CONSTRUCTION OF 8-GEV C-BAND ACCELERATOR FOR XFEL/SPring-8

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Abstract

An 8-GeV C-band (5712 MHz) accelerator is employed as the main accelerator of the XFEL in SPring-8. Since the C-band accelerator generates high acceleration gradient of 35 MV/m, the accelerator becomes compact and low cost. Since 2006, the mass-production of the 64 units of the accelerator components has been completed. The production quality was confirmed by a high power rf test. The installation of the C-band accelerator components started in August 2009. Currently we almost complete the installation on schedule.

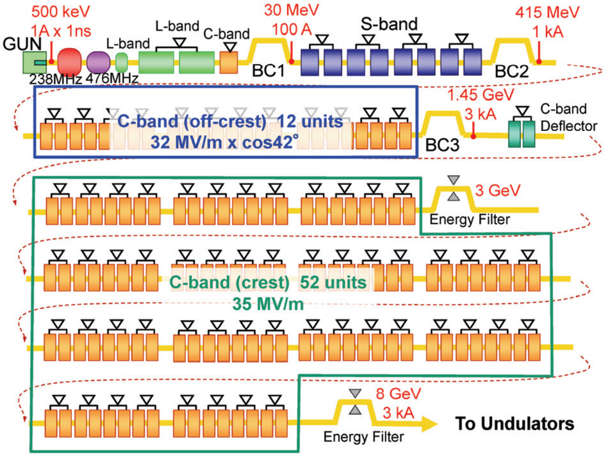

Figure 1: Configuration of the accelerator.

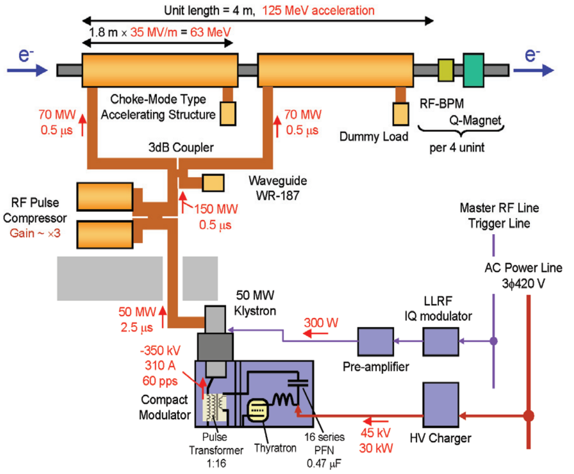

Figure 2: One unit of the C-band accelerator system.

INTRODUCTION

A C-band accelerator is employed as the main accelerator of the X-ray free-electron laser (XFEL) facility in SPring-8 [1]. The frequency of the C-band accelerator is 5712 MHz, which is the double of a conventional S-band accelerator frequency. The higher frequency is chosen because the higher power efficiency can be obtained, which makes the accelerator compact. Since the C-band accelerator has a high acceleration gradient of 35 MV/m, the total length of the accelerator is fitted within 400 m, including the injector and three bunch compressors. This compactness is necessary to construct the XFEL facility in the SPring-8 site, and to save the construction cost. A normal conducting rf technology is employed for the C-band accelerator. It runs in the pulse mode at 60 pps, which is well suited for the XFEL operation.

OVERVIEW OF THE C-BAND ACCELERATOR SYSTEM

Figure 1 shows the accelerator configuration. First 12 unit of C-band accelerator uses with off-crest (-42 degree) phase, which makes energy chirp for the final bunch compression chicane (BC3). After BC3, 52 C-band units accelerate the beam with crest phase.

Figure 2 shows one unit of the C-band accelerator system. The high power rf source is the 50 MW pulse klystron (Toshiba, Model:E37202). The rf pulse compressor condenses a 50 MW, 2.5 µs square pulse to a 150 MW, 0.5 µs pulse, which is fed in two accelerating structures.

For the development of each component, we emphasize following four key words;

High Acceleration Gradient

For realization of the high acceleration gradient, we have made an effort to avoid the risk of the rf discharge (breakdown) at the accelerating structures, the rf pulse compressors, klystrons and all of the waveguide components. The high gradient is achieved with 1) structure design not to have a sharp edge or a concentration of the field, 2) good quality of material and the fabrication and 3) clean assembly during the installation.

Compact

The high acceleration gradient requires the high density of the rf sources and compact power supplies. The

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Figure 3: Photograph of the installed C-band accelerator in the tunnel.

Figure 4: Photograph of the klystrons, the modulators and the control cabinets, placed alternately at every 4 m unit length, in the klystron gallery.

klystron should be placed at every 4 m unit length. The conventional modulator power supply with resonant charging system is too huge. We have developed compact klystron modulator combined with inverter-type high voltage charger.

Stability

Since the electron bunch length is highly compressed, rf field giving the energy chirp should be extremely stable. According to the sensitivity of the peak current on the rf field variation, requirement of the amplitude and phase stabilities are 100 ppm and 0.2 degree, respectively [2]. The largest source of the pulse-to-pulse instability is the voltage jitter of the PFN charging. Therefore, we have developed the PFN high voltage charger with stability much better than 100 ppm. We have also constructed the trigger timing & low level rf system with high stability and low noise. In order to suppress the temperature drift, cooling water effectively stabilizes the temperature of the electronic components and cables [3]. For the accelerating structure and the rf pulse compressor, we prepared a water temperature control system which stabilizes the cavity temperature better than 0.1 degree [4].

Reliability

Since the XFEL accelerator consists of about 70 of units, the reliability of each unit is important. Dead time rate of the XFEL facility corresponds to the summation of the failure rate of 70 units, unless any stand-by (redundant) units are prepared. We consider to preparing several stand-by units, but the assignment will be determined after the rf conditioning. In order to reduce the failure rate, we carefully check the reliability of each component.

HISTORY OF THE CONSTRUCTION

The C-band accelerator was initially developed for the e^+e^- linear collider project. At KEK, the accelerating structure, many of waveguide components, and the klystron were developed. Since 2001, our project adopted C-band technology, and we continued the development of components. The first model of present brazed type accelerating structure was fabricated in 2003. In 2004, we performed the high power rf test, and confirmed the good performance up to 33 MV/m. Then we constructed SCSS test accelerator, which is the prototype EUV-FEL machine, with two C-band units in 2005~2006. Daily operation with 37 MV/m of the acceleration gradient proves the reliability of the C-band components [5].

In 2006, we started the construction of the XFEL facility. 64 sets of C-band components were mass-produced in several Japanese companies. Qualities of these mass-produced components were confirmed by the high power rf test.

After the building construction has been completed in April 2009, we started the installation in August. Now, we have almost completed the installation on schedule. Figure 3shows the accelerator components in the tunnel. Figure 4 shows the photograph in the klystron gallery. A control system and a low-level rf system are installed in a series of electronic cabinets [3]. The precise high voltage charger has not been installed, because some modification works still remain. Hereafter we will carry out the cabling, cooing water piping, and the preparation of the control system.

KEY COMPONENTS

Choke-mode-type Accelerating Structure

The 1.8 m long accelerating structure is formed 91 acceleration cavities. The high power rf is stored to each cavity with $3\pi/4$ travelling wave mode, which generates the high acceleration field. A unique feature is “choke-mode-structure”. Outside of each acceleration cavity, a choke cavity and a SiC absorber are coaxially equipped. This structure effectively eliminates the wakefield of electron beams for future multi-bunch operation [6]. Because of the choke-mode-structure, we could not tune the cavity frequency by a dimpling method. Therefore, the cavity cells were carefully shaped on a high-precision lathe, in order to adjust the cavity frequency. After rf measurements, they were brazed. The accelerating structures were fabricated by Mitsubishi Heavy Industries, Ltd. Thanks to the improvement on the lathe shaping and brazing, they steadily fabricated 128 accelerating structures. The cavity frequency was mostly matched between 5711.8 to 5712.0 MHz, and the square-averaged phase error was within 2 degrees [7]. These are the enough accuracy for XFEL.

RF Pulse Compressor

The rf pulse compressor consists of one pair of high-Q cavities and one 3-dB coupler. The cavity has cylindrical rf mode ($TE_{0,1,15}$), which provides low power loss and high-Q value (~185,000). At the entrance of each cavity an rf mode converter is attached. It smoothly converts the waveguide mode (TE_{10}) to the cylindrical mode. At the opposite side of the cavity, a frequency tuner with a differential screw is attached. It enables us to adjust the frequency to 5712 MHz ±10 kHz, in order to maximize the gain, and to minimize the rf reflection to the klystron. At the first model of the compressor, we experienced that the amount of the reflection changed after the evacuation of the cavity. We considered the end plate was slightly moved due to the small gap between the screws by the pressure of the atmosphere. Therefore we changed the screw tighter. Thanks to the improvement, 64 sets of the rf pulse compressor was stably adjusted. The VSWR is less than 1.05, which is small enough for the klystron. The rf pulse compressors and other waveguide components have also been fabricated by Mitsubishi Heavy Industries, Ltd. Further details are described in [7].

Compact, Oil-filled Modulator

The 110 MW modulator supplies a pulsed high-voltage of -350 kV, 310 A to the klystron. We developed a compact modulator [8], which is shown in Figure 4. In a steel tank (1.7m×1.0m×1.2m), all of the high-voltage components, including a PFN circuit, a thyratron tube, and a pulse transformer, are immersed in insulating oil. Direct connection of the PFN circuit and the pulse transformer in the oil tank avoids the risk at the high voltage cable connection. The steel tank works as a perfect 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. Oil is cooled by water running through copper pipe and copper plate. The first modulator was fabricated in 2007. By end of 2008, it works well without serious problem at the test bunker for more than 700 hours. Then we started the mass-production.

Installation of the klystrons and modulators started in August 2009. All the klystrons and the modulators are checked with 8 hours of continuous operation, before the installation to the klystron gallery. This final check is important to reduce the initial trouble on the high power devices. So far about 60 of the klystron units have been installed at the klystron gallery, as shown in Figure 4.

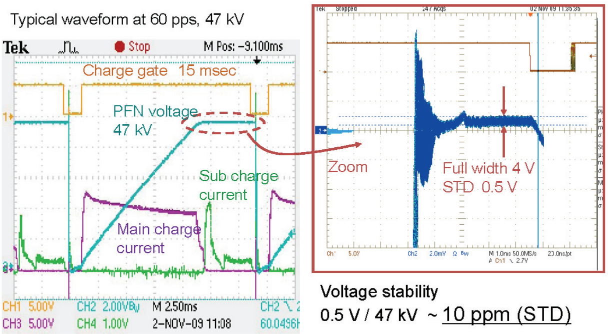

Figure 5: Typical waveform of the PFN voltage and the charging current. The right figure shows the waveform of the PFN voltage around the target voltage, overlaid during 1 minute.

PFN High-Voltage Charger

We use an inverter-type high-voltage power supply for PFN charging up to 50 kV. As we described before, XFEL requires very high stability on the accelerating rf field. Then we have developed 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. 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 more than 99% of the target voltage, the sub charger precisely charges the remaining voltage. Figure 5 shows a typical waveform of the charging cycle. The voltage jitter is measured as 10 ppm in standard deviation. This stability much satisfies the requirement for the XFEL.

HIGH POWER RF TEST

In order to check the production quality of the mass-produced C-band components, we performed the high power rf test at the test bunker [9]. Figure 6 shows the photos of the test bunker. All the components of one C-band unit, including a vacuum system, a cooling water system, a low level rf system, and a control system were installed with almost actual layout and cabling. This means as the complete test of the C-band accelerator system.

So far, we tested three different sets of the rf components. After certain period (200~300 hours) of the high-power rf processing, we obtained the nominal acceleration gradient (35~40 MV/m) at the accelerating structure. Figure 7 shows the waveform with the maximum operational condition, which was limited by the capacity of the power line. The acceleration gradient was calculated from the rf power of the pulse compressor output, to be 42 MV/m.

During the rf processing, we counted the fault rate. Figure 8 shows the fault rate due to the rf discharge (interlocked by the vacuum pressure). Under 38 MV/m, the fault rate is less than 1 count per day with 60 pps machine operation. We found the fault rate significantly decreased after the progress of the rf processing. We confirmed the quality of the rf components is good enough to work with high acceleration gradient at XFEL.

Figure 6: Birds' eye view of the test bunker, when the ceiling shield blocks were dismounted.

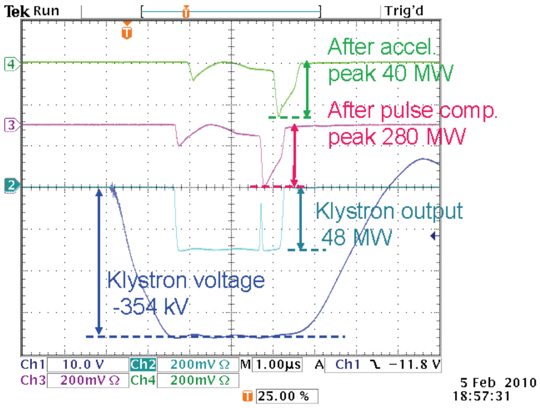

Figure 7: Typical waveform with the maximum operational condition.

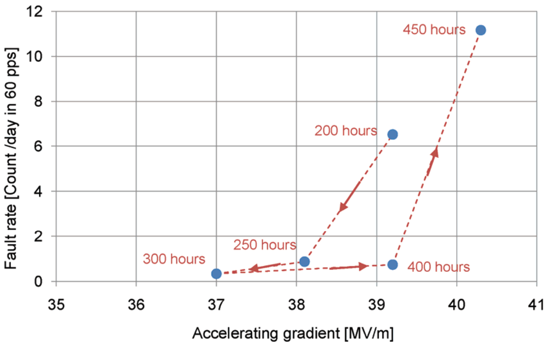

Figure 8: Fault rate due to the rf discharge, depending on the accelerating gradient (horizontal axis) and the elapsed hours of the rf processing.

SUMMARY AND SCHEDULE

The 8 GeV C-band accelerator has been constructed in XFEL. 64 units of the accelerator components were produced at several companies in Japan, with sufficient qualities. Currently we have mostly installed accelerator components. In this autumn, we plan to start the high-power rf commissioning. In the early period of the next year, we will start the beam commissioning.

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