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The LUCID Detector for LHC Run-2 †

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Abstract: LUCID (LUminosity Cerenkov Integrating Detector) is the main luminosity monitor of the ATLAS (A Toroidal LHC Apparatus) experiment at the Large Hadron Collider (LHC) and in particular is the only one capable of providing bunch-by-bunch luminosity information, both online and offline, for all beam conditions and luminosity ranges. LUCID-2 refers to the detector upgrade designed to cope with the running conditions to be met in Run-2 (2015–2018): a center of mass energy of 13 TeV, with 50 pp interactions per bunch-crossing on average and a 25 ns bunch-spacing. This report summarizes all changes with respect to the detector deployed in Run-1 (2010–2012), including smaller sensors for higher granularity, new readout electronics for early signal digitization, and a completely new calibration concept guaranteeing long-term stability of the detector response. In addition, the overall detector performance in Run-2 and preliminary results on luminosity measurements are presented.

Keywords: LHC; luminosity; HEP; ATLAS

1. Introduction

Among the figures of merit of colliders, the instantaneous luminosity, L, directly relates the cross section, σ, of any process to its production rate, R: $R = \sigma L$. As a consequence, luminosity measurements at colliders are necessary for a number of different tasks, ranging from the extraction of cross sections from the number of observed candidate events to beam optimization based on frequent measurements of the instantaneous delivered (before any trigger) luminosity. In ATLAS [1], online measurements of the delivered luminosity for each individual bunch in the beam are additionally necessary to optimize trigger performance.

When the collider performance exceeds the readout capability of the experiments in terms of number of interactions per bunch crossing (pileup), online luminosity monitoring is also mandatory to implement the so-called luminosity leveling: at the beginning of each fill, the beams are kept at a certain separation so as to limit the pileup within acceptable values and are slowly moved head-on when the beam current decreases. This procedure results in a constant luminosity profile as a function of time until the maximum beam overlap is reached, after which a typical exponential decay can be observed. Luminosity leveling is, to date, the only proposed way to fully exploit the future physics potential of the LHC and poses rather stringent requests on luminosity monitors.

Several detectors in ATLAS provide luminosity information—either online, offline, or both—with different frequencies, granularities, dynamic ranges, and precisions. In particular, measurements based on the total energy as monitored by the calorimeters (the end-cap region of the liquid-argon electromagnetic one, EMEC, the hadron calorimeter, TILE, and its liquid-argon forward region, FCal, as detailed in Reference [2]) are available online every few tens of seconds but cannot resolve individual bunches. This is also true for particle fluxes as recorded by stacks of hybrid silicon pixel sensors (the Timepix detectors, or TPX [3]) located in the ATLAS experimental hall. Finally, Z-boson and track counting require detailed offline analysis and are affected by trigger inefficiencies. While different detectors and recorded-data analyses are needed to assess the overall reliability of the final measurements and to study systematics, the luminosity Cerenkov integrating detector (LUCID) is, to date, the only one covering all requirements for effective luminosity measurements and monitoring at the LHC, both online—in terms of frequency of measurements (few seconds) and granularity (each bunch individually)—and offline.

2. Detector and Readout Electronics

The LUCID detector operated during LHC Run-1 and was similar to the Cherenkov Luminosity Counter (CLC) [4] of the Collider Detector at Fermilab (CDF). Designed to measure luminosity with 5% precision and up to pileup values of about seven, LUCID-1 provided data until the end of Run-1, although various limitations became apparent at pileup values close to 20. There was a clear call for a detector upgrade to cope with the LHC conditions expected in Run-2. The LHC parameters most relevant for LUCID operation in Run-1 and Run-2 are summarized in Table 1, which motivated the need for a faster and radiation harder detector, with sensors of smaller acceptance and, in general, better stability, robustness, and flexibility than in the previous period. Detector simulations have, in fact, shown that the combined effects of increased energy and luminosity, as well as the replacement of the stainless-steel beam pipe with an aluminum one, would result in a 60% to 80% increase in the sensor-pulse rate [5].

Table 1. The Large Hadron Collider (LHC) parameters most relevant for operations of the luminosity Cerenkov integrating detector (LUCID) in Run-1 and Run-2. L refers to the instantaneous delivered luminosity in pp collisions, and μ_{max} to the typical pileup at the beginning of each run. More details can be found in References [6,7].

	E_{CM} (TeV)	$\int$L dt (fb^{-1})	μ_{max}	Bunch Spacing (ns)
Run-1 (2010–2011)	7	0.05	<20	50
Run-1 (2012)	8	28.26	30	50
Run-2 (2015–2018)	13	158	50	25

The physical location of LUCID-2 [5] did not change with respect to its precursor: two identical modules were still placed on either sides of the ATLAS detector, around the LHC beam-pipe at a distance of about 17 m from the interaction point. The aluminum tubes filled with Cherenkov gas radiators and coupled to photomultipliers (PMTs) which were used in LUCID-1 were replaced with two simple rings of 16 PMTs, one ring per side, where the very quartz window of the PMTs acts as a Cherenkov radiator. Four quartz fibre-bundles coupled to the PMTs located about 1.5 m away from the beam pipe were also installed on each side. A drawing of one of the two modules of LUCID-2 is shown in Figure 1. In each ring, the 16 PMTs are grouped into four subgroups, one of which was meant to provide spares to PMTs which stop working during operations. This precaution was taken because the PMTs cannot be accessed unless other parts of the ATLAS detector are removed, which is typically limited to winter or longer shutdowns. PMTs labelled as “Modified” in Figure 1 refer to sensors whose photocathode is partially masked off by an aluminum layer so as to reduce the acceptance. All PMTs are small R760s by Hamamatsu, with a window diameter of 10 mm, which replace the R762s (ϕ = 14 mm) used in LUCID-1. They are also enclosed in a mu-metal protection cylinder. The photomultipliers have have been subjected to radiation-resistance studies up to a dose of 200 kGy [8]. Such a dose was actually reached by the end of the 2017 running period.

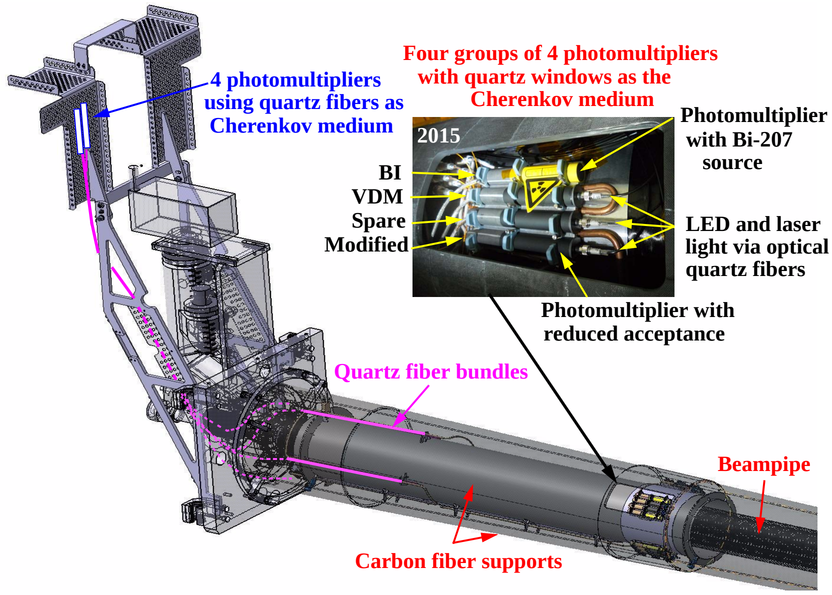

Figure 1. Schematics of one of the modules of the LUCID-2 detector. The inset shows the setup in 2015, including photomultipliers (PMTs) calibrated via LED (Light-Emitting Diode) or laser light (labelled as VDM in the picture since initially thought to be best for Van Der Meer scans), recently replaced by PMTs equipped with ^{207}Bi radioactive sources [5]. The centers of the photomultipliers are 125 mm from the beam line.

In LUCID-1 the signal pulses produced by the PMTs had to travel more than 100 m before being digitized by the electronics, and pulse deformations were apparent. In the new detector, four custom Versa Module Europe (VME) boards known as LUCROD (two per side) and located only 15 m from the PMTs provide early signal amplification, digitization, discrimination, and integration. Pulses are well contained in the 25 ns length of each bunch slot and, if above a programmable threshold, define a hit in the corresponding orbit segment. Hits from all LUCRODs are sent via optical fibers to other VME boards (known as LUMAT) which combine digital information from both detector modules on a bunch-by-bunch basis. Among the possible hit patterns, side AND and OR are defined: at least one hit in both sides of the detector corresponds to the former, and a hit anywhere in the detector corresponds to the latter. Such events, as well as hits and pulse-integrals (charge) produced by each PMT, are accumulated for each of the 3564 bunch slots in the LHC orbit, in the Field-Programmable Gate Arrays (FPGA) of the LUMAT and LUCROD boards over periods of about one minute. They represent the main raw data for luminosity measurements and are independent of the ATLAS trigger. Hit and charge data for beam optimization and leveling are accumulated over periods of 2 s irrespective of the bunch slot and are immediately made available to provide feedback for LHC operations. In order to allow for performance studies and PMT-gain calibration, the current produced by the PMTs is additionally sampled over periods of eight bunch crossings (200 ns) and read out via VME with a dedicated stream.

3. Principle of Luminosity Measurements

Since at the LHC there are typically many inelastic interactions per bunch crossing, the luminosity is not simply proportional to the trigger rate of any detector sensitive to pp inelastic interactions. Instead, two main groups of algorithms are implemented: hit (or event) counting and charge integration. Hit and event counting algorithms measure the visible pileup (μ_{vis}), which depends on the efficiency and acceptance of the specific method to detect a single interaction, and relate it to luminosity via a Poisson probability distribution. On the other hand, total charge is directly proportional to the luminosity. In LUCID-2, custom electronics implement both kinds of algorithms. In addition, the variety of possible patterns and sensor groupings guarante the availability of data even in case of hardware failure in parts of the readout electronics and sensors.

For each algorithm a calibration constant corresponding to the visible cross section (σ_{vis}) is needed. It is evaluated in special low luminosity LHC fills known as Van der Meer (VDM) scans. During these scans, beams are separated both horizontally and vertically while rates are measured: the calibration constant σ_{vis} is obtained from the width and the maximum of the resulting rate versus beam separation curve, and the beam currents as provided by LHC instrumentation and detailed in Reference [2]. The precision of the calibration constant does not depend on knowledge of the pp inelastic cross section.

VDM scans are performed only few times per year, making the detector stability of utmost importance to control the error on integrated luminosity measurements. In the end, these errors add to other systematics in the evaluation of the cross section of any observed process as well as placing exclusion limits on possible new ones.

4. Calibration System

Based on the Run-1 experience, the long-term stability of the PMT gain was a major concern in the design of the new detector. The old system of LED signals was complemented in two ways: PIN diodes to monitor the LED themselves, and ^{207}Bi radioactive sources directly deposited on the windows of a subset of the PMTs. ^{207}Bi decays into $\sim$1 MeV electrons via the internal conversion of ^{207}Pb* intermediate states and is thus able to mimic the effect of charged particles produced during collisions and hitting the PMT windows. The activity of the sources was chosen so as to be low enough to avoid affecting measurements during collisions and VDM scans, but still enough to provide good statistics in relatively short calibration periods. Since the new system showed better performance than the LED and laser ones, it was extended to all PMTs except those coupled to quartz fibers during the winter shutdown between 2016 and 2017.

PMT-gain losses up to several % occurring during high luminosity LHC fills are recovered at each inter-fill by calibration runs measuring the average amplitude and charge of the ^{207}Bi and LED signals, for the PMTs and fibers, respectively. This calibration is followed by an automatic re-adjustment of the high voltage (HV) of each PMT. The HV evolution of the PMTs as a function of integrated luminosity, radiation dose, and charge produced by the PMTs themselves up to the end of 2017 is shown in Figure 2 and is symptomatic of PMT aging. Changes in the PMT supply voltage affect the electron transit time and thus the final pulse shape. As a consequence, calibration-pulse charge and amplitude could not be kept constant at the same time. Thus, the calibration procedure had to be targeted to the relevant variable depending on the kind of luminosity measurement chosen for the corresponding sensor, either total charge or hit counting.

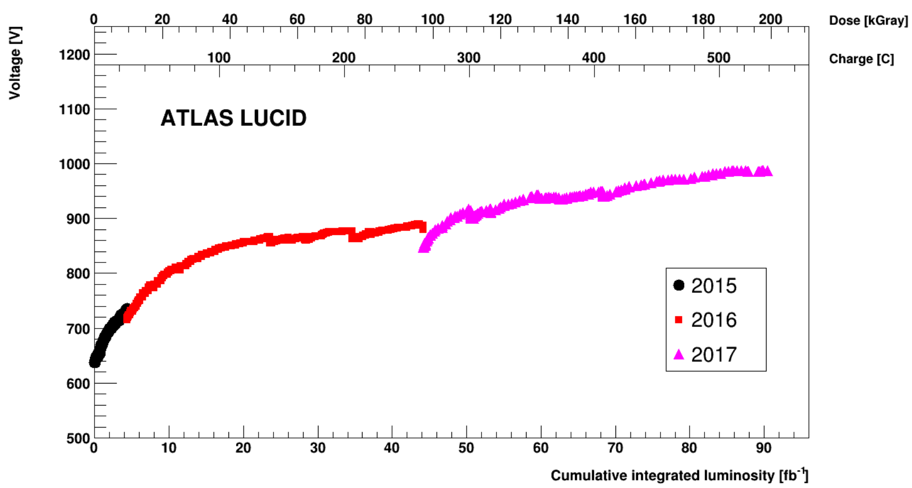

Figure 2. Average high voltage (HV) applied to four PMTs as a function of cumulative luminosity delivered by the LHC from 2015 to 2017 [5]. The maximum HV the PMTs can sustain is 1250 V.

5. Results

LUCID-2 has provided luminosity measurements for ATLAS and the LHC since 2015 and up to the end of running in 2018. Several of the PMTs located close to the beam pipe stopped working or showed unstable response at the end of 2017 and during the running period in 2018, whereas none of the PMTs connected to fibers showed any problems, pointing to radiation damage as the main origin of the losses. Single event upsets in the electronics close to the detector have been handled so as to avoid data losses for more than two minutes in a row, where one minute is the time-scale over which luminosity is supposed to be constant, and it never affected the two sides of the detector at the same time. Electron transit time changes in the PMTs caused by high voltage adjustments had to be closely monitored and corrected for during operations to guarantee good time alignment between LHC synchronization signals and PMT pulses.

Luminosity measurements based on hit and hit-pattern counting are affected by pileup of several below threshold signals which combine into fakes, and corrections need to be implemented offline at high pileup. The corrections are based on information from the ATLAS tracker, which is the only other subsystem able to provide bunch-by-bunch luminosity information, although not online. LUCID luminosity measurements based on charge are, in fact, directly affected by PMT gain fluctuations occurring during fills, whereas hit counting algorithms are affected only marginally. A few high-efficiency algorithms based on particular hit-patters suffer from saturation for pileup values in excess of about 30. The dynamic range of the electronics together with the selected working point prevented the charge-integration algorithms from saturating for any Run-2 conditions. The overall detector stability can be evaluated by comparing measurements with different algorithms and detectors as is shown in Figure 3, where the fractional difference in run-integrated luminosity between the preferred LUCID algorithm (hit counting) and other detectors in 2017 is shown. Similar results were obtained in the other periods including the latest.

The final precision of the integrated luminosity, which is useful for analysis of collision data, is dominated by uncertainties in the absolute calibration performed with VDM scans, its transfer to large pileup, and the detector long-term stability. Total systematics to be used for pp data analysis were as low as 2.1% and 2.2% for 2015 and 2016, respectively. Preliminary analysis of 2017 data confirms a precision within 2.4%. All systematics were evaluated following a methodology similar to that detailed in Reference [2].

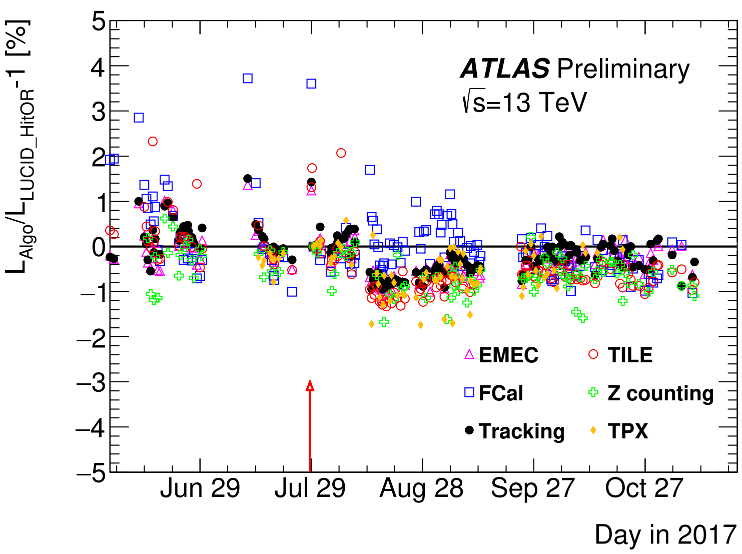

Figure 3. Fractional difference in the run-integrated luminosity between the preferred LUCID algorithm and other detectors as defined in the introduction, in 2017 [7]. The red arrow points to the run chosen as reference.

6. Conclusions

Due to its simple and robust design, the LUCID-2 detector has fully satisfied all the needs it was designed for. Keys for such a success were a reliable calibration system based on radioactive sources, custom built electronics, and a redundancy of available algorithms. No major upgrades of the electronics or calibration systems are planned for LHC Run-3.

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Conflicts of Interest: The author declares no conflict of interest.

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