STUDY OF BEAM-BASED ALIGNMENT FOR THE LCLS-II SC LINAC*

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Abstract

The Linac Coherent Light Source (LCLS) is an x-ray free electron laser facility. The proposed upgrade of the LCLS facility is based on construction of 4 GeV superconducting (SC) linac. The achievable performance of linac is determined by beam sensitivity to various component errors. In this paper we review misalignment tolerances of LCLS-II SC linac and discuss possible beam-based alignment algorithm to meet these tolerances.

INTRODUCTION

The proposed upgrade of Linac Coherent Light Source (LSLS) –II [1] is based on construction of SC linear accelerator (linac) which will operate in continuous wave (CW) regime. It will use TESLA [2] accelerating structure to accelerate the electron beam from kinetic energy of 0.75 MeV to 4000 MeV. The SC linac is segment into five sections in order to include warm sections which are designed for specific purpose such as laser heating, diagnostic and bunch compressions. Number of elements and operational parameters in each section are summarized in Table 1. In order to deal with technological constraints and beam dynamics issues, beam optics of SC linac is continuously evolving. Thus, number of elements and operational parameters shown in Table 1 may differ than those have been presented elsewhere [3].

Table 1: Configuration of Each Section in SC Linac

Linac section	Phase (deg)	Gradient (MV/m)	No. of CM's	Avail. cavities	Energy (MeV)
L0	~0	14.78	1	8	0.75-95
L1	-21.0	13.43	2	16	95-303
HL	-165	13.25	3	12	303-250
L2	-21	14.56	12	96	250-1600
L3	0	14.46	18	144	1600-4000

GENERAL

One of the primary accelerator design and operation objectives for LCLS-II SC linac is the preservation of beam emittance along the linac. The principal source of emittance dilution in a linac is typically misalignment of beam line elements. Transverse misalignments of quadrupoles introduce undesired dispersion while transverse misalignments of cavities cause excitation of wake fields that produce transverse kick to the beam. A tilted cavity results in time dependent transverse kick to the beam. Misalignment of cryomodule (CM) may also happen in linac and it is introduced a sort of correlated misalignment of elements in the cryomodule. All these effects associated with misalignment of elements lead to beam emittance dilution along the linac. Thus, preservation of ultra-small emittance requires stringent tolerances on alignment of beam line elements. These alignment tolerances are far beyond that which can be achieved using traditional mechanical and optical techniques. Beam based alignments or correction algorithms are used in modern accelerator to compensate emittance dilution.

In this paper, we present studies performed to understand linac performance in presence of misalignments of beam line elements and review effectiveness of orbit correction algorithm to meet these tolerances.

MISALIGNMENT TOLERANCES

On the basis of experience gained from existing facilities and studies performed for proposed SC linear accelerator facilities such as XFEL, ILC, TESLA etc., a set of alignment requirements for beam line elements in SC linac of LCLS-II facility is generated and specified in Table 2.

Table 2: RMS Alignment Tolerances of Elements in SC Linac of LCLS-II Facility [4]

Error Source	w.r.t	1 RMS tolerances
Cavity X.Y offset	CM	0.5 mm
Quadrupole X,Y offset	CM	0.5 mm
BPM X, Y offset	CM	0.5 mm
Cryomodule X,Y offset	Linac	0.3 mm
Cavity Z offset	CM	2.0 mm
Quadrupole Z offset	CM	2.0 mm
BPM z offset	CM	2.0 mm
Cryomodule Z offset	Linac	2.0 mm
Cavity Tilt	CM	0.5 mrad
Quadrupole tilt	CM	3 mrad
BPM tilt	CM	3 mrad
Cryomodule tilt	Linac	0.05 mrad
Cavity Roll	CM	10.0 mrad
Quadrupole Roll	CM	3.0 mrad
BPM roll	CM	3.0 mrad
Cryomodule Roll	Linac	2.0 mrad

Effects of misalignments of components in LCLS-II SC linac are studied using beam dynamics code LUCRETIA [5]. Simulation is performed for 300 pC bunch charge. The major portion of linac is composed with L2 and L3 sections. Therefore, those sections determine requirement

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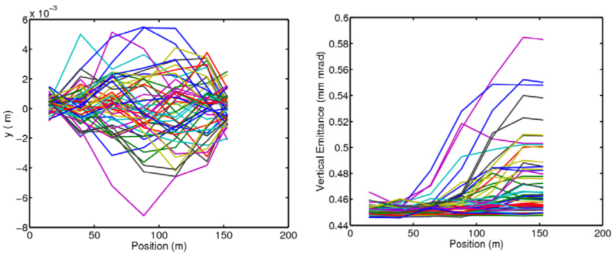
of alignment tolerance in linac. This work is mainly focused on L2 and L3 which are studied independently.

L2 Section

Initial normalized rms beam emittance at the beginning of L2 section is 0.45 mm mrad in horizontal and vertical plane respectively. RMS bunch length and relative energy spread are 0.28 mm and 1.31 % respectively. Misalignments errors specified in Table 2 are applied in vertical plane and studies are performed for L2 beam line.



(a) (b)

Figure 1: (a) Beam vertical trajectories and (b) normalized rms vertical emittances for 50 seeds of applying all nominal misalignments to the L2 section.

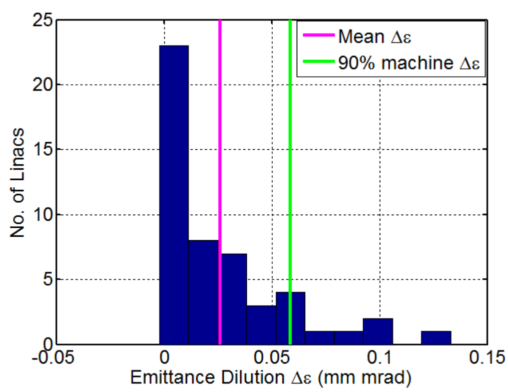
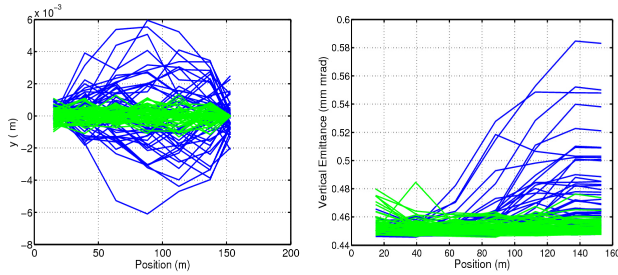


Figure 2: Resulting emittance growth distribution for 50 seeds. 90% and mean emittance growth are shown in green and magenta respectively.

It can be observed from Figure 1(a) that vertical beam trajectory might get shifted up to 6 mm in presence of all nominal misalignments. Figure 1(b) and Figure 2 show some seeds may result in emittance growth ($\Delta\varepsilon_y$) of 0.12 mm mrad. However, 90% emittance growh is about 0.05 mm mrad. It implies emittance growth will not exceed more than 0.05 mm mrad in 90 % machines (45 out of 50 in this case).

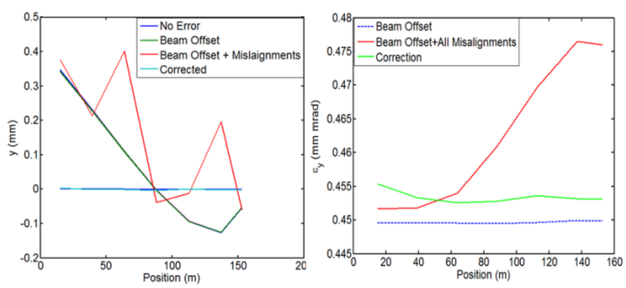
In order to correct beam trajectory and minimizing emittance growth along the section, one to one steering algorithm is applied. Settings in correctors are chosen in such a way that beam is steered to center of all beam position monitors (BPMs). It is one of simplest still effective tuning algorithm. However, performance of one to one steering depends on alignment of BPMs. In presented optics there is one vertical corrector and BPM associated with each vertical focusing quad (similarly one horizontal corrector and BPM with each horizontal focusing quad) in L2 section.



(a) (b)

Figure 3: (a) Beam trajectories and (b) normalized rms vertical beam emittance for 50 seeds before (blue) and after (green) applying 1-1 correction algorithm.

The golden beam trajectories (that include BPM offset + centroid vertical position) after applying one to one correction is shown in green in Figure 3(a). It can be noticed that all beam trajectories are confined within 1 mm offset. The trajectory correction also suppresses other effects (dispersion, excitation of structural wakes etc.) that results in compensation of emittance dilution which can be easily noticed in Figure 3(b). Beam emittance dilution for all seeds after applying one to one correction is below 7%. An initial beam offset also results in coherent betatron beam oscillation along the linac. Thus initial beam offset of 1σ rms is applied with all misalignment errors.



(a) (b)

Figure 4: (a) Average beam trajectory and (b) average beam emittance in L2 section.

Average vertical beam trajectory in L2 section for different cases is shown in Figure 4(a). It can be noticed that one to one steering correction algorithm effectively correct initial beam offset trajectory. Average beam emittance growth is shown in Figure 4(b). Initial beam offset does not introduce significant emittance growth.

L3 Section

L3 is longest section in linac. It consists of 20 cryomodules. RMS bunch length and energy spread used at the beginning of L3 section are 0.044 mm and 0.439 % respectively. Initial normalized rms emittances are same as used in L2 section. Figure 5 (a) and 5(b) show mean vertical trajectory and mean emittance growth for various cases in L3 section. It can be noticed that emittance growth is significant but largely compensated after applying one to one correction. It is reduced 20 % to 1 % after applying correction and it helps to restore beam quality along the section.

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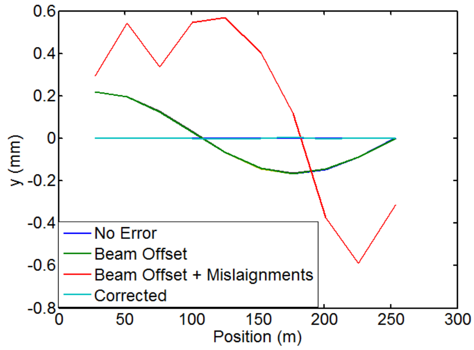
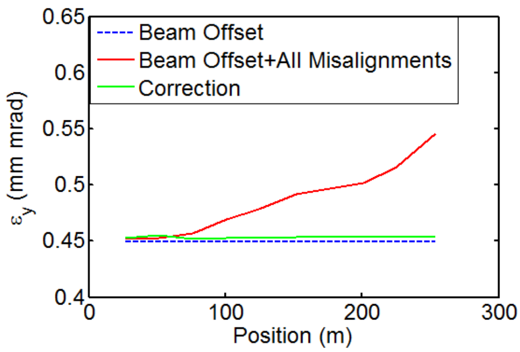


(a)

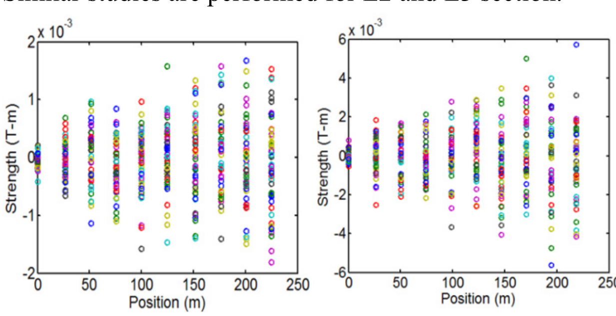


(b)

Figure 5: (a) Average beam trajectory and (b) average beam emittance in L3 section.

Misalignments with Double in Magnitude

In order to understand threshold and margin of tolerances with nominal misalignment, all misalignments errors specified in Table 2 are doubled in magnitude. Similar studies are performed for L2 and L3 section.



(a) (b)

Figure 6: Distribution of corrector fields in L3 section for all 50 seeds with (a) nominal misalignment errors (b) twice of nominal misalignments errors.

It is observed that emittance dilution after applying one to one correction is 3.2 % and 3.5 % in L2 and L3 section respectively. Those are fit well inside emittance budget for these sections. However, as shown in Figure 6, strong fields are required in correctors in order to steer beam to the center of BPMs. In some correctors it is as strong as ~6 m-T. The design specification of steering corrector in those sections is 5 m-T. Thus, it is required to install strong steering correctors if we decide to relax alignment tolerances by a factor of two. All the results for various cases are summarized in Table 3.

Table 3: Projected Emittance Dilution in L2 and L3 Section for Different Cases

	$\Delta\epsilon_y/\epsilon_y$ (%)	**90 % ϵ_y** (mm mrad)	$\Delta\epsilon_y/\epsilon_y$ **(%)** (corrected)
Nominal set of misalignments			
L2	6.7	0.06	1.1
L3	18.4	0.2	1.0
Twice of Nominal misalignments			
L2	21.6	0.2	3.2
L3	54.1	0.4	3.5

CONCLUSION

Studies are performed to analyse alignment tolerances of beam line elements in LCLS-II SC linac. It is found that misalignments errors result in significant emittance growth. In order to preserve ultra-small emittance, it is necessary to apply beam based alignment. Studies show that 1-1 steering correction is very effective in terms of compensation of emittance dilution. Emittance dilution in L2 and L3 sections is limited to ~ *1%* after applying 1-1 correction. It is also demonstrated that lattice is robust enough to deal with misalignments which are twice in magnitude on nominal misalignments. Emittance dilution after applying 1-1 steering in this case is less than *4 %* for L2 and L3 sections.

REFERENCES

[1] Linac Coherent Light Source-II :Conceptual design report http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-978.pdf

[2] B. Aune et al., 2000 Superconducting TESLA cavities Phys.Rev. ST Accel. Beams 3 092001-1-25.

[3] P. Emma et al., "Linear Accelerator Design for the LCLS-II FEL facility," FEL'14, Basel (2014).

[4] T. Raubenheimer, "SCRF 1.3 GHz Cryomodule," Physics Requirements Document (PRD), LCLSII-4.1-PR -146- R0.

[5] http://www.slac.stanford.edu/accel/ilc/codes/Lucretia/