RECENT RESULTS OF THE JAERI ENERGY-RECOVERY LINAC FEL

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Abstract

In Japan Atomic Energy Research Institute (JAERI), we are developing an energy-recovery linac (ERL) for a high-power free-electron laser (FEL). The ERL was completed in 2002 by remodeling the original superconducting accelerator. In this paper, we summerize recent research activities at JAERI-ERL.

INTRODUCTION

A research program towards a high-power free-electron laser (FEL) has been conducted at Japan Atomic Energy Research Institute (JAERI) since 1987. The initial target of the program, FEL lasing in kilowatt level, was achieved in 2000[1], and the research program is now stepping forward to the next stage, demonstration of a 5-10 kW FEL.

It is considered that same-cell energy-recovery in a superconducting linac is the only practical solution to put such a high-power FEL in work efficiently[2]. Hence, we decided to remodel the superconducting accelerator into an energy-recovery linac (ERL)[3]. 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 [4].

In this paper, we present recent research activities at JAERI-ERL FEL: upgrading major components of the superconducting accelerator, investigation of long-macropulse operation, beam dynamics studies and others.

COMPONENTS UPGRADE

Injector RF Sources

Increasing the injector beam current is a straightforward approach to enlarge the FEL power by taking full advantage of the energy-recovery. In the original JAERI-FEL without energy-recovery was operated at 5 mA injector beam current. Two single-cell cavities of the injector were driven by 6 kW solid state amplifier for each, enough capacity for 5 mA operation. The solid state amplifier has been replaced by an IOT-klystrode of 50 kW, which enables one to inject a 40 mA beam into the ERL. The IOT is designed for CW operation as well as pulsed operation, while the original amplifier allowed only pulsed operation with small duty-cycle such as 1 ms $\times$ 10Hz. We also plan to replace RF amplifiers for 5-cell main modules by the same IOT systems for future long-pulse operation.

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Gun Grid Pulser

The electron gun is equipped with a thermionic cathode and operated at 230 kV DC voltage. A train of electron bunch is generated by grid pulser. In the original configuration, the gun was designed to produce 0.5 nC electron bunches at 10.4 MHz repetition, that is 5 mA. We installed a new grid pulser working at 20.8 MHz, doubled repetition of the original one, and a 10 mA beam is now available [5]. The new grid pulser is designed at Budker Institute of Nuclear Physics and can be operated in CW-mode as well as pulse-mode.

We measured electron beam properties with the new grid pulser and confirmed that it keeps similar performance to the original one. The pulse width and the normalized rms emittance at the gun are 590 ps (FWHM) and 20 πmm-mrad, respectively.

As presented above, the injection cavities are ready for 40 mA beam, which requires 83 MHz operation of the grid pulser. Design of a grid pulser for the higher repetition rate, 41.5 MHz and 83 MHz, is under investigation.

RF low-level controllers

Stable operation of an FEL relies much on the stability of an accelerator. In a superconducting accelerator, an RF low-level controller is one of the key components for achieving good stability. The original JAERI-FEL was equipped with a low-level controller, which kept phase flatness at ± 1 degree within a 1 ms macropulse. This controller had been contributed to the 10-year operation of JAERI-FEL. After the remodeling into the ERL, however, we found that the stability of the low-level controller was insufficient to extract the full performance of the ERL. Since the controller had no special function to compensate temperature drift, we could hardly obtain long-time stability against the change of room temperature.

The low-level controller was replaced by new one. The new system is based on phase and amplitude control of the cavity RF field coupled with a tuner controller, which is same as the original system. In the design of the new low-level controller, we introduced the following functions for the better stability: the feedback gain and bandwidth can be varied during operation to obtain good flatness of RF phase and amplitude within a macropulse, all the circuits are contained in boxes with temperature stabilization.

The original controller was placed at the operation room, and the feedback loop involved 50-m cables to connect the controller and the RF cavity. We found that large temperature drift was caused by this long cables. The new con-

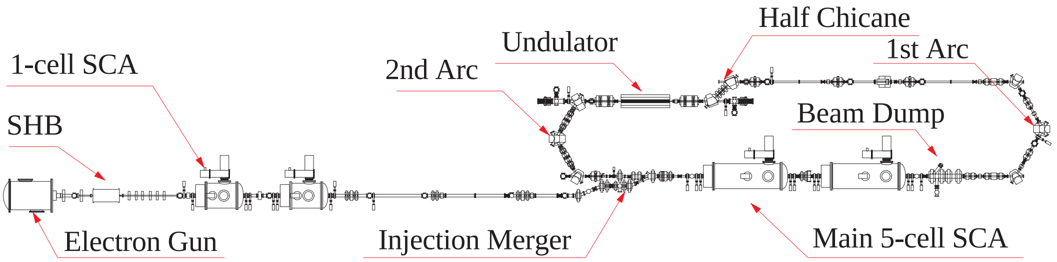

Figure 1: The layout of JAERI Energy-Recovery Linac. An electron bunch generated by 230 kV electron gun is accelerated to 2.5 MeV and injected into the energy-recovery loop. The electron bunch is accelerated to 17 MeV by main superconducting cavities and transported to the FEL undulator. The electron bunch is, then, reinjected to the main cavities and decelerated down to 2.5 MeV and collected by a beam dump. All the superconducting cavities are driven at 499.8 MHz.

troller is installed just beside the cavity to make the cable length as short as possible. Furthermore the cables between the controller and the cavities are contained in a temperature-controlled pipe to suppress the temperature drift.

After these upgrade, the accuracy and stability of accelerating RF has been greatly improved. The flatness of RF phase and amplitude within a 1 ms macropulse are 0.20 deg. and 0.013% for the old system, 0.06 deg. and 0.013% for the new system, where all the values are RMS. Phase and amplitude fluctuation for 5 minutes in the new system are measured as 0.15 deg. and 0.015%, respectively. In this measurement, mechanical vibration of the cavity due to the refrigerator is the dominant source of the fluctuation.

Operation Control System

The operation control system of JAERI-ERL has also been upgraded. The old system based on CAMAC and PC-9801 with Windows-95 became obsolete and difficult to maintain and make further extension. We have developed a new system consisting of CAMAC and local controllers working with μ-ITRON [6], which are robust hardware without mechanical component such as hard-disc drives. Console applications for the operation are written by JAVA and CORBA, modern software independent of platform. We have also prepared data-logging and database services using WEB and MySQL.

FEL Transport Line

A laser-beam transport line has been built to deliver FEL pulses to an experiment room. We have installed an optical-beam expander, which consists of two elliptic mirrors, at the end of FEL optical cavity to convert a diverging beam from a center-hole at a FEL cavity mirror into a parallel beam. The expanded beam is transported to the experimental room through a 24 m-long evacuated pipe.

LONG-MACROPULSE OPERATION

The superconducting accelerator of JAERI-ERL FEL has been operated in a pulse-mode, 1 ms (flat top) $\times$ 10 Hz, which is restricted by refrigerator capacity. For the demonstration of a high-power FEL in industrial applications, however, the longer macro pulses are preferable. In the upgrade of JAERI-ERL FEL, we designed all the new components to meet CW operation. The grid-pulser and the IOT's are CW-ready. Since the refrigerator has capacity for 3% duty cycle, long-pulse operation is only available with keeping this duty cycle such as a 1 second macro pulse every 30 seconds.

Several technical issues should be resolved for the long-pulse operation of the superconducting cavities, which were originally designed for 1 ms pulses. One is pressure rising of the cryostat during a macro pulse due to the heat unbalance between the dissipated RF power and the refrigerator power. This pressure rising causes detuning in the cavity resonance frequency. In the JAERI cryostat, a refrigerator is directly installed at the top of cryomodule. Mechanical vibration of the refrigerator is, therefore, another source of the cavity frequency detuning. We investigated the effect of pressure rising and mechanical vibration, and confirmed that long-pulse operation of 1-5 seconds is possible after minor modification of the existing piezo tuner[7].

BEAM DYNAMICS STUDIES

Injector Optimization by Simulated Annealing

It is known that spontaneous frequency-chirping is induced in a high-gain FEL oscillator. Such chirped pulses can be used to excite unharmonic potential ladder of molecular systems, one of coherent chemical processes. We demonstrated 14.3% frequency chirping in a FEL pulse at JAERI-FEL before the ERL modification[8].

To construct an ERL, the injector beam line was modified from a straight path into a 2-step staircase. This modification made it difficult to generate an electron bunch as short as before, 5 ps (FWHM), which is important for the chirped-pulse generation. In the ERL design, we obtained the bunch length as 15 ps (FWHM) from particle simulations[9], and the measurement during the ERL operation almost agrees with this simulation result.

The bunch length is determined by electrons motion in the longitudinal phase space. In the JAERI-ERL injector, we have six parameters to manipulate electrons motion in the longitudinal phase space, which are amplitude and phase of the subharmonic buncher and two 1-cell cavities. We considered that these parameters can be further optimized to generate the shorter bunch, and applied simulated annealing algorithm[10] to the optimization. From the optimization using simulated annealing, we have found a parameter set of the injector, which gives 5.6 ps (FWHM) electron bunch[11]. The ERL operation with these new parameters will be tried soon.

Emittance Growth in the Merger

Energy redistribution in an electron bunch caused by longitudinal space charge force or coherent synchrotron radiation (CSR) along a dispersive path induces transverse emittance growth. The emittance growth by CSR in the constant wake regime, where the bunch keeps constant temporal profile, can be analyzed by linear matrix approach[12]. The linear analysis shows that the emittance growth can be minimized by matching the beam ellipse to the direction of displacement of bunch slices in the (x, x') phase space.

In the JAERI injection merger, longitudinal space charge force causes the emittance growth through the energy redistribution. We are studying the emittance growth during the merger by particle tracking simulations instead of the linear analysis, because the bunch length is not constant, 20 ps (FWHM) at the entrance and 10 ps at the exit of merger in typical operation. From `PARMELA` [13] simulation, it has been found that the emittance can be minimized by using appropriate beam envelope along the merger. As the best result, we obtain normalized RMS emittance and FWHM bunch length at the merger exit, $\varepsilon_x = 35\pi$mm-mrad, $\varepsilon_y = 26\pi$mm-mrad, and 9.4 ps.

OTHER R&D'S

An electron gun with low-emittance and high average-current is a key component for a high-power FEL and a future light sources based on the ERL technology. A DC photocathode gun with a NEA cathode is considered as the most promising device for high average-current ERLs, 10-100 mA [14]. We, therefore, started research activity on a DC photocathode gun. A test bench to study a DC photocathode gun is under development with components from a 200 kV gun [15] and an old MBE system. A mode-locked Ti:Sap. laser of 83.3 MHz is also prepared. Details are presented in an accompanying paper[16].

For FEL applications, we are proposing laser pealing of stainless steal surface to suppress stress-corrosion crack (SCC), which is a critical problem in nuclear reactors in Japan[17].

SUMMARY

An energy-recovery linac has been developed for a high-power free-electron laser at JAERI. An R&D program towards a 5-10kW FEL and future ERL light sources is in progress. We have upgraded major components of the ERL, RF low-level controller, injector RF sources, operation control system, a gun grid pulser, for stable operation of the ERL and high-power FEL demonstration. The upgrade has been almost completed, and we restart the ERL soon.

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