EMPLOYING BEAM-GAS INTERACTION VERTICES FOR TRANSVERSE PROFILE MEASUREMENTS

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Abstract

Interactions of high-energy beam particles with residual gas offer a unique opportunity to measure the beam profile in a non-intrusive fashion. Such a method was successfully pioneered at the LHCb experiment using a silicon microstrip vertex detector. During the recent Large Hadron Collider shutdown at CERN, a demonstrator Beam-Gas Vertexing system based on eight scintillating-fibre modules was designed, constructed and installed on Ring 2 to be operated as a pure beam diagnostics device. The detector signals are read out and collected with LHCb-type front-end electronics and a DAQ system consisting of a CPU farm. Tracks and vertices will be reconstructed to obtain a beam profile in real time. Here, first commissioning results are reported. The advantages and potential for future applications of this technique are discussed.

INTRODUCTION

Measuring beam profiles in the LHC is an important task to optimise the luminosity and monitor the beam emittance. The currently used instruments to measure the LHC beam profiles are wire scanners, synchrotron light monitors and residual-gas ionisation monitors. Another method to measure the beam shape and position, which was pioneered in LHCb [1] during the CERN LHC Run 1, is the beam-gas imaging (BGI) technique, where a noble gas (e.g. neon) is injected into the vertex locator (VELO) vacuum to measure the interactions between the gas and the beams. The resulting charged particles of these inelastic interactions are measured with high precision tracking detectors to compute the vertex positions. The BGI method at LHCb proved to be successful to measure beam profiles and luminosity [2]. However, the VELO performance is drastically degraded, when it measures vertices in a retracted position. In order to protect the detector from orbit excursions during energy ramping and optics squeeze, the VELO can only be closed, when the beams in the LHC are declared "STABLE", which means that the LHCb BGI method is limited to these conditions. Given the good results that were achieved with the LHCb BGI method, a system dedicated to measuring beam-gas interaction vertices during all states and energies of the LHC was designed and built during the first long shutdown (LS1) of the LHC between 2013 and 2015. The new system, called beam-gas vertex (BGV) detector, is described here.

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THE BEAM GAS VERTEX DETECTOR

BGV Demonstrator Goal

The BGV demonstrator will provide a precise, but non-destructive method to measure the transverse beam profile and beam width during all states and energies of the LHC. The transverse beam shape and structure will be measured bunch-by-bunch as well as on average for the whole beam [3]. A rate of about 100 Hz per 10^{11} protons is expected. From the measured beam width σ, the transverse emittance ϵ of the beam can be obtained from $\sigma^2 = \epsilon\beta$, assuming negligible dispersion. Hereby, the β functions of the magnetic lattice are assumed to be measured independently. The BGV can furthermore be used to measure ghost charges, particles which are outside the nominal filled bunches of the accelerator and remain invisible to the fast bunch current transformers.

BGV Design

The BGV demonstrator replaces a part of the beam line of the LHC Ring 2 at point 4. It consists of a vacuum chamber that allows for injection of (neon) gas with a gauge pressure between 2×10^{-9} and 2×10^{-7} mbar, which serves as a target for the beam. As is shown in Fig. 1, two detector stations downstream of the vacuum chamber track the charged particles that result from the inelastic beam-gas interactions. The detector readout modules are triggered by two sets of scintillating detectors. One detector is situated upstream just before the vacuum chamber, and is used to veto beam-gas interactions occurring too far upstream of the vacuum chamber. In addition, this trigger arrangement ensures a strong rejection of particles resulting from spurious beam-gas interactions of Ring 1, reducing the measured amount of these interaction significantly. To ensure the quality of the LHC vacuum, two pumps on either side of the BGV remove most of the injected gas before it can diffuse into the beam pipe.

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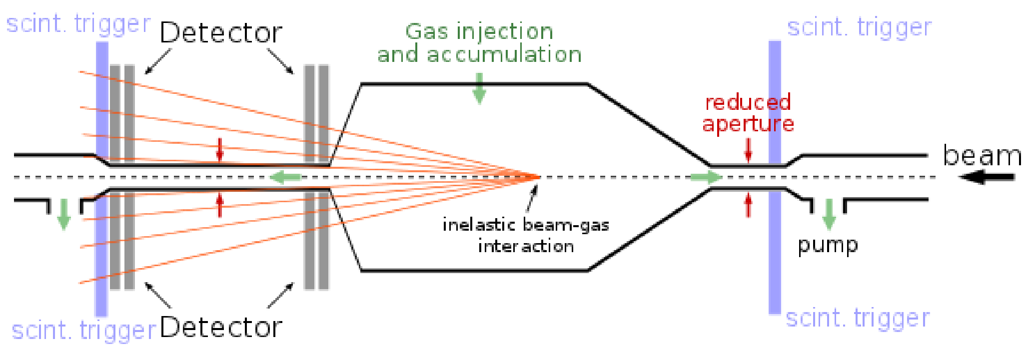

Figure 1: Sketch of the BGV layout with the vacuum chamber for gas injection, the two tracking detector stations and the two sets of trigger scintillators.

Detector and Readout

The two detector stations are made up of four scintillating fibre (SciFi) modules each. These fibre modules contain two fibre mats, which are rotated by 2° with respect to each other to facilitate pattern recognition. The detector modules were developed in collaboration with the SciFi Tracker project [4] of the LHCb upgrade and consist of 4-layer mats at the station closer to the vacuum chamber and 5-layer mats at the station at 1 m distance of the vacuum chamber. The fibre diameter is 250 μm and the length of each fibre ranges between 240 and 340 mm, depending on its position on the mat. The modules are identical which means that the orientation of the fibres on a mat is always the same. To provide x-y position measurements, two modules are installed behind one another and rotated by 90° as is illustrated in Fig. 2. Approximately 20 photon counts per minimal ionizing particle are expected for the 4-layer modules and 25 for the 5-layer modules.

To increase the light yield, a mirror is glued onto one end of the fibre mats while the other end is equipped with 128 channel silicon photomultipliers (SiPMs) to read out the fibres. The SiPM signal passes an attenuator circuit to match the input current of the radiation hard, analog LHCb Beetle front-end chip [5] which is used to read out the SiPM signal. A detector module comprises 16 SiPMs and 16 Beetle chips. The modules also include a cooling and dry air system, which allows the SiPMs to be cooled down to −40° C to decrease (thermal) dark counts. The Beetle signals are amplified by VELO repeater boards (one repeater per module) and sent over 60 m cables to the Tell1 readout boards [6] where the signals are digitised. The Tell1s also apply zero-suppression (clusterisation) and corrections before sending the multi-event packets to the computing farm. During commissioning of the BGV system, the data are analysed offline, however it is planned to equip the computing farm such that it can perform the analysis in real-time.

Current Status

The BGV's installation was finished during the technical stops (TS) in late 2015 and is currently being commissioned. The current steps are adjusting the fine timing of the readout system, finding clusters in the data as well as determining the correction values for cross talks between the channels that are caused in the above mentioned attenuator circuit. In order to find the correct time alignment of the different readout components, data were taken while scanning through coarse delay steps of 25 ns [7] as well as changing the fine delay by 1 ns. Scanning over the coarse delay of 25 ns (see Fig. 3), which corresponds to the LHC clock cycle, gives an insight into the delay range in which the actual SiPM signal can be measured. The fine delay scan provides the pulse shape of the signal. The combination of SiMPs, attenuator circuit and Beetle chips results in the pulse shape shown in Fig. 4. To measure this pulse shape over 125 ns, data are taken with 5 consecutive triggers for 25 steps of 1 ns increment in the fine delay. By choosing the optimal delay not too close to an edge, the correct sampling point is located and can be fixed.

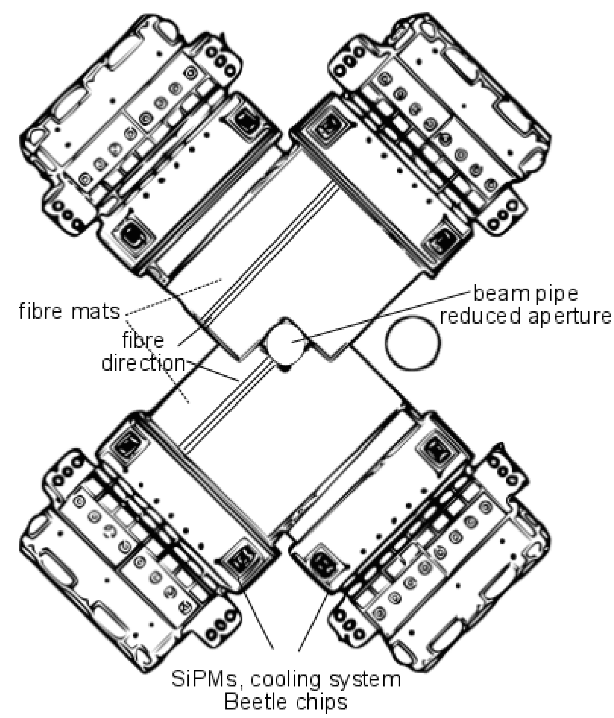

Figure 2: Orientation of the 4 scintillating fibre modules on each of the 2 detector stations.

In this case the optimal sampling delay would be between −25 and −20 ns. Note that the data of Fig. 4 were taken with a coarse delay equal to slot 4 of Fig. 3.

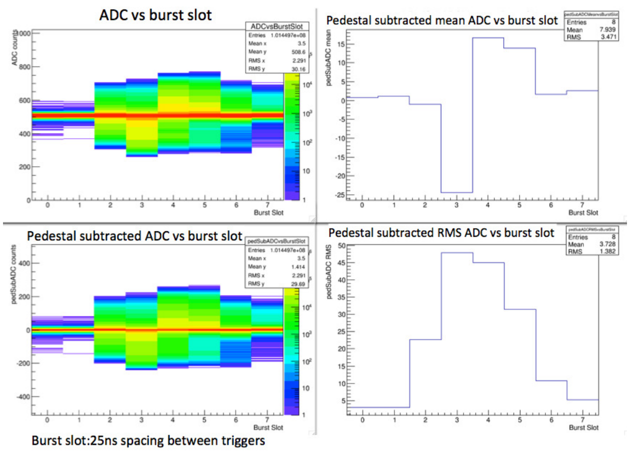

Figure 3: Coarse timing scan results for the BGV. The x-axis always shows the 25 ns slots. The top left plot illustrates the actual ADC counts, the bottom left shows pedestal subtracted ADC counts. The top right plot shows the pedestal subtracted mean ADCs and the bottom right shows the pedestal subtracted RMS ADCs. According to this dataset, the best coarse delay setting is a delay equal to slot 3.

Applying the correct delay values for the system will facilitate clusterisation of future data samples and allow for track and vertex reconstruction.

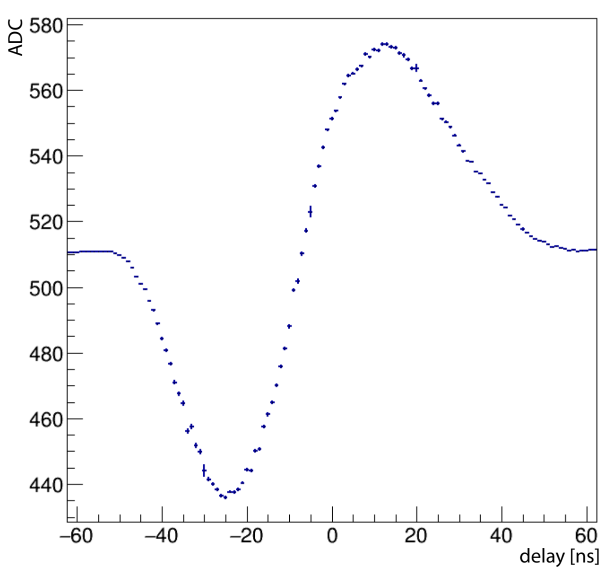

Figure 4: Pulse shape of 1 link acquired during a fine delay scan. The x-axis shows the sampling delay in ns, the y-axis shows ADC counts.

As mentioned above, the BGV can also be used to measure ghost charges. Figure 5 shows the distribution of beam-gas in-teractions over the 3564 bunch slots of the LHC. The twelve bunch counters with approximately 1500 events correspond to the 12 nominal Beam 2 bunches in the LHC during the fill while the bunches with an order of 10 entries correspond to spurious triggers due to the nominal Beam 1 bunches. The remaining entries can be considered as ghost charges.

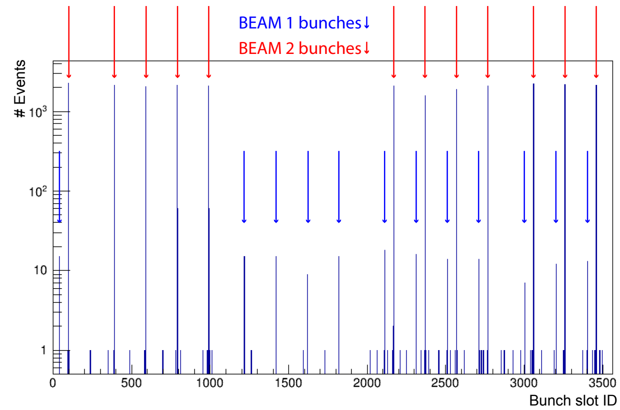

Figure 5: Measured beam-gas interaction triggers during a fill with 12 nominal bunches per beam. The red (blue) arrows show the expected locations of the Beam 2 (1) bunches.

SUMMARY

A non-destructive transverse beam-profile monitor, using beam-gas vertices, was developed, built and installed at the LHC. It will be able to measure the transverse beam profile at any LHC beam intensity through all phases of the accelerator cycle. This will allow an insight on the beam width and emittance evolution during a fill. In addition, the BGV is capable of measuring ghost charges and can be used as an additional tool to monitor the distribution of the particles in the beam. The detector is currently being commissioned and data to measure the transverse beam profile will be taken during the 2016 LHC run.

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