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LLRF and timing system for the SCSS test accelerator at SPring-8

Yuji Otake [a,b,*], Takashi Ohshima [a,b], Naoyasu Hosoda [b], Hirokazu Maesaka [a,b], Toru Fukui [a,b], Masanobu Kitamura [c], Tsumoru Shintake [d]

[a] RIKEN, SPring-8 Center, XFEL Research and Development Division, 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan
[b] JASRI, XFEL Division, 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan
[c] Hitachi Zosen Corporation, 7-89, Nanko-kita 1-chome, Suminoe-ku, Osaka 559-8559, Japan
[d] The Okinawa Institute of Science and Technology Graduate University, Tancha, Onna-Son, Kunigami, Okinawa 904-0495, Japan

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A B S T R A C T

The 250 MeV SCSS test accelerator as an extreme-ultra violet (EUV) laser source has been built at SPring-8. The accelerator comprises a 500 kV thermionic gun, a velocity bunching system using multi-sub-harmonic bunchers (SHB) in an injector and a magnetic bunch compressor using a chicane of 4 bending magnets, a 5712 MHz main accelerator to accelerate an electron beam up to 250 MeV, and undulators to radiate the EUV laser. These bunch compression processes make short bunched electrons with a 300 A peak current and a 300 fs pulse width. The pulse width and peak current of an electron beam, which strongly affect the pulse width and intensity of the laser light, are mainly decided by the pulse compression ratio of the velocity bunching and the magnetic bunch compressing processes. The compression ratio is also determined due to an energy chirp along the beam bunch generated by an off-crest rf field at the SHB and cavities before the chicane. To constantly keep the beam pulse-width conducted by rf and timing signals, which are temporally controlled within subpicoseconds of the designed value, the low-level rf and timing system of the test accelerator has been developed. The system comprises a very low-noise and temporally stable reference signal source, in-phase and quadrature (IQ) modulators and demodulators, as well as VME type 12 bits analog-to-digital and digital-to-analog converter modules to manipulate an rf phase and amplitude by IQ functions for the cavity. We achieved that the SSB noise of the 5712 MHz reference signal source was less than -120 dBc/Hz at 1 kHz offset from the reference frequency; the phase setting and detecting resolution of the IQ-modulators and demodulators were within $+/-0.5^{\circ}$ at 5712 MHz. A master trigger VME module and a trigger delay VME module were also developed to activate the components of the test accelerator. The time jitter of the delay module was less than 0.7 ps, sufficient for our present requirement. As a result, a beam energy variation of 0.06% was achieved and a time jitter of 46 fs between the acceleration rf signal and the beam was realized.

1. Introduction

The 250 MeV SCSS test accelerator, which is an extreme-ultra violet (EUV) laser source based on the principle of self-amplified spontaneous emission (SASE) [1], at RIKEN HARIMA Institute has been constructed to check the feasibility of an X-ray free-electron laser (XFEL) [2]. The XFEL opens up new experimental methods of science, such as single-shot and single-particle X-ray diffraction imaging [3]. The key components of an XFEL machine are an accelerator with an energy of more than 8 GeV. The accelerator comprises a 500 kV thermionic electron gun, a 238 MHz sub-harmonic buncher (SHB) and a 476 MHz booster cavity in an injector, 2856 MHz accelerating structures, 5712 MHz accelerating structures with an acceleration electric field of 35 MV/m, and in-vacuum undulators. Realizing stable SASE generation to guarantee the assured new experimental method is strongly dependent on the stability of the components of an XFEL machine, which is directly associated with the X-ray laser-intensity stability. To evaluate the feasibility of the XFEL, a 250 MeV SCSS test accelerator at SPring-8, as shown in Fig. 1, including the main key elements mentioned above, was constructed by November, 2005, and is under user experiments using an extreme ultra-violet (EUV) free-electron laser (FEL). The main parameters of the test accelerator and the EUV FEL are given in Tables 1 and 2.

An accelerated electron beam with a pulse width of about 300 fs is necessary in order to make about a 300 A peak current for constantly exciting SASE, and to stably generate the EUV FEL in

* Corresponding author at: RIKEN, SPring-8 Center, XFEL Research and Development Division, 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan.
Tel.: +81 791 58 9801; fax: +81 791 58 1517.
E-mail address: otake@spring8.or.jp (Y. Otake).

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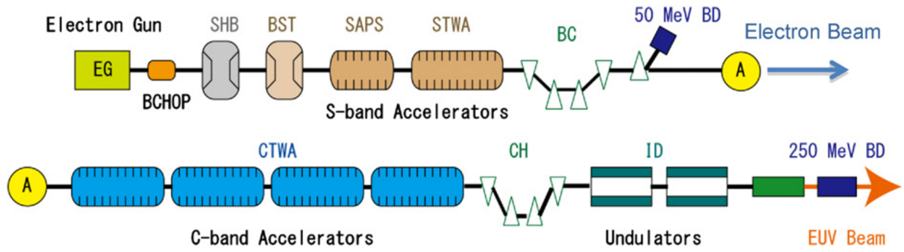

Fig. 1. Machine configuration of the SCSS test accelerator. The machine mainly comprises an electron gun (EG), a beam chopper (BCHOP), a 238 MHz sub-harmonic buncher (SHB), a 476 MHz booster cavity (BST), an S-band alternating-periodic structure (SAPS), an S-band traveling-wave accelerating structure (STWA), a bunch compressor (BC), C-band traveling wave accelerating structures (CTWA), a chicane (CH), in-vacuum undulators (ID) and beam dumps (BD).

Table 1
Main parameters of the test accelerator.

Electron beam	
Beam energy	250 MeV
Bunch charge	~0.3 nC
Repetition rate	60 Hz (max)
Peak current	~300 A
Bunch length	~0.7 ps (FWHM)
Accelerator parameters	
Gun voltage	500 kV
Initial peak current	1 A
Deflector pulse width	1 ns (FWHM)
238 MHz SHB rf voltage amplitude	~200 kV
238 MHz SHB rf phase[*1]	−110°
476 MHz booster rf voltage amplitude	~700 kV
476 MHz booster rf phase[*1]	−25°
S-band APS rf voltage amplitude	12 MV
S-band APS rf phase[*1]	−24°
S-band TWA rf voltage amplitude	38 MV
S-band TWA rf phase[*1]	−29°
Bunch compressor R_{56}	−20 mm
C-band TWA-1 accelerating gradient	21 MV/m
C-band TWA-1 rf phase[*1]	0°
C-band TWA-2 accelerating gradient	37 MV/m
C-band TWA-2 rf phase[*1]	0°
Undulator parameters	
Periodic length	15 mm
Number of periods	300 × 2
Maximum K	1.5
Minimum/Maximum gap	3/25 mm

Table 2
Main parameters of the EUV laser.

Item	Achieved performance
Wavelength range	50–60 nm
Repetition rate	60 Hz
Pulse energy	~30 μJ at 60 nm
Pulse energy fluctuation	~10% (STD)
Laser size[*2]	~3 mm (FWHM)
Pointing stability[*2]	~5% to the beam size (STD)
Averaged spectrum width	0.6% (FWHM)

the test accelerator. The electron beam with a transverse size of less than 100 μm (rms) should also pass through a straight orbit within 100 μm along an undulator section with a length of 12 m. These facts were experimentally confirmed by using the test accelerator [4,5]. The energy stability of the beam should be on the order of 10^{-4}, and the timing jitter between the beam and the acceleration rf signals should be less than 300 fs in rms. These values were also confirmed to be necessary for achieving the orbit and a stable beam pulse width compressed by a bunch compressor (BC) chicane. These demanded energy stability and pulse width can be figured out from calculations by using the *R56* value in the BC [6]. These facts result in a SASE fluctuation of 10% in rms, which means an almost constant peak beam current within 10% [4]. In addition to the above-mentioned conditions, the necessary beam energy variation of 10^{-4} was also experimentally verified [7]. This energy variation corresponds to an rf amplitude variation of 10^{-4} in the cavities of the injector and a phase change of about 1° (about 500 fs) from the rf crest point in 5712 MHz rf acceleration. For the present, in the case of the test accelerator, these values of the rf phase and the amplitude stability are sufficient for stably generating and amplifying 60 nm laser light with about a 300 fs pulse width (FWHM). To realize these stabilities, we have developed the low-level rf (LLRF) and timing system for the test accelerator.

When the system was designed, we considered how to realize the above-mentioned stability. There were mainly two conditions to realize this stability. One was that LLRF components must exhibit extremely low noise, a low temperature dependence and reduced effects from vibration. The other was controllability, which means the control speed (frequency bandwidth) and accuracy, of the system that indirectly secures the stability by feedback control. If the previously mentioned conditions should be provided, the use of solid-state devices is crucial, since these devices usually provide a very low-noise characteristic of a nV/$\sqrt{}$Hz regime, low-power rf driving below milliwatts and low-control voltages for a LLRF system easily adaptable to a computer control system. Furthermore, since the heat capacity of the solid-state devices is usually very low, because of its small size, temperature of the devices is controllable by a small-power heat-controller.

To drive a high-power rf source, such as a klystron with several ten megawatts of output, a medium rf power of several hundred watts is necessary. Therefore, medium-power rf control devices to control an rf phase and amplitude, such as IϕA in SLAC using a faraday rotator driven with a motor and a sub-booster klystron to probably drive the 8 high-power klystrons [8,9] were traditionally used, because of an underdevelopment of rf solid-state rf devices until several tens of years ago. However these solid-state devices are now well developed by IT and cellular-phone technologies. For these reasons, a LLRF system mainly using the solid-state devices, as mentioned below, was developed for realizing ultra-low noise and extreme stability to secure stable lasing of a FEL. One of the important points to use these devices is to extremely reduce any noise effects from high-voltage noise generated by klystron modulators. We finally established large isolation from the high-voltage noise generated by klystron modulators to the solid-state rf devices, ultra-low noise by using a phase-locked loop in a signal source, ultra-stable rf phase and amplitude by choosing ultra-low noise rf devices and an effective temperature isolation, and control methods for rf devices. The long-term stability is also established by computer feedback control.

This paper describes the details of the LLRF and timing system to establish the present test accelerator specifications and the system performance.