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DEVELOPMENT OF QUANTUM GAS JET BEAM PROFILE MONITOR FOR sub-mm BEAMS

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Abstract

The development work of a high-resolution quantum gas jet beam profile monitor for highly energetic sub-mm particle beams is in progress at the Cockcroft Institute (CI), UK. This device is designed on the principle of detecting the secondary ions from the ionisation induced in the interaction between the quantum gas jet and charged particle beams. This monitor aims to generate an intense gas jet with a diameter of less than 100 µm, which can ultimately lead to superior position resolution and high signal intensity resulting from a strongly focused quantum gas jet. This is done by exploiting the quantum wave feature of the neutral gas atoms to generate an interference pattern with a single maximum acting as an ultra-thin gas jet using an 'atom sieve' which is similar to the light focusing with a Fresnel zone plate. This device will be minimally interceptive and will work analogously to a mechanical wire scanner. This contribution gives a general overview of the design, working principle of the monitor and experimental results obtained from the electron beam profile measurements carried out at the Cockcroft Institute.

INTRODUCTION

Beam diagnostics are essential for the operation, optimization and protection of accelerators and their subsystems. The requisite of non-invasive high resolution beam diagnostics has been increasing with the growing demand for high intensity and high power accelerators worldwide. Wire scanners are the currently existing invasive monitors for high power accelerators such as the Spallation Neutron Source (SNS) or Accelerator Driven System, having the limitation of handling the huge beam peak power and hence, will be used at low beam duty cycle [1, 2]. Non-invasive monitors such as residual gas ionization profile monitors (IPM) suffer from distortions due to the non-uniformity of the extraction field, space charge effects of the primary beam and the initial momentum spread of the ionization products [3]. These concerns have triggered a demand for the development of a new generation of non-invasive beam profile monitors with high resolution and the least distorted beam profiles. Development work for a quantum gas jet scanner based beam profile monitor is in progress at the Cockcroft Institute (CI), Daresbury. This monitor is based on the previous development work on the supersonic gas jet based IPM carried out by the QUASAR group at CI for high intensity beams such as the CLIC Drive beam and the European Spallation Source [4-6].

A focused gas jet with a diameter less than a few 10 µm named as Quantum gas jet will be used to generate the beam profile in this profile monitor instead of a gas jet curtain. In order to generate the complete beam profile of the primary beam, this quantum gas jet will be scanned over the beam, analogous to a wire scanner. The quantum gas jet can be used in several other applications i.e. for generating a confined plasma source [7], as a probe for microscopy [8], etc. Initial design calculations for this monitor were carried out using the fundamental physics principles and results obtained from the CST simulations [9, 10]. In this work, the general overview of the design and working principle of the quantum gas jet monitor are presented along with the beam profile measurement results obtained for a 3.7keV electron beam at CI.

OVERVIEW AND WORKING PRINCIPLE OF THE MONITOR

The schematic of the whole setup is shown in Fig. 1. In this setup, supersonic gas jet curtain is created using a nozzle-skimmers assembly with differential pumping stages. Details of the gas jet curtain generation can be found in our previous work [4].

In this development work, the pinhole shown in Fig. 1 will be replaced by an atom sieve designed on the principle of Fresnel zone plate (FZP) for x-rays to generate quantum jet. The design details of atom sieve can be found in previous work done by our group [9]. A FZP designed for x-rays is usually made up of concentric metallic rings embedded in an x-ray transparent substrate. However for an atom sieve, holes are required to provide passage for the gas molecules. Figure 2 shows the design of the atom sieve to be used for this work. The atom sieve is fabricated on a 2 µm thick silicon nitride membrane grown on a silicon wafer of diameter 150 mm. The circular holes in the pattern are within 60 µm diameter.

The interaction chamber is coupled with an electron gun that can generate a beam of energy up to 10 keV which propagates perpendicular to the direction of the flow of the quantum gas jet. The interaction between the electron beam and the supersonic gas leads to ionization of the gas molecules and these ions will be extracted using an external electrostatic field generated by a series of hollow metallic electrodes. The ion signal is amplified using a Micro-channel plate (MCP) which is converted into scintillating light using phosphor screen stacked after the MCP. This light is then viewed by a CMOS camera.

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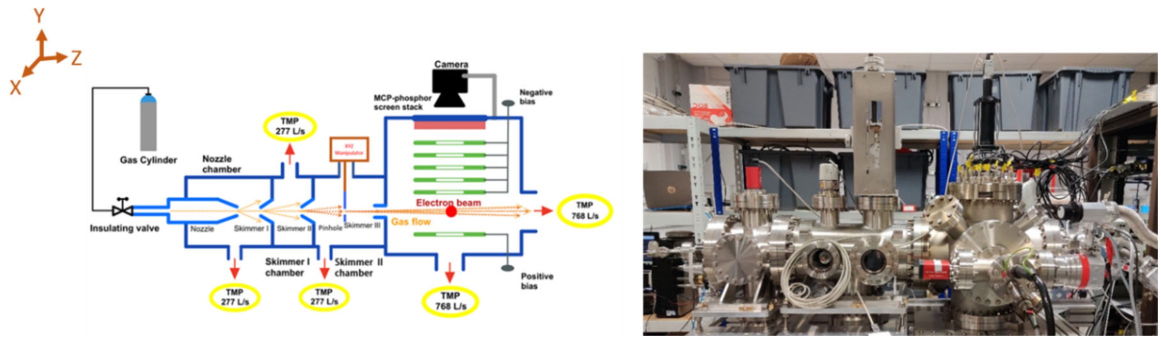

Figure 1: Schematic (left) and actual picture (right) of the gas jet curtain based quantum gas jet beam profile monitor.

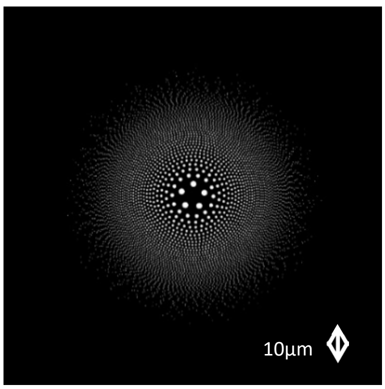

Figure 2: Design of the atom sieve on Si wafer (dia. 150 mm).

In order to scan the quantum gas jet over the primary beam, the atom sieve will be mounted on a vacuum compatible xyz manipulator. The vacuum compatible xyz manipulator will provide the flexibility in the movement in x and y direction and helps in scanning the primary beam. The movement in the z direction will assist in focusing the quantum gas jet at desired location with respect to the nozzle as well as the extraction system for imaging the beam. The experimental work was initiated with installing pinholes of various sizes ranging from 1mm to 50µm. Pinholes acted as an additional aperture and provided the circular supersonic gas jet to interact with the electron beam.

The advantage of atom sieve over the pinholes is that it acts as an optical thin lens whose focal length depends on the design of the atom sieve and the wavelength of the gas molecules. This optical thin lens could be used for generating the high density quantum jet. The wavelength of the gas molecules is determined using De-Broglie equation for the dual nature of matter. The key factors which determine the wavelength of the gas molecules are the longitudinal velocity and velocity spread. The velocity dictates the location of the focal spot and the velocity spread expands the focal spot size in a finite range. The velocity of gas molecules in this differential pumping system can vary because of several factors i.e. injection gas pressure, background pressure of the chambers, the temperature of the gas, etc. In order to compensate for the factor contributing to the change in velocity of the gas molecules and eventually the location of the focal spot, z motion for atom sieve is already considered for future experiments.

By using a quantum gas jet, the position resolution can be significantly improved and at the same time issues related to space charge can be mitigated. The jet can be scanned slowly across the beam or, to avoid problems with loss of alignment, the beam can be steered to produce a scan through the jet. The profile resolution depends only on the jet thickness and a diameter of less than 100µm would be sufficient for most applications. This is very challenging to achieve due to the mechanical constraints of typical nozzle/skimmer systems. The measurement of the beam intensity at each jet position is done by collecting the ions or electrons.

BEAM PROFILE MEASURMENT RESULTS OF ELECTRON BEAM USING PINHOLES

The beam profile measurements were performed for a 3.7 keV electron beam with a filament current of 2.6A, using different pinholes having a diameter varying from 500µm to 50µm. Figure 3 shows the various images obtained for the beam profile measurements with different pinholes. With reduction in the pinhole size, the number of gas molecules at the interaction point decreases. To compensate for this, the integration time has been increased with each reduction in pinhole size as shown in Fig. 3.

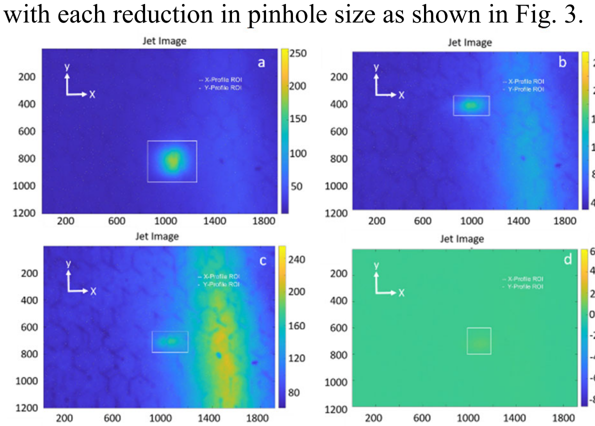

Figure 3: Beam profile images obtained for various pinholes diameters: (a) 500µm, (b) 200µm, (c) 100µm and (d) 50µm. The integration time for each image is 6, 9, 30 and 300 seconds respectively.

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Figures 4 and 5 show the respective x and y profiles of the beam after interacting with different sizes of the supersonic gas jet. The x-profile contains the information about the part of electron beam which is interacting with the gas jet. The y-profile provides information about the dimensions of the gas jet interacting with the electron beam.

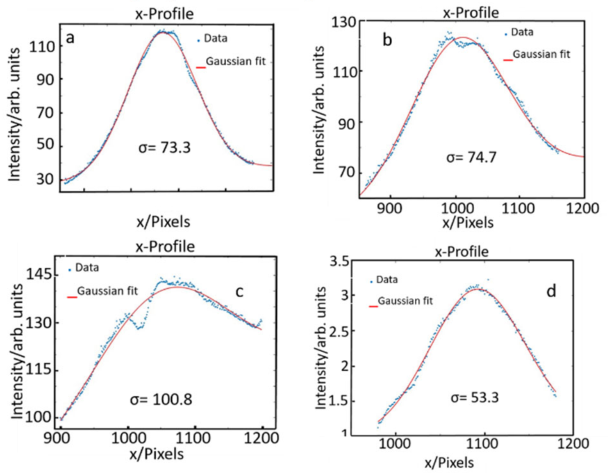

Figure 4: X beam profile obtained for various pinholes diameters: (a) 500µm, (b) 200µm, (c) 100µm and (d) 50µm.

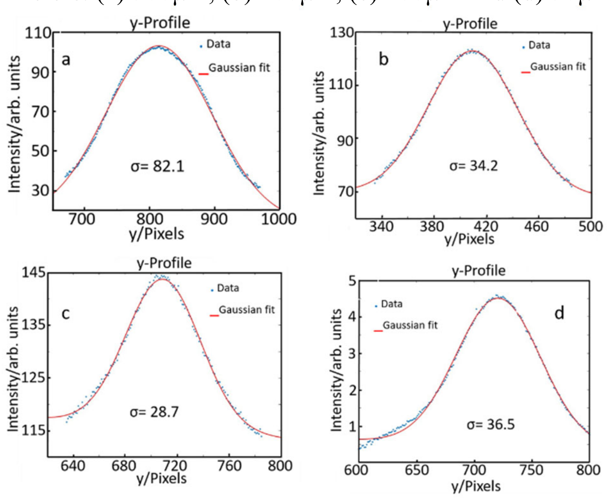

Figure 5: Y beam profile obtained for various pinholes diameters: (a) 500µm, (b) 200µm, (c) 100µm and (d) 50µm.

In Fig. 4, the measured sigma σ, derived by a Gaussian fit to the profile, depends on the size and part of the beam interacting with the gas jet so the σ is different for each measurement. On the other hand, in Fig. 5, the σ depends on the size of the gas jet originated from different pinholes, hence the σ decreases until 100µm and for 50µm is somewhat higher than for 100µm pinhole which can be due to very low signal strength and large background noise.

In Fig. 6, the beam profile image, x profile and y profile for the same electron beam are shown for gas jet generated using the 50µm pinhole separated by a distance of 200µm from each other. The signal strength was very low for these measurements, but it was still possible to detect the slight variations in both the profiles measured at two different location w.r.t. to the vertical axis of the beam. The next step is to mount the atom sieve instead of pinholes and perform the length optimization for the whole system to obtain the focused quantum gas jet for the beam profile measurements.

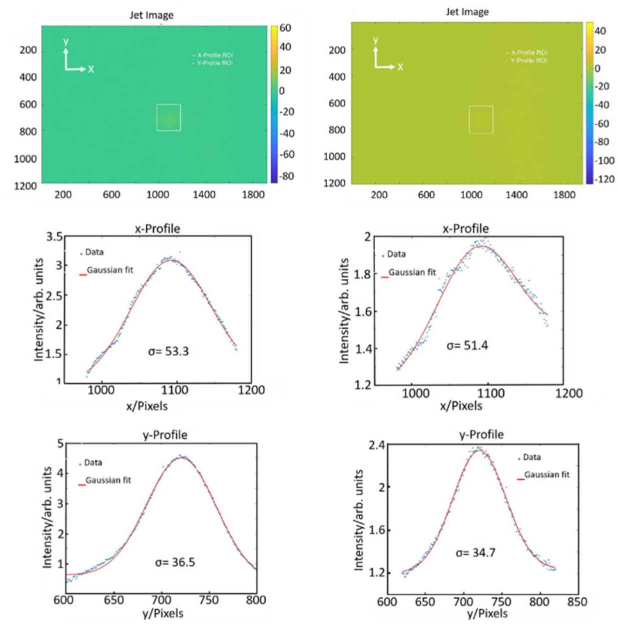

Figure 6: Beam profile images obtained for 50µm pinhole along with X and Y profiles for the same electron beam at two different locations for gas jet separated by a distance of 200µm.

CONCLUSION

In this contribution, the progress on the ongoing development of a quantum gas jet based profile monitor has been presented. The beam profile measurements demonstrated that this device can be used as a viable profile monitor that utilises the beam induced ionization in the gas jet for high power and high-intensity accelerators. The work on improving the gas jet density using the atom sieve and optimizing the design of the monitor in order to ease the integration into the complex accelerator structure is currently in progress. This new design of the quantum gas jet scanner will make it useful for an even wider range of accelerators. The applications of the quantum gas jet in other relevant research areas such as microscopy, plasma physics, etc. will aid in its development.

ACKNOWLEDGEMENT

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