JINST
PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *March 6, 2026*
ACCEPTED: *March 27, 2026*
PUBLISHED: *May 14, 2026*

7th INTERNATIONAL WORKSHOP ON NEW PHOTON-DETECTOR
BOLOGNA, ITALY
3–5 DECEMBER 2025

Cherenkov detectors in the extreme LHC environment: LUCID PMTs and fibers

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ABSTRACT: The LUCID-2 detector is the main luminometer of the ATLAS experiment and is the only one capable of delivering a reliable luminosity measurement in all beam configurations and luminosity regimes. During LHC Run-2, ATLAS achieved a luminosity precision of 0.83%, the most accurate determination ever obtained at a hadron collider. LUCID-2 is providing luminosity measurement to the ATLAS experiment also during Run-3 with performance similar to the one achieved during Run-2. The ATLAS physics program at the High-Luminosity LHC calls for a luminosity precision better than 1%. LUCID-2 is not able to guarantee this precision in this environment therefore a new detector, called LUCID-3, is planned. Two types of prototypes were built and are currently under testing: one relying on photomultiplier tubes (PMTs), similar to LUCID-2 but positioned farther from the beam pipe to reduce acceptance and prevent luminosity algorithm saturation; and a second detector that uses optical fibers as Cherenkov radiators, read out by PMTs placed in a low-radiation region. All PMTs will be calibrated and monitored with a ^{207}Bi radioactive source to ensure long-term stability better than 1%. This contribution discusses the performance of the prototypes of a luminosity detector based on a photon detector.

KEYWORDS: Cherenkov detectors; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others)

https://doi.org/10.1088/1748-0221/21/05/C05014

2026 JINST 21 C05014

Contents

1 LUCID-2

LUCID-2 [1], the main ATLAS luminometer, is made of 2 symmetric modules 17 m away from the Interaction Point (IP) along the beampipe. Each module is made of 4 groups of 4 PMTs (Hamamatsu R760) and, in Run-2 only, 4 quartz fibers coupled with PMTs [1]. Radioactive sources of ^{207}Bi are deposited on the PMT windows to monitor their ageing while, for fiber monitoring, LED light is used. PMT pulses are fed to custom made VME boards (LUCROD) [1] where signals are amplified, digitized, discriminated and integrated. Thanks to this setup, it was possible to acheive a total uncertainty of 0.83%, the best ever achieved at a hadron collider. Similar performances are expected also during Run-3 data taking but due to higher pile-up and higher radiation damage, LUCID-2 won't be able to operate during the HL-LHC data taking. The main limitations of LUCID-2 in HL-LHC conditions are the saturation of the luminosity algorithms due to the higher number of interaction per bunch crossing (called also pileup or μ) from 60 to 200 and to the higher radiation damage due to higher luminosity. All these factors will prevent LUCID-2 from guaranteeing a total uncertainty $< 1\%$. For these reasons, a new LUCID is required.

2 LUCID-3 prototypes

The upgrade strategy [2] for the detector focuses on reducing both the PMT acceptance and the particle flux. To decrease the acceptance, smaller PMTs are studied: Hamamatsu R1635 [3] with an 8 mm diameter window, compared to the 10 mm window of the currently used R760. A complementary approach is to lower the particle flux reaching the PMTs by relocating them. One option is to position the PMTs further away from the beamline. Alternatively, they can be placed in the shadow of the muon shielding. A third solution involves using optical fibers as the Cherenkov medium, with the PMTs placed in a shielded area. To test the design of LUCID-3, three prototypes (figure 1) are currently under testing in ATLAS.

2.1 PMT type prototypes

The first PMT prototype installed for Run-3, called LUCID JF, consists of 4 PMTs each side of the ATLAS detector, some of them being Hamamatsu R760 (LUCID-2 PMTs) and other being Hamamatsu R1635 (new smaller PMTs) attached to one of the ATLAS forward shielding via a rail system to ease the replacement of PMTs during shutdowns. R760 luminosity measurement has been compared with the one measured by electromagnetic calorimeter (EMEC) to evaluate its long term stabity. The long

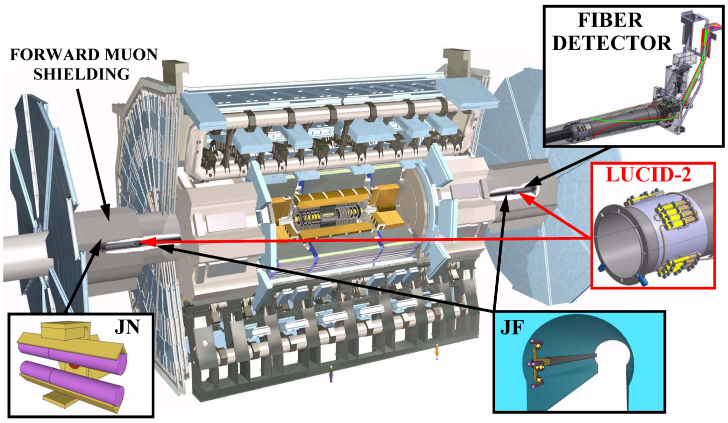

Figure 1. Design and placement of LUCID-2 and LUCID-3 prototype (JF, JN and Fiber) inside the ATLAS experiment. Reproduced from [4]. CC BY 4.0.

term stability is very good as seen in figure 2 left with fluctuations that are of the order of 0.3%. A higher threshold has been tested to reduce the efficiency to count hits and mitigate the saturation and no effect on the long term stability has been observed.

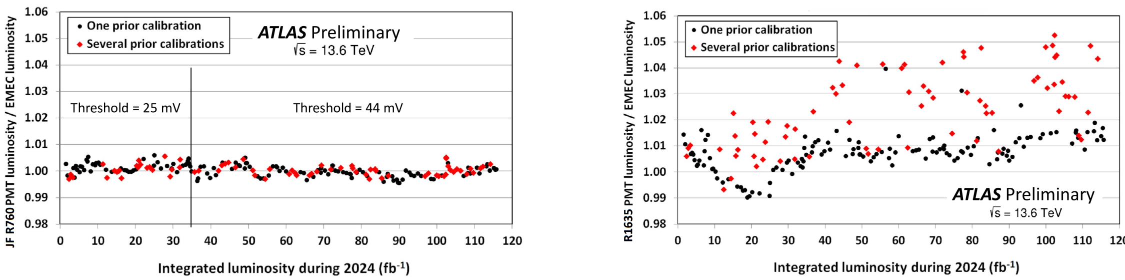

Figure 2. Ratio of the luminosity measured by LUCID JF equipped with R760 (left) and R1635 (right) to the one measured by calorimeter as function of the integrated luminosity. Reproduced from [5]. CC BY 4.0.

R1635 PMTs exhibit large run-to-run fluctuations (figure 2, right). These variations are correlated with the number of high-voltage adjustments (Bismuth calibrations) performed during the interfills (black point represent runs with just one set of HV adjustment before, while red points represent runs with multiple sets). To investigate this effect in a controlled environment, a dedicated laboratory setup was assembled. It consists of a LED (λ = 385 nm) to reproduce the typical LHC conditions from collisions and a ^{207}Bi source to monitor the PMT gain. Figure 3 shows the mean amplitude of the Bismuth signal as a function of time. During the first 20 h, only Bismuth monitoring was carried out. The LED was then switched on for 8 h (indicated by the arrows), producing a PMT anode current of 30 µA in the R1635 and 85.3 µA in the R760. At the end of the LED exposure, the PMT gain was monitored for 15 h. A short LED run (60 s, indicated by the arrow) was subsequently performed, again followed by gain monitoring. After each LED exposure, a decrease in the mean amplitude of the Bismuth signal was observed in R1635, lasting for a few hours (figure 3 left). The origin of this behavior is not yet fully understood. This effect is not observed in the R760, where the amplitude drop occurs immediately after LED exposure and is then stable (figure 3 right).

2026 JINST 21 C05014

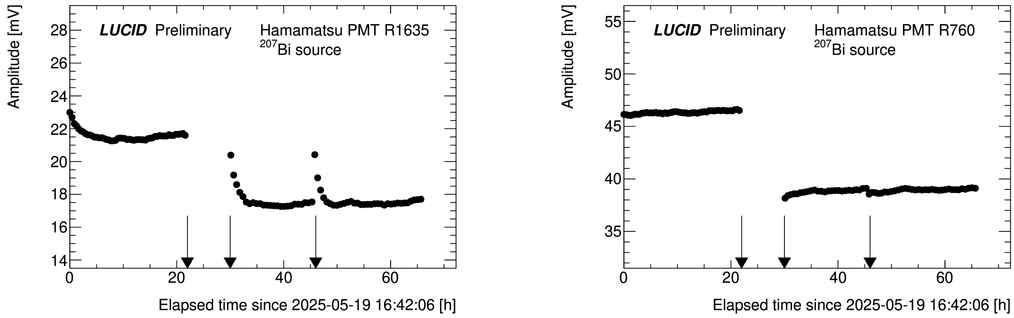

Figure 3. Evolution of the mean signal amplitude of ^{207}Bi electrons detected with a Hamamatsu R1635 PMT (left) and R760 (right). Reproduced from [6]. CC BY 4.0.

An auxiliary PMT detector, called JN, consists of two Hamamatsu R760 PMTs placed behind the forward muon shielding. It is operated with a low current, low occupancy and low radiation conditions. The drawback is that it will not be sensitive in the very low luminosity regime of special calibration runs (like Van der Meer scans) and therefore must be cross calibrated. It is characterized by a good overall stability (drift < 0.5%) (see figure 4) with fluctuations of the order of 0.6%.

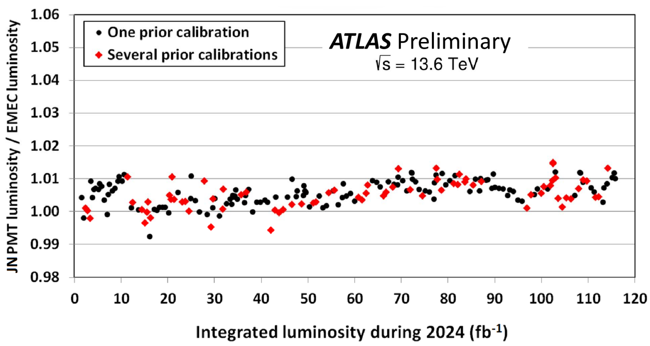

Figure 4. Ratio of the luminosity measured with LUCID JN to the one measured by the EMEC calorimeter as function of the integrated luminosity. Reproduced from [5]. CC BY 4.0.

2.2 Fiber type prototype

The Fiber detector is an upgraded version of the fiber detector that was used during LHC Run-2 data taking. It's made of two radiation hard quartz fiber bundles coupled with two Hamamatsu R7459 PMTs for the readout. The main upgrade consists in the use of ^{207}Bi for the PMT gain monitoring. The degradation of the fiber bundle due to irradiation is monitored by a system featuring 6 LED wavelengths; light is injected both directly into the PMT (prompt signal) and into some of the bundle fibers (delayed signal), creating two separated signals (figure 5 left); the evolution in time of the ratio of the delayed to prompt signal is expected to be proportional to the fiber degradation.

An irradiation campaign was performed to study the degradation of the fiber due to radiation damage as function of the light wavelength. The irradiation session showed that the fiber transmissivity loss is much faster in UV region than in visible region (figure 5 right). Therefore, one of the prototypes is also equipped with an UV filter to cut out the UV component and improve the stability over the long period.

2026 JINST 21 C05014

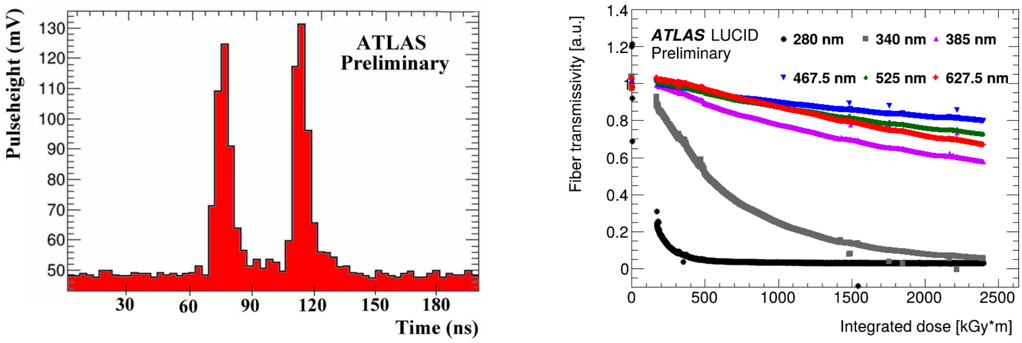

Figure 5. Left: Example of a signal generated by an LED inside the PMT. LED light is divided in two part: the first one is injected directly into the PMT (prompt signal) while the second one travels through the fiber (delayed signal). Reproduced from [6]. CC BY 4.0. Right: Transmissivity of the fiber measured as function of the integrated absorbed dose at various wavelengths. Reproduced from [7]. CC BY 4.0.

During a typical LHC fill, a significant amount of charge is measured in nominally empty bunches (Q_{BKG}). Studying the evolution of Q_{BKG} with respect to the signal charge (Q_{signal}) during the year, an increase was observed as reported in figure 6 left. The reason of this increase is not fully understood but it is possible that impurities inside the fiber are generated due to irradiation with hadrons and these impurities are producing scintillation light [8]. A second problem is the fact that charge produced during a given bunch crossing spills into subsequent crossings, resulting in an overestimation of their measured luminosities.

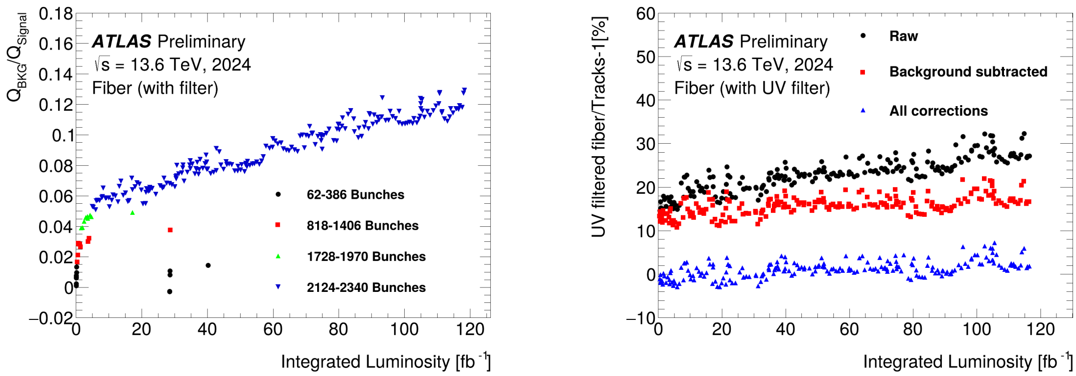

Figure 6. Left: Ratio between the background charge (Q_{BKG}) with respect to the signal charge (Q_{signal}) as function of the integrated luminosity. Each point represents a physics run. Right: Relative difference between the luminosity measured with the fiber with UV filter without any correction (black), with only background (red) and with background and charge leakage corrections (blue) and the luminosity measured with the track counting algorithm (Tracks) as function of the integrated luminosity. Reproduced from [9]. CC BY 4.0.

Two offline corrections have been developed to correct for these two effects. Background charge is evaluated every 60 s and subtracted to the measured charge. The fraction of charge spilling into the following BCID is evaluated in some specific runs and subtracted. After applying these corrections, the prototype equipped with UV filter is stable in the long term (figure 6 right) while the one without suffers from fiber degradation, proving the effectiveness of the UV filter solution. Both prototypes suffer for significant run to run fluctuations (3%) that are under study.

2026 JINST 21 C05014

3 Conclusions

The LUCID-2 detector has demonstrated excellent precision and stability throughout Run 2 and Run 3. This level of performance has been achieved thanks to the intrinsic simplicity and redundancy of the system, combined with continuous optimization of the operational parameters and extensive analysis efforts. In view of the upcoming HL-LHC phase, a new detector design will be required to cope with the future challenging experimental conditions.

During Run 3, several prototypes were deployed to evaluate their performance and assess their suitability for the future upgrade. The small Hamamatsu R1635 PMTs exhibit instabilities, which are currently under investigation. The JF detector, equipped with Hamamatsu R760 PMTs, performs in accordance with expectations. The JN detector shows good stability and is presently considered a solid candidate for the HL-LHC configuration. Finally, the fiber detector has demonstrated good long-term stability after the application of offline corrections, while efforts are ongoing to understand and mitigate the residual run-to-run fluctuations.

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2026 JINST 21 C05014