PERFORMANCE OF RF SYSTEM FOR XFEL/SPRING-8 INJECTOR

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Abstract

In the X-ray free electron laser facility SACLA, to realize a stable bunch-compression process for an electron beam without emittance growth, an injector adopts the combination of an extremely low-emittance thermionic gun and multi-stage sub-harmonic RF cavities (238 MHz, 476 MHz and 1428 MHz) for velocity bunching. Further, 1428-MHz accelerating structures were introduced to expand the RF acceptance. The two 1428-MHz accelerating structures of the APS type compress a 1 MeV beam bunch, and accelerate it up to 30 MeV. An RF power of 10 MW with a pulse width of 6 μs and a repetition rate of 60 pps is fed into each accelerating structure. The RF processing of the cavities in the injector were completed in 20 days. After the RF processing, the stability performances of the RF cavities were measured, and turned out to be almost up to the satisfaction of the target values, which the acceptable levels of the RF amplitude and time jitter were 0.01% (σ) and 120 fs (σ), respectively. The stability of beam energy at the end of the injector has been achieved up to 0.013% (std.) because of high-level stabilization of the RF system.

INTRODUCTION

The construction of the 30-MeV injector of the X-ray free electron laser facility SACLA was completed in January of 2011 as shown in Fig. 1. Beam commissioning of an 8-GeV linac including the injector and undulators was started since February after RF processing of the cavities in the injector. We observed a 1.2 Angstrom SASE light at the beginning of June. To obtain more intense SASE lights, precise beam tuning of the linac and undulators is in progress [1].

The most remarkable feature of the injector is employing a thermionic gun. This carefully designed thermionic gun can generate a solid cylindrical beam pulse holding uniform charge densities without any nonlinear space-charge effect, therefore the initial beam emittance can be as low as the thermal emittance [2]. An injector with a thermionic gun, however, requires stepwise bunching of an electron beam by means of complex multi-stage RF cavities so as not to degrade the initial emittance.

A 500 keV electron beam with current of 1 A peak is emitted from a thermionic gun using a CeB_6 single crystal. The emittance at the exit of the thermionic gun has measured 1.1 π mm mrad. The 1-μs pulsed beam from the gun forms a pulse width of 1 ns by using a beam chopper. To generate a peak beam current of 20 A with a beam energy of more than 30 MeV at the end of the injector, multi-stage RF cavities (238-MHz SHB (Sub Harmonic Buncher), 476-MHz booster and two 1428-MHz accelerating structures) are used for gradually bunching and accelerating the beam to maintain the initial beam emittance.

In addition, in order to enhance the bunching efficiency and to avoid over-bunching, we introduced two sets of harmonic RF cavities. 1428-MHz twin RF cavity (L-band correction cav.) is installed following the 476-MHz booster, and linearizes the velocity-bunching process. A 0.6-m long traveling-wave structure of 5712 MHz (C-band correction cav.) downstream of the 1428-MHz accelerating structures compensates for the nonlinearity of the bunch-compression process downstream of the three-stage bunch compressors [3].

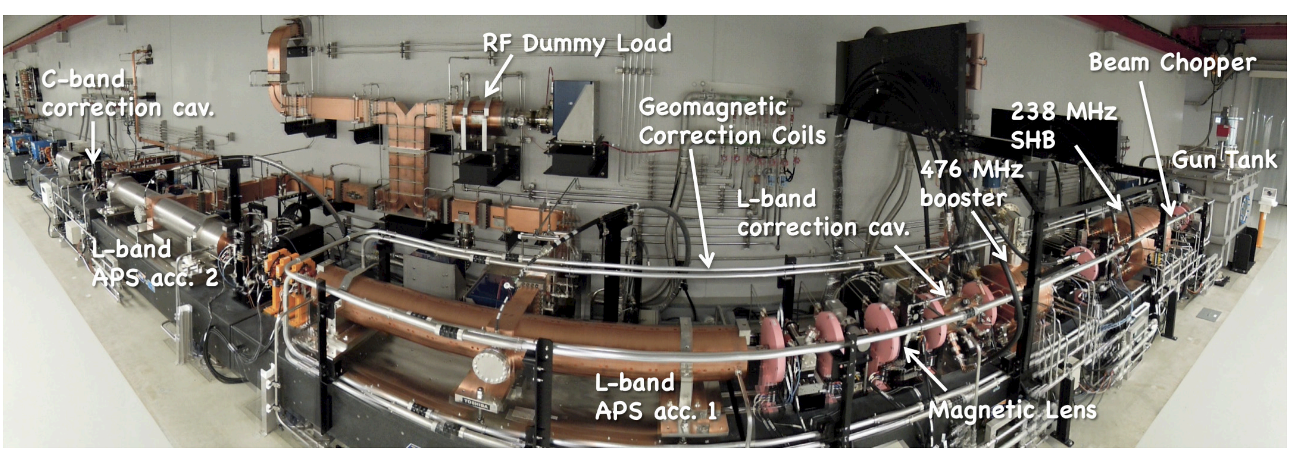

Figure 1: 30-MeV injector installed in the tunnel. The injector consists of 500-keV thermionic gun, a beam chopper, multi-stage RF cavities (238-MHz SHB, 476-MHz booster, 1428-MHz correction cavity, two 1428-MHz accelerating structures and 5712-MHz traveling-wave structure), ten magnetic lenses and geomagnetic correction coils.

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It is important to maintain this beam performance with high-level stability. Because even slight beam variation in the injector causes unstable laser oscillation in the undulator, the RF equipment for the cavities has to be very carefully designed so as to minimize its variations in the RF amplitude and phase. The acceptable instabilities of the RF voltages in the cavities, which permit a 10% (σ) variation of the peak beam current, are only about 0.01% (σ) in amplitude and 120 fs (σ) in phase according to a beam simulation. The long-term variations in the RF amplitude and phase are controlled by the feedback system. On the other hand, we have taken the short-term variations in the RF amplitude and phase into greater consideration when we design the RF equipment.

PERFORMANCE OF RF SYSTEM

Figure 2 shows a block diagram of the RF system in the injector. Reference RF signals are generated by a master oscillator part. The signal source generates 238-, 476-, 1428-, 2856- and 5712-MHz signals. The signals are inputted into each amplifier through an IQ modulator, which is controlled by a DAC. Then, each amplified RF signal is fed to the corresponding cavity. Directional couplers and pick-up ports for RF monitoring are mounted on the RF cavities and monitored RF signals are inputted into an IQ demodulator with an ADC.

All of the solid-state amplifiers adopt thorough stabilization countermeasures, such as temperature control with cooling water, employing low-noise power supplies and suppression mechanical vibration in the chassis. Those low-level RF instruments and the solid-state amplifiers are installed into the 19" enclosures, which are equipped with a precise air-conditioning system. Actually, the environment temperature of the low-level RF instruments in the 19" enclosure can be maintained to within 26±0.2˚C. Further, the transmission lines, such as coaxial cables and waveguides, are thermally stabilized by means of cooling water and heat jackets.

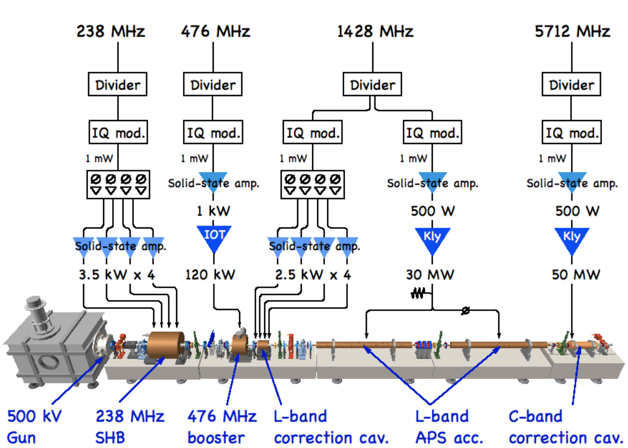

Figure 2: Block diagram of the injector's RF system.

SHB & Booster

The 238-MHz SHB is a reentrant single cavity, and is equipped with four input couplers. The maximum gap voltage of 250 kV can be generated by using four solid-state amplifiers when the RF power of 3.5 kW from the amplifier is fed into each coupler. The 476-MHz booster is driven by a 120-kW IOT (Inductive Output Tube), and generates the maximum gap voltage of 900 kV.

Although the filling time of these RF cavities are about 7 μs, an RF pulse width of 50 μs or longer are fed into the cavities to realize high-level stabilization of the gap voltage. In the RF processing of these cavities, the initial RF conditions were a pulse width of 5 μs and a repetition rate of 10 pps. When the RF power achieved the maximum level, the RF processing had continued with increasing the RF pulse width and the repetition rate. RF processing was completed within 7 days.

1428-MHz Acceleration System

A 1428-MHz klystron generates an RF power of 25 MW and the power is divided to both accelerating structures through a directional coupler (DC). A vacuum-type waveguide circuit is installed without a circulator. Therefore, the circuit has to be carefully designed to cancel the reflected powers from the accelerating structures so that a reflection to the klystron doesn't cause RF instability in the klystron output cavity [4]. The reflected power can be spent in a compact high-power RF dummy load that had been developed for the 1428-MHz acceleration system [5].

The VSWR at the input port of the DC checked less than 1.2 when the phase difference between two accelerating structures performed 90˚, which gave close agreement with the design value. The measured values of the RF parameters of 1428-MHz acceleration system are summarized in Table 1.

Table 1: Parameters of 1428-MHz Acceleration System

Accelerating structure	
Frequency	1428.0 MHz
Unloaded Q	24,700
Shunt Impedance	36.0 MΩ/m
Coupling β	1.460
Number of cells (with coupler)	19 cell
Effective length	2.0 m
Filling time	2.2 μs
Klystron	
Power, Pulse width and Repetition rate	30 MW, 6 μs, 60 pps
Waveguide circuit	
VSWR at the input port for the DC	< 1.2

In the first, the high power test for main RF components, such as a phase shifter and the RF dummy load, were individually carried out. When the RF power of 5 MW was fed into the RF dummy load, RF breakdown and multipacting problems occurred. To avoid the multipacting in the RF dummy load, as one of the countermeasure, a corona ring was attached to edge of an RF absorber (SiC). After that, the RF power of 25 MW with pulse width of 5.5 μs and repetition rate of 60 pps was able to be stable operation.

The comprehensive RF processing of the assembled waveguide circuit and accelerating structures was completed in 20 days as shown in Fig. 3. This system has continued the operation without vacuum faults after the RF processing.

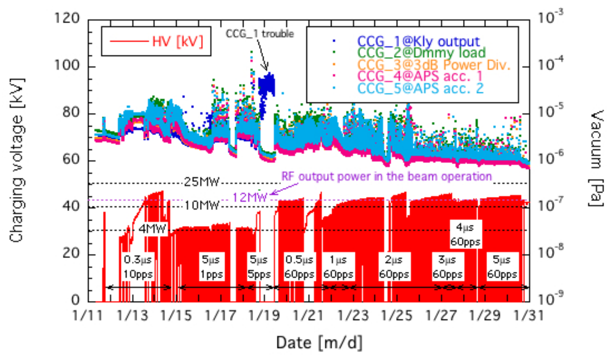

Figure 3: RF processing of the 1428-MHz acceleration system. The maximum RF power from the klystron is obtained with the PFN charging voltage of 50 kV in the klystron modulator.

Correction Cavities

The 10-kW output power from the 1428-MHz solid-state amplifier is fed into the twin cavity, which has two couplers per cavity. The cavity has nose cones to enhance the shunt impedance.

The 5712-MHz correction cavity is a short version (26 cells, $3\pi/4$) of the C-band accelerating structure, the chock mode cavity type, used in a main accelerating section. The 5 MW output power with a 1-μs width from the 5712-MHz klystron is fed into the correction cavity.

Stability Evaluation of RF System

The RF power and phase variations in each cavity are measured by using the IQ demodulator. All data of the RF powers and phases with the repetition rate of 10 pps are stored in the database system. The tolerances and measurement results of the RF stabilities are summarized in Table 2. The measured variations were calculated from the 10-event moving averages of the raw data acquired during 10 minutes. The moving average was employed to reduce noises in the raw data. The measurement results were obtained under the condition of optimum RF parameters for the X-ray lasing. The achievements for RF stability are almost satisfactory for the target values.

Table 2: Measurement Results of the RF Cavities in the Injector

	Tolerance (σ)		Measurement (std.)	
	Voltage	Phase	Voltage	Phase
238 M SHB	0.01 %	0.01°	0.010 %	0.006°
476 M booster	0.01 %	0.02°	0.004 %	0.009°
1428 M corr. cav.	0.03 %	0.06°	0.02 %	0.02°
1428 M APS acc. 1	0.01 %	0.06°	0.06 %	0.03°
1428 M APS acc. 2	0.01 %	0.06°	0.03 %	0.05°
5712 M corr. cav.	0.1 %	0.1°	0.06 %	0.05°

BEAM ENERGY STABILITY

To verify the beam-energy stabilization with the RF stability, the beam energy was measured by using a multi strip line type beam position monitor installed in the first bunch compressor following the injector. The measurement was made with a 32-MeV beam bunch of 1.0 nC at a repetition rate of 10 pps. Figure 4 shows the variations in the beam centre energy; stability of the centre energy reached 0.013% (std.) when the all RF parameters were optimized for the X-ray lasing.

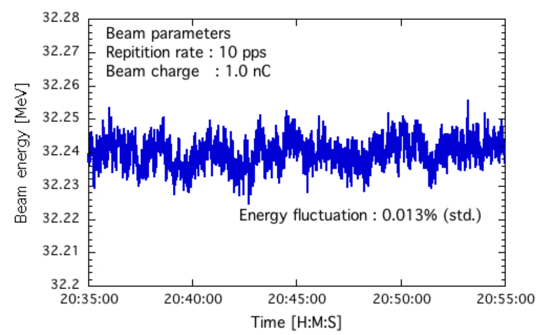

Figure 4: Stability of the beam energy at the end of the injector was measured by using the multi strip line type beam position monitor.

SUMMARY

All the RF instruments in the injector were completed accurately and fully for specification including RF stability. In especially, the 1428-MHz acceleration system is able to realize the stable beam acceleration without the RF instability, which is caused by the reflected power from the accelerating structures.

The beam energy stability of 0.013% (std.) was achieved at the end of the injector due to the high-level stabilization of the RF system. We are progressing towards high quality of X-ray lasing for the sake of more stabilization.

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