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1 mA STABLE ENERGY RECOVERY BEAM OPERATION WITH SMALL BEAM EMITTANCE

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Abstract

A compact energy-recovery linac (cERL) has been operating since 2013 at KEK to develop critical components for ERL facilities. To achieve a high averaged beam current of 1 mA with continuous-wave (CW) beam pattern while keeping small emittance from 500 kV DC-photocathode gun, it is essential to design and perform a beam-tuning at low-energy beam transport. Also, we found that the combination of beam collimators and the various kind of beam-tuning can improve the beam-loss ratio below 10^{-7} order. Sometimes the cERL has been operated under wide variety of machine parameters, for example, the highest total beam energy is decreased from 20 MeV to 17.6 MeV depending on a condition of super-conducting cavities, and the beam rep-rate of 1300 MHz or 162.5 MHz depending on the purpose of CW experiments. In each operational parameters, we successfully conducted the 1 mA CW operation and the efficiency of the energy recovery was confirmed better than 99.9 %.

INTRODUCTION

The compact energy-recovery linac (cERL) has been constructed and operating in KEK. Main purpose of the cERL is to develop key components for future high average-current electron source with low emittance, such as a DC-photocathode gun and a cutting-edge superconducting cavity technologies. Also, to maintain low-emittance beam, understanding and handling of beam dynamics are the key issues to be proofed in the cERL. Figure 1 shows the layout of the cERL. Electron beam produced by the 390–500 kV gun is accelerated in the injector superconducting (SC) cavities about 2–5 MeV (shown as E_{inj} in the figure), then accelerated in the main linac (ML) SC cavities up to 17.6–20 MV (shown as E_{cir}). The beam travels the re-circulation loop, which can compress the bunch for THz experiment or laser-compton scattering experiment. After the recirculation loop, the beam is decelerated in the ML-SC down to the same energy as the injection energy, and delivered to the beam dump. Benefit of using the SC cavity enables the beam energy to be recovered for the acceleration of next beam. After

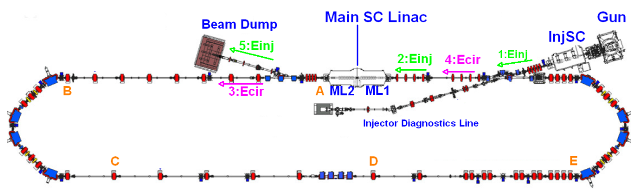

Figure 1: Layout of the cERL. E_{inj} and E_{cir} indicates the beam energy after the injector linac and after the first passage of main linac, respectively. After the recirculation loop, the beam is decelerated down to E_{inj}.

the first beam commissioning in December 2013, a maximum beam-current has been increased step-by-step each year, namely, 1 µA in 2013, 10 µA, in 2014 and 100 µA in Mar/2015. Details of design, construction and the result of initial commissioning were already reported in ref. [1]. After the initial commissioning, we carried out the beam tuning to achieve the 1 mA average current at first [2], and also tried to establish the beam operation for laser-compton scattering (LCS) experiment to show the full advantage of ERL type machine as the compact X-ray imaging source [3]. Also, bunch compression has been examined because the cERL has a potential to be an intense THz radiation source which cannot be achieved in other types of accelerator. Recent remarkable result for coherent terahertz radiation is reported in another paper [4].

This paper describes the R&Ds to realize stable 1 mA CW operation while keeping low emittance beam under the various RF cavity conditions.

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STRATEGY FOR HIGH-AVERAGE CURRENT OPERATION

One of the design targets of the cERL is to achieve stable 10 mA average-current operation in CW beam pattern. We decided to use the bunch charge 7.7 pC with the beam repetition rate of 1.3 GHz to avoid heavy space-charge effects at the low-energy beam transport. Because the maximum average current is restricted to 1 mA by regulation for now, we used the following strategy for machine studies: after establishing the operation with 1 mA, which consists of 0.77 pC with 1.3 GHz rep-rate, we decrease the rep-rate to 162.5 MHz and increase the bunch charge to 6.0 pC to study beam dynamics related to the space-charge effects for future 10 mA CW operation. The beam pattern and charge are summarised in the Table 1. In each condition, machine tuning for low emittance and small beam loss are performed.

Beam Pattern for Tuning

Most of accelerator tuning must be performed with pulsed beam before going to 1 mA CW operation. In order to keep the same space charge effects, the bunch charge should be kept the same both for tuning and high average current. So, we used a macro-pulse which has the width of 0.1–1 µs with repetition rate of 3–5 Hz for tuning. After the tuning with the macro-pulse mode, beam pattern is changed to CW mode. The CW mode started from low charge and increased the charge step-by-step while checking the beam loss until the beam current to the target current of 1 mA. After the current reached to 1 mA, we confirmed that we were able to open or close the beam gate in arbitrary time. So the high-average current operation can start or stop immediately without the step-by-step increase in current after the initial beam tuning.

Table 1: Beam parameters for 1 mA CW operation. Gun HV in the table stands for high-voltage of the electron-gun, ML stands for Main Linac.

	unit	case 1	case 2	case 3
Beam Rep-rate	MHz	1300	1300	162.5
Bunch Charge	pC	0.77	0.77	6.0
Gun HV	kV	390	500	390
Injector Vc	MV	2.2	1.69	2.2
ML Vc	MV	17.2	14.6	17.2
Injector Energy	MeV	2.9	3.0	2.9
ML Energy	MeV	20.0	17.6	20.0
Momentum Ratio		1:7	1.6	1:7
RF Frequency			1300 MHz	

Beam Tuning for Various Accelerating Gradients

During the operation in 2018, we experienced a degradation in the performance of SC cavity. An accelerating voltage of the ML is decreased from 17.2 MV to 14.6 MV due to thermal break down inside the cavity [5]. As a result, the total beam energy is limited to 17.6 MV due to the field emission and thermal break down of the ML. Because a finite aperture at the injection chicane limits the momentum ratio smaller than 1/6, the energy at the injector part must be decreased to 3.0 MeV. This means the beam tuning must be done again in low energy region.

Of course, the degradation is not desirable but this is one of the topics to be examined in the cERL. Figure 2 shows the re-designed beam parameters for new beam energy. Original design is reported in Ref [1]. The newly designed emittances is successfully kept small to 0.34 and 0.24 mm· mrad in horizontal and vertical, respectively.

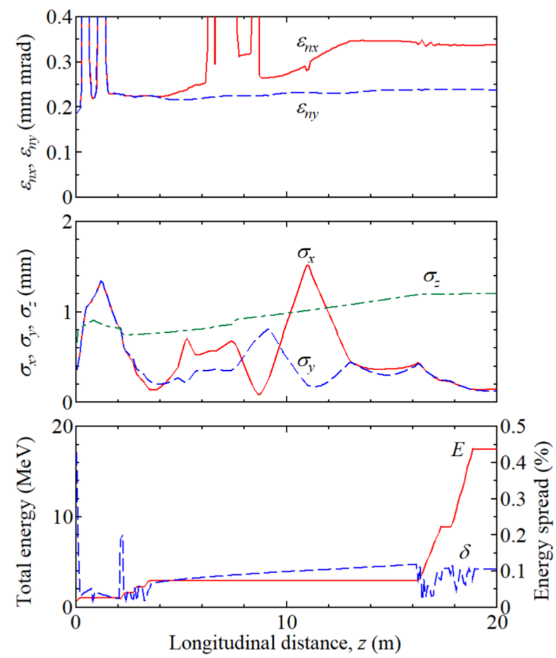

Figure 2: Design of beam transport from gun to the exit of ML for 0.77 pC/bunch with the total energy of 17.6 MeV.

RESULTS

Emittance Measurement

The normalized rms emittance is measured by using conventional Q-Scan method [1] at the several locations in recirculation loop (B,C,D in Fig. 1). At low-energy location where the Q-scan method is not suitabe due to the space-charge effects, we measured the emittance with a slit-scanner at the injector diagnostics line [6]. The normalized transverse emittance was approximately 0.14 mm· mrad at low bunch-charge about 0.014 pC. The result was consistent with the theoretical emittance of the photocathode of 0.13 mm· mrad [1].

In case-1 shown in Table 1, a design emittance is 0.26/0.24 mm· mrad in horizontal/vertical direction, respectively, and measured value is 0.32/0.22 mm· mrad at point ’B’ in the Fig. 1. Hereafter we express the horizontal and vertical emittances separated by a slash between them in the same way as this expression.

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In case-2, design emittance is 0.34/0.24 mm· mrad and the measured emittance was approximately 0.29/0.26 mm· mrad. Even in the degraded SC cavity condition, the emittance is kept almost the same value as designed one.

In case-3, design emittance is 0.45/0.44 mm· mrad, and the measured result was 1.8/1.0 mm· mrad. The value is larger than the design value, but it was still small enough for 1 mA CW operation. When the bunch charge is getting larger, asymmetry of emittance in horizontal and vertical direction becomes prominent. We are now investigating the source of the asymmetry. One of the possible sources is a asymmetrical structure of the input coupler in the injector cavity. Numerical and experimental study is under way [6].

Beam Losses

Small beam losses are desirable during CW operation. The order of 10^{-7} losses during 10 mA operation will result in 1 nA beam losses in total. Typical thickness of concrete side-wall of 1.5 m is enough to keep the outside safe, but the roof has only 1.0 m thickness. We need to control and localize the loss point for stable operation. We developed fast beam loss monitor which consists of CsI crystal scintillator with PMT (Hamamatsu R11558) and installed near the locations where beam loss is expected during the beam operation [7]. Total of 16 fast loss monitors are installed along the beam path both for fast machine protection and diagnostics/tuning purposes.

Due to the time-response of cathode material, beam tail is produced after the short laser pulse and forms a beam halo in transverse direction because the tail part feels different accelerating voltage compared to the core part of the beam [8]. Figure 3 shows an example of beam collimation. The low-energy part of the beam was successfully reduced with a collimator where the dispersion is about 0.23 m.

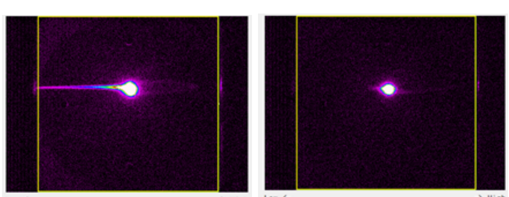

Figure 3: Beam profile at dispersive location. Left and right figures show profiles with and without beam collimator, respectively. Note that the core part is saturated and only the tail part is enhanced in the figure.

Energy Recovery Efficiency

Figure 4 shows an example of beam current for 2 hours. The CW operation was started about 900 μA to avoid exceeding the 1 mA regulation. The beam current gradually decreased in time due to a decrease in quantum efficiency of the cathode. This is not an issue because the current can be compensated easily by increasing the laser intensity. The electron beam is accelerated during the first passage of superconducting main linac (ML) and decelerated in the second

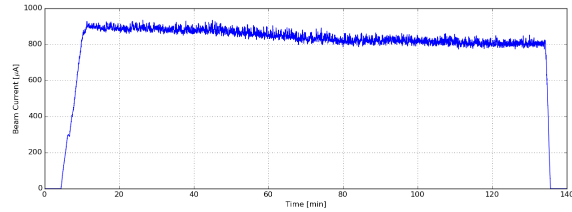

Figure 4: Beam current for 2 hours.

passage, hence the energy is recovered during the deceleration. The ML uses two nine-cell cavities (ML1 and ML2) in a cryomodule as shown in Fig. 1. Figure 5 shows the difference in the cavity forward power and reflected power ($P_{in} - P_{ref}$) of ML1 and ML2 with respect to the average beam current under the operational parameter "caseB". The value indicates the efficiency of energy recovery and goes to zero in case of 100 % recovery. The cavity voltage of each cavity is 6.0 MV and 8.6 MV. It is clear that the difference in power is extremely smaller than the power without energy recovery, namely, 8.6 kW. The recovery efficiencies are estimated to 100.35 % in ML1 and 99.65 % in ML2 due to the fact that the velocity of electron beam is not exactly equal at the first and the second passages through the cavities. In total of two cavities, power recovery is estimated from the sum of the two difference : ML1($P_{in} - P_{ref}$) + ML2($P_{in} - P_{ref}$), to be 100 %±0.05 %.

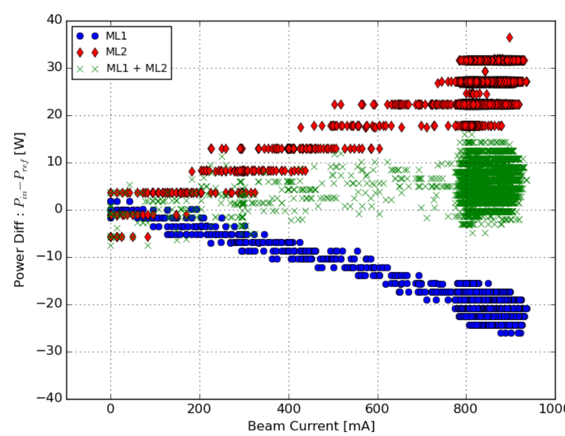

Figure 5: Cavity power during CW operation.

SUMMARY AND FUTURE PLAN

The compact ERL was successfully operated with 1 mA average current despite the performance deterioration of superconducting cavity. Two beam patterns, 0.77 pC/Bunch with 1300 MHz and 6.0 pC/bunch with 162.5 MHz are also confirmed to keep low-emittance beam from the electron-gun. We expect that the 10 mA operation will be enabled with the already achieved level of the beam loss.

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