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Physics

ATLAS Hadron Tile Calorimeter: Modules Development and Mass Production Experience

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ABSTRACT. The paper addresses the 1994–2006 experience of the Joint Institute for Nuclear Research (JINR, Dubna) in establishment of and participation in large international cooperation of scientific centers and industrial plants of Russia, JINR Member States (Byelorussia, Czechia, Georgia, Russia, Slovakia, Romania), W-Europe and the United States in development of the ATLAS hadron barrel calorimeter.

The ATLAS is a new generation experiment on the Large Hadron Collider (LHC) now being constructed at the European Organization for Nuclear Research (CERN, Geneva).

Emphasis is placed on research and development phase and quality control techniques, the role of laser metrology developed at JINR in providing highly accurate assembly of the calorimeter modules and submodules is stressed.

Key words: *ATLAS, hadron calorimeter.*

Introduction

The ATLAS collaboration is preparing a new-generation multipurpose experiment aimed at studying fundamental properties of matter manifesting themselves in proton-proton interaction at 14 TeV at the Large Hadron Collider (LHC, CERN-European Organization for Nuclear Research, Geneva). This collider provides the largest particle energy ever achieved under laboratory conditions, which is comparable only with the energy of particles arriving from outer space.

Parameters of the ATLAS detectors allow a wide range of expected physical processes to be studied and regions of new, unexpected physical phenomena to be penetrated [1].

One of the most important parts of the ATLAS facility is the Hadron Calorimeter with the so-called honeycomb structure: scintillation tiles are inserted in the steel absorber and are read out through wave-shifting optical fibers. The tiles are located in the plane perpendicular to the direction of the colliding beams (Fig. 1). The calorimeter consists of three sections, a barrel and two extended barrels. Each section is assembled of 64 wedge-like modules, 5.6 m long and 20 t in weight for the barrel and 2.8 m long and 10 t in weight for the extended barrels. A module is made up of submodules assembled with the required relative linear and angular accuracy on a common base – a girder.

The design specifications of the calorimeter are as follows:

- jet energy resolution $\sigma / E = 50\% / \sqrt{E} \oplus 3\%$
- energy linearity ±2%.

Some other severe requirements to accuracy of mechanical assembly of modules must be observed. The main one is the allowed non-planarity of the module side surface (1.9 m Ч 5.6 m), which should not be larger than 600 μm. It is a high accuracy, which is hard to achieve in view of the weight and dimensions of the module and its specific structure: the module is actually assembled from

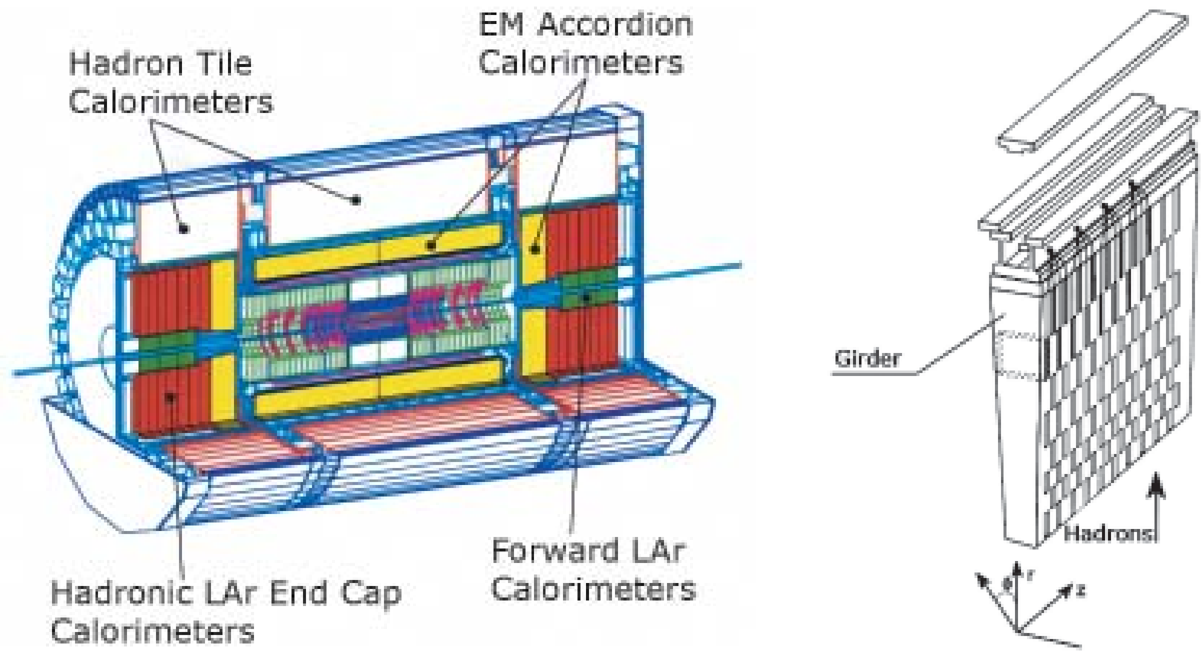

Fig. 1. Arrangement of the ATLAS calorimeter system (A) and the hadron calorimeter barrel module with respect to the beam (B).

steel plates (nuclear absorbers, Fig. 2) amounting to a total of a few hundred thousand in the entire calorimeter, each to a tolerance of ±100 μm for the contour and ±30 μm for the thickness. The weight of the absorber in the calorimeter is a few thousand tonnes. To achieve the best acceptable compromise between the physics, technology, and assembly accuracy requirements, a combination of adhesive, bolted, and welded joints was used in ATLAS calorimeter modules.

The design structure of the calorimeter dictated by the physics requirements demands adequate technologies for mass production of components and for assembly of submodules, modules, and the full-size calorimeter. Clearly, all the above stages required development and use of adequate precise metrological control measures, including the laser control technique used in the assembly of particularly large detectors for the first time.

The solution of the problem includes three key stages:

1. High-accuracy production of approximately 300 000 submodule components: master and spacer plates.

2. Highly accurate assembly of submodules and their high-precision positioning on the girder in the module.

3. Development and use of precise metrology to control calorimeter assembly accuracy.

Submodules should be mounted on the girder in such a way that their symmetry axis is vertical to an accuracy of 0.15 mm/1.6 m, which corresponds to the 8th degree of accuracy in machining of parts. This high accuracy (considering that one module comprises 19 submodules weighing about 1 t each) became possible with the unique laser control technique developed and introduced at the JINR [2].

The full-size production of submodules and modules at the JINR was preceded by research and development that comprised the following important stages:

- construction of a meter-long prototype submodule within the shortest possible period of time (2–3 months in 1994), whose quality allowed the JINR to become a full member of the international collaboration,

- construction of a full-size prototype module, so-called module 0, at the JINR in 1996, whose high quality of assembly and the demonstrated precision control technique resulted in that the decision was taken to assemble all 65 six-meter long modules in Dubna.

Development and use of the technique for laser control of the accuracy (≈ 50 μm) of the assembly of six-meter, 20-tonne modules, which is an advance in metrology, allowed not only a required accuracy but also a high production rate of two modules a month. This production rate ensured timely fulfillment of JINR commitments: on 3 July 2002 the last, 65th module of the hadron calorimeter was delivered timely at CERN.

The required tolerances achieved in the assembly of modules with precise instruments and the laser technique are extraordinary because modules were not made with precision machine-tools but actually assembled "by hand" while their side surface non-planarity of 0.2–04 mm over the area of ≈ 2 Ч 6 m^2 is exceptional and comparable with the machining accuracy of modern many-meter-long milling machines.

The high-accuracy assembly techniques developed at the JINR can find use in the construction of not only the calorimeter but also the entire ATLAS facility and the LHC.

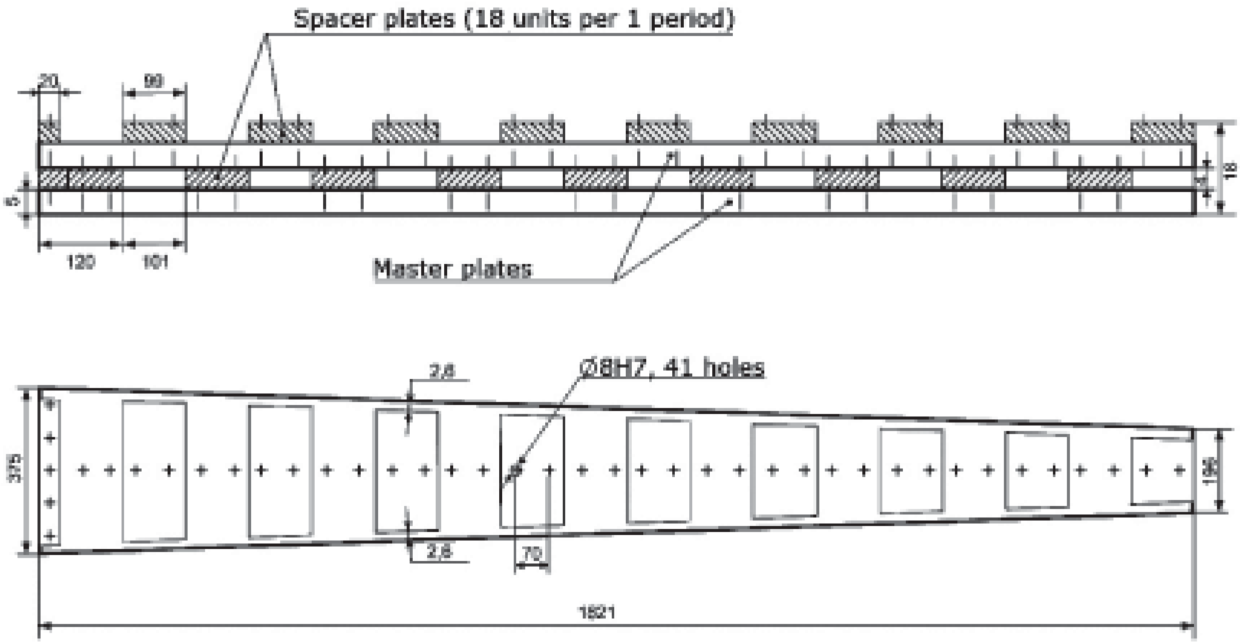

Fig. 2. Schematic view of one of 55 periods of the 1-meter prototype submodule.

Test runs of the calorimeter fragments consisting of the modules assembled in the above-described way showed that the ATLAS calorimeter meets the requirements on the energy resolution $\sigma / E = 50\% / \sqrt{E} \oplus 3\%$ and on linearity ±2% [3], which makes it the only most precise facility among this type in the world.

1. Formulation of the problem

The work on the ATLAS hadron calorimeter began at the JINR on 23.02.1994, when it was agreed that the JINR would make 120 master and over 500 spacer highly accurate steel nuclear-absorber plates for the prototype submodule, also called the one-meter submodule. The prototype submodule is a stratified structure of 55 periods, each period comprising two large master plates 5 mm thick and two layers of smaller spacer plates 4 mm thick arranged on the master plate with an interval of 100 mm and displaced relative to the previous ones by 100 mm. Each period was 18 mm thick (Fig. 2). The tolerance for thickness was ±0.05 mm for master plates and ±0.1 mm for spacer ones. These accuracy requirements are extremely severe as they are higher than the Russian Industrial Standard requirements (+0.3…-0.4 mm). The contour accuracy for all plates was ±0.1 mm with the maximum linear dimensions of 1821 mm for master plates and 200–370 mm for spacer plates.

Five-mm-thick master plates are isosceles trapezoids with the height 1821 mm and the bases 375 and 196 mm [4]. According to the preliminary design each master plate has 41 highly accurate holes 8H7 mm in diameter; 36 of them are arranged along the symmetry axis of the plate with the position tolerance ±50 µm and the other 5 holes are located 20 mm off the larger base (Fig. 2).

Four-mm-thick spacer plates of 18 standard sizes are also isosceles trapezoids with the height 99 mm and various bases depending on the positions of the space plates on the master plates in the submodule assembly. Each spacer plate has 2 highly accurate holes 8H7 mm in diameter arranged along the symmetry axis of the plate and spaced 70 mm apart with the position tolerance ±50 µm.

In the assembly master plates are separated by spacer plates arranged at equal intervals between them and staggered in height (Fig. 2). All master plates are connected by 41 rods inserted in all holes and fastened with nuts. Each spacer is additionally fastened to the master by two elastic bushings, which quite accurately set the mutual arrangement of masters and spacers.

2. Design of submodules and modules

In June 1994 the one-meter prototype submodule was assembled from Dubna nuclear absorber plates at CERN with the participation of JINR specialists. The assembly process revealed considerable disadvantages of the initial submodule design indicated by the Dubna group. Those disadvantages greatly hampered mass production of submodules and were unacceptable for the full-size of the module and the tile calorimeter as a whole. Therefore, a number of fundamentally new features were developed [5] and then implemented in the design of submodules and modules and in their assembly procedures.

Added to the submodule design were (Fig. 3):

(a) two grooves on the axis line at the trapezoid bases,

(b) strips at four angles of the trapezoid.

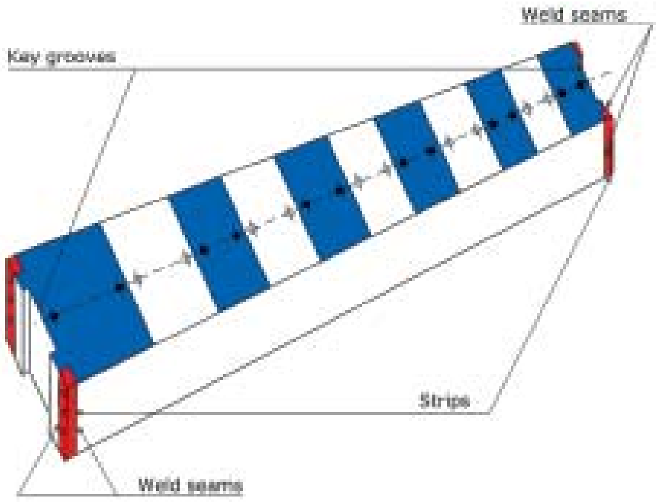

Fig. 3. Schematic view of the submodule: grooves and four strips at angles are introduced.

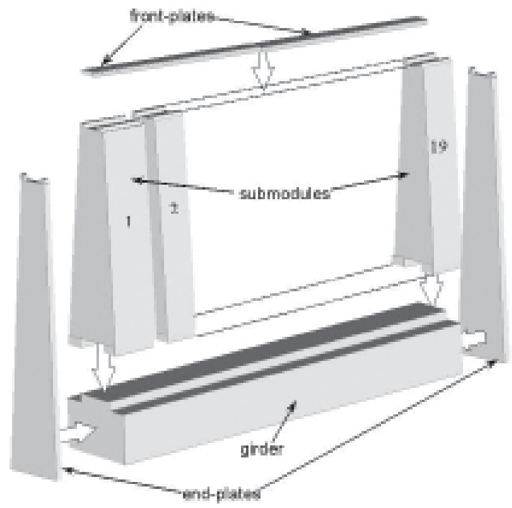

Fig. 4. Module assembly diagram.

Grooves in master plates for submodules (Fig. 4) radically changed the module assembly procedure and made it possible:

(a) to easily stack plates between holders within the range of permissible relative shift,

(b) to assemble a submodule vertically and symmetrically in plan.

In module assembly (Fig. 4) the grooves at the wide base of submodules allowed the position of submodules to be centered to the required accuracy as they were mounted on the girder and the strips at the angles allowed submodules to be bolted to the girder and their position to be adjusted with respect to the vertical axis for high planarity (to 0.2 mm over the area 1.9 m Ч 5.6 m) of module side surfaces. Long front plates connecting submodules at the top of the module and fixing their mutual arrangement were welded into the grooves at the narrow bases of submodules. On the basis of the adopted tolerances the required mutual arrangement and the maximum permissible non-planarity of module side surfaces (0.6 mm over the area 1.9 m Ч 5.6 m) were calculated and the distance between modules in the calorimeter (1.5 mm) was set [6]. These two key parameters were subject to particularly thorough metrological control during the assembly of modules and were decisive for successful preassembly of the barrel on the ground [7] and final assembly to design tolerances in the underground area (December 2004).

3. Development of technology for components and devices for assembly and transportation of module 0

It was planned to produce submodules in several institutes, some of which did not have adequate production capacity. Therefore the proposal to mount 19 modules on the girder in the module instead of 6 was an important step of a principal significance. The length of a submodule was decreased from H≈1 m to H≈300 mm and accordingly its weight is decreased from 3 t to 800–900 kg [6]. Later this step greatly simplified assembly of modules and, which is particularly important, allowed precise metrological control of the assembly procedure.

Thus, the module design was detailed: the size of the master and spacer plates, angle plates, threaded holes, welded seams, etc. were optimized. By the beginning of 1995 all basic approaches for assembly of submodules and modules were developed [8] and officially approved. The JINR also presented its proposals as to lifting machinery and rigging for submodules and modules, possible designs of the module assembly berth, and a simplified diagram of a device for transportation of a module to CERN.

By mid-1995 the design of “module 0” as a full-size prototype module of the tile calorimeter was approved and designing of the assembly berth for “module 0” has begun at the Design Department of the JINR DLNP (Dzhelepov Lab. of Nuclear Problems) [9].

After the collaboration approved the design of the assembly berth and the proposed model assembly procedures, the design of the assembly berth was finished at the JINR [10] and at the end of 1995 the JINR made a contract for its manufacture with the Nuclear&Vacuum (Bucharest, Romania). In March 1996 the assembly berth was delivered to Dubna.

16–19 April 1996, in accordance with the plans of the ATLAS collaboration, the 6-meter “module 0” was successfully assembled at JINR [11]. In view of the uniqueness and instructiveness of the assemble procedure, for it was the first of three “zero” modules (the other two half as large in size were to be assembled later in Spain and the United States), colleagues from other institutes came to Dubna to take part in the assembly.

Fig. 5. April 1996. ATLAS Module 0 at the 6-meter chuck plate of the vertical boring and turning machine, JINR, Laboratory of Nuclear Problems.

The main requirement to the module production accuracy – non-planarity within 0.6 mm over the area 1.9 m Ч 5.6 m – was met by using a special industrial gauge – a one-meter straight-edge of sufficient rigidity. Non-planarity of module side surfaces was checked twice, before and after welding the front plate to it. Measurements showed that the chosen welding technology was correct, the module suffered practically no warpage, and the maximum non-planarity was 0.45 mm/m while the tolerance was 0.6 mm/m. The length of the module was 5641 mm while the nominal value was 5640 mm, which falls within the required tolerance.

On 30 April 1996 module 0 (Fig. 5) was sent to CERN.

4. Production of master and spacer plates

As was said above, the JINR Dubna was responsible for the assembly of 65 barrel modules and manufacture of the basic submodule parts, namely, master and spacer plates. To manufacture the above number of modules, 1170 standard and 65 special submodules should have been made by gluing and 40 800 master plates and 20 400 sets of spacer plates, each comprising plates of 12 standard sizes, should have been made for all 1235 submodules. Large-scale production like this (≈300 000 items) is very unusual for JINR and the success fundamentally depended on the ability to establish appropriate quality control.

In the course of production of master plates each 30th stamped plate was checked with a gauge and each 600th plate was inspected at the three-coordinate measurement center with ≈20-50 μm precision. By May 1998 all master plates were made and sent to Pisa, Prague, Protvino and Dubna.

5. Production of submodules, quality control

At the end of December 1998 a special production line for assembly of submodules was made at the JINR Experimental Workshop to the specifications elaborated by the DLNP Design Department and mass production of submodules has began at the JINR.

The results of checking linear and angular dimensions of finished submodules and essential production data are written in the quality certificates. The thickness H_i was measured at 20 points. It is the main geometrical characteristic of submodules because it characterizes uniformity of distribution of tiles over the length of the module and affects the correctness and possibility of assembling a module.

The thickness of the submodule is dictated by the thickness of the plates to be glued together and the amount of glue used. All the other geometrical characteristics of submodules are dictated by the size of master plates and are ensured by the production process.

Considering all these factors, new tolerances for the submodule thickness +0.3…-1.5 mm and for the design gap 0.4 mm between submodules in the module were approved.

A submodule should be assembled to the tolerance of +0.3…-1.5 mm for its thickness H_i measured at 20 points over the perimeter and central symmetry axis. The measurement accuracy was 20 μm with the reading accuracy 0.01 mm.

The surface plate of the JINR Experimental Workshop was used for precision measurement of H_i. Its surface was measured with available laser measuring device. Non-planarity of the surface plate was 70 μm at the measurement accuracy 20 μm, which ensured the required H_i measurement accuracy. Distribution of maximum values H_i-H_{nom} for 308 submodules assembled at the JINR is shown in Fig. 6.

Thus, adjustment of tolerances, observance of assembly procedures, justified choice of the measurement equipment, and adequate degree of non-planarity of the surface plate ensured quite stable high quality of submodule assembly.

The JINR produced 243 standard (291.7 mm high) and 65 special (341.2 mm high) submodules, all within tolerances, over the period December 1998–May 2001.

6. Assembly of modules, quality control, transportation

On 8 July 1999 the JINR began assembling “module 1”, the first of 65 modules, for the barrel of the ATLAS hadron calorimeter. Unlike module 0, the first and all other modules were assembled in a specially prepared and equipped production section.

Unlike the case in the module 0 assembly procedures, the highly accurate adjustment of positions of submodules in the module required for ensuring the design module side surface non-planarity of 0.6 mm was provided with a laser measuring system. With this instrument and a developed technique [12] module side

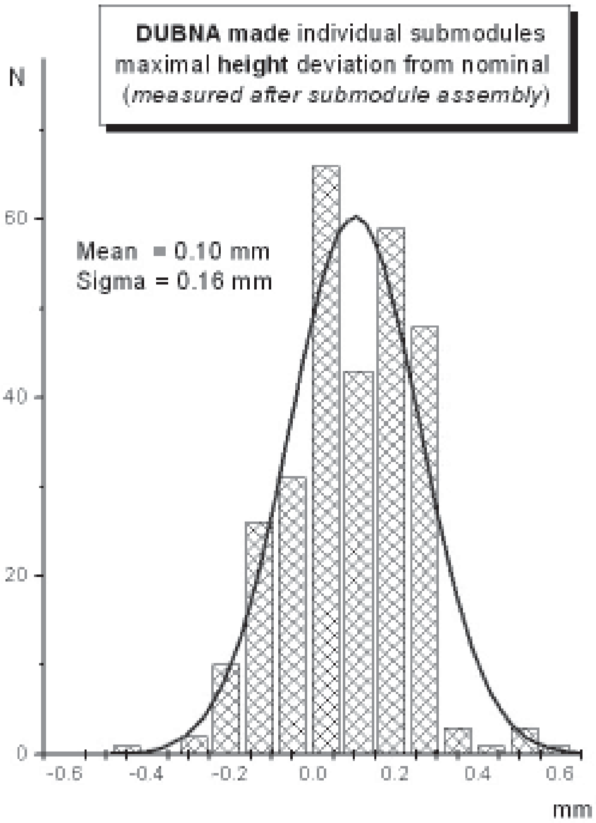

Fig. 6. Distribution of maximum values H_i-H_{nom} for 308 submodules assembled at the JINR.

surface non-planarity was measured before and after welding the front plate to the submodules. The optimum weld-making sequence allowed the curvature of modules to be quite successfully corrected and module side surface non-planarity to be improved. With the tolerance of 0.6 mm, the module side surface non-planarity was normally within 0.2–0.3 mm and rarely as large as 0.6 mm.

Let us consider in more detail the main technological aspects of the assembly of modules in the case of their quantity production.

Our task was to develop a module assembly technology that would allow the lowest possible module side surface non-planarity. The main causes for the module side surface non-planarity are

- non-straightness of the girder (0.2 mm);
- accuracy of its horizontal positioning (0.1 mm);
- submodule side surface non-planarity (0.1mm) and perpendicularity of its positioning on the girder (maximum 0.2 mm, see Fig. 7).

During the module assembly the girder was first horizontally positioned with a minilevel to an accuracy of 0.1 mm per 1-m length. The reading accuracy was 0.01 mm per 1-m length.

Next, submodules were successively mounted on the girder. In the longitudinal direction, perpendicularity of the submodule was determined and checked by the metrological precision square while in the transverse direction it was necessary to determine the slope angle of the side surfaces of submodules with respect to the vertical. Since minilevel could only check perpendicularity and horizontality of very small angles (< 1°) while the slope angle of the submodule side surface with respect to the vertical is about 3°, a wedge-shaped plate was mounted at a particular height on the submodule side surface so that its outer side made up a common vertical surface with the lower edge of the girder. Thus, by checking the verticality of this surface with a 2-m straight-edge and the minilevel to within 0.1–0.4 mm, it became possible to ensure the required verticality of the position of the submodule symmetry plane and the tolerable deviation of the submodule side surface from the “ideal” module side surface.

The position of the submodule was adjusted by varying the thickness of shims between the lower strips of the submodule and the upper surface of the girder (Fig. 7) until deviation from the vertical was not larger than $\Delta X = 0.2$ mm, which meets the design requirement and, with an additional shim $\Delta S = 0.02$ mm placed under the submodule, allows the deviation of the submodule top to be only 0.1 mm (Fig. 7).

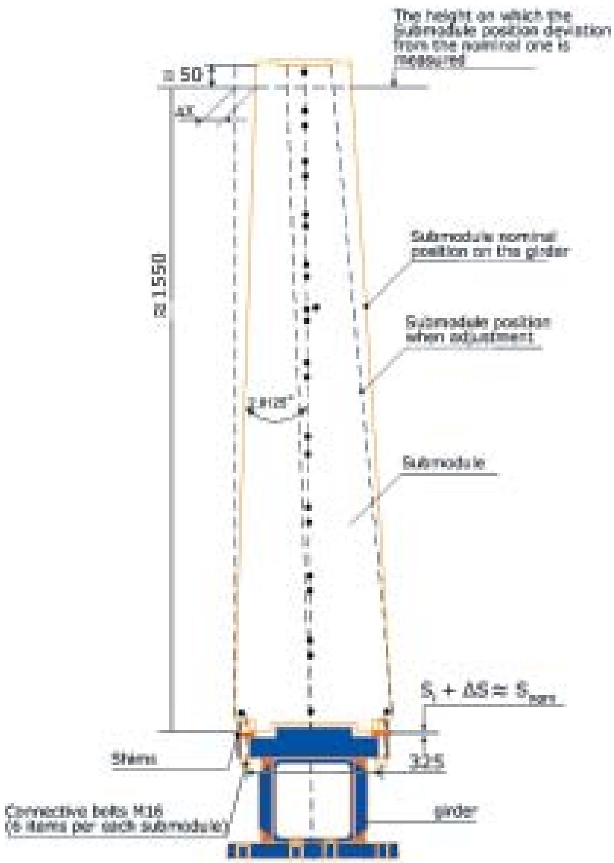

Fig. 7. Schematically depicted adjustment of positions of submodules on their assembly into a module. S_i is the initial thickness of shims at the given place, ΔS is the thickness of additional shims, S_{nom} is the theoretically required thickness, ΔX is the deviation of the position of the submodule from the nominal one.

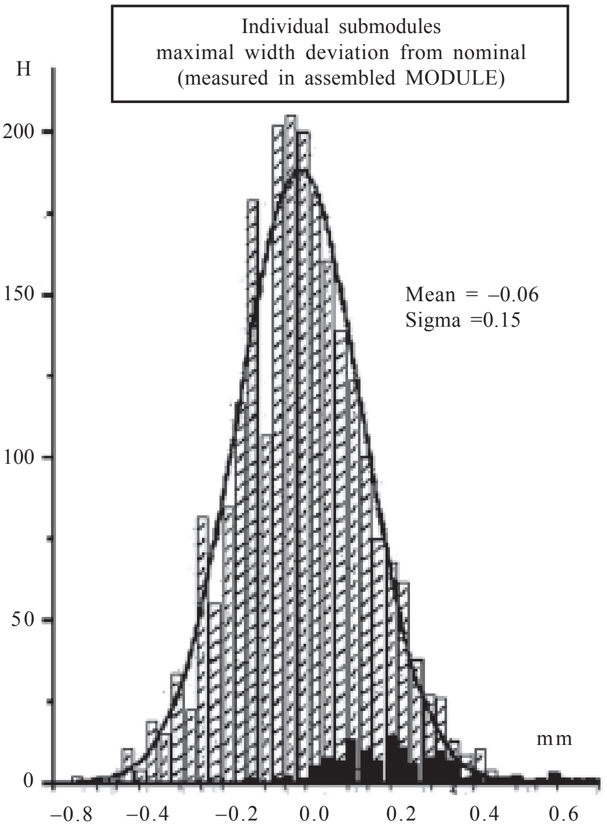

Fig. 8. Distribution of maximum deviations of submodules H_i-H_{nom} in the modules assembled at the JINR.

The laser metrology we developed allowed adjustment of submodules with the required accuracy and appreciably simplified assembly of modules: since it was too laborious to adjust each submodule with a minilevel and additional devices in quantity production, it was decided that this adjustment procedure would be applied only to the 1st and 19th submodules while positions of submodules between them will be checked by a laser beam; in that case the ΔX measurement accuracy was 0.05 mm.

Thus, the modules which we assembled practically "by hand" surpassed in accuracy of assembly industrial items of comparable size machined on a high-precision shop-machine. The achieved result is illustrated in Fig. 8, which shows deviations of all submodules from the nominal position in the assembled modules. The shadowed area shows the maximum deviations of submodules for each of 65 modules. It is seen that nonplanarity of modules obtained by us falls within the interval 0-0.4 mm, which is in general appreciably better than the design value 0.6 mm.

All 65 modules were delivered at CERN without damage, which was confirmed by comparing records of module side surface measurements before and after delivery.

On 3 July 2002 the last, 65th module arrived at CERN. The task set to the JINR eight years ago was successfully fulfilled.

Conclusion

This is a brief chronological summary of some most important milestones over the period 1994–2002:

- Conceptual designing of the principal calorimeter structure elements; accompanying research and development; manufacture of prototypes.
- Industrial production of ≅ 300 000 steel nuclear absorbers, girders.
- Manufacture of submodules and modules; development and application of precision technologies, including the laser technique.

The authors would like to stress again the extreme efficiency of the efforts jointly made by workers, technicians, engineers, and physicists from a lot of scientific centers and industrial plants to solve a unique technological problem, which ultimately resulted in successful construction of modules and their delivery to CERN.

Epilogue

The further fate of the Dubna created and delivered to CERN modules of the barrel (central) part of the hadron calorimeter is as follows: prior to the final assembly in the underground LHC experimental hall (at the depth of 100 meters) the whole procedure was repeated at CERN on the surface level to avoid some unexpected situations and problems one might expect when final assembling in the area where the possibilities to change and repair are highly limited.

The experience accumulated during this preliminary, on the earth surface, assembly was used when final assembling; Fig. 9 shows the central barrel assembled of Dubna modules on the surface. All these assembly works both on the surface and in the experimental hall were executed with an active participation of the JINR engineers and technicians.

Fig. 9. The central barrel assembled of Dubna modules on the surface at CERN

Fig. 10. Basic modules with the support before the descending into the experimental area

Fig. 12. The Central Dubna part of the hadron calorimeter had been assembled

After the preliminary assembly the barrel part of the calorimeter (consisting of 64 modules) was disassembled to 8 modules unit and all of them together with the support have been delivered by 250 tons crane to the experi-

Fig. 13. The barrel has arrived to its final position at the ATLAS centre

Fig. 11. Basic modules before the final assembly at the experimental area

Fig. 14. The calorimeter complex assembly is completed

mental area where works were continued to assemble full 64 modules set (Figs. 10-12).

The barrel assembly place was not a final destination. After assembly the barrel started its “travel” to the experimental hall centre on the specially created transportation mechanism using the air-cushion. And in December 2004 the barrel arrived at its final position (Fig. 13), leaving its former place free for the remaining calorimeter parts assembly – the EBA and EBC units which also passed the preliminary surface assembling. By the middle of 2006 all works to assemble the full scale calorimeter were completed (Fig. 14).

The huge experimental data flux from the calorimeter and other ATLAS subsystems during data taking runs will be directed to the data control board. Therefore in parallel to the ATLAS parts assembly also was executing cabling (High-Voltage, Low-Voltage, High-Frequency, etc) to connect ATLAS subdetectors with the data acquisition and control stations. The unique scientific data, arriving as "raw material", will further be with INTERNET and GRID distributed and analyzed among many world research centers, enabling the national groups in different countries to be active participants of the realization of the scientific program of the world largest proton collider LHC.

As during the ATLAS assembly physicists met many unforeseen obstacles the date of the final detector start up (originally end of 2005) was changed a few times and currently this date is foreseen in the middle of 2008… Let us hope this date will happen to be the final one and the unique ATLAS research complex on the world greatest collider will start as scheduled and will collect scientific results on the energy and luminosity of the colliding particles, unprecedented in laboratory conditions… This moment is being so impatiently waited by the world scientific community!

ფიზიკა

დანადგარ ატლასის თეილ-კალორიმეტრი: პროტოტიპების შექმნისა და მასობრივი წარმოების გამოცდილება

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(წარმოდგენილია აკადემიკოს ა. ხელაშვილის მიერ)

შრომა ასახავს ბირთვული კვლევების გაერთიანებული ინსტიტუტის (ბკგი, ქ.დუბნა, რუსეთი), 1994–2006 წლების გამოცდილებას ფართომასშტაბიანი საერთაშორისო გაერთიანების ფარგლებში — რუსეთის, ბკგი-ის მონაწილე ქვეყნების (ბელარუსი, საქართველო, ჩეხეთი, რუმინეთი, სლოვაკეთი), დასავლეთ ევროპისა და აშშ-ის სამეცნიერო ცენტრების და სამრეწველო საწარმოები — დანადგარ ატლასის ადრონული ბარელ-კალორიმეტრის შექმნის ორგანიზაციასა და მონაწილეობაში.

ATLAS-ი არის ახალი თაობის ექსპერიმენტი დიდ ადრონულ კოლაიდერზე (LHC), რომლის მშენებლობაც ამჟამად მთავრდება ბირთვული კვლევის ევროპულ ცენტრში (CERN-ი), ქ.ჟენევა, შვეიცარია.

არსებითი ყურადღება ექცევა საცდელ-კონსტრუქტორულ დამუშავებას და ხარისხის კონტროლის მეთოდებს, აგრეთვე ბკგი-ში შექმნილ ლაზერული მეტროლოგიის როლს მაღალი სიზუსტეების მიღწევაში, კალორიმეტრის ძირითადი სტრუქტურული ელემენტების — სუბმოდულებისა და მოდულების შექმნის სამონტაჟო სამუშაოების შესრულებისას.

REFERENCES

1. *W.W. Armstrong et al*. (1994), Atlas. Technical Proposal. CERN/LHC/94-43.
2. *V. Batusov et al.* (2001), Development of laser measurements at the ATLAS Tile Calorimeter module production , Pr.JINR, Dubna E-13-2001-257.
3. *E. Berger et al*. (1995), Construction and performance of an Iron-Scintillator hadron calorimeter with longitudinal tile configuration. ATLAS International Note TILECAL-N-055, August.

4. *J. Budagov et al*. (1994), Report on fabricating of ATLAS hadron calorimeter prototype #5 in Dubna. ATLAS Internal Note, TILECAL-N-014, June.
5. *J. Budagov et al*. (1994), Tile calorimeter module assembly. ATLAS International Note, TILECAL-N-021, July.
6. *J. Budagov et al*. (1994), ATLAS Tile hadron calorimeter module assembly design. ATLAS International Note, TILECAL-N-036, December.
7. *V. Batusov et al*. (2004), Development and application of high-precision metrology for the ATLAS Tile-Calorimeter construction. Pr. JINR, Dubna. E-13-2004-177.
8. *J. Budagov et al*. (1995), ATLAS barrel hadron calorimeter module design. Comm. of the JINR, Dubna. E13-95-20.
9. *J. Budagov et al.* (1995), ATLAS barrel hadron calorimeter module assembly and tooling design description. Comm. of the JINR, Dubna. E13-95-254.
10. *J. Budagov et al.* (1995), ATLAS barrel hadron calorimeter module: tooling description for module assembly. Comm. of the JINR, Dubna. E13-95-467.
11. *J. Budagov et al*. (1997), ATLAS barrel hadron calorimeter 0-module assembly technology. Comm. of the JINR, Dubna. E13-97-23. ATLAS Internal Note, TILECAL-NO-94.
12. *J. Budagov et al*. (1997), Some auxiliary technology equipment for ATLAS hadron calorimeter module and submodule manipulations and the quality control of the assembled module. Comm. of the JINR, Dubna. E13-97-22. ATLAS Internal Note, TILECAL-NO-90.
13. *V. Yu. Batusov et al*. (2005), Hadron Tile-Calorimeter of ATLAS: The Experience of Prototypes Construction and Modules Mass Production. Pr. JINR R13-2005-130.

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Astronomy

On the Nature of Pluto

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ABSTRACT. **Pluto is a planet in process of formation. A swarm of particles formed around it traps particles from the space. Part of these bodies then fall down, another part in future will make satellites. After the passage of cosmogonic scale of time, a great planet must be created containing 13 Earth's masses.** *© 2007 Bull. Georg. Natl. Acad. Sci.*

Key words: *Pluto, formation, swarm of particles.*

Is Pluto a planet?

At the present Pluto has become the object of discussion: Is it a normal planet or only a minor one? The argument for the last opinion is that outside Pluto's orbit many bodies (Plutoids) of nearly the same size have now been discovered.

This problem was studied by the author in papers dedicated to the origin of the rotation of the planets [1 - 6]. Lately, the results of these investigations were summed up in a monograph [7].

The main idea of these studies is that during the process of formation some planets with short periods of axial rotation (from the Earth to Neptune) had very great cross-sections, necessary for them to acquire recent spins. This would be possible if swarms of small particles around them were formed, opaque to similar particles.

Then, part of these bodies (particles) with low spin moments fall down (on the planet), while the part with great spin moments will form satellites in future.

Mercury and Venus had not such swarms, accordingly they rotate slowly and have no satellites.

Thus, the presence of satellites is connected with the fast rotation of planets, as both of these phenomena result from the existence of particle swarms around central bodies in the past. It is curious that such simple dependence remained unnoticed for a long time.

The structure of circumplanetary particle swarms has been investigated in [5, 8].

In these studies the main results connected with Pluto were formulated as the following predictions:

1. The mass of Pluto is no more than 0.09 Earth's mass [1 - 3];
2. Pluto has a satellite [4];
3. Pluto is surrounded with swarms of particles and is still growing [9 - 11], the radius of the swarm is 1 -2 million km and its mass is about of 10^{-6} Pluto's mass;
4. The total mass of material moving outside Pluto's orbit is about 13 Earth's masses [7];
5. Mean radius of small particles outside Pluto's orbit is estimated as about 0.3 mm [6].

The first two predictions were based on the conclusion about the connection between the presence of satellites and fast rotation of planets. Inasmuch as Pluto's rotation is fast (relative to Pluto's year), the conclusion follows: it must have at least one satellite.

Because of a great distance from the Sun the relaxation time of the accretion process for Pluto is many times greater than the age of the solar system. Hence, Pluto has not completed its evolution and now it must have its own swarm of particles - not visible from the Earth.

Indirect arguments supporting this point of view are given by photometric data: since the moment of the discovery of Pluto its albedo has been permanently decreasing and the color index growing [9 - 11]. In my opinion, it happens because all this time Pluto has been recessing from the ecliptic plane (where the spatial density of inter-planetary material is maximal) and, accordingly, the total mass of swarm decreases with time.

The discovery of two small satellites of Pluto in 2006 by the Hubble Space Telescope also seems to strengthen my conclusion about the presence of a swarm around Pluto: these satellites seem to be the greatest members of this object.

Finally, basing on the estimation of particle sizes [6] and on the still hypothetic fact of a swarm's presence around contemporary Pluto, for the total mass of inter-planetary material in the neighborhood of Pluto's orbit we obtain 13 Earth's masses as the lower boundary [7]. This material is slowly accreted by Pluto's swarm and in future must partly fall down, partly form satellites.

Conclusions

Thus, at present Pluto is a planet in the unfinished process of formation. The swarm of particles around it traps particles from the space. Part of these bodies with low spin moment fall down, another part with great spin moment in future will create satellites. The radius of the swarm is 1-2 million km and its mass is about of 10^{-6} Pluto's mass.

After the passage of cosmogonic scale of time, as a result of the competition during the growing process between Plutoids, a great planet containing about 13 Earth's masses will be created instead of many bodies at present moving outside Pluto's orbit.

ასტრონომია

პლუტონის ბუნების შესახებ

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აკადემიის წევრი, ე.ხარაძის საქართველოს ეროვნული ასტროფიზიკური ობსერვატორია, აბასთუმანი

პლუტონი არის ფორმირების პროცესში მყოფი პლანეტა. მის გარშემო არსებული ნაწილაკების გროვა იტაცებს ნივთიერებას გარშემო სივრციდან. ამ სხეულების ნაწილი ძირს ცვივა, ხოლო მეორე ნაწილი მომავალში წარმოშობს თანამგზავრებს. კოსმოგონიური მასშტაბით საკმაო დროის გასვლის შემდეგ წარმოიშობა დედამიწის 13 მასის მქონე დიდი პლანეტა.

REFERENCES

1. *R. I. Kiladze* (1965), Bull. Abastumani Astrophys. Observatory, **32**, 231-234 (Russian).
2. *R. I. Kiladze* (1967), Astronom. Vestnik, **1,** 4, 223-225 (Russian).
3. *R. I. Kiladze* (1968), Brit. Astr. Ass., **78,** 2, 124-125.
4. *R. I. Kiladze* (1977), Bull. Abastumani Astrophys.Observatory, **48**, 191-212 (Russian).
5. *R. I. Kiladze* (1979), Bull. Georgian Acad. Sci., **95**, 3, 589-592 (Russian).
6. *R. I. Kiladze* (1980), Bull. Georgian Acad. Sci., **99**, 3, 589-592 (Russian).
7. *R. I. Kiladze* (1986), Sovremennoe vrashchenie planet, kak rezul'tat razvitija okoloplanetnykh roev melkikh chastits (Contemporary Rotation of Planets as the Result of Development of Circumplanetary Swarms of Small Particles), Tbilisi, 244 p (Russian).
8. *R. I. Kiladze* (1989), Bull. Abastumani Astrophys. Observatory, **68**, 125-134 (Russian).
9. *R. I. Kiladze* (1988), Astronom. Vestnik, **22,** 1, 79-82 (Russian).
10. *R. I. Kiladze* (1991), *V. J. Kukhianidze* Astronom. Vestnik, **25,** 4, 439-441 (Russian).
11. *R. I. Kiladze*., *V. J. Kukhianidze* (1995) Astronom. Vestnik, **29,** 6, 504-505 (Russian).

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