ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-MOP45

A NEW LUMINOSITY MONITOR FOR THE LHC RUN 3

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Abstract

The Beam RAte of Neutrals (BRAN) is a monitor that provides a relative luminosity measurement for the four LHC experiments. BRANs are used during operations as a tool to find and optimise collision and to cross-check experiments luminosity monitors. While each LHC experiment is equipped with BRANs, in this contribution we will focus on the new monitors installed for ATLAS and CMS that will replace the ageing gas chambers during LHC run 3. These will also serve as prototypes for the future High Luminosity LHC monitors that will need to sustain an even higher collision rate. A description of the BRAN as well as the first results obtained during the LHC Run 3 start-up will be presented.

INTRODUCTION

The BRANs are luminosity monitors installed on both sides of the four LHC experiments to measure the relative luminosity. The working principle is the detection of electromagnetic showers produced inside a target absorber by neutral particles (neutrons and high-energy photons) from the collisions. The detected signal I is thus proportional to the collision rate, that can be related to the luminosity $\mathcal{L}$ through [1]

$$I \propto N = \sigma \mathcal{L} \ , \tag{1}$$

where N is the collision rate and σ the relative cross section. Neutral particles propagate in the direction of the colliding particles and can be intercepted at a sufficient distance from the Interaction Point (IP) when the two LHC beams are sufficiently separated by the D1 dipole. In the case of the Interaction Regions (IR) 1 and 5 - Atlas and CMS respectively - the BRANs are inserted inside the Target Absorber of Neutrals (TANs) at approximately 140 metres from the IP, in a position as close as possible to the maximum of the shower produced in the TAN.

BRANs are *relative* bunch by bunch luminosity monitors that are mostly used by LHC operators as a simple and reliable tool to find and optimise collisions and to cross-check the *absolute* luminosity monitors maintained by the LHC experiment that measure the actual instantaneous and integrated luminosities. As mentioned, the absolute calibration of the BRANs is not per se a requirement, the emphasis being on the stability, linearity and resolution. Table 1 contains a summary of the BRAN requirements. During the LHC runs 1 and 2, the BRANs installed in IR 1 and 5 were gas ionisation chambers [2] produced by Lawrence Berkeley

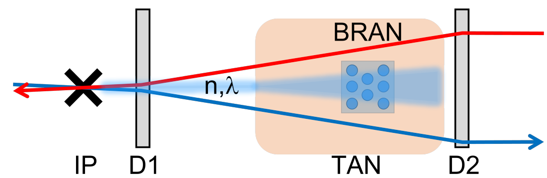

Figure 1: Layout of IR 1 and 5. BRANs are installed in the TANs approximately 140 metres from IP.

National Laboratory. While these detectors worked well through the LHC runs, they have been operating since 2009 in a high radiation environment and suffer from ageing components. In addition, these cannot be operated in the future High Luminosity (HL) run 4 of LHC as new absorbers with different geometry will replace the TANs to cope for the increased collision rate. It was therefore decided to develop new BRANs for IR 1 and 5 with the aim of replacing the gas chambers for LHC run 3 and to serve as a prototype to test materials and detection principles for the HL run 4. Two such detectors have been installed in February 2022 during the LHC year-end technical stop (YETS), at the right of IP1 and left of IP5. The two remaining BRANs are being assembled in view of an installation during the 2022-23 YETS. In this contribution we will describe the instruments and present the very first data available to date from Run 3 commissioning.

INSTRUMENT DESIGN

The principle of the new BRANs is the measurement of Cherenkov radiation produced in fused silica rods that are crossed by the showers produced by the TANs. Eight 603 mm long, 10 mm diameter fused silica rods are hosted in a mixed copper and aluminium enclosure that is inserted in the 100 mm wide TAN slot as shown in Fig. 2a. The rods are made of an ultra-pure, Hydrogen-free synthetic silica with low OH content. This type of material - Suprasil 3302 by Heraeus Quarzglas - was chosen among other types of fused silica that have been irradiated inside the IR1 TAN during the 2nd LHC run as it showed the minimum drop of transmission over the range 160-650 nm, attaining 20% of the transmission of the non-irradiated sample after being exposed to a dose of 0.8 MGy [3]. These results have been confirmed by a post run analysis of the spectral transmission of five rods performed in 2018 at the university of Illinois [4] showing that transmission of Suprasil in the visible range (400-600 nm) is practically unaffected by radiation exposure. As for the UV, all samples show a decrease of transmissivity particularly around 214 and 325 nm where

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Table 1: Summary of BRAN Requirements from Ref. [5]

Use case	**Resolution [Hz/μb]**	**Rel. accuracy**
Initial beam finding and overlap	10^{-2} (nominal bunch) 10^{-4} (pilot bunch)	±10%
Luminosity maximisation	±1%	±1% nice to have ±5% sufficient

most of the Cherenkov photons are produced. The presence of hydrogen affects the rate at which this process takes place, with hydrogen-free silica degrading almost instantaneously but attaining a stable value, as opposed to hydrogen-rich samples that have a slower decay but exhibit transmission variation over time at steady state. Cherenkov radiation

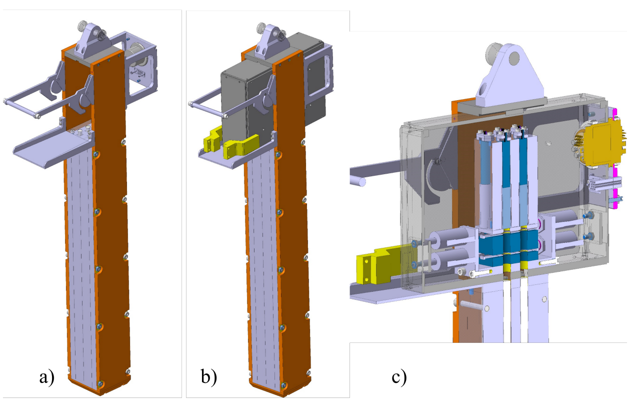

Figure 2: BRAN design: glass rods enclosure (a). The Photo Multiplier (PMT) light-tight enclosure is slid on top (b). Section (c) shows the solenoid-actuated light apertures and the PMTs.

produced in the fused silica bars propagates to its extremities, the top one in contact with a PMT. The type chosen (Hamamatsu R2496) is a fast time response, 8 mm diameter head-on bialkali PMT with a fused silica window that has been used, in its version with borosilicate glass window, in the Run 2 studies of Ref. [3]. Each of the eight PMTs is protected by a magnetic shield case and is hosted inside a light tight enclosure that is slid on top of the silica bars enclosure (see Fig. 2b). The sliding mechanism is equipped with a handle to facilitate the connection/disconnection of the PMT enclosure and to facilitate robotic handling. The amount of Cherenkov radiation impinging on the detectors can be controlled by means of variable aperture that are inserted in front of the PMTs (see Fig. 2c) by means of push solenoids. Three transmission levels of approximately 100%, 10% and 1% can be set independently to the first line of three PMTs closer to the IP (see Fig. 1) to have two sets of channels with different sensitivity to cope with the large instantaneous luminosity range that is achieved during machine commissioning and operation. Solenoids have been chosen against other technologies (e.g. pneumatic actuators) for simplicity and tolerance against the very high dose that is achieved in IR 1 & 5.

SIGNAL PROCESSING

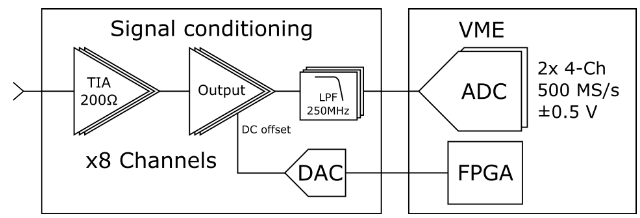

Figure 3: Schematic of the BRAN data acquisition.

The signals from the PMTs are conditioned using custom-made front-ends composed of trans-impedance amplifiers (G=200 V/A) followed by 250 MHz anti-alias filters (see Fig. 3). High radiation dose in the LHC tunnel causes the analogue electronics to fail quickly, so the front-ends cannot be placed close to the PMTs. They are instead installed in the service galleries through 213 and 138 metres-long cables for IR 1 & 5 respectively.

The analogue signals are digitized using digital acquisition systems (DAQ) installed as well in the service galleries. The signals are digitized using two FMC form-factor 4-channel 500 MSPS 14-bit ADCs, each hosted in an in-house built VME FMC Carrier [6], which provides necessary FPGA resources to perform digital signal processing and communication upstream using the VME bus.

Due to cable length, noise is induced by electromagnetic coupling, with significant perturbations in the bandwidth up to ≈ 200 kHz, peaking at 600 Hz, causing as well DC baseline shifts. As such DC displacement can cause saturation of the ADC, it has to be corrected before the signal is converted to the digital stream by injecting an opposite voltage to the amplifier stage using DAC. The DAC stores the default value internally, and can only be re-programmed through the VME interface. The 600 Hz noise component is significantly lower than the LHC revolution frequency of 11.2 kHz, it can be digitally removed.

The digital processing chain is shown in Fig. 4. The entire processing is performed over four 16-bit words ADC frames, a word being composed of 14-bit MSB aligned sample and two zeroed LSBs. With four ADC channels that represents a total of 256 bits per frame running at a frame rate of 8 ns, the sample rate of 500 MSPS is achieved. The two unused LSBs in each word are used to tag in each channel the samples by the turn and bunch marks. The timing information comes from the LHC beam synchronous timing (BST). As the two data sources are asynchronous - ADC running at 500 MHz,

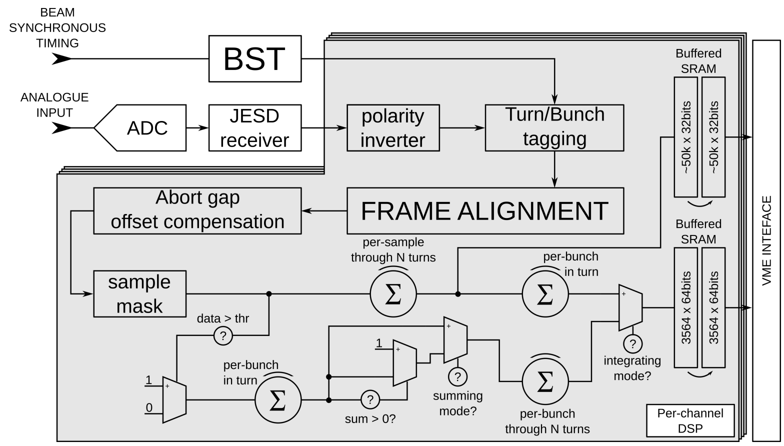

Figure 4: Simplified schematic of the BRAN digital data processing.

BST at 160 MHz, the stream tagging incurs in an uncertainty of 1 ADC sample (2 ns), hence integral of one LHC bunch slot corresponds to a sum of 12 or 13 samples.

As the BRAN is a turn-based measurement instrument, all the words within a single LHC turn must be aligned such that the first word in the turn starts at the boundary of the frame. This simplifies the synchronization of the per-sample and per-bunch accumulators to the turn. The frame aligned data are compensated for the offset by subtracting at each turn a pedestal corresponding to the average signal measured in the LHC abort gap region of the previous turn. A sample mask can be setup to clear individual samples within a bunch slot.

The firmware currently supports three mutually exclusive operating modes, which return a vector of 3564 × 64 bits signed values:

- **Integrating mode** - cumulation of individual samples over N turns followed by their integration per bunch slot
- **Summing mode** - expresses number of samples in the bunch slot exceeding a given threshold when cumulated over N turns
- **Counting mode** - how many times in the given bunch slot there was at least one sample exceeding the threshold when cumulated over N turns

Firmware further exports the raw output of the per-sample accumulator as a vector of 44500 × 64 bits signed values. These data are used to set up correctly the timing relation to the measured beam signal, and serve for debugging as well. Dual-port memory blocks used to store the results are equipped with locking mechanism assuring enough time for the SW layer to load the data. IRQ is triggered when new data arrive to the output buffers.

The memory buffers content is periodically fetched through the VME interface, published and logged through the CERN's Front End Server Architecture (FESA) server running on the VME crate front-end computer.

FIRST DATA FROM LHC RUN 3 COMMISSIONING

Counting Mode for Low-Luminosity Fills

The first collisions at 6.8 TeV took place between May and June 2022. Plotted in Fig. 5 is the very first data from the

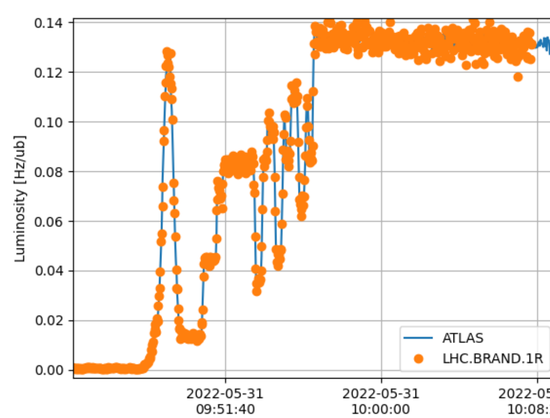

Figure 5: First BRAN data from IR1: low luminosity commissioning run with pilot bunch (orange points). Data are plotted against the reference instantaneous luminosity published by ATLAS.

BRAN detector installed in IR1 right (orange points) against the reference instantaneous luminosity published by the ATLAS experiment. The plot shows the beginning of luminosity scans with one colliding nominal bunch at $\beta^* = 19.2$ m. The BRAN is set-up for low-luminosity fills, that is in counting mode and with 0% attenuation. The BRAN shows a very good agreement with the experiment luminosity data over the entire scan range. Data at 0.14 Hz/μb show a large scattering due to the fact that some parameters (amplifier gain, counting threshold, ...) were not optimised and the overall data processing scheme was still in commissioning. The standard deviation of the noise at $\sigma = 2.3 \times 10^{-4}$ Hz/μb, defines the *initial* per-bunch luminosity resolution. As mentioned earlier, fused silica bars will loose optical transmission due to

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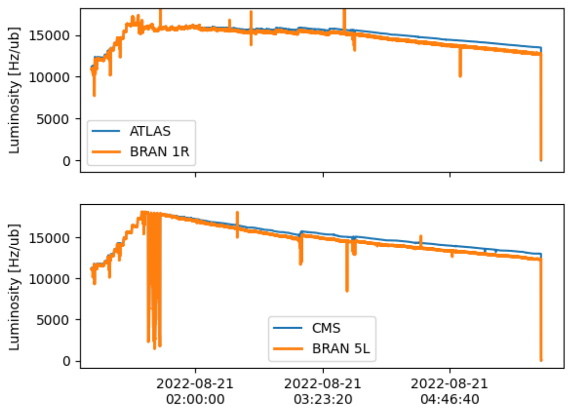

Figure 6: High luminosity fill 8147 with data from IR1 (top) and IR5 (bottom). It can be noticed how the BRAN signal tends to decrease with respect to the respective experiment instantaneous luminosity.

radiation exposure, expecting to level out at approximately 20% of the initial value. As such, the steady-state sensitivity per bunch (i. e. to relative luminosity variations) is expected to be approximately 10^{-3} Hz/µb. This fulfills the requirement for nominal bunches but is some 10 times larger than the one for pilot bunches.

Integrating Mode for Physics Fills

For full physics beams with order of 2500 colliding bunches and $\beta^* = 0.3$ m, the instantaneous luminosity can reach values up to $\mathcal{L} \propto 1.7 \times 10^4$ Hz/µb. The high number of colliding bunches makes it imperative to attenuate Cherenkov light to the maximum value (1% transmission), and for such low β^* integrating mode is preferred over photon counting method that no longer yields the correct relative variation to luminosity per bunch due to the high number of photoelectrons produced per collision event. Figure 6 shows BRAN data from IR1 (top) and IR5 (bottom) for fill 8147 with 2400 colliding bunches. While the agreement between BRAN and experiment luminosity is fair, there can be noticed spike-like data perturbations, and a progressive drop of the BRAN signal that, for this specific fill, reaches 5.9% and 4.8% for IR1 and 5 respectively over a fill duration of approximately 5 hours. Such a behaviour is still under investigation, a possible explanation for the slow signal drop being the progressive loss of transmission of fused silica bars, as discussed earlier. Another possible explanation is a progressive ageing of the PMTs that can happen when exposed to an excessive amount of light, even when the produced anode current is below the maximum rated value (30 µA for R2496 type). The average anode current per PMT however is estimated between 1 and 3 µA. That, according to the manufacturer's guidelines, is a safe level when PMT response stability over time is the priority. Typical resolution for full physics fills is of the order of 50 Hz/µb RMS, so in general better than 1% as required.

Fused Silica Transmission Loss

A progressive loss of transmission in the UV of the fused silica bars affects the overall BRAN light yield. Figure 7 shows the average total luminosity signal from the BRANs during stable beam mode (each point is a physics fill), normalised to the respective experiment absolute luminosity monitor. In accordance with preliminary tests during LHC Run 2, the transmission is expected to drop approximately 80% when at steady state. The decrease in light yield per collision event can be compensated by increasing the aperture from 1 to 10% for high luminosity fills, but will decrease the resolution for the low luminosity use case. The last point of BRAN left of IP5 is significantly lower than expected. This is due to a displacement of the signal baseline that lowers the overall signal intensity. The amplitude of the luminosity signal per bunch however is in line with the previous fill. This effect is still being investigated, but it is unrelated to transmission loss.

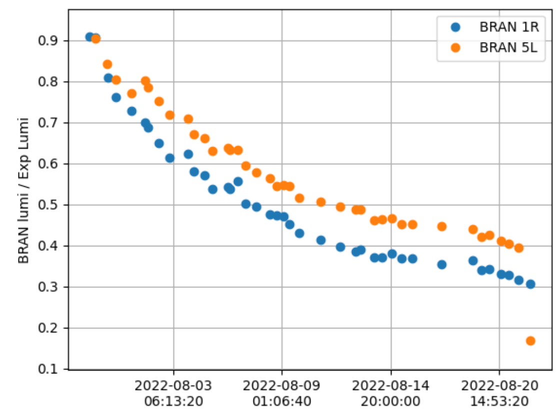

Figure 7: Decay of BRAN vs. Experiment luminosity signal as a function of time during 40 LHC fills in August 2022.

CONCLUSION

We have presented the design and preliminary data of the new BRANs for the LHC High luminosity IRs that will be operated during Run 3. The first two instruments have been installed during the 2021-22 LHC YETS and are being commissioned. Preliminary data show that the BRANs can fulfill most of the requirements for resolution and relative accuracy in both low and high luminosity fills. The relative accuracy is at present around 5% within a fill but a general trend is present probably due to transmission loss of the silica bars. It is expected that at steady state the long-term relative accuracy will be between 5% and 1%. Two additional BRANs will be installed during the 22-23 LHC YETS. The performance and behaviour of the four instruments during Run 3 will be instrumental to the design of the future HL-LHC BRANs that will be operated in the even harsher environment of Run 4, where instantaneous luminosity reach values as high as 6×10^4 Hz/µb and the yearly dose order of 1 GGy.

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