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DEVELOPMENT AND APPLICATION OF HIGH-PRECISION METROLOGY FOR THE ATLAS TILE-CALORIMETER CONSTRUCTION
(Pre-Assembly Experience and Lessons)

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Разработка и применение высокоточной метрологии
для создания тайл-калориметра установки АТЛАС
(опыт и уроки предварительной сборки)

Для предстоящей сборки установки АТЛАС под землей был проведен предварительный наземный монтаж тайл-калориметра. Дано описание комплекса метрологических методов (лазерного, фотограмметрического, теодолитного, механического, а также программы PREDICTION), разработанных на решающей стадии создания установки и позволивших успешно провести сборку баррелей с высокой точностью.

Препринт Объединенного института ядерных исследований. Дубна, 2004

Batoussov V. Yu. et al. E13-2004-177
Development and Application of High-Precision Metrology
for the ATLAS Tile-Calorimeter Construction
(Pre-Assembly Experience and Lessons)

In view of the forthcoming ATLAS assembly in the pit the pre-assembly of the Hadron Tile Calorimeter BARRELS was undertaken at the laboratory hall. A complex of metrology methods (laser, photogrammetry, theodolite, mechanic, PREDICTION programme) developed at the principal stages and resulted in successful high-precision erection of the barrels has been described.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2004

INTRODUCTION

The ATLAS Hadron Calorimeter [1] consists of three so-called BARRELS of cylindrical form: a central one of 6 m long, weighing 1350 t, and two «extended» parts, each being 3 m long and weighing 700 t. The full-size calorimeter is therefore 12 m long and weighs 2750 t. The external/internal calorimeter diameters are 8.470 and 4.580 m.

Assembly of each BARREL is a complex, large-scale technological process. It is quite unique in the HEP practice:

- relative precision of $\cong 1.2 \cdot 10^{-3}$ for the diameter of the assembled BARREL;
- 10^{-4} rad precision of controlled angular dimensions

are to be achieved with the above-mentioned weight/dimensions of the full-scale calorimeter after connecting 64 MODULES per one BARREL, central and two extended.

Each MODULE is mounted and referred on a precise machined beam called the girder; actually, a single MODULE is a successive assembly of 19 prismatic sub-modules for the BARREL (9 for EBA and EBC), the girder being the common reference piece [2] for all these sub-components.

The BARREL MODULES were assembled at the Joint Institute for Nuclear Research in Dubna; the extended BARREL EBA was produced in the USA (Argonne National Laboratory) and the EBC one was made in Spain (Instituto de Fisica d'Altes Energies). The MODULE metrology control after delivery to CERN is presented in Sec. 1; more details may be found in [2, 3, 4].

The coordinate reference system for the MODULE metrology control is based on a set of Fiducial Marks (FM) [3] made directly on the MODULES. FM location measurements were carried out by a high-precision CERN theodolite method described in Sec. 2.

The pre-assembly of two calorimeters (one central + one extended) in an assembly hall revealed a number of complex technological problems, the most significant of which were *plastic deformations* of the steel shims between the MODULES. Section 3 contains the related details.

These deformations are such that if one formally follows the original assembling scenario, they will be accumulated and could bring so much together two next to last MODULES that the last MODULE #64 will fail to simply enter the gap remaining for it.

Therefore, geometrical control is necessary during the assembly process. It is based on coordinates measurements of the geodesic Fiducial Marks (FM) located on the edges of the MODULES [5].

The theodolite method highly developed at CERN gives a high precision ($\sigma_T = \pm 0.2$ mm) in 3D measurements of FM coordinates. However, theodolite data acquisition and processing of geometrical parameters of an assembled BARREL are a relatively time consuming procedure. Theodolite measurements are very well adapted to the global 3D control at important steps, but another method, even less global, should be used in the course of the day-to-day assembly.

Loading (positioning) of each next couple of MODULES changes — due to the plastic deformations of shims* — the shape of the already built part of a BARREL. Therefore one needs rather fast (synchronic with MODULES positioning) another *independent method* of pre-determining of FM coordinates of MODULES under positioning.

Such a new method based on calliper measurements and named the PREDICTION programme is described in detail in Sec. 4. Its essential features are as follows:

• we measure the distances between the FMs of each neighboring couple of MODULES with callipers and then using a special algorithm developed by us

• we determine the FM coordinates in a *local* coordinate system and transform these data (FM coordinates) into the *global* coordinate system used for the 3D controls.

As a result, we have two quite *independent and complementary* methods for BARREL assembly precision control. It would be appropriate to recall that the calliper measurement procedure is very fast whereas in the high precision theodolite method we were able to drive our measurement data towards the «final figures» only for five configurations of MODULES when assembling the BARREL.

This is of principal significance to stress that the calliper data and associated programme make it possible to *predict* FM coordinates of *not yet* positioned MODULES. The prediction precision depends on whether it is possible, and with what precision, to take quantitative account of many factors and first of all plastic deformations of shims.

The plastic deformations of shims are the leading factor determining the BARREL shape evolution in the case of positioning of new MODULES. Predictions of the BARREL geometry are being made for some fixed, «realistic» set of average deformation figures used as input data. In Sec. 5 we present and discuss the experimental data. The Conclusion summarizes the accumulated experience.

*Elastic deformations of the BARREL during its erection cause by an order of magnitude smaller change in the calorimeter shape than plastic deformations of the shims.

1. QUALITY CONTROL MEASUREMENTS OF INDIVIDUAL MODULES

The 5.6-m-long, 21-t-heavy MODULES are the main structural units of the central BARREL. The whole BARREL assembly success depends on the MODULE assembly precision:

1) A MODULE must be — by its overall dimensions — within an «envelope» whose dimensions are the nominal dimensions of the MODULE increased by the allowed tolerances.

2) Planarity of better than ± 0.6 mm must be achieved for the 5.6×1.9 m^2 MODULE side surfaces in order to guarantee the necessary safe distance between any pair of the neighboring MODULES.

To achieve of the above ± 0.6 mm planarity is not at all a trivial engineering task for a 21-t unit; yet, in fact, the practically achieved planarity was even within 0.3 mm.

The geometry of all MODULE components (girders, sub-modules) was controlled after production*. The assembly correctness of each individual submodule on the girder was controlled in their original place** and then full validation of the finished MODULE was carried out before the transportation to CERN. A high-precision laser measurement system was especially developed and used for the production and quality control of the BARREL MODULES at JINR in Dubna [6], the others having been controlled by a mechanical procedure.

Because of the differences in the techniques, possible risks of modifications of the geometry during the shipping to CERN, demanded as a validation in place to proceed to a regular control of the geometry of some of these MODULES after their delivery at CERN, especially the BARREL ones.

1.1. The Digital Close-Range Photogrammetry Technique for the Geometrical Control of the Tile MODULES at CERN

The main points to control were «the envelope» and the shape of MODULES, especially the planarity of the faces, the distance from the lateral face to the other at regular levels and the relative angle between the two lateral faces.

Several of the BARREL MODULES were also controlled independently at CERN using the JINR laser measurement system. The comparative data analysis demonstrates agreement of the measurements within ± 70 μm [2].

The control at CERN was performed on a representative set of points regularly distributed on the sub-modules. All these points must be measured in 3D space and in the same reference system to allow the calculation of the relationships

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*Bucharest, Dubna, Pisa, Prague, Protvino.

**Argonne, Barcelona, Dubna, Protvino.

between the two faces. The precision required is of the order of 0.1 mm at 1 sigma especially in the direction perpendicular to the main faces.

1.1.1. Measurement Conditions and Environment. After its delivery to CERN, each MODULE (BARREL, EBA and EBC) was put in place at an available zone, not always the same actually, for the geometrical validation measurement to be performed. One of the conditions was that the measurements should not be carried out in a dedicated location because of the lack of free zones and should be as short in time as possible.

1.1.2. Choice of the Measurement Method. The final choice of the photogrammetry and/or theodolite techniques was directly linked to those environmental conditions and also to the fact that *they were not used for the controls during the production*. Therefore those completely independent ways of controlling were all considered and finally only the digital close-range photogrammetry technique was preferred to the theodolite standard method.

The digital close-range photogrammetry allows obtaining the 3D coordinates of a′ priori targeted points placed on an object from several overlapping digital pictures taken from camera stations and under different view angles. In very good configurations and with the good rules of art applied, an uncertainty of 1/100 000 of the object size can be achieved. Considering the needs, this method is well adapted to our purpose.

Portability, easiness to use plus flexibility of the method — no dedicated area — make the photogrammetry perfectly suitable to environmental conditions: the needed space can be limited, no precise microgeodetic network is needed, as opposed to sequential point-by-point theodolite methodology, and the picturing time is far smaller dependent on the number of points than the theodolite procedure, even if the targeting time is taken into account. In order to get the connection between different faces of the measured MODULE, the overlapping pictures are taken from different positions necessarily distributed all around the object.

CERN uses a photogrammetric system (provided by AICON 3D System GmbH*) for nearly 6 years. It consists of a high-resolution — DCS 460 camera (Fig. 1) Nikkon (box, Kodak CCD 3072×2048 pixels of 9 μm) and Aicon DPA-Win software comprising image analysis functions to extract image coordinates from the pictures and a 3D-bundle adjustment program to calculate the object coordinates.

Several key options make it possible to control the internal parameters of the camera, to control the systematic by applying self-calibration procedures and the propagation of the geometrical errors.

The scale of the measured object is obtained by the addition of calibrated scale bars in the pictured model. These bars are made of carbon fibre and the

*AICON #D Systems GmbH Biberweg 30C – D 38114 Braunschweig.

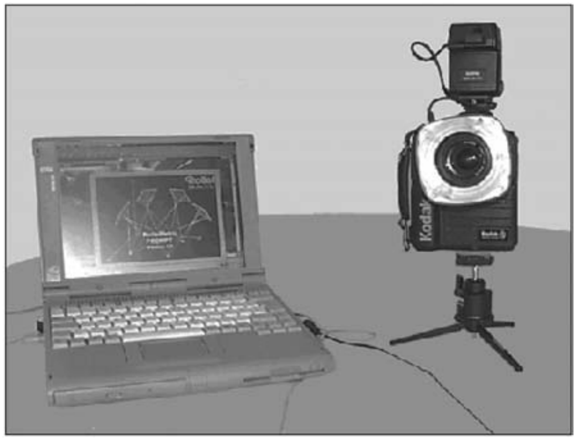

Fig. 1. View of the photogrammetry system

distance between the targets placed at both ends is calibrated with a 20 μm precision. Nevertheless it was decided to perform some additional measurements by a theodolite equipped with a calibrated distancemeter like relative spatial distances between some pictured reference points of the MODULE. These supplementary measurements improve the scale factor calculation and help to trace errors if any.

1.1.3. Setup and the Data Acquisition. The MODULE, a large «thin» structure, can be noticeably twisted (still remaining within the «envelope») by a few millimeters; a special bench made of adjustable feet was built on which the MODULE could be adjusted in such a way that the bottom surface of the girder was in a quasihorizontal plane within 0.1 mm.

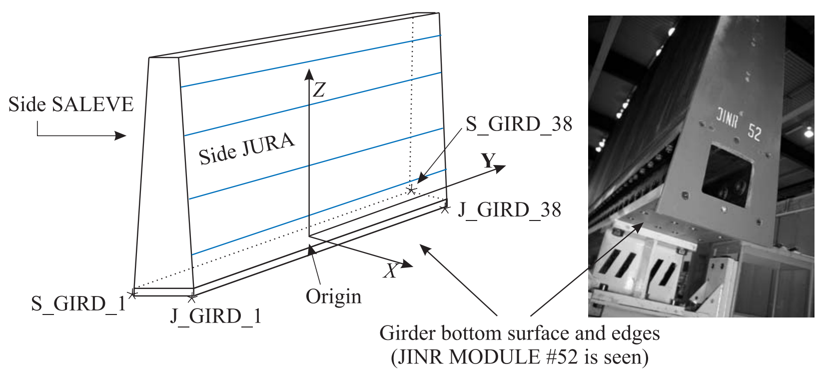

Fig. 2. Tile BARREL MODULE coordinate system

In order to get the same coordinate system (Fig. 2) for all MODULES, the accessible and well-machined bottom and edge surfaces of the girder were used to define the reference axis.

Each face (side surface) of the BARREL and EB MODULES, was equipped with 150 and 75 magnetic retro-reflective coded targets, respectively — central target diameter — 10 mm, code diameter — 30 mm, 516 different possible codes which are automatically recognized and named by the analysis software.

In addition, spherical targets of 20 mm in diameter, were placed on the top surface and on the end plates, so that they were visible from the two sides of the MODULES and could be used as common points for the geometrical connection of the two faces.

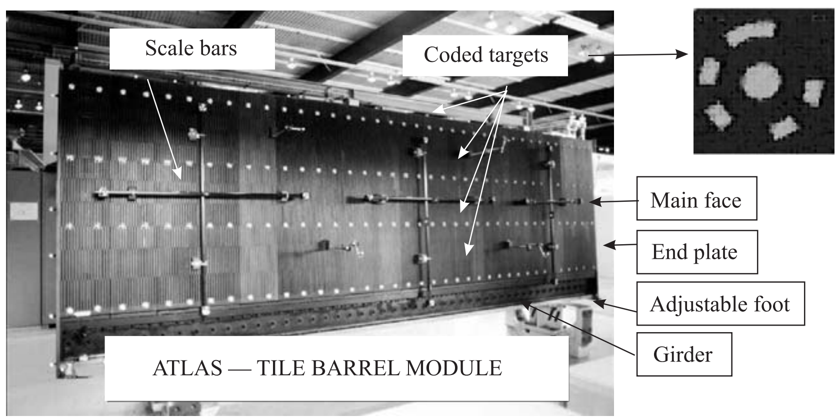

Fig. 3. BARREL MODULE equipped for photogrammetry

The camera was equipped with 24-mm focal length lens. The average distance between the camera and the MODULE being 3 m, the diameter of the image of the 10 mm target on the CCD is close to 9 pixels, 5 pixels being the lowest limit for a good reconstruction of the target image centre position on the CCD with a subpixel precision.

70 pictures were taken for each EB module and 100 — for each BARREL MODULE with a small diaphragm aperture in order to get only high-contrast retro-reflective targets highlighted with a flash against a black background on the image and to avoid parasitic effect during the image analysis.

Finally, considering very important 10 points placed on the girder for the girder plane and system definition, 150 points on each BARREL MODULE face were distributed along lines at four different levels defined by sub-modules (see Fig. 3) and some other auxiliary points such as the sphere for connection, a total of 350 points were measured for each BARREL MODULE. The total number of points for the EB modules is 200 considering that the number of targets by face is 75.

The scale of the calculated model was defined by using of 1.5-m-long scale bars calibrated with a 20-μm precision. Six of them were on each BARREL MODULE face and four — on each EB module face.

For the BARREL MODULES long distances ($\sim$ 6 m) between reflectors placed at the girder ends and on the MODULE top in the same target holders used for the photo were measured with a 0.3-mm precision by the theodolite technique.

For each MODULE installed on a special feet and with the bottom surface of the girder adjusted in a plane, one day was needed for the measurements, including determination of the relative distances with a theodolite, equipping of the MODULE with the photogrammetry tooling (targets, scale bars), image acquisition, and removal of the photoequipment.

1.1.4. Results. The geometrical validation was performed at CERN for the iron part of twelve BARREL MODULES and for eight Extended Barrel (EB) MODULES. Note that the EB MODULES were already equipped with the optical fibre inserted between the iron master-plates of the submodules.

After the image analysis, the image coordinates of the target spots on the CCD were detected with an average precision of 0.4 μm (1/20 pixel) as a result of image analysis and calculation.

Finally the bundle adjustment calculation gave the 3D position of the targets with an average precision of to 0.1 mm for each coordinate. These results were used by the Tile Team for the final analysis and acceptance.

As an example of the results obtained after the data analysis Fig. 4, *a, b* shows the offsets to the best fit plane of one face of Tile BARREL MODULE#32 and the distribution of distances to the best fit plane.

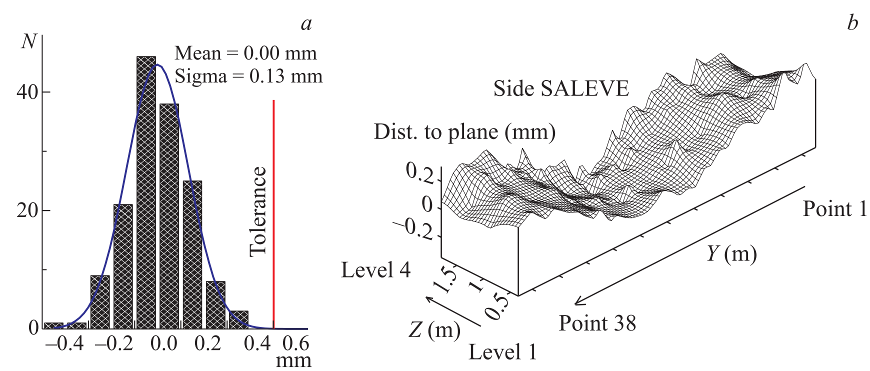

Fig. 4. *a*) Distribution of distances to the best fit plane. *b*) Distances to the best fit plane, relief («+» — point «outside», «−» — point «inside»)

As one can see from Fig. 4, *a*, the experimental planarity measured at CERN is less than 0.4 mm (for MODULE#32). These data were obtained by the photogrammetry and consequently independent confirm the same parameter measurements at JINR.

Therefore we can say with sure:

All BARREL MODULES were transported (on special transport support designed and manufactured at JINR) to CERN (~ 3000 km) without changing of their geometry.

1.1.5. Other Uses of Photogrammetry for the Tile. Photogrammetry combined with the theodolite technique was also used for the dummy weight tests (simulation for the LAr Barrel detector installed in the Tile) during the BARREL pre-assembly at the stages of 32 and 48 MODULES and for the EBA pre-assembly survey at the stage of 24 MODULES (Fig. 5).

Fig. 5. Geometrical control during pre-assembly of EBA, 18 MODULES

This combined technique will also be used for the final assembly surveys in the cavern. Some tests have already been performed for 30 MODULES with 100 shots per face (in photogrammetry) in addition to theodolite measurements for the geometrical connection of the assembled BARREL faces; the achieved precision for the coordinates of the Fiducial Marks is 0.3 mm.

1.2. Use of the Dubna LMS for Module 3D-Geometry Measurement

The Laser Measurement System (LMS) was developed in 2001 mainly by the JINR (Dubna) research team (two full size sets were produced) for the Quality Control of the main ATLAS Tile-Calorimeter elements: girders, submodules, MODULES. Recall that the most stringent requirement to the MODULE assembly is the planarity limitation within ± 0.6 mm of its side surface (5.6×1.9 m) as the tolerance gap between two adjacent MODULES is 1.5 mm to allow correct stacking of the cylinder during the final assembly.

1.2.1. LMS Description and Measurement Principle. The LMS has been designed and constructed for the control of the surface geometry of the main BARREL construction units: girder, sub-module and MODULE. Its operation is based (Fig. 6) on the measurements of the distance H(i) between the surface under control (LL') and the axis of the laser beam used as a sort of «coordinate axis» directed quasi-parallel to that surface. By positioning the quadrant photodetector (QPhD) at different positions A(i), the associated values of H(i) are determined by adjusting (with a system of microscrews) the center of the photodetector to fit the laser beam. The full surface geometry is determined by a series of such measurements.

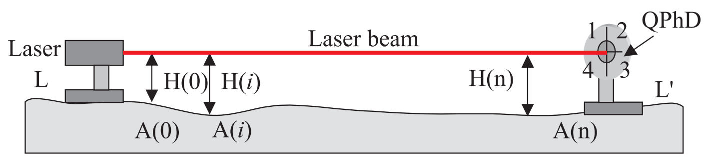

Fig. 6. Principle of operation of the LMS

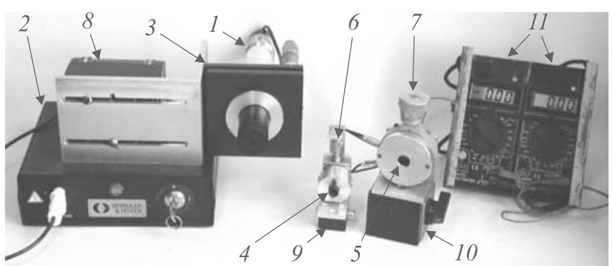

Fig. 7. The main elements of the Dubna LMS. *1* — laser; *2* — power module; *3* — adjustment module. Quadrant photodevices: *4* — type I; *5* — type II. Positioning modules: *6* — type I; *7* — type II. Magnetic bases: *8* — type I; *9* — type II; *10* — type III; *11* — multimeters

This laser axis is the line along which the laser beam has a maximum power density distribution across the beam. The main LMS components are as follows (Fig. 7):

• The laser (*1*) positioned inside the adjustment module (*3*) which allows to setting the laser beam direction with a space angle precision of 0.1 mrad for 0.1 rad of the range interval.

• The quadrant photodetector (*4* or *5*) positioned on the adjustable positioning module (*6* or *7*) which allows the photodetector's sensitive surface to be fixed perpendicular to the laser beam direction by means of microscrews. The positioning module adjustment interval is 0–5 mm with ± 5 μm precision.

The quadrant photodetector is a quadrant-type photosensor. The laser beam spot centre is considered to be at the centre of QPhD when one reaches the condition U1 $=$ U3, U2 $=$ U4 for four QPhD-generated signals.

The measurement precision is limited by the precision of the adjustment system and by the air convective fluxes, which can be noticeably improved by positioning the laser beam inside a special telescopic dielectric tube.

Multiple measurements with this LMS (production and quality control of JINR submodules and MODULES) have shown that the precision σ_h for individual H (n) measurements on a 6-m long calibrated base is $\sigma_h = 30$ μm. Taking account of the intrinsic precision — the precision of the positioning of the LMS system on the surface to be measured (specific submodule surface) — the resulting measurement precision σ_m for the entire area (1.9×5.6 m) of the MODULE side surface was found to be $\sigma_m = \pm 50$ μm [2].

1.2.2. Measurement Results for 65 BARREL MODULES. In Dubna a total of 276 individual points were measured for each BARREL MODULE. This information was stored in individual Quality Sheets on dedicated WWW pages*. The maximal planarity deviations of the side surfaces for the entire assembly of 65 JINR MODULES are presented in Figs. 8 and 9. These distributions prove that the Laser Measurement System really guarantees the high-quality MODULE assembly. All positive deviations are within the allowed tolerance ($+0.60$ mm); in fact, they mainly are by the factor of 2–3 smaller than the tolerance. The negative «$-$» deviations are more noticeable. This might be explained by a rather stable tendency of the submodule manufacturers to avoid the «drift» of the submodules beyond the tolerance in the positive deviation region.

The comparison of the measurement data obtained at JINR and at CERN shows that the maximal deviations of the MODULE surfaces from the nominal dimensions are close to each other in both series of measurements (Table 1). Although at JINR and CERN the MODULES, when measured, were twisted in slightly different ways, all our data are well within the required tolerances.

As is seen the maximal deviations measured at CERN differ from those measured at JINR because of the difference in MODULES «twists». The results of these measurements are also shown in Fig. 10 for the top line of MODULE #8. Here one can see that the measurements made at CERN agree well with those made at Dubna.

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*http://atlasinfo.jinr.ru

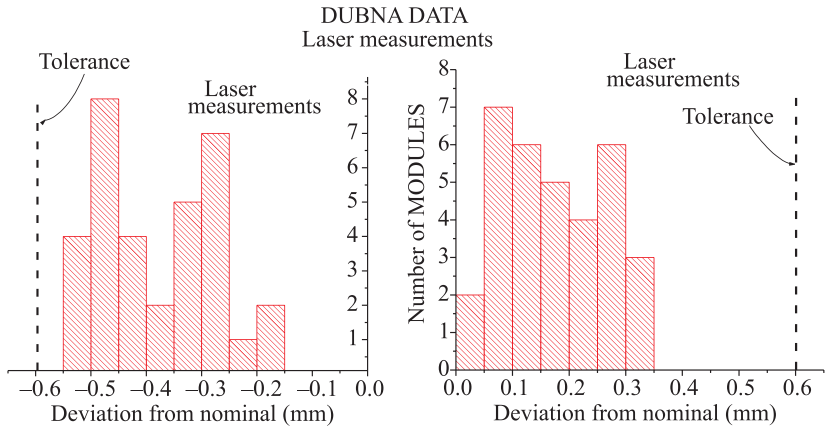

Fig. 8. Maximal negative («−») deviations of the MODULE surface from the nominal dimensions (mm)

Fig. 9. Maximal positive («+») deviations of the MODULE surface from the nominal dimensions (mm)

Table 1. **Maximal deviations from nominal values for measurements made at JINR and CERN (in mm)**

MODULE #	7	8	9	19	20	21	22	23	24	25	26
JINR	0.14	0.18	0.26	0.07	0.09	0.00	0.07	0.26	0.27	0.16	0.23
CERN	0.30	0.29	0.27	-0.01	0.11	0.03	0.07	0.14	0.31	0.15	0.11

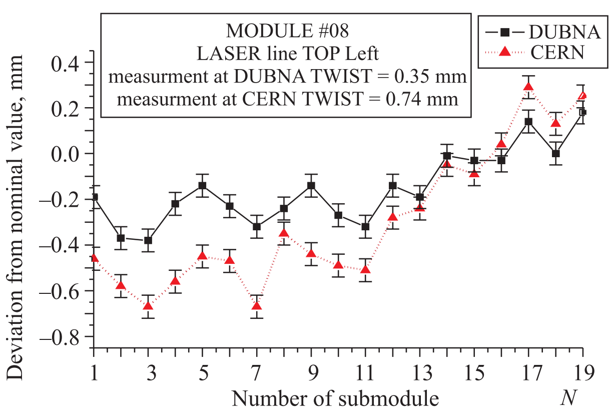

Fig. 10. Comparison of measurements made by LMS at JINR and at CERN

In general, measurements of the finished MODULE by LMS have proved correctness of the Dubna-chosen MODULE assembly procedure. It guarantees the necessary precision of submodule positioning on the girder, which resulted in that the assembled MODULES were within the design tolerances. Photogrammetric measurements at CERN confirm that no problems have occurred because of the transport from JINR to CERN.

2. FIDUCIAL MARK POSITION ANALYSIS ON THE BASIS OF THEODOLITE MEASUREMENTS

The metrology control «philosophy» during the assembly of BARRELS is based on the use of a large number of FMs on the MODULE surfaces at strategic points. The combined CERN–JINR team has attached and controlled these FMs.

In October–December 2002 the JINR–CERN TileCal Survey team performed the crosscheck of the final positions of the Fiducial Marks (FM) on the EBC MODULES. All MODULE measurement data are available as CERN EDMS publications. The results give the difference between the measured and the nominal position of 5 FM for 12 installed MODULES in X, Y and Z directions [7].

Table 2.

N	MODULE name	FM on the girder		
		X (mm)	Y (mm)	Z (mm)
1	IFA38	0.15	0.24	–0.03
2	IFA42	0.10	–0.18	–0.19
3	IFA24	0.11	–0.07	–0.01
4	IFA35	0.11	0.4	–0.06
5	IFA44	0.03	0.38	0.04
6	IFA20	–0.08	–0.25	0.03
7	IFA47	0.00	0.03	–0.12
8	IFA11	0.32	0.01	–0.21
9	IFA16	0.03	–0.03	–0.11
10	IFA36	–0.02	0.07	–0.08
11	IFA15	–0.05	0.10	0.06
12	IFA48	0.18	0.07	0.03
	AVERAGE	**0.07**	**0.06**	**–0.05**
	STDEV	**0.11**	**0.20**	**0.09**

By way of example Table 2 presents the differences between the real measurement and the nominal coordinates of some girder FMs. Figure 11 shows the difference distributions fitted by the normal curve in the X, Y, Z coordinates for FMs.

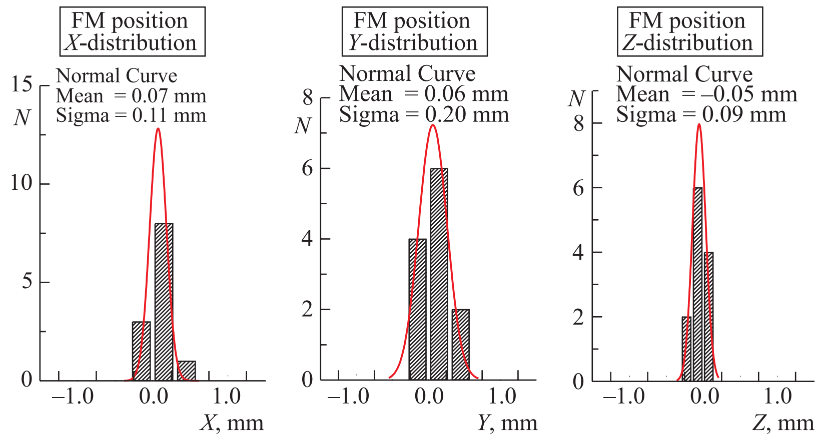

Fig. 11. Histograms of the differences between real and nominal coordinates of the FM for 12 IFA MODULES

3. PLASTIC DEFORMATIONS DURING ASSEMBLY. ACCOMPANYING METROLOGY

The BARREL assembly sequence is illustrated in Fig. 12.

At the beginning the first 18 MODULES were placed on the cradle (positions from P40 to P57). The neighboring MODULES are rigidly connected by link elements and form one unit. Then the unit is moved on the saddles and disconnected from the cradle. Figure 13 shows 20 MODULES assembled.

Noticeable deformations of shims arise after 5 or 6 MODULES are positioned over these shims. Figure 14 shows quantitatively the decrease in the distances between the MODULES caused by plastic deformations of shims (calliper measurements). These data are for BARREL inner radius after MODULE position 63 was installed. This is the stage when the maximal shim deformations have been observed.

The «shims-leak» effect is also demonstrated in Fig. 15. It shows the change of the DIFF values on the inner radius as a function of the number of the MODULES positioned additionally to MODULE #30.

DIFF is the difference between

— the nominal distance d_{nom} for FMs of the neighboring MODULES and

— the same distance d_{meas} measured by the callipers.

In our callipers-measurements the precision $\sigma_C = 50$ μm was determined experimentally.

As one can see from Fig. 15 the change in the DIFF value is quite large and reaches the level of 0.37 mm for two neighboring MODULES P34 and P35.

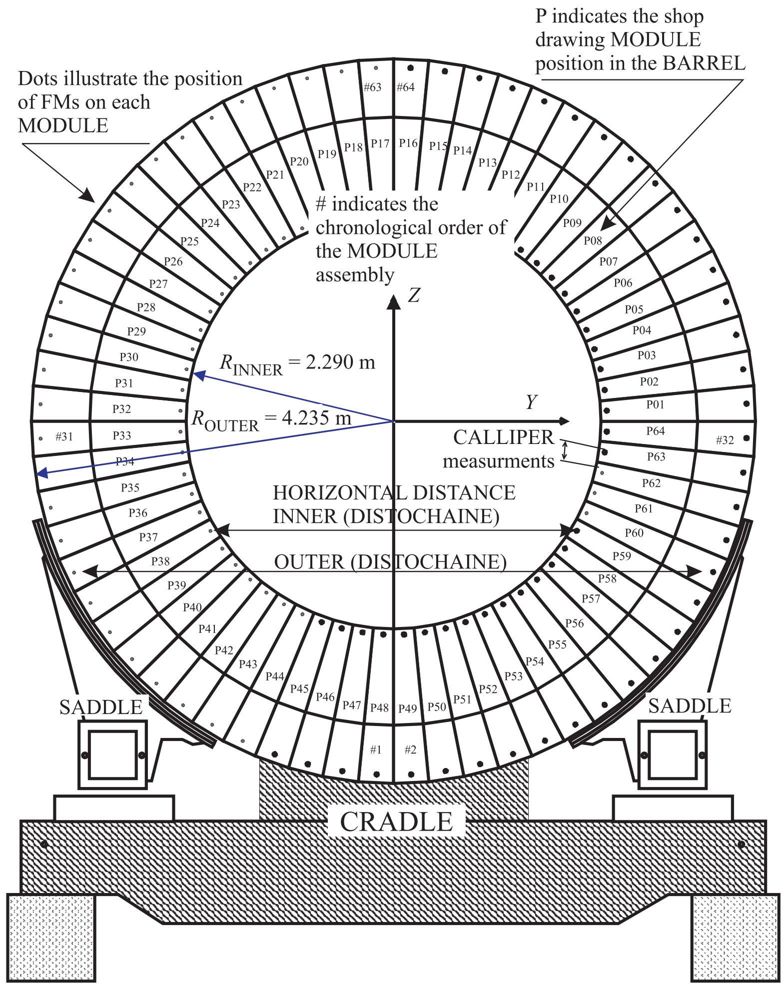

Fig. 12. External BARREL assembly general view

The «shims-leakage» effect becomes quite «macroscopic» if one measures the «deviation» which is the difference between:

— $d_{\rm nom}$ — the nominal (shop-drawing) horizontal distance between the FMs of the symmetric* MODULES, and

— the experimental value $d_{\rm exp}$ obtained by the distochaine.

*MODULES which are positioned symmetrically about the vertical plane.

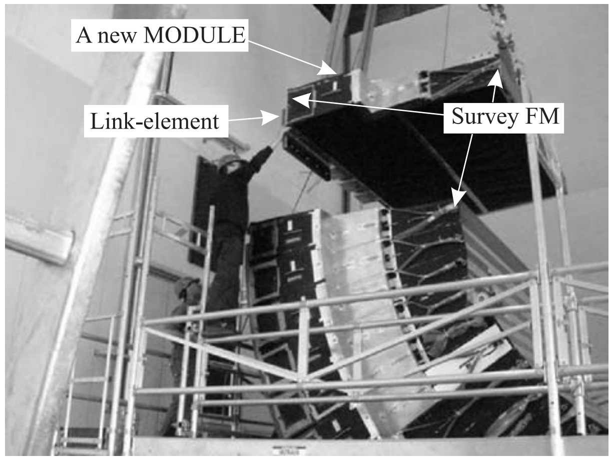

Fig. 13. A new MODULE being connected to the assembled set

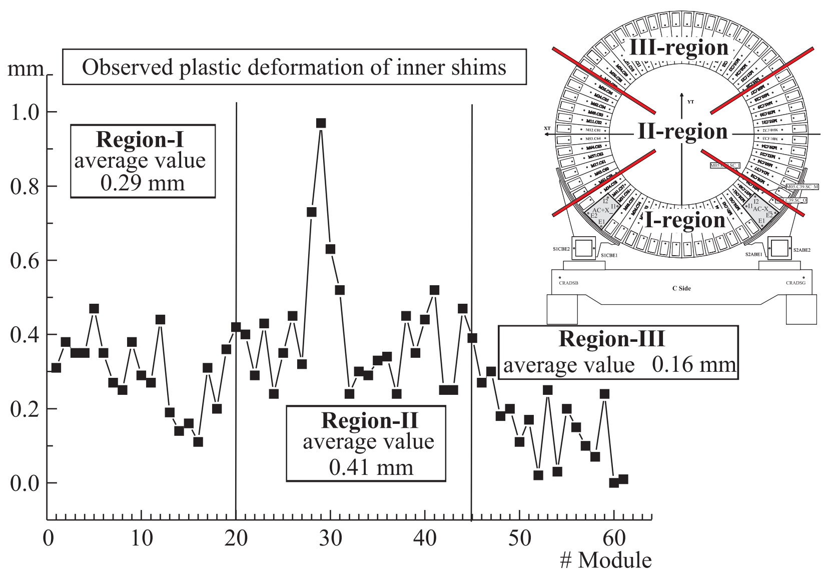

Fig. 14. Changes in distances between MODULES. Inner radius data (calliper measurements)

The distochaine (Fig. 16) is an instrument developed at CERN for simple and precise distance measurements. It is based on the use of a standard ruler

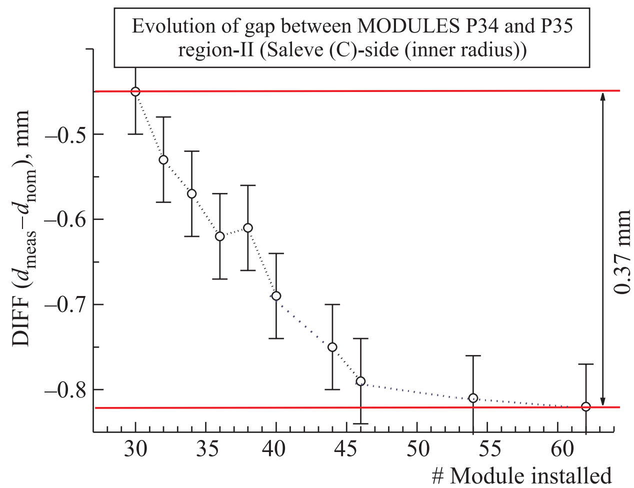

Fig. 15. Plastic deformation evolution

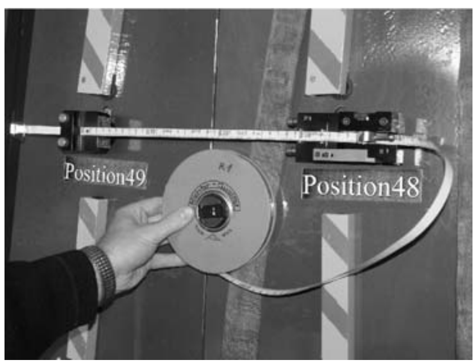

Fig. 16. Distochaine in work

(class II) stretched at a constant tension with a spring system. It can be used in any direction. The distance is read directly on the ruler and corrected with the calibration curve obtained in the CERN Calibration Baseline. The precision of distochaine is 0.3 mm.

The comparison results for the internal radius of the EBC are presented in Fig. 17. One can easily see that the MODULES are getting closer and this closeness is dangerously increasing. The MODULES in positions P42 $\div$ P43 about 26 mm closer in comparison with the nominal location (the allowed tolerance is ± 10 mm).

Summarizing one may say that:

— plastic deformations of shims are significant;

— these deformations are to be taken into account to perform an assembly with the right BARREL shape.

Thus there arose the necessity to have a PREDICTION program allowing *predictive description* of the BARREL configuration taking into account both

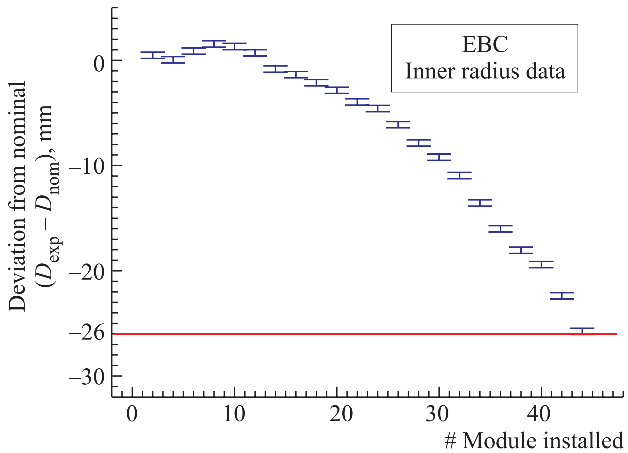

Fig. 17. «Deviation» distribution on the EBC assembly stage when 44 MODULES are positioned

coordinates of already positioned MODULES and the optimally chosen shim thicknesses for the MODULES to be positioned.

Such a PREDICTION program was developed and the data obtained with it were taken into account during the BARREL assembly.

For the input data the PREDICTION program uses the set of distances between the FMs of each couple of the neighboring MODULES.

4. THE PREDICTION PROGRAM

For easier understanding of some essential details, Fig. 18 shows as an illustration, the BARREL shape distortion against nominal data caused by shims leakage. The PREDICTION program

• determines the FM coordinates for the MODULES which have already been positioned into the BARREL and

• gives the FM coordinates of the MODULES to be installed.

The PREDICTION program describes the evolution of the shape and predicts the position of the BARREL MODULES which are yet de′ facto absent.

The input data for the PREDICTION program are:

1) The distances between the FMs of the same inner, middle, outer radii for neighboring MODULES

2) de′ facto values of the gaps between the MODULES; the gaps were found from the comparison of

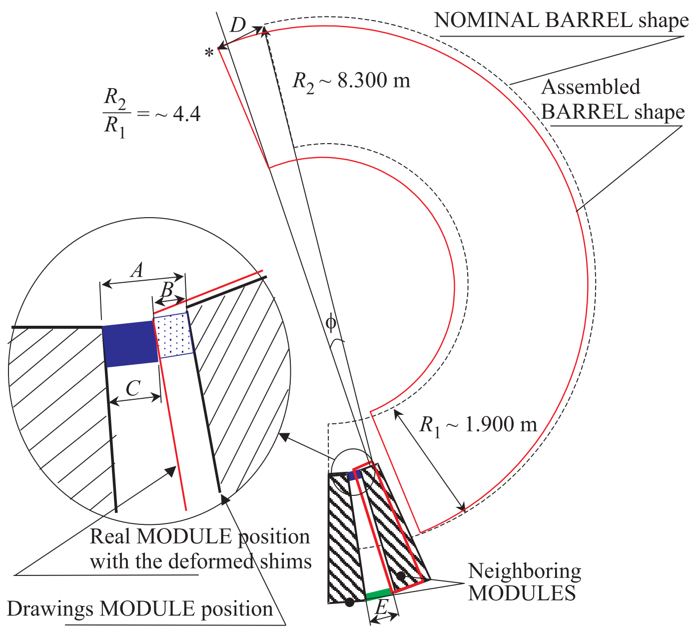

Fig. 18. Barrel shape distortion due to inner shim deformation: the point «*» in the barrel top part is shifted by ~ 2.2 mm from its nominal position. This very noticeable shift is caused by the shim thickness decrease as large as $B = 0.5$ mm. A — 1.5 mm is nominal shim thickness at the inner radius; B — $\sim$ 0.5 mm (average) is plastic deformation of the original A-shim; C — $\sim$ 1 mm is the residual shim thickness (C is the deformed shim); D — $\sim$ 2.2 mm is the cylinder top edge displacement caused particularly by B deformation. $D = B \cdot (R_1/R_2) \sim 2.2$ mm; E — $\sim$ 1.9 mm is a normal shim at the outer radius. This shim is practically undeformed

• the measured distances between the FMs of the neighboring MODULES with

• the corresponding nominal distances.

As all the above-mentioned values are related to the already assembled part of the BARREL, we recall that shims are already deformed.

3) The set of thicknesses of the shims and their deformations which are *expected* to take place for that part of the BARREL which is to be assembled. *These data are obtained from the EBC pre-assembly analysis.*

As a result, the PREDICTION program

• calculates the FM coordinates for the assembled part of the BARREL;

• determines (predicts) the FM coordinates for the not yet assembled part of the BARREL (note that the FM coordinates on the assembled BARREL part are determined anew);

• determines the differences between the nominal and calculated values of the horizontal distances between FMs of

— the already positioned MODULES and

— the MODULES to be positioned.

The FM coordinates measured by the theodolite method are presented in the Tile Coordinate System. The day-to-day data originally obtained in a different coordinate system are easily transformed to the main (Tile) system by simple linear transformations.

In the next section we present the data obtained with the PREDICTION program for the BARREL.

5. EXPERIMENTAL DATA

After putting on all the available experimental data and the calculations results to the common Tile Coordinate System we have the possibility of making the necessary comparisons.

5.1. The EBC-Data

After assembling 18 EBC MODULES we measured the distances between the FMs of the neighboring MODULES over both the inner and the outer radii.

Figures 19 and 20 show the deviation distributions. Recall that the deviation (see Fig. 12) is a difference $d_{\mathrm{meas}} - d_{\mathrm{nom}}$ between

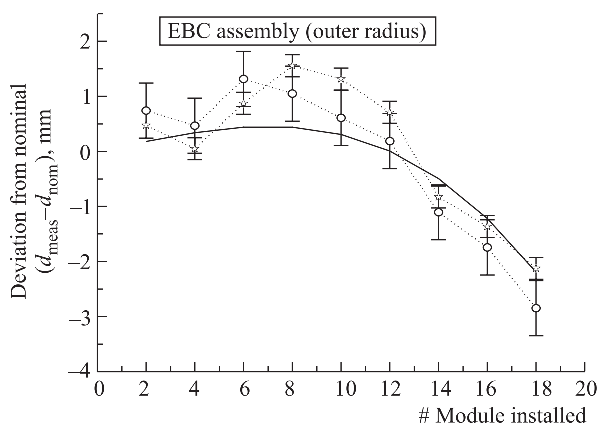

Fig. 19. EBC outer-radius measurements and calculations data. $\star$ — calculation with the use of Theodolite data; $\circ$ — calculation with the use of PREDICTION program obtained FM coordinates (calliper-based measurements); — — calculation with the use of PREDICTION program obtained FM coordinates, program input data were the average DIFF values: $\langle \mathrm{DIFF}_{\mathrm{in}} \rangle = d_{\mathrm{nom}} - 0.34$ mm; $\langle \mathrm{DIFF}_{\mathrm{out}} \rangle = d_{\mathrm{nom}} + 0.09$ mm

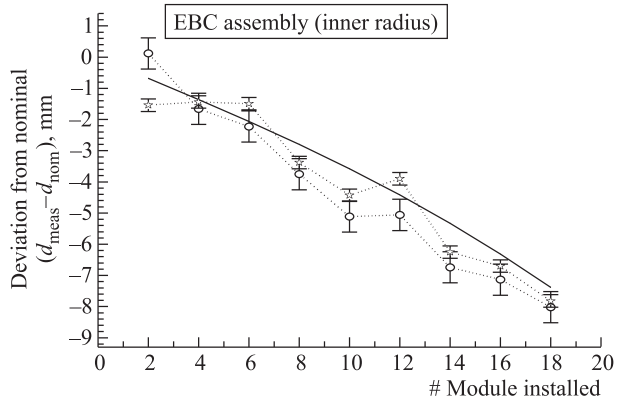

Fig. 20. EBC inner-radius measurements and calculations data. $\star$ — calculation with the use of theodolite data; $\circ$ — calculation with the use of the PREDICTION program obtained FM coordinates (calliper-based measurements); — — calculation with the use of the PREDICTION program obtained FM coordinates, program input data were the average DIFF values: $\langle \mathrm{DIFF_{in}} \rangle = d_{\rm nom} - 0.34$ mm; $\langle \mathrm{DIFF_{out}} \rangle = d_{\rm nom} + 0.09$ mm

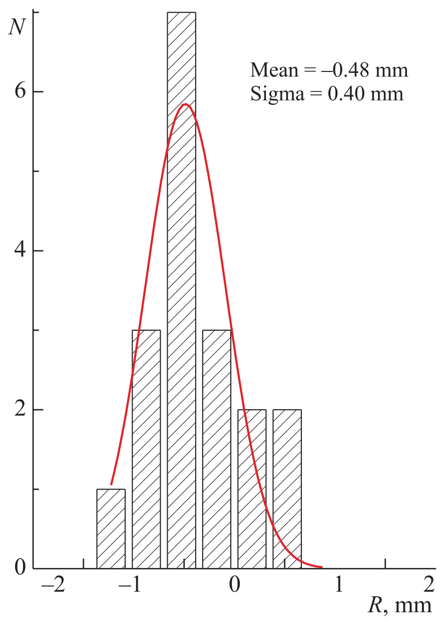

Fig. 21. Distribution of differences (R) of experimental «deviation» values (EBC) obtained by the theodolite and calliper methods (the data were taken from Figs. 19 and 20)

— the nominal value $d_{\rm nom}$ of the horizontal distance for two symmetrically opposite MODULES and

— the value of the same horizontal distance $d_{\rm meas}$ calculated with the use of two independent experimental (theodolite and calliper) data.

Solid lines in Figs. 19, 20 are the calculated deviations obtained with the PREDICTION program for the case where the FM distances over the inner radius for all MODULES were taken to be identical: $d_{\rm nom}^{\rm inner}$ -0.34 mm. Here -0.34 mm is the DIFF (see Fig. 15 for definition), obtained by averaging all the experimental DIFF values at the inner radius (the EBC case with 18 MODULES) and the similar figure for the outer radius was taken to be $d_{\rm nom}^{\rm outer}$ $+0.09$ mm (recall that: $d_{\rm nom}^{\rm inner} = 229.64$ mm; $d_{\rm nom}^{\rm outer} = 408.05$ mm).

As one can see, all the experimental results agree within ~ 0.5 mm.

Agreement of these experimental data with the results yielded by the PREDICTION program using averaged DIFF values (simplified procedure) gives a rather good qualitative description of the «deviation» values. It will be used further on for fast processing of FM coordinates measurements in order *to predict* the FM coordinates of the MODULES which are not positioned yet.

Figure 21 shows the distribution of differences (R) between

— the experimental EBC «deviation» data obtained with the theodolite method and

— the similar values obtained by the calliper method.

The agreement is satisfactory: $\langle R \rangle = 0.48$ mm and $\sigma_R = 0.40$ mm. For the known theodolite precision $\sigma_T = 0.2$ mm our estimate of the proposed method precision is $\sigma_{PM} = \sqrt{\sigma_R^2 - \sigma_T^2} = 0.35$ mm.

5.2. BARREL Data

It was experimentally established that plastic deformation of shims over the inner radius grows very noticeable after 48 MODULES were assembled and were increasing as more MODULES were positioned. Clearly, it leads to deviation from the nominal BARREL form.

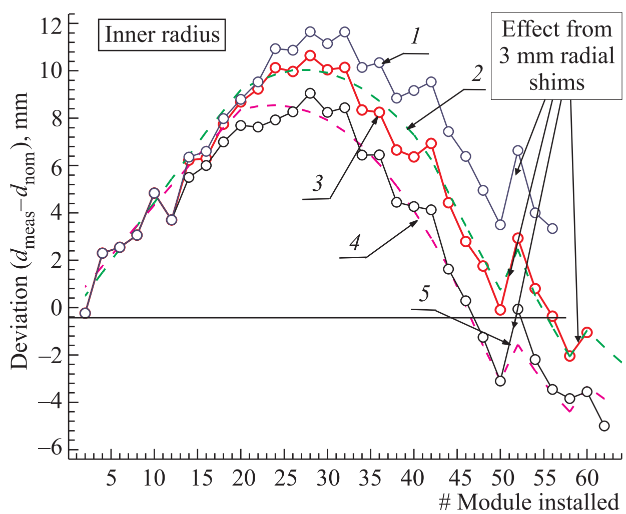

Fig. 22. BARREL inner-radius measurement and calculation data. *1* — 56 MODULES assembled; *2* — simulation with «additional deformation I» — 0.1 mm; *3* — 60 MODULES assembled; *4* — simulation with «additional deformation II» — 0.1 mm; *5* — 62 MODULES assembled

Figure 22 shows the «deviation» values obtained by different methods. All the cited data are for the inner radius. The «deviations» describe the BARREL shape change. They were obtained by comparison of the nominal[*] horizontal distances d_{nom}, between the FMs of the opposite MODULES with the corresponding horizontal distances of the «experimental origin»:

• measured by distochaine (lines *1, 3, 5*),

• calculated by the PREDICTION program used as input the calliper measurements for the already erected part of the BARREL (lines *2* and *4*).

Figure 22 also presents the line *2* which shows the effect of the so-called *«additional deformations I»* taken to be -0.1 mm. These are deformations which are expected to *appear* in addition to the already existing shim deformations after adding MODULES #57–58–59–60 to the *already* assembled part of BARREL. The line *4* demonstrates *«additional deformation II»* (taken to be –0.1 mm) after loading MODULES #61 and 62.

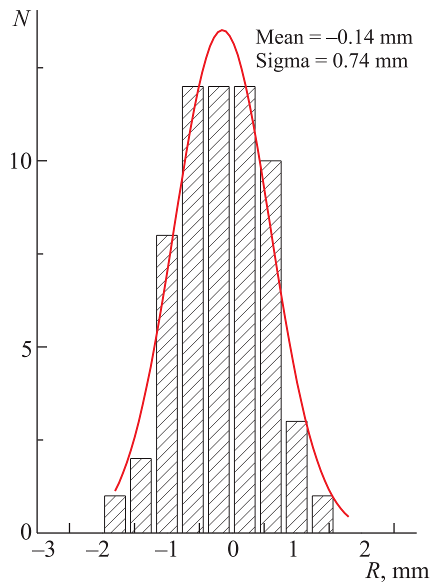

Fig. 23. The R distribution of differences of experimental deviation (BARREL) values obtained by the ruler and the program (the input data were taken from Fig. 22)

As follows from the EBC pre-assembly experience, these additional deformations could be fixed at the –0.1 mm level in the positioning sequence of the above-mentioned MODULES #57 ÷ 60. The additional deformations are expected for the shims separating MODULES #20–40.

Let us return to Fig. 22 for more detailed considerations. All the experimental data quoted there (distochaine based data) were obtained just after positioning «last» MODULES:

$$\left.\begin{array}{l} \text{line } \mathit{1} \text{ — after positioning MODULES } \#55 \div 56, \\ \text{line } \mathit{3} \text{ — after positioning MODULES } \#57-58-59-60, \\ \text{line } \mathit{5} \text{ — after positioning MODULES } \#61-62. \end{array}\right\} \text{Distochaine}$$

[*] Shop drawing figures.

The measurement data for the above three cases are shown by lines (*1*), (*3*), (*5*). The corresponding calculated deviation values are shown by lines (*2*) and (*4*) to be compared with lines *3* and *5*, respectively.

The BARREL assembly chronology at the conclusive stage was as follows:

• first the deviation values were measured by the distochaine, corresponding data are shown by line (*1*);

• then all the FM coordinates were calculated by using of the PREDICTION program and taking into account the load of next (expected) MODULES #57–58–59–60 to be installed. They must appear additionally to the *already* positioned 56 units. Corresponding result is represented by line (*2*);

• the above-determined (or — essentially — *predicted!*) deviation values *were then measured* by the precision distochaine; the results are shown by line (*3*).

Then the situation when MODULES # 61 and 62 positioned was considered in a similar way. The corresponding couple of the deviation distributions is given by lines *5* (distochaine measurements) and *4* (calculations).

The data in Fig. 23 show that we are able to predict rather precisely (within $\sim \pm 0.8$ mm) the expected positions of MODULE (their FM coordinates essentially). The *similarity of the shapes* of distributions in Fig. 22 indicates that these distributions were obtained with *close resolutions*; we would also add that this similarity makes us confident that our understanding of the assembly process is quite correct.

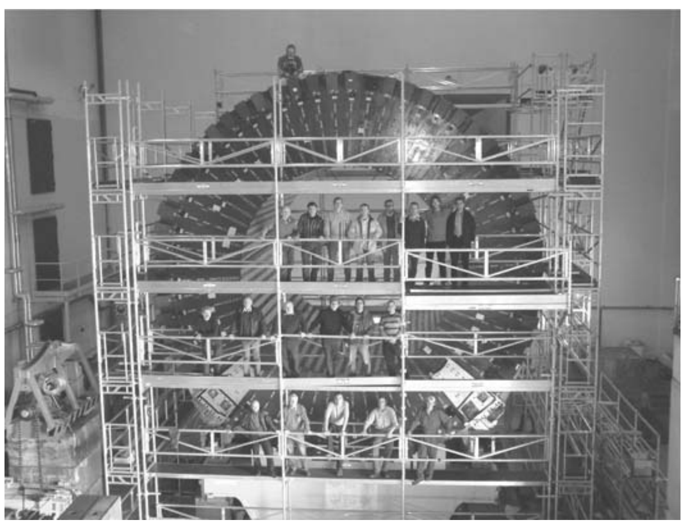

Fig. 24. BARREL pre-assembly is completed

Recall that we stopped in our analysis at the assembly configuration with MODULES #61 and 62 already positioned. A comparison of line (*4*) (deviation prediction for MODULES #61 and 62) with line (*5*) (the measured deviations for the same couple of MODULES) shows that

— the calculated deviation value is –4 mm,

— the measured deviation value is –5 mm.

For our weights, dimensions, and assumed shim deformations the achieved precision is satisfactory.

After MODULE #63 was positioned the array became non-symmetric relative to the vertical symmetry plane. Therefore «the standard» set of deviation values was not measured. Instead, we measured the «horizontal» distance «δ» between the FMs (inner) for MODULES #62 and 63; «δ» turned out to be –7 mm against its nominal value.

From the very beginning the «δ»parameter was meant to be *negative* in order to avoid appearing of *difficult-to-removing gap* (after the last 64th MODULE was installed) between MODULES #63 and #62.

To insert the last 64th MODULE, thin (~ 0.5 mm) teflon-covered steel shims positioned on contacting MODULES surfaces for better sliding, were used. Consideration of the complex of forces acting on the MODULES adjacent to MODULE #64 being inserted to the final position into the gap between MODULES #62 and #63 showed that the force pushing aside the left and right BARREL halves could reach the maximal level of 80–85 t.

In reality this force did not exceed 20–30 t, as was shown by quantitative consideration of forces acting on the BARREL as a whole and by inspection of shims for plastic deformation made after BARREL disassembly. The force in question caused only safe (within Hook law) elastic deformations of the BARREL as a whole.

Thus, the BARREL assembly was safely completed (Fig. 24).

CONCLUSION

The courageous and conceptually new design of the ATLAS BARREL Hadron Tile Calorimeter [8] was a challenge promising noticeable realization difficulties but also possessing some obvious advantages for the new generation HEP experiments in the LHC TeV region. Problems were expected both of the stages of the calorimeter's main structure unit production (stamping of ~ 300000 nuclear absorber steel plates, manufacturing of girders, gluing of submodules and assembly of MODULES with thin welding operations) and during the erection of large BARRELS.

The achieved high precision of BARREL pre-assembly is therefore the result of the advanced metrology and of coherent efforts of a large international team within the ATLAS Collaboration.

The geometrical control carried on at all steps from the design to the final assembly and base on independent and complementary dimensional measurements; the very fast «as build geometry» analysis and prediction tools, and the high reactivity of a large international team were the keys of the success of the pre-assembly task.

The pre-assembly experience and lessons have already been and will be used for the assembly of the full-size calorimeter in the cavern.

It seems that due to its flexibility this methodology can also be useful — in a wider sense — for high-precision assembly of massive large units in industry and other fields of activity.

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