LCLS-II Technical Note

# LCLS-II injector optimization with limited cryomodule CM01 performance

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# 1 Introduction

The LCLS-II has been commissioned over the past two years and achieved first lasing in August 2023. The LCLS-II injector is crucial for the facility's success, delivering low-emittance continuous-wave (CW) electron beams. However, field emission has recently been observed in the cryomodule CM01 of the injector since end of September 2023, leading to low-gradient operation for some cavities. Consequently, the total beam energy after CM01 with the original configuration falls outside the range of the laser heater [1]. To address this issue, the second cavity in CM01, previously set to OFF in the injector's optimizations [2], is being considered for activation to increase the total beam energy. This technote discusses the optimization of the LCLS-II injector, considering the limited performance of CM01 with lower gradients for some cavities due to field emissions.

Simulations of the LCLS-II injector are conducted using Astra [3], while optimizations are carried out using the Genetic Algorithm in Xopt [4].

# 2 CM01 performance

Figure 1 illustrates the maximum cavity voltage of each cavity in CM01 before and after the field emission event. Before the field emission, all cavities the maximum voltage was administratively set to 16.6 MV; The impact of field emission affects CAV2 to CAV5, and the most significant one is the 4th cavity (CAV4), where the maximum voltage decreased from 16.6 MV to 5 MV. We also provide the cavity voltages actually used during commissioning (for example, CAV2 was OFF for best emittance), revealing that the primary source for compensating the energy loss of CAV4 is the first two cavities (CAV1 and CAV2). However, operating CAV1 at a high voltage would compromise beam emittance, as indicated by simulations. Therefore, we are considering activating CAV2 and optimizing beam quality accordingly. It is important to note that, for stable operation of the cavity in CM01, the minimum cavity voltage required is 5 MV.

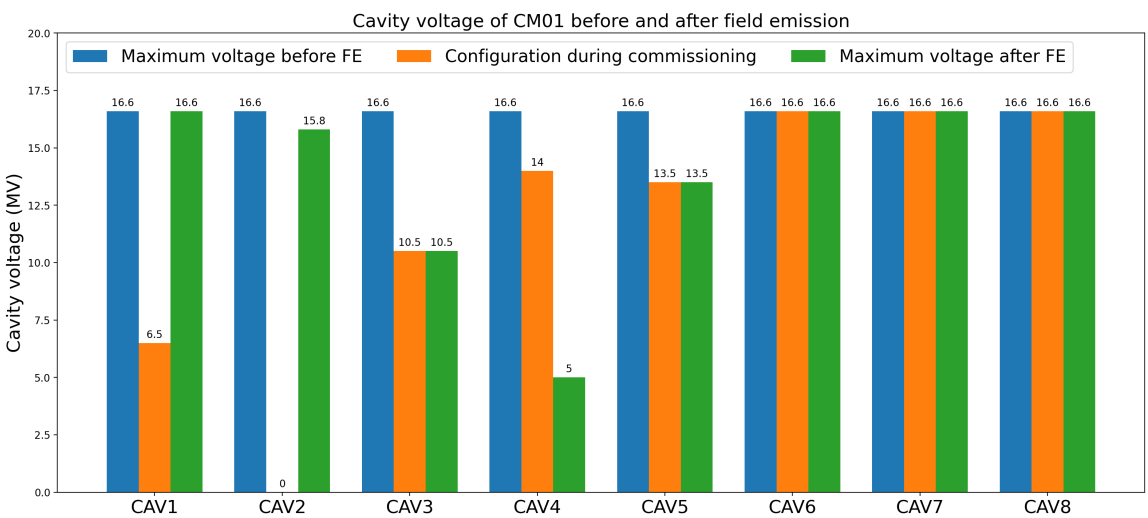


**Figure 1 Cavity voltage of CM01 including maximum voltage before and after field emission, and the configuration used in the commissioning.**

Additionally, a new undulator with a lower resonant energy in the laser heater is also under

consideration. This technote aims to provide optimal beam quality for a wide range of beam energies, which can serve as a reference for determining the detailed parameters of the new undulator.

# 3 Constants and variables in optimizations

The constants and variables relevant to the LCLS-II injector optimizations are summarized in Table 1. Note comparing to previous optimizations [2], here the gun energy has been reduced to approximately 650 keV. The drive laser has a Gaussian temporal profile and uniform transverse distribution. To account for dark current considerations, the first solenoid, SOL1, must be greater than 0.04415 kGs·m. The buncher phase is utilized for controlling beam compression. All CM01 cavities are operated on-crest. In practice, the cavity voltage must exceed 5 MV for stable operation. The voltages of the first three cavities are utilized in the optimization process, while those of the remaining cavities are employed for final beam energy control. CAV2 may be either off or on.

**Table 1 Constants and variables in the LCLS-II injector optimizations**

| Constants in GA optimizations | | |
|---|---|---|
| **Parameter** | **Value** | **Unit** |
| Gun energy | ~650 | keV |
| Gun phase | 0 (on-crest) | deg |
| Bunch voltage | 200 | kV |
| Laser temporal profile | Gaussian | |
| Laser FWHM / RMS | 16.5 / 7 | ps |
| MTE / thermal emittance | 330 / 0.8 | meV / um/mm |
| CAV1-8 phase | 0 (on-crest) | deg |
| CAV4 energy gain | 5 | MeV |
| CAV5 energy gain | 13.5 | MeV |
| CAV6-8 energy gain | 16.6 | MeV |
| **Variables in GA optimizations** | | |
| **Parameter** | **Range** | **Unit** |
| Laser uniform spot radius | 0.2 ~ 1.0 | mm |
| Buncher phase | -140 ~ -20 | deg |
| Solenoid SOL1 | 0.04415 ~ 0.05 | kGs·m |
| Solenoid SOL2 | 0.017 ~ 0.034 | kGs·m |
| CAV1 energy gain | 6.5 ~ 16 | MeV |
| CAV2 energy gain | 0 or 5 ~15.8 | MeV |
| CAV3 energy gain | 5 ~ 10.5 | MeV |

# 4 Injector optimization with CAV2 ON/OFF

In this section, we compare injector optimizations with CAV2 either ON or OFF for charge values of 100 pC, 50 pC, and 20 pC, respectively. For the convenience of practical operation, we also include the optimization results where the energy gain of CAV2 is fixed at 5 MeV.

Figure 2 shows the three cases for a charge of 100 pC, we can see that a rms bunch length of 1 mm, the optimal emittance is 0.71 µm with CAV2 ON and 0.57 µm with CAV2 OFF. If the energy gain of CAV2 is fixed at 5 MeV, the optimal emittance is 0.80 µm. The settings of the variables for these three cases are shown in Table 2.

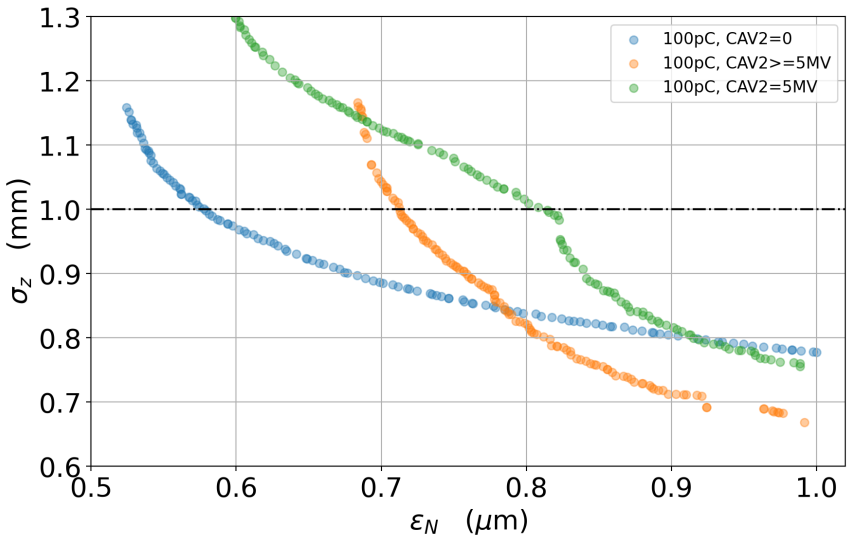


**Figure 2 Pareto front of LCLS-II injector emittance and bunch length with CAV2 ON and OFF. The beam charge is 100 pC.**

**Table 2 Injector settings for rms bunch length of 1 mm with CAV2 ON and OFF. The beam charge is 100 pC.**

| Parameter | Laser Radius (mm) | Buncher phase (deg) | SOL1 (kGs·m) | SOL2 (kGs·m) | CAV1 energy (MeV) | CAV2 energy (MeV) | CAV3 energy (MeV) | Total CM energy (MeV) | Emittance (µm) |
|---|---|---|---|---|---|---|---|---|---|
| CAV2 OFF | 0.67 | -79.9 | 0.04415 | 0.02487 | 6.5 | 0 | 10.5 | 85.3 | 0.57 |
| CAV2 ON | 0.75 | -80.5 | 0.04415 | 0.02451 | 7.2 | 15.8 | 10.5 | 101.8 | 0.71 |
| CAV2 ON (@5 MV) | 0.76 | -81.7 | 0.04415 | 0.02451 | 6.5 | **5** | 10.5 | 90.3 | 0.8 |

For a charge of 50 pC and a rms bunch length of 0.8 mm, the optimal emittance is 0.49 µm with CAV2 ON and 0.37 µm with CAV2 OFF. If the energy gain of CAV2 is fixed at 5 MeV, the optimal emittance is 0.49 µm. The settings of the variables for these three cases are shown in Table 3.

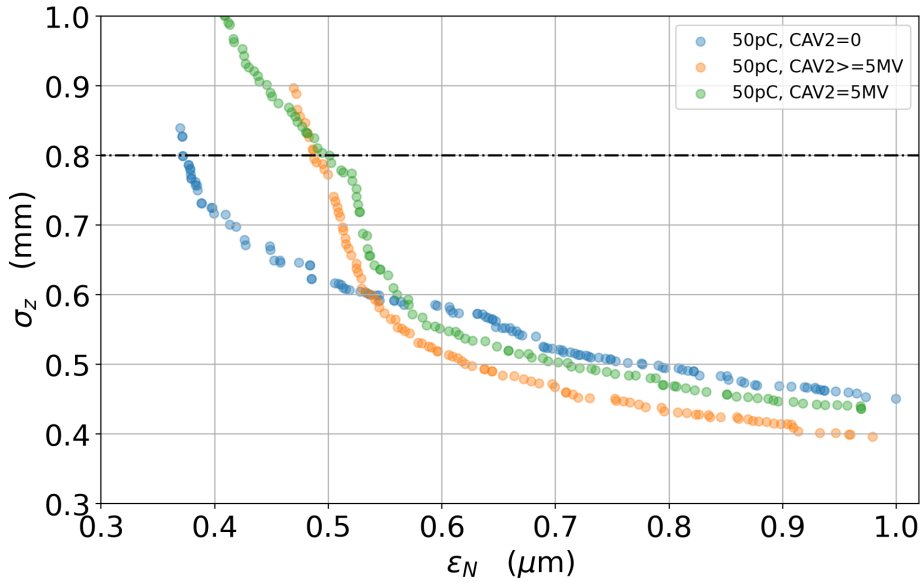


**Figure 3 Pareto front of LCLS-II injector emittance and bunch length with CAV2 ON and OFF. The beam charge is 50 pC.**

**Table 3 Injector settings for rms bunch length of 0.8 mm with CAV2 ON and OFF. The beam charge is 50 pC.**

| Parameter | Laser Radius (mm) | Buncher phase (deg) | SOL1 (kGs·m) | SOL2 (kGs·m) | CAV1 energy (MeV) | CAV2 energy (MeV) | CAV3 energy (MeV) | Total CM energy (MeV) | Emittance (μm) |
|---|---|---|---|---|---|---|---|---|---|
| CAV2 OFF | 0.49 | -66.5 | 0.04421 | 0.02542 | 6.5 | 0 | 10.5 | 85.3 | 0.37 |
| CAV2 ON | 0.63 | -70.7 | 0.04417 | 0.02583 | 7.2 | 15.8 | 10.5 | 101.8 | 0.49 |
| CAV2 ON (@ 5MV) | 0.57 | -68.99 | 0.04415 | 0.02575 | 6.5 | **5** | 10.5 | 90.3 | 0.49 |

For a charge of 20 pC and a rms bunch length of 0.6 mm, the optimal emittance is 0.30 μm with CAV2 ON and 0.26 μm with CAV2 OFF. For 20-pC beam charge, the optimal emittance is achieved when the energy gain of CAV2 is 5 MeV. The settings of the variables for these two cases are shown in Table 4.

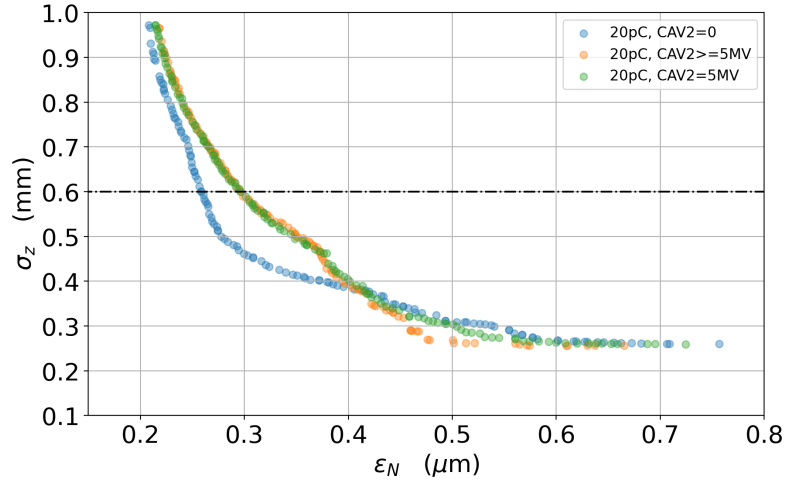


**Figure 4 Pareto front of LCLS-II injector emittance and bunch length with CAV2 ON and OFF. The beam charge is 20 pC.**

**Table 4 Injector settings for rms bunch length of 0.6 mm with CAV2 ON and OFF. The beam charge is 20 pC.**

| Parameter | Laser Radius (mm) | Buncher phase (deg) | SOL1 (kGs·m) | SOL2 (kGs·m) | CAV1 energy (MeV) | CAV2 energy (MeV) | CAV3 energy (MeV) | Total CM energy (MeV) | Emittance (μm) |
|---|---|---|---|---|---|---|---|---|---|
| CAV2 OFF | 0.27 | -53.7 | 0.04448 | 0.02567 | 7.1 | 0 | 10.5 | 85.9 | 0.3 |
| CAV2 ON | 0.21 | -50.3 | 0.04417 | 0.02506 | 6.8 | 5.0 | 10.5 | 90.6 | 0.26 |

# 5 Maximum and minimum beam energy

In this section, we investigate the maximum and minimum beam energy levels at which both the beam emittance and bunch length are preserved, considering various beam charges and configurations. To run the injector at a relatively lower energy level, in general one can reduce the gradient of the last few cavities since they are set high. Also since setting the CAV2 OFF helps emittance as seen from the Section-4 results, when the energy goal is more than 5 MeV lower, we can choose to keep CAV2 OFF.

For the configuration with a charge of 100 pC and CAV2 ON, it is possible to reduce the energy gain of the last four cavities in CM01 to 5 MeV, thereby lowering the beam energy from 102 MeV to 59 MeV. Simulation results depicted in Figure 5 indicate that the emittance is preserved during this energy reduction process.

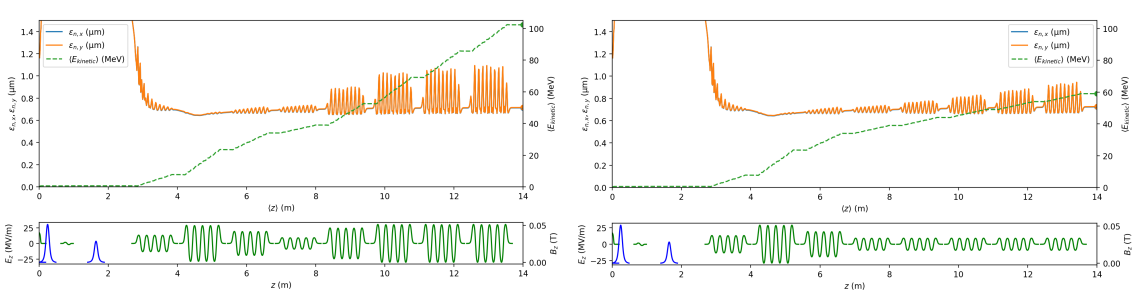

**Figure 5 100 pC and CAV2 ON: beam emittance and energy along the beamline (top) including field plots (bottom). The left one is maximum beam energy while the right one is the minimum beam energy.**

For the configuration with a charge of 100 pC and CAV2 OFF, it is possible to reduce the energy gain of the last three cavities in CM01 to 5 MeV, thereby lowering the beam energy from 86 MeV to 51 MeV. Simulation results depicted in Figure 6 indicate that the emittance is preserved during this energy reduction process.

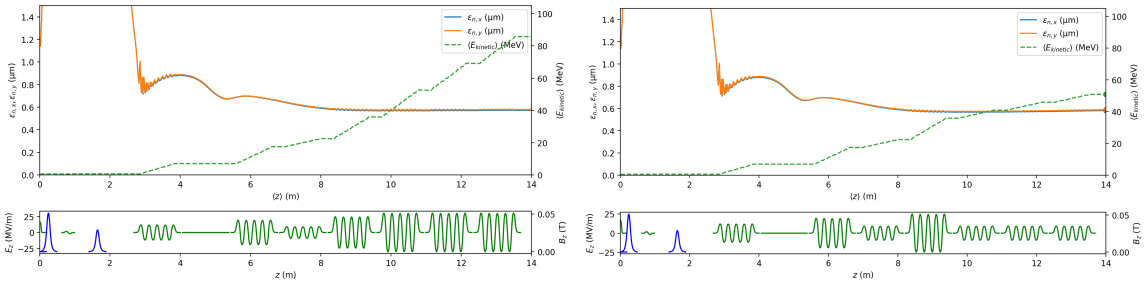


**Figure 6 100 pC and CAV2 OFF: beam emittance and energy along the beamline (top) including field plots (bottom). The left one is maximum beam energy while the right one is the minimum beam energy.**

For the configuration with a charge of 50 pC and CAV2 ON, it is possible to reduce the energy gain of the last three cavities in CM01 to 5 MeV, thereby lowering the beam energy from 102 MeV to 59 MeV. Simulation results depicted in Figure 7 indicate that the emittance is preserved during this energy reduction process.

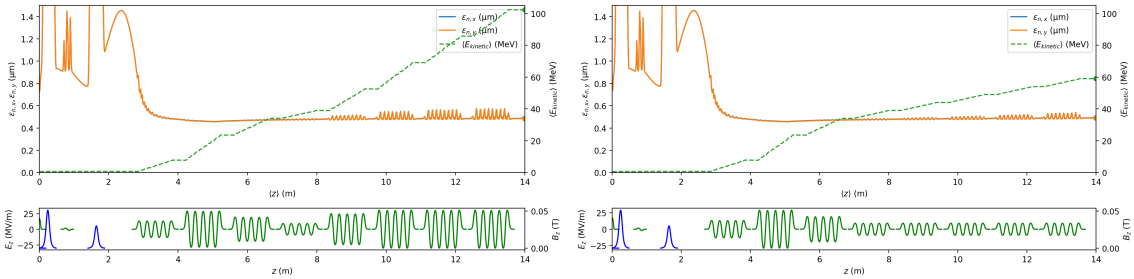


**Figure 7 50 pC and CAV2 ON: beam emittance and energy along the beamline (top) including field plots (bottom). The left one is maximum beam energy while the right one is the minimum beam energy.**

For the configuration with a charge of 50 pC and CAV2 OFF, it is possible to reduce the energy gain of the last four cavities in CM01 to 5 MeV, thereby lowering the beam energy from 86 MeV to 42 MeV. Simulation results depicted in Figure 8 indicate that the emittance is preserved during this energy reduction process.

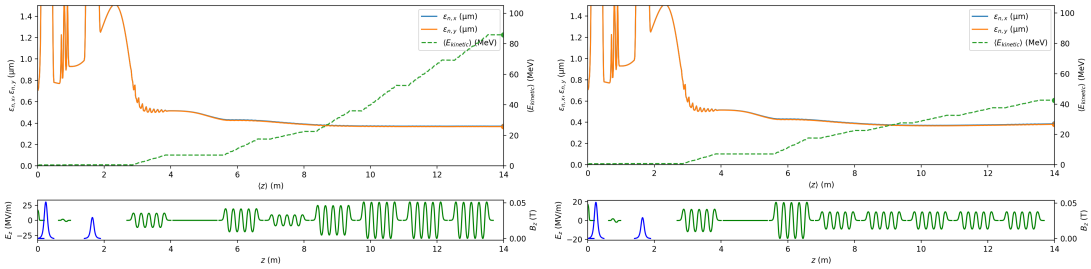


**Figure 8 50 pC and CAV2 OFF: beam emittance and energy along the beamline (top) including field plots (bottom). The left one is maximum beam energy while the right one is the minimum beam energy.**

For the configuration with a charge of 20 pC and CAV2 ON, it is possible to reduce the energy gain of the last four cavities in CM01 to 5 MeV, thereby lowering the beam energy from 91 MeV to 48 MeV. Simulation results depicted in Figure 9 indicate that the emittance is preserved during this energy reduction process.

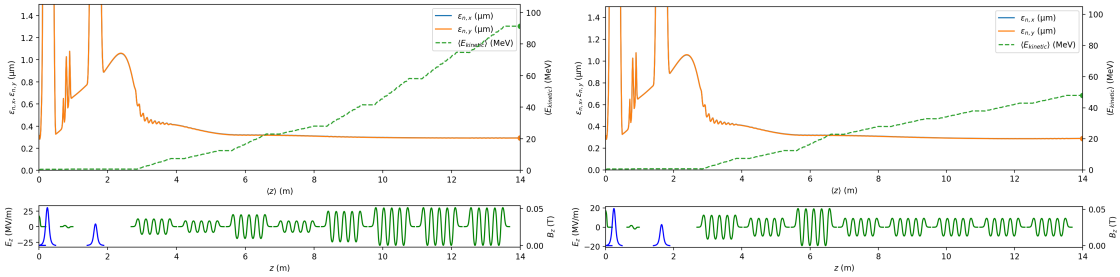

**Figure 9 20 pC and CAV2 ON: beam emittance and energy along the beamline (top) including field plots (bottom). The left one is maximum beam energy while the right one is the minimum beam energy.**

For the configuration with a charge of 20 pC and CAV2 OFF, it is possible to reduce the energy gain of the last four cavities in CM01 to 5 MeV, thereby lowering the beam energy from 86 MeV to 43 MeV. Simulation results depicted in Figure 10 indicate that the emittance is preserved during this energy reduction process.

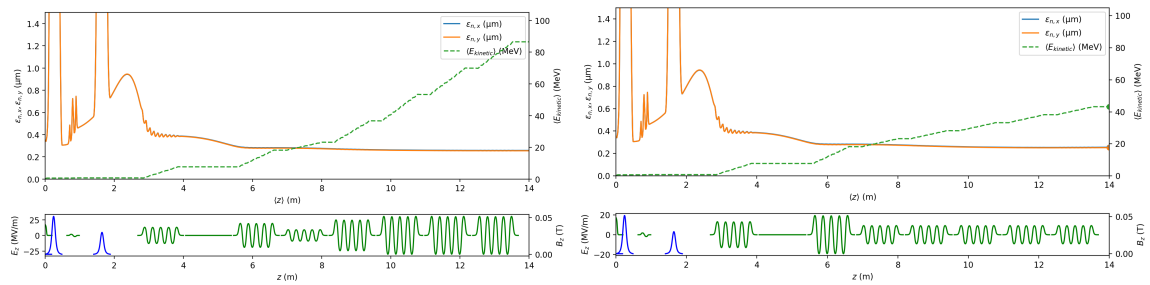

**Figure 10 20 pC and CAV2 OFF: beam emittance and energy along the beamline (top) including field plots (bottom). The left one is maximum beam energy while the right one is the minimum beam energy.**

Based on the simulation results above, we can summarize the achievable injector beam emittance for different beam energies. Note that for columns with total energy larger than 85 MeV, the CAV2 needs to be ON (>= 5 MeV), All other columns the emittance results are from the CAV2 OFF configuration.

**Table 5 Achievable injector emittance at different beam energies for different beam charges.**

| | | Achievable injector beam emittance (μm) | | | | |
|---|---|---|---|---|---|---|
| Bunch charge (pC) | Rms bunch length (mm) | 60 MeV | 70 MeV | 80 MeV | 90 MeV | 100 MeV |
| 100 | 1.0 | 0.58 | 0.58 | 0.57 | 0.71 | 0.71 |
| 50 | 0.8 | 0.39 | 0.39 | 0.37 | 0.48 | 0.48 |
| 20 | 0.6 | 0.26 | 0.26 | 0.26 | 0.29 | / |

# 6 Comparisons with previous optimizations

Table 6 compares the results presented in this technote with previous injector optimizations in Ref. [2], as noted "No Constraints" in the table. It is important to note that several significant constraints and changes were identified during commissioning that could degrade beam quality in this technote. For instance, the gun energy was reduced from 750 keV to approximately 650 keV, and the first solenoid SOL1 must be stronger than 0.04415

kGs·m to suppress dark current transmission. This degradation effect appears more pronounced at high beam charge.

**Table 6 Comparisons of the injector optimization results with different conditions.**

| Beam charge (pC) | Optimization scheme | Emittance (μm) | Bunch length (mm) |
|---|---|---|---|
| 100 | No Constraints | 0.49 | 1.04 |
| | CAV2 OFF | 0.57 | 1.00 |
| | CAV2 = 5MeV | 0.80 | 1.00 |
| | CAV2 ≤ 15.8 MeV | 0.71 | 1.00 |
| 50 | No Constraints | 0.36 | 0.78 |
| | CAV2 OFF | 0.37 | 0.80 |
| | CAV2 = 5MeV | 0.49 | 0.80 |
| | CAV2 ≤ 15.8 MeV | 0.48 | 0.80 |
| 20 | No Constraints | 0.28 | 0.56 |
| | CAV2 OFF | 0.26 | 0.60 |
| | CAV2 = 5MeV | 0.29 | 0.60 |
| | CAV2 ≤ 15.8 MeV | 0.29 | 0.60 |

# 7 Acknowledgments

The authors wish to thank Z. Huang, F, Zhou and A. Brachmann for helpful discussions.

**Reference:**

[1]. Z. Huang, LCLSII-2.2-PR-0086-R1.

[2]. Z. Zhang, Y. Ding and F. Zhou, LCLS-II technical note LCLS-II-TN-22-03.

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

[4]. Roussel, R., C. Mayes, A. Edelen, and A. Bartnik. "Xopt: A simplified framework for optimization of accelerator problems using advanced algorithms." Proc. IPAC 23 (2023): 4796-4799.