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JAERI ERL-FEL: status and future plans

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Abstract

An energy-recovery linac (ERL) for a high-power free-electron laser (FEL) is under development in JAERI. We completed the construction of the ERL, and demonstrated the first energy-recover operation and FEL lasing in 2002. For realizing FEL lasing in 5-10kW average power, further upgrade of the ERL is carrying on, which includes reinforcement of the injector, replacement of the RF control system and so on. Future plans for high-power FEL application and basic research towards future ERL light sources are also described.

INTRODUCTION

A research program of a high-power free-electron laser (FEL) at JAERI (Japan Atomic Energy Research Institute) started in 1987, and we achieved the initial goal, kilowatt FEL lasing, in 2000[1]. The program is now proceeding to the next stage, demonstration of a 5-10kW FEL with an energy-recovery linac (ERL). The energy-recovery technology with a superconducting linac is the most promising device for high-power FELs [2] and next generation Xray light sources[3]. We consider that the development of the energy-recovery linac at JAERI will contribute to future FELs and light sources.

The ERL was designed by adding a return arc to the original superconducting linac at JAERI-FEL[4]. The original linac was shut down in the spring of 2001, and the ERL was completed after a half year construction period. We demonstrated first energy-recovery operation at 19 February, 2002, and first FEL lasing at 14 August, 2002 [5].

In this paper, we present recent results from the R&D program at JAERI-FEL, and a future plan.

CONFIGURATION OF JAERI-ERL

The layout of JAERI-ERL is shown in figure 1. An injector, main SCA modules, an undulator and the first arc are inheritance from the original FEL. An injection merger, a half-chicane before the undulator, and the second arc were newly installed for the ERL.

The injector consists of 230kV electron gun with a thermionic cathode, 83.3MHz subharmonic buncher (SHB), and two cryomodules, each of which contains a single cell superconducting cavity driven at 499.8MHz. An electron bunch of 0.5nC with length of 800ps (FWHM) is generated by grid pulser at 10.4MHz repetition, that is 5mA average current, and compressed by SHB and following drift. The electron bunch is accelerated to 2.5MeV by two single cells, and further compressed by velocity bunching during a 9m drift. The bunch duration becomes 60ps (FWHM) at the entrance of the injection merger and 15ps (FWHM) after the merger as a designed value.

An electron bunch injected to the main module is accelerated up to 17MeV, and transported to the undulator. After the FEL interaction, the electron bunch is reinjected into the main module at deceleration phase for the energy recovery. The reinjection phase is controlled by changing recirculation path length. We installed the second arc on movable tables for this purpose.

The recirculation loop consists of two triple-bend arcs and a half chicane before the undulator. Each arc has two families of quadrupoles which enable to vary R_{56} while maintaining achromaticity. This variable R_{56} is especially required in the second arc, because we need energy-spread compression in the return-path. The second arc also has two families of sextupoles to compensate second-order aberrations T_{166}, T_{266}, T_{566} arising from large energy spread due to the FEL interaction. The energy acceptance of the return arc was studied by particle tracking and found to be 7% (full energy spread) [6].

EXPERIMENTAL RESULTS

Energy-recovery operation was demonstrated at 19, February 2002. The energy recovery was confirmed from a beam current signal and an RF amplifier signal. Figure 2 is a beam current signal from a current transformer at the exit of the second main module. We can see both accelerating and decelerating bunches alternatively. In this experiment, the bunch interval is 96ns and the recirculation time is 133ns.

We measured RF forward power from the RF amplifier to the main superconducting cavity for evaluating the energy-recovery ratio, which is the ratio of recovered RF power to the beam power. Figure 3 shows RF forward signal for a 100μs beam macropulse. When we interrupt the recirculation beam by screen to turn off the energy recovery, the signal shows beam loading -105mV from the base level, which is -230mV from the ground level and corresponds to reflected power for beam-off. If we turn on the energy recovery, the beam loading is almost canceled by two accelerating and decelerating beams. Although we still have small fluctuation, 4mV at peak, inside the macropulse with energy recovery, the energy-recovery ratio is evaluated as 98% assuming the linearity of the envelope detector.

First FEL lasing with the ERL configuration was obtained at 14 Aug. 2002. Figure 4 is an example of cavity length detuning curve for FEL power. The detuning

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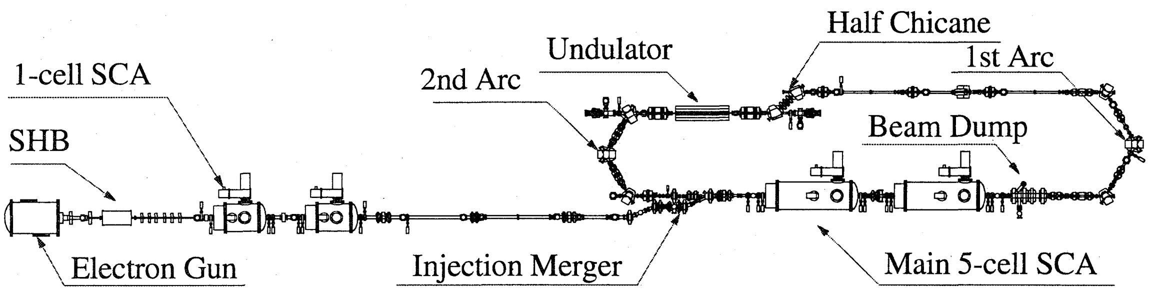

Figure 1: The layout of JAERI Energy-Recovery Linac. An electron bunch generated by 230kV electron gun is accelerated to 2.5MeV and injected into the energy-recovery loop. The electron bunch is accelerated to 17MeV by main superconducting cavities and transported to the FEL undulator. The electron bunch is, then, reinjected to the main cavities and decelerated down to 2.5MeV and collected by a beam dump.

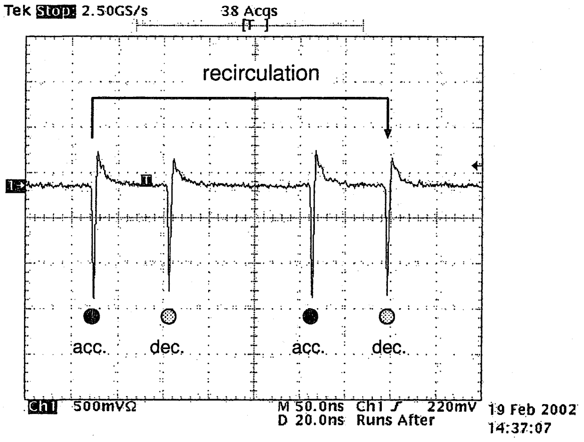

Figure 2: Beam current signal from a current transformer at the exit of the second main module.

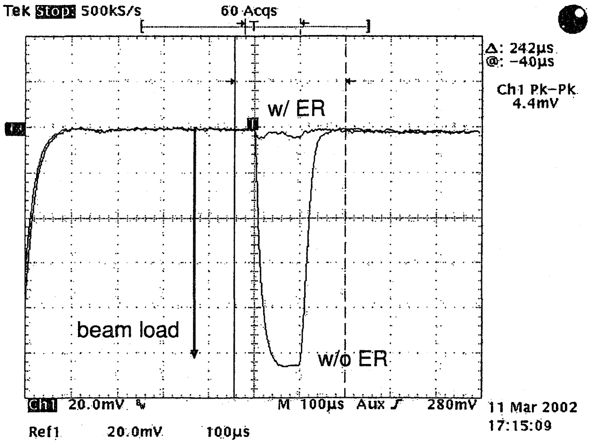

Figure 3: RF forward power to the first main module.

length, ΔL, is relative value from the position at peak, and an FEL pulse is pushed forward by $4\Delta L$ every interaction, in the operation of 10.4MHz. FEL macropulses from the HgTeCd detector suggest single supermode lasing for large ΔL, and superradiance for small ΔL, although we have not made gain, loss and spectral measurements yet.

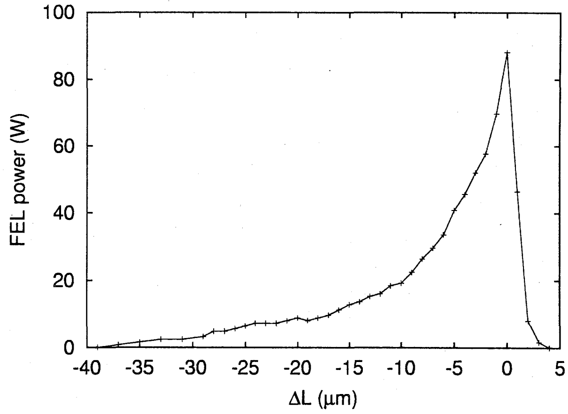

Figure 4: A cavity length detuning curve for FEL power.

UPGRADE FOR A 5-10KW FEL

To achieve the FEL power of 5-10kW, we need to increase both electron beam power and FEL efficiency. Since the higher FEL efficiency induces the larger energy spread in the electron beam, the FEL efficiency is restricted by energy acceptance of the return arc. Numerical simulations based on a 1-D FEL code and PARMELA showed that FEL efficiency of 1.5% is possible with the present arc configuration.

The beam current is now limited by the injector. Each single cell cavity in the injector has been driven by 6kW RF amplifier, which is designed for 5mA. We are replacing it by a 50kW klystrode-IOT, which will enable us to accelerate 40mA beam current. The grid pulser has been modified to generate electron bunches with 20MHz repetition, doubled repetition of the original one [7]. The injection of electron beam, 10mA, will be started soon. Design of a 83MHz grid pulser for 40mA beam injection is also under investigation.

After all the injector upgrade is completed, the electron beam power at the undulator will be 680kW (40mA, 17MeV) and will produce 10kW FEL power with 1.5% efficiency. It is, however, noticed that a some amount of FEL power is lost in the optical cavity due to diffraction. Design of an optical cavity with small diffraction loss is under way[8].

In an energy-recovery linac, it is known that transverse beam break up (BBU) triggered by higher order mode (HOM) instability restricts beam average current[9]. We, therefore, carried out a HOM stability analysis by using a two dimensional BBU code together with measured HOM parameters and designed beam optics. The analysis shows the instability threshold is about 3A and our design current 40mA is far below the threshold[10]. We conclude that the HOM instability is not a critical issue in our ERL.

OTHER R&D ISSUES

Research towards the high-power FEL is our primary goal as described above. We have, however, other research activities on accelerator technology, FEL physics, FEL applications, ERL applications.

In the operation of our superconducting accelerator, variation of RF amplitude and phase due to temperature drift of the atmosphere has been the most critical problem, which destroys stability and reproducibility of the accelerator. It has been found that long cables of the feed-back loop ($\sim$100m) should be shortened to a few meters, and modification of the low-level controller is necessary. We decided to fabricate a new RF low-level controller and install it in the accelerator room, where the cables of the feedback loop for each cryomodule becomes less than 2m long. A special cable with better stability against the temperature drift is also prepared to deliver the reference signal to the low-level controllers[11]. These upgrade of the RF control system will be completed by the end of this fiscal year. We also plan to replace the control system of the magnet and the electron gun. The new system using μTRON will be installed soon [12].

For an FEL application, we investigate material processing using ultrashort FEL pulses such as drilling, cutting and welding. By using FEL pulse shorter than pico-second, we can avoid thermally induced stress and debris generation, which has been unavoidable in material processing with Q-switched YAG lasers or CO_2 lasers.

Application of self-chirped FEL pulses is also studied. We recently found that frequency chirp is induced in an FEL pulse, if the FEL oscillator has large gain and is operated at perfectly synchronized cavity length[13]. We demonstrated generation of an FEL pulse with frequency chirp of 14.3% and duration of 319fs. A laser pulse with such large frequency chirp can be used for quantum control of chemical reaction: the resonant excitation of atomic or molecular systems, which have an anharmonic potential ladder[14].

We also explore a future light source based on the ERL technology, high-flux photon sources in a wide range of photon energy from THz radiation to gamma-ray. In the study of ERL light sources, we designed an ERL-loop to accelerate an electron beam over 100mA in average current without HOM instability[15], and made cost estimation for a 6GeV ERL light source[16]. Dilution of beam emittance due to coherent synchrotron radiation in an ERL-loop is investigated via matrix approach, which enables us to scan numerous parameters for the design of achromatic cells of minimum emittance dilution [17].

CONCLUSION

An energy-recovery linac has been developed for a high-power free-electron laser at JAERI. The energy-recovery operation has been demonstrated successfully and the linac is now operated as designed. An R&D program towards 5-10kW FEL is in progress, which includes injector upgrade, a HOM analysis, optical cavity optimization. We plan to demonstrate material processing and quantum control of chemical reaction using the high-power short-pulse FEL. Basic research for future ERL light sources is also in progress.

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