



The BRAN luminosity detectors for the LHC



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ABSTRACT

This paper describes the several phases which led, from the conceptual design, prototyping, construction and tests with beam, to the installation and operation of the BRAN (**B**eam **R**ate of **N**eutrals) relative luminosity monitors for the LHC. The detectors have been operating since 2009 to contribute, optimize and maintain the accelerator performance in the two high luminosity interaction regions (IR), the IR1 (ATLAS) and the IR5 (CMS). The devices are gas ionization chambers installed inside a neutral particle absorber 140 m away from the Interaction Points in IR1 and IR5 and monitor the energy deposited by electromagnetic showers produced by high-energy neutral particles from the collisions. The detectors have the capability to resolve the bunch-by-bunch luminosity at the 40 MHz bunch rate, as well as to survive the extreme level of radiation during the nominal LHC operation. The devices have operated since the early commissioning phase of the accelerator over a broad range of luminosities reaching $1.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a peak pileup of 45 events per bunch crossing. Even though the nominal design luminosity of the LHC has been exceeded, the BRAN is operating well.

After describing how the BRAN can be used to monitor the luminosity of the collider, we discuss the technical choices that led to its construction and the different tests performed prior to the installation in two IRs of the LHC. Performance simulations are presented together with operational results obtained during p - p operations, including runs at 40 MHz bunch rate, Pb - Pb operations and p - Pb operations.

1. Introduction

This paper describes the BRAN (**B**eam **R**ate of **N**eutrals) segmented ionization chambers installed at CERN's Large Hadron Collider (LHC) [1]. These chambers, proposed in 1998 [2], are designed to provide a tool for the optimization of the LHC's luminosity. Earlier, a similar concept was suggested for the SSC [3]. The BRAN detectors are fast ionization chambers designed to monitor the relative luminosity at LHC at the interaction regions IR1 (ATLAS Experiment) and IR5 (CMS Experiment) by sampling the shower energy produced by forward neutrons and photons from p - p , p - Pb and Pb - Pb collisions [4–9]. This paper describes the design criteria and fabrication of the BRAN, and documents comparisons between simulated and actual BRAN performance. In addition, comparisons are made with complementary luminosity information from the ATLAS and CMS experiments.

2. Luminosity considerations

The luminosity at each Interaction Point (IP) can be expressed as the sum of the bunch-by-bunch luminosities L_{sb} from the b_i pair of colliding bunches with population N_1 , N_2 in Beam₁ and Beam₂ over the

number of pairs of bunches k_b colliding at the i th IP [10]:

$$L(IP_i) = \sum_1^{k_b} L_{sb}(b_i). \quad (1)$$

For transverse Gaussian bunch distributions, the bunch-by-bunch luminosity at a particular interaction point, IP_{*i*}, from the b_i pair of bunches in Beam₁ and Beam₂ has the general expression:

$$L_{sb}(b_i) = f_{rev} \left(\frac{N_1 N_2}{2\pi \Sigma_x \Sigma_y} \right)_{b_i} F_1(\theta_i) F_2(z_{bi}^{os}). \quad (2)$$

The function F_1 quantifies the luminosity reduction produced by the crossing angle [11]. Deviations from the nominal crossing angle due to closed orbit distortions, which are driven by long-range beam-beam forces, can affect in a time-dependent way the bunch-by-bunch luminosities. The function F_2 represents the luminosity reduction factor in presence of a non-zero impact parameter z_{bi}^{os} i.e. the separation, in both planes, between the charge centers of the pair b of bunches colliding at IP_{*i*}. The impact parameter is routinely compensated during the LHC operation by varying the bunch relative transverse positions by means of orbit bumps generated by orbit correctors (Vernier Scans). The quantities Σ_x and Σ_y are the convoluted transverse bunch sizes in collision (in

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Table 1
Nominal LHC parameters at IP1 and IP5.

Parameter	Symbol	<i>p-p</i> Run	Units
Beam Energy	E	7.0	TeV
Lorentz factor	γ	7.46×10^3	
Rev. freq.	f_{rev}	11.2455	kHz
RF freq.	f_{RF}	400.790	MHz
Collision freq.	f_c	40.790	MHz
Bunch spacing	τ_b	7.485 24.951	m ns
Bunches/beam	k_b	2808	
Normalized emittance	ϵ_n	3.75×10^{-6}	m
IP β -value	β^*	0.55	m
Bunch sizes	σ^*	16.7	μm
Bunch length	σ_s	$7.55 0.28$	cm ns
Protons/bunch	$N_{1,2}$	1.15×10^{11}	
IP crossing angle	θ^*	285	μrad
Form factor	F_1	0.836	
Luminosity/Crossing	L_x	3.2×10^{26}	cm^{-2}
Bunch luminosity	L_{sb}	3.6×10^{30}	cm^{-2}/s
Nominal luminosity	L	1.0×10^{34}	cm^{-2}/s

expression (3) the subscript z corresponds to either x or y):

$$\Sigma_z(b_i) = \left[\sqrt{(\sigma_{1z}^*)^2 + (\sigma_{2z}^*)^2} \right]_{b_i} = \left[\sqrt{(\epsilon_{1z}\beta_{1z}^* + \epsilon_{2z}\beta_{2z}^*)} \right]_{b_i} \quad (3)$$

Assuming the same optical properties for both beams, expression (2) reads:

$$L_{sb}(b_i) = \frac{f_{rev}}{4\pi\epsilon_n} \left(\frac{N_1 N_2}{\sqrt{\beta_x^* \beta_y^*}} \right)_{b_i} \cdot F_1(\theta) F_2(z_{b_i}^{os}) \quad (4)$$

where $\epsilon_n = \gamma\epsilon$ is the normalized bunch emittance.

For reference, the nominal parameters at the high luminosity interaction points [12,13] in *p-p* collision mode are collected in Table 1. (Lattice parameters are evaluated at the IP).

3. The BRAN detectors

The BRAN LHC luminosity monitors consist of gas ionization chambers that detect minimum ionization particles (MIPs) near the maximum of the shower generated by the neutral particles emerging from collisions in the IP in the zero degree neutral particle absorbers (TAN). They are installed where the LHC beam transitions from one to two beam pipes, at IP1 and IP5. Fig. 1 shows the position of one of the BRAN detectors in one side of the interaction region. The information on the shower energy is proportional to the neutral particles energy flux and, therefore, to the luminosity at the IP of interest. This concept lends itself to a luminosity measurement on a bunch-by-bunch basis.

4. System requirements

The system must comply with extremely stringent requirements. The speed of operation of the detector must match the 40 MHz bunch repetition rate of the LHC while with standing extremely high radiation

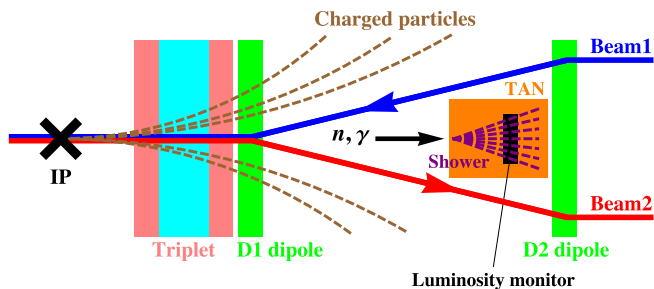


Fig. 1. Schematic of one of the LHC interaction regions.

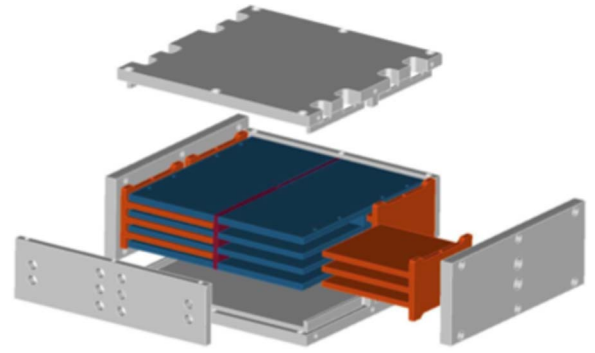


Fig. 2. Exploded view of the detector showing the ceramic housing and the six gaps copper structure segmented in four quadrants.

doses (up to 180 MGy/y at nominal luminosity). The requirements for the LHC luminosity monitors, specified in [14] call for a relative luminosity signal stable to 1%, a bunch-by-bunch measurement capability, crossing angle monitoring and ‘reasonable integration times’, where several tens of seconds is considered acceptable.

4.1. Mechanical design

The specified requirements dictate the choice of a small gap, segmented gas ionization chamber built entirely out of copper, ceramic and stainless steel. The chamber has been designed to allow for a slow gas flow, so that fresh medium is always available for the ionization process. A gas with no organic compounds was selected so that the interaction with the beam produces minimal contamination. Fig. 2 shows an exploded view of the detector, which is eventually mounted into a sealed ceramic housing.

The number of gaps and their thickness have been chosen trading off between signal strength, which is proportional to the number of parallel gaps, and speed, which is negatively affected by the capacitance created by the parallel gaps. The final compromise, supported by MAGBOLZ modeling, has been to use 6 gaps, 1 mm each, allows for bunch-by-bunch monitoring at the nominal LHC operation. Table 2 summarizes the baseline parameters of the detectors.

To allow for crossing angle monitoring, each chamber is segmented into four electrically isolated quadrants, so that a measurement of transverse position of the shower is possible. As the ionization chamber is designed to operate with pressure in the range from 1 to 10 bar, a pressure vessel encloses the full detector. The ionization chamber is designed with a single ground plane electrode in a four-quadrant comb structure. Four independent signal combs interleaved with the ground plane comb provide six 1-mm gaps each. A precision-machined housing made of mica-glass composite structurally supports the ground plane comb and signal combs. Each chamber is mounted onto the end of a 605 mm long copper bar with a stainless steel end flange, and subsequently inserted into a stainless steel pressure case. The complete housing matches the instrumentation slot width in the TAN and the

Table 2
Ionization chamber design parameters.

Quadrant area	1600 mm ²
Gap between plates	1.0 mm
Number of gaps in parallel	6
Gas composition	94% Ar+6% N ₂
Gas Pressure	6 bar
Ionizing pairs	58.32 mip-mm
E/P	200 V/mm-bar
Gap voltage	1200 V
Electron drift velocity	45.0 mm/ μs
Amplifier/Shaper gain	0.16 $\mu\text{V}/e^-$
rms noise	1.24 mV

length of a single copper bar absorber as shown in Fig. 2. The electrical and gas feedthroughs are supported at the top flange.

The BRAN ionization chambers use a 94% Ar +6% N₂ gas mixture running at a nominal 6 bar pressure. This combination provides a high electron drift velocity without making use of organic molecules, helping to avoid radiation-induced polymerization. The gas pressure controls the charge yield from the detector for a given shower intensity and the HV bias on the chamber plates is adjusted to maintain the electron drift speed near the maximum. Eq. (5) gives the relationship between the applied electric field and gas pressure:

$$\frac{E}{P_{\text{gas}}} = 200 \frac{V}{\text{mm}\cdot\text{bar}}. \quad (5)$$

At the LHC design luminosity (shown in Table 1), we simulated using the Mars Cascade code [15] that a shower population of 6800 minimum ionizing particles (MIPs) per bunch crossing will be produced in the ionization chamber. At the 6 bar nominal working pressure, the required HV bias on the chamber plates is 1.2 kV. This shower, calculated by the Mars code, produces, at the operating gas pressure, a mean ionization electron charge of 2.4×10^6 electrons. The gas mixture flows to the ionization chamber from the assembly top flange by way of a tube and holes in the ionization chamber walls. For a gas flow rate of 1 l per hour (at 10 bar) the flow regime is laminar and the pressure drop between the inlet and outlet of the assembly is less than 15 mbar, requiring one assembly volume change per hour.

Gas is supplied to the luminosity monitor assembly from premixed gas bottles residing at the bypass tunnel area near the IRs. A change-over panel and a gas distribution rack provide uninterrupted gas supply and remote control of pressure and flow rate to the monitors. At the nominal flow speed of 1 l/h, a typical sized gas bottle requires a replacement approximately once every 2–3 months. Although the distribution rack is about 150 m from the monitors, the total pressure drop is less than 0.7 mbar due to the low flow rate.

Image charges of the electrons produced in the ionization process are collected and integrated by a fast front-end amplifier, followed by a shaper and a digitizing system. This signal processing chain has been designed [16] to support the nominal 40 MHz bunch rate.

4.2. IR installation

The luminosity monitor assembly is mounted in the TAN instrumentation slot [17,18] and takes the place of a single copper bar absorber. Ceramic spacers isolate the monitor assembly, which is also plasma coated with ceramic. Fig. 3 shows a model rendition of the detector and front-end electronics housing in the TAN. Construction layouts of the IR assembly are shown in Fig. 4. The BRAN detector is positioned near the shower maximum of the hadronic electromagnetic

showers.

5. Electronics design

The electronics readout comprises two separate parts, the analog processing electronics installed in the tunnel, connected to the analog shaper and the digital back-end, installed in the ATLAS and CMS service areas. The high level of radiation in the LHC tunnel requires the use of rad-hard cables between the detector quadrants and the electronics readout channels, and a careful selection of components.

5.1. Frontend preamplifiers

The main challenge of the front-end stage is to maintain a peaking time shorter than the 25 ns bunch spacing to avoid pile-up effects [19]. Since the detector signal is a current pulse, the analog front-end electronics integrate it using a charge sensitive preamplifier with a cold-termination technique. The preamplifier is built around a classic folded cascode stage followed by a gain and buffer one to send the signal to the shaping amplifier. The time constant associated with the quadrant's capacitance and the preamplifier's input impedance is the dominant pole of the system, which is compensated in the shaper electronics. Since the preamplifiers need to be in the tunnel near the detector, they receive a significant amount of radiation. To minimize downtime, two separate preamplifiers are installed and can be remotely switched on a quadrant by quadrant basis.

5.2. Shapers and signal distribution

The shaping amplifier's main function is to reduce the time occupancy of the preamplifier signal to less than 25 ns. The shaper's design has evolved through several iterations to a two-pole shaper, benefiting from the well-known pole-zero (PZ) cancellation scheme. The zeros cancel two poles, one associated to the detector capacitance and the preamplifier's input impedance and the other associated to the preamplifier's feedback network. The poles of the shaper implement a pseudo-Gaussian function built using a Sallen-Key low-pass filter configuration. Proper pole-zero compensation is essential in order to optimize the return of the signal to the baseline and each zero is implemented with PZ compensation capabilities. Once the signals for the individual quadrants are processed, they are buffered and distributed to the digitizers as well as to local diagnostic ports.

5.3. Digitizers

The Individual Bunch Measurement System (IBMS) board developed by the AB/BI GROUP at CERN digitizes the analog signals. The IBMS boards have been developed as mezzanine boards for the DAB64x, a VME64x Data Acquisition Board developed by TRIUMF for LHC beam instrumentation [20]. Such a circuit board provides a very flexible platform for signal processing combining a good amount of on-board memory with the versatility and processing power of the Altera Stratix family of FPGAs. Dedicated firmware running on the DAB64x have been developed to control the instrument and to process the data. Once digitized and processed, the resulting values are shared and made available to the control room and the community through the LHC control system.

6. Detector applications

As stated in the Luminosity Specifications [12] the BRAN detectors have been conceived as relative luminosity monitors. They are used to help tune the accelerator parameters with the goal of optimizing the luminosity performance during operation without interfering with the data taking at the experiments. More specifically they are used at every store to bring beams into collision and through the beta squeeze before

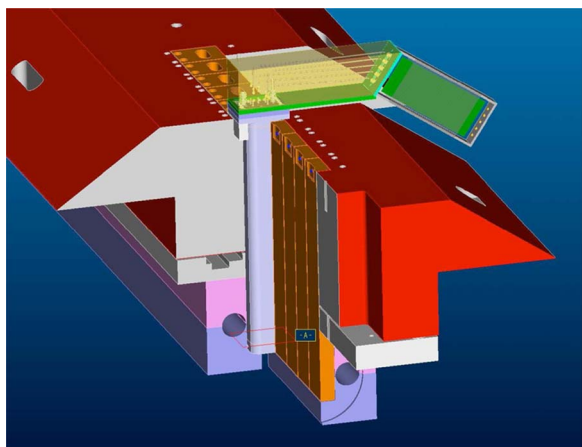


Fig. 3. Detail of the BRAN installation inside one of the TANs.

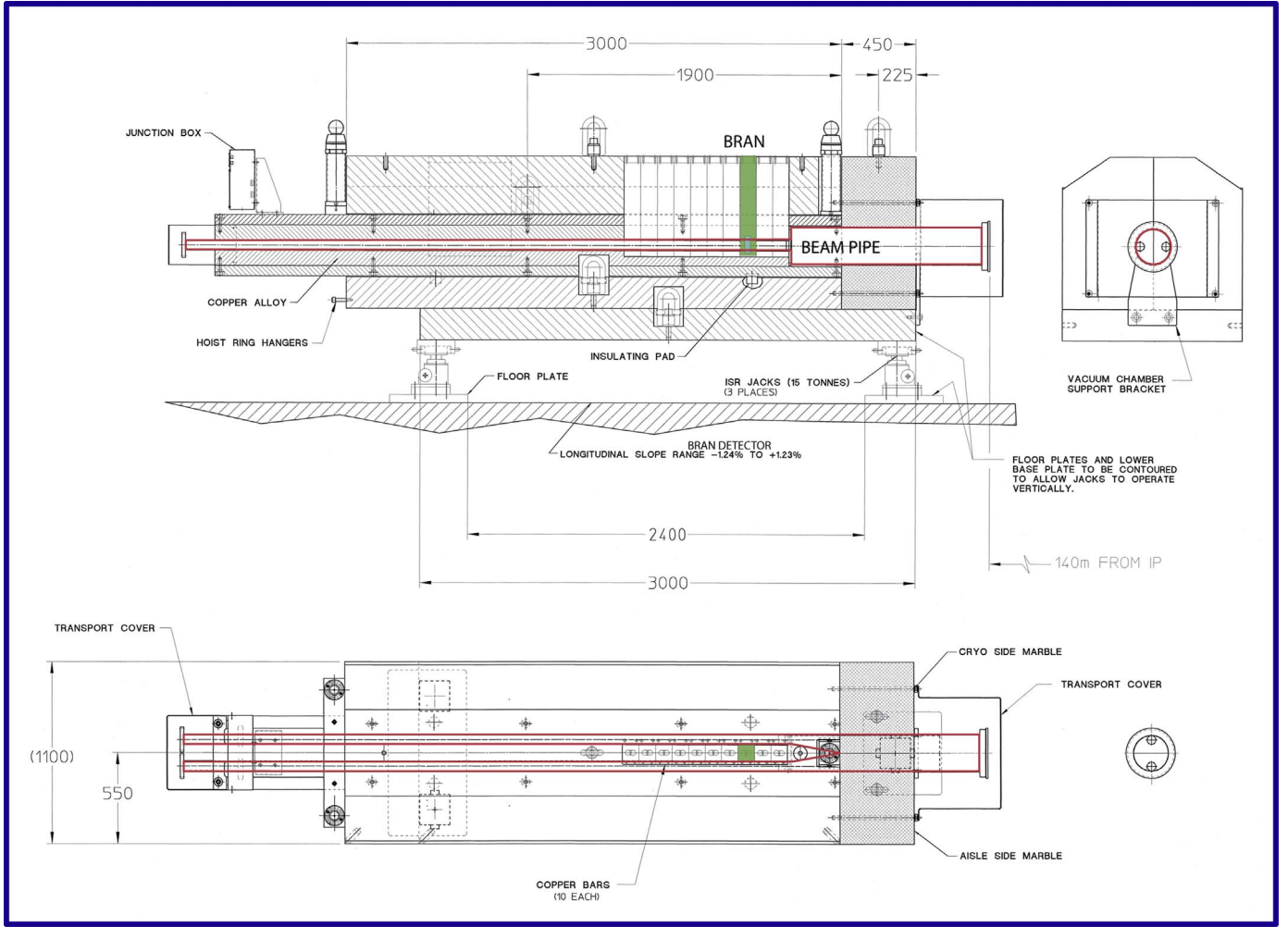


Fig. 4. Construction layout of the BRAN installation inside the TAN absorbers in the IR.

the start of collision production mode and the ‘stable beams’ used during the store.

6.1. LHC operations optimization

Three time-dependent effects govern the time dependence of the LHC Luminosity: bunch charge decay, bunch emittance growth, and collision offsets. After the optical functions of each ring have been tuned to the design figures, substantial deviations from the design luminosities may result from charge differences in the colliding bunches at a given interaction point and from collision features (crossing angle, bunch-to-bunch overlap) specific to the orbits of bunches occupying different azimuthal positions in the rings (Pacman bunches). Information on the bunch-by-bunch luminosity is used to bring the beams into collision and maintain optimum luminosity via the optimization of the bunch overlap. It also helps in identifying deviations of the optical beam parameters from the design values and therefore complements the task-oriented beam instrumentation for orbit quality control and emittance measurements.

6.2. Emittance evolution

Besides a ‘direct’ observation of the transverse dimensions of the beam interaction area only accessible to the experiments, a powerful tool for monitoring the time evolution of the colliding bunch combined emittance is represented by the bunch-by-bunch Specific Luminosity:

$$L_{sb}^*(b_i) \equiv \left(\frac{L_{sb}}{N_1 N_2} \right)_{b_i} = \frac{f_{rev}}{A_i^*} F_1 F_2. \quad (6)$$

The interaction area at an IP calculated from expression (4) is

$$A_i^* = 4\pi\epsilon \sqrt{\beta_{x_i}^* \beta_{y_i}^*} \quad (7)$$

where $\epsilon = \epsilon_n / \gamma$ is the geometric emittance.

For a given crossing angle and after compensation of any unwanted collision offset (Vernier scans), the quantity (6) offers a powerful tool to record the time evolution of the interaction area and of the associated emittance growth due, for example, to Intra Beam Scattering in absence of adequate radiation damping.

The time behavior of the specific Luminosity characterizes the beam-beam physics in storage rings. It depends substantially on the nature of the colliding beams and can be quite different from the flat trend one could expect in presence of an invariable collision area. In the case of e^+e^- colliders, the quantity (6) exhibits a positive trend in the initial part of the operation if the beams collide at the beam-beam limit, where the bunch dimensions are larger than nominal, reaching a steady value when the bunch population decreases. In the case of $p-p$ or $p-\bar{p}$ colliders the specific luminosity decreases with time providing a signature of emittance growth for one or both the colliding bunches.

The time evolution of the interaction area (7) can be monitored using the logged information on bunch charges and Luminosity. Integration times and bunch gating can be envisaged for a suitable comparison with data on the luminous regions from experiments.

An application has been implemented to display the interaction

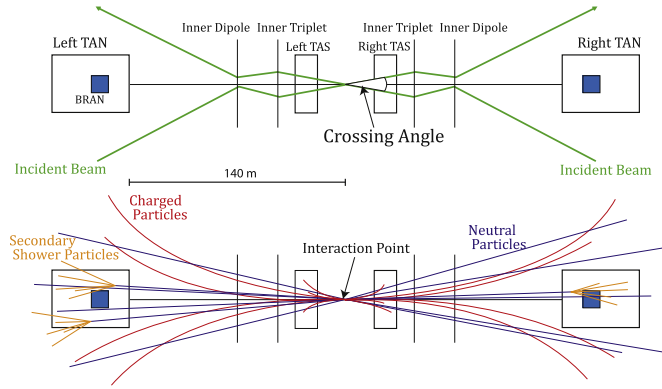


Fig. 5. Schematic view of one of the Interaction Regions showing the crossing angle between the colliding beams. The lower figure depicts the separation between charged and neutrals in a hypothetical particle shower resulting from an interaction.

area of the proton bunches colliding in IP1 and IP5 during the physics runs. This provides a tool to help identify the contribution to the luminosity time decay originating from possible bunch emittance blow-up. Experimental results confirm the ability to characterize the emittance behavior during the store and to study possible differences among bunches in the same fill.

6.3. Crossing angle monitoring

The information from the four quadrants of each of the BRANs can be used to evaluate and monitor the Crossing Angle at the IP1 and IP5 interaction points [21]. This effect is schematically shown in Fig. 5. Each of the four detectors installed at both sides of the IPs is used as a four-button position monitor to determine the transverse location of the shower via the asymmetry (Δ/Σ) information (up-down in IP1, right-left in IP5) from the individual quadrants. The expression

$$\theta_{x,y} \propto \frac{k_{BRAN}(\Delta_{rl}, \Delta_{ud})}{L_{sh}} \quad (8)$$

provides the angles of the outgoing beam referred to the zero-angle reference trajectory passing through the geometrical center of the BRAN. Here Δ_{rl} , Δ_{ud} are the signal amplitude differences between the right-left and up-down quadrants, k_{BRAN} is a scale factor and L_{sh} is the distance of the shower maximum from the IP. The total crossing angle at a given IP is the sum of the angles (8) determined from the Left and the Right BRANs. This application is intended to monitor the stability of the crossing angle rather than its actual value.

7. System modeling

We developed a FLUKA model [22,23] of the BRAN detector and integrated it into the LHC beam line model. The full detail of the beam line is included up to the TAN absorber, which shields the outer beam separation dipole from the forward neutral flux from the IP and houses the BRAN. Modeled TAN geometries are shown in Figs. 6 and 7. Detailed FLUKA simulations have been carried on for the BRAN luminosity monitor from 3.5 to 7.0 TeV at both IR1 and IR5 for p-p collisions. They can be used to predict the behavior of the BRAN as the LHC advances to its design luminosity and energy.

Using the DPMJET [24] option of FLUKA, we have simulated the p-p, p-Pb and Pb-Pb reactions over the expected operating range of the LHC. Fig. 8 shows the shower formation for p-p and Pb-Pb. The simulations [25,26] show how the energy is deposited in the detector as a function of the beam energy and crossing angle.

Fig. 8 shows the relative amount of energy in the BRAN for different combinations of colliding particles. When the LHC collides p on Pb, the signal strength from the BRAN is close to a factor of twenty higher on the side that the Pb beam approaches and is in good agreement [27] with the

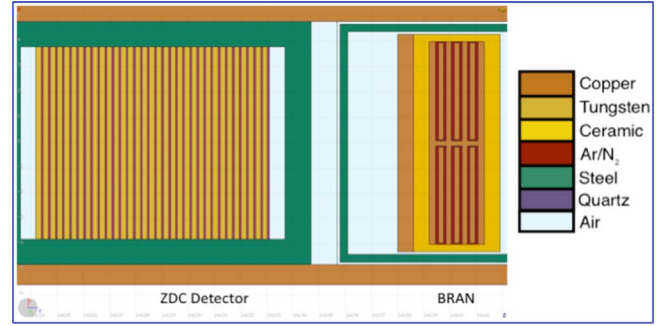


Fig. 6. FLUKA model of a BRAN unit installed in the TAN slot behind the ZDC detector during the 2011 LHC run.

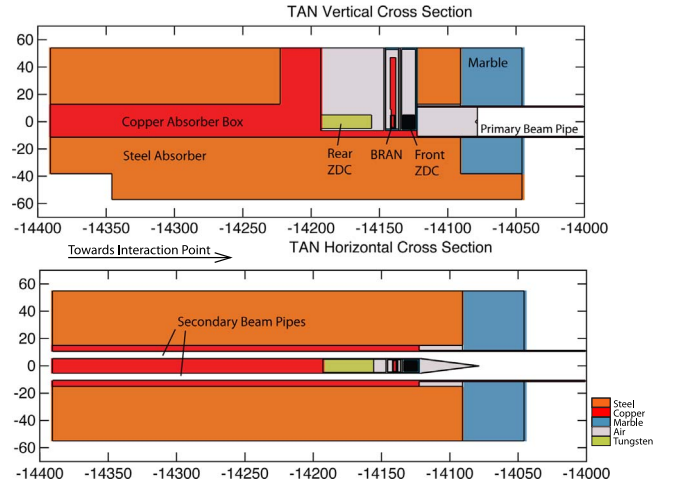


Fig. 7. Top and side view of the BRAN. The color white indicates the region of vacuum.

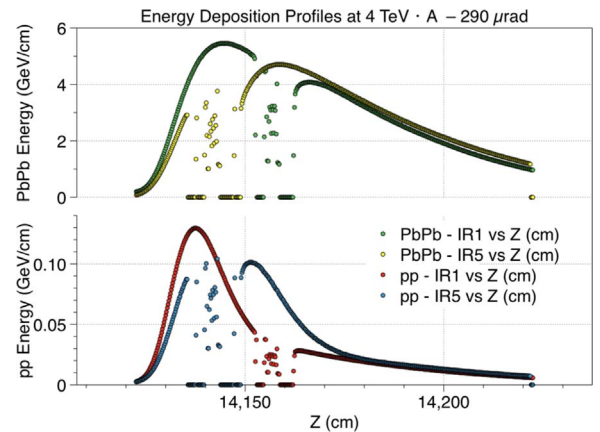


Fig. 8. Simulation of the TAN energy deposition for p-p and Pb-Pb collisions at 4 TeV. In each IR the BRAN is located in a different location, so there is an asymmetry in the shower depositions between the two IRs. The horizontal scale is the distance from the IP. The coordinate, Z, is the distance from the collision point of the IR.

observations from the BRAN reported in the next section. Simulation results for the IP1 crossing angle (Fig. 9) for three beam energies [28] confirm the anticipated increase of the shower collection efficiency at higher beam energies as the shower spread becomes more concentrated. The resulting horizontal angle is consistent with zero as expected. We performed the same simulations for IR5 and the results are identical within statistical fluctuations. A simulated comparison of the amount of energy deposited in the detector in four different modes of operation is shown in Fig. 10. Here each pair of bars refers to one of the four-collider modes and shows the response at the IP1 and IP5 detectors.

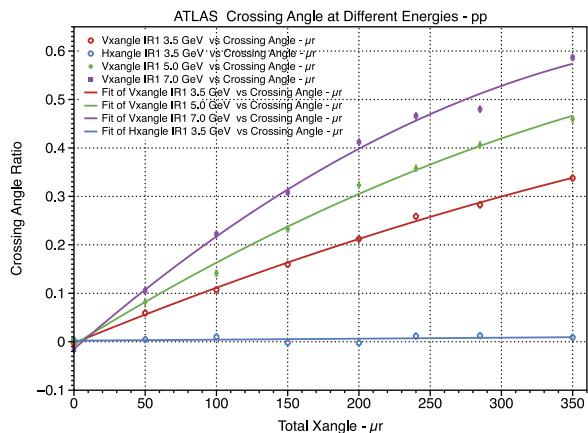


Fig. 9. Simulation of crossing angle ratios for the ATLAS BRAN for three LHC beam energies in p - p operation as a function of total crossing angle.

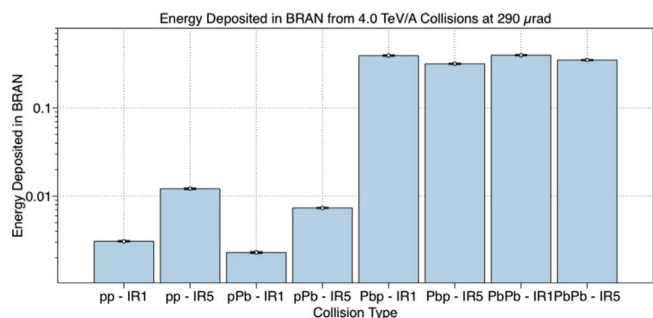


Fig. 10. Comparison of the amount of energy deposited in the detector with p - p , p - Pb , Pb - p and Pb - Pb collision. Note, that the y-axis is a logarithmic scale.

8. R & D program and tests

During the experimental R&D phase of the BRAN design, a prototype of this detector has been tested extensively at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, at RHIC at Brookhaven National Laboratory, and at CERN's SPS. We used an electron beam at the ALS to validate the conceptual design and demonstrate the 40 MHz operation. The performance of the prototype detector was then compared to that of the existing luminosity monitors at RHIC. Finally, we validated the model with a high-energy proton beam at CERN's SPS. The results of these experiments are presented in this section. During these studies, we carefully studied the radiation properties of the materials.

8.1. 40 MHz resolution and signal speed at the ALS

The ALS, which is a synchrotron machine, was used to test the detector speed with the help of a dedicated fill pattern and an x-ray beamline. Using a special housing with a thin wall to allow photon penetration, we irradiated the chamber and compared its signal time sequence with that from a BPM [29]. Intensity scans demonstrated good linearity with no sign of saturation, even at signal amplitudes much higher than those expected at the LHC. Signal deconvolution techniques were adopted to compensate minor residual pileup. These experiments allowed us to validate the modeling results and to demonstrate the capability of full signal processing within the desired 25 ns resolution.

Then at the ALS, we used the 1.2–1.5 GeV electron beam at the BTS (Booster-To-Storage ring) transfer line and operated it in single bunch mode at 0.5 Hz. With this setup, we could also complete a set of measurements to validate the model of the system. In particular, we found the highest detector speed by increasing the bias voltage at a fixed pressure until the drift speed reached a plateau. The time to peak

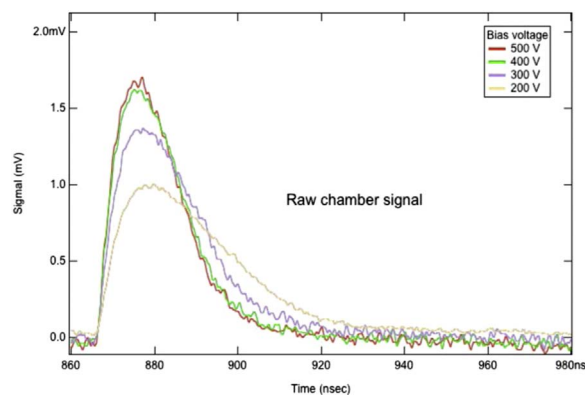


Fig. 11. Bias voltage scan.

height (10 ns) shown in Fig. 11 demonstrates that the luminosity of adjacent bunch pairs with 25 ns separation can be resolved with $E/p=200$ V/(bar·mm).

8.2. Rad hardness studies at BNL and CERN

Due to the extreme levels of radiation, we organized two radiation damage tests, one at BNL's RHIC using the RHIC linac high intensity beam and one at the CERN ISOLDE ion source facility. The results of these tests [30] helped confirm the final choice for the materials of the detector elements.

8.3. Collider tests at RHIC

In order to validate the expected performance of the device, we had the opportunity to test the prototype BRAN detector in a collider environment and compare its performance with the Zero Degree Calorimeters (ZDC) [31] that are used at RHIC as the primary luminosity monitors for collisions. The prototype detector was installed between two ZDC modules. The chamber was operated with a 94% Ar and 6% N gas mixture at a pressure of 8 bar. Due to the voltage rating of the prototype connectors, we operated the chamber at 400 V, which did not optimize the speed of the signal at that pressure. The discriminated analog output from all four quadrants was recorded by the RHIC control system using scalers. Fig. 12 shows the correlation between one of the LUMI quadrants and the ZDC scaler during a dedicated Vernier scan. The scatter plot shows a very good linear agreement between the BRAN and the RHIC ZDC.

8.4. Shower studies at the SPS

Tests at CERN's SPS North Experimental Area provided the opportunity to characterize the device and, in particular, to study the

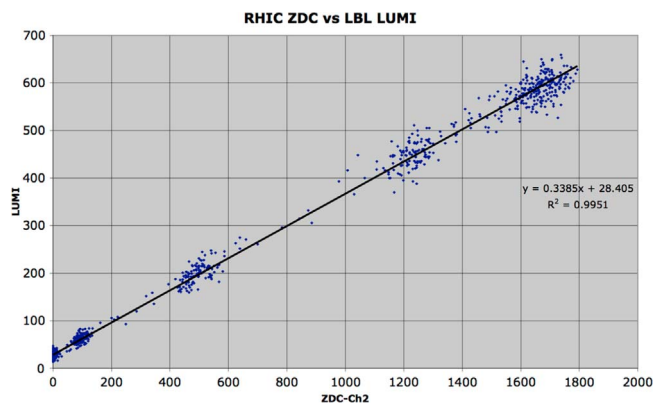


Fig. 12. Correlation between the counts from ZDC-Ch2 and the LUMI quadrant 2.

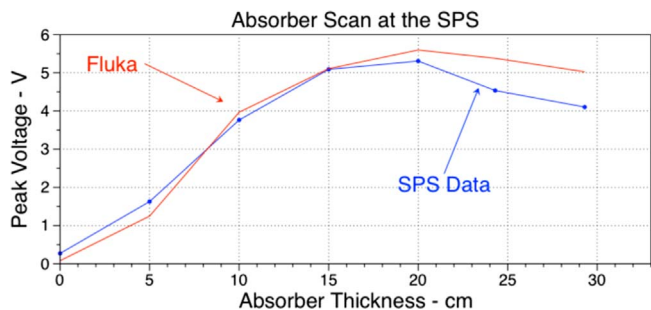


Fig. 13. Average energy deposited in a quadrant versus absorber thickness compared with FLUKA-predicted numbers. This data were taken at CERN's SPS accelerator.

propagation of the hadronic shower in copper. This is important as the neutral products from the beam interaction at the LHC IPs produce additional showers in the TAN absorber housing the BRANs. For this measurement, the 350 GeV extracted proton beam from the SPS hit the chamber, which operated at a pressure of 8 bar. The system was installed on a 2-axis stage and the chamber positioned to have the beam hitting the center of a quadrant.

Digitized waveforms from each quadrant were recorded. The measured data are compared to those predicted by the Monte Carlo simulation program FLUKA in Fig. 13. Each data point refers to a different copper absorber thickness. The results [32] show that the shower amplitude increases up to a 20-cm thickness of copper absorber before decreasing, in excellent agreement with the simulation.

9. Experimental results

9.1. Modes of operation

The BRAN detectors are used in two different ways. In “Counting Mode” a hit for each bunch crossing is declared every time the voltage exceeds a threshold. This method works well at low luminosity, but can saturate due to pile-up when the number of p-p interactions per bunch crossing exceeds unity. In the second method, called “Pulse Height” mode, the average pulse height from each collision is recorded. The pulse height mode is linear but it tends to be dominated by system noise at low luminosity. To study these phenomena, we used the data simulated by FLUKA on an event-by-event basis. For each value of the average number of p-p collisions per bunch crossing, we generated the number of collisions using a Poisson distribution and summed the collected charge from one interaction. The results are plotted in Fig. 14 for several thresholds. In this plot a flat curve is indicative of a linear response of the BRAN. By interpolating these results one can see the linearity for a threshold level close to about 13 mV is approximately correct in the range from 10 to 30 average collisions per bunch.

9.2. Total luminosity in p-p collisions

Since the early days of the LHC commissioning, the BRAN has been a reliable tool for operating the machine and configuring the IPs for optimized collisions [33,34]. The device has been used in every production run to bring the beams in collision and through the beta squeeze, leading to the production mode configuration of the LHC (stable beams) when the experiments publish their results. Fig. 15 compares the luminosity recorded by the BRAN detectors and ATLAS and CMS in the early operation of the LHC.

In most of the proton runs up to LS1 [35–37], the LHC has operated with a 50 ns bunch spacing, an energy up to 4 TeV per beam exceeding by more than 50% the nominal bunch charge, and with an emittance significantly smaller than design value. This effort resulted in peak luminosities up to $7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The BRAN responded without problems to the challenge posed by the increased pileup effects that resulted from the improved machine performance.

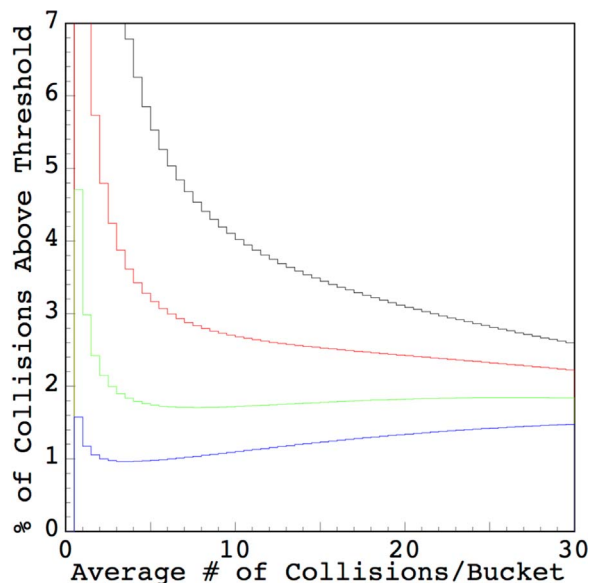


Fig. 14. Simulation of the fraction of collisions detected by the BRAN in counting mode as a function of the average number of collisions per bunch crossing. Thresholds are 10 mV, 15 mV, 20 mV and 25 mV from the upper curve (black) to the lower one.

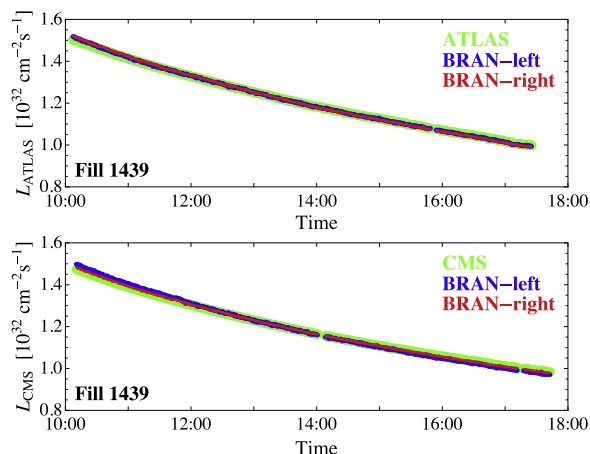


Fig. 15. Time dependence of the Luminosity in IP1 and IP5 experiments by the LHC experiments and the BRAN detectors.

During the 2011 run, we configured the LHC's data logging system (Timber)* to collect data in counting mode for the left side of an interaction region (as viewed from someone standing in the center of the LHC ring), and in pulse height mode for the right side. In addition, both modes are simultaneously read out for each BRAN detector and available for monitoring. For counting mode, the number of counts for each colliding bunch pair was accumulated for 1 s. For pulse height mode, the pulse height of each colliding bunch pair was also averaged over 1 s. Figs. 16 and 17 show the response from both the IR1 and IR5 BRAN detectors. The left side (operating in counting mode) has less statistical noise than the right side (which operates in pulse height mode). If the time period of the pulse mode were increased, its statistical error per measured point would decrease. This data show that most of the charge is collected in half of the ionization chamber (two quadrants) when the beams collide at a 240 μrad crossing angle. Both Figs. 16 and 17 show a slight change of the energy deposition in the most populated quadrants at the time 5:20 after the beams are brought into collision. This shift in energy deposition was confirmed by data from the LHC BPM data which recorded a $\sim 100 \mu\text{m}$ orbit shift at the same time.

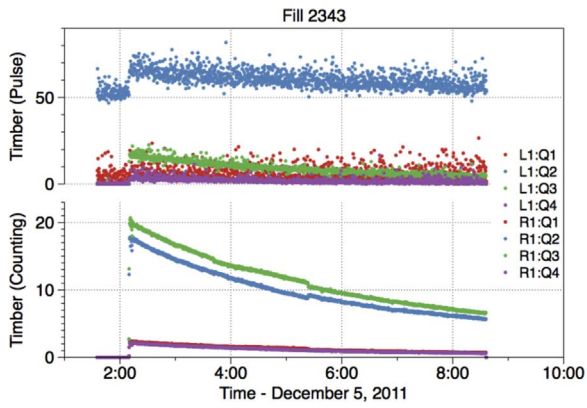


Fig. 16. Timber values collected for Fill 2343 for each quadrant of the IR1 BRAN detector. The top plot is for the right side in pulse height mode; the bottom plot is for the left side in counting mode.

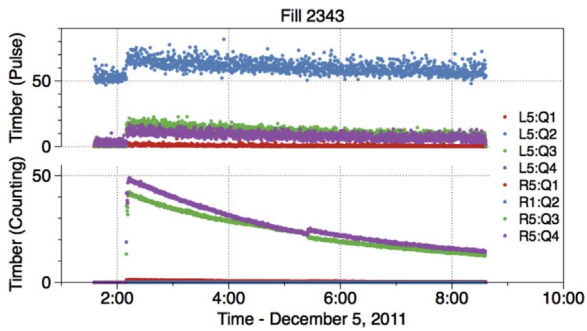


Fig. 17. Timber plots for the IR5 BRAN.

9.3. Bunch-by-bunch luminosity

Fig. 18 shows a comparison between measurements of bunch-by-bunch luminosity at IP5 recorded with the BRAN and the CMS detectors. The data were taken for one proton fill with 150 ns bunch spacing and 348 colliding bunch pairs at the beginning of the fill with a total luminosity of about $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. Each data point shows the average value and the standard deviation of measurements taken over 10 min. The agreement between the results from the two independent detectors is very good and the histogram of the relative differences for all 348-bunch pairs shown in the lower plot is consistent with a 1.0%

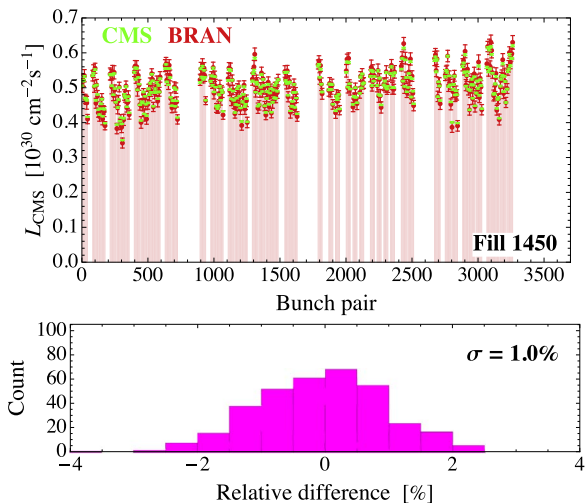


Fig. 18. Snapshot of bunch-by-bunch luminosity measurements at IP5 from CMS and the BRAN (upper plot), and histogram of the relative difference between the two data sets (lower plot).

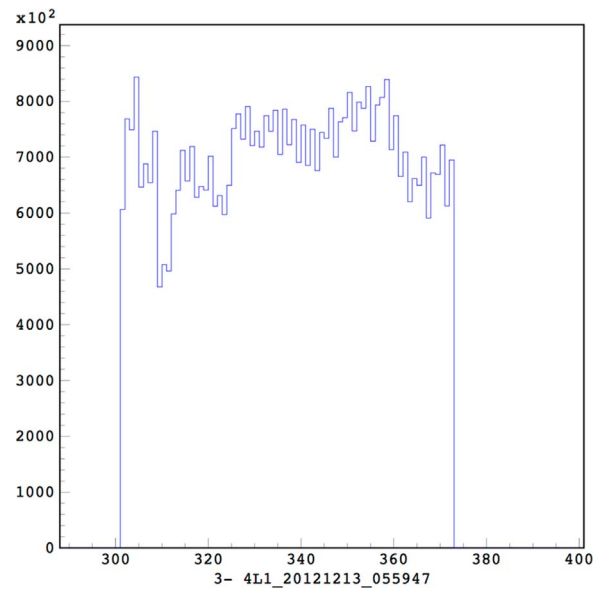


Fig. 19. Data collected at 40 MHz bunch collision rate. The x-axis is the collision bunch number and the y-axis shows the relative bunch intensity.

standard deviation.

The standard deviation of the relative differences remains at the same 1% level up to the end of the about 12 h fill with a luminosity level of about $1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. When operated in counting mode, the BRAN can provide, after proper calibration, a 1% precision level both for the total and the bunch-by-bunch luminosity.

9.4. Monitoring 40 MHz (25 ns) collisions

Starting during the last weeks of the 2012 run, the LHC was configured to collide trains of bunches separated by the 25 ns design time interval. This allowed both the experiments and the accelerator to test and validate their systems at the design bunch separation. Bunch-by-bunch collision data at 40 MHz rate were recorded at the BRAN detectors. The data are shown in Fig. 19. The absence of a tail following the end of the pulse train at approximately 374 bunch pairs confirms the ability of the detector to resolve the nominal 40 MHz collision rate.

Fig. 20 shows the histogram of the signal from the four quadrants for the left BRAN in IR1. Most of the signal is going into the lower two quadrants because of the vertical crossing angle in that IR. The data

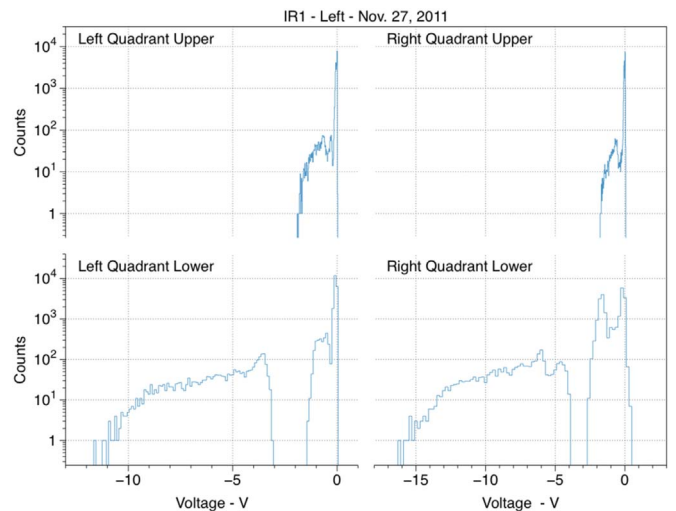


Fig. 20. Pulse height distribution of the analog signals from the left BRAN in IR1. The quadrants are arranged in the geometry that is viewed from the collision point in IR1.

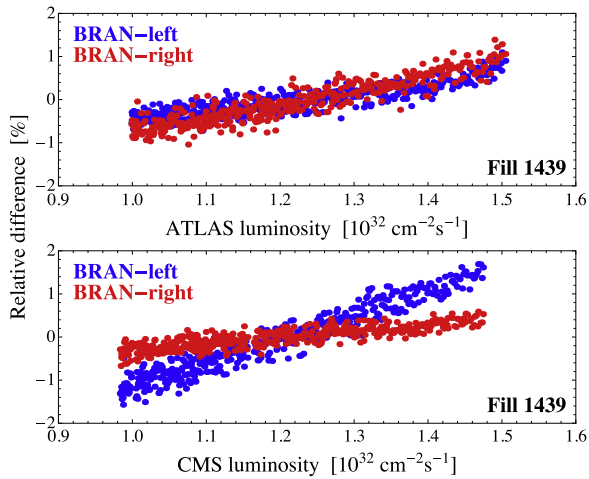


Fig. 21. Relative difference between the luminosity measurements from the BRAN and the ATLAS and CMS experiments in early p - p collision mode of operation.

includes beam bunches that are empty and thus contribute to the pedestal. The pedestal is very narrow indicating that the noise is low compared to the signal. The lower curves show that the detector is not saturating and therefore can measure the full dynamic range of the shower.

9.5. Comparison with the ATLAS and CMS luminosity detectors

Fig. 21 shows the relative difference between the luminosity data from the BRAN detectors and the detectors in IP1 and IP5 for an early p - p run. Besides the BRAN detector in the left side of IP5 (CMS, bottom plot), which had a noise issue, the other counters exhibit systematic errors of about $\pm 1\%$ in agreement with the BRAN design goals.

A performance comparison recorded in a more recent run in 2011 is plotted in Fig. 22 showing the relative difference between the rate observed at each IP1 BRAN detector versus the values provided by the ATLAS luminosity detectors. While there is a very good agreement for the left BRAN (pulse height mode, red plot) the non-zero slope from the left BRAN in counting mode is explained with saturation and electronics noise.

Another study of the BRAN linearity is shown in Fig. 23. This figure shows better linearity in pulse height mode than in counting mode as expected, with an agreement with the experiment within 1%.

9.6. Lead-lead Ion collisions

Although the BRANs were designed for proton operation, they are

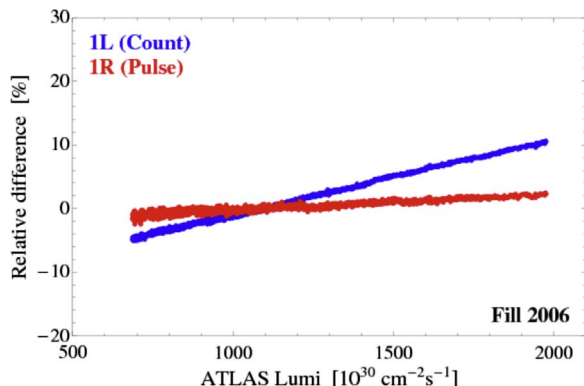


Fig. 22. Comparison of the relative difference between the BRAN right side (pulse height mode) and left side (counting mode) for IP1 under p - p operation.

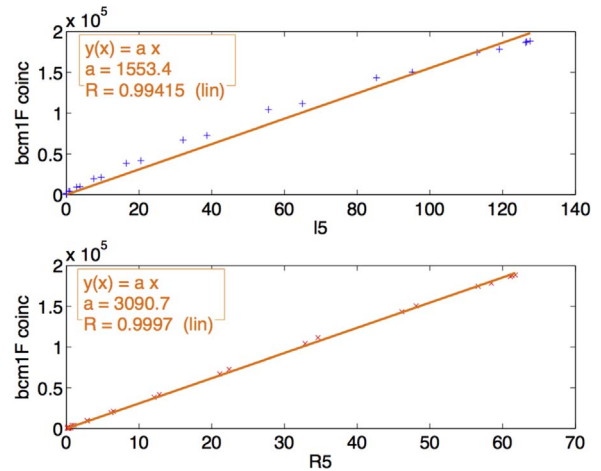


Fig. 23. Comparison between the performance of the Left and Right IP5 BRAN detectors (horizontal) and the CMS bcm1F coincidence detector (vertical) at different luminosities.

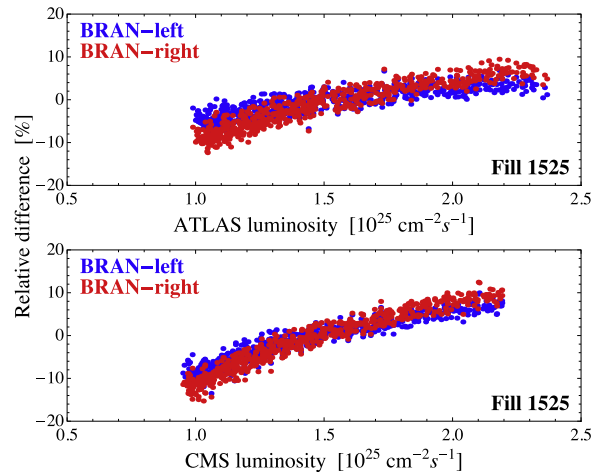


Fig. 24. Comparison of the relative difference between the right (pulse height mode) and the left side (counting mode) of the BRAN detector with ATLAS and CMS in Pb - Pb operation.

also operated routinely during lead ion collisions. The data shown here are from November 2010, when the luminosity was on the order of $10^{25} \text{ cm}^{-2} \text{ s}^{-1}$ corresponding to a collision rate of several kHz, typically two to three orders of magnitude lower than in proton operation. Fig. 24 shows the relative differences between the BRANs and experiments for one lead ion fill. Compared to proton operation in Fig. 21 the BRANs exhibit systematic errors about $\pm 10\%$ larger.

9.7. Proton-lead Ion Collisions

In another novel configuration that was first implemented during the LHC's last run before LS1, the performance of the four detectors at both sides of the IP1 and P5 interaction regions was assessed during the accelerator operation with p - Pb collisions. Results collected at IP1 are shown in Figs. 25 and 26 for both the pulse height and counting modes of operation. The asymmetry of the distributions generated by the vertical crossing angle is clearly visible. Similar results were collected in at IP5 where the asymmetry is in the horizontal plane.

Comparisons between signals from the right and left side detectors shown in Figs. 24 and 25 indicate that the shower from the *Lead* beam is approximately 18 times stronger than the corresponding shower from the *Proton* beam. Each figure shows the quadrants “as seen” from an observer situated at the beam interaction point looking toward each detector. Thus, the top two quadrants in the figures are the top

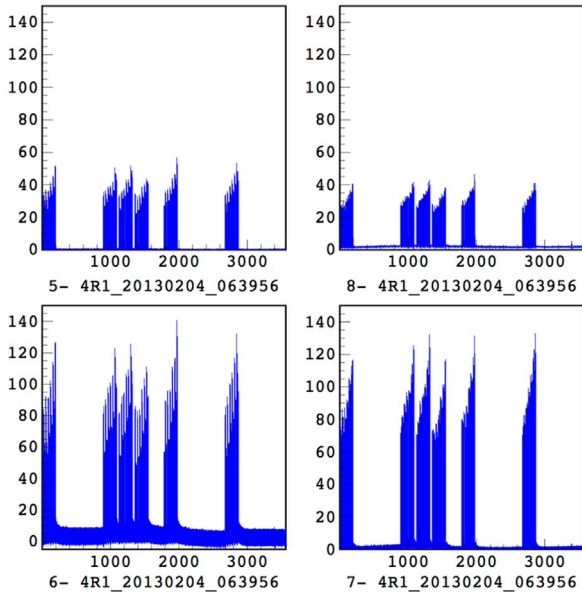


Fig. 25. ATLAS BRAN in pulse height mode in p - Pb operation. Data is from detector at right side of IP1 capturing the lead ion beam shower.

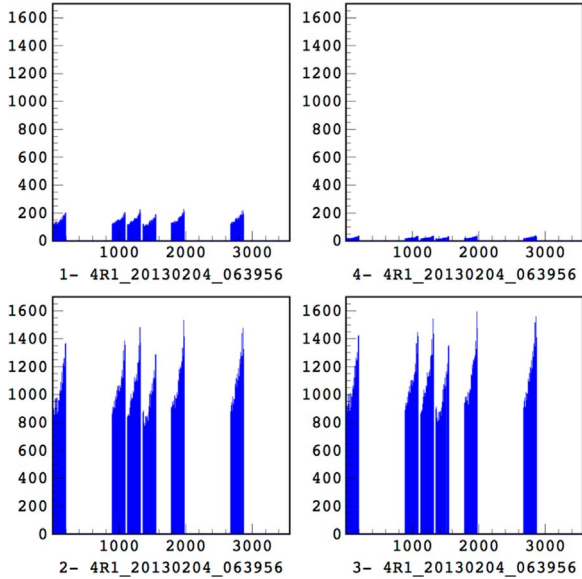


Fig. 26. ATLAS BRAN in counting mode, p - Pb operation. Data are from left side detector looking at the p beam. Only the bottom portion of the BRAN quadrant is significantly populated due to the vertical crossing angle.

quadrants of the BRAN.

9.8. Van der Meer scans

Fig. 27 shows a comparison of the performance of the BRAN detectors in IP5 with data from CMS taken during a Van der Meer scan. At this time, the LHC operated at 4 TeV for each proton beam and had a $290 \mu\text{rad}$ full crossing angle. The response from the left detector operating in counting mode saturates as expected, while that from the right one is very linear with the CMS detector.

A Gaussian fit shows a standard deviation of $(31.94 \pm 0.14) \mu\text{m}$ for the right BRAN detector data as compared to a $(32.06 \pm 0.06) \mu\text{m}$ measurement from the CMS HF detector and a $(32.95 \pm 0.07) \mu\text{m}$ one from the CMS BF detector. The slightly higher error in the BRAN could be improved with a longer integration time. These measurements show that the BRAN's accuracy is comparable to that of the CMS detectors.

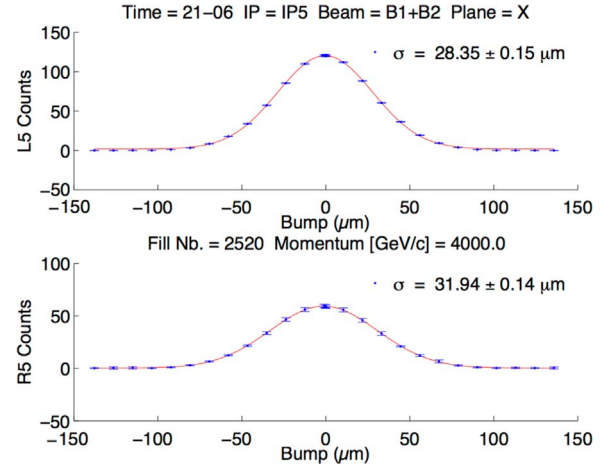


Fig. 27. Fit of the Van der Meer scan for the IR1 and IR5 detectors in pulse height mode. The beam energy is 4.0 TeV/beam.

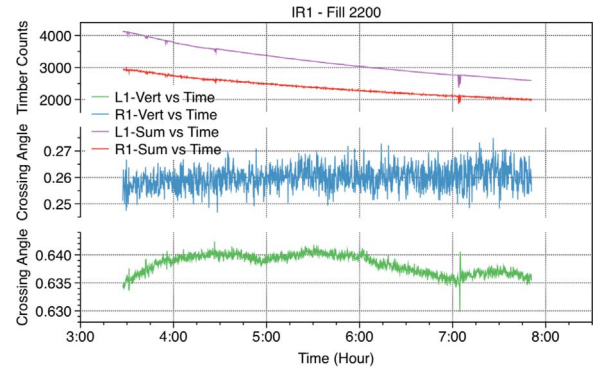


Fig. 28. Monitoring of the crossing angle for Fill 2200. Top curves show the time decay of the total shower intensity. The normalized bottom plots show a constant behavior of the crossing angle. Larger fluctuations from the R1 detector are due to the pulse height operation.

9.9. Monitoring the crossing angle

Fig. 28 shows a time plot of a monitoring of the crossing angle in IR1 for the 2011 LHC run with a nominal vertical crossing angle of $240 \mu\text{rad}$. The two upper plots show the amplitude of the total shower in the four quadrants of the BRAN, proportional to the Luminosity and decreasing with time. The lower graphs show the information from the top quadrants normalized to the total shower intensity, proportional to the crossing angle. The green curve shows larger fluctuations because the R1 BRAN operates in pulse height mode. The time plot also shows one instance when the ratio changes at the same time as the luminosity. Analysis of the LHC BPMs data confirmed deviations at the same.

9.10. Beam property measurements and operator user interface

Fig. 29 shows a 12 h segment of Fill 1372. The BRAN data (red curve) and the Timber CMS data (green scatter plot) document the time evolution of the bunch-by-bunch luminosity and of the rms beam size of the interaction area. This information was obtained by combining the BRAN luminosity information and the bunch population from the LHC beam intensity monitors via Eq. (6).

The Operator Interface panel depicted in Fig. 30 shows the LHC operators the information obtained by the BRAN. The two graphs on the top, display the evolution of the instantaneous bunch-by-bunch luminosity in IP1 and IP5, respectively. These graphs provide information on the contribution to the luminosity time decay originating from bunch emittance blow-up. The lower four plots in Fig. 30 document a batch of protons injected with larger-than-nominal emittance just after

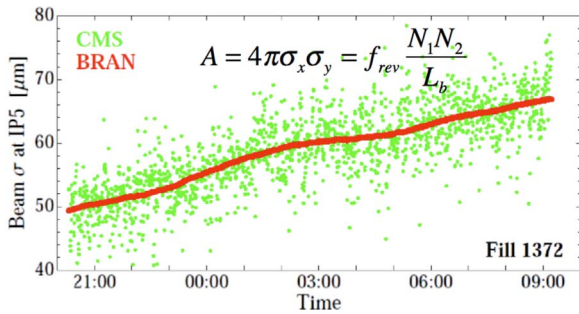


Fig. 29. Monitoring of the emittance growth via the time evolution of the interaction area evaluated from the specific luminosity measure at IP5 from the CMS detectors and the BRAN in pulse height mode.

bunch 500 with the consequent loss in luminosity.

Among other plots captured with the BRAN, Fig. 31 shows the luminosity behavior for a Pb-Pb run. This plot shows an excellent picture of the profile of the colliding heavy-ion beams.

9.11. The structure of an LHC turn

By observing Fig. 32, one can see the general structure of a turn. In the upper left graph, one sees the full turn. There are 15 bunch trains followed by the abort gap. The upper right hand graph shows two of these bunch trains followed by a third, while the lower left shows one of the bunch trains. The lower right hand graph shows that the BRAN

observes counts only in one RF bucket and it does not detect collisions for the next seven buckets until protons collide at bucket nine. This information is very valuable, as it confirms the effects of intra beam scattering in the SPS. There the leading bunches sit at injection while the SPS ring is getting filled and their emittance grows due to intra beam scattering. As a result, trailing bunches have higher luminosities than leading bunches.

10. Conclusions/outlook

We have described the design and the operation of a device (BRAN) that is installed in the LHC high luminosity interaction points (IR1 and IR5). This device can measure the relative bunch-by-bunch luminosity, the rms beam size and the crossing angle of the beam. The BRAN is a collider operations controlled device that can help operators and beam physicists diagnose the LHC and optimize its performance.

Currently the LHC's luminosity [38] reaches $1.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a peak pileup of 45 events per bunch crossing. The nominal design luminosity of the LHC has been exceeded. At this intensity, the BRAN detectors continue to operate well and are routinely used by the LHC machine operators.

We have shown how by measuring the bunch-by-bunch specific luminosity it is possible to extract the corresponding values of the bunch emittances in collision, and to monitor their behavior during a beam storage cycle. We have shown that the BRAN measurements of luminosity track the luminosity measured by the ATLAS and CMS experiments. Also, the BRAN can detect subtle changes in the LHC beam.

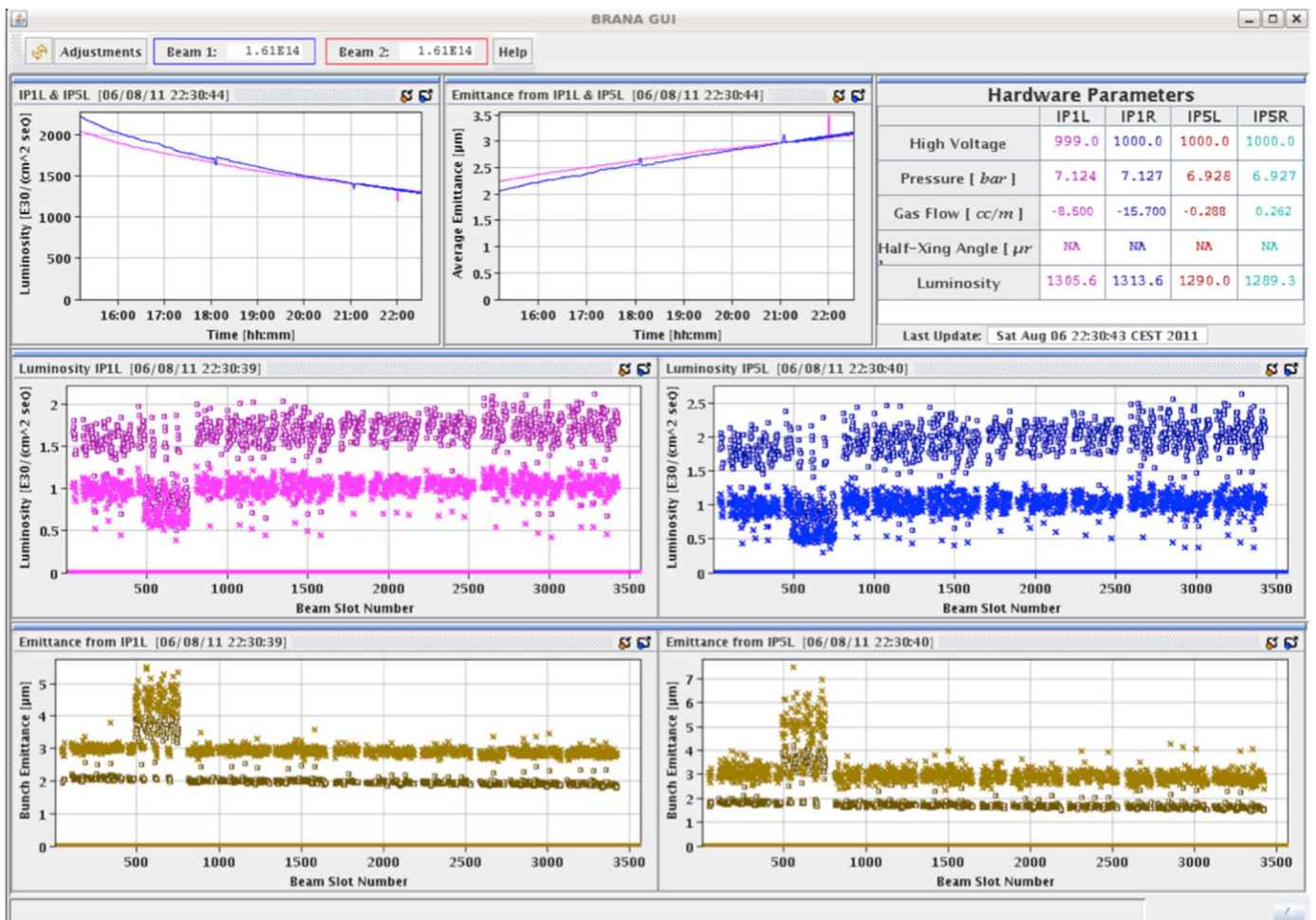


Fig. 30. The BRAN Operator Interface. Shown on the top left are the measurements of luminosity and the top center the measured emittance taken on August 6, 2011. The abscissa of these plots is the bunch number. They show the luminosity time decay and the emittance growth. This data in blue is from IR1, while the data in red is from IR5. The middle two plots show the luminosity in IR1 and IR5 as a function of beam slot number, while the lower two plots show the emittance as a function of beam slot number.

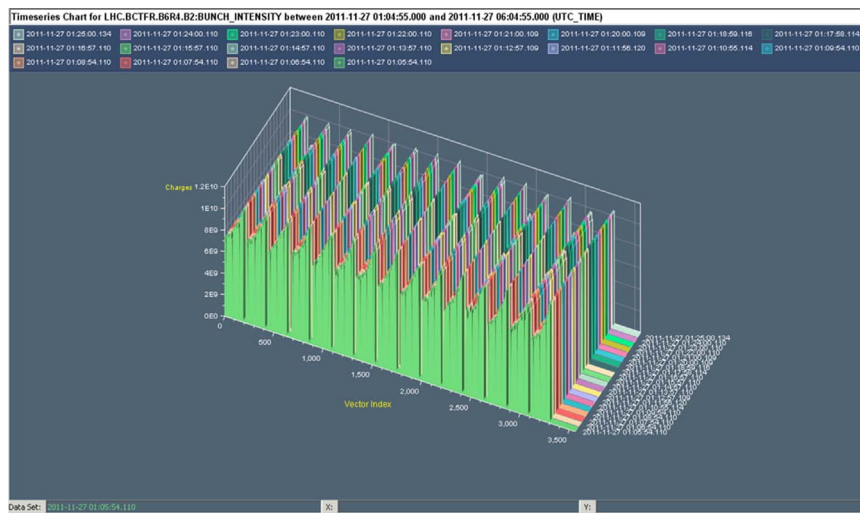


Fig. 31. The TIMBER plot showing the time dependence of the luminosity measured in *Pb-Pb* LHC operation for Fill 2328 on Nov. 27, 2011. On the long abscissa is the bunch number with the abort gap at the bottom right. The other axes give the time of the measurement and the bunch charge.

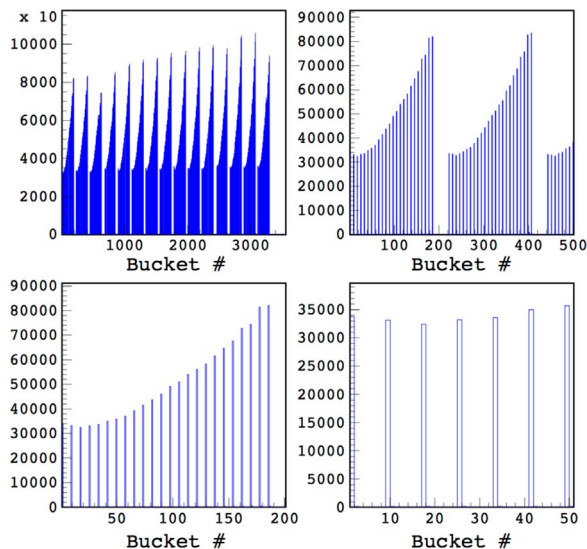


Fig. 32. The summed number of counts in IR5 for one turn. The difference in each panel is the bunch number. This counting mode data were taken during the PbPb 2011 run.

A very important aspect of the BRAN is that it is capable of detecting fluctuations in time and on a bunch-by-bunch basis. In addition, it is the only instrument detecting beam-beam collisions during machine development studies when ATLAS and CMS are typically turned off to protect the readout systems of their electronics.

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