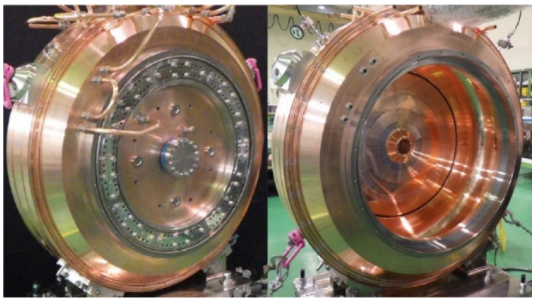
Manufacturing Technology of Electron Accelerator for 3GeV Synchrotron Radiation Facility NanoTerasu



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The 3GeV synchrotron radiation facility NanoTerasu, which has been started operation from April 2024, is a facility incorporating the latest accelerator technology, and has an accelerating cavity and structure manufactured by Mitsubishi Heavy Industries Machinery Systems, Ltd. (MHI-MS). Accelerating cavities structures are precision devices that require high precision in machining, assembly, and adjustment. Over the years, MHI-MS has contributed to the construction of accelerator facilities by providing components and has continued to improve its manufacturing technology. This report focuses on the manufacturing technology MHI-MS has developed.

1. Introduction

1.1 Overview of NanoTerasu [(1)]

The 3GeV synchrotron radiation facility NanoTerasu, which has been started operation from April 2024, is a facility with the world's highest level of analytical capabilities. Bending the orbits of electrons accelerated to near light speed produces "synchrotron radiation". NanoTerasu generates synchrotron radiation has a brilliance more than one billion times higher than sunlight to visualize the structure and function of materials at the level of nanometer (one-billionth of a meter). The range of its applications is diverse, including materials science (development of new energy materials and elucidation of the properties of materials), life science (analysis of the structure and interaction of proteins and biomolecules), and medical science (analysis and imaging in the development of new treatments and new drugs). It is also expected to play a role in supporting research and development to solve social issues as represented by the SDGs.

1.2 Accelerated cavity for NanoTerasu

NanoTerasu consists of a storage ring, which serves as a synchrotron radiation source, and an injection linac, which injects electron beams into the storage ring (**Figure 1**[(2)]). NanoTerasu was needed to be completed with limited resources.

For this purpose, it was designed to be thoroughly compact by actively incorporating the achievements and developed technologies of accelerator laboratories in Japan.

The linac for accelerating electrons generated by an electron source up to 3 GeV employs a system proven at SACLA (SPring-8 Angstrom Compact Free Electron Laser), an X-ray-free electron laser facility at RIKEN, and a 238-MHz accelerating cavity, a 476-MHz Sub Harmonic Buncher, and a C-band (5,712-MHz) disk-loaded type accelerating structure were installed.

The storage ring has a large number of electromagnets to achieve high brilliance with a limited circumference, and the space for an accelerating cavity to compensate for the energy loss was limited to about 5m. The conventional accelerating cavity structure could not provide the necessary acceleration voltage and stable beam, so a beam-accelerating RF cavity with new HOM (higher-order mode) damping structure is installed for the first time in the world.

Figure 2 shows our accelerating cavities and structures installed in NanoTerasu. The above "accelerating cavities" and "accelerating structures" are technically distinguished, but they both have a function to accelerate electrons.

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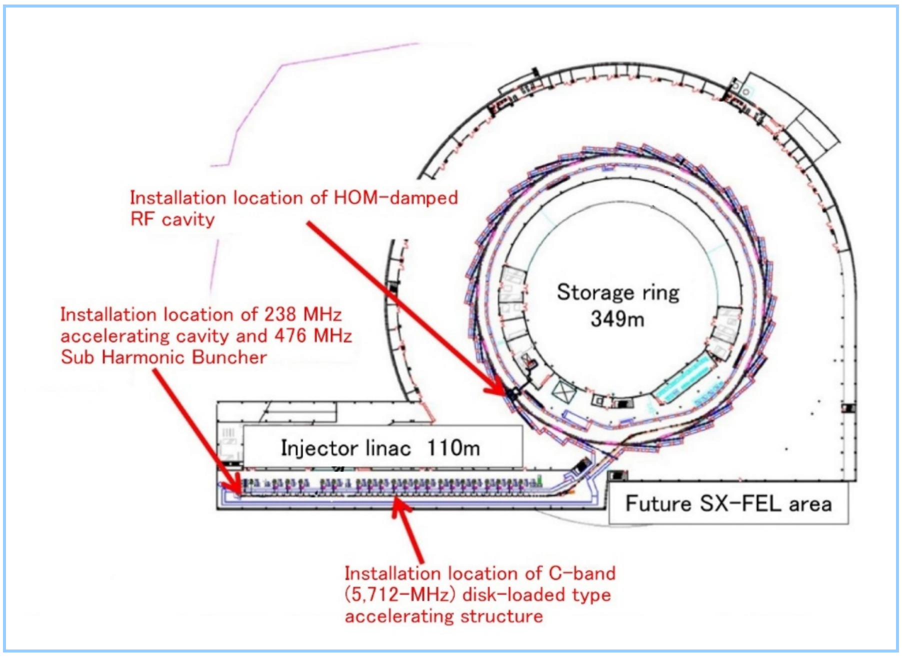
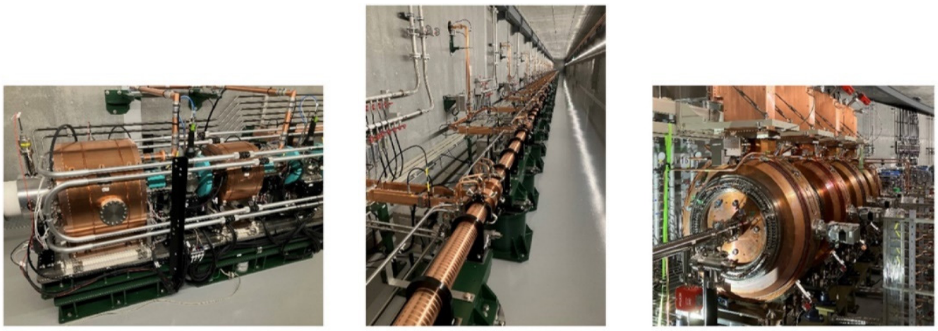


Figure 1 Layout of the 3 GeV light source NanoTerasu.



238 MHz accelerating cavity and 476 MHz Sub Harmonic Buncher

C-band (5,712-MHz) disk-loaded type accelerating structure

HOM-damped RF cavity

Figure 2 Installation of our accelerating cavities and structures

2. Accelerated cavity manufacturing technology

This chapter describes our accelerating cavity manufacturing technology, using the HOM-damped RF cavity as an example. For the manufacturing technology of 238 MHz accelerating cavity, 476 MHz Sub Harmonic Buncher, and C-band disk-loaded type accelerating structure, refer to our previous reports [(3), (4)].

2.1 Overview of HOM-damped RF cavity

The HOM-damped RF cavity was basically designed by RIKEN[(5), (6)]. This accelerating cavity enables both beam acceleration with a short cavity length and countermeasures against beam instability by utilizing resonant modes (which characterize the configuration and oscillation of the electromagnetic field) different from those of conventional acceleration cavities for beam acceleration. On the other hand, the inner diameter of the accelerating cavity becomes larger, which requires precision surface machining, assembly and bonding technologies, and frequency tuning technology for manufacturing.

Figure 3 shows the configuration of this accelerating cavity, which is a re-entrant type with a center inner diameter of approximately 1,000 mm, an overall length (distance between beam port ends) of approximately 450 mm, and a beam port inner diameter of approximately 70 mm. For the cavity body, oxygen-free copper for electron tubes (grain size requirement conforms to ASTM F68 CLASS1) is used, and for the flange, JIS-standard SUS316L is used.

This accelerating cavity has a space on the wall at a certain distance from the center axis and incorporates a HOM absorber for damping HOMs that cause harmful vibrations to the accelerated electrons, thereby eliminating the instability of the electron beam. The HOM is converted to heat when absorbed by the ferrite block for UHF band RF absorption on the HOM absorber and the heat is eliminated by cooling water.

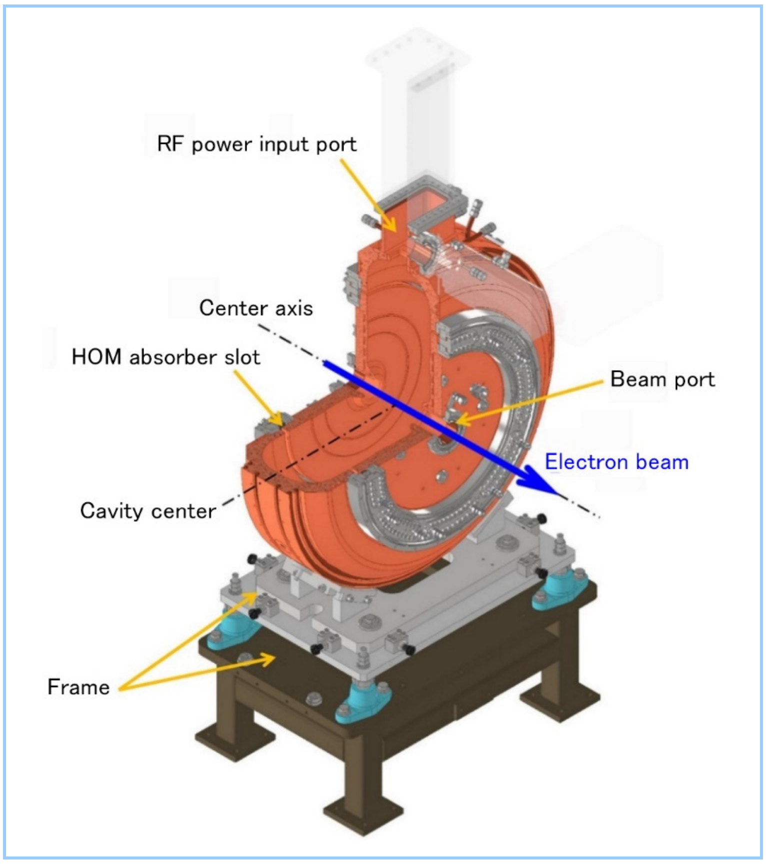


Figure 3 Configuration of HOM-damped RF cavity

2.2 Machining

Since the machining of the cavity body requires high resonance frequency accuracy and a high Q value (a performance index for RF power loss of the cavity; the higher the Q value, the lower the RF power loss), we used turning (a machining method that applies a cutting tool to a material rotating at high speed) to achieve precision machining with a dimensional error of ±0.05 mm or less and a surface roughness of Ra 0.8 µm or less.

When machining copper, it is important to control the temperature (the linear expansion coefficient is large, so temperature conversion of dimensions is necessary), to maintain the cutting tool edge (cutting resistance is large and tends to cause plucking), and to prevent rust (rust stains or corrosion caused by cutting fluid may occur).

After the machining was completed, we cleaned the surface of the machined parts with dilute sulfuric acid and immersed them in a chromate solution to protect the surfaces against rust.

2.3 Assembly

Oxygen-free copper parts were joined by brazing in a large vacuum heat treatment furnace owned by us, as shown in **Figure 4**. The uniform spreading of molten braze over the entire joining surface results in a strong joint with no gaps, and good electrical and thermal conductivity can be obtained.

During brazing assembly, brazing material selection (considering brazing metal flow and step brazing temperature), brazing material placement (considering brazing metal flow and amount of brazing material), gap control (considering brazing metal flow and fillet formation), and temperature control are important.

In the brazing of the cavity body, the temperature was gradually increased over a period of about 24 hours so as not to cause a temperature difference in the parts. Cooling by natural heat release in a vacuum took about 48 hours. The airtightness of the brazed surfaces was confirmed by a helium leakage test with a detection sensitivity of a leakage rate of 1×10^{-10} Pa-m^3/sec or less that there was no leakage.

The HOM absorber was assembled by a single brazing step. As shown in **Figure 5**, 12 ferrite blocks, each with a length of 25.5 mm x width of 10.26 mm x height of 4 mm, were joined to each HOM absorber.

To confirm that the ferrite blocks were joined with sufficient strength, a load of 4 to 5 kgf was applied from the side of the ferrite blocks, and no cracking or delamination was observed. Also, after vacuum baking at 150°C for degassing prior to installation in the accelerating cavity, no cracking or delamination was observed.

Figure 4 Large vacuum heat treatment furnace

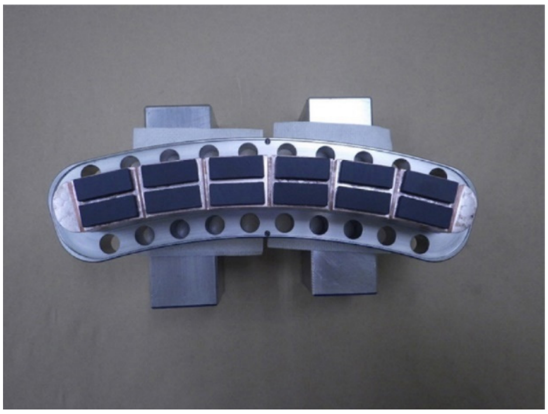


Figure 5 HOM absorber

2.4 Frequency adjustment

The resonant frequency of an accelerating cavity is determined by its internal dimensions, and the frequency is generally adjusted by deforming the whole or a part of the inner wall surface or by inserting another part to change the volume of the space. For the frequency adjustment of this cavity, we used a method to precisely adjust the frequency by machining a specific part of the inner wall surface. We confirmed the correlation between the amount of machining and the amount of frequency change by calculation using SUPERFISH, the electromagnetic field simulation code in two-dimensional Cartesian in advance.

Figure 6 shows the history of frequency adjustment by inner wall adjustment machining. The slopes of the plots of the calculated values and the frequency adjustment results were almost identical. Then we predicted processing volume and adjusted to the target frequency.

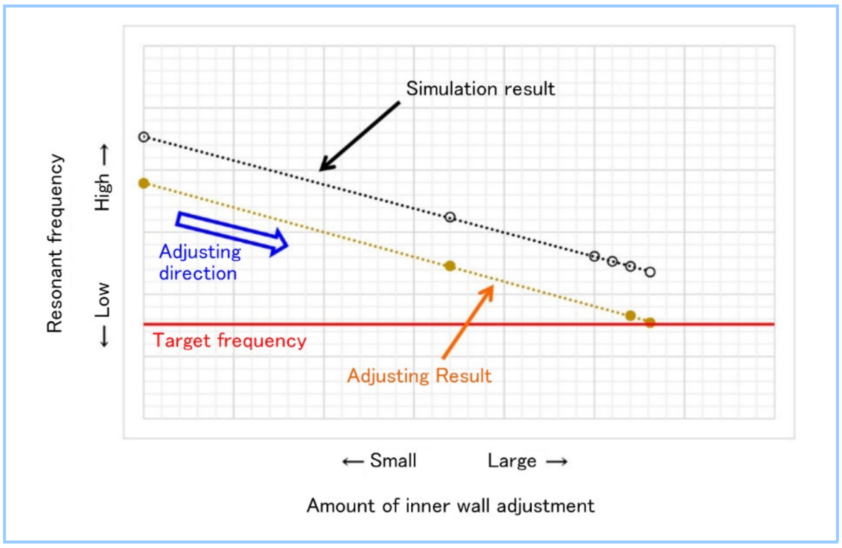


Figure 6 Frequency adjustment history

2.5 Low-power RF test

We measured the resonant frequency, unloaded Quality factor, coupling coefficient β, and shunt impedance using a network analyzer. **Figure 7** shows the low-power RF test system.

The unloaded Quality factor and coupling coefficient β were calculated using a Smith chart [7].

We measured the shunt impedance using the bead perturbation method. While measuring the resonant frequency of the cavity, the metal bead is pulled at a constant speed through a string on the central axis of the cavity. The shunt impedance can be calculated from the change in resonance frequency.

Table 1 shows the results of the low-power RF test.

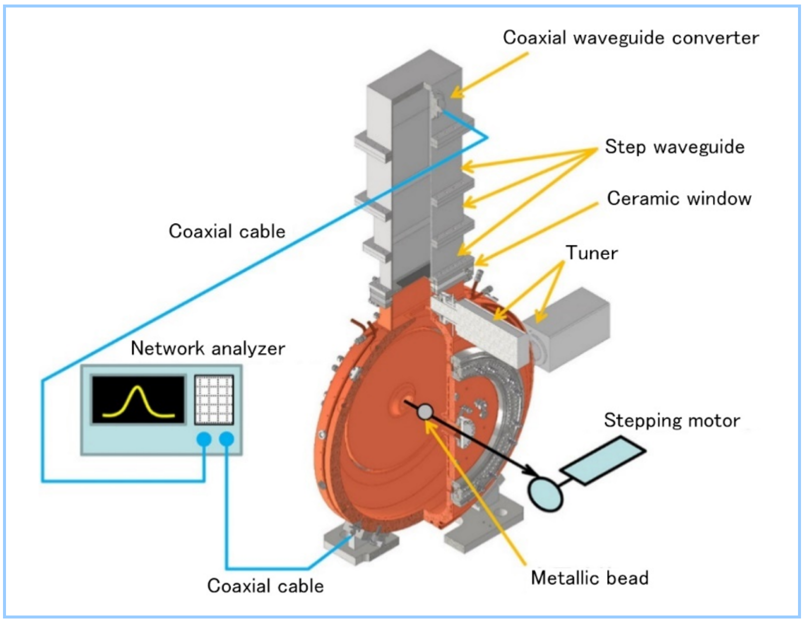


Figure 7　Low-power RF test system

Table 1　Results of low-power RF test

	Specification value	Measured value (S/N 10014-5)
Resonant frequency(25°C, vacuum)	508.759±0.1 MHz	508.827 MHz
unloaded Quality factor	57000 or higher	59934
coupling coefficient β	Around 1.1	1.09
Shunt impedance	6.6 MΩ or higher	6.709 MΩ

3. Conclusion

In this report, the acceleration cavity manufacturing technology of MHI‐MS was described, and the acceleration cavity for NanoTerasu was taken up as the latest production activity. NanoTerasu has begun commissioning in April 2023[(8)], and a first beam (the first observation of synchrotron radiation X-rays from an insertion source installed in a circular accelerator into the experimental hall) was achieved on December 7, 2023[(9)]. And the operation started as scheduled on April 1, 2024 [(10)]. This has renewed MHI-MS's achievements through practical use of the 238 MHz accelerating cavity, 476 MHz Sub Harmonic Buncher and 5,712 MHz (C-band) accelerating structure, and also through the first practical use of the HOM-damped RF cavity, which we have worked on since its early development. We will continue to improve our technology to contribute to the planning of new accelerator facilities in the future.

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