PERFORMANCE AND UPGRADE OF THE JAERI ERL-FEL

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Abstract

The free-electron laser (FEL) linac has been modified to the energy recovery linac (ERL) at the Japan Atomic Energy Research Institute (JAERI) to achieve the higher power FEL of the next stage of 5-10kW. Energy recovery has been successfully demonstrated up to 5mA of average current. Upgrade of the injector is in preparation to accelerate the higher average current of 40mA. We review transverse instabilities and present experimental data on transverse beam breakup (BBU) obtained at the JAERI ERL-FEL. We compare measurement with simulation.

INTRODUCTION

JAERI has been developing a high-power FEL with a superconducting linac. After the initial goal of kilowatt FEL lasing was achieved in 2000 [1], the linac has been modified into an ERL. Energy recovery is the process by which the energy invested in accelerating a beam is returned to the rf cavities by decelerating the beam. Energy recovery of an FEL beam driven by a superconducting linac is a possible way of greatly increasing the efficiency of the laser since most of the beam energy remains after lasing occurs. This energy-recovery technology with a superconducting linac is the most promising for the next stage of 10kW FEL lasing owing to increasing the beam current without additional rf power sources.

In a recirculating linac, a feedback system is formed between the beam and the rf cavities, so that instabilities can arise at high currents. These instabilities become important and can potentially limit the average beam current especially for the high-Q superconducting cavities. Instabilities can result from the interaction of the beam with transverse higher order modes (HOMs) (transverse beam breakup (BBU)), with longitudinal HOMs (longitudinal BBU) and with the fundamental accelerating mode (beam loading instability). Of the three types of instabilities, transverse BBU appears to limit the average current in the ERL [2].

In the present paper we will describe the resent result and upgrade plan of the JAERI ERL-FEL, and transverse HOM instability research by simulation and measurement.

JAERI ERL CONFIGURATION

The JAERI original FEL superconducting linac consisted of an injector, two main modules of 499.8MHz 5-cell superconducting accelerators, a 180-degree bending arc and an undulator. The injector consists of a 230kV thermoionic electron gun driven by a grid pulser, an 83.3MHz normalconducting subharmonic buncher (SHB) and two modules of 499.8MHz single-cell superconducting accelerators. The JAERI ERL-FEL has been constructed by adding an injector merger, a half-chicane before the undulator and the second arc to the original FEL linac. Figure 1 shows the layout of the JAERI ERL-FEL.

Electron microbunches with a charge of 0.5nC at repetition of 10.4125MHz are produced and accelerated to 230keV in a DC electron gun. The average current corresponds to 5mA. The bunches are compressed by the SHB, pass though the two single-cell modules and are accelerated to 2.5MeV. The output beam is injected into the two 5-cell main modules where it is accelerated up to 17MeV. The beam then passes through the first arc, the half-chicane and the undulator. Afterward it is recirculated through the second arc, returned into the main modules in the decelerating rf phase and dumped at the injection energy of 2.5MeV.

ENERGY RECOVERY EXPERIMENT

Energy recovery has worked well in the JAERI ERL-FEL with beam current of 5mA. We measured the rf forward power from the rf power source to the cavity to estimate the energy-recovery ratio, which is defined as the ratio of the recovered rf power to the beam energy. Figure 2 shows the rf forward power signal for one of the main modules with and without energy recovery. When a 100μsec beam pulse is injected into the cavity in the absence of energy recovery, the forward power signal reaches to -343mV to compensate for beam loading. With

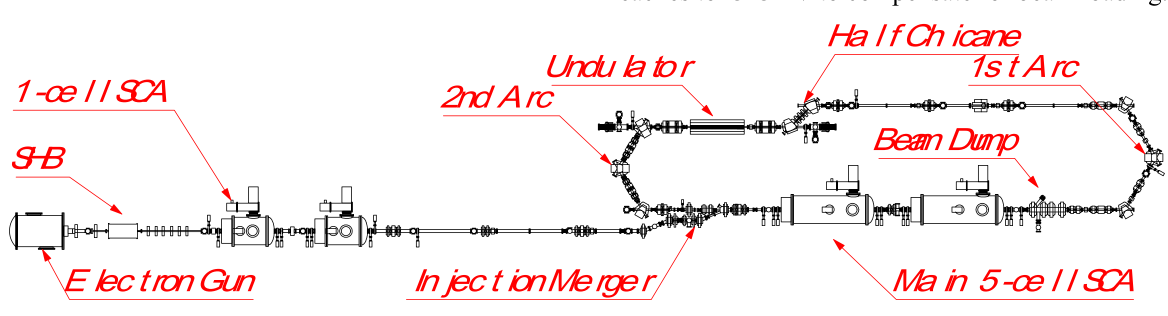

Figure 1: Layout of the JAERI energy-recovery linac

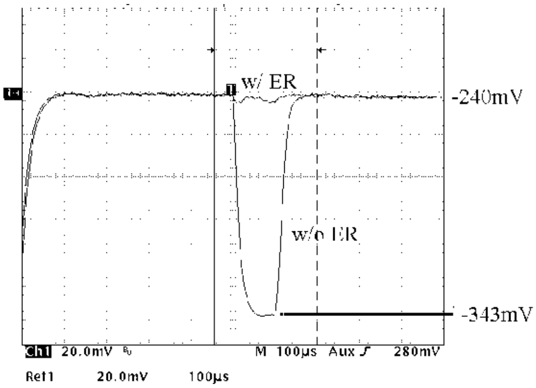

Figure 2: Energy recovery with a 100µsec beam pulse: Response of the rf forward power signal with (-240mV) and without (-343mV) energy recovery

energy recovery, this signal is close to -240mV (where -240mV corresponds to the DC voltage required to drive the accelerating field in the cavity), as the accelerating and the decelerating beam vectors cancel each other resulting in nearly zero net beam loading. The level of the forward power with energy recovery has small fluctuation so that we estimate the energy-recovery ration to 98%.

TRANSVERSE BBU

Transverse BBU has been long known to be a potential limiting factor in the operation of high current linac-based recirculating accelerators. Transverse beam displacement on successive recirculations can excite HOMs that further deflect the initial beam. The effect is worse in superconducting rf cavities because of higher Q values of HOMs. The threshold current depends on the various parameters of cavity and beam optics such as Q values, frequencies and R/Q of the HOMs, beam energy, beta functions and phase advance in the paths and recirculation path length.

HOM Instability Simulation

A simulation code, named BBU-R, has been developed to calculate the threshold current at an actual machine configuration. Analytic model for simulation is impulse approximation, where the transverse position of the bunch is treated as one point and the transverse deflection through the cavity as single deflecting force [3].

This simulation code requires the transfer matrices between the adjacent cavities and the HOM parameters such as frequency, R/Q and loaded Q value. The HOM frequencies and R/Q of the JAERI superconducting cavity was calculated with the2.5-D rf cavity code PISCES II, which can evaluate all the eigenfrequencies and fields for arbitrarily shaped axially symmetric rf cavity [4]. The loaded Q values and frequencies of the HOMs were measured with a network analyzer connected to the HOM coupler, from which reflection power was measured. The transfer matrices were calculated with the code TRANSPORT.

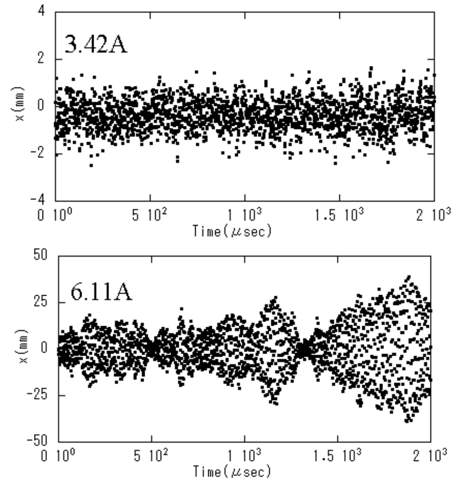

Figure 3: Bunch position vs. time for 3.42A beam current, approximately threshold (top), and for 6.11A beam current, above threshold (bottom)

In the JAERI ERL-FEL two main modules of 5-cell superconducting accelerators are used for energy recovery. The microbunch interval is 10.4125MHz corresponding to 96 times and recirculation period is to 131 times of half period of the fundamental frequency of 499.8MHz. Figure 3 shows the calculated beam positions in the second main module as a function of the time at the various average current. The initial beam has 1mm diameter and 0.5mm offset from the axis. The beam diameter increases with the current. The threshold current is defined as the current where the beam can be transported within 5 times of diameter of the initial. Table 1 lists the threshold currents when one of 10 HOMs is excited and all of 10 HOMs are excited. The threshold current when all of 10 HOMs are excited is 3.42A, which is large enough to increase the beam current for the next stage of our plan.

HOM Power Spectrums

Each module has five rf couplers such as a main power coupler, a pick-up coupler and three HOM couplers. Two HOM couplers are designed to damp transverse modes and the other to damp longitudinal modes. All HOM

Table 1: Threshold current

No.	Mode	Threshold Current (A)
#1	TE111 π/5	666.40
#2	TE111 2π/5	487.31
#3	TE111 3π/5	34.36
#4	TE111 4π/5	10.74
#5	TE111 π/5	578.94
#6	TM110 π	32520.32
#7	TM110 4π/5	16.79
#8	TM110 3π/5	5.47
#9	TM110 2π/5	7.03
#10	TM110 π/5	1482.74
#1-#10	All modes	3.42

couplers are terminated to the dummy loads out of the cryomodules. This makes it possible to measure the excited HOM powers inside the cavity through the HOM couplers. The terminator was exchanged for a real-time spectrum analyzer to measure frequencies and powers of the HOMs. Figure 4 shows the power signals from the HOM couplers. When a 120μsec beam pulse is injected into the cavity with and without energy recovery, the power signals rises. Although the signals seem to be large, they include many spectrums with harmonic frequencies of the microbunch repetition of 10.4125MHz. These spectrums are thought to be induced in the couplers by the electron bunches on the grounds that the HOM power signals fall rapidly after beam-off. Figure 5 shows the amplitude of the HOMs after removing the harmonic frequencies of the microbunch repetition. There seems to be four groups of the HOMs or more. The group near 630MHz is considered to be TE111 mode and that near 700MHz to be TM110 mode. The groups over 850MHz have not been identified yet.

The mode of the highest power of TE111 is considered to be 3π/5 mode of 634MHz and that of TM110 to be 4π/5 mode of 715MHz. The calculated threshold current is 34.36A for TE111-3π/5 mode and 16.79A for TM110-4π/5 mode. While these modes of small threshold current show high HOM powers, the modes of the smaller threshold current for such as TM110-3π/5 and TM110-2π/5 modes show fairly low HOM powers. Measurement of HOM coupling factors is required to estimate more precise HOM powers in the cavity and to investigate the HOM instabilities in further detail.

5-10KW UPGRADE

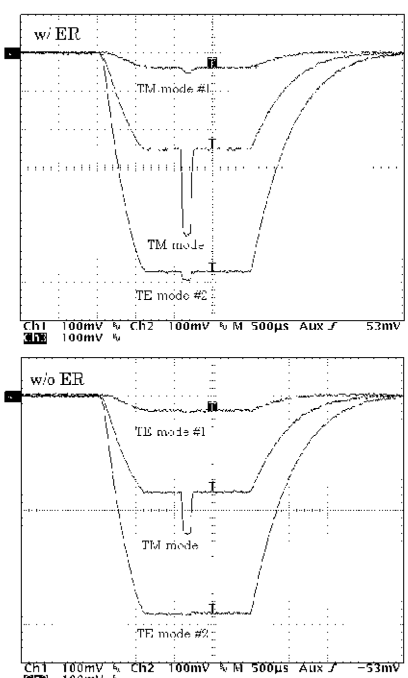

Figure 4: Power signals from the HOM couplers with (top) and without energy recovery (bottom)

To achieve the higher FEL power of 5-10kW, we must increase the beam current and FEL efficiency. The operation of the higher beam current is available at the main modules owing to energy recovery and not sufficient at the injector where the energy recovery does not work. The rf amplifier of 6kW, which is sufficient for 5mA acceleration through the single-cell cavity, is replaced to the rf power source of 50kW IOT to accelerate 40mA electron beam. Modification of the grid pulser is now in progress to increase the repetition from 10.4125MHz to 83.3MHz and beam current from 5mA to 40mA. The higher beam current experiment will start soon.

CONCLUSION

The original JAERI FEL has been modified to ERL-FEL to result in 98% energy recovery. Additional elements of the injector are being prepared to increase the beam current and the FEL power. The threshold current of the JAERI ERL-FEL limited by the HOM instability is calculated to 3.42A, which is large enough to increase the beam current from 5mA to 40mA of our next stage. The HOM spectrums were measured from three HOM couplers. The mode of the smallest threshold current by calculation is not detected from the HOM couplers. The more precise measurement is required to well-understand the HOM instabilities.

ACKNOWLEDGMENTS

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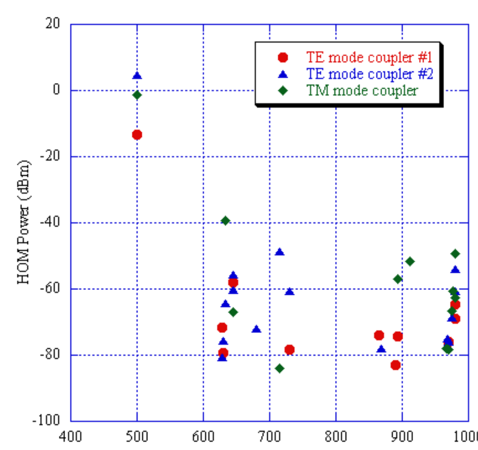

Figure 5: HOM power spectrums