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LUCID-3: the upgrade of the ATLAS luminosity detector for High-Luminosity LHC

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Abstract: The ATLAS physics program at the High Luminosity LHC (HL-LHC) calls for a precision in the luminosity measurement of 1%. A larger uncertainty would represent the dominant systematic error in precision measurements, including those in the Higgs sector. To fulfill such requirement in an environment characterized by up to 140 simultaneous interactions per crossing (200 in the ultimate scenario), ATLAS will feature several luminosity detectors. At least some of them must be both calibratable in the van der Meer scans at low luminosity and able to measure up to the highest values. LUCID-3, the upgrade of the present ATLAS luminometer (LUCID-2), will fulfill such a condition. The reasons for an upgrade of LUCID-2 and the envisaged solutions are discussed and a description of the LUCID-3 project is given. Finally, the first results obtained with the prototypes installed in ATLAS during the present LHC Run-3 are discussed as means of the validation of the final design.

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

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2024 JINST 19 C03053

Contents

1 Introduction **1**

2 The LUCID-2 detector **2**

3 The LUCID-3 upgrade **3**
3.1 The new location 4
3.2 The smaller acceptance photomultipliers R1635 4
3.3 The LUCID-3 detector 5

4 The LUCID-3 prototypes **6**
4.1 PMT prototypes 6
4.2 Fiber prototypes 9

5 Conclusions **9**

1 Introduction

The precise determination of the luminosity delivered by a collider to the experiments is crucial for most physics measurement. In ATLAS, these include both precision measurements aimed at verifying the predictions of the Standard Model and searches for New Physics to set limits on the production of potential new particles. Also measurements which are not aimed at measuring production cross sections often need the knowledge of the luminosity for the normalization of the various background sources. The uncertainty in the luminosity determination directly enters the overall uncertainty of the measurements and can represent one of the main components. Luminosity monitoring in real time is also crucial for the operation of the accelerator and for the optimization of the data taking by the experiment. For these purposes, a luminosity detector must perform a reliable and stable online measurement of the luminosity at a higher frequency with respect to the offline measurement (in ATLAS every 2 sec to be compared to the 60 sec of the offline), although with a less demanding precision (an absolute calibration determination at the level of few percent is considered acceptable). The information is used by the LHC to monitor the quality of the beams, the delivered luminosity in the interaction point (IP) and to operate in *luminosity levelling* mode. It is also used by the experiment to optimize the trigger pre-scales following the beam degradation in order to ensure the maximum band-width for all of them.

The luminosity determination can be logically sub-divided into two steps: luminosity monitoring (relative luminosity) and absolute calibration (absolute luminosity). Various detectors generally contribute to the first step, and some must be directly calibratable to provide the absolute value (main luminometers), while others can be cross-calibrated to these, and are used both to control their long-term stability or other systematic effects, to correct potential non-linearity or other limiting factors, and to assess the final systematic uncertainty on the luminosity determination (see [1] for a description of the ATLAS luminosity measurement in Run-2). The absolute calibration is generally performed via the so-called van der Meer scans, i.e. data taking periods in optimized conditions and at very low

2024 JINST 19 C03053

luminosity (about 4 orders of magnitude lower than in the physics data taking) in which the beams are moved relative to each other separately in the two transverse planes in order for the luminosity detectors to determine the beam overlap width. Together with the knowledge of the beam-currents provided by the machine, it is possible to calibrate the luminometers. The precision on the calibration achieved by ATLAS combining the systematic uncertainties for all Run-2 pp vdM sessions at 13 TeV is 0.65%. This uncertainty is combined with the systematic uncertainty affecting the luminosity measurement during the physics data taking (long-term effects, non linearity, background subtraction, etc) to give a final Run-2 luminosity uncertainty of 0.83%, an unprecedented precision at any collider [1].

In section 2 a description of the main ATLAS luminometer in Run-2 and Run-3, LUCID-2, is given, as this technology will also be used in the HL-LHC LUCID-3 upgrade. In section 3 the reasons for the detector upgrade for HL-LHC are explained and a description of LUCID-3 is given. In section 4 the LUCID-3 prototypes installed in Run-3 are described and the first results from Run-3 collisions are given, validating the proposed design.

2 The LUCID-2 detector

LUCID-2 [2] has been the main luminosity detector in ATLAS in Run-2 and is such also in Run-3, both online and offline, in all beam conditions and both in pp and heavy ions collisions. LUCID-2 is the only ATLAS luminometer able to reliably measure the luminosity separately for each bunch-crossing. It is composed of two modules located on each side of the IP (Side-A and Side-C) at about 17 meters from it. Each module contains 16 Hamamatsu R760 photomultipliers (PMT) distributed in a ring of radius $R = 12$ cm around the beam pipe. Charged particles crossing the PMTs at each bunch-crossing are detected through the Cherenkov light produced in the PMT quartz window. For radiation hardness reasons, suitable PMTs must have a quartz window. In the following the search for alternative PMTs for LUCID-3 is discussed, assuming this crucial feature to be unavoidable. The signals from the PMTs are routed to a custom read-out board, LUCROD [2], specifically designed for LUCID. The board amplifies and digitizes the signals at 320 Msps. The algorithms used to measure the luminosity are implemented in the firmware of the LUCROD FPGAs. Each PMT is an independent detector, but various PMTs can also be grouped together in so called combined algorithms, either separately for the A- and C-side, or combined (as the Bi2HitOR algorithm shown in figure 4 which is based on the sum of the hits recorded by a group of 8 PMTs). In this way LUCID can provide several totally or partially independent measurements which allow for internal redundancy and flexibility in case one or more PMTs experience problems during the data taking. One of the main problems that these algorithms can experience is the so-called saturation, meaning that the detector observes a hit in each bunch-crossing, thus becoming blind to any further increase of the luminosity. This can happen when the number of interactions per bunch-crossing, i.e. the pile-up parameter (μ), becomes large. The typical values $\mu \lesssim 70$ reached by the LHC in Run-2 and Run-3 did not saturate any of the LUCID algorithms. In HL-LHC, the pile-up parameter will reach values up to 140 (200 in the ultimate scenario) which will saturate all algorithms with LUCID-2. This is the main reason to upgrade the detector for the HL-LHC.

An innovative PMT gain monitoring system is used in LUCID. A small amount of radioactive ^{207}Bi source ($\sim$ 50 kBq) is deposited on the window of the PMTs. Additional to the β-decay, monochromatic electrons from internal conversion are emitted with energy $\sim$ 1 MeV, producing Cherenkov light inside the window mimicking, both in terms of number and wavelength of the Cherenkov photons, the signal

2024 JINST 19 C03053

from charged particles produced in high-energy proton-proton collisions at LHC. The activity of the source is chosen as a compromise between two constraints: do not interfere with the luminosity measurement even in the low luminosity regime (for example in the vdM scans) and allow to perform calibration runs within the typical LHC inter-fill duration ($\sim$ 1 h). The pulse-height distributions accumulated during the calibration runs are compared with a reference distribution at the beginning of the yearly data taking. In the presence of a gain loss of the PMT, the mean of the distribution is lower than the reference. In this case, a high-voltage increase is automatically applied to the PMT and a new calibration run is taken to verify that the initial conditions are recovered. In this way, a better than 1% yearly stability of the PMT gain is reached, as can be seen in figure 1 for one year of Run-2, ensuring a stable luminosity measurement. One of the main problems with the LUCID-2 luminosity measurement

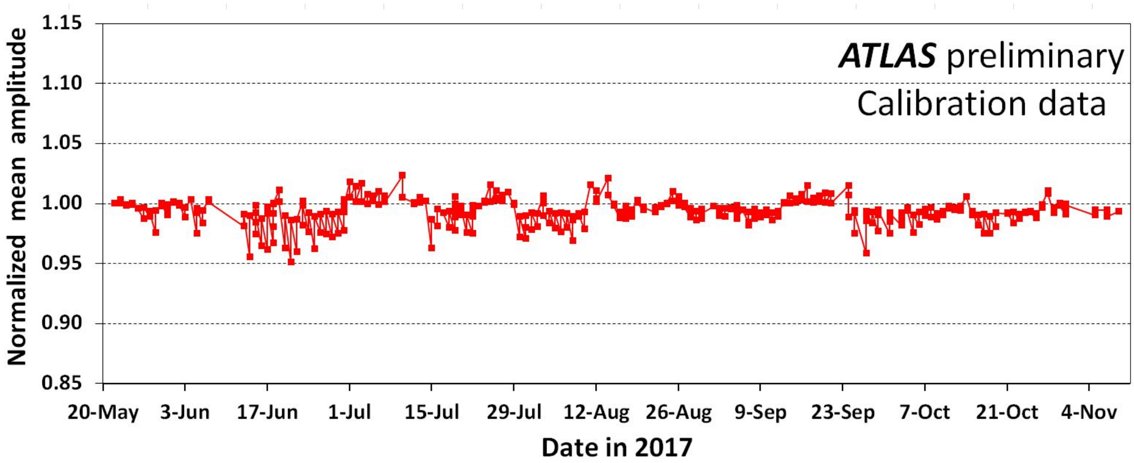

Figure 1. PMT gain stability during 2017. Reproduced with permission from [3].

is the non-linearity of the detector as a function of μ when going from the vdM conditions ($\mu < 1$) up to the standard data taking conditions ($\mu \lesssim 70$). A total non-linearity in this range of μ of up to about 10% was measured in Run-2. This is corrected using the luminosity measurement provided by the Inner Tracker and the so-called track-counting algorithms [1]. This correction can potentially be even larger when the pile-up will increase by a factor of up to three at the HL-LHC.

3 The LUCID-3 upgrade

Despite the success of the luminosity measurement performed by LUCID-2 during LHC Run-2 and Run-3, an upgrade of the detector is required to face and solve the following main limitations:

- pile-up: the increase of the pile-up parameter up to 140–200 will produce a saturation of the LUCID luminosity algorithms if the occupancy of the detector is not reduced;
- radiation damage and maintenance: a detector located around the beam-pipe will be difficult to maintain with the replacement of the damaged PMTs due to the high levels of radioactivity reached by the new vacuum instrumentation that LHC will install close to the LUCID-2 location. This is a point of attention, as the PMT lifetime is significantly shorter than the HL-LHC operation time, and they need to be replaced typically every 1–2 years;

- non-linearity: extrapolating the present LUCID-2 non-linearity up to μ values of 140–200, large corrections will presumably be needed. There is no guarantee that the non-linearity trend above the presently tested μ-range will be the same, but it is clear that this represent a challenge to the required 1% overall luminosity precision.

Solutions must therefore be found to:

- reduce the occupancy of the detector in order to avoid the saturation of the algorithms. This can be achieved either by finding a location with a reduced flux of particles or by using PMTs with a smaller effective area (or both);
- find an alternative location where it easier to maintain the detector;
- improve the linearity of the detector as a function of μ.

3.1 The new location

A new location has been identified at a distance from the beam-pipe (R) of about 30 cm to be compared to the 12 cm of LUCID-2, and a distance from the IP (z) of about 16 meters [5]. This can be achieved by mounting LUCID-3 on the inner wall of the so-called $JFC3$ absorber, one of the ATLAS forward iron shielding protecting the muon detector wheels. During every winter shutdown the $JFC3$ is removed, brought to surface and stored in a hall waiting to be re-installed in the experiment before the start of the following data taking. Installing LUCID-3 in the JFC3 allows therefore to maintain the detector in an easy and safe environment above ground. Moreover, a system is foreseen to extract the PMTs from the activated shielding to a distance of about one meter to allow for a safe maintenance. In the following a LUCID-3 detector in this location will be called JF-detector. Another possible location (at least for a subset of PMTs) was identified in the shadow of the JFC3 absorber [5] at about 40 cm in radius and 18.7 meters from the IP. In the following a detector in this location will be called JN-detector.

Monte Carlo simulations predict that the particle flux through a PMT in the JF-detector is reduced by about 30% with respect to LUCID-2, while the acceptance of the JN-detector is about 95% smaller. In the next sections, a quantification of the effect on the saturation due to the change of location is discussed, together with the effect of the (additional) reduction of the acceptance obtained by using PMTs with a smaller window.

3.2 The smaller acceptance photomultipliers R1635

In order to reduce the acceptance of the detector and mitigate the saturation of the luminosity algorithms, another possibility is to reduce the occupancy of the PMTs. Upon request of the LUCID group, Hamamatsu has produced custom PMTs based on the R1635 model with a quartz window instead of the standard Borosilicate glass, which would not have the required radiation hardness. The R1635 have a $\phi = 8$ mm cathode diameter compared to 10 mm for the R760 used so far. This by itself reduces by about 35% the acceptance of a single PMT. In figure 2 the expected statistical error (based on Poisson statistics) is shown as a function of μ for one pair of colliding bunches in a time interval of 60 s in which the run is subdivided and the luminosity is measured. Various configurations are compared: using the R760 PMTs in the present LUCID-2 location (around the beam pipe), one or a set of eight R760 PMTs in the JF-location and, finally, one R1635 in the JF-location. Setting a limit on the statistical uncertainty of 1%, a PMT in the LUCID-2 location would exceed this value at $\mu \sim 90$, a value far too low for HL-LHC. A JF-detector would reach this limit at $\mu \sim 140$ (170) with one (eight) R760 PMTs, while it would not reach this limit even at $\mu = 200$ using one R1635 PMT. These values are compatible with the standard pile-up scenario, but only the R1635 would meet the needed precision in the ultimate scenario. The use of R1635 in addition to the change of location to the JF shielding is

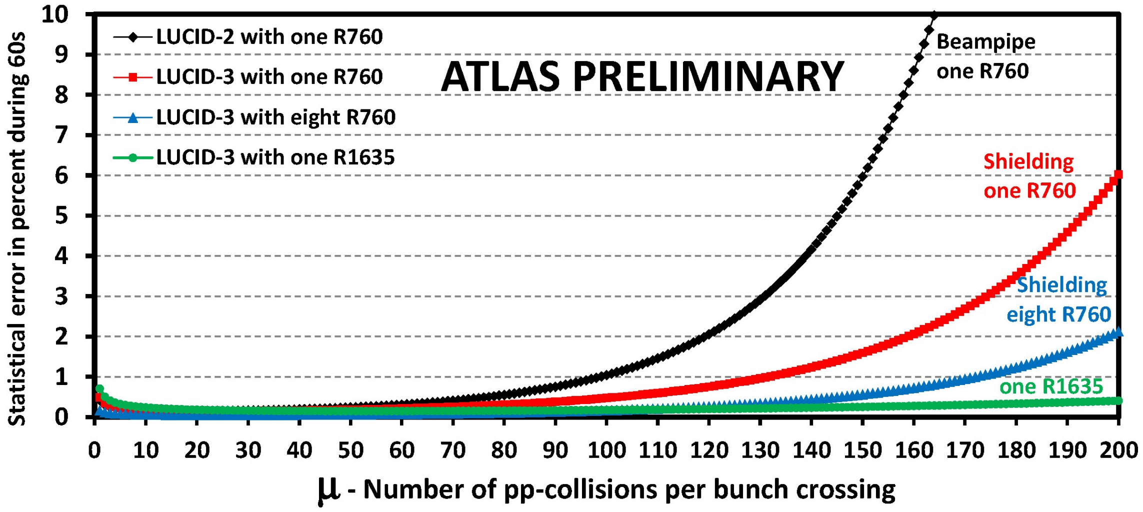

Figure 2. Statistical uncertainty for a single bunch-pair and a Luminosity Block of 60 s for various detector locations and PMT configurations. Black dots (marked as Beampipe) refer to the LUCID-2 location while all the other colors (Shielding) refer to the JF location. Reproduced with permission from [4].

therefore the most promising solution. For this reason R1635 are being characterized both in the lab and in ATLAS. Studies are made of possible limitations due to the lower maximum anodic current that these PMTs can produce, as well as measurements of the absolute gain as a function of the applied HV and the type of signals produced (amplitude and duration). Some results are reported in section 4.

3.3 The LUCID-3 detector

Based on the previous discussion, a concept for the LUCID-3 detector was presented and approved by the ATLAS Collaboration [5], consisting of:

- a baseline detector made of eight R760 or R1635 PMTs per ATLAS side in the JF-location. A possible addition of PMTs in the JN location is also considered relevant, although it has to be decided the exact location given the change in the LHC beam-instrumentation in the LUCID region which prevents them from being installed in the present exact location.

- a complementary detector based on quartz fibers read-out by PMTs located in a low-radiation region will be considered depending on the R&D currently ongoing (see section 4) and if the main detector will prove to have limitations.

The proposed design relies on the Monte Carlo simulations of the particle flux described in the previous sections. It is crucial to verify these predictions in order to validate the concept. For this reason, several prototypes were installed in ATLAS and are taking data in Run-3. In the next section the first results from these prototypes are described.

4 The LUCID-3 prototypes

In figure 3 the prototypes of both the PMT (called JF and JN from their location) and the fiber detectors installed in Run-3 are shown. All these detectors are taking data and are measuring the luminosity delivered by LHC and are being characterized for what concerns the acceptance and occupancy, the linearity with μ, the long-term stability and (for the fibers) the ability to monitor and correct for the fiber ageing due to radiation. A selection of preliminary results is presented.

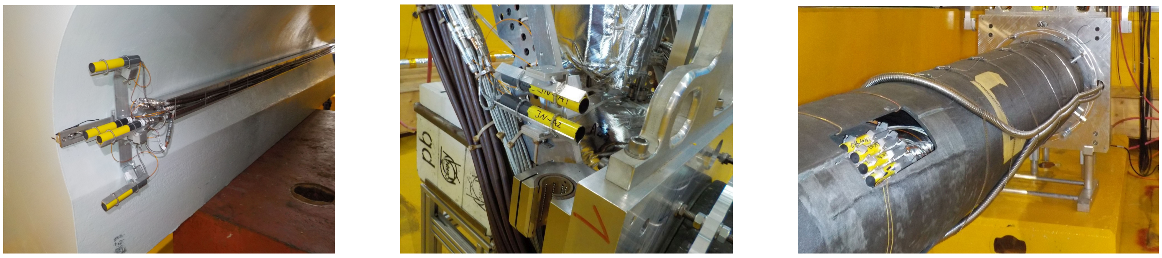

Figure 3. The LUCID-3 prototypes in Run-3. Left: the JF-detector (both R760 and R1635). Center: the JN-detector (R760). Right: the fiber detector. Reproduced with permission from [6].

2024 JINST 19 C03053

4.1 PMT prototypes

The first crucial validation test of the PMT detector is the comparison of the hit-rate measurement with what is predicted by the Monte Carlo simulation as this defines if the luminosity algorithms will saturate or not. An agreement at the percent level of the hit-rate relative to LUCID-2 is measured for the JF (both with R760 and R1635) and the JN R760 PMTs, therefore validating the choice of both locations and PMT types for LUCID-3. Also the different occupancy of the R760 and R1635 in the same location confirms that the R1635 choice is desirable. Overall, the occupancy of the R760 (R1635) in the JF-location relative to LUCID-2 is 75% (35%), while for R760 in the JN-location it is about 5%.

The linearity of the various PMTs is shown in figure 4 as compared to the known to be linear track-counting algorithm [1]. The LUCID-2 non-linearity is shown for comparison in all of the figures with the red dotted line and corresponds to $0.18\%/\mu$. While the JF PMTs (both R760 and R1635) show a similar non-linearity as LUCID-2 (indicated by the *Slope* parameter in the figures), the JN PMTs have a four times lower non-linearity, namely $0.04\%/\mu$ (bottom figure). This is attributed to the lower occupancy ($\sim$ 5% of LUCID-2, compared to $\sim$ 75% of the JF R760). This implies that the JN-detector will need in HL-LHC the same overall non-linearity correction as LUCID-2 needs in Run-2 and Run-3, but at 3 times larger μ values. Studies are ongoing to possibly further reduce this non-linearity. In figure 5 the long-term stability of the various PMT prototypes is shown with respect to LUCID-2. Each point in the figure corresponds to a physics run and the x-axis reports the cumulated luminosity fraction during one year of data taking. In the top figure all prototypes are shown for the 2022 data taking. The JF R760 PMT (blue squares) shows the same very good stability of LUCID-2; the JN R760 PMT (black points) is also very stable, although with somewhat larger run-to-run statistical fluctuations due to the smaller occupancy. Two R1635 are shown in the figure: one located in the JF (magenta triangles) and the other in the LUCID-2 location around the beam-pipe, therefore subjected to a larger particle flux (red circles). The first shows larger run-to-run fluctuations but is still reasonably stable, while the second clearly shows a degradation with time. The reason for

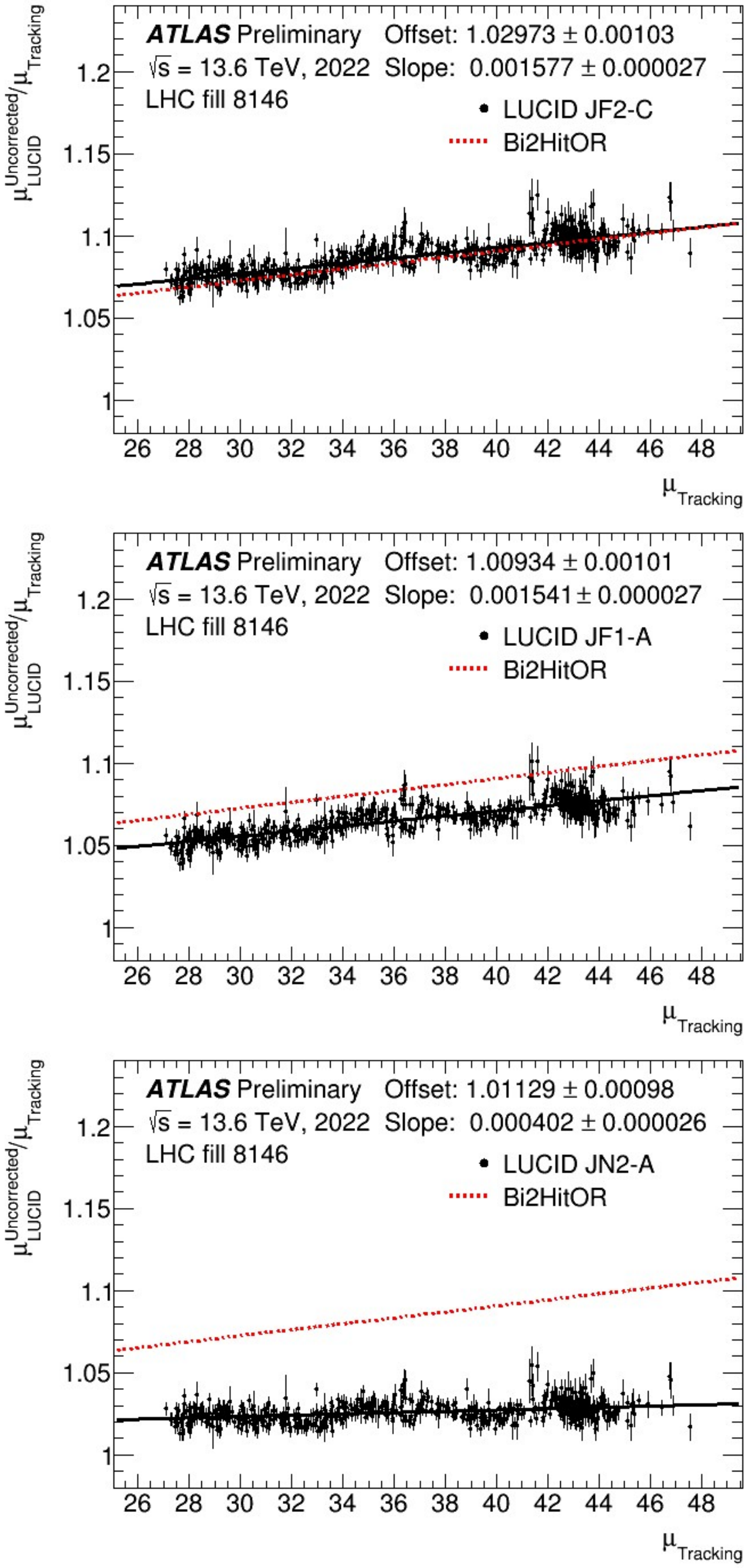

Figure 4. Linearity as a function of μ for the various PMT prototypes as compared to the track-counting algorithm. Top: JF R760 PMT. Middle: JF R1635 PMT. Bottom: JN R760 PMT Reproduced from [7]. CC BY 4.0.

2024 JINST 19 C03053

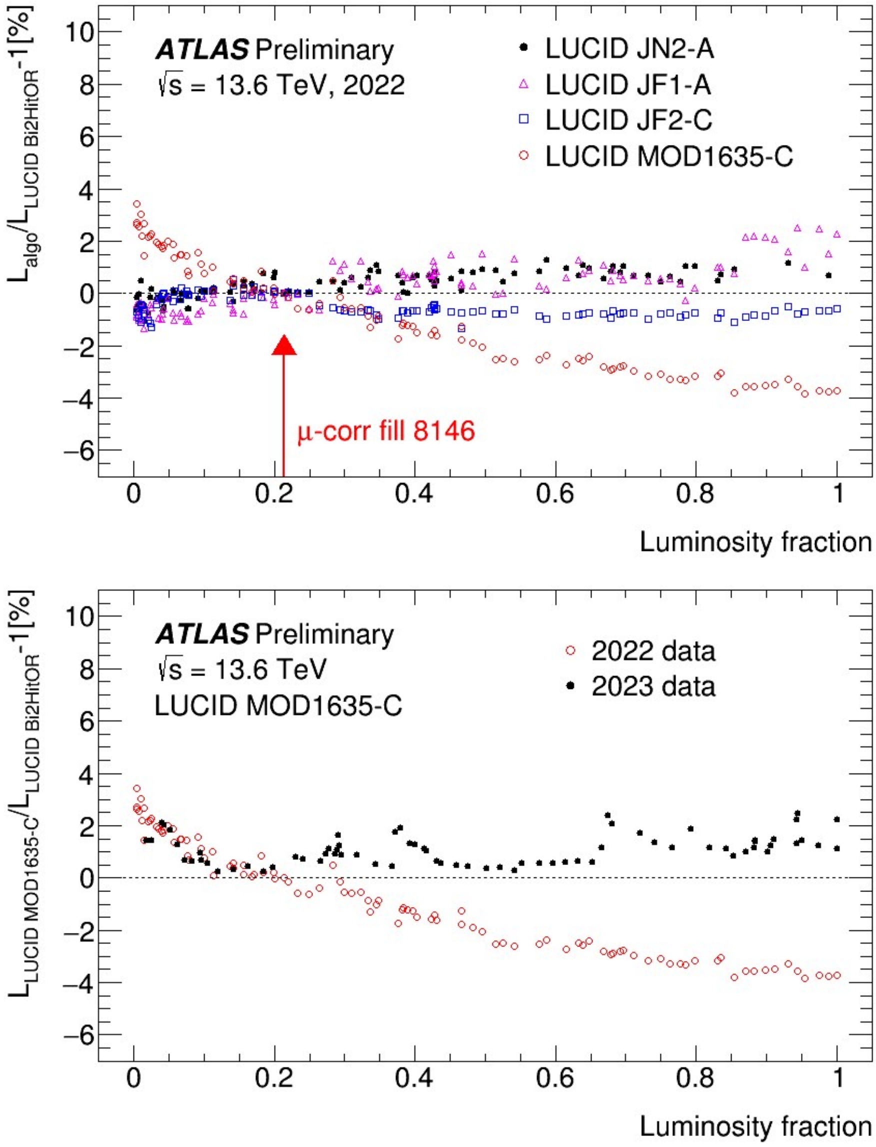

Figure 5. Long-term stability of the various prototypes with respect to LUCID-2 BI2HitOR. Top: prototypes stability in 2022 data taking. Bottom: stability of the only R1635 PMT in the LUCID-2 location (around the beam-pipe) in 2022 and 2023. See text for explanation. Reproduced from [7]. CC BY 4.0.

both effects (fluctuations and degradation) is identified in the HV increase the PMT experience after each Bismuth calibration (see section 2) and the consequent change of the transit time in the dynode chain. The R1635 have a signal duration which is $\sim$ 3 ns compared to the $\sim$ 6 ns of the R760. The sampling of the signals by the LUCROD board is performed at 320 Msps, which is insufficient for the R1635 signals and, moreover, very sensitive to the drift of the signal when the transit time varies. In figure 6 (left) the shape of the R1635 signal is shown as sampled by the LUCROD Flash ADC (FADC): the signal is contained in only two bins of 3.125 ns duration (the FADC sampling time) and moreover, a clear undershoot is visible after the signal. Being impossible for the moment to change the FADC with a faster one, a filter was inserted in the analog section of the board before the 2023 data taking,

2024 JINST 19 C03053

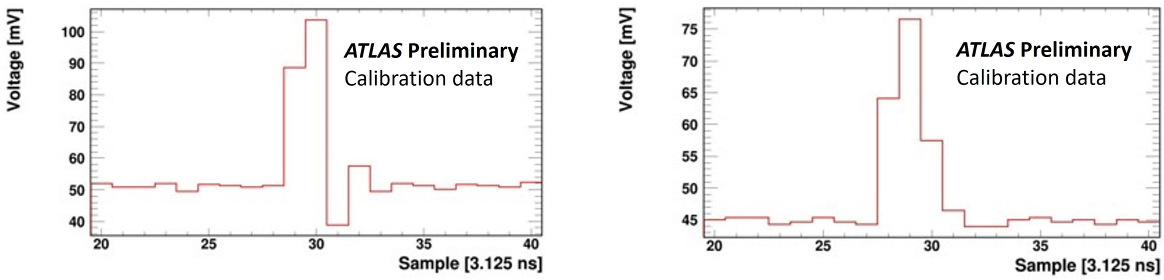

Figure 6. R1635 signal as sampled by the LUCROD FADC. Left: before the insertion of the filter. Right: after the insertion of the filter. Reproduced with permission from [3].

in order to widen the R1635 signal to a level comparable to the R760 one (see figure 6 right). The effect of this change can be observed in figure 5 (bottom), where the 2022 long-term stability (before the use of the filter) is compared to the 2023 one (after the filter was inserted). Larger fluctuations compared to LUCID-2 are still visible and need further investigations, but an overall better stability is reached in 2023. In the upgrade of the LUCROD board, new FADC with double frequency will be used in order to preserve the desirable feature of shorter signals (to prevent signal leakage from one bunch crossing to the next) while properly sampling the R1635 short signals.

4.2 Fiber prototypes

A complementary LUCID-3 fiber detector is foreseen in case the performance of the main detector will not be sufficient. The fiber detector running in Run-2 showed positive aspects regarding the linearity as a function of μ but also a large long-term degradation which was attributed to the absence of both the PMTs and fiber ageing monitoring. Two LUCID-3 prototypes have been installed featuring a new readout PMT (Hamamatsu R7459) with a large window able to host both the radioactive source and the fiber bundle which runs around the beam-pipe (see figure 3 right). This allows to reach the same PMT stability as for the main detector. In order to study the ageing of the fibers, an irradiation campaign with a γ source was performed at a dose corresponding to the first three years of HL-LHC, which showed up to 80% loss in the light transmission as a function of the absorbed radiation in the UV range, while less than 20% in the visible range. For this reason, one of the two prototypes was equipped with a UV filter in order to remove the most affected wavelength range, at the price of reducing the overall collected Cherenkov light. Moreover, an LED monitoring system was installed which injects simultaneously light of 5 different wavelengths, from UV to red, both into the PMT (prompt light) and to the end of the fiber (delayed light). The ratio of the two pulses is expected to indicate the fiber ageing. Calibration runs are taken in the inter-fills in order first to maintain the PMT gain stability (as for the main detector) and to collect the amplitude of the prompt and delayed LED signals, to be used to correct offline the luminosity measurements for the fiber ageing. The analysis of fiber detectors data has recently started.

5 Conclusions

LUCID-2 has been the main ATLAS luminometer in Run-2 and Run-3. In Run-2 a precision of 0.83% in the determination of the luminosity delivered by the LHC was achieved by the experiment. This excellent result will not be possible at the HL-LHC with the present LUCID detector. The LUCID-3 upgrade has been approved by ATLAS and includes a main detector, based on the LUCID-2 PMT

2024 JINST 19 C03053

technology, and a complementary fiber detector. For the PMT detector, the change of location and the use of smaller acceptance PMTs will allow it to avoid the saturation of the luminosity algorithms, as proven by the prototypes installed in Run-3. The low-occupancy PMTs show in addition a reduced, although non-zero, non-linearity. Two fiber prototypes were also installed featuring an innovative monitoring system aimed at both keeping the readout PMT gain constant, as done for the main detector, and at allowing to correct offline for the radiation induced ageing of the fibers. The results obtained in Run-3 suggest that the main detector will comply with the HL-LHC requirements, provided that an upgraded LUCROD board is designed with a larger FADC sampling frequency. Fiber detector data are being analysed to validate this technology as well.

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2024 JINST 19 C03053