BEAM CURRENT DOUBLING OF JAEA ERL-FEL

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Abstract

An energy-recovery linac (ERL) R&D program for a high-power free-electron laser (FEL) is in progress at Japan Atomic Energy Agency (JAEA; formerly JAERI and JNC). The first energy-recovery operation and FEL lasing was demonstrated in 2002 by remodeling the superconducting linac of the JAERI-FEL driver. In the first demonstration, the accelerated beam current was same as the original linac. One of the advantages of an ERL is that the accelerating beam current can be increased by only changing micro-pulse repetition rate without increasing the RF power of the main linac. The advantage of an ERL has been demonstrated by the current doubling.

INTRODUCTION

For the high-power free-electron laser (FEL), the FEL extraction efficiency or the drive beam power should be increased. Increasing of the drive beam power is more effective than increasing of the FEL extraction efficiency because the FEL extraction efficiency is limited in several percent. For the beam power increasing in a usual linac, there are some problems as follows: high-power RF source and coupler corresponding with the beam power are needed, high-power and high-energy beam should be dumped, radiation shield at the beam dump is very tough. A high-power beam can be accelerated by small RF power in an energy-recovery linac (ERL) because the beam power not extracted to the FEL light is recovered and used to the acceleration. The radiation shield and thermal design of the beam dump becomes easy because the dumped beam power and energy is reduced by the deceleration at the linac. Using an ERL as an FEL driver therefore solves the problems for the beam power increasing.

An ERL-FEL R&D program is in progress at Japan Atomic Energy Agency (JAEA; formerly JAERI and JNC). The first energy-recovery operation and FEL lasing was demonstrated [1] in 2002 by remodeling the superconducting linac of the JAERI-FEL [2]. In the first demonstration, the accelerated beam current was same as the original linac. One of the advantages of the ERL is that the accelerating beam current can be increased by only changing micro-pulse repetition rate without increasing the RF power of the main linac. To demonstrate the advantage, the e-gun, the injector RF source, the low-level RF (LLRF) controller, and the operation system have been improved. As a result of the improvement, the doubled beam acceleration and the FEL power improvement have been successfully achieved.

IMPROVEMENT OF THE JAEA ERL-FEL

The layout of JAEA ERL-FEL is shown in Fig. 1. The injector consists of a DC electron gun with thermionic cathode driven by a grid pulser, an 83.3 MHz sub-hermonic buncher, and two 499.8 MHz 1-cell superconducting modules. The merger is a two-step staircase type that consists of four bending magnets and three quadrupole magnets. The main linac consists of two 499.8 MHz 5-cell superconducting modules. The beam transport system to the undulator consists of a triple-bend achromatic (TBA) arc and a half-chicane achromatic system. The undulator is a hybrid type with period

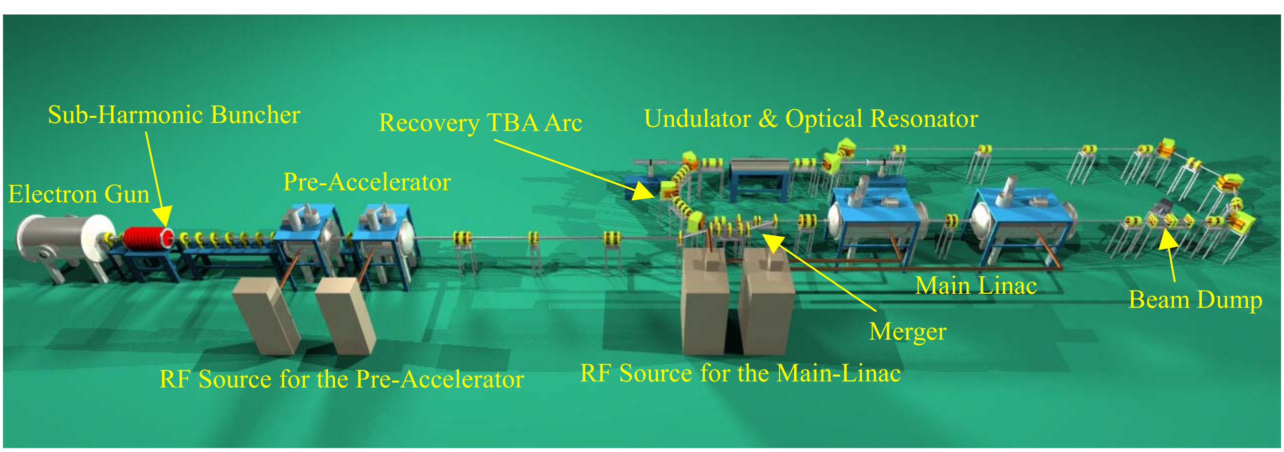

Figure 1: Layout of JAEA-ERL.

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number of 52 and period length of 33 mm. The optical resonator is a near-concentric Fabry-Perot type that consists of two gold-coated mirrors with center-hole output coupler. The recovery beam transport system is a TBA arc.

In the original linac, the electron beam was accelerated in burst mode with 10 Hz macro-pulse and 10.4125 MHz micro-pulse repetitions. The macro-pulse average current was 5 mA that was mainly limited by the RF power sources and the grid pulser. To demonstrate that the higher beam current than the RF source capacity of the main linac can be accelerated, the ERL has been improved.

The electron gun is equipped with a thermionic cathode and operated at 230kV DC voltage. A train of electron bunch is generated by the grid pulser. To generate 20.825 MHz bunch train, doubled repetition of original one, a main-circuit of the grid pulser was replaced to new circuit [3]. The bunch length and timing jitter of the electron beam at the electron gun are 590 ps-FWHM and 12.8 ps-rms, respectively. The bunch length and timing jitter are compressed into about 1/100 through the beam transport system to the undulator.

In the original linac without energy-recovery, two 1-cell superconducting modules were driven by two 8 kW solid-state amplifiers for each, enough capacity for 5 mA operation. The solid-state amplifiers were replaced by two IOT of 50 kW [4], which is enough capacity for 40 mA operation.

Stable operation of an FEL depends much on the stability of an accelerator. In a superconducting accelerator, a LLRF controller is one of the key components for achieving good stability. The original LLRF controller was designed for phase flatness at ±1 deg. within a 1 ms macro-pulse. This LLRF controller contributed to the 10-year operation of JAERI-FEL. After the remodeling into the ERL, however, the original LLRF controller performance was insufficient for the ERL operation. The LLRF controller was replaced by new one. The new controller is based on analog phase and amplitude control of the cavity RF field coupled with a tuner controller, which is same as the original controller. In the new controller, the following functions were introduced for the better stability: the feedback gain, time constant and loop phase offset can be varied during operation to obtain good flatness of RF phase and amplitude within a macro-pulse, all the circuits are contained in a temperature regulated oven [5]. By the new controller, the phase and amplitude stabilities at the beam acceleration are 0.07 %-rms and 0.07 deg-rms, respectively. The original controller was placed at the control room, and the feedback loop involved 50 m cables to connect the controllers and the RF cavities. These long cables have large phase drift due to the temperature dependence of the electrical length. The new controller are installed just beside the cavities to make the cable length as short as possible. Furthermore the cables between the controllers and the cavities are contained in a temperature-regulated pipe to suppress the effect of the changing of the room temperature [6]. The phase stability in any season has been achieved less than 0.1 deg-rms by the temperature-regulated cable system.

The electron motion in the longitudinal and transversal phase space is very complex because the injector has long drift spaces before and after the pre-accelerator. The achromaticity of the merger and the bunch length of the electron beam are sensitive to the quadrupole magnets parameter. Therefore, the beam transport parameter adjustment of the injector and the merger is not easy. To support systematic parameter search, the accelerator operation system of the JAEA-ERL is equipped with a data-logging system and database services [7]. The initial parameter set of the injector was decided by the numerical optimization [8]. In the result, the electron bunch length of less than 10 ps has been achieved at the undulator.

The length of the optical resonator was changed along with remodeling to the ERL. The optical resonator geometry was optimized by a Fox-Li procedure utilized simulation code[9]. In the optimization, the center-hole thickness was not taking into account. The center-hole thickness causes additive loss. If the center-hole thickness is taking into account, the radius should be enlarged more than the ideal case. The center-hole radius of 1.0 mm was adopted in consideration of the loss by the center-hole thickness because the optimum radius was 0.8 mm in the ideal case. The misalignment tolerance of the resonator was estimated by the Fox-Li simulation code [10]. The offset and tilt tolerance for the FEL power fluctuation of 1% are 0.1 mm and 40 μrad, respectively. The vibration of the floor is less than 1 μm. The accuracy of the He-Ne alignment system of the optical resonator is less than 20 μrad. The offset and tilt tolerance of the optical resonator is therefore sufficiently large for the FEL power fluctuation of less than 1%.

ERL AND FEL DEMONSTRATIONS

In the adjustment of the beam transport, the higher current beam than the RF source capacity cannot be accelerated because the energy-recovery is not enough. The energy-recovery acceleration and beam transport have been adjusted in the condition of original micro-pulse repetition of 10.4125 MHz. Under the micro-pulse repetition in 10.4125 MHz, because the beam lost is allowed, the screen monitor can be used for the beam transport adjustment. After the adjustment, doubled beam in the repetition frequency of 20.825 MHz has been accelerated only changing of the micro-pulse repetition. The current increase only by changing the micro-pulse repetition is scalable. The successful current doubling shows that the current can be increased easily up to 40 mA corresponding with the repetition of the SHB frequency. Typical signal of the current monitor at the entrance of the main linac is shown in Fig. 2. These signals are the injection beam to the main linac and the re-circulated beam from the recovery beam transport system in the repetition of 20.4125 MHz. The amplitudes of the injection and the re-circulated beam signal are the almost same.

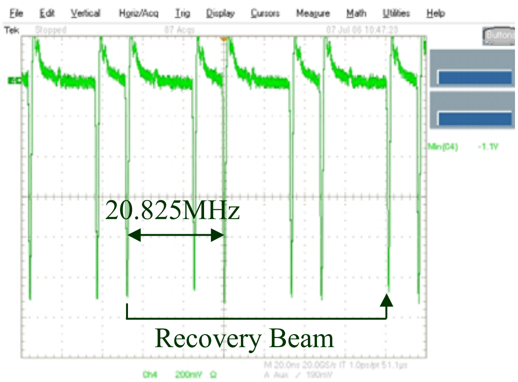

Figure 2: Typical signal of the current monitor at the entrance of the main linac.

Typical signal of output power of the main linac RF source is shown in Fig. 3. The RF source is operated in the pulse mode in the repetition of 10 pps and the pulse width of 2 ms. The electron beam has been accelerated with 1ms in the latter half. In the case of Fig. 3, the macro-pulse width of the electron beam is 230 μs. The RF output power with and without the electron beam are the almost same because the RF power is recovered by the decelerated electron beam. As shown in Fig. 3, the high-current electron beam can be accelerated if there is an RF power only of the amount of exciting the acceleration field. The spike at the edge of the electron beam macro-pulse is caused by the feedback of the RF low-level controller. In the pulse mode, the RF power to compensate the disturbance such as the edge of the electron beam macro-pulse is needed as shown in Fig. 3.

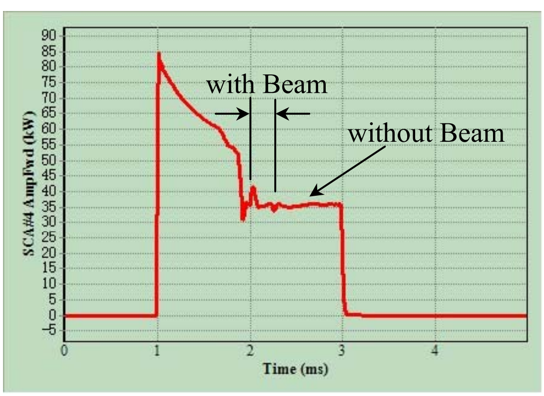

Figure 3: Typical signal of output power of the main linac RF source.

After the energy-recovery acceleration, the FEL lasing is successfully achieved by adjusting the length and the beam position of the optical resonator. The beam position is adjusted while monitoring the stored spontaneous emission with a liquid-nitrogen-cooled HgCdTe detector. The FEL extraction efficiency is obtained by measuring the energy loss of the electron beam. The energy loss and energy spectrum of the electron beam is measured by a wire-monitor set up on the way of the recovery TBA arc. The amount of the beam lost by the wire monitor is less than the RF power source capacity. The detune curve of the FEL extraction efficiency is shown in Fig. 4. The Maximum efficiency and power are 2.7 % and 0.7 kW, respectively. The output efficiency of the optical resonator is about 30 %. The output efficiency of the optical resonator is about 37 % in the numerical simulation. The difference of the measured value and calculated one is caused by the thickness of the output center-hole, and misalignment of the resonator.

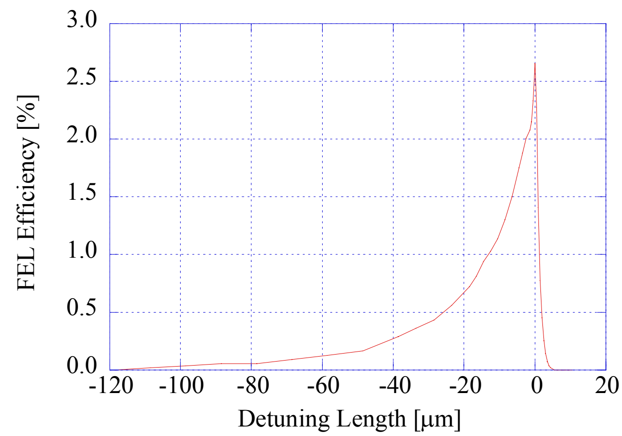

Figure 4: Detune curve of the FEL extraction efficiency.

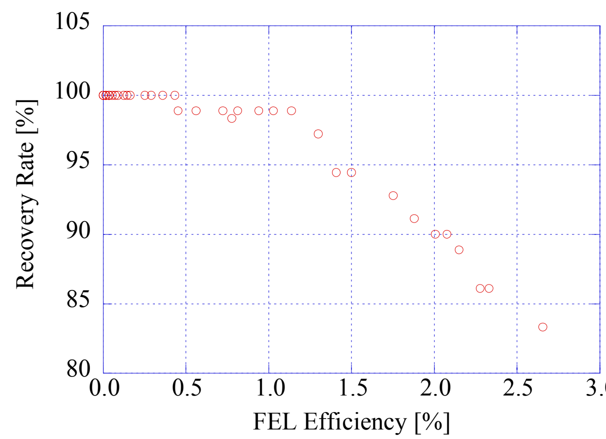

Figure 5: Recovery rate of the electron beam at the beam dump.

The recovery transport system with a large energy acceptance is necessary because after lasing the electron beam has large energy spread. The energy spread is about 5 times of the extraction efficiency. The recovery rate of electron beam at the beam dump is shown in Fig. 5. The electron beam is almost recovered up to the extraction efficiency about 1 %. Under the present condition, the beam loss at the FEL lasing is less than the RF source capacity. To increase the beam current, the recovery rate should be close to 100 %. Measured energy spread at the maximum output power is about 13.5 % (tail to tail). The energy acceptance of the recovery TBA arc is about 16 % in the calculation, and almost electron beam can be transported. There is actually little bremsstrahlung radiation in the arc part. The beam is therefore lost mainly in deceleration at the main linac. To recover the almost electron beam, after lasing the energy spread of the electron beam should be compressed because it is too large into the energy after decelerating [11]. Therefore, R56 of the recovery TBA arc and deceleration phase should be optimized to achieve fully recovery. The optimization of the energy compression is in progress.

CONCLUSION

One of the advantages of an ERL is that the high beam current over the RF source capacity of the main linac can be accelerated. The advantage of an ERL has been successfully demonstrated by the current doubling with only changing of the micro-pulse repetition rate. The current increase only by changing the micro-pulse repetition is scalable. The successful current doubling shows that the current can be increased easily up to 40 mA corresponding with the repetition of the SHB frequency.

To achieve in the future the 10 kW class high-power FEL, the beam current will be increased by solving the problem of the recovery rate and increasing the repetition of micro-pulse up to the SHB frequency of 83.3 MHz. The RF sources of the pre-accelerators are ready for 40 mA beam. For the 83.3 MHz operation, the drive frequency of the grid pulser should be improved up to 83.3 MHz. Design of a grid pulser for the higher repetition rate is under investigation. A photo cathode electron gun driven by a laser as another option for the 83.3 MHz operation is under investigation also.

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