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RECENT STUDIES ON HIGH CURRENT OPERATION AT THE COMPACT ERL

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Abstract

The compact ERL (cERL) is operated at the mid-energy region around 17 MeV for beam studies on industrial applications since 2017. In 2020, two undulators were installed with the objective of R&Ds on a high-power EUV-FEL source for next generation lithography. One of the R&D issues is the high average beam current operation and the other is the energy recovery under the FEL amplification. Regarding to the former issue, high beam current operation was demonstrated as a first step at a low bunch charge (0.77pC). In 2023, machine learning is employed to optimize the beam tuning process, thereby reducing the radiation level at the same bunch charge. For the latter issue, we tried the energy recovery operation while undulator light was amplified at a high bunch charge of approximately 60 pC.

INTRODUCTION

The compact ERL was constructed to verify a principle of energy recovery linac (ERL) at KEK. In 2013, the first beam was delivered and transported, and the energy recovery operation was also demonstrated successfully. In 2016, the average current with energy recovery mode was almost achieved at 1 mA [1]. In 2020, two undulators were installed and a first free-electron laser (FEL) light was observed with a burst-mode and non-energy-recovery operation [2].

The next step in 2023 operation is as following:

1. We demonstrate 1mA CW operation with a small aperture vacuum chamber at the undulators at low bunch charge (0.77pC).
2. Machine learning is employed to optimize the beam tuning for radiation level reduction even in the high average current operation.
3. We conduct an experiment to investigate the feasibility of beam operation for FEL light emission with energy recovery, utilising a high bunch charge (60pC).

The vertical chamber size of the undulators is very narrow, with an oval shape and a long diameter of 50 mm and a short diameter of 8 mm. Hence, beam loss around the undulator section is most likely occurred and dedicated beam tuning around this part is crucial.

COMPACT ERL

Figure 1 shows the layout of the compact ERL. A low-emittance electron beam is generated by a photo-cathode DC gun with a voltage of 450 kV. In the low bunch charge beam operation, the beam is induced by a high repetition rate pulse laser. Then, the electron beam is directed to an injector system and accelerated to a beam energy of 2.9 MeV. The beam is accelerated to 17.2 MeV by a main superconducting cavity. The beam goes through a recirculation loop. After passing through the undulator section, the beam returns to the main SC cavity so that the beam is decelerated to the same energy as the injection energy of 2.9 MeV. The energy generated by the deceleration of the previous beam is recovered and utilized to accelerate the subsequent beam. Finally, the beam is directed to a beam dump.

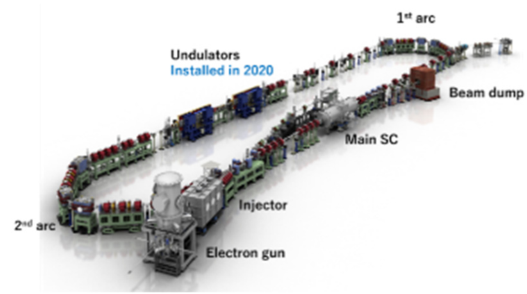

Figure 1: A layout of cERL.

COMISSIONING FOR 1 mA OPERATION

Optics Matching

To realize beam operation without beam loss, optics matching is a key component at cERL. Matching is conducted based on the beam profile of the screen monitor. It is demonstrated at the low current in burst mode with a short pulse length of ~1 µsec and a repetition rate of 5 Hz.

- It is of importance to ensure that the optics matching employed at the injector is compatible with a small beam size, which should be maintained throughout the entire beam line.
- Dedicated beam tuning at the undulator section.

Figure 2 shows the cERL beam line and the obtained beam profile at each point. Owing to the small beam tuning at the injector, the beam could be transported around the recirculation loop with minimal disruption to its size.

Then, the optics matching was completed at each location. As a result, the beam was completely energy recovered during the burst mode.

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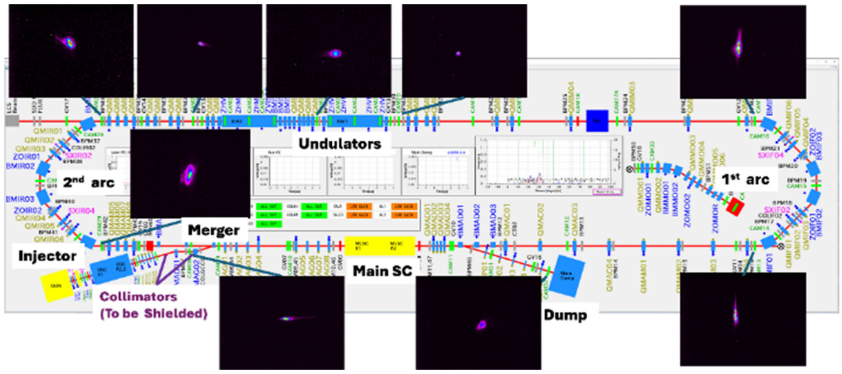

Figure 2: cERL beam line and beam profiles obtained for 1 mA CW operation at each point during burst mode.

Tackling Beam Loss

To achieve a low radiation during CW operation, the beam optics and collimator position should be optimized in the burst mode. High current operation is carefully demonstrated in CW mode with the radiation level being checked, in which only the gun laser intensity is the tunable parameter. To struggle beam loss, we utilized loss monitors, strategically placed at various points along the beam line. And collimators were installed at the entrance and midpoint of the merger section cut the beam halo and tail at the low beam energy (see Fig. 2). To recognize the beam loss during the burst mode operation, the trajectory and other components were adjusted to reduce the loss signal while monitoring the loss monitor. While the signals from all the loss monitors appeared to be within an acceptable range, the beam current could not reach ~1 mA.

To find unknown beam loss points, we relocated the loss monitors and searched for significant loss signal point. Finally, the point with huge loss signal was found at the chicane located at the exit of the first undulator. Figure 3 shows the loss signal when the loss monitor scans for unknown loss points in the vicinity of the undulators. The loss monitor is sensitive. Therefore we can find loss points for beam tuning even in the burst mode. This survey was a strong help toward ~1 mA CW operation.

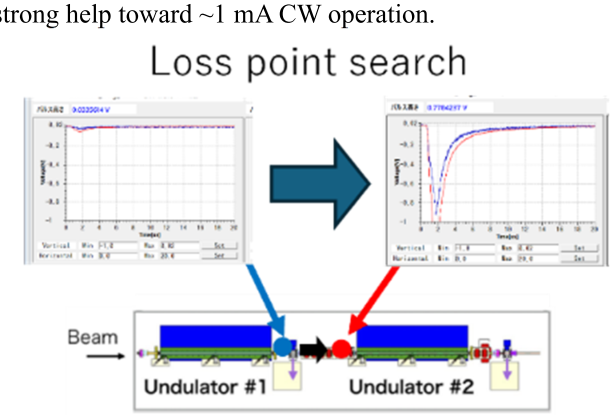

Figure 3: Loss monitor position optimization to search for unknown large loss point.

After the beam tuning, collimators were inserted into dispersive area to reject low energy and nuisance components which create beam loss. The collimators located where energy spread was emphasized due to the dispersion. After the collimator optimization, beam losses which occurred especially at the entrance of the 1st arc and at the undulator section were effectively reduced. Figure 4 shows the collimator setting example (left figure) and the comparison of the 1st arc beam loss signal before and after collimator optimization (middle and right figures).

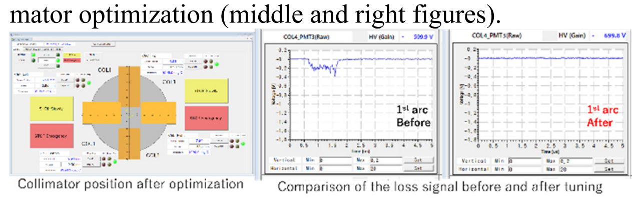

Figure 4: Collimator setting (left) and comparison of before and after collimator optimization (middle and right).

Finally, beam current of 952 μA was successfully attained. We maintained this beam current for approximately 30 minutes. Figure 5 shows the trend of beam current during 952 μA operation.

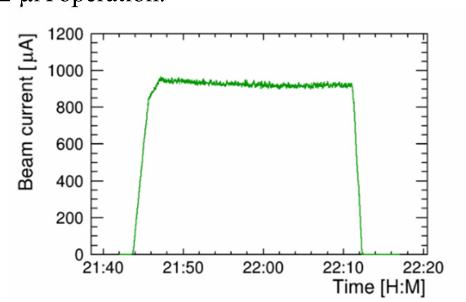

Figure 5: Trend of the beam current during CW operation.

The electron beam is accelerated during the initial passage of the superconducting main linac (ML) and decelerated in the subsequent passage. This process enables the recovery of energy during the deceleration. The ML consists of two nine-cell cavities in a cryomodule. Figure 6 shows the differential in the cavity forward power and reflected power ($P_{in} - P_{ref}$) of two cavities (ML1 and ML2) in comparison to the average beam current. The cavity

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voltage of each cavity is 5.7 MV of ML1 and 8.6 MV of ML2, respectively. The difference in power of each cavity is significantly less than the power without energy recovery. The power recovery of ML1 and ML2, ML1(Pin − Pref) + ML2($P_{in} - P_{ref}$), is estimated to be 100 ± 0.02% in total.

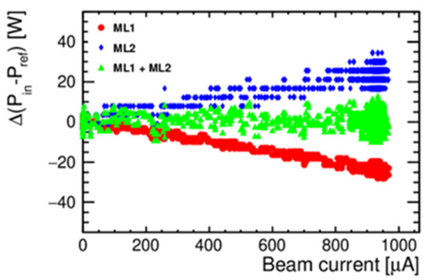
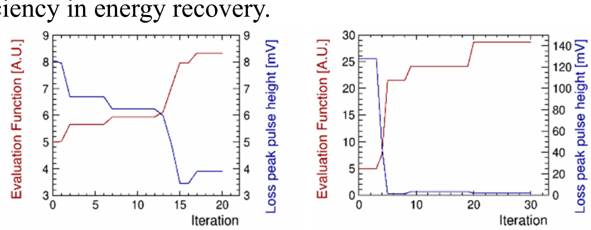


Figure 6: The differential in the cavity forward power and reflected power.

BEAM TUNING USING MACHINE LEARNING

The process of beam tuning, which is designed to reduce radiation and facilitate successful energy recovery, can be challenging due to the complex correlation between tuning parameters and the necessity of advanced knowledge regarding beam adjustment. The application of machine learning is a promising approach to realize automatic tuning. In the context of beam tuning for high current CW operation, Bayesian optimization has been utilized as a tool for this purpose. Bayesian optimization is a method of estimating the shape of a black box function and of obtaining the global maximum (or minimum) from a limited set of observed data [3]. Parameter estimation in Bayesian optimization is achieved through the maximization of an evaluation function. Therefore, the evaluation function was designed to minimize beam loss and to ensure adequate efficiency in energy recovery.



Machine learning tuning before the dump Machine learning tuning of the collimators

Figure 7: Machine learning beam tuning at cERL.

Figure 7 shows the outcome of Bayesian optimization. The left is the tuning process in front of the dump, while the right is the simultaneous tuning of the two collimators. It is evident that the maximization of the evaluation function and loss signal suppression were effectively achieved.

Following the implementation of machine learning beam tuning, CW operation was conducted, resulting in an increase in the beam current from 140 μA to 600 μA. A detailed study of hyperparameters, which Bayesian optimization incorporates to enhance optimization efficacy, is necessary. Furthermore, we should devise a strategy for machine learning beam tuning to achieve comprehensive overall beamline loss suppression, thereby enabling 1 mA CW operation following machine learning tuning.

HIGH BUNCH CHARGE OPERATION

In the high bunch charge beam operation, we aimed FEL generation with energy recovery. We used a different gun laser with 81.25 MHz and generated a bunch with charge of 60 pC. We set the injector energy to 3.5 MeV and the main energy to 17.5 MeV. As with high-current CW operation, we performed dedicated optics matching for high-charged beams to reduce beam loss under burst mode.

We obtained both undulator 1 (U1) and undulator 2 (U2) radiation simultaneously. Figure 8 shows the FEL signal intensity for each of U1 and U2 during beam tuning.

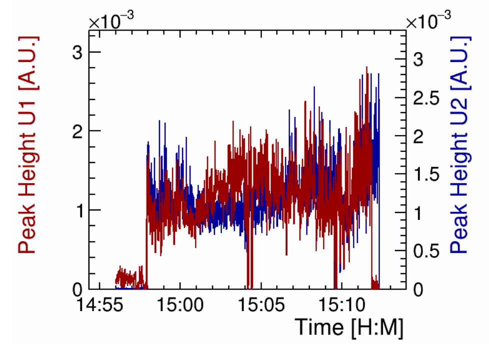


Figure 8: Trend of FEL signal strength during beam tuning in undulator section.

And then, we continued beam tuning so that energy recovery had been successfully operated. As a result, small part of the total beam current arrived at the main dump for the first time. The beam energy could not be fully recovered due to the unusual profile of the high charged bunch, which made it challenging to manipulate the beam. Detailed study and control of such a beam is the next step.

SUMMARY

A 952 μA CW beam operation with undulators and energy recovery was successfully demonstrated. To reduce a radiation, monitoring the loss monitor closely and searching for an unknown loss point around the undulators were crucial. The 10 mA operation will be planned for future implementation.

Machine learning beam tuning is promising to realize automatic loss-free beam tuning. The next step is a detailed study of hyperparameters and establish the strategy of beam tuning to reduce radiation effectively and thoroughly.

This was the first operation to combine FEL generation with energy recovery of a part of the beam. FEL generation and energy recovery operation will be compatible.

ACKNOWLEDGEMENT

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