NON-INVASIVE BEAM PROFILE MONITORING

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Abstract

Highest energy and intensity accelerators require new approaches to transverse beam profile monitoring as many established techniques will no longer work due to the high power stored in their beam. In addition, many accelerator applications such as ion beam cancer therapy or material irradiation would benefit significantly from the availability of non-invasive beam profile monitors. Research in the QUASAR Group has focused on this area over the past 5 years. Two different approaches were successfully developed: Firstly, a supersonic gas jet-based monitor was designed and commissioned. It enables the detection of the 2-dimensional transverse beam profile of essentially any charged particle beam with negligible disturbance of the primary beam and accelerator vacuum. Secondly, a monitor based on the Silicon strip VELO detector, originally developed for the LHCb experiment, was tested as an online beam monitor at the Clatterbridge Cancer Center in the UK. The design of both monitors and results from measurements are presented in this contribution.

INTRODUCTION

Least intrusive beam profile measurement techniques that allow continuous operation of an accelerator whilst providing comprehensive information about the particle beam would be ideal for many applications, ranging from high energy/high intensity accelerators such as the LHC at CERN and its future upgrades or the high power proton driver linac at ESS where conventional diagnostics would simply not work. Various non-invasive methods have been developed for the determination of the transverse beam profile. These include Ionization Profile Monitors (IPM) [1] which are based on the collection of the ions produced by impact ionization of rest gas by the main beam and the Beam Induced Fluorescence Monitor (BIF) [2] which relies on the detection of the light produced from the excited residual gas. IPM's are truly non-invasive devices which can operate parasitically if the residual gas pressure is sufficiently high and offer very good spatial resolution down to 100 µm and time resolution in the order of 10 ms with a fast camera or a few µs with a fast readout system. However they are usually limited to high energy accelerators. BIF's are parasitical as well, but require higher residual gas pressures in excess of 10^{-6} mbar and longer signal integration times.

Gas Jet-based Beam Profile Monitor

A possible approach to overcome these limitations is to utilize a cold (< 20 K) neutral supersonic gas jet shaped into a thin curtain. The core of this monitor consists of an expansion of a room temperature high pressure gas (1-10 bars) into vacuum through a nozzle with 30 µm diameter, resulting in an adiabatic expansion and the formation of a jet with a very stable and cold inner core.

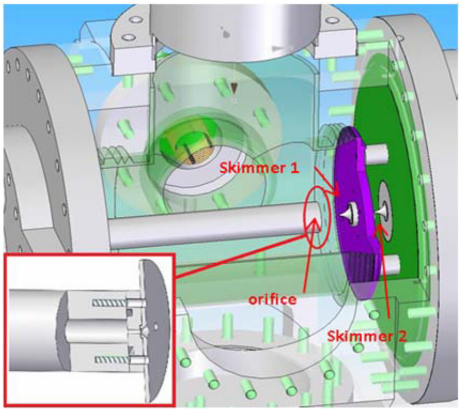

Figure 1: CAD drawing of the nozzle chamber where the first two skimmers are highlighted.

This jet is then further shaped by several skimmers. The first part of the experimental setup is illustrated in Fig. 1. Skimmers separate several differentially pumped vacuum chambers through which the jet passes until it reaches a final "reaction chamber", held at a pressure of 10^{-9}-10^{-12} mbar [3]. When entering this chamber the jet has already been shaped by a final rectangular skimmer into a curtain that crosses the primary beam to be analyzed under an angle of 45°. In this interaction impact ionization of the jet particles occurs and the resulting ions are imaged by a moderate electric field of some kV/m onto a position-sensitive double layer Micro Channel Plate (MCP) detector. The MCP provides signal amplification of up to 10^6. Finally, the resulting beam profile is observed by a Phosphor screen-camera combination that is mounted on the top of the reaction chamber, see Fig. 2.

At low energies of the primary beam the extraction electric field can lead to its displacement when passing through the reaction chamber. This is compensated by deflecting electric fields before and after the interaction region (not shown in the figure).

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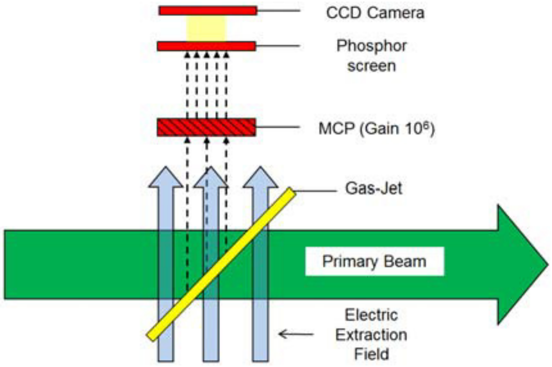

Figure 2: Illustration of the gas jet monitor operation principle. The gas jet is travelling into the page.

Proof-of-principle measurements were recently completed at the Cockcroft Institute [4]. An example profile obtained by crossing the gas jet with a 5 keV electron beam is shown in Fig. 3 [5]. It shows the profile of the electron beam as measured with the gas jet, as well as a signal obtained from ionization of the residual gas.

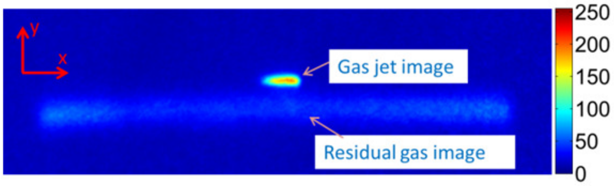

Figure 3: Beam profile of a 5 keV electron beam as measured with the gas jet and the residual gas.

The broadening of the image and resulting poorer signal quality caused by the thermal velocity of the residual gas particles as compared to the signal from the cold jet can be clearly observed. Also, a higher intensity from the jet as compared to the signal from the residual gas can be seen. Note that the lateral displacement between the two profiles is a direct result of the high jet velocity.

One initial challenge was the high gas load from the inlet nozzle onto the overall system. Gas reflections from the surrounding vacuum chamber walls caused instabilities in the jet and contributed to general alignment problems. This was overcome by the addition of a Festo solenoid pulsed valve. By synchronizing the camera with the pulse valve and setting a proper shutter time, it was shown that the signal ratio between the supersonic gas-jet and the residual gas can be increased significantly. Current studies focus on the optimization of the electric extraction field, impact of different gas species on signal quality and studies into the gas dynamics. In addition, the monitor is being adapted for integration into the HL-LHC and under consideration for the ESS main linac.

Silicon Strip Detector as Beam Monitor

The VErtex LOcator detector (VELO) is the most proximal device to the interaction region of the LHCb experiment. It provides track coordinates of the secondary vertices from B-mesons decays in the investigations of CP violations and other rare phenomena [6]. Its design allows precise measurements to be taken a few millimeters from the primary beam, without affecting it.

VELO is a multi-strip silicon detector and has been tailored to meet both the stringent requirements of the operation in a high-level radiation environment and facilitate data collection at high frequencies, matched with the bunch crossing at LHC. Each sensor embeds 2048 diode strips resolving the position of the hit in r – and φ-coordinates. The r – measuring side is divided into four 45° sections, thus lowering the overall strip capacitance and occupancy [7]. The φ – side consists of inner- and outer- section of radially oriented strips with a skew angle being introduced between the regions to support the ghost hit recognition algorithms. VELO has a central hole through which the primary beam passes and the detector surface surrounding this area. The geometry of the sensors allows approaching the beam to as little as 8.2 mm radial distance. Such high proximity enables resolving track vertices with high spatial resolution. This special detector geometry has also proven to be advantageous for applications as a non-invasive beam monitor for medical applications. Acting as a proton counter in the tail distribution of the beam, the monitor can serve as a beam position, profile and halo monitor, and potentially – once signals have been cross-calibrated against absolute current measurements from another detector – as an online intensity and hence dose monitor. This would add significant benefit as intensity could be monitored non-invasively during patient treatment, hence effectively eliminating setup and calibration times.

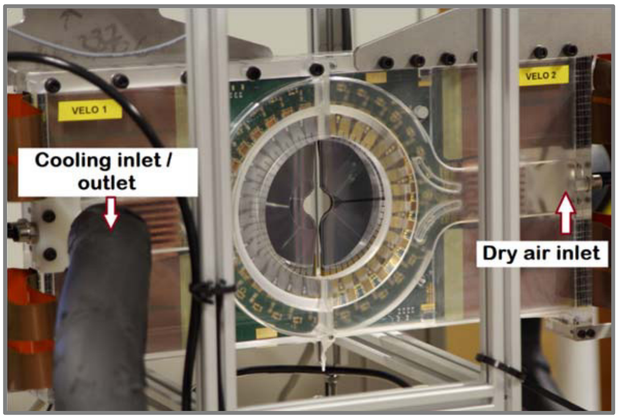

Figure 4: Photograph of the VELO detector after a local positioning, ventilation and cooling system has been added.

During normal operation the LHCb VELO detector works under LHC vacuum conditions. Its integration into the treatment beam line of an ion beam center, however, requires it to work under ambient pressure and at room temperature. Therefore, a designated support structure was developed, encompassing a 3D positioning system, remote read-out, together with a local ventilation and cooling system [8]. Performance tests carried out in the Cockcroft Institute laboratories yielded noise levels at a bias voltage of -100V at the level of 2–3 analogue to digital counts (ADCs).

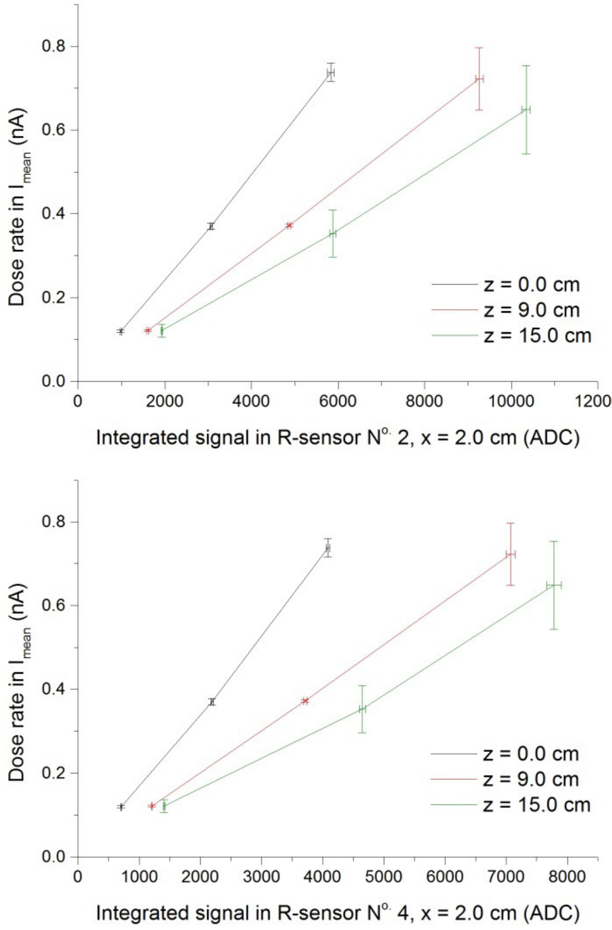

Figure 5: Signal of two sensors at x = 2.0 cm around the beam axis. Sensors No. 2 and 4 are on opposite sides of the beam.

With a maximum energy of 62 MeV, provided by a Scanditronix MC-60 PF cyclotron, the Clatterbridge Cancer Center (CCC) is specialized in the treatment of ocular tumors. As part of the preparations for measurements with VELO, studies into beam transport through the CCC treatment line have been carried out [9]. For measurements with beam the whole detector assembly was then integrated into the CCC treatment beam line in 2014. The detector was placed at the isocenter. It was mounted on a 3D translation stage that allowed for transverse movement, as well as shifting the whole assembly to different positions near the isocenter that corresponded to the range typically used for treatment.

An example from these measurements is shown in the above Fig. 5 which shows the measured dose rate as a function of total counts at three different longitudinal positions z=0.0/9.0/15.0 cm and at a radial distance of 2 cm from the beam center. The two sensors were located on opposite sides of the beam. A good linearity between integrated signal and delivered dose can be seen. The dose was obtained by a Faraday Cup used for absolute intensity measurements.

Initial analysis of this data supports the idea that the proton beam halo produced by a passive beam delivery system based on scattering for a medical accelerator can be used for an estimation of the beam current and hence dose delivered to the patient. Benefiting from VELO's unique semi-circular architecture it was shown that clear signals can be obtained without causing detector saturation or excessive noise levels. Further measurements are now planned to better understand the correlation between the halo and core reading and to develop automated algorithms for signal processing.

CONCLUSION AND OUTLOOK

Two new technologies for least invasive beam monitoring have been developed by the QUASAR Group and were successfully tested with beam. The particular advantages of the gas jet monitor are that integration into beam lines and storage rings operating at vacuum pressures as low as 10^{-12} mbar is possible, that the 2D transverse beam profile of the primary beam can be obtained in a least invasive way, and that the monitor can essentially be used for any type of beam, starting at lowest keV energies, and stretching all the way up to TeV energies. Beam and gas jet densities, together with the interaction frequency and respective ionization cross sections will then determine the event rate for a specific application. Optimization studies are currently being undertaken and focus on the integration into the HL-LHC vacuum environment and the impact from space charge on image quality in the case of high current beams, as found e.g. at ESS.

Furthermore, the LHCb VELO detector has been developed into a stand-alone monitor for use in treatment beam lines and was tested at the Clatterbridge Cancer Centre. Initial data taken during a beam time in summer 2014 shows a clear correlation between halo readings and dose delivered to the patient. More measurements are however required to fully understand intensity limitations, noise levels and automate signal processing.

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