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A SUPERSONIC GAS JET-BASED BEAM PROFILE MONITOR USING FLUORESCENCE FOR HL-LHC

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Abstract

The High-Luminosity Large Hadron Collider (HL-LHC) project aims to increase the machine's luminosity by a factor of 10 as compared to the LHC's design value. To achieve this goal, a special type of electron lens is being developed. It uses a hollow electron beam which co-propagates with the hadron beam to act on any halo particles without perturbing the core of the beam. The overlapping of the two beams must be carefully monitored. This contribution presents the design principle and detailed characteristics of a new supersonic gas jet-based beam profile monitor. In contrast to earlier monitors, it relies on fluorescence light emitted by the gas molecules in the jet following interaction with the primary hadron beams. A dedicated prototype has been designed and built at the Cockcroft Institute and is being commissioned. Details of monitor integration, achievable resolution and dynamic range will be given.

INTRODUCTION

To enhance the capability for the observation of rare processes within the current scope of the Large Hadron Collider, the High-luminosity LHC (HL-LHC) project [1] was announced in 2013 and will be operational by 2025. The key improvement is the luminosity, which will be increased by a factor of 10 compared with the LHC's current value. Along with the increase in luminosity, the intensity of the beam halo particles will also increase, which would potentially damage the machine due to their destructive energy. Therefore, reinforcement of machine protection was proposed, and a hollow electron lens [2] is part of the scheme. The hollow electron lens is an insertion device in which a 10 keV 12 A continuous hollow electron beam is generated and co-propagated with the LHC proton beam. The hollow shape of the electron beam will be maintained by a superconducting solenoid field. It uses the electric field of the electron beam to give a transverse kick to halo particles of the LHC beam out to a large radius, where they can be easily removed by the collimators which follow. To ensure good performance of this device, the concentricity of both beams should be monitored regularly. However, most of contemporary diagnostics for beam profile monitoring, such as flying wires [3] and scintillating screens [4], will suffer from the destructive power of both beams inside this device. In this instance, a non-invasive or minimally-invasive beam profile monitor is needed.

Previously, a supersonic gas jet based ionization profile monitor (IPM) was developed in Cockcroft Institute [5-8] and then was proved to be used in fluorescent mode [9, 10]. This monitor is a candidate for HL-LHC beam profile monitoring. The principle of these monitors is to use a supersonic curtain-shaped gas jet as a 45-degree tilted screen to interact with the beams to be monitored; the products from the interaction, either the ions or the fluorescent photons, can then be collected to represent the profiles of the primary beams. Comparing to the traditional IPM or residual gas fluorescent monitor, this monitor can greatly reduce the integration time by several orders of magnitude because of the increased localized density in the gas jet used. The directionality of the gas jet itself ensures that it will not spill around the existing vacuum system. For the principle of detection, impact ionization typically has a larger cross-section than fluorescence; in other words, the integration time is smaller given the same gas jet density, gas species and detecting charged particle beam status. However, in this electron lens application, the ions collected in IPM mode would be severely affected by the surrounding solenoid field, causing a significant distortion of the profile from the real distribution of the primary beams. The fluorescent mode will, therefore, be the preferred option.

The gas jet beam profile monitor previously tested in the Cockcroft Institute was modified from the version used in IPM mode and used in fluorescent mode only for proof of principle, in which a large interaction chamber and a lower pumping speed are presented. To apply this diagnostic in the LHC, some important issues need to be studied in theory, simulation and experiment such as operating pressure, gas type, integration time, and resolution. For testing purposes, a dedicated monitor has been designed and is currently under development in the Cockcroft Institute.

MEASUREMENTS ON THE CURRENT EXPERIMENTAL SETUP

Recently, we upgraded the electron gun (Varian Rheed Gun 450) with a higher current (<100μA) and energy (<10 keV) to reduce the integration time for the modified version of the monitor. To achieve the best integration time, the electron gun was set to 5 keV and the related

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beam current was about 30 μA. The other upgrade was a dedicated optical system [11] as shown in Fig. 1. It is expected to perform better in photon transmission by a factor of 3 or more. It was designed for the dedicated electron lens gas jet monitor. The long optical channel is to avoid the effect on the MCP of the high magnetic field from the superconducting solenoid. Details of the optical system can be found in [11].

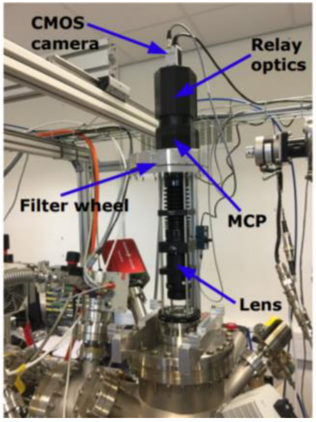
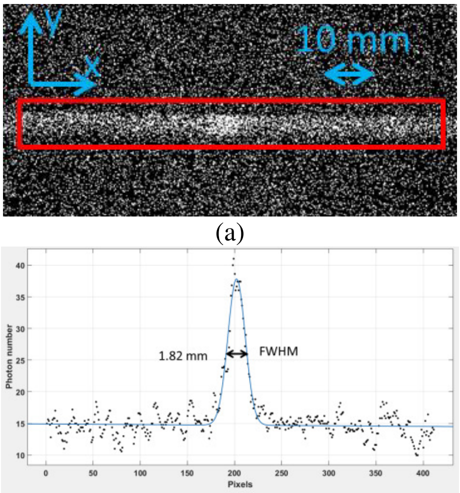


Figure 1: The upgraded optical system for the gas jet beam profile monitor.

In the data collecting process, a single photon counting mode was adopted due to the low signal, in which each picture was taken with appropriate MCP gain and 2 s integration time, to show individual photons (including signal photons, background photons and dark counts). The coordinates of these photons were then recorded. Series of pictures were taken and the same process was applied to them. The number of photons in each pixel collected in a certain time was then obtained by summing the photons in that pixel over all pictures. By grouping all the pixel information, we find the overall distribution of photons. The total integration time is the number of pictures × two seconds. For example, using data from experiments in 2017 [9], we obtain a photon map such as that in Fig. 2 (a). The x profile of the region of interest is shown in Fig. 2 (b). The total number of photons from the gas jet was estimated as ~534 by Gaussian fitting.

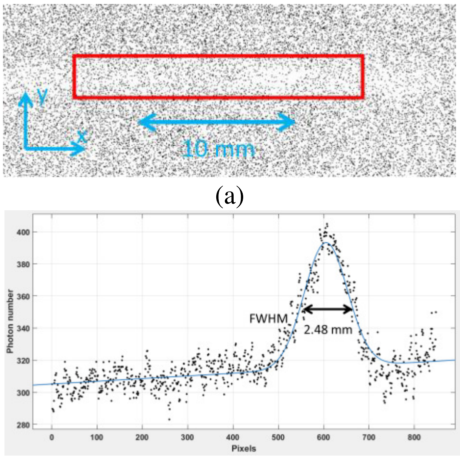


(a)

(b)

Figure 2: Data analysis using single photon counting for data from 2017, with a 3.5 keV, 7 μA electron beam, 8000s integration time and 5 bar inlet pressure nitrogen gas jet. (a) Photon distribution for both the gas jet image and the residual gas image. (b) Gaussian fitting for the x-profile of the region of interest.

With the upgraded electron gun and optical system, we obtained an image as shown in Fig. 3 (a). Compared with Fig. 2 (a), we can see that there are more dark count photons, making the residual gas image and gas jet image hard to see. The reason is that the MCP has a higher-noise photocathode. We plot the x-profile of the region of interest in Fig. 3 (a) to show the distribution from the gas jet image as in Fig. 3 (b). In the fitting, the linear curve represents the background and the residual gas image, while the Gaussian part represents the gas jet image. The total photon number from the gas jet image is estimated as 9,343, which is about 20 times higher than the previous measurement. If the same ~500 photons as suggested by Fig. 2 are enough for profile imaging, the integration time could be reduced to 200 s for the 30 μA beam.



(a)

(b)

Figure 3: (a) Image from the fluorescent mode using upgraded electron gun and optical system with the electron beam set to 5 keV and 30 μA, 4000 s integration time, and 8 bar inlet pressure nitrogen gas jet; (b) Gaussian fit for the x-profile of the region of interest.

DESIGN AND DEVELOPMENT OF A DEDICATED PROTOTYPE FOR LHC

In the modified version of the system, the key issues preventing us from reducing integration time are the signal level or electron beam intensity, and the signal to noise ratio of the residual gas image from the relatively high base pressure. For the first issue, there is no direct effect because the currents of both the electrons and protons for the electron lens are several orders of magnitude higher than for our test electron beam. In order to further reduce the integration time in our test setup, we purchased an even higher intensity electron source, with a maximum current of 10 mA independent of the energy adjustment. We expect the integration time to drop to the millisecond range. In addition, a dedicated system has been designed to meet the requirement of the LHC environment, as shown in Fig. 4. The whole gas jet system will be mounted onto a movable rail on the frame instead of being fixed to it directly. This will allow us to easily make small modifications for gas dynamics studies. The nozzle is fixed so that only longitudinal motion is allowed, which increases the stability of the gas jet during the on-and-off transition. A laser will be used to ensure the accuracy of the alignment between nozzle and skimmers to the micron level. As shown in the top-left corner subfigure, the distance between the nozzle and the first two skimmers can be changed by adjusting the length of the spacer pins, allowing us to optimise the location of these three components to generate a high-density gas jet with low divergence. In addition, turbopumps with large pumping speeds are connected to increase the rate of pressure drop, as well as to meet the pressure requirement of the LHC environment. We retain the scanning gauge system in this prototype to study the gas jet density distribution. In the bottom right subfigure, a target and scintillator can be inserted with a linear bellows drive to calibrate the optical systems, as well as to provide an alternative method of measuring the beam profile for comparison.

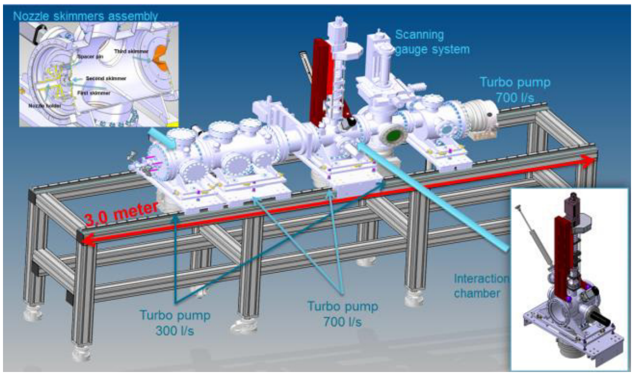


Figure 4: Schematic drawing of the dedicated prototype gas jet monitor using fluorescent mode.

At present, most of the parts for this prototype are ready and assembled in the laboratory as shown in Fig. 5. Initial pumping tests have shown that this system can reach a pressure of 10^{-8} mbar within an hour and better than 10^{-9} mbar overnight, without baking. The target and scintillator were tested with 3.5 keV electron beams. A laser alignment system is ready as shown in the figure and includes a 3-D translation stage and mirror mount. The laser currently used is a 'pointer' type, but can be upgraded if necessary.

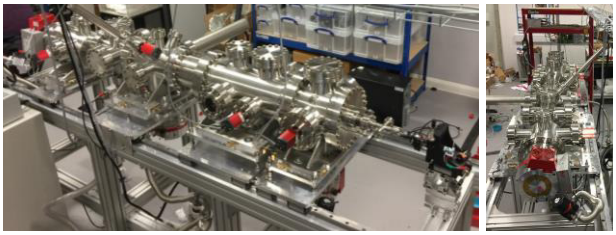


Figure 5: Photos of the dedicated prototype of the gas jet monitor system.

We have designed two versions of the 30 μm nozzle part as shown in Fig.6 (a) and (b), and either of them can be screwed to the injector. For the first type, the hole was drilled on the left piece by tiny drill bits and then welded to the right piece. The outer surface of the right piece is then machined to satisfy concentricity. The second type will use a platinum aperture 3.04mm diameter × 0.25mm thickness with a 30 μm hole, commercially available from Agar Scientific. The aperture will then be clamped between the left and right piece. Both of them are similar in size and shape, but while the first has better concentricity and will be easier for alignment than the latter, it needs more manufacturing effort. One other benefit of the latter is that the aperture can be easily changed with a different hole size. A De Laval nozzle with converging and diverging structure is suggested, as shown in Fig.6 (c); this was proven to provide a better gas jet density. We have also designed one such nozzle, to be mounted on our gas injector.

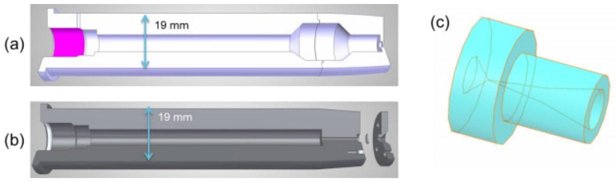


Figure 6: Schematic drawings of three types of the nozzle.

CONCLUSION & OUTLOOK

In this contribution, we have discussed the recent progress of the supersonic gas jet-based beam induced fluorescence profile monitor. A 100 s integration time was demonstrated with a 30 μA electron beam and upgraded optical system, which is equivalent to a millisecond integration time for the electron-lens project and HL-LHC proton beam. A dedicated prototype has been designed and is currently under commissioning in the laboratory at Cockcroft Institute. In this setup, gas jet dynamics will be studied with different nozzles, skimmers and intervening distances, to optimize gas jet density and distribution for the HL-LHC application. Gas species such as neon and argon will be tested since they are better working gases for the NEC coated pipe in the LHC. These studies will help us in the final design of a monitor suitable for HL-LHC installation.

ACKNOWLEDGEMENT

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