IMPACT-T simulations for LCLS-II injector commissioning with a unified cryomodule CM01 setting

LCLS-II-TN-22-03

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Zhen Zhang, Yuantao Ding, Feng Zhou
SLAC, Menlo Park, CA 94025, USA

1 Introduction

The previous LCLS-II injector and superconducting (SC) linac optimization studies have provided the optimal configurations based on a Gaussian-profile laser pulse for LCLS-II injector with bunch charge of 20 pC, 50 pC and 100 pC, respectively [1]. The optimal configurations of the LCLS-II injector for Gaussian-profile laser pulse are obtained by Genetic Algorithm optimization, which lead to some randomness in the parameter settings, e.g., the phases of the 8 cavities of the first cryomodule (CM) [1]. This randomness in parameters would increase the complexity of facility commissioning and make it difficult to switch the state of the machine between different beam charges. The purpose of this technote is to get a “smooth” configuration of LCLS-II injector at the different bunch charges while preserving the beam emittance. This unified configurations at different beam charges could provide a clear path for switching the state of the injector.

This technote will also summarize some correlations between beam emittance/bunch length and critical knobs to help commissioning the LCLS-II injector.

Note the simulations of the injector in [1] were performed with Astra [2]. However, since the retirement of OAK cluster at SLAC, parallel version of Astra is not available anymore. We also observed non-negligible discrepancy in the final values of beam emittance between the single-core and parallel versions of Astra. Therefore, we decided to adopt IMPACT-T [3] as the particle-in-cell code for this simulation task of LCLS-II injector commissioning.

2 Simulation results

We start from the optimal configuration of 100 pC beam charge with Gaussian-shape laser profile [1] and modify settings based on the request.

2.1 Laser pulse length from 20 ps to 16 ps

According to the recent measurement of the laser pulse, the full width at half maximum (FWHM) of the laser pulse is ~16 ps, shorter than the 20 ps in the optimal configuration for the beam charge of 100 pC [1]. In the early stage of commissioning, we don’t plan to make big changes in the laser system and would use the 16-ps laser. The comparison of simulation results with 16/20-ps laser pulse length are shown in Figure 1. All other parameters in the simulations are kept the same.

When the laser pulse length is reduced from 20 ps to 16 ps, the bunch length at the exit becomes longer (1.05 mm to 1.33 mm) and the emittance is similar. This is because compared with the case of 20-ps laser pulse, a shorter laser pulse length will result in larger beam size and shorter bunch length due to the strong space-charge force during the electron emission process. A shorter bunch length means higher intensity and stronger longitudinal space-charge-induced energy chirp in the drift from the gun to the buncher. With the same RF-induced chirp from buncher, the remaining chirp, equal to sum of the RF chirp and the space-charge chirp (they have opposite sign in chirp), will be smaller compared with the original case, which leads to a weaker velocity bunching before the beam is accelerated to relativistic energy to freeze the longitudinal distribution of electrons.

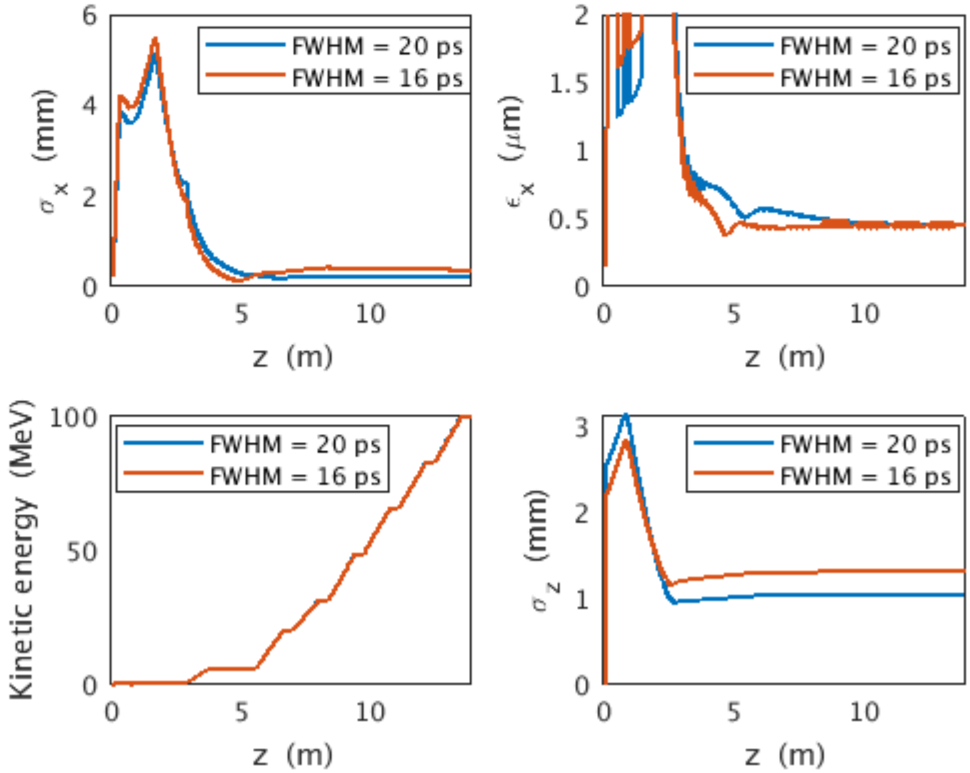

Figure 1 Simulation results of 16- and 20-ps laser pulse length including beam size, emittance, kinetic energy, and bunch length along the beamline.

The change of laser pulse duration may change the phase of the RF cavities. We need to scan the phase of each cavity to verify the relative phase, which makes more sense in beam physics. The phase scan result of the gun is shown in Figure 2. The phase in the input file is 358.2 deg, leading to an off-crest phase 8.2 deg.

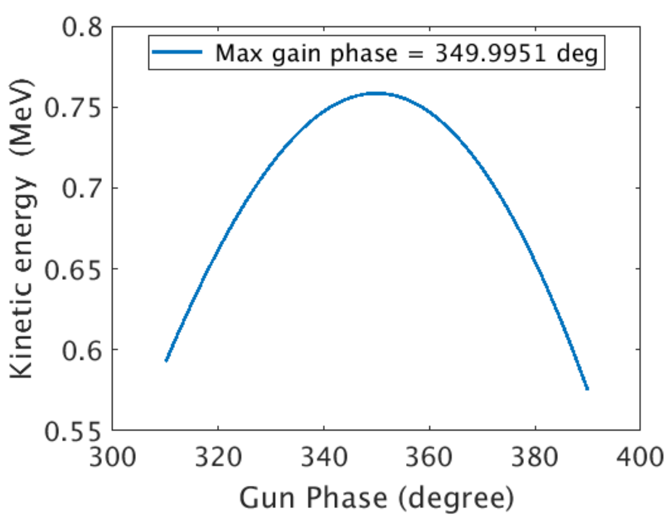

Figure 2 Phase scan of the gun for 16-ps laser pulse.

Fixing the gun off-crest phase at 8.2 deg, we can scan the phase of the buncher cavity to determine the zero-cross phase (zero energy gain phase) at 20.5 deg, as shown in Figure 3.

Then 23.5 deg buncher phase means the -87 deg off-crest phase. Note that the maximum energy gain of the buncher is ~200 keV when the gradient set in the input file is 1.8 MV/m.

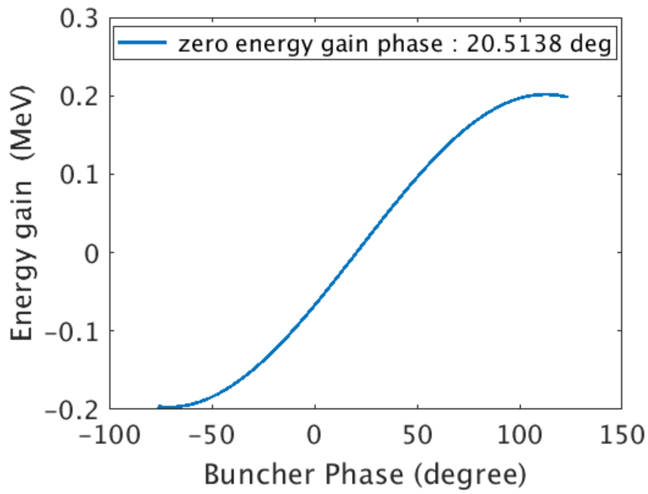

Figure 3 Phase scan of buncher cavity with gun off-crest phase 8.2 deg.

Fixing the gun and buncher phase, the phase scan of the 1st and 3rd cavity in CM is shown in Figure 4. Note that the change of gradient in cavity 1 may change its on-crest phase too. The cavity 2 in our simulations is always off.

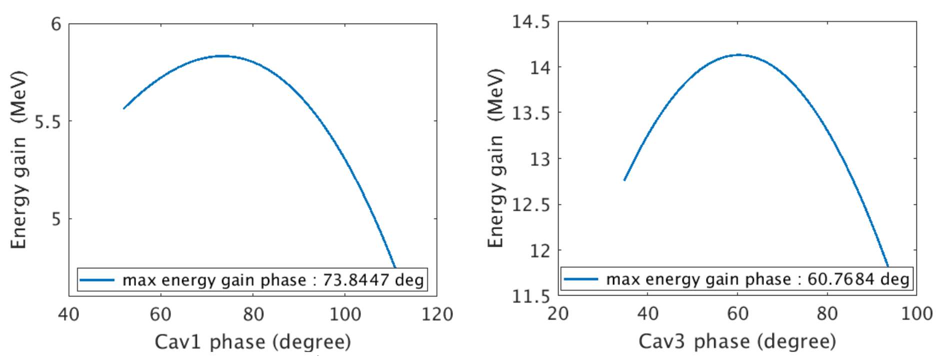

Figure 4 Phase scan of 1^{st} and 3^{rd} cavity in CM. The average gradient is 5.7 MV/m in cavity 1 and 13.47 MV/m in cavity 3.

The phase scan of the cavity 4-8 can be obtained the same way. It is worth pointing out that the time of flight for a relativistic electron beam is a multiple of RF periods (1/1.3e9 s), which leads to the same on-crest phase for cavity 4-8.

Figure 1 shows that the final bunch length is longer with 16-ps laser pulse while the emittance is similar. The emittance at 16-ps pulse can be further reduced by optimizing the second solenoid and the gradient of the cavity 1. For each setting of the second solenoid, we can find an optimal gradient of the cavity 1 to minimize the emittance. The best emittance can be obtained by choosing the smallest emittance among these minimums. The final emittance of 100 pC with 16-ps laser pulse is ~0.42 μm and the corresponding bunch length is ~1.33 mm (as shown in Figure 5). Both the strength of the second solenoid and the gradient of the cavity 1 are reduced compared with the initial settings for 20-ps laser (2^{nd} solenoid 300Gs → 290 Gs and the gradient of cavity 1 5.7 MV/m → 4.9 MV/m).

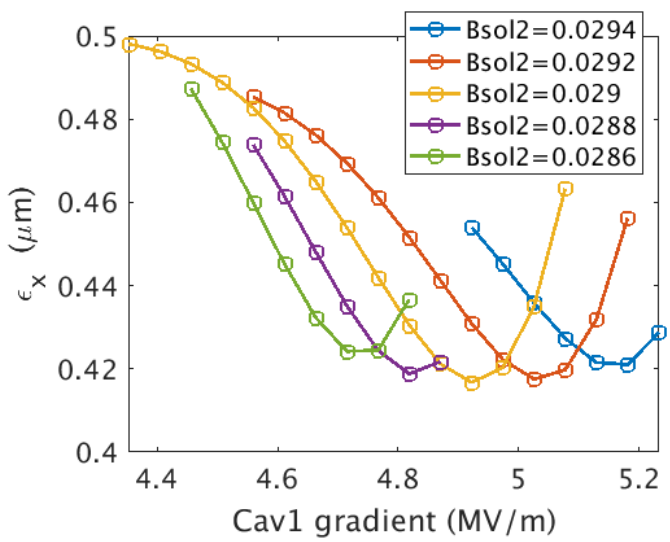

Figure 5 Emittance optimization of 16-ps laser pulse and 100-pC beam charge. The final rms bunch length is ~1.33 mm.

2.2 Control of electron bunch length

As seen in Figure 1, the bunch length of the electron beam becomes larger if we simply reduce the laser pulse length from 20 ps to 16 ps (1 mm → 1.33 mm). The buncher phase is already very close to the zero-crossing phase (-87 deg) so it is hard to increase the RF chirp from the buncher if we cannot increase its gradient. To compress the beam down to ~1 mm rms bunch length, we have two options. One is to use cavity-1 of the CM to compress the bunch with off-crest phase acceleration (velocity bunching). The other one is to reduce the space-charge-induced energy chirp in the drift from gun to buncher. From the previous analysis, we should increase the bunch length after the cathode emission. This can be achieved by decreasing the transverse beam size (controlled by the laser spot size). In this technote, we will use the second method to enhance the beam velocity bunching. The diameter of the laser spot is 1 mm in the previous simulations. We can reduce it to 0.8 mm to increase the bunch length after the gun and hence decrease the final bunch length. Note that the change of the laser spot size will not affect the phase of all downstream RF cavities (to be more precise, the phase of RF cavities is independent from the space-charge force).

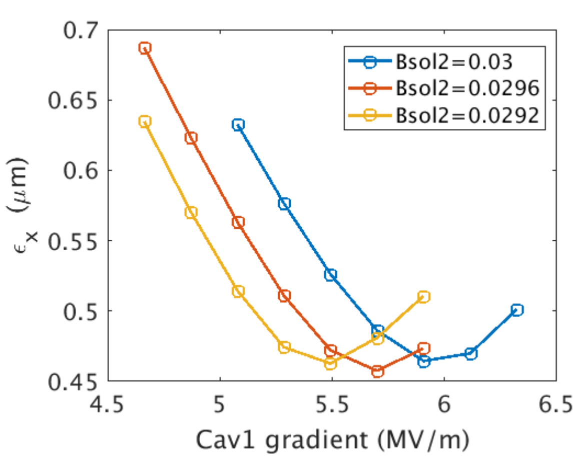

Figure 6 The optimization of beam emittance when laser spot diameter is 0.8 mm.

The emittance optimization for 0.8 iris diameter is presented in Figure 6. The final emittance is ~0.45 μm at the bunch length ~1 mm. The comparisons of different laser spot size are shown in Figure 7. The optimal strength of the second solenoid is 296 Gs and the peak gradient of the buncher is 5.7 MV/m. We will take this configuration as the optimal one for 100-pC beam charge with 16-ps laser pulse. The detailed settings of the simulations will be summarized below in Table 1.

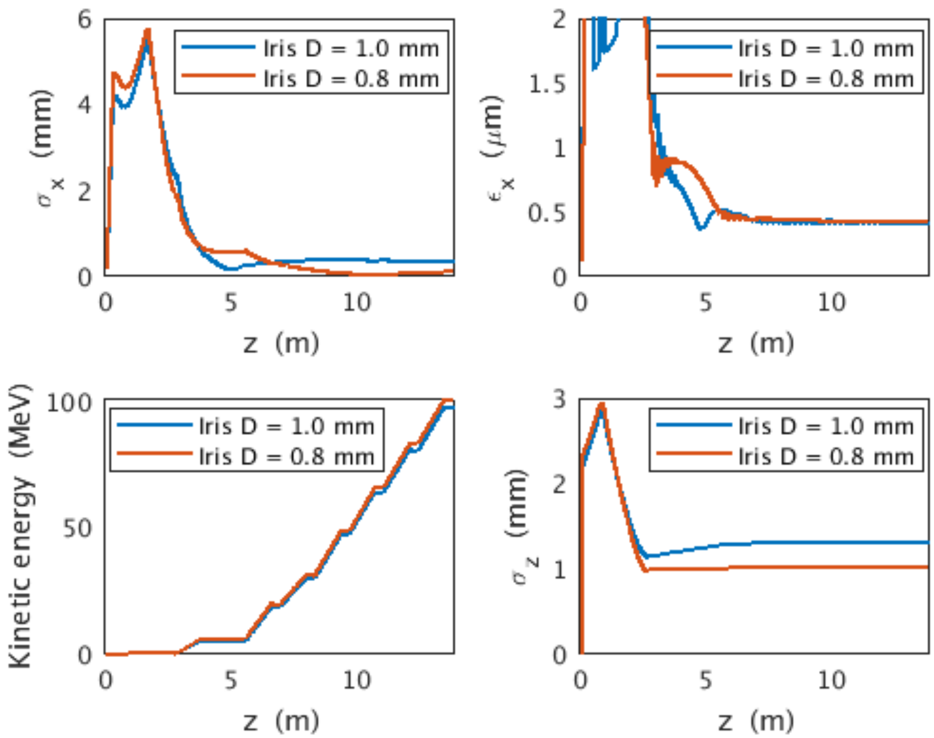

Figure 7 Simulation results of iris diameter 1.0 mm and 0.8 mm including beam size, emittance, kinetic energy, and bunch length along the beamline.

2.3 Configuration for 50-pC and 20-pC beam charge

We can get the configuration for 50/20-pC beam charge by modifying the 100-pC configuration step-by-step. First, we reduce the beam charge from 100 pC to 50/20 pC without changing the laser pulse length and spot size. The compression will be larger at the end because the lower beam charge reduces the space-charge-induced energy chirp before buncher. We can vary the buncher phase (move further from the zero-crossing phase) to control the beam compression. The change of the buncher phase will change the beam energy after buncher. For the low-energy (<1MeV) beam, the change of energy will affect the time of flight to CM. Therefore, we need to re-scan the phase of CM cavities. After resetting all CM cavities to be on-crest phase, we can optimize the emittance by matching the second solenoid and the gradient of the cavity 1. Though the change of gradient will affect the on-crease phase of cavity 1, this effect is small and negligible within the gradient range we consider.

The optimization of beam emittance for 50- and 20-pC beam charge are shown in Figure 8 and Figure 9, respectively. The minimum emittance is ~0.29 μm for 50 pC and 0.24 μm for 20 pC. In the optimal configuration, the strength of the 2nd solenoid is 308 (336) Gs and the peak gradient of cavity 1 is 6.7 (8.0) MV/m for 50 (20) pC, respectively.

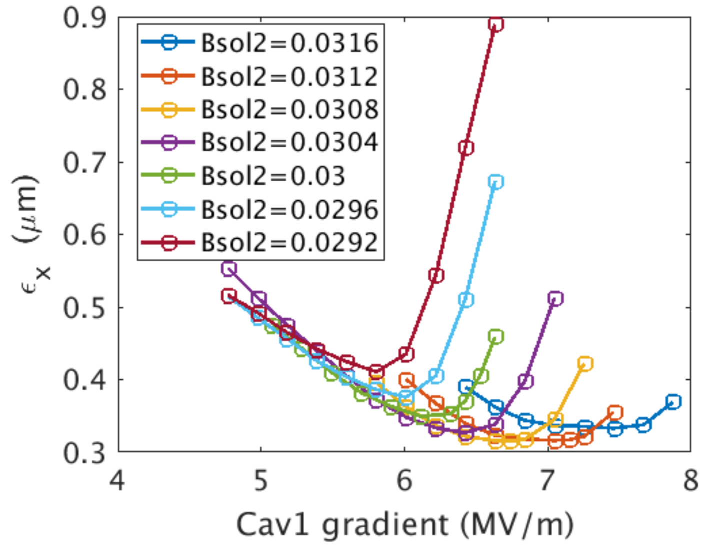

Figure 8 The optimization of beam emittance for 50-pC beam charge.

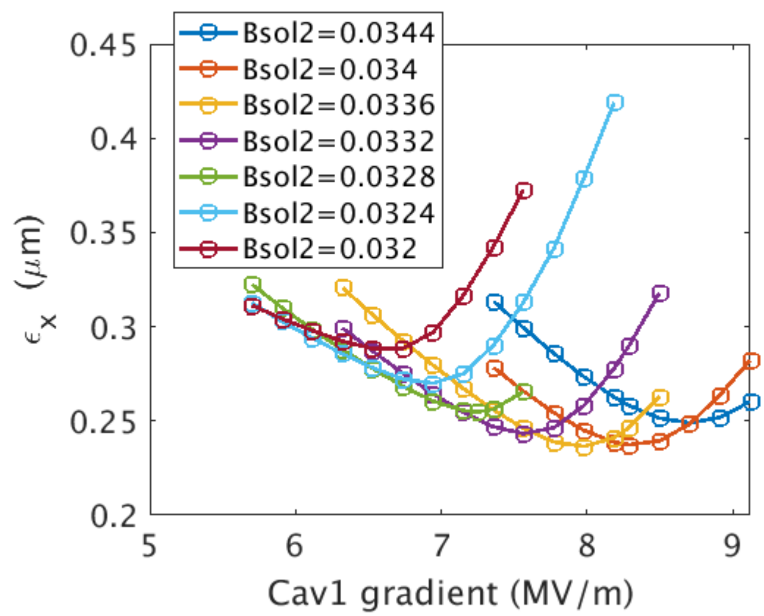

Figure 9 The optimization of beam emittance for 20-pC beam charge.

The simulation results of the optimal configurations for 100/50/20-pC beam charges are shown in Figure 10. The final bunch lengths are 1/0.78/0.56 mm and emittance 0.44/0.29/0.23 μm. The detailed settings of the simulations can be found in Table 1.

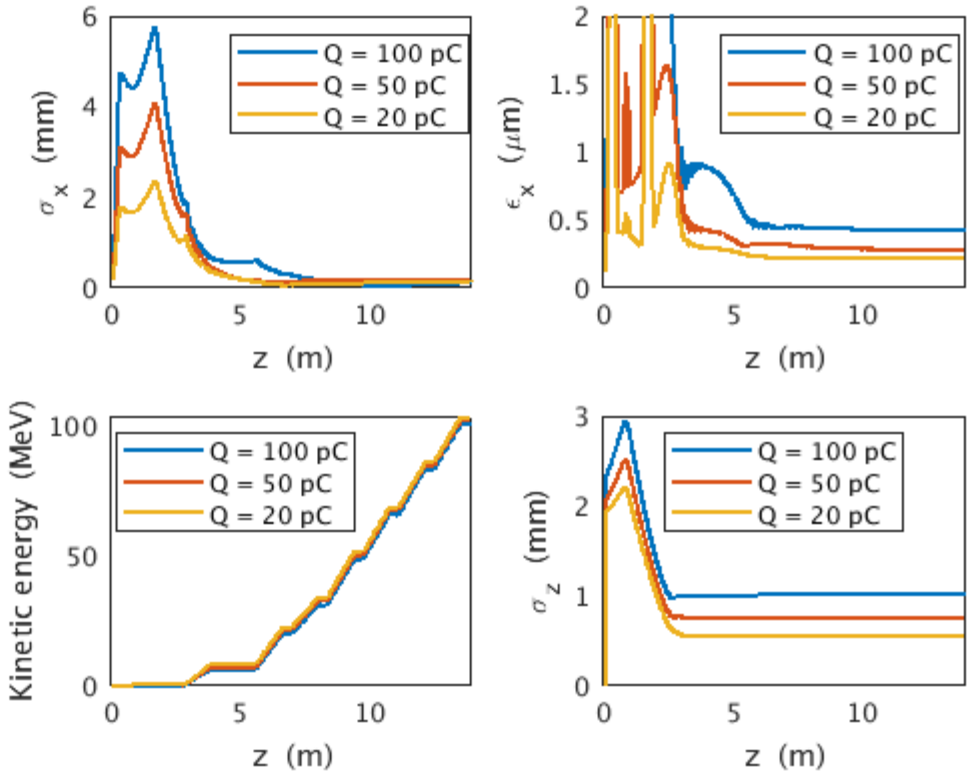

Figure 10 Simulation results of optimal configurations for 100/50/20 pC including beam size, emittance, kinetic energy, and bunch length along the beamline.

2.4 Laser iris size for low charge

In the simulations for 50/20 pC, we did not change the laser spot size. The 0.8-mm-diameter iris is relatively large for low charge (20 pC). The beam emittance probably can be further reduced if we adopt a smaller iris. Preliminary simulations show that the minimum emittance is reduced from 0.23 μm to 0.22 μm and the bunch length is reduced from 0.56 mm to 0.52 mm if we use a 0.5-mm iris to replace the original 0.8-mm iris. In the early stage of commissioning, we could just use 0.8-mm iris for all beam charge. The effect of smaller iris on emittance can be tested in the future optimization of injector emittance.

2.5 Thermal emittance

In the above IMPACT-T simulation examples, the thermal emittance is 0.6 μm/mm, which is smaller than the number used in the Astra simulations (0.8 μm/mm). This probably explains why the emittance we obtained from IMPACT-T is a bit smaller than the one from Astra in the previous optimization [1]. We also perform simulations for different beam charges with increased thermal emittance (0.8 μm/mm). The simulation results show that the increase of the thermal emittance will not change the optimal configuration but will increase the values of beam emittance. The optimizations of emittance for each beam charge are given in Figure 11. The final beam emittance is increased from 0.44/0.29/0.23 μm to 0.49/0.35/0.28 μm. These new values are close to the results in the previous optimizations [1].

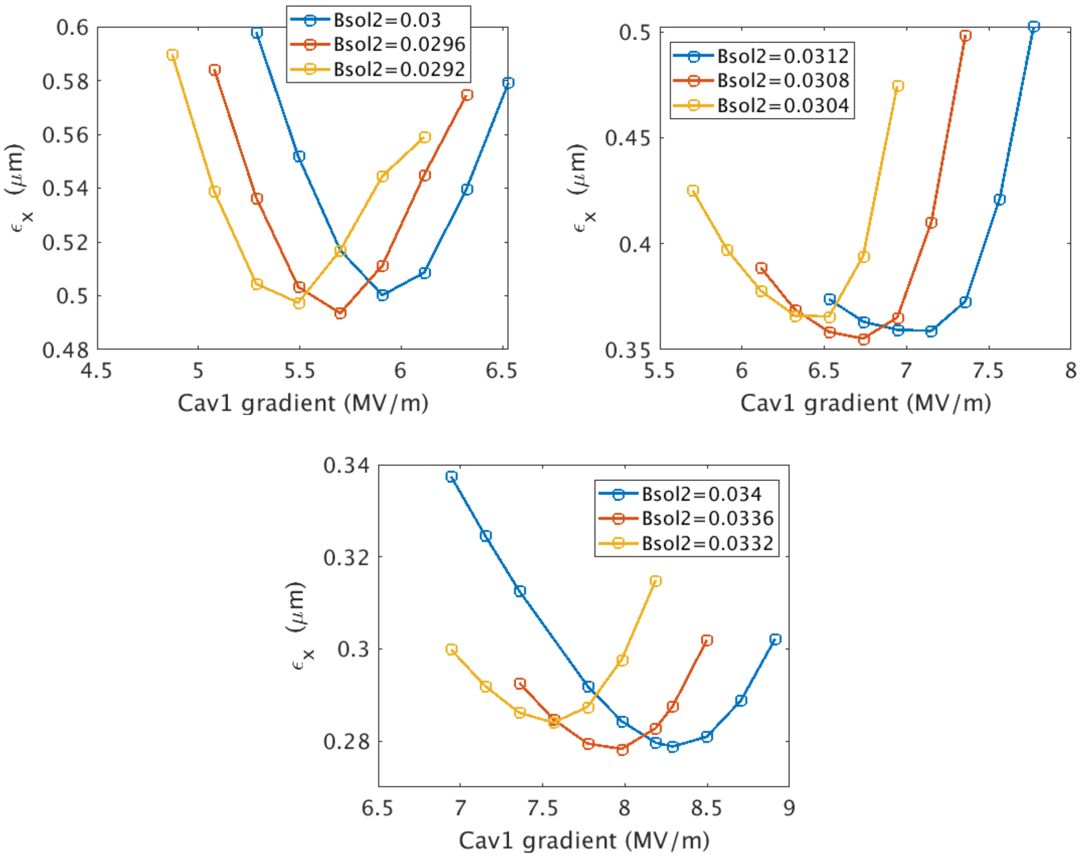

Figure 11 The optimization of beam emittance for 100/50/20 pC respectively with 0.8 μm/mm thermal emittance.

3 Summary of simulation parameters

We summarize the parameter settings of the three optimal configurations for 100/50/20 pC in Table-1. Note that the emittance values are obtained with 0.8 μm/mm thermal emittance. All phases of RF cavities are relative phases with respect to the on-crest phase (0 deg). The gradient of the CM cavities represents the average gradient, which is equal to the peak gradient set in the input deck divided by 1.93. The three main knobs that we need to adjust when changing the bunch charge are buncher phase, solenoid-2, and cavity-1 gradient.

We also plotted the longitudinal phase space in Figure 12 based on the Table-1 settings. Note using the Table-1 on-crest phase setting, there is some residual chirp on the beam. This can be corrected by tweaking the last cavity phase (or cavity-6 if the last two cavities are used for feedback). We show in Figure 13 the longitudinal phase space with changing the last (or the 6th) cavity phase: -13 deg for 100pC; -5 deg for 50pC; and +5 deg for 20pC.

Table 1: Injector parameter for 20/50/100 pC with a Gaussian-shape laser pulse.

	20pC	**50pC**	**100pC**
Gaussian Laser FWHM (ps)	16	16	16
Iris diameter (mm)	0.8	0.8	0.8
Gun Phase (deg)	8	8	8
Gun E_{peak} (MV/m)	20	20	20
Buncher E_{peak} (MV/m)	1.8	1.8	1.8
Buncher Phase (deg)	**-71.5**	**-83.5**	**-88.5**
Solenoid 1 (kG-m)	0.0482	0.0482	0.0482
Solenoid 2 (kG-m)	**0.0289**	**0.0265**	**0.0255**
Cavity 1 Phase (deg)	On-crest	On-crest	On-crest
Cavity 1 E_{avg}(MV/m)	**7.98**	**6.74**	**5.70**
Cavity 2	Off	Off	Off
Cavity 3 Phase (deg)	On-crest	On-crest	On-crest
Cavity 3 E_{avg}(MV/m)	13.47	13.47	13.47
Cavity 4-8 Phase (deg)	On-crest	On-crest	On-crest
Cavity 4 E_{avg}(MV/m)	10.88	10.88	10.88
Cavity 5-8 E_{avg} (MV/m)	16.6	16.6	16.6
Injector σ_z (mm)	**0.56**	**0.78**	**1.04**
100% Norm. emittance (um)	**0.28**	**0.36**	**0.49**
Kinetic energy (MeV)	**104.1**	**102.9**	**101.3**

* Thermal emittance 0.8 μm/mm.

** CM cavity gradient represents average value ($E_{avg} = E_{peak}/1.93$).

*** Solenoid effective length Leff = 0.086 m. The strength (kG-m) is peak field × Leff.

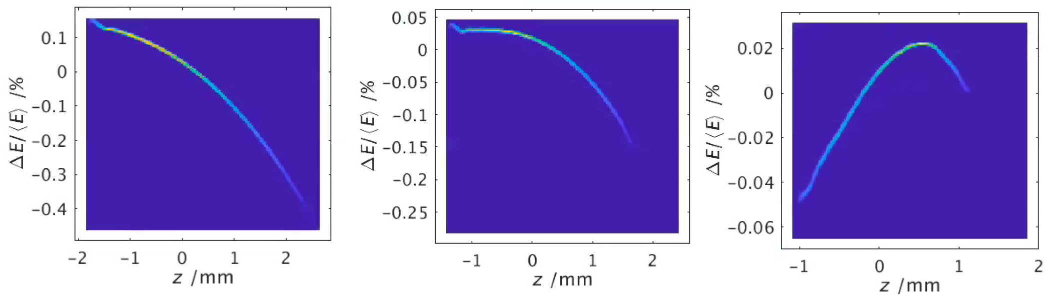

Figure 12 The longitudinal phase space of the three bunch charges (from left to right: 100pC, 50pC, 20pC) based on the settings in Table-1.

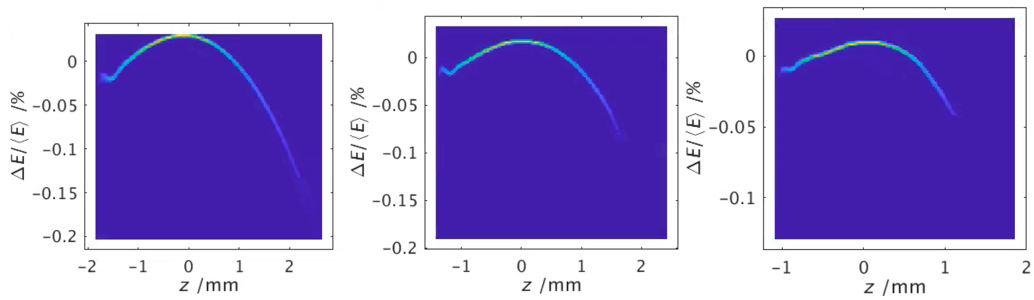

Figure 13 The longitudinal phase space of the three bunch charges (from left to right: 100pC, 50pC, 20pC) after adjusting the last (or 6th) cavity phases: -13 deg for 100pC; -5 deg for 50pC; and +5 deg for 20pC.

4 Linac and compressor settings

These injector beams for the three bunch charges from the configurations in Table-1 (after chirp correction, i.e., beams like in Figure 13) have been tested for further downstream acceleration/compression in LCLS-II. We are using the "standard" linac/compressor settings as listed in Table-2 of Ref [1]. The results from LiTrack simulations show the established "standard" linac/compressor configurations in Ref [1] work well with the beams output from this IMPACT-T simulation; we only need to tweak slightly the L2 phase (and amplitude accordingly) to achieve a similar final beam as shown in Ref [1]. More detailed Elegant simulations can be performed in the next step.

Reference:

[1]. N. Neveu and Y. Ding, LCLS-II technical note LCLS-II-TN-21-01.

[2]. K. Floettmann, ASTRA: A Space Charge Tracking Algorithm, http://www.desy.de/~mpyflo/

[3]. J. Qiang, IMPACT-T: A 3D parallel particle tracking code in time domain. https://amac.lbl.gov/~jiqiang/IMPACT-T/index.html