ALIGNMENT ISSUES AND TECHNIQUES FOR PROTON THERAPY CLINICS

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Abstract

The use of Protons to treat cancer tumours was first proposed by R R Wilson in 1946 [1], the first experimental treatments were done at Berkeley and Uppsala in the 1950's and Massachusetts General Hospital in 1961. Over the past 50 years, some 50 clinics are now in operation worldwide. All clinics use cyclotrons or synchrotrons to produce protons or other heavy ions. The facilities employ beam transport systems, rotating gantries and patient positioning systems. The accelerator and beam transport system use conventional alignment techniques such as laser trackers and FARO arms. Determination of isocenter and patient positioning present unique challenges.

PROTON THEARPY

When charged particles pass through tissue ionization occurs. Ionization damages the molecules especially the genetic material (DNA). Damaging the DNA destroys the ability of cells to reproduce. Enzymes develop in the cells in an attempt to repair this damage, if the damage is too extensive the injury cannot be repaired. Both normal and cancerous cells undergo this process, but cancerous cells are less likely to succeed while healthy cells can recover.

Both X rays and protons can cause damage to cells. The advantage of protons is in the Bragg peak where the protons stop in a well-defined location according to their energy hence depositing most of their energy in a few milli-meters. Whereas X Rays ionize in a linear fashion along their path.

By varying the energy of the proton beam in conjunction with the ability to sweep the beam a cancerous tumour can be treated with little damage to surrounding healthy tissues. Changing the energy leads to what is known as the Spread Out Bragg Peak SOBP figure 1. The dose is uniformly applied along the depth of the tumour while transverse and vertical scanning of the beam allows for irradiation of the entire tumour volume.

The major problem with proton therapy is the cost. While for many cancers proton therapy is more effective with less side effects the investment in equipment is significantly larger than for LINACS that generate X Rays. Pro Nova seeks to reduce upfront costs and installation time to make proton therapy more cost effective.

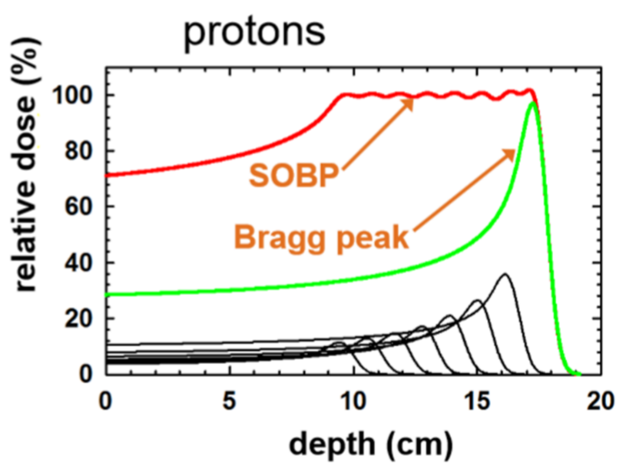

Figure 1: Spread Out Bragg Peak.

PRO NOVA FACILITIES

Pro Nova uses isochronous cyclotron to generate proton beams of up to 230 MeV with intensities of up to 300 nano-Amps. Protons are transported via conventional, permanent, and superconducting magnets to the treatment rooms. The beam energy is degraded by use of beryllium wedges in each external beamline. This allows the cyclotron to run at a constant energy and each patient treatment room to be setup independently. For the fixed energy transport permanent magnet, quadrupoles and Lambertson magnets are used. Figure 2 shows a typical layout with one fix beam room and one gantry room. Multiple rooms can be installed in any facility. Currently there are two ProNova facilities one in Knoxville Tennessee and one on Nashville Tennessee.

The beamline consists of series of trim dipoles and quadrupoles to adjust the position and focus of the beam as it leaves the cyclotron. The initial trim magnets are used in a feedback loop to compensate for position and angle

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variation of the beam emerging from the cyclotron. For each treatment room there is a fast kicker and a permanent magnet Lamberston to direct the beam into a conventional magnet achromatic bend. The total bend angle is 90 degrees. Between each room there are a series of permanent magnet quadrupoles to ensure the same spot size at each degrader.

For the fixed beam room there is a quadrupole triplet, a scanning magnet that can sweep the beam in the horizontal and vertical directions up to 25 cm, then strip ion chambers that determine the positon and intensity of the beam.

For the rotating gantry there are two superconducting achromatic bends one of 60 degrees and one of 150 degrees. Superconducting magnets are used to reduce the weight and size of the gantry. The rotating gantry can position the nozzle over 370 degrees (+185 degrees to -185 degrees).

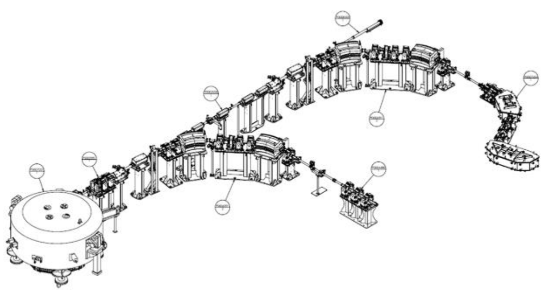

Figure 2: Layout of Pro Nova beamline.

ALIGNMENT OF THE MAGNETS

Before installation of any beamline elements a survey network is constructed in the beam vault and treatment rooms. The networks are designed and installed by outside vendors. The network at the Nashville clinic consists of 173 laser tracker nests on the wall and floor of the beam vault and treatment rooms. In addition temporary monuments are installed as needed. This would be typical for any three room installation.

The conventional dipoles, quadrupoles, trim magnets, and permanent magnets are made by various outside vendors [2]. As part of the process, the vendors measure the fiducials and reference them to the mechanical or magnet center. The program MADx [3] is used to design the beam transport. A file of magnet centers is generated by MADx. From this file and the fiducial data provided by the vendors a csv file is generated that readable by our laser tracker to locate each magnet.

All magnets have at least 4 fiducial we have standardized on the 12.7 mm shank laser tracker nests. The transverse and vertical alignment tolerance is ±0.25 mm and the station tolerance is ±1.0 mm. Installation proceeds in phases;

- Layout of stands followed by grouting.
- Rough positioning of beamline elements on the stands.
- Precision alignment of beamline elements.
- Final as founds of beamline elements.
- Final documentation that all beamline elements are within tolerance.

SUPERCONDUCTING ACHROMATS

Each gantry has two sets of superconducting achromatic bends. The first bends the beam through 60 degrees the second through 150 degrees figure 3. Both achromats consist of two dipoles one at the entrance and one at the exit with a quadrupole triplet in between. All magnets are in a common cryostat. The intent is to have a small spot size at isocenter. The magnets are pinned to two thick (50 mm) copper plates with precision holes to align each magnet. On the top copper plate are two alignment fixtures. A FARO arm is used to transfer the location of these fixtures to monuments on the outside of the cryostat.

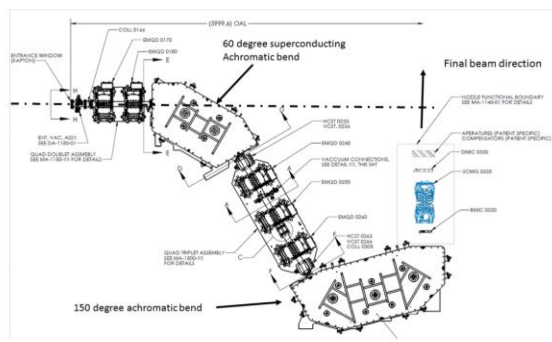

Figure 3: Gantry magnets plan view.

There are 4 tensioner posts on each of the 6 sides of the 60 degree dipole and 8 on the sides of the 150 degree achromat. During construction the tensioners are adjusted to position the cold mass to be centered on the entrance and exit flanges of the cryostat. Then the outer fiducials are used to position the cryostat on the beamline. There are no internal measurements made after the achromats are cooled to 4 Kelvin.

GANTRY ALIGNMENT

Patients are treated in the prone position. For some cancers such as prostate a fixed trajectory beam can be used and the patient rotated so that the beam can enter from either the left or right side. For more complex cases the beam may need to enter at various angles with respect to the horizontal axis. To achieve this a rotating gantry is used. The beam transport system is suspended from a frame that can rotate through 370 degrees. ProNova uses superconducting achromatic bends to reduce the weight and the size of the gantry. The beam bends through 270 degrees to ensure a focal point and small spot at the isocenter

The gantry is first assembled on a horizontal table, several laser tracker setups are used to ensure the outer rim is circular and will conform to the cradle and all the cams are set to ideal positions within 0.05 mm figure 4. Next the gantry is disassemble and rebuilt in the vertical position on the cradle at the factory.

Since the gantry can be rotated through 370 degrees the achromats and quad triplet are aligned by defining a plane in Spatial Analyser based on the center of the upstream flange of the 60 degree achromat and the downstream flange of the 150 degree achromat. This is done with the gantry at the 270 degree position (9 o'clock) using laser trackers.

It is vital that the gantry rotated concentrically around the incoming beam to minimize the need to different beamline tunes for each gantry angle. The gantry rides on a precision machined cradle set on a cast in place concrete base. There are 72 rollers around the circumference of the gantry each has to be positioned by eccentric cams such that the gantry rotates in a smooth fashion. Figure 5 shows the 8.1 meter diameter gantry as setup for testing in the factory. The beamline is in the rear with beam pointing up. The patient would be located in the center of the gantry. The 72 cams can be seen around the edge with the cradle at the bottom. Laser trackers are used to monitor the motion and adjust the cams for smooth operation.

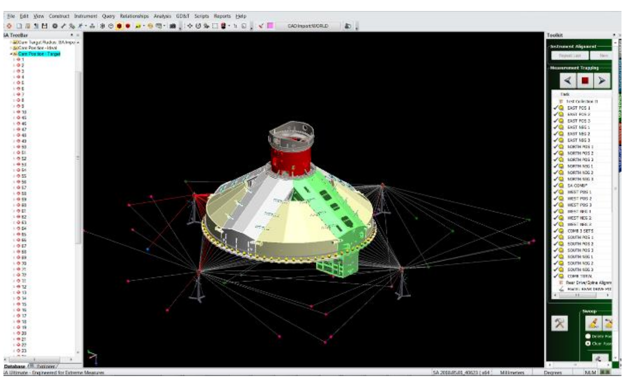

Figure 4: Alignment of the gantry on the assembly table.

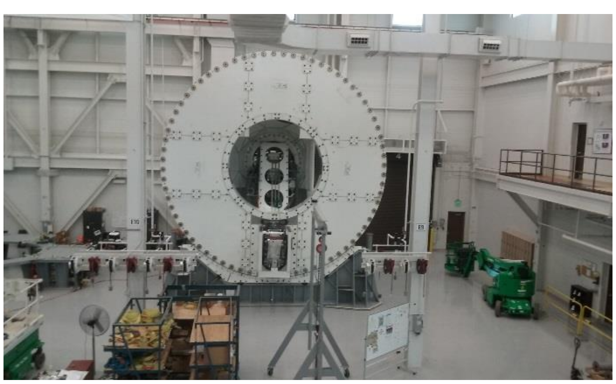

Figure 5: The rotating gantry undergoing factory testing.

After rotational checks the beamline elements, the superconducting achromatic bends a quad triplet and doublet are installed. Final rotational checks are done under full load conditions. The gantry is designed such that it can be loaded into standard shipping containers. It is disassembled and shipped to the customer site.

One of the beam tests on positional accuracy of the gantry is to perform a star shot. A piece of film is located at isocenter perpendicular to the beam. Short exposures are made at various gantry angles. The center overlap or circle of confusion shows how well the beam can intersect a tumour figure 6. Figure 7 shows the fit to the data giving the circle of confusion at ±1 mm. Further corrections can be made with the scanning magnet to reduce this error.

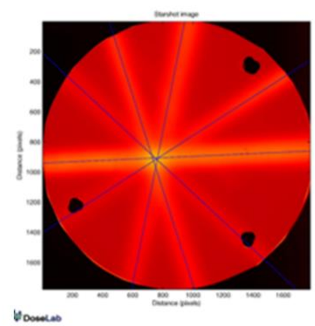

Figure 6: Star shot during gantry commissioning.

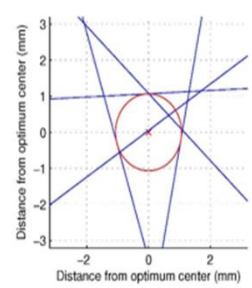

Figure 7: Fitted star shot data.

SCANNING MAGNET AND PENCIL BEAM SCANNING

Pencil Beam Scanning (PBS) sweeps the beam in the horizontal and vertical direction to "paint" the tumour with protons. The depth is controlled by changing the energy of the beam. ProNova uses a scanning magnet designed by Indiana University [4]. The magnet has two sets of coils inside a common laminations figure 8.

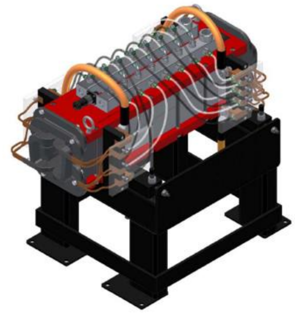

Figure 8: Scanning magnet.

The magnet is driven by an Analogic power supply [5] that can run up to 200 amps at 150 hertz. To account for the non-linearity of the field at the edges pillow corrections are made. A 25 by 25 cm scan pattern of 121 spots is generated for 15 energy ranges figure 9. The ideal pattern would have all spots equally spaced. The actual pattern is recorded on a scintillation camera. The difference from ideal for each spot is measured and the data are fitted to a 3rd order polynomial.

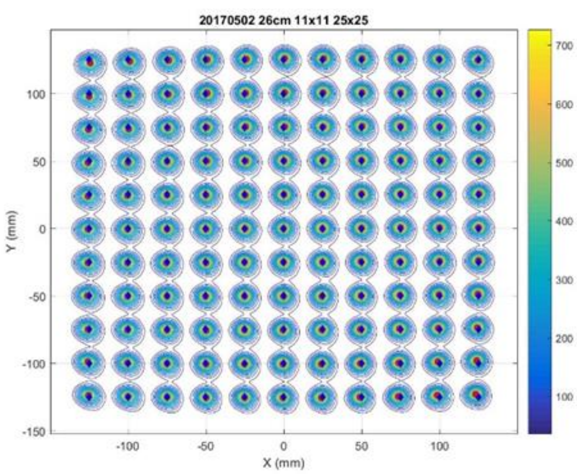

Figure 9: Spot pattern used to determine corrections.

From these data the control voltages for the scanning magnet power supply are determined. The corrections can be as large as 1.5 mm at the edges for lower beam momentum. Figure 10 shows the horizontal spot error correction for 26 cm range beam.

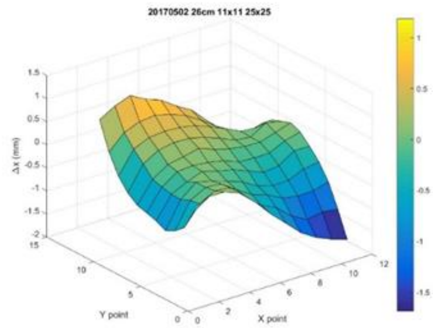

Figure 10: Horizontal spot corrections for scanning magnet.

ISOCENTER ALIGNMENT

It is important to accurately determine the isocenter that is where the beam is relative to the couch coordinates. One of the techniques is to the Niek Plastic Phantom (NPP) [6] this consists of a Lucite block with 9 2 mm diameter BBs in a rectangular array spaced 25 mm apart figure 11 and 12. The NPP is located on the couch by means of 4 precision pins to locate it relative to the couch internal coordinate system. There are 4 laser tracker nests on the base plate to allow for measurement of the NPP to room coordinates. The entire assembly was referenced using a FARO arm; all BBs are located relative to the laser tracker nests. The NPP is imaged using the cone beam Xray and then positioned such that the central BB will be at isocenter. A series of 9 beam pulses are sent through the NPP each one catered on a BB. Figure 13 shows the spot pattern and figure 14 the analysis of the central BB.

From these data and the positions of the couch the isocenter relative to the couch coordinates and room coordinates can be determined.

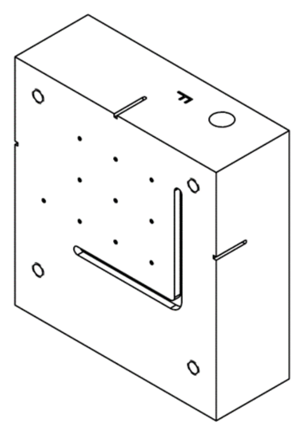

Figure 11: Niek Plastic Phantom the dots are 2 mm BBs.

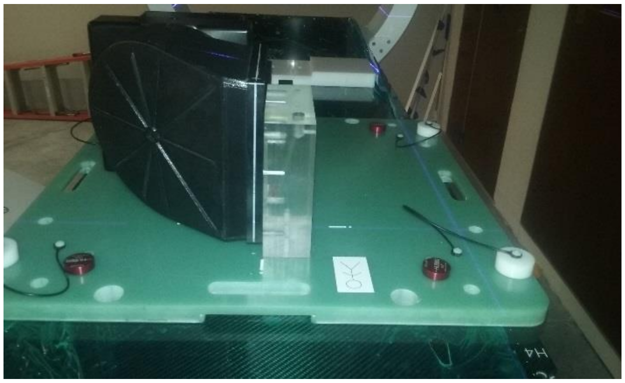

Figure 12: NPP in beam with scintillation camera.

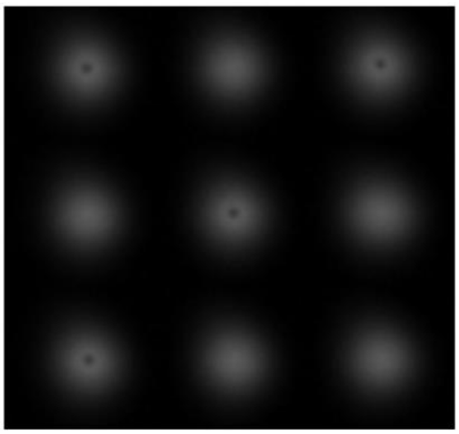

Figure 13: NPP exposed to 22 cm range beam.

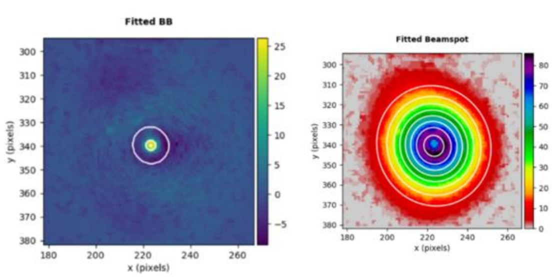

Figure 14: Fitted centers of the NPP.

The NPP data is also used to align LAP Apollo lasers [7] attached to the walls and ceiling. These lasers help to position the patient on the couch by locating the isocenter.

PATIENT POSITIONING

To achieve 1 mm accuracy in irradiating tumours it is necessary to position the patient at the isocenter. A Leoni robot [8] in conjunction with a Med Photon imaging system [9] is used. The robot can move in all 6 degrees of freedom with sub milli-meter accuracy. The Med Photon imager uses a cone beam computed tomography to locate the patient and the tumour on the bed. The patient is placed on the bed moved to the imaging position; the X ray generator and imaging panel rotate around the patient taking several hundred images that are then converted into a 3 D image to compare with a previous CAT Scan image. These are then fused using both hard and soft tissue to determine the position of the couch such that the tumour will be at isocenter.

Figure 15: Leoni robot and Med Photon imaging system.

STERO CAMERAS

The couch on the Leoni robot is made of carbon fiber for maximum strength with minimum weight. In addition, due to the low density the proton beam will transmit through the couch with minimal loss or scattering. The bed will flex due to patient weight. To correct for this four Optitrack Prime 41 [10] cameras are used. Figure 16 shows one of the Optitrack cameras and a wall-mounted laser. There are 17 reflective markers attached to the couch on the sides and underneath. The Optitrack Motive software determines the couch position from the markers and broadcasts the data over NATNET [11]. The Patient positioning system software uses these data to correct for couch sag in a correction loop with the Leoni patient positioning system. The Optitrack system is cross-calibrated with a laser tracker to determine the accuracy. The RMS accuracy of X, Y and Z has been measured to be 0.3 mm.

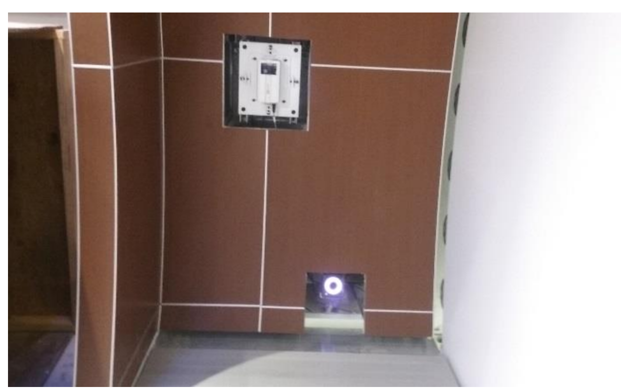

Figure 16: Lower Optitrack Prime 41 camera upper alignment laser.

Figure 17 shows the offset of the couch due to a load of 70 kilograms with no correction. Figure 18 shows the couch after sag correction.

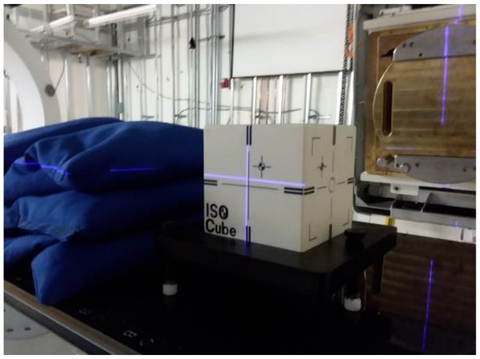

Figure 17: Couch before Optitrack correction

Figure 18: Couch after Optitrack correction.

ACKNOWLEDGMENT

The authors would like to acknowledge the hard work and dedication of the entire ProNova staff They are all responsible for bringing these concepts together in a little over 5 years.

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