# Commissioning Results of the LLUMC Beam Switchyard and Gantry*

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*Abstract*

Results from the commissioning of the LLUMC beam switchyard and gantry are described. Measurements of the beam profile at numerous locations are compared with model predictions for three energies. On the basis of the beam profile and magnetic measurements, the extracted beam emittance and Twiss parameters are determined.

## I. INTRODUCTION

The medical accelerator for proton therapy at the Loma Linda University Medical Center utilizes an extensive beam switchyard to transport the proton beam to different treatment areas. The medical accelerator facility, described in detail elsewhere[1-3] is being commissioned in two phases. Phase 1 includes a stationary beam treatment room with two treatment beam lines and a rotatable isocentric gantry treatment line, as shown in Figure 1. Results from commissioning of this Phase 1 beam switchyard are described herein. Phase 2 will include two additional gantries and a stationary beam room whose optics are essentially identical to that described here. The optics of the Phase 1 beam switchyard have been demonstrated at three proton energies 100, 155 and 200 MeV. The beam emittance has been determined from measurements of the magnets and the beam profile at various locations.

## II. DISCUSSION

### A. *System Description*

The optics system of the LLUMC discussion switchyard begins at the electrostatic extraction septum of the medical accelerator where the extracted beam is created through half integer resonant extraction from the synchrotron. The extracted beamlet continues to make another orbit before it is sufficiently displaced horizontally from the circulating beam so that it may be vertically deflected by -10° out of the ring by a Lambertson septum magnet. The beam is subsequently deflected by +20° and -10° by two small dog leg magnets so that it may be transported horizontally at a nominal height of 36 inches from the floor.

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The beam is aligned and focused on a set of multi-wire ion chamber's (MWIC) specifically developed for the Loma Linda beam switchyard. The MWICs consist of two sets of horizontal and vertical wires with one millimeter spacing to simultaneously measure the beam profiles in both transverse planes.

Three quadrupole doublets with MWICs located between them are used to transport the beam to the 90° bend towards gantry 1. When the two 45° dipoles which comprise this 90° bend are energized the beam is directed towards gantry 1. Subsequent focusing in two additional doublets transport the beam to gantry 1. MWICs are located between these two doublets and at the entrance to the gantry.

The optics design of the rotating gantry is based upon the corkscrew geometry developed by a Harvard-MGH-MIT[4] consortium. The beam is first transported through a 90° achromatic bend. This bend consists of four quadrupole magnets sandwiched between two 45° dipole magnets. The

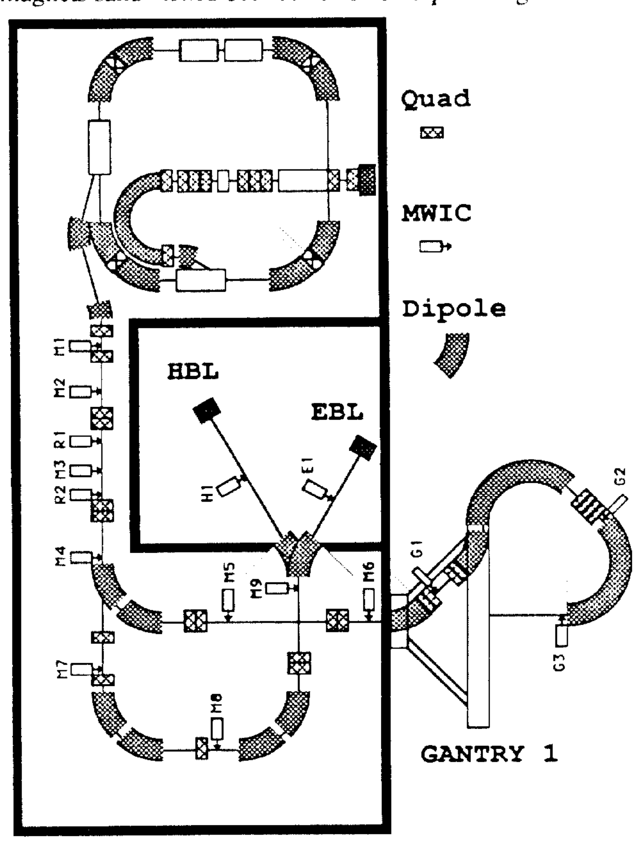


Figure 1. Loma Linda Accelerator and Beam Transport

angle of this bend with respect to the incident trajectory is continuously adjustable through ±180°. The beam is then transported through 270° in a second achromat whose bend plane is perpendicular to both the first achromat and the incident direction of motion. This achromat consists of four quadrupole magnets sandwiched between two 135° dipole magnets. The beam is thus directed to intersect with the axis of rotation of the gantry allowing for irradiation from any angle in a plane. MWICs are located in the middle of each achromatic bend as well as at the exit of the second 135° dipole as shown in Figure 1. The gantry structure was designed by SAIC[5] and each achromat is aligned to±.010 inches with an overall alignment tolerance of better than ± .020 inches.

When the switchyard dipoles, which direct the beam to gantry 1 are de-energized, the beam passes through the return yoke of the first 45° dipole and may be transported through 180° to the stationary beam room or allowed to pass into the remainder of the switchyard.

The 180° bend into the stationary beam room consists of four identical 45° dipoles with a single quadrupole at the midpoint to adjust the chromaticity. A subsequent quadrupole doublet provides focusing to control the spot size a the beginning of the treatment beam line. A small dipole magnet with a special bipolar power supply then allows the operator to select the specific treatment station in this room. The two treatment lines in this room, eye beam line (EBL) and horizontal beam line (HBL), have been commissioned in the past year.

Numerous trim steering dipoles and intensity monitors (transmission ion chambers and Faraday cup) are located throughout the beam switchyard in addition to the MWICs shown in Figure 1. The MWICs and other intercepting monitors are only inserted into the beam line for tuning purposes and then removed. Fixed MWICs are located at the beginning of each treatment line to continuously monitor the beam profile during irradiation.

The treatment room that receives the beam is controlled by a high current selector switch which determines the specific treatment room to which the beam is delivered. Redundant safety features and interlocks govern the operation of this high current switch. The switch thus provides important safety features and also minimizes the quantity of high current power supplies required. Two additional switches provide power to the two types of gantry dipoles.

### B. *Measurements and Analysis*

The beam profile was measured at each of the MWIC locations shown in Figure 1 for each energy and treatment station. The EBL is restricted to 100 MeV. The primary function of the MWICs is to provide diagnostic information on the beam centering in the vacuum channel in order to prevent losses. The losses in the beam transport were measured to be significantly less than 5% of the extracted beam. This fact coupled with the high extraction efficiency (>90%) and small acceleration losses results in very small amounts of induced radioactivity in the machine components.

The MWICs are integrated into the accelerator control system with typical output as shown in Figure 2. The horizontal and vertical profiles shown here represent a single pulse observed at the entrance of one of the treatment lines. Each wire corresponds to one millimeter and is read out individually on a pulse to pulse basis. The variation in the spot size and centroid within a pulse may also be recorded.

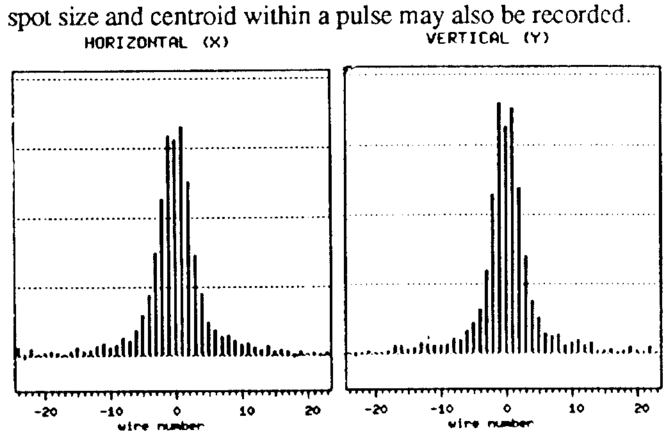

Figure 2. Typical MWIC horizontal and vertical profiles

Spot size measurements taken at three locations separated by a drift space (R1, M3, R3) may be used to determine the beam emittance as described by Jacobs, et. al.[6]. Difficulties in the measurements arise when the beam is dispersive (the dispersion of the extracted beam is 9 meters in this region) and due to the finite resolution of the MWICs. To overcome these difficulties the optics of the beam switchyard were modeled using TRANSPORT[7]. The beam profile at each MWIC could then be predicted on the basis of the beam line layout and magnetic measurements of the magnets. The starting point for the transport modeling was chosen to be the electrostatic extraction septum.

The beam spot, divergence and phase ellipse orientation of the beam in both transverse planes were allowed to vary in order to obtain the best fit to the measured beam profiles. This analysis was performed for beam energies of 100, 155 and 200 MeV in the HBL. The results of this measurement are presented in Table 1. The emittances presented correspond to 95% of the beam (± 2$\sigma$).

The energy dependence is due to many competing factors. The effect of the sextupole and octupole in the synchrotron and the multiple fields of the dipoles play a major role. The relative strength of the transverse momentum as the energy is increases also a factor. A code which models extraction from the Loma Linda synchrotron was developed at FNAL. The results presented here for the horizontal emittance are consistent with the predictions of this code when most of the multipole fields in the ring are corrected for TRANSPORT predictions for the measured spot size (1$\sigma$) are compared with the data in Figure 3. As shown in this figure the agreement is excellent. The typical difference between the predictions and data for the FWHM of the spot is less than 0.5 mm.

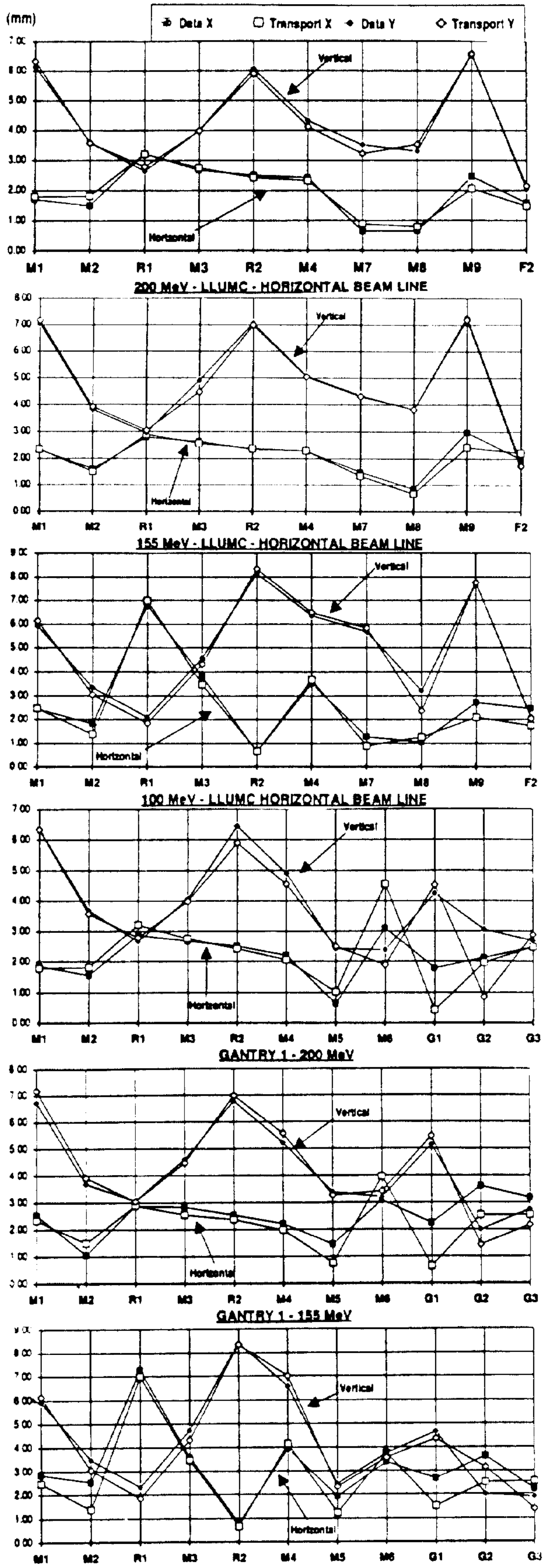


Figure 3. Comparisons between measurements and TRANSPORT predictions

Table 1
Beam Emittance (unnormalized)

| Energy [MeV] | 100 | 155 | 200 |
|---|---|---|---|
| $\varepsilon_x$ [$\pi$(mm-mrad)] | 3.56 | 2.56 | 2.44 |
| $x_o$ [mm] | 6.64 | 6.2 | 4.70 |
| $\theta_o$ [mrad] | 0.64 | 0.46 | 0.54 |
| $r_{12}$ | 0.55 | 0.43 | 0.25 |
| $\varepsilon_y$ [$\pi$(mm-mrad)] | 12.08 | 14.32 | 10.00 |
| $y_o$ [mm] | 6.60 | 5.8 | 5.2 |
| $\phi_o$ [mrad] | 2.82 | 2.86 | 2.30 |
| $r_{34}$ | -.76 | -.50 | -.55 |

The beam emittance and phase ellipse orientation were fit to the data for the horizontal beam line. This input was then used to develop the optics and field strengths for the gantry. This allowed the beam to be transported through the gantry with >95% transmission at three energies in a single shift on only the second shift of operations. Similar results were obtained at other gantry angles. The 100 MeV EBL results are essentially identical to the 100 MeV HBL results.

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