OPERATION STATUS OF C-BAND HIGH-GRADIENT ACCELERATOR FOR XFEL/SPRING-8 (SACLA)

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Abstract

To fit our XFEL machine of SACLA (SPring-8 Angstrom Compact Free Electron Laser) in the small campus of SPring-8, a C-band (5712 MHz) high-gradient accelerator with a designed acceleration gradient of 35 MV/m is indispensable. Highly-stable acceleration for an energy chirp in bunch compression process is required for stable lasing. The low-trip rate and the low-dark current of C-band accelerating structures are also crucial for stable accelerator operation. After 1000 hours of the RF conditioning, the C-band accelerator has daily accelerated electron beams up to 7.0-7.4 GeV, with the designed accelerator gradient of about 35 MV/m. The trip rate of the whole accelerator is once per 30 minutes, which is an acceptable rate for beam commissioning. The energy stability of the electron beam was 0.014% (STD), owing to the stabilization of a PFN charging voltage with a 10 ppm (STD) accuracy by a high-precision high-voltage charger. The amount of dark current was several pC/pulse, which was small enough for operation.

INTRODUCTION

SACLA (SPring-8 Angstrom Compact Free Electron Laser) is a unique XFEL facility, aiming to generate an X-ray laser with a compact electron accelerator and an in-vacuum undulator. The compactness is important to be able to construct at the available space in the SPring-8 campus, and for lower construction cost. In order to shorten the accelerator length, a C-band (5712 MHz) accelerator is employed. A higher frequency is chosen to produces a higher accelerating gradient.

Figure 1 shows the configuration of the SACLA accelerator. The first 12 units of the C-band accelerator are set at an off-crest (-48 degree) phase, which produces an energy chirp for the bunch compressor (BC3). After the BC3, 52 C-band units accelerate the beam with a gradient of 35 MV/m. The total length of the accelerator with the gradient is consequently 400 m.

The low-trip rate of klystron high-voltages and the low-dark current of C-band accelerating structures attained by high-power RF conditioning were demanded for secure accelerator operation. The RF conditioning was started in Oct. 2010. Since March 2011, the C-band accelerator has been operated for beam commissioning, with the designed accelerator gradient of 35 MV/m, with a low trip rate.

In XFEL, electron bunch is highly compressed to obtain the high peak current. Therefore RF field giving the energy chirp should be extremely stable. According to the sensitivity of the electron peak current on the RF field variation, the requirements of the amplitude and phase stabilities are 0.01% (STD) and 0.2 degree (STD), respectively [1]. We realized the stability owing to the stabilization of the charging voltage of the modulator.

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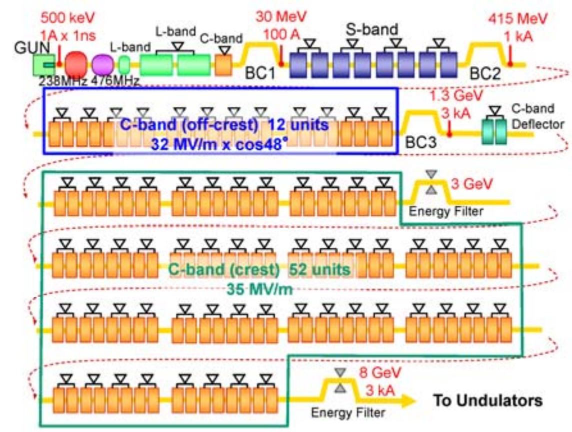

Figure 1: Configuration of the SACLA accelerator.

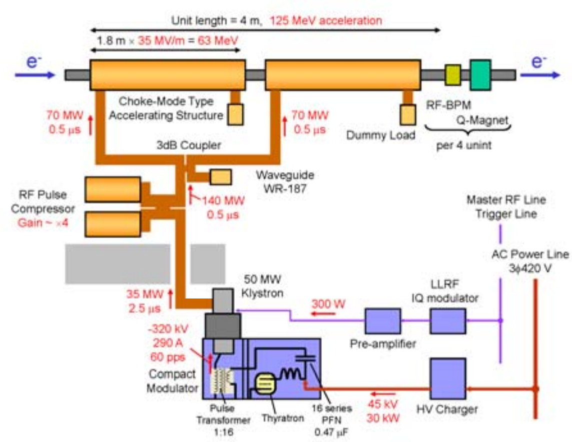

Figure 2: Configuration of C-band accelerator system.

C-BAND ACCELERATOR SYSTEM

Figure 2 shows one unit of the C-band accelerator system. A high-power RF source is the 50 MW pulse klystron. An RF pulse compressor being the SLAC energy doubler (SLED), which consists of one pair of high-Q cavities and one 3-dB coupler, condenses a 35 MW, 2.5 μs square pulse to a 140 MW, 0.5 μs pulse. Then the RF power is fed into two travelling wave accelerating structures. The 1.8 m long, quasi-constant-gradient structure is formed with 91 acceleration cavity cells, which generate an accelerating gradient of 35 MV/m. Detail of each component is described in [2].

Highly Precise High-Voltage Charger

Concerning pulse-to-pulse instability, the most significant source of it is the voltage jitter of a PFN circuit in the modulator. So far, the stability of an inverter-type HV charger was typically about 0.1%, which was one order worse than that of the requirement (0.01% in STD). Therefore, we have developed the highly-precise HV charger. The stability was realized by the following techniques; 1) optimization of the feedback control of the PFN voltage, using a special HV probe with a fast time response, 2) combination of a “main charger” and a “sub charger” operated in parallel. Figure 3 shows a typical waveform of the charging cycle. After the main charger charges more than 99% of the target voltage, the sub charger precisely adjusts to the target voltage with 10 ppm (STD) accuracy. This stability satisfies the requirement for the XFEL.

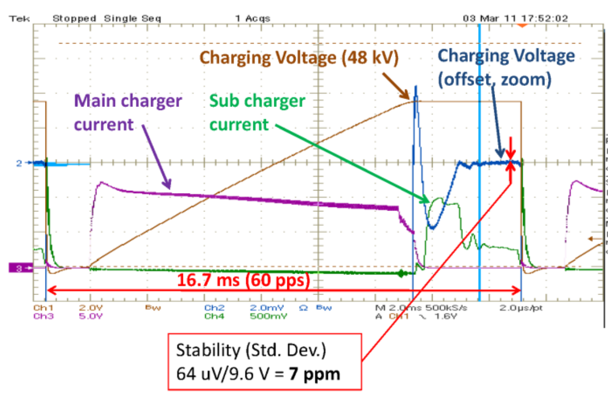

Figure 3: Typical waveform of the PFN voltage and the charging current. The blue waveform shows the waveform of the PFN voltage around the target voltage.

OPERATION STATUS

High Power RF Conditioning

The high power RF conditioning was carried out by the following procedure:

1) In a shorter RF pulse (0.1 μsec), we gradually increased the RF power, from several MW to about 45 MW, with maintaining the vacuum pressure below a threshold value of 1×10^{-5} Pa.

2) When the RF power reached to the target value, we expanded the pulse width. (0.2 μsec, 0.3 μsec,...).

3) From 1 μsec to 2.5 μsec, we applied the phase reversal to execute the RF pulse compression.

The RF conditioning was executed with a 60 pps repetition. The RF conditioning took roughly 1000 hours to operate in the designed gradient of 35 MV/m with a low RF trip rate (once per day at 10 pps).

Waveform Shaping

The waveform of the SLED output naturally has a spiky part due to a phase reversal. This part may cause RF discharge. The energy gain of the electron beam corresponds to the RF power integrated over the filling time of the accelerating structure (300 nsec). Therefore, it is advantageous to flatten the spike if the integrated power is kept same level. We applied amplitude modulation by a low-level RF (LLRF) system to flatten the spike. Figure 4 shows the waveform. ”AM 100ns” means the amplitude modulation for 100 nsec after the phase reversal. In the case of “FIR 130ns”, the phase reversal speed is modulated by FIR filtering for 130 nsec. Table 1 summarizes the peak power and the power averaged for 300 nsec in each waveform. The amplitude modulation effectively reduces the peak power of the spike. We applied “AM 100ns” modulation to all C-band RF units.

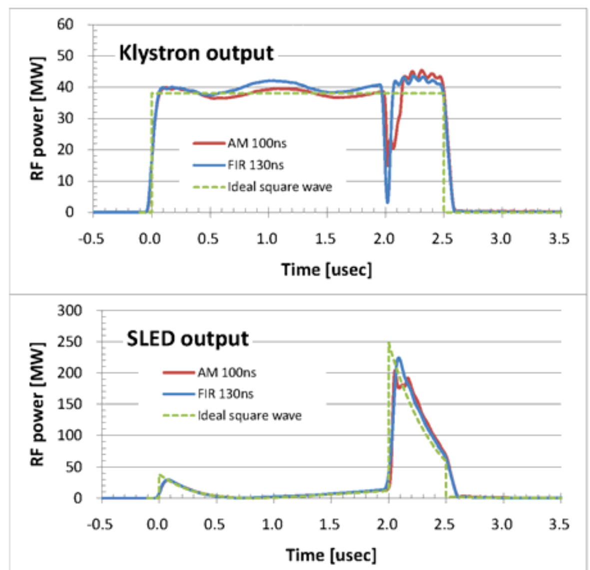

Figure 4: Typical waveform of the klystron output (upper), and the SLED output (lower), along with different amplitude modulations (see text). The green dashed line is an “ideal” waveform, assuming a square waveform with an infinity phase reversal time.

Table 1: Peak power and “300 nsec averaged” power of the SLED output.

Modulation	Peak power	Averaged power
AM 100ns	204 MW	166 MW
FIR 130ns	224 MW	167 MW
Ideal	248 MW	171 MW

Accelerating Gradient and Trip Rate

Figure 5 shows the accelerating gradient and the trip rate during beam commissioning. The accelerating

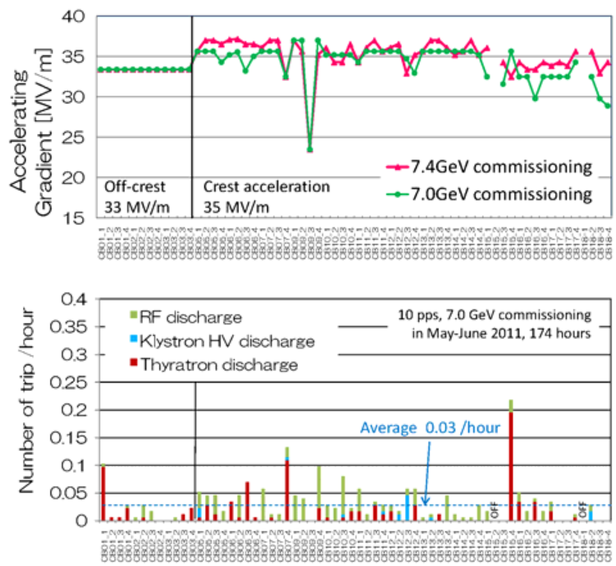

Figure 5: (Upper) Accelerating gradient of each RF unit, in typical operational. (Lower) Trip rate of each RF unit.

gradient E_a(MV/m) plotted on this figure was calculated by the simplified equation; $E_a = 0.9 * V_{ch} - 3.5$, substituting the charging voltage of V_{ch}(kV), because the measured RF power of each unit still has a calibration uncertainty of 10%.

At the 12 units located upstream of the BC3, the accelerating gradient of 33 MV/m for the off-crest acceleration was set. After the BC3, the accelerating gradient of about 35 MV/m, which is the same as the designed value, was set. The gradient of each unit was adjusted dependent on the trip rate. At the 14 units in the downstream (CB15-CB18), the acceleration gradients were relatively low (about 33 MV/m). This is because we did not have enough time for RF conditioning (about 500 hours), due to a delayed installation schedule. In order to increase the gradient, further RF conditioning is necessary in the vacant time of beam commissioning.

The beam energy was measured at the several dispersive sections of magnetic chicanes. The energy between the BC3 and the accelerator end was compared to the calculated acceleration energy. It agreed within a calibration error of 5%.

During 7.0 GeV beam operation with a repetition of 10pps, the trip rate of each unit was about 0.03 times/hour in an average. We have about 70 units, so the total trip rate of the SACLA accelerator was once per 30 minutes. In the case of 7.4 GeV operation, it was once per 20 minutes. These rates are acceptable for beam commissioning. As shown in Figure 6, the trips are categorized according to three dominant sources: 1) the self-discharge of the thyratrons (46%), 2) the HV discharge of klystrons (6%), and 3) the RF discharge in the high-power RF components (48%).

During the SACLA operation, two units could not use: CB15-2 had a damaged pulse transformer. CB18-1 had a damaged klystron. CB09-3 operated with a quite lower power, due to frequent RF discharging around the klystron window. In this summer, we replaced these klystrons and the pulse transformer. Apart from these units, the C-band accelerator has been daily operated for a total of 4000 hours without any serious problem.

Stability

Owing to the highly precise HV charger and the stable, low-noise LLRF system, the short-term (10 minutes) stability of the RF phase of the accelerating structure was measured to be 0.03 degree in STD [3]. The stability of its RF amplitude was 0.05% (STD), although the measured values limited by measurement accuracy do not show genuine values. The long-term drift of the RF phase is compensated by the feedback control of the LLRF [3].

The short-term stability of the beam energy at the accelerator end was 0.014% (STD), which can be used for FEL commissioning.

Dark Current

The dark current from the accelerating structure was measured by current transformers. Since the dark current is emitted by a high surface electric field in the structure, a dark current pulse width of 300 nsec (FWHM) is the same as the RF waveform. The amount of the dark current was 4 pC at CB14, and less than 1 pC at CB02 and CB12. On the other hand, an electron beam charge for the commissioning is usually several 100 pC. The dark current is small enough for beam commissioning.

SUMMARY

The C-band accelerator has been daily operated with an accelerating gradient of about 35 MV/m. The trip rate of the whole accelerator was once per 30 minutes, which was an acceptable rate for beam commissioning. The energy stability of 0.014% (STD) was also at an acceptable level. The dark current of ~4 pC was negligibly small. Performance and reliability of the C-band accelerator was proved. In order to increase the beam energy, we plan to restore the failed components and to continue further RF conditioning.

REFERENCES

[1] H. Tanaka, et. al., "Bunch length variation and timing jitter caused by RF system instability in XFEL/SPring-8", 4th Annual Meeting of Particle Accelerator Society of Japan, 2007.

[2] T. Inagaki, et. al., "Construction of 8-GeV C-band accelerator for XFEL/SPring-8", FEL'10, 2010.

[3] T. Ohshima, et. al., "Performance of timing and LLRF system of XFEL/SProng-8 SACLA", 8th Annual Meeting of Particle Accelerator Society of Japan, 2011.