BEAM BASED STEERING IN THE LANSCE PROTON LOW ENERGY BEAM TRANSPORT*

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Abstract

Beam based alignment is widely used in both high-energy accelerators and beam transfer lines to minimize beam emittance growth. It is important to preserve beam quality in Low-Energy Beam Transport (LEBT) to reduce beam losses in the subsequent accelerator cavities. At LANSCE, the 750-keV protons produced from the source injector are transported 10 meters in LEBT to the Drift Tube Linac (DTL). This region uses 22 quadrupoles, 6 steering magnets, 2 bending magnets, a prebuncher and main buncher combination, a beam deflector and some collimators. Matching of the beam with the transport structure requires beam waists at the entrance of the RF cavities and in the middle of the beam deflector. It is also necessary for the beam Twiss parameters to be matched at the entrance of the DTL. Typical relative beam emittance growth in beamline was observed at the level of 2-2.5. A beam based steering procedure was implemented to minimize emittance growth in the beamline. It included the determination of beam offset and beam angle upon entering a group of quadrupoles, which requires a subsequent correction of beam centroid trajectory to minimize beam offset. Application of this procedure resulted in significant reduction of emittance growth.

750-keV PROTON BEAM TRANSPORT

The H^+ beam injector contains a duoplasmatron proton source mounted at 750 keV Cockroft-Walton accelerating column and a low-energy beam transport line (LEBT). The 750-keV LEBT (see Figs. 1, 2) consists of a quadrupole lattice, 81° and 9° bending magnets, RF prebuncher, main buncher, diagnostics and steering magnets for preparation of the beam injection into the DTL. Beam emittance measurements at 750 keV are performed at three slit-collector locations - TAEM1, just after the Cockroft-Walton column, TAEM2, after pre-buncher and TDEM1, before the entrance to the DTL. Additionally, there are three harps (TAHP1-3) used for control of the beam profile. They are located close to the slit positions of each emittance station. The quadrupole lattice starts with six quadrupoles (TAQL1-TAQL4) before the emittance station TAEM1. The two quadrupole doublets TAQL5_1-2 and TAQL6_1-2 and a 81° bending magnet match the beam in front of the prebuncher (creating a beam waist with transverse size of 0.4 cm). The quadruplet TAQL7_1-4 matches beam to the ground level deflector. The TAQL8_1-4 quadruplet creates a beam waist in front of the main buncher, with transverse beam size of 0.4 cm. TDQL4_1-4 matches the beam to drift tube linac. The LEBT includes five steering magnets

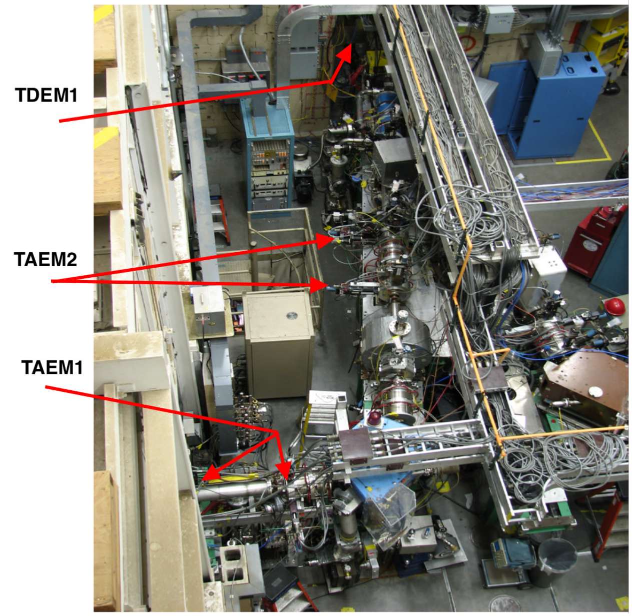

Figure 1: Layout of 750-keV proton Low Energy Beam Transport of LANSCE linear accelerator.

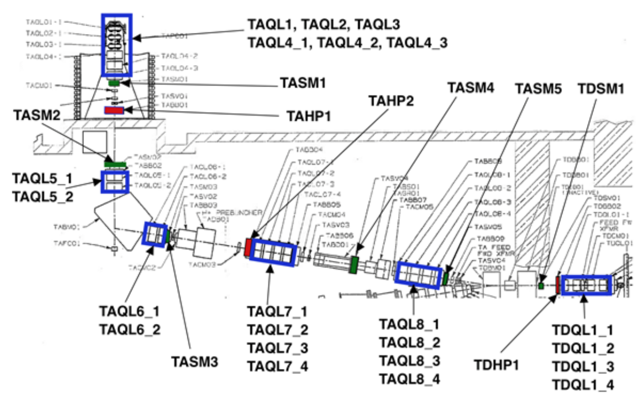

Figure 2: Focusing structure of 750-keV proton LEBT.

TASM1-5 and the common steering magnet TDSM1 (shared with the H^- beam).

BEAM BASED ALIGNMENT

The well-established procedure for beam-based alignment utilizes multiple measurements of the beam centroid position and the solution of the resultant matrix to determine the offsets of the magnets, beam position monitors (BPM) and beam centroids [1]. Recent beam alignments in the accelerator facility performed by the LANSCE Mechanical Team produced comprehensive

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ISBN 978-3-95450-182-3

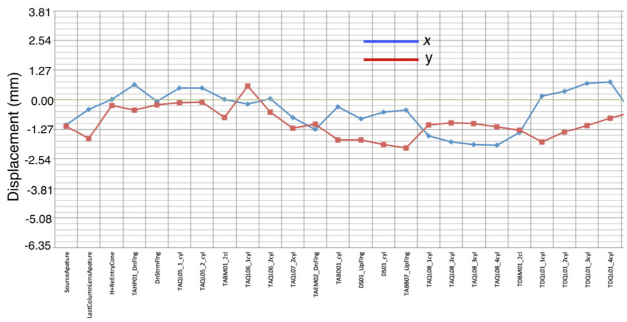

Figure 3: Measured misalignment of proton LEBT beamline elements.

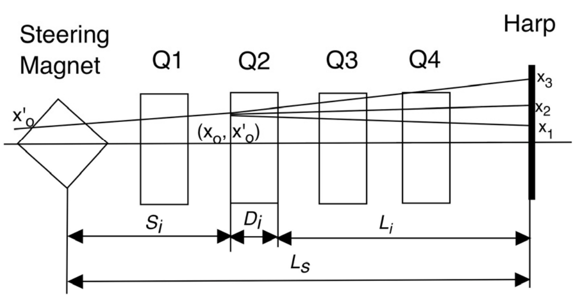

Figure 4: Determination of beam offset and beam angle at a quadrupole.

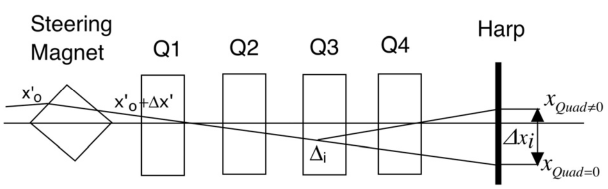

Figure 5: Minimization of beam offset in a sequence of quadrupoles.

data for the misalignment of accelerator facility components. Figure 3 illustrates this misalignment for the magnets of the proton low-energy beam transport line. Most of components have mutual displacement within ±1 mm. The purpose of the present study is to determine the beam offset in quadrupole lenses and select steering magnets to minimize it.

This beam steering procedure was applied subsequently to portions of the beamline containing combinations of quadrupoles preceded by a steering magnet and a harp to monitor the beam centroid (see Fig. 4). Because only single steering magnet is used for beam-based alignment in a group of quadrupoles, the procedure is applied to steer the beam in a selected (usually central) quadrupole with subsequent verification of steering effect in the whole collection of quadrupoles. Initial setup required all magnets to be off in the region being evaluated. To determine beam offset and beam angle at the entrance of a selected quadrupole, the value of the quadrupole field was varied from zero up to a point were visible displacement of the beam could be seen on the measurement device. Dynamics of the beam centroid at the entrance of quadrupole on to the measurement device is determined by the product of the quadrupole and drift space matrices:

$$\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} = \begin{pmatrix} 1 & L_i \\ 0 & 1 \end{pmatrix} \begin{pmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{pmatrix}, \quad (1)$$

where Q_{ij} are elements of the quadrupole matrix (focusing or defocusing), and L_i is the distance from selected quadrupole to the measurement device (see Fig. 4). Taking three measurements at three different values of the quadrupole field, one gets the system of equations:

$$x_1 = a_{11}(1)x_o + a_{12}(1)x_o^{'} + \delta x \quad (2)$$

$$x_2 = a_{11}(2)x_o + a_{12}(2)x_o^{'} + \delta x \quad (3)$$

$$x_3 = a_{11}(3)x_o + a_{12}(3)x_o^{'} + \delta x, \quad (4)$$

where observed values of beam centroid displacements x_1, x_2, x_3 depend on the offset of the measurement device with respect to quadrupole axis, δx. Taking the difference between measurements $\Delta x_1 = x_2 - x_1$ and $\Delta x_2 = x_3 - x_2$,

$$\Delta x_1 = [a_{11}(2) - a_{11}(1)]x_o + [a_{12}(2) - a_{12}(1)]x_o^{'}, \quad (5)$$

$$\Delta x_2 = [a_{11}(3) - a_{11}(2)]x_o + [a_{12}(3) - a_{12}(2)]x_o^{'}, \quad (6)$$

one gets the system of equations to determine beam offset and centroid angle, x_o, $x_o^{'}$, which are independent on the measurement device offset:

$$x_o^{'} = \frac{\Delta x_2[a_{11}(2)\text{-}a_{11}(1)] - \Delta x_1[a_{11}(3)\text{-}a_{11}(2)]}{[a_{11}(2)\text{-}a_{11}(1)][a_{12}(3)\text{-}a_{12}(2)]\text{-}[a_{11}(3)\text{-}a_{11}(2)][a_{12}(2)\text{-}a_{12}(1)]} \quad (7)$$

$$x_o = \frac{\Delta x_1 - [a_{12}(2) - a_{12}(1)]x_o^{'}}{a_{11}(2) - a_{11}(1)}. \quad (8)$$

Calibration of steering magnets is performed through two measurements of the beam centroid at the measurement device x_{1s}, x_{2s}, while changing the current of the steering magnet ΔI_{sm}, and keeping all quadrupoles off. Strength of steering magnet is determined by

$$k = \frac{(x_{2s} - x_{1s})}{L_s \cdot \Delta I_{sm}} \quad [rad/A] \quad (9)$$

where L_s is the drift length from the steering magnet to measurement device (see Fig. 4). The steering kick only compensates beam offset at a certain quadrupole:

$$\Delta x' = -\frac{x_o}{S_i}, \quad (10)$$

where S_i is the distance from the steering magnet to selected quadrupole. This offset is affected by beam misalignments in preceding quadrupoles. The value of $\Delta x'$ has to be eventually corrected to provide minimum beam offsets in a group of quadrupoles (see Fig. 5). The change of steering magnet current to get a desired kick is given by $\Delta I_{sm} = \Delta x'/k$.

The final step is verification of beam offset in each quadrupole. After selection of steering magnet kick, the field in each quadrupole was varied from zero until displacement is seen. All downstream quadrupoles were kept off. This process began with the quadrupole nearest to the steering magnet and was repeated until the last quadruple before measurement device. Beam offset in *i*-th quadrupole is given by

$$\Delta_i = \frac{(x_{Quad\neq0} - x_{Quad=0})}{D_i L_i \Delta G_i} \left(\frac{mc\beta\gamma}{q}\right), \quad (11)$$

where $\Delta x_i = x_{Quad\neq0} - x_{Quad=0}$ is the variation of beam centroid at measurement device, ΔG_i is the change in quadrupole gradient and D_i is the quadrupole length. Equation (11) is the thin-lens approximation of Eq. (8). The "zero quadrupole steering" corresponds to the minimal value of rms variation of the beam centroid position among all *N* quadrupoles:

$$\Delta = \frac{1}{N}\sqrt{\sum_{i=1}^{N}\Delta_i^2}\,. \quad (12)$$

BEAM BASED ALIGNMENT IN THE PROTON BEAMLINE

The described procedure was used to provide beam based steering of the low-energy proton beam transport. The first six quadrupoles (TAQL1–TAQL4) after the 750-keV Cockroft-Walton accelerating column are not preceded by a steering magnet. Variation of field gradients in these quadrupoles did not result in any significant variation of the beam centroid. Centering of the beam began with the quadrupole doublet TAQL5_1, TAQL5_2 in front of the 81° bending magnet.

Beam based alignment of quadruple TAQL5_1 started with determination of beam offset in TAQL5_1. Quadrupoles TAQL5_1, TAQL5_2, TAQL6_1, TAQL6_2 were powered off. Beam centroid variation was observed at harp TAHP02, while gradient at TAQL5_1 was varied from zero to 46 Gauss/cm. It resulted in change of beam centroid at harp Δx = 0.147 cm, Δy =-0.153 cm. Change of matrix elements Δa_{11_x} = 0.3098, Δa_{11_y} = -0.3736, Δa_{12_x} =1.63x10^{-3} cm/mrad, Δa_{12_y} = -2.03x10^{-3} cm/mrad were determined using TRACE code [2]. Incoming beam slopes x_o' =1.717 mrad, y_o'=2.366 mrad, were determined from beam emittance scans. The values of the beam offset at the entrance of TAQL5_1 using equation (8) are:

Table 1. Normalized rms beam emittance (π mm mrad).

Emittance Station	Before Steering (Horizontal/Vertical)	After Steering (Horizontal/Vertical)
TAEM1	0.02 / 0.02	0.03 / 0.02
TAEM2	0.05 / 0.05	0.02 / 0.02
TDEM1	0.04 / 0.07	0.03 / 0.04

$$x_o = \frac{\Delta x - \Delta a_{12\_x} \cdot x_o'}{\Delta a_{11\_x}} = 0.465\,cm, \quad (13)$$

$$y_o = \frac{\Delta y - \Delta a_{12\_y} \cdot y_o'}{\Delta a_{11\_y}} = 0.396\,cm\,. \quad (14)$$

Calibration of steering magnets was done preliminary. The average value of the steering magnets strength was around k = 1.2 mrad/A. The distance from steering magnet TASM01 to quadrupole TAQL5_1 was S_i = 163.251 cm. Therefore, the required kick from steering magnet TASM01 to compensate beam offset at quadrupole TAQL5_1 was:

$$\Delta x' = -\frac{x_o}{S_1} = -2.85\text{ mrad}, \quad \Delta y' = -\frac{y_o}{S_1} = -2.42\text{ mrad}\,. \quad (15)$$

Minimization of beam offset in next quadrupole doublet TAQL6_1, TAQL6_2 was performed with variation of the field for bending magnet TABM01 and the subsequent determination of beam offset in each quadrupole. The value of vertical steering TASM01_V kick was corrected to - 3.6 mrad to provide minimum beam offset in quadruplet TAQL5 - TAQL6.

This method was applied in the rest of beam transport to determine the required steering. Steering magnet TASM3 was used to align beam in quadruplet TAQL7_1-4. Subsequent quadruplet TAQL8 was off and TAQL7 was retuned to provide 100% beam transmission until harp TDHP1. After that, steering TASM4 was used to steer beam in quadruplet TAQM8. Determined setup of low-energy beam transport provided significantly smaller beam emittance growth (see Table 1). Operation of the beam within 2015 - 2017 run periods with different beam specifications indicated that required beam steering changed slightly, while the proton beam current and quadrupole setup were varied significantly.

ACKNOWLEDGEMENTS

The author is grateful to the LANSCE Mechanical Team for providing the key alignment necessary for this analysis. Author is indebted to Charles Taylor for careful reading of manuscript and providing multiple useful comments.

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