A SUPERSONIC GAS-JET BASED BEAM INDUCED FLUORESCENCE PROTOTYPE MONITOR FOR TRANSVERSE PROFILE DETERMINATION

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Abstract

Supersonic gas jets have been used in transverse beam profile monitoring as Ionization Profile Monitors (IPMs) and Beam Induced Fluorescence (BIF) monitors. The former method images ions generated by the projectile beam, whilst the latter is based on the detection of photons. This is a promising technology for use in high energy accelerators, such as the High Luminosity Large Hadron Collider (HLLHC).

In this paper, the suitability of a supersonic gas jet in combination with a BIF detection system for the measurement of the transverse beam profile of a low energy electron beam is discussed. The technical layout and experimental results from measurements at a test installation at the Cockcroft Institute are also presented.

INTRODUCTION

Beam profile monitors are important diagnostic tools allowing modern accelerators to be commissioned and operated in a safe and efficient manner. This is particularly important for high-energy and high-intensity beams such as the ones in the Large Hadron Collider (LHC) and European Spallation Source (ESS). Due to their destructive power, knowing the beam profile can prevent unwanted beam losses and thus reduce the probability of any damage to the machine. However, conventional beam profile monitoring methods such as scintillating screens have strict limitations concerning the maximum beam power they can withstand. Therefore, non-invasive or least-invasive beam profile monitors are highly desirable.

A beam profile monitor based on the interaction between the projectile beam and a screen-like supersonic gas jet has been developed at the Cockcroft Institute [1-5]. With the help of an external moderate electrical field, the generated ions from the interaction are collected and their spatial distribution, as measured by a position sensitive detector, represents the transverse profile of the projectile beam. In some specific machines, the space limitations prevent the installation of the electrodes inside the accelerator tubes to create an extraction field. Moreover, in a high magnetic field environment, such as the proposed electron lens [6] for high luminosity LHC (HLLHC), the ambient field from the superconducting main solenoid (yielded 6.5 T at 1780 A) [7] will distort the distribution of the generated ions and thus affect the measurement. As a result, a new concept needs to be developed to compensate these effects. Beam induced fluorescence (BIF) would be an interesting alternative.

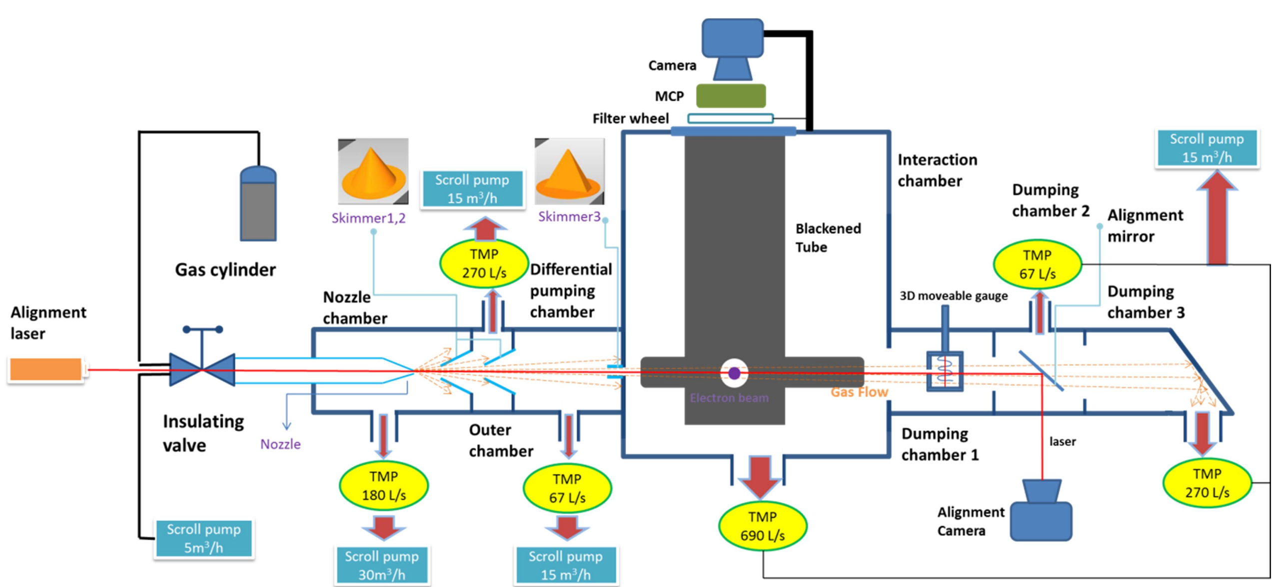

Figure 1: Schematic of the supersonic gas jet beam profile monitor based on BIF mode.

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BIF beam profile monitors [8] suffer from a low reaction rate if the low-density residual gas in the chamber is used. Normally, the operation of such monitors requires a local to use a valve to intentionally increase the pressure to 10^{-6} mbar or higher. Here, we adopt the BIF concept, but instead of using a valve to create a local pressure increase, we use our shaped supersonic gas jet. Because of the directionality and high speed of the jet, the injected gas molecule will be easily pumped and the vacuum condition can be maintained.

In this paper, we report on a transverse beam profile monitor based on a supersonic gas jet working in the BIF mode.

MEASUREMENT PRINCIPLE AND EXPERIMENTAL SETUP

In [2, 3], we discussed the gas jet formation and the interaction of the projectile beam with the gas jet. One interaction product, the ion, was used in the beam profile monitor because impact ionisation has a larger cross section than induced fluorescence. The alternative method of beam-induced fluorescence used in this paper will, in contrast, rely on the following process [9]

$$\mathrm{N_2 + p/e^- \rightarrow (N_2{}^+)^* + e^- + p/e^- \rightarrow N_2{}^+ + \gamma + e^- + p/e^-} \quad (1)$$

$$\mathrm{N_2 + e^- \rightarrow (N_2)^* + e^- \rightarrow N_2 + \gamma + e^-} \quad (2)$$

The electronic transition of the excited molecular ion has a characteristic wavelength of around 391 nm, whilst the electronic transition of the neutral molecule results in photons with a characteristic wavelength of around 337 nm.

The cross sections for these processes are much lower than the one for impact ionisation. For the case of a projectile electron beam with 3.5 keV energy, the cross section is $\sigma_{e,391} = 2.1*10^{-18}$ cm^2. As for the case of the proposed electron lens to be implemented in the HLHLC, the cross section for a 7 TeV proton beam will be $\sigma_p = 2.8*10^{-20}$ cm^2 and for a 10 KeV electron beam will be $\sigma_{e,337} = 1.48*10^{-23}$ cm^2 and $\sigma_{e,391} = 9.20*10^{-19}$ cm^2.[9].

As shown in Figure 1, the new monitor follows the setup of the gas jet beam profile monitor [3]. A nozzle with 30 μm diameter, a first conical skimmer with an opening diameter of 180 μm, a second conical skimmer with an opening diameter of 400 μm and a third pyramid-shaped skimmer with 7.2 * 1.8 mm^2 slit opening separate the setup into different chambers indicated in the figure. Differential pumping techniques are used to make sure the pressure in the interaction chamber is below 10^{-8} mbar. From previous results [4, 5], the usage of the larger size third skimmer will reduce the resolution of the measurement, but the benefit is that we can increase the jet density and thus reduce the integration time for the benchmark experiment.

An enlarged view of the interaction chamber can be seen in Figure 2. Instead of the stacked electrodes generating an electric extraction field to guide the ions, a 7-way chamber is used inside the interaction chamber to allow both electron beam and gas jet to go through as well as the fluorescent light to reach the viewport. There is one tube at 45° (not shown in the figure) between the electron beam tube and gas jet tube, which allows insertion of a phosphor screen for direct beam profile measurement. Here, this screen is mainly used to focus the camera and assist in steering the electron beam to intersect with the gas jet. The entire surface of the inner chamber is blackened using a graphite coating. Outside of the viewport, there is a filter wheel with two narrow-band optical filters (10 nm bandwidth) with central wavelengths of 337 nm and 391 nm, a chevron micro-channel plates (MCP) image intensifier and a CCD camera. When experiments are conducted, a black cloth will tightly cover the detection system to prevent stray light from reaching the detector.

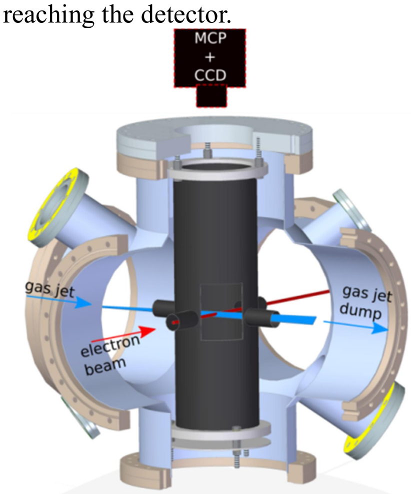

Figure 2: Schematic drawing of the interaction chamber of the BIF monitor.

Considering the light loss from the optics including the acceptance angle, the transmission of the optical filters, the transmission of the optical system including windows, the efficiency of the MCP's photocathode and the detection efficiency of the MCP, the light collection efficiency will be 1.95 * 10^{-7} [9]. The calculated photon detection rate will be proportional to the process cross section, projectile beam current, gas jet density and thickness, and the light reduction. For the HLLHC case, with the gas jet conditions similar to the Cockcroft setup (a gas number density n = 2.5*10^{10} cm^{-3}, a curtain thickness d = 0.5 mm), the estimated integration times are 10 seconds for proton beam detection and less than one second for the detection of the electron beam [9]. For the electron beam used at the Cockcroft Institute, the beam current is only about 10 μA much lower than in the case of the HLLHC, and even though the cross section is little higher because of the lower beam energy, we still expect a much longer integration time of around few thousands of seconds.

EXPERIMENTAL RESULTS

To measure the beam size, the stagnation pressure of the injected gas tank was 5 bars, and the pulsed valve was

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set to the continuous mode. Whilst running the experiment under these conditions the pressure in the interaction chamber remained in the range of 10^{-8} mbar. The reason that a continuous gas jet was used instead of a pulsed jet was to create a stable jet for a long-time integration. The amplification of the MCP is set as to provide a good signal to noise ratio. A large series of 16-bit images are acquired, each with an integration time of four seconds, which was much less than the total integration time. This allows for single photon detection since it strongly reduces the probability of overlapping signals as well as preventing any excessive light accumulating and causing damage to the MCP intensifier and the camera. The overall integration time could be achieved by simply taking and summing multiple pictures. Before the summing process, several noise-reduction techniques were applied. Firstly a median filter was applied to remove any salt and pepper noise. Secondly, a threshold value of about 1000 was set to remove any fake photon detection. The processed images were then summed and normalised to create the final image. Such an image can be viewed in Figure 3 with a total integration time of 8000 seconds. The electron beam current has not been accurately measured, but the electron gun manual indicates that the current of the produced beam should be about 7 μA when the filament of the gun is set to 2.6 A. The reason for the very long integration time is mainly due to the low current of the electron beam that is used (maximum 10 μA). During the experiment, the integration time could be reduced to 1000s, but that would result in a low-quality image with a worse signal to noise ratio. Figure 3 shows the image generated by the interaction of the gas jet lying on top of the image from the residual gas. In contrast, when imaging in the IPM scheme the images that were previously obtained from collecting ions show the two images are separated by a distance. The reason for this separation is due to the fact that the ions from the gas jet still carry the jets parallel velocity and will continue to drift in the collection process, which lasts about 3 ms. Here, although the excited molecules from the gas jet still have a high initial velocity in the direction of the gas jet, the fluorescence process is so fast that they do not separate themselves from the excited residual gas molecules before emitting photons.

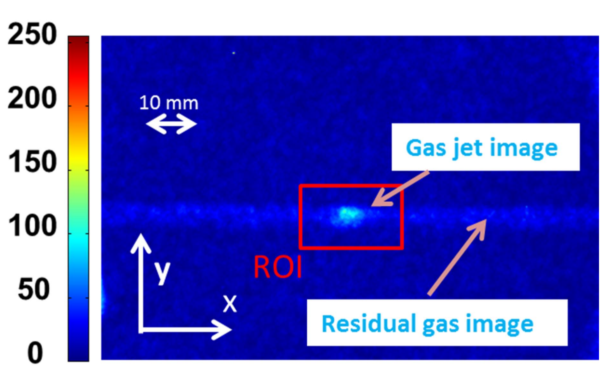

Figure 3: beam image of a 3.5keV electron beam with current about 7 uA.

A region of interest is selected in Figure 3 to highlight the beam profile imaged with the gas jet. We integrate the image in the x or y-axis to obtain a one-dimensional profile shown in Figure 4. Knowing a pixel to millimetre ratio of 0.215 the beam size can be obtained from a Gaussian fit as Xrms = 1.96 mm and Yrms = 1.33mm. As said before, the larger size of Xrms could be due to the increased size of the jet width when using a larger skimmer. Long integration times could also affect the image size if either the electron beam or the jet is jittering. A new electron gun with a higher current of about 100 mA will be installed soon in order to reduce the integration time in the future.

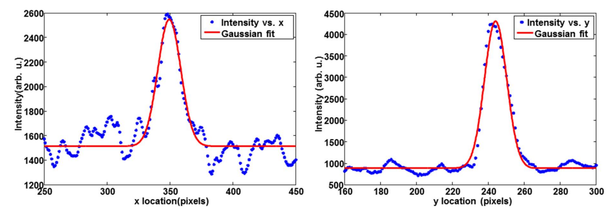

Figure 4: 1D beam profile and Gaussian fit.

CONCLUSION & OUTLOOK

In this paper, we discussed the design of a supersonic gas jet based beam induced fluorescence profile monitor and demonstrate that it is working by measuring a profile of a laboratory electron beam. Further experiments are planned to expand the gas species such as helium, neon or argon using different fluorescent spectrum line, and to characterise the resolution of such monitors. Simulations of the gas dynamics are still ongoing in our group to help us better understanding the jet formation process and then the relevant velocity, temperature and density distribution of the jet. The latter parameters will determine the intrinsic resolution of such monitors. A new setup for gas jet beam profile monitor has been designed and currently under manufacturing process. This setup will be a prototype monitor which focuses on the BIF mode and will dedicate into the diagnostic development for electron lens project of the HLLHC. After the full function of the new setup, the current setup could be used to develop a pencil jet using Fresnel zone plate. The aim of such study could greatly reduce the jet size and thus increase the resolution of such monitor into a range of tens of microns.

ACKNOWLEDGMENT

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REFERENCES

[1] M. Putignano and C. P. Welsch, *Nucl. Instruments Methods Phys. Res. Sect. A*, vol. 667, 2012.
[2] V. Tzogani *et al.*, *Vacuum*, vol. 109, 2014.

[3] V. Tzoganis and C. P. Welsch, *Appl. Phys. Lett.*, vol. 104, no. 20, 2014.
[4] H. Zhang *et al.*, in *Proc. IBIC'15*, Melbourne, Australia, TUPB075, 2015.
[5] V. Tzoganis *et al.*, accepted by *PRAB.*
[6] S. Redaelli *et al.*, in *Proc. of IPAC'15*, Richmond, VA, USA, WEBB1, 2015.
[7] G. Stancari *et al.*, arXiv:1405.2033.
[8] F. Becker *et al.*, in *Proc. BIW'08*, Tahoe City, California, USA, TUPTPF054, 2008.
[9] S. Udrea *et al.,* in *Proc. IBIC'16*, Barcelona, Spain, TUPG73, 2016.

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