15 years of experience with quality control of WLS fibres for the ATLAS Tile Calorimeter

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Abstract

We describe a test bench to measure the optical properties of scintillating and Wave-Length-Shifting fibres, called the *Fibrometer*. The accuracy, stability and reproducibility were assessed, and the quality control of WLS fibres for the upgrade of the STIC luminosity monitor at DELPHI and for the Tile calorimeter of ATLAS is reported.

1 Introduction

Plastic optical fibres have found a widespread use in the construction of detectors for HEP experiments, both for tracking and calorimetric applications. Scintillating fibres are used since the 80's in calorimeters [1,2], providing simultaneously the active medium and the light output guiding device. Devices based on scintillating fibres operated as trackers and calorimeters of experiments like Chorus [3], D0, g-2 [4], KLOE and others. Wave-Length Shifter (WLS) plastic fibres have also become commonly used with the advent of the now very popular scintillating tiles calorimeters with readout by WLS fibres used among others in the hadronic calorimeters of ATLAS [5] and CMS [6].

The testbench described have been used for the quality control of plastic fibres for the DELPHI [8] experiment at LEP, for Tilecal/ATLAS [5] and it is in use for ageing studies of Tilecal and for the quality control of the fibres for the ALFA [11] luminosity detector of ATLAS.

The DELPHI [8] experiment at LEP adopted the *'Shashlik'* type configuration for the high precision luminosity monitor - STIC (**S**mall Angle **TI**le

Calorimeter) (see [9,10] and references therein), and used 1 mm diameter WLS fibres.

TILECAL, the central region hadronic calorimeter of the ATLAS detector [7] for the LHC collider, uses plastic scintillating tiles and is equipped with 1 mm diameter WLS fibres.

ALFA, the new luminosity detector of ATLAS, is a tracker that uses square 0.5x0.5 mm^2 scintillating fibres staggered in 20 layers.

The quality control of detector components is an important task for the optimization of detector properties such as linearity, energy resolution and signal uniformity.

The optical properties of plastic fibres for calorimetric applications can be characterized in terms of the light yield and attenuation length. In the past several devices were constructed for the measurement of these parameters. In the simplest configuration a single fibre is longitudinally scanned by an excitation source and the light output is read by a photomultiplier tube (PMT). This type of device was used in the measurement of scintillating fibres for the SPACAL calorimeter, namely in radiation hardness studies [12]. The main disadvantage is the time spent in changing the fibres to be measured and in the stabilization of the system, in particular when a large number of fibres needs to be tested. An important improvement was achieved by introducing an additional degree of freedom allowing the transversal movement between the radiation source and the fibres. With this configuration several fibres can be installed on a supporting table that is moved to position the selected fibre facing the readout system. The quality control of the scintillating fibres equipping the CHORUS calorimeters was undertaken with this type of device [13].

In this paper we report on the implementation and performance of a test bench for large scale quality control of scintillating and WLS fibres. This test bench is operating since 1992, for the quality control of the WLS fibres that equipped the STIC calorimeter, when 10 000 fibres were scanned for a final selection of approximately 8 000 fibres. It was used also in extensive tests of WLS fibres for the TILECAL calorimeter and in the quality control of 10% of the WLS fibres used in this calorimeter. Presently it is in use for aging tests of the WLS Tilecal fibres and for the quality control of aluminized scintillating fibres for the ALFA luminosity detector. The results from the measurements for the STIC calorimeter and for the TILECAL are also presented and could be considered a benchmark for the performance of the setup.

2 Experimental setup

The test bench to perform characterization and quality control of optical properties of scintillating and WLS fibres, called the *"Fibrometer"*, was built in 1992 to characterize and qualify the fibres for STIC and for the R&D for the Tile calorimeter of ATLAS. The fibrometer is schematically shown in figure 2. It consists of three main components: The main support (which is fixed), the supporting table and the radiation source holder, the photodetector and the control and data acquisition system.

2.1 The XY table

A 2.54 m long X–Y MicroControle optical table, is provided with two independent movements, driven by two stepping motors along orthogonal directions.

The radiation source holder moves along the X–axis, and the distance between the holder and the supporting table changes by less than few tenths of a millimeter when displacing the holder between the two extremities.

The supporting table is loaded with the fibres plate, with capacity up to 32+1 fibres, and moves along the Y–axis. The movement of the table ensures a constant distance between all fibres and the light readout system based on a PMT, within a precision of the order of 50 μm.

This table supports the removable plate that contains the fibres to be tested. The longitudinal position of the fibres is adjusted with a special metallic tool (figure 1) in such a way that the extremity that faces the PMT is 0.5 mm out of the plate, preventing the possibility of having the fibre slightly recoiling inside the groove that could result in light loss. Each fibre is positioned in front of the light readout using the Y step motor and the X step motor moves the radiation source along the fibre length. At each position, the light output from the fibre positioned in front of the light readout is recorded.

The test bench is automatically controlled by a MacIntosh Personal Computer through GPIB interfaces taking care of the movements of both motors and the control and readout of a picoammeter connected to the light readout system. Dedicated software was developed using the LabView [1] (**LAB**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench) package, allowing an online QC analysis. The room temperature is kept at 25 ^{o}C.

In figure 3 it is shown a cross view of the supporting table and one fibre plate.

[1] ©National Instruments

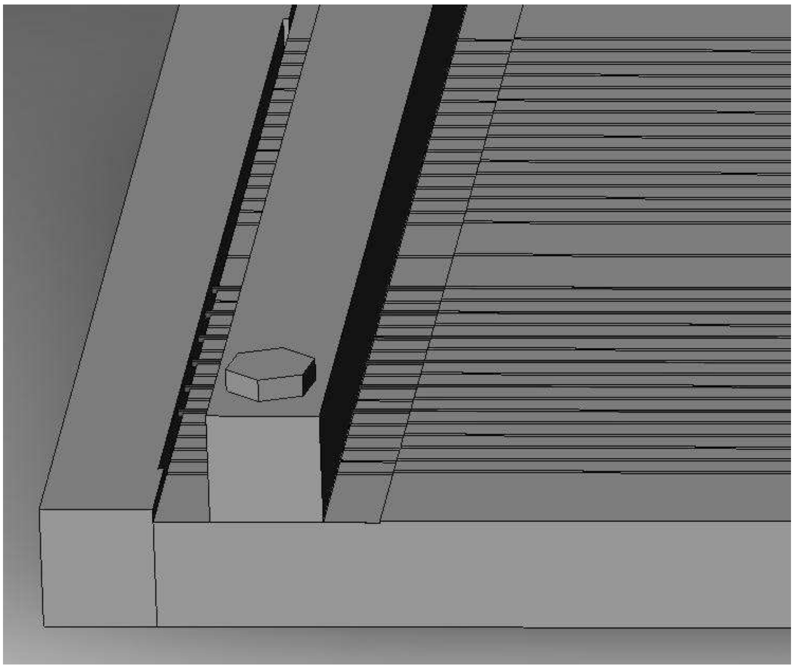


Fig. 1. Alignment of the fibres at the extremity facing the PMT. The metallic bar is used to ensure that all the fibres come out of the plate by 0.5 mm.

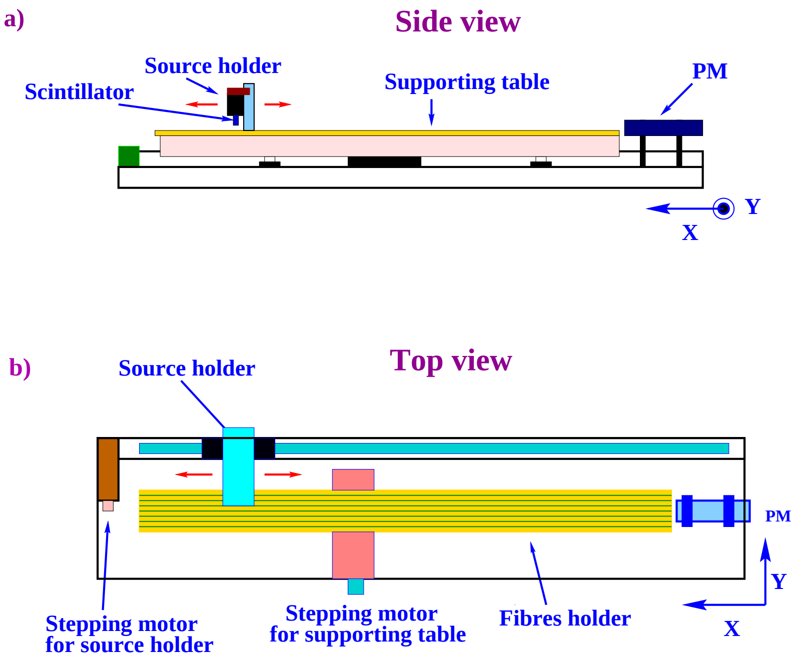


Fig. 2. The test bench *Fibrometer*: a) side view; b) top view

One reference fibre is fixed in a black painted groove drilled along the table length and is attached to the supporting table. The signal from this fixed reference fibre provides a monitorization of the stability of the entire system.

The XY supporting table made of black anodized aluminium stands on a

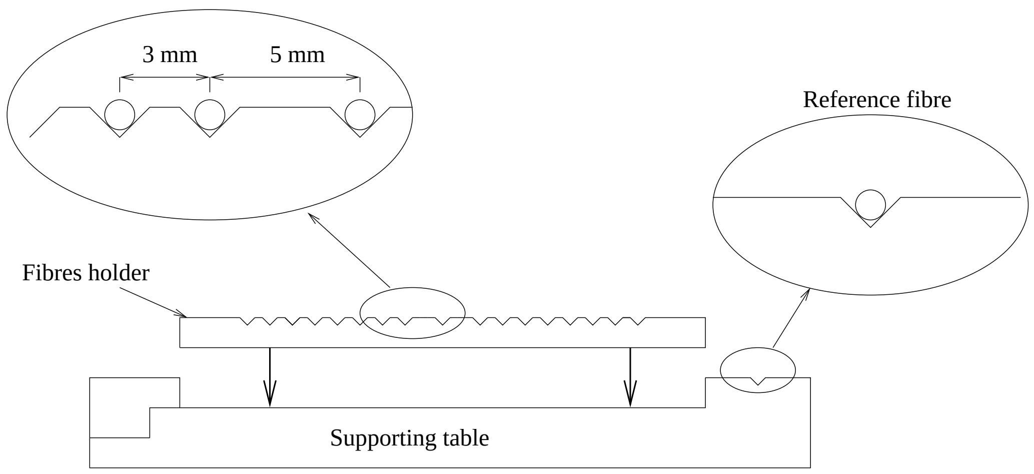


Fig. 3. Cross view of the supporting table and one fibre plate.

concrete table that allows a stable positioning.

The XY table consists of a matt black anodized aluminium plate with 33 V-shaped grooves, allowing to place one fibre in each groove. The distance between adjacent grooves is 3 mm. The central groove is 5 mm apart from the neighbours and receives one reference fibre. This reference fibre is aligned together with the loaded fibres, to mimic the eventual position misalignment and mechanical damage during the filling of the table with fibres.

Two 60 cm long or two 250 cm long plates are used depending on the length of the fibres to be tested. The use of two identical plates allows to reduce the dead time since one set of fibres is automatically measured while the second plate is filled with new fibres, minimising also the time needed to stabilise the electronics and PMT temperature just after closing the black box.

2.2 The radiation source

The *Fibrometer* can operate with three alternative sources of radiation. When testing scintillating fibres, electrons from a ^{90}Sr radioactive source are used to excite the fibres directly. If WLS fibres are under test, a blue LED is used or a 3 mm thick blue scintillator [2] is inserted in front of the ^{90}Sr source. The light from the scintillator is then used to excite the WLS fibres. To enhance its light output the scintillator is wrapped with aluminized mylar. A schematic

[2] Injection molded polystyrene doped with 1.5% PTP and 0.05% POPOP.

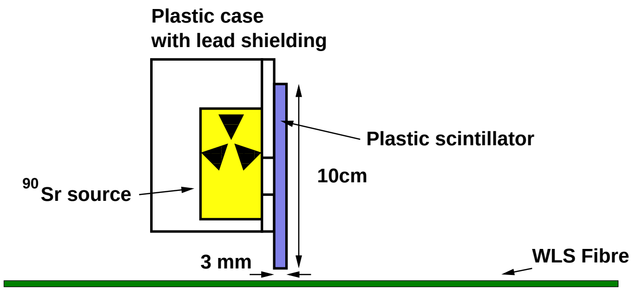


Fig. 4. The excitation source assembly used when testing WLS fibres.

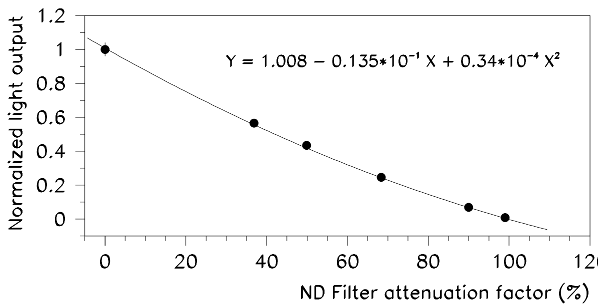


Fig. 5. The light output vs neutral density filter attenuation factor.

illustration of this assembly is shown in figure 4.

The linearity response is systematically checked for the different source configurations and different types of fibres using neutral density filters. In figure 5

Any possible saturation resulting in nonlinearity of the light yield from the WLS fibres was checked by placing several Neutral Density filters of different attenuation factors between the scintillator and one fibre. In figure 5 the measured signal normalised to the signal obtained without any filter is plotted against the filter attenuation factor. The data was fitted with a second order polynomial; the quadratic term is a factor of 300 smaller than the linear term, from which it is concluded that no saturation exists in the range of light intensities that are usually tested.

2.3 The light readout

The light readout system consists of a blue sensitive *EMI 9813KB* PMT air coupled to a light mixer (LM), to allow long term studies. The signal from the PMT is read by a *KEITHLEY* 485 auto-ranging picoammeter, equipped with a *KEITHLEY* 4853 IEEE–488 interface.

The PMT and light mixer are enclosed in a cylindrical metallic case closed at the end near the fibre by a light opaque black disc with a 300 μm slit in the center. The slit width can be changed. The slit allows the detection of the

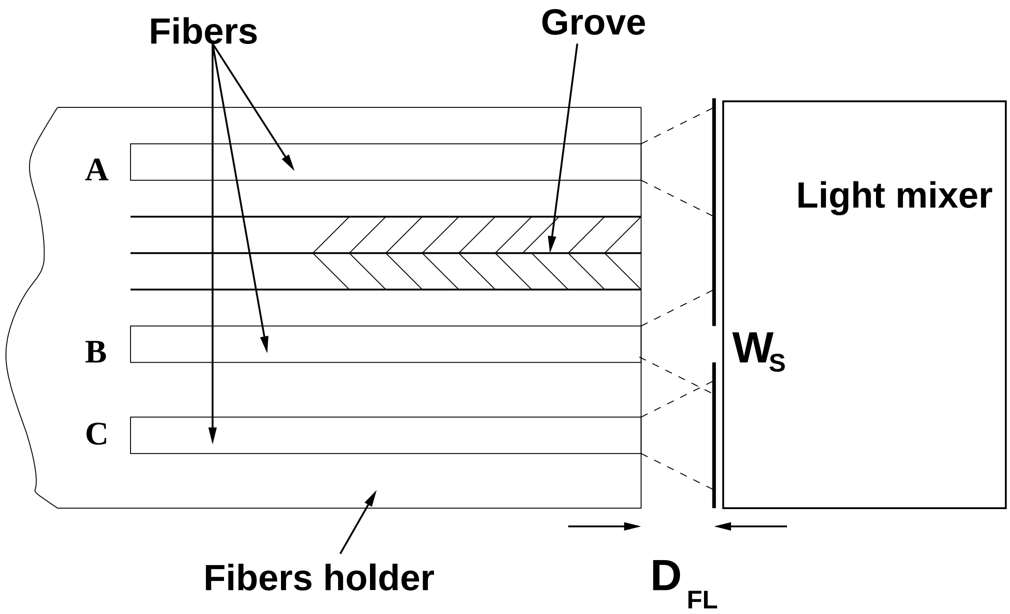


Fig. 6. The role of the slit in cutting the light from the fibres adjacent to the selected one is illustrated in this picture.

light from the selected fibre, while avoiding the light from the neighbouring fibres, as it is illustrated in figure 6. This effect versus the slit width (W_S), the distance between the fibres and the light mixer (D_{FL}), and the distance between adjacent fibres (Δ_{FF}), is studied in section 3.

2.4 Fibre measurement cycle

The user interface consists of a front panel where several parameters can be checked and/or modified. The electronic noise level is determined in the beginning of each measurement cycle after moving the radiation source out of the fibres region, to be subtracted from the fibres signal. The noise is of the order of 2 nA while the signal is not less than about 100 nA for a typical WLS fibre. Therefore, for usual WLS fibres a signal to noise ratio of 50 or better is achieved with the scintillator coupled with the ^{90}Sr source .

The optimal position of each fibre in front of the slit is then searched by performing a transversal scan (Y direction) with a 200 μm step. The result is a peak structure with the maxima occurring when each fibre is centered with the slit. After several studies, the maxima of the current was considered the best parameter for purposes of fibre characterization and quality control. The positions of these maxima are determined by parabolic fits to the peaks. Each fibre is moved to the optimal position found in the previous step and the radiation source scans the fibre in predefined longitudinal positions.

The *"fixed"* reference fibre is measured in the beginning and in the end of each cycle. The measured light output (I_{meas}) from each fibre is normalised through:

$$I = I_{meas}/K \qquad with: \quad K = 1000 \times \frac{I_{rf}^{begin} + I_{rf}^{end}}{2} \tag{1}$$

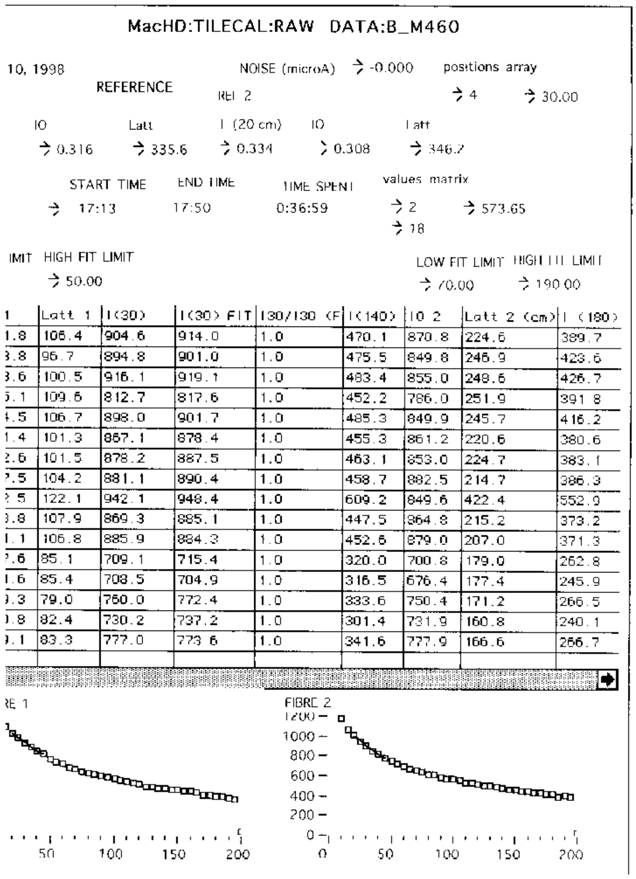
where I_{rf}^{begin} and I_{rf}^{end} are the light output of the *"fixed"* reference fibre, measured at a fixed longitudinal position, respectively in the beginning and in the end of each cycle.

The software also performs the online data analysis, consisting mainly in the computation of the light yield (I_0) and attenuation length (L_{att}) of each fibre, through a fit to a simple function easily parametrized that has been identified previously in systematic measurements. The spectral response of scintillating or WLS fibres to a light source depends not only on the dopants but also on geometric effects such as the different path lengths following the initial direction of the rays and their wavelengths. Several parametrizations based on the sum of exponentials can describe the fibre light response to an excitation source. After careful study it is possible to find an easy parametrization that can be given by a sum of 2 exponentials or by one single exponential if the region is restricted to a short length of the fibre. For the online QC of the fibres we used one exponent in regions near the beginning and near the end of the fibre, each region characterized by the respective I_0 and L_{att}:

$$I(x) = I_0 e^{-\frac{x}{L_{att}}} \tag{2}$$

The results are presented in a report page as shown in figure 7. It contains, besides some relevant data concerning the measurement of the reference fibre and the noise level, a table with the results of the on-line analysis. The plot showing the light output as a function of the source position is displayed for each fibre.

This report page is very useful for a real time control of the ongoing measurements and an efficient trouble handling. The raw data and the results of the online analysis are also stored on disk, for offline analysis.



MacHD:TILECAL:RAW DATA:B_M460

10, 1998 REFERENCE NOISE (microA) → -0.000 positions array

REI 2 → 4 → 30.00

IO → 0.316 Latt → 335.6 I (20 cm) → 0.334 IO → 0.308 Latt → 346.2

START TIME → 17:13 END TIME 17:50 TIME SPENT 0:36:59 values matrix → 2 → 573.65 → 18

IMIT HIGH FIT LIMIT → 50.00 LOW FIT LIMIT → 70.00 HIGH FIT LIMIT → 190.00

1	Latt 1	I(30)	I(30) FIT	I30/I30 (F	I(140)	I0 2	Latt 2 (cm)	I (180)
1.8	106.4	904.6	914.0	1.0	470.1	870.8	224.6	389.7
3.8	96.7	894.8	901.0	1.0	475.5	849.8	246.9	423.6
3.6	100.5	916.1	919.1	1.0	483.4	855.0	248.6	426.7
5.1	109.6	812.7	817.6	1.0	452.2	786.0	251.9	391.8
4.5	106.7	898.0	901.7	1.0	485.3	849.9	245.7	416.2
1.4	101.3	867.1	878.4	1.0	455.3	861.2	220.6	380.6
2.6	101.5	878.2	887.5	1.0	463.1	853.0	224.7	383.1
7.5	104.2	881.1	890.4	1.0	458.7	882.5	214.7	386.3
2.5	122.1	942.1	948.4	1.0	609.2	849.6	422.4	552.9
3.8	107.9	869.3	885.1	1.0	447.5	864.8	215.2	373.2
1.1	106.8	885.9	884.3	1.0	452.6	879.0	207.0	371.3
7.6	85.1	709.1	715.4	1.0	320.0	700.8	179.0	262.8
1.6	85.4	708.5	704.9	1.0	316.5	676.4	177.4	245.9
9.3	79.0	760.0	772.4	1.0	333.6	750.4	171.2	266.5
0.8	82.4	730.2	737.2	1.0	301.4	731.9	160.8	240.1
9.1	83.3	777.0	773.6	1.0	341.6	777.9	166.6	266.7

Fig. 7. Report page produced by the online monitoring program.

3 Slit width of the black opaque film

It was seen that the slit width has influence not only on the intensity of the light detected from the fibres (for a larger slit, more light enters the PMT), but also on the measured attenuation length.

Since the light output is normalised to the *"fixed"* reference fibre (c.f. section 2.4), the slit width does not influence the relative comparison between different types of fibres. On the other hand, if the measured attenuation length depends on the slit width, the comparison between different fibres can be biased. This is particularly important for long fibres like the ones equipping the TILECAL calorimeter, for which the average fibre length is 200 cm.

Several tests were performed: four slit widths (W_S= 0.5 mm, 1.5 mm, 3 mm and 5 mm), and two distances from the fibres to the light mixer, D_{FL}= 1.4 mm and 0.9 mm. For each test the fibres were longitudinally scanned (X–axis) in steps of 5 cm.

Four 190 cm long Y11(200)MS double cladding Kuraray fibres, were chosen for these tests. The attenuation length (L_{att}) is taken from a fit with equation 2 to the light output data in the region $x > 70$ cm.

Figure 8-left shows the fibre attenuation length as a function of the slit width revealing a systematic decrease with increase of the slit width (W_S) and with the decrease of the fibre-light mixer distance (D_{FL}). This can be due to two effects:

(1) When the slit is small, it cuts light rays with more reflections inside the fibre, which come out at larger angles. Those light rays have a higher attenuation due to its longer path. Shorter attenuation length components are thus suppressed, resulting in a higher measured attenuation length.
(2) The attenuation length of the cladding component is smaller than that from the core. Therefore if the slit aperture is reduced the contribution from the cladding light decreases and the measured attenuation length increases.

In terms of the detected light cone, increasing D_{FL} with fixed W_S has the same geometrical effect as reducing W_S with fixed D_{FL}.

Figure 8-right shows the ratio $\frac{I}{I_{5mm}}$ of the light output (I) for a given slit width, to the light output measured with the 5 mm slit (I_{5mm}). The 5 mm slit should contain the full light cone for both values of D_{FL}, so this ratio gives the fraction of light *seen* by the PMT.

For D_{FL}= 1.4 mm, the 3 mm width slit cuts 4–5% of the light, while for D_{FL}= 0.9 mm the full light cone is viewed by a 3 mm slit ($\frac{I_{3mm}}{I_{5mm}} \sim 1$). This is clearly shown by the results shown for two transversal scans (in the Y direction). In these tests, the fibres pass in front of a 0.5 mm wide slit in steps of 0.2 mm. In the first case D_{FL} was set to 1.4 mm, while in the second case D_{FL} was set to 0.9 mm. The excitation source was fixed at a distance of 30 cm from the PMT.

The first transversal scan is presented in figure 9–left, showing that the full light cone is contained within about 4.2 mm.

Figure 9–right shows the second transversal scan. One can see that, by reducing the fibres to light mixer distance to 0.9 mm, the full light cone of the fibres is contained within 3 mm.

In conclusion, it is recommended to have a distance between the fibres and the light guide D_{FL}= 0.9 mm, and a 3 mm wide slit, in order to detect the

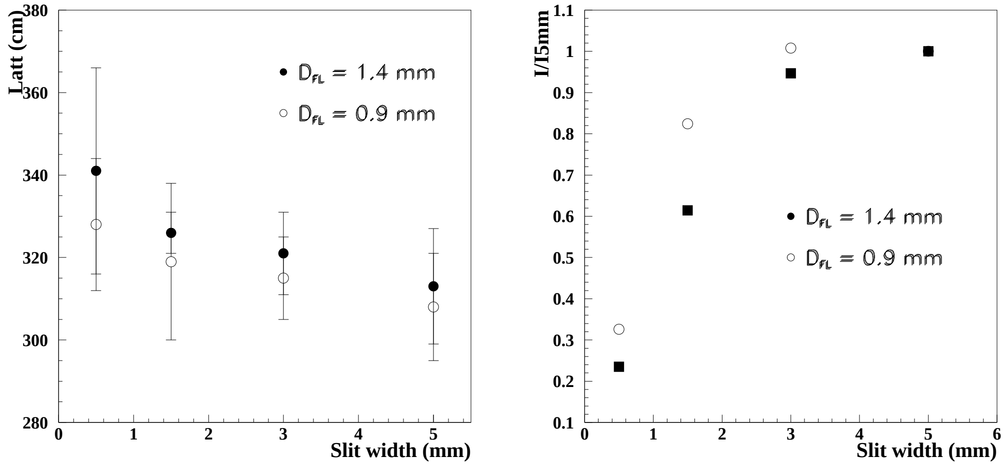


Fig. 8. Average attenuation length (left), and light output normalised to I_{5mm} measured with the 5 mm slit (right), of four Y11(200)MS fibres as a function of the slit width. Results are shown for D_{FL}= 1.4 mm (black circles) and D_{FL}= 0.9 mm (open circles). The error bars are the RMS of 4 fibres.

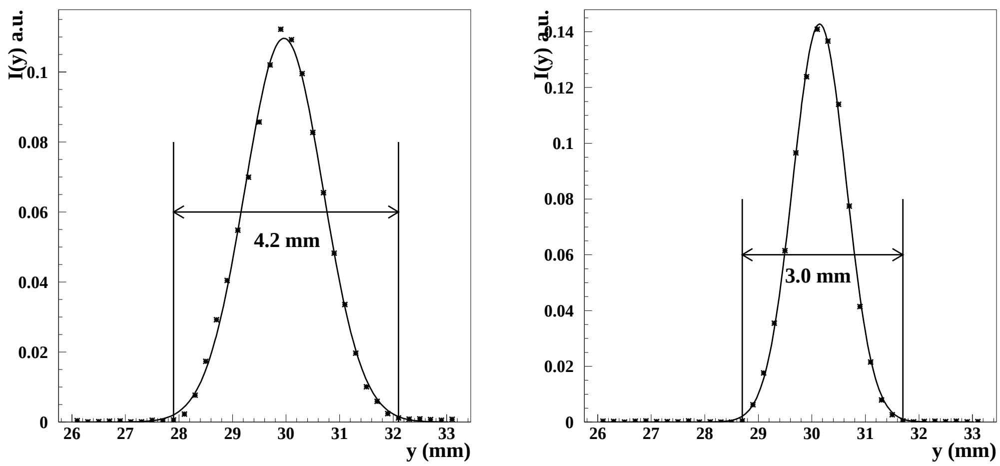


Fig. 9. Transversal scan of one fibre with the 0.5 mm slit width, for a fibres-light mixer distance D_{FL}= 1.4 mm (left), and D_{FL}= 0.9 mm (right).

whole signal from the fibre. As already pointed out, other suitably chosen combinations of (D_{FL},W_S) could also be used with the same result. However, the light cross-talk from the neighboring fibres comes also into play and, in order to maximize the number of fibres in the fibres plate, it is desirable to minimize D_{FL}.

The fraction of light that is collected from one neighboring fibre to the signal

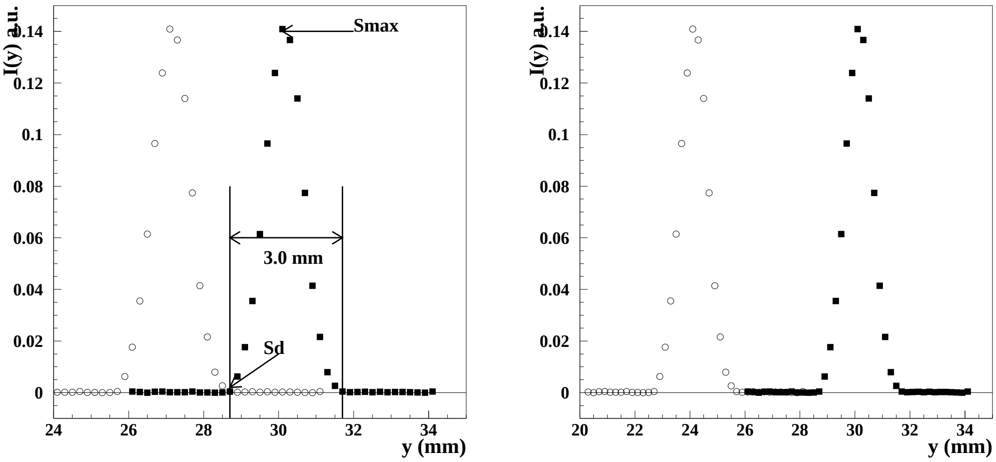


Fig. 10. Two distributions of the same fibre displaced by Δ_{FF}=3 mm, *left* plot, and Δ_{FF}=6 mm, *right* plot. In both cases D_{FL} =0.9 mm and W_S =3 mm.

of the fibre that is centered with the slit, defines the light cross-talk:

$$Cross\ talk = \frac{S_d}{S_{max}} \tag{3}$$

where S_{max} is the maximum of the signal (obtained when the fibre is centered with the slit) and S_d is the signal measured when the distance between fibres Δ_{FF} is 3 mm or 6 mm (see figure 10-left).

Figure 10-left shows two distributions of the same fibre displaced by Δ_{FF}= 3 mm, corresponding to the distance between adjacent grooves, a distance D_{FL}= 0.9 mm and a slit width of 3 mm. The cross–talk in this case is less than 1%, but the signal of the neighboring fibre is *"close"* to be observed by the PMT. For Δ_{FF}=6 mm (figure 10-right), the distance between fibres is large enough to have a negligible cross-talk.

The measurement of several types of WLS test fibres for the TILECAL calorimeter, used the *Fibrometer* parameters taken from these studies, i.e.: fibres-light mixer distance D_{FL}= 0.9 mm, slit width W_S= 3 mm and the distance between neighboring fibres Δ_{FF}= 6 mm.

With this choice of parameters, the maximum number of fibres per plate is 16 plus a *movable* reference fibre (one per plate), which sits in the central groove.

4 Stability and reproducibility of the *Fibrometer*

The stability of the *Fibrometer* is monitored by reference fibres. For each plate there is a reference fibre (called *movable*), which sits in the middle groove (c.f. figure 3). These fibres allow to monitor the alignment and all other mechanics treatment suffered by of the fibres being tested (c.f. section 2.1).

The stability of the light source and readout chain is monitored by a fixed reference fibre that is fixed directly to the table, that was for several years a 230 cm long Kuraray Y11(200)MS aluminized in opposite end of the readout PMT. Systematic response decrease of the fixed reference fibre is expected, specially when the scintillator excited by the ^{90}Sr source is used, due to global ageing of the scintillator mostly caused by radiation damage.

Figure 11 shows the time dependence of the rescaled signal (as defined in section 2.4) from the *"movable"* reference fibre of a 60 cm plate on the left plot (STIC fibres) during one month, and of a 250 cm plate on the right plot (TILECAL test fibres) for 3 periods of time, SP1 (1 month), SP2 (2 weeks) and SP3 (2 weeks).

The inset plot in figure 11-left show the histogram of the signal in the main plot. The spread of this distribution is of the order of 2.5%, while this spread is 1.6% for the *movable* reference fibre in the 250 cm plate.

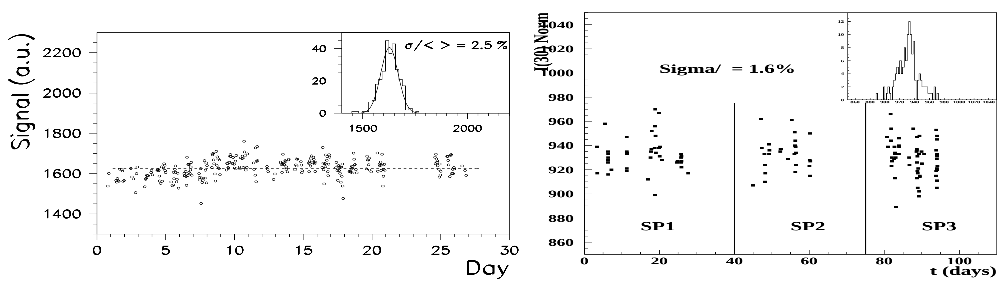


Fig. 11. Rescaled signal from the reference fibre of each plate as a function of time. Left: *"Movable"* reference fibre with 54 cm for the STIC fibres measurements. The inset plot show the signal distribution of this fibre. Right: *"Movable"* reference fibre with 200 cm for the TILECAL test fibres measurements.

Since the movable reference fibre of each plate undergoes the same operations as all the fibres under test, it is concluded that the total experimental error in our measurements is of the order of 2.5% for short fibres, and 1.6% for long fibres. In section 6.1 there is another result for long fibres for a 1 year period and the value found was 1.7%.

Moreover, the test-bench is reproducible (within the errors), over a long period of time. The use of reference fibres allows to get a light output measurement independent from any instability of the readout chain or changes in the scintillator light yield due to aging processes.

5 Quality control of WLS fibres for the STIC/DELPHI upgrade

In the beginning of 1994 a new luminosity monitor was installed in the DELPHI [8] experiment at LEP: the STIC - Small angle TIle Calorimeter [9,10]. The main purpose was to reach an experimental systematic error on the luminosity measurement below 1‰.

STIC is a lead-scintillator "Shashlik" type calorimeter with a sampling structure consisting of 47 layers each made of 3.4 *mm* thick continuous lead plate and 3 *mm* thick scintillating tiles (made of injection molded polystyrene doped with 1.5% PTP + 0.05% POPOP). The scintillation light is collected over the whole depth of the calorimeter by $\sim$ 50 cm long, 1 mm diameter WLS plastic fibres. The total number of fibres inside STIC (four modules plus a spare module) is of the order of 8000.

Until the end of 1996, Y7(150) WLS fibres from Kuraray equipped the detector. As initially envisaged, those fibres were replaced in the beginning of 1997 by Kuraray Y11(300)MS fibres doped with 200 ppm UltraViolet Absorber (UVA).

Detailed comparative studies of the optical properties of WLS fibres can be found in reference [14], and a summary of the improvements achieved can be found in ref. [15].

The quality control and selection of the WLS fibres used in the STIC upgrade are presented in the following sections.

5.1 Quality control of the STIC WLS fibres

The fibres equipping the STIC calorimeter were polished at both ends, first at CERN during the cutting to size operation, and later a minute polishing was obtained using an air cushion diamond mill (GEBEX, Uster, Switzerland). Finally one fibre extremity was mirrored by aluminium sputtering technique (PRECITRAME, Tramelan, Switzerland). For polishing and aluminization purposes, the fibres were assembled "à la SPACAL" in eight bundles, each containing 1261 fibres.

For mirrored fibres the light output as a function of the excitation point, is described by the sum of at least two exponentials. But, when comparing fibres in terms of light yield and attenuation length and in particular when a large sample of fibres of the same type must be characterised, it is usual to employ a single exponential model which has less parameters (equation 2). This parametrisation is valid only in limited regions, in which case the L_{att} is an effective attenuation length.

5.2 Results from the quality control measurements

The 10 000 fibres were polished, aluminized and measured for a final selection of $\sim$ 8 000 fibres to be installed in STIC. According to the position inside the calorimeter the fibres length is 52.2 cm (inner rings) or 54.0 cm (outer rings). The number of fibres to be inserted and the number of fibres tested are summarised in table 1.

Table 1
Number and length of fibres tested and used to equip the STIC.

Length (cm)	52.2	54.0
Tested	7500	2500
Inside STIC	6200	2080

The main purpose of the quality control measurements was to be able to select fibres with very similar light output for insertion in the same calorimeter cells, in order to improve the detector signal uniformity. Fibres with poor or very high light output were rejected. Selected fibres were then grouped in different sets according to the measured light yield.

The light output from each fibre was measured at 21 equidistant positions of the scintillator along the fibre length, starting at 6 cm from the light readout, with 2 cm steps. The signal *vs* scintillator position data was fitted with an exponential function (eq. 2) in two regions: $[6, 20]$ cm and $[20, 40]$ cm.

The most significant quantity for characterisation and in particular simulation of the detector performance, is the fibres light yield in the region where the electromagnetic shower deposits the maximum energy. For STIC, the incoming particles are mostly electrons with an energy ranging from 45 GeV (during the LEP I phase) to $\sim$ 100 GeV (when LEP has reached the maximum center of mass energy). For these energies the shower maximum is located at a calorimeter depth of around 5 cm, i.e. at a distance of 45 cm from the fibres end near the light readout. For selection and grouping purposes, the extrapolated light yield from the fit in the region $[20, 40]$ cm, $I_{0[20,40]cm}$, is used.

The distribution of $I_{0[20,40]cm}$ for the fibres of each bundle (composed of 1261 fibres each), assembled for polishing and aluminization, was fitted with a gaussian. The mean value and spread of $I_{0[20,40]cm}$ and $L_{att[20,40]cm}$ for each of the eight bundles are summarised in table 2. In figure 12 are shown the histograms for all fibres of length $L = 54$cm. It can be seen that the light yield fluctuation on the 2 100 fibres with a length of 54 cm is 4.2%, while in the attenuation length this value is 10%.

Table 2
Mean value and σ of $I_{0(20-40\ cm)}$ and $L_{att(20-40\ cm)}$ distributions for each fibre bundle.

Bundle #	**fibre length** (mm)	**# fibres Selected**	$\mathbf{I}_{0(20-40\ cm)}$ **Mean** (a.u.)	σ	$\mathbf{L}_{att(20-40\ cm)}$ **Mean** (cm)	**RMS**
1	522	977	2010	3.5 %	179	8.9 %
2	522	955	2040	3.6 %	170	8.8 %
4	522	978	1920	4.4 %	176	9.1 %
5	522	1014	1970	3.6 %	184	9.8 %
7	522	902	1900	4.1 %	161	8.7 %
8	522	875	1990	3.4 %	185	10.3 %
3	540	1097	1890	4.0 %	171	8.8 %
6	540	1015	1920	4.2 %	172	10.5 %
Last set	522	694	1990	3.4 %	182	11.5 %
Last set	540	130	1940	3.7 %	176	10.1 %

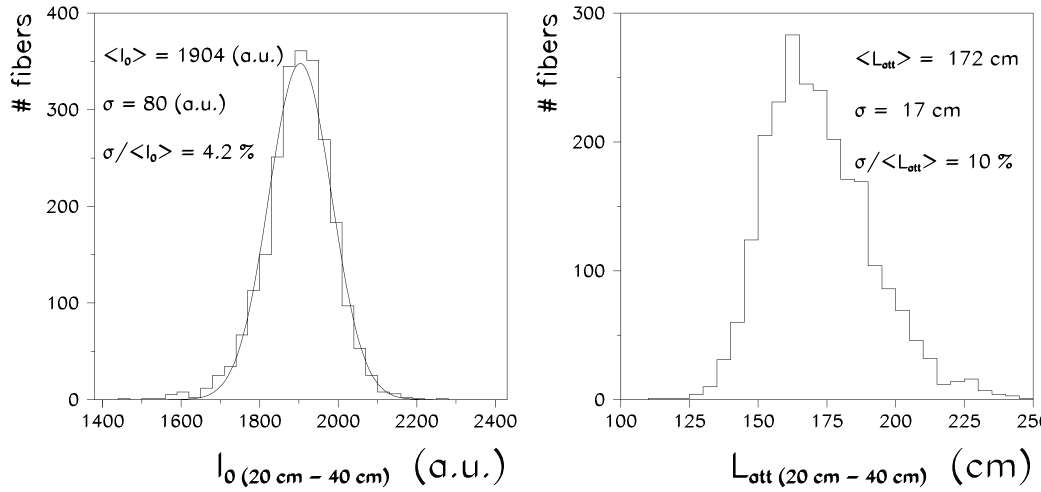


Fig. 12. The extrapolated light yield $I_{0(20-40\ cm)}$ (left) and attenuation length $L_{att(20-40\ cm)}$ (right) distributions for all fibres of length 54.0 cm (2384 fibres).

6 Quality control of the WLS fibres for TILECAL

The WLS fibres acceptance quality control consisted on the measurement of some optical and mechanical properties of the fibres. Those properties and the respective acceptance criteria are described in detail in a TILECAL note [16] and are summarized in Table 3.

The 572761 fibres of the regular production were divided in 7 batches received and controlled in Lisbon and in Pisa from April 1999 to May 2000, and each batch was composed of several preforms. The Lisbon group received 32% of each batch, giving a total number of 181677 fibres. The number of fibres of the extra production is 5300 and the respective QC was done in Lisbon in March 2002. For the acceptance QC, 32 fibres with a length of 200 cm were selected from each perform. The total number of fibres that were controlled in Lisbon was 2080 (1.1%). The optical properties were measured in the "Fibrometer" described in this paper, and the diameter and eccentricity were measured using a mechanical micrometer with a precision of 0.005 mm.

The optical and mechanical properties and QC acceptance criteria are shown in Table 3.

Table 3
Optical and mechanical properties that are controlled and the respective requirements in the acceptance QC.

Parameter	Def. or units	requirements
Light yield	$I(140)/I(140)_{ref}$	$\geq$0.8
Latt	Latt(cm)	$\geq$250cm
RMS (ly)	RMS(%)	$\leq$7%
RMS(latt)	RMS(%)	$\leq$7%
Diameter	$\lvert D-1.00\rvert$	$\leq$0.02mm
Eccentricity	$\lvert D_{max} - D_{min}\rvert$	$\leq$0.03mm
Mechanical stress	$1 - I_{bent}/I_{straight}$	$\leq$5%

A summary is given about the measurement conditions. The light output of the fibres was measured between 10 and 200 cm from the PMT in steps of 5cm. For each fibre, the value measured at a distance from the excitation source to the PMT, x=140 cm, is compared with and normalized to the value obtained with reference fibres. The effective attenuation length is taken from a single exponential fit between 70 and 190 cm. The loss due to mechanical stress is obtained by the ratio of the light output at x=140 cm before and after the bending around a 7cm diameter circle, $R(140)=I(140)_{bent}/I(140)_{straight}$. The side opposite to the PMT was not painted black, but all fibres were polished in both sides using a milling machine, in order to get better reproducibility.

6.1 *Stability and reproducibility of the system during the TILECAL fibre acceptance QC*

The first batch of WLS fibres arrived at Lisbon in April of 1999 and the last batch of the regular production (#7), arrived in May 2000. The extra fibres arrived in 2002. The time schedule of the fibres arrival is presented in Table 4. The QC for acceptance of each batch was performed during one week after its arrival to Lisbon, so the QC of the regular production took place during 7 periods of one week along a time interval of one year.

Table 4
Composition and date of arrival of all batches.

Batch	Arrival date	number of preforms	number of fibres
1	30-4-1999	11	7161
2	10-7-1999	6	18760
3	10-9-1999	5	18454
4	10-11-1999	9	32213
5	10-1-2000	10	34978
6	10-3-2000	10	34924
7	10-5-2000	11	34896
extra	20-3-2002	3	5300
TOTAL		65	186686

To guarantee the reproducibility of the measurements during the acceptance QC procedure, in addition to the normal monitorization of the "Fibrometer", a set of 16 reference fibres was monitored during all the QC period. Figure 13 shows the average light output of those 16 fibres, measured along time. The standard deviation of those values has $\sigma = 1.7\%$, giving a good overall stability of the system during the whole period of measurement (1 year), almost equal to the 1.6% value obtained in a similar period when testing fibres for STIC and referred in section 4.

6.2 *Acceptance of all batches*

The next tables (5 to 12) present a summary of the results of the measurements made for the acceptance QC of all the batches. Each table shows the values

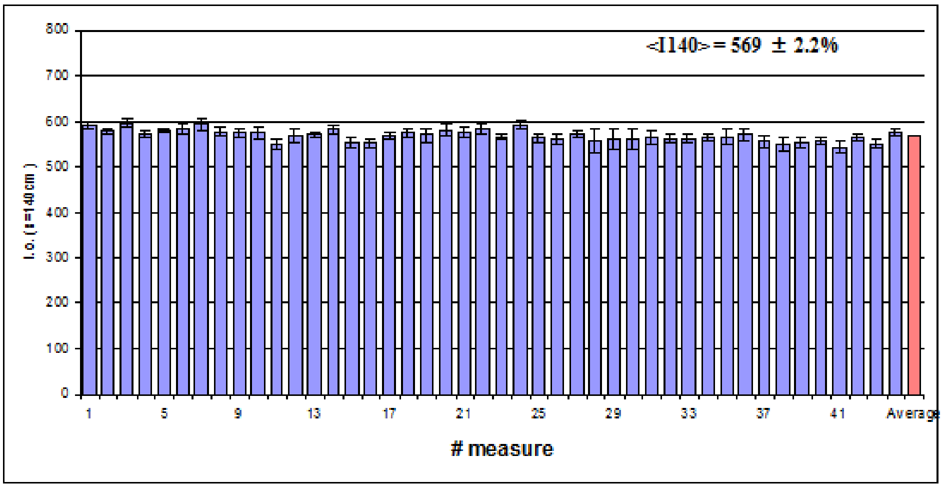


Fig. 13. Average value of the light output at x=140 cm for the 16 reference fibres during the period of the acceptance QC of the regular production of fibres.

of the parameters tested for each preform, and the last row shows the average for all fibres of the batch. The diameter and eccentricity were measured in 2 fibres per preform, 6 points in each fibre. The mechanical stress was measured using only 2 fibres per preform, since this measurement is a destructive test. In the first batch, the fibres used as reference were the Y11(200)MSJ from the tendering production. The average light output of all fibres of the first batch was 6% higher than the light output of the reference fibres. Since the light output of the fibres of the first batch should set the value for the rest of the production, those values were used as reference from batch 2 to batch 7. In this way, the average light output of batch 1 is set to 1.00 in table 6.

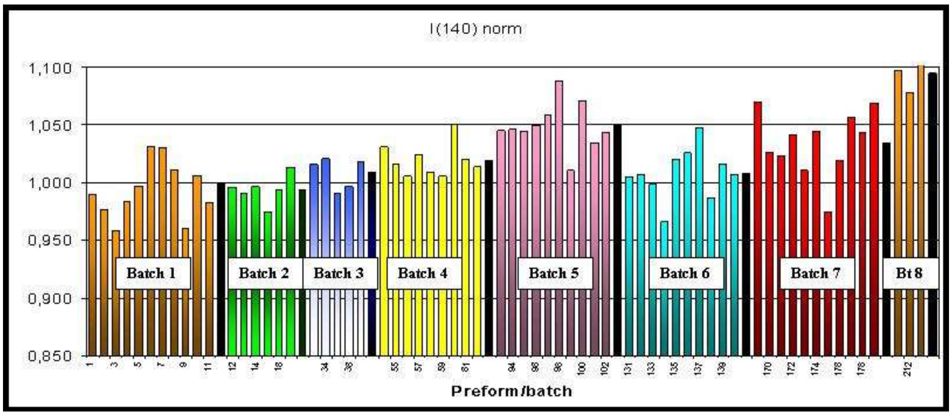


Fig. 14. Summary of the light output measured at x=140 cm for all the preforms.

Table 5
Summary of the results for the acceptance QC of batch 1. The reference used for I(140) is the average light output <I(140)> measured at x=140 cm of the fibres of the tendering.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al001	1.05	1.60	295	3.12	0.04
Al002	1.03	0.65	302	2.08	0.04
Al003	1.01	1.68	293	1.32	0.04
Al004	1.04	3.07	288	2.09	0.04
Al005	1.06	1.50	304	2.20	0.04
Al006	1.09	0.64	307	1.10	0.04
Al007	1.09	1.47	295	1.48	0.04
Al008	1.07	2.20	289	3.56	0.04
Al009	1.02	1.26	294	4.37	0.04
Al010	1.07	1.94	302	3.83	0.04
Al011	1.04	1.15	297	1.77	0.04
Total average	1.06	2.71	295	3.67	0.04

Table 6
Summary of the results for the acceptance QC of batch 2. The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al012	1.00	1.97	294	2.98	0.06
Al013	0.99	2.72	290	4.32	0.05
Al014	1.00	2.57	292	3.57	0.03
Al015	0.97	2.29	284	4.48	0.03
Al016	0.99	4.12	292	4.38	0.00
Al017	1.01	2.54	277	1.77	0.02
Total average	0.99	2.97	288	4.19	0.03

7 Summary

The Fibrometer is in use for 15 years, and contributed already to 3 different detectors of the experiments Delphi and ATLAS. It was used for the quality

Table 7
Summary of the results for the acceptance QC of batch 3. The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al033	1.02	2.75	298	2.68	-0.01
Al034	1.02	1.47	291	2.84	0.04
Al035	0.99	2.51	281	2.73	-0.01
Al036	1.00	1.95	281	3.74	0.01
Al037	1.02	1.57	283	3.22	0.03
Total average	1.01	2.40	287	3.83	0.01

Table 8
Summary of the results for the acceptance QC of batch 4. The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al054	1.03	1.52	291	2.85	0.04
Al055	1.02	1.88	296	2.15	0.04
Al056	1.01	1.83	286	2.95	0.05
Al057	1.02	1.48	278	4.20	0.03
Al058	1.01	1.95	279	3.47	0.04
Al059	1.01	1.58	280	4.40	0.02
Al060	1.05	1.49	265	2.57	0.00
Al061	1.02	2.84	286	2.91	0.03
Al062	1.01	1.50	278	3.74	0.04
Total average	1.02	2.24	282	4.41	0.03

control of the first set of WLS fibres for STIC, the luminosity monitor of the Delphi experiment and for the respective upgrade. It was used for the choice of WLS fibres for the Tile calorimeter of ATLAS, and ageing tests. During 3 years it was fully dedicated to the acceptance QC of WLS fibres for the Tilecal and for the QC of the same fibres after mirror aluminization. In the late years it has been in use for the tests of the scintillating fibres that will equip the ALFA luminosity detector of ATLAS.

It was used for the quality control of the first set of 10000 WLS fibres for STIC, the luminosity monitor of the Delphi experiment and for the respective

Table 9
Summary of the results for the acceptance QC of batch 5. The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al093	1.04	2.04	290	3.81	0.05
Al094	1.05	3.46	277	3.70	0.05
Al095	1.05	1.58	284	2.67	0.03
Al096	1.05	1.72	274	3.80	0.04
Al097	1.06	2.36	283	5.11	0.02
Al098	1.08	2.00	298	3.69	0.05
Al099	1.02	2.77	283	4.42	0.04
Al100	1.07	2.05	285	2.16	0.04
Al101	1.03	1.54	280	3.47	0.05
Al102	1.05	2.21	283	3.35	0.02
Total average	1.05	3.01	284	4.29	0.04

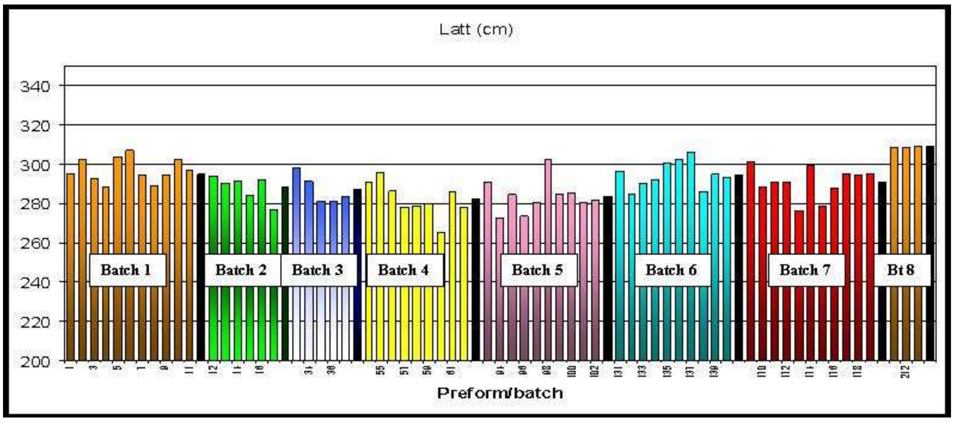


Fig. 15. Summary of the attenuation length for all the preforms.

upgrade, when the WLS fibres where entirely replaced by new WLS fibres with better optical properties and mechanical stress tolerance. In 1997 the Kuraray Y7(150) WLS fibres were replaced by Y11(300)MS fibres, also from Kuraray. The light yield increased by $\sim$ 50% and the attenuation length became at least 20% higher. The spread in light yield was found to be of the order of 4%, and 10% in attenuation length.

The Tile calorimeter of ATLAS have given heavy use to the Fibrometer. Tests of candidate WLS fibres to this detector and R&D for mirror aluminization of the fibres were done with the Fibrometer. Later, the Fibrometer was used

Table 10
Summary of the results for the acceptance QC of batch 6. The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al131	1.00	3.23	297	3.47	0.04
Al132	1.01	2.03	285	3.47	0.02
Al133	1.00	1.25	290	3.81	0.01
Al134	0.97	3.68	292	3.70	0.02
Al135	1.02	1.44	301	2.67	0.02
Al136	1.03	2.33	302	3.80	-0.01
Al137	1.05	1.90	306	5.11	0.04
Al138	0.99	3.37	286	3.69	-0.04
Al139	1.02	2.02	295	4.42	0.99
Al140	1.01	1.75	294	2.16	0.98
Total average	1.01	3.17	295	4.21	0.99

for the acceptance quality control of the Y11(200)MSJ fibres used in the Tile calorimeter, and after mirror aluminization of the fibres it was used again for the quality control before inserting the fibres in profiles and send them to the modules assembly plants.

All the fibres from Kuraray received in Lisbon passed all quality control criteria and were accepted. All the Tile calorimeter modules were produced and tested, and are assembled in the ATLAS experimental cavern, being already used for the detection of cosmic muons as part of the ATLAS commissioning program.

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Table 11
Summary of the results for the acceptance QC of batch 7. The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
Al169	1.07	2.76	301	4.19	0.02
Al170	1.03	4.90	289	4.01	0.01
Al171	1.02	1.71	291	3.79	0.02
Al172	1.04	2.24	291	2.81	0.01
Al173	1.01	1.75	277	3.65	0.00
Al174	1.04	1.77	299	3.24	-0.02
Al175	0.98	3.20	279	3.46	-0.01
Al176	1.02	2.83	288	4.28	-0.01
Al177	1.06	1.30	295	3.85	0.00
Al178	1.04	2.61	294	3.36	0.01
Al179	1.07	2.32	295	4.11	0.02
Total average	1.03	3.62	291	4.38	0.00

Table 12
Summary of the results for the acceptance QC of the extra batch (batch 8). The reference used for I(140) is the <I(140)> of the fibres of batch 1.

Preform	I(140)	RMS	Latt	RMS	light loss by mech stress
AY211	1.10	2.03	309	4.70	n.a.
AY212	1.08	2.36	309	3.96	n.a.
AY213	1.11	2.07	309	4.04	n.a
Total average	1.09	2.15	309	4.23	n.a.

References

[1] H.Burmeister *et al.*, Electromagnetic calorimetry using scintillating plastic fibres, Nucl. Inst. and Meth., 225 (1984) 530-533.

[2] P. Sonderegger, Nucl. Instrum. Methods A257, 523 (1987).

[3] S. Buontempo *et al.*, Proc. 3^{rd} Int. Conf. on Advanced Technology and Particle Physics, Como, Italy, 22-26 June 1992, Nucl. Phys. **B** (Proc. Suppl.) 32 (1993) 70.

[4] S.A. Sedykh et al., Nucl. Instrum. Methods A455, 346 (2000).

[5] ATLAS Collaboration, *ATLAS Tile Calorimeter TDR*, CERN/LHCC/96-42 (1996).

[6] CMS Collaboration, Had calo TDR

[7] ATLAS Collaboration, *ATLAS, Technical Proposal.*, CERN/LHCC/94-43, LHCC/P2, 15 December 1994.

[8] DELPHI Collaboration, P.Aarnio *et al.*, Nucl. Instr. and Meth. **A303** (1991) 233.

[9] A. Benvenuti *et al.*, *"Prototype design, construction and test of a Pb/scintillator sampling calorimeter with wavelength shifter fibre optic readout"*, IEEE Transactions on Nuclear Science, 40 (1993) 537.

[10] Y. Guz, et al. *"The performance of the DELPHI STIC detector at LEP"*, 6th International Conference on Calorimetry in High-energy Physics, ICCHEP '96, Frascati, Italy, 8 - 14 Jun 1996, Ed. by A Antonelli, S Bianco, A Calcaterra and F L Fabbri, INFN, Frascati, 1996 - Frascati Physics Series 6 - pp. 177-186.

[11] S. Ask *et al.*, Luminosity measurement at ATLAS Development, construction and test of scintillating fibre prototype detectors, Nucl.Instrum.Meth. **A568** (2006) 588-600

[12] D. Acosta *et al.*, Nucl. Instrum. and Methods **B62** (1991) 472.

[13] S. Buontempo *et al.*, Nucl. Instrum. and Methods **A344** (1994) 92.
S. Buontempo *et al.*, Nucl. Instrum. and Methods **A348** (1994) 131.

[14] A. Maio *et al.*, *"State of Art of (Green) Wavelengthshifting fibres"*, Proc. of the 6^{th} Topical Seminar on Experimental Apparatus for Particle Physics and Astrophysics, San Miniato, 1996.

[15] S. J. Alvsvaag *et al.*, Nucl. Instrum. and Methods **A425** (1999) 106.

[16] M. David *et al.*, Acceptance quality control of the Tilecal WLS fibres performed in Lisbon, ATLAS Internal Note ATL-TILECAL-2002-004, 2002

[17] J. G. Saraiva *et al.*, IEEE Trans. Nucl. Science, VOL. 51 NO. 3, 2004