Mitsubishi Heavy Industries' Normal Conducting/ Superconducting Accelerating cavities - Contributing to the Development of Highly-advanced Particle Accelerator Systems -

Mitsubishi Heavy Industries Mechatronics Systems, Ltd.*1

At the beginning of 2014, highly-advanced particle accelerator projects in Japan successively verified beam acceleration. One of the projects was the intensification of linac energy in Japan Proton Accelerator Research Complex (J-PARC).*2 In this project, Annular-ring Coupled Structure (ACS) cavities with excellent axial symmetric properties of the Accelerating electric field were used as the accelerating cavity and started commercial operation of the world's first proton beam accelerator . The other project was the KEK-cERL (Compact Energy Recovery Linac) Project of the High Energy Accelerator Research Organization (KEK) in Tsukuba city. In this project, a superconducting accelerating cavity capable of continuous-wave operation in a high-acceleration electric field was used and the technological verification operation of a next-generation light source accelerator for the realization of high-quality beam recovering and reusing the accelerated electron beam energy was implemented. In both of the projects, Mitsubishi Heavy Industries, Ltd. (MHI) was in charge of the development and actual manufacturing of cavities, and realized a high-acceleration electric field higher than the customer request.

*1 Mitsubishi Heavy Industries Mechatronics Systems, Ltd., a subsidiary of MHI, took over MHI's accelerator business on October 1, 2015, and has been developing the business since that time.

*2 J-PARC is the name of the proton accelerator complex located in Tokai-mura, Ibaraki, Japan.

1. Intensification of linac energy and utilization of ACS cavity in J-PARC

1.1 Overview of intensification of linac energy in J-PARC

J-PARC is the proton accelerator and the experimental facility group at Tokai-mura, Ibaraki prefecture constructed jointly by the Japan Atomic Energy Agency and the High Energy Accelerator Research Organization. In J-PARC, highly-advanced research in a wide range of fields including material science, life science, particle physics and nuclear physics is implemented using various secondary particle (neutron, meson, muon, neutrino, etc.) beams generated by irradiating the target with the world's highest-level proton beam. The facilities for the initial stage were completed in 2008, and the linac energy was intensified from 181 MeV to 400 MeV in 2013 through 2014 for the enhancement of the beam output.

1.2 ACS cavity

The average beam current of the J-PARC linac is as high as 0.333 mA, and therefore beam loss during acceleration causes activation of the equipment. For this reason, an ACS cavity is adopted for the intensification of linac energy because its in-cavity electric field component that is perpendicular to the beam axis and contributes to beam loss is virtually non-existent and it has excellent axial symmetric properties. **Table 1** indicates the principal specifications of the ACS cavity. **Figure 1** shows the shape of the ACS cavity cell and the external view of the module. The ACS cavity module consists of two accelerating tanks and one bridge tank that separates and supplies large power microwaves for proton acceleration to the accelerating tanks. The approximately

two-meter long accelerating tank has a structure in which about thirty oxygen-free copper cells with an external diameter of 430 mm and a plate thickness of 50 to 60 mm (refer to the left of Figure 1), the whole of both faces of which are specular cut, are laminated together. They are manufactured by vacuum brazing and unifying the cells so that even a slight vacuum leak will not occur in order to establish an ultra-high vacuum cavity interior. MHI combined ultra-precision cutting technology that handle a diameter as large as 500 mm, joining technology using a large vacuum furnace and microwave measurement in order to supply products with high productivity and high quality stability. Twenty-five modules were manufactured and precisely installed to the beam lines in and after the summer of 2013. Among these, 21 acceleration modules and two buncher modules were installed with the accuracy of several hundred microns over approximately 120 meters. Next, conditioning and beam tests were implemented, 400 MeV beam acceleration was verified in January 2014 and commercial operation has been performed since that time.

Table 1 Principle specifications of accelerating cavities

	ACS cavity (normal conducting cavity)	cERL injector cavity (superconducting cavity)	cERL main linac cavity (superconducting cavity)
Frequency	972 MHz	1,300 MHz	1,300 MHz
Accelerating field	4.1 MV/m (design value) 4.5 MV/m (attained value)	15 MV/m (design value) 30 MV/m (attained value)	20 MV/m (design value) 25 MV/m (attained value)
Q value	17,000-20,000	2.0×10^{10}	1.0×10^{10}@15 MV/m
Material	Oxygen-free copper	Pure niobium	Pure niobium
Module construction	2 × 17 cell: acceleration module (2 × 5 cell: buncher module) (2 × 6 cell: debuncher 1 module) (2 × 9 cell: debuncher 2 module)	3 × 2 cells/module	2 × 9 cells/module
Units deliverd	25 (including buncher and debuncher)	1	1

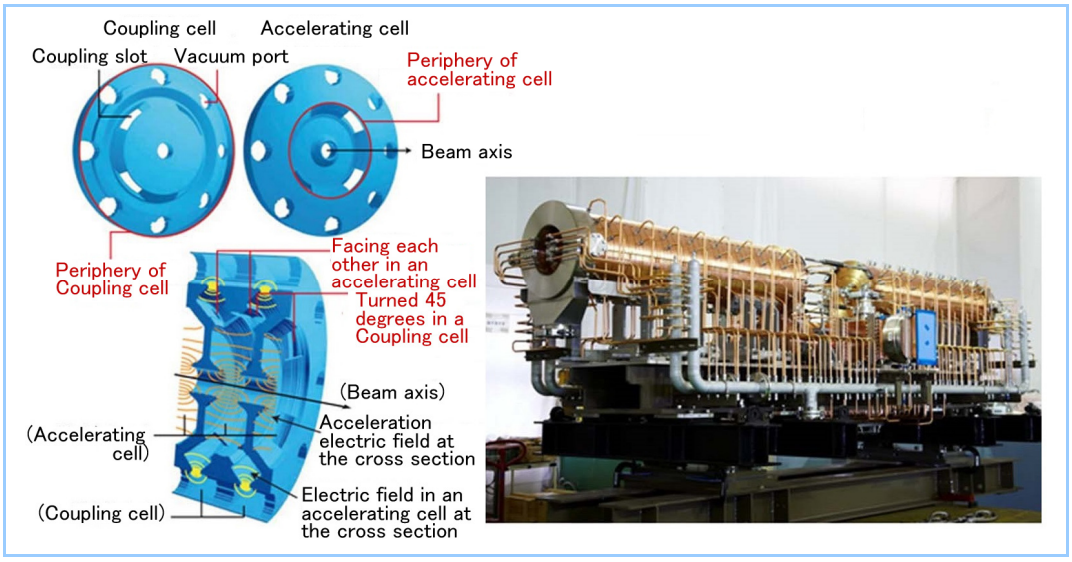

Figure 1 Shape of ACS cavity cell (left) and external view of module (right)

*The figure on the left courtesy of JAEA

2. Superconducting accelerating cavity in KEK-cERL

2.1 Overview of KEK-cERL

KEK-cERL is a prototype of an energy recovery linac (ERL) at the High Energy Accelerator Research Organization. The electromagnetic radiation emitted when charged particles are accelerated radially is called synchrotron radiation. It is used for molecular or atomic scale observation in the material science and life science fields. ERL will provide a high brilliance and short pulse X-ray. When an electron goes around an accelerator in conventional synchrotron radiation facilities, the Synchrotron radiation deteriorates. However, ERL characteristically discards an electron every time it goes around the accelerator to enable constant high-quality synchrotron radiation. ERL recovers energy from the discarded electron, and it is used for new electron acceleration. That is the very reason the linac is said to be an “energy recovery linac.” KEK-cERL is a small accelerator operated with energy of approximately 3.5 MeV to 200 MeV. Technological development for an ERL that requires energy of around 3 GeV is also under way.

2.2 Application of superconducting accelerating cavity

An accelerating cavity is a device for generating an electric field to give the electric energy to an electron. KEK-cERL adopted superconducting accelerating cavities, which use the superconducting phenomenon to reduce electric resistance toward zero as much as possible and then facilitate the continuous generation of a high-acceleration electric field with a small amount electric power. Superconducting accelerating cavities manufactured by MHI are used for the three injector cavities (pre-accelerator) and the two main linac cavities. Table 1 indicates the principal specifications of the cavities. **Figure 2** shows the overall view of cERL.

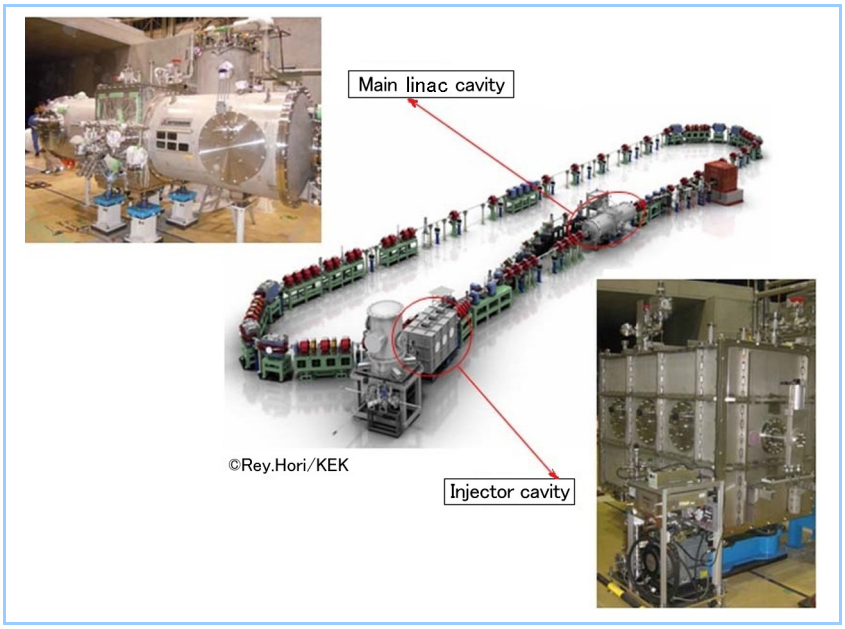

Figure 2 Overall view of cERL and cavities manufactured by MHI

2.3 Characteristics of superconducting accelerating cavity

A superconducting accelerating cavity for cERL is manufactured by welding and connecting cells with a diameter of 200 mm formed from high-purity niobium material with a thickness of 3 mm and a diameter of 300 mm. **Figure 3** shows the external view of the injector cavity and the main linac cavity. For the manufacture of a superconducting accelerating cavity, high-precision niobium thin plate forming technology, as well as a uniform thickness machining and the cleaning of the welding groove surface, non-spatter and flat-bead welding technology and welding and assembling technology used under a highly-clean environment are required. The welding quality is very important to influence superconducting cavity performance.

MHI contributed to the realization of stable beam Accelerating operation of cERL by offering superconducting accelerating cavities with high welding quality using electron beam welding machine and a clean area within MHI. For manufacturing the superconducting accelerating cavities for cERL, MHI passed an inspection based on the High Pressure Gas Safety Act.

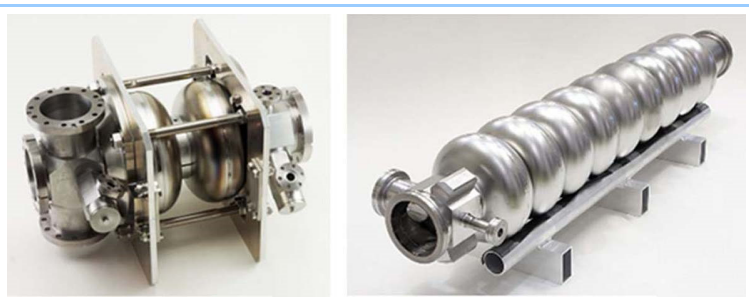

Figure 3 cERL injector cavity (left) and main linac cavity (right)