ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP012

BEAM-BASED MEASUREMENT OF LCLS-II INJECTOR SOLENOID MISALIGNMENTS*

A. Osman†, T. Maxwell, F. Zhou
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Abstract

Solenoid focusing is commonly used in accelerators for electron-beam containment and to compensate for space-charge induced emittance growth at low beam energies. However, misalignment between the solenoid field and the beam trajectory can result in degraded emittance compensation due to orbit kicks, dispersive effects, and non-linearities in the magnetic field profile. This paper presents a technique for beam-based measurement of solenoid misalignments, using expressions derived from a hard-edged solenoid linear transfer matrix with known beam parameters. The results of measurements conducted at the LCLS-II injector are presented as a validation of this method, along with simulation studies that estimate the impact of solenoid misalignments on emittance growth.

INTRODUCTION

The LCLS-II injector features a low-power RF photocathode gun, two solenoids, and an RF buncher (see Fig. 1), which prepare the electron beam for injection into the main linear accelerator [1]. At these early stages, the low energy beam is particularly susceptible to emittance growth due to space-charge forces. Solenoid magnets are used both to confine the beam and to compensate for emittance growth [2, 3].

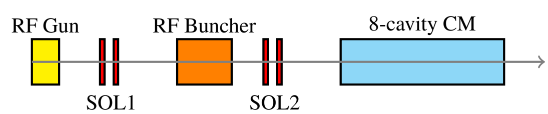

Figure 1: Schematic of injector layout showing RF gun, solenoids (SOL1, SOL2), buncher, and 8-cavity SRF cryomodule.

Table 1: Beam and Solenoid Parameters (Hard-Edged)

Parameter	Value
Beam momentum (p)	1.03 MeV/c
Maximum B_0	0.074 T
Effective length (L)	0.21 m
Larmor rotation angle (θ_L)	2.26 rad
Effective focal length (f)	41 mm

Precise alignment of the beam trajectory through the solenoids is crucial to achieving low final emittance. Misalignments introduce orbit kicks and dispersive effects that compromise beam quality. The effects of higher-order magnetic field terms, commonly referred to as geometric aberration, also become more pronounced at larger radial distances from the magnetic axis [3-5].

In this paper, we develop a beam-based method for measuring solenoid misalignments. By fitting the beam deflection at a downstream beam position monitor (BPM) as a function of solenoid field, we extract the transverse offsets and angles of the incoming beam relative to the solenoid magnetic axis. This requires knowledge of the beam energy, drift length to the measurement BPM, and accurate magnetic measurements of the solenoid.

We also present simulation results that estimate the impact of solenoid misalignments on transverse emittance growth in the LCLS-II injector.

SOLENOID MODELING AND TRANSFER MATRIX FORMALISM

The LCLS-II injector solenoids exhibit approximately Gaussian on-axis magnetic field profiles, as shown in Fig. 2. Nonetheless, the effect of the solenoid on the trajectory of the beam can be effectively modeled using a hard-edged solenoid transfer matrix. Spatial separation between the solenoid and RF fields is important for this approximation, although in principle this limitation can be overcome with further modeling (see Ref. [5]).

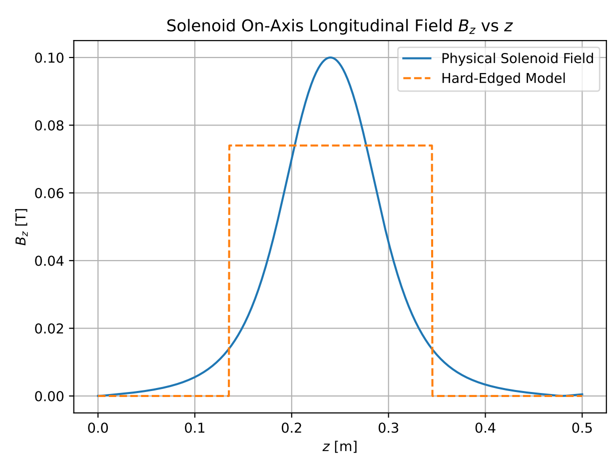

Figure 2: Comparison of measured solenoid field profile with equivalent hard-edge model used for linear beam dynamics modeling.

The transfer matrix for an ideal hard-edged solenoid of length L and a uniform longitudinal field B_0, acting on a particle with momentum p, can be expressed as [6]:

* Work supported in part by US Department of Energy contract number DE-AC02-76SF00515.
† aosman@slac.stanford.edu

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP012

$$M_{\text{sol}} = \begin{bmatrix} c^2 & \frac{sc}{k} & sc & \frac{s^2}{k} \\ -ksc & c^2 & -ks^2 & sc \\ -sc & -\frac{s^2}{k} & c^2 & \frac{sc}{k} \\ ks^2 & -sc & -ksc & c^2 \end{bmatrix}$$

where $c = \cos(kL)$, $s = \sin(kL)$, and $k = \frac{eB_0}{2p}$ is the solenoid focusing strength.

The beam momentum can be determined using the solenoid itself (for example, as described in Ref. [7]). Another method is to compare the solenoid field strength that minimizes beam size on a downstream profile monitor with beam-dynamics simulation, such as IMPACT-T or ASTRA.

To ensure that the hard-edge approximation accurately models the physical solenoid, we match their effective focal strengths and Larmor rotation angles. This requires choosing appropriate values for the solenoid length L and field strength B_0 such that [8]:

$$\theta_L = \int_{\text{solenoid}} \frac{eB_z(z)}{2p}\,dz = \frac{eB_0}{2p}L$$

$$\frac{1}{f} = \int_{\text{solenoid}} \left(\frac{eB_z(z)}{2p}\right)^2 dz = \left(\frac{eB_0}{2p}\right)^2 L$$

Where θ_L is the Larmor rotation angle, f is the effective focal length, and $B_z(z)$ is the on-axis longitudinal field of the physical solenoid.

Following Ref. [6], the appropriate hard-edge solenoid parameters B_0 and L can be calculated from the integrated on-axis field profile of the physical solenoid. In our matrix formalism, we set:

$$B_0 = \frac{\int B_z(z)^2\,dz}{\int B_z(z)\,ds} \quad \text{and} \quad L = \frac{\left(\int B_z(z)\,dz\right)^2}{\int B_z(z)^2\,ds}$$

with all integrals being taken over the physical solenoid. Table 1 shows the resulting parameters for the field profile plotted in Fig. 2.

By combining the solenoid matrix with an appropriate drift matrix to account for transport to a downstream BPM, we generate a set of linear equations that relate beam displacement at the BPM to beam misalignments x, x', y, y':

$$\begin{aligned} x_{\text{bpm}} = {} & (dksc - c^2)x + \left(\frac{sc}{k} + dc^2\right)x' \\ & + \left(dks^2 - sc\right)y + \left(\frac{s^2}{k} + dsc\right)y' + C_x \end{aligned} \tag{1}$$

$$\begin{aligned} y_{\text{bpm}} = {} & \left(sc - dks^2\right)x - \left(\frac{s^2}{k} + dsc\right)x' \\ & + \left(dksc - c^2\right)y + \left(\frac{sc}{k} + dc^2\right)y' + C_y \end{aligned} \tag{2}$$

where d is the distance from the solenoid to the downstream BPM and the constant terms C_x, C_y are included to account for arbitrary BPM offsets.

Scanning the solenoid strength over $N >= 3$ settings and recording the resulting horizontal and vertical beam displacements obtains $2N$ equations in 6 unknowns. This allows us to solve this system and extract the beam offsets and angles with respect to the solenoid axis.

Define a vector of misalignment parameters:

$$\vec{v} = \begin{bmatrix} x & x' & y & y' & C_x & C_y \end{bmatrix}^\top$$

and measurement vector:

$$\vec{m} = \begin{bmatrix} x_1 & x_2 & \cdots & x_N & y_1 & y_2 & \cdots & y_N \end{bmatrix}^\top$$

Using coefficients from Eq. 1 and Eq. 2, we construct a matrix of the following form:

$$M = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X_{N1} & X_{N2} & X_{N3} & X_{N4} & 1 & 0 \\ Y_{11} & Y_{12} & Y_{13} & Y_{14} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ Y_{N1} & Y_{N2} & Y_{N3} & Y_{N4} & 0 & 1 \end{bmatrix}$$

with the first N rows corresponding to the horizontal displacement measurements and the following N rows corresponding to the vertical displacement measurements.

We see that the system takes the form:

$$\vec{m} = M\vec{v}.$$

The misalignment vector $\vec{v}$ can be easily recovered using linear inversion techniques, such as the Moore-Penrose pseudoinverse or singular value decomposition (SVD).

EXPERIMENTAL METHOD AND RESULTS

A solenoid misalignment measurement is performed by scanning the solenoid field and observing the beam position at a downstream BPM at each solenoid setting (See Fig. 3). We fit the displacement data to the matrix model described above. This allows us to recover both the beam position and angle, in both planes, at the entrance to the solenoid.

As a check on the accuracy of this method, we used upstream corrector magnets to introduce known horizontal or vertical beam displacements at the solenoid. We then performed a solenoid misalignment measurement at each corrector setting, allowing us to compare the results of our beam-based solenoid misalignment method with a more direct measurement. [1]The results of these measurements can be seen in Fig. 4.

As shown, the matrix model successfully translates the highly coupled motion induced by the magnetic solenoid into the desired vertical and horizontal misalignment parameters.

[1] By setting the solenoid field to zero and scanning an upstream corrector magnet while observing the measurement BPM, we can use known distances between the corrector, the solenoid, and the measurement BPM to reconstruct the beam parameters at the entrance to the solenoid.

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP012

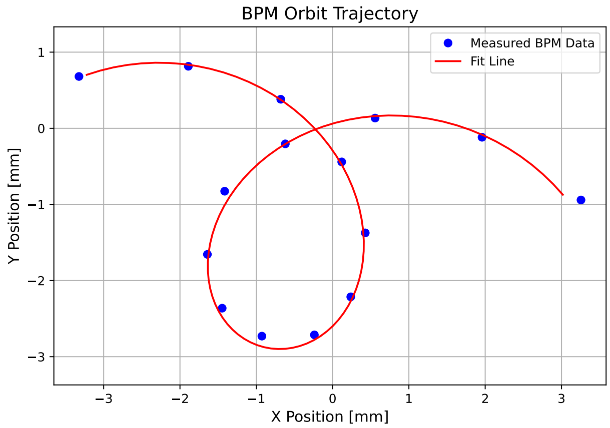

Figure 3: BPM and fit data from typical solenoid misalignment scan, exhibiting the characteristic 'spiral' trajectory indicative of coupling and solenoid misalignment.

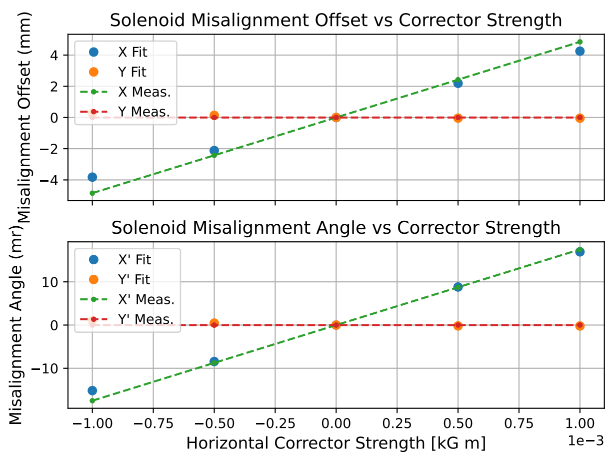

Figure 4: Comparison of extracted solenoid misalignments versus applied corrector offsets, validating the matrix-based fitting method.

SIMULATION RESULTS

To estimate the contribution of solenoid misalignment to emittance growth, we simulated beam transport through the first injector solenoid using the particle tracking code IMPACT-T. IMPACT-T is a three-dimensional relativistic tracking code that includes space-charge effects [9]. The code allows for simulation of both solenoid offsets and rotations, allowing investigation of the sensitivity of transverse emittance to solenoid misalignment.

We initially discovered that emittance growth was dominated by very strong orbit kicks induced by the misaligned solenoid, which results in large orbit offsets in downstream elements (RF buncher, second solenoid, cryomodule RF cavities, etc.). In practice, much of this can be corrected using magnetic correctors. To isolate the contribution of solenoid misalignment to emittance growth, we corrected the induced angular kick at the exit of the solenoid in our simulations. This prevented excessive orbit excursions during beam transport in simulation, as shown in Fig. 5.

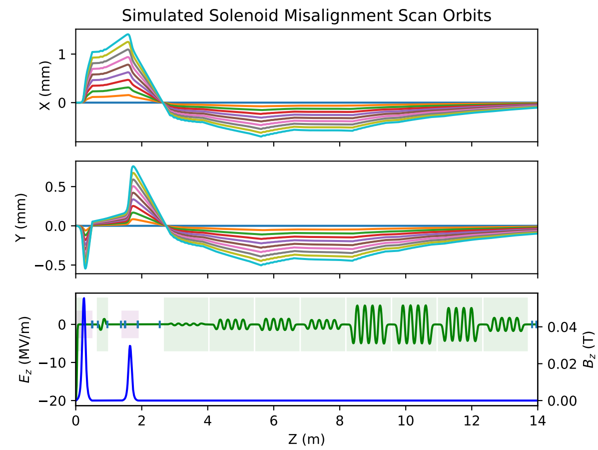

Figure 5: Simulated beam orbits and field profiles after orbit correction. Large orbit excursions are suppressed.

The results are shown in Fig. 6. Simulations with IMPACT-T confirm that solenoid angular misalignments are more harmful than offsets. Even with orbit correction, 10 mrad misalignment causes ~20% horizontal and ~10% vertical emittance growth.

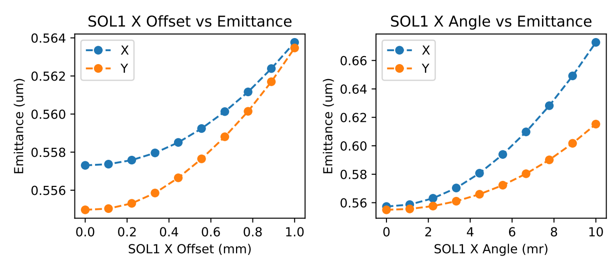

Figure 6: Simulated emittance growth due to solenoid misalignment offsets (left) and angular rotations (right). Angular errors dominate.

CONCLUSION

This paper presents a method for measuring solenoid misalignments using beam-based measurements and transfer matrix analysis. The technique has been demonstrated using experimental data from the LCLS-II injector and shows good agreement with the predictions of the matrix model.

Accurate determination of beam alignment through solenoids is essential for preserving emittance in low-energy beamlines. The method outlined here provides a relatively simple and non-invasive way to quantify misalignments and could be integrated into injector startup and commissioning procedures. This allows for fairly straightforward correction of misalignments, such as by mechanical adjustment of the solenoid in the field or by orbit correction.

Future work includes development of a remotely controlled solenoid alignment system using motorized multi-axis translation stages.

ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP012

REFERENCES

[1] "LCLS-II Final Design Report", SLAC, Menlo Park, USA, Rep. LCLSII-1.1-DR-0251-R0.

[2] L. Serafini and J. B. Rosenzweig, "Envelope analysis of intense relativistic quasilaminar beams in RF photoinjectors: a theory of emittance compensation", *Phys. Rev. E*, vol. 55, no. 6, pp. 7565–7590, Jun. 1997. doi:10.1103/PhysRevE.55.7565.

[3] T. Rao and D. H. Dowell (eds.), *An Engineering Guide to Photoinjectors*, 2014, pp. 24–34. https://arxiv.org/abs/1403.7539

[4] D. H. Dowell, "Sources of emittance in RF photocathode injectors", SLAC, Menlo Park, CA, USA, SLAC-PUB-16895, Jul. 2016. https://www.slac.stanford.edu/pubs/slacpubs/16750/slac-pub-16895.pdf

[5] C. Gulliford and I. Bazarov, "New method for generating linear transfer matrices through combined rf and solenoid fields", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 15, p. 024002, Feb. 2012. doi:10.1103/PhysRevSTAB.15.024002.

[6] S. M. Lund, "Solenoid transport". https://people.frib.msu.edu/~lund/msu/phy905_2020/lec_lund/03.solenoids.pdf

[7] I. Pinayev *et al.*, "Measuring beam parameters with solenoid", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2739–2741. doi:10.18429/JACoW-IPAC2019-WEPGW105.

[8] M. Reiser, *Theory and Design of Charged Particle Beams*. New York, NY, USA: Wiley, 1994, pp. 88-89.

[9] J. Qiang, IMPACT-T User Document. http://portal.nersc.gov/project/m669/IMPACT-T