IMAGING A HIGH-POWER HOLLOW ELECTRON BEAM NON-INVASIVELY WITH A GAS-JET-BASED BEAM PROFILE MONITOR*

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Abstract

The Hollow Electron Lens (HEL) was proposed to actively remove the beam halo of the proton beam for the HL-LHC upgrade. Currently, the concept of generating such an electron beam is being tested in a dedicated Electron Beam Test Stand (EBTS) at CERN. For the tests discussed here, a hollow electron beam, with 7 keV energy and 0.4 A, with 25 µs pulses at 2 Hz was used. It was confined in a strong solenoid field. A gas curtain-based beam profile monitor was developed to characterize the beam almost non-invasively during operation. It injects a directional gas sheet at 45 degrees to interact with the electron beam. Gas particles are excited through collisions with the beam and emit fluorescent photons which are collected by an intensified camera system. This allows the reconstruction of the profile of the hollow electron beam.

This contribution presents the design of the monitor and discusses the initial results obtained with a hollow electron beam at the EBTS.

INTRODUCTION

Halo formation in the LHC, especially after the High Luminosity upgrade, will be a challenge for machine protection and a potential noise source for the particle physics experiments. One of the proposals to actively remove the beam halo in the proton beam is the Hollow Electron Lens (HEL) [1]. The idea is to generate a hollow electron beam co-propagating with the proton beam. Halo particles in the proton beam will experience a nonlinear transverse kick which drives them to higher amplitudes so that they can later be removed by the LHC collimation system. To maximize the efficiency of such a device, the proton and the hollow electron beam need to be perfectly aligned, for this reason, the transverse distribution of the hollow electron beam needs to be measured. Due to the potentially destructive effect of LHC beams, traditional methods used for measuring transverse beam profiles, such as scintillation screens are discarded. Therefore, a gas-jet-based beam profile monitor or beam gas curtain monitor (BGC) was proposed and produced [2–5]. As shown in Fig. 1, the BGC uses a supersonic molecular beam shaped like a thin curtain with a tilted angle of 45°. When the electron or proton beam traverses the molecular beam, the gas molecules will be ionized, thus generating secondary particles such as electrons and ions, or be excited and emitting fluorescent photons. By collecting the secondary particles using an external electrical field (Ionisation profile monitor or IPM mode) [4] or observing the fluorescence (beam induced fluorescence or BIF mode) [5], the transverse profile of the charged particle beam can be restored. In the current application, the space charge effect due to the proton beam and the strong magnetic field in the hollow electron lens device will distort the profile in the collection process of the charged secondaries. The BIF mode will be most suitable for imaging the hollow electron lens. In this contribution, the molecular beam characteristics such as the density and its distribution will be discussed as well as the installation of such a monitor into the Electron Beam Test Stand (EBTS) for the HEL. The result of preliminary measurements using the hollow electron beam will be presented with a discussion.

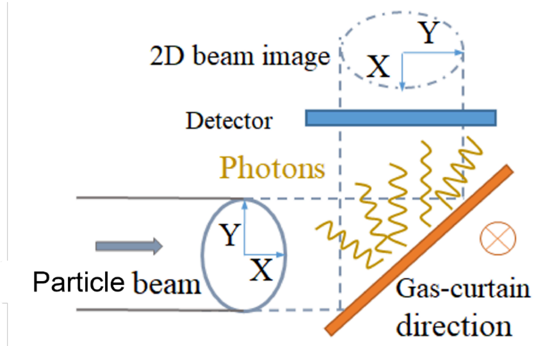

Figure 1: Principle of a gas-jet-based beam profile monitor.

BGC MONITOR AND THE MOLECULAR BEAM

As shown in Fig. 2, the BGC monitor includes a jet formation chamber, an interaction chamber, and a jet dump chamber. Two gate valves separating these three chambers linked with a pressure reading from the Penning gauges prevent accidentally venting from jet formation and dump chambers. In the jet formation chamber, gas flows from a reservoir with a stagnation pressure of 5 bars through a 30 µm diverge-flat nozzle into the vacuum chamber to form a supersonic gas jet. The jet is further collimated to form a curtain-like molecular beam by a conical skimmer with a diameter of 400 µm, a pinhole skimmer with a diameter of 2 mm, and a slit skimmer with a size of 0.3 mm×9 mm tilted

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by 45°. The skimmers divide the chamber into differential pumping stages and each stage is pumped by a HIPACE 300 Turbo-Molecular Pump (TMP) followed by a scroll pump. The interaction chamber is pumped by the same TMP and a scroll pump which can be isolated through a gate valve as well. A blackened copper liner is introduced to reduce the reflectivity of the vacuum chamber's inner wall and reduce the conductance introduced by the extra ports of the chamber. An imaging system including a viewport, an apochromatic triplet lens, a bandpass filter, an image intensifier, and a CMOS camera was attached to the chamber. A target can be inserted to calibrate the imaging system. A fourth skimmer with a 7 mm×35 mm slit in front of the jet dump chamber prevents the back-flow of the molecular beam. The vacuum pressure in each chamber is shown in Table 1.

Table 1: Measured pressure (mbar) in each vacuum chamber, with gas jet off and gas jet on at a stagnation pressure of 5 bar.

Jet	Nozzle	SkimmerI	SkimmerII	Interaction	Dump
On	8.7×10^{-3}	1.2×10^{-5}	1.2×10^{-6}	8.7×10^{-8}	1.3×10^{-7}
Off	1.4×10^{-8}	2.8×10^{-10}	5×10^{-9}	4.7×10^{-8}	1.1×10^{-8}

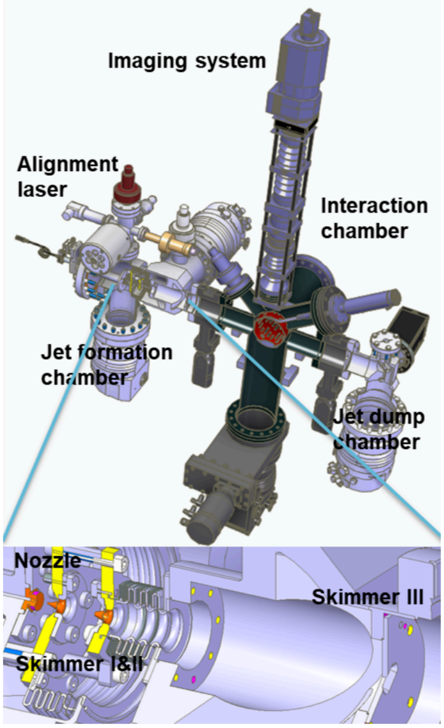

Figure 2: Schematic drawing of the BGC monitor and enlarged nozzle-skimmers assembly.

To characterize the molecular beam curtain used for monitoring purposes, a density distribution measurement was performed using a movable compression gauge method [6], which is shown in Fig. 3 (a). Note that the resolution of the measurement is limited by the accepting pinhole size of the compression gauge, therefore the jagged shape of the curtain edges is seen. This can be verified by a hybrid simulation from a continuum flow to a free molecular flow [7]. The continuum flow was treated with analytical formulas listed in Ref. [7]. The collision in the free molecular flow region was ignored and the molecules were treated as particles moving in free space. A 'Quitting Surface' model was used to describe the transition between the two regions in Ref. [7]. With the same geometry of the nozzle-skimmer assembly and operation condition, a quasi-uniform gas molecular beam curtain can be expected as shown in Fig. 3 (b). The convolution of this density distribution with a round pinhole with a diameter of 1 mm will result in a distribution shown in Fig. 3 (c). This convoluted distribution matches the experimental results well.

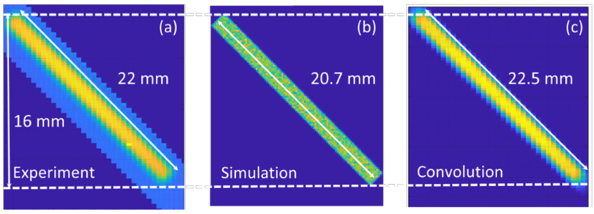

Figure 3: Comparison of the jet number density distribution between: (a) Measurement from the movable gauge; (b) Simulation using molecule tracing; (c) Convolution of the simulated distribution with the 1 mm pinhole used in the measurement.

INSTALLATION OF BGC INTO EBTS

Figure 4 shows the installation of the BGC monitor into the EBTS described in detail in Ref. [8]. The electron gun, installed currently at the setup, produces a hollow electron beam with an energy up to 10 keV and 5 A of peak current. The gun is immersed in a solenoid magnetic field to magnetise and guide the beam alongside the magnetic field lines. Right after the first solenoid, there is an Yttrium Aluminum Garnet (YAG) and a pinhole Faraday cup measurement setup for characterizing the beam close after the emission. The BGC is located further downstream to measure the beam transverse profile after the beam propagation through the solenoid field. Before the BGC was installed at the EBTS, an Optical transition Radiation (OTR) screen was installed at the same position to characterize the transverse profile of the beam. At the end of the setup, a collector is installed to dump the beam and observe the absolute electron current of the beam.

MEASUREMENT AND DISCUSSION

Figure 5 shows a measurement of the hollow electron beam using the BGC monitor with nitrogen as a working gas. The hollow electron beam was at 7 keV energy and 400 mA peak current. Due to the limited cooling capability of the beam dump, the electron beam was operated in a pulsed mode with a duration of 25 µs and a repetition rate of 10 Hz. The measurement took 10 minutes and integrated 6000

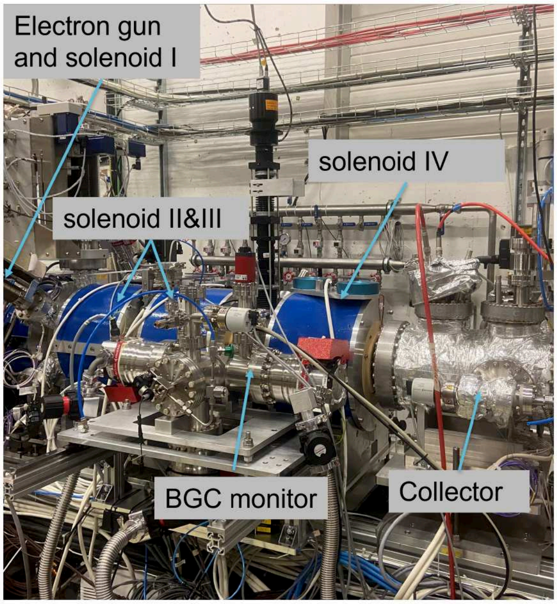

Figure 4: Layout of the BGC installed in the EBTS.

pulsed hollow electron beams. This is equivalent to 150 ms integration time for a DC beam which is the expected operation mode of the hollow electron lens. The integration time matches with the estimation in Ref. [5]. If a higher current was used, e.g. the HEL case where the current is 10 A, the integration time could be further reduced. Since the gas molecular curtain is designed to fit the smaller beam size of the final HEL beam, with the curtain length of 16 mm, it can only resolve here a part of the hollow beam on the EBTS as shown in Fig. 3 (a). The centroid of the hollow electron beam is also off-centered with respect to the molecular curtain. In this case, a C-shaped beam was observed. Two current settings (200 A and 300 A) of the solenoid II were applied to verify that the signals are from the interaction of the gas curtain and the hollow electron beam. The measurement shows an inner ring diameter and outer ring diameter of (6.9 mm, 14.4 mm) and (8.2 mm, 16.5 mm) for the focused and defocused beam, respectively. Some detailed structures which can be seen on the left side of the C-shape from the focus case are not noise. This behaviour still requires additional studies, which goes beyond the scope of this paper. Note that the hollow electron beam also interacts with the residual gas, therefore there is a fluorescent signal shown as a stripe with around 15° in both images in Fig. 5. In order to measure the full ring shape of the hollow electron beam, a kicker can be used to correct the centroid differences between the beam and the curtain to make use of the full curtain size. Such a kicker is under test at this moment.

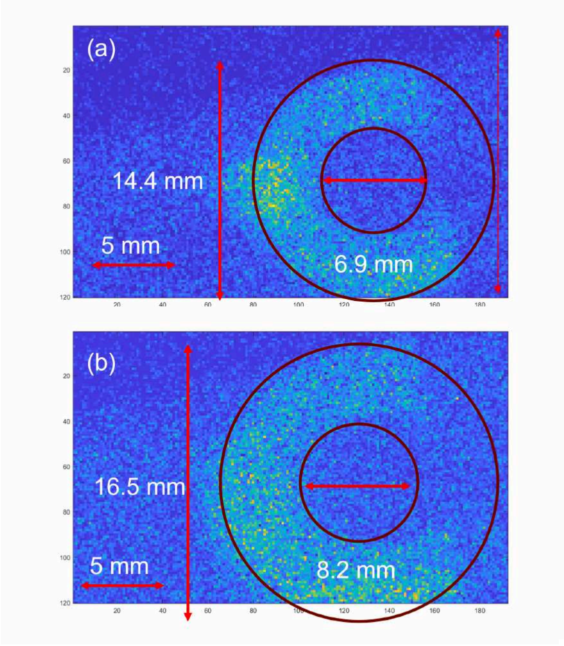

Figure 5: Measurement of a high-intensity hollow electron beam with two solenoid settings: (a) 200 A solenoid current; (b) 300 A solenoid current.

CONCLUSION

This contribution presented a supersonic molecular curtain-based beam profile monitor and its integration into the EBTS at CERN. Preliminary experimental results showed that it can be used for measuring a high-power low energy hollow electron beam. In the future, with the kicker magnet, the result can be improved to cover the whole hollow electron beam. These results can be compared with other intercepting methods using screens that are also used with lower pulse duration and lower beam current [9]. In the meanwhile, a dedicated design is under investigation for a monitor with a larger molecular curtain which can cover the whole hollow electron beam, even defocused and with a certain centroid offset. This new monitor could be used to understand the beam dynamics under high current and DC beam operation of the hollow electron lens at the EBTS.

ACKNOWLEDGEMENTS

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