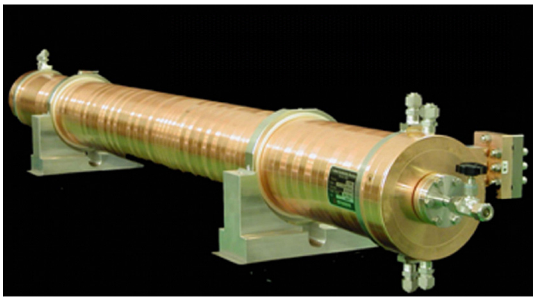
A C-band Accelerator for an X-ray Free-electron Laser (XFEL) Facility



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In the fields of nuclear physics and elementary particle physics, accelerating cavities or structures are used to accelerate particles such as electrons, positrons, and protons to high energies. Mitsubishi Heavy Industries, Ltd. (MHI) has been developing various production technologies in order to provide the accelerating cavities and structures required for new research and experimental work. The C-band accelerator used in the X-ray free electron laser facility SACLA (the SPring-8 Angstrom Compact Free Electron Laser) was manufactured using one of these production technologies. Here, we describe our C-band accelerator products and the associated manufacturing technology.

1. Introduction

(1) Overview of the C-band accelerator

A C-band accelerator is an electron beam accelerator system based on radio frequency (RF) technology using the C-band frequency range, and is capable of generating a high accelerating gradient. An S-band accelerator, which has been used as the main accelerator in conventional electron beam accelerator systems, has a resonance frequency of 2,856 MHz. Alternatively, the resonant frequency of a C-band accelerator is 5,712 MHz, double that of an S-band accelerator. Use of a C-band accelerator as the main accelerator enables a higher accelerating gradient (35MV/m or more) to be achieved together with a reduction of the accelerator length. Furthermore, since a higher frequency corresponds to a shorter wavelength, the system components become smaller in proportion to the wavelength, resulting in a reduction of the required installation area.

(2) Applications of MHI's C-band accelerator

Mitsubishi Heavy Industries, Ltd. (MHI)'s C-band accelerators are used as the main accelerator in the Spring-8 angstrom compact free electron laser (SACLA) XFEL facility[1], which is located adjacent to the large synchrotron radiation facility the Super Photon ring-8 GeV (SPring-8) at RIKEN Harima Research Institute in Harima Science Garden City (Hyogo Prefecture). From 2007 to 2009, MHI supplied 128 C-band accelerating structures and 64 C-band RF pulse compressors. The components that MHI fabricated for SACLA are shown in **Figure 1**. MHI constructed the accelerator cavities and structures enclosed in red lines, and also partly handled the fabrication and installation of the equipment at the injector section, ranging from the RF gun at the furthermost upstream section of the whole system to the C-band correction structure. Apart from this application, C-band accelerators are also used in MHI's radiotherapy machine (TM-2000). Here, we describe MHI's C-band accelerator as well as the technology used in its production.

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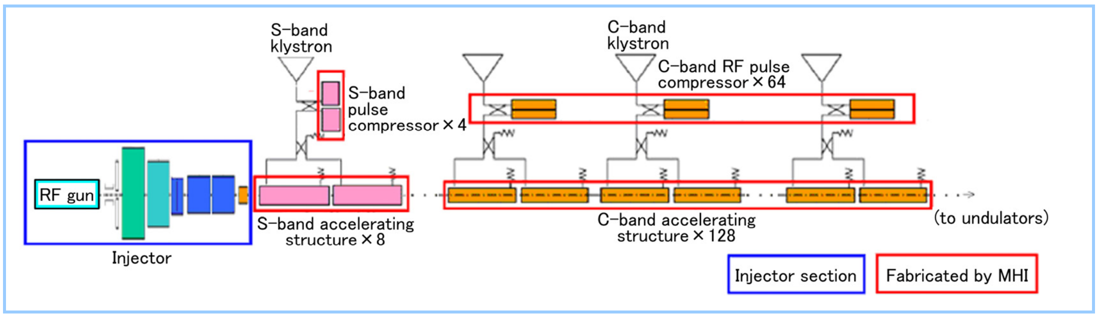

Figure 1 Schematic block diagram of the XFEL electron accelerator system

2. Configuration and features of the C-band accelerator system

The configuration of the C-band accelerator system is shown in **Figure 2**. This system consists of two main accelerating structures, a klystron (installed outside the wall in Figure 2) that supplies RF for accelerating electrons, waveguides connecting the klystron to the main accelerating structures, and a C-band RF pulse compressor that amplifies the RF power supplied to the accelerating structures. Here, we describe the configuration and features of our C-band accelerator and the C-band RF pulse compressor.

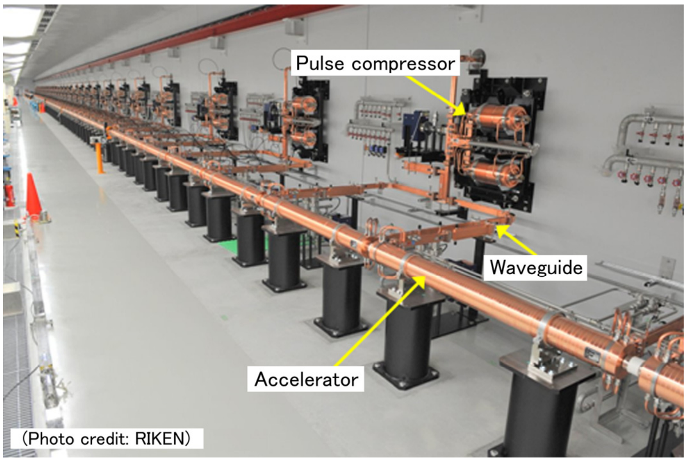

Figure 2 C-band accelerator system at SACLA
Configuration of the C-band accelerator system

(1) C-band accelerating structure

The C-band accelerating structure in SACLA is a choke-mode accelerating structure[2], and is shown in **Figure 3**. It consists of an accelerator cavity, choke filter, and higher-order mode absorber. High-power RF with C-band accelerating frequency is enclosed within the accelerator cavity by the choke filter. However, as the beam passes through the accelerator cavity, electromagnetic noise called as higher order mode, which spreads over a wider band range than the accelerating frequency, is induced. This noise passes through the choke filter, and is then absorbed by a silicon carbide (SiC) microwave absorber placed around the accelerator cavity. Hence, the choke-mode accelerator has the features of damping electromagnetic noise induced at the accelerator and accelerating the following beam in a stable manner, without the effects of noise.

The C-band choke-mode accelerating structure is composed of 89 regular cells and 2 coupler cells. These cells are made from pure oxygen-free copper processed by hot isostatic pressing (HIP). To achieve the required accelerating gradient of 35 MeV/m, the dimensional accuracy for each cell is controlled to the μm order, and the surface roughness of the inner cell walls is suppressed to 0.1 μm or less (mirror finish). A SiC ring is embedded into each cell to attenuate the electromagnetic noise induced by the electron beam passing through the accelerating structure. Coupler cells are placed at the upstream and downstream ends of the accelerator, to connect the accelerating structure to the output from the waveguide. In order to fulfill the required specifications, a particular design termed the J-type double-feed coupler[3] is incorporated into the C-band choke-mode accelerating structure.

Detailed specifications of the C-band choke-mode accelerator are shown in **Table 1**.

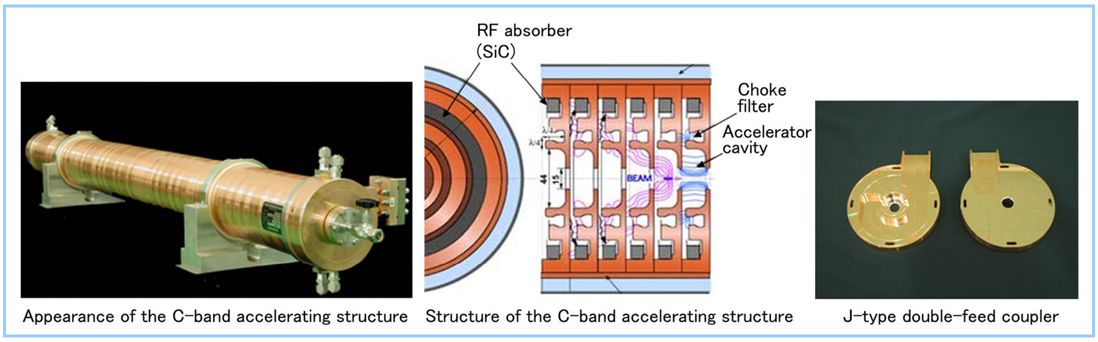

Figure 3 C-band choke-mode accelerating structure
Appearance and detailed configuration of the C-band choke-mode accelerating structure

Table 1 Specifications of the C-band choke-mode accelerator

Item	Specification
Structure	Choke Mode Type
Accelerating Gradient	35 MV/m (designed value)
Quality Factor	10,000
Resonance Frequency	5,712 MHz
Length	1.8 m
Phase Shift	$3\pi/4$

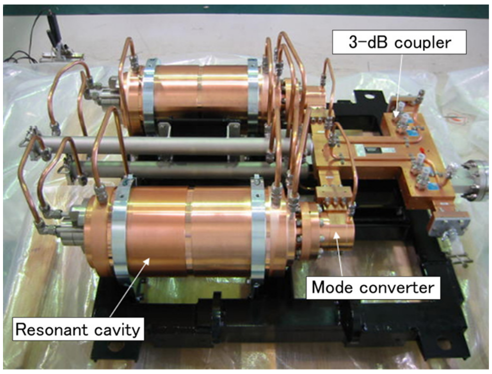

Figure 4 C-band RF pulse compressor
Appearance and main components of the C-band RF pulse compressor

(2) C-band RF pulse compressor

The C-band RF pulse compressor has the function of doubling the peak power of the RF pulse from the klystron. It consists of two pairs of resonant cavities and mode converters, and a 3-dB hybrid coupler (refer to **Figure 4**). At the 3-dB hybrid coupler, the pulsed RF output from the klystron is equally distributed to both resonance cavities with a 90-degree phase difference. The transfer mode is converted from the rectangular mode at the 3-dB hybrid coupler into the cylindrical mode at the resonance cavity. The converted high frequency is accumulated and compressed in the resonance cavities, and by reversing the input RF phase, a higher RF peak power is obtained at the output of the C-band RF pulse compressor.

The efficiency of RF energy storage (Q factor) of the C-band RF pulse compressor needs to be very high ($Q \geq 180{,}000$) to compress the output RF from the klystron into a high peak power. To meet the required Q factor, the resonant frequency of the resonance cavity needs to be adjusted to the target frequency (5,712 MHz) with an accuracy of ±10 kHz (0.01 MHz) or less. The resonant frequency difference between each pair of resonant cavities needs to be suppressed to 10 kHz or less to prevent an increase in the RF reflection to the klystron, which negatively affects its performance. Because the sensitivity of the resonant frequency to the total length of a resonant cavity is about 10 kHz/μm, the cavity length of each pair needs to be controlled with a margin of error of 1 μm or less.

Detailed specifications of the C-band RF pulse compressor are shown in **Table 2**.

A high-power RF test was conducted in the test stand at RIKEN to verify the performance of both the manufactured C-band choke-mode accelerating structure and the C-band RF pulse compressor. The RF output of the klystron (output power of 48 MW, pulse width of 2.5 μs) was amplified by the C-band RF pulse compressor, and was supplied to the C-band choke-mode accelerating structure. The test results confirmed that the accelerating gradient of the accelerating structure reached a maximum of 42 MV/m[4], which was substantially above the minimum required value of 35 MV/m for the XFEL project.

Table 2 Specifications of the C-band RF pulse compressor

Item	Specification
Composition	Resonant cavity × 2, mode converter × 2 3-dB coupler, mounting frame
Material	Oxygen-free copper (OFC-CLASS 1&2) SUS304, SS400
RF Flange	A-DESY type
Resonant Frequency	5,712 MHz (30°C in vacuum)
RF mode	TE 0,1,15
Quality Factor	≥ 180,000
Coupling Factor	β = 9 – 9.5
VSWR	≤ 1.10
RF Power	Input: 50 MW, pulse width: 2.5 μs, repetition: 60 Hz
Tuning Mechanism	Diaphragm structure with differential screw
3-dB coupler	3-dB coupler: coupling 3 dB, isolation ≥ 25 dB RF monitor: coupling 60 dB, isolation ≥ 25 dB

3. MHI's production technology and RF measurement technology

The following are the features of our production technology that was utilized to achieve the required performance.

(1) High-precision processing technology using an ultra-precise lathe

Prior to the high-precision processing at MHI, the C-band choke-mode accelerating structures were pre-processed at the material manufacturer, leaving a margin of 0.03 mm for ultra-precision, with an accuracy of up to ±0.01 mm. After this process, the inner surfaces of the cells, 91 of which were used per accelerating structure, were cut to a mirror finish by using the ultra-precise lathe at MHI (refer to **Figure 5**), with a surface roughness of 0.1 μm at the maximum height. When corrective machining is performed, however, the thickness variation of the cavities and the axial variation of the machine can result in excessive or insufficient cutting. To solve these problems, the end face of the cavity was measured on-machine using a laser, and its position was controlled for precise machining. This method made it possible to achieve a dimensional accuracy of 2 – 3 μm or less.

However, for the C-band RF pulse compressor, it was difficult to achieve the target frequency only by machining the resonance cavity, because its size (about ϕ220 mm × L440 mm) was large relative to the cells (about ϕ160 mm × L20 mm) within the C-band choke-mode accelerating structure. Therefore, the resonance cavities were machined in advance, leaving a margin of 0.1 mm, with an accuracy of up to ±0.01 mm. These cavities were then delivered to MHI and machined precisely by using a frequency measurement to obtain the finished size. However, because the dimensional accuracy of ±0.01 mm of the finishing process corresponds to a frequency accuracy of ±100 kHz, this does not satisfy the required value of ±10 kHz shown in 2-(2). Therefore, a frequency adjustment was conducted to achieve a dimensional accuracy of 1 μm or less (frequency of 10 kHz or less) by using the tuner installed on the resonance cavities for ease of adjustment.

(2) RF measurement technology covering a wide frequency range from the UHF band to the X-band

Prior to the final process, the C-band choke-mode accelerating structures and C-band RF pulse compressors were optimized using a precision RF measurement, as shown in **Figure 6**. The measurement results were fed back for final processing and adjustment by the tuner. A network analyzer was used for the RF measurement. With its experience in RF measurement and manufacturing of varied accelerators that operate at frequencies from 238 MHz (UHF band) to 11.4 GHz (X-band), MHI can provide equipment supporting a wide range of frequency bands. Since the coupler cells for the C-band choke-mode accelerating structures have a particular configuration, the usual method could not be applied to the RF measurement and the adjustment of these cells. Therefore, MHI developed and applied a new adjustment method for the coupler cells.[5]

(3) Low-strain brazing technologies by one of the largest vacuum brazing furnaces in Japan

The C-band choke-mode accelerating structure was composed of 91 cells, which were all combined and brazed in a large vacuum furnace, as shown in **Figure 7**. The C-band choke-mode accelerating structure had an elongated shape (2 m in length and 160 mm in diameter); thus it was likely to be deformed and bent because of the high temperature and the work position in the furnace. Therefore, a specialized attachment was used to suppress this strain. MHI has one of the largest vacuum brazing furnaces in Japan (1.3 m in diameter and 3.5 m in height), which makes it possible to braze items of various sizes.

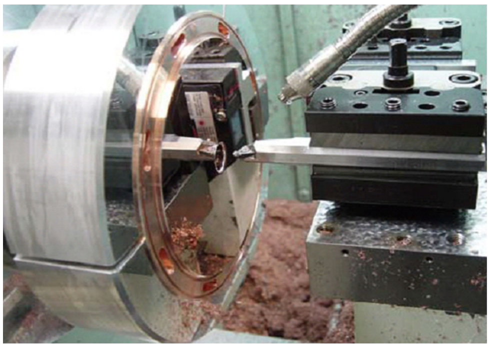

Figure 5 Precision machining of the C-band choke-mode accelerating structure
C-band choke-mode accelerating structure under high precision processing using an ultra-precise lathe

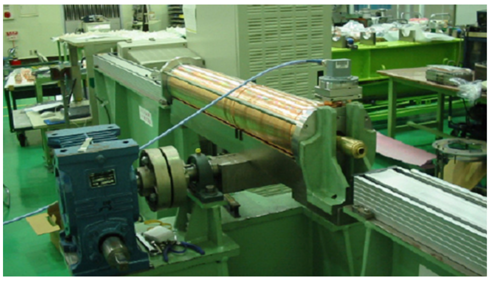

Figure 6 RF measurement of the C-band choke-mode accelerating structure

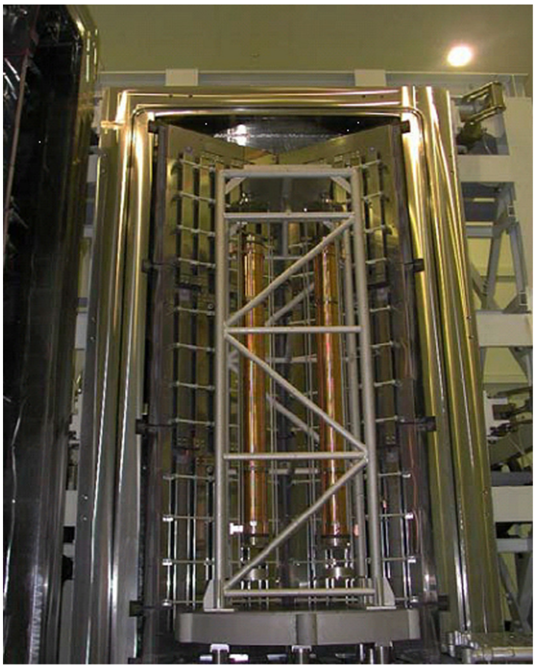

Figure 7 Brazing furnace for the C-band choke-mode accelerating structure
The C-band choke-mode accelerating structure brazing process, using one of the largest vacuum brazing furnaces in Japan

4. Conclusion

A C-band choke-mode accelerating structure and C-band RF pulse compressor has been fabricated by MHI's production technology. RF high power tests for the products were conducted by RIKEN, and a high accelerating gradient that exceeded the required performance values was confirmed. Every C-band accelerator at SACLA is operated daily with an accelerating gradient of more than 35MV/m, as designed. MHI's C-band accelerator contributes to the realization of a laser with the world's shortest wavelength. In the future, the C-band accelerator is expected to be widely applied to accelerator research facilities and medical institutions worldwide. MHI will work actively to meet these demands.

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