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EXPERIMENTAL INVESTIGATION INTO SUPERSONIC GAS JET INDUCED BEAM PERTURBATION

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Abstract

In radiotherapy, treatment beams require precise margins to ensure the preservation of surrounding healthy tissue. Clinical studies have shown that to mitigate range deviations of the Bragg peak, safety margins of typically less than 5% around the target volume are employed. Consequently, real-time or online diagnostic techniques should be designed to minimize beam perturbation to the greatest extent possible. A minimally-invasive gas jet beam profile monitor for medical treatment facilities is being developed at the Cockcroft Institute (UK) to provide online monitoring. The monitor operates a thin, low-density, gas jet curtain, transecting with the beam. A proof-of-concept experimental study was carried out to quantify the degree of perturbation the gas jet has on a beam, using a 10 keV electron gun with a maximum current of 100 µA. Any changes in beam profile and current were measured via a scintillator screen and Faraday cup respectively in path of the beam after the gas curtain. In the future, a simulation study will also be carried out using BDSIM, a Beam Delivery Simulation program built on GEANT4, with the experimental beam parameters along with medical hadron beams. This contribution provides the details of an experimental study into the perturbation experienced by an electron beam from a gas jet monitor.

INTRODUCTION

The QUASAR group, based at the Cockcroft Institute (UK) is developing a minimally invasive gas jet in-vivo profile monitor for the purpose of online beam diagnostics for medical accelerator beams. The key aims of this gas jet monitor is to deliver real time profile monitoring to possibly reduce frequent calibration to progress treatment efficiency [1]. The gas jet monitor has undergone 15+ years of development from original conception to continuing optimization and improvements [1-5]. The monitor was first created and has now been tested for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) [6,7]. In order to be installed in medical LINACs in the future, the treatment beam must be negligibly affected by the gas jet monitor. This experimental research is vital as the dosage levels transferred to the patient and beam parameters are not compromised. This contribution endeavours to quantify the level of perturbation or ”invasiveness” a gas jet may have on a particle beam. The study examines the effects of nitrogen and argon gas jets have on several beam parameters for a low energy, low momentum electron beam (4.9 keV – 5.3 keV).

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GAS JET SYSTEM

Existing invasive monitors such as wire scanners experience from short lifetimes and continual maintenance. Minimally-invasive monitors like residual gas monitors suffer from beam profile distortions. Diagnostics like the residual gas monitors experience distortion because the yield of the ionization will undergo momentum spread initially and the primary beam can cause space charge effects [3]. Hence, there is a requirement present for the development of minimally- or non-invasive beam profile monitors that offer both high resolution, non-distorted beam profiles, and real-time feedback. This potential solution comes in the form of a minimally-invasive supersonic gas jet beam profile monitor. This monitor operates by having a thin, supersonic, low density, gas jet curtain of neutral gas molecules, tilted at 45°, intersecting with the charged particle beam in order to provide a 2D transverse beam profile via ionization [1-6]. Figure 1 below shows a schematic of the extraction system and the gas jet intersecting the beam perpendicularly. Thus far, extensive research and development has been completed by the Gas Jet group, within the QUASAR group, into the design and optimisation of a gas jet beam profile monitor. The key advantage of this system is its minimally-invasive nature and it can provide the 2D transverse beam profile. A schematic of the gas jet monitor can be found in Fig. 2.

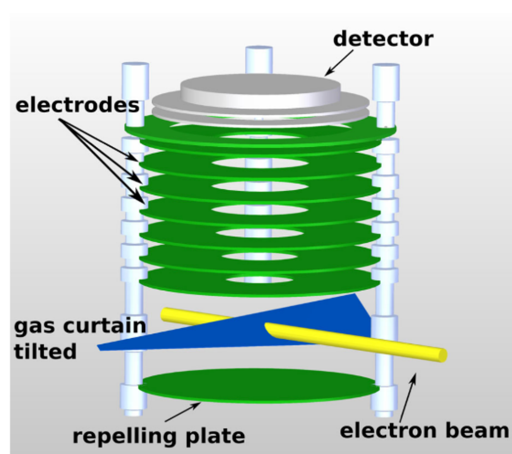

Figure 1: Visualization of the extraction system and gas jet-particle beam interaction [2].

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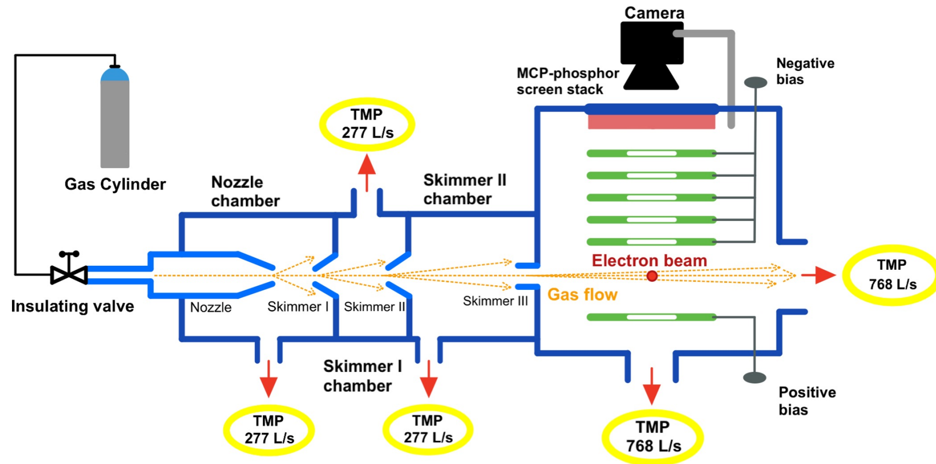

Figure 2: Gas jet monitor schematic displaying the nozzle-skimmer setup, gas jet formation and ion extraction system [7].

EXPERIMENTAL SETUP & METHOD

To evaluate the degree of perturbation imparted by the gas jet system on a charged particle beam, measurements of the beam current were acquired, and beam imaging was performed with and without the gas jet intersecting an electron beam (4.9 – 5.3 keV) using the experimental setup seen in Fig. 3. Beam imaging enabled the characterization of several parameters, specifically the Full-Width at Half-Maximum (FWHM), centroid position, and beam intensity. The gas species used in the experiment were nitrogen and argon. At the interaction region, the gas jet density was 1.8×10^{16} m^{-3} and the chamber pressure was 1.44×10^{-8} mbar. The electron beam was generated using an EGG-3103A / EGPS-3103 Electron Gun and Power Unit, mounted directly onto the interaction chamber, with the beam axis oriented perpendicular to the gas jet. On the opposite side of the chamber, a six-way cross chamber housed a phosphor screen (mounted on a manual linear actuator), a Faraday cup (mounted on a pneumatic linear actuator), and an optical viewport. Both detectors were mounted on actuators to allow the phosphor screen and Faraday cup to be retracted in and out of the beam path (vertically and horizontally, respectively), thereby ensuring measurements were consistently performed at the same location.

The beam current was measured using a custom Faraday cup equipped with a suppressor electrode voltage of -150 V. The Faraday cup output was transmitted via a high-voltage BNC cable to a picoammeter, with its analogue output digitized by a RIOGOL DS1074 Z Plus oscilloscope. The oscilloscope was configured with axis settings of 5 V /div (vertical) and 10 ms /div (horizontal) and connected to a computer via USB, where custom MATLAB routines were used to record current values. Beam images were obtained using a P40 phosphor screen (13.41 × 13.41 mm^2), imaged by a CMOS camera fitted with a 25 mm focal length lens and an additional 50 mm focusing lens. The phosphor screen was positioned at a 45° angle relative to the beam and camera-lens optical axis to preserve the image aspect ratio. Custom MATLAB analysis scripts were then applied to extract the FWHM, centroid position, and intensity from the recorded images.

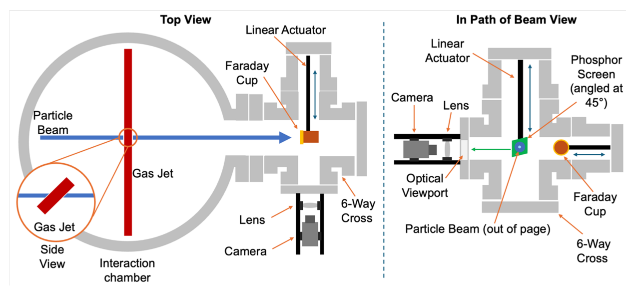

Figure 3: Schematic of the experimental setup used to determine the invasiveness of the gas jet. This included a 6-way cross chamber housing a Faraday cup, phosphor screen and optical viewport. Beam images were acquired via a CMOS camera and an additional focusing lens.

RESULTS

Before taking data, the electron gun was given a two-hour stabilization period. The electron gun properties such as energy, source voltage, grid and focus, in addition to any necessary X and Y deflection of the electron gun, were set. The phosphor screen data was taken by recording 280 images, with an exposure time of 34 μm and zero gain. Measurements were initially acquired with the gas jet off; following a brief stabilization period, data with the gas jet on were subsequently collected. This period in-between measurements allowed for the gas jet and electron gun to stabilize. The data collection method for beam current using the Faraday cup followed the same experimental order as the phosphor screen data, and 60 beam current data points were taken for both datasets. For each beam energy, the data was sequentially taken from the phosphor screen and then Faraday cup. Vacuum levels within the gas jet system chambers were allowed to return to previous values in between the two measurements.

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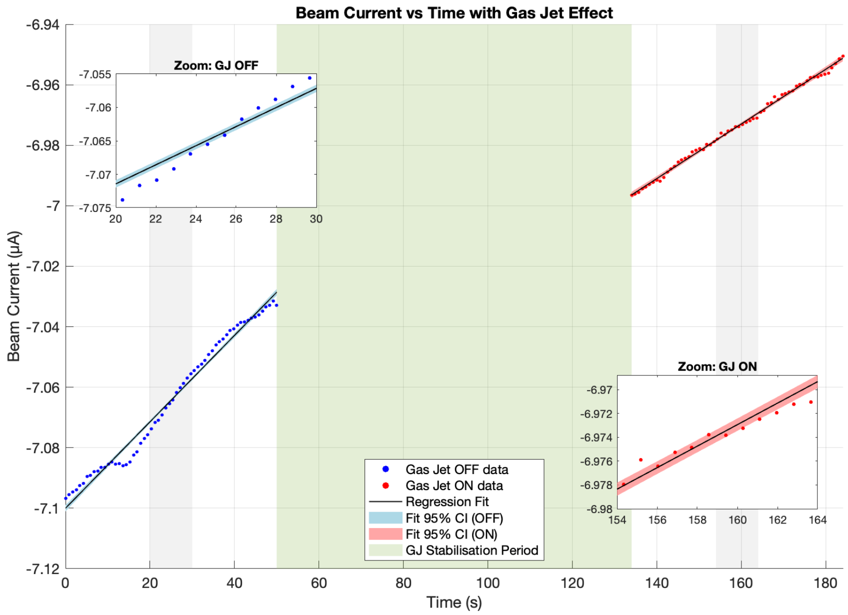

Figure 4: Graph showing beam current against time. The dots show raw beam current data points of gas jet off (blue) and gas jet on (red). The black line shows the regression model fit with 95% confidence intervals. Two zoomed subplot were added for clarity and to show how fine the confidence intervals were. The two grey regions indicate where the zoomed subplots originate from. The green region in the centre of the plot was the gas jet stabilization period (approximately 5 seconds) plus additional time between two measurements to allow for electron gun stabilization.

Figure 4 above shows an example of the beam current regression model result plot for 4.9 keV beam energy for a nitrogen gas jet. Similar regression model plots were made for all energies and gases for the beam current and intensity values recorded. During the course of the experiment, the beam current was observed to be continually increasing by small increments (decreasing in magnitude). To facilitate comparison between the 'gas jet off' and 'gas jet on' datasets and to assess the potential influence of the gas jet system, a linear regression model was employed to account for variations in current. The regression model was essential for a meaningful analysis of the beam current data, as direct comparison of mean current values between the two datasets was not appropriate. This was due to the inherent temporal drift in beam current, independent of the gas jet, caused by beam instability. In addition, the datasets were acquired sequentially with an intervening time gap to allow for jet stabilization and the recording of vacuum levels in the interaction chamber. Consequently, differences in mean beam current could arise from the gas jet, temporal drift, or a combination of both. The regression model was therefore identified as the most suitable analytical approach, as it enabled the simultaneous isolation of multiple effects and the correction for unequal baseline currents. Statistical and systematic errors determined from the experimental setup and recorded data were incorporated as weighted sigma values within the regression framework.

CONCLUSION

The measurements obtained in this experiment indicate that, under the given experimental conditions, the gas jet induces less than a 5 % effect on the beam FWHM, centroid position, intensity, and current for a low-energy, low-momentum electron beam. Accordingly, if the gas jet exerts only a minimal influence on these parameters at low energies, its impact on the properties of high-energy, high-momentum medical beams may be considered potentially negligible. To comprehensively assess the impact of the supersonic gas jet system on a charged particle beam, further detailed studies will be conducted to substantiate these findings. Future plans additionally involve completing simulation studies using GEANT4/BDSIM in order to compare to the experimental results. This simulation work will also look to predict the level of invasiveness the gas jet monitor might have for protons beam within the medical energy range (70 – 250 MeV). This research will provide a complete picture of the experiment examining the level of invasiveness of the gas jet system on a particle beam.

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