BUNCH COMPRESSION AT THE RECIRCULATION LOOP OF COMPACT ERL

M. Shimada†, N. Nakamura, T. Miyajima, Y. Honda, T. Obina, R. Takai, A. Ueda, K. Harada, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

Bunch compression and its energy recovery are demonstrated at Compact Energy Recovery Linac (cERL) in KEK Tsukuba campus. A coherent optical transition radiation (CTR) measurement system is built up to confirm that the bunch length become shorter in the recirculation loop. The bunch length is extended to the initial bunch length in return arc for the beam deceleration and energy recovery without significant beam loss. The bunch compression is performed in several optics and the performance is compared with the simulation result of a start-to-end (S2E) tracking simulation.

INTRODUCTION

The ERL project has been studied as the next generation X-ray light source based on an extremely high quality beam. The key components of ERL, such as the CW superconducting cavity and the high brilliance DC gun, are also considered to be applied for CW XFEL. On the other hand, it is also a good candidate for the high intensity EUV light source of the lithography because both short pulse and low emittance beam are feasible at the same time. One of the goals of the commissioning of 20 MeV cERL is acquiring the beam operation technique and skill as well as developing the key components. The bunch compression is critical issue to obtain the short electron bunch without degradation of the beam quality [1].

The bunch compression is performed after 20 MeV full acceleration to supress the degradation of the electron beam at low energy due to the space charge effect and CSR wake. The short electron bunch is achieved by an off-crest acceleration of the main linac and the non-isochronous arc in the recirculation loop. In order to evaluate the bunch length shorter than 1 ps the THz-CTR measurement system has been developed at the south straight line in cERL recirculation loop since 2015 [2]. In this report, the demonstration results of the bunch compression are compared with the numerical tracking simulation.

TRACKING SIMULATION

Bunch Compression

The longitudinal position z shifts with the momentum deviation Δp as follows,

$$\Delta z = R_{56}\frac{\Delta p}{p_0} + R_{566}\left(\frac{\Delta p}{p_0}\right)^2 + \cdots, \quad (1)$$

where R_{56} and R_{566} is the first and second order of the element of the transport matrix in the recirculation loop, respectively. The nominal momentum p_0 is approximately 20 MeV/c. When the second order is neglected, the longitudinal phase space can be shown in Fig. 1.

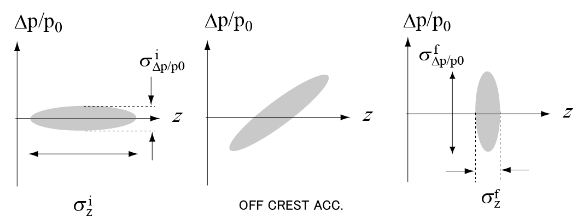

Figure 1: Schematic figure of longitudinal phase space in 1st order at bunch compression.

According to the simplified model, we can estimate the optimum RF phase ϕ_{RF} and the minimum bunch length as following equations,

$$R_{56} \sim \frac{c}{2\pi f_{RF}}\frac{1}{\sin\varphi_{RF}}, \quad \sigma_z^f \sim R_{56}\sigma^i_{\Delta p/p0}, \quad (2)$$

where f_{RF} is the RF frequency 1.3GHz. The superscript i and f mean before and after bunch compression, respectively.

The second order of the longitudinal phase space distortion is caused by 1.3GHz RF curvature and the higher order of the transport matrix of the arc section, and so on. To achieve the bunch length shorter than sub-ps, R_{566} in Eq. (1) should be controlled to correct the second order.

Layout of cERL and Optics Design

The lattice layout of cERL is shown in Fig. 2. The longitudinal phase space is tilted by the off-crest acceleration of the main linac. There are two arc sections consisting of quasi-triple bending achromat lattice. The tilted electron bunch is compressed at the non-isochronous arc, which has two triplets to control the bunch length by tuning R_{56}. In addition, two sextupole magnets with 0.1 m thickness are installed in each arc section to control R_{566} to correct the second order distortion [3].

The second arc is optimized to reduce the energy spread at the end of the main linac after energy recovery to avoid the significant beam loss at the high average beam current operation. The pair of the steering magnets in the second arc can change the path-length to control the RF phase for the energy recovery. The RF phase or the path-length is optimized as well as R_{56} and R_{566} in the second arc.

† miho.shimada@kek.jp

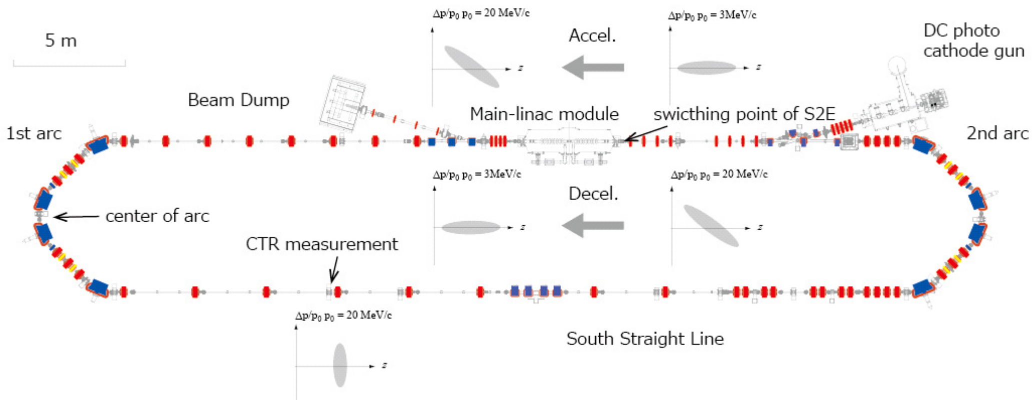

Figure 2: Schematic figures of longitudinal phase space of bunch compression and energy recovery in cERL. Simulation code used in start-to-end simulation is switched from GPT to elegant at the switching point.

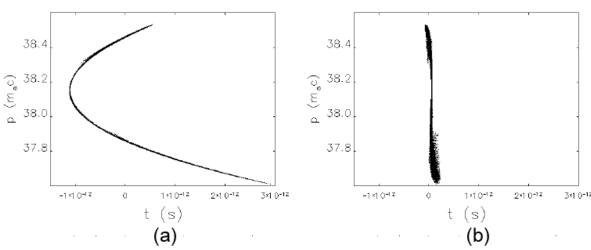

Figure 3: Longitudinal phase space at the CTR measurement system. (a) SX is off, σ_t = 670 fs (b) SX is optimized, , σ_t = 26 fs.

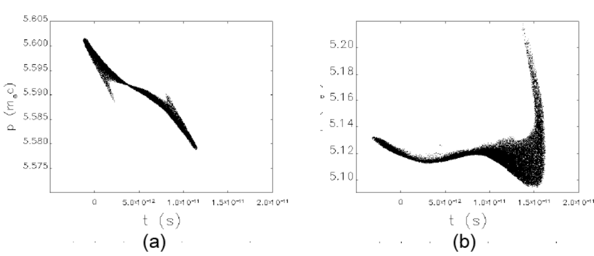

Figure 4: Longitudinal phase space of (a) entrance of the main linac before full acceleration (switching point) and (b) exit of the main linac after energy recovery.

Start-to-end Simulation

The S2E simulation is performed for the numerical simulation of the bunch compression from the DC electron gun to the exit of the main linac after energy recovery [4-6]. General Particle Tracer (GPT) is utilized for lower energy beam to take into account the space charge effect and acceleration at the non-relativistic energy region. ELEGANT is utilized for the linear optics design and optimization of the bunch compression with considering 1D CSR wake effect. The two simulation codes are switched at the switching point shown in Fig. 2. Although the 2k particle data is used for the optimization to save the simulation time, the 100k particle data are shown as the final results.

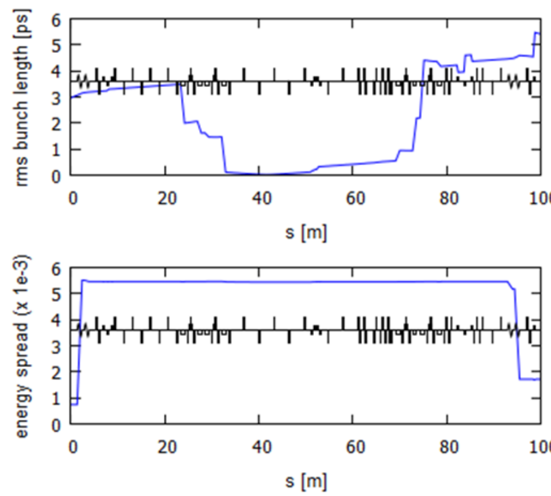

Figure 5: Numerical tracking results of S2E simulation in the recirculation loop.

The initial parameters of S2E simulation are the same with the commissioning operation: the bunch charge is 0.5 pC, the beam energy at the entrance of the main linac is approximately 3 MeV. The RF phase is 8 degree, in which the head of the electron bunch is accelerated higher. The transport matrix element R_{56} is optimized to minimize the bunch length σ_t at the THz-CTR measurement system located in the south straight section while the linear optics of the first arc keeps the achromat condition and the mirror symmetrical optics. Next, one of the two sextupole magnets is utilized for correction the second order distortion. The longitudinal phase space are compared in Fig. 3. The sextupole magnet makes the bunch length shorter by factor 25.

The linear optics of the second arc is designed to satisfy the isochronous condition for the whole recirculation loop including the non-isochronous first arc section. The RF phase at the energy recovery and one of the two sextupole magnets in the second arc are optimized to minimize the energy spread at the exit of the main linac after energy recovery. Figure 4 shows the longitudinal phase space at

ISBN 978-3-95450-147-2

the switching point and just after the energy recovery. It is successfully to supress the energy spread after energy recovery comparable to before the full acceleration of the main linac. On the other hand, the center of the beam energy after energy recovery is slightly smaller than before full acceleration. The developments of the rms beam size and energy spread in the whole recirculation loop are shown in Fig. 5. The energy spread just after the energy recovery is twice of that at the switching point.

DEMONSTRATION IN CERL

The acceleration phase of both two cavities in the main linac are shifted by 4, 8, 16.5, and -16.5 degree. The acceleration field is tuned to maintain the energy of the electron bunch at 20 MeV. The beam energy is confirmed at the screen monitor just after the first bending magnet in the first arc section. Next, R_{56} and R_{566} is optimized to maximize the intensity of CTR in sequence. The intensity of CTR is measured by using the narrow-band diode detector (Virginia Diode Instruments, WR-3.4ZBD).

Although the direct measurement of R_{56} is difficult in the current condition, we roughly estimate R_{56} from the dispersion function η. It is described by the following equation,

$$R_{56} = \int \frac{\eta(s)}{\rho(s)} ds, \qquad (3)$$

where ρ is the bending radius and has a finite value only in the bending magnets. However, it is slightly different from the effective R_{56} because it neglects the discrepancy in the speed of light and a low energy electron beam [2]. The linear optics of the arc are designed to satisfy the achromat condition with a mirror symmetrical optics. In the case of the cERL, R_{56} is approximated as a linear function of the dispersion function of the center of the arc η_c; $R_{56} = 1.41\,\eta_c - 0.34$. Figure 6 shows the optimum R_{56} at each RF phase have good agreement between the experimental and simulation results. The first order approximation of Eq. (2) has discrepancy with the S2E simulation because the velocity of the electron is slightly different from the light and the correlation between z and Δp at the switching point is non-zero. The excitation of the sextupole magnet is -50 m^{-3} against -67 m^{-3} in the S2E simulation (Fig. 3). According to the S2E simulation, the estimations of rms bunch length for 4, 8, 16 degree RF phase is 54, 26, 670 fs, respectively. The relationship between the RF phase and the rms bunch length is different from Eq. (2).

The energy recovery is demonstrated at the 8 degree RF phase. The path-length, R_{56} and R_{566} of the second arc are optimized to minimize the energy spread at the screen monitor just after the bending magnet at the entrance of the dump line. Thanks to this optimization, the energy recovery is succeeded without significant beam loss. The measurement results of the dispersion function are agreed with the design one as shown in Fig. 7.

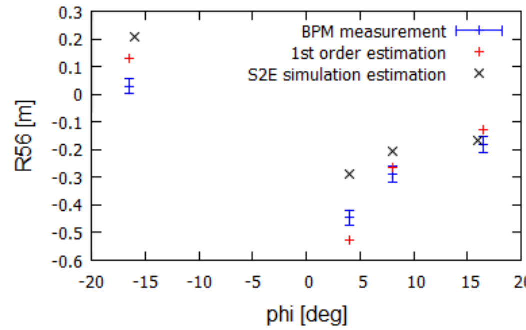

Figure 6: Relationship between RF phase and R_{56} of the first arc. The sign of R_{56} is opposite to the definition of ELEGANT.

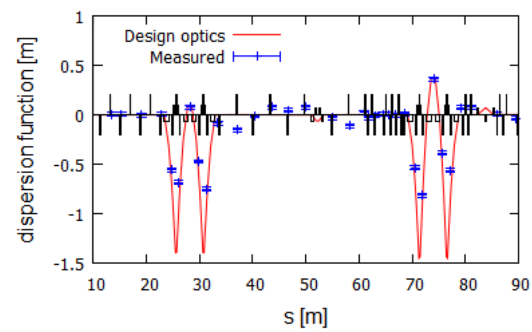

Figure 7: Dispersion function of the design optics of S2E simulation and measured one at energy recovery operation. The error bar is corresponding to 0.2 mm of BPM measurement.

CONCLUSION

We demonstrated the bunch compression and the energy recovery at cERL. S2E simulation is performed with the same condition with the commissioning and compared with the measurement results. They show a good agreement so it can be expected the bunch length less than 100 fs is achieved. We try to numerical estimation of the bunch length with THz-CTR system in the next step.

REFERENCES

[1] N. Nakamura *et al.*, "Simulation study on bunch compression and decompression for the compact ERL," *Proc. of IPAC'15,* Richmond VA, USA, p.1591 (2015).

[2] T. Obina *et al.*, "Recent developments and operational status of the compact ERL at KEK," *Proc. of IPAC'16*, Busan, Korea, TUPOW036, these proceedings.

[3] A. Ueda *et al.*, "Design and fabrication of the compact-ERL magnets," *Proc. of IPAC'16*, Busan, Korea, TUPMB005, these proceedings.

[4] *Pulsar Physics*, *http://www.pulsar.nl/gpt/index.html*

[5] *User's Manual for ELEGANT*, *http://www.aps.anl.gov/Accelerator_Systems_Division/Accelerator_Operations_Physics/manuals/elegant_latest/elegant.pdf*

[6] M. Shimada *et al.*, "Approach to a start-to-end simulation of 2-loop compact energy recovery linac," *Proc. of IPAC'11*, San Sebastian, Spain, p.1909 (2011).