14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL067

DEVELOPMENT AND TESTING OF QUANTUM GAS JET BEAM PROFILE SCANNER

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Abstract

A quantum gas jet-based beam scanner is under development at the Cockcroft Institute (CI) in the UK. This device is based on detecting the ionisation induced in a gas jet by a beam of charged particles. It aims at generating a dense gas jet with a diameter of less than 100 µm by exploiting the quantum wave nature of neutral gas atoms to generate an interference pattern with a single maximum. Work analogously to a mechanical wire scanner while being minimally interceptive, a tightly focused gas jet promises superior position resolution and high signal intensity. This contribution gives an overview of the design and functioning principle of the monitor, presents initial modification in the system for gas density measurement, as well as results from beam profile measurements obtained with a 3.7 keV electron beam.

INTRODUCTION

Beam diagnostics play a vital role in the operation, optimization and protection of accelerators and their subsystems. Novel diagnostic solutions are required for high power accelerators such as Spallation Neutron Source (SNS) or Accelerator Driven System, which can easily handle beam intensities and generate high resolution beam profiles while simultaneously being non-destructive to the primary beam. High power accelerators currently deploy invasive monitoring techniques such as wire scanners, Faraday cups, etc. which are limited by the handling of the huge beam peak power and hence, will be used at low beam duty cycle [1, 2].

Residual gas ionization profile monitors (IPM) comes under the category of non-invasive profile monitors, but they also 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. A quantum gas jet beam profile scanner is under development at the Cockcroft Institute (CI), Daresbury. The design of the quantum gas jet monitor is driven from 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 100 µm named as Quantum gas jet will be used to generate the beam profile in this beam profile scanner instead of a gas jet curtain or sheet.

In order to generate the complete beam profile of the primary beam, this focused jet will be scanned over the beam, analogous to a wire scanner. The quantum gas jet can be applicable in several other research areas 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 functioning principle of the quantum gas jet monitor are presented along with the beam profile measurement results obtained for a 3.7 keV electron beam at CI. In addition to it, this work also includes the initial modifications in the system assembly in order to conduct gas jet density measurements and future plans for this work.

OVERVIEW AND WORKING PRINCIPLE OF THE MONITOR

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

In this development work, a pinhole holder has been introduced in between the 2nd and 3rd skimmer. The 3rd skimmer is replaced from a slit skimmer to a circular skimmer (dia. 3.5mm) to provide more aperture for quantum gas jet. The pinhole skimmer 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 a quantum gas jet. The details of atom sieve design can be found in our previous work [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. 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. A pinhole holder is designed to accommodate either a pinhole or an atom sieve and is coupled to the system with a XYZ manipulator. 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.

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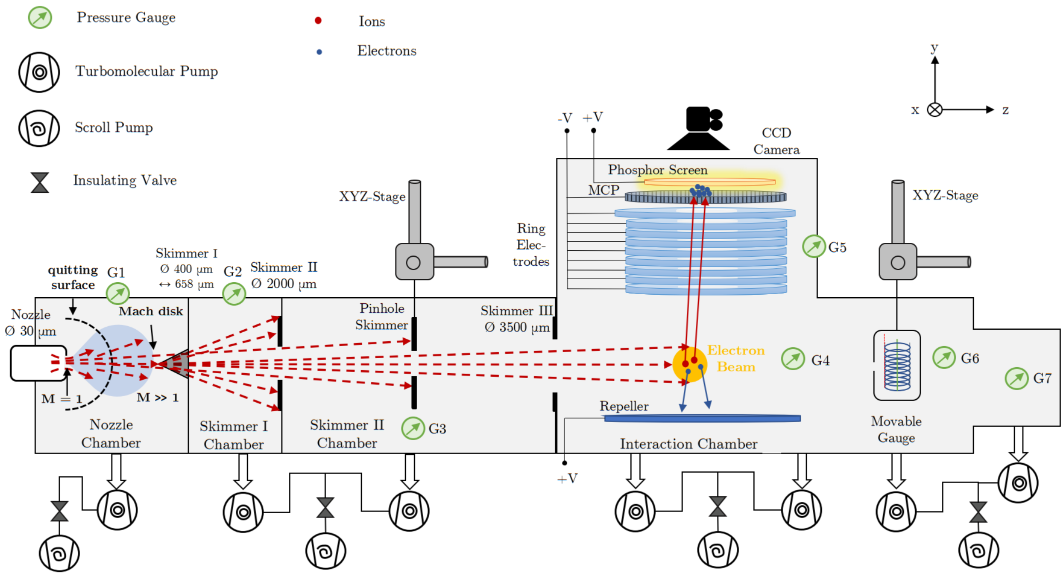

Figure 1: Schematic of the gas jet curtain based quantum gas jet beam profile monitor along with movable gauge diagnostic system.

These ions are extracted using an external electrostatic field generated by a series of hollow metallic electrodes biased with high DC voltage. 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 CCD camera.

In order to scan the quantum gas jet over the primary beam, the atom sieve will be moved using the vacuum compatible XYZ manipulator. The work was initiated with installing pinholes of various sizes ranging from 1mm to 50 µm and measuring the beam profile using the supersonic gas jet generation via these pinholes. Pinholes acted as an additional aperture in between 2^{nd} and 3^{rd} skimmer and provided the circular supersonic gas jet to interact with the electron beam.

Atom sieve has its own unique advantage over the pinholes as it acts as an optical thin lens and focal length of this lens depends on the design of the atom sieve and the wavelength of the gas molecules. In comparison to pinholes which can generate a continuously but slowly expanding gas jet, atom sieves could be used for generating the high-density focused gas jet, named as quantum gas jet. The wavelength of the gas molecules is determined using the De-Broglie equation for the dual nature of matter. The longitudinal velocity and longitudinal velocity spread are the key factors to the wavelength and associated bandwidth of the gas molecules. 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 movement of the atom sieve is already considered for future experiments.

Quantum gas jet due to its small dimensions can significantly improve the position resolution 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 100 µm 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.

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 2.6 A, using different pinholes having a diameter varying from 500 µm to 50 µm. Fig. 2 shows the example image obtained for the beam profile measurements after subtracting the background. The rectangular box indicates the region of interest (ROI), the image generated due to the interaction between the gas jet and the electron beam.

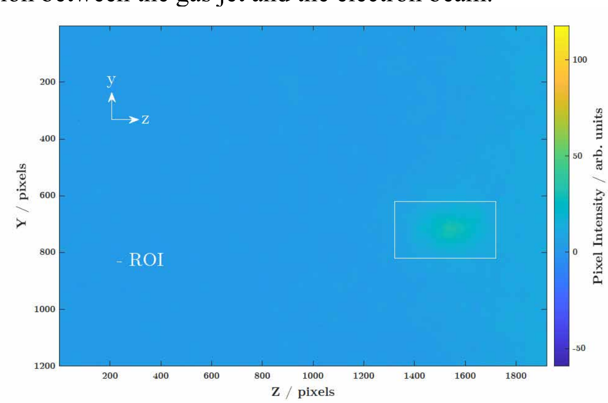

Figure 2: Beam profile image obtained for 100 µm pinhole with 3 seconds integration time.

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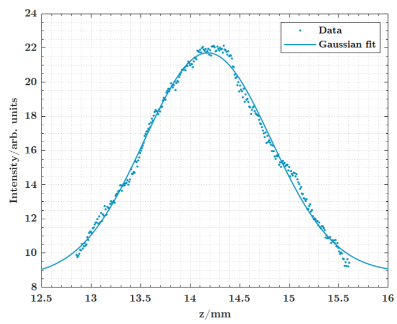
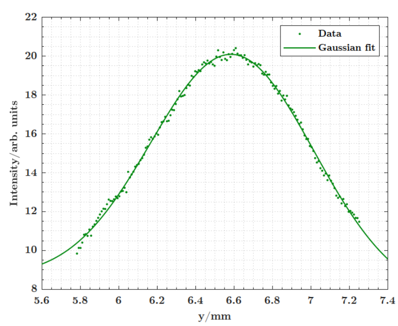
Figure 3 shows the respective Z and Y profiles of the electron beam after interacting with the supersonic He gas jet generated using 100 µm pinhole. The Z profile contains the information about the section/part of the electron beam which is interacting with the gas jet. As the quantum gas jet scanned over the electron beam, it will produce different results based on the variation in the size of electron beam along the z axis. The Y profile provides information about the dimensions of the gas jet interacting with the electron beam.



(a) Z-Profile



(b) Y-Profile

Figure 3: Beam profile obtained after image analysis (a) Z-profile and (b) Y-profile.

INITIAL DESIGN CHANGES AND FUTURE PLANS

Figure 4 shows the schematic of the moving gauge, which will be used to characterize the gas jet density of the quantum gas jet. For diagnostic purposes, two additional chambers are attached to the interaction chamber. The moving gauge with a Bayard-Alpert (BA) type ionization gauge is mounted on the chamber directly after the interaction chamber on a XYZ manipulator, as shown in Fig. 1. The gauge is covered by a metallic cylinder allowing the gas to enter through a 0.5 mm hole. An additional dumping chamber is connected afterwards. In the near future, we will conduct gas jet density measurements for both the pinholes of various diameters and the atom sieve to quantify the gas jet profile at the location of the interaction point. Also, work on improving the density of the quantum gas jet to enhance the signal strength will continue.

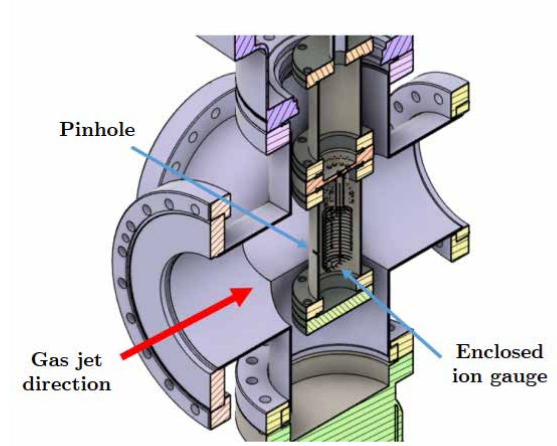


Figure 4: Schematic drawing of moving gauge [11].

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 measuring and improving the gas jet density using the atom sieve and the pinholes is in progress. Efforts will also be made for optimizing the design of the monitor in order to ease the integration into the complex accelerator structure. 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

This work is supported by the STFC grant ST/W000687/1, InnovateUK Germinator project 10004615, the HL-LHC-UK project funded by STFC and CERN, and the STFC Cockcroft Institute core grant ST/V001612/1. We acknowledge the technological support in terms of an UHV xyz-manipulator, provided by UHV Design Ltd, as one of the key components for a "wire" scanner made out of a quantum gas jet.

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