Precise Alignment of Magnetic Quadrupole Axes for PETRA III

Bernward Krause, Alexander Petrov, Johannes Prenting, Markus Schloesser, Klaus Sinram, all
Deutsches Elektronen-Synchrotron DESY

***Abstract*—For the alignment of the magnetic axes of PETRA III quadrupoles the tolerances are very tight. The accuracy requirements by the machine optics for the magnets in one girder cell are below 50 µm in both lateral and height. This leads to a girder concept commonly used in several synchrotron facilities around the world. A new alignment concept using multiple laser trackers is shown in detail and the principle of adjustment is explained. A new concept of rigidly connecting the magnets to the massive girder structure is shown, which is very effective in terms of stability and nevertheless cost efficient. Experiments show the feasibility of these ideas and prove an alignment accuracy well below 40 µm. The results of dynamic analysis of this new girder system are shown.**

***Index Terms*—alignment, magnetic axes, PETRA III, modal analysis**

I. Introduction

WHILE the alignment tolerances especially for some components of the new 1/8th of the PETRA III ring are very tight, the downtime allowance for survey tasks is low. This leads to a concept of placing magnets on girders, as it has been done already at other synchrotron light sources. This approach has two major advantages: First, the precise alignment of components on the girder can be done outside the tunnel in an air-conditioned and quiet environment. Second, it is possible to keep some girders readily assembled in stock, to be able to change them quickly in case of a defect. This optimizes downtime requirements.

The standard deviation for the alignment of magnets on one girder with respect to each other (intra-girder) in lateral and height must not exceed $\sigma_{lat,h}$ = 50 µm. The standard deviation for the girder to girder alignment (inter-girder) is $\sigma_{lat,h}$ = 100 µm. In longitudinal direction the situation is somewhat relaxed with σ_{lon} = 500 µm [1].

However some aspects of this girder concept need to be addressed thoroughly to avoid problems with the installation later on. First it has to be guaranteed that the alignment tolerances are still maintained, when the girder is placed in the tunnel, i.e. no uncontrolled permanent deformations may occur during transport. Second, the girder has to meet certain requirements concerning its dynamic behavior, which to a certain extent contradicts the requirement of mechanical stability.

II. Measurement Principle

All the PETRA III girder magnets are fiducialized individually. For the dipoles it is sufficient to measure the mechanical center of the gap and to transfer these coordinates to outside monuments attached to the magnet. For the quadrupoles, however, the situation is more complex. The fiducialization of the quadrupoles is done by determining the magnetic axis with the rotating coil method, the axis of the coil is then measured optically and transferred to outside monuments. The fiducialization of the new PETRA III quadrupoles is described in detail in [2].

After the magnets are placed on the girder they are coarsely aligned with laser trackers in a common coordinate system which is roughly oriented to the girder axes. This is done to make the installation of other components, such as vacuum chambers, beam position monitors, absorbers, etc. possible.

All subsequent installations on the girder and the magnets are performed prior to the precise alignment of the magnets to prevent additional displacements of the magnets with respect to the girder. That applies even for power and water connections on the magnets which are installed and then attached to the girder with a strain relief.

As a last step the girder is transported into a climatized room in the new PETRA III hall. After the girder has reached the specified temperature the magnets are precisely aligned. Because there is no accurate representation of the girder coordinate system, it is no longer taken into account. The magnets are aligned *to each other* with an accuracy of σ_P = 10 µm / σ_R = 10 µrad.

A. Coarse Alignment

A coordinate system of the girder is defined by measuring the surface and the edges of the girder. This system represents the mechanical axis of the girder to better than 1 mm. This tolerance is sufficient for all the subsequent work on the girder and has no implication for the fine alignment, which is done without reference to the girder.

After all the magnets have been coarse aligned the remaining error with respect to the girder system is less than σ_P = 300 µm / σ_R = 300 µrad. The relative accuracy between magnets is better by factor three, that is σ_P = 100 µm /

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B. Krause, A. Petrov, J. Prenting, M.Schloesser and K.Sinram are with the Deutsches Elektronen-Synchrotron DESY, 22607 Hamburg, Germany (+49-40-8998-2943; fax: +49-40-8994-2943;
e-mail: markus.schloesser@desy.de).

σ_R = 100 µrad.

B. Precise Alignment

During the precise alignment process the magnets are positioned to each other with an accuracy of σ_P = 10 µm / σ_R = 10 µrad. Two laser trackers which are precisely related to each other are measuring simultaneously to accomplish this rather tight accuracy requirement (Fig. 1). Besides that a very well climatized room with temperature stability below 1 K is needed.

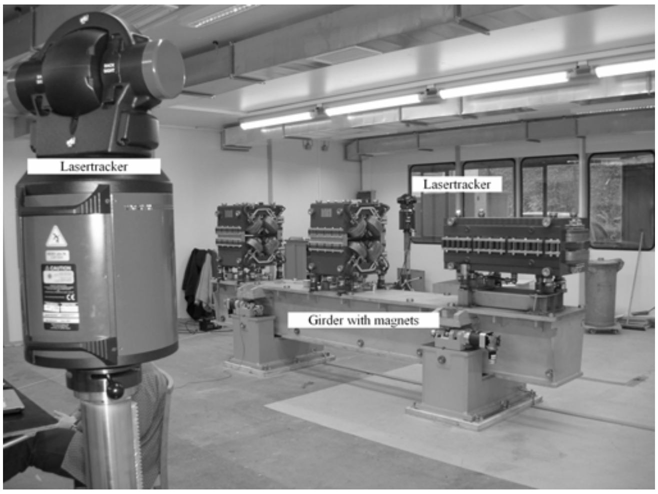

Fig. 1. Girder with magnets and two laser trackers installed in a climatized room for precise alignment.

It is important to note that the mechanical girder does not bear any coordinate information. All information about the girder coordinate system – which is the common coordinate system of all the magnets on the girder – is contained in the collectivity of the magnet monuments.

III. Mechanical Considerations

A. Positioning of Magnets

To be able to reach the desired accuracy of the magnet positions they have to be adjustable with a resolution well below 10 µm. This is done by using the standard DESY turnbuckle & ball-shaped height screw system with fine threads.

Each magnet is placed on three ball-shaped height screws on hardened steel plates. Translation in Z (height), as well as rotations around X and Y (horizontal axes) are done with these screws. Two turnbuckles in lateral direction are used to move the magnet along Y (lateral girder axis) and perform the rotation around Z, the longitudinal shift along X is done by an additional turnbuckle.

This leads to a system of independent motion for each shift and each rotation, resulting in a very effective and easy way of aligning the magnets.

B. Ensuring position stability of the magnets

While the height screws and turnbuckles are secured after adjustment, they are by no means rigid enough to ensure a position stability of the magnets in the 10 µm level during the transport of the girder. To make a sufficiently stable connection the magnets are glued to the girder by a two component epoxy which is radiation hard and is almost shrinkage-free.

Each magnet has four stable feet which fit into four corresponding pots that are welded to the girder. The remaining gap between foot and pot is about 5 mm in each direction. This gap is filled with the two component epoxy after the precise alignment of the magnets. After curing of the epoxy the connection between magnets and girder is stable enough to ensure the position stability of the magnets even during rough treatment of the girder (see IV).

C. Transport of the girder

Experiments have shown that it is essential to avoid a shift of moments in the girder during transport. That means that it is crucial to insert the forces during transport in exactly the same positions at the girder as during operation and alignment. Furthermore the insertion of forces should be strictly vertical. A special traverse (Fig. 2) has been constructed to accomplish that.

Fig. 2. Girder with traverse, force insertion is in the same position as the stands.

IV. Stability tests

The mechanical stability of the girder system has been checked in various scenarios. It has been found that the position stability of the magnets can be guaranteed during normal transport by crane. Even after hard treatments (e.g. hard drop to the ground) a displacement of magnets could not be detected within the measurement accuracy of σ = 10 µm.

To detect displacements of magnets the shift of the outside monuments caused by the relevant mechanical treatment of the girder has been measured. Because the measured shifts are generally very close to the measurement accuracy of the laser tracker system the resulting shifts have been divided into classes. If there is no shift of the magnet, the frequency of occurrence should follow a normal distribution. If the magnet did move in one direction the curve would be off-center, a rotation of the magnet would result in two peaks in the function.

Tests showed that no displacement of magnets is detectable if the girder is transported by crane through the hall (Fig. 3). Even if the girder was dropped hard to the ground (also by crane) the results did not vary significantly.

However, if the girder was smashed laterally into a concrete wall some scattering of the magnets occurred (Fig. 4).

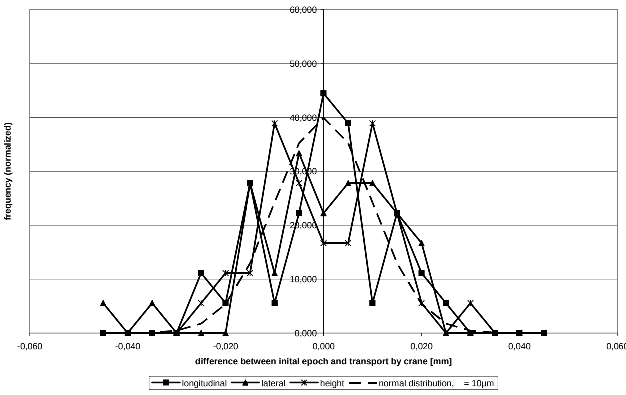

Fig. 3. Frequency of differences between initial epoch and transport by crane. All the curves follow the normal distribution in first approximation, i.e. no movement has occurred.

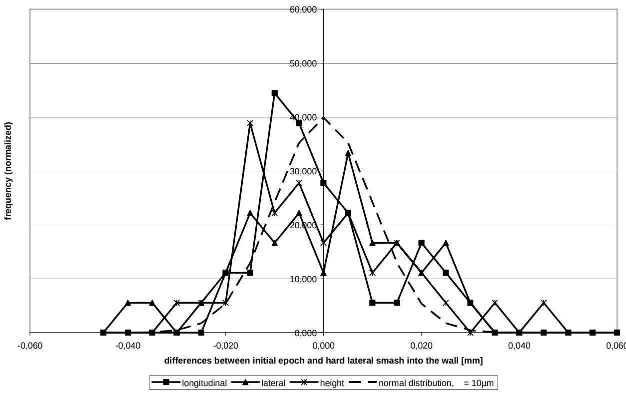

Fig. 4. Frequency of differences between initial epoch and lateral smash into a concrete wall. All the curves are off-center, lateral and height seem to be flattened somehow. A (small) movement of the magnets has occurred.

V. ACCURACY

The alignment process consists of several steps which contribute to the overall error budget as shown in Table I.

TABLE I Error budget of single steps

Source of error	**Size of error σ (µm)**
Determination of magnetic axis	5
Center of revolving target circle	5
Measurement to single monument	20
Accuracy of mechanical adjustment	10
Shift of magnets during transport	<10

By using the law of error propagation the accuracy of the different tasks can be determined as shown in Table II.

TABLE II Error budget of alignment tasks

Source of error	**Size of error σ (µm)**
Fiducialization	21
Adjustment of magnets on girder	22
Transport	<10

Combining these tasks to an overall accuracy leads to

$$\sigma_{total} < 32\ \mu m$$

which is well below the required accuracy of $\sigma_{req} = 50$ µm.

VI. DYNAMICS OF GIRDER

As accuracy requirements are very tight the dynamic behavior of the girder system (stands, girder, fixation elements and magnets) has to be taken into account. A modal analysis of the girder system has been made, showing the first vertical mode of the girder at 116 Hz (Fig. 5).

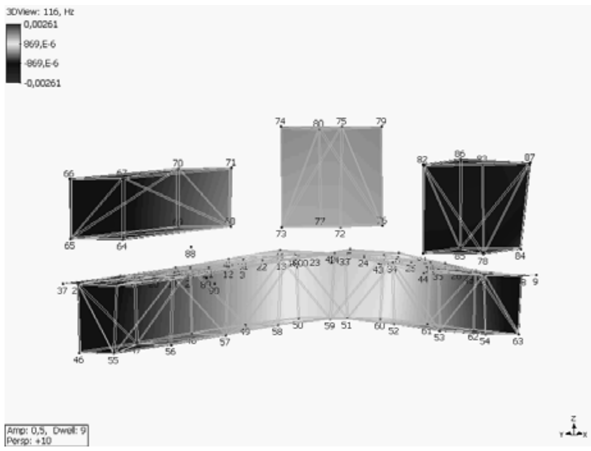

Fig. 5. First vertical mode of complete girder at 116 Hz

Transfer functions between floor and girder have also been estimated. As there are no spectra for the new PETRA III hall available yet, the goal is to have as little modes as possible especially in the range below 50 Hz. Fig. 6 shows a transfer function between bearing of the girder and middle magnet. The mode at 116 Hz shown in Fig. 5 can be found at 118 Hz here, because the two experiments were carried out with different girder systems. It is essential that there are only weak modes at 8 Hz and 24 Hz with a magnitude of 3. Modes above 100 Hz can be neglected, because the amplitude of ground motion in this frequency range is generally very small.

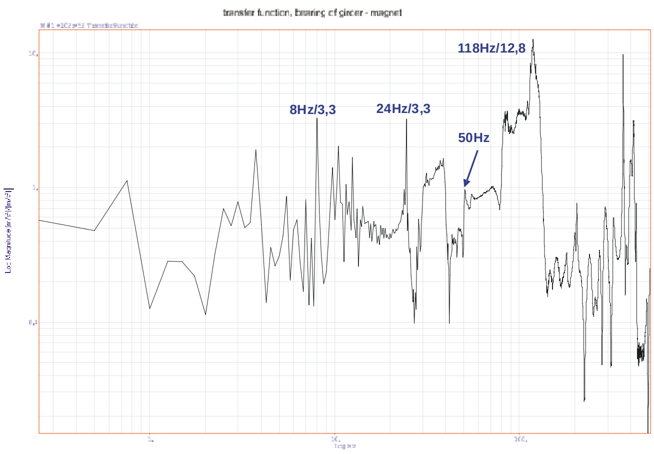

Fig. 6. Transfer function between bearing of girder and middle magnet for the vertical axis. The first dominant mode is at 118 Hz, only weak modes below 50 Hz, no modes in the region around 50 Hz.

VII. SUMMARY

A precise concept of aligning magnetic axes of quadrupoles and dipoles on girders has been developed. The accuracy is as low as $\sigma < 32$ µm for the relation between two magnetic axes on the same girder. A new method of rigidly connecting the magnets to the girder has been used, the stability of this connection has been proved. The dynamic behavior of the girder system has been checked.

REFERENCES

[1] DESY, *The Technical Design Report (TDR)*, *"PETRA III: A low Emittance Synchrotron Radiation Source"*, DESY 2004-35, Germany, February 2004.

[2] Y. Holler, B. Krause, A. Petrov, J. Prenting, M. Schloesser, Precise transfer measurements of the magnetic axis to outside monuments, *IEEE Trans. Appl. Supercond.*, submitted for publication.