8-GeV C-BAND ACCELERATOR CONSTRUCTION FOR XFEL/SPring-8

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Abstract

The C-band (5712 MHz) accelerator is used as the main accelerator of the X-ray free electron laser (XFEL) facility in SPring-8. We will use 64 units of them for the 8 GeV XFEL accelerator. Since the C-band generates a high accelerator gradient, as high as 35 MV/m, it makes the accelerator compact. Since May 2008, we have operated one of the C-band units in the SCSS test accelerator with a high accelerator gradient of 37 MV/m. We have experienced no trouble, no serious rf discharge, and no degradation of FEL performance. We confirmed high reliability of the C-band accelerator at high-gradient.

Mass-production of high-power rf components was started in 2007. They have been delivered on schedule. In order to maintain the production quality, we constructed a high-power rf test bunker.

For the power supply, special design was taken to improve stability. The new high-voltage charger has extremely high stability, which satisfies the requirement for the XFEL.

INTRODUCTION

The Japanese X-ray free electron laser (XFEL/SPring-8) is under construction at the SPring-8 site [1,2]. It aims to achieve excellent laser performance with a compact, low-cost, highly reliable machine. It is based on three key technologies; 1) a low-emittance injector using the thermonic electron gun, 2) a C-band high-gradient accelerator, 3) an in-vacuum short-period undulator. The frequency of C-band is 5712 MHz, which is double of conventional S-band accelerator. Higher frequency is chosen due to the higher power efficiency, which makes the accelerator compact. Since the C-band generates a high accelerator gradient, as high as 35 MV/m, the total length of the accelerator fits within 400 m, including the injector and three bunch compressors. The C-band uses normal conducting rf technology, thus it runs in the pulse mode at 60 pps, which is well suited for XFEL operation, and is less expensive.

Figure 1 shows a computer image of our facility. The total length of the FEL facility is 700 m, which fits with available length in our site.

Figure 2 shows the accelerator layout. After the injector and S-band sector, the first C-band sector with 12 C-band units accelerates an electron beam from 415 MeV to 1.45 GeV. At this sector, the rf phase is set at 42 degrees from the crest, which makes energy chirp for the bunch compression chicane (BC3). After BC3, 52 C-band units accelerate the beam to 8 GeV.

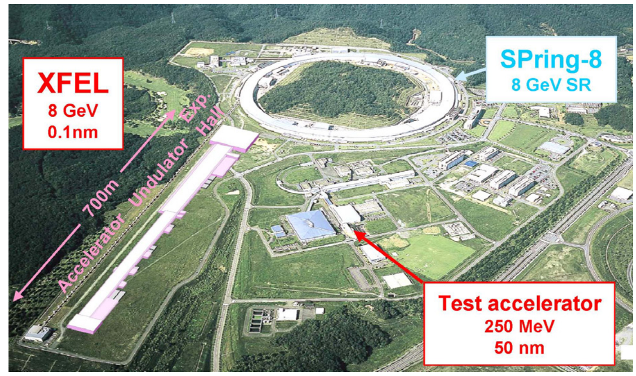

Figure 1: Computer image of the XFEL facility in SPring-8 site.

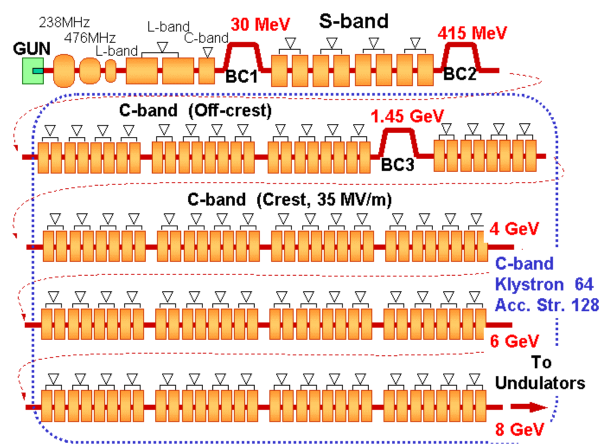

Figure 2: Accelerator layout of XFEL/SPring-8.

C-BAND ACCELERATOR SYSTEM

Figure 3 shows one unit of the C-band accelerator system. The rf source is the 50 MW pulse klystron. An rf pulse compressor compresses a 50 MW, 2.5 μs square pulse to a 150 MW, 0.5 μs pulse. It is then fed to two 1.8 m accelerating structures.

The C-band accelerator was initially developed for the e^+e^- linear collider project. At KEK, the first model of the accelerating structure, the rf pulse compressor, waveguide components, and the klystron were developed [3,4,5,6]. We adopted C-band technology for XFEL. XFEL is the first practical application of the C-band accelerator in a large facility..

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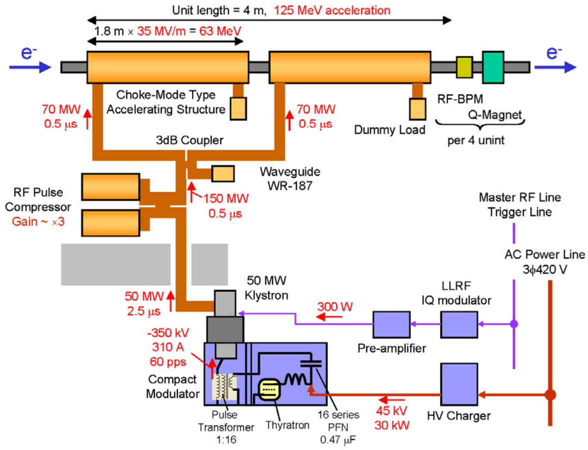

Figure 3: C-band accelerator system.

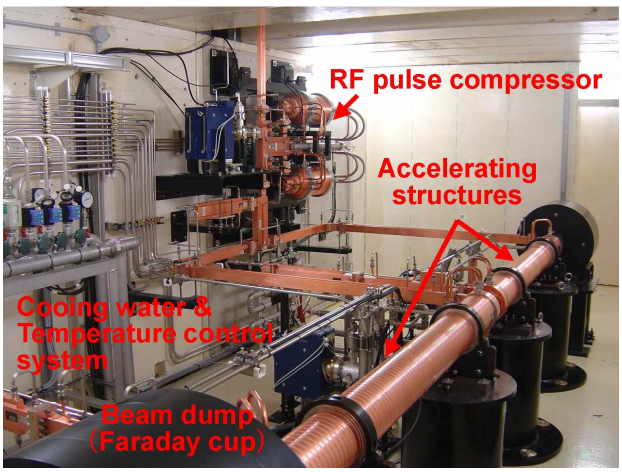

Figure 4: Two accelerating structures and the rf pulse compressor are installed at a high-power test bunker, which is the exact model of 8 GeV accelerator.

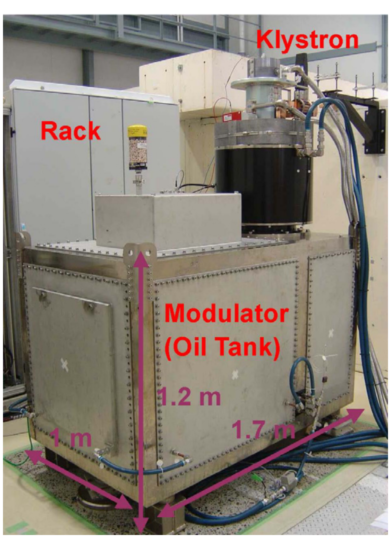

Figure 5: The first model of new oil-filled modulator, where the klystron is attached directly on the modulator.

Choke-Mode-Type Accelerating Structure

Figure 4 shows the C-band accelerator unit. The 1.8 m long accelerating structure is formed 91 cells, quasi-CG structure. The rf mode is $3\pi/4$ traveling wave. The shunt impedance is 54 MΩ/m on average. The attenuation parameter is 0.53. The filling time is 300 nsec. A unique feature is "choke-mode-structure". It eliminates the wakefield of electron beams for future multi-bunch operation [4].

The cavity structure is made of high-purity oxygen-free copper with hot isostatic pressing (HIP). Each cavity cell is carefully shaped on a high-precision lathe, in order to adjust the cavity frequency. After rf measurements, they are brazed. Fabrication of this accelerating structure is well established by MITSUBISHI HEAVY INDUSTRIES, LTD [7].

Since the C-band accelerator generates high-gradient, it has higher heat dissipation. In order to compensate the heat dissipation, we prepare a precise temperature-control system [8]. Measuring the body temperature, the feedback system controls the heater of the cooling water. Thanks to this feedback loop, we can easily change the pulse repetition. At the test accelerator, this system controls the temperature to within ±0.04 degree.

RF Pulse Compressor

SLED-type rf pulse compressor is used. It consists of one pair of high-Q cavities and one 3-dB coupler. The rf mode of the cavity is $TE_{0,1,15}$. The measured Q_0 is 190,000, and β is 9.5. A unique feature is that each cavity has an rf mode converter [5]. It converts the waveguide mode (TE_{10}) to the cylindrical mode (TE_{01x}). The rf pulse compressor is also fabricated by MITSUBISHI HEAVY INDUSTRIES, LTD.

The cavity frequency is tuned at the factory. After installation in the accelerator tunnel, the frequency can be finally adjusted by a precise temperature-control system.

50-MW Pulse Klystron

The maximum output power is 50 MW, 2.5 μsec. We use model E37202 of TOSHIBA ELECTRON TUBES & DEVICES CO., LTD. The design and the development are presented in [6]. The compatible klystron is available at MITSUBISHI ELECTRIC CORP.

Compact, Oil-Filled Modulator

The 110 MW modulator supplies a pulsed high-voltage of -350 kV, 310 A to the klystron. Last year we developed a new compact modulator. Figure 5 shows an outer view of the modulator. In a steel tank (1.7m×1.0m×1.2m), all of the high-voltage components, including an 16 series PFN circuit, a thyratron tube, and a pulse transformer, are immersed in insulating oil. The steel tank works as an EM shield against thyratron noise. Insulating oil eliminates any trouble due to humidity or dust. Cooling is performed by natural convection of oil, without a fan [9]. Oil is cooled by water running through copper pipe and copper plate.

Last year, the first prototype of this modulator was fabricated by NIHON KOSHUHA CO., LTD. So far, it has worked well for more than 600 hours. A previous model of the oil-filled modulator is used at a test accelerator [10]. Four modulators have worked for more than 3,000 hours without any serious problem. We conclude that the concept of the oil-filled modulator has been realized.

PFN High-Voltage Charger

We use an inverter-type high-voltage power supply for PFN charging. The maximum charged voltage is 50 kV. The averaged charged current is about 2 A.

The XFEL accelerator requires very high stability on the accelerating rf field. According to a beam-optics consideration, the stability of the acceleration energy of each unit should be on the order of 10^{-4} [2]. The jitter of the PFN charged voltage is one of the largest sources of pulse-to-pulse instability. Our requirement concerning the PFN voltage jitter is about 100 ppm (0.01%), although a conventional inverter-type high-voltage charger has a one-order larger jitter.

We have been developing a high-voltage charger with stability better than 100 ppm. The charger has a feedback control of the PFN voltage using a high-voltage probe attached to the modulator. A new 50 kV high-voltage probe with a fast time response and a low thermal drift was developed by JAPAN FINECHEM COMPANY, Inc. [11]. For the high-voltage charger, special design was taken to improve stability. The charger is equipped with two switching power supply units in parallel. One is the "main charger" with 2 A output, and the other is the "sub charger" with a two-order smaller output. After the main charger charges up to about 99.7% of the target voltage, the sub charger precisely charges the remaining voltage. Last year NICHICON CORPORATION made a high-precision charger [12]. Figure 6 shows a typical waveform of the charging cycle. The voltage jitter is measured as 60 ppm in peak-to-peak (10 ppm in standard deviation). This stability satisfies the requirement for the XFEL.

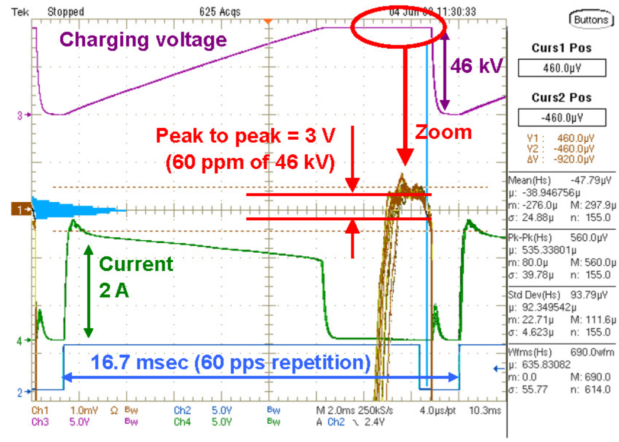

Figure 6: Typical waveform of the PFN voltage and the charging current using the high-precision charger. Tens of the waveforms are overlapped. The left blue histogram shows the stability of the PFN voltage accumulated during 1 minute operation.

Low-Level rf System and Timing System

The rf phase and amplitude are precisely controlled by the low-level rf system. It consists of IQ modulators / IQ demodulators and VME waveform generators / digitizers. It is also used for pulse shaping and phase reversal for rf pulse compression. A precise timing system, which is synchronized to the master rf is developed. Details of the low-level rf system and the timing system are described in [13].

HIGH-GRADIENT OPERATION AT THE SCSS TEST ACCELERATOR

In order to demonstrate SASE-FEL in the EUV range, the SCSS (SPring-8 Compact SASE Source) test accelerator was constructed in 2005 [14]. We built the 250 MeV accelerator and two in-vacuum undulators in a 60 m tunnel. After careful beam commissioning, we successfully observed SASE amplification at 49 nm wavelength with a 250 MeV beam energy in June, 2006. In 2007, laser amplification reached to the SASE saturation, which was verified by a measurement of the radiation characteristics [14]. Since 2007, several scientific experiments have started. The test accelerator stably supplies FEL radiation to the users.

In the test accelerator, two C-band accelerator units (named CB1 and CB2) are used. Until April 2008, the acceleration gradient of CB1 and CB2 was set at 29 MV/m (100 MeV gain per one unit), which is sufficient to obtain 250-MeV at the end. Besides the operation, we conducted 500 hours of rf processing. We measured the trip rate and confirmed that we sustain a high electric field gradient. We performed a beam acceleration test, and confirmed the field gradient [15].

Since May 2008, we have increased the rf power of CB2. Final energy is limited to 250 MeV due to the radiation safety. Therefore, we decreased the power of CB1 to adjust the final energy to 250 MeV.

Figure 7 shows the typical waveform during high-gradient operation at CB2. The pulse width of the klystron output is 2.5 μsec, with phase reversal at 2 μsec. In order to suppress the spike peak at the pulse compressor output, amplitude modulation makes a roughly flat pulse for over 200 nsec. Phase reversal and amplitude modulation are performed with the IQ modulator. The klystron output is about 50 MW. After the rf pulse compressor, the peak power is about 200 MW, and the average power in the 300 nsec filling time is about 150 MW. Therefore, the power gain using the rf pulse compressor is about 3.

The acceleration energy at CB2 was measured with a bending magnet, which is located 3 m after CB2. By comparing the beam energy with/without CB2, the acceleration energy was measured to be 131 MeV. Dividing by the active length of 3.6 m, the accelerating gradient was determined to be 37 MV/m.

After beam commissioning, we achieved that FEL lasing was easily obtained as same as before. We maintain CB2 in high-gradient (37 MV/m) for FEL operation for daily user run.

Figure 8 shows the trend graph of the vacuum pressure during high-gradient operation. The base pressure was on the order of 10^{-8} Pa. Small spikes were observed at a rate at one per hour. But it was much lower than the interlock level of 2×10^{-5} Pa. During 300 hours (10 pps) of the user run, we had only 2 interlock stops due to the rf discharge at CB2. We confirmed that we can practically use the C-band accelerator with high-gradient of nominal 35 MV/m in XFEL.

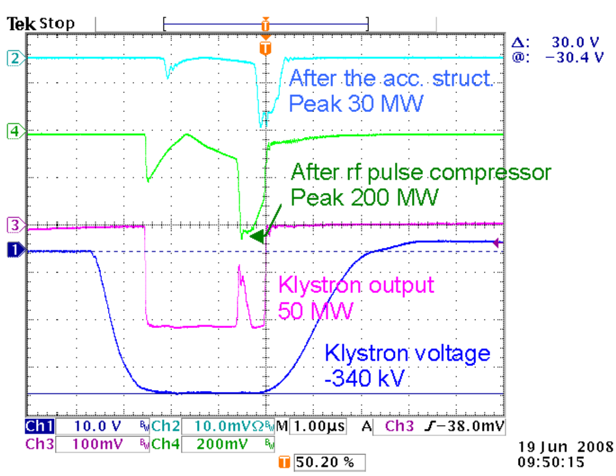

Figure 7: Typical waveform of the klystron voltage and the rf pulse at CB2.

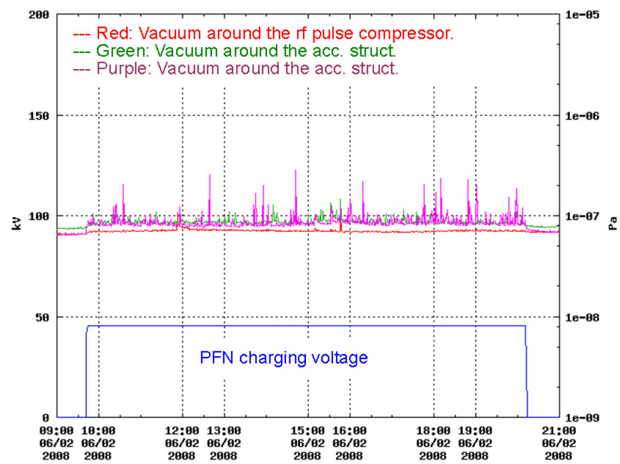

Figure 8: Typical trend graph of the vacuum pressure in the CB2 system. The accelerator operation started at 9:40, and ended at 20:10, with 10 pps repetition.

HIGH-POWER RF TEST BUNKER

In order to check the quality of many high-power rf components delivered from the factory, we constructed a test bunker. Figure 4 and 5 are photos of the test bunker. The first set of rf components were installed. In order to perform complete tests of the C-band accelerator, we also installed vacuum components, water pipes, and the support structures with almost the same layout in XFEL,

We started rf processing at the end of July. The rf processing is in progress. After a certain period, we have a plan to replace another set of the accelerating structures and the rf pulse compressor. We expect that about ten sets of rf components can be tested before installation to the XFEL tunnel. It is a reasonable number as sample checks of 64 units.

SUMMARY AND SCHEDULE

In the SCSS test accelerator, we have operated one of the C-band units with a high accelerating gradient of 37 MV/m. Nominal acceleration gradient of 35 MV/m is well confirmed.

High-power rf components, which include the accelerating structure, the rf pulse compressor, waveguide components, and the klystron, have been produced on schedule. So far, roughly 30 % of the 64 units have been delivered. Concerning the modulator and the PFN high-voltage charger, the prototype model has extremely high stability, which satisfies the requirement for the XFEL. The first models for XFEL are being fabricated at the company.

The XFEL building will be completed in April 2009. We plan to install the C-band units from 2009 to 2010. After rf processing, we plan to start commissioning by the early period of 2011.

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