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S-band Accelerating Structures for the PAL-XFEL

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One hundred seventy-two accelerating structures are required for the Pohang Accelerator Laboratory X-ray free-electron laser's (PAL-XFEL's) 10-GeV main linear accelerator. So far, we have purchased 80 structures from Mitsubishi Heavy Industry (MHI), which have quasi-symmetric couplers in the accelerating structure to reduce the quadruple and the sextuple components of the electric field in the coupling cavity. High-power tests have been conducted for the first structure of the MHI structure, and Research Instruments (RI) has developed a 3-m long accelerating structure that has an operating frequency of 2856 MHz and in/out couplers of quasi-symmetric racetrack shape for the PAL-XFEL linear accelerator. This structure also has been tested by PAL and RI in the Pohang accelerator laboratory (PAL) to check the maximum available electric field gradient. We will describe the test results of these structures and the current status for the fabrication of the other accelerating structures in this paper.

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I. INTRODUCTION

Pohang Accelerator Laboratory X-ray free-electron laser (PAL-XFEL) consists of a linear accelerator, undulators, and beamlines. The linear accelerator plays the role of increasing the electron beam's energy to 10 GeV. Photon beams are generated when the electron bunches pass through the undulators, and several experiments have been conducted at the beamlines with the photon beams generated by the undulators. In a linear accelerator, a high-power radio frequency (RF) at 2856 MHz is used to enhance the electron beam's energy. The major components of the linear accelerator are the modulators that supply pulse electric power to klystrons which are RF amplifiers, and the Stanford Linear Accelerator Center's (SLAC's) energy doublers (SLED), which increase the peak power of the RF pulse by reducing the pulse length. These are devices for supplying this high RF power to the accelerating structures. The role of an accelerating structure is to increase the kinetic energy of the electron bunches with the RF energy, three-stage bunch compressors are used to reduce the longitudinal bunch length. The first-stage is located at the position where the electron beam's energy is 330 MeV. The second and the third stages are positioned, respectively, at positions where the beam's energy are 3.0 GeV and 3.45 GeV, as shown in Fig. 1. We have classified the linear accelerator into five sectors. The injector is the first sector from the RF gun emitting electrons to the position where the electron beams obtain a kinetic energy of 135 MeV. The linear accelerator, L1, is the second sector of the linear accelerator and increases the electron beam's energy from 135 MeV to 330 MeV. Four accelerating structures without any SLED are used. The linear accelerator between the first and the second bunch compressor is named L2. L3 is between the second and the third compressors, and L4 is the remaining part of the

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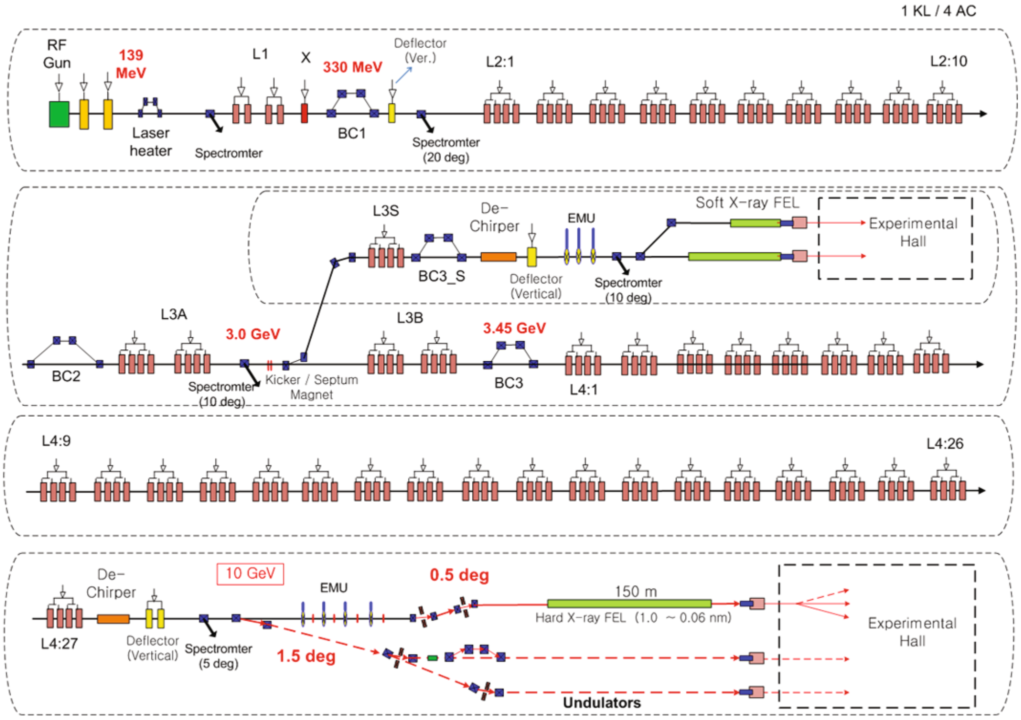

Fig. 1. (Color online) PAL-XFEL layout.

Table 1. Characteristics of the PAL-XFEL S-band accelerating structure.

Operation frequency	2856.00 MHz (30 °C, in vacuum)
Accelerator type	Constant-Gradient, Traveling-Wave
Operation mode	$2\pi/3$
Attenuation constant	0.57 neper
Shunt impedance	≥ 53 MΩ/m
Filling time	~0.83 μs
Q	> 13000
Phase error	$\Sigma\theta i < \pm 2.5$ deg
Operation temperature	30 ± 0.1 °C
Overall length	3.120 (acceleration length 2.91475) m

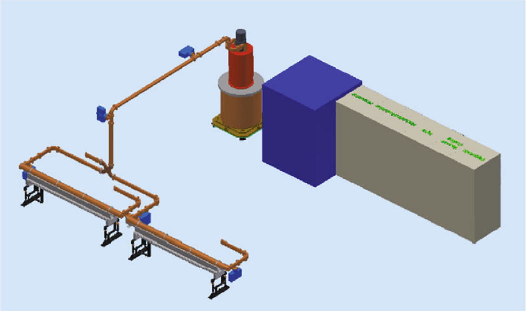

Fig. 2. (Color online) Microwave system layout of the linear accelerator L1.

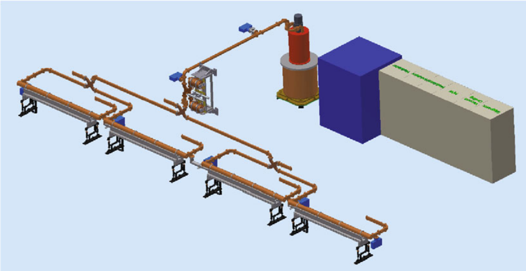

Fig. 3. (Color online) Microwave system layout of the linear accelerators L2, L3 and L4.

linear accelerator.

The total length of the PAL-XFEL main linear accelerator is about 710 m. The main linear accelerator contains 44 S-band klystrons, 42 SLEDs and 172 accelerating structures except for the injector. The RF system of the L1 sector consists of two klystrons and four accelerating structures without any SLED, as shown in Fig. 2. The characteristics of the accelerating structure are described in Table 1. And the remainder of the main linac has four accelerating structures and a SLED in each klystron and modulator, as shown in Fig. 3. Forty accelerating structures with 10 SLEDs exist in the L2 sector, and 20 structures with 5 SLEDs in the L3 sector. Four accelerating structures are also used with a SLED in the soft X-ray linear accelerator branch, as shown in Fig. 1.

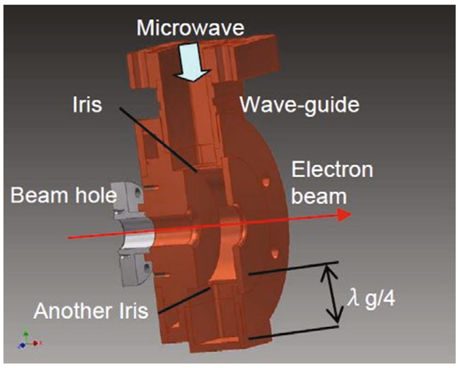

Fig. 4. (Color online) Coupler shape of the quasi-symmetric structure (by Mitsubishi Heavy Industries, Ltd).

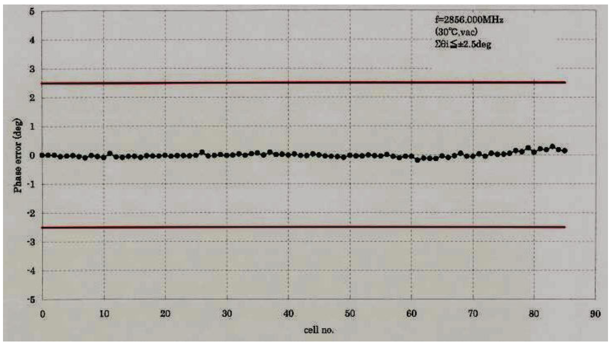

Fig. 5. (Color online) Cumulative phase deviation from a normal 120° phase difference for the MHI structure (by using a metallic plunger).

In addition, 108 accelerating structures and 27 SLEDs are necessary in the L4 sector.

Several types of accelerating structures, such as traveling or standing wave structures and constant impedance or constant gradient structures, can be used [1]. The PAL-XFEL main linear accelerator is designed as an S-band system, like the PLSII linear accelerator. The accelerating structure is a traveling and constant-gradient type structure whose characteristics shown in Table 1. The field asymmetry of the couplers of the accelerating structure is well known to cause an emittance growth of the electron beams [2]. Therefore, we decided to use an accelerating structure with couplers of quasi-symmetric shape for the main linear accelerator to reduce the emittance growth due to time-dependent multipole fields. So far, we have ordered 82 accelerating structures with quasi-symmetrically-shaped couplers from MHI and one prototype racetrack quasi-symmetrically-shaped coupler from RI. In addition, two more companies are developing the accelerating structure for the PAL-XFEL project. One is a domestic company (Vitzrotech), and the other is in China (IHEP). Vitzrotech is doing the RF tuning of the structure with a racerack quasi-symmetrically-shaped coupler and IHEP is doing the high-power test of the first structure with J-shape coupler.

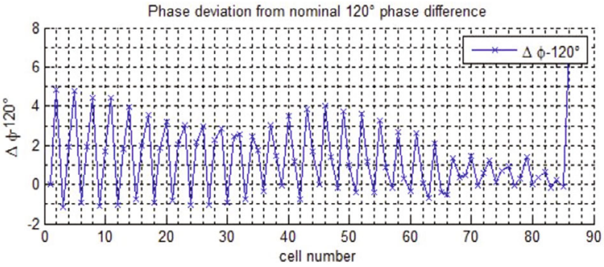

Fig. 6. (Color online) Cumulative phase deviation from a normal 120° phase difference for the RI structure (by using a bead).

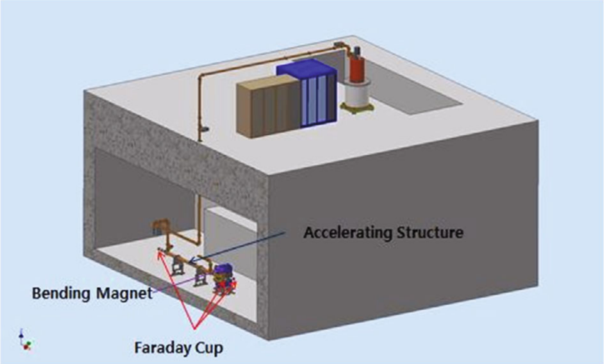

Fig. 7. (Color online) Layout of the high-power test facility.

II. EXPERIMENTS AND DISCUSSION

So far, we have two kinds of the accelerating structures, one fabricated by MHI in Japan and the other, by RI in Germany. The cumulated measured phase data of the MHI structure and the RI prototype are shown in Figs. 5 and 6, respectively. A difference is seen in the phase measurement method. MHI used a short plunger to measure the RF phase lengths of each cavity in the structure, and RI adopted a bead method to measure the RF phase length of the cavities. The MHI data are better than the RI data as shown in pictures. However, the RI data are also within our specifications.

1. High-power Test Facility and Procedure

We need a test facility to confirm the performance of the structure. Therefore, we modified a facility that had been used for RF gun tests. A SLAC 5045 klystron, which has the maximum RF output power of 65 MW, is used as a high-power RF source and waveguide component to deliver a high RF power to the accelerating structure, as shown in Fig. 7. Three Faraday cups and a bending magnet are installed to check the dark current of the structure and the beam energy of the dark current. For this test, we developed a program for conditioning

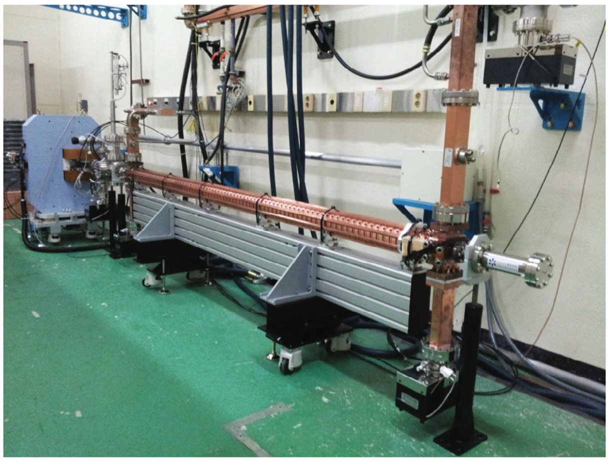

Fig. 8. (Color online) Photo of the tunnel of the high-power test facility for the accelerating structure (MHI structure).

the structure and monitoring data such as the modulator high voltage, the vacuum levels, the dark current etc. During the high-power conditioning, we have to monitor the vacuum level to prevent damage from arcing. Therefore, if the vacuum level jumps to a set position, the modulator voltage should be kept at the current level or decreased to some lower level. If the vacuum level reaches at the maximum setting value, then the modulator voltage should be reduced to zero to prevent an arcing damage to the accelerating structure due to the next RF pulse. At that time, this test was done manually. Therefore, we made a program for doing the high-power test of the structure without an experimenter.

In the high-power test of the structure, the RF power should be increased gradually as much as possible without arcing inside of components. If significant arcing occurs inside the structure, it may suffer irreversible damage. Therefore, we need to be careful when increasing the power and implementing. First, the RI structure is installed as shown in Fig. 8 and is tested to check the maximum available field gradient of the structure, where 27 MV/m is the required field gradient of the structure for the 10 GeV linear accelerator. Two phases make up the high-power test. In the first phase, the repetition rate is fixed at 5 Hz, and the RF power increased to 65 MW at pulse lengths of 0.2, 0.5, 0.9 and 1.2 us. After these steps, the RF peak power is fixed at 65 MW, and the repetition rate is increased from 5 to 60 Hz.

2. Dark Current Measurement and Processing Time

While we are doing the RF processing of the RI structure according to the procedure in the previous subsection, we measure the processing time, and after finishing all the steps for the RF processing, we measure the maximum dark currents for 60 Hz operation at pulse lengths of 0.2, 0.45, 0.9, and 1.2 us and at varying the repetition rates by setting the voltage of the modulator to get the maximum RF peak power of the klystron. Before testing the RI structure, we made a relation table between the modulator voltage and the RF out power of the klystron because the measurement of the RF power through a waveguide directional coupler has a large error. According to this table, we set the modulator voltage at 42 kV to get the maximum RF output power of 65 MW, which is the required RF power to get a field gradient of about 27 MV/m in the structure. The total field gradient of a SLAC-type 3 m long accelerating structure is well known to have a relation of 10 times the square root of the RF power. After the test of the RI structure with this table had been finished, a MHI structure was installed and tested in the same way, but troubles were encountered in the modulator system. After the problems had been fixed, we made the relation curve again, as shown in Fig. 9, and found that some mistake had

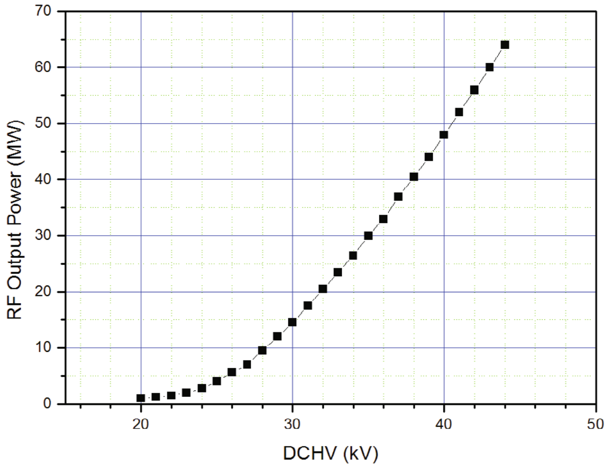

Fig. 9. (Color online) Relation between the dc high voltage (DCHV) of the test facility modulator and the RF output power (MW) of the SLAC 5045 klystron.

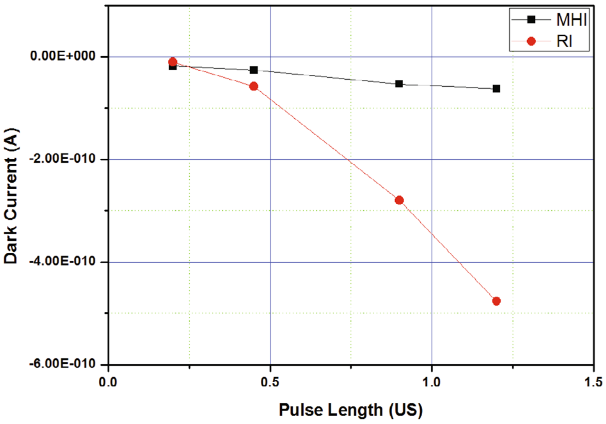

Fig. 10. (Color online) Dark currents of the MHI and the RI accelerating structure vs. RF pulse length (60 Hz, 45 kV).

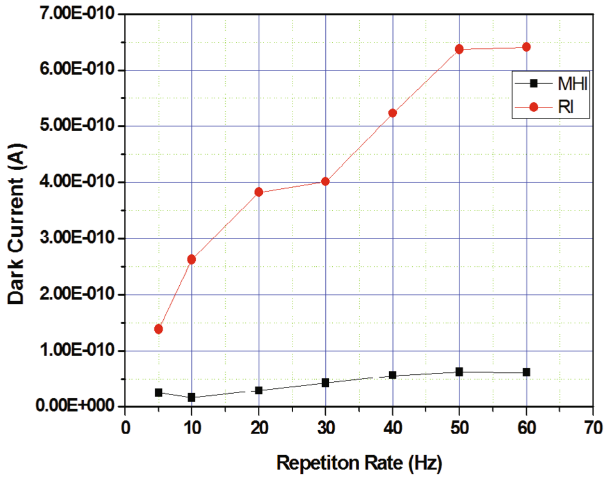

Fig. 11. (Color online) Dark current of the MHI and the RI accelerating structure vs. repetition rate (45 kV).

been made in the previous table. The modulator voltage should be set 45 kV to get a field gradient of 27 MV/m in the structure.

Therefore, we had to do the test again for the RI structure to make comparisons between the two. Figure 10 shows a comparison between the measurements of the RI structure and the MHI structure. The maximum dark current of the RI structure is about 8 times higher than that of the MHI structure, even though the RF input power of the RI structure is less than that of the MHI structure (about 10 MW). In the case of the RF processing time, 3 days were required to expand the RF pulse length to 1.2 μs at 5 Hz operation and 2 days to enhance the repetition rate from 5 to 60 Hz with on RF pulse length of 1.2 μs. However, in the MHI case, 31 days were required for the entire process. After the test of the MHI structure had been finished, we installed the RI structure again for a test under the same test conditions as were used for the MHI structure. Figure 11 shows the variation of the peak dark current of the RI and the MHI structures according to the RF pulse length. However, the total processing time of the RI structure was about 95 days. We can guess that this kind of difference comes from the surface roughness, the characteristics of the oxygen free high thermal conductivity (OFHC) copper, and the fabrication processes used by the companies.

III. CONCLUSION

The first high-power test of the RI structure had been done successfully. About a week was spent to achieve the required RF processing for the RI structure. In the case of the MHI structure, 31 days were spent to complete the entire RF processing. Although the maximum peak dark current of the MHI structure was about 62.5 pA, the dark current of the RI structure was about 476.5 pA. In the second test case of the RI structure, the peak dark current went up due to the increase in the RF input power of the structure, but the RI structure was confirmed to be available for operation with an electric field gradient of 27 MV/m even though the RF processing time of the RI structure was about three times longer than that of the MHI structure. Therefore, we decided not to use the RI structure for the PAL-XFEL accelerating structure.

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