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GAS JET IN-VIVO DOSIMETRY FOR PARTICLE BEAM THERAPY

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Abstract

Medical applications of charged particle beams require a full online characterisation of the beam to ensure patient safety, treatment efficacy, and facility efficiency. In-vivo dosimetry, measurement of delivered dose during treatment, is a significant part of this characterisation. Current methods offer limited information or are invasive to the beam, meaning measurements must be done offline. This contribution presents the development of a non-invasive gas jet in-vivo dosimeter for treatment facilities. The technique is based on the interaction between a particle beam and a supersonic gas jet curtain, which was originally developed for the high luminosity upgrade of the large hadron collider (HL-LHC). To demonstrate the medical application of this technique, an existing HL-LHC test system with minor modifications will be installed at the University of Birmingham's 35 MeV proton cyclotron, which has properties comparable to that of a treatment beam. This contribution presents the design and development of this test setup, plans for initial benchmarking measurements, and plans for a future optimised medical accelerator gas jet in-vivo dosimeter.

INTRODUCTION

All radiation-based therapy is guided by a treatment plan. These plans are created by clinical experts using a combination of patient scans, simulations, and the radiobiological properties of the target tumour. These are extensive and include variables such as beam parameters, how many fractions the dose should be split into, delivery angle for gantry systems, and patient positioning. The ultimate goal of any radiation therapy is to deliver the treatment plan to the patient as accurately as possible.

There are uncertainties and limitations to this delivery accuracy, which can be separated into two areas: patient positioning (e.g. nozzle alignment, breathing, heartbeat); and beam properties (e.g. profile, position, energy). The former can be controlled to a certain extent with patient engagement (e.g. holding their breath) and in-vivo imaging (e.g. Cone Beam CT [1]). However, facilities will always maintain a tighter control on the latter. To accomplish this, a range of quality assurance (QA) measures are used to characterise the beam, but there is little homogeneity and no standard regulations for how this is achieved. This contribution will provide an overview on how gas jet based diagnostics can be applied to this overall QA process, help optimise facility performance, and give access to beam steering techniques not currently possible.

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EXISTING DIAGNOSTICS IN THERAPY BEAMLINES

Despite the differences in layout and use, most instrumentation used for beam characterisation is some combination of several standard systems.

Most common are scintillating screens [2]; used to produce high resolution (~100 µm) beam profile, position, and intensity measurements. They operate through direct interaction with a beam, which causes scattering and can also damage the screen surface. A less invasive alternative to screens are secondary emission monitors [3], where resolution is determined grid spacing (~1 mm). These can be operated in-vivo, but are easily damaged and constant degradation leads to ongoing calibration needs. The current best practise systems for online beam monitoring are ionisation chambers [3]. Many years of development have led to systems which are robust, reliable, and flexible; e.g. from single foils for total dose, to grids for dose profile. However, they do perturb the beam and require ongoing degradation related maintenance and calibration. Novel silicon based detectors [4] are also beginning to appear on the market, which offer high resolution profile dosimetry, but perturb the beam during operation and are susceptible to quenching in high fluence treatment modalities. For all of the above, Faraday cups [5] are often used in calibration measurements; as they destroy the beam in operation they cannot run in-vivo.

Energy deposition is the most important aspect for all of these intercepting devices; both in terms of the measurement process but also degradation and maintenance. This becomes especially true in novel treatment modalities such as FLASH [6], where the dose rate is significantly increased; the instrumentation currently in use will either struggle or not function at all in these situations, which risks making new and improved treatments impossible. New detector technologies are urgently required. To this effect, the University of Liverpool (UoL) leads the OMA project [7, 8], which has a focus on novel diagnostics R&D. The insights gained from this project have helped to shape the work presented in this contribution.

INTRODUCTION TO GAS JET TECHNOLOGY

The premise of a gas jet profile monitor is to replace the invasive section of the previous systems with a supersonic, low density, gas jet curtain [9–11]. Figure 1 is a schematic of how this works. A gas jet inclined at 45° propagates left to right. An incoming particle beam passes, unperturbed, perpendicularly through the low density gas curtain. The interaction between the gas molecules and the beam is cap-

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tured by an acquisition system, which provides the profile, position, and intensity of the beam. The system can be operated in two ways to capture this interaction: ionisation capture and florescence imaging.

Figure 1 demonstrates ionisation capture, where the beam causes the gas molecules to become ionised. High voltage electrodes collect the ions onto a microchannel plate to amplify the signal, which then impinges upon a phosphor screen imaged by an optical camera. This method can provide a very strong signal from a very weak interaction source; this is why the density of the gas jet can be so low. The other mode of operation, fluorescence imaging, directly images the fluorescence photons produced by the excited gas particles. This provides a higher resolution measurement, but requires a larger source signal.

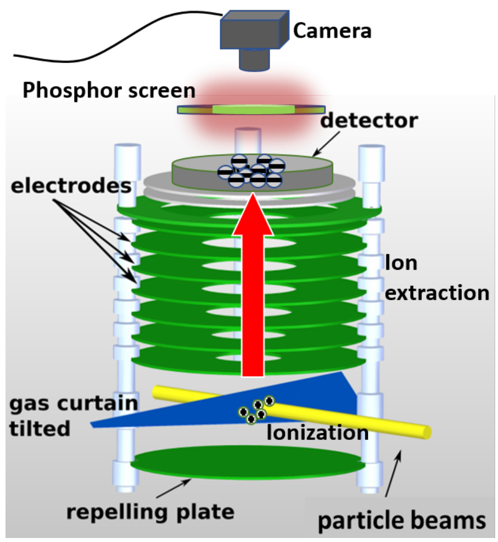

Figure 1: A schematic demonstrating the operating principle of the gas jet profile monitor.

CURRENT RESEARCH ACTIVITIES

A flourescence system schematic is shown in Fig. 2. This was developed as part of the STFC and CERN supported HL-LHC UK project, in collaboration with UoL/Cockcroft, CERN, and GSI. This work developed a method of measuring a 2D profile image of the co-propagating beams within the hollow electron lens (HEL) system [12].

In Fig. 2, the particle beam propagates through the hole in the centre and the gas jet travels left to right. The circled section is the nozzle/skimmer assembly used to create and shape the supersonic gas jet. This then passes through the central interaction chamber, before being extracted from the system on the right. Due to the velocity of the jet and the method of extraction, there is no significant impact on the vacuum environment of the interaction chamber. This system contains many gas jet diagnostics and as such has a transverse size of approximately 3m.

Figure 3 presents an example image of the beam from a 0.66 mA 5 keV electron gun used for tests. The beam-gas interaction point is clearly visible in the image. Sub-mm

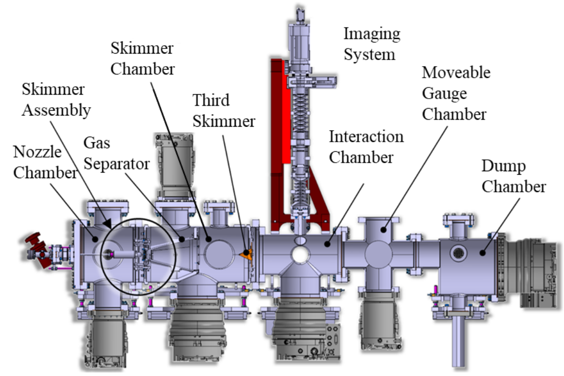

Figure 2: Gas jet monitor used for flourescence-mode R&D.

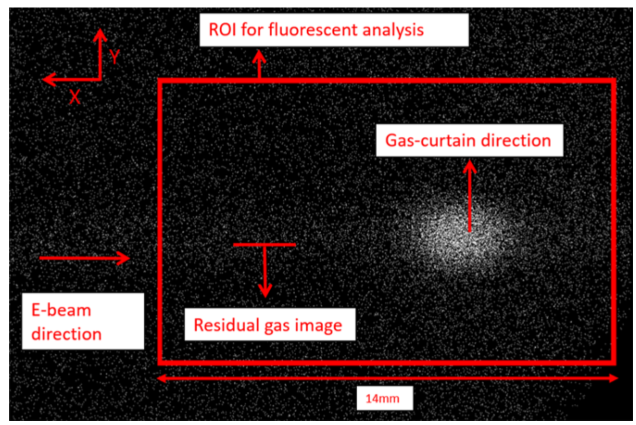

Figure 3: Example gas jet profile image from the system presented in Fig. 2.

profile widths can be easily extracted with a resolution of ~10 µm [9, 13]. This was verified with a scintillation screen. This system therefore produces the type of measurements therapy facilities require. The non-perturbing nature of the gas jet system, combined with the lack of damage related maintenance or ongoing calibration, make a compelling case for the application of this technology in the medical sector.

More compact designs have been developed and optimised as part of the STFC funded HL-LHC UK phase 2 project, with a longitudinal length of ~0.5 m from flange to flange, and a transverse size of ~1 m. This system is in the process of being built and benchmarked at the Cockcroft Institute, presented in Fig. 4, before being shipped to CERN for installation on the HL-LHC HEL test stand [12]. This compact system has been developed and optimised for operation in the unique environment of the LHC, but this could form the basis of a future treatment facility system. The key elements that require development for application in this sector are a further reduction in size, and a push towards turn-key operation; i.e. little calibration or ongoing maintenance, whilst being simple to operate and use on a patient-by-patient basis.

INTEGRATING GAS JET TECHNOLOGY INTO A THERAPY FACILITY

Several possible applications of this gas jet technology in treatment facility beamlines have been identified [13].

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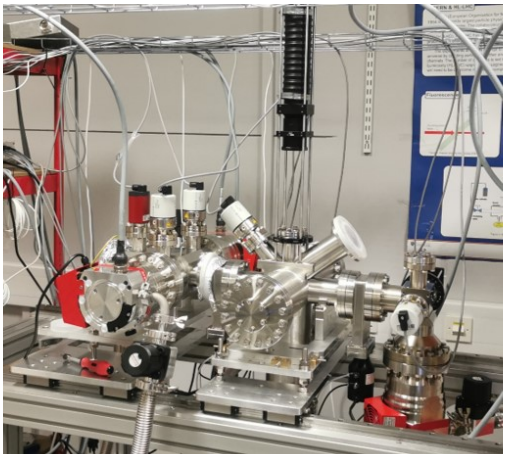

Figure 4: New compact system design under construction at the Cockcroft Institute.

As a means of guiding further development, baseline measurements have been planned in collaboration with the University of Birmingham (UoB) and D-Beam [14]. The system presented in Fig. 5 is an existing prototype at the Cockcroft Institute with some minor simplifications; this has reduced the overall length of the system to ~1.5 m. This will be installed at a user area of the UoB MC40 35 MeV cyclotron [15]. Although this is not a medical facility, the beam has similar parameters whilst providing the opportunity to run tests with a range of beam energies, shapes and currents. Studies will be performed to validate images obtained from the gas jet system against independent beam intensity and distribution measurements. Analysis of these measurements will provide a benchmark for the performance of the system as is, and guide future R&D efforts to tune the system for operation in a treatment environment.

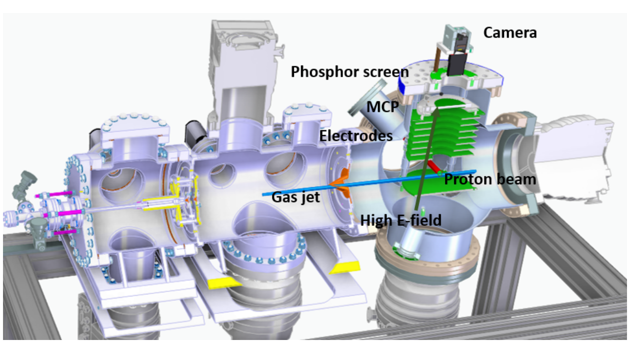

Figure 5: Test gas jet profile system designed for measurements at the University of Birmingham MC40 cyclotron.

Four main R&D work streams will drive the development of this technology towards commercialisation and the end goal of a turn key clinical product.

First is optimisation. The current system has been developed for the unique environment of the LHC. The measurements at the UoB will be the first phase of an optimisation plan in collaboration with established clinical centres, OEM manufacturers, and commercialisation partner D-Beam [14]. Alongside treatment facility tests, concepts such as different nozzle/skimmer setups and different working gases will also be explored to tune the system for specific particle species, and different beam energies and sizes. Comprehensive modelling frameworks for this have been developed within the QUASAR Group and are an ideal basis for this next step of designing a monitor for medical facilities.

Second is integration. This could be via existing QA processes, or independent online beam monitoring. End user discussions will guide where online 2D dosimetry is best placed in the beamline. The dose map produced could then also be used as a post-treatment verification method via comparison with the treatment plan; adding an additional layer of patient protection.

Third is applications in novel treatment methods. For future high dose rate treatment modalities such as FLASH [16], most current diagnostic systems will either be damaged or not function correctly [17]. This poses a significant bottleneck to treatment applications. As a gas jet is constantly replenished and unable to degrade, a potential gas jet profile dosimeter could be one of the main diagnostics required in future therapy systems.

Finally, future work will also target the application of machine learning to the control, analysis, and utilisation of the gas jet system. This will take the form of improved diagnostics for the gas jet itself, improvements to the analysis of gas-jet images, and the automated control of treatment beamlines based on measurements from the gas jet system.

CONCLUSION

The QUASAR Group has pioneered the development of novel gas jet-based beam profile monitors for various applications, from low energy antiproton and ion beams, to high energy colliders. This monitor type also shows great promise for applications in medical accelerators, where it provides significant advantages over conventional devices. This technology can contribute to existing QA and provide novel non-invasive in-vivo beam monitoring. Additionally, for novel high dose rate treatment modalities, a gas jet-based system poses potentially the only option for in-vivo dosimetry. With the effective non-invasive mode of operation, lack of ongoing calibration, and the ability to perform in-vivo dosimetry, this technology platform is an exciting option for improving treatment facility efficacy and patient outcomes.

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