EFFECT OF CAVITY COUPLERS FIELD ON THE BEAM DYNAMICS OF THE LCLS-II INJECTOR*

A. Vivoli†, A. Lunin, A. Saini, N. Solyak, FNAL, Batavia, IL 60510, USA
D. Dowell, Z. Li, T. Raubenheimer, J. F. Schmerge, T. Vecchione, F. Zhou,
SLAC, Menlo Park, CA 94025, USA
D. Filippetto, R. Huang, C. Papadopoulos, H. Qian, S. Virostek, R. Wells,
LBNL, Berkeley, CA 94720, USA
A. Bartnik, I. Bazarov, B. Dunham, C. Gulliford, C. Mayes,
CLASSE, Cornell University, Ithaca, NY 14853, USA

Abstract

LCLS-II is a new light source based on a continuous wave (cw) superconducting linac to be built at SLAC. The Injector section of the linac creates the elecron beam and accelerates it up to about 100 MeV. The couplers of the accelerating cavities produce an asymmetric field resulting in a beam offset and, most importantly, in a significant transverse emittance dilution, if not compensated. In this paper we describe the simulations of the LCLS-II injector taking into account the cavity couplers effect and some mitigation techniques to reduce its impact on the beam quality.

INTRODUCTION

The Linac Coherent Light Source II (LCLS-II) project consists in a linac-based, seeded, free electron laser (FEL) with high repetition rate (up to 1 MHz) and broad photon energy range (0.2 KeV-5.0 KeV) to be built in the next few years [1]. The linac will be cw superconducting, working at an RF frequency of 1.3GHz and accelerating the beam up to an energy of 4 GeV. In order to deliver a very high quality beam to the undulators, attention should be paied to the study of the beam dynamics in the Injector [2], comprehensive of beam generation and acceleration up to about 100 MeV. Among the effects that can possibly produce emittance growth at such low energy, consideration is given to the effect of the cavity couplers on the accelerating field. The accelerating structures employed in the Injector are the 1.3 GHz 9-cell TESLA cavities, which have an upstream higher order mode (HOM) power coupler, for damping of higher-order mode power, a fundamental power coupler, to power the cavity, and another HOM coupler downstream, as shown in Fig. 1.

These couplers results in an axially asymmetric field, that produces an offset of the beam and emittance dilution. Analytic calculation of the RF kicks in these cavities have been carried out [3] with the parameters of the LCLS-II design. In this paper we present the results of tracking simulations and emittance growth estimations from tracking code TraceWin [4], after a preliminary benchmark with tracking code Astra [5] is performed to establish the validity of the results.

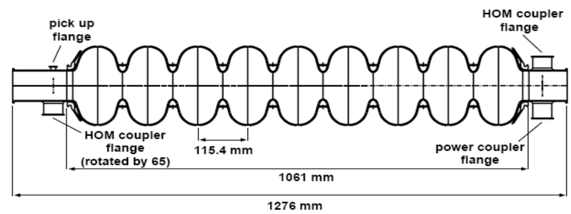

Figure 1: Schematic of the TESLA cavity showing the power and HOM couplers.

SIMULATIONS OF 1-DIMENSIONAL CASE

The study of the RF couplers contribution to the emittance growth was treated independently from the optimization of the layout for the Injector [6]. The latter was done using Astra with 1-dimensional (1D) field maps of the cavities (the values of longitudinal electric field at different points of the longitudinal axis). The study presented here was done taking one of the not optimized lattices under study (layout 1), and replacing the 1D field maps with 3D field maps calculated with Ansoft HFSS and CST Microwave Studio at Fermilab [3], for the Injector design values of Q_{ext} and V_{acc}. The lattice used for the study consists of RF gun, solenoid 1, buncher, solenoid 2 and a cryomodule containing 8 equally spaced cavities. A schematic layout of the injector is reported in Fig. 2.

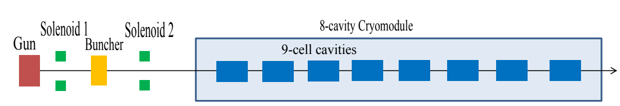

Figure 2: Schematic layout of the injector lattice used in the simulations.

The same 1D field maps of the cavities were used as input to Astra and TraceWin, each code then expanded the field assuming cylindrical symmetry. For simplicity TraceWin simulations concerned only the cryomodule: a first simulation with Astra was run up to around 5 cm from the start of the first cavity, then the output distribution was extracted in

* Work supported by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.
† vivoli@fnal.gov

Table 1: Input Parameters for Astra and TraceWin Simulations

Parameter	Astra	TraceWin
Number of particles simulated	250000	250000
Mesh for particle tracking integration	Zemit=4000, H_max=0.001 H_min=0.0, Lproject_emit=.F Local_emit =.T	Step calculation per $\beta\lambda$ = 1000 Max memory for field map allocation =400 MB
Mesh for space charge calculation	Nrad=75, Nlong_in=130 Cell_var=2.0, min_grid=0.4e-6 Max_scale=0.01, Max_count=10	PICNIR (2D)-(r,z) = 50, 100 Space charge and step per meter=1000
Other options	C_smooth()=10, C_higher_order()=T	SET_SYNC_PHASE option

a field free region and given as input distribution for both TraceWin and Astra. The beam parameters at the end of the simulations of the remaining part of the lattice were then compared. To find good agreement between the codes a number of input parameters needed to be adjusted. In Table 1 the relevant parameters used in the simulations are reported, especially the ones defining the mesh used for integration of the motion and for space charge calculations.

The results of the benchmark are reported in the tables below, corresponding to the cases of 1D simulations.

SIMULATION OF COUPLERS EFFECT

Simulations of the injector using 3D field maps were performed to estimate the emittance growth and beam offset produced by the asymmetry of the field in presence of the cavity couplers. The simulations done for the benchmark mentioned above were used as the ideal case, where the axial simmetry of the cavities is not perturbed and the couplers have no effect. Simulations using Astra with 1D field maps are indicated in Tables 2–4 as simulation case "Astra 1D" while the ones using TraceWin with 1D field maps are indicated as "TraceWin 1D". The case referring to TraceWin runs using 3D field maps of the cavities with couplers are named "TraceWin 3D". The increase in the emittance and the beam's offset seen in this case give an estimation of the couplers effect. Since the beam enters the cavities at a lower energy than when it exits, it is expected that the first HOM coupler may produce the biggest effect on the emittance compared to the couplers downstream. Following the same reasoning we can expect that the biggest effect is seen in the first cavity rather than in the following ones. The energy at which the particles enter the first cavity is about 0.8 MeV, while the exit energy is about 10 MeV and similarly for the other cavities, up to 100 MeV.

To check the contribution of the first HOM coupler of the cavities, a new field map was produced from the one of the standard cavity, numerically removing the asymmetry in the field produced by the first HOM coupler, as can be seen in Fig.3–4. Then a simulation was run replacing the field map of the cavities with the new one. This case is referred to in the tables as "No HOM all". To check what is the contribution of the first cavity compared with the one of the

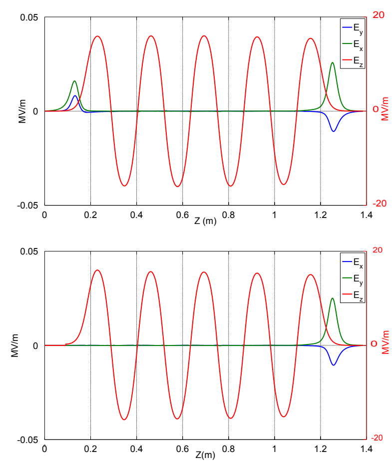

Figure 3: Electric field along the axis in the TESLA cavity, including all couplers for nominal gradient and Q_{ext} (up) and after numerical removal of the upstream HOM coupler (down).

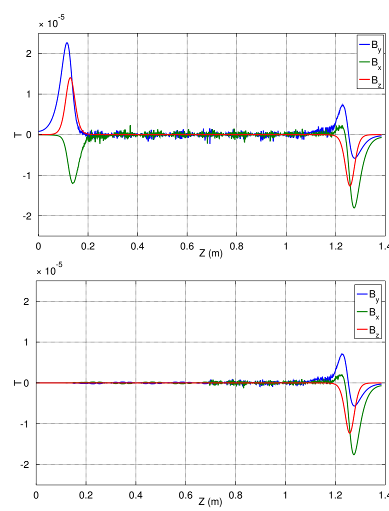

Figure 4: Magnetic field along the axis in the TESLA cavity, including all couplers for nominal gradient and Qext (up) and after numerical removal of the upstream HOM coupler (down).

others it was also run a simulation with only the field map of the first cavity replaced with the modified one, leaving all the other cavities with the coupler asymmetry in it. In practice a cavity with the modified field map would require manipulation of the TESLA cavity HOM couplers and possibly of the cryomodule where the cavities are installed. It can be more feasible and less expensive to modify only the first cavity, if the mitigation is successful. This last option is referred to as "No HOM 1^{st}" in the tables. Simulations were carried out for different bunch charge configurations (300 pC, 100 pC, 20 pC). The beam enters the cryomodule on axis with input emittance 3.1, 1.4, 0.3 μm and rms transverse size 1.7, 1.2, 0.56 mm respectively. The final energy in all cases is around 100 MeV. Differences between the cases studied are in the order of few percent for the final energy as well as for bunch length and energy spread. The results of the emittance reported in the tables refer to the calculated projected emittance of the 100% of the particles simulated.

Table 2: Simulation results for 1D field maps and 3D field maps and 2 mitigation case studies for 300 pC case.

Simulation	$\gamma\epsilon_x$ (mm mrad)	$\gamma\epsilon_x$ (mm mrad)	Δx (mm)	Δy (mm)
Astra 1D	0.485	0.487	–	–
TraceWin 1D	0.497	0.500	–	–
TraceWin 3D	0.473	0.663	-1.46	-0.21
No HOM 1^{st}	0.481	0.555	-1.33	-0.10
No HOM all	0.502	0.526	-0.71	0.29

Table 3: Simulation results for 1D field maps and 3D field maps and 2 mitigation case studies for 100 pC case.

Simulation	$\gamma\epsilon_x$ (mm mrad)	$\gamma\epsilon_x$ (mm mrad)	Δx (mm)	Δy (mm)
Astra 1D	0.291	0.293	–	–
TraceWin 1D	0.301	0.301	–	–
TraceWin 3D	0.292	0.407	-1.48	-0.21
No HOM 1^{st}	0.269	0.304	-1.33	-0.10
No HOM all	0.288	0.307	-0.71	0.29

Table 4: Simulation results for 1D field maps and 3D field maps and 2 mitigation case studies for 20 pC case.

Simulation	$\gamma\epsilon_x$ (mm mrad)	$\gamma\epsilon_x$ (mm mrad)	Δx (mm)	Δy (mm)
Astra 1D	0.103	0.103	–	–
TraceWin 1D	0.105	0.105	–	–
TraceWin 3D	0.103	0.127	-1.50	-0.21
No HOM 1^{st}	0.100	0.114	-1.33	-0.08
No HOM all	0.104	0.107	-0.74	0.30

CONCLUSION

From the tables above we can conclude that the effect of the couplers on the beam produces an emittance dilution of 25-35% in the vertical plane and a slight decrease in the horizontal one, meaning possible emittance exchange between the two planes.

The final beam offset is about 1.5 mm in the horizontal plane and 0.2 mm in the vertical one. Our mitigation method results effective in reducing the emittance growth. Removing the field asymmetry produced by the upstream HOM coupler from all the cavities in the cryomodule reduces the vertical emittance growth to 5% in the worst case (300 pC) and few percent increase in the horizontal plane. Nevertheless this solution may be impracticable or too expensive to realize. Removing the field of the upstream HOM coupler only from the first cavity would still reduce the emittance growth to < 15% in vertical plane (worst case 300 pC) and no increase in horizontal one. New designs of the first cavity implementing a modification of the first HOM coupler are already under study and preliminary simulations using their field maps confirm the results presented here.

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ISBN 978-3-95450-142-7