DEVELOPMENT OF AN ENERGY-RECOVERY LINAC FOR A HIGH-POWER FEL AT JAERI

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Abstract

An energy-recovery linac (ERL) has been developed at Japan Atomic Energy Research Institute (JAERI). We completed the construction of the ERL, and demonstrated first energy-recover operation and FEL lasing in 2002. The ERL consists of a 2.5 MeV injector and a 17 MeV recirculation loop. Major components of the ERL are inherited from the JAERI superconducting linac which demonstrated 2 kW FEL lasing in 2000. For realizing FEL lasing in 5-10 kW average power, further upgrade of the ERL is carried on, which includes enlargement of the injector beam current, replacement of the RF control system and so on. We also investigate HOM-induced beam break up and emittance growth due to coherent synchrotron, which are critical issues for future Xray light-sources and high-power FELs based on energy-recovery linacs.

INTRODUCTION

A research program towards a high-power free-electron laser (FEL) at JAERI (Japan Atomic Energy Research Institute) started in 1987, and the initial goal of the program, kilowatt FEL lasing, was achieved in 2000 [1]. The research program is now proceeding to the next step, demonstration of a 5-10 kW FEL with an energy-recovery linac (ERL). The same-cell energy-recovery in a superconducting linac is a key technology for high-power FELs [2] and next generation Xray light sources [3]. The R&D of ERL-FEL at JAERI will contribute to future FELs and light sources utilizing the ERL technology.

The JAERI-ERL was developed by reconstructing 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].

DESIGN OF JAERI-ERL

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

The injector consists of a 230 kV DC gun with a thermionic cathode, an 83.3 MHz subharmonic buncher (SHB), and two cryomodules, each of which contains a single cell superconducting cavity driven at 499.8 MHz. An electron bunch of 0.5 nC with length of 800 ps (FWHM) is generated by grid pulser at 10.4125 MHz repetition rate, that is 5 mA average current, and compressed by SHB and following drift. The electron energy becomes 2.5 MeV after the two cryomodules, and the bunch is further compressed by velocity bunching during a 9-m drift. The bunch length becomes 60 ps (FWHM) at the entrance of the injection merger and 15 ps (FWHM) after the merger as design values.

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

Two triple-bend arcs are the main component of the recirculation loop. Each arc has two families of quadrupoles to vary R_{56} with keeping achromaticity. This variable R_{56} is necessary in the second arc for 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} due to large energy spread after the FEL interaction. The energy acceptance of the return arc was evaluated by particle tracking and found to be 7% (full energy spread) [6].

DEMONSTRATION OF ENERGY-RECOVERY

First energy-recovery operation was achieved 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. It shows that both accelerating and decelerating bunches are picked up alternatively. In this experiment, the bunch interval is 96 ns and the recirculation time is 133 ns.

Forward power from the RF amplifier to the main superconducting cavity was measured 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 100 μs beam macropulse. When we stop the recirculation beam by screen to turn off the energy recovery, the signal shows beam loading -105 mV from the base level, which is -230 mV from the ground level and corresponds to reflected power for beam-off. If we turn on the energy re-

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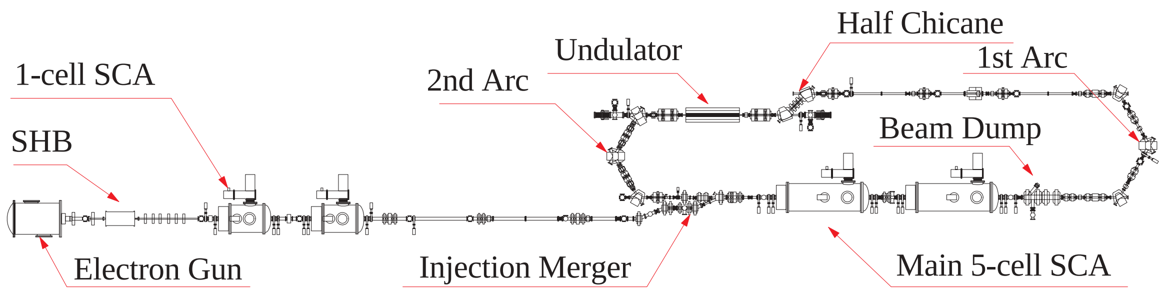

Figure 1: The layout of JAERI Energy-Recovery Linac. An electron bunch generated by 230 kV electron gun is accelerated to 2.5 MeV and injected into the energy-recovery loop. The electron bunch is accelerated to 17 MeV by main superconducting cavities and transported to the FEL undulator. The electron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

covery, the beam loading is almost canceled by two beams. Although we still have small fluctuation, 4 mV at peak, during the macropulse with energy recovery, the energy-recovery ratio is evaluated as 98% assuming the linearity of the envelope detector.

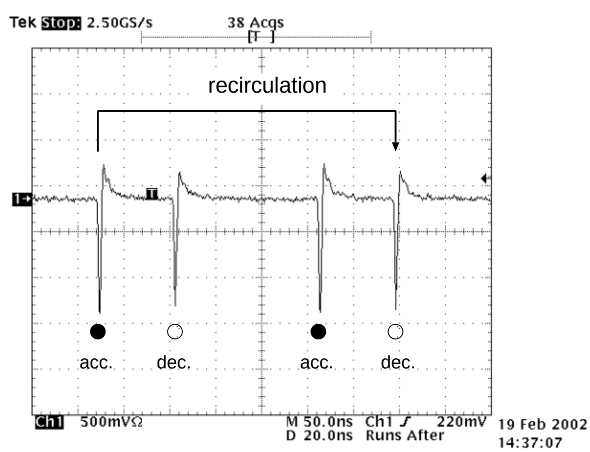

Figure 2: Beam current signal from a current transformer at the exit of the second main module.

First FEL lasing with the ERL configuration was obtained at 14 Aug. 2002. FEL macropulses from a HgCdTe detector suggest that both single supermode lasing and superradiance appear depending on the cavity-detuning length [5].

INJECTOR UPGRADE

The beam current is now limited by the injector. Each single cell cavity of the injector was originally driven by 6 kW RF amplifier, which was enough power for 5 mA. To increase the RF supply for the injector, we newly installed 50 kW klystrode-IOT's, which are sufficient for 40 mA beam current. The grid pulser has been modified to generate electron bunches with 20 MHz repetition, doubled repetition of the original one, and a 10 mA beam is available [7]. Design of an 83 MHz grid pulser for 40 mA beam

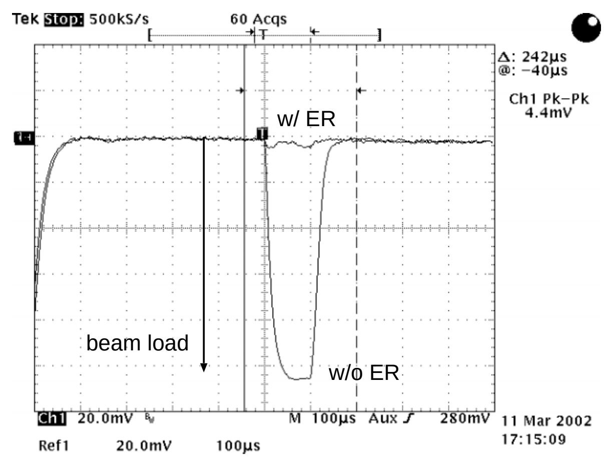

Figure 3: RF forward power to the first main module.

injection is also under investigation.

OTHER R&D ISSUES

Research towards a high-power FEL is our primary goal as described above. We have, however, other research activities on accelerator technologies, FEL physics, and application research.

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

Transverse beam break up (BBU) triggered by higher order mode (HOM) instability restricts beam average current in an energy-recovery linac [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 3 A and our design current 40 mA is far below the threshold [10]. We conclude that the HOM instability is not a critical issue in our ERL.

In the operation of the JAERI 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. To improve the RF stability, we developed a new RF low-level controller, which has excellent stability upon the temperature drift. The RF-phase stability is now better than 0.2-degree both in the temperature drift and shot-to-shot jitters.

We are also replacing the control system of the accelerator operation. A PC-based distributed control system, FELOWS (FEL Operators Window System), has been in work since 1992 at JAERI-FEL [11]. Taking advantages of the rapid progress in computer hardware and software in these 10-years, we have developed a new system, a CAMAC controller working on μITRON operating system with a Java and CORBA environment [12].

For FEL applications, we investigate material processing using ultrashort FEL pulses. By using FEL pulse shorter than pico-second, it is possible to avoid thermally induced stress and debris generation, which has been unavoidable in material processing with Q-switched YAG lasers or CO_2 lasers [13]. Recently we found that non-thermal surface-peeling of stainless steel by ultrashort laser pulses can be adopted to eliminate stress-corrosion-cracking, which is a critical problem in nuclear power plants. A pilot experiment using Ti:Sap. laser showed that we can remove the residual stress of stainless steel by laser peeling.

Application of self-chirped FEL pulses is also studied. We reported that frequency chirp is induced in an FEL pulse, if the FEL oscillator has large gain and is operated at perfectly synchronized cavity length [14]. We demonstrated generation of an FEL pulse with frequency chirp of 14.3% and duration of 319 fs. 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 [15].

We also explore a future light source using 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 [16], and made cost estimation for a 6GeV ERL light source [17]. 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 [18].

SUMMARY

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 5-10 kW 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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