# BEAM-BASED ALIGNMENT MEASUREMENTS OF THE LANSCE LINAC*

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*Abstract*

We have made measurements of the alignment of the Los Alamos Neutron Science Center (LANSCE) Drift Tube linac (DTL) and Side Coupled linac (SCL) using beam position measurements and analyzing them with linear models. In the DTL, we varied the injection steering and focusing lattice strengths, measured the beam position after each DTL tank, and analyzed the data with a linear model using R-matrices that were either computed by the Trace-3D computer program or extracted from analysis of the data. The analysis model allowed for tank-to-tank misalignments. The measurements were made similarly in the SCL, where the analysis model allowed for misalignments of each quadrupole doublet lens. We present here the analysis techniques and the resulting beam-based alignment measurements.

## INTRODUCTION

The LANSCE linac accelerates protons and $H^-$ ions from 750keV to 100MeV in a DTL and to 800MeV in an SCL. During beam operations, the presence of misalignments became apparent. During short (<1 day) accelerator development periods we used the particle beams to make measurements of the relative misalignment of the focusing elements in both the DTL and the SCL. These data were intended to supplement data from optical instruments that require more time, preparation and access to the beam tunnels.

Measurements of beam positions were made with profile monitors, as no beam position monitors are available in the areas of interest. To facilitate these measurements, a smaller emittance, 1mA peak beam was used.

## DTL ALIGNMENT MEASUREMENTS

The DTL consists of four tanks. The drift tubes contain quadrupole magnets for transverse focusing of the beam. We can measure the beam position and angle at the entrance and exit of the DTL and the beam position between each pair of tanks. Two types of measurements were made: 1) We varied the position and angle of the injected beam and measured the effect on the beam position and angle downstream; 2) We varied the strength of the quadrupole magnets in the drift tubes and measured the effect on the beam position and angle downstream. The assumptions of the analysis models are: 1) The focusing lattice within each of the tanks is straight, 2) No x-y coupling is present, 3) A linear beam optics model is valid.

Suppose the beam is injected into the DTL with measured injection position and angle ($x_0,\theta_0$) and that there is a misalignment ($\delta_{0,1},\phi_{0,1}$) between the injection measurement system and tank 1. The position of the beam as it exits tank 1 of the DTL will be:

$$x_1 = R_{11}\left(x_0 + \delta_{0,1}\right) + R_{12}\left(\theta_0 + \phi_{0,1}\right) + \delta_1 \qquad (1)$$

where $\delta_1$ is an offset in the measurement and $R_{mn}$ is the $(m,n)^{th}$ element of the transport matrix[1] from the injection point through DTL tank 1 to the beam position measurement device. This equation can be applied to both the vertical and horizontal planes. A set of such equations can be formed by making $N$ measurements of $x_1$ with different injection parameters or with different focusing lattice strengths (which varies the R-matrix elements.) To determine the misalignment parameters and measurement offset, the set of equations can be written in the form $A{\cdot}x=b$ where $A$ is an $N\times3$ matrix, $b$ is a vector of the $N$ measurements and $x$ is the vector of the three quantities to be estimated. This over-determined matrix equation can be solved by a variety of techniques; we employed the method of singular value decomposition. (See, for example, reference [2].)

When the injection parameters are varied, the matrix equation is:

$$\begin{bmatrix} R_{11} & R_{12} & 1 \\ R_{11} & R_{12} & 1 \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} \delta_{0,1} \\ \phi_{0,1} \\ \delta_1 \end{bmatrix} = \begin{bmatrix} x_1(1) - R_{11}x_0(1) - R_{12}\theta_0(1) \\ \vdots \\ x_1(N) - R_{11}x_0(N) - R_{12}\theta_0(N) \end{bmatrix}$$

When the focusing lattice strength is varied, the matrix is equation is:

$$\begin{bmatrix} R_{11}(1) & R_{12}(1) & 1 \\ \vdots & \vdots & \vdots \\ R_{11}(N) & R_{12}(N) & 1 \end{bmatrix} \begin{bmatrix} \delta_{0,1} \\ \phi_{0,1} \\ \delta_1 \end{bmatrix} =$$

$$\begin{bmatrix} x_1(1) - R_{11}(1)x_0 - R_{12}(1)\theta_0 \\ \vdots \\ x_1(N) - R_{11}(N)x_0 - R_{12}(N)\theta_0 \end{bmatrix}$$

(The indices in parentheses indicate the measurement number.) The R-matrix elements can computed using a model of the DTL and the Trace-3D computer program[3], however for tank 1 we were able to extract the values of the R-matrix elements from the data.

One cannot distinguish the three fit parameters by varying the injection alone since each produces a constant offset in the measurements. These measurements can be useful when combined with those taken when the focusing lattice strength is varied.

For measurements of the beam position made downstream of DTL tanks 2, 3 and 4 additional terms for tank-to-tank misalignments must be included in Equation 1. The beam position measured downstream of tank $j$ will be:

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$$x_j = R_{11}^{\;0\to j} x_0 + R_{12}^{\;0\to j}\theta_0 + \sum_{i=0}^{j-1}\left(R_{11}^{\;i\to j}\delta_{i,i+1} + R_{12}^{\;i\to j}\phi_{i,i+1}\right) + \delta_j$$

where $R_{mn}^{\;i\to j}$ is the (m,n)$^{th}$ component of the transport matrix from the beam position measurement device downstream of tank $i$ to that downstream of tank $j$ (with $i$=0 indicating the injection area,) ($\delta_{i,i+1}$,$\phi_{i,i+1}$) are the misalignment offset and angle between tanks $i$ and $i+1$, and $\delta_j$ is the offset in the measurement device downstream of tank $j$.

### *Measurement of R-matrix Elements*

The analysis model for the misalignment measurements relies on our ability to calculate the transport matrix elements through the DTL tanks; we were especially concerned about our ability to accurately calculate the transport matrices in tank 1 since the focusing by the accelerating field is strongest in this tank due to the low kinetic energy (<5MeV) of the beam. Because we measure the position and angle of the beam at the injection into tank 1 and the position at the exit, we can measure $R_{11}^{\;0\to 1}$ and $R_{12}^{\;0\to 1}$, the R-matrix elements from the injection through tank 1, by making measurements with $N$ settings of the injection parameters and solving a matrix equation of the following form:

$$\begin{bmatrix} x_0(1) & \theta_0(1) & 1 \\ \vdots & \vdots & \vdots \\ x_0(N) & \theta_0(N) & 1 \end{bmatrix} \begin{bmatrix} R_{11} \\ R_{12} \\ c \end{bmatrix} = \begin{bmatrix} x_1(1) \\ \vdots \\ x_1(N) \end{bmatrix}$$

where the constant $c$ is the constant offset produced by the misalignment and the measurement offset.

Table 1: Comparison of measured and calculated transport matrix elements for $H^-$ beam through DTL tank 1

| | Measured | Calculated |
|---|---|---|
| $R_{11}$ | +0.9 ±0.2 | +0.7 ±0.2 |
| $R_{12}$ (mm/mrad) | +0.00 ±0.06 | +0.15 ±0.05 |
| $R_{33}$ | +0.9 ±0.2 | +1.1 ±0.2 |
| $R_{34}$ (mm/mrad) | +0.10 ±0.01 | +0.07 ±0.05 |

The uncertainties shown for the calculated values reflect the effect of small changes to the accelerating fields in the model.

Because of additional uncertainties in the calculated values of the transport matrix elements, we used these measured values in the analysis of the misalignment data.

### *Measurements of Tank-to-Tank Misalignments*

The results of the beam-based tank-to-tank misalignment measurements are shown in Table 2. We did not get a good measurement of the misalignment between tanks 1 and 2 because of the uncertainty in computing the transport matrix elements through tank 1. (We couldn't measure all that were required for the analysis, namely $R_{21}$ and $R_{43}$, because there is no way to measure the beam angle between these two tanks.)

Ultimately we will compare these beam-based measurements with optical survey data. We have recently acquired a laser tracker and associated tooling for this purpose, and measurements are in progress.

Table 2: Beam-based misalignment measurements of the DTL

| Parameter | Beam-Based Measurement |
|---|---|
| Horizontal $\delta_{0,1}$ | –0.8 ±0.5 mm |
| Horizontal $\phi_{0,1}$ | +6.4 ±1.5 mrad |
| Vertical $\delta_{0,1}$ | +1.7 ±0.2 mm |
| Vertical $\phi_{0,1}$ | +0.6 ±1.5 mrad |
| Horizontal $\delta_{2,3}$ | +0.9 ±0.1 mm |
| Horizontal $\phi_{2,3}$ | –1.3 ±0.2 mrad |
| Vertical $\delta_{2,3}$ | +0.4 ±0.1 mm |
| Vertical $\phi_{2,3}$ | –0.5 ±0.1 mrad |
| Horizontal $\delta_{3,4}$ | –3.6 ±0.2 mm |
| Horizontal $\phi_{3,4}$ | +0.6 ±0.1mrad |
| Vertical $\delta_{3,4}$ | +0.7 ±0.1mm |
| Vertical $\phi_{3,4}$ | +0.9 ±0.1 mrad |

### *Sources of Errors and Improving the Measurements*

The uncertainty in the actual distribution of the accelerating fields in the DTL complicate the calculation of the transport matrices, especially where the beam energy is low. Making the measurements with the accelerating fields turned off could make these calculations more reliable, however the focusing lattice strength would need to be changed drastically from the operational condition since the un-accelerated beam is not stable in the normal lattice.

One assumption in the model for these measurements is that each tank of the DTL is straight, i.e. that the magnetic centers of all of the quadrupole magnets lie on a line. Tanks 2, 3 and 4 are each 15 to 20m long and mechanically supported at locations between the two ends. Bending moments produced by these supports or by thermal gradients in the structures could distort the magnetic axis and render this assumption invalid. Additionally, random or other systematic misalignments of the drift tubes within a tank could render this assumption invalid. One could determine a lower limit on the straightness by attempting to find a beam trajectory upon which no beam deflection occurs as the quadrupole strengths are varied; we have not yet made this measurement.

## SCL ALIGNMENT MEASUREMENTS

The SCL at LANSCE accelerates beams from 100MeV to 800MeV. The focusing lattice consists of quadrupole doublets between each pair of accelerating tanks. We wished to measure the misalignment offsets of the quadrupole doublets, i.e. misalignment angles were not considered.

When a beam that is traveling at a position and angle specified by ($x_{in}$,$\theta_{in}$) relative to the reference trajectory traverses a quadrupole doublet whose center is displaced by a distance δ from the reference trajectory, the beam exiting the doublet will travel as specified by:

$$x_{out} = \left(R_{11}{}^{Q} x_{in} + R_{12}{}^{Q}\theta_{in}\right) + \delta(1 - R_{11}{}^{Q})$$

$$\theta_{out} = \left(R_{21}{}^{Q} x_{in} + R_{22}{}^{Q}\theta_{in}\right) - \delta R_{12}{}^{Q}$$

where the R-matrix elements $R_{mn}{}^{Q}$ are those from the entrance to the exit of the quadrupole doublet. The measured position of the beam at location *j* after passing through *M* such doublets will be:

$$x_j = x_0 R_{11}{}^{0\to j} + \theta_0 R_{12}{}^{0\to j}$$
$$+ \sum_{i=1}^{M} \delta_{Q(i)} \left[R_{11}{}^{Q(i)\to j}(1 - R_{11}{}^{Q(i)}) - R_{11}{}^{Q(i)\to j} R_{11}{}^{Q(i)}\right]$$
$$+ \delta_j$$

The sum is over all quadrupole doublets upstream of the measurement location. As before, $\delta_j$ is the offset in the measurement device and ($x_0$,$\theta_0$) are the injection parameters. The transport matrix elements $R_{mn}{}^{Q(i)}$ and $R_{mn}{}^{Q(i)\to j}$ are those from the entrance to the exit of the doublet, and from the exit of the doublet to the beam position measurement location respectively. $R_{mn}{}^{0\to j}$ is the transport matrix element from the injection point to the $j^{th}$ beam position measurement device. The accelerating fields were turned off during these measurements in order to enable more reliable calculation of the transport matrices.

One can make measurements of beam positions in the linac with several sets of injection parameters, create an over-determined set of linear equations and solve the equations for the quantities of interest, namely the $\delta_{Q(i)}$'s and $\delta_j$'s. However a system of equations where only the injection parameters are varied does not allow one to distinguish misalignments from measurement offsets; one must vary the quadrupole strengths.

A data set, where the beam injection alone was varied, is in hand. In future beam development periods we will collect data with variations in the focusing lattice strength.

## SUMMARY

One can make measurements of DTL tank-to-tank misalignments and of the misalignments of the individual quadrupole doublets in an SCL using particle beams. Because these measurements are made with the beam itself, they are an essential complement to optical measurements.

In order to distinguish between component misalignments and offsets in the measurements one needs to make measurements with various settings of the focusing lattice strength. Varying the beam injection steering reduces the uncertainties in the measurements and allows direct measurement of the transport matrix elements that are required in the analysis of the data.

The ability to accurately calculate transport matrices through the DTL was a limiting factor in the analysis presented here. Making the measurements with the accelerating fields turned off, as was done in the SCL, would reduce the uncertainty in the calculation, but this requires extensive manipulation of the focusing lattice strength, and thus a great deal more time. Additionally it may change the effective centerline of the tank since the defocusing of the accelerating fields would be removed.

## REFERENCES


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