EFFECT OF LATTICE MISALIGNMENTS ON BEAM DYNAMICS IN LANSCE LINEAR ACCELERATOR*

Y. K. Batygin†, S. S. Kurennoy, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

Accelerator channel misalignments can significantly affect beam parameters in long linear accelerators. Measurements of misalignments of the LANSCE linac lattice elements were performed by the Mechanical Design Engineering Group of the Los Alamos Accelerator Operations and Technology Division. In order to determine effect of misalignment on beam parameters in the LANSCE linac, simulations of high-energy part of LANSCE linear accelerator were performed including measured displacements of quadrupoles and accelerating tanks. Effect of misalignments was compared with those due to beam space charge and distortion of RF field along the channel. Paper presents results of simulation and comparison with experimental data of beam emittance growth along the machine.

LANSCE ACCELERATOR FACILITY

Los Alamos Linear Accelerator consists of 201.25 MHz Drift Tube Linac (DTL) accelerating particles from 0.75 MeV to 100 MeV, and 805 MHz Side-Coupled Linac (CCL), accelerating particles from 100 MeV to 800 MeV (see Fig. 1). The accelerator facility is equipped with two independent injectors for H^+ and H^- beams, merging at the entrance of a 201.25-MHz Drift Tube Linac. The DTL accelerates the two beams to 100 MeV. After the DTL, the Transition Region (TR) beamline directs the 100-MeV proton beam to the Isotope Production Facility (IPF), while the H^- beam is accelerated up to the final energy of 800 MeV in an 805- MHz Coupled Cavity Linac. The H^- beams, created with different time structures by a low-energy chopper, are distributed in the Switch Yard (SY) to four experimental areas: Lujan Neutron Scattering Center, Weapon Neutron Research Facility (WNR), Proton Radiography Facility (pRad), and Ultra-Cold Neutron Research Facility (UCN). The goal of this study is to evaluate effect of measured misalignments of the LANSCE linear accelerator on beam emittance growth, and to compare the effect of misalignments with other phenomena affecting beam degradation including beam space charge and RF field distortion in accelerating tanks.

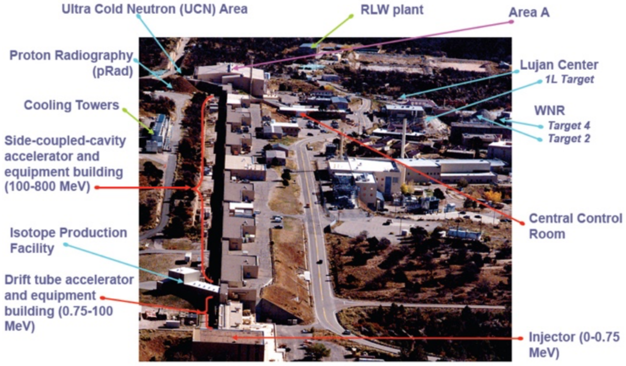

Figure 1: Layout of Los Alamos accelerator facility.

Table 1: Normalized Transverse RMS Beam Emittance in Linac (π cm mrad)

Beam (Facility)	0.75 MeV	100 MeV	800 MeV
H^- (Lujan/pRad/UCN)	0.022	0.045	0.07
H^- (WNR)	0.028	0.058	0.124
H^+ (IPF), DTL only	0.005	0.026	

BEAM EMITTANCE GROWTH AND MISALIGNMENT MEASUREMENTS

Beam emittance in LASNCE accelerator is controlled by multiple emittance measurement stations. Emittance of the beam with energy up to 100 MeV is measured using the slit-collector method. There are seven beam emittance measurement stations in the Low-Energy Beam Transport, and three stations after DTL. At the energy of 800 MeV, beam emittance is determined through measurement of beam sizes at various locations utilizing wire scanners, while emittance is recalculated using a matrix method.

Beam emittance in LANSCE accelerator facility experiences significant growth (see Table 1). The main sources of beam emittance growth and beam losses in the linac are mismatch of the beam with the accelerator structure, variation and instabilities of accelerating and focusing fields, transverse-longitudinal coupling in the RF field, misalignments and random errors of accelerator channel components, field nonlinearities of focusing and accelerating elements, beam energy tails from un-captured particles, particle scattering on residual gas and intra-beam stripping, non-linear space-charge forces of the beam, excitation of high-order RF modes. An extensive experience in beam dynamic simulations and understanding of LANSCE beam physics was achieved with previously developed models of beam dynamics in LANSCE accelerator. Results of simulations are summarized in Refs. [1, 2].

Among all phenomena affecting the beam, the impact of misalignment of LANSCE beam channel on beam dynamics has not been studied systematically. Laser tracker measurement of misalignment of the accelerating channel was performed within 2011-2015 by Claude Conner and coworkers of the LANSCE AOT Mechanical Design Group (see Fig. 2) [3]. Measured data were translated into

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* Work supported by US DOE under contract 89233218CNA000001
† batygin@lanl.gov

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transverse displacement and slopes of each accelerating tank, and displacement of quadrupole doublets between tanks (see Fig. 3 and Fig. 4). Results indicate significant deviation of axes of accelerator in x- and y- directions with random variation of positions of accelerating and focusing elements around axis. The misalignment data in DTL are limited because positions of quadrupole lenses inside drift tubes are unavailable. The numerical study of effect of misalignment was performed in high-energy Coupled Cavity Linac, which consists of 104 tanks grouped into 44 accelerating modules (modules 5-48), separated by focusing quadrupole doublets.

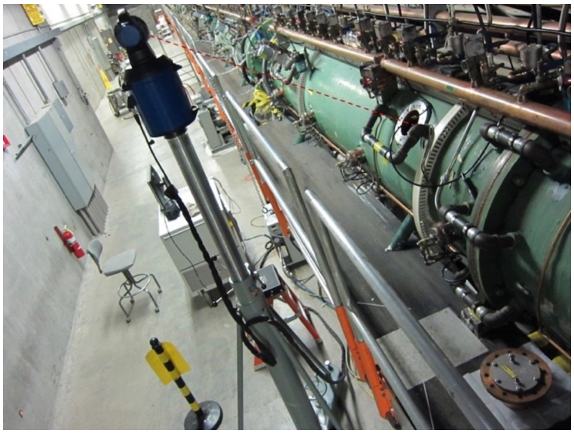

Figure 2: Setup for misalignment measurements of Drift Tube linac through the fixed slug tuner ports [3].

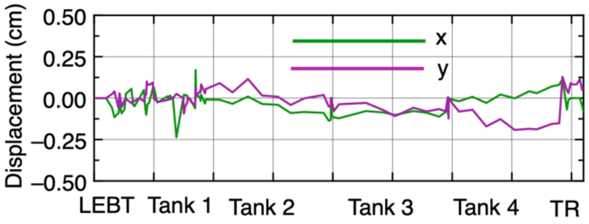

Figure 3: Measured misalignments of lattice components in LEBT, 201.25 MHz Drift Tube Linac, and Transition Region (TR).

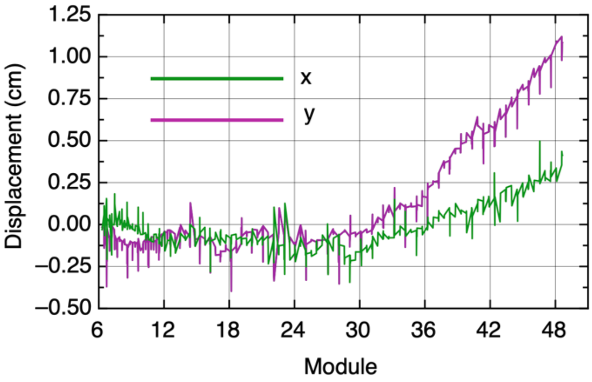

Figure 4: Measured misalignments of lattice components in the 805 MHz Coupled Cavity Linac.

SIMULATION OF BEAM DYNAMICS WITH LATTICE MISALIGNMENT

Effects of lattice misalignment were simulated with the code Beampath [4]. Modeling was performed taking into account displacements and tilts of accelerating tanks, displacements of quadrupole lenses with ideal linear fields, and 1997 measurement data on RF field gradients in tanks (see Fig. 5). Values of quadrupole gradients were selected to be historically averaged for every lens. Position of each accelerating tank was measured with initial (x_{in}, y_{in}) and final (x_{out}, y_{out}) offsets (see Fig. 6). The axes of tanks determined in the laboratory system are

$$x_{axis} = x_{in} + \alpha_x (z - z_{in}), \quad y_{axis} = y_{in} + \alpha_y (z - z_{in}), \tag{1}$$

where α_x, α_y are slopes of the axes:

$$\alpha_x = (x_{out} - x_{in}) / L, \quad \alpha_y = (y_{out} - y_{in}) / L, \tag{2}$$

and L is the tank length. The particle position in the misaligned tank, $(\tilde{x}, \tilde{y}, \tilde{z})$, is connected with that in laboratory system (x, y, z) as

$$\tilde{x} = x - x_{axis}, \quad \tilde{y} = y - y_{axis}, \quad \tilde{z} \approx z. \tag{3}$$

Taking into account the values of slope angles are small, $\alpha_{x,y} \sim 10^{-4}...10^{-5}$, one can assume in the first order approximation that $\cos\alpha_{x,y} \approx 1$, $\sin\alpha_{x,y} \approx \alpha_{x,y}$, and the components of the RF electric field determined in misaligned frame are related to that in laboratory system as

$$E_x \approx \tilde{E}_x + \alpha_x \tilde{E}_z, \; E_y \approx \tilde{E}_y + \alpha_y \tilde{E}_z, \; E_z \approx \tilde{E}_z - \alpha_x \tilde{E}_x - \alpha_y \tilde{E}_y, \tag{4}$$

while components of transverse RF magnetic field in the same point can be assumed unchanged, $B_x \approx \tilde{B}_x$, $B_y \approx \tilde{B}_y$. The initial beam parameters were selected to be those of a matched beam. Initial values of transverse beam Twiss parameters, $\alpha_x = 1.239$, $\beta_x =$ 5.56 m, $\alpha_y = 0.337$, $\beta_y =$ 3.29 m are determined by CCL lattice structure [5]. Experimental determination of longitudinal beam emittance in the accelerator was performed through measurement of the longitudinal beam size after Tank 3 in the DTL at a beam energy of 70 MeV, and measurement of momentum spread

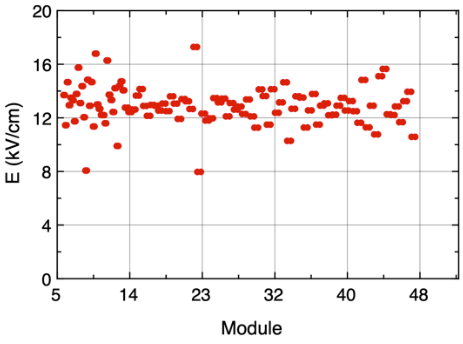

Figure 5: RF field amplitudes in CCL linac.

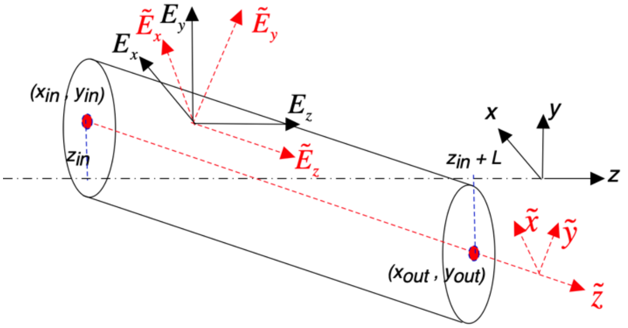

Figure 6: Simulation of field components in the misaligned accelerating tank.

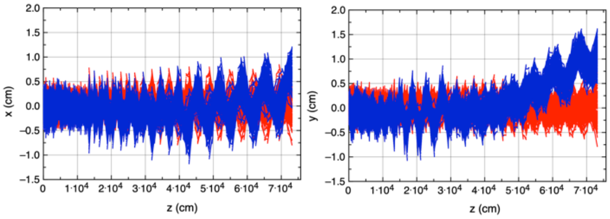

Figure 7: Particle trajectories in CCL lattice: (red) neglecting misalignment, (blue) including misalignment.

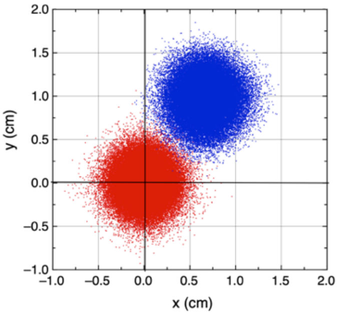

Figure 8: 800 MeV beam spot in CCL lattice: (red) neglecting misalignment, (blue) including misalignment.

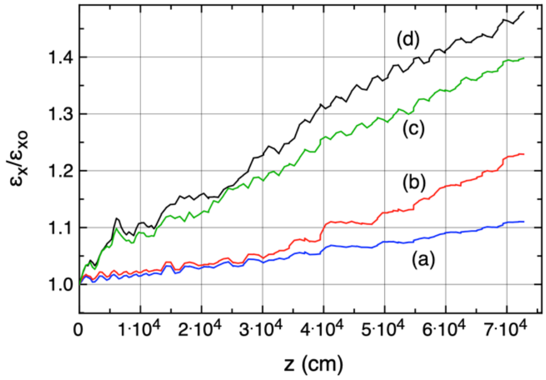

Figure 9: Beam emittance growth along CCL linac: (a) neglecting misalignment, beam current, and RF amplitude variation (b) including misalignment and neglecting beam current and RF amplitude variation, (c) including misalignment, and beam current $I = 10\,\text{mA}$, neglecting RF amplitude variation, (d) including misalignments, RF amplitude variation, and beam current $I = 10\,\text{mA}$.

of the 800-MeV beam in a high-dispersive point of high-energy beam transport. The typical value of the phase length of the bunch at 70 MeV is 7° on 201.25 MHz scale, and that of the 800 MeV beam momentum spread is $\Delta p / p \approx 10^{-3}$. Due to adiabatic damping of phase oscillations in a linear accelerator, the momentum spread is changing as $\Delta p / p \sim \beta^{-5/4}\gamma^{-1/4}$. A combination of the beam size and momentum spread gives an estimate of the longitudinal normalized beam emittance at 70 MeV as $\varepsilon_z = 4\varepsilon_{z\_rms}$ = 0.7 π-cm-mrad with matched longitudinal beam radius R_z = 5.9 mm, and beam half-momentum spread, $p_\zeta / mc = 1.26\cdot 10^{-3}$ at the entrance of CCL. The typical value of H^- bunched beam current in the operation of LANSCE linac is I = 10 mA. Space charge depression parameters of transverse and longitudinal oscillations under this value of beam current are μ_t / μ_s = 0.8, μ_z / μ_{zo} = 0.9, correspondingly, and weakly affect zero-intensity matching parameters.

Figure 7 illustrates the difference in transverse beam trajectories in the CCL channel with or without lattice misalignments. As seen, misalignments result in a noticeable mismatch of the beam with the accelerating channel and in the displacement of the beam from the base axis (see Fig. 8). Figure 9 illustrates beam emittance growth versus various factors determining the expansion of the beam phase space volume. The effect of misalignments is compared with that of beam space charge, and measured RF amplitude variation in CCL linac. Figures 9a – 9c are obtained assuming accelerating field gradient is constant along accelerator, E = 13 kV/cm, while results presented in Fig. 9d take into account variation of RF amplitudes presented in Fig. 5. Experimentally observed beam emittance growth in CCL linac is estimated as 50% (see Table 1, first row). Simulations show, that contribution of misalignment in beam emittance growth based on available measured data is around 10%, while other factors (space charge, RF amplitude beam distortion) have a comparable or larger effect on beam emittance.

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