The New ATLAS/LUCID detector

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Abstract—The new ATLAS luminosity monitor has many innovative aspects implemented. Its photomultipliers tubes are used as detector elements by using the Cherenkov light produced by charged particles above threshold crossing the quartz windows. The analog shaping of the readout chain has been improved, in order to cope with the 25 ns bunch spacing of the LHC machine. The main readout card is a quite general processing unit based on 12 bit - 320 MS/s Flash ADC and on FPGAs, delivering the processed data to 1.3 Gb/s optical links. The article will describe all these aspects and will outline future perspectives of the card for next generation high energy physics experiments.

Index Terms—Cherenkov detectors, Luminosity, LHC, Photomultipliers, Readout electronics.

I. INTRODUCTION

THE LUCID (acronym for LUminosity Cherenkov Integrating Detector) detector is one of the ATLAS [1] luminosity monitors.

The initial version of this detector (“old” LUCID) is described in [1] and took data providing the luminosity in ATLAS as main detector in years 2009-2010 [2] and in combination with other detectors in the years from 2011 to 2013 1. The reasons that called for a substantial redesign of the detector (named in the following “new” LUCID) and its electronics for RUN 2 are:

• the LHC machine peak instantaneous luminosity increase of a factor about two passing from RUN 1 (∼ 0.77 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}) to RUN 2 (∼ 1.7 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1});
• the change of the LHC beam pipe material in the old LUCID zone from stainless steel to aluminum;
• the decreased bunch spacing in the LHC machine (from ∼ 50 \text{ ns} to ∼ 25 \text{ ns}).

The last point had as a consequence the redesign of the readout electronics. The first two points had as consequence a significative increase of the detector occupancy which affects:

1) luminosity algorithm saturation (see for instance comment following Eq. 1);
2) photomultipliers (PMT) saturation;
3) PMT lifetime;
4) PMT radiation hardness.

The common cure to all these problems is to decrease the detector granularity and dimensions. The new detector will use the quartz window of the PMT itself as Cherenkov detector granularity and dimensions. The new detector will be named in the following “new” LUCID and its readout card will be described.

The new detector, differently from the initial version which used aluminum tubes filled with \( \text{C}_3\text{F}_{10} \) as Cherenkov radiator readout by PMT, will simply use PMT reading out the Cherenkov light produced in their own quartz window. This detection method was already used from the end of year 2011, when the peak luminosity of LHC was exceeding the design specifications for the old LUCID. This innovative choice was proven to be successful and, given the experience that was gained with this type of technique, it was decided to adopt it also for the new detector.

The PMT used in the old LUCID were of type Hamamatsu R762 with a quartz window of 14 mm of active diameter.

Simulations performed using this type of PMT, have shown that the rate of particles above Cherenkov threshold in the acceptance of the R762 would have lead to an unacceptably high value of current, heavily ageing these devices after about one year of operation, even running the PMT at the lowest gain possible. As a consequence, after some tests and studies performed on different PMT tubes, the Hamamatsu model R760, having a 10 mm quartz window diameter, smaller than R762 and very similar features, was finally selected.

This article is organised as follows. Section I-A provides an introduction to the luminosity measurement which presents the guidelines for the design of the detector and its electronics. In Section I-B the new LUCID detector is described, Section I-C reports about the front end and readout electronics, Section I-D the way the detector stability will be monitored. Section I-E reports about the results on the R760 PMT performances after heavy irradiation with \( \gamma \) and neutron sources and finally, in Section I-F, the future developments foreseen for the new LUCID and its readout card will be described.

A. Luminosity algorithms

There are two ways of measuring luminosity implemented in the new LUCID.

The first method relies on counting hits (or events). A hit is defined as the presence of a pulse amplitude above a preset threshold in a LUCID readout channel, and an event has at least one hit detected in LUCID. It can be shown that the luminosity per bunch \( L_B \) can be expressed as

\[
L_B = \frac{\ln(1-f) \cdot f_{\text{rev}}}{\sigma_{\text{vis}}} \quad (1)
\]

where \( \sigma_{\text{vis}} \) is the visible cross section, which represents ultimately the detector calibration constant extracted by the so called Van der Meer scan runs [2], and \( f_{\text{rev}} \) is the LHC machine revolution frequency. In the case of hits counting \( f = \frac{N_{\text{vis}}}{N_{\text{hit}} \cdot N_{\text{PMT}}} \) where \( N_{\text{hit}} \) is the total number of hits, \( N_{\text{PMT}} \) is the total number of LUCID PMT and \( N_{\text{BC}} \) is the total number of colliding bunch crossings filled with protons.
In the case of events counting \( f = \frac{N_{\text{events}}}{N_{\text{BC}}} \) where \( N_{\text{events}} \) is the total number of events. In the limit \( f \to 1 \) small variation of \( f \) correspond to large variation of \( L_B \) and this is called saturation regime. The hits (events) counting method has been the main method used in RUN 1 and it will be also adopted in RUN 2. The relation between \( f \) and \( L_B \) is determined, under certain assumptions, using a statistical model and therefore it has a systematic uncertainty associated.

Thanks to the newly designed electronics, it will be possible to adopt a new promising method for RUN 2. It is based on the fact that the total charge per bunch crossing (BC) is proportional to the luminosity per BC. This relationship does not depend on statistical model and therefore, while the detector is not saturating, it is theoretically free of statistical uncertainty. This has been proven on real data already in RUN 1 as shown in Fig. 1. The top plot shows the mean number of interactions per bunch crossing (\( \mu \)) obtained from the total charge integrated over one BC by an old LUCID fibre channel versus the value measured by ATLAS/BCM (red circles) compared to the value obtained with a standard luminosity algorithm (blue triangles). The correlation between the \( \mu \) value obtained with charge integration and the one with ATLAS/BCM is linear up to high \( \mu \) values. The red circles data point are fitted with a straight line. The bottom plot shows the ratio data over fit for the two methods: the hit counting algorithm shows \( \mu \) dependencies while the charge integration doesn’t present any effect. The measured data spread around the linear fit is within \( \pm 2.5\% \) for the charge integration method.

Although the charge integration method is theoretically immune by model assumptions, it critically depends on the PMT gain stability. For this reason a great care has been devoted to provide a precise and reliable calibration system to the new LUCID, as explained in the Section I-D.

**B. Detector**

The new LUCID geometry is shown in Fig. 2. It consists of two detectors, placed around the beam pipe symmetrically at about 17 m from the ATLAS Interaction Point (IP). Each detector is formed by 16 PMT grouped by four and deployed in the ATLAS TAS [1] shield region, as shown in the upper part of Fig. 2. The detecting medium is the quartz window of the PMT itself acting as Cherenkov radiator. There are also 4 channels for which the radiator is a bundle of quartz fibres. These fibres are readout by PMT (one per bundle) placed on top of the ATLAS shielding (see the upper and middle part of Fig. 2). This readout method has been already tested successfully for the old LUCID, and has the advantage that the readout PMT sit in an area with a low level of radiation. The detector is placed around the LHC beam pipe in a supporting carbon fibres cylinder as shown in the middle part of Fig. 2, and inserted in the carbon fibres beam pipe supporting cone. All the 20 readout PMT are inserted in mu-metal cylinder in order to shield them from stray magnetic fields. Details about the cross sectional view of the detector are shown in the lower part of Fig. 2.
temperature reached by the beam pipe during the baking out phase, a suitable cooling system for LUCID has been provided.

The new LUCID is actually composed by three different detectors (refer to Fig. 3). The main detection scheme is

![Image of Hamamatsu R760 PMT with quartz window of 10 mm diameter](image1)

![Image of Hamamatsu R760 PMT modified to have a quartz window of 7 mm diameter](image2)

![Image of Bundles of new LUCID readout fibres](image3)

Fig. 3. Upper part: Hamamatsu R760 PMT with quartz window of 10 mm diameter. Middle part: Hamamatsu R760 PMT modified to have a quartz window of 7 mm diameter. Lower part: Bundles of new LUCID readout fibres.

to measure the light produced by charged particles above Cherenkov threshold crossing the windows of Hamamatsu R760 PMT (see upper part of Fig. 3). One of the main design criteria was to keep the detector acceptance low because of the increased occupancy in RUN 2. For this purpose, a Hamamatsu R760 PMT has been produced with a sensitive window reduced from 10 mm to 7 mm which roughly corresponds to a factor 2 decrease in the rate. The modification, that was specifically done for LUCID, was produced by Hamamatsu by aluminizing the PMT photocathode area.

An alternative readout method, already commissioned during RUN 1, consists of measuring Cherenkov lights produced in bundles of long quartz fibres (Fig. 3, lower part) readout by R760 PMT placed far from the beam pipe, where the radiation level is enormously reduced.

Each arm of the detector consists of 16 PMT using quartz windows as Cherenkov medium. In the sketch the details of the beam pipe support cone are shown. The support cone has 4 openings which ease the exchange of faulty PMT. The 16 PMT are grouped in 4x4 and each group of 4 is formed by 3 normal PMT and 1 modified PMT. One of the normal PMT has a deposit of $^{207}$Bi on the quartz window for calibration purposes explained in Section I-D. The other 3 PMT have a calibration system composed by both led and laser light source.

As far as the fibres readout are concerned, the Cherenkov light produced in the quartz fibres is guided by the fibres themselves to the R760 readout PMT placed in an area with low radiation level. There are 4 bundles of fibres per side used for this purpose. The fibres are routed to the surface of the beam pipe by aluminum pipes.

The designed detector is suitably radiation hard for RUN 2 (see Section I-E), it can deliver about 100 of different luminosity algorithms and, thanks to the new readout electronics, each PMT can be considered as an independent luminosity monitor.

C. Front end and readout electronics

![Image of LUCROD block scheme for two input channels](image4)

Fig. 4. Detailed sketch of the new ATLAS/LUCID detector.

![Image of LUCROD block scheme for two input channels](image5)

Fig. 5. The LUCROD block scheme for two input channels.

The new LUCID readout system is based on the LUCROD (LUCid ReadOut Driver), whose main block scheme for two input channels is reported in Fig. 5. This card is deployed very close to the detector, at about 15 m distance, in an area with negligible radiation level, and using low loss transmission coaxial cable, in order to preserve the signal original shape and avoiding pole-zero compensation circuitry. In this way the signal duration is guaranteed to be below the 25 ns LHC BC interval, as shown in Fig. 10 reported in Section I-D.

The signals from the PMT are fed into an input amplifier providing a variable gain in the range $1 \div 15$. A replica of these signals is also amplified and sent to the old LUCID readout electronics. After the amplification the signals undergo an anti-aliasing filter and they are then fed into a Flash ADC (FADC) (Analog Devices AD9434BCPZ-500) sampling...
at 320 MS/s, 12 bit, the LSB corresponding to a sensitivity of 370 µV. The outputs of two FADCs are the input to a FPGA (Cyclone 4 ALTERA EP4CE40) which integrates the pulses and also measure their amplitude. This FPGA is also used to finely adjust the delays, the thresholds and the signal alignment with the ATLAS data acquisition system (TDAQ). The LUCROD is implemented in a VME 9U card, with 16 input channels, and therefore each card contains 8 of the above described units. The output from the first 8 FPGAs are fed into a main FPGA (Cyclone 4 ALTERA EP4CGX30) which is adding up the charge from different PMT for individual BC and calculating hit patterns for individual BC. The hit patterns are sent via optical FINISAR links transmitting at 1.3 Gbit/s to another processor card already used in RUN 1: the LUMAT (Luminosity Monitor And Trigger) card [3] performing operations on the hit patterns in order to produce a fast trigger and to calculate luminosity with many different algorithms. After an ATLAS level 1 trigger [1] is received, the event formatted in the FPGA is sent via the same type of optical links to the ATLAS TDAQ.

In Fig. 6 a picture of a LUCROD VME 9U readout card is reported.

![Picture of LUCROD VME 9U readout card](image)

Fig. 6. Picture of the final LUCROD board.

The new LUCID detector and its electronics have already successfully taken data during the first 13 TeV collisions at the LHC, as shown in Fig. 7 for the fiber detector part.

**D. Calibrations**

In Fig. 8 some pictures and a sketch of the new LUCID calibration system are reported.

The new LUCID detector has greatly improved the system to monitor the detector stability, by adding two new methods to the LED one used in the old detectors’ version. Moreover, the LED system has been improved too, since in the new version the stability of the LED signals is monitored by a pin diode. As shown in the sketch of Fig. 8 the LED signals are transmitted via quartz fibres to the PMT. For redundancy, two independent LED systems per detector are used.

The first new method consists of a $^{207}$Bi electron source placed on the quartz window of 4 out of 16 PMT per side. The intensity of the source is small with respect to the expected event rate, but enough to calibrate in short time (few minutes) the detector when there are no interactions in LHC.

The second new method is based on the laser light signals provided by the ATLAS TileCal detector [1]. The use of a $^{207}$Bi Internal Conversion (IC) electron source is quite new and promising. The about 1 MeV electrons from the source have enough kinetic energy in order to completely cross the quartz window and release an amount of photons equivalent to the signal of a high energy particle crossing the same window.

This is shown in Fig. 9, where the amplitude distribution of signals from the source, as measured with the LUCROD card, is reported. An evident peak shows up in correspondence of the electrons crossing completely the window. These signals mimic the signal of a high energy charged particle, with momentum above the Cherenkov threshold, crossing the same quartz window thickness. The signal duration as recorded by the LUCROD card is within the 25 ns LHC BC interval as shown in Fig. 10.

The Fig. 11 reports the stability curve obtained measuring the mean of the amplitude distribution as a function of a few volt variation of the High Voltage (HV) PMT power supply.
Fig. 9. Pulse height distribution of signals from the $^{207}\text{Bi}$ radioactive source placed in the quartz window of a PMT, as recorded by the LUCROD FADC.

Fig. 10. $^{207}\text{Bi}$ signal as recorded by the LUCROD card. The signal duration is within the 25 ns LHC BC duration.

Fig. 11. Mean value of the pulse amplitude distribution reported in Fig. 9 vs PMT High Voltage variation with respect to the working point.

Fig. 12. Calibration signals recorded by the LUCROD card. Upper Part: LED signals from pin diode amplitude distribution. Lower Part: Laser signals from PMT amplitude distribution.

Preliminary results show that the simple measurement of the mean of the amplitude distribution can monitor the stability of the gain better than at 1% level.

The FADCs in the LUCROD boards are also used to measure the amplitude and charge distributions of signals from the LEDs and TileCal laser. As shown in Fig. 8, the LEDs give signals simultaneously in the PMT and the pin diodes.

In the top plot of Fig. 12 the amplitude distribution from LED light measured by a pin diode is shown.

The ATLAS/TileCal laser signal gives signals only in the PMT. The lower plot of Fig. 12 shows the amplitude distribution from the TileCal laser measured with a PMT.

E. Radiation hardness

A major part of the new LUCID detector is deployed in a high radiation level area around the LHC beam pipe. The ionising radiation dose per unit of luminosity was measured directly during RUN 1. The absorbed dose was about $0.77 \text{ kGy/}\text{fb}$ at a $pp$ center of mass energy of 8 TeV. Using this number and estimating the total integrated luminosity for RUN 2 yield an upper limit of 200 kGy. The neutron flux was not measured directly, but has been extrapolated using a GCALOR simulation [4] of the LHC beam line, obtaining an upper limit of $2.6\cdot10^{14} \text{n/cm}^2$ having an energy of the order of 1 MeV.

The material was irradiated initially up to $\sim 200 \text{kGy}$ using an intense $^{60}\text{Co}$ gamma source, at the CALLIOPE facility, and successively up to $\sim 2.6\cdot10^{14} \text{n/cm}^2$ using the TAPIRO [6] facility, a fast neutron reactor with highly enriched $^{135}\text{U}$ fuel, equipped with several irradiation channels with the capability to provide a set of different neutron spectra.

The PMT and the bases have been extracted and characterised three weeks after the irradiation.

All the irradiated material samples passed positively the performed test. In the following some detail will be given about the tests on the Hamamatsu R760 PMT, since these are the most critical devices for the new LUCID detector.

In Fig. 13 the visible effect of the $\gamma$ irradiation on a R760 PMT, can be appreciated. The non radiation hard part of the bulb glass loses its transparency.

The performances of the PMT before and after the irradiation were quantified by studying the variation of the current drawn as a function of the variation of the PMT HV by submitting the PMT to the light of a stable Xenon lamp. The measured current is proportional to the PMT gain ($G$) and the...
latter is proportional to the relative variation of the HV ($V$) following the relation

$$\frac{\Delta G}{G} = \alpha \frac{\Delta V}{V}$$

where $\alpha$ is a factor which is related to the number of dynodes of the PMT.

The sample of PMT to be irradiated were first calibrated using the Eq. 2 together with all the other PMT to be used for LUCID. The calibrations of the irradiated PMT and some reference non-irradiated PMT were then repeated after the $\gamma$ and neutron irradiation cycles. The results of the tests are reported in Table I, where the value of the $\alpha$ constant is reported for the tested PMT before and after the $\gamma$ and neutron irradiations and compared with the calibration of the non irradiated reference PMT. From the reported values, it can be appreciated that the calibration constant of the irradiated PMT did not change appreciably after the irradiation.

<table>
<thead>
<tr>
<th>Source</th>
<th>PMT</th>
<th>$\alpha$ Before Irradiation</th>
<th>$\alpha$ After Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>R760 Irradiated</td>
<td>7.76±0.04</td>
<td>7.76±0.04</td>
</tr>
<tr>
<td></td>
<td>R760 Reference</td>
<td>7.76±0.04</td>
<td>7.76±0.04</td>
</tr>
<tr>
<td>$n$</td>
<td>R760 Irradiated</td>
<td>6.11±0.04</td>
<td>6.11±0.04</td>
</tr>
<tr>
<td></td>
<td>R760 Reference</td>
<td>5.75±0.04</td>
<td>5.75±0.04</td>
</tr>
</tbody>
</table>

Table I: $\alpha$ Coefficient As Defined In Eq. 2 Measured Before And After $\gamma$ And $n$ Irradiation For Some R760 PMT. The Stability Of The Measuring Setup Was Cross Checked Using Some Non Irradiated R760 PMT As A Reference.

**F. Future developments and conclusions**

The measurement of luminosity is of fundamental importance since it provides the normalization scale for all the observed processes.

The new LUCID detector, has many innovative aspects and has been designed having in mind robustness, radiation hardness and redundancy in

- Detection methods
- Calibration methods
- Luminosity Algorithms.

The new readout card, LUCROD is a powerful general purpose card which integrates front end, signal processing and interfacing to the ATLAS online luminosity and TDAQ. Improved performances are therefore expected, keeping the system more compact than in the past. The new LUCID detector and the LUCROD card have already successfully taken data during the first 13 TeV collisions at the LHC. The use of this card, or improved version of it, is planned in other demanding projects, like for instance in the readout of the electromagnetic calorimeter of the SHiP experiment [7], or as readout element for solid state detectors based chains, for high energy x-rays spectroscopy at FEL/XFEL facilities.

Besides providing the luminosity to ATLAS, thanks to the different detection methods implemented, the new LUCID is expected to provide important inputs for the luminosity detector to be built after after the LHC machine High Luminosity upgrade.

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**REFERENCES**