PERFORMANCE OF A CONVENTIONAL ANALOG Φ-A TYPE LOW-LEVEL RF CONTROLLER

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Abstract

For a free-electron laser application and energy-recovery linac based light source, high-stability of accelerator RF amplitude and phase is required. A low-level RF controller of the JAEA-ERL has been improved to ensure high-stability accelerating RF field. The controller is a conventional analog Φ-A type controller. The controller performance is evaluated with a 499.8 MHz superconducting cavity and a 1300 MHz copper cavity. The phase and amplitude stabilities of the 499.8 MHz superconducting cavity within latter half of an RF pulse are 0.0055 deg-rms and 7.64×10^{-5}, respectively. For the 1300 MHz copper cavity, the performance of pulse and CW modes are evaluated. In the case of pulse mode, the phase and amplitude stabilities are 0.011 deg-rms and 7.64×10^{-5}, respectively. In the case of CW mode, the phase and amplitude stabilities are 0.011 deg-rms and 6.68×10^{-5}, respectively. Therefore, the performance of the analog Φ-A type low-level RF controller is sufficient for a free-electron laser stable operation and an energy-recovery linac based light source.

INTRODUCTION

Stable operation of a free-electron laser (FEL) and performance of an energy-recovery linac (ERL) based light source depend much on the stability of an accelerator. In a superconducting accelerator, a low-level RF (LLRF) controller is one of the key components for achieving good stability. An ERL R&D program for a high-power FEL is in progress at Japan Atomic Energy Agency (JAEA; formerly JAERI and JNC). A LLRF controller based on analog phase and amplitude feedback system was improved in the R&D program. An analog Φ–A system has the faster response than a digital feedback system because there is no delay caused by the computation. There is however the following disadvantages: the feedback parameters are not adjustable easily, the temperature coefficient of the circuit parts are larger than the digital feedback system. To solve the disadvantages, the following functions were introduced: the feedback gain, filter time constant and phase-lock loop (PLL) offset phase can be varied during operation, all the circuits are contained in a temperature regulated oven. As a result of the improvement, the accelerator phase stability of 0.06 deg-rms was achieved within latter half of an RF pulse [1].

The feedback filter of the LLRF controller is a low-pass filter of a single-pole RC circuit type. Only the resistance can be varied to change the time constant. The operation frequency of the PLL is 499.8 MHz, which is the same frequency of the superconducting cavity. To satisfy the requirements of the ERL based next generation light source, the following functions are added: the filter time constant can be varied by changing the resistance and capacitor, the frequency converter and band-pass filter can be added for the various frequency operation.

The improved controller performance is evaluated with a 499.8 MHz superconducting cavity and a 1300 MHz copper cavity. The stabilities are measured by the error signal of the controller. For the 499.8 MHz superconducting cavity, the RF mode is a pulse mode which is the same mode with the JAEA-ERL usual operation mode. For the 1300 MHz copper cavity, the phase and amplitude stabilities are measured in the pulse and CW modes. In the CW mode, the phase stability is estimated by also the phase noise measurement.

STABILITY MEASUREMENTS

Stability of the 499.8 MHz Superconducting Cavity

The RF field stability is measured for the 499.8 MHz superconducting cavity used as a pre-accelerator of the JAEA-ERL. The JAEA-ERL is operated by pulsed RF mode in the width of 2 ms and the repetition of 10 pps. The stability in the part of latter half used to accelerate the electron beam is measured in the setup as shown in Fig. 1. The setup is similar to the usual operation of the JAEA-ERL. The signal of 499.8 MHz from the master oscillator (Hewlett-Packerd 8665A) is input to the controller as a reference signal. The output of the controller is amplified with 400 W pre-amplifier (THAMWAY T145-56AAA) and 50 kW IOT (CPI CHK2500W5508) [2], and input to the superconducting cavity. The monitor signal of the superconducting cavity is returned to the controller for the feedback loop. The signals of the phase and amplitude of the cavity are output from the controller and measured by a signal monitor. The signal monitor consists of a digitizer (Yokogawa WE7000) and a computer. The signals of the phase and amplitude from the controller are digitized and acquired to the computer. The phase and amplitude stabilities are calculated with real-time from the digitized data. The feedback gain, filter time constant and PLL offset phase of the controller are adjusted in real-time monitoring of the stabilities.

Typical signal of the phase and amplitude within a pulse is shown in Fig. 2. The phase and amplitude stabilities within latter half of an RF pulse are 0.0055 deg-

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rms and 7.64×10^{-5} rms, respectively. The accelerating gradient and loaded Q of the superconducting cavity are 5.2 MV/m and 1.3×10^{6}, respectively. In this case, main disturbance is an RF shaking due to the pulse operation.

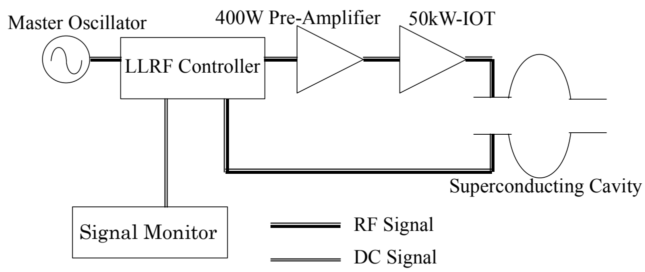

Figure 1: Stability measurement setup for the 499.8 MHz superconducting cavity.

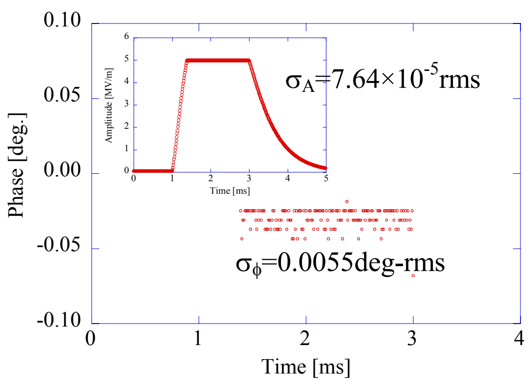

Figure 2: Typical result of the phase and amplitude (inset) within a pulse for the 499.8 MHz superconducting cavity.

Stability of the 1300 MHz Copper Cavity

To evaluate the performance of the LLRF controller at the 1300 MHz operation, the phase and amplitude stabilities are measured using a copper cavity in the pulse and CW modes. The loaded Q of the copper cavity is about 5800. The measurement setup is shown in Fig. 3. The signal of 1300 MHz from the master oscillator (Hewlett-Packerd 8341B) is input to the controller as a reference signal. The signal of 800.2 MHz from the local oscillator (Agilent 8662A) is input to the controller for a frequency conversion. The output of the controller is amplified with +28 dBm amplifier (Mini-Circuits ZHL-4240W), and input to the copper cavity. The monitor signal of the copper cavity is returned to the controller for the feedback loop. A part of the returned signal is input to a spectrum analyser (Tektronix RSA230) for the phase noise measurement in the CW mode. The master oscillator, local oscillator and spectrum analyzer are synchronized with the local signal of the master oscillator.

For the pulse mode measurement, the phase and amplitude stabilities are measured with the width of 3 ms and the repetition of 10 pps. The feedback parameters are adjusted according to the similar procedure of the superconducting cavity case. Typical signal of the phase and amplitude within a pulse is shown in Fig. 4. The phase and amplitude stabilities within latter half of an RF pulse are 0.011 deg-rms and 7.64×10^{-5} rms, respectively. For the CW mode measurement, the feedback parameters are re-adjusted. The phase and amplitude stabilities are 0.011 deg-rms and 6.68×10^{-5} rms, respectively.

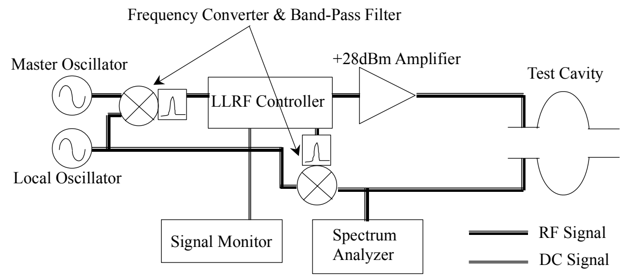

Figure 3: Stability measurement setup for the 1300 MHz copper cavity.

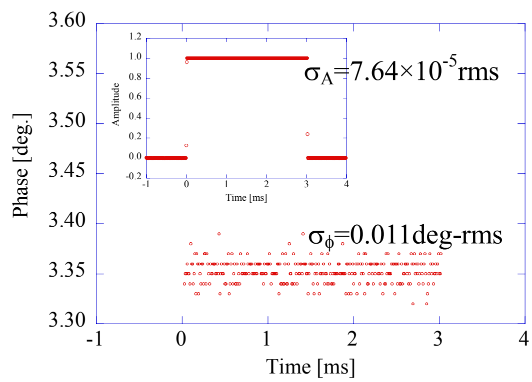

Figure 4: Typical result of the phase and amplitude (inset) within a pulse for the 1300 MHz copper cavity.

For the CW mode, the phase stability is estimated by also the phase noise measurement. The phase fluctuation (phase stability), σ_φ over a frequency range from f_1 to f_2 is given by

$$\sigma_\varphi = \left(\int_{f_1}^{f_2} 2L(f)\, df \right)^{1/2} \quad [rad], \qquad (1)$$

where $L(f)$ is a single sideband (SSB) phase noise [3]. In this measurement, the frequency range is 2 Hz to 10 kHz. The measurement accuracy of the spectrum analyzer used for this measurement is about -100 dBc/Hz. The phase noise of the master oscillator is not negligible small. The phase stability of the cavity is therefore estimated by

$$\sigma_\varphi = \left(\sigma_{\varphi m}^2 - \sigma_{\varphi 0}^2 \right)^{1/2}, \qquad (2)$$

where $\sigma_{\varphi m}$ is measured phase stability and $\sigma_{\varphi 0}$ is phase fluctuation of the oscillator and spectrum analyzer. The measured SSB phase noise against offset from the carrier frequency (offset frequency) is shown in Fig. 5. The inset is a phase noise of the oscillator and the spectrum analyzer. The phase stability is 0.013 deg-rms as a result of the measurement. Even if two phase noises in Fig. 5 are compared, the difference is hardly seen. The phase noise of the spectrum analyzer and the oscillator is not small enough to measure such a very high stability (less than 0.01deg-rms). The high-accuracy measurement of the phase noise by a low-noise measurement system is under arranging.

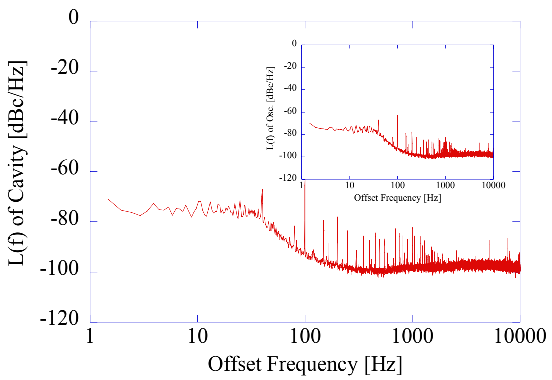

Figure 5: SSB phase noise of the copper cavity and the oscillator (inset).

The main disturbance of the ERL is a minute vibration of the acceleration cavity which is called microphonic [4,5]. To evaluate the microphonic disturbance, the phase noise is measured with the mechanical vibrated cavity. The phase and amplitude stabilities measured by the error signal of the controller are 0.014 deg-rms and 7.60×10^{-5}, respectively. The measured phase noise is shown in Fig. 6. The large phase noise (-37 dBc/Hz) due to the mechanical vibration is observed around 25 Hz without the feedback. When feedback is on, the phase noise is almost the same as the background level (-75 dBc/Hz). Therefore, the feedback gain of the phase around this frequency is 38 dB or more. The phase stability estimated from the phase noise is 0.034 deg-rms. The estimated value differs from the measured by the error signal due to the accuracy of the measurement system in this condition.

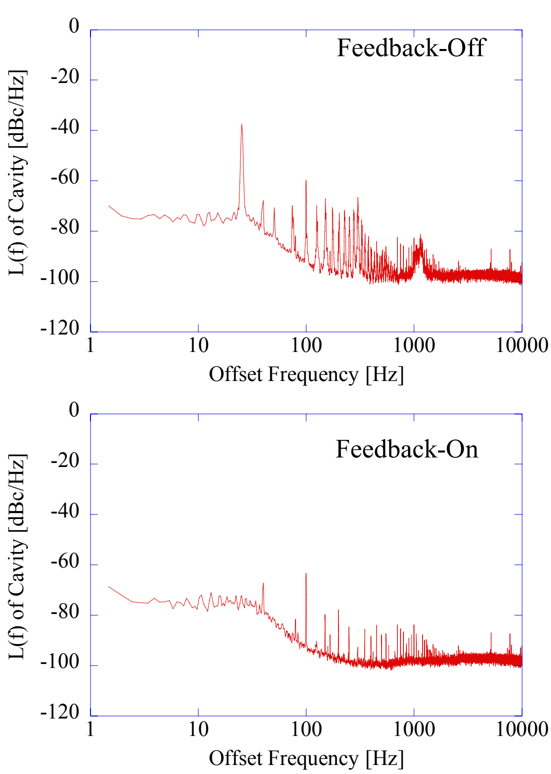

Figure 6: SSB phase noise with mechanical vibration.

CONCLUSION

The phase and amplitude stability requirements for an ERL based light source are 0.06 deg-rms and 3×10^{-4} rms, respectively [5]. The performance of the conventional analog Φ-A type LLRF controller is sufficient for the ERL-FEL stable operation and the ERL based light source as a result of the stability measurement.

The measurement of the SSB phase noise is useful for the performance evaluation of the controller with frequency resolved disturbance analysis.

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