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HIGH PRECISION LASER CONTROL OF THE ATLAS TILE-CALORIMETER MODULE MASS PRODUCTION AT JINR

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We present a short description of our last few years experience in the quality control of the ATLAS hadron barrel tile-calorimeter module mass production at JINR. A Laser Measurement System (LMS) proposed and realized in Dubna guarantees a high-precision module assembly. The nonplanarity of module side surfaces (1.9 × 5.6 m) controlled area is well within the required ±0.6 mm tolerance for each of JINR assembled modules. The module assembly technique achieved with the LMS system allows us to deliver to CERN one module every 2 weeks. This laser-based measurement system could be used in future for the control measurement of other large-scale units during the ATLAS assembly.

Представлено краткое описание нашего опыта контроля качества модулей адронного тайл-калориметра барреля установки АТЛАС, накопленного за последние несколько лет при массовом производстве в ОИЯИ. Лазерная измерительная система (ЛИС), предложенная и реализованная в Дубне, гарантирует высокую точность сборки модулей. Неплоскостность контролируемых боковых поверхностей модуля $(1,9 \times 5,6$ м) прекрасно укладывается в требуемые пределы допуска $\pm 0,6$ мм для каждого из собранных в ОИЯИ модулей. Разработанная техника сборки с использованием ЛИС позволяет направлять в ЦЕРН один модуль каждые 2 недели. Измерительная система, основанная на применении лазера, может быть использована в будущем для контрольных измерений других крупномасштабных объектов при сборке АТЛАСа.

INTRODUCTION

The ATLAS hadron barrel tile-calorimeter module production is a multistage process. A module consists of the following main elements: 1 girder, 19 submodules, 2 end-plates and 2 front-plates (Fig. 1). Each of the above elements is supposed to be produced within the required geometrical tolerances. The most stringent requirement on the module assembly is the planarity of its side surface (1.9 × 5.6 m), thus to allow a correct stacking of the cylinder during the final assembly. By design, the allowed gap between two adjacent modules is 1.5 mm, therefore the individual module surface planarity has been fixed at the level of ± 0.6 mm. It is fundamental that each module meets this tolerance requirement.

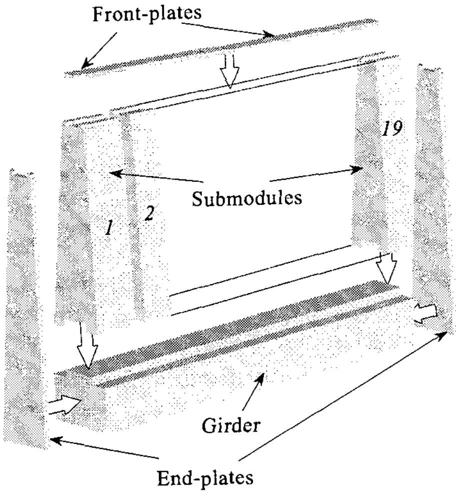


Fig. 1. Schematics of the module assembly

It is therefore quite natural to demand that the errors introduced by the measurement devices and the assembly tools have to be well within the required assembly tolerances. We consider that these instrumental errors must not contribute more than 0.2 mm to the surface planarity measurement.

Parts of the measurement equipment we use are precision instruments industrially produced: CALIPERS ($\pm$ 20 μm precision) and MINILEVEL ($\pm 10^{-5}$ rad/m precision).

The special Laser Measurement System (LMS) we have designed and constructed has a potential of precision of ± 50 μm when operated over a typical distance 6 m long. The gaining factor consists in the combination of this precision with an operation and manipulation simplicity for this device.

1. LASER MEASUREMENT SYSTEM

The LMS has been designed and constructed for the control of the surface geometry. The LMS (Fig. 2) consists of a laser and a photo-detector (PhD) built up of 4 independent parts; both the laser and the PhD are fixed on special and high precision adjustment units.

The LMS principle was proposed by the authors for an earlier [2] application. It is based on the measurements of the distance $H(i)$ between the surface under control (LL') and the axis of the laser beam directed in a quasi-parallel way to that surface. By placing the PhD at different positions $A(i)$, the associated values of $H(i)$ are determined by adjusting (using a system of microscrews) the centre of the photo-detector relative to the laser beam. The full surface geometry is determined by a series of such measurements.

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 done with our LMS have shown that the standard deviation value for individual $H(n)$ measurements on a 6 m long calibrated base is 30 μm. By adding to this the intrinsic precision, the precision of the positioning of the LMS system on the surface to

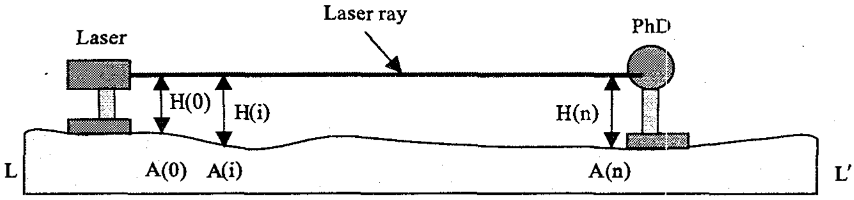


Fig. 2. LMS principle

be measured (specific submodules surface), the resulting measurement precision for the entire area (1.9 × 5.6 m) of the module side surface is within ± 50 μm.

2. MEASUREMENT OPERATIONS DURING MODULE ASSEMBLING

The use of the LMS — as we now have understood — is the major factor that guarantees necessary operation flexibility and necessary high precision in the submodule alignment on the girder. Here are various steps in the operations.

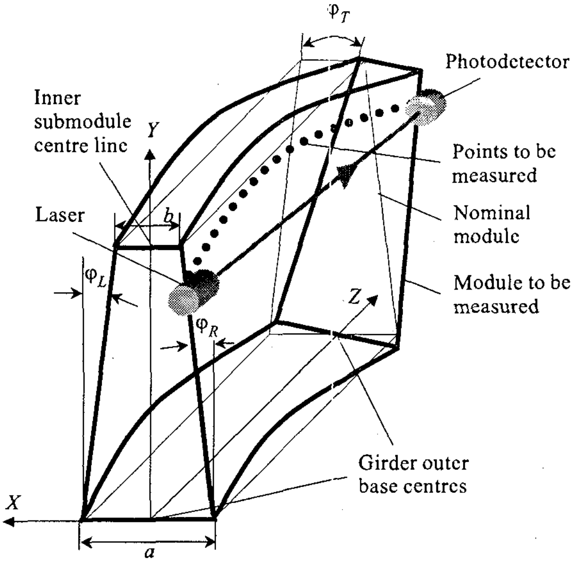


Fig. 3. Module and laser measurement system

2.1. Girder Positioning. Each girder is inspected and remeasured before being positioned on the dedicated horizontal support to verify the fabrication tolerance parameters, measured as parts of the QC plan just before acceptance. Each girder is positioned on the module assembling beam with special gaskets and its position is fixed in such a way that its top surface is as much as possible close to the horizontal plane. In fact, this surface is not perfectly flat and we make it «averagely flat». The precision of this operation is determined by the accuracy of the measurement of the girder top surface inclinations done with the digital MINILEVEL.

2.2. Submodules Positioning. While initially performing our measurements we have found that when modules are positioned on an uneven surface, they undergo a quite noticeable elastic deformation and — especially — they are twisted along their longitudinal axis. (By twist we understand an angle φ_{T} shown in Fig. 3 between the extreme submodules in the XY plane; it can be measured by our LMS diagonal technology). Therefore all assembly and adjustment operations of submodules are to be executed according to a given sequence.

After placing the girder in its nominal position, submodules 1 and 19 are placed one after another on the girder. In the course of this operation, each submodule is in the first place self-adjusted to the girder by the girder key. The inclination relative to the girder longitudinal axis is determined by measuring the submodule vertical position with the MINILEVEL. Using individual gaskets inserted under the submodule bottom surface, in contact with the girder surface, each submodule is placed in the correct position. Because later we will use these two submodules as a base for our LMS surface measurement, the correct vertical adjustment of these two submodules is fundamental. The criterion of verticality is the equalization of the submodule inclination angles $\varphi_{\mathrm{L,R}}$ (Fig. 3); after all submodules are put into place on the girder we cross-check this fundamental criterion measuring the twist angle φ_{T} by means of LMS and set the angle φ_{T} to zero if it is not.

Once these two submodules are positioned, then the laser and the photo-detector are put into place on the topside part of submodules number 1 and 19 so that the laser beam will pass about 60 mm below the submodules top surface. Each internal submodule will then be placed and referenced relative to this beam. After all submodules are positioned on the girder, a measurement is taken with the PhD to determine the distances of their side surfaces relative to the laser beam. With the help of individual gaskets, to be placed between submodules bottom surface and girder surface, we adjust the internal submodules in such a way that the laser beam height over all submodule surfaces is identical. Therefore as soon as submodules 1 and 19 are positioned vertically, all the subsequent submodules are also positioned in the same way on the girder. This procedure has proven to be very efficient.

2.3. End-Plates Positioning. After all submodules have been adjusted and fixed, the next step is to position the end-plates with the help of digital inside calipers. The criterion for a correct position is the equalization of the distances between the end-plate side edges and side surfaces of submodules 1 and 19. After all the necessary adjustment operations are performed, the bolts and pins will fix the end-plates in place.

The next critical operation is front-plates welding. Measurements of finished modules have shown that welding of the gap between two front-plate parts in the middle of the module is to be executed at the very last moment (last operation) and welding must be directed from the module centre towards the front-plate edge to avoid additional module deformations.

2.4. Module $3D$-Geometry Measurement. The module coordinate system we used is shown in Fig. 3. Here the Z axis connects the middle points of the girder bottom edges; the Y axis comes through the middle of the first submodule top as shown in Fig. 3. (As a comment, we should observe that in principle we could connect the Y axis with the last or any other submodule as well.)

$3D$-measurements are done with LMS resting on the end-plates. Therefore first of all one must measure top and bottom dimensions a, b (Fig. 3) of the end-plates. This is done using a caliper. The nonlinearity of the side edges of the end-plates is measured by LMS. These values are then used for the module form reconstruction.

Because of the way submodules are assembled and the fact that master plates have been constructed using a precision die stamping technique, we have decided that it is sufficient to perform the measurements of both side surfaces of the module at 3 levels: at 60 mm from the module top edge, in the middle of the submodules height and at 60 mm from the submodules bottom edge. At each level one measures the $H(i)$ distances (see Fig. 2) of the laser beam relative to the surface in 21 points: one on each end-plate (2 units) and one on each submodule (19 units) in its middle point. In the same way one measures $H(i)$ on the girder side surfaces (5 points, on each side).

Using the obtained $H(i)$ values for submodules and girder surfaces for each line, the measured end-plates dimensions and their positions relative to submodules number 1 and 19, it is possible in principle to reconstruct the surfaces in the common coordinate system XYZ.

2.5. Module Measurement Data Presentation. To better associate the data to the surface quality and make comparisons with the required tolerances, it is convenient to present the results not in absolute XYZ coordinates, but as deviation from the nominal module dimension (we shall call it the «nominal module» below). For this purpose we put the image of the nominal module in the position shown in Fig. 3, when its axes of symmetry coincide with the chosen coordinate system. It means that the Y axis of the nominal module would coincide

Table 1. **Results of module No.33 measurements at Dubna in December 2000 (deviations from the nominal dimensions of the master plates in mm)**

— Right —						— Left —		
Girder	Bottom	Middle	Top	Npos	Top	Middle	Bottom	Girder
−0.23	−0.52	−0.60	−0.55	EP1	−0.52	−0.71	−0.72	−0.40
0.00	−0.07	−0.14	−0.12	1	0.01	−0.06	−0.04	0.00
—	−0.14	−0.17	−0.15	2	0.12	−0.04	0.02	—
—	−0.08	−0.13	−0.07	3	0.10	0.01	−0.01	—
—	−0.10	−0.12	−0.02	4	−0.02	−0.06	−0.01	—
−0.01	−0.11	−0.12	0.05	5	−0.04	−0.06	0.02	0.05
—	−0.10	−0.08	0.06	6	−0.01	−0.19	0.02	—
—	−0.10	−0.08	−0.02	7	−0.01	−0.02	0.06	—
—	−0.03	−0.05	0.03	8	−0.06	−0.09	−0.04	—
0.04	−0.09	−0.10	−0.04	9	0.04	0.02	0.09	−0.01
—	−0.09	−0.20	−0.13	10	0.04	−0.10	0.09	—
—	−0.14	−0.08	0.02	11	−0.04	−0.08	0.04	—
—	−0.10	−0.14	−0.13	12	0.00	0.00	0.09	—
—	−0.16	−0.11	0.08	13	0.00	0.01	0.06	—
0.03	−0.12	−0.03	0.04	14	−0.06	−0.08	0.09	−0.04
—	−0.07	−0.03	0.02	15	−0.07	−0.11	0.01	—
—	−0.15	−0.14	−0.03	16	−0.07	−0.02	0.11	—
—	−0.13	0.06	0.12	17	−0.12	0.02	0.11	—
—	−0.13	−0.05	0.11	18	−0.08	0.02	0.06	—
0.01	−0.06	0.03	0.10	19	−0.10	−0.08	−0.03	0.01
−0.33	−0.72	−0.52	−0.22	EP2	−0.83	−0.79	−0.30	−0.02
0.04	−0.03	0.06	0.12	MAX	0.12	0.02	0.11	0.05

Definitions of submodule numbering and sides:

1. Special submodule has number 1;
2. EP1 is at the special submodule 1, EP2 is at the submodule 19;
3. Left (right) side of the module is defined on the left-(right-)hand side when one is looking from the EP1 along the module.

— Girder nonplanarity —
Top : 0.17 mm
Side: 0.07 mm
— Equalization angle —
Fi : −0.039 mrad
Delta: −0.07 mm.

only with the Y axis of the first submodule. After simple calculation we can transform the measured $H(i)$ values into distances (we call them deviations) between the module and nominal module surfaces. In principle we have already received results we needed. But because the chosen position of the nominal module to some extent is arbitrary, we found it natural to adjust the nominal module and consequently the tolerance envelope in the «equalized position» to get maximal positive deviations equal to each other on both sides of the module.

To do this we turn the nominal module around the Z axis on a small angle, which we calculate using the deviations we obtained above. This turn is equivalent to setting gaskets between neighbouring modules during barrel assembly. After that we transform deviations into final or equalized deviations.

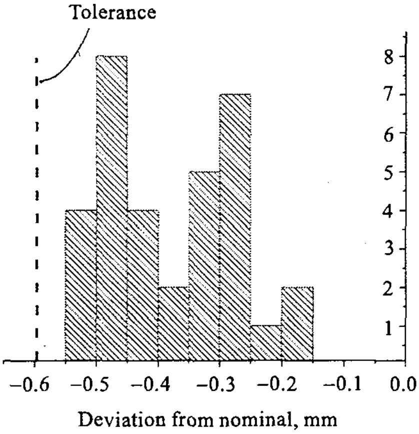
All above-mentioned calculations represent a set of simple linear transformations, which take into account the module twist and the nominal module turn.

All the calculation procedures are completely automated and computerized. As an example the resulting data are presented in Table 1 as deviations of the module surface coordinates from the nominal module surface for module number 33 measured at JINR.

3. MEASUREMENT RESULTS

In total one executes 276 individual measurement points for each module. This entire information is stored on dedicated quality sheets for each module on dedicated WWW pages. For 33 JINR assembled modules, the maximal deviations of the side surfaces are presented in Figs. 4 and 5. These distributions prove that the LMS used for the module assembling process really guarantees the high quality of this operation. Most of positive deviations are well within the allowed tolerance (+0.60 mm); in fact, they mainly are by a factors of 2–3 less than the tolerance. The negative «–» deviations are more noticeable. This might be explained by a rather stable tendency of the submodules manufacturers to avoid the «drift» of the submodules outside the tolerance in the positive deviation region.

The result of the comparison of the measurement data obtained at JINR and at CERN shows that the maximal deviations of modules surfaces from the nominal dimensions are close to each other in both series of measurements (Table 2). However, one should keep in mind that when executing our measurement at CERN we met the problem of positioning the modules on the supports as precise as it was done in Dubna. As a result modules were twisted in different ways. Therefore, the results of the comparison quoted in Table 2 are up



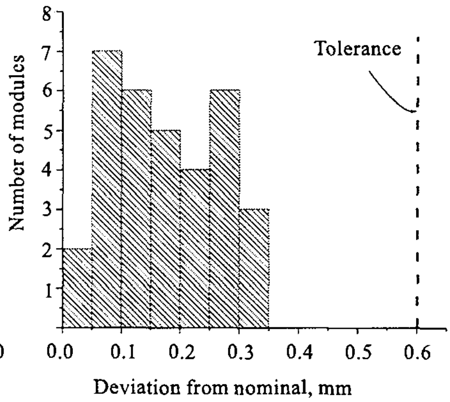


Fig. 4. Maximal module surface negative (–) deviations from the nominal dimensions (mm)

Fig. 5. Maximal module surface positive (+) deviations from the nominal dimensions (mm)

Table 2. **Maximal deviations from nominal for measurements made at JINR and CERN (in mm)**

Module No.	7	8	9	19	20	21	22	23	24	25	26
At JINR	0.14	0.18	0.26	0.07	0.09	0.00	0.07	0.26	0.27	0.16	0.23
At CERN	0.30	0.29	0.27	−0.01	0.11	0.03	0.07	0.14	0.31	0.15	0.11

to some extent approximate. Essential, however, is that all our data are within the required tolerances.

As one can see the maximal deviations measured at CERN differ from those measured at JINR owing to difference in modules «twists». The results of these measurements are also shown in Fig.6 for the top line of module 8. Here one can see that the measurements made at CERN follow well those made at Dubna. The difference again is due to the nonadequate positioning of the module at CERN.

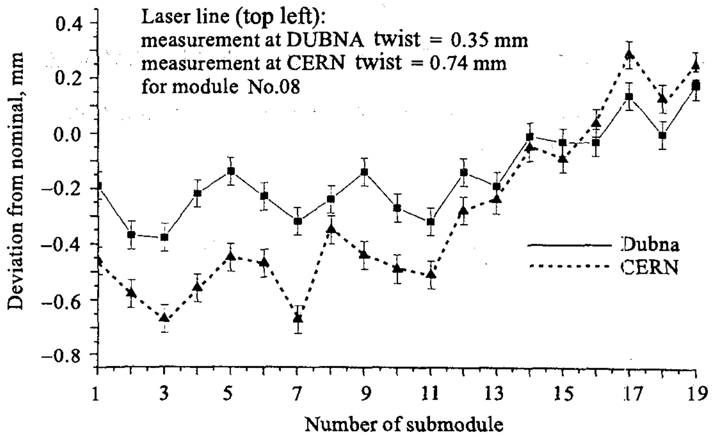


Fig. 6. Comparison of measurements made by LMS at JINR and CERN

In general, the results of the ready module measurements (now we have assembled 33 modules) by LMS have proved the correctness of the chosen module assembly procedure. It guarantees the necessary precision of submodules positioning on the girder which resulted in the assembled modules obeying the designed tolerances. And no problems have occurred because of the transport from JINR to CERN.

4. CONCLUSION

- The Laser Measurement System guarantees the desirable high precision (50 μm) for the module assembling operation.
- The laser based measurement system we developed is perfectly convenient for the measurement of side surfaces of modules and can be used for control measurements of other large-scale units.

- The measurements have proved the reliability of the chosen module assembly technology and of the design of the module transport supports.

For the future, we propose to automate the adjustment procedure and the «zero-keeping», and increase the measurement precision by using screens around the laser beam to decrease the influences of external factors (such as air convection, etc.) on the laser beam propagation.

We also think that this method, in combination with some other techniques, can be used as a significant element of a more general adjustment procedure during assembling of tile-calorimeter cylinders and in general of ATLAS.

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