

Laboratory 2B: Characterization of the optics properties of a scintillating plastic Tile read by WLS fibres using ⁹⁰Sr source

Laboratory script

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Name: Dosimeter serial number: Dosimeter reading at the start: Dosimeter reading at the end:

1. Introduction

NOTE: Every participant should be in a possession of a personal radioactive dosimeter For information about radioactive sources see ref.1

To achieve its physics program, the ATLAS detector requires good jet energy resolution, for instance in the study of heavy bosons decaying in jet, top quarks. Translated to the performance of its hadronic calorimeter the needed energy resolution is:

$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 3\% \qquad \text{(Eq 1.)}$$

The requirement on the stochastic term (1rst term on the right hand side of Eq 1.) comes from the wish of having an energy linearity of 2% up to 4 TeV, for sufficient sensitivity to new physics. For the constant term (2nd term in the right hand side of Eq 1.) the requirement comes from the need of a 1% uncertainty in the jet energy scale, important for instance for the top quark mass measurement. For the top about one third of the jet transverse energy is deposited in the hadronic calorimeter. Finally good measurement of missing energy is required for identifying new physics signatures as may occur in the SUSY and other exotic scenarios. This imposes sufficient thickness, and excellent hermeticity of the calorimeters.



Figure 1. Schematic view of the ATLAS detector

The TileCal detector is part of the hadronic calorimeter system and covers its central region $|\eta|<1.7$. It is built out of 3 cylinders, constituted of 64 modules each, see figure above. The modules are built out of steel interleaved with plastic scintillator tiles, each read out on two sides. The light from several tiles is collected together to photomultipliers, defining a pseudo projective and longitudinal segmentation of 5182 cells.

The figure below shows the arrangement of the steel absorber and the scintillator tiles to form modules. Notice the non conventional orientation of the tile in the r- ϕ plane.



Figure 2. Arrangement of the scintillating tiles in the steel absorber

Dedicated studies have shown that a random nonuniformity of the cell response with a RMS of 10% would give a contribution to the constant term of 1%. Non-uniformity contributions arise from: nonuniformity inside a tile, tile- to-tile fluctuations, tileto-fiber coupling, fiber-to-fiber fluctuations, variations of the response across the PMT photocathode, and fluctuations inside a cell due to the fact that more than one tile is read by the same fiber. This last effect introduces radial fluctuations of the order of 5% and cannot be improved without substantially increasing the number of readout fibers.

To realize an overall non-uniformity of 10% rms, it is necessary to keep non- uniformity inside a tile, tile to tile fluctuations (and fiber to fiber) fluctuations each below 5%. This laboratory will shed some light on some of the steps taken to achieve this requirement.

For completeness other hadronic calorimeters in ATLAS are using liquid argon as active material and copper or tungsten as absorber. HEC and FCAL, as they are called, cover the pseudo-rapidity range to 5.2

The real schematic of a scintillating tile work is a rather complicated thing. In a short it consists of the following main sub-processes:

• An ionization particles losing its energy while passing trough polystyrene (PST) material excites big molecules which in their turn gave part of the excitation energy to a close dopant#1 molecule

• This dopant#1 molecule discharges and produces UV light (photon). The UV light can pass through PST no more than 3-5 mm and be absorbed either PST or picked up with a dopant#2 molecule. This guy immediately discharges too but the produced light has much bigger wave length – green

• The main advantage of the green light is that it can travel through PST much longer than UV one – tens cm (our reality is 20 - 50 cm). The tile material has optical quality surfaces and thin (3 mm thickness) flat shape so, the light can reach the tile edges after numerous reflection from the tile insides according to all the tile intrinsic features – shape, transparency, defects, holes etc.

• When light comes out of the tile it is captured by a fiber – transparent wire coated with another wavelength shifting material (paint). The green light absorbed by that coating is reproduced with even longer wavelength inside the transparent fiber central part (kern) where it can propagate to both fiber ends. The attenuation length of a fiber is of an order meters (reality is 2-3 meters). If one fiber end is a mirror (Al coated e.g.) the light yield on the other end increases by factor 20-50%.

• At last the fiber delivers the light to PMT photocathode and if the light spectrum matches to the photocathode absorbing one (our case) - it can be properly valuated and its amount connected with the energy of the initial particle passes through the tile.

So, one can see that the performance of a single tile (thus whole calorimeter), depends on its ability of the light production, transformation and transportation as well as surfaces optical quality and uniformity over whole tile volume. All the deviations from "an ideal one" lead to light losses, miscalculations and finally to a bad calorimeter performance.

2. Scope of the laboratory

The aim of the laboratory is to study the performance of plastic scintillating tile, read out via wave length shifting (WLS) fibres into the photomultiplier.

We will discuss the main parameters and techniques used in the ATLAS Tile Calorimeter to optimize its optics properties in terms of light yield, attenuation, uniformity and hermeticity, such as the use of double readout, tyvek paper, black masks and aluminized fibres.

We will measure the light output of a scintillating Tile to a radioactive ⁹⁰Sr source in different configurations, single and dual readout, fibres with and without aluminium mirror.

We will analyse the data to measure the uniformity of the response, light attenuation length and signal to noise ratio.

3. Laboratory setup

The heart of the laboratory is the light-tight scanning box, shown at Figure 3. It contains the following components:

- 1. Scintillating tile, made of polystyrene doped with 1.5% PTP and 0.04% of POPOP.
- 2. 25 MBq 90 Sr radioactive β source (β energy 546keV, half life 28.8 years)

- 3. Scanning mechanism
- 4. WLS green fibres. (Y11 polystyrene based from Kuraray Co.,Ltd.)
- 5. Photomultiplier and light guide, (Hamamatsu R7877)
- 6. Reference tiles (not used in this laboratory)

Inside the scintillating tile (1), light rays propagate, reflecting on the surfaces of the tile if their angle with the surfaces are less than the critical angle $\theta_c = \sin^{-1}(\frac{n_{dir}}{n_{iile}=1.59}) = 38.9^{\circ}$. Beyond the critical angle a fraction of the light refracts out of the tile. Therefore the tile is wrapped in special paper, brand named tyvek. The tyvek paper acts as a diffuser to the light coming out of the scintillator and it allows to recover about 5-10% more light, thanks to its irregular surface, increasing the chance of reinjecting light under the right angle. On the inside edges of the tyvek envelope one can see strips of black ink, this technique is used to decrease the excessive light output close to the edges of the scintillator, and therefore to improve signal uniformity.

Due to light losses, depending on the level of impurities, the quality of the surface, \dots the light intensity decreases exponentially with the distance crossed. So the light collected by the WLS fibre when the scintillator is exited at distance x of the fibre can be expressed as:

$$I(x) = I_0 \exp(-\frac{x}{L_{att}})$$

Where L_{att} is the attenuation length, which depends on the wavelength of the light. This will help you explain some of the features you will observe.

The tile is connected to the PMT (5) with one or two wavelength shifting (WLS) fibres (4), which are attached to the sides of the tile with plastic profiles. To improve the light collection, the open end of the fibre is polished and coated with aluminium, providing a reflective mirror to collect back more light, which would otherwise escape from the fibre. In this setup we have both coated and uncoated fibres, to study the effect of the mirroring.

Two small rectangular tiles (6) are used as position and signal calibration for 2D measurements which are out of scope of this laboratory.

During the scan the head (2) with the 90 Sr source is moving in two coordinates by positioning mechanism (3) driven by step motors, with the precision of 1mm in both coordinates, illuminating the tile underneath.

It is important to ensure the absence of light inside the box to reduce the noise of the signal. Excessive light might also damage the photomultiplier.



Figure 3. Scanning box layout

The ⁹⁰Sr scanning table setup consists of the following major parts, seen in Figure 4:

- Light-tight scanning box with scintillating tile and ⁹⁰Sr radioactive source
 Electronics crate with scanning box motion control, LV and HV source for the motor and the photomultiplier respectively.
- 3. Multi-channel digital multi-meter (Keithley 2000)
- 4. Control computer (Linux PC)



Figure 4. Sr90 setup overview

The signal (current) from the PMT is integrated (10ms integration time) to collect the small signal without fast trigger electronics. The output of the integrator circuit provides the voltage proportional to the collected charge.

It is then read out by high precision (6.5 digits) digital voltmeter (Keithley 2000 model). The same voltmeter is also used to monitor the high voltage applied to the photomultiplier.

The data from voltmeter are collected into the control computer via the USB-GPIB adapter.

The movement of the ⁹⁰Sr source is performed with the step motors in two coordinates, controlled by the commercial control system (Pacific Scientific 6420) situated inside the electronics crate, connected to the control PC via serial RS232 port.

The control program is written in Python programming language, using extension libraries for GPIB and serial port communication. A GNUplot based online data display is used to provide fast visual feedback during scan. Data, saved as text, are converted into .root format for further analysis with ROOT framework. A couple of ROOT macros are provided for convenience, with the source code in the appendix.

4. Measurements

4.1. Single fibre (without mirror) scan

In this test we will measure the light output with single non-mirrored fibre, making the onedimensional scan along the X axis, in the centre of the scintillation tile. First one should prepare the experimental setup, following the steps below:

- 1. Make sure that HV is OFF (1). Turn off table motion control (2) as well if it is on.
- 2. Open the scanning box cover and put it aside.
- 3. Locate the ⁹⁰Sr scanning head (3) and switch the lever to the OFF position (arrow facing left) to prevent any radiation exposure during fibre manipulations.
- 4. Move away the scanning head (3) to the bottom-left position.
- 5. Identify and carefully insert the required fibre #1 into the left side of the scintillating tile until the end of it is just visible at the other extremity. **Please be extremely careful not to break the fibre and do not bend it too much.**
- 6. Move the scanning head (3) to the top-left position and put the lever to the ON state (arrow facing bottom) to open the source container window.
- 7. Carefully close the scanning box cover and make sure of the snug fit. Light leaks will disturb the measurements and might event damage the PMT.
- 8. Turn on the power of the electronics crate by the switch in the back.
- 9. Turn on the motion control unit by the big rectangular red button (2).
- 10. Turn on Danfysik high voltage power supply by flipping up the switch (1) at the bottom.
- 11. Turn on Keithley 2000 digital multimeter by pressing in the power button (4).
- 12. Check that correct HV of -850V is applied by setting the multimeter to the second channel (press right arrow button (5) on the multimeter couple of times, until ch.2 is selected). You should see -0.850 VDC readings (HV monitoring output has 1:1000 factor).
- 13. Wait 1-2 minutes to stabilize PMT readings, check that ch.1 shows values <20mV.





Figure 5. Electronics

Now we are ready to make the scan:

- 1. Open the terminal window on the control PC
- 2. Define environment: source ~tilecs/public/setup_cs.sh
- 3. Switch to the test directory: cd ~/public/labs/table
- 4. Start the scan script: ./tablelab.shfile-name
- 5. If the HV is not applied or table motion control unit is off you will get an error message. Fix the problem and start again.
- 6. After the start, the control program would begin the data taking and show online display.
- 7. Follow the evolution of the scan with this plot
- 8. Wait until the end of the scan (message in the data taking window). It takes ~6 minutes.
- 9. Turn off HV and table control unit.



Figure 6. Online display showing the photomultiplier output signal as function of the distance of the source to the left edge the tile, where light is collected by the WLS fibre.

4.2. Measurement 2 - Single fibre (with mirror) scan

The purpose of this measurement is to see the improved light output from the fibre with mirror coating of the end.

Make the scan as described before in the section 4.1, using the fibre #2 (with aluminium mirror coating) attached to the left side of the tile.

4.3. Measurement 3 – Dual fibre (with mirror) scan

The aim of this measurement is to see the improvement of the optical properties using dual fibre readout, where light is collected on both extremities of the tile.

Keep the fibre #2 on the left side and connect the fibre #3 to the right side of the tile.

Make the scan as described above in section 4.1

4.4. Measurement 4 – Dual fibre 2D scan (done in advance)

As it takes about 7 hours, this scan has been done in advance and the data file is provided for your analysis.

4.5. Turn OFF HV and motion control

5. Data analysis

Now you will analyse the data collected in the measurements with simple ROOT macros (source code in appendix).

Run them and fill the table below. You can also print the obtained plots to conserve them with this document using the printer in the room

Go to the ~/public/labs/table directory. Start ROOT framework by typing root at the command prompt.

To calculate the light attenuation length you can use the macro latt.C:

.x latt.C("filename.root") where filename.root is the data file which you analyse. The macro will fit the profile histogram with two parameters exponential function I=I0*Exp(-X/Latt) and will display the results of the fit. Note that we fit the region of tile without masks, in the range 10mm<x<350mm. Close to the tile edge several effects affect the exponential behaviour:

- Attenuation due the presence of the ink.

- Increase due to absence of paper attenuating the flux from the source.

- Larger fraction of the light spectrum being collected, even wavelengths with smaller L_{att} start contributing.

To calculate the mean and RMS and to calculate signal to noise ration use the macro lsnr.C: .x lsnr.C("filename.root")

In this macro a histogram of PMT response is plotted. We select the scan points outside of the tile boundaries for the pedestal measurements and tile region for the signal measurement. For the signal to noise ratio a standard definition is used: $SNR_{db} = 20 \log_{10} (A_{signal}/A_{noise})$.

| Latt | | | | N/A | N/A |
|---|----------|-----------------------------|-----------------|-----------------|---------|
| \mathbf{I}_0 | | | | | V/N |
| χ^2/ndf | | | | N/A | N/A |
| SNR | | | | | |
| Noise (X>400) | RMS | | | | |
| | mean | | | | |
| Signal (10 <x<350)< td=""><td>mean/RMS</td><td></td><td></td><td></td><td></td></x<350)<> | mean/RMS | | | | |
| | RMS | | | | |
| | Mean | | | | |
| Measurement | | Single fibre #1 (no mirror) | Single fibre #2 | Dual fibre #2#3 | 2D scan |

Once you finished your analysis and have filled the results table you can answer these simple questions to recapitulate what you have learned in this laboratory.

- 1. What is the benefit of wavelength shifting from blue to green?
- 2. What is the benefit of fibre end polishing and mirror masking?
- 3. Why tile is wrapped in a tyvek paper?
- 4. Why black coat masking is applied to the edges of the tyvek envelope
- 5. What are the main advantages of dual fibre readout vs. single fibre?

You will also be provided with the general questionnaire about the laboratory, please fill it out, as feedback for improve it is very much appreciated.

6. References

[1] Use of Radioactive Sources at CERN, EDMS 856968,

[2] The Production and Qualification of Scintillator Tiles for the ATLAS Hadronic Calorimeter, <u>ATL-TILECAL-PUB-2007-010</u>,

[3] The Optical Instrumentation of the ATLAS Tile Calorimeter, <u>ATL-TILECAL-PUB-2008-005</u>,