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BGC MONITOR: FIRST YEAR OF OPERATION AT THE LHC

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Abstract

The Beam Gas Curtain (BGC) monitor was installed in the beam one of the Large Hadron Collider (LHC) during Long Shutdown 2 (LS2) and the Year-End Technical Stop (YETS) 2022. The monitor detects the fluorescence signal generated by the interaction between the charged particle beams in the LHC and the neon atoms in the supersonic gas curtain. This provides 2D images of the primary beam. In the 2023 run, it was demonstrated that transverse beam profile measurement for both, proton beam and lead ion beams in the LHC is possible across injection, energy ramp-up and top energy operation. The BGC has shown the potential to be an operational instrument and efforts to integrate the monitor into the main machine control system are being undertaken. In this contribution, we will present measurement results and discuss operational experience including observed gas loads to the LHC, observed impact on beam losses, and demonstrated resolution of the monitor. Finally, we will also discuss plans for the continued optimization of this monitor and the installation of a second monitor into beam two.

INTRODUCTION

Since the Large Hadron Collider started to operate in 2010, it has led to many discoveries, which are the frontier of high-energy physics. A stable operation of the accelerator complex will be required to achieve the integrated luminosity to reach certain statistics for these discoveries. To do that, the beam instrumentation is a key. The transverse beam profile monitor is one of many beam diagnostics in the LHC which is used for beam size measurement and emittance estimation. Widely used transverse beam profile monitors in the CERN accelerator complex include scintillating screens, wire scanners, synchrotron radiation monitors, secondary emission monitors, and ionisation profile monitors. They all have their pros and cons. A new concept of beam profile monitoring was proposed using a supersonic gas curtain and fluorescence [1]. Based on this concept, the Beam Gas Curtain monitor (BGC) was installed during long shutdown 2 (LS2) and the year-end technical stop (YETS) in 2022. During the 2023 LHC run, the monitor was successfully commissioned. The measurement of beam profiles in all stages of LHC operation including injection, energy ramping up, and the stable beam was demonstrated for both the proton beams and the lead-ion beams. Since then, efforts have been made to transfer this device to a fully operational device for daily LHC operation.

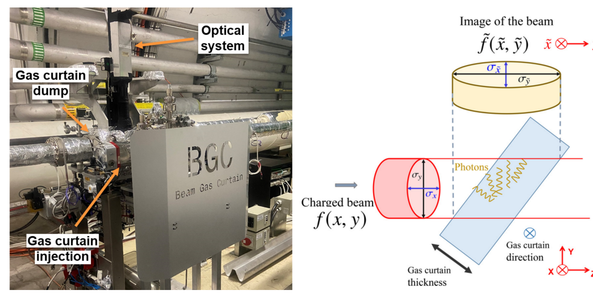

Figure 1: Picture of the BGC installed in the LHC and the detection principle.

METHOD

Using beam-induced fluorescence (BIF) to detect the beam profile was applied before. This method is minimum-invasive and the detecting system is a simple optical imaging system. In the past, because of the low cross-section of the fluorescence process and a small fraction of the signal detected due to the restrained solid angle, gas injection was always needed to reach a certain signal-to-noise ratio (SNR) and acceptable integration time. The easiest way to inject gas is to use a needle valve, but the obvious drawback is the gas load to the whole system. Using a supersonic gas curtain can avoid these issues because of the high speed and directionality of the gas molecules in the curtain. The gas expanded through a small nozzle from a high-pressure region to a low-pressure region to form a supersonic jet. Then the jet was collimated by three consecutive skimmers to form a thin curtain with an equivalent pressure of $\sim 1 \times 10^{-6}$ mbar. These skimmers are used to create differential pump stages to ensure that the pressure in the beam pipe is at a low level where the beam dump is not triggered. A fourth skimmer together with a gas dump section is used to collect the unused gas molecules from the curtain to maintain the pressure in the beam pipe. A schematic diagram of the system can be seen [2]. For the detection system, as shown in Fig. 1, the charged particle beams interact with the molecule inside the gas curtain, causing the molecule to an excited state. Then the excited molecule will emit fluorescence whose distribution is directly proportional to the previous charged particle beams. If a suitable gas, e.g. Neon, was used which has

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a naturally emitting fluorescent line, the distortion due to the space charge could be eliminated and thus a high resolution can be achieved which is only limited by the optical properties. The fluorescence signal will be recorded by an assembly of a filter wheel, intensifier and CMOS camera. A bandpass filter with 10 nm was used to reduce straight light and most of the synchrotron radiation. However, the synchrotron radiation and the beam loss will still be the main source of the noise for our system.

CURRENT STATUS

Securing the vacuum system is a key task for the smooth operation of the BGC monitor. Vacuum validation was verified before installation [3]. During the LHC annual commissioning and stable operation, precautions were taken such as installing the interlock system and manual operation of the gate valves to prevent any unwanted beam dump due to the gas injection from the BGC into the LHC tunnel. The manual control GUI, seen from Fig. 2 has been included in the LHC control system. The monitor has been successfully operated for a year now, has a minimum impact on the vacuum system of the LHC and thus does not affect the stable operation of the LHC. Pressures are constantly monitored by the pressure gauges installed upstream, at the BGC and downstream. A typical measurement before and after turning on the gas curtain can be seen in Fig. 2. The pressure inside the BGC chamber increased from $\sim 1 \times 10^{-10}$ mabr to $\sim 1 \times 10^{-8}$ mbar.

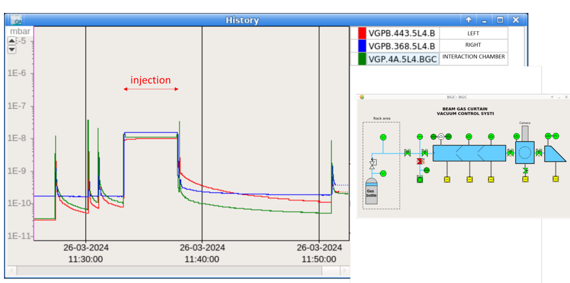

Figure 2: BGC vacuum control and operating vacuum condition.

There are beam losses associated with the introduction of the gas curtain. The level of beam loss can be seen in several beam loss monitors downstream as seen in Fig. 3. The local beam loss increases by 7.5×10^{-20} Gy/s/p in Point 4. This level is about 2-3 times higher than the normal noise level which is distinguishable, but it is still less than 1% dump losses. A similar simulation study to [4] was performed which confirmed the loss level. Further detailed study of the beam loss could help to better shield the detecting system such as the MCP and CMOS camera to reduce the noise and improve the lifetime of such devices, which is still an ongoing task. Another study carried out recently shows a potential halo monitor based on the loss measurement from the gas curtain is possible. To achieve this, the signal level, gas curtain orientation and location need to be identified for the halo measurement.

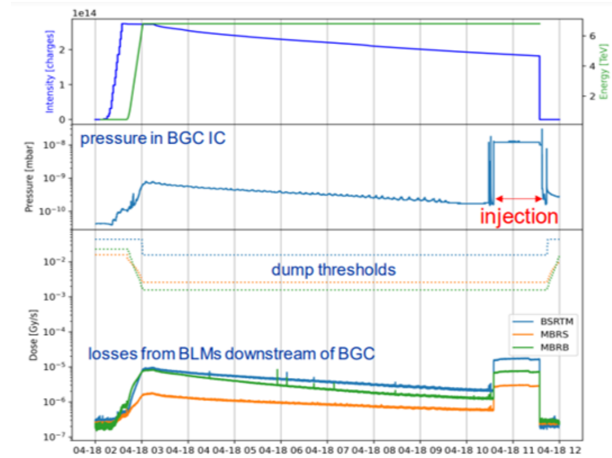

Figure 3: Beam loss due to the BGC seen from the downstream beam loss monitors.

Optical resolution is key to resolving small beam sizes. A recent calibration of the optical system with internal calibration target and LED ring during YETS2023 shows a resolution of ~ 65 µm consistently with independent techniques. This can be seen from the measurement of a resolution target in the BGC optical system in Fig. 4. Beam profiles of both the proton beam and the lead ion beam were measured under various conditions in the 2023 run. Typical measurement in the stable operation of the lead ion beam is shown in Fig. 5. The integration time is set to 1 mins. The noise is mainly contributed by the beam loss and synchrotron radiation upstream. The loss of beams is associated with the intensity of the beams. The synchrotron radiation is reversely proportional to the mass of the beam species. Thus, with similar intensity and integration time, the SNR will be better for the lead-ion beam than the proton beams. For different energies, the signal will increase because the beam size reduces with increasing beam energy. On the other hand, the noise will increase as well due to synchrotron radiation. Currently, the default integration time was set to be 2.6 mins, making this monitor an average profile monitor.

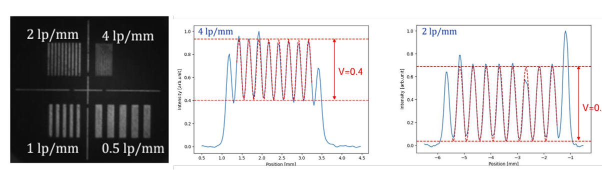

Figure 4: Resolution measurement of the BGC optical system.

The beam sizes can be calculated from the two-dimensional images. The horizontal size will represent the true size of the beam while the measured vertical size will be a convolution of the true size and gas curtain distribution. For a uniform gas curtain distribution and Gaussian beam, a deconvolution should be sufficient to find the true size. But in reality, the distribution of the gas curtain is not ideally uniform and the beam is not Gaussian. The work toward this issue is still in progress. Another way to solve

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this is to reduce the gas jet thickness. However, in the meantime, the reaction rate will reduce as well which causes a longer integration time. This needs to be considered when designing a new monitor. There is a trade-off between the resolution in the vertical direction and the integration time. The emittance can be calculated from the beam size measurement if the beta function is known. Since the emittance is a conserved quantity, it can be compared across the LHC. Such comparison was done between the BGC, ATLAS and CMS and the measurement from the BGC agrees within 10% with emittance scans at the start of the stable beams. With ~ 2 mins integration time, the average measurement fluctuates with a standard deviation of < 4%. The emittance growth throughout the stable beam operation is detectable in all fills as well.

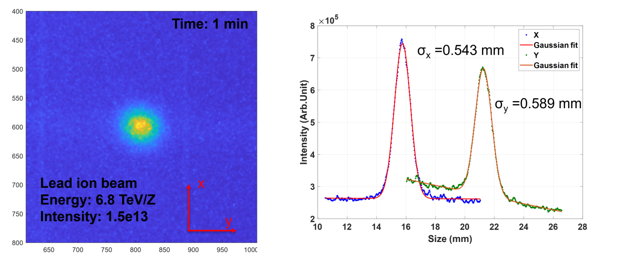

Figure 5: Results of the LHC measurement using BGC monitor

Since the successful measurement of the beam size from the BGC monitor, efforts were made to turn it into an operational instrument in the Central Control Centre (CCC). Currently, the gas injection still needs to be manually controlled and prerequisites need to be made before opening the gate valves which separate the gas injection, the LHC beam pipe and the gas dump.

A new real-time display module was developed for the CCC as shown in Fig. 6, which gives you the rolling frame, photon counting image and stacking image of 2 mins integration time, beam sizes and emittances in both horizontal and vertical planes with the SNR information. Now all the information is stored in the Timber data system of CERN. Photon accounting needs to have a smaller exposure time to allow individual photons to be identified and to avoid photon clustering. It shows a slightly better resolution than image stacking and will allow an estimation of the cross-section for the fluorescence process. For high photon density when beams are small and loss is high at the beginning of the stable beam operation, a frame rate faster than current 20 Hz is needed. If there is photon clustering in the photon counting mode, the sizes measured from the photon counting method are systematically larger than the stacking method.

CONCLUSION

The BGC monitor has been successfully installed and commissioned in the LHC. A dedicated vacuum control system and data-taking GUI were developed to potentially use this device as an operational monitor for the control centre.

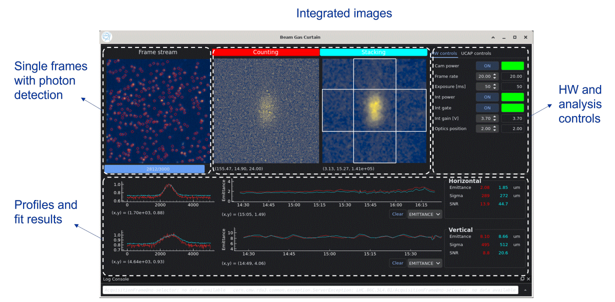

Figure 6: Real-time display of BGC module in the Central Control Centre

During the 2023 run, the monitor successfully operated for more than 10 h for the proton beam (limited availability of proton beams in the 2023 run) and 70 h for the lead ion beam which was good validation for such monitor working as an average beam size or emittance diagnostics. The beam loss due to the injection of the gas curtain can be observed but still far from the dump threshold. The systematic study of the lead ion beam was performed to identify the signal-to-noise ratio related to the integration time where 1 minute integration is required for a beam profile measurement with a good SNR. A detailed emittance comparison with the BSRT and wire scanner in the ATLAS and CMS detectors was studied which showed a good agreement with 10% differences. Currently, with the 2024 run, a systematic study with the proton beam is still ongoing. There are also efforts to optimise the current monitor such as increasing the optical resolution, increasing the gas jet density, and studying the trade-off between gas jet thickness and integration time. The option of installing another monitor for beam 2 is still under discussion.

ACKNOWLEDGEMENT

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