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Upgrade of the LUCID detector for High Luminosity LHC(*)

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Summary. — LUCID-2 has been the ATLAS luminometer for the LHC Run-2 data taking (2015-1018), achieving very good performance (0.8% total uncertainty on luminosity) and a similar is expected for Run-3 (2022-2025). But, due to the harsher conditions, the present LUCID won't be able to operate in HL-LHC. Several proposals for a new detector were made. To test the proposed designs, several prototypes were installed in ATLAS and are under testing. One of these consists in quartz optic fibers that are used both as a Chereknov radiator and as a mean of transport for light. Fibers are read out by a PMT. The novelty of this detector is the double calibration system that is able to monitor both the ageing of the fiber and the PMT gain. In this contribution the first results obtained with the fiber prototype in LHC Run-3 are presented. The first results obtained by an irradiation session and a beam test to characterize the fibers are also discussed.

1. – Introduction

Luminosity($\mathcal{L}$) [1] is a fundamental parameter in any particle collider since it is related both with the cross section of any process, $\mathcal{L} = \frac{R}{\sigma}$ and with the collider performances, $\mathcal{L}_b = \frac{f_r\, n_1\, n_2}{2\pi\, \Sigma_x\, \Sigma_y}$, where R is the rate of the process and σ is its cross section, $\mathcal{L}_b$ is the luminosity of a colliding proton bunch pair, f_r is the revolution frequency, n_1 and n_2 are the number of protons in the two colliding bunches while Σ_x and Σ_y are the beams overlap transversal size. Thus, a precise luminosity measurement is crucial for every collider.

LUCID-2 [2], the main ATLAS [3] 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. 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) [2] where signals are amplified, digitized, discriminated and integrated. Different algorithms can be used to measure the luminosity with LUCID

(*) IFAE 2024 - "New Technologies" session (event/hit counting and particle counting), achieving a precision of 1% and a long term stability of about 0.1%. 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:

- saturation of the luminosity algorithms due to the higher number of interaction per bunch crossing (called also pileup or μ) from 60 to 200;
- higher radiation damage due to higher luminosity;
- impossibility to guarantee a precision of 1%.

For these reasons, a new LUCID is required.

2. – LUCID-3

The main requirements LUCID has to satisfy for the HL-LHC are:

- avoid saturation of luminosity algorithm even at $\mu = 200$;
- total uncertainty in offline luminosity less than 1%;
- precision of 2/3% in 2 s-long period;
- new electronics to cope with new ATLAS standard.

Two main designs are under study for the future: a PMT detector and a Fiber detector. The PMT detector should be characterized by a lower acceptance compared to LUCID-2. It will consists of 8 PMTs attached to the beampipe hole in the forward muon shielding on each side of the interaction point via a rail system that allows the extraction of PMT from the shielding during shutdowns. The Fiber detector, that will be used as a complementary detector to the PMT, consists of quartz fiber bundle placed inside beampipe hole in the forward muon shielding coupled with PMTs for the readout. The novelty of this design is the calibration system: ^{207} Bi to monitor PMT gain, LEDs to monitor fiber ageing due to radiation damage. The main advantage of this type of detector is that the charge read by PMT is proportional to $\mathcal{L}$.

To test the design of the future LUCID, three prototype (fig. 1) are currently under testing in ATLAS. The main PMT prototype installed for Run-3, called LUCID JF, consists of 4 PMTs per side, some of them being Hamamatsu R760 (LUCID-2 PMTs) and other being Hamamatsu R1635 (new smaller PMTs) attached to the shielding via a rail system similar to the one proposed for LUCID-3 PMT detector. An auxiliary PMT detector, called JN, consists of two Hamamatsu R760 PMTs placed behind the forward muon shielding. It is expected to run at low current, low occupancy and low radiation conditions and should be characterized by a much better linearity with respect to μ compared to LUCID-2 and the JF prototype. The drawback is that it will not be sensitive in the very low luminosity regime of special calibration runs (like Van der Meer scans).

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 monitoring system since it implements a double calibration system:

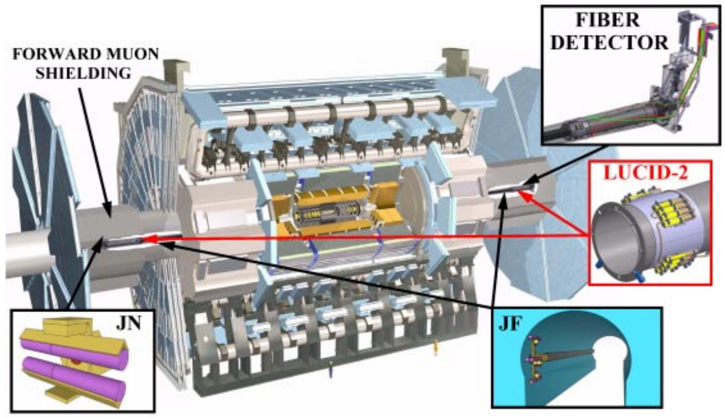

Fig. 1. – Design and placement of LUCID-2 and LUCID-3 prototype (JF, JN and Fiber) inside the ATLAS experiment [7].

- a ^{207}Bi source is deposited on PMT window to monitor gain like all LUCID-2 PMTs;
- 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 signals (fig. 2); the evolution in time of the ratio of the two signals 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

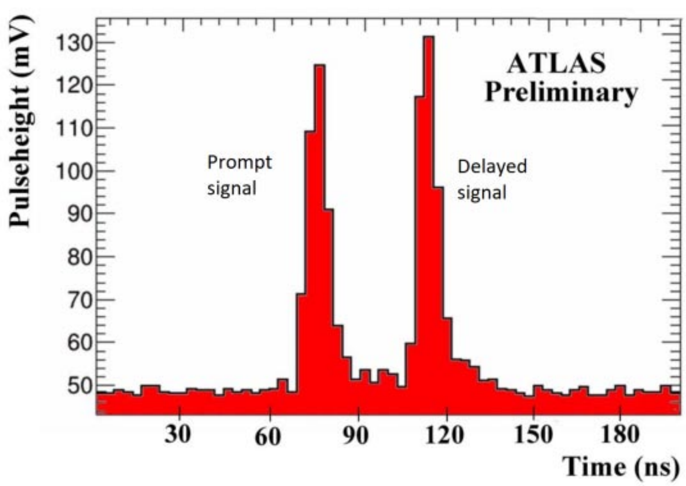

Fig. 2. – Example of a signal generated by an LED inside the PMT. LED light is divided in two part: the first one goes directly to the PMT (prompt signal) while the second one goes through the fiber (delayed signal) [8].

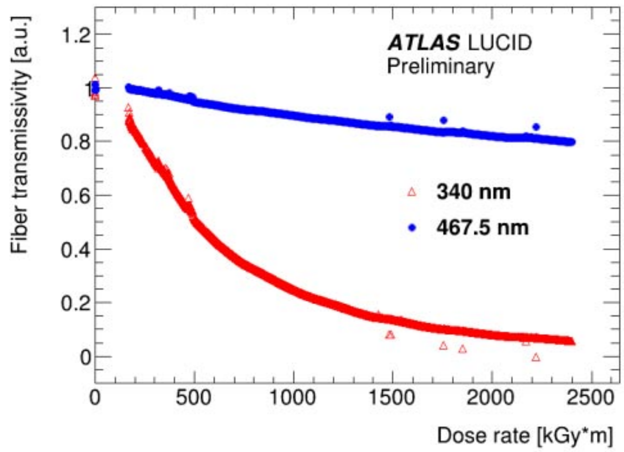

Fig. 3. – Fiber transmissivity loss at 340 nm (red) and at 467.5 nm (blue) as function of the absorbed dose [9].

that the fiber transmissivity loss is much faster in UV region than in visible region (fig. 3). 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. The data collected by the fiber calibration system, the simulation of the particle flux through the fiber, the fiber degradation as function of the dose and the dependence of the signal generated inside the fiber by a particle as function of incident particle direction will be used to correct offline the luminosity measured by the fiber detector.

3. – Characterization of the fiber prototype

Among the different behaviours of the fibers to be characterized, the first one is the linearity of the measurement with respect to μ. The ratio μ_{fiber}/μ_{tracks} as function of μ_{tracks}, where μ_{fiber} is the luminosity measured with each Fiber detector and μ_{tracks} is the luminosity measured with track counting [6], is fitted with a linear function to extract the slope and the intercept. To evaluate the eventual filling scheme dependence, the fit is performed separately over the isolated bunches (colliding bunches that does not have any colliding bunches before or after) and for every train (series of consecutive colliding bunches) position (1^{st}, 2^{nd}, 3^{rd}, ...). The fiber with the UV filter showed a linearity 4 to 5 times better than LUCID-2. The fiber without the UV filter showed a linearity slightly worst than the one with.

To evaluate the stability over the long period, the luminosity measured by fibers over the one measured by LUCID is calculated as a function of the luminosity fraction (fig. 4). The fiber without the UV filter (black dots) shows a drift of 20% over the full year while the fiber with the UV filter shows only a sawtooth shape of 5%, due to a non-sensitive enough PMT High Voltage to keep the PMT gain stable. A beam test was performed to study the dependence of the light collected by the readout PMT as function of the incident particle direction. Moreover, by hitting the fiber in different position, the results obtained during the irradiation session (fig. 5) with Cherenkov light can be validated. In order to change the angle between the fiber and the beam, a rotating support was

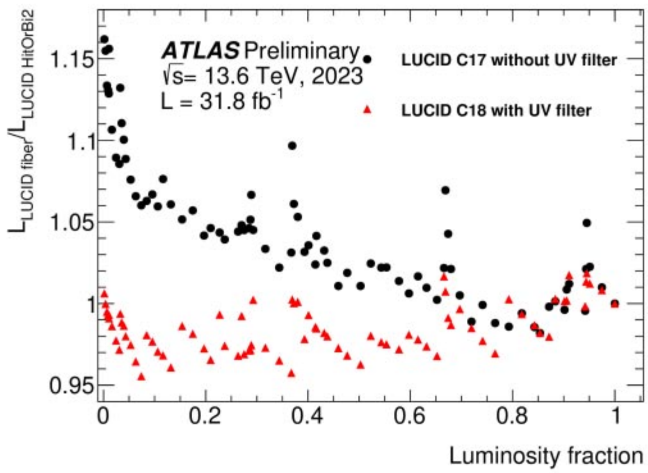

Fig. 4. – Fill by fill ratio of luminosity measured by the both fiber prototypes (without UV filter black dots, with UV filter red triangles [10]).

specifically designed. For this beam test, a beam of 200 MeV (10 pC) was used. In fig. 5, the signal amplitude as a function of the angle between the beam and the fiber, and of the time (acquisition starts after a trigger synchronized with the beam) is reported. The main signal is in the region [20°,80°] and [50, 90] ns. This main signal gets reflected on PMT window, travels thought all the fiber and gets reflected back by the LEDs that were used to monitor fiber degradation during the beam test. This double reflection generates signals in the region [35°,60°] and [120, 140] ns. For negative angles, Cherenkov light goes to the LEDs and gets reflected generating signals in the region [100, 130] ns. The arc shape of this signal is due to the internal reflections inside the fiber.

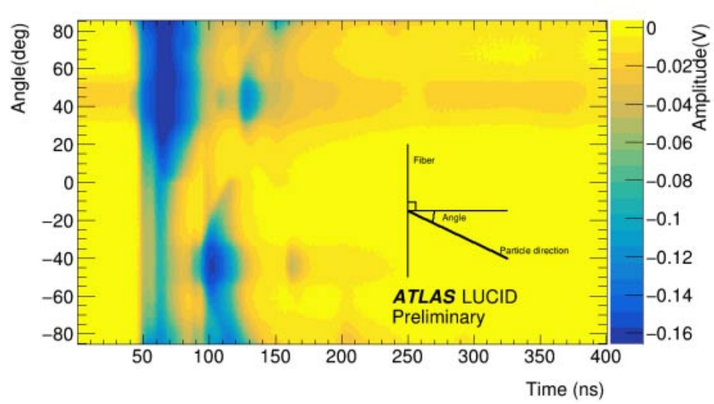

Fig. 5. – Signal generated inside the fiber by a beam of 200 MeV electrons as function of the beam direction [9]

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An offline correction to recover the light loss due to radiation damage is still under study: the final goal is to use a simulation of the ATLAS detector to estimate the particle flux through the fiber. These particles will generate a signal inside the fiber similar to the one obtained during the beam test (fig. 5). This light is then propagated inside the fiber and absorbed due to radiation damage following fig. 3. Combining these information with the online monitoring of fiber degradation, luminosity can be corrected offline.

4. – Conclusions

LUCID-2 showed very good performance in Run-2 reaching a total uncertainty on luminosity of 0.8%. Similar performances are expected also for Run-3 but it won't be able to operate during HL-LHC due to the saturation of luminosity algorithm and higher radiation damage. Several proposals for the design of the new LUCID were made. To test these proposals, prototype detectors were installed before the start of LHC Run-3 and are currently under testing. One of this prototypes is a Fiber detector. It consists of 2 bundles of quartz fibers coupled with PMTs for readout. One of the bundles is also equipped with an UV filter to cut out the UV component of the Cherenkov spectrum. The novelty of this detector is the calibration system: ^{207}Bi to monitor PMT gain and an LED system to monitor fiber degradation. One of the main aspects to characterize is the linearity response with respect to μ. The best results were obtained by the prototype with the UV filter which showed a linearity 4 to 5 times better than the one of LUCID-2. From the point of view of stability, prototype with UV filter showed the best performance since it is characterized by fluctuations of a couple of percent while the one without the UV is characterized by a drift of 15%. A beam test was also performed to study the production of Cherenkov light inside the fiber as function of incident particle direction. The results from this beam test will be combined with a simulation of the ATLAS detector to evaluate particle flux through the fibers, the transmissivity loss as function of the dose and the online monitoring of the fiber degradation to correct offline luminosity.

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