HARMONIC ANALYSIS OF LINAC ALIGNMENT

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Abstract

An analysis is being performed of the requirements on alignment of the focusing elements (quadrupole doublets) in the Los Alamos Neutron Science Center (LANSCE) side coupled linac. The analysis is performed in terms of harmonics of the quadrupole spacing. This allows one to determine the effect of intentional deviations from a straight line, such as following the curvature of the Earth, and of unintentional deviations introduced by measurement and alignment errors.

INTRODUCTION AND MOTIVATION

Recent measurements indicate that the accelerating components (side-coupled tanks) and focusing components (quadrupole doublet (QD) lenses) of the LANSCE side coupled linac (SCL) are misaligned[1]. The misalignment has caused difficulty in optimizing the tune-up of the accelerator for single-species (H^- ions) operations and this difficulty is likely to be much worse when we resume dual-species (H^+ and H^-) 800MeV operations in the near future. Moving the accelerating structures is difficult and risky because of the numerous mounting fixtures and the knife-edge vacuum seals between the tanks and bridge couplers, so we will attempt to find a compromise alignment solution that allows us to move only the QD lenses without moving the focusing axis too far from that of the accelerating structures. Additionally, the accelerator axis must bend to align with the beam switchyard. The following issues must be addressed when specifying requirements for the alignment solution:

- How gentle must the bends of the focusing axis be?
- How do errors introduced by station moves of the laser tracker alignment system affect the beam?
- To what tolerance must the QD lenses follow the ideal alignment solution?

These questions have prompted an analysis of the alignment in harmonic terms.

FORMULATION OF THE ANALYSIS

For a lattice of N QD lenses, the position $x(n)$ (i.e. the transverse distance from the axis) of QD lens n is expressed as a Fourier sine series:

$$x(n) = \sum_{m=1}^{N-2} a_m \sin\left(\frac{m\pi(n-1)}{N-1}\right)$$

The expansion is carried out in terms of the QD lens number instead of in longitudinal position because the focusing lattice cell length varies by a large amount, whereas the phase advance per cell varies slowly over a small range. The sine series requires that one transform the coordinate system to place the first and last QD lenses on the axes. Since two of the QD lenses lie on the axes, the number of modes m required to fully describe the system is $N-2$.

The goal is to specify alignment criteria in terms of the modes m.

QUANTIFYING THE EFFECTS OF THE MODES OF MISALIGNMENT

Because of the variation of the phase advance per cell, a computational, rather than an analytical, approach has been taken in the analysis. We used a TRACE [2] model of the SCL, and focused attention on the behavior of H^+ ions in the horizontal plane. The behavior of H^- ions and behavior in the vertical plane should be very similar.

The recent alignment data were available for only the first 56 QD lenses (of the 103 total,) so attention was restricted to this region of the linac.

This analysis lends itself only to transverse offsets of the QD lenses only; pitch and yaw angles have not been considered. Also, horizontal-vertical coupling has been ignored here.

The quantities of interest here are the maximum excursion of the beam center from the reference axis (x_{max}) and from the centers of the QD lenses (ξ_{max}.) Presumably long wavelength, large amplitude modes are intentional as part of compromises in the alignment solution; in this case ξ_{max} would be of greater interest. For short-wavelength, small amplitude modes, such as those introduced by pointing errors of the optical alignment instruments, x_{max} is a more germane quantity.

One could also consider the RMS deviations, as these might reflect the integrated effect in terms of beam losses or radio-activation of beamline components.

EFFECTS OF THE MODES OF MISALIGNMENT

The severity of the effect of a mode is expressed in a dimensionless way as x_{max} or ξ_{max} per unit amplitude of the mode. The data in the model of the linac were manipulated to offsett the QD lenses, then the beam is traced through the model, keeping track of the maximum beam excursions. For the studies presented here, the beam injection is always aligned along the reference axis. We have made some attempts to optimize the injection, by minimizing ξ_{max} for example, but we have not obtained satisfactory results.

The spectra of effects thus obtained are shown in Figure 1. The spectra of x_{max} and ξ_{max} are very similar. There is a broad peak near m=20 and pronounced dips at m=23 and m=44. As expected, the effects are relatively weak for small mode numbers, where the beam can follow the slow variations, and for large mode numbers, where the variations are fast.

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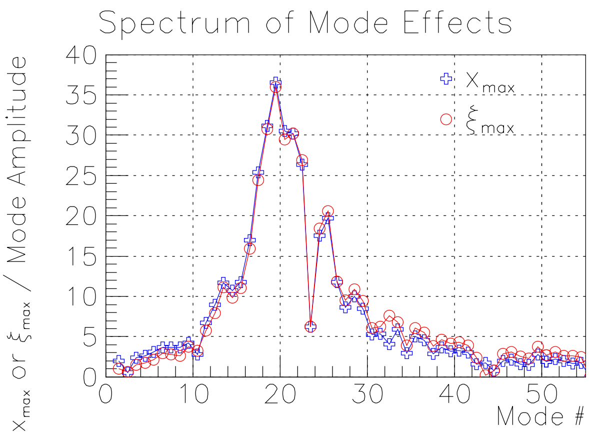

Figure 1: The effects, in terms of x_{max} and ξ_{max} as defined in the text, of the various modes *m* of misalignment.

The peak near *m*=20 can be attributed to the fact that the frequencies of these modes are similar to the frequency of the natural betatron motion of the beam.

We suspected at first that the width of the peak was due to the variation of the phase advance per lattice cell. This would indicate that the analysis could be very sensitive to small changes to the strengths of the individual QD lenses. To investigate this possibility, we constructed a model of a beamline with no acceleration and a constant phase advance per lattice cell, and performed the same analysis as for the real beamline. The result is shown in Figure 2.

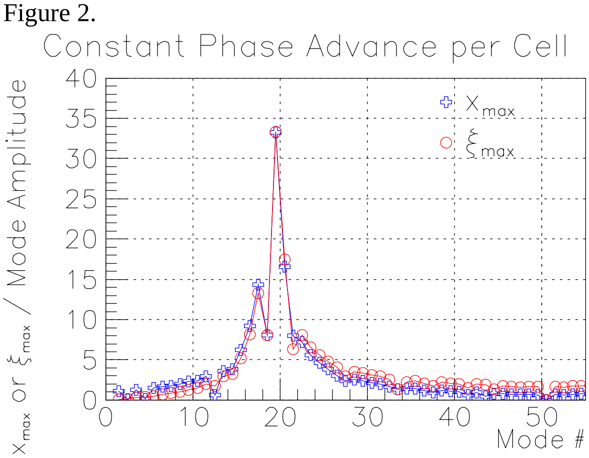

Figure 2: The spectra of effects of the misalignment modes in a hypothetical beamline with a constant phase advance per cell.

Again, there is a peak with considerable width near *m*=20. This indicates that the width of the peak in Figure 1 is not due to variations in the phase advance per cell. Figure 2 also shows interesting dips at *m*=12, 18, 21, and 50. These have not been investigated.

ADDING THE EFFECTS OF MODES

Many modes will be present in a realistic alignment solution, so it is important to understand how the effects of the modes add. As a first step, the beamline model was run with the QD lenses displaced according to the sum of two modes. The amplitudes of the each pair of modes were identical and both sign combinations were analyzed. The result is shown in Figure 3.

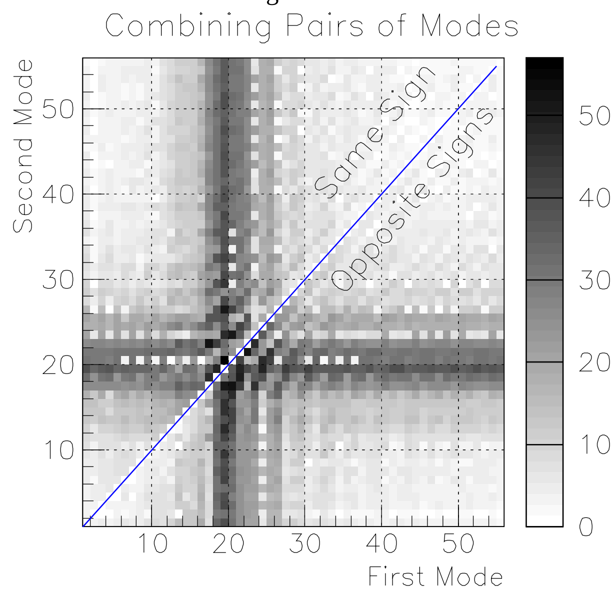

Figure 3: The spectrum of effects (x_{max} / mode amplitude) of combinations of pairs of misalignment modes. The modes had identical amplitudes. The upper left half shows the effect of adding the modes with the same sign and the lower right half shows the effect of adding the modes with opposite signs.

Again, there is a strong peak near *m*=20. The signs of the mode amplitudes don't seem to have a strong effect overall. There appear to be some cancellations. This is shown in Figure 4, which is a horizontal slice of the 2-D histogram above, and shows the effect of combining mode *m*=20 with other modes. The cancellations of effects show up for several even-numbered modes between 6 and 36.

How the effects of more than two modes add have not been investigated

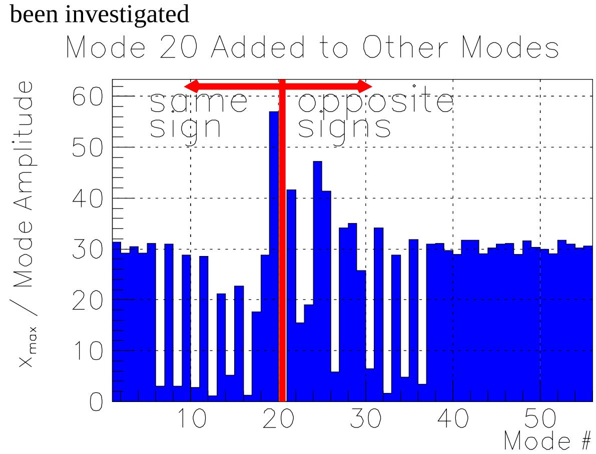

Figure 4: The effects of combining mode 20 with other modes.

HARMONIC SPECTRA OF RECENT ALIGNMENT DATA

The positions of the QD lenses were measured during the summer of 2004 using a laser tracker[1]. These data have been analyzed to extract the harmonic spectra of misalignments; these are shown in Figure 5.

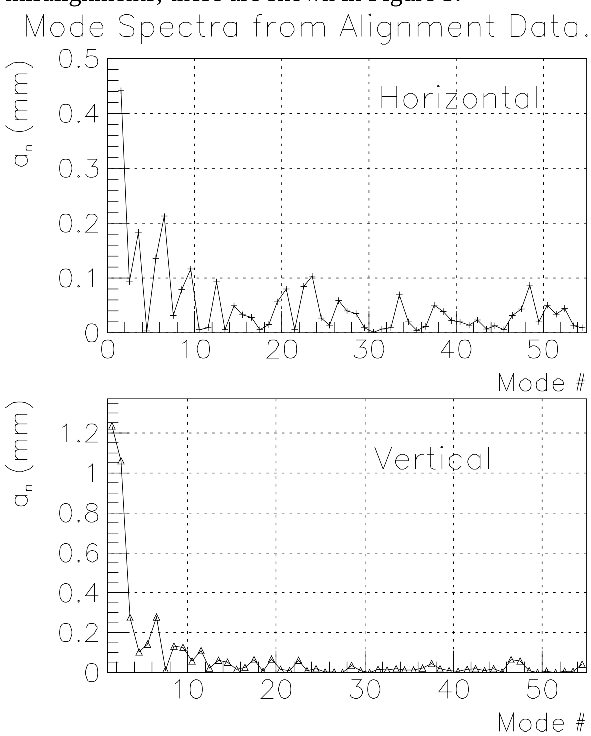

Figure 5: Harmonic spectra (horizontal and vertical) of the measured misalignments of the first 56 QD lenses in the LANSCE linac.

The effects of the measured misalignments can be estimated by multiplying, bin-by-bin, the spectra in Figure 5 by the effect of each mode as shown in Figure 1. This is shown in Figure 6. This shows the effect, in terms of the maximum beam excursion from the focusing axis, of each misalignment mode if it were present without the other modes. Again, how these effects add is still under investigation.

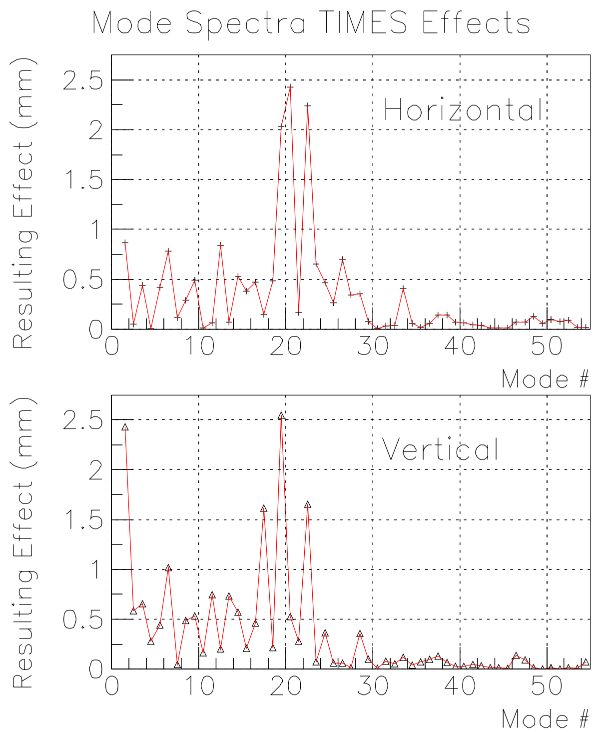

Figure 6: The bin-by-bin product of the misalignment mode spectra (from Figure 5) and the spectrum of mode effects (Figure 1) for the recent measurements of the LANSCE linac.

SUMMARY AND FURTHER WORK

An investigation of the effects of misalignments of the focusing elements in the LANSCE linac in terms of a Fourier sine series is underway in an attempt to specify requirements on alignment tolerances and on compromise alignment solutions. As expected, slow variations in the focusing axis and very rapid variations produce small effects. Variations with frequencies comparable to the natural betatron frequency produce strong effects on the beam.

Further work is required on the following issues:

- How the effects of the individual modes add.
- What modes are introduced by station moves of the laser tracker alignment system.
- Analysis of data from alignment solutions that were operationally satisfactory in the past.

Finally, we must translate this information into a set of requirements for use by the alignment team personnel.

REFERENCES

[1] L. Rybarcyk and B. Bergmann, Laser Tracker Alignment Data, 2004, Unpublished.

[2] K. R. Crandall, D. P. Rusthoi, Documentation for TRACE: An Interactive Beam-Transport Code, LA-10235-MS, UC-32, 1985