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STATUS OF THE ATLAS HADRONIC TILE CALORIMETER[1]

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Short status of the Tile Calorimeter project is given. Major achievements in the mechanical construction of the detector modules, their instrumentation, cylinders assembly, as well as the principles of the detector front-end electronics, are described. The ideas of Tile Calorimeter modules calibration are presented.

Кратко дан статус проекта тайл-калориметра. Описаны основные достижения в механическом создании модулей детекторов, их оснащении и цилиндрической сборке. Также описан принцип работы интерфейсной электроники детекторов.

INTRODUCTION

The Tile Calorimeter is one of the subdetectors of the ATLAS (see Fig. 1) general-purpose *pp* detector [1] designed for the Large Hadron Collider (LHC) to be built at CERN. It is a large hadronic sampling calorimeter which makes use of steel as the absorber material and scintillating plates read out by wavelength shifting (WLS) fibres as the active medium. The new feature of its design is the orientation of the scintillating tiles which are placed in plane perpendicular to the colliding beams and are staggered in depth. A good sampling homogeneity is obtained when the calorimeter is placed behind an electromagnetic compartment and a coil equivalent to a total of about two nuclear interaction lengths of material. This has been verified with Monte Carlo simulation and has been proven by the test beam results.

The Tile Calorimeter [2] consists of a cylindrical structure with an inner radius of 2280 mm and an outer radius of 4230 mm. It is subdivided into a 5640-mm-long central barrel and two 2910-mm extended barrels (see Fig. 2). The scintillating tiles lie in the $r-\phi$ (radius-azimuthal angle) plane and span the width of the module in the ϕ direction. WLS fibres running radially collect the light from the tiles along their two open edges. Readout cells are then defined by grouping together a set of fibres into a photomultiplier (PMT), to obtain a three-dimensional segmentation. Radially, the calorimeter is segmented into three layers, approximately 1.4, 3.9 and 1.8 interaction lengths thick at pseudorapidity $\eta = 0$; the $\Delta\eta \times \Delta\phi$ segmentation is 0.1×0.1.

[1]Talk given at the 3rd International Workshop on Very High Multiplicity Physics, Dubna, June 3–5, 2002.

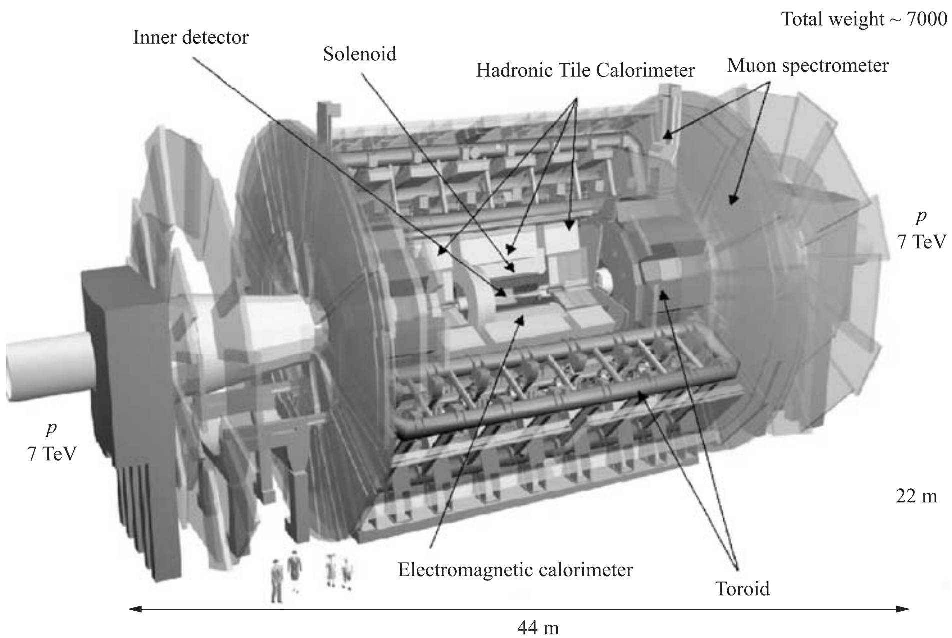

Fig. 1. The ATLAS detector

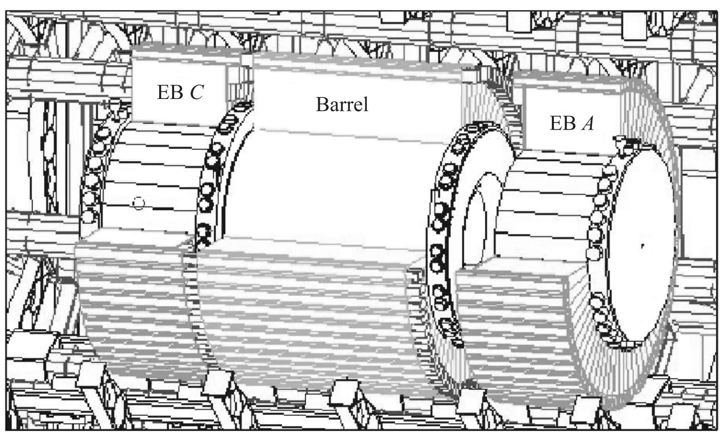

Fig. 2. The three cylindres of the TileCal subdetector

1. MECHANICS

The Tile Calorimeter passive absorber is a laminated steel structure with pockets at periodic intervals to contain the scintillating tiles. The structure is built in a modular fashion to facilitate the construction. It is a self-contained unit with the readout electronics being fully contained within the calorimeter itself. In addition to its function as passive absorber, the Tile Calorimeter also provides the magnetic flux return for the ATLAS solenoid.

The Tile Calorimeter is built in three sections: a central barrel covering approximately from -1 to $+1$ in rapidity and two extended barrels extending the rapidity coverage to approximately ± 1.6. Each of the three calorimeter sections is constructed from 64 modules, each covering 5.6° in azimuth. The barrel module is built out of 19 submodules mounted on a strong-back support girder which houses the readout electronics. Its cross section is sufficient to form the primary magnetic flux return. Except for one «special» submodule used to assure the final length of the module, all submodules are identical steel laminations approximately 300 mm long. The assembled calorimeter structure is self-supporting through a bearing connection between modules at the inner radius and aborted plate connection at the outer radius of the girder. The support saddles connect the calorimeter to rails which provide movement for installation and alignment. The TileCal also supports the Liquid Argon Calorimeter and presents a great engineering challenge. Except for some details associated with integration with other ATLAS subsystems, the design of an extended barrel module is identical to that of a barrel module, although it involves nine rather than 19 submodules.

1.1. The Production. The mechanical design and the construction method for the barrel and for the extended barrel calorimeters have been worked out using a combined engineering effort from all the institutions involved. The modules have been constructed in three regional centres. Each centre had the task of constructing the modules of one entire cylinder. Around these three regional centres we had nine submodule assembly plants, equipped with the necessary submodule assembly tooling and ready to construct and providing about 350 submodules for the regional centres over a period of three years. In time being all modules are mechanically constructed.

1.2. The Assembly. The basic concept underlying the calorimeter assembly procedure is that the 64 modules, once assembled into the calorimeter, form a cylinder which is a self-supporting structure. Each module rests on the module below and is supported on two well defined bearing surfaces at the innermost and at the outermost radii. The main structural elements in the assembly are the girders, which are coupled by connection plates fastened at the outer radius. These connecting plates will also be used for radial alignment of modules during the assembly process.

A second important concept is the assembly sequence. The cylinder will be built up, using an assembly fixture, starting from the lower modules and built up until the final module is inserted. The assembly must be stable in all intermediate configurations, and special assembly cradle is used at its start. Shims, placed at the two bearing surfaces, ensure that the contact between modules is well controlled and occurs only at these two surfaces and allow individual adjustment of the position of each module within the design azimuthal gap. The shim sizes will also take account of overall structure deformation as measured during the assembly such that sufficient space is available for the installation of the final modules. The entire structure sits on dedicated supports (saddles) placed symmetrically on the left and on the right side, resting on the main rail system. The barrel and the two extended barrel calorimeters are mechanically independent and may move individually on the rail system to provide access to the inner part of the ATLAS detector.

As an additional complexity, the Tile Calorimeter must provide the support of the detectors placed inside, and in particular of the Liquid Argon cryostat. The weight of this is of the order of 300 t for the barrel and 250 t for each of the end-caps. Concerning the barrel, the cryostat is directly supported on four feet placed at the four extremes and resting directly on the saddle and the overall calorimeter support system. The four feet are placed at an angle of 45° and are housed inside the gap region. For the extended barrels the situation is more complex because of the differences in the internal support of the mass of the Liquid Argon Calorimeter inside the cryostats and the need to minimize the amount of dead material in front of the calorimeter. In this case, the support is different for the front (the location closest to the interaction point) and back of the cryostat. In front, the cryostat will rest directly, through two dedicated feet, on the inner surface of the Tile Calorimeter. On the back, the two feet sit on heavy end-plates which transmit the weight directly to the support saddle. The particular position of the cryostat feet required an important modification of few modules in that region.

Fully assembled barrel cylinder is shown in Fig. 3.

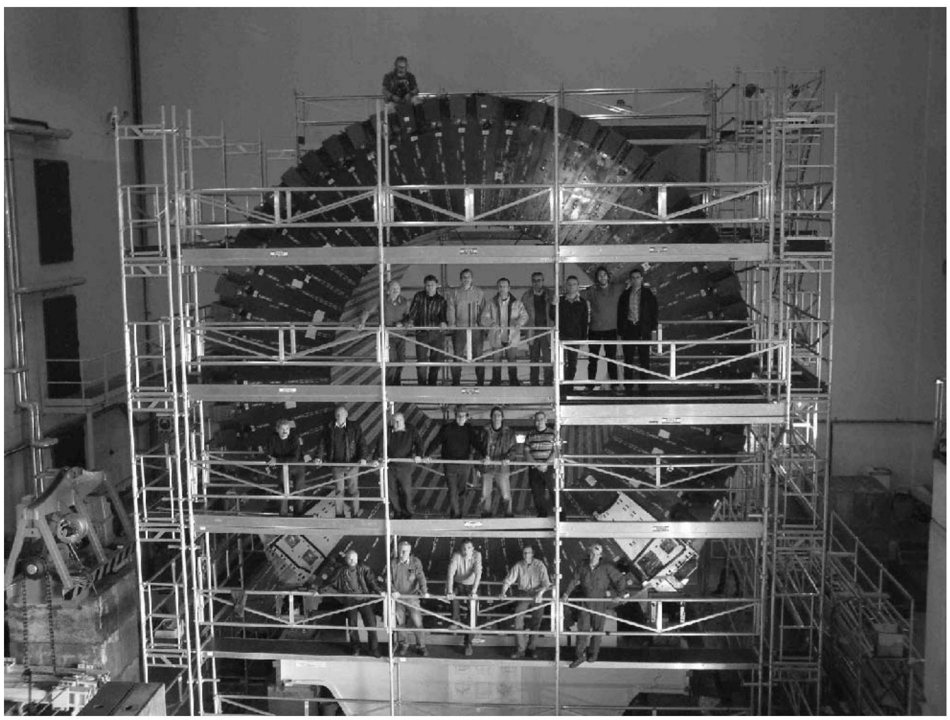

Fig. 3. The TileCal barrel assembled

2. OPTICS

The Tile Calorimeter is a sampling calorimeter using steel as the passive absorber and scintillating tiles as the active medium. A pair of wavelength shifting (WLS) fibres running radially collect light from the tiles at both of their edges. Readout cells are defined by grouping together a set of fibres onto a photomultiplier tube (PMT), to obtain three-dimensional segmentation.

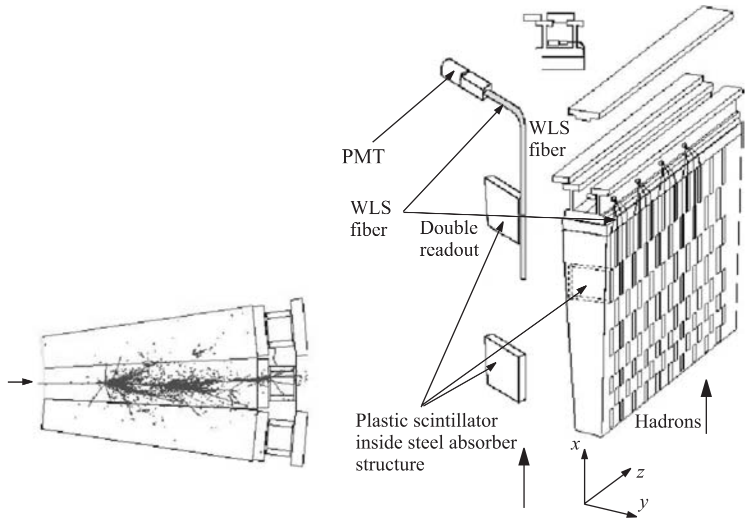

Fig. 4. The principle of the TileCal: it measures light produced by charged particles in plastic scintillator

The principle of the TileCal is illustrated in Fig. 4. Ionizing particles crossing the tiles induce the production of light in the base material of the tiles, with wavelengths in the UV range which subsequently is converted to visible light by scintillator dyes. This scintillation light propagates through the tile to its edges, where it is absorbed by the WLS fibres and shifted to a longer wavelength (chosen to match the sensitive region of the PMT photocathode). A fraction of the light re-emitted in the fibre is captured and propagated via total internal reflection to the PMT where it is detected.

2.1. Scintillator Tiles. The cost per scintillator tile and production rate are important parameters in the choice of the tile materials and production technology. These issues have led us to the choice of injection molding technology for tile production for the Tile Calorimeter. Having selected this technology, it is important to determine the performance factors. Light yield, uniformity of response within a tile and tile-to-tile uniformity are key performance issues. A total of approximately 460,000 scintillating tiles have been required for the Tile Calorimeter, half in the barrel, one quarter in each of the extended barrel sections. The barrel and extended barrels are equipped with tiles of the same dimensions.

The Tile Calorimeter contains 11 different sizes of trapezoidal shaped tiles, ranging from about 200 to 400 mm in $R\phi$ length and 97 to 187 mm in radial width. The wavelength shifting fibres are placed in contact with the non-parallel edges of the tiles. All tiles are 3 mm thick. Each tile has two holes, 9 mm in diameter, through the surface for the passage of the calibration source tubes.

Finite photostatistics gives a contribution to the calorimeter resolution, to be added in quadrature to the intrinsic sampling resolution. A requirement that we adopted was to be able to see the muon signal within each depth sampling. Furthermore, the detector is expected to operate for a minimum of ten years. To provide safety margin for ageing and other effects, we set as requirement a minimum light yield 1.2 pe/mip/tile at production.

2.2. The WLS Fibres. Four fibres are required to read out one side of each half-period. The total number of fibres required to build the 65 barrel and the 130 extended barrel modules is 640,000. In the barrel the length of the fibres ranges between 85 and 210 cm, depending on which cell is to be read and the location of the half-period. In the extended barrel the fibre length ranges from 90 to 230 cm. The total length of fibre required is 550 km for the barrel modules and 275 km for each extended barrel, which includes a 5% contingency, leading to 1120 km of fibre. WLS fibres, 1 mm in diameter, doped with a fast ($<$ 10 ns decay time) shifter have been chosen as our baseline. Such fibres have been commercially available.

Figure 5 illustrates various steps during the optical instrumentation of the modules. The instrumentation of all TileCal modules is now completed.

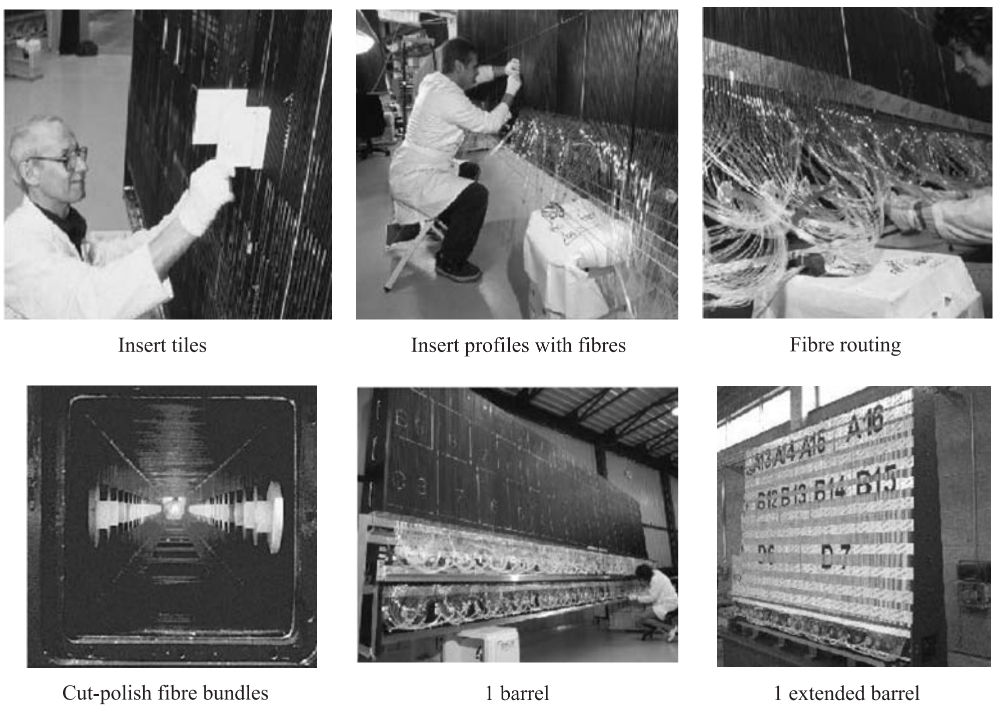

Fig. 5. Various steps of the TileCal instrumentation

3. ELECTRONICS

The overall design of the Tile Calorimeter readout is very compact. All front-end and digitizing electronics are situated in the back-beam region of the calorimeters on a system of removable superdrawers (see Fig. 6) containing up to 45 photomultipliers. Phototube high voltages are locally regulated. Pipelines and digitizers are located locally, and the digital information is transferred to the RODs in the counting room via optical fibres. Each cell of

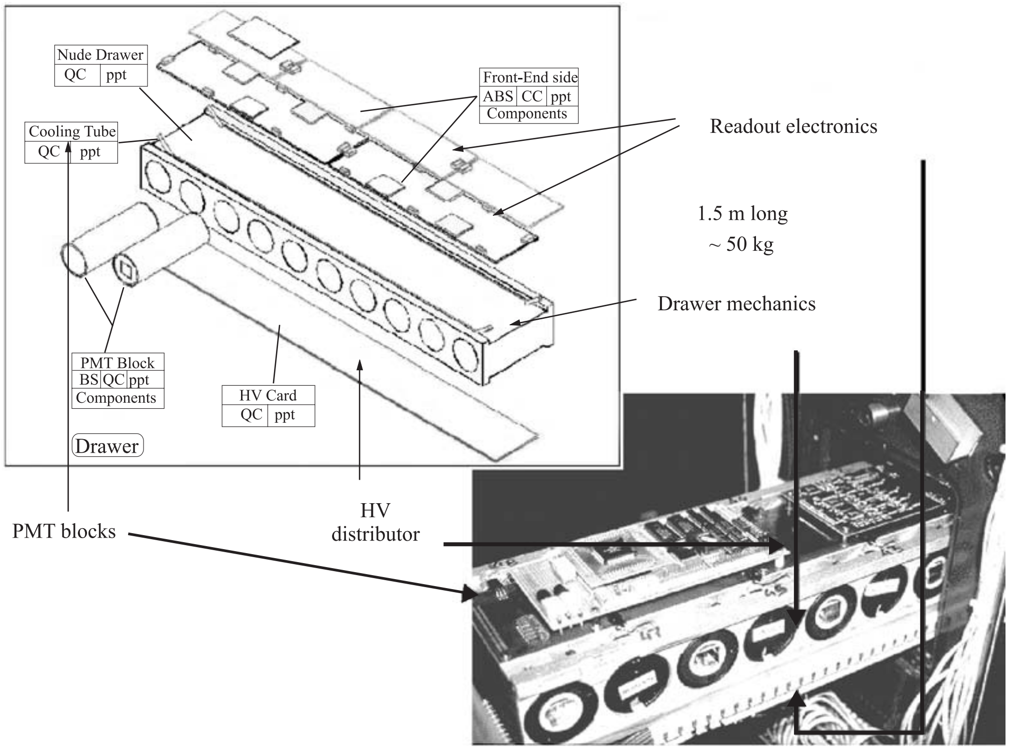

Fig. 6. The drawer with the TileCal electronics

the Tile Calorimeter is read out by two PMTs in order to provide redundancy in the light readout and improve spatial uniformity. The total number of channels is 9856.

The design of the electronics readout is constrained mainly by the available space, residual magnetic fields from the solenoid and toroids, and radiation. All of the Tile Calorimeter readout electronics are located inside the calorimeter modules, within the iron girders which also serve as the first level of magnetic shielding for the PMTs.

The remnant magnetic fields inside the drawers are not equal in every direction or location, but they are always below 20 Gs. The most sensitive components, such as the PMTs and their individual HV regulation system, must be arranged or designed for these specific conditions in order to maintain a cell calibration accuracy of 1%.

Monte Carlo simulations of radiation levels show that the iron of the hadronic detector itself (and in addition the large amount of plastic tiles) considerably reduces radiation levels inside the girders. The maximum expected dose from ten years' operation at full luminosity is about 20 Gy.

The large iron mass of the Tile Calorimeter contributes also to the temperature stability inside the modules, but a dedicated cooling system must evacuate heat dissipated by the electronics, maintaining stable local temperatures to within 1°C.

From test beam results, we expect the photoelectron yield will be at least 50 pe/GeV. Detailed simulations have shown that, at full luminosity, several events per year will deposit the equivalent of 1.5 TeV in a single cell, while energetic muons typically deposit 350 MeV in a single cell. This implies a 16-bit dynamic range for the Tile Calorimeter energy measurements. At the same time, the energy resolution of the Tile Calorimeter is such that an electronics precision of 10 bits is adequate to measure the largest signals.

3.1. PMT Blocks. The function of a PMT block is to convert light signals from the calorimeter cells into electronic signals. Each PMT block contains a photomultiplier tube, the light mixer which serves as the interface between the PMT and the fibre bundle, a high-voltage divider, and a 3-in-1 base which is the interface with the electronics readout. The PMT block is installed in a dedicated hole inside a drawer.

The output of the PMT block is a shaped electronic signal which is subsequently digitized by electronics inside the superdrawer. The conversion of the light signal from the fibre bundles to electrical charge is done by the photomultipliers in the PMT blocks. Test beam studies indicate that a minimum gain of 10^5 is required to allow measurements of muons, which would deposit roughly 350 MeV in a single cell. At the same time, pulses coming from the highest energy particles must be measured without a saturation of the readout pipeline. Simulations have shown that, at full luminosity, several events per year are expected to deposit the equivalent of 1.5 TeV in a single cell. The commercially available PMT has been used.

3.2. Superdrawers. The superdrawer consists of two drawers. A drawer houses up to 24 PMT blocks, and supports electronics boards which are connected to each PMT block and provide the high voltage to the divider, the low voltages to the HV cards and the 3-in-1 card, and the control and calibration signals to the 3-in-1 card. They also contain electronics to process the signals coming from the shaper and the integrator. These electronics boards are arranged on the top and bottom sides of the drawers, with signal processing at the top and the HV distribution at the bottom.

3.3. Front-End Electronics. The readout electronics is divided into several parts. The front-end electronics is located on the 3-in-1 cards within the PMT blocks described above. Here the current pulse from the PMT is shaped and converted to a voltage signal which is transmitted by short shielded cables to the fast digitizers located at one end of the superdrawers. They receive services from the mother boards which run the length of the drawers. In order to meet the physics goals of ATLAS, it must be possible to measure particles which deposit a wide range of energies in the Tile Calorimeter. A dynamic range of 16 bits is needed to measure both minimum ionizing energy deposits from muons and deposits of up to 1.5 TeV in single cell from the highest energy jets. Since the intrinsic resolution of the calorimeter is less than 16 bits, it is desirable to compress the dynamic range and digitize the signals using two ADCs with a resolution of 10 bits.

We use two linear outputs for each channel, differing in gain by a factor of 64. Each output covers a dynamic range of 10 bits and is linear in the charge of the input signal. In addition, provision has been made for an output for analog trigger summation.

The formation of analog sums for the LVL1 trigger towers is done on small printed circuit boards which form the third layer of the electronics drawer. Up to nine boards are needed in a superdrawer. To reduce the amount of cabling, the boards are distributed over the length of the drawer close to the source of their five input signals. The output signal from each board is routed along this layer on a shielded twisted pair cable to the patch panel at the end of the drawer.

All integrators in a superdrawer are read out sequentially by a single ADC. The ADC receives signals via an analog bus which runs along the entire length of the mother board, and each integrator is sequentially connected to the analog bus by closing a CMOS switch located on the 3-in-1 card. Integrator digitization is performed on a separate board, which is mounted on the mother board.

3.4. Power Supply and High-Voltage Distribution. The Tile Calorimeter PMTs are supplied by a high-voltage (HV) power supply system. The system reflects the division of the Tile Calorimeter into 256 submodules, which are electronically equivalent and independent. Each HV channel leads into the submodule drawer, where a special HV distributor supplies up to 45 PMTs. The HV distributor inside each submodule is able to set individual PMT voltages at up to 350 V below the supplied level. Only 2 HV power supply levels are needed to supply high voltages between 500 and 900 V, including wide overlap regions. The source consists of two racks, each containing 8 crates. Each crate has 8 cards with 2 HV channels per card, and a communication and control unit.

The photomultipliers in each superdrawer are supplied with one channel of the high-voltage main power source. To maintain all PMTs in the superdrawer at the same gain, each high-voltage channel of the superdrawer must be individually controlled and regulated. This is done by the high-voltage distributor in each superdrawer.

Mass production of superdrawers started in the summer of 2003.

4. CALIBRATION AND PERFORMNANCE

The Tile Calorimeter calibration consists of two main steps: PMT gain equalization using Cs radioactive source calibration system and setting the absolute electromagnetic scale for 1/8 of modules constructed.

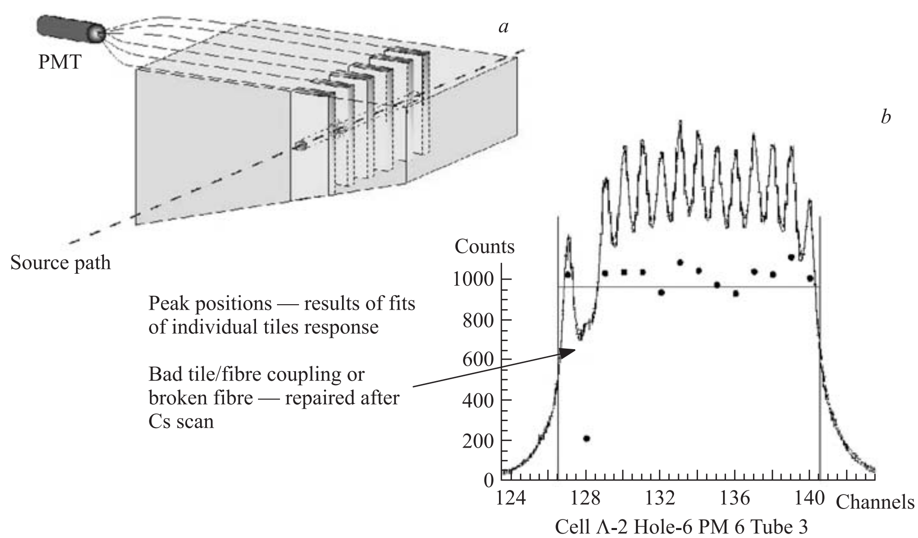

Fig. 7. Certification of modules using Cs radioactive source

4.1. Cs System. The Tile Calorimeter design includes the capability of running a ^{137}Cs radioactive source along axial holes, through each scintillator tile, inside the rods compressing the calorimeter modules. This feature permits us to check the response of each scintillator tile. Furthermore, it is important to know how well the calorimeter tracks the source calibration. This is important in order to have confidence that the sample of production modules not exposed to beam will have performance characteristics as well known as those modules which were calibrated in a beam.

As the source is run through the holes, the average current produced by tile activation is integrated and recorded for the tile's respective PMT. The high voltage is then set such that the integrated current is the same for each group of scintillators coupled to a phototube.

The principle and results from the Cs runs are illustrated in Fig. 7.

4.2. Test Beam Program. The Tile Calorimeter test beam program was started in 1993. Since then it has evolved into a major collaborative ATLAS effort with not only the Tile Calorimeter group, but also in collaboration with the Liquid Argon (LAr) community. To this date, we can categorize the test beam setups as follows:

- Tile Calorimeter stand-alone measurements with a reduced-scale prototype stack of five modules,
- Combined measurements with the LAr electromagnetic prototype and Tile Calorimeter prototype modules,
- Full-scale barrel sector (Module 0) in stand-alone measurements,
- Final calibration of production modules.

The beam lines were instrumented with threshold Cherenkov counters, wire chambers for both x and y coordinates, and scintillators to define a trigger. The scintillators defined a beam spot of around 2–3 cm, while the chambers allowed the reconstruction of the impact point on the calorimeter face to better than 1 mm. Data were taken with muons, pions and electrons between 10 and 400 GeV. The momentum bite of the H8 beam, $\Delta p/p$, was always less than 0.5%. Recorded event rates evolved from about 150 per burst to today's value of 5000 per burst.

For the needs of the Tile Calorimeter a full simulation package has been developed based on the GEANT program which describes in full detail the detector prototypes that have been used for the test beam runs. A comparison between the test beam data of the Tile Calorimeter prototype modules and different hadronic shower simulation codes (FLUKA, GHEISHA, CALOR) in the framework of the GEANT program has been made.

An extensive program of beam tests has been carried out demonstrating the good performance of the calorimeter that fulfils the requirements for the ATLAS hadronic barrel calorimetry. Extensive tests with pions, electrons and muons have been undertaken with the prototype modules, from which we learned most of the features of the Tile Calorimeter described in the following sections. The performances of the first full-scale pre-series module for the barrel hadron calorimeter (Module 0) have also been investigated. Finally, we have shown that it is indeed possible to understand the response of an ATLAS wedge, taking data with the Liquid Argon test calorimeter upstream of the Tile Calorimeter in an almost projective geometry.

4.3. Modules Calibration with Particles. Since 2001 we have been making calibartion of completed modules using electron beams of 10, 20, 100 and 180 GeV. The main aim of these tests is to set the absolute energy scale in the cells of the first and second longitudinal sampling of the calorimeter, where electrons deposit their energy. Calibration coefficients are then transported to other cells using Cs calibration results and special tests done with muons impinging the calorimeter modules at 90° incident angle.

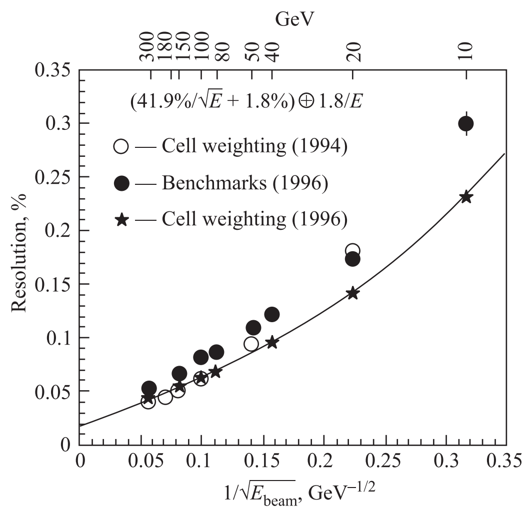

Fig. 8. Hadron energy resolution from the LAr and TileCal combined tests

Many important results have been collected in the past years. For illustration, the resolution of combined system of Liquid Argon and TileCal prototypes and Module 0 are shown in Fig. 8. The energy resolution is compatible with a designed value of 50% for the stochastic term with relatively small constant term which is caused by the noncompensated nature of the Tile Calorimeter.

Other results have been published about development of hadronic showers and reconstruction of hadron energy [3], Tile Calorimeter response to muons [4], energy losses of high-energy muons [5] and from the combined tests [6] and in many internal notes.

CONCLUSIONS

The Tile Calorimeter project is in an advanced stage. All modules have been produced and instrumented with the optical elements. The modules have been calibrated using particle beam at CERN. One extended barrel and barrel cylinders have been pre-assembled. Works now concentrate towards the mass production of electronics drawers and to the integration of the Tile Calorimeter into the ATLAS detector environment. The installation of the Tile Calorimeter in the ATLAS cavern will start in March 2004.

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