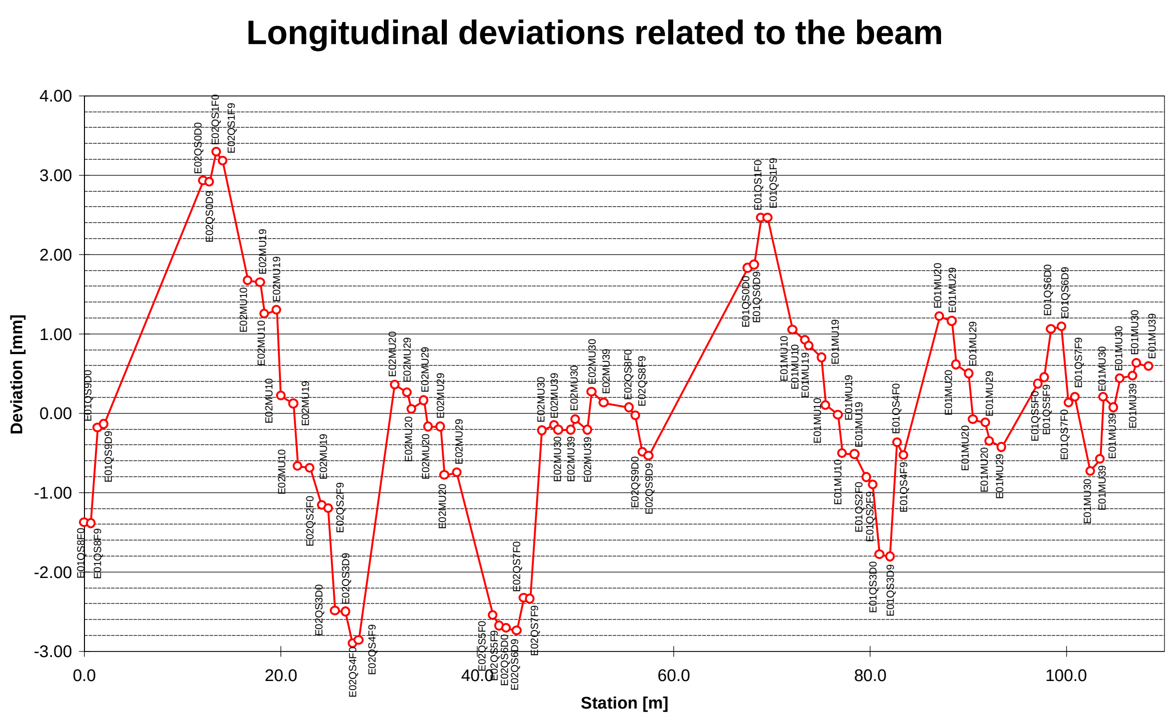

Figure 3.3: Longitudinal deviations of the ESR components related to the beam line before the alignment process

3.3.2 Interface of ESR and FRS / HEST

The network for the Fragment Separator (FRS) and the High Energy Transportation Beam Line (HEST) was measured due to time constraints in two phases of October and December of 1996. It was defined by 39 pillars respectively consoles on the wall. The same equipment just as in the ESR was used, angle- and distance measurements were carried out and the actual positions of all magnets were determined.

In order to combine the networks of ESR and FRS / HEST several magnets and reference points of the ESR were measured once again. The points were transformed into the global GSI coordinate system that had again no fixed points for the orientation but is defined by the nominal data of the components.

Two variations of setting the combined network were analyzed:

1. Setting the system onto the measured points of the ESR: which has the advantage of aligning the machines of FRS and HEST related to the same coordinate system as the elements of the storage ring. A disadvantage of this method is that large correction values appear at components far away of the storage ring although the relative position of the magnets to each other is good enough.
2. Setting the system onto the nominal data of the FRS and HEST elements: which has the advantage of getting small adjustment offsets. However the subsystems FRS / HEST and ESR are not in the same coordinate system, so in theory the two systems are twisted.

Finally it was decided to fix the horizontal datum by setting the FRS / HEST system onto the nominal data of the elements in FRS / HEST while the elevation datum was fixed by connecting the measurements onto the heights of the elements of the ESR, because they were already aligned to the level of SIS.
This decision effected a rotation between these two systems which is compensated by the hardware: the deviation angle of a beam steering magnet was modified to correct the center of beam axis.

3.4 Alignment procedure

3.4.1 Alignment Tolerances

In order to transport particles around the arcs and deliver beam of acceptable quality the alignment tolerances of storage ring magnets have been defined as follows:

Table 1
ESR Alignment tolerances

Element	**Quantity**	**Tolerance**			
		longitudinal	radial	vertical	roll
		mm	mm	mm	mrad
Dipol / total	6	± 0.5	± 0.3	± 0.3	
Dipol / single	24	± 0.2	± 0.2	± 0.15	± 0.1
Quadrupol	20	± 0.2	± 0.1	± 0.1	± 0.1
Sextupol	8	± 0.2	± 0.1	± 0.1	± 0.1
Kicker, Septa, Solenoide	10	± 0.2	± 0.2	± 0.15	± 0.1

Table 2 lists the required tolerances for the various magnets at FRS / HEST.

Table 2
FRS / HEST Alignment tolerances

Element	**Quantity**	**Tolerance**			
		longitudinal	radial	vertical	roll
		mm	mm	mm	mrad
Dipol	28	± 0.5 / 0.3	± 0.3	± 0.2	± 0.1
Quadrupol	95	± 1.0	± 0.2 / 0.25	± 0.2	± 0.1
Sextupol	12	± 1.0	± 0.2	± 0.2	± 0.1
Girder	10	± 1.0	± 0.2	± 0.2	± 0.1

3.4.2 Implementation

The realignment of the Experimental Storage Ring ESR took place in August 1996. The components were brought to their nominal positions taking into consideration the given tolerances. While carrying out the orientation measurement the stability of the reference network was controlled. Resulting from these checks the absolute accuracy of the network points can be declared as 0.15 mm.

The actual coordinates of the two fiducial marks of a component were determined by polar measurements; the radial tilt is measured on-line. In order to calculate necessary magnet motion in radial, vertical and longitudinal direction the actual and the given nominal positions of the fiducial points are compared and displayed on the monitor.

The magnet positioning is an iterative process which consists of surveying and shifting. It was repeated 4-5 times until the position errors were within tolerance. The principal reason for repeated attempts is due to the characteristic of all components at GSI: instead of using three feet the geometrical position of the elements is overestimated by four supports. In some cases these overvaluation causes a magnet wobbling around the diagonal axis which is not easy to handle.
The difference between the measured radial tilt at beam-in and beam-out indicates twisted magnets. In this case a mean value of tilt was adjusted.

All components at the ESR - except of certain elements without suitable fittings - could be realigned within the given tolerances shown in table 1. The four segments of a dipole had to be shifted a mean value because they are connected and could not be aligned on their own. Due to the high accurate angle and distance measurements magnet motions of about 0.1 mm were significant detectable. Tilts better than 0.1 mrad could be adjusted.

The results of aligning the components of the Experimental Storage Ring is shown in figure 4.

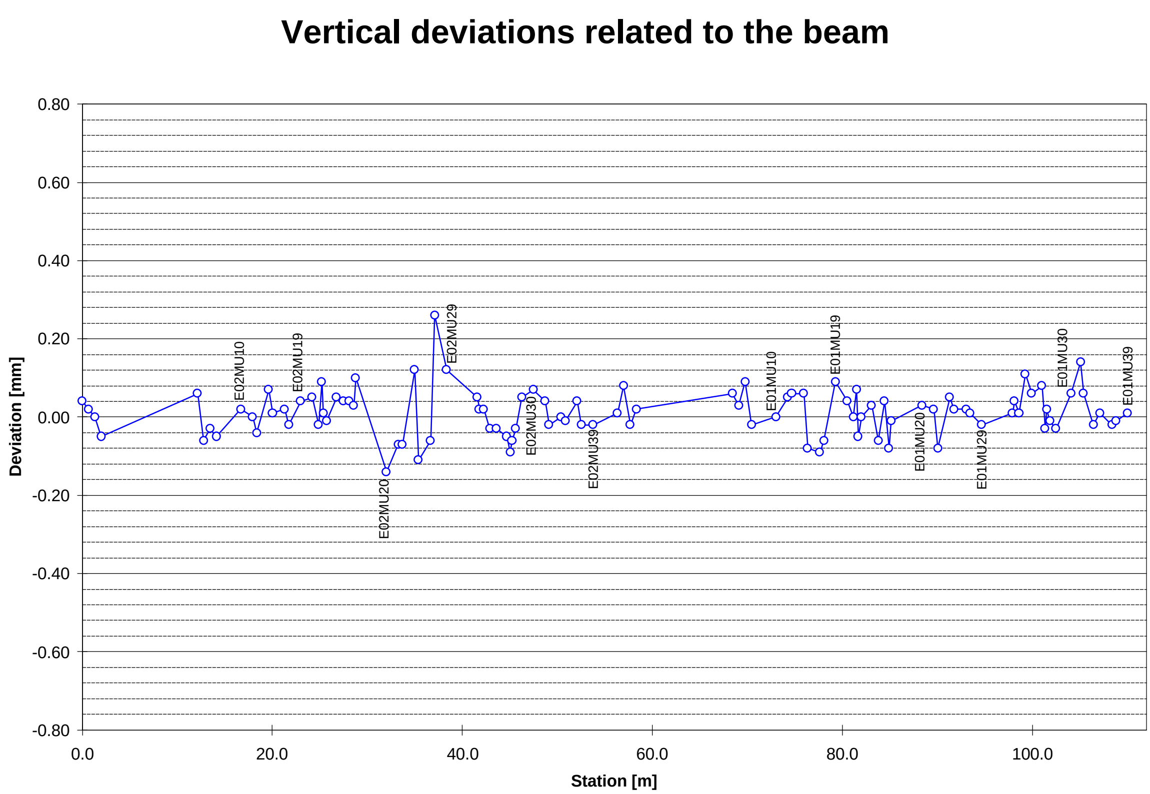

Figure 4.1: Remaining vertical deviations of the ESR components related to the beamline

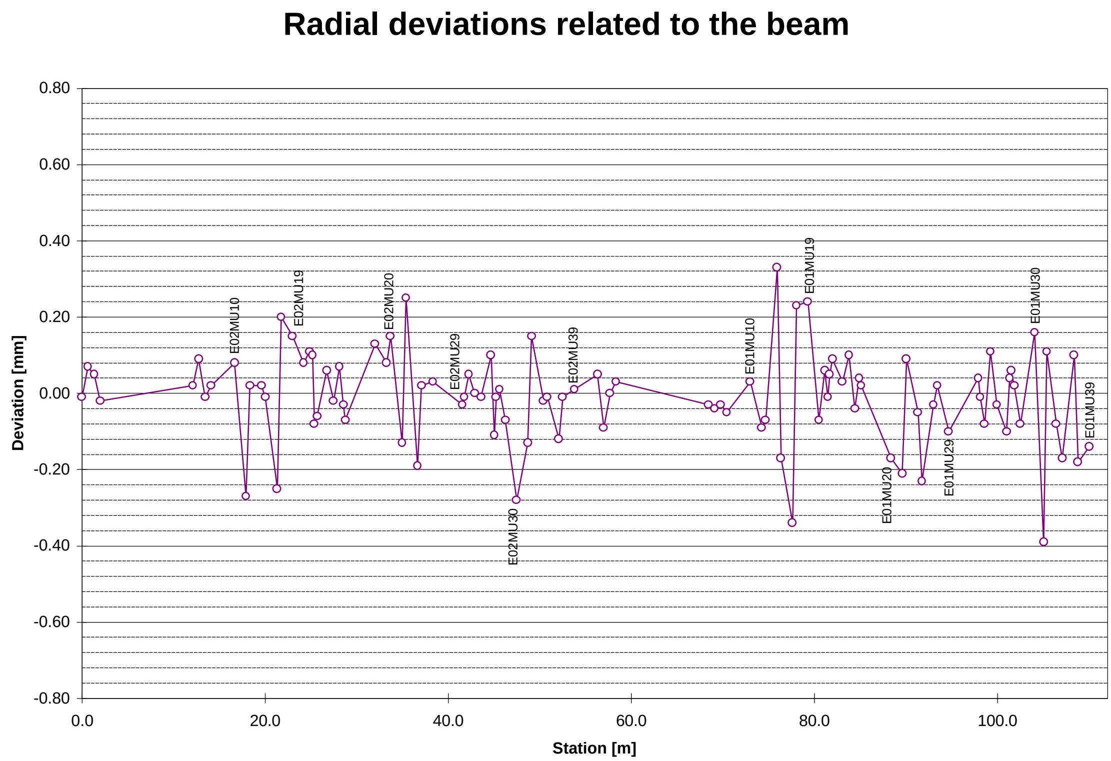

Figure 4.2: Remaining radial deviations of the ESR components related to the beamline

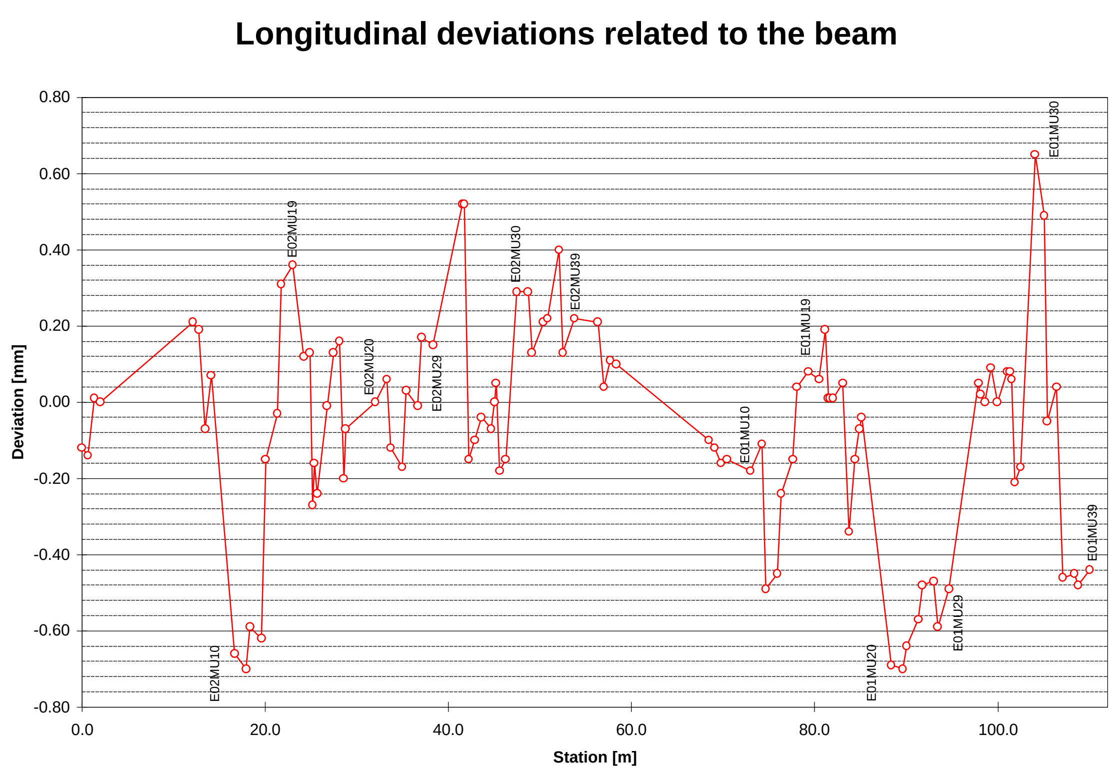

Figure 4.3: Remaining longitudinal deviations of the ESR components related to the beamline

As well as single arranged magnets, Fragment Separator includes several components placed on girders. The magnets have remained stable on their girders, simplifying the realignment process. The girder could also be positioned using one fiducial mark of the first and last element on the girder. The coordinates of these points were established and compared with their nominal values. While moving the girder the calculated differences were not set to zero but to given values so that the distance of all magnets to their ideal position is at a minimum. After that all other fiducial points of the remaining magnets on the girder assembly were checked if they are within the required tolerances.

4. EMPLOY A LASER TRACKER WITHIN TASA

4.1 Transfer measurements using the SMX Laser Tracker 4000

To employ a laser tracker for surveying and alignment tasks at GSI was discussed ever since the first instrument came into use. The system that will be applied for transfer measurements described in 3.2 should meet the following requirements:

- Accuracy: 0.05 mm
- Working Volume: 10m × 5m × 3m
- Portability: measurements must be done in cramped facilities
- Leveling: all measurements must be leveled

In 1995 we had the opportunity to test the LEICA SMART 310 and its capability. The given accuracy has been enough for our purpose, but several reasons concerning the handling of the SMART 310 were responsible for a refusal. One reason is the inability of changing the height of the instrument without big efforts. Stands in a height of about 3m - be found in ESR while transfer measurements - are not possible to satisfy. Except this, the tracker leveling is compared to other systems very uncomfortable. Another reason to reject the SMART is the time you need to calibrate the system: 2 to 6 hours are not acceptable.

The SMX Laser Tracker 4000 is a more flexible system. It can be mounted on a Brunson tripod. In addition to the working volume of horizontal 270° and vertical 120° it is easy to place the tracker almost everywhere you need it. The accuracy, the SMX Tracker could achieve in determination of coordinates, meets the requirements given above.

In September 1996 the transfer measurements for FRS / HEST subsystem started where the SMX Laser Tracker 4000 was applied for the first time.

4.1.1 Plausibility check

To check plausibility of transfer measurements in spite of using different instruments several components were transferred twice. 3D-coordinates of the fiducial points (consoles and mobile plates) received out of ECDS on the one hand and laser tracker measurements on the other hand are compared in figure 5. The application of the mobile adapter have to be taken into consideration while looking at the results critically.

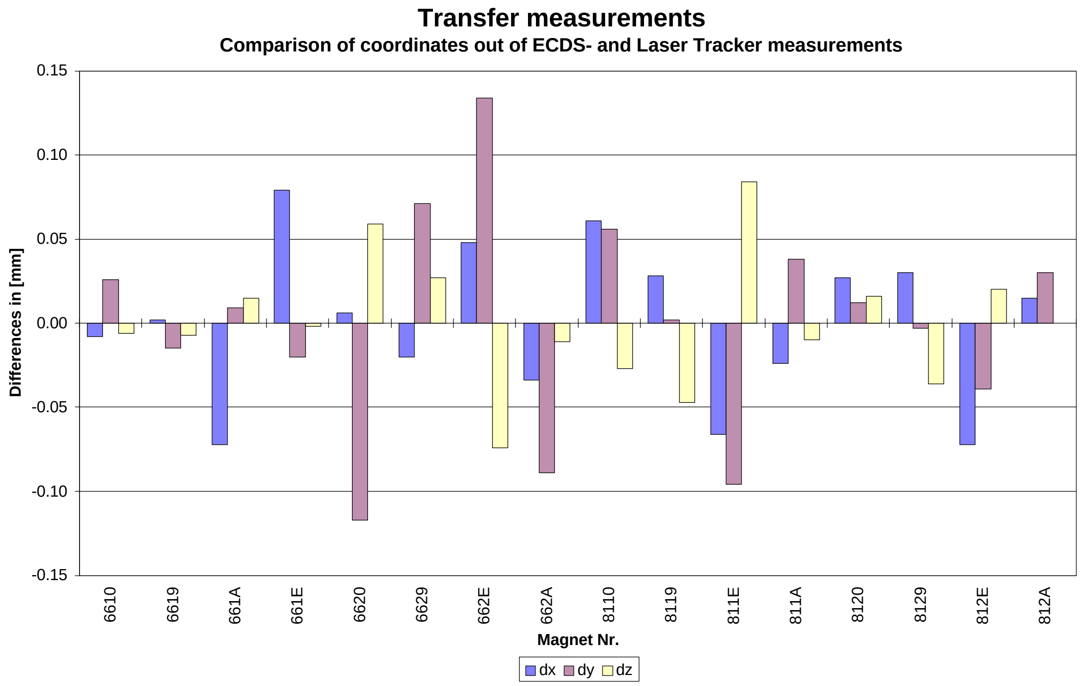

Figure 5: Comparison of results out of ECDS- and Laser Tracker measurements

Due to these tests it was found logical to continue the transfer measurements using the faster, high accurate sensor.

4.1.2 Scanning the twist effect of magnets

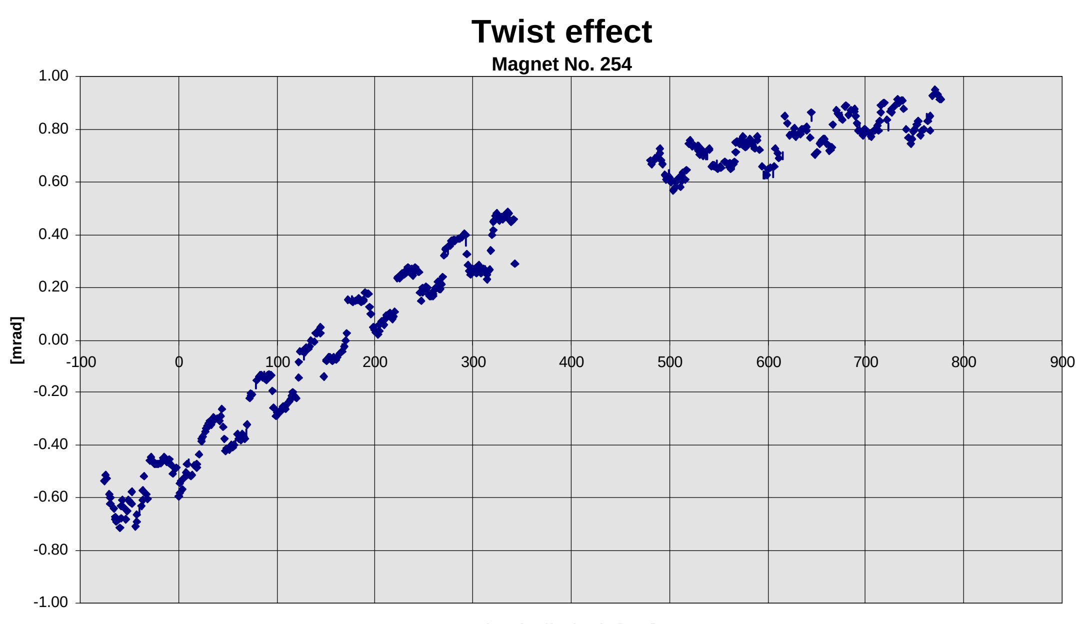

Fig. 6: Scan along the longitudinal axis to detect twist effects

As mentioned in 3.2.2 tilt measurements were now carried out by scanning the magnets instead of point-wise measurements. Consequently, twists of components can be detected more precise. The magnets were checked by scanning the fins along the longitudinal axis on each side.
2 % of the estimated magnets were found out to have a twist bigger than ± 0.3 mrad. An example is shown in figure 6.

The plot shows a scanning over a length of 900 mm with a point interval of 1 mm. An obstacle prevented a continuous measurement and caused the displayed gap. The twist of component can be read as ± 0.8 mrad

4.1.3 Transfer measurements of components not yet introduced into beamline / HADES

Transfer measurements of magnets that belong to the new experimental area HADES, which is under construction at present, were carried out following a modified concept: in comparison to the realization of transfer measurements up to now, these magnets were not yet installed, so that for the first time it was possible to determine the geometrical magnet axis directly. Adapter, that represented the old fiducial points on top of the magnet, were not necessary to transfer nominal coordinates to the TASA consoles. This way one step were dropped. Due to this fact reliability of data was increased. The repeatability of transfer measurements for different components carried out with the laser tracker is established as ± 0.1 mm.
In order to receive actual radial tilts of magnets slots on both sides were scanned. The measured points are displayed in figure 7.

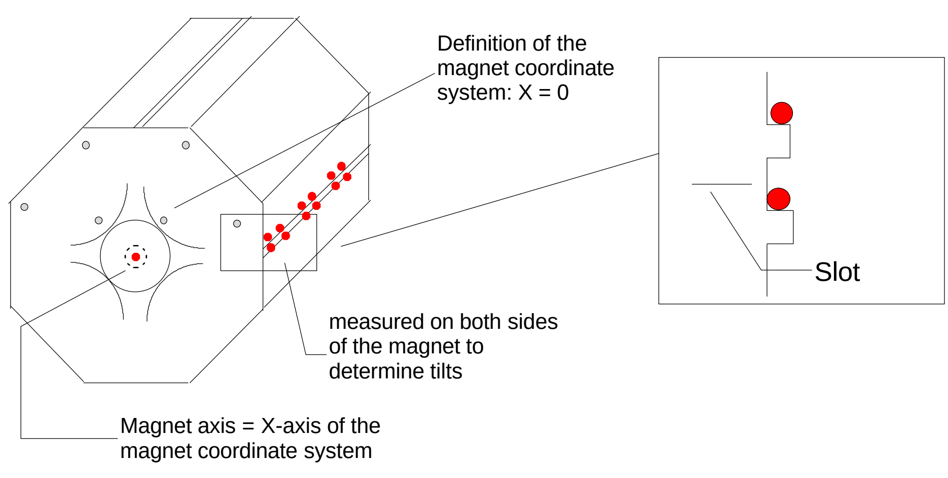

Fig. 7: Description of measured points at a Quadrupol

4.2 Alignment using the SMX Laser Tracker 4000

Completing an alignment with a laser tracker is nothing new. The alignment at GSI is hardly based on the usage of the LEICA TC2002, therefore the tracker is only applied in exceptions.
Orientation is only possible by free-stationing. In our case, pillars - if they were still on their place - and fiducial points of adjacent magnets that were already realigned served as connecting directions.
The inclinometers were fixed on the TASA consoles to control the radial tilt of magnets. The mirrored target (SMR / spherical mounted retro-reflector) were put into the two sockets of the component alternately where usually the Taylor Hobson sphere is fixed.
We made the experience of time savings again, using the laser tracker instead of the TC2002 for magnet positioning (including orientation measurement etc.). The remaining shift values could be given faster after one iteration which consists out of surveying, changing the place of the SMR and shifting; magnets could be moved in very small steps. The remaining deviations related to beamline were smaller than ± 0.1 mm.

Changing the retro-reflector between the consoles at beam-in and beam-out is no longer necessary using the new SMX Laser Tracker 4500, that is in use by Metronom GmbH since October 1997. The improved system is equipped with ADM (absolute distance measurement). Now, it is possible to use several mirrored targets that are tracked in a rapid succession. Therefore small displacements can be observed nearly on-line.

5. CONCLUSION

The TASA concept has been presented for the first time in 1992 [5]. Five years later the realignment of about 70 % of the accelerator elements at GSI is finished successfully.

TASA is specifically designed for polar alignments based on the above described hard- and software. However, while preparing the new alignment concept great importance was placed into the compatibility with regard to development of instruments in order to avoid a repeated change of the alignment method. Using the laser tracker for alignment tasks was not possible only two years ago. Now, another software module will be inserted to be able to process the data receiving from the laser tracker within TASA.

The advantage of a laser tracker in comparison to the alignment procedure with the LEICA TC2002 is the ability to control the motion of the component during the alignment on-line. However, in order to carry out network measurements it is always necessary to apply the TC2002 and mobile pillars. Due to the GSI characteristic of separating the accelerator subsystems by movable concrete blocks there are no fixed points on a wall or ceiling that could be used by the laser tracker for repeatedly free stationing.
GSI possesses no laser tracker on their own. All jobs with the SMX Laser Tracker are done by Metronom GmbH.

The authors want to express their appreciation to Dr. G. Moritz from GSI for suggestions, continuous support of our work at GSI and helpful information.

6. REFERENCES

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