STUDY OF COUPLER'S EFFECT IN THIRD HARMONIC SECTION OF LCLS-II SC LINAC*

A. Saini#, A. Lunin, N. Solyak, V. Yakovlev FNAL, Batavia, IL 60510, USA
T. Raubenheimer, SLAC, Stanford, CA 94309, USA

Abstract

The Linac Coherent Light Source (LCLS) is an X-ray Free Electron Laser (FEL) facility. The proposed upgrade of the LCLS facility is based on construction of 4 GeV superconducting (SC) linac which will use two stage bunch compression scheme to achieve ultra-short bunches with high peak current. In order to reduce non-linear effects in the first bunch compressor, third harmonic section is utilized to linearize longitudinal phase space of the beam. However, transverse phase space of beam may get distorted due to coupler RF kicks and coupler wake kicks resulting from the rotational asymmetry of 3.9 GHz cavity in presence of power and higher order modes (HOMs) coupler. In this paper, we discuss coupler's effects and analyse resulting emittance dilution in third harmonic section. Local compensation of coupler kicks using different orientations of cavities is also addressed.

INTRODUCTION

The LCLS-II [1] is a proposed high repetition rate FEL facility to be built at SLAC. It is primarily based on SC linac that will be capable to perform the acceleration of electron beam with the repetition rate of 1 MHz from kinetic energy of 0.75 to 4000 MeV in continuous wave (CW) mode. 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. These sections are named as L0, L1, HL, L2 and L3. All sections except HL are composed of 9-cell 1.3 GHz SC TESLA like cavities [2]. HL section consists of 9-cell, 3.9 GHz SC cavities [3]. Number of SC cavities and their nominal operational RF 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, operational parameters of SC linac shown here (Table 1) may differ than those have been presented elsewhere [4].

In order to generate high brightness coherent light in the range of X-ray, ultra short bunches with high peak current are required in undulator section. Therefore, bunch compression scheme is used to perform linear transformation of longitudinal phase space that reduces bunch length and increases energy spread. However, accelerating section prior to bunch compressor introduces non-linear distortion in longitudinal phase space due to acceleration of beam close to crest of sinusoidal RF field.

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

It limits the minimum bunch length that can be obtained in bunch compressor. Non-linear distortion in longitudinal phase space may also be amplified in bunch compressor and it can drive some undesirable collective effects that ultimately influence quality and brightness of X-rays produced in undulator section. Thus, it is essential to cancel non-linear distortion in longitudinal beam phase space prior to a bunch compressor.

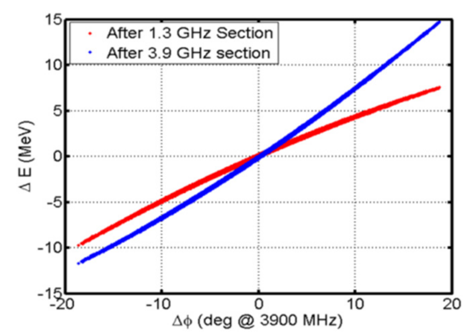


Figure 1: Longitudinal phase space before (red) and after (blue) third harmonic section of LCLS-II SC linac.

It has been studied elsewhere [5] that a short section, using RF accelerating field operating at higher harmonics of field in primary accelerating section, can compensate non-linear distortion up to second order. Nine cell, 3.9GHz (3rd harmonics of 1.3 GHz cavity) SC cavity is used in harmonic section (HL) of LCLS-II SC linac. Figure 2 shows longitudinal phase space of beam at upstream (in red) and downstream (in blue) of HL section. One can easily observe linearization of longitudinal profile after HL section. However, transverse profile of beam may get distorted due to coupler's RF and wake kicks. In this paper, we address impacts of coupler kicks and their local compensation using different orientations of cavity in HL section of LCLS-II SC linac.

COUPLER RF KICK

The third harmonic cavity is developed at FNAL and each 9-cell cavity is equipped with two HOM couplers

*Work supported by Fermi Research Alliance, LLC under Contracts No. De-Ac02-07CH11359 with the DOE, USA.
#asaini@fnal.gov

ISBN 978-3-95450-142-7

and one power coupler. Figure 2 shows orientation and locations of the power and HOM couplers in the 9-cell, 3.9 GHz third harmonic cavity.

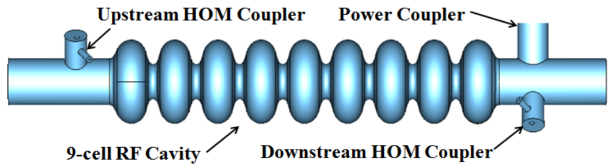


Figure 2: Third harmonic cavity with power and HOM couplers.

Insertion of coupler in the cavity results in breaking of azimuthal symmetry of the cavity that leads to generation of on-axis transverse fields in the vicinity of coupler. It also leads to excitation of coupler transverse wake field by beam even it is moving along the axis. Thus, coupler's effects can be classified in two category i.e. coupler RF kick and coupler wake kick. These effects produce transverse kick to the beam that results in degradation of beam quality and emittance dilution in transverse planes.

Coupler RF Kick

Coupler RF kicks in a cavity is partly compensated by choosing the orientations of coupler in such a way that kick due to upstream coupler and downstream coupler are in opposite direction. On-axis coupler RF kick in 3.9 GHz cavity is calculated using RF simulation code HFSS [6] for the geometry shown in Figure 2. The antenna of power coupler is adjusted to provide $Q_{ext} \sim 10^7$ for kick estimation. RF kick due to upstream coupler, downstream couplers and full structure is summarized in Table 2.

Table 2: On-axis coupler RF kick in 3.9 GHz Cavity.

	$(V_x/V_z).10^6$	$(V_y/V_z).10^6$
Upstream	-73.8 + j 250	-19.4+ j 147
Downstream	-609 -j 25.9	25.1 + j 136
Full	-682 + j 227	5.5 + j 282

In presented optics, HL section is composed of three cryomodules and each cryomodule consists of four 3.9GHz cavities. In simplest configuration, named Fermilab type configuration, all cavities are aligned identically. Beam optics is studied through HL section for Fermilab type configuration. Normalized rms emittance growths in horizontal and vertical plane are shown in Figures 4 (a) and 4(b) respectively. It can be observed that there is no emittance growth in transverse planes when 1-D field map (no transverse field along the axis) of 3.9 GHz cavity is used. However, emittance dilution of 1.7 % and 16.9 % is observed in horizontal and vertical plane respectively for 3D field map of 3.9 GHz cavity. It implies that remaining on-axis coupler RF kick is primary source of transverse emittance dilution in the HL section.

As direction and magnitude of coupler kick is same for all accelerating structures, contribution from each structure adds coherently that results in a significant emittance growth. However, rotation of a cavity changes the direction of the kick and it can be utilized to compensate the coupler RF kick locally.

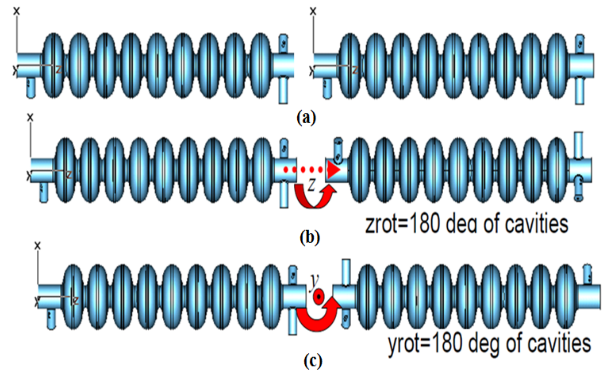
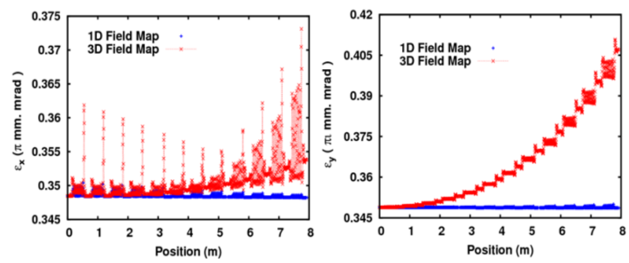


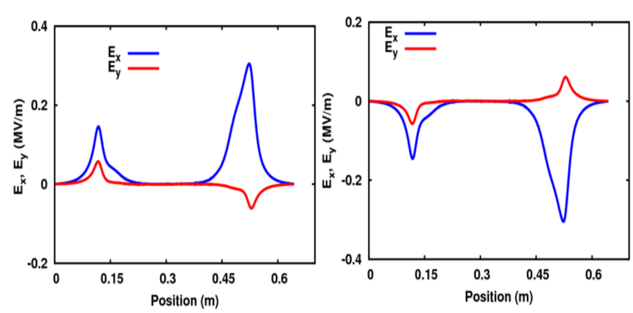
Figure 3: Configuration of cryomodules on the basis of orientation of adjacent cavities: (a) Fermilab type configuration, (b) XFEL type configuration and (c) FLASH type configuration.



(a) (b)

Figure 4: (a) Horizontal and (b) vertical emittance growth without (blue) and with (red) coupler RF kick in HL section for Fermilab type configuration.

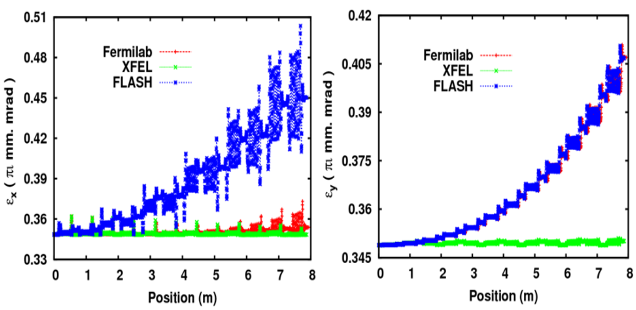
In order to mitigate effects of coupler RF kick in HL section, two configurations i.e. XFEL and FLASH are studied. In XFEL configuration, alternating cavities in a cryomodule are rotated by 180^0 along the z axis while alternating cavities are rotated by same degree along y axis in FLASH configuration. Figure 3 (b) and figure 3(c) show XFEL and FLASH configurations respectively.



(a) (b)

Figure 5: On axis transverse electric fields in a 3.9 GHz cavity for (a) nominal orientation and (b) 180^0 rotation along the z axis.

Figure 5 shows on axis transverse component of electric field in 3.9 GHz cavity for operating gradient of 13.25 MV/m. It can be observed that direction of field components are reversed after 180^0 rotation of cavity along the z axis. Emittance growths in the HL section for Fermilab, FLASH and XFEL configurations are shown in Figure 6. It can be observed that emittance growths in both horizontal and vertical planes are minimal for XFEL configuration. It implies that rotation of alternative cavities in a cryomodule by 180^0 along z-axis is the most effective way to compensate coupler RF kick. FLASH configuration is not effective for this optics and large emittance growth in both planes are observed.

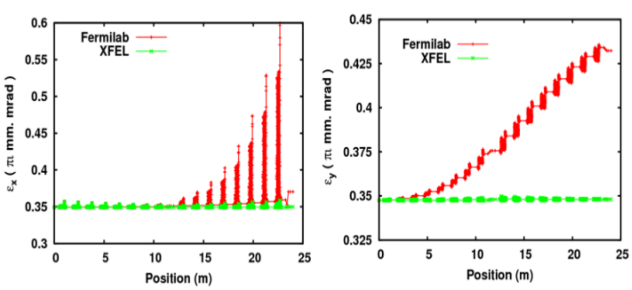


(a) (b)

Figure 6: (a) Horizontal and (b) vertical emittane growth in HL section for Fermilab (red), FLASH (blue) and XFEL (green) configuration of cryomodule.

Long Cryomodule with 8 Cavities

It is proposed to use ILC type cryomodule in the HL section. This cryomodule can accommodate eight 9-cell, 3.9 GHz cavities. The drift space between adjacent cavities will be longer that will allow assembly of HOMs absorber between them to damp HOM modes and to reduce HOMs power deposition in cavities. Modified HL section consists of 16 cavities assembled in two cryomodules. More number of cavities also permits to operate the cavities at lower gradient.



(a) (b)

Figure 7: (a) Horizontal and (b) vertical emittane growth in HL section for Fermilab (red) and XFEL (green) configuration of 8 cavity cryomodule.

Beam optics is studied for modified HL section. It can be observed from Figure 7 that there is no significant emittance growth in the HL section for XFEL configuration. It confirms that use of longer cryomodule does not lead to any adverse effects on beam optics. Emittance dilution due to coupler RF kick in HL section for various cases is summarized in Table 3.

Table 3: Emittance dilution in HL section for various configurations.

	Fermilab	FLASH	XFEL
4 Cavities per Cryomodule			
$\Delta\ \varepsilon_x$ (%)	1.7	29.3	0.04
$\Delta\ \varepsilon_y$ (%)	16.9	16.6	0.07
8 Cavities per Cryomodule			
$\Delta\ \varepsilon_x$ (%)	6.0	-	0.09
$\Delta\ \varepsilon_y$ (%)	24.4	-	0.15

COUPLER WAKE KICK

Coupler wake kick in the 3.9 GHz cavity is calculated using same approach as used for standard TESLA cavity [7]. It can be observed from Figure 8 that on-axis horizontal and vertical wake kick factor are nearly independent of bunch length and their magnitudes are about an order smaller than nominal wake [8] excited by 1 mm offset beam in 3.9 GHz cavity. Thus, its effects are expected to be minimal as compared to coupler RF kick and nominal transverse wake kick.

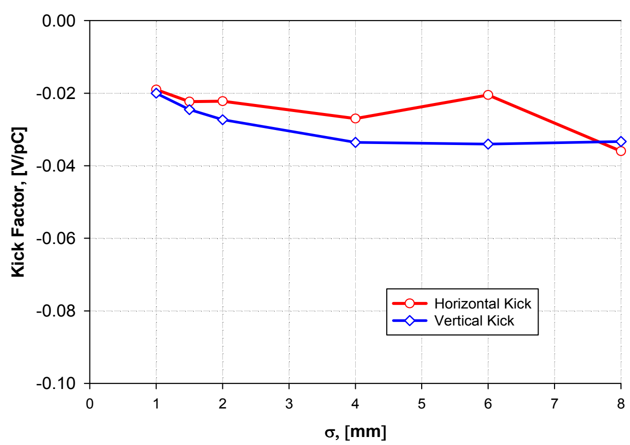


Figure 8: Horizontal (red) and vertical (blue) on–axis coupler wake kick factor in 3.9 GHz cavity.

CONCLUSION

Studies have been performed to understand coupler's effects in third harmonic section of the LCLS-II SC linac. Local compensation of coupler kick can be achieved using rotation of alternating cavities in a cryomodule. However, it leads to modifications in existing design of the 3.9 GHz cryomodule. Optics is also studied for longer version of cryomodule. It is observed that XFEL configuration is most effective in terms of mitigation of coupler's RF kick effects. Coupler wake kick factor is calculated for 3.9 GHz cavity and its effect is expected to be minimal as compared to coupler RF kick.

REFERENCES

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

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

[3] E. Harms et al, "Status of 3.9 GHz Superconducting RF cavity technology at Fermilab," THP028, LINAC'08, British Columbia, Canada (2008).

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

[5] J. Sekutowics et al, "A Design of a 3rd Harmonic Cavity for the TTF 2 Photoinjector," TESLA-FEL 2002-05.

[6] HFSS, Ansys, Inc.

[7] A. Lunin et al, "Final Results of RF and Wake kicks caused by the couplers for the ILC cavity," IPAC'10, WEPE034, Kyoto, Japan(2010).

[8] M. Awida et al, "Wakefield Loss Analysis of the elliptical 3.9 GHz Third Harmonic Cavity," WEPAC32, these proceedings, PAC'13, Pasadena, USA (2013).