DEVELOPMENT STATUS OF RF SYSTEM OF INJECTOR SECTION FOR XFEL/SPRING-8

T. Asaka#, H. Ego, H. Hanaki, T. Kobayashi, S. Suzuki, JASRI/SPring-8, Hyogo 679-5198, Japan
T. Inagaki, Y. Otake, K. Togawa, RIKEN/SPring-8, Hyogo 679-5148, Japan

Abstract

The XFEL/SPring-8 facility, now under construction, is designed to generate coherent, high brilliance, ultra-short femto-second X-ray pulses at wavelengths of 0.1 nm or shorter. The injector consists of a 500 kV thermionic gun (CeB6), a beam deflecting system, multi-stage RF cavities and ten magnetic lenses. The multi-stage RF cavities (238 MHz, 476 MHz, 1428 MHz) are used for bunching and accelerating the beam gradually to maintain the initial beam emittance. In addition, in order to linearize the energy chirp of the beam bunch at three-stage bunch compressors after the injector section, we prepared extra RF cavities of 1428 MHz and 5712 MHz. It is important to stabilize the gap voltage of these RF cavities because the intensity of an X-ray pulse is sensitive for a slight variation of the RF power and phase in the injector section. We developed some stable amplifiers for these RF cavities, and then confirmed the amplitude and phase stability of an RF signal outputted from the amplifiers. The measurement results nearly reached the required levels of the design parameters.

INTRODUCTION

The construction of XFEL/SPring-8 is in progress, with completion scheduled for this year [1]. To realize a stable X-ray Free Electron Laser (FEL), the electron beam in a 90-m long undulator section must achieve a 3 kA peak current with a normalized emittance of 1π mm mrad or less. In addition, it is important to maintain this beam performance at a high level of stability. Since X-ray FEL performance strongly depends on the density distribution of the electron beam in a six-dimensional phase space, the amplitude and phase variation of RF equipment must be extremely small, and their amplitude and phase drift must also be very small.

The accelerator system of XFEL/SPring-8 consists of an injector section [2], three-stage bunch compressors and a main accelerating section as shown in Fig. 1. An electron beam with energy of 500 keV and a current of 1 A peak is emitted from a thermionic gun using a CeB6 single crystal. The 1-μs pulsed beam from the gun forms a pulse width of 1ns by using a beam deflecting system. Moreover, the electron beam forms a bunch length of 50 ps with 238-MHz SHB (Sub Harmonic Buncher) and 476-MHz Booster. The bunched beam is accelerated to 30 MeV by two 2-m long accelerating structures of APS (Alternative Periodic Structure) type (L-APS acc.), which are operated at 1428 MHz. The peak beam current at the end of the injector section is 20 A without the emittance growth in the bunching and acceleration process. Then, the bunched beam is compressed to 3 kA/300 fs by using the three-stage bunch compressors (BC1~3) before the main accelerating section.

In order to enhance the bunching efficiency and avoid over-bunching, we introduced two sets of harmonic RF cavities as illustrated in Fig. 1. The 2 cell RF cavity of 1428 MHz (L-correction cav.) is installed downstream of the 476-MHz Booster, and linearizes the velocity-bunching process. The 0.6-m long travelling-wave structure of 5712 MHz (C-correction acc.) downstream of the L-APS accelerating structures compensates for the nonlinearity of the bunch compression process at the downstream of the three-stage bunch compressors.

Because even slight beam variation in the injector section affects unstable laser oscillation in the undulator, the RF equipment for those cavities has to be very carefully designed to minimize its variation in the RF amplitude and phase. The tolerances of RF amplitude and time stability for those cavities are given by a 1-D beam simulation code based on the Monte Carlo method. The acceptable levels of RF amplitude and time jitter are 0.01% (rms) and 120 fs (rms), respectively. These are determined so as to stabilize laser oscillation in the undulator; specifically, a variation of the peak beam current at the end of the main accelerating section required less than 10% (rms). The RF amplitude and phase variation in the long-term components are controlled by the feedback system. On the other hand, the design and assembly of RF equipment take the variations in short-term components into greater consideration.

The amplitude and phase stability of 238- and 476-MHz RF equipment were already verified as satisfying levels by using the SCSS test accelerator. Moreover, in order to achieve more stable and high-performance X-ray FEL, the RF equipment has been improved in reliability and durability. In this paper, we describe the development status and achieved performances of the RF equipment in the injector section.

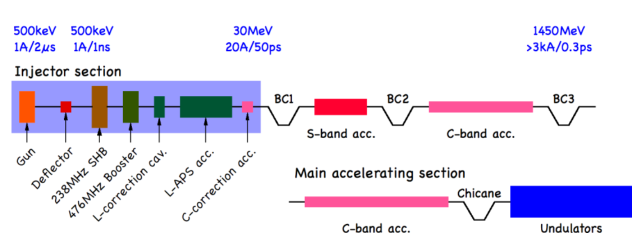

Figure 1: Schematic view of the XFEL/SPring-8.

#asaka@spring8.or.jp

CONFIGRATION OF THE RF SYSTEM

Figure 2 shows a block diagram of the RF system in the injector section. Reference RF signals are generated by a master oscillator part. The RF signal source generates 238-, 476-, 1428-, 2856- and 5712-MHz signals [3]. These signals are inputted into each amplifier through the IQ modulator which is controlled by a high-speed 14-bit DAC. Then, each amplified RF signal is fed to the cavity. Directional couplers and pick-up ports for the RF monitors are installed in the input ports of the amplifier and cavity, and the monitored RF signals from the RF equipment are inputted into the IQ demodulator with a high-speed 16-bit ADC. In order to gain precise temperature control around these low-level RF instruments, a thermally controlled 19" enclosure is employed. The temperature of the re-circulating air inside this enclosure can be regulated within ±0.2˚C, even though, the enclosure's surrounding temperature changes by 3~4˚C.

All of the solid-state RF amplifiers adopt thorough stabilization countermeasures, such as temperature control with cooling water, employing a low-noise power supplies and suppression of mechanical vibration in the chassis.

The main parameters and tolerances of stability for the RF equipment of the injector section are summarized in Table 1. In the 238-MHz SHB and the L-correction cavity, RF power around 10 kW to each cavity are supplied from the solid-state amplifiers through a coaxial cable. The 476-MHz Booster is driven by a 120-kW IOT (Model CHK2800W, CPI Inc.) after amplifying the RF power of 1 kW with a solid-state amplifier. A 1428-MHz klystron (Model E37612 Toshiba Electron Tubes and Devices Co., Ltd.) generates an RF power of 30 MW and the power is divided to L-APS accelerating structures through a 3 dB directional coupler as shown in Fig. 2. The klystron has a gain of 48.8 dB, and an RF power of 500 W is inputted to it by using a solid-state amplifier. The 5712-MHz RF signal is supplied to a C-band klystron (Model E3748 Toshiba Electron Tubes and Devices Co., Ltd.) through a 500-W solid-state amplifier.

In order to suppress the RF phase drift of the transmission lines, such as coaxial cables and waveguides, the temperature of those transmission lines is controlled within ±0.2˚C by using cooling water with a heat insulator.

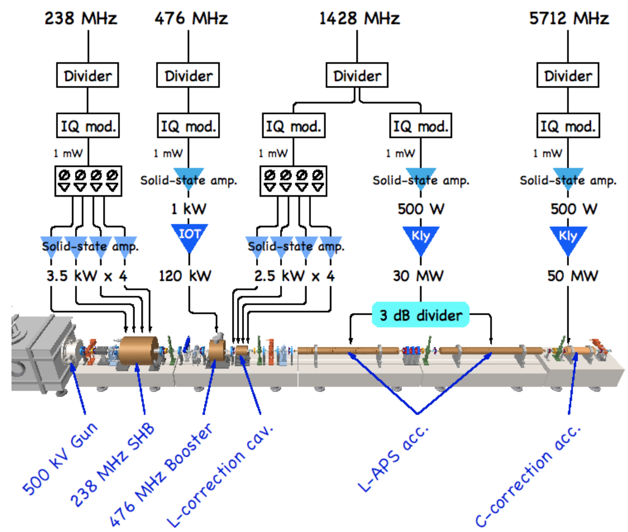

Figure 2: Block diagram of injector's RF system.

STABILITY TEST OF RF SYSTEM

1428-MHz RF system for the correction cavity

The test results of the RF stability of the amplifiers at 238, 476 and 1428 MHz are summarized in Table 1. The solid-state amplifiers were made by NIHON KOSHUHA Company. Although the frequencies and power levels of those RF amplifiers are different, the RF amplifiers have a similar guiding design. For example, the details of the 1428-MHz RF system are given as follows.

The 1428-MHz main RF system consists of four solid-state amplifiers and two RF cavities, which have a nose-cone shape. It is possible to tune the independent RF amplitude and phase for each cavity. In order to obtain the symmetrical electric field for centre axis in the cavity, two couplers are placed at opposite angles on the external diameter. The amplified RF power is inputted into each cavity through a coaxial cable (10 ppm/20˚C, Model HF-20D cable, HITACHI Cable Ltd.).

The RF amplifier system consists of a power divider, low-noise power supplies, a control unit with a graphic panel and four RF amplifiers, which are able to generate an output power of 2.5 kW. The power divider is equipped with a regulator of low-level RF power and phase. Four amplifiers are installed in the 19" enclosure with the temperature control system.

Table 1: Main parameters, tolerances of stability and evaluated results of RF equipment in the injector section.

Cavity or Structure	SHB	Booster	L-correction cav.	L-APS acc.	C-correction acc.
Frequency	238 MHz	476 MHz	1428 MHz	1428 MHz	5712 MHz
Type of amplifier	Solid-state*4	Solid-state + IOT	Solid-state*4	Solid-state + Klystron	Solid-state + Klystron
Output power	3.5 kW*4	2 kW + 120 kW	2.5 kW*4	0.5 kW + 30 MW	0.5 kW + 50 MW
Pulse width	100 μs	50μs	10μs	6μs	0.5μs
Tolerance of power stability	±0.02% (σ)	±0.02% (σ)	±0.06% (σ)	±0.02% (σ)	±0.2% (σ)
Tolerance of phase stability	±0.01˚ (σ)	±0.02˚ (σ)	±0.06˚ (σ)	± 0.06˚ (σ)	± 0.06˚ (σ)
Power stability (Measurement)	-	0.026%/min. (std.)	0.052%/min. (std.)	-	-
Phase stability (Measurement)	0.02˚/10 min. (std.)	0.014˚/min. (std.)	0.062˚/min. (std.)	-	-

The RF amplification units in the amplifier are arranged on a board of a strip-line type. The amplifier circuit boards are fixed on a copper plate with the cooling water in order to maintain the temperature constant. Using the cooling water has the higher efficiency of heat exchange than a cooling fan and a reduction in mechanical vibration.

To minimize noises caused by the DC power supply, the following countermeasures are employed:

- A series-regulator method was chosen.
- Routes of the DC lines and AC lines in the power supply are perfectly separated.
- Rectifiers and control circuit are separately shielded.
- A cooling fan is fixed with gel bushes to suppress mechanical vibration.

Stability evaluation of 1428-MHz 2.5-kW solid-state amplifier

The RF power and phase stability measurement system of RF amplifier is shown in Fig. 3. In order to evaluate the high-level RF power stability of 20 ppm (rms), we used a low-barrier Shottky diode detector (SDD) and a differential amplifier (Model DA1855A, LeCroy Corporation) to improve the RF power measurement accuracy. The RF phase measurement was done using a double balanced mixer (DBM) which was calibrated for its RF characteristics beforehand. Furthermore, in order to reduce temperature dependence of the measurement system during the stability test, the SDD, differential amplifier and DBM were installed in a constant-temperature chamber. Consequently, the noise level of RF measurement was 75 ppm or less, and the RF phase measurement accuracy was 0.05˚ at 1428 MHz. The detected RF output power and phase in the amplifier were inputted into an oscilloscope (Model DS06054, Agilent Technologies, Ltd.) with the repetition rate of 50 Hz.

The short-term variations of RF signals have to be reduced as far as possible, because the long-term ones can be sufficiently compensated by a PLL technique. The RF power and phase fluctuation were measured during 10 seconds (about 500 RF pulses) to evaluate the short-term variation of the amplifier. The RF power and phase of the 2.5-kW amplifier fluctuated 0.021% (std.) and 0.057˚ (std.), respectively. The obtained data satisfies the tolerance of RF stability as shown in Table 1.

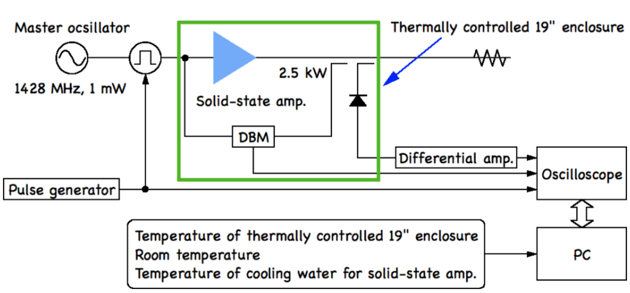

Figure 3: Schematic of RF measurement system.

To obtain the RF power and phase stability of the 2.5-kW amplifier during the long-term use in the test stand, the environmental temperature in the amplifier and the cooling water temperature were recorded by a data-taking recorder, and all data were stored by the same trigger signal. The oscilloscope and data-taking recorder used for temperature measurement were controlled by a PC through a GP-IB. Figure 4 shows the results of RF power and phase drift in a long drive of 8 hours. The recorded RF signals showed saw-tooth variations synchronizing with the temperature of the coolant. The variation of the RF power, phase and the temperature were 0.8% (peak to peak), 0.4˚ (peak to peak), and 25±0.5˚C, respectively. The specified temperature variation of the coolant is ±0.2˚C, that is half of the experimental condition. We thus conclude that the tolerances will be satisfied in the realistic operation of the amplifier.

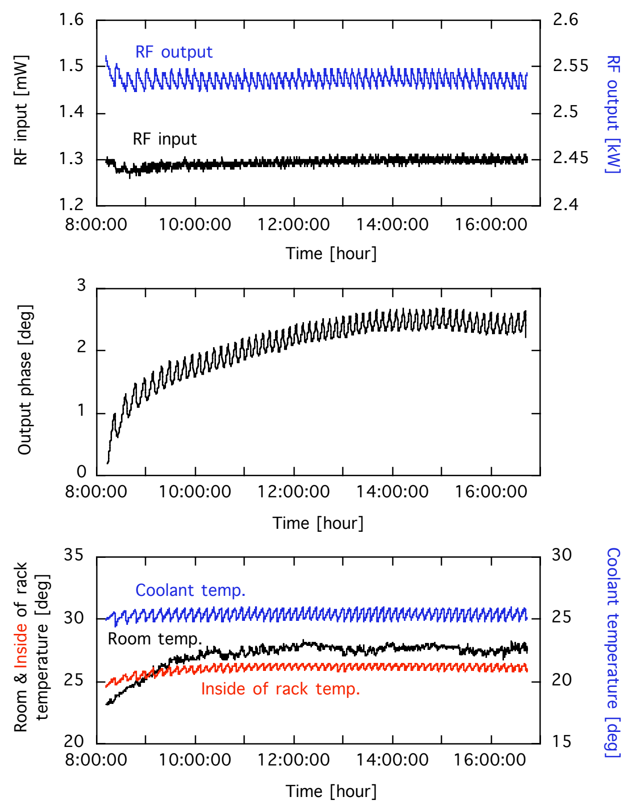

Figure 4: RF power and phase drift of the 1428-MHz 2.5-kW amplifier for continuous run of 8 hours.

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