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R. Miyamoto
Brookhaven National Laboratory, Upton NY

E. Bravin
CERN, Geneva, Switzerland

H.S. Mattis, A. Ratti, T. Stezelberger, W.C. Turner, H. Yaver
Lawrence Berkeley Laboratory, Berkeley, CA

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OPERATIONAL RESULTS FROM THE LHC LUMINOSITY MONITORS*

R. Miyamoto†, BNL, Upton, NY, USA
E. Bravin, CERN, Geneva, Switzerland
H. S. Matis, A. Ratti, T. Stezelberger, W. C. Turner, H. Yaver, LBNL, Berkeley, California, USA

Abstract

The luminosity monitors for the high luminosity regions in the LHC have been operating to monitor and optimize the luminosity since 2009. The device is a gas ionization chamber inside the neutral particle absorber 140 m from the interaction point and monitors showers produced by high energy neutral particles from the collisions. It has the ability to resolve the bunch-by-bunch luminosity as well as to survive the extreme level of radiation in the nominal LHC operation. We present operational results of the device during proton and lead ion operations in 2010 and make comparisons with measurements of experiments.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN can accelerate proton and lead ion beams to 7 TeV and 547 TeV and produce collisions of these particles. Luminosity measures performance of the LHC and is particularly important for experiments in high luminosity interaction points (IPs), ATLAS (IP1) and CMS (IP5). To monitor and optimize the luminosities of these IPs, BRAN (Beam RAte Neutral) detectors [1, 2] have been installed and operating since the beginning of the 2009 operation [3].

A neutral particle absorber (TAN) protects the D2 separation dipole from high energy forward neutral particles produced in the collisions [4]. These neutral particles produce electromagnetic and hadronic showers inside the TAN and their energy flux is proportional to the collision rate and hence to the luminosity. The BRAN detector is an Argon gas ionization chamber installed inside the TANs on both sides of the IP1 and IP5 and monitors the relative changes in the luminosity by detecting the ionization due to these showers. When the number of collisions per bunch crossing (*multiplicity*) is small, the shower rate inside the TAN is also proportional to the luminosity. Hence, the detector is designed to operate by measuring either the shower rate (*counting mode* for low and intermediate luminosities) or the average shower flux (*pulse height mode* for high luminosities). The detector is also designed 1) to survive the extreme level of radiation ($\sim$1 GGy in the nominal condition), 2) to resolve the shower from each bunch crossing (40 MHz in the nominal condition) and measure the bunch-by-bunch luminosities, and 3) to have four independent square shaped channels, each occupying a quadrant, making the detector sensitive to the crossing angle [1, 2].

During the proton operation in 2010, the beam energy was 3.5 TeV and the multiplicity did not exceed four. Because the counting mode is still effective in such a condition [5], the BRAN were operated in the counting mode in 2010. This paper presents operational results of the BRANs during the operation in 2010 (mainly the proton operation) and makes comparisons with measurements of the experiments. The luminosity optimization is discussed in detail in [6] and so this paper focuses on measurements during the normal operation.

TOTAL LUMINOSITY

Proton Operation

Figure 1 shows the luminosities of the IP1 and IP5 during one cycle (*fill*) of the proton operation, measured by the BRANs and experiments. The *left* and *right* sides of an IP are defined by an observer inside the LHC ring. The luminosities of the BRANs are the shower rates scaled based on the measurements of the experiments. We can see good agreements among the BRANs and experiments.

Figure 2 compares the raw shower rates of the BRANs to the proton-proton (*pp*) collision rates of the experiments for the data of Fig. 1. The collision rates at the IPs are estimated with the measured luminosities and the 72 mb inelastic *pp* cross section [7]. The difference among the BRANs is due to the difference in materials in front of the BRAN inside the TAN [8] and also in the cable attenuation. We note that the detector on the left side of the IP5 has

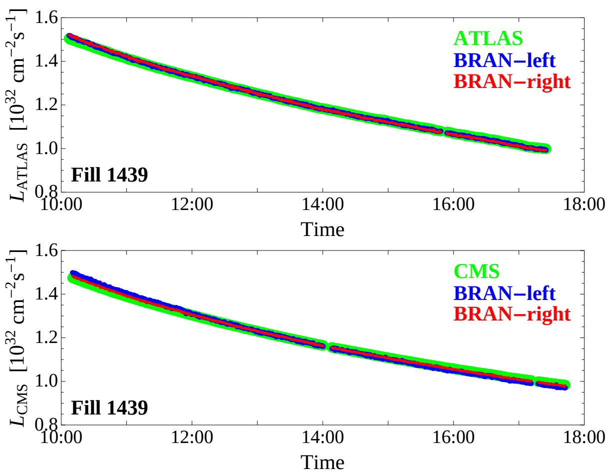

Figure 1: Luminosities at the IP1 and IP5 measured by the BRANs and experiments.

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† miyamoto@bnl.gov

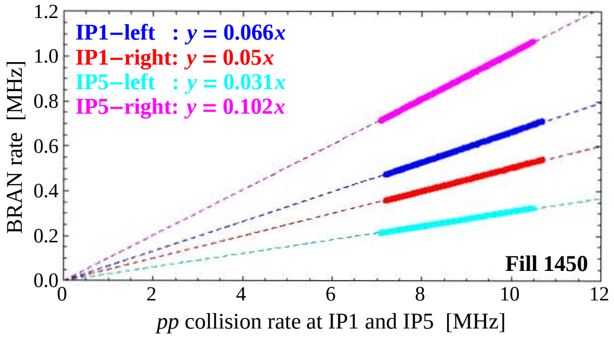

Figure 2: Shower rates observed by the BRANs vs. the *pp* collision rates at IP1 and IP5.

been suffering from 100 kHz noise and operating with a higher threshold than other three detectors, making the rate of this detector smaller. A recent simulation predict about 5% of *pp* collisions is detected by the BRAN [8] and the measurements are consistent with the prediction.

Figure 3 shows relative differences between the measured luminosities of the BRANs and experiments for the same data as Figs. 1 and 2. We can see that the BRANs have small systematic errors of about $\pm 1\%$, except the detector on the left side of the IP5 with the noise issue. The cause of this systematic error may be the multiplicity but is still under investigations. The target precision of the detector is 1%, assuming a reasonable averaging time, and this was achieved in the condition of the proton operation in 2010.

Lead Ion Operation

Although the BRAN was designed mainly for the proton operation, it was also tested during the lead ion operation in November 2010. During the lead ion operation, the luminosity was on the order of 10^{25} and this corresponds to the collision rate of several kHz, which is two to three orders of magnitude smaller than the proton operation (Fig. 2). Figure 4 shows the relative differences between the BRANs and experiments for one lead ion fill. Compared to the proton operation in Fig. 3, the BRANs have large systematic errors of about $\pm 10\%$. We have not fully investigated yet the cause of these systematic errors.

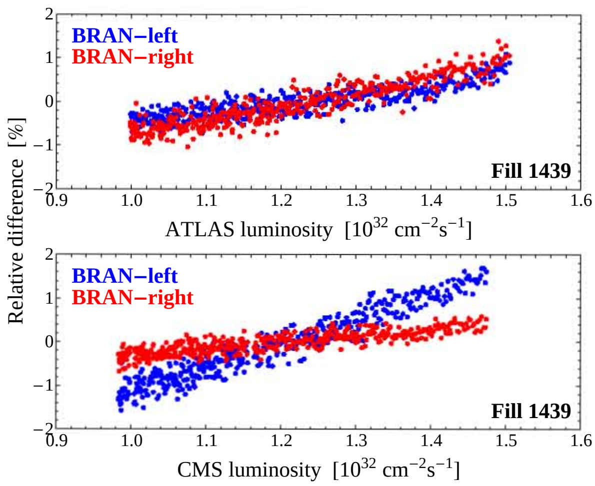

Figure 3: Relative differences between the BRANs and experiments. The systematic errors are on the level of the target precision (1%) except the one on the left side of the IP5.

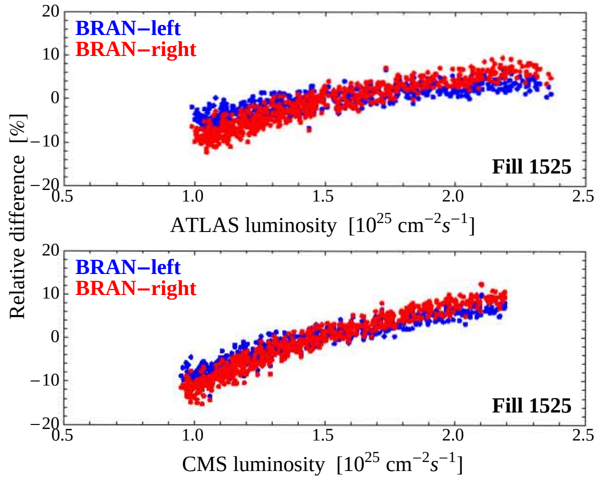

Figure 4: Relative differences for the lead ion operation. Systematic errors ($\pm 10\%$) are much larger than the proton operation in Fig. 3.

BUNCH-BY-BUNCH LUMINOSITY

Figure 5 shows a snapshot of the bunch-by-bunch luminosities at the IP5, measured by the BRAN and CMS. The data was taken for one proton fill with 150 ns bunch spacing and 348 bunch collisions at the IP5. An each marker shows the average value and standard deviation of measurements over 10 minutes. We can see good agreements between the two measurements. The lower part of the figure shows the histogram of the relative differences for all 348 bunch pairs and their standard deviation is 1.0%. The figure is a snapshot at the beginning of this fill, where the total luminosity is about 2×10^{32}, and the standard deviation of the relative differences remains on the same 1% level at the end of this fill after about 12 hours, where the luminosity is about 1×10^{32}. This concludes that, if the scale is properly calibrated, the BRANs on the counting mode can provide 1% level of precision not only for the total luminosity but also for the bunch-by-bunch luminosities in the condition of the 2010 proton operation.

INTERACTION AREA

The luminosity is inversely proportional to the cross sectional areas of the beams at the IP and so the luminosity measurement, together with the bunch intensity measurement, provides an information of the beam sizes. If all the bunches in both beams have an identical round Gaussian

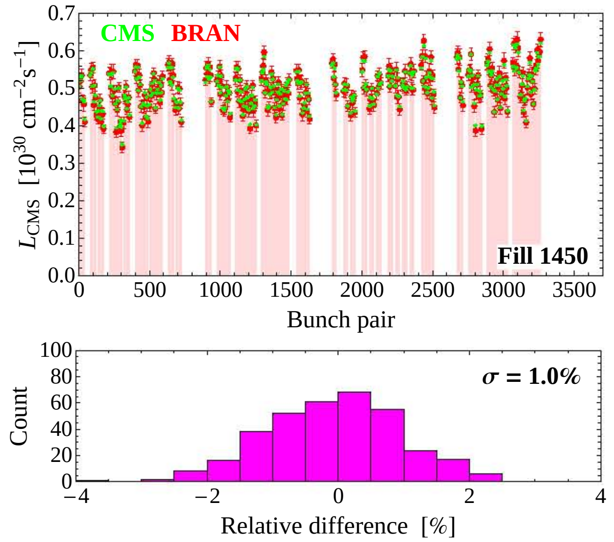

Figure 5: A snapshot of the bunch-by-bunch luminosities measured by the BRAN and CMS (upper) and the histogram of the relative differences (lower).

distribution, the luminosity L is given by

$$L = \frac{fkn^2}{4\pi\sigma^2}F = \frac{fkn^2}{8\pi\sigma_L^2}, \quad (1)$$

where f is the revolution frequency, k is the number of colliding bunch pairs, n is the bunch intensity, F is the geometrical reduction factor due to the crossing angle (0.92 for 200 μrad during the 2010 proton operation), σ is the RMS beam size at the IP, and σ_L is the RMS size of the luminous region observed by the experiment. Figure 6 shows an evolution of the RMS beam size at the IP5 during one proton fill, where we observed slightly larger beam size growths than other fills. The RMS beam size σ is reconstructed based on Eq. (1) with the luminosity of the BRAN, L, or the size of the luminous region measured by CMS, σ_L. We can see a good agreement between the two measurements. When a linear fit is applied to the correlation of the two measurements, the proportionality coefficient and r^2 are

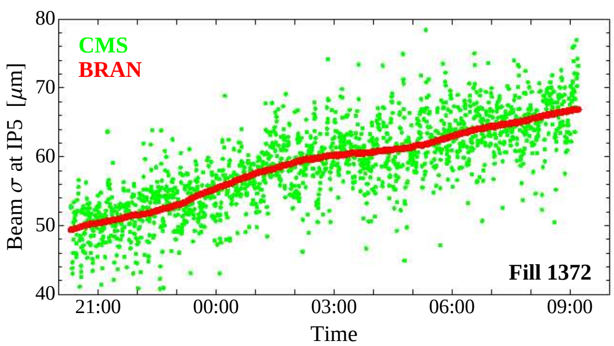

Figure 6: Evolution of the effective beam size at IP5, reconstructed from the luminosity of the BRAN and the luminous region of CMS.

0.9968 and 0.9954 for each, which are consistent with the accuracy of the BRAN (Fig. 3). We can also see that the measurement based on the luminosity has less fluctuations but it can only observe the average over two planes and two beams.

CROSSING ANGLE

During the proton operation in 2010, the LHC ran with a full crossing angle of 200 μrad at IP1 and IP5. The asymmetry among the channels were recorded during some proton fills and compared with measurements of beam position monitors and a predictions of a simulation. Preliminary analysis confirms that the detector is sensitive to the crossing angle, but the observed asymmetry was more than 50% larger than the predicted value and the cause of this discrepancy is still under investigations. Details of the preliminary analysis can be found in [8].

CONCLUSIONS

The BRAN luminosity monitors for the IP1 and IP5 have been in operation since 2009. Their measurements have been available on live in the control room and used to monitor and optimize the luminosities at these IPs. We demonstrated that BRANs could provide the total and bunch-by-bunch relative luminosities with precision of 1% level, which has been the design target, in the condition of the 2010 proton operation. The detectors were also tested during the lead ion operation but large systematic errors of about ±20% were observed. The BRANs were used in the counting mode in 2009 and 2010, but the multiplicity approaches to or may even exceed ten from 2011 and so they will be operated in the pulse height mode from 2011.

ACKNOWLEDGMENT

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