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Luminosity monitoring in ATLAS with MPX detectors

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ABSTRACT: The ATLAS-MPX detectors are based on the Medipix2 silicon devices designed by CERN for the detection of multiple types of radiation. Sixteen such detectors were successfully operated in the ATLAS detector at the LHC and collected data independently of the ATLAS data-recording chain from 2008 to 2013. Each ATLAS-MPX detector provides separate measurements of the bunch-integrated LHC luminosity. An internal consistency for luminosity monitoring of about 2% was demonstrated. In addition, the MPX devices close to the beam are sensitive enough to provide relative-luminosity measurements during van der Meer calibration scans, in a low-luminosity regime that lies below the sensitivity of the ATLAS calorimeter-based bunch-integrating luminometers. Preliminary results from these luminosity studies are presented for 2012 data taken at $\sqrt{s} = 8$ TeV proton-proton collisions.

KEYWORDS: Performance of High Energy Physics Detectors; Particle tracking detectors; Accelerator Applications

[1] On behalf of the ATLAS and Medipix-2 collaborations.

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Contents

1 Introduction

Pixel detectors have a widespread use in various research fields and applications such as particle and nuclear physics, as well as medical and industrial imaging. A Medipix2 (MPX) chip developed at CERN in the framework of the Medipix2 Collaboration [1] is an example of such a device. The data of the MPX devices is recorded in frames which contain the status of all the 65,536 pixels after a given exposure time of the order of 1 s to 100 s. The dead time after each frame is about 6 s for data readout. The MPX devices can effectively be used for continuous measurements of the composition of complex radiation fields [2]. A network of MPX devices was installed within the ATLAS experiment [3] at CERN. It was primarily designed to provide real-time measurements of the composition (photons, neutrons and charged particles) and of the spectral characteristics of the radiation environment inside the ATLAS detector. The large dynamic range of the MPX devices allows the measurement of the natural radiation background, and of the induced activity during and after collision periods. The devices record the decay of radioactive nuclei generated in ATLAS during LHC collisions. This measurement of the LHC-generated radiation field composition permits the validation of radiation simulation studies. Recently, descriptions and results from 2008-2011 MPX radiation field measurements have been released [4].

The use of the MPX network for relative-luminosity measurements in proton-proton collisions has been studied in detail and the results are summarized in this report. Sixteen devices placed in the ATLAS detector are read out independently. Out of these, two had high noise and one was located in the data-acquisition room, so only thirteen are used in this analysis. Table 1 lists the location and number of registered events (clusters) per sensor area and per unit integrated luminosity of these thirteen MPX devices.

The luminosity monitoring is based on the measurement of the integrated rate of particles interacting with the 300 μm thick silicon-sensor (hit rate measurement in the so-called counting mode [4]). The hit rates per frame are converted into luminosity using a normalization factor

Table 1. MPX device locations with respect to the interaction point. Z is the longitudinal distance from the interaction point and R is the distance from the beam axis. The number of measured MPX clusters per sensor area and per unit integrated luminosity is given. Only devices with low cluster rates are used for the neutron counting analysis as indicated. The devices are grouped according to their ordering in figure 3 as indicated by the horizontal lines.

Device	Z [m]	R [m]	Measured MPX clusters per sensor area and per unit luminosity $[\mathrm{cm}^{-2}/\mathrm{nb}^{-1}]$	Used for neutron counting
MPX01	3.42	0.77	55000	No
MPX13	−3.42	2.44	380	No
MPX02	3.42	2.50	230	No
MPX03	2.94	3.57	31	No
MPX06	7.20	3.36	20	Yes
MPX05	7.20	2.36	47	No
MPX08	4.02	4.40	1.2	Yes
MPX07	0.35	4.59	0.45	Yes
MPX04	7.12	1.30	110	No
MPX09	15.39	1.56	5.8	Yes
MPX12	7.23	6.25	3.9	Yes
MPX10	22.88	5.19	1.0	Yes
MPX11	4.86	16.69	0.30	Yes

for each MPX device. The integrated hit rate corresponds to the integrated luminosity reported by the reference ATLAS luminosity algorithm (BCMV_EventOR algorithm [5] using the Beam Conditions Monitor, BCM [6]), during an ATLAS run chosen as a reference (LHC fill 2649, 21 May 2012). The MPX devices operated reliably starting from 2008 even in places where the radiation level was high. The advantage of the devices is that they have 65,536 independent channels (pixels). Figure 1 shows an example of the hit luminosity measured with MPX01 and the ratio of the MPX luminosity with respect to the ATLAS BCM reference luminosity. The relative linearity of the MPX and BCM luminosity measurements is illustrated by figure 2. In a run selected for covering a particularly wide span of bunch-luminosity values, the residual of a linear fit displays no systematic non-linearities down to the sub-percent level, for a bunch-averaged pile-up parameter $\langle\mu\rangle$ varying from 8 to 26 inelastic interactions per bunch crossing. The purpose of the plot is to show that there is a linear relationship between the BCM and MPX luminosities. Since the luminosity range is limited, it is possible that the linearity is not perfect when extrapolating to zero luminosity.

In addition to the counting mode, devices with low cluster rates (MPX06 to MPX12) can also be operated in the so-called tracking mode [4], which allows recognition and categorization of different types of radiation by their characteristic track signature (cluster shape). This mode is used for luminosity measurements by counting thermal neutrons.

In the process of performing the luminosity determination with MPX devices, the activation of the ATLAS detector material has been investigated and found to have a negligible effect.

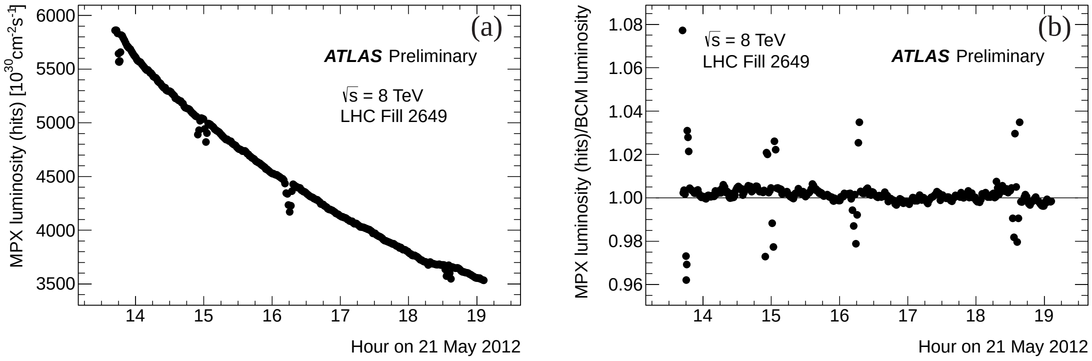

Figure 1. Time history of (a) the MPX luminosity and (b) the MPX/BCM luminosity ratio. The small luminosity dips apparent in (a), and the associated outliers in (b), correspond to times when the LHC operators perform small-amplitude beam-separation scans to optimize the luminosity. During these brief intervals, the luminosity varies more rapidly than can be sampled by the online luminosity and MPX data-taking infrastructure, resulting in unphysical variations of the apparent MPX/BCM luminosity ratio.

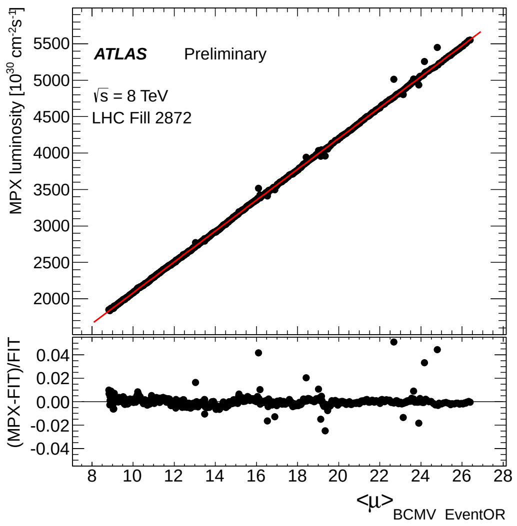

Figure 2. MPX01 hit luminosity vs. bunch-averaged number $\langle \mu \rangle$ of inelastic interactions per crossing reported by the reference ATLAS luminosity algorithm (BCMV_EventOR). This LHC fill was chosen because the data span a particularly wide range of $\langle \mu \rangle$ values. The residual of a linear fit to the data is shown in the bottom frame. The outliers correspond to times when the LHC operators performed small amplitude beam-separation scans to optimize collisions, during which the luminosity varies more rapidly than can be reliably sampled by the online luminosity and MPX data-taking infrastructure.

2 MPX luminosity from hit counting

An advantage of the MPX network for luminosity measurements is that there are multiple independent devices at different locations installed in the ATLAS detector and in the cavern. This allows comparative studies to cross-check independent hit luminosity measurements by the thirteen MPX devices which have been used for this analysis.

In order to ensure that the results do not depend on the analysis method used, three independent analyses have been performed and the results are compared. The MPX luminosity data are saved

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in a different time window (acquisition frame time) than the ATLAS luminosity. The basic time unit for storing ATLAS luminosity for physics use is the Luminosity Block (LB), which is typically one minute long. The three methods differ in the procedure and criteria for noisy pixel removal (a potential source of systematic uncertainty in hit-counting mode), and for scaling the raw hit counts from the exposure window of each MPX device to the duration of the matching ATLAS LB. The three methods are described as follows.

- Method 1: A noisy pixel is defined as having a counting rate that differs from the mean rate by more than five standard deviations. If a pixel is found to be noisy in a 24 hour reference period (chosen as the day in 2012 that had the largest number of noisy pixels) it is removed from the entire 2012 data-taking period. A linear interpolation is made between the rates in different frames. The value at the middle of a LB obtained from this interpolation is used.

- Method 2: Noisy pixel removal is done frame by frame, i.e. in each frame a different set of noisy pixels is removed. Noisy pixels are defined by having a count rate that differs from the mean by more than a luminosity-dependent threshold. The MPX luminosity from frames falling within a LB is used without an interpolation. A correction is made for the relative duration of the MPX frames and of the LB.

- Method 3: Noisy pixel removal is done frame by frame. The counts of 15 frames (the frame under investigation and 7 frames before and after) are summed and a pixel is removed if the sum of these counts is above a threshold. An interpolation of the frame hit rate at the time of each LB is done as in method 1.

In MPX01, all three methods show a significant increase of the number of noisy pixels with time. As this sensor sustains the largest particle flux of the analysed devices, this observation could be an indication of radiation damage. This might result from defects in either the silicon or the readout chip. Using method 1 (method 2), the number of noisy pixels in MPX01 increases from less than 10 (300) in April 2012 to about 300 (1800) at the end of November 2012.

The luminosities determined by the three methods were compared in short (frame-by-frame) and long (7 months) time periods. Depending on the MPX device considered, the frame-by-frame agreement varies from a few percent to less than 0.1% (for MPX01). For the long-term comparison, the MPX hit luminosities from the three methods were studied with respect to the BCM reference luminosity. About the same variations of the MPX/BCM luminosity ratio as a function of time were observed with the different methods.

In order to study the relative long-term stability of the luminosity measurements, the ratio of the MPX luminosity to the ATLAS reference luminosity, from May to November 2012, is shown in figure 3 with a binning in 14 time periods. For this analysis we have taken method 1 as a baseline for hit counting.

The ratios measured by different MPX devices are divided in three groups. The devices shown in figure 3a display an increase of about 2% over the 2012 running period, while the ratios in figures 3b and 3c show an increase of 1% or less over the same period. The three groups of devices are listed in table 1 together with their cluster rates and although there is some indication that high rate devices show an increase while low rate devices do not, the picture is not conclusive. The slightly different time dependence of the results from the different MPX devices is not understood

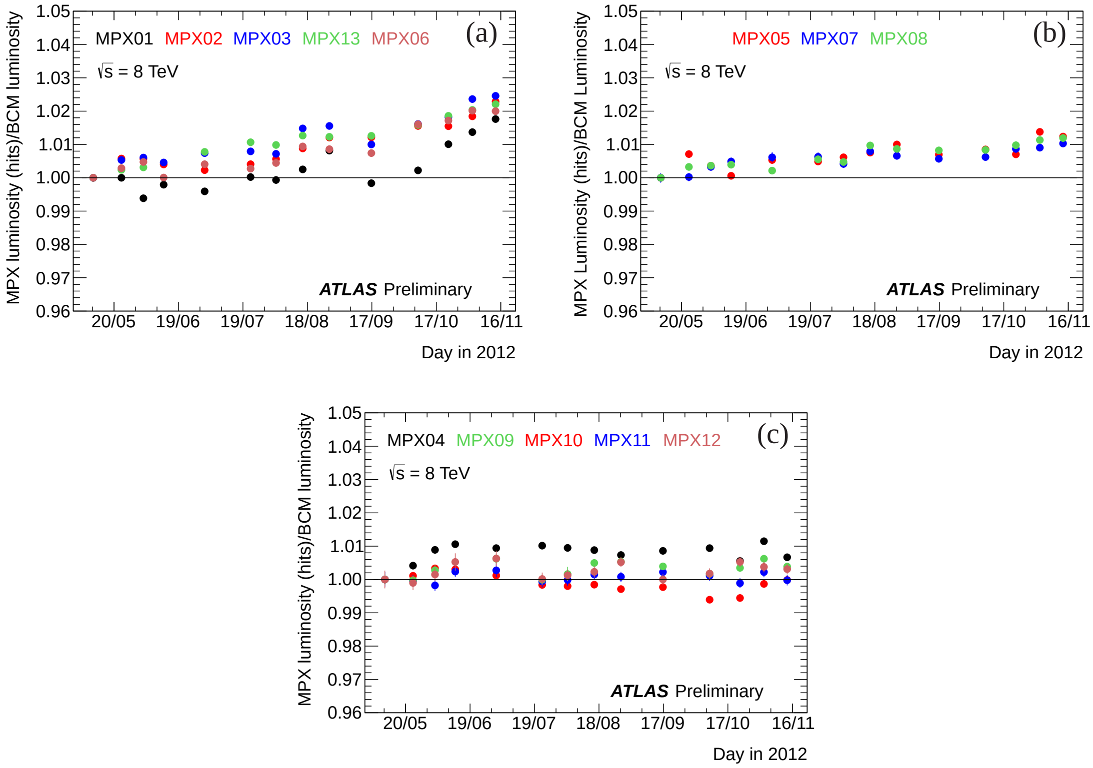

Figure 3. Fractional deviation of the luminosity reported by different MPX devices from the ATLAS reference luminosity (BCM) as a function of time in 2012. The ratio is shown for 14 time periods. For each device the time periods are chosen to have the same number of frames. The statistical uncertainties are comparable to or smaller than the size of the markers. The data are scaled such that the value of the first bin is unity.

at present and the conclusion is therefore that the long-term internal consistency of the MPX system is at the 2% level.

3 MPX luminosity from thermal neutron counting

Thermal neutrons are detected by MPX devices via $^{6}\mathrm{Li}(\mathrm{n},\alpha)^{3}\mathrm{H}$ reactions in a ^{6}LiF converter layer [4]. In the MPX tracking mode tritons and alpha particles are registered as so-called heavy blobs (large round-shaped pixel clusters). The number of heavy blobs below a ^{6}LiF converter is used to calculate the thermal neutron fluence using a detection efficiency obtained for each MPX device in a standardized isotropic thermal neutron field. The typical detection efficiency of thermal neutrons is 1% [4].

The chosen acquisition times allow the measurement of the thermal neutron counts for MPX06 to MPX12 as for these devices the total cluster occupancy per frame has a correctable overlap, i.e., at most a few hundred clusters per frame. A dedicated study was performed to determine the misidentification of heavy blobs which are lost due to the overlap with other clusters [4]. The resulting correction factors, which are specific to each MPX device, depend on the number of clusters per frame (i.e. on the luminosity and on the device location); they vary between one and

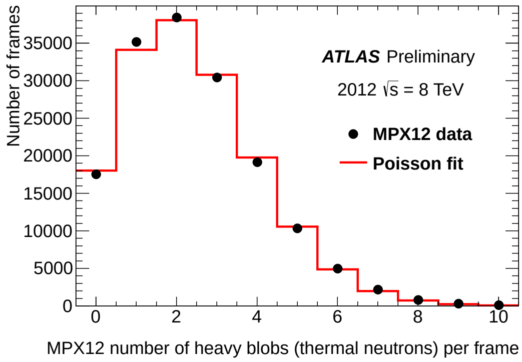

Figure 4. Distribution of the number of heavy blobs per frame, recorded with MPX12 below a ^{6}LiF converter, during LHC collision periods in 2012. The line shows a histogram with a fitted Poisson distribution.

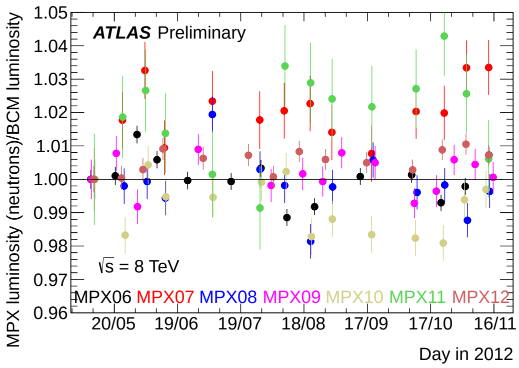

Figure 5. Fractional deviation in the luminosity (thermal neutron counting mode) reported by the MPX06 to MPX12 devices from the ATLAS reference luminosity (BCM) as a function of time in 2012. The ratio is shown for 14 time periods. For each device the time periods are chosen to have the same number of frames. The data are scaled such that the value of the first bin is unity.

about two. The precision of these correction factors was estimated to be below 1% using different data sets. These results were also confirmed by an independent analytic study, that calculated the cluster overlap probability for a simple cluster type and found very good agreement with the experimentally determined overlap probability.

Figure 4 shows the distribution of the number of heavy blobs per frame below the ^{6}LiF converter for MPX12. The results from MPX luminosity measurements using thermal neutron counting are shown in figure 5 for the MPX06 to MPX12 devices.

There is no indication of a significant slope from the luminosity measured by the heavy blob analysis (thermal neutron counting) in any of the MPX devices, when normalized to the BCM measurement, although for some devices the statistical precision is not sufficient to test deviations at the percent level. We recall that MPX06 indicates a 2% slope for the luminosity from hit counting and the same device measured no slope for the luminosity from neutron counting. In the current analysis of the MPX data the difference between the luminosity monitoring using hits and heavy blobs is noted and further studies are required for an understanding of the underlying reason.

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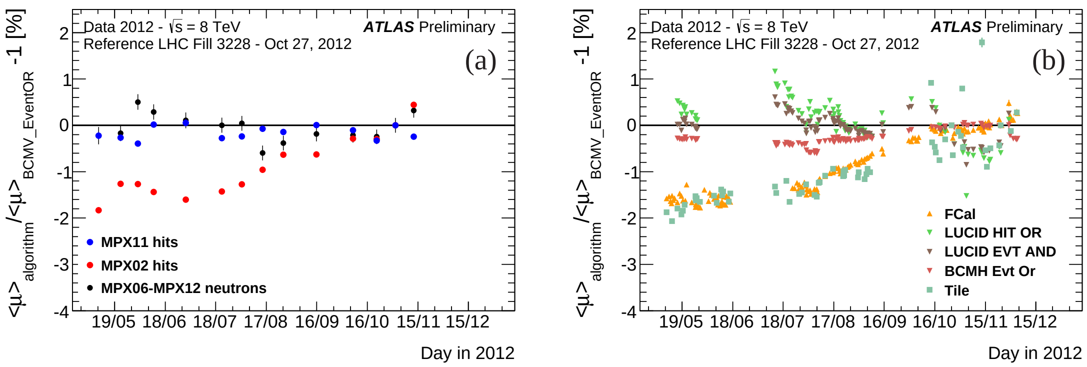

Figure 6. Fractional deviation in the number of interactions per bunch crossing (averaged over all colliding bunch pairs), obtained using (a) MPX results and (b) other ATLAS luminometers, with respect to the BCMV_EventOR value [5] and as a function of time in 2012. Each point shows the mean deviation for a single run compared to a reference run taken on October 27, 2012. Statistical uncertainties are shown per point, but in most cases are negligible. The MPX hit luminosity from a device that gives a constant ratio (MPX11) as well as that of a device with one of the largest increases (MPX02) are shown together with the luminosity measured with the MPX from thermal neutron counting averaged over MPX06 to MPX12.

4 Internal consistency of MPX and other ATLAS relative-luminosity measurements

The relative long-term stability of the MPX luminosity measurements is compared to that of other ATLAS luminometers (BCM, LUCID, FCal and Tile) [5] in figure 6a. Both LUCID algorithms as well as the BCMH_EventOR algorithm remain consistent, within about 1%, with the reference algorithm BCMV_EventOR, as does the MPX-averaged neutron measurement (figure 6b) and the MPX-hit luminosity reported by MPX11 (see also figure 3c). In contrast, the calorimeter-based, bunch-averaged luminosity measurements display a systematic drift of about 2% with respect to the results of the reference algorithm over the 2012 running period, as do the MPX02 hit-luminosity measurements (figure 3a). It is difficult to draw any clear conclusion since the full set of thirteen MPX devices analyzed in this note have slopes as a function of time that span the range of slopes observed in the other ATLAS luminosity detectors. Further analysis may identify specific features of these detectors that would explain the slope variations, but for now, an overall uncertainty of about 2% appears to be required to describe the data. Overall, the relative long-term stability of the MPX luminosity measurements is comparable to that of the other ATLAS luminometers.

5 Van der Meer scans

Van der Meer (vdM) scans are used for absolute luminosity calibration at the LHC [5]. In studies of ATLAS vdM data with MPX devices the focus is on the comparison of the ratio of MPX versus the BCM luminosity measurement in order to quantify the relative stability of the BCM and MPX luminosity calibrations, both from one vdM scan session to the next (April, July and November 2012), and between the low-luminosity regime of vdM scans and the high-luminosity regime of routine physics running. The beams are scanned transversely across each other in typically 25 scan steps. During each step, the beam orbits are left untouched ("quiescent beams") and the luminosity remains constant for approximately 29 s. The beam separation is then incremented by several

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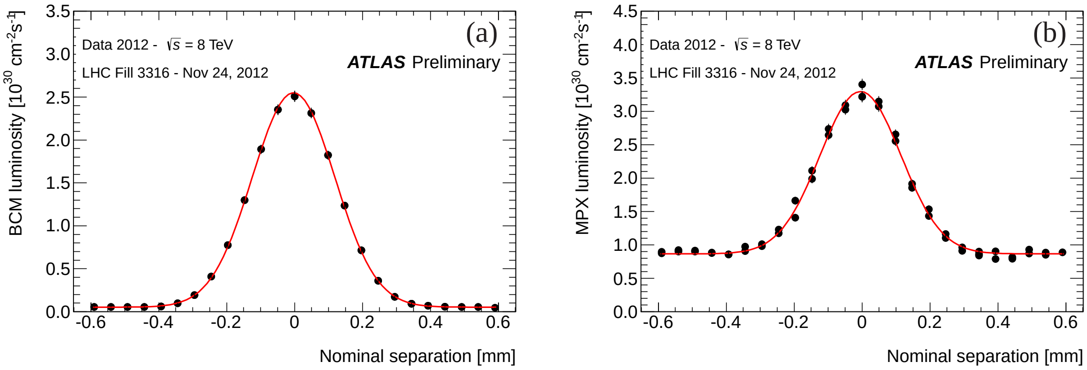

Figure 7. (a) BCM luminosity during the last horizontal November 2012 vdM scan summed over all bunches as a function of nominal beam separation. Each data point shows the measured instantaneous luminosity before background subtraction and averaged over the entire duration of a scan step. Data from the scan steps during which the beam separation is varied (non-quiescent beams) are not shown. The fit function is the sum of the proper luminosity that is well represented in this scan by a single Gaussian and of a constant term that accounts for instrumental noise and single-beam background. (b) MPX01 hit luminosity during the last horizontal November 2012 vdM scan summed over all bunches as a function of nominal beam separation. Each data point shows the measured instantaneous luminosity before background subtraction and averaged over one sampling interval of the MPX01 device. The MPX samplings that partially or totally overlap with non-quiescent scan steps (varying beam separation) are not shown. The fit function is the sum of the proper luminosity that is represented in this scan by a single Gaussian and of a constant term that accounts for instrumental noise and single-beam background.

tens of microns (“non-quiescent” beams) over an interval of several seconds, during which the luminosity varies rapidly and the luminosity measurements are unreliable. As the MPX acquisition time is about 5 s per frame, followed by a 6 s readout period, typically two frames occur within each quiescent-beam scan step. Occasionally, the MPX devices need to reload their configuration files, in which case the dead time can be as long as 30 s and therefore in some scan steps only one frame is recorded.

The beam-separation dependence of the measured luminosity is reasonably well represented by the sum of a single Gaussian plus a constant for both the BCM data (figure 7a). and the MPX data (figure 7b). The data show that the sensitivity of the MPX01 device is sufficient to measure the luminosity down to about $5 \times 10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, four orders of magnitude smaller than the luminosity typical of routine physics running. The sensitivity of the hit method, therefore, potentially allows the MPX to be used to cross-check the calibration transfer of other luminometers (BCM, LUCID, Tile) from van der Meer scans to physics conditions.

Figure 8 demonstrates that, on average, the MPX response is a linear function of the ATLAS reference (BCM) luminosity down to very low luminosities ($\approx 10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$), albeit with fluctuations of up to 10% (at constant luminosity) that cannot be explained by statistical arguments. It has been established that the fluctuations arise from the MPX measurements rather than the BCM measurements by comparing scan step by scan step and by comparing the luminosity values reported by multiple BCM and LUCID algorithms which are consistent within a fraction of a percent. Similar fluctuations of the MPX response, also of apparently non-statistical origin, have been observed at much higher luminosity during routine physics running. These issues remain under study.

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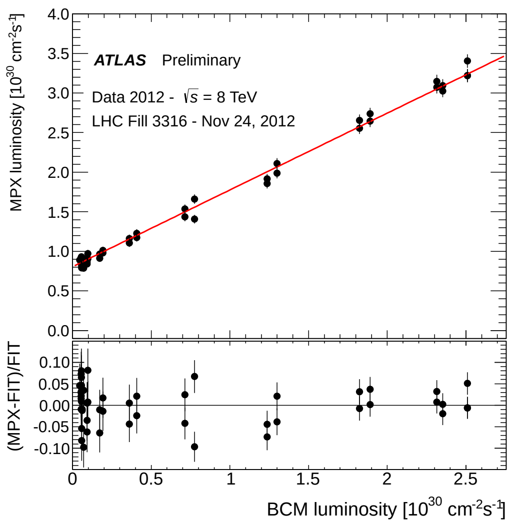

Figure 8. MPX01 hit luminosity vs. BCM luminosity for the last horizontal November 2012 vdM scan. The line is a linear fit to the data. The non-zero intercept corresponds to the difference of the MPX and BCM noise and background contributions. The bottom frame shows the fractional residual of the linear fit.

6 Conclusion

The network of MPX devices installed in ATLAS has successfully taken data from 2008 to 2013 and proven to be sufficiently radiation hard for the high-luminosity data taken in 2012 at $\sqrt{s} =$ 8 TeV proton-proton collisions. The study presented here focuses on luminosity measurements during proton-proton collisions from April to December 2012. The study has demonstrated that the MPX network has an internal consistency of about 2% using different detectors and techniques for hit counting and heavy blob (thermal neutron) counting as measures of luminosity. This number is comparable to the present preliminary discrepancy found in the long-term comparisons between other luminosity detectors in ATLAS in the same time period. In addition, the MPX network has been used to study in detail the three van der Meer scan periods performed in 2012, in a regime where the luminosity is four orders of magnitude lower than during routine physics data-taking. Although not specifically designed for luminosity measurements in ATLAS, the MPX network gives reliable supplementary information for the overall ATLAS luminosity determination over a wide dynamic range (luminosities from about $5 \times 10^{29}\,\mathrm{cm^{-2}s^{-1}}$ to $7 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$). The present study represents a proof of principle and will be extended to address systematic uncertainties with the aim to increase the precision of the MPX luminosity monitoring using the accumulated high-statistics data set.

Acknowledgments

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