# ALIGNMENT OF A NOZZLE-SKIMMER SYSTEM FOR A NON INVASIVE GAS JET BASED BEAM PROFILE MONITOR*

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*Abstract*

A non-invasive gas jet-based beam profile monitor has been developed in the QUASAR Group at the Cockcroft Institute, UK. This shall allow monitoring ultra-low energy, as well as high energy particle beams in a way that causes least disturbance to both, primary beam and accelerator vacuum. In this setup a nozzle-skimmer system is used to generate a thin supersonic curtain-shaped gas jet. However, very small diameters of both, the gas inlet nozzle and subsequent skimmers, required to shape the jet, have caused problems in monitor operation in the past. Here, an image processing based technique is presented which follows after careful manual initial alignment using a laser beam. An algorithm has been implemented in Labview and offers a semi-automated and straightforward solution for all previously encountered alignment issues. The procedure is presented in detail and experimental results are shown.

## INTRODUCTION

Modern particle accelerators produce very high energy and high current beams, but there is also a growing interest in low energy beams, particular antiproton and radioactive ion beams. Whilst these beams are used for very different applications and experiments, they share the same high demands on the beam diagnostics system. Least interceptive instrumentation is highly desirable to preserve the quality of a particle beam and minimize interaction between detector and beam. Established techniques for transverse beam profile monitoring are in many cases invasive and cannot be used e.g. at the energy frontier. On the other hand, some non-invasive techniques such as residual gas monitor take a significant amount of time to acquire a profile which may not be acceptable by all applications. A rather new technology that meets the criteria for non-invasive measurements of the 2-dimensional transverse beam profile applicable across a large range of beam energies is based on the use of a supersonic gas jet.

## GAS JET DESCRIPTION

A prototype setup has been designed and built by the QUASAR Group at the Cockcroft Institute, UK [1]. There, a neutral gas ($N_2$) from a high pressure tank (1 bar) expands into vacuum through a 30 μm aperture nozzle. Because of the pressure differential the gas expands into a supersonic jet traveling in vacuum. The jet passes through a series of chambers separated by skimmers, which allow for differential pumping, see Fig. 1. The role of the skimmers is to collimate the jet, shape it into a thin sheet and drive it towards the interaction chamber. The final rectangular skimmer is fixed in such a way that it inclines the jet at 45° to the beam axis.

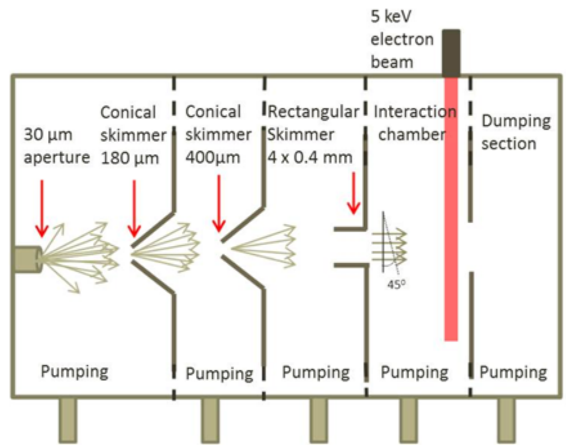


Figure 1: Illustration of the gas jet setup.

In the current setup the gas jet interacts with a 5 keV electron beam, generating ions and electrons. A 12 kV/m electric field perpendicular to the beam then extracts the ions and directs them to the detection system. The latter is composed of a Micro Channel Plate (MCP) detector paired with a phosphor screen. The ions produce a shower of electrons in the MCP giving amplification of up to $10^6$. The produced electrons impact on the phosphor screen generating light which is then imaged by a CCD camera. The cross section for impact ionization of $N_2$ molecules by electrons, protons and antiprotons at energies between 20-300 keV is in the range of 1 – 5 $Å^2$ [2]. For simplicity it is assumed to be 1 $Å^2$. For a gas target thickness of about 0.5 mm and a density of ~2.5 $x10^{16}$ particles/$m^3$ a reaction rate of about $1.5x10^9$ ionizations/s per mA of current can be expected, see [1]. The above mentioned parameters were chosen to meet the requirements of the Ultra-Low Energy Storage Ring (USR) [3] which shall be built at the future Facility of Antiproton and Ion Research (FAIR) in Germany.

After interaction with the beam the gas is evacuated from the chamber efficiently via a dedicated dumping section. This is basically a turbo molecular pump, tilted by 45° thereby allowing extraction of the gas jet through its blades, minimizing reflections. The differential pumping along the jet's path and the dumping section give access to pressures as low as $10^{-11}$ mbar. Alignment of the nozzle–skimmer system is a delicate task given the

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very small nozzle diameter and tight tolerances. The most crucial part is the nozzle-1st skimmer alignment as they have the smallest dimensions in the system. The initial manual alignment requires a laser beam to be shined through the nozzle and all skimmers.

Misalignment of (parts of) the setup has been an issue for a long period of time. Even when initial alignment was correct, it was observed that it was not maintained during operation, suggesting that elements moved during pump-down.

For continuous monitoring of the setup and applying any required corrections, two high definition (HD) cameras were used. Their signals are then fed to an edge detection algorithm in Labview. Similar techniques have been used in machine vision applications and robotics [4].

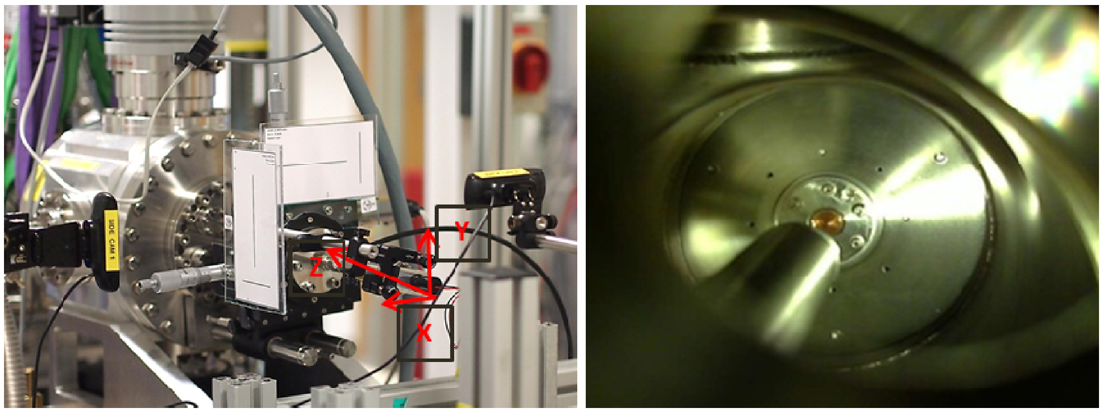


Figure 2: Left: translating stage with 2 cameras for X and Y plane, right: image from the interior of the first vacuum chamber, nozzle's tube and first skimmer can be seen.

## ALIGNMENT ISSUES

### *Observations*

It has been observed that when the pressure in the vacuum chamber drops, alignment is lost. Measurements of pressure profiles in the different parts of the setup indicated that there might be problems related to parts of the setup moving during pump down. For this purpose a dedicated movement detection system had to be installed to provide qualitative and quantitative information about the observed displacements. The main source of the above mentioned displacements is probably mechanical tolerances of the translation stage that supports the gas inlet tube, see Fig.2 (left): This yields to small movements when the pressure in the chamber gets lower than atmospheric pressure or when the translation stage moves along Z axis to change the distance between nozzle and 1st skimmer.

### *Methodology*

In the current application the most important considerations are the accuracy requirements due to the small nozzle-skimmers dimensions. It is also very important to identify good measurement spots, have detection in different directions simultaneously, as well as acquire and analyse information quickly. The movement detection system consists of two HD Logitech C902 cameras. They are top of the line web cameras operating at 2592 x 1944 resolution and 8 bit colour depth. They are equipped with a high quality lens with 20 steps manual or auto focus. The cameras come with USB2 connection that makes their control an easy task. For the edge detection algorithm a pattern with high contrast gradient is required.

After trials with various combinations of shapes, a pattern consisting of two perpendicular black lines of known dimensions printed on white paper was selected, see Fig. 3.

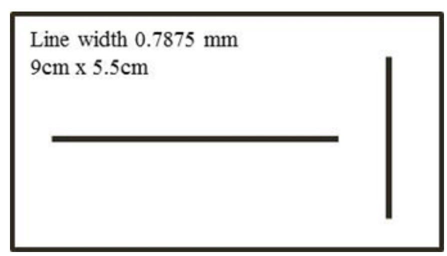


Figure 3 : Alignment pattern consisting of two lines.

Two of those patterns were placed on the two faces of the translation stage for displacement in X and Y direction, respectively. The cameras were fixed opposite of the patterns at a distance of 20 cm, see Fig.2 (left).

Labview was chosen to control the detection system as it offers drivers for a great range of cameras, a user-friendly environment and can be integrated into the overall gas jet control system. The here-presented solution consists of an image processing algorithm based on pattern recognition and edge detection. Fig. 4 shows the software's flowchart.

The inherent parallelism of dataflow programming makes the Labview environment ideal for parallel execution. This allowed the algorithm to run in two parallel loops for both cameras in real time. Note that to start detection an initial Region of Interest (ROI) around



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each line had to be selected manually and also the edge detection parameters have to be set.

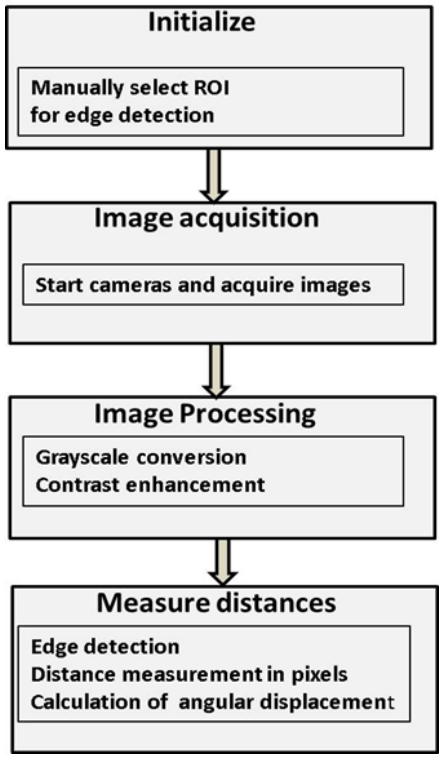


Figure 4: Labview algorithm flowchart.

### *Algorithm Description*

Once images have been acquired a single colour plane is extracted and a smoothing low-pass filter is applied. The edge detection algorithm scans the ROI vertically and horizontally along a group of 9 path lines until it detects the set of 2 lines as shown in Fig. 5. The distance from the edge of the ROI until the first point on the detected line is then determined by Labview. Most important are the central points which give the average linear displacement from the edge of the ROI, as well as the 2 corner ones which are used to calculate any angular displacement.

The end user interface consists of a table showing the vertical and horizontal displacements for X and Y direction for each camera. Angular displacements are of the order of $1^{\circ}$ and can hence be considered as negligible.

The algorithm takes the initial position when alignment is achieved as reference position. After any displacement occurs the new position is subtracted from the reference position giving the difference in pixels. All distances remain in pixels as there is no interest in the actual displacement, but only for recovering the initial position. When this difference is zero it means that the initial position is restored. As the algorithm runs in real time, the user can recover the reference position with the translator's dials to minimize the difference.

For the proof of operation of the algorithm a high power laser was shined through the aligned nozzle–skimmer system and imaged by a camera from the other side. The algorithm recorded this position as reference position and with the laser turned off a random displacement in X and Y direction was introduced. Using the dials and consulting the readings the initial position was restored.

## INITIAL ALIGNMENT

For the apparatus to operate properly highly accurate alignment is required. The same 2 cameras are also used in this step but are placed in different locations. The alignment starts with the last skimmer which is the closest to the interaction area and has to be rotated by $45^{\circ}$. All skimmers are mounted on disks which are fixed with screws on specific locations in the vacuum chamber thereby minimizing any movement. The second and first conical skimmers with diameters of 400 and 180 μm, respectively, are also manually fixed in position. The following step is to shine a laser through all skimmers and detect the light at the other side with a camera. The intensity is then maximised while moving the skimmers slightly with fine manipulation of the disks. After a few iterations very good alignment can be achieved. It was found that the most critical part in this procedure was the alignment of the nozzle.

The nozzle is mounted on a hollow aluminium cylinder of 2 mm internal diameter and 30 cm length. In a separate setup, with the nozzle's tube removed from the main setup, a laser is shined through it and light is detected using a web camera right after the nozzle. By observing the image which has to match the diffraction pattern through a circular aperture, the shape and the condition of the aperture can be examined. If the aperture is blocked or is not perfectly circular the diffraction pattern is affected as can be seen in Fig. 5 (upper row). Because of the small diameter of the aperture light that reaches the other side is minimal so the camera needs to operate in high saturation and high gain mode.

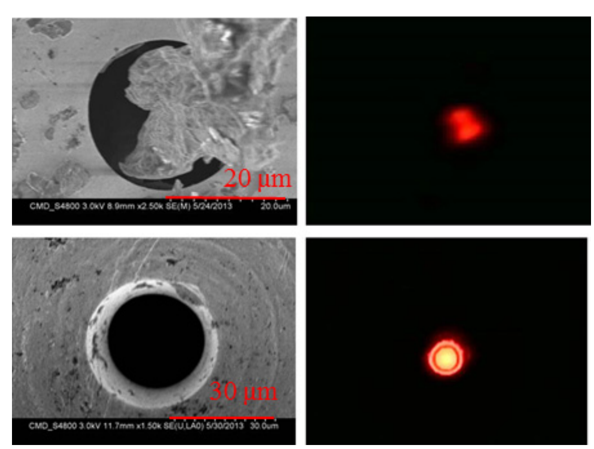


Figure 5: Upper row: orifice blocked; Lower row: orifice is cleaned.

With the aperture tube mounted on the setup and the laser in operation, two cameras are required for final alignment. The first camera observes the interior of the first vacuum chamber, see Fig.2 (right). The second one is

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placed after the dumping session, imaging light that reaches the end of the line.

Using the first camera and the translating stage that holds the aperture's tube, the light is directed on the first conical skimmer. Looking at the video stream from the second camera while trying to find maximum intensity and after very fine manipulation of the translation stage the aperture is aligned with the skimmers.

The gas jet setup was recently upgraded to allow a laser to be shined along the gas expansion path while the chamber is evacuated, see Fig 6. Thereby one can verify that the movement detection algorithm is tracking any displacement as there is camera permanently positioned after the dumping section imaging the laser beam. It is composed of a T-connector that leads to the gas tank from one side and to a glass viewport via a safety valve from the other side.

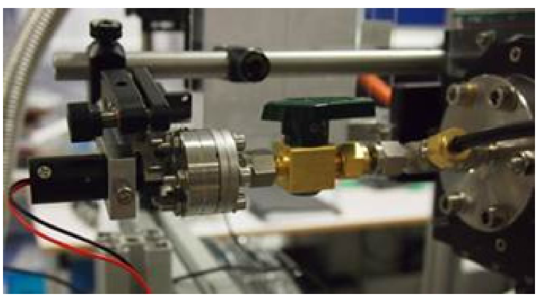

Figure 6 : Photograph of modified gas inlet section.

## CONCLUSION

A gas jet-based beam profile monitor is highly desirable for online non-destructive monitoring of the 2-dimensional transverse beam profile. Due to its functioning principle it could potentially be used in almost any accelerator, covering different particle types, various beam energies and a very wide vacuum pressure range, reaching down to the XHV.

First operational experience has shown that careful alignment of all components is crucial as otherwise the ultra-cold gas jet will not form correctly. Here, an alignment procedure was presented that offers a fast and accurate solution for movement detection and correction of any displacement. It was demonstrated that this image processing technique can monitor and compensate for displacements as large as ~500 µm that occur during operation.

This system allowed to address all alignment issues of the gas jet based beam profile monitor. However, there is one more challenge related to the absolute position of the jet and in overlapping it with the primary beam. Recent results from simulations indicate that a Fresnel Zone Plate could be used as a focusing element instead of a rectangular skimmer [5]. Such system shall be integrated into the existing setup in the near future.

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