SLAC-PUB-15801

# USING THE BRAN LUMINOSITY DETECTORS FOR BEAM EMITTANCE MONITORING DURING LHC PHYSICS RUNS*

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*Abstract*

The BRAN Ionization Chambers installed at the IP1 and IP5 Interaction Points of the LHC provide a relative measurement of the total and bunch-by-bunch luminosities. This information, combined with the logged bunch charges from a fast BCT monitor, offers the possibility of evaluating the Interaction Area in collision for each of the colliding bunch pairs and monitor its time evolution. An application has been implemented for operators to display the interaction area of the proton bunches interacting in IP1 and IP5 during each of the Physics Runs. This provides a tool for measuring the contribution to the luminosity time decay originating from possible emittance blow-up when operating the Accelerator close to the beam-beam limit. Early results confirm the ability to characterize the bunch-by-bunch emittance behavior during the store and study possible differences among bunches in the same fill. We describe the applications of the detector to beam measurements, from the rate of collisions, to the calculation of crossing angles as well as the measurements of transverse emittance of the beams in collision.

## THE BRAN DETECTORS

The BRAN (Beam RAte of Neutrals) detector is a fast ionization chamber designed to measure the relative luminosity of the LHC at the IR1 (ATLAS) and IR5 (CMS) interaction regions. The device, described in several recent papers [1-3], is used as a high intensity luminosity detector with a wide dynamic range. Four BRAN chambers are installed in the TANs, steel and copper absorbers located on either side of IP1 and IP5, and measure the flux of neutrons and photons from *p-p* collisions in the forward direction. Figure 1 shows the position of the detectors in the interaction region.

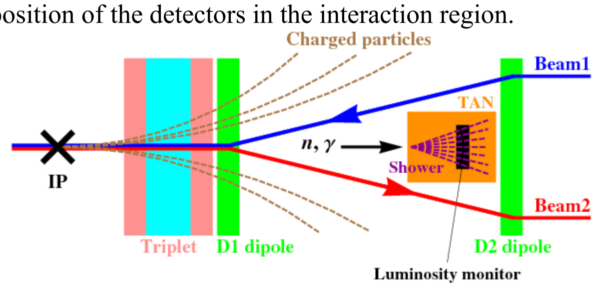


Figure 1: Schematic of one of the LHC Interaction Regions. Neutral products from collisions between B1 and B2 are aligned on the beam directions at the IP.

*Work supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and the US LARP program.
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Each detector (Figure 2) is a high-pressure (Ar+6%$N_2$) gas ionization chamber composed of four quadrants symmetrically distributed around the line of flight of Beam1 and Beam 2. The subdivision of the BRANs into four quadrants allows for the monitoring of the vertical and horizontal beam crossing angles, evaluated with suitably defined ratios of the signals in the quadrants.

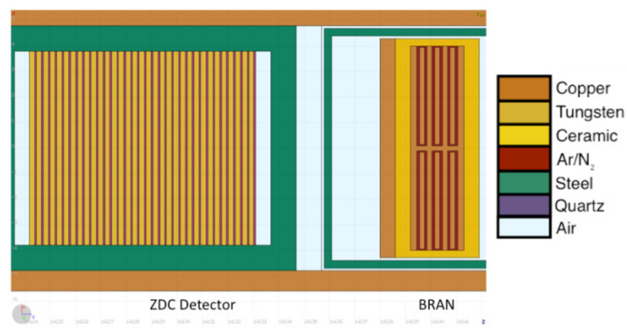


Figure 2: FLUKA model of a BRAN unit installed in the TAN slot behind the ZDC detector (in the 2011 run).

The system is built to address two major challenges: resolving the bunch by bunch structure of the beam at 40 MHz, and withstanding very high levels of radiation (up to 1 GGy/year at design luminosity and beam energy). These constraints dictate the choice of a small gap, segmented gas ionization chamber built entirely out of copper, ceramic and stainless steel. The chamber has the ability to slowly flow the gas so a refreshed medium is always available for the ionization process. Figure 3 shows an exploded view of the detector, which is then mounted into a sealed chamber that can be pressurized up to 10 atm.

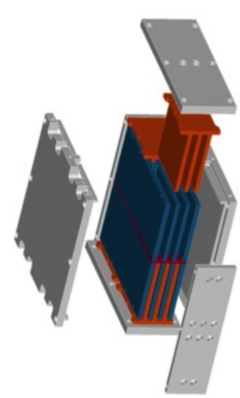

Figure 3: Exploded view of the sensor, showing the ceramic housing and the copper structure segmented in four quadrants and with six gaps.

*Presented at the 3rd International Particle Accelerator Conference (IPAC 2012)*
*New Orleans, Louisiana, USA, May 20 - 25, 2012*

*Work supported in part by US Department of Energy under contract DE-AC02-76SF00515.*

## *Emittance Calculation from BRAN Data*

The time behavior of the LHC luminosity, both in *p-p* and *Pb-Pb* operation, is governed, with the present 50ns bunch spacing, by three time-dependent effects:

- the bunch charge decay,
- the bunch emittance growth and
- the onset of an overlap impact parameter.

The luminosity at each Interaction Point (IP) is expressed in (1) 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:

$$L(IP_i) = \sum_{1}^{K_b} L_{sb}(b_i) \qquad (1)$$

where

$$L_{sb}(b_i) = f_{rev}\,\frac{N_{1m}N_{2n}}{2\pi\Sigma_{xi}\Sigma_{yi}}\cdot F_1(\theta_{i,mn})\cdot F_2(z^{os}_{i,mn}) \qquad (2)$$

is the bunch-by-bunch luminosity from the $b^{th}$ pair $(m,n)$ of bunches in Beam1 and Beam2.

The function $F_1$ accounts for the reduction effect from the crossing angle. Deviations from the nominal crossing angle due to closed orbit distortions from long-range beam-beam forces, as well as drifts in the power supplies can be time-dependent effects and affect the bunch-by-bunch luminosities in a more subtle way. Monitoring the pair-by-pair crossing angle can provide useful insight.

The function $F_2$ represents the reduction from a possible (un)wanted impact parameter $z^{os}$ ($z$=$x$ or $y$) defined as the transverse separation between the centroids of the colliding bunches normalized to the convoluted transverse dimensions:

$$F_2(z^{os}_{i,mn}) = \exp\left[-\frac{1}{2}\left[\left(\frac{x^{os}_{i,mn}}{\Sigma_{xi}}\right)^2 + \left(\frac{y^{os}_{i,mn}}{\Sigma_{yi}}\right)^2\right]\right] \qquad (3)$$

The Interaction Area at the crossing is evaluated from (2):

$$A_i = 2\pi\Sigma_{xi}\Sigma_{yi} = \frac{f_{rev}}{L^*_{sb}} \qquad (4)$$

where $\Sigma_{xi}$ and $\Sigma_{yi}$ are the convoluted bunch sizes and

$$L^*_{sb} = \frac{L_{sb}(b_i)}{N_{1m}N_{2n}} \qquad (5)$$

is the specific bunch-by-bunch luminosity at the $i^{th}$ IP.

After compensation for any occasional change in impact parameter (such as during vernier scans) a decrease in the quantity (5) involves an increase in the area (4) and is a signature of emittance growth for one or both the colliding bunches. This is shown in Figure 5 among the experimental results later in this document.

The time evolution of the interaction area (4) can be monitored using the logged information on bunch charges (Fast BCCT) and luminosity (BRAN). Integration times and bunch gating can be envisaged for a suitable comparison with data on the luminous regions from the physics experiments.

## *Operator Interface*

To facilitate access to the results provided by the system, we have developed an application for operator use. It shows all detector parameters, such as bias voltage and gas pressure and flow, as well as the calculated crossing angles for each beam at both IPs.

The panel also shows (Fig. 4) the plots of the time evolution of the luminosity and emittance from Equ. (2) and (4) and their pattern in IR1 and IR5, both at the beginning of the store and at the time of the plot.

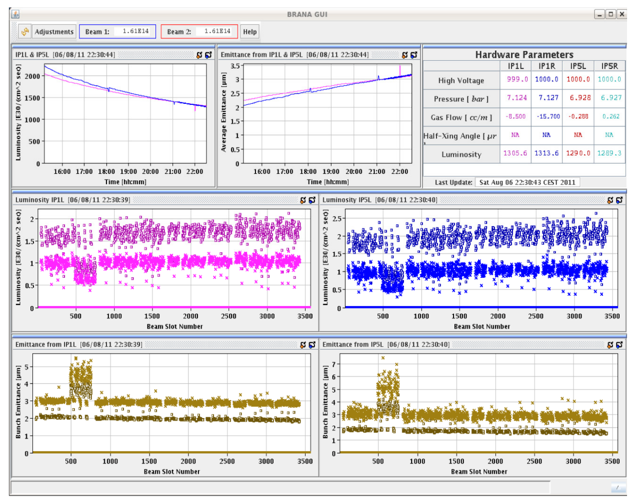

Figure 4: The BRAN operator interface.

Figure 4 was selected as it shows an example where a batch of protons with larger emittance was injected into the machine. Because of the BRAN's ability to measure on a bunch-by-bunch basis, it can easily detect the bad batch just after bunch 500. The plot shows a bunch train with a high emittance and consequently low luminosity. The two plots on each graph show the measurement at the beginning of a store and the current position. These plots were obtained using the BRAN at IR1. A similar measurement was done with the detector at IR5. Figure 6 shows the detail of the bunch-by-bunch luminosity and emittance charts from the operator interface.

## *Beam Measurements*

Using the luminosity measured by the BRAN and the number of circulating particles determined from LHC beam intensity monitors we calculate the rms beam size. Its time evolution during Fill #1372 is shown in Figure 5. The BRAN data are shown by the red curve and the Timber CMS data by the green dots.

The relationship (4) shown in the picture is valid for the case of same emittance bunches.

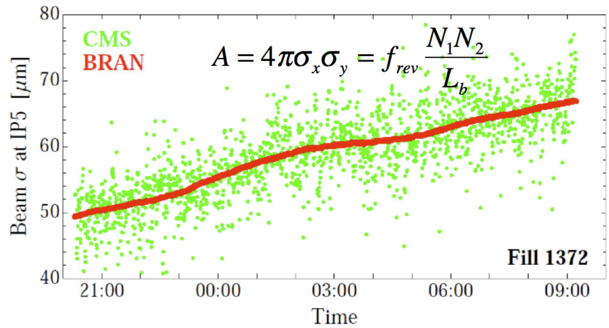


Figure 5: Emittance growth in Fill 1372.

As was shown in Figure 4, the operator panel plots the instantaneous bunch by bunch luminosity for each IP. Figure 6 shows the detail of these plots, where the darker color points are at the beginning of the store and the lighter ones are the values at the time the plot is made.

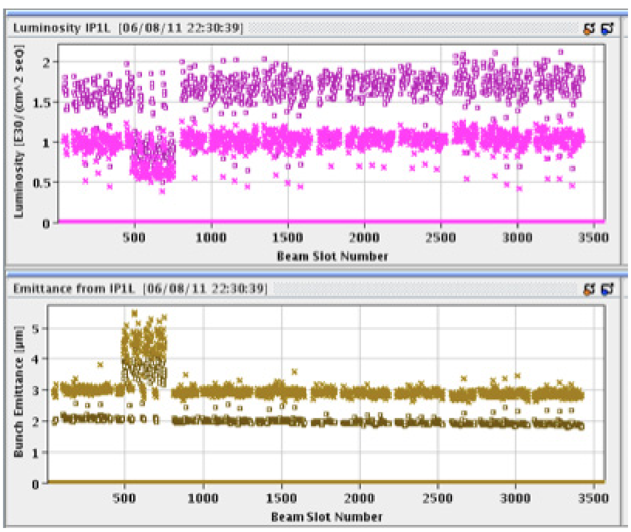


Figure 6: The luminosity and emittance taken on August 6, 2011. On the x-axis is the bunch number.

Among other relevant plots captured with the BRAN, Figure 7 shows a Pb bunch train during the run in November 2011. The top left image represents a full turn, with the following plots progressively zooming on the initial part of the train. The decrease in luminosity inside each train is due to emittance blow-up in the front of the train. This effect, seen also by the experiments, is potentially the result of intrabeam scattering at injection, when the initial bunches are stored for a longer time at low energy in the SPS as the ring is being filled with bunches.

## CONCLUSIONS

After successful construction and installation of the BRAN detectors, we are developing a set of tools to help operators and beam physicists diagnose the LHC and optimize its performance. For example, the BRAN is the only instrument detecting collisions available during machine development studies, since the experiments are typically off to protect their electronics readout systems.

We have shown how by calculating the bunch-by-bunch specific luminosity it is possible to extract the corresponding values of the bunch emittances in collision, and monitor their behavior during the store.

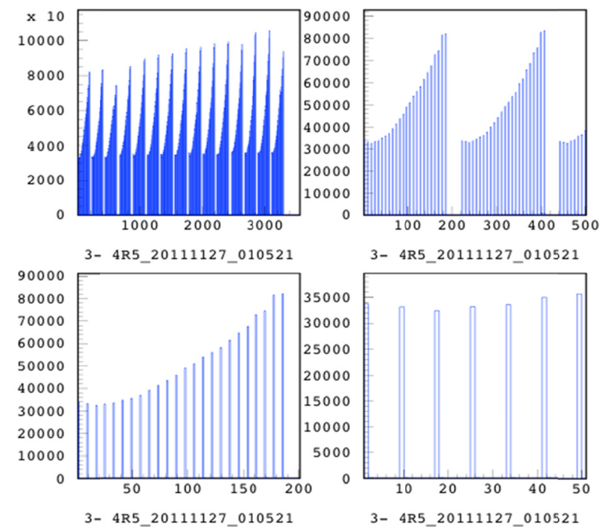


Figure 7: Bunch by bunch luminosity for a Pb store.

## ACKNOWLEGEMENTS

Among the many contributors to this work we would like to thank Dave McGinnis and the LAFS group at Fermilab, who in collaboration with CERN's BE/CO controls group provided valuable software support for the LHC. Very important help from FLUKA modeling came from P. Humphries, J. Stiller and S. Hedges. Last, we would like to acknowledge the support of the US-LARP program that funded the BRAN design and construction and part of this work.

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