The ATLAS luminosity monitor

M. Bruschi^{*,a}, on behalf of the ATLAS LUCID detector group

^a*CERN, Switzerland and I.N.F.N. Sezione di Bologna, Italy*

Abstract

The main luminosity monitor of the ATLAS experiment consists of an array of Cherenkov counters. The intrinsically fast response of the detector and its readout electronics makes it ideal for measuring the number of interactions per *LHC* bunch crossing, and for providing an interaction trigger to the ATLAS experiment. The detector already took some data during the first beam interactions produced by the *LHC*. An original method to derive the detector response with an analytical approach is presented here.

Key words:

Cherenkov detector, Photomultipliers, Luminosity, LUCID, ATLAS, Detector

1. Introduction

The *LUCID* (LUminosity Cherenkov Integrating Detector) detector consists of an array of 40 gaseous Cherenkov detectors. The main purpose of the detector is to measure and monitor the relative luminosity delivered to *ATLAS* by the *LHC* machine for each bunch crossing as well as the integrated luminosity in a certain time period. Due to its intrinsically fast response it will in addition provide one of the experiment's minimum bias triggers during the low luminosity phase.

This kind of detector was first developed to monitor luminosity by the *CDF* experiment [1]. A detailed description of the detector installed in *ATLAS* and its final design can be found in [2].

In this article, after a short review of the detector and its main achievements during the first short period of running of the *LHC* machine in autumn 2008, an original method to derive the detector response with an analytical approach will be presented. This method was found to be useful during the detector design and test beam phases since it could provide a sufficiently accurate prediction of

the detector response as a function of the detector geometry and the gas pressure before simulating it using the time consuming full detector MonteCarlo (*MC*) simulations, based on GEANT4 [3]. The method can be applied generally when dealing with gaseous Cherenkov detectors with cylindrical geometry.

2. Detector description

As described in [2], the detector is made of two modules located symmetrically at 17 m from the interaction

point. Each module consists of 20 Cherenkov tubes of length 150 cm and 15 mm diameter filled with perfluorobutane gas. Sixteen of these tubes are read out by photomultiplier tubes (*PMT*) directly coupled at the tube end. For four of them, the light is fed into quartz optical fibers, which transport it away from the high radiation area around the beam pipe to a multi anode *PMT*. This readout scheme is an alternative to the baseline, and has been implemented for future developments of the detector when the *LHC* machine will run at its maximum design luminosity and the area around the beam pipe will be heavily irradiated (7 Mrad/year are expected in the area where the *PMT*s are presently deployed).

The baseline readout scheme starts with a differential transmission over about 100 m to the back-end electronics which digitizes the signals into hits if they have an amplitude above a certain threshold. The hits are then fed into a *VME* board in which they are processed by a *FPGA* which provides both luminosity and trigger algorithms for each individual *LHC* bunch.

The calibration of each Cherenkov tube is performed with a *LED* pulser system providing a single photoelectron (*p.e.*) signal at the tube entrance. In this way, the long term stability of the readout chain will also be monitored. The on-line luminosity will be measured using different methods based on the counting of hits, for instance by counting the number of bunch crossing in which either the whole detector registered at least one hit, or in which there is at least one hit in each arm of the detector (coincidence mode); alternatively, also the counting of bunch crossing containing no hits (zero counting mode) can provide a measurement of the luminosity.

The final goal of the detector is to provide an absolute luminosity measurement at level of 5% or better after it has been calibrated using the roman pot detector *ALFA* [4] which will be installed in 2010.

^{*}Corresponding author. Tel.: +41-22-767-4418; fax: +41-22-766-8993.

Email address: marco.bruschi@cern.ch (M. Bruschi)

The building of the detector was started at the beginning of year 2007. In the summer of the same year the construction phase was terminated. The whole detector has been calibrated in a test beam at the end of 2007. The installation around the *LHC* beam pipe was performed in the summer 2008 and *LUCID* was able to successfully record the very first events produced in *ATLAS* by the *LHC* machine. The detector is presently in an advanced state of commissioning.

3. The model used to predict the detector response

The photon yield per unit of wavelength (or energy) at the end of the Cherenkov tube can be obtained analytically by using a parameterization of a) the gas refractive index, b) the number of reflections of the light inside the tube, c) the Aluminum reflectivity and d) the gas transmittivity.

In the following, we will assume i) that the tube surface is made of mechanically polished Aluminum, ii) the charged particle tracks crossing the detector will all be directed along the tube axis, iii) the radiative medium is Isobutane gas (which was used during the test beam runs), iv) diffuse reflection on the Aluminum surface will be neglected and, finally, v) any possible Cherenkov light polarization effects are neglected.

The values of most of the constants used in the following equations are summarized in Table 1.

3.1. The refractive index of the gas

The relationship between the Isobutane refractive index and the photon energy can be found in [5]. Using this relationship, and assuming that the refractive index and the beta of the particle are close to unity, and that the particle momentum is well above the Cherenkov threshold, we get:

$$\theta_c^2 \approx \frac{3KP}{\left(1 - \left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2\right)} \quad (1)$$

in which θ_c is the Cherenkov photon opening angle, P is the gas pressure in bar, λ is the photon wavelength measured in nm and K , E_0 and $C_{\lambda E}$ are constants, the latter one representing the conversion constant from photon energy to wavelength (its value is approximately $1240 \text{ eV} \cdot nm$).

3.2. The number of reflections inside a tube

The number of reflections N_r inside a tube of diameter D and length L (both expressed in cm), experienced by a Cherenkov photon having the opening angle θ_c and being produced at some distance x (in cm) along the tube axis, can be easily computed by taking into account the fact that the incidence angle of the photon on the Aluminum

tube surface is equal to the reflected one. By assuming tracks traveling along the tube axis, we get:

$$N_r(\lambda, x) \approx \frac{(L-x)}{D} \theta_c \approx \frac{(L-x)}{D} \sqrt{\frac{3KP}{1 - \left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2}} \quad (2)$$

where the x coordinate interval is from 0 to L .

3.3. The reflectivity of mechanically polished Aluminum

A typical mechanically polished Aluminum surface reflectivity $R(\lambda)$ curve as a function of the photon wavelength can be found in [6]. This curve has been fit with the empirical formula containing three parameters (R_0 , λ_{R0} and λ_R)

$$R(\lambda) = R_0 \left(1 - e^{-\frac{(\lambda - \lambda_{R0})}{\lambda_R}}\right) \quad (3)$$

which was found to well represent the data. The total transmitted fraction of light, $\rho(\lambda, x)$, produced at a certain point x along the tube axis, can therefore be expressed as:

$$\rho(\lambda, x) = R(\lambda)^{N_r(\lambda, x)} = e^{-\frac{(L-x)}{D} F_R(\lambda, P)} \quad (4)$$

where the function F_R is defined by:

$$F_R(\lambda, P) = -\sqrt{\frac{3KP}{1 - \left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2}} \ln(R(\lambda)) \quad (5)$$

3.4. The Isobutane Transmittivity

The typical light fraction transmitted in a distance ξ of 75 cm of Isobutane gas at 1 bar pressure, $\frac{I}{I_0} \Big|_{\xi=75cm, P=1bar}$, versus photon energy can be found in [5]. This curve is well fitted by an empirical formula containing three parameters (T_0 , λ_{T0} and λ_T) after transforming the photon energy to wavelength:

$$\frac{I}{I_0} \Big|_{\xi=75cm, P=1bar} = T_0 \left(1 - e^{-\frac{\lambda - \lambda_{T0}}{\lambda_T}}\right)^2 \quad (6)$$

The total transmitted fraction of light, $T(\lambda, x)$, produced at a distance x in the tube axis and at a gas pressure P is therefore given by:

$$T(\lambda, x) = \frac{I}{I_0}(\lambda, x) = e^{-\frac{(L-x)}{\xi} F_T(\lambda, P)} \quad (7)$$

where the function F_T is defined by:

$$F_T(\lambda, P) = -\frac{P}{P_0} \ln \left(T_0 \left(1 - e^{-\frac{\lambda - \lambda_{T0}}{\lambda_T}}\right)^2 \right) \quad (8)$$

3.5. The distribution of the number of photons at the end of the tube

It is now possible to calculate the number of photons at the end of the tube as a function of the photon wavelength. The calculation is done by starting from a derivation of the fundamental formula which gives the number of photons produced per unit path length of a particle with charge 1 and per unit wavelength interval:

$$\frac{dN_{ph}}{d\lambda} = 370 \sin^2 \theta_c \cdot \frac{C_{\lambda E}}{\lambda^2} \cdot \int_0^L \rho(\lambda, x) T(\lambda, x) dx \quad (9)$$

Using the Equations 1, 4, 5, 7 and 8 we finally get:

$$\frac{dN_{ph}}{d\lambda} = \Phi(\lambda) = 370 \frac{3KP}{1 - \left(\frac{C_{\lambda E}}{E_0 \lambda}\right)^2} \cdot \frac{C_{\lambda E}}{\lambda^2} \cdot \frac{D \xi \left(1 - e^{-L \left(\frac{F_T}{\xi} + \frac{F_R}{D}\right)}\right)}{D F_T + \xi F_R} \quad (10)$$

which gives the photon distribution as a function of the photon wavelength, $\Phi(\lambda)$, at the end of the Cherenkov tube in terms of the gas pressure P (in *bar*) and of the tube dimensions D (*cm*) and L (*cm*). It is worth to note that all the relevant quantities which are studied in the design phase of this type of detectors are here synthesized. In order to get the total yield of *p.e.*, a numerical integration of the convolution of $\Phi(\lambda)$ given by Equation 10 with the photocathode quantum efficiency curve ($QE(\lambda)$) has to be performed. This efficiency curve is of course depending on which *PMT* is being used.

Table 1 contains a summary of the constants used in the Equations above and their values. Note that the value of the constant K is given for a temperature of $293.16^\circ K$. For a generic temperature T the relationship $K(T) = \frac{0.257}{T} \frac{^\circ K}{bar}$ holds.

	Symbol	Value	Units
Isobutane refractive index [3]	E_0	13.5	eV
	K	$8.767 \cdot 10^{-4}$	$^\circ K/bar$
Aluminum reflectivity	R_0	0.975	
	λ_{R0}	147.6	nm
	λ_R	163.0	nm
Isobutane transmittivity	ξ	75.0	cm
	T_0	0.978	
	λ_{T0}	170.5	nm
	λ_T	161.2	nm

Table 1: Summary of the constants used in the Equations in the text and their numerical values.

3.6. Test beam studies

The whole *LUCID* detector has been tested and calibrated with a beam of 180 *GeV* pions at the CERN SPS (*H8* line) in the autumn of 2007. In the second row of Table 2 are given the results of the measured *p.e.* yield

as a function of the gas pressure for a typical *LUCID* Cherenkov tube¹. In the same Table the prediction of the full *MC* simulation provided for the *LUCID* detector is reported and the *p.e.* yield predicted by the model presented earlier. A disagreement at only few percent level for gas pressure greater than 0.6 bar, is found between the *p.e.* yields of the analytical model and the full *MC* simulation of *LUCID* and with the measured data.

P(bar)	0.1	0.3	0.6	0.8	1.1	1.3	1.6	1.8	2.1
DATA	40±1	51±1	59±1	63±1	67±1	69±1	71±1	-	-
MC	40	50	57	62	67	70	73	76	79
Model	33	45	53	57	63	67	71	74	78
Δ(%)	11	11	6	6	5	5	3	3	1

Table 2: The photoelectron yield as a function of the gas pressure for one typical *LUCID* tube from test beam data, *MC* simulations and the analytical model. In the last row, the percentage difference between the *MC* and the analytical model is reported.

4. Conclusions

The *LUCID* detector is designed to provide *ATLAS* with an on-line and off-line luminosity determination (integrated and differential) and a minimum bias trigger. An analytical model to effectively predict the differential photons yield has been presented. The *LUCID* detector is installed in *ATLAS* since the summer of 2008 and has already successfully recorded data during the short running of the *LHC* machine in 2008.

References

- [1] D. Acosta et al., The CDF Cherenkov luminosity monitor, Nucl. Instrum. Meth. A 461 (2001) 540.
- [2] The *ATLAS* Collaboration, G. Aad et al., The *ATLAS* Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.
- [3] S. Agostinelli et al., Nucl. Instrum. Meth. A 506 (2003) 250-303.
- [4] The *ATLAS* collaboration, *ATLAS* Forward Detectors for Measurement of Elastic Scattering and Luminosity, CERN/LHCC/2008-004, *ATLAS* TDR 18, 17 January 2008
- [5] R. Arnold et al, NIM A270 (1988) 289.
- [6] W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, Ed. Springer-Verlag, page 201.

¹The total measured *p.e.* yield contains also the one produced by the *PMT* quartz window at the passage of the charged track. Such a contribution has also be included in our model with a calculation which is a trivial extension to the one described in the text, and therefore not reported here.