# RF PROPERTIES OF THE JAERI ERL-FEL FOR LONG-PULSE OPERATION

M. Sawamura, R. Nagai, N. Kikuzawa, N. Nishimori, R. Hajima, E. Minehara
JAERI, Ibaraki, Tokai, 319-1195 Japan

### *Abstract*

After the success of energy recovery linac (ERL) for the superconducting free-electron laser (FEL) in the Japan Atomic Energy Research Institute (JAERI), the JAERI ERL-FEL has been upgrading for high-power and long-pulse operation. The properties of the superconducting linac required for long-pulse operation were measured such as pressure in the cryostat, vibration of cavity frequency and piezo tuner response.

## INTRODUCTION

JAERI has been developing a high-power FEL with a superconducting linac (SCA). After the initial goal of kilowatt FEL lasing was achieved in 2000 [1], the linac has been modified into an ERL [2]. 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 SCA 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 SCA is the most promising for the next stage of 10kW FEL lasing owing to increasing the beam current without additional RF power sources.

Aiming for the higher FEL power the new grid pulser for the thermoionic cathode gun is under development in order to increase the beam current by multiplying the repetition rate of 10 MHz to 20 MHz. The new RF sources of CW mode for higher power to the non-energy-recovery parts have been installed and tested.

In spite of using the SCA the JAERI ERL-FEL has been operated in pulse mode because of the following reasons.

1) The JAERI FEL linac uses closed-loop refrigerator systems directly attached to the SCA module. The cooling power of this refrigerator system is not sufficient enough to operate in CW mode.
2) The shield of the building for the linac is not thick enough for the radiation protection

The linac has been operated in pulse mode of 1 msec macro pulse length and 10 Hz repetition rate. There are increasing many requirements for operation mode such as higher duty or long pulse from the view of various applications.

In the present paper we will describe the properties of the JAERI ERL-FEL at high power or long pulse operation.

## JAERI ERL-FEL CONFIGURATION

The JAERI ERL-FEL SCA consists of an injector, an injector merger, two main modules of 499.8 MHz 5-cell superconducting accelerators, two 180-degree bending arcs, an undulator and a half-chicane before the undulator. The injector consists of a 230 kV thermoionic electron gun driven by a grid pulser, an 83.3 MHz normal conducting subharmonic buncher (SHB) and two modules of 499.8 MHz single-cell superconducting accelerators [2].

Electron micro bunches with a charge of 0.5 nC at repetition of 10.4125 MHz are produced and accelerated to 230 keV in a DC electron gun. The average current corresponds to 5 mA. The bunches are compressed by the SHB, pass though the two single-cell modules and are accelerated to 2.5 MeV. The output beam is injected into the two 5-cell main modules where it is accelerated up to 17 MeV. 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 2.5 MeV.

## RF SYSTEM FOR SCA

RF power sources for SCA are all-solid state amplifiers, whose powers are 6 kW for the single-cell cavity and 50 kW for the 5-cell cavity. These RF power sources are operated in pulse mode of macro pulse width of 2 msec, repetition of 10 Hz. In order to increase the beam power and the macro pulse width, IOT (Inductive Output Tube) amplifier systems of 50 kW CW operation are going to be replaced with, and two IOT systems have been installed already for the two single-cell cavities, which require more power to increase the beam power because of the non-recovery parts. The other two power sources for the 5-cell cavities are going to be installed this year.

### *Pressure Rise in SCA cryostat*

The JAERI ERL-FEL SCA has been using a unique refrigerator system that consists of a liquid He recondensor and a shield cooler using close-loop He gas refrigerators attached directly to the cryostat [3]. He gas evaporated due to the standby loss and the RF wall loss is recondensed by a heat exchanger of the 4K refrigerator inserted into the liquid helium container. The cooling power of the refrigerator is about 8W and the standby loss is estimated to be about 4W. A heater within the cryostat is used to keep pressurizing the cryostat by dissipating the residual cooling power. Though the pressure in the cryostat can be kept constant by controlling the heater power, the pressure cannot be kept stable in long-pulse operation in the order of seconds. Figure 1 shows the pressure in the cryostat of the single-cell for the single-pulse operation of 5-second length. From the start of the pulse the pressure increased linearly and after the pulse

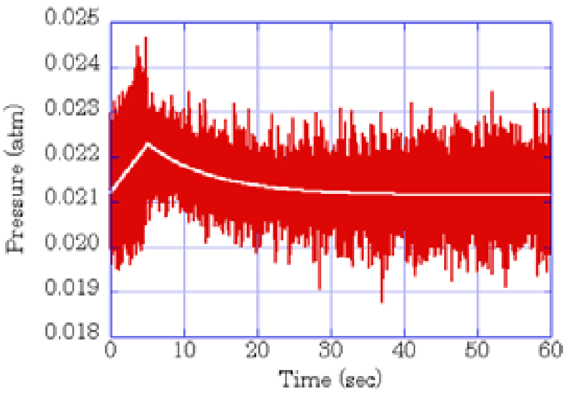


Fig.1 Pressure rise and decay in the cryostat for 5sec pulse operation.

the pressure decreased exponentially. According to the falling time constant of this operation was about 9 seconds. This indicates that the single-cell cavity can be operated at 10% duty without adding another helium refrigerator.

## *Vibration of SCA*

The He refrigerators use a piston action to compress and expand the helium gas, whose repetition rate is about 1 Hz, The refrigerators are attached to the SCA module insulated by using rubber insulators and bellows so that this action should not vibrate the cavity. Though this vibration is so slow and small that the accelerating field

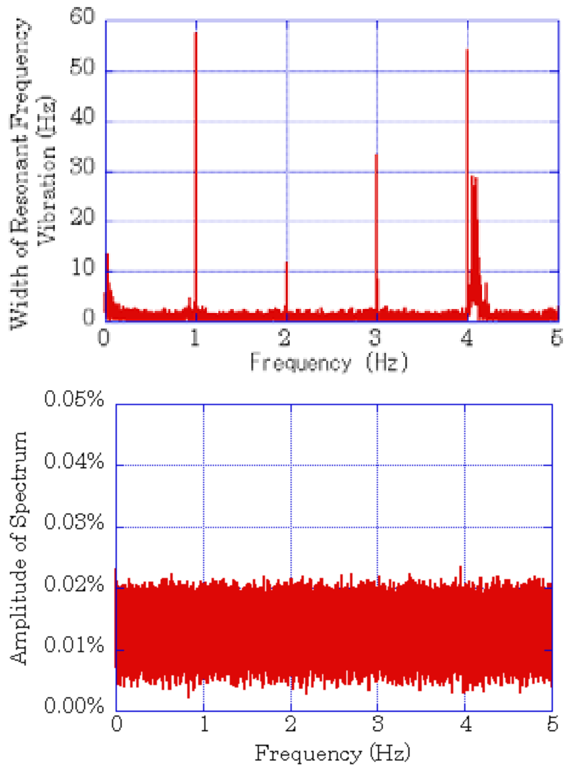


Fig.2 Spectrums of forward power (upper) and pickup power (lower) for high coupling and pulse mode.

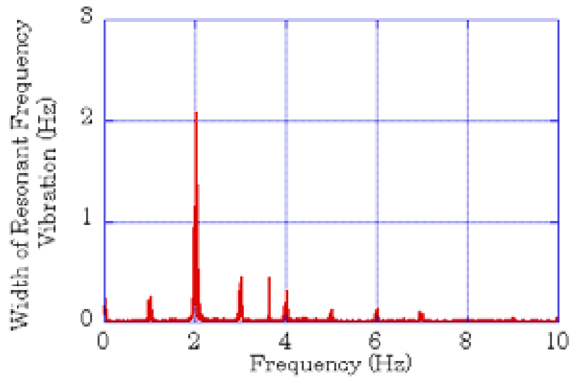


Fig.3 Spectrum of resonant frequency vibration for low coupling and CW mode.

can be controlled by the feedback loop system, it might affect the cavity in the high Q-value coupling operation for the high efficient ERL operation. The influence of the refrigerator to the cavity was measured in two cases; one is high coupling and pulse mode (same as before) and low coupling and CW operation (for the future operation). The RF power from the pickup coupler of the cavity and the forward power of the RF power source were acquired by sampling the amplitudes at the same point of every pulse. These time domain data were transformed into the frequency domain by FFT (Fast Fourier Transform) as shown in Fig.2. While the pickup power spectrum has no peak below 5 Hz because of the good control of the feedback system, the forward power spectrum has several peaks of multiple of 1 Hz. The maximum peak around 1 Hz suggests that there is resonant frequency vibration of about 60 Hz. Another measurement for the low coupling and CW operation was done by controlling the oscillator frequency with a phase lock loop (PLL) and measuring the control voltage for frequency modulation. Figure 3 shows the result of FM control voltage in frequency domains. Compared to the pulse mode operation, the vibration frequencies are almost same but the amplitude of the resonant frequency vibration of the cavity is very small. This is thought to be due to the main coupler position and/or the effect of Lorentz force detuning of pulse operation.

## *Piezo Tuner Response*

The resonant frequency of the SCA cavity is tuned by adjusting the cavity length with two tuners; one is a course tuner using a stepping motor and another is a fine one using piezo elements which is mainly used during the operation. As the response of the piezo tuner is so slow that it is impossible to tune the frequency during the duration of a macro pulse, the phase error signal is detected during the macro pulse and the piezo tuner moves in the intervals between the macro pulses, which means that the piezo tuner is operated below 10 Hz. In the case of CW operation it is important to know the piezo tuner response not to induce an unexpected instabilities caused by the tuner action. The piezo tuner responses were measured by adding the sinusoidal piezo control

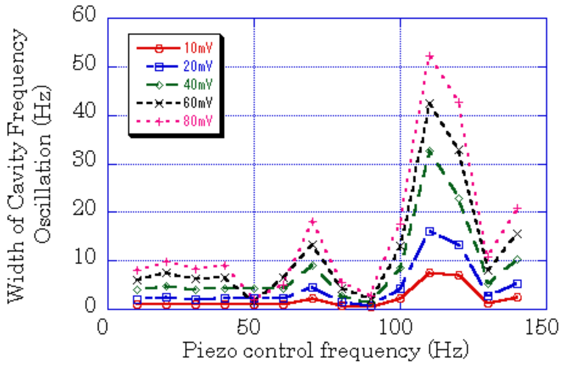


Fig.4 cavity frequency oscillation as a function of the frequency of the piezo control signal.

signal, changing the voltage and frequency and measuring the FM control voltage of PLL. Figure 4 shows the cavity frequency oscillation as a function of the frequency of the piezo control signal. The cavity frequency was stably controlled below 40Hz but above 50Hz there are some resonance.

## RF SYSTEM FOR SHB

While the main part of the JAERI ERL-FEL consists of the superconducting cavities, the SHB is normal conducting. The RF power source for the SHB also uses an all-solid state amplifier of 4kW pulse operation. This amplifier is also replaced with the two-stage triode amplifier of 10kW CW operation. As the SHB was designed for the low duty operation, the possibility for CW or high duty operation of the SHB was investigated.

### *Frequency Shift due to High Duty Operation*

The high duty operation of the SHB causes the temperature rise due to the increase of the RF power dissipation, which induces the frequency shift of the cavity. Figure 5 shows the measured frequency shift. The resonant frequency decreases with increase of the duty at the ratio of -13.4 kHz per 1% duty. As the upper frequency margin is about 47 kHz, the duty is limited below 3.5%. This result is compared to calculation of heat and frequency shift problem with SUPERFISH and MIFIA. The frequency shift due to the temperature rise is about -1.3 kHz/K, measured by changing the cooling water temperature for the SHB without RF power. This corresponds well to the calculation from the SUPERFISH results. Figure 6 shows the calculated temperature distributions of the SHB, from which the calculated frequency shift is -72 Hz per 1% duty. This is much smaller than the measurement. This is thought to be

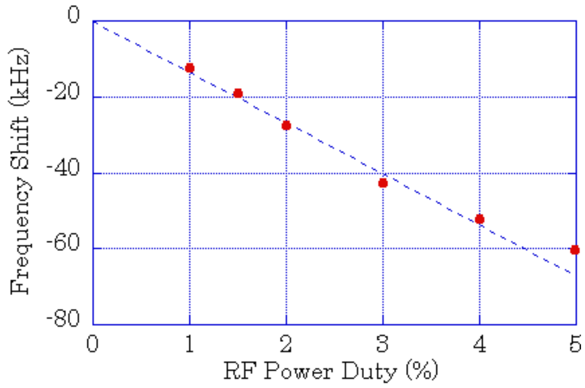


Fig.5 Measured frequency shift as a function of duty factor of the RF power.

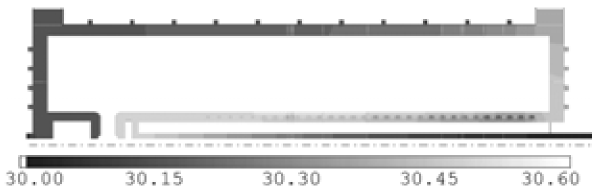


Fig.6 Calculated SHB temperature distribution of 3% duty.

deformation of the tuner that is not cooled enough with the result of much higher temperature than the SHB cavity. When the tuner can be cooled properly, it is expected to use the SHB for the CW or long pulse operation as it now stands.

## CONCLUSION

The properties for the JAERI ERL-FEL were measured. The single-cell cavity can be operated in the duty of more than 10%. The frequency vibration caused by the refrigerators was detected around 2 Hz at the resonant frequency vibration amplitude from 2 to 60 Hz for the different operation conditions. We are going to investigate what the differences come from: coupling or operating mode.

## REFERENCES

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