COMMISSIONING OF JAERI ENERGY RECOVERY LINAC

N. Nishimori*, R. Hajima, R. Nagai, M. Sawamura, N. Kikuzawa,
T. Shizuma, E.J. Minehara, JAERI, Ibaraki, Japan

Abstract

An energy recovery linac with superconducting accelerator was constructed in JAERI (Japan Atomic Energy Research Institute) FEL, and commissioning started in January 2002. Electron bunches are injected into the energy recovery linac at 2 MeV, accelerated up to 17 MeV and dumped after deceleration down to 2 MeV by the same accelerator. The bunch charge is 0.5 nC with micro-pulse repetition rate of 10 MHz. The energy recovery rate was estimated to be more than 95 % from an RF input power with and without energy recovery. In this paper, we show the present results of energy-recovery experiments.

1 INTRODUCTION

The JAERI-FEL facility has been constructed to produce a high power FEL at wavelength in far infrared region (20-30μm). The laser output power exceeded 1 kW in average with 500 μs macropulse duration at repetition rate of 10 MHz without energy-recovery in 2000 [1]. In order to increase the FEL output power higher than 10 kW and demonstrate the technology and commercial profit of high-power FELs for industrial applications, we have developed an Energy Recovery Linac (ERL) at the Japan Atomic Energy Research Institute (JAERI) FEL facility [2]–[4].

An ERL with a superconducting accelerator has been developed as a driver of high-power IR-FEL at JLab [5], in which beam average current can be increased four times with keeping RF generator power by increasing the bunch repetition rate. The high power IR-FEL developed at JLab has been used for processing materials and studying applied and basic science [6]. A synchrotron light source using ERL based on a superconducting accelerator and a recirculation beam transport line is also proposed to produce ultra-high brilliance x-ray beams as alternative to storage ring synchrotron light sources [7].

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In the original JAERI-FEL configuration, the high power FEL is owing to high efficiency rather than high average beam power in the IR-FEL at JLab. The high efficiency lasing has been realized when the length of an optical resonator is exactly matched with interval between electron bunches [8], although such lasing is not allowed due to the laser lethargy effect (see Ref. [9] and references therein). Study on mechanism of the high efficiency lasing is underway in our laboratory. A systematic measurement of the maximum efficiency with several gain and loss parameters indicates that there is upper limit of maximum efficiency around 9 % with JAERI-FEL parameters [8], and it seems difficult to increase the FEL output power with the high efficiency operation any more.

In the spring of 2001, we shut down JAERI-FEL without energy recovery, and started construction of an ERL. The ERL was designed to fit limited space of our accelerator room, based on the original configuration. Choices in designs of recirculation arcs and a merger are restricted due to the limited space in our laboratory. Although an isochronous and achromatic recirculation has been successfully realized with MIT/Bates-type arc at JLab [5], which consists of a single π-bend and two half chicane bends, a triple-bend arc is adopted at JAERI-FEL [2]. The isochronism and achromaticity have been realized by setting position and strength of quadrupole magnets between bends at appropriate values. An achromatic merger is also realized by a triple-bend in JLab [5] though, it is impossible to inject electrons into a merger from an oblique direction at JAERI-FEL due to the space limitation. A staircase chicane was adopted as the merger because the emittance growth is minimum among several mergers we can use [3]. In order to realize isochronous and achromatic arcs and an achromatic merger, strengths of the quadrupole magnets between bends have to be determined appropriately at JAERI-FEL, while such quadrupole magnets are not required in JLab in principle.

Figure 1 shows the JAERI-ERL system. Longitudinal and transversal beam dynamics from gun to the end of accelerator are calculated by PARMELA [3, 10]. An electron bunch of 0.5 nC with length of 800 ps FWHM at 230 keV injected from a gun is compressed to 120 ps at the entrance of the first cavity by velocity bunching with a SHB and following drift space [11]. The normalized rms emittance grows from 14 mm-mrad at the gun exit to 20 mm-mrad at the last solenoid just before the first cavity due to mismatch of the strength of the solenoid with respect to space charge force. The electron bunch is accelerated up to 2 MeV by two sets of single cell RF cavities and compressed by velocity bunching with appropriate phase value of the second single cell cavity and following drift space. The compressed bunch length before the merger is 60 ps, and further compressed to 15 ps FWHM by a magnetic compression in the merger. The emittance grows from 20 mm-mrad to 40 mm-mrad at the merger due to the space charge effect (see Ref. [3] and references therein). The electron beam is accelerated up to 17 MeV by two sets of five cell cavities (main accelerators) with frequency of 499.8 MHz and electric field of 7.5 MV/m.

Horizontal and vertical betatron functions and horizontal dispersion function from the end of main accelerators

* nisi@milford.tokai.jaeri.go.jp

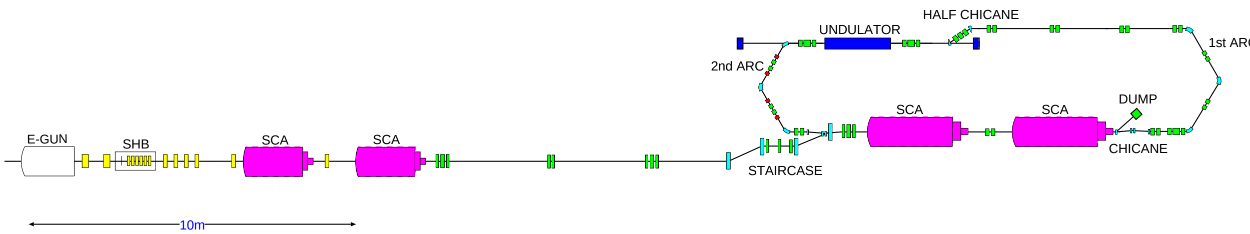

Figure 1: JAERI-ERL system layout.

to the entrance of main accelerators through the recirculation transport were calculated by DIMAD [3, 12]. The accelerated electron bunch is transported into an undulator through the 1st triple-bend achromatic arc and a half chicane and is re-injected into main accelerators through the 2nd achromatic arc with sextupole magnets, which are used to compensate transversal and longitudinal spread due to T_{166},T_{266} and T_{566} in the 2nd arc when energy spread of the electron bunch becomes large as a result of FEL interaction [2]. All the components of the 2nd-arc are placed on movable stages to change path length in order to inject the recirculated bunches into the main accelerators at decelerating phase.

3 ENERGY RECOVERY EXPERIMENT

The recovery rate of the electron beam in the main accelerator is measured with three different methods. In the first method, beam current of recovered electrons at a beam dump after the main accelerators is measured with a Faraday cup made of a copper plate. Since it is difficult to capture the whole amount of low energy electrons such as 2 MeV due to Rutherford scattering, the maximum recirculated current amounts to only 80 % of the full beam. In the second method, a current transformer signal shown in Fig. 2 is used. The bunch interval is 96 ns, and the recirculated beam is re-injected 133 ns after the injection which corresponds to about 40 m. The diameter of the current transformer is 60 mm, and the magnitude of the signal depends not only on the beam current but also on radial distance from the center axis of the transformer. It is difficult to estimate the recovery rate from the signals because the recirculated signal can become larger than the injected signals under a certain condition. The final method is to measure a waveform of the forward signal of RF amplifier for the main accelerator with a diode detector. The RF power used for acceleration of the electron beam is almost returned back by re-injection as shown in Fig. 3. The signal level is proportional to the squared root of the RF power, and loading due to electron beam can be estimated from the difference between signals with and without the electron beam. The ratio of the beam loading with and without energy recovery is also obtained from those signals and the recovery rate has been estimated to be larger than 95 %.

The path length of our recirculation loop was changed by ±5 mm with the movable stages of the 2nd arc, but no apparent change of recovery rate was observed at that time. This may arise from an unexpected long bunch length, which is described in the next section.

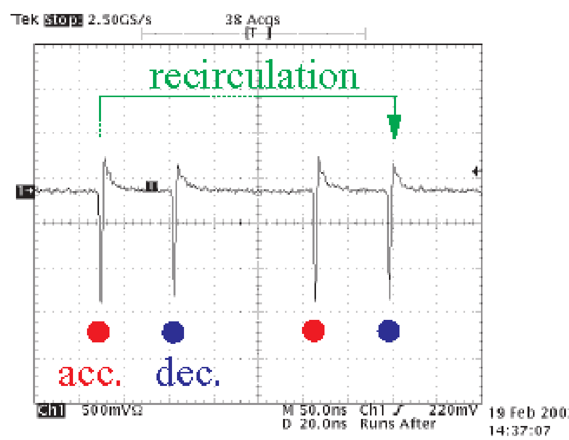

Figure 2: Signal of a current transformer placed after the main accelerators.

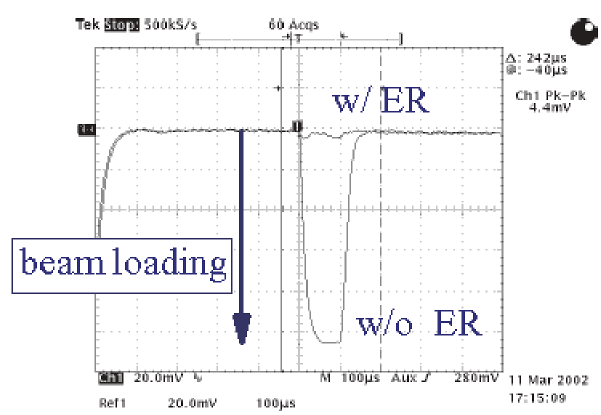

Figure 3: A waveform of the forward signal of RF amplifier for 100 μs macropulse.

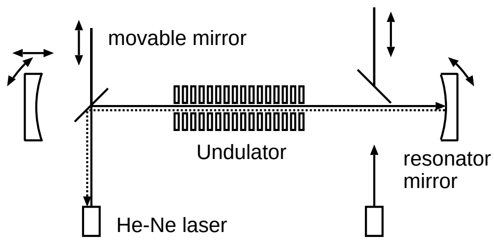

Figure 4: An optical resonator alignment system.

4 FEL EXPERIMENT

An experiment for FEL lasing has been also performed with the ERL configuration. The length of an optical resonator was set to 7.20 m, which corresponds to 1/4 th of the electron bunch interval, and the stored FEL in the resonator can interact with newly injected electron bunches every two round-trips. A gold-coated resonator mirror with curvature of 3.88 m and 120 mm in diameter without hole is used for both downstream and upstream mirrors. The Rayleigh range is 1.00 m which is the same with the original configuration.

The tilts of resonator mirrors without holes are aligned by a system shown in Fig. 4, where movable mirrors can be set on the resonator axis. The tilt of each mirror is adjusted so that an injected He-Ne laser on the movable mirror is reflected back by the corresponding resonator mirror. All the components including RF cavities, magnets, undulator, and resonator mirrors are aligned by 3-D measurement tool [13], and the center of the reflecting mirrors is also aligned in the resonator axis. The alignment error of all the components is less than 0.5 mm [4].

The stored spontaneous radiation is coupled out by a gold coated scraper mirror of 10 mm in diameter and measured with a liquid-nitrogen-cooled HgCdTe detector. The radiation signal enhances four times with the optical resonator compared with a single pass radiation. In the original configuration, the enhancement was six times though, the loss becomes effectively large in the present configuration because the length of the resonator becomes half. Then the four times enhancement indicates that resonator mirrors are appropriately aligned and the resonator loss is enough small to establish lasing. The resonator length was scanned by $\pm$ 3 mm, but no lasing has been obtained yet.

In order to search the reason why the lasing does not occur at JAERI-ERL, length of the electron bunches inside the undulator was measured with a synchroscan streak camera (M1954-10, Hamamatsu). The length was 300 ps FWHM which is eight times longer than the expected value in our simulation [3]. The main reason of the long bunch length may be that the achromaticity was not realized in our merger at that time. The achromaticity can be realized by flipping dispersion with quadrupole magnets just after the second bend and just before the third bend, so that the strength of the quadrupole magnets must be carefully determined. In order to determine the strength of the quadrupole magnets, a slit of 2.5 mm in width was installed into the position where the horizontal dispersion is zero. After the modification, the bunch length of 40 ps FWHM has been successfully obtained in the undulator center at the bunch charge of 0.4 nC, which corresponds to the peak current of 10 A enough high to initiate lasing with JAERI-FEL parameters. It is expected that lasing at JAERI-ERL will be established in the near future.

5 SUMMARY

We started commissioning of JAERI-ERL. The fully accelerated electron beam is re-injected into the main accelerator at deceleration phase, and dumped after the main accelerator. The recovery rate is estimated to be larger than 95 % from the forward signal of RF amplifier for the main accelerator. FEL experiments are also performed with the ERL configuration, but lasing has not been established yet. The main reason may be the difficulty in determining the appropriate strength of quadrupole magnets in our merger for the achromaticity. After installing a slit into our merger in the position where the horizontal dispersion is zero, the bunch length of 40 ps is obtained in the undulator center. It is expected that the first lasing will be established with JAERI-ERL configuration in the near future.

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