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PRESENT STATUS OF THE INJECTOR AT THE COMPACT ERL AT KEK

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Abstract

The Compact ERL at KEK is a test accelerator to develop ERL technologies and their possible applications. The first target of injector operation to demonstrate IR-FEL was to generate high bunch charge electron beams with low longitudinal emittance and short bunch length. In 2020, the injector was operated with the bunch charge of 60 pC, the DC gun voltage of 480 kV, the injector energy of 5 MeV and the bunch length of 2 ps rms, and the required beam quality for the IR-FEL has been achieved for a single-pass operation mode. The next target is to demonstrate IR-FEL generation for recirculation mode. The injector energy is decreased to 3.5 MeV due to a limitation of the energy ratio between injection and recirculation beams. Moreover, the DC gun voltage decreases to 390 kV due to the troubles of the DC gun. Therefore, control of the space charge effect is more important to design and optimize the beam transport condition of the injector. In this report, a strategy of the injector optimization together with its realization results and future prospects are summarized.

INTRODUCTION

The Compact Energy Recovery Linac (cERL) at KEK was originally built to operate high average beam current and beam quality [1]. The cERL consists of an injector using a photocathode DC electron gun, a superconducting accelerating cavity (main linac) with energy recovery operation, a recirculation loop, and a beam dump (see Fig. 1). In 2019 the cERL IR-FEL project was launched to meet a goal of developing high-power middle infrared lasers for high-efficiency laser processing using cERL [2]. Subsequently, the work on the injector optimization for successful production of the IR-FEL light was done [3], and the goal was achieved in a single-pass operation mode [4]. At that time the injector was operated with the bunch charge of 60 pC, the DC gun voltage of 480 kV, the injector energy of 5 MeV and the bunch length of 2 ps rms at the exit of the main linac.

The next target of the cERL operation for IR-FEL light generation is required to reproduce the previous result by an energy-recovery mode. To meet the new target, the injector energy was decreased to 3.5 MeV to allow energy recovery with an energy ratio of 1/5 (Einj = 3.5 MeV / Ecirc = 17.5 MeV). We also experienced some troubles with a DC gun. So the gun voltage was dropped to 390 kV. The beam performance is assured by the stable and high accelerating voltage supply of the DC gun. Once voltage drops, the space charge control at the injector becomes more challenging. Thus, our goal is to deliver the beam of proper quality to the exit of the main linac to assure both the FEL generation and the energy recovery. The layout of the cERL injector is shown in Fig. 2. Correspondent beam parameters are given in Table 1. The table also includes a comparison of machine parameters for two different operation modes: single-pass FEL and those with recirculation. More details on cERL injector optimization strategy and technique can be found in [3].

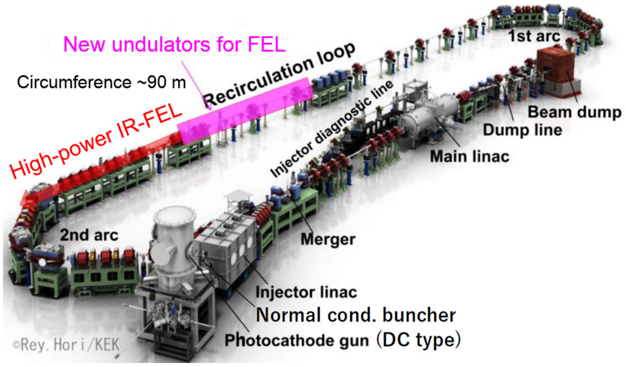

Figure 1: Schematic of the cERL.

Table 1: Design Parameters of the cERL

	Single-pass FEL	**Recirculation mode**
DC gun voltage	480 kV	390 kV
Repetition rate	1.3 GHz	1.3 GHz
Injector energy	5 MeV	3.5 MeV
Recirculation energy	17.5 MeV	17.5 MeV
Charge per bunch	60 pC	60 pC[1]
Rms bunch length[2]	2 ps	3.5 ps
Norm. rms transverse emittance[2]	< 3π mm mrad	< 3π mm mrad
Laser temporal distribution (FWHM)	40 ps single Gaussian	40 ps single Gaussian[3]

INJECTOR DESIGN

At the first step of the study we have optimized injector parameters using General Particle Tracer (GPT, [5]) with Multi-Objective Genetic Algorithm (MOGA, [6]). The target at the main linac exit is set up to a simultaneous minimization of a bunch length and a longitudinal emittance with an additional condition on a transverse emittance to be less than 3π mm mrad. For the required injection energy (3.5 MeV) and gun voltage (390 kV) the algorithm suggested a set of 13 variables including the currents of the 1st and the 2nd solenoids, the buncher's voltage and phase offset, the injector cavities' accelerating field, the 1st injector cavity's phase offset, and the straights of selected quadrupoles (see Fig. 2).

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[1] 1 pC in operation.
[2] At the exit of the main linac.
[3] FWHM 40 ps single Gaussian and 3 ps rms single Gaussian in operation.

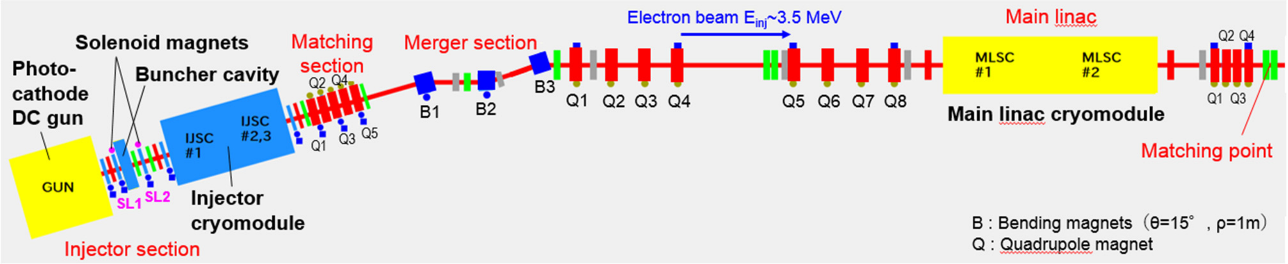

Figure 2: Layout of cERL injector line.

A detailed description of the injector optimization method could be found in [7], and the results of the previous study are given in [3]. As mentioned in the Introduction, recirculation of the beam (i.e. energy recovery) should be achieved in this injector design on the top of FEL light generation. The previous injector design, that considered FEL light generation solely, required the following beam performance at the matching point (see Fig. 2, [8]):

- Bunch charge of 60 pC;
- Rms bunch length of 2 ps;
- Energy spread of 0.1 %;
- Normalized rms transverse emittance more than 3π mm mrad.

A comparison of temporal evolutions of Twiss parameters through the injector is given in Fig. 3. Parameters for injector design for 480 kV gun voltage and 5 MeV injection energy are opposed to those for 390 kV gun voltage and 3.5 MeV injection energy. From the top graph to the bottom: transverse beam sizes, bunch lengths and energy spreads, transverse emittances, and longitudinal emittances are compared. One can conclude that for the lower gun voltage and injection energy conditions the beam performance at the exit on the main linac is degraded due to the influence of the space charge effect. While the transverse beam size stays relatively same, the bunch length and the energy spread increase by 1.9 and 1.4 times correspondently. transverse emittance increased by 1.2~1.5 times, and longitudinal emittance increased by 1.2 times at the matching point as summarized in Table 2.

In practice to switch between the single-pass FEL mode to the recirculation mode smoothly, we introduced a two-step strategy. The steps are following:

1. Tune the injector at a low charge (~1 pC per bunch) to match single-particle dynamics first and then establish an energy recovery.
2. Tune the injector at the target high charge of 60 pC per bunch to assure the FEL power.

Injector tuning at low charge allows the adjustment of single-particle dynamics. A linear model is simpler and easy to be dealt. Once this step is done, we switch to a high charge mode that allows an effective FEL generation. But dealing with multi-particle dynamics is demanding: the discrepancies between the model and the real machine will be shown up. The required machine performance should be achieved if the model-based tuning is complemented by the proper beam-based tuning, that is the topic of our next work.

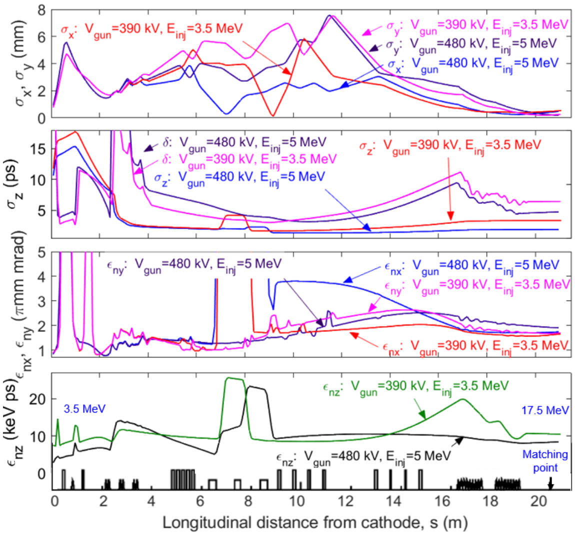

Figure 3: Comparison of temporal evolutions of Twiss parameters through the injector (480 kV gun, 5 MeV injection vs 390 kV gun, 3.5 MeV injection).

Table 2: Beam Parameters at the Main Linac Exit[1]

Design Beam parameters	Single-pass FEL	Recirculation mode
Hor. beam size	0.69 mm	0.72 mm
Ver. beam size	0.35 mm	0.38 mm
Energy spread	0.25%	0.34%
Bunch length	1.8 ps	3.5 ps
Hor. emittance	1.74 π mm mrad	2.61 π mm mrad
Ver. emittance	1.92 π mm mrad	2.39 π mm mrad
Long. emittance	8.4 keV ps	10.47 keV ps

MODEL BASED INJECTOR TUNING

Now let us discuss the overall strategy of the injector tuning. The goal of the injector tuning is to generate and to transport the appropriate beam to the entrance of the undulator section. More information on cERL injector strategy can be found in [9]. Our typical tuning procedure starts with a task to accelerate 1 pC beam from 3.5 to 17.5 MeV by main cavities and transport the beam to the matching point under conditions close to design.

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[1] rms values.

To compare the designed performance and measured results, we first aligned the simulated responses of solenoids SL1-2 at the downstream screen with actual measurements in the same situation. Then, when the trajectory is properly centered using a beam-based alignment, the energy tuning can be started. The energy tuning includes the phases and amplitudes adjustment of the buncher cavity and injector cavities 1-3 so that the energy at the injector exit becomes equal to the target one. In order to adjust longitudinal dynamics, an energy response to the buncher phase is measured. The beam energy is measured on the screen in the merger section. The result of the measurement is given in Fig. 4. Saturated points in the measurement occurred when the beam spot is out of the area of the screen. After fine accelerator voltage and phase tunings, the measured response is perfectly consistent with the design response.

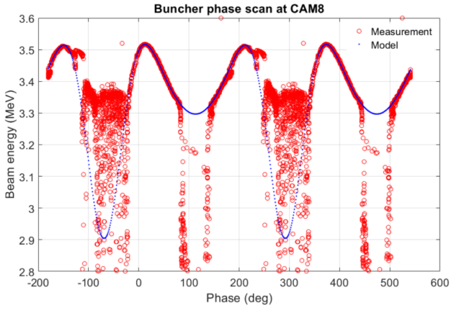

Figure 4: Buncher cavity phase response.

To connect the linear optics and to adjust a multi-particle motion, a well-known quadrupole-scan response measurement is used, where the measured response matrix helps to calculate correction values for quadrupole magnets by solving the inverse measured response matrix. After the quadrupole-scan responses were corrected at each matching point, beam size at each screen in the injector line is measured up to the exit of the main linac. This is another step to judge how close our injector tuning result with respect to the model. In Fig. 5, the measured beam sizes are well-agreed with the design beam sizes at locations where the optics matching is done except two screens. The reason for the deviation of the vertical beam size at the location of around 10 m is the absence of matching knobs. The beam size discrepancy at the exit of the main linac is due to nonlinear disturbances introduced by the main linac cavities (a scanning quadrupole magnet placed after the cryomodule, while quadrupoles for correction are before it). Therefore, we are developing a new matching procedure for this matching point to avoid the influence of accelerating cavities. The last step was to study is the emittance at the end of the main linac. Thus, design values read ε_{nx} = 0.69 π mm mrad, ε_{ny} = 0.44 π mm mrad. While the measurement gave $\varepsilon_{nx} = 0.64 \pm 0.02$ π mm mrad and $\varepsilon_{ny} = 0.56 \pm 0.01$ π mm mrad. Easy to see that measured horizontal emittance is in a good agreement with the design value. But the difference in vertical emittances still remains since the real values may differ from design values.

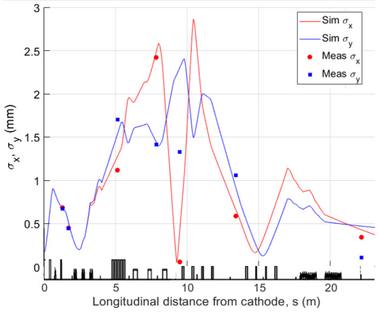

Figure 5: Designed and measured horizontal and vertical beam sizes after optics matching.

CONCLUSION

We have established the injector design that makes both FEL generation and energy recovery simultaneously possible. We have adjusted machine parameters with respect to our model for the low-charge operation mode as a first step. The next step is operating with a high-charge (60 pC) to generate FEL light with this setup and increasing a repetition rate of electron bunch to achieve CW-FEL.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Akemoto, *et al.,* “Construction and commissioning of the compact energy recovery linac at KEK”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 877, pp. 197-219, 2018. `doi:10.1016/j.nima.2017.08.051`.

[2] R. Kato *et al.*, “Construction of an Infrared FEL at the Compact ERL”, in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 1608-1611. `doi:10.18429/JACoW-IPAC2021-TUPAB099`

[3] O. A. Tanaka, N. Higashi, and T. Miyajima, “Injector Optimization for the IR-FEL Operation at the Compact ERL at KEK”, in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 4531-4534. `doi:10.18429/JACoW-IPAC2021-FRXB07`

[4] Y. Honda, *et. al.*, “Construction and commissioning of mid-infrared self-amplified spontaneous emission free-electron laser at compact energy recovery linac”, *Rev. Sci. Instrum.*, vol. 92, p 113101, Nov. 2021. `doi:10.1063/5.0072511`

[5] General Particle Tracer, `http://www.pulsar.nl/gpt/`.

[6] S. B. van der Geer, M. J. de Loos, “Multi-objective Genetic Optimization with the General Particle Tracer (GPT) Code”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 492-494. `doi:10.18429/JACoW-IPAC2015-MOPJE076`

[7] O. A. Tanaka, N. Nakamura, T. Miyajima, and T. Tanikawa, “Injector design towards ERL-based EUV-FEL for lithography”, in *Proc. IPAC’22*, Bangkok, Thailand, June 2022, paper MOAB01, this conference.

[8] R. Kato, private communications, Jan. 2021.

[9] T. Miyajima, “Injector Development at KEK”, presented at the 63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs (ERL'19), Berlin, Germany, Sep. 2019, paper THCOZBS04, unpublished.