

# START OF CONSTRUCTION FOR THE INTERNATIONAL FACILITY FOR ANTIPROTON AND ION RESEARCH (FAIR) – ASPECTS OF SURVEY AND ALIGNMENT

I. Pschorn<sup>#</sup>, T. Miertsch<sup>+</sup>, GSI, Darmstadt, Germany

## Abstract

After years of intensive planning, the construction work for the new accelerator facility FAIR, located next to the existing GSI Helmholtz Centre for Heavy Ion Research in Darmstadt / Germany, has finally started. As first action in December 2011, the forest clearance was done, the construction area was prepared and dedicated construction roads were built. The accompanying activities for establishing a spacious 3D surface point network for building survey, monitoring and later for linking the different machine positions to each other, are still ongoing. Other comprehensive measures are the structural monitoring of the existing GSI buildings and machines.

Less eye-catching for the public was the contracting of the series production of 113 superconducting dipoles for the synchrotron SIS100. Prior exhaustive tests on prototypes included investigations on deformation of the cryostat by photogrammetric means as well as on deformation and movement of the cold mass vs. its cryostat under different conditions, performed by conventional geodetic instruments. Measurement procedure and results are shown here.

## FAIR NUMBERS

FAIR is one of the biggest research project and most complex accelerator centre of the world [1]. The facility is dominated by the new superconducting double synchrotron SIS100/SIS300 with a circumference of 1,100 m that will be installed about 17 m below ground. An extensive system of storage rings and experiment stations go along with it. The existing GSI accelerators will be upgraded and integrated into FAIR in order to use them as pre-accelerator and injector.

For this purpose a construction site on the scale of 200,000 m<sup>2</sup> was prepared in the first months of 2012. After final completion that is aimed for 2018 a total of eight circular and two linear accelerators together with approx. 3,500 m beam transport lines will be installed here. Besides a lot of other devices such as ca. 400 beam diagnostic devices, about 500 superconducting magnets and composite modules and approx. 1,000 normal conducting magnets of 64 types with weights from 100 kg to 100 t are to be designed, developed, constructed, tested, fiducialised, installed and aligned. They will be encased by 24 new buildings and tunnels, which need roughly

600,000 m<sup>3</sup> concrete and 35,000 t steel. Due to possible radiation the tunnel walls will partly show a thickness of 8 m.

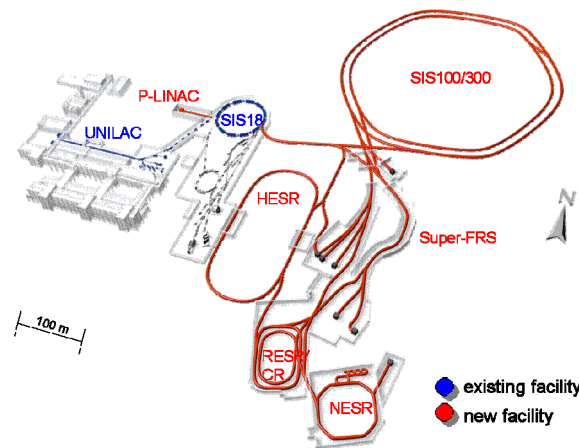


Figure 1: Layout of FAIR (red) together with the existing SIS18 and UNILAC (blue)

In order to provide a stable foundation and to prevent a descent of the heavy buildings into the forest soil, about 1,500 bored piles with a diameter of 1.2 m will be drilled into the ground, which will reach a depth of -60 m below unspoiled land. This starts probably in fall 2012. Nevertheless, building settlements of totally up to 0.3 m needs to be reckoned according to a dedicated structural study, but just 0.06 m after the scientific assembling.

Among other unnamed important numbers: The total investment costs until 2018 for the final completion of FAIR is currently estimated to 1.6 billion euro.

## INTERFACES BETWEEN BUILDING SURVEYING AND ACCELERATOR ALIGNMENT

GSI's survey and alignment (S&A) team is forced to concentrate on high precise measurements at accelerator components within the machine and experimental areas, including influence on magnet design, component supports, shielding et al. For all preliminary and construction survey concerning FAIR an external surveying company was necessarily contracted. Since some of these works have influences on the later installation of the accelerator machines, the two parties are in close collaboration on these points. Two subjects will be presented as examples.

<sup>#</sup> i.pschorn@gsi.de

<sup>+</sup> t.miertsch@gsi.de

### Surface point network

A surface network is - from the alignment point of view - needed for the absolute orientation of the connected machines (existing and planned) in space and relative to each other as well as to strengthen and to increase the accuracy of the later tunnel network(s). This surface point net is to be consolidated and transferred into the single machine buildings and tunnels. A two-tier three-dimensional reference machine network has to be established that finally serves as a basis for the alignment of each accelerator component.

A basic primary network is - from the building surveyor's point of view - needed to transfer the complex geometry of the buildings and technical installations into real site (marking out) as well as to survey and monitor during construction.

The two objective call for vertical sight shafts, concrete or steel pillars and consoles, floor points etc. that should be designed and configured to be used with synergetic effect.



Figure 2: Monument nearby the cleared construction site

A quantity of 31 newly installed monuments and 5 existing pillars are already distributed over an area of about 1.3 km x 1.3 km. The great number of monuments results amongst others from the thick forest, which surrounds the construction site and which prohibits largely the use of GPS/GNSS technology. Most of these points will be affected by the construction activities, so that some monuments are placed outside the concerned area.

According to DIN 18710-1 standard the required accuracies for the surface network points are  $1 \text{ mm} < \sigma_L \leq 5 \text{ mm}$  in position and  $0.5 \text{ mm} < \sigma_H \leq 2 \text{ mm}$  (high accuracy) respectively  $\sigma_H \leq 0.5 \text{ mm}$  (very high acc.) for the height.



Figure 3: Cleared construction site next to existing GSI halls (seen from east) ©Niko Schneider

Appropriate simulation computations for the estimation of achievable accuracies and reliability were done (see fig. 4): a combined 1D+2D network, based on the use of total station and digital level, was chosen, which yield to mean standard deviations of  $0.7 \text{ mm}$  ( $\sigma_L$ ) and  $1.4 \text{ mm}$  ( $\sigma_H$ ); a pure 1D network, e.g. for monitoring tasks, is predicted to achieve a standard deviation of  $0.3 \text{ mm}$  [2] \*\*\*. In consequence the prospective point accuracies cope with both purposes.

The real network measurements, which contain amongst others 34 km leveling distances, are planned to be carried out in fall 2012.

### Structural monitoring

During construction of the FAIR buildings, the operation of the existing GSI accelerators shall be continued; at least until work for the linking building between old SIS18 and new SIS100 starts, which is currently scheduled for 2015. The overall mass of ground that needs to be removed due to the huge construction pits together with a previous needed strong lowering of the groundwater is supposed to lead to ground settlements, which will appear at existing GSI buildings and tunnels and thus on the accelerator machines, too.

#### Buildings

For this reason a first precise leveling campaign was carried out before starting the development measures for the construction site \*\*\*. A number of bolts and floor points, installed at parts of possibly concerned buildings (fig. 5), were measured as an overestimated network. These measurements serve as preservation of evidence and clarification of reasons for possibly occurring structural damages caused by the construction activities.

According to DIN 4107 standard the required accuracy for height differences was defined to  $\sigma_{dH} \leq 0.5 \text{ mm}$ ; a value, which was deemed to satisfy a reliable information about building deformation.





Figure 4: Basic primary network

After accomplishing the first real measurements during winter 2011/2012, which serve as reference measurements, a mean standard deviation of 0.2 mm ( $\sigma$ ) was reached after adjustment calculation [3].

The first following measurements are actually done in order to detect possible seasonal effects (winter vs. summer). The next sets of measurements shall be performed after the first lowering of the groundwater, and again after appropriate occurrences (another groundwater lowering or enrichment, load changes, identification of very critical areas etc.). Data are to be interpreted by deformation analysis.

#### Accelerators

The actual position of as critical classified machine parts have also to be precisely known before starting groundwater lowering in order to be able to verify the amount of movements and deformations caused by construction works for FAIR. Appropriate measurements shall be linked to the leveling results for the buildings. Adequate activities are supposed to start within the next shutdown period. It is preferred to do 3D measurements of magnet's alignment fiducials with laser tracker combined with digital leveling of existing floor and wall points, and not to perform pure 1D measurements like outside. However, the particular amount of work and cost effectiveness needs to be weighed up against each other.

The installation of (online) monitoring systems, like hydrostatic level systems or similar, is not economically justifiable, because it is actually planned to operate the existing GSI machines just until the end of 2014. After upgrading the linear accelerator UNILAC and

synchrotron SIS18 and subsequent to the completion of the major construction works an overall re-alignment of the GSI machines is surely unquestionable.

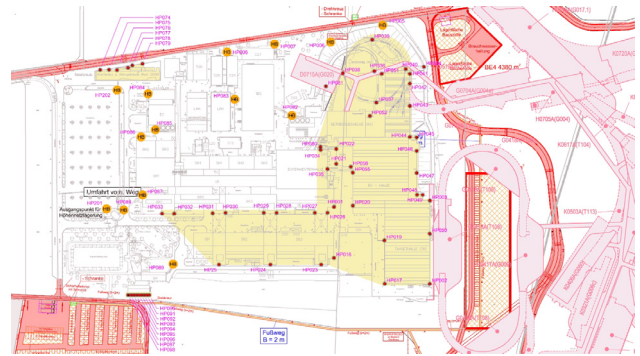


Figure 5: Point distribution for deformation monitoring at existing GSI buildings (pink labeled)

### TESTS ON SUPERCONDUCTING DIPOLE MODULES: DISPLACEMENT AND DEFORMATION

The projected FAIR synchrotron SIS100 will accelerate heavy ions and protons which will be bent by 112 superconducting dipole modules, placed along the theoretical particle trajectory. The 3 m-long dipoles have a curved shape and are enclosed in a cryostat, where they are suspended with four pairs of crossed, opposing load and tie rods (fig. 6, 7). This suspension system should keep the magnet central axis symmetrically within its initial position although the yoke is shrinking and stretching during cool down and warm up processes.

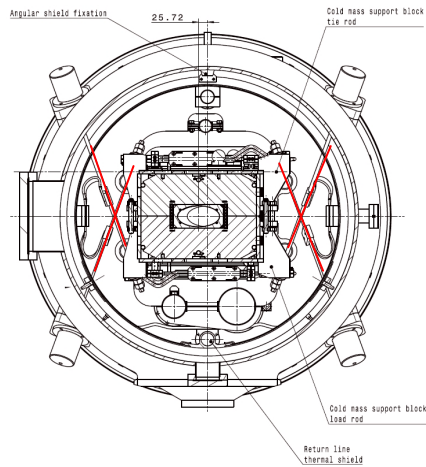


Figure 6: Cross-section of the dipole module with suspension rods (red)

Two prototypes of the dedicated dipole were extensively tested during the last years. Concerning alignment aspects, one of the questions to be answered was the behavior of the dipole yoke with respect to its surrounding cryostat during pumping processes, thermal cycles and after transport. More applications arose later (e.g. position after a quench etc.).

Further interest existed in the stability of the cryostat itself, particularly at the zones next to the suspension points and the fiducial points. The latter will serve for survey and alignment in the tunnel, because the dipole will not be directly accessible after installation on its final place.

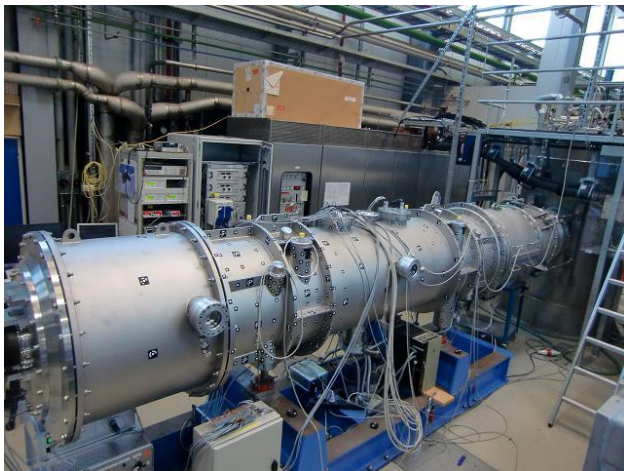


Figure 7: Prototype of a superconducting dipole module for SIS100 on the test bench

The first was done with existing 3D measurement equipment, while possible deformation of the cryostat was investigated by photogrammetry, too.

\*\*\* Work carried out by Heinen & Fischer, D-64846 Groß-Zimmern  
 \*\* Work supported by Metronom Automation GmbH, D-55130 Mainz  
 \* Work carried out by sigma3D GmbH, D-48712 Gescher

## Magnet movement and yoke deformation

For financial reasons there was for a start no explicit development of a totally new measuring system for monitoring the displacement of a (in operative phases) non-accessible magnet at temperatures of 4 K. In fact, an existing KERN E2 theodolite combined with a FARO SI.2 laser tracker and supplemented by suitable tools for lighting and sighting together with an appropriate measuring methodology were chosen in order to be able to detect movements and deformations of the magnet yoke at least in vertical and longitudinal direction as well as its roll and tilt angle.

This measuring concept\*\* calls for three vacuum capable glass windows, integrated alongside the cryostat tank, and a number of fiducial points on the magnet. For fiducialisation purposes a number of fit bores on top of the magnet yoke, precisely known with respect to the ideal beam path, were manufactured (fig. 8a). These bore holes can be equipped with conventional pin nests for laser tracker use when the cryostat vessel is opened, but can also be fitted with customized targets (fig. 8b) which can remain in the bore holes and can be observed by theodolites during magnet operation. These targets are designed in a way, that they are both visible in one line of sight. They are able to survive repeated cool down and warm up processes from about 297 K to 4 K.

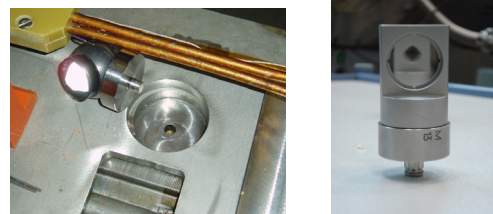


Figure 8a: Fit bore in dipole yoke  
 Figure 8b: Customized targets

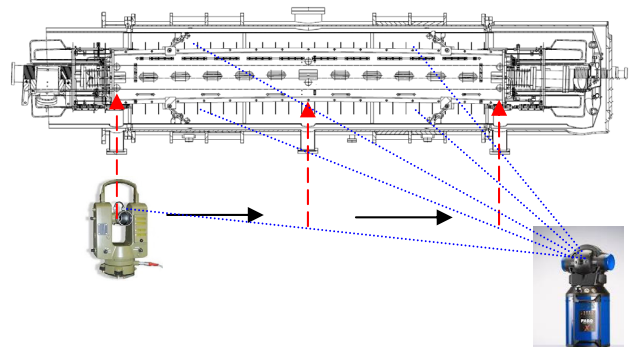


Figure 9: Measurement setup in front of cryostat and enclosed sc dipole with fit bores (top view)

The theodolite is placed rectangular to the magnets beam axis, each in front of the three cryostat windows in order to observe the 6 inside targets which are located next to the edges and at the center of the upper yoke (fig. 9). Observations are possible in evacuated, cold condition of the superconducting dipole module as well as when the magnet has room temperature and the vacuum vessel is

ventilated. Correction values for the glass window and the lighting unit with its semitransparent mirror are considered. The positions and orientation of the theodolite itself in relation to the outer cryostat fiducials are precisely determined by the laser tracker. As a result of fiducialisation measurements the relation between the magnets fit bores and the cryostat fiducials in warm condition with an opened cryostat is precisely known.

Thereby it is possible to transform each measurement of the theodolite, performed in different dipole module condition, into the cryostats coordinate system, and thus to detect displacements and deformation of the magnets yoke with respect to its surrounding cryostat.

This measuring procedure was performed at the same prototype in a total of 22 rounds during a period of 12 months, whereas 9 measurements - including fiducialisation - were carried out at warm (~297 K), 5 runs at cold (~10 K) and 8 runs at graded yoke temperatures from 18 K to 265 K \*\*. In doing so the tests were executed at very different condition of the module like opened (ventilated) and closed cryostat (under vacuum), with and without vacuum chamber and other mechanical fittings, after quenches.

The ability of this method for a defined precision of  $\pm 0,1$  mm was confirmed both by a predominant good self-consistency of measuring results and calculated theoretical values for the deformation of the yoke induced by thermal contraction, and by the high repeatability. By reason of only three glass windows alongside the cryostat and the impossibility of having a window in the end cap no information about magnet yoke deformation in lateral direction (e.g. change of the curvature radius) can be given.

From the amount of data just a few results can be mentioned here.

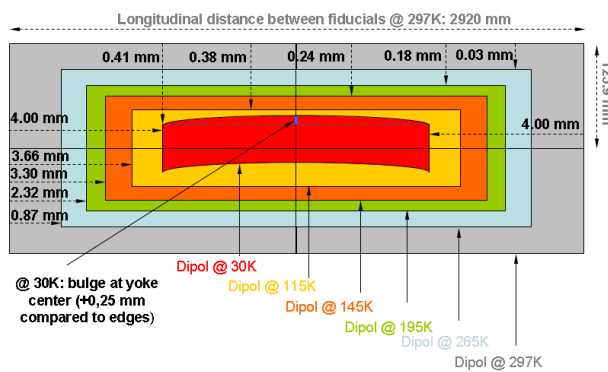


Figure 10: Schematic view of the shrinking values of the upper magnet yoke in longitudinal and vertical direction, determined at the fiducial points at decreasing temperatures (side view)

Even after a number of thermal cycles the positions of the fiducial points that are placed on the surface of the upper magnet yoke are highly reproducible with mean standard deviations of  $\pm 0.06$  mm. The data of the fiducial positions must not be seen as absolute displacements of the yoke but need to be corrected by appropriate material correction values in order to get real information about

the movement of the magnet center axis. Doing this it can be stated that this investigated dipole remains at the edges in its axial position both in warm and cold condition within  $\pm 0.1$  mm. An exception is the yoke center which shows a non explicable bulge of +0.25 mm at almost operative temperature. This likewise highly reproducible bulge appears at ~60 to 70 K and is already gone at 90 K.

In longitudinal direction there is 0.4 mm less shrinkage at each yoke side compared to the theoretical correction value (fig. 12). The reason is possibly the inhomogeneous composition of the yoke at which it is not really a proper approach to apply just one correction value [4], [5].

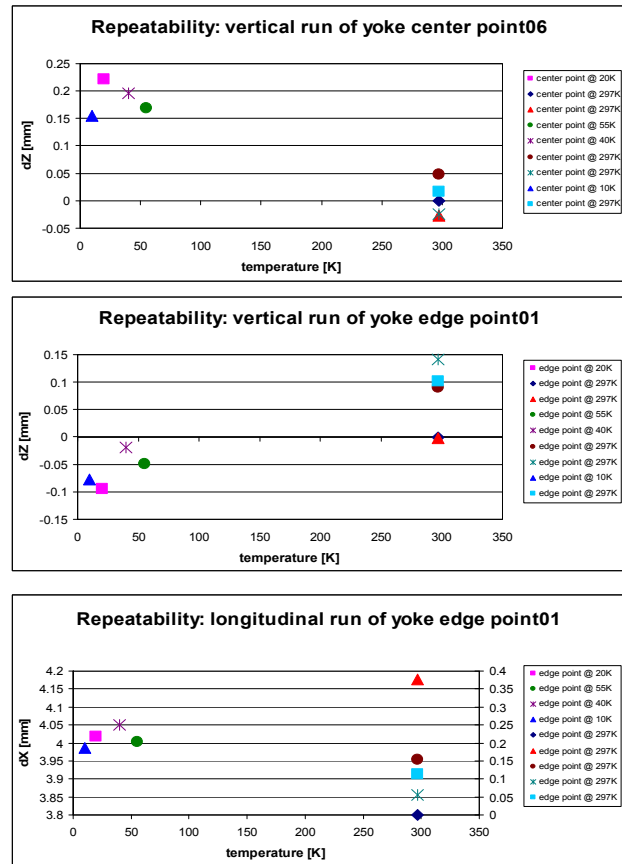


Figure 11: Repeatability of measured fit bores at the center and the yoke edge at warm and cold condition (last case: longitudinal values are not corrected for thermal contraction)

In spite of accurate and highly reproducible results coming from the measurement method explained above, its deficiencies (applied on the prototype dipole) are apparent: lateral movements of the yoke are not detectable since no observation window exists. More reliable values for the vertical shrinkage could be gained again by having more windows in order to observe the lower yoke half as well. This would cause a higher heat input at magnets operative condition that is possibly not acceptable. The online detection of displacements and deformation is not possible but solely at defined points in time. And last but not least the relatively high effort of time that is needed for each single measurement period,



will probably prevent the usage of this system for the future series magnets.

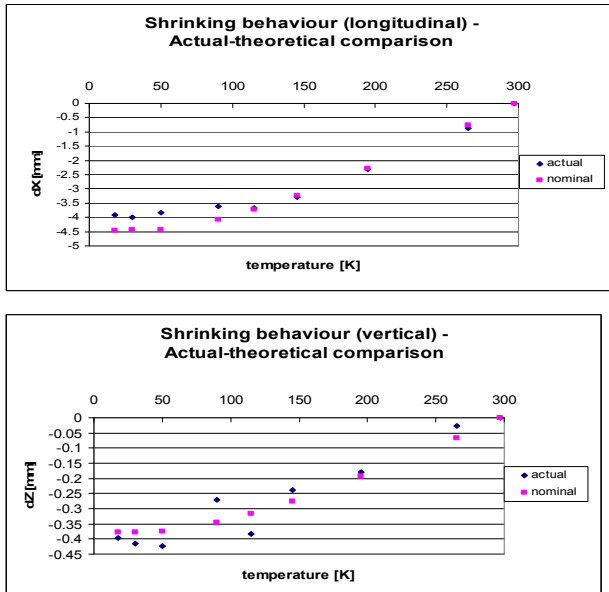


Figure 12: Comparison of averaged, uncorrected, measured shrinkage values of the dipole half yoke at different temperatures and correspondent nominal data for longitudinal (X) and vertical (Z) direction

### Cryostat deformation

All measurements for detecting cold mass movements within its vacuum vessel were related to the cryostat fiducials (fig. 13), but not to any other point around. The stability of the fiducials and thus of the cryostat shape is of high importance. These reference points hold the precise positional information of the non-accessible magnet in every different module condition and need to be quasi invariant to each other. A maximum allowed asymmetric change of position of the fiducials to each other was therefore specified to  $\pm 25 \mu\text{m}$ . This value ignores the typical effects of linear thermal expansion that purely result from different temperatures of the outer cryostat shell (that can be observed and corrected by material temperature sensors). It only considers mechanical changes that can occur due to the non-stability of the cryostat vessel (e.g. deformation by vacuum pumping, by cool-down or warm-up the cold mass or even by transport of the tank).

**A real value for the fiducial point stability** of the prototype cryostat was found by ten independent measurements with the laser tracker during the different theodolite measuring procedures at warm and cold condition. Each calculated distance between the four points was compared to its equivalent of the different measuring periods. This comparison result into standard deviations from 10 to  $29 \mu\text{m}$  which can be interpreted as the variations of the point positions including measurement errors. Weighted standard deviations due to different lengths from 0.5 m to 1.7 m between the fiducials reach values under  $20 \mu\text{m}$  [4].



Figure 13: Fiducial on cryostat

**Another stability test of the entire cryostat tank** was done by photogrammetry. The shape of the vessel under different internal pressure of 1,000 mBar to 10 mBar was to be studied, while deformations of  $0.1 \text{ mm}$  were assumed.

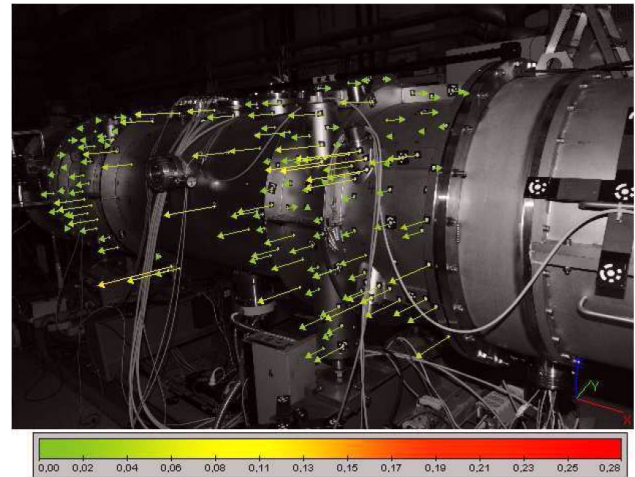


Figure 14: Exemplary vector presentation of cryostat deformations due to pumping

Using AICON DPA Pro with NIKON D3X results in mean deformation values of about  $55 \mu\text{m} \pm 15 \mu\text{m}$  (3D) [6]. No area that includes several measuring points was identified which shows systematic deformation values of higher than  $80 \mu\text{m}^*$ .

### ACKNOWLEDGMENT

Many thanks to the Heinen and Fischer company, namely Matthias Stenglein, for his enthusiasm for the project and the great working attitude.

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