ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO06

STUDY OF PULSED JET OPERATION FOR BEAM GAS CURTAIN MONITORS

S. P. Sethi, H. D. Zhang*, O. Stringer, C. P. Welsch
University of Liverpool / Cockcroft Institute, Daresbury, Warrington, UK

Abstract

A beam gas curtain (BGC) monitor was installed in the LHC for continuous transverse beam profile and emittance measurement. A molecular gas curtain was injected into the LHC continuously. In this work, a pulsed gas jet operation was proposed to minimize the introduction of gas molecules to the beam line and optimize the background pressure. The study was conducted on a gas curtain beam profile monitoring system using nitrogen gas. In this case, the pulse gas jet mechanism enables controlled gas injection into the multiple skimmer chamber to generate a supersonic pulse gas curtain. To achieve maximum current intensity and minimum chamber pressure, key parameters were optimized, such as pulse duration or duty cycle of gas jet, nozzle-skimmer distance, and inlet gas pressure. The results demonstrate a well-tuned pulse jet system can significantly reduce background and enhance the signal-to-noise ratio to monitor a pulse beam. The proposed study exhibits potential applications for beam diagnosis, especially for medical accelerators and laser-based linear accelerators.

INTRODUCTION

A beam profile monitoring system is a crucial instrumentation setup for emittance measurement and beam profile monitoring of the Large Hadron Collider (LHC) [1]. For non-invasive measurements of particle beams, Beam Gas Curtain (BGC) monitors are preferred over other beam diagnostics instruments. Gas curtain-based Beam-induced fluorescent (BIFs) monitors [2,3] and ionization profile monitors (IPMs) [4, 5] are the two important monitoring systems developed based on the beam gas curtain (BGC) monitors.

In this study, gas curtain-based BIF monitors are the only focus. The BIF operational mechanism is solely driven by the phenomena of gas and beam interaction. In this technique, a supersonic gas jet, which is shaped to a ‘curtain’, interacts with the beam, and the interaction byproducts are collected in the form of fluorescence photons. The generated fluorescence photons are detected using a stand-alone optical system that provides a one-dimensional distribution of the primary beams, from which the beam profile is reconstructed. The developed process is a non-invasive technique, and can measure the beam profile for both lead ion and proton beams for all the stages of LHC operation [6]. The application of BGC can also be extended to other beam diagnostics, in particular for medical accelerators. In radiotherapy, the radiation sources are usually pulsatile rather than continuous. Most clinical linear accelerators (linac) or medical accelerators typically have a pulse duration from 3 ms to 300 ms based on the type of proton or electron beams [7]. Also, a pulsed molecular beam could be defined as a spatially and temporally discrete molecular beam when the beam is traveling through a vacuum under collision-free conditions. Although for designing medical accelerators, other parameters are taken into consideration such as dose rate, pulse repetition rate but they are primarily designed for pulsating beam sources. The proposed method aims to extend the application of the BGC monitors beyond profile monitoring in the LHC. It highlights the outcomes of pulse jet operation of the BGC monitors, and also outlines the key parameters to achieve optimum background pressure and maximum current density.

EXPERIMENTAL SETUP

BGC Setup Description

To conduct a pulse jet injection study, nitrogen gas was injected into the beam profile monitoring system to generate a supersonic gas jet as shown in Fig. 1. Previously, a beam profile monitoring setup was developed by the QUASAR group at the Cockcroft Institute (CI) and commissioned at CERN for beam profile monitoring of the LHC. It’s the only monitoring system that can be utilised for the profile monitoring of both proton and lead ion beams of the LHC. The setup operates based on the principle of beam-induced fluorescence, where generated ions due to fluorescence are used to reconstruct the profile of the LHC non-invasively. The setup is made of five vacuum chambers: those are nozzle chamber, the skimmer chambers I and II, the interaction chamber, and the dump chamber. The pumping operation of each chamber is performed by individual turbo-molecular pumps backed by scroll pumps to achieve the required ultra-high vacuum environment.

To mitigate the effect of diffused gas molecules and preserve an ultra-high vacuum environment in the interaction chamber, differential pumping stages separated by skimmers were designed. The sizes of the first skimmer are conical shape, 0.4 mm diameter, the second skimmer is a circular shape with 2 mm diameter, the third skimmer is a rectangular shape with 0.4 × 30 mm size, and the fourth skimmer is a rectangular geometry with 4 × 60 mm size. A supersonic gas jet is injected through a 0.1 mm diameter pulsed nozzle by Parker-Hannifin at varied inlet pressures. It travels mono-directionally through multi-stage skimmers of different geometries to generate a supersonic gas jet curtain, which we refer to as a beam gas curtain.

* haozhang@liverpool.ac.uk

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO06

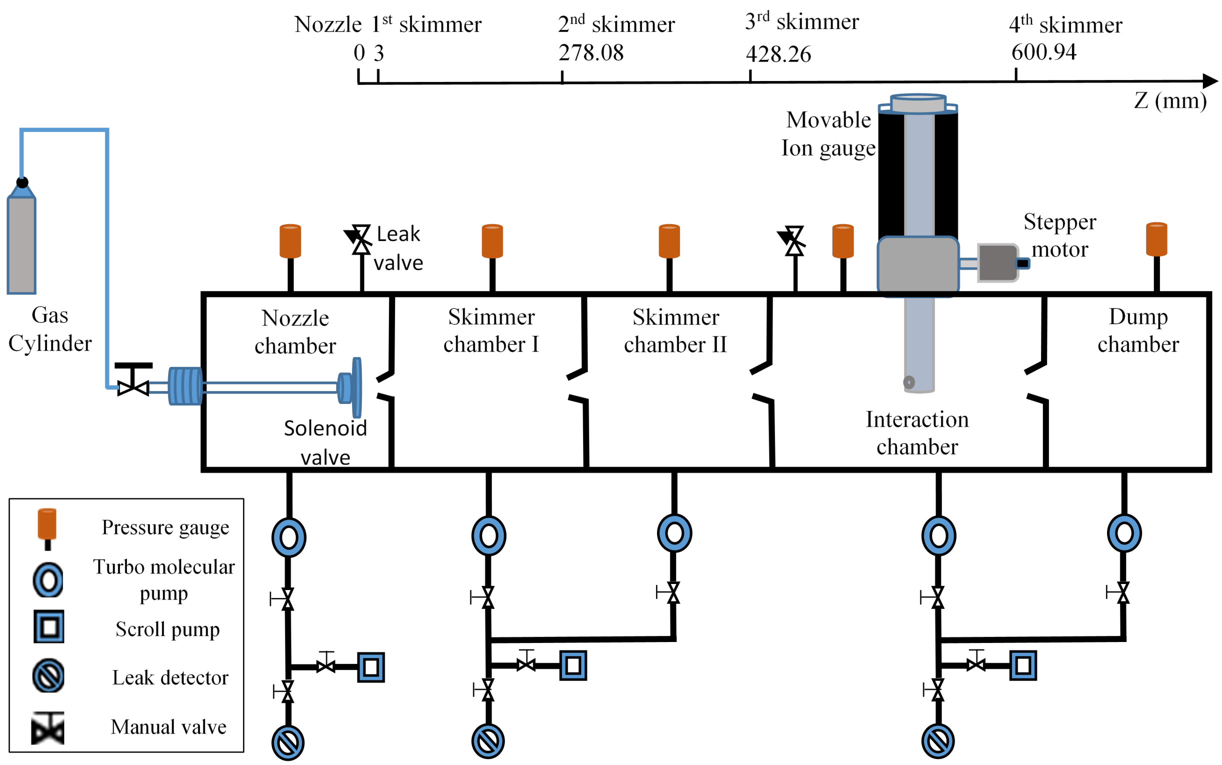

Figure 1: The layout of the beam gas curtain (BGC) setup with solenoid valve and movable ion gauge assembly.

Scanning Gauge System

A movable gauge assembly system was installed between the third and fourth skimmers in the interaction chamber, as shown in Fig. 1. In the interaction chamber, a curtain-shaped supersonic gas jet interacts with a beam of protons, electrons, or lead ions, depending on the experiment's goal. In this instance, the beam is replaced by a movable gauge [1]. The movable gauge is assembled with a small chamber comprising a DN40CF straight connector, with the top side connected to an ionization gauge of the Bayard–Alpert (BA) type and the bottom side sealed by a fixed flange. To enable three-dimensional movement, the gauge assembly is then coupled to a VACGEN Miniax XYZ manipulator with a minimum resolution of 5 µm. The connector's tube has a pinhole with a diameter of 1.0 mm.

The schematic representation of the whole process of the BGC monitor is shown in Fig. 1. When a supersonic molecular beam travels through the system into the interaction chamber, the tiny pinhole in the movable gauge assembly is positioned in front of it. Through the pinhole, a portion of the molecular beam enters the small chamber and accumulates there, increasing the current intensity linearly. Before performing a systematic experimental study, the moving gauge underwent vertical and horizontal scanning to identify the center of the supersonic gas jet curtain. The location was identified based on the maximum current intensity at different scanning positions.

EXPERIMENTAL STUDY

In this study, nitrogen gas was first injected at 5 bar inlet pressure in a continuous mode into the nozzle chamber. The quantity of dissociated ions collected by the gauge yields a proportional current density at the interaction point. The measured current density implies the quantity of gas density at the interaction point.

All the experiments were conducted for varied nozzle-skimmer distances and a constant operating voltage of the valve. Initially, the increase in the current intensity of the gauge due to the continuous gas jet was measured, and it was further taken as a reference for the pulse jet study that operates at different conditions shown in Fig. 2. The continuous gas jet operation was performed at 5 bar inlet pressure, and it was observed that the gas density (current intensity) decreased initially as the nozzle-skimmer distance increased, and gradually increased after 5 mm nozzle-skimmer distances. It is expected that the increase in nozzle-skimmer distances will decrease molecular beam inflows into subsequent chambers due to differential pumping and gas jet expansion. The significantly under-expanded supersonic jet characteristics measured for a continuous jet may be influenced by the sizes of the nozzle and the first skimmer. However, the chamber pressure values varied little with the changes of the nozzle-skimmer distances.

In comparison to the continuous jet experiment, a set of systematic experiments was conducted for the pulse mode operation with various pulse widths and inlet pressures. The operating conditions for the pulse mode are listed in Table 1.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO06

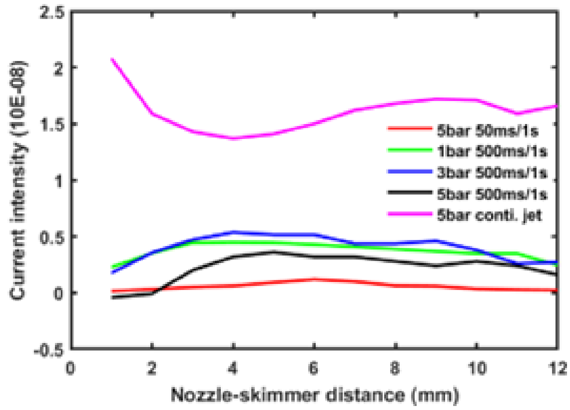

Figure 2: Measured current density of continuous gas jet and pulse jet at different conditions.

For each pulse jet experiment, the contribution of the residual gas is subtracted from the recorded gauge current values to get the contribution from the gas curtain itself. The measured current density was found to sustain reasonably low stagnation values when the gas jet was first injected at 5 bar for 50 ms/1 s duty cycle. In this particular experiment, we assumed that the creation of the jet had been much faster than the response time of the transducer for the 50 ms/1 s duty cycle. Also, as less gas flows into the chambers due to the 50 ms pulse width, consequently, the nozzle chamber records low pressure values, as shown in Table 1.

Table 1: Pressure of the Nozzle Chamber at Different Operating Conditions (mbar)

N-S*	Operation conditions 5 bar 50 ms/s	1 bar 500 ms/s	3 bar 500 ms/s	5 bar 500 ms/s	5 bar Cont. jet
0	3.41E-05	8.05E-04	1.26E-03	1.83E-03	2.12E-02
1	3.47E-05	8.47E-04	1.22E-03	2.13E-03	2.09E-02
2	3.26E-05	6.58E-04	1.24E-03	2.16E-03	2.07E-02
3	3.07E-05	8.37E-04	1.25E-03	2.27E-03	2.06E-02
4	2.87E-05	6.83E-04	1.24E-03	2.32E-03	2.05E-02
5	2.33E-05	6.49E-04	1.23E-03	2.43E-03	2.04E-02
6	2.65E-05	6.00E-04	1.23E-03	1.79E-03	2.17E-02
7	2.62E-05	5.64E-04	1.22E-03	1.84E-03	2.23E-02
8	2.54E-05	5.17E-04	9.80E-04	1.83E-03	2.27E-02
9	2.61E-05	4.98E-04	9.55E-04	1.82E-03	2.34E-02
10	2.54E-05	4.95E-04	9.21E-04	1.84E-03	2.37E-02
11	2.54E-05	7.94E-04	9.37E-04	1.81E-03	2.33E-02

As in Table 1, another experiment was conducted at 5 bar inlet pressure, and the pulse width was increased to 500 ms with the same periodicity. The measured current density was higher when compared with the experiment at 50 ms/1 s duty cycle; however, the nozzle chamber pressure is only an order better than the continuous jet. Note that the pressure in the nozzle chamber is quite stable regarding to the nozzle-skimmer distance, and only related to the total gas load (Duty cycle times inlet pressure). This means only a tiny portion of gas flow through the first skimmer.

In another set of experiments, the duty cycle of the pulse jet was kept constant at 500 ms/1 s, and the inlet pressures were 1 bar, 3 bar and 5 bar, respectively. For these conditions, the measured current intensity was a bit higher for 1 bar and 3 bar for most of the nozzle-skimmer distances. The reason why the gas curtain density is higher in those pressures is still under investigation, and one of the reasons could be less scattering in the nozzle chamber. With the condition at 500 ms/1 s duty cycle, 3 bar inlet pressure and 4-6 mm nozzle-skimmer distance, the pulsed gas curtain operated at an optimum state which maintains a higher curtain density with a relatively small nozzle chamber pressure (less load for the Turbo-molecular pump). This suggests that the BGC monitor can be operated in a pulse mode with an improved vacuum environment.

DISCUSSION AND CONCLUSION

The experiments conducted for the pulse jet study on the beam gas curtain (BGC) monitor provide some vital information for the advancement of the BGC monitor towards other areas of beam diagnostics. Initially, a continuous supersonic jet was injected, the current density and chamber pressures were recorded, and the measured parameters were taken as a reference for other operating conditions under pulse jet injection.

Among the different pulse widths and inlet pressure conditions, the optimum background pressure was recorded at 3 bar and 500 ms/1 s duty cycle condition. In this condition, the maximum current density was attained due to lower background gases, and the optimum chamber pressure was attained, indicating a decrease in gas load and better pumping conditions. The latter will enhance the longevity of the pumps. Therefore, a controlled gas jet injection in pulse mode will improve crucial parameters for beam diagnostics, such as background pressure, current density, and pumping speed.

Currently, the study is still in a preliminary state for the pulsed BGC operation. While other parameters, such as the shape of the nozzle, nozzle size, and first skimmer neck shape, and alignment of the skimmer, do play a crucial role in determining optimum background pressure and gas molecules to the beam line. Although the pulsed mode is not suitable for the LHC operation since the integration time is very long, and the current mechanical pulse nozzle cannot operate in the MHz frequency range of the LHC. It, however, could be used for the beam diagnostics of medical accelerators or laser-based linear accelerators, which operate in much lower frequencies.

ACKNOWLEDGEMENTS

This work was supported by the High Luminosity LHC project and by STFC through HLLHC UK phase II project no. ST/T001925/1, and the Cockcroft core grant no. ST/G008248/1.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPCO06

REFERENCES

[1] H. D. Zhang, A. Salehilashkajani, O. Sedlacek, and C. P. Welsch, "Characterization of a supersonic molecular beam for charged particle beam profile monitor", *Vacuum*, vol. 208, p. 111701, 2023. doi:10.1016/j.vacuum.2022.111701

[2] A. Variola, R. Jung, and G. Ferioli, "Characterization of a non-destructive beam profile monitor using luminescent emission", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 10, no. 12, p. 122801, Dec. 2007. doi:10.1103/PhysRevSTAB.10.122801

[3] T. Tsang, D. Gassner, and M. Minty, "Residual gas fluorescence monitor for relativistic heavy ions at RHIC", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 16, no. 10, p. 102802, Oct. 2013. doi:10.1103/PhysRevSTAB.16.102802

[4] P. Forck and A. Bank, "Residual gas fluorescence for profile measurements at the GSI UNILAC", in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper THPRI056, pp. 1885–1887.

[5] F. Becker, C. A. Andre, P. Forck, and D. Hoffmann, "Beam induced fluorescence (BIF) monitor for transverse profile determination of 5 to 750 MeV/u heavy ion beams", in *Proc. DIPAC'07*, Venice, Italy, May 2007, paper MOO3A02, pp. 33–35.

[6] O. Stringer *et al.*, "Gas jet-based beam profile monitor for the electron beam test stand at CERN", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2225–2228. doi:10.18429/JACoW-IPAC2024-WEPG18

[7] M. R. Ashraf *et al.*, "Dosimetry for FLASH radiotherapy: a review of tools and the role of radioluminescence and Cherenkov emission", *Front. Phys.*, vol. 8, 2020. doi:10.3389/fphy.2020.00328