ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMA016

COUPLER RF KICK IN THE INPUT 1.3 GHz ACCELERATING CAVITY OF THE LCLS-II LINAC

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Abstract

Main and HOM couplers break the cavity axial symmetry, distort RF field and, thus, create a transverse kick, even for a particle moving along the cavity axes. Dependence of a kick on the RF phase causes beam emittance dilution and degrade the FEL radiation quality. The transverse kick is most dangerous for a beam passing through the first accelerating structure of a linac, where particles energy is low. In this paper we analyse the coupler RF kick in the first accelerating structure of the LCSL-II linac.

INTRODUCTION

The 1.3 GHz ILC accelerating structure is chosen as a baseline for the LCLS-II linac. The cavity contains 9 elliptical cells, a main power coupler, and two HOM couplers, upstream and downstream, see Figure 1.

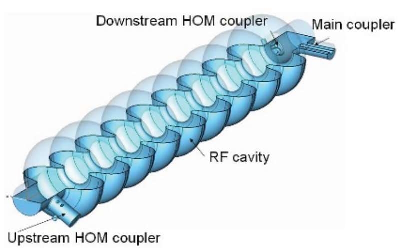

Figure 1: The 1.3 GHz ILC accelerating cavity with main and HOM couplers.

Main and HOM couplers break the cavity axial symmetry, distort electromagnetic field and, thus, create a transverse kick, even for a particle moving along the cavity axes. Dependence of the kick on the RF phase causes beam emittance dilution and may degrade the FEL radiation quality [1, 2]. Bellow we analyze a coupler RF kick in the first accelerating structure of the LCLS-II linac [3]. Beam and cavity parameters relevant to the coupler kick and emittance growth calculations are listed in the Table 1.

Table 1: Parameters for the RF Kick Simulations

Bunch transverse size, rms, σ_t	1 [mm]
Bunch length, rms, σ_z	1 [mm]
Input beam energy, E_{inp}	0.75 [MeV]
Accelerating gradient	12 [MeV/m]
Operating frequency	1.3 [GHz]
Cavity Q-external	4E7

*Operated by Fermi Research Alliance, LLC, under Contract DE-AC02-07CH11359 with the U.S. DOE.
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GENERAL

The longitudinal component of electric field near the cavity axis is few orders of magnitude larger than the transverse one. Therefore, any misalignment of mesh elements in respect to the axis may result in appearance of a nonzero transverse projection of the longitudinal component and, thus, produce spurious transverse components of electric field. Since a magnetic field is usually derived from the solution of an electric field we have the same problem for an accurate magnetic field representation near the cavity axis. The remedy is use a regularized mesh with the elements aligned to the cavity axis. The regular mesh pattern near the cavity axis and the vertical component of electric field are shown in Figure 2 as a result of ANSYS HFSS simulation [4].

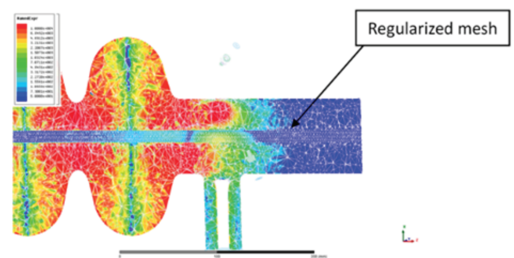

Figure 2: Map of the vertical electric field component E_y.

The transverse RF kick is the total beam transverse momentum change along the trajectory. For a low relativistic beam which is moving not along a straight line, dependence of the transverse momentum on the accelerating gradient becomes non-linear. Therefore we characterize RF kick in this case as a non-normalized transverse kick accumulated along the actual beam trajectory at a given accelerating gradient:

$$V_x = \Delta P_x \frac{c}{e_0} = \int_{t_1}^{t_2} (E_x - \beta_z Z_0 H_y) e^{i(\omega t + \varphi_s)} dt \tag{1}$$

where t_2-t_1 is the beam transit time, β_z is the longitudinal beam velocity as a fraction of speed of light, φ_s is the synchronous RF phase, e_0 is electron charge and c is the speed of light. The beam tracking in the accelerating structure is realized with MATHCAD script using the paraxial approximation for particles motion [5, 6].

CAVITY RF FOCUSING

A beam RF focusing at the entrance of first accelerating structure, where particles energy is low, is not fully compensated by defocussing forces at its exit [7]. Thus, the structure itself is producing a non-zero net

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RF kick linearly growing with the beam offset. The main parameter of the cavity RF focusing, which causes beam emittance dilution, is a derivative of the produced transverse voltage over the RF phase. It is weakly dependent on the cavity gradient and falls down rapidly as $\sim\gamma_i^{1.5}$ with the beam input energy.

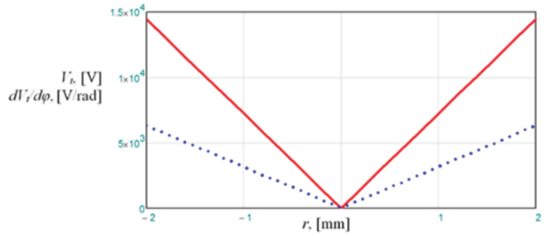

Figure 3: Transverse kick (red curve) and its phase derivative (blue doted curve) in a cavity without couplers.

In order to separate RF kick components produced by structure and couplers, we first simulated RF kick in an ideal structure without HOM and power couplers. The result is shown in Figure 3. The red curve corresponds to the real part of the RF kick and the blue dotted curve represents its phase derivative at the synchronous point. One has to note that for a non-relativistic beam the real and imaginary parts of the RF kick are not exactly cosine and sin functions and, thus, the actual phase derivative of the real part has to be taken into account.

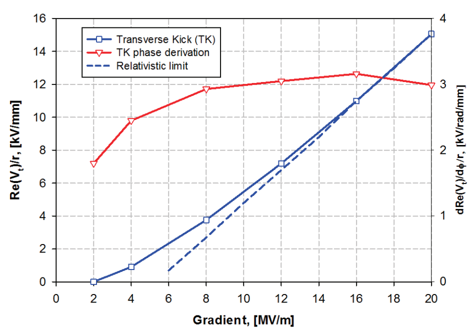

Figure 4: Scaling of a cavity RF focusing versus accelerating gradient, real part of a transverse kick (blue curves) and kick phase derivative (red).

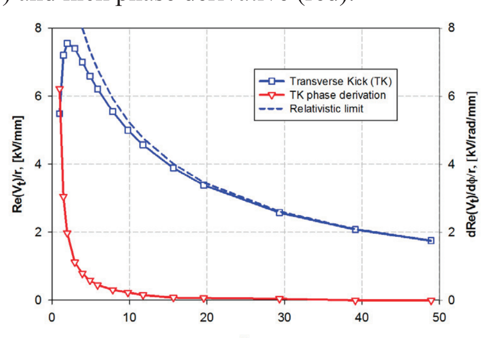

Figure 5: Scaling of a cavity RF focusing versus input beam energy, real part of a transverse kick (blue curves) and kick phase derivative (red).

Scaling of a cavity RF focusing as functions of the accelerating gradient and the input beam energy are shown in Figures 4 and 5 respectively. For a relativistic approach the real part of transverse voltage is proportional to the cavity gradient and inverse proportional to the energy of the input beam. In the contrary, when the input beam energy is low, the synchronous phase is a function of the cavity gradient and scaling of the cavity RF focusing becomes highly non-linear.

HOM COUPLERS RF KICK ANALYSIS

Adding couplers to the cavity makes the RF kick non-symmetrical in respect to the beam offset. Since in simulations the total RF kick is a mix of the kicks produced by HOM couplers and by the cavity itself, we have to subtract the cavity background first for restoring kicks produced by upstream and downstream couplers only. The results are illustrated in Figure 6 for the vertical component of couplers RF kick. Both upstream and downstream couplers have kick phase derivatives of the same sign and therefore they do not compensate a beam emittance growth by each other.

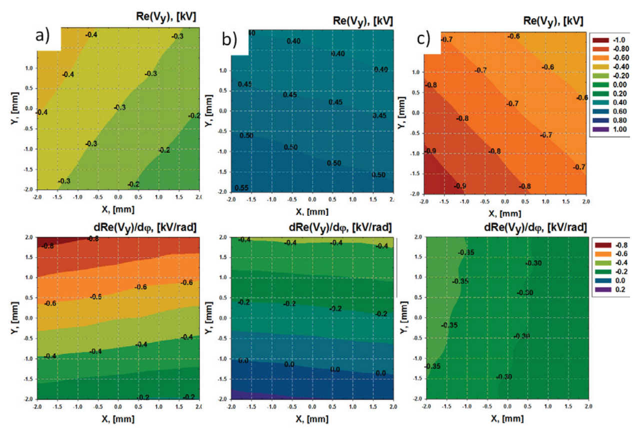

Figure 6: Vertical couplers RF kick (up) and its phase derivative (down) in the full cavity (a), cavity with only downstream HOM coupler (b) and cavity with only upstream HOM coupler (c).

A comparison of the RF kick produced by the upstream HOM coupler and the cavity kick due to RF focusing is presented in Figure 7. Evidently the effect of coupler kick outperforms the cavity RF focusing only if the beam offset is less than 0.2 mm in a horizontal plane and 0.1 mm in a vertical plane. It means that if the bunch transverse size or the offset at the moment when it passes near the couplers is greater than 0.2 mm rms, the major portion of the beam emittance dilution will be induced by the structure itself.

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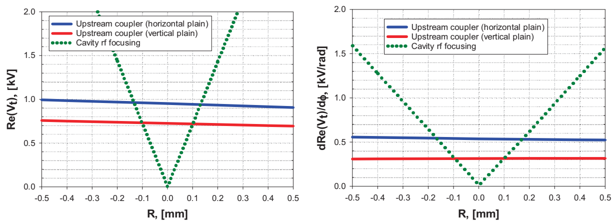

Figure 7: The real part of RF kick (left) produced by the upstream HOM coupler (blue and red) and by the cavity (green) and corresponding phase derivatives (right).

The normalized transverse emittance growth for the Gaussian bunch with parameters listed in the Table 1 can be estimated as follows [8, 9]:

$$d\varepsilon_t = d\sigma_{t'}\sigma_t \beta\gamma \qquad (2)$$

$$d\sigma_{t'} = \frac{d\sigma_{p_t}}{p_z} = \left|\frac{dp_t}{d\varphi}\right|_{\varphi=\varphi_0} \frac{k\sigma_z}{p_z} \qquad (3)$$

where $d\sigma_{t'}$ is the normalized transverse momentum spread at synchronous phase, σ_t is the bunch size in the transverse plain, σ_z is the bunch length and k is the wavenumber. The expected growth of horizontal and vertical emmitanses due to couplers RF kick are about 0.12 mm*mrad and 0.05 mm*mrad respectively.

Finally we calculate dependencies of upstream and downstream couplers transverse RF kicks on the cavity accelerating gradient and the input beam energy. The results are shown in Figures 8 and 9 in a comparison with the effect of RF focusing. One can see that over the wide range of accelerating gradients a phase derivative of the RF kick is dominated mostly by the RF focusing mechanism and the couplers contribution overcomes the cavity part only if the input beam energy is greater than about 5 MeV.

CONCLUSION

Simulations of the couplers RF kick in the 1.3 GHz accelerating structure for non-relativistic regime are presented. Scalings of the coupler RF kick and the cavity RF focusing are compared for various beam input energies and cavity accelerating gradients. Finaly, we conclude that the 1.3 GHz 9-cells ILC structure can be used for the acceleration of a non-relativistic electron beam while preserving the beam emittance only if it is operating at a low accelerating gradient and proper beam optics is used for minimizing the beam transverse size at the cavity entrance.

a)

b)

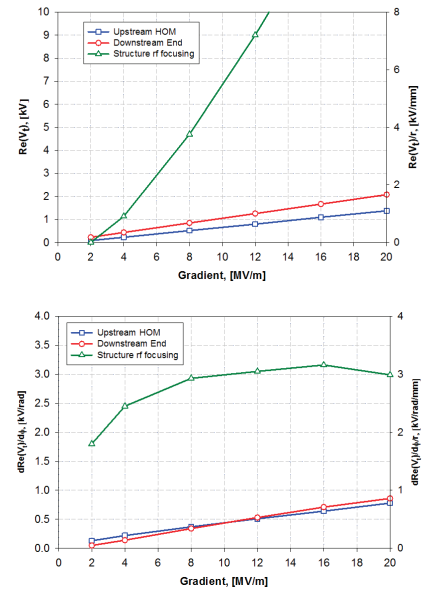

Figure 8: Scaling of the transverse RF kick (a) and its phase derivative (b) as a function of the accelerating gradient for the upstream HOM coupler (blue), downstream end couplers (red) and accelerating structure (green).

a)

b)

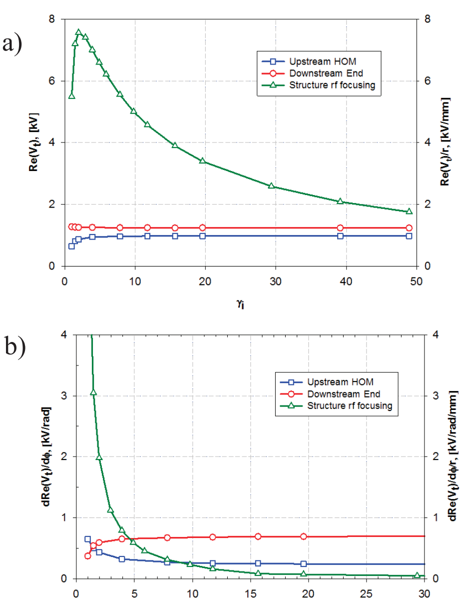

Figure 9: Scaling of the transverse RF kick (a) and its phase derivative (b) as a function of the beam input energy for the upstream HOM coupler (blue), downstream end couplers (red) and accelerating structure (green).

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