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STABLE BEAM OPERATION IN COMPACT ERL FOR MEDICAL AND INDUSTRIAL APPLICATION AT KEK

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Abstract

A superconducting Compact Energy Recovery Linac (cERL) was constructed in 2013 at KEK to demonstrate energy recovery concept with low emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL [1]. Recently, this cERL was operated to promote a variety of the industrial applications such as FEL, THz operation and Rare Isotope (RI) production for medical application. In this paper, we will present the status of the studies to realize the stable high-current, low-emittance CW beam and briefly report some industrial and medical applications with this beam in cERL.

INTRODUCTION FOR COMPACT ERL

Compact ERL Accelerator

Compact ERL (cERL) [1] is a test facility, which was constructed on the ERL Test Facility in KEK. Its aim was to demonstrate technologies needed for future multi-GeV class ERL light source [2]. In 2016 and 2018, we successfully operate the CW 1 mA beam in the energy recovery condition [3]. From 2017, KEK directorates kept the importance of the R&D for industrial application based on ERL technologies instead R&D of ERL light source.

cERL consists of a 500 kV DC photocathode gun [4], which made high charge and low emittance electron beam, the injector cavities [5], the main linac cavity [6], which made energy recovery, recirculation loop and the beam dump. Detailed design beam parameters are shown in Table 1. After cERL construction, we met severe field emission of main linac cavities of 8.6 MV. Therefore, we started beam operation with 20 MeV beam energy [7].

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Table 1 : Design Parameters of the cERL

Nominal beam energy	35 MeV
Nominal injection energy	5 MeV
Beam current	10 mA (initial goal) 100 mA (final goal)
Normalized emittance	0.1 – 1 mm-mrad
Bunch length (bunch compressed)	1-3 ps (usual) 100 fs (short bunch)

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cERL Beam Operation for the Applications

Superconducting accelerator with ERL scheme gives us high current linac-based beam with high quality of the electron beam such as small emittance and short bunch. The unique performance of cERL gives us several important industrial applications as follows:

1. RI manufacturing facility for nuclear medical examination
2. IR-FEL experiment with high current ERL beam
3. Intense THz light generation with ERL

In a few years from 2018, we performed these applications in cERL, Figure 1 shows the latest applications in cERL. First, the new beam line for ^{99}Mo RI production &

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material irradiation was built in cERL from 2019 [8]. Second, we installed new undulators to produce FEL with this high current beam in the IR regime, which is one of the proof of concept of EUV-FEL[9]. Third, we also tried THz operation via resonated coherent diffraction radiation produced by a few hundred fs bunch length beam in cERL [10]. We note that we have already achieved the laser Compton X-ray application by using in cERL in 2015 [11]. Among these industrial application by using cERL, we briefly introduce RI production in cERL and IR-FEL production in this report.

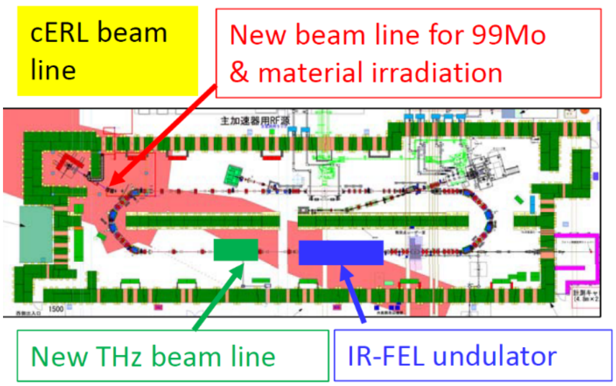

Figure 1: New beam lines for some applications in a few years at cERL from FY2018 to FY2020.

EFFORTS TO KEEP STABLE BEAM OPERATION IN cERL DURING LONG-TERM OPERATION OF SRF CAVITIES

Before introducing industrial applications in cERL, we show our efforts to keep stable beam operation concerning with SRF cavities. In 2017, one of the main linac cavity (ML1) suffered from the thermal breakdown due to unknown burst event. Therefore, in 2018 total beam energy reduced from 20 MeV to 17.5 MeV [12]. One of issues for stable beam operation is how to overcome field reduction from 17.5 MeV and keep stable operation. The other is sometimes injector cavity suffer from field emission (FE). For the suppression of field emission for both injector and main linac in cERL, we normally applied the high peak pulse processing for both cryomodules [7],[13]. Even though sudden FE increased, high peak pulse processing worked well for both cryomodules. Therefore, we kept stable field of 7 MV/m for injector cavities and 6 MV of ML1 cavity and 8.6 MV of ML2 cavity for main linac cavities during the latest three years.

Figure 2 shows the measured-Q values of main linac cavities from 2012 to 2021 with several field. As shown in Fig. 2, after the sudden burst event in 2017, we did not increase more than 7 MV/m due to thermal breakdown and nominal Q-values down to 2.5 x 10^9 at 6 MV, which affect our operational energy and down to 17.5 MV operation from 2018. For irradiation line to produce ^{99}Mo, we would like to increase field for making ^{99}Mo efficiently.

In order to overcome the field deterioration, we change the operation temperature of cryomodule. We kept 3.0 kPa

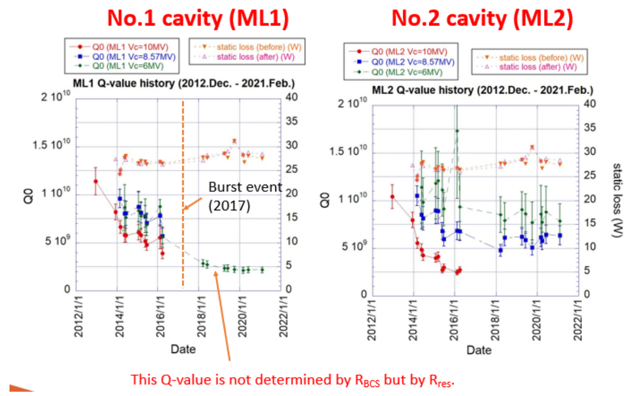

Figure 2: Measurement of the Q-values of 6, 8.57 and 10 MV cavity voltage during long-term beam operation from 2012 to 2021 including high power test of Main linac 1 (left) and 2 (right). The measured static loss was also plotted in both figures.

operation in 2018 to keep 2 K operation. But Q-value of ML1 cavity was now dominated by residual resistance not BCS resistance as shown in Fig. 2. In this case, we have little difference of surface resistance between 3.0 kPa and 3.5 kPa. On the other hand, cryogenic capacity is linear to the pressure of Helium pressure tank. In our case 85 cubic meter per hour is capacity at 3.0 kPa and limited our field. If we change the 3.5 kPa, 99 cubic meter per hour is our capacity at 3.5 kPa. In 2019, we tried 3.5 kPa operation under all cryomodule were working. Figure 3 shows the trend of change of operation pressure under operating nominal field of injector and main linac cryomodule. Total field was changed from 17.5 MeV to 19.5 MeV. Helium flow increased from 72 cubic meter per hour to 90 cubic meter per hour, which is difficult for 3.0 kPa operation. However, when we changed the Helium pressure to 3.5 kPa, we kept 19.5 MeV field as shown in Fig.3. From this test, we could operate under 3.5 kPa and could increase the beam energy to 19.5 MeV. We note that we obtained more margin for stable beam operation.

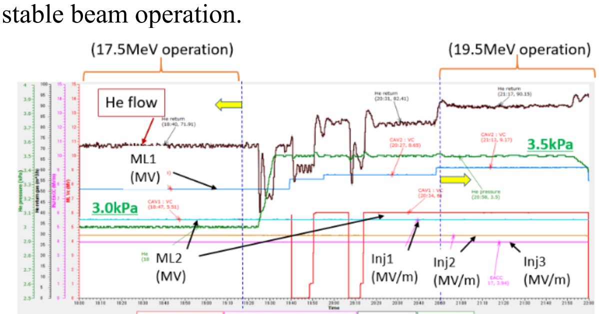

Figure 3: Total performance after changing He pressure from 3.0 kPa to 3.5 kPa.

MEDICAL AND INDUSTRIAL APPLICATIONS IN cERL

Beam Operation for ^{99}Mo Production in cERL

For nuclear medicine diagnosis, ^{99}Mo is basically used. However, this was almost 100 % imported. Most ^{99}Mo is

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manufactured in nuclear reactor. If ^{99}Mo was produced stably compared to nuclear reactor, we stably supplied ^{99}Mo to the patient. ^{99}Mo was created from natural ^{100}Mo via gamma-n reaction by hitting bremsstrahlung gamma-ray come from converter hit electrons of a few 10 MeV if we use the electron beam. If we need to satisfy our demand of medical use in the world, we operated 20-50 MeV electron beam of several mA. SRF accelerator is good candidate to produce large current with more than 20 MeV beam. Before constructing high power accelerator for ^{99}Mo production with high current CW beam, we would like to check the yield of the production in cERL in order to realize a real machine. Therefore we made beam line to demonstrate ^{99}Mo production with SRF accelerator in cERL[8]. First, we started beam operation with 10 μA of CW beam at about 20 MeV beam energy.

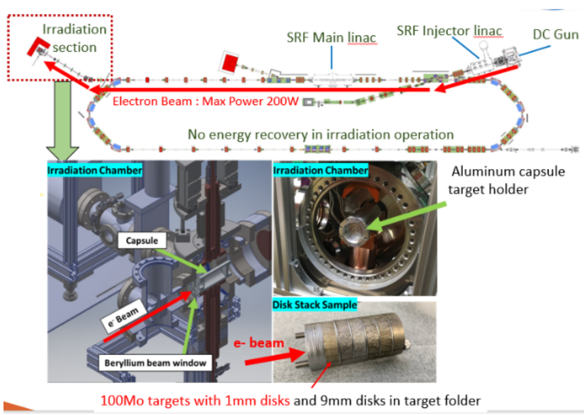

Figure 4: Setup of RI production beam line.

Upper figure of Fig. 4 shows our beam line schematics for irradiation beam line. In 2019, we produced beam line at the end of north line. In these operations, we did not operate under energy recovery. Lower pictures of Fig.4 show our target system. In order to enclose the generated radioisotope, the target sample is fixed in the sealed capsule. After we set the ^{100}Mo targets in this capsule and installed this capsule at the center of irradiation chamber, we start the beam operation with CW mode. Figure 5 shows the trend of beam operation under 17.5 MeV energy, we could stable beam operation of 9 μA with CW mode. We note that we tried around 20 MeV operation to check the yield of ^{99}Mo. With low emittance beam with CW mode in cERL beam, we could get precise yield information of ^{99}Mo via gamma-n reaction by using cERL stable CW beam operation. Detailed analysis will be published elsewhere.

Beam Operation for IR-FEL Production in cERL

Next we show the IR-FEL production in cERL. When we use the short bunch beam in ERL mode, we could make high power FEL. The beam energy of cERL is about 20 MeV. This energy suit to produce IR-FEL and could high power FEL when high current ERL operation can do. The organic material has the vibration absorption in the mid-infrared region for example from 5 μm to 25 μm. Our application is making tuneable high-power laser based on IR-FEL in cERL to create database for laser processing scanned MIR regime supported by NEDO (Ministry of Economy, Trade and Industry). Our task is producing IR-FEL from 10 μm to 20 μm regime and test the processing material from FY2018 to FY2020.

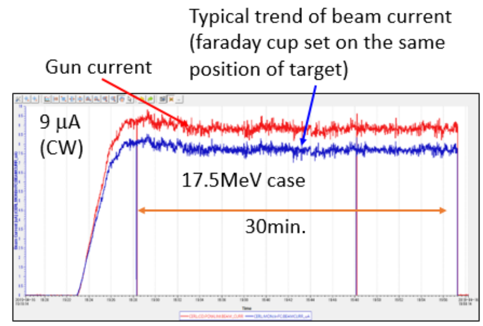

Figure 5: Trend of beam operation for irradiation beam line with 17.5 MeV energy.

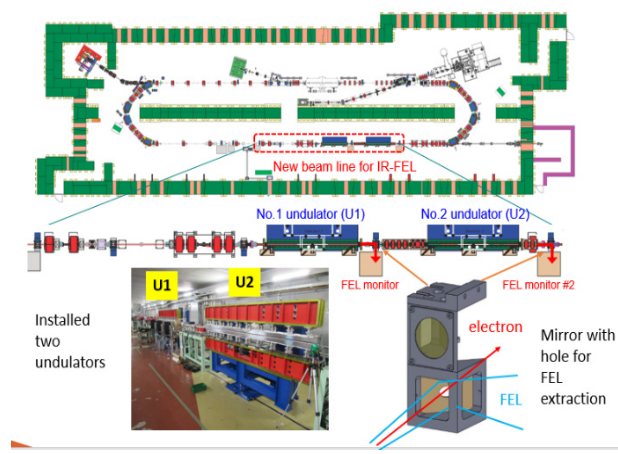

Figure 6: Layout of the cERL after modification for MIR-FEL (upper) and enlarged drawing of the undulators installed in the south-straight section with installed undulator picture (lower).

The FEL beam line was constructed in 2019 and 2020 at cERL [14]. Figure 6 shows the schematic layout of our IR-FEL in cERL. Two 3 m undulators were installed on the south section of the recirculation loop in cERL and create IR-FEL with SASE scheme. The adjustable phase undulator type was developed [15]. This period is 24 mm and this gap was fixed to about 10 mm. We could change the FEL wavelength from 10 to 20 μm by using these undulators. The FEL light was ejected via mirror with hole set the end of each undulator as shown in Fig. 6. Electron went through the hole. On the other hand, produced FEL diverged and reflected by this mirror and detected by IR detector.

At this operation, in design we operate under energy recovery condition with 1 mA CW beam. However, first it is important to obtain sufficient FEL gain in this scheme. Therefore, we operate the burst mode. We made two laser system for photocathode gun. One is 1.3 GHz and the other is 81.25 MHz with 60 pC/bunch. 0.1 μs or 1 μs macro pulse beam was circulated in cERL with 5 Hz repetition, respectively. Our target power is 1 W level in macro pulses which corresponds to 12 nJ/pulse.

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Figure7 shows the trend of our FEL production. This beam operation was carried out under the burst mode of 1.3 GHz of 5 Hz repetition with 100 ns macro pulse. Both FELs come from U1 and U2 were measured by HdCdTe (mercury cadmium tellurium) detector (MCT). Purple square in Fig. 7 denotes each optics tuning. For example, we change the beam profile to match the undulator section and tune the bunch compression parameter named as R_{56}. These all tunings are very complicated, so we use the AI for tuning. Thanks to the stable cERL beam under AI tuning, we could increase FEL as shown in Fig.7. And finally, we successfully obtained about 10 times higher gain from U2 than that of U1. We note that the intensity of this FEL is stable. We could keep stable FEL power within 7 % r.m.s in 30 min-utes. Detailed results were summarized in [16].

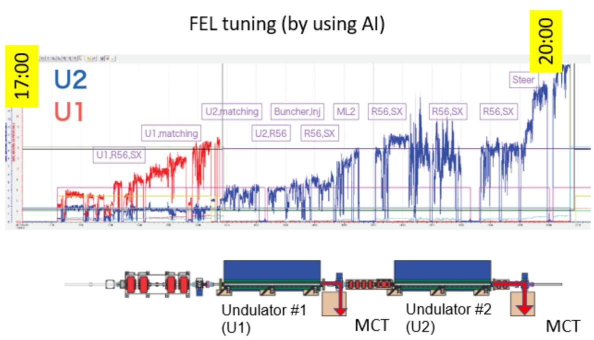

Figure 7: Trend of FEL tuning. Red (blue) data shows the measured FEL by MCT on U1 (U2).

SUMMARY AND FUTURE PROSPECT

We show the industrial and medical applications in cERL. One is ^{99}Mo production by using cERL CW beam by fabricating new beam line. The other is high power IR-FEL production with SASE-scheme by using 2 undurator for laser processing to organic material application. Both experiments were successfully carried out thanks to the long-term efforts for keeping SRF cavities performance by processing and cryogenic control.

We will plan to increase 10 mA beam operation with ERL mode in cERL. If we can ERL-FEL operation with 10~mA beam in cERL, the 10 kW class high power EUV light source will not just a dream [9]. In a radiation beam line, we will continue to irradiate other RI materials and so on.

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We would like to express our gratitude to the members of the cERL team for their cooperation in the design, construction and experiments of cERL.

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