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Author/s:

Yap, JSL;Steinberg, AF;Clarke, SJ;Norman, HXQ;Appleby, RB;Sheehy, SL

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Progress Toward TURBO: A Novel Beam Delivery System for Charged Particle Therapy

J SL Yap¹, A F Steinberg^{1,2,3}, S J Clarke⁴, H XQ Norman^{1,2,3}, R B Appleby^{2,3} and S L Sheehy^{1,5}

¹ School of Physics, University of Melbourne, Melbourne, VIC 3010, Australia

² Cockcroft Institute, Daresbury, Warrington WA4 4AD, United Kingdom

³ Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom

⁴ University of Sydney, Camperdown, NSW 2006, Australia

⁵ Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, NSW 2234, Australia

E-mail: jacinta.yap@unimelb.edu.au

Abstract. TURBO – Technology for Ultra Rapid Beam Operation – is a novel beam delivery system (BDS) in development at the University of Melbourne. The BDS determines several aspects of treatment delivery where a key bottleneck is the deadtime associated with beam energy variation. Beamlines at treatment facilities have a $\pm 1\%$ momentum acceptance range, requiring all the magnetic fields to adjust to deliver different energy beams at multiple depths in the tumour volume. A BDS using Fixed Field Alternating Gradient (FFA) optics could reduce the energy layer switching time (ELST) by enabling the transport of a large range of beam energies within the same fixed fields. We present recent progress and ongoing developments with TURBO, a proof-of-concept demonstrator adapted for low energy protons. Characterisation measurements were performed to determine realistic parameters for beam transport and particle tracking modelling. Simulation and experimental studies are shown for an energy degrader. We mention considerations of canted-cosine-theta magnets and further work to explore the clinical feasibility of a scaled-up BDS for charged particle therapy.

1. Introduction

Charged particle therapy (CPT) is an advanced modality of radiotherapy which can deliver radiation to cancerous tumour sites with greater precision and radiobiological impact than conventional X-ray photon therapy. The availability of CPT is increasing with the proliferation of facilities worldwide, driven by developments in technologies and techniques enabling the possibility of improved clinical benefits. However, prohibitive costs and technical limitations remain key challenges which restrict exploitation of the full potential of CPT [1]. There are many avenues for further development: improvements in the beam delivery system technology are likely to achieve better treatment efficiency and efficacy [2].

Currently, most modern CPT facilities use pencil beam scanning to deliver multiple fields and beams for conformal coverage of radiation to target sites. Beams are modulated in depth by varying their energies and directed from various angles around the patient by rotating the last section of the BDS: the gantry, typically employed at clinics which offer proton therapy treatment, as well as some heavy ion facilities. Delivering beams with different energies through typical clinical beamlines requires changing the fields of all the magnets in the BDS for each



irradiation layer (i.e. 5 mm change in depth). This deadtime (from ~ 100 ms to secs) to switch between energies is a bottleneck constraint: for large sites and complex cases, this accumulates and can extend the total beam delivery time up to a factor of 10 times longer [2]. Reducing the ELST can result in faster treatments hence increased patient throughput but also higher quality treatments: shorter beam delivery times can reduce the impact of physical uncertainties and patient motion [3].

Increasing the momentum acceptance range is one approach to minimising the ELST. As such, several gantry designs achieving a large energy acceptance (LEA) have been proposed [4, 5], incorporating canted-cosine-theta (CCT) magnets [6, 7] and FFA optics [8, 9] for both protons and heavy ions – notably it is much more difficult to accommodate the requirements of heavier particle types [10].

Significant improvements in patient imaging and positioning have also renewed the possibility to deliver treatments upright and specific tumour sites sensitive to motion may especially benefit from upright immobilisation [11]. In practice, employing a fixed beamline instead of a gantry may be more feasible and have added advantages when coupled with fast energy switching: this may increase the utility of CPT for different tumours and a gantry-less approach can also significantly decrease costs given the BDS incurs a substantial proportion of the total expenditure (including infrastructure, shielding, magnets, and operations [12]). The complexities and applicability of a LEA fixed beamline BDS will be considered with TURBO: a proof-of-principle demonstrator for rapid CPT beam delivery using an FFA design concept to transport hadrons in a scaled-down environment.

2. Beamline Studies

TURBO is being developed as a novel beamline for implementation with the NEC 5U Pelletron accelerator at UniMelb, accommodating low energy (0.5–3.5 MeV) DC proton and He^+ beams at 100's nA to a few μA . Given these conditions, several components must be designed specifically for the TURBO system including diagnostics, an energy degrader, magnets for the FFA arc, and downstream scanning. The beam transport line must constitute a closed-dispersion arc, with zero dispersion over the full energy range: the design study for this arc is discussed in [13].

2.1. Pelletron Characterisation

As the Pelletron is used for a range of different user applications [14], an initial characterisation study was required to resolve the output beam distribution and stable operating parameters. Previous measurements [15] showed that the beam position and transverse profile could be obtained using the UniBEam detector [16, 17], this device has a single fibre and must be rotated to measure in the orthogonal plane.

As the controls for the Pelletron beam energy, current, and feedback system are interdependent and beam parameters can vary with operation, it was necessary to establish a working range of stability for reproducible beam characteristics. Time-dependent noise was observed in horizontal profile measurements and periodic fluctuations of the beam current, independent of machine settings. Further measurements identified the interceptive helical wire beam profile monitors [18] as a major contributor to these fluctuations: as the wires rotate at 32 Hz, dips in the beam current and profile were observed with the same frequency. Another source of the current ripple is variation in the voltage over the Pelletron terminals which can be exacerbated by poor choice of Pelletron settings, but is difficult to predict.

The high energy slits (Fig. 3) can be adjusted vertically and horizontally, limiting the size of the output beam. The vertical slits are also used in a feedback loop to regulate beam current: at small apertures, the feedback fails and the beam stability deteriorates. As other information such as the beam divergence is essential for beamline design and simulation, slit-grid measurements [19] were performed to probe the beam phase space. Two plates of tantalum separated by 100 μm

or 200 μm were held in the beam path using a custom-built mount (shown in [15]). The slit was translated in 508 μm steps with a linear feedthrough, and the traversing beam was detected downstream by UniBEaM. Measurements were taken in the vertical and horizontal direction at varying beam energies to reconstruct the phase space at the slit position: an example is in Fig. 1. By averaging over many measurements, a set of representative Courant-Snyder parameters were obtained, with $\beta_x = 8.45\text{ m}$, $\alpha_x = -5.42$, and a geometric emittance of 0.31 mm mrad.

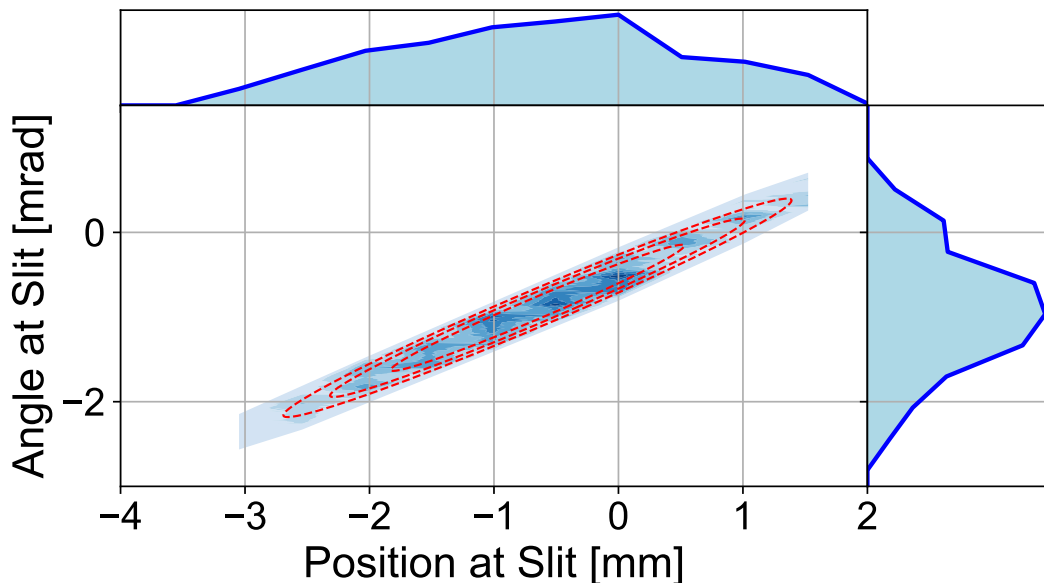


Figure 1. Slit-grid horizontal phase space measurement for a 2 MeV proton beam. Ellipses for 1, 2, and 3 σ are shown, assuming a Gaussian distribution.

2.2. Energy Degradation Tests

Demonstrating the transport and delivery of beams of multiple energies through the FFA arc requires a method enabling rapid energy changes. As the beam flux is limited to a power density $<0.1\text{ W/mm}^2$ for the fibre scanner, 3 MeV was chosen as the pristine beam energy. Therefore the choice of absorbing material requires several considerations: it must be thin, robust, radiation hard, practical to source, have a high melting point etc. Preliminary studies [15] indicated the feasibility of Kapton® film and subsequent simulations performed in TOPAS v3.9 [20, 21] determined for 25.4 μm sheets: 5 Kapton layers fully absorb a 3 MeV proton beam and 1–4 sheets would result in a beam energy and spread of 2.58, 0.026 MeV; 2.10, 0.035 MeV; 1.52, 0.046 MeV and 0.71, 0.088 MeV, respectively.

Four layers of Kapton film were affixed in a staircase stack and translated horizontally (in x) in a mount across the beam path (Fig. 3). This was irradiated at $\sim 0.5\text{ }\mu\text{A}$ resulting in permanent darkening at the beam spot (carbonisation) and shrinkage. Although the film remained intact under exposure to continuous currents, it was easily torn when handled physically. The UniBEaM transverse beam profiles (Fig. 2) show a clear blowup of the beam after passing through the Kapton. More layers increase the amount of scatter and there is significant signal degradation after 3 & 4 sheets; values recorded below 0 are due to a small bias.

Although the carbonisation had no observable impact on the beam, the performance and reproducibility of Kapton is likely to decline under longer irradiation times: it may only be useful as a disposable absorber. Alternative materials were investigated; Mylar (23 μm) was

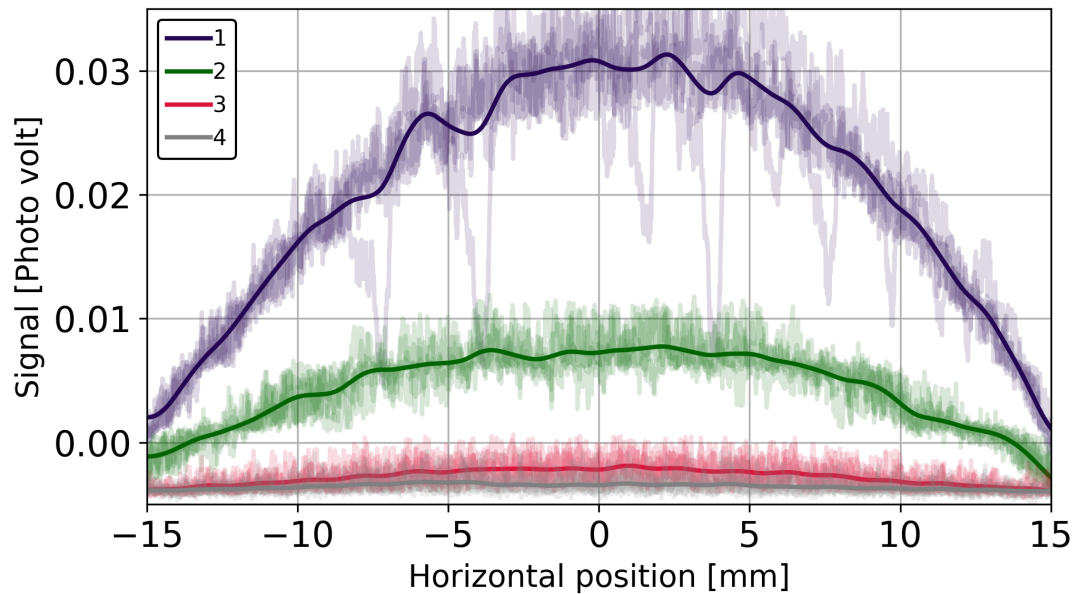


Figure 2. Measured beam profiles after 1–4 sheets of Kapton. A low-pass filter has been applied to the raw UniBEaM data (shaded) and averaged over multiple runs.

tested under the same conditions however immediately vaporised at points of contact with the beam. A thin film of single crystal diamond will be tested next and may be better suited as a degrading material. As seen in Fig. 2, it is evident that downstream collimators or other components are necessary to limit the beam divergence after degradation, to produce a useful beam that is approximately energy-independent.

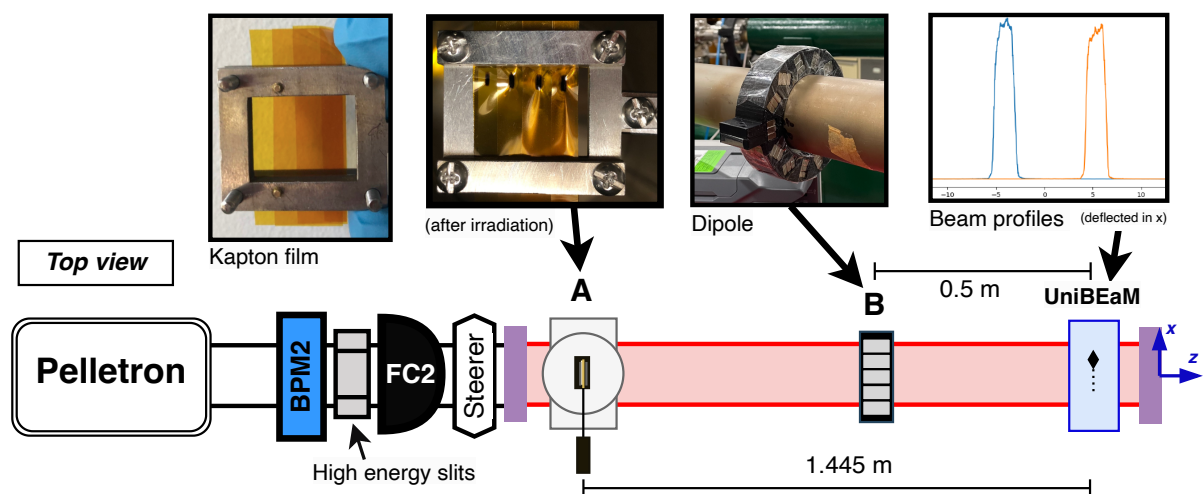


Figure 3. Components integrated into the existing (red) beamline for experimental measurements. Beam profile monitor (BPM2), high energy slits, Faraday cup (FC2) and steerer are upstream on the Pelletron beamline. Vacuum chamber with actuating degrader system (A), custom built dipole (B) and transverse beam profiles obtained with the UniBEaM system.

A simple spectrometer setup was devised to verify the degraded beam energy using a dipole

placed between the degrader and the UniBEaM. Simulations gave a final beam energy range of 0.72–3.0 MeV, which our 3D printed dipole [15] (integrated field 4.5×10^{-3} T m) would kick 37–18 mrad respectively: this was confirmed by measuring the shifted position of pristine 3 MeV beam (top right, Fig. 3). As the thickness of Kapton was increased, the beam deflection was seen to decrease, suggesting that the mean energy had risen. This was understood to be due to the large beam divergence: collimation from the beampipe preferentially impacts higher angles, so a larger spread results in a smaller deflection, independent of energy. As seen in Fig. 2, the beam distributions flatten out and extend past the fibre scanning range. Additional diagnostics will be designed and integrated into the TURBO system; YAG screens will also be tested (30 & 50 μm thick) to assess their suitability for online imaging given the Pelletron beam parameters.

3. Scaling up

To adapt TURBO for clinical operation at the minimum and maximum kinetic energy ranges for several different particle species for treatment (Table 2 in [15]), further considerations have been made towards a suitable magnet design. Due to the fixed magnetic field during operation, superconducting magnets can be used to transport the higher rigidity beams required for ion therapy without needing to quickly vary the field strength, therefore avoiding quenching. We continue to investigate a CCT arrangement as a potential option for the closed-dispersion FFA arc. The model for a scaled-up TURBO BDS will be based on a superconducting, curved CCT dipole with alternating-gradient (AG) focusing-defocusing layers [8]: the parameters of this magnet adapted for the TURBO BDS are given in Table 1. The strong curvature of the magnet and combined-function layers may help to reduce the number of magnets required in the arc.

Table 1. AG-CCT parameters for a scaled-up TURBO BDS

Main Bending Field B_{dip} [T]	1.25–3.63
Max Quadrupole Gradient [T/m]	$\pm 10^1$
Physical Bend [$^\circ$]	30
Bending Radius [m]	2.0
Aperture (diameter) [mm]	60^2

^{1,2} taken from [22]

Assessing the suitability of the CCT for TURBO will first involve tracking particles through the magnet’s 3D fieldmap. Current studies investigate the impact of nonlinear fields in curved CCT magnets in the context of a compact ion therapy synchrotron [23, 22], which will be extended to particle tracking off-centre, as is necessary for FFA optics. The strong curvature of the magnet will result in nonlinear effects from field contributions by the horizontal and longitudinal components, and tracking will be performed using Zgoubi [24] to observe any distortion in the beam phase space. Further work will involve tracking simulations in the full-scale beamline with the AG-CCT implemented to study the effect on treatment beam quality and its applicability for TURBO.

4. Outlook

Characterisation studies have established a working range of Pelletron beam parameters, necessary for simulation and design studies to develop a TURBO demonstrator. Additional measurements will test different components to build a degrader and diagnostics suitable for these scaled-down conditions. We consider technological parameters for future clinical application and work toward a prototype to de-risk and demonstrate the possibilities of a LEA BDS for CPT.

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