A SPECIALIZED HIGH-POWER (50 kW) PROTON BEAMLINE FOR BNCT

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Abstract

D-Pace has developed a specialized high-power beamline for transporting a 20 mA, 2.5 MeV, CW proton beam for a Boron Neutron Capture Therapy (BNCT) application. The 2 m horizontal by 4 m vertical layout transports the space-charge dominated beam with less than 1% beam-spill using two sets of 10 T/m quadrupole doublets, DC XY steerer, 90 degree bending magnet, and AC XY magnets for raster-scanned, flat-topped, round or square intensity distributions deposited over targets with 40 – 100 mm maximum dimensions. Diagnostics include New Parametric Current Transformers (NPCT), graphite, water-cooled, electrically-isolated collimators with readbacks, and a low-power sapphire beam profile monitor for macro-pulsed beams (~100 micro-second wide pulses at low frequency). This paper describes the specialized: beam-optics, intensity distributions, and device designs.

INTRODUCTION

BNCT is a non-invasive therapeutic treatment of cancer (high-grade gliomas, cerebral metastases of melanoma; and head, neck, and liver cancer) [1] that involves two steps. First, tumour-localizing non-radioactive boron-10 delivery agents (such as boronophenylalanine i.e. BPA, or sodium borocaptate i.e. BSH) are injected into the patient [1]. Second, the patient is exposed to epithermal neutrons, which have a very high probability of reacting with the concentrated boron-10 residing in the cancer cells. This yields an energetic alpha particle, and a recoiling lithium nucleus which ionize a tremendous number of atoms and molecules within 5-9 microns (~size of cancer cell). This results in cancer cell death [1,2].

BNCT has a 50 year history at research nuclear reactors [3], and is established i.e. 16th International Congress on Neutron Capture Therapy, ICNCT (2014), is to be held in Helsinki. For widespread use of BNCT better delivery agents, improved dosimetry, and independence of nuclear reactors is required [3]. Barth [3], IAEA [4], Blue and Yanch [5] all emphasize the development of particle accelerators for BNCT. Strong growth in BNCT implementation in hospitals is anticipated since it can now be de-coupled from nuclear reactors through low energy (p,n) reactions provided by relatively inexpensive safe compact particle accelerator systems that can be turned off (as compared to a reactor) [6].

This paper describes the High Energy Beam Transport (HEBT) beamline developed for the BNCT treatment system utilizing an AccSys 2.5 MeV, 20 mA, CW proton Linac and the Li-7(p,n)Be-7 reaction.

HEBT BEAMLINE

The 10 rms RFQ beam was modeled thru HEBT (Figure 1) with 1st order Beamline Simulator [7] using acceptances greater than 3x the 10 rms emittances in both transverse phase-planes to define conservative apertures. TRACE-3D [7] simulations confirmed high beam transmission at 20 mA CW space-charge conditions. The finalized system in Figure 2 follows the principles [8-10].

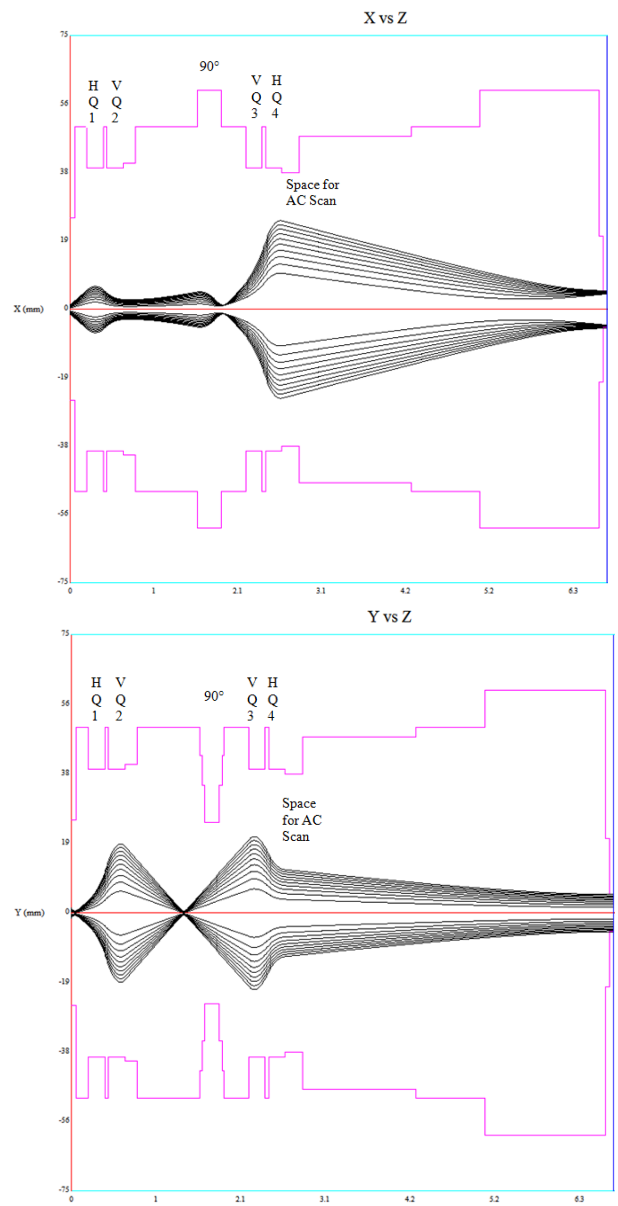

Figure 1: HEBT Horizontal & Vertical 1-10rms Beams.

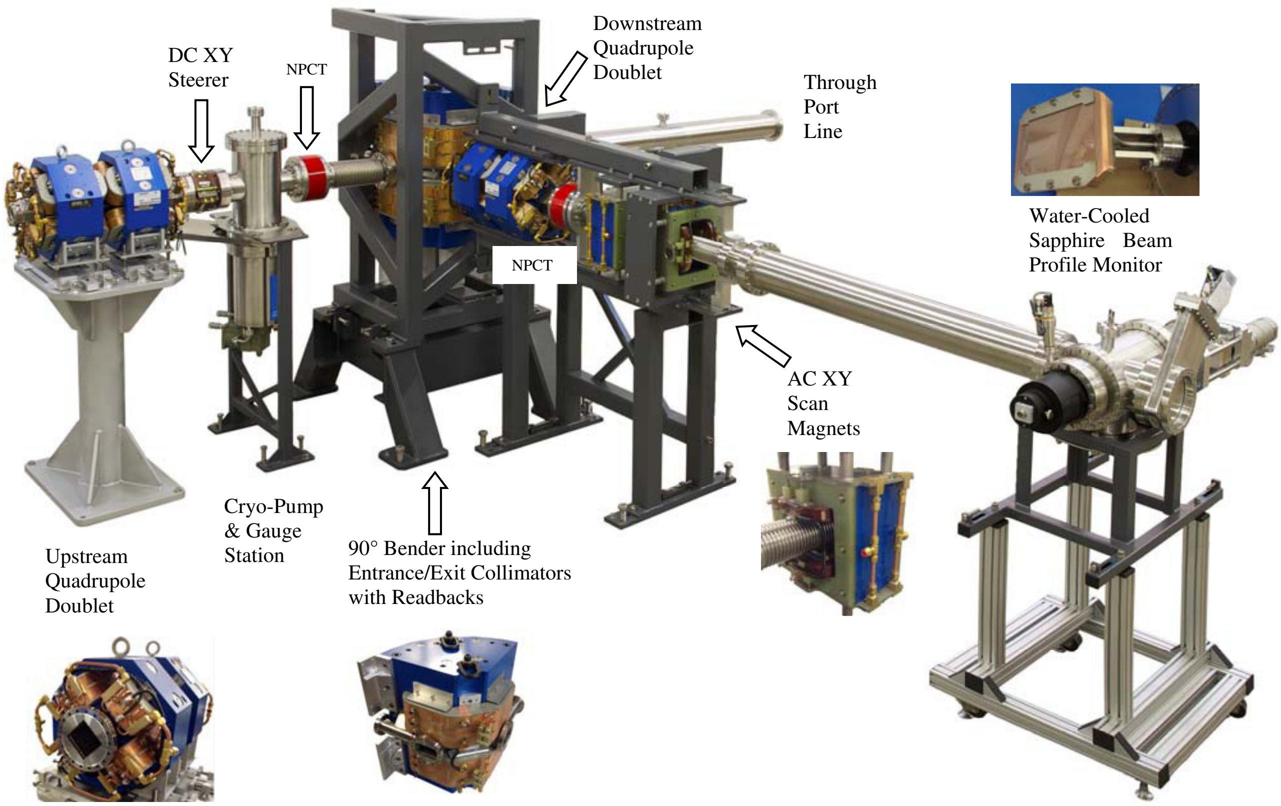

Figure 2: The HEBT system. The proton beam is injected into the HEBT from the RFQ at upper left, and the scanned beam exits at right (downstream of Beam Profile Monitor). The supports can be arranged in a horizontal format for factory testing as shown, or in a format where components downstream of the 90° Bender are in the vertical direction.

Ion-Optical Elements

The ion-optical elements are as follows: (1) Upstream Quadrupole Doublet {Bore = 82.3 mm, Effective Length (EL) = 202.3 mm, B_{Max} = 0.4 T}, (2) DC XY Steering Magnet {Iron Gap = 105 mm, EL = 184 mm, B_{Max} = 0.01 T}, (3) 90° Bender Magnet {Iron Gap = 52 mm, EL = 300 mm, B_{Max} = 1.3 T, Rogowski Pole Face Rotations = 0°}, (4) Downstream Quadrupole Doublet {Bore = 82.3 mm, EL = 202.3 mm, B_{Max} = 0.4 T}, and (5) AC XY Scan Magnet {Iron Gap = 97 mm, EL = 212 mm, B_{Max} = 0.0165 T, Frequency = 45 Hz}. All magnets designed with alignment fiducials for Ball Mounted Reflectors (BMR) used during final alignment with a laser tracker.

Upstream Horizontal Section Description

The Upstream Quadrupole Doublet is placed close to the RFQ (~200 mm space for a VAT™ gate valve, bellows, and flanging) since it serves to capture the diverging RFQ beam and to focus it through the 90° Bender which has a narrow gap resulting in reduced magnet cost, size, and power consumption. The transverse beam envelopes are largest through the Quadrupole Doublets and thus they are fitted with diamond-shaped beampipes that afford a larger acceptance than round beampipes for the very same magnet bore diameter (refer to lower left of Figure 2).

Immediately after the upstream doublet is the DC XY Steering Magnet which provides ± 8 mrad of steering capability. It is located downstream of the first doublet where a sensitivity analysis has shown it to be efficacious.

A cryo-pumping station with ports for gauges and leak testing are provided. The cryo-pump is separated from the beamline by a gate valve, so that it is not necessary to be purged to atmosphere if the HEBT is vented.

A Bergoz NPCT (96 mm diameter) provided by GMW measures the beam current in the upstream portion of the line. It comes with Conflat™ flanging as does all of the vacuum equipment. Experiments shall be undertaken to ensure H2+ is not affecting the proton beam current measurement [11].

A bellows is located immediately upstream of the 90° Bender Magnet. The bender magnet vacuum box is outfitted with electrically-isolated water-cooled 46 mm diameter graphite entrance and exit collimators with beamspill current readbacks to the control system. The device's handle greater than 2 kilo-watt beamspill power on average, but shall be used as a threshold interlock at 0.5% of total beam current for rapid "beam off" in the case of a component failure (i.e. power supply). The collimator ceramic insulators are protected by metal shrouds to prevent short-circuiting in the event of any migration of metal vapour from the targets. The bender vacuum box also has a thru port with gate valve and beampipe with pumping station port for DC beam experiments when the bender is off.

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Downstream Vertical Section Description

The Downstream Quadrupole Doublet captures the strongly diverging beam immediately downstream of the bender magnet. A Bergoz NPCT is next and provides a 2nd beam current measurement to establish transmission rates. The support structure can be used in both a horizontal and vertical configuration. A sapphire water-cooled low-power beamstop with a radhard MegaRAD3 Thermo CIDTEC camera for viewing low frequency macro-pulsed beams (~100 micro-second) is provided. The downstream vertical section is shielded to contain the neutron flux from the target.

D-Pace's standard <100 Hz AC XY Scan Magnet product can provide both generic raster and circular scanned beams as shown in Figures 3 and 4.

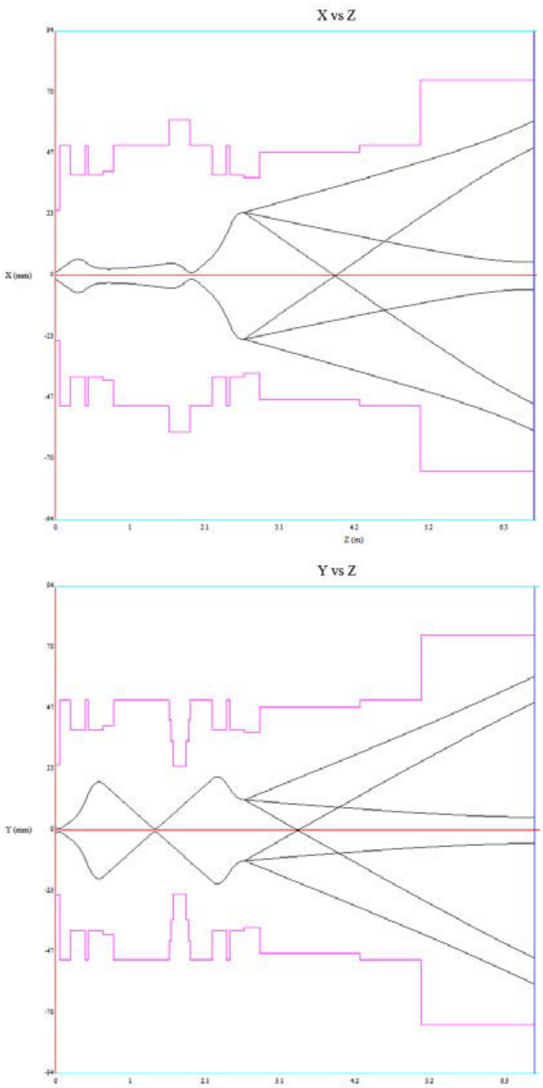

Figure 3: Horizontal and vertical 10 rms beam profile extents of AC Scanning ($\theta_{Max}= \pm 13.4$ mrad) with 10 mm DC beam spot on target. Apertures confirmed.

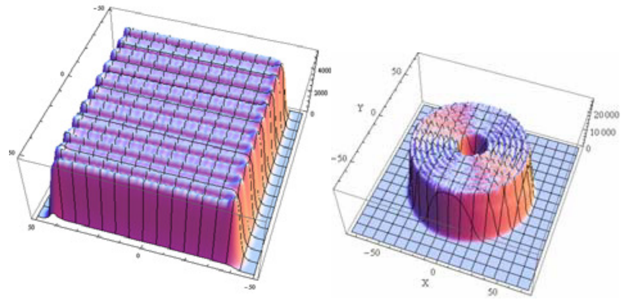

Figure 4: An example of generic square raster-scanned beam (left), and generic circular scanned beam (right) that D-Pace's standard product AC Scan Magnets can deliver. The customer shall tailor the undisclosed beam distributions on target according to their own proprietary algorithms through D-Pace's programmable two channel signal generator.

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REFERENCES

[1] R.F. Barth et al., "Boron Neutron Capture Therapy of Cancer : Current Status and Future Prospects", Clin. Cancer Res. (2005);11(11).
[2] Mohamed Alotiby, "Boron Neutron Capture Therapy for Cancer Treatments", Master of Science Thesis, Dept. Physics, University of Surrey (2012).
[3] R.F. Barth, "Boron Neutron Capture Therapy at the Crossroads: Challenges and Opportunities", Applied Radiation and Isotopes 67 (2009) S3-S6.
[4] IAEA-TECDOC-1223, (2001).
[5] T.E. Blue and J.C. Yanch, "Accelerator-based Epithermal Neutron Sources for Boron Neutron Capture Therapy of Brain Tumours", J Neurooncol. (2003);62(1-2):19-31.
[6] T.P. Wangler. J.E. Stovall, T.S. Bhatia, C.K. Wang, T.E. Blue, R.A. Gahbauer, "Conceptual Design of an RFQ Accelerator-Based Neutron Source for Boron Neutron-Capture Therapy", IEEE PAC, Vol. 1, pp. 678-680, (1989).
[7] Beamline Simulator, TRACE3D, www.ghga.com/accelsoft
[8] Morgan P. Dehnel et al, "The Design and Operation of an Industrial Beam Transport System for 15-30 MeV Protons", IEEE Trans. Ind. App's, Vol. 28, No. 6, pp. 1384-1391, (1992).
[9] Morgan P. Dehnel et al, "Beamline Developments in Commercial Cyclotron Facilities", CAARI2004, NIM B 241, pp. 655-659 (2005).
[10] Morgan P. Dehnel et al, "Industrial Beamline Design for Radioisotope Production", 17th Int'l Conf. on Cyclotrons, pp. 486-488 (2004).
[11] H. Deitinghoff, "Beam Dynamics Calculations for the Simultaneous Simultaneous Acceleration of Ions with Different Charge to Mass Ratios in a RFQ", EPAC96, pp.1218-1220, (1996).