PROCEEDINGS OF SCIENCE

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

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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 some precision measurements, including the Higgs sector. To fulfil such requirement in an environment characterized by up to 140 simultaneous interactions per bunch crossing (200 in the ultimate scenario), ATLAS will feature several luminosity detectors. At least some of them must be possible to calibrate in the van der Meer scans at low luminosity and be able to measure luminosity up to its highest values. LUCID-3 is the upgraded detector of the present main ATLAS luminometer (LUCID-2) and should fulfil such a condition. Two main detector options are under study. The first one is based on photomultipliers located at a larger distance from the beamline compared with LUCID-2 and with a smaller active area. This will reduce the acceptance of the detector and avoid the saturation of the luminosity algorithms. The second option is based on optical fibers acting as both Cherenkov radiators and light-guides to route the produced light to the readout photomultipliers. Both detectors will have photomultipliers monitored continuously with Bi-207 radioactive sources deposited on the photomultiplier window. The second detector will also use LED light injected simultaneously to the PMT and at the end of the fibers in order to monitor a possible ageing of the fibers due to radiation. Several new prototype detectors that have been installed in ATLAS are discussed, together with the first results obtained in LHC Run-3.

*41st International Conference on High Energy physics - ICHEP2022*
*6-13 July, 2022*
*Bologna, Italy*

*Speaker





PoS(ICHEP2022)669

## 1. Introduction

An accurate measurement of the luminosity is an essential part of the ATLAS physics program, both for Standard Model cross-section measurements, but also in searches for new physics when background and search sensitivity is estimated. The ATLAS physics program at the High Luminosity LHC (HL-LHC) calls for a precision in the luminosity measurement of ±1% and this is a very challenging requirement since the average number of $pp$ interactions every bunch crossing ($\mu$) is expected to increase to 140 in a first stage and to 200 in an ultimate scenario.

The ATLAS experiment is determining luminosity by measuring the rate of inelastic interactions. This rate is calibrated by so-called beam separation scans, also known as van der Meer (VDM) scans, in which the rate is measured as the two LHC beams are moved apart. This measurement determines the convolved beam sizes in the vertical and horizontal directions, and together with the precise knowledge of the beam current a luminosity calibration can be determined. The LUCID detector can measure luminosity for individual pairs of colliding bunches and this is particularly important in the beam separation scans where the $\mu$ value is at most around one and the detector needs a high acceptance in order to provide small statistical errors in the tails of the scans.

The detector can also provide luminosity measurements both offline in periods of 60s and online in periods of only 2s and in the latter case acceptance can also become an issue at high $\mu$ running and measurements with single colliding bunch-pairs. For the final offline luminosity measurement, where the data is combined from all colliding bunch pairs, the statistical error is almost always negligible and so the main question in this type of luminosity analysis is what systematic accuracy can be achieved.

The main future challenge when doing luminosity measurements with the present LUCID is that the acceptance of the detector is too large and at the HL-LHC it is predicted that most online 2s periods, and many of the offline 60s periods, will have hits in all bunch-crossings. This phenomenon is called hit-saturation.

## 2. The LUCID-2 detector

The LUCID-2 detector was the main luminosity detector in ATLAS during the LHC Run-2 and will be that also in the present Run-3. This detector consists of 16+16 small Hamamatsu R760 photomultipliers that are located 17m away from the interaction point at a distance of 125mm from the proton beams and on both side of the experiment [1]. Figure 1 shows the location of the LUCID detectors in ATLAS.

The detector is not very complicated since it mainly consists of commercially available photomultipliers (PMTs). However, the windows of the photomultipliers have to be made of quartz (pure $SiO_2$) in order to survive the high radiation dose they are exposed to close to the beamline. These 1.2mm thick quartz windows act as Cherenkov radiators and produce photons that in turn produce electrons in the cathode and these electrons are multiplied in the dynode chain which results in a fast signal.

It is well known that a problem with photomultipliers is that the gain goes down with time if they are used extensively. Attempts have been made to monitor and correct for these changes of the gain with both LED signals and with radioactive Bi-207 sources. It turned out that the latter method, with a Bi-207 source deposited on the PMT surface, was the superior method. The Bi-207 source produces a constant emission of internal conversion electrons above the quartz Cherenkov threshold and the resulting Cherenkov light is very similar to that produced by high energy particles. Data is recorded of the mean amplitude of the signals from the source in measurements between the LHC fills and the high voltage is then adjusted so that the amplitude and the gain is kept constant during a year of data-taking. The rate of Cherenkov photons from the source is kept so low that it does not produce a significant background in beam separation scans where background could otherwise be an issue. The 31.6 years half-life of the sources is not a concern since one is measuring the average amplitude and not the rate of signals.

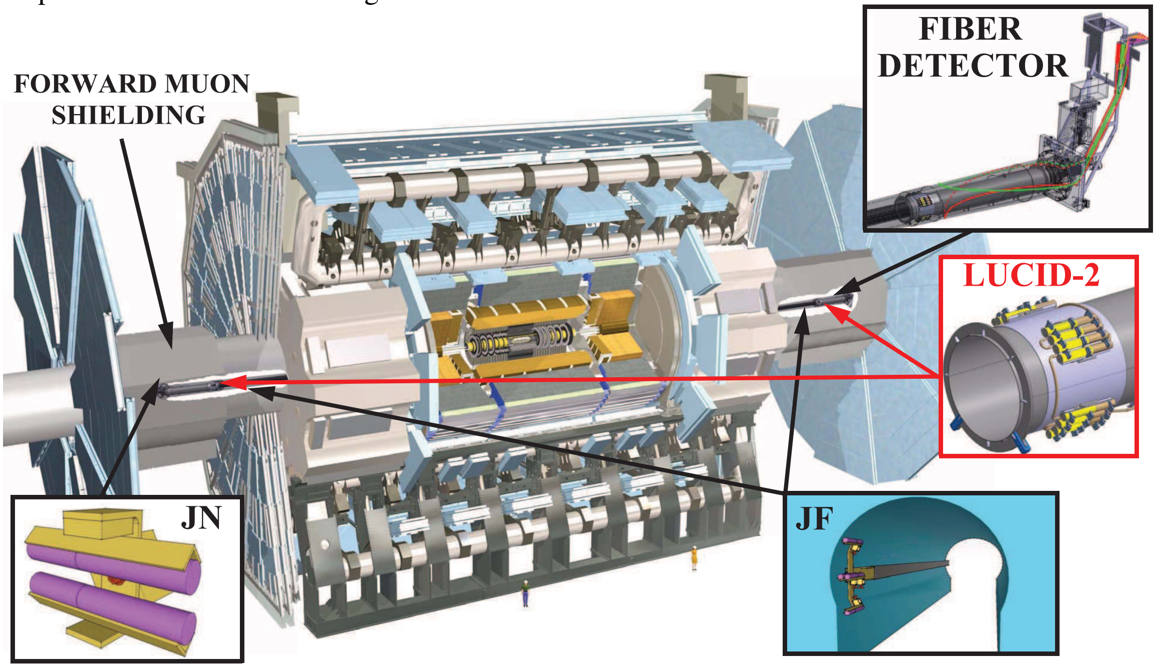


**Figure 1:** The location of the LUCID-2 detectors and the LUCID-3 prototype detectors in ATLAS [2].

## 3. The LUCID-3 detector

LUCID-3 [3] is an upgrade project in the ATLAS experiment for the HL-LHC since the present LUCID-2 detector will not work at the HL-LHC due to hit-saturation. Additional challenges for LUCID at the HL-LHC will be the high radiation levels which requires the possibility to change photomultipliers every year and new LHC vacuum equipment which will be installed close to the location of the present LUCID-2 detector.

### 3.1 A LUCID-3 detector attached to the beampipe

The LUCID-2 detector uses Hamamatsu R760 PMTs with a 10 mm diameter cathode since they were the smallest available PMTs with a flat quartz window. In order to lower the acceptance the Hamamatsu company has provided ATLAS with specially made R760 PMTs that have a thin ring of aluminium with a 7mm diameter hole between the window and the cathode. These so-called modified PMTs have been tested in the previous LHC run. Unfortunately they suffer from large non-linearity when small signals that are below the threshold pile-up from different pp-collisions.

Hamamatsu has now provided ATLAS also with R1635 PMTs specially made with a radiation hard quartz window. These PMTs have an 8mm diameter cathode and a thinner quartz window.

One of these PMTs have been operational in LUCID-2 during 2022. The hit frequency at low luminosity for this smaller PMT is 48% smaller than for the standard R760 PMT and similar to that of the modified PMTs. Studies of the non-linearity have shown that those are much smaller than for the modified PMTs and slightly smaller than for the standard R760 PMTs. The R1635 PMT also produces pulses with shorter duration which is an advantage when the signals from different bunch crossings has to be measured since those are only separated by 25ns. However, this makes a good digitization of the pulse shape difficult with the present electronics since the FADCs used has not enough resolution and the electronics will probably need an upgrade.

An important and tested principle for LUCID-2 is that it is not necessary to measure the rate of particles coming from the primary interactions. Particles from secondary interactions, for example electrons created in the beamipe, work as well in the measurement of luminosity with LUCID-2. A new location behind some of the forward muon shielding with standard R760 PMTs is therefore being tried out as an alternative to smaller PMTs around the beampipe. The hit frequency at low luminosity for this low-rate so-called JN detector has been measured to be 93%-98% smaller than for the standard R760 PMT in LUCID-2 and close to those predicted by simulations. The non-linearity due to pile-up is almost non-existent. The rate is, however, probably too small for VDM calibrations of individual bunch crossings. A detector that uses

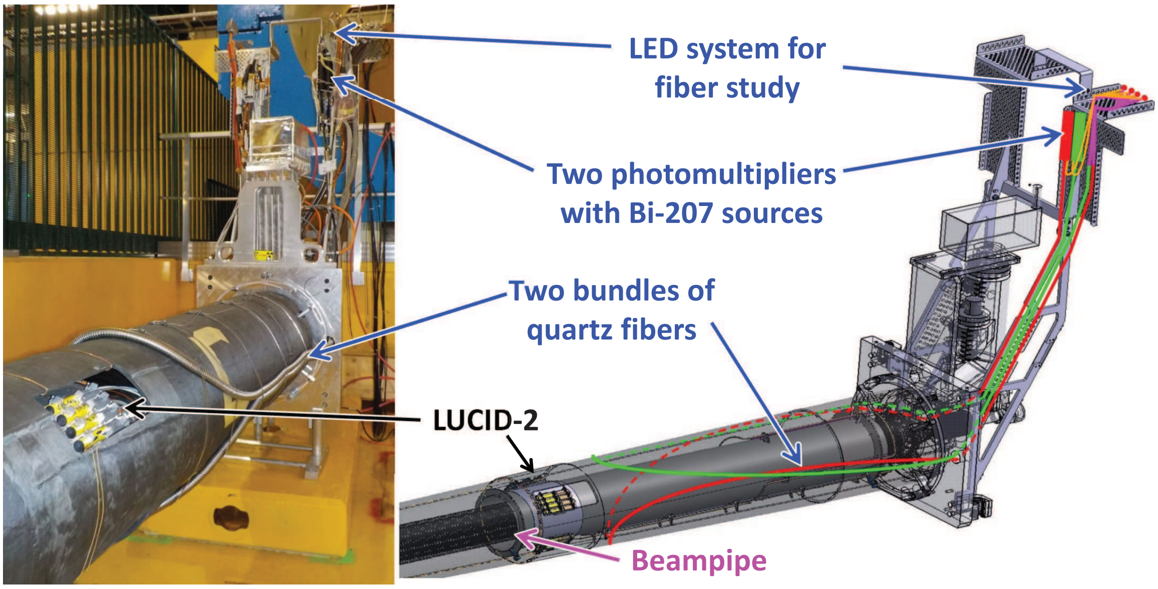


**Figure 2:** The LUCID-3 fiber prototype detector. The photo on the left shows the detector before installation in ATLAS and the drawing on the right shows the location of the different parts [2].

quartz fibers as Cherenkov medium that are attached to photomultipliers in a shielded location has been tried by ATLAS in the previous LHC run. A fiber detector creates many small signals and hit counting gives so large non-linearity that the luminosity measurement becomes useless. The signals from the detector are therefore integrated and the sum of all integrated pulses during a 60s long time period is used to estimate the luminosity (so-called "charge counting"). The disadvantage with this method is that the result is more sensitive to PMT gain variations. The gain monitoring of the PMTs in this detector was done by injecting LED signals via fibers to the photomultipliers during special charge measurements that were carried out between LHC fills and this system did not manage to provide the required stability in the luminosity measurements. A new fiber detector with two channels has now been built and installed in ATLAS (see Figure 2). It uses Bi-207 sources to monitor the gain of the photomultipliers. LEDs with 6 different wavelengths can inject signals simultaneously, both at the end of the fibers, and directly into the PMTs to monitor any degradation of the fiber bundles. The optical fibers are 6.2m long and has a silica core with a 600$\mu$m diameter and a fluorine-doped silicia cladding. One of the two bundles contains 46 fibers and the other 54 fibers. The latter bundle has an optical filter that removes UV light between it and the PMT since radiation tests have shown that the degradation that gamma radiation causes affects mostly the UV light. The idea is to measure the LED signals going both directly to the PMT and via the fibers and from this estimate the degradation of the fibers. While the PMT gain will be kept constant by increasing the high voltage, the degradation of the fibers will be corrected for offline with the help of the measured ratio of the amplitude of the prompt and delayed signals (see Figure 3).

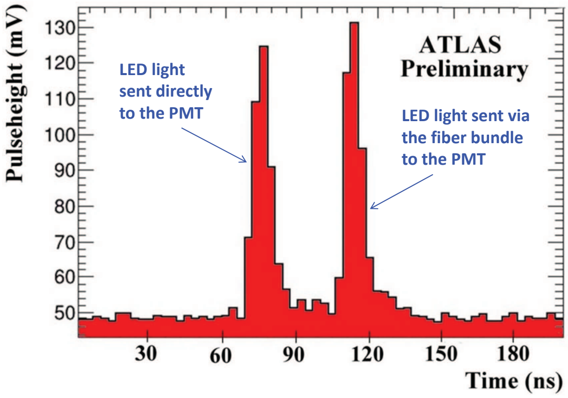


**Figure 3:** Pulseshape measurments of the LED light going directly to the PMT and via the fiberbundle [2].

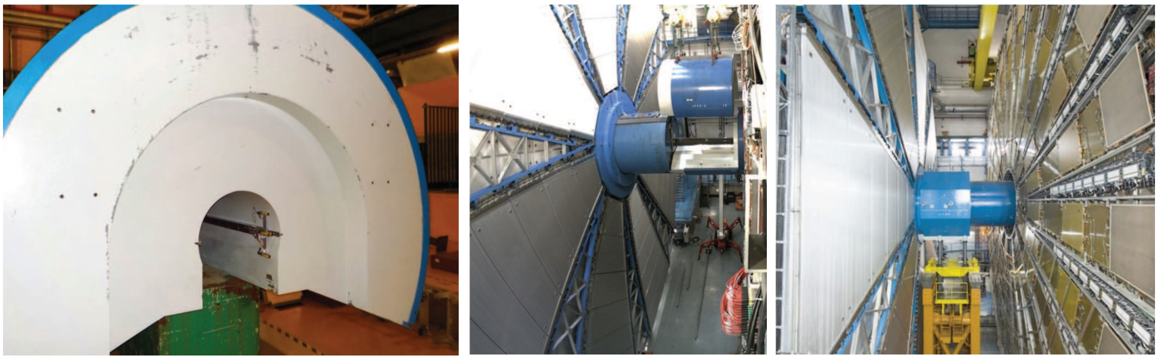

**Figure 4:** The LUCID-3 JF prototype detector attached to the shielding. The left photo shows the hole in the shielding for the beampipe and 4 PMTs attached in it. The middle photo shows the installation of the shielding piece with the detector in ATLAS. The righthand photo shows the situation after all the forward muon shielding is installed [2].

### 3.2 A LUCID-3 detector attached to the forward muon shielding

The baseline proposal for a LUCID-3 detector is now one with PMTs attached to the centre hole in the forward muon shielding instead of to the beampipe. This proposed so-called JF detector is one meter closer to the IP and the distance to the beamline can be increase from 126mm to 291mm. The aim with this is to lower the acceptance to avoid hit-saturation and make the photomultipliers easily accessible so that they can be replaced in every winter shutdown. Figure 4 shows a photo of one of the new JF prototype detectors and different phases of the installation of the shielding.

One of the JF detectors uses four R760 PMTs and the other one consists of one R1635 and one R760 PMT. Measurements shows that the acceptance of the R760 PMTs in the JF detector is 25% smaller than for the R760 PMTs in the LUCID-2 detector and the R1635 PMT in the JF detector has a 65% smaller acceptance. From these measurements it is possible to estimate the statistical errors under the assumption of binomal statistics and the result is shown in Figure 5 as a function of $\mu$. The calculation is done for the small $\mu$-range and 30s long measurements used in van der Meer calibrations and the much higher $\mu$-range and 60s long measurements used for physics runs. The error is estimated for an individual pair of bunch crossings. The statistical error is, however, not an issue in a typical combined luminosity measurement of more than 2000 colliding bunch pairs. The conclusion from the plot is that a new LUCID-3 detector consisting of eight R760 PMTs can measure the luminosity with an error smaller than 1% error up to a $\mu$ of 175. A single R1635 PMT has no problem with measuring the luminosity with an error smaller than 1% error to a $\mu$ above 200. It has been proven that a single R760 PMT in LUCID-2 has enough hits in 30s VDM measurements at very low $\mu$ to adequately measure the luminosity for single bunch pairs but this will not be the case with a single R1635 PMT in LUCID-3. Figure 5 shows that at least four R1635 PMTs will be needed for VDM calibrations of the LUCID-3 detector.

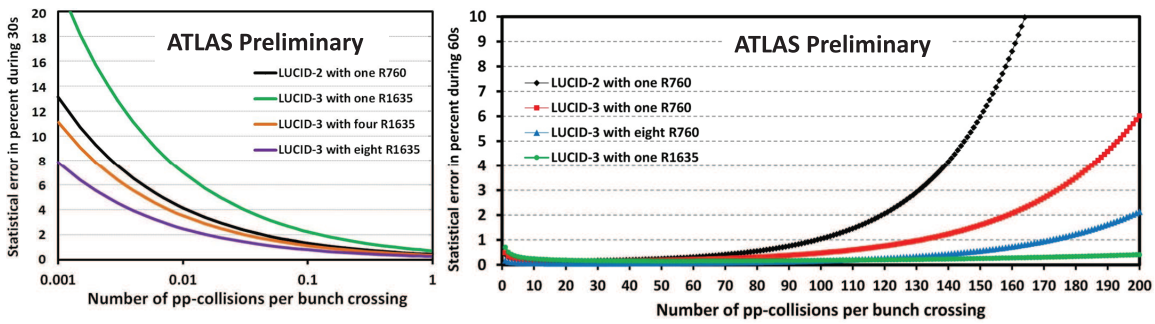


**Figure 5:** The binomial statistical errors for different LUCID detectors and for single bunch crossings. The left plot shows the $\mu$-range used in VDM calibrations and the right plot the $\mu$-range used for physics analysis [2].

## 4. Conclusions

The present LUCID-2 detector was not designed to cope with the hit-saturation that is predicted for the HL-LHC. The collaboration has therefore come up with several strategies to overcome this problem and reduce the acceptance of the detector. Different prototypes have been built and are now under evaluation. The most promising detector is one that uses new small R1635 PMTs that are attached to the forward shielding instead of to the beampipe.

## References

[1] *"The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS"*, G. Avoni et al 2018 JINST 13 P07017.

[2] *"Photos and drawings of the LUCID-3 detector"*, https://lucid3.web.cern.ch/

[3] *"The LUCID 3 detector for the ATLAS Phase-II Upgrade"*, Initial design report, CERN-LHCC-2021-016.