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QUANTUM GAS JET SCANNER BASED BEAM PROFILE MONITORS

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Abstract

A quantum gas jet scanner-based beam profile monitor is under development at the Cockcroft Institute (CI), UK for beam diagnostics based on the principle of ionization detection induced in a quantum gas jet interacting with an ionizing primary beam that shall be characterized. It promises superior position resolution and high signal intensity resulting from a strongly focused quantum gas jet. In order to achieve the gas jet with a diameter of less than 100 µm, a novel focusing method exploiting the quantum wave function of the neutral gas atoms, generate an interference pattern with a single maximum acting as ultra-thin gas jet. An 'atom sieve' has been designed for generating the interference pattern, applying the principle of a photon sieve. It will be analogous to a mechanical wire scanner though with minimal interception. The idea of moving a quantum gas jet through the beam is proposed for transverse profiling. This contribution provides a general overview of the design, working principle, the results obtained from initial measurements carried out at CI and University of Bergen (Norway), for designing the same and possible methods for optimizing the scanner's design.

INTRODUCTION

The requisite of non-invasive high resolution beam diagnostics has been increasing with the growing demand for high intensity and high power accelerators worldwide. Beam diagnostics are becoming critical for the operation, optimization and protection of accelerators and their subsystems. Currently existing invasive monitors are mostly wire scanners which cannot handle the huge beam peak power in high power accelerators such as the Spallation Neutron Source (SNS) or Accelerator Driven System and 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. A quantum gas jet scanner based beam profile monitor is under development at Cockcroft Institute (CI), Daresbury. This monitor is based on the previous development work on the IPMs 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].

In a quantum gas jet scanner, 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 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. Quantum gas jet can be used in several other applications i.e. for generating confined plasma source [7], as a probe for microscopy [8], etc. Initial design calculations for this scanner were carried out using the fundamental physics principles and results obtained from the CST simulations [9]. In this work, the generation of the quantum gas jet, working principle of the quantum gas jet scanner are presented along with the design of the components which are currently available at CI and/or under development. The possible ways to optimize the monitor's design are also presented in the paper.

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 gas jet curtain generation can be found in our previous work [4].

In this development work, the 3rd skimmer shown in Fig. 1 will be replaced by an atom sieve designed on the principle of Fresnel zone plate (FZP) for x-rays. The design details of the atom sieve can be found in previous work done by our group [9]. FZP designed for x-rays is usually made up of concentric metallic rings embedded in an x-ray transparent substrate. However for atom sieve, holes are required to provide passage for the gas molecules. Fig. 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 due to 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 CCD camera. In order to scan the quantum gas jet over the primary beam, the atom sieve will be mounted on a vacuum compatible xyz manipulator.

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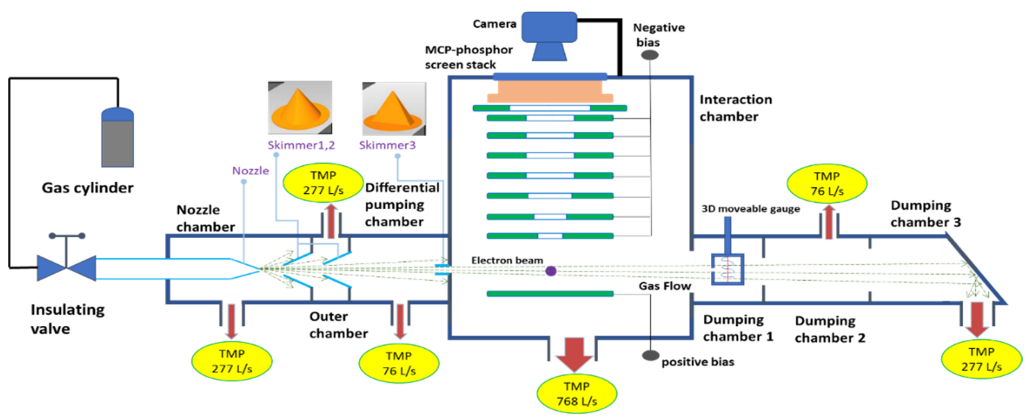

Fig 1: Schematic of the gas jet curtain based Ionization profile monitor.

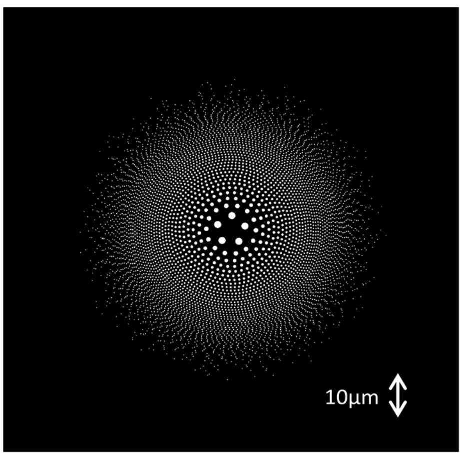

Figure 2: Design of the atom sieve on Si wafer (dia. 150 mm).

The differential chamber shown in Fig. 1 will be replaced by a new chamber that will accommodate the atom sieve along with xyz manipulator. This design of the chamber is shown in Fig. 3 and will be developed in near future.

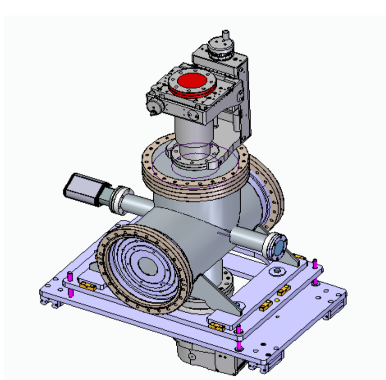

Figure 3: Design of the chamber with supporting structure to accommodate the atom sieve and xyz manipulator.

The reason for choosing vacuum compatible xyz manipulator for mounting the atom sieve is the movement in x and y direction will help in scanning the primary beam and z movement 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 studies conducted to measure the gas jet density profile at 262 mm away from the 2nd skimmer location, as shown in Fig. 4, provided the basis for moving the atom sieve in xy plane to generate a gas jet scanner. In these studies, it was observed that with the existing system, a gas jet of FWHM ~4.02 mm can be easily generated with 2nd skimmer of diameter 400 µm in place. In case of a primary beam with even larger diameters, the 2nd skimmer can be replaced with a bigger diameter skimmer or can be removed for special cases (FWHM of gas jet ~20.72 mm) like Hollow Electron test stand at CERN, where beam diameter can be as large as 20 mm.

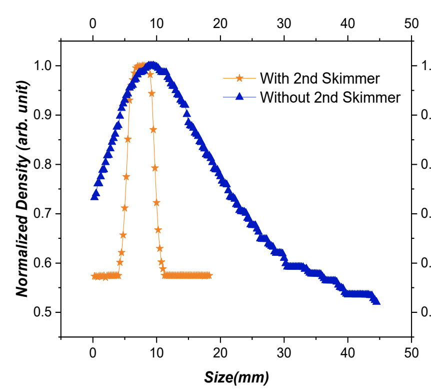

Figure 4: Normalized density of the gas jet at 262 mm from 2nd Skimmer (0.4 mm Diameter) with and without a second skimmer.

The atom sieve acts as an optical thin lens whose focal length depends on the design of the atom sieve and the wavelength of the gas molecules, used for generating the 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

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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 considered for future experiments. Fig. 5 shows a snap shot of the gas jet intensity measurement carried out with one of our atom sieves at Bergen University, indicating the achieved FWHM of the focal spot is about 35 µm.

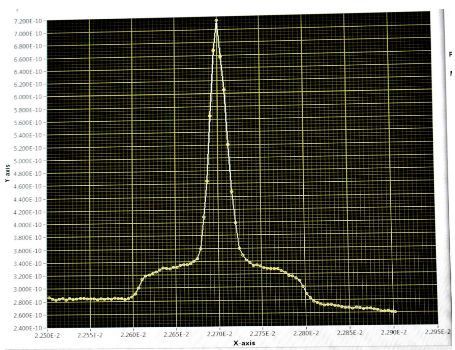

Figure 5: Snap-shot of Intensity vs. x position showing x profile of the quantum gas jet.

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 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 or electrons.

FUTURE OPTIMIZATION OF THE SCANNER'S DESIGN

As mentioned above, the atom sieve acts as an optical thin lens for matter waves. It can generate the quantum gas jet with dimensions equivalent to the aperture size of the nozzle. Fig 6 shows the required distance of image location for variable object location with respect to the atom sieve's location (normalized with the focal length of the atom sieve). The minimum length of the system required to generate the same sized image as of the nozzle (object) is four times the focal length of the atom sieve (in case of very narrow velocity distribution).

In previous studies [9], the focal length of the atom sieve designed for our system was 196.7 mm (based on the simulation results indicating that the helium atoms at 5 bar injection pressure in our system achieve velocity of ~1200m/s). Based on these numbers, the required length for the system is 4f ~791 mm plus the length of the injection and dump system. The focal length is directly proportional to the velocity of the gas molecules and square of the diameter of the atom sieve along with inverse proportionality on the number of zones [8]. Based on kinetic molecular theory, if the temperature of the injection gas can be reduced, the decrease in root mean square (R.M.S.) velocity of the gas molecules will be proportional to the square root of the ratio of final temperature to the initial temperature i.e. a change from room temperature to 77K of the injection gas, can reduce the velocity by half of the velocity at room temperature, which can ultimately shorten the minimum length required for the system to half of its original value. This would help in achieving the compactness in the design of the quantum gas jet monitor for simplifying the integration of the system in various accelerators i.e. medical accelerators [9]. There is one another possibility which is to increase the number of zones in given diameter for the atom sieve or to reduce the diameter of the atom sieve for the same number of zones, which currently limited by size of the holes to be achieved towards the end zones of the atom sieve.

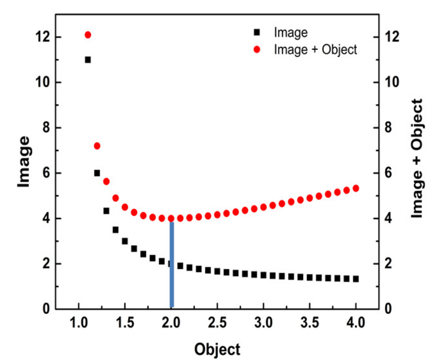

Figure 6: Variation in the location of the focal spot of a quantum jet (image) with the variation of nozzle position (object) with respect to the location of atom sieve (normalized with the focal length of atom sieve).

CONCLUSION

In this contribution, the progress on the ongoing development of a quantum gas jet based profile monitor has been presented. It has been demonstrated that this device can be used as a viable profile monitor that utilises the beam induced ionization in the gas curtain for high power and high-intensity accelerators. The optimization of 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 the development of the same.

ACKNOWLEDGEMENT

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