コンパクト ERL の CW*運転用の入射器設計

INJECTOR DESIGN FOR COMPACT ERL CW* OPERATION

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Abstract

Achieving continuous wave (CW) operation in a Compact Energy Recovery Linac (cERL) injector requires meticulous tuning and accurate model preparation. However, a startup issue arose on November 27th. The buncher response deviated from expectations, and an unexpectedly high field in INJ1 necessitated lowering the field in INJ2-3. This revealed shortcoming in the initial RF optimization. The culprit? The standard two-step optimization process, which minimizes transverse emittance vs bunch length followed by longitudinal emittance vs bunch length minimization, was incomplete. Only the first step was performed. Fortunately, after completing the full optimization process, the final injector parameters closely resembled those achieved during tuning. This experience underscores the importance of a step-wise optimization approach that factors in actual injector parameters like injection energy, gun voltage, and initial beam distribution. Moreover, it highlights the need for continuous model refinement to minimize discrepancies between the model's predictions and the real injector's behavior – a key focus of our current study.

1. INTRODUCTION

KEK's cERL was originally constructed to operate with high average beam current and beam quality [1]. The accelerator consists of a photocathode DC electron gun, a superconducting accelerating cavity (main linear accelerator) equipped for energy recovery operation, a recirculation loop, and an injector (refer to Fig. 1).

The goal for cERL operation in 2023 was to prove 1mA CW operation as it was done in 2019 [2] but for the beam line including undulators in energy recovery mode [3]. To achieve this new goal, the injection energy was set to 2.9 MeV, enabling energy recovery with an energy ratio of 1/6 (E_{inj} = 2.9 MeV / E_{circ} = 17.4 MeV).

Figure 2 presents the layout of the cERL injector, and Table 1 lists the corresponding beam parameters. This table also includes a comparison of injector parameters for two different operation modes: CW mode with energy recovery and single-pass FEL.

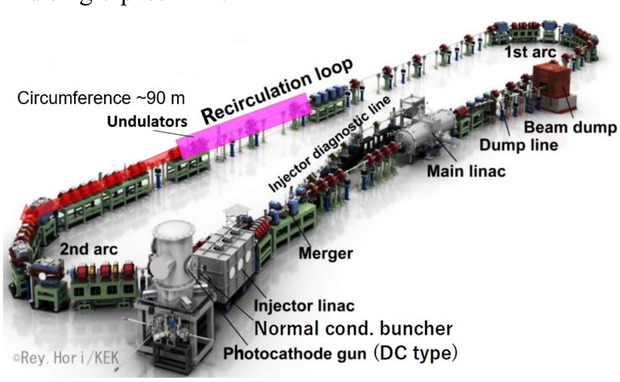

Figure 1: Schematic of the cERL.

* Continuous-wave (CW) operation of an accelerator means that it is continuously operated, i.e., not pulsed.

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Table 1: Design Parameters of the cERL Injector

	CW mode (recovery)	Single-pass FEL
DC gun voltage	450 kV	450 kV
Repetition rate	1.3 GHz	81.5 MHz
Injector energy	2.9 MeV	3.5 MeV
Recirculation energy	17.4 MeV	17.5 MeV
Charge per bunch	0.77 pC	60 pC
Laser temporal distribution	3 ps rms single Gaussian[1]	40 ps FWHM single Gaussian
Laser XY distribution	radial Gaussian+ 0.5 mm pinhole	radial Gaussian+ 2.0 mm pinhole

[1] in the optimization process

2. INJECTOR OPTIMIZATION PROCESS FOR CW OPERATION

Achieving CW operation in cERL necessitates a precise 1:6 energy ratio between the injector and recirculation loop, a low bunch charge of 0.77 pC, minimal beam size, and accurate beam centering. A stable, high accelerating voltage from the 450 kV DC gun is crucial for optimal beam performance. However, conventional optimization methods focused on minimizing bunch length and transverse emittance are insufficient for CW mode due to the significant impact of longitudinal dynamics in the injector on overall beam quality. To address this, a two-step optimization process for the injector model, considering a 450 kV gun, 2.9 MeV injector energy, 0.77 pC bunch charge, and 3 ps rms Gaussian pulse, was implemented.

Due to time constraints, only the first stage of the optimization, focusing on simultaneously minimizing bunch length and transverse emittance, was completed. When attempting to implement the injector model based on

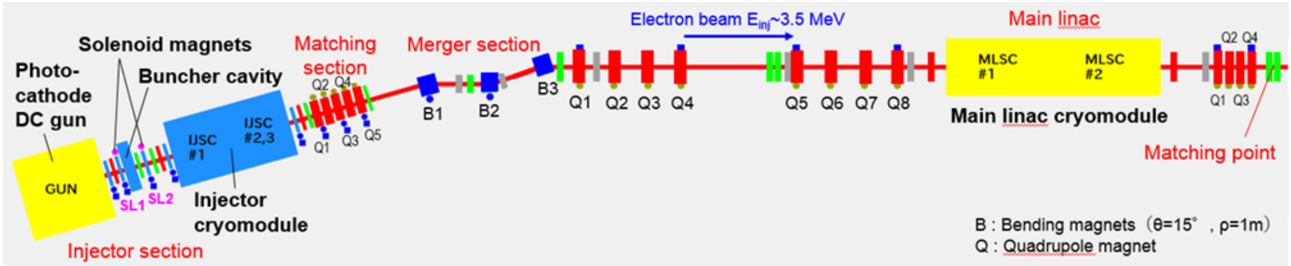

Figure 2: Layout of cERL injector line.

this incomplete model during the November 2023 startup, the beam proved impossible to tune, and the RF settings were incorrect. To initiate the injector operation, we resorted to reloading RF and magnet settings from the previous run. Given the differing initial injector parameters for this operation, manual adjustments were necessary. Through this careful tuning, we eventually enabled the startup of the remaining accelerator components. Table 2 summarizes both the injector settings proposed by the incomplete model ('stdz vs enxy' column) and the values achieved through manual tuning ('operation' column).

Upon completion of the run, we conducted the second stage of optimization (column 'stdz vs enz' in Table 2) to compare the parameter settings obtained from the optimized model predictions with those determined through manual tuning.

Table 2: Injector Settings

Parameters	Stdz vs enxy	Stdz vs enz	Operation
Solenoid #1 voltage (A)	8.31	8.20	7.13
Solenoid #2 voltage (A)	5.09	5.35	5.32
Buncher voltage (kV)	40.91	41.91	41.20
INJ1 field (MV/m)	3.39	3.54	3.17
INJ2 field (MV/m)	3.57	3.78	3.29
INJ3 field (MV/m)	3.21	3.04	3.05
INJ1 phase offset	-29.89	-29.88	-29.00
INJ2 phase offset	0	0	0
INJ3 phase offset	0	0	0
K1QMGC01 (1/m2)	-7.60	-7.27	1.80
K1QMGC02 (1/m2)	0	0	0
K1QMGC03 (1/m2)	8.64	12.24	-23.25
K1QMGC04 (1/m2)	0	0	0
K1QMGC05 (1/m2)	-2.89	-8.15	5.52
K1QMAG01 (1/m2)	-8.55	-6.25	-8.85
K1QMAG02 (1/m2)	17.22	15.13	0.02
K1QMAG03 (1/m2)	-5.42	0.17	-4.73
K1QMAG04 (1/m2)	-2.47	-7.06	10.77
K1QMAG05 (1/m2)	1.51	3.35	-6.31
K1QMAG06 (1/m2)	0	0	0
K1QMAG07 (1/m2)	0	0	0
K1QMAG08 (1/m2)	0.39	-1.97	2.87

3. DISCUSSION

Figure 3 presents a comparison of optimization results. Pareto fronts are shown for the simultaneous minimization of both bunch length and transverse emittance, as well as bunch length and longitudinal emittance. The upper panel illustrates the relationship between bunch length and transverse emittance, while the lower panel depicts the relationship between bunch length and longitudinal emittance.

Comparing injector parameters reveals that the two-step optimization improved parameter values, bringing them closer to operational RF settings. However, discrepancies between simulation and experimental optics persist.

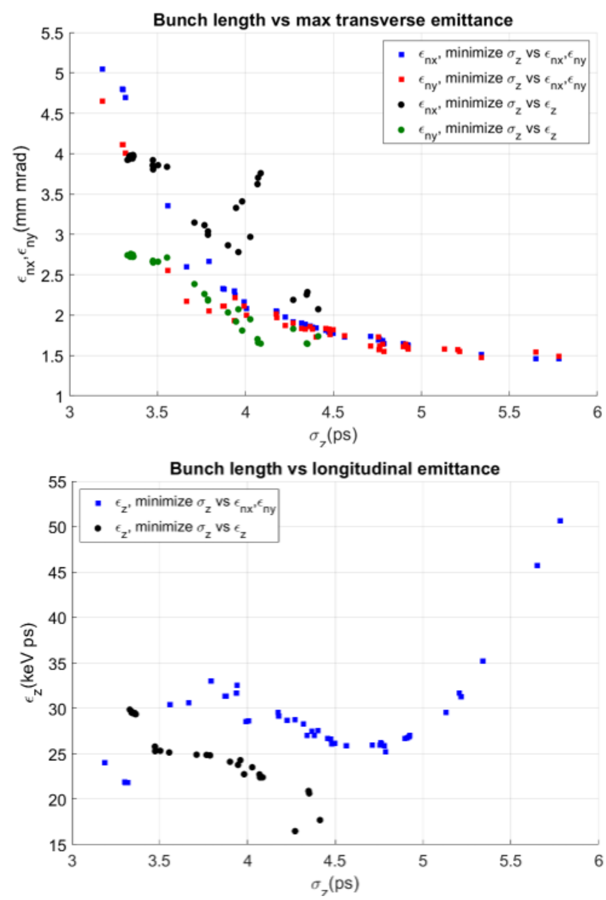

Figure 3: Optimization results comparison.

A significant discrepancy in the K-values of the injector magnets might originate from the optics matching process during injector tuning. This process involves measuring the beam-based magnet response and aligning it with the model response. However, if the initial real response deviates substantially from the model, the matching program based on the inverse matrix method may fail to converge. Consequently, manual adjustments are made to align the actual response with the model, resulting in K-values that deviate from the optimized values. While this approach effectively matches the injected beam to the recirculation loop [4-6], the optimal method for achieving proper optics through optimization remains unclear.

The accuracy of magnet field modeling, both in simulation and reality, may influence optimization results. Future steps include precise magnet field modeling and measurements for refined simulations, followed by further optimization incorporating this magnet field data. The two-step optimization approach effectively narrows down the solution space, concentrating on regions closer to optimal parameters, thereby increasing model efficiency.

4. CONCLUSION

Achieving stable CW operation in a cERL injector necessitates a comprehensive optimization strategy. The two-step optimization approach has demonstrated its potential in aligning simulation parameters with operational values, especially for RF settings. However, enhancing model accuracy to bridge the gap between simulated and real-world optics remains crucial. Magnet field precision significantly impacts optimization results and warrants further investigation. Future efforts will concentrate on refining magnet field modeling and integrating these advancements into the optimization process.

The current method of optics matching during injector tuning, reliant on manual adjustments, is insufficient for achieving optimal injector performance. Accurate magnet field modeling and a more robust optimization process are necessary to address the discrepancy between simulated and actual magnet responses, leading to improved beam quality and overall accelerator efficiency.

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