ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THP013

BEAMLINE OPTICS DESIGN OF A NEW TWO-ROOM TREATMENT SUITE AT THE MCLAREN PROTON THERAPY CENTER*

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Abstract

A fixed-beam, two room suite with upright chairs for patient positioning, is being installed at the McLaren Proton Therapy Center (MPTC). The MPTC is an operational multi-room cancer treatment center. The new suite adds a third (A) and fourth (B) room by branching upstream of the two clinically active treatment rooms. It was required to fit into a pre-existing single treatment room vault. This imposed a number of constraints on the beamlines of the new suite. The new beamline uses a Y-shaped selection dipole to switch between the suite's room A and room B. The design was further constrained by the need to replicate the clinically active rooms' beam characteristics at the new patient locations. This paper provides an overview of the methodology of the design studies for the new beamlines together with selected results. The work helped to establish the feasibility of installing a two-room treatment suite into a space originally designed for a gantry-based single treatment room.

INTRODUCTION

The new treatment rooms [1] at the MPTC center around the use of two upright patient chairs of the LEO design [2]. This treatment modality offers a cost-effective alternative to conventional gantry-based treatment [3]. The two rooms are located in an existing room area designated TR3 at MPTC. The location of the TR3 room, together with rooms TR1 and TR2 at MPTC, was shown in Fig. 1 of reference [4]. The layout of the beamlines required them to fit within existing shield walls, while also allowing space for the patient treatment chair, monitoring and positioning equipment. The task was to design beamlines that could deliver existing synchrotron beams [4] to the TR3 isocenters for A and B with beam characteristics that match of those at the isocenters of the existing rooms TR1 and TR2. Figure 1 shows the final beamline layout discussed in this paper.

DESIGN CONSTRAINTS

The constraints imposed upon the design derived from two primary requirements. The new 2-room treatment suite needed (1) to fit within an existing room and (2) deliver a beam at new isocenter locations as good as those delivered to the current treatment isocenters. The requirement (2), on the beam parameters at the new isocenter locations, is critical for the optics design, and derives directly from the need to minimize the impact on the existing treatment planning system. The existing room was originally designed for a gantry type treatment room, essentially identical to the existing TR1 and TR2 rooms. However, the LEO chair and new nozzle system have a longer air gap to isocenter distance, an increase of 290 mm compared to the existing treatment rooms. The result is a longer distance between the last magnetic optics component and the new treatment isocenters. The installation and commissioning of the new beamlines could not impact existing operations nor result in any facility down time. The existing TR3 room selection magnet CBM1 was to be used. The quadrupoles needed to be air-cooled so no new water lines would be added. The locations of all magnets, diagnostics, and vacuum system components were further restricted to be consistent with existing shielding and vault walls.

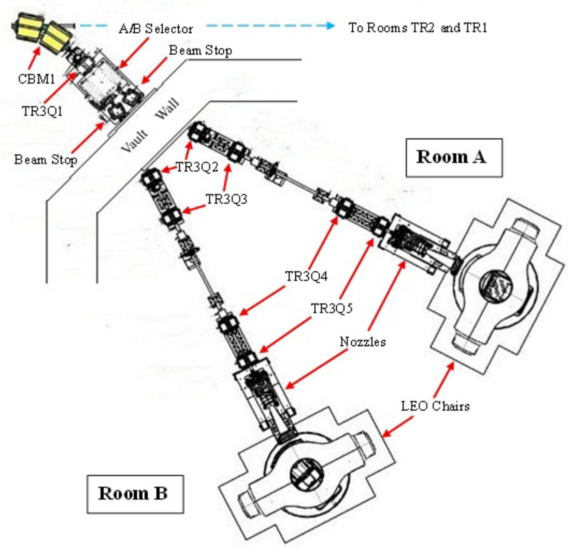

Figure 1: Room TR3 final beamline layout.

A primary consequence of the requirement to fit within the existing TR3 room was that the angle between the two beamlines A and B was constrained to be within a narrow range near 30°. The maximum distance, from the exit of the existing CBM1 magnet which directs the beam into the TR3 area, to the locations of the A and B isocenters is just over 11.6 meters. The resulting total effective (reference trajectory) lengths of the beamlines to the patient isocenters were thus constrained to be about 12 m. A 1.3-meter section of each beamline was unavailable for magnetic elements due to the vault wall. The last 3-meter section was reserved for the nozzle and air gap sections. The magnets and associated beam diagnostics were confined to be

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ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THP013

within two beamline segments of lengths 2.3 m and 5.4 m, before and after the 1.3-meter vault wall, respectively.

MAGNET DESIGNS

Quadrupoles

The quadrupoles for the beamlines were designed to be scaled-up versions of the existing TR2 and TR1 beamline quadrupoles. The quadrupole lengths were taken to be the same, 19.5 cm, but the aperture radii were increased from 1.5 cm to 2.0 cm. This permitted the vacuum pipe aperture ID to be increased from 27.6 nm to 36.5 mm.

Room A/B Selector Magnet

The locations of the patient isocenters defined by the LEO chairs, together with the location of the vault wall, placed limits on the location of the A/B selector magnet and the angle of the bend associated with the room A and B beamlines. Reduced beamline tuning requirements suggested that rooms A and B utilize identical beamline optics. A deflection angle of ±17.5° in the A/B selector magnet that would meet these requirements was adopted.

The magnet was designed to deflect beams with energy up to 300 MeV as a provision for possible future proton tomography studies [5], but the maximum for normal clinical use is 250 MeV. The beam had to be capable of switching between the A and B branches in a similar time to the synchrotron refill and ramp, typically 1.5 seconds. A 30 mm pole gap was selected as a compromise between the size and power consumption of the magnet, while providing sufficient beam envelope space in the non-bend plane.

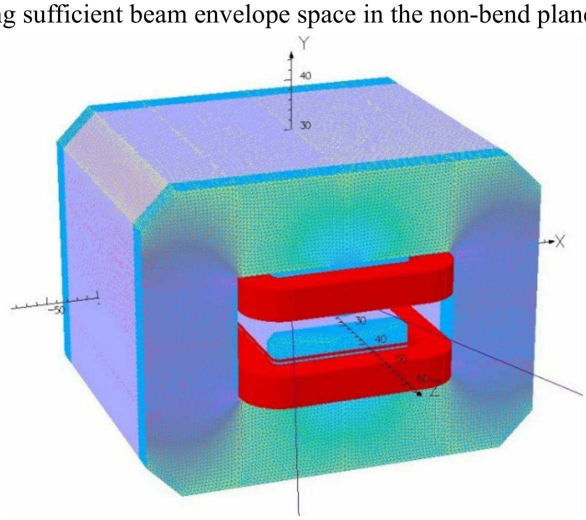

Figure 2: Opera model of the A/B selector dipole.

No pole face rotations or pole gradients were used, leaving beam focus control to the quadrupole magnets. The distance from the A/B selector magnet to the patient position was around 10 m. A 0.5 mm beam stability budget at the patient required angular control of +/-0.025 mrad. Projecting the deflected beam back up the magnet center line indicated a virtual deflection point 2 mm before the physical center, and was used for room layout calculations.

Electromagnetic modelling was performed using a typical B-H curve and packing factor for the silicon steel laminations using the Opera code [6]. Figure 2 illustrates the Opera model of the dipole. The hollow conductor specified for the coils resulted in a magnet design rated up to 300 coil current, with B-I curve linearity better than 1% up to 250 A. This was the expected current to deflect 300 MeV protons by 17.5 degrees. The peak gap field was 1.32 T at 250 A, and the magnet mass around 2200 kg. Calculated load parameters are L = 130 mH and R = 162 mΩ.

BEAMLINE OPTIMIZATION STUDY

The beamline optimization calculations used the TRANSPORT [7] and MINOS [8] modules of PBO Lab™ [9]. A figure of merit (*FOM*) function, for minimization by MINOS, was the root-mean-square (rms) sum of the transverse beam sizes at isocenter:

$$FOM = (X_{iso,rms}{}^2 + Y_{iso,rms}{}^2)^{1/2} \ . \tag{1}$$

The optimization studies looked for quadrupole locations and field strengths (“solutions”) that could deliver beams that met the isocenter spot size requirements and were within the constraints imposed on the physical layout and quad strengths. Initial beamline optimization studies concentrated on selecting from two conceptual versions of the layout defined as the (1) Doublet Model and the (2) Triplet Model. The names refer to the quadrupole configuration of the final focus lens just prior to the nozzles.

PBO-Lab computer models for the two beamline concepts were developed that included constraints on the quadrupole locations, the quadrupole field strengths, and the maximum beam sizes inside the quadrupoles. Constraints on beamline length segments before and after the vault wall were imposed using TRANSPORT’s Methodical Accelerator Description (MAD) formulation [7] of parameters via algebraic expressions. Split quadrupole models were used, with the fields of the two halves of each split quad element made identical, also using MAD algebraic expressions. Nonlinear MINOS constraints were imposed at the center of each TR3Q*i* (i=1,5) quad that the rms beam envelopes ($X_{i,rms}$, $Y_{i,rms}$) be less than 50% of the vacuum pipe radial aperture. MINOS constraints were also imposed on the maximum absolute values of the quadrupole fields, set by the acceptable power dissipation in the quad coils.

The clinical requirement of round beams at isocenter was implemented by an additional MINOS nonlinear constraint on $| X_{iso,rms} - Y_{iso,rms} |$ by requiring that:

$$-\Delta < X_{iso,rms} - Y_{iso,rms} < +\Delta \ , \tag{2}$$

where Δ is a small parameter, initially taken as 0.2 mm. The optimization procedure involved running MINOS-TRANSPORT simulations [4,9] looking for a minimum value of the *FOM*, Eq. (1), while simultaneously satisfying all of the constraints including Eq. (2). For the Doublet Model, this optimization involved 9 constrained variables (5 quad strengths, 4 distances) and 11 nonlinear constraints on beam envelopes. The Triple Model concept was similar.

The required A/B selector location, the TR3Q1 quadrupole length, the existing TR3 bending dipole (CBM1), vault wall, and the need for beam stops isolating each room

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individually, made the region of beamline between CBM1 and the A/B selector the most constrained aspect of the design. The overall configuration of this beginning of the TR3 beamline led to a preference for the Doublet Model.

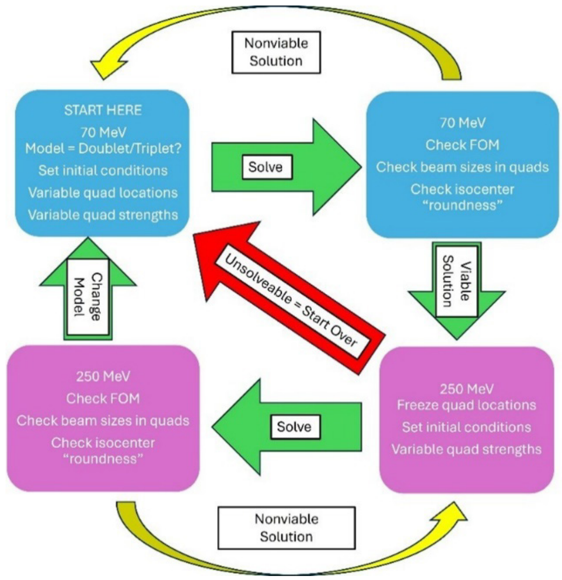

Figure 3: Optimization flow chart.

The design optimization studies proceeded as illustrated in Fig. 3. The MINOS optimization module of PBO-Lab adjusts the length and the quadrupole strength variables, for TR3B using the MPTC 70 MeV beam [4]. All upstream magnets are set to the clinical configuration for TR2 gantry 90° beam [4]. TRANSPORT results for $X_{i,rms}$ and $Y_{i,rms}$ at the quad centers, the distance parameters for the quad locations, as well as the isocenter values $X_{iso,rms}$ and $Y_{iso,rms}$, are then returned to MINOS. MINOS compares the results against the constraints, and then iterates the adjustment of the variables to seek a minimum in the *FOM* of Eq. (1). This often required several sequential runs of MINOS. MINOS is a multi-algorithmic optimizer and has several parameters used to adjust performance. Little effort was devoted to those parameters beyond the PBO Lab default values. Iterative MINOS calculations generally proved to be an acceptable alternative, and provided some insight if "solutions" appeared to be out of reasonable bounds.

Once a solution for 70 MeV was found, the study proceeded to find a solution for 250 MeV, but in this case the quadrupole location (distance) variables were removed from the problem (changed to MINOS constant parameters) and only the quadrupole strength variables were adjusted by MINOS. Of course, the upstream magnets for the clinical configuration of the 250 MeV TR2 G-90 beamline and associated beam parameters [4] were utilized for the 250 MeV optimization study. Figure 3 shows the solution schema progression of optimization from 70 MeV through 250 MeV and what variables are utilized or isolated.

ADDITIONAL CALCULATIONS

Other efforts were undertaken as part of the design work, and to support beamline commissioning. Space limitations preclude presentation of that work here, but included:

- Nozzle & air scattering calculations with TOPAS [10].
- Sensitivity studies to known beam uncertainties [4].
- Verification of solutions for both rooms A and B.
- Design verification for other beam energies.
- Model adaption to optimize power supply currents.

SUMMARY AND CONCLUSIONS

The beamline design has been used in the construction of both rooms TR3A and TR3B. To date, the TR3B beamline has been completed and tuned for all 76 clinical energies. TR3A has all magnetic components in place and has shown that the "five canonical energies" [4] can be tuned to hit isocenter with quadrupole settings similar to TR3B, indicating the A/B selector is effective and properly placed.

Innovative compact proton therapy concepts [1,3] offer the promise of greater patient access worldwide. This paper delineates the design of a new solution for a predefined space that navigates the constraints and requirements of a new treatment modality and existing clinical standards. The described beamlines will provide a new two-room treatment suite at the McLaren Proton Therapy Center constructed without disrupting clinical activities.

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