BEAM EMITTANCE MEASUREMENTS AND BEAM TRANSPORT OPTIMISATION AT THE CLATTERBRIDGE CANCER CENTRE*

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Abstract

The QUASAR Group is preparing tests of the high energy physics LHCb VELO detector as a non–invasive online dose monitor at the 60 MeV proton therapy beam at the Clatterbridge Cancer Centre (CCC), UK. The proposed method relies on the cross-correlation between the beam halo signal as measured by VELO and the dose delivered to the patient, linked via the absolute intensity of the beam. In order to estimate the expected halo signal and the total beam intensity, studies into proton beam transport through the whole CCC beam line have been carried out. This required the measurement of beam emittance at several positions of the beam delivery system. Quadrupole scans have been realized using a CsI (Tl) scintillating screen in combination with an 8 bit, 13 MPixels CCD camera. In this contribution, results from measurements are presented and discussed.

INTRODUCTION

The SCANDITRONIXMC60PF cyclotron has been a source of a 62 MeV proton beam [1] for eye tumour treatment at the Clatterbridge Cancer Centre (CCC) for nearly 24 years [1]. Initially commissioned in 1984 for neutron therapy trials of radio-resistant tumours, supported by the Imperial Cancer Research Fund, a new ocular treatment room and beam line was built soon thereafter. Still remaining the only hadron therapy centre in the UK, it has been an important facility for many research projects in both, medical physics and accelerator science. Among them, emittance measurements were carried out in 1998 by J.A. Clarke et al. to assess the cyclotron's suitability as an injector for an energy upgrade by a booster linac [2]. One of the research projects in the QUASAR Group focuses on the implementation of the high-energy physics LHCb VELO detector as a stand-alone, non–invasive, real-time beam current monitor for the hadron therapy beam line. The proposed method relies on the correlation of consecutive proton beam 'halo' maps determined in planes orthogonal to the beam propagation direction with the absolute beam current measured by a purpose-built Faraday Cup. Pre-experiment numerical beam line simulations require detailed knowledge about the transverse beam dimensions and betatron amplitude in order to assess the precise proton transport through the scattering foils and generation of a uniform 'halo' by scattering on air molecules. In this context new emittance measurements were performed in October 2012 to identify a concise beam line model and the beam's Twiss parameters in front of the scattering foils.

TREATMENT BEAM LINE AT CCC RESOURCES AND METHOD

The CCC treatment beam line consists of a Scanditronix MC60PF cyclotron and two straight sections of beam line with three sets of strong focusing quadrupole triplets, see Fig. 1. The switching magnet diverts the beam by 5 degrees with respect to the initial direction, feeding it directly to the treatment room. A system of two scattering foils, each 25 µm thick, spreads the beam and shapes its lateral profile to be a plateau. At this point, the beam leaves the vacuum pipe through a Kapton window and covers a distance of approximately 1.5 m in air to reach the treatment isocentre.

Access limitations in the beam line made quadrupole scans possible in only a few places. Also, limited information about the beam line design and performance, coerced into performing the measurements at two independent places: in the accelerator vault - at the end of the first quadrupole (Q1) - and in the treatment room - after the third quadrupole (Q3), see Fig. 1. This enabled benchmarking the theoretical predictions against experimental resuls and excluding any possible beam losses caused by improper quadrupole arrangements.

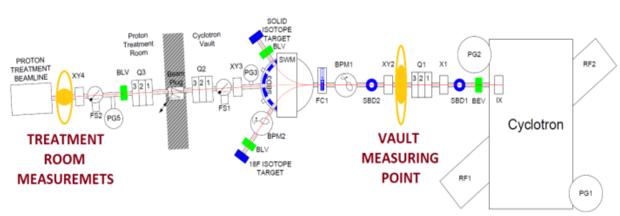

Figure 1: CCC treatment beam line outline. Q1, Q2, Q3 – consecutive quadrupole triplets, X, XY – horizontal or horizontal and verical steering mangets, SW – switching dipole magnet, yellow marks – quadrupole scan experimental places.

The experimental setup consisted of a vessel housing a CsI(Tl) scintillating screen centered on the beam axis. The images were captured by a 1.3 Mega-pixel uEye U-1540-M-GL camera. In succesive measurements, the same vessel was used to house a Faraday Cup for determination of the beam current.

Figure 2: Experimental vessel integrated into the beam line in the accelerator vault (in the right bottom corner of the picture – image of the scintillating screen with marked axes for relating physical dimensions to distances on the image).

The chosen emittance measurement method uses a linear matrix formalism [4]. The beam parameters described by σ can be propagated through any linear optical system based on the following formulas:

$$\sigma = R\sigma_i R^T \tag{1}$$

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix} \tag{2}$$

Where $\langle x^2 \rangle$ and $\langle x'^2 \rangle$ are the second order moments of coordinate and divergence, and $\langle xx' \rangle$ is the correlation between them. σ and σ_i are the beam matrices at the screen position and at the quadrupole entrance, and R is the transfer matrix from the quadrupole entrance to the screen and R^T is the transposed transfer matrix. By varying the quadrupole strength a system of linear equations can be obtained and the emittance ϵ can be derived from the equations:

$$\sigma_{11} = R_{11}^2\sigma_{i11} + 2R_{11}R_{12}\sigma_{i12} + R_{12}^2\sigma_{i22} \tag{3}$$

$$\epsilon = \sqrt{\det \sigma} \tag{4}$$

DATA ANALYSIS

Data analysis proved to be a challenge in terms of finding an algorithm suitable for both precise determinations of the beam profiles in horizontal and vertical directions for different quadrupole strengths for all available images and an automated calculation of the initial Twiss parameters at the entrance of the first quadrupole triplet.

Obtained variation scan images were analysed in MATLAB [5] by a purpose-written routine. First, noise was subtracted from all images, correcting also for glares at the edge of the scintillating screen, see Fig. 3. Due to the non-Gaussian beam profiles three different algorithms were investigated to find the most reliable method for determining the profiles at the maximum of the beam intensity.

As mentioned before, measurements had to be performed under strong spatial constraints, hence it was decided to rely on quadrupole current variation scans, rather than profile measurements at several different locations along the beam line. Different quadrupole strengths provided a set of differential equations (3), and yielded the Twiss parameters. The obtained results were benchmarked against measured profiles by simply transporting them through the optical system using the transport matrices (1). The obtained results are shown in the graphs in Fig. 4 and Fig. 5. Note that the initial beam parameters were determined for the first quadrupole triplet only. The beam line incorporates a switching magnet, which is located between the first and the second quadrupole triplets. Here, the beam gets directed to the treatment line section by changing its initial direction by 5 degrees in the horizontal plane. The dipole field increases the beam 'tail' region in the horizontal plane, which is significantly larger for the beam in the treatment room compared to the measurements in the accelerator's vault. This is believed to be caused by the beam energy spread. Therefore, it was impossible to analyse profiles obtained in the accelerator vault and the treatment room using the same MATLAB algorithm. The treatment room beam profiles were used, though, to benchmark the assumed beam line model against the real beam images.

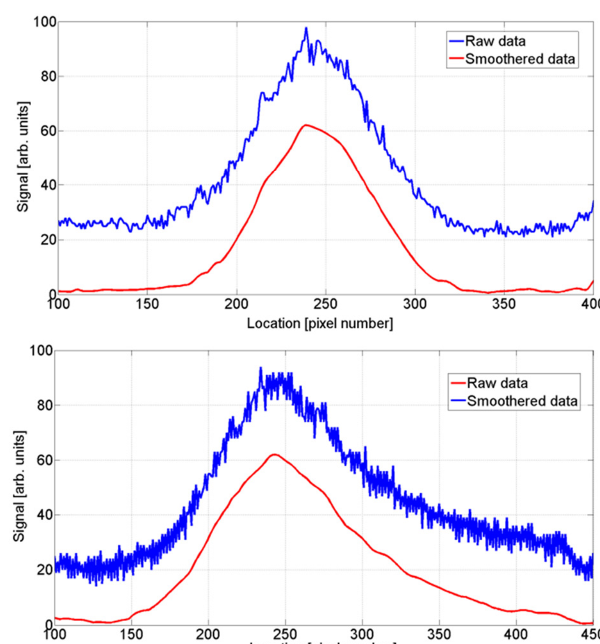

Figure 3: Beam profiles in raw format and smoothened by MATLAB 'smoothn' algorithm [6] in the horizontal (upper) and vertical (lower) planes.

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Table 1: Twiss Parameters Calculated at the Entrance of the First Quadrupole Triplet

Axis	α [mm mrad]	β [mm]	γ [mrad]
Horizontal	2.504	8.45	3.25
Vertical	19.000	50.44	32.92

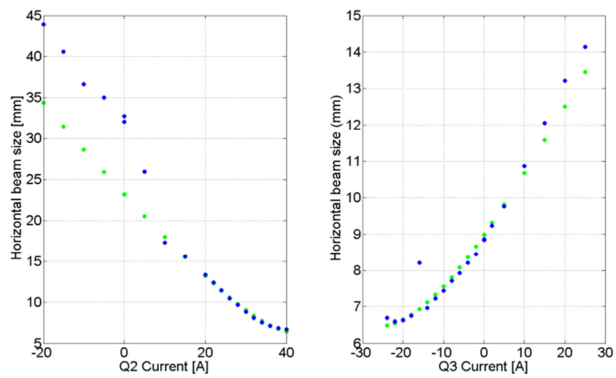

Figure 4: Quadrupole current scan results for the first triplet in horizontal direction - lenses 2 and 3.

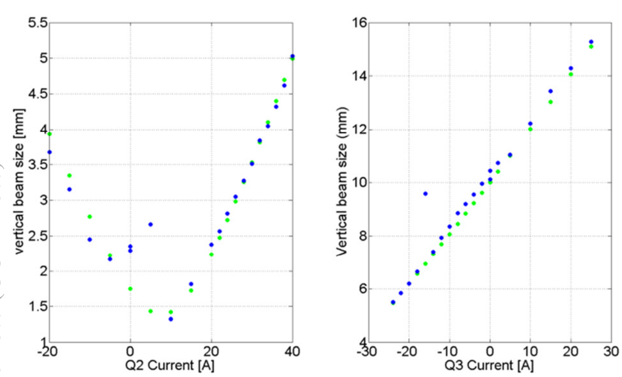

Figure 5: Quadrupole current scan results for the first triplet in vertical direction – lenses 2 and 3.

BEAM TRACKING

Particle tracking was performed in MATLAB, where a system of differential equations of motion was solved numerically. The initial particle distribution was generated on the basis of the Twiss parameters obtained from data analysis. The quadrupole and dipole fields were calculated based on measured positions and currents applied to the coils. Step-by-step integration particle tracking through the beam line was then performed to obtain the particle distribution in the treatment room. The comparison between the obtained beam images and simulated particle tracking results shows good agreement between the measurements and the theoretical predictions.

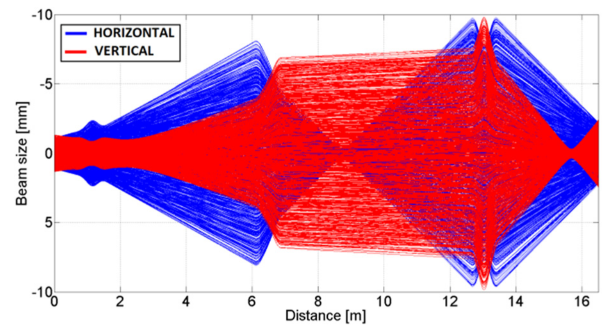

Figure 6: CCC beam line tracking model.

Comparison with earlier measurements, performed in 1998, show a similar phase space ellipse orientation; however the emittance value is different due to different fitting algorithms and cyclotron regimes. It is noted that a focus in this analysis was put on identifying the phase space ellipse orientation rather than the absolute emittance value due to the non-Gaussian beam shape.

SUMMARY

Quadrupole variation scans were performed at the Clatterbridge Cancer Centre cyclotron beam line. The proton beam orientation in phase space was determined in order to find a suitable beam line model and simulate the beam dynamics. It was the first time such measurements have been carried out at the treatment beam line since its commissioning. The calculated beam parameters are essential for a detailed modelling of the proton beam transport through the scattering foils for both, medical physics models and future measurements of the beam 'halo' with the VELO detector. Discussions now focus on possible beam transport optimisation schemes and efficiency improvement of the treatment beam line.

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