Particle Accelerator Products for Advanced Research and High-precision Radiation Therapy Equipment using Accelerator Technology

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Particle accelerators, which are used for advanced research in fields such as high energy physics and radiation physics, accelerate charged particles (e.g., electrons and protons) to nearly the speed of light at which particles possess high energy. Mitsubishi Heavy Industries, Ltd. (MHI) has provided domestic and overseas research institutions with several types of accelerating cavities or structures, which are the heart of an accelerator. We are also internally developing state-of-the-art accelerator manufacturing technologies. The ultra-compact accelerating structure we have thus developed is mounted on our Vero4DRT high-precision radiation therapy equipment (marketed under the MHI-TM2000 Linear Accelerator System brand name). This report introduces our superconducting accelerating cavities, normal-conducting accelerating structures and radiation therapy equipment as applied products thereof.

1. Superconducting accelerating cavities

1.1 Features

Superconducting accelerating cavities can lower electrical resistance to nearly zero by cooling the niobium constituting the cavities down to an extremely low temperature by using of refrigerants such as liquid helium and thereby achieving superconductivity. These cavities are mainly used in accelerators that are operated in high acceleration electric fields and in a continuous-wave mode. This is because radio-frequency power loss in superconducting accelerating cavities can substantially be reduced relative to normal-conducting accelerating structures in which oxygen-free copper is used.

1.2 Applications

As superconducting process requires a large-scale refrigerant supply/recovery system, these types of accelerating cavities are mainly used in large particle accelerators for the research of elementary particle physics. MHI provided the High Energy Accelerator Research Organization (also known as KEK) with a “superconducting crab cavity” intended for the electron-positron collider (called KEKB). KEKB contributed to the validation experiments that led to the 2008 Nobel Prize in Physics. As an overseas example, MHI supplied the “superconducting accelerating module” to be installed at the Taiwan Photon Source (TPS) of the National Synchrotron Radiation Research Center (NSRRC), which is currently under construction.

MHI also has developed and supplied superconducting accelerating 9-cell prototype cavity for the International Linear Collider (ILC) Project, which attempts to unravel the mysteries of the origin of matter and the creation of the universe (and there is an expectation that Japan will host the facility), as well as for the Energy Recovery Linac (ERL) Project, which is involved in research for the next generation of synchrotron light sources (**Figure 1**).

1.3 Manufacturing technologies

In the superconducting accelerating cavity, contamination by even the microscopic impurities in the niobium or minute defects/projections on the inner surface of the cavity can cause the failure of generating a high electric field. For this reason, the following manufacturing technologies are used.

(1) High-precision forming: A press forming technology to manufacture the hemispherical cells that constitute the cavity with high accuracy.

(2) High-precision electron-beam welding: A technology that is used to assemble the hemispherical cells, by which the surfaces of a cavity to be assembled are smoothed out inside of a highly clean vacuum environment to prevent impurity contamination while precisely welding the cells using an electron beam (**Figure 2**).

Figure 1 Superconducting accelerating 9-cell prototype cavity for the ILC Project

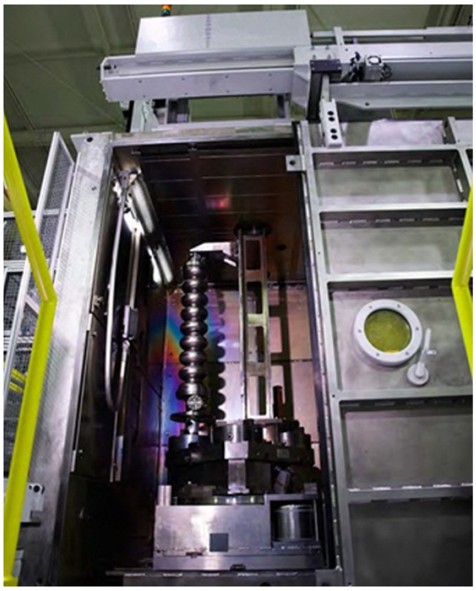

Figure 2 Electron-beam welding machine for superconducting cavities

2. Normal-conducting accelerating structures

2.1 Features

Normal-conducting accelerating structures are mainly made of oxygen-free copper and are operated at room temperature. Therefore, compared with superconducting accelerating cavities, these structures require fewer auxiliary devices and the cleanliness control of accelerators can be less strict. On the other hand, as their radio-frequency power loss is greater than superconducting accelerating cavities, these structures are not suitable for continuous-wave operation, but can create a very high acceleration electric field with pulsed mode operation. The electron accelerating structure designed to accelerate electrons (which are of little mass), and the proton accelerating structure intended for the acceleration of protons (which are of large mass) are different in their basic structures/dimensions. The proton accelerating structure is generally larger in size.

2.2 Applications

The electron accelerating structure is used as beam injection into large-scale ring accelerators at KEK or SPring-8. The main accelerator of the X-ray free-electron laser of RIKEN, known as the SPring-8 angstrom compact free electron laser ("SACLA"), has adopted our original "C-band choke-mode accelerating structure." As an overseas example, we have provided a "quasi-symmetrical S-band accelerating structure" intended for the X-ray free-electron laser that is under construction at the Pohang Accelerator Laboratory (PAL) of South Korea (**Figure 3**).

The proton accelerating structure is used in the main accelerators of the Japan Proton Accelerator Research Complex (J-PARC), which was jointly constructed by KEK and the Japan Atomic Energy Agency (JAEA). Accelerated protons are beamed to the special targets to generate neutrons. Efforts to utilize these neutrons for the public benefit have begun, such as used for cancer treatment or non-destructive inspection (for the industrial sector).

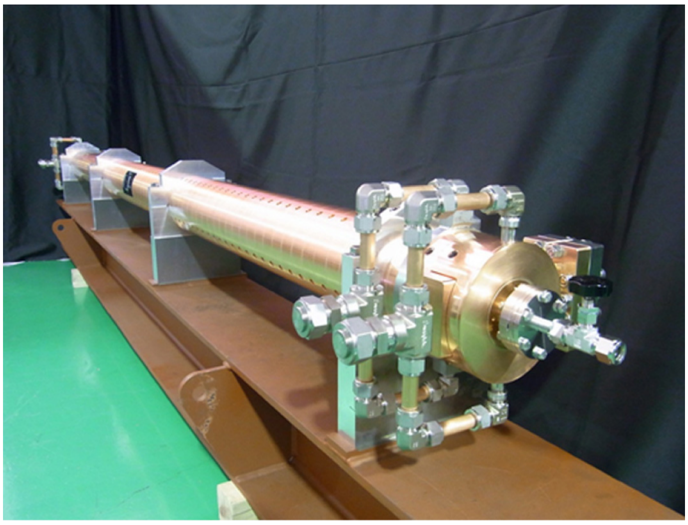

Figure 3 Quasi-symmetrical S-band accelerating structure

2.3 Production technologies

Because normal-conducting accelerating structures require precise resonance frequencies control and therefore their required dimensional accuracy is very strict, the following production technologies are used (**Figure 4**).

(1) Ultra-precise machining to achieve a surface roughness of 0.1 μm or less and a dimensional error of 2-3 μm or less.

(2) Low-strain multilayered and dissimilar materials brazing, using one of the largest vacuum brazing furnaces in Japan (maximum acceptable workpiece: 1.2 m in diameter and 3 m in height).

(3) Accurate frequency measurement and adjustment, which can cover a wide range of frequencies (300 MHz to 12 GHz).

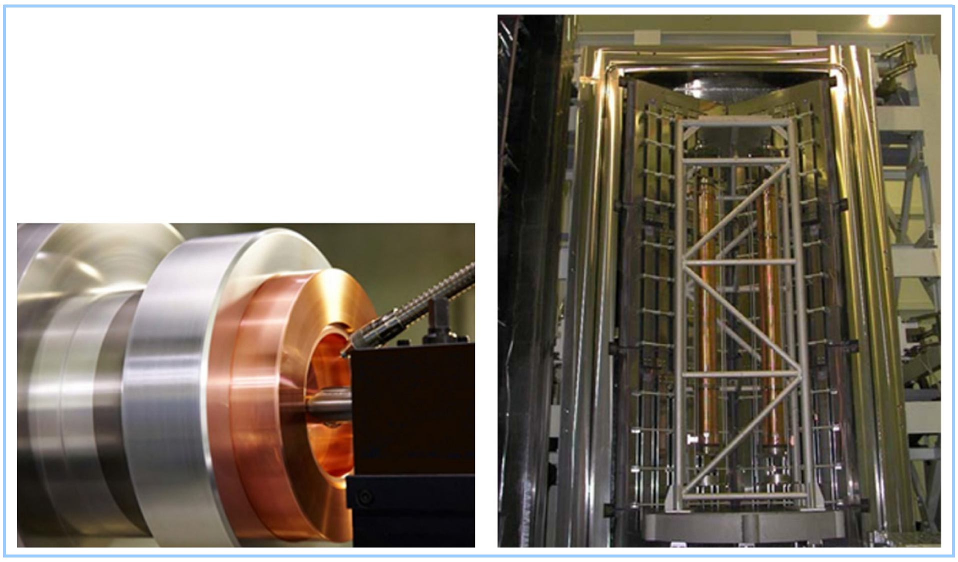

Figure 4 Part of an accelerating structure being processed by ultra-precise machining (left) and the vacuum brazing furnace (right)

3. Vero4DRT – high-precision radiation therapy radiation therapy equipment

3.1 Features

The Vero4DRT (marketed under the MHI-TM2000 Linear Accelerator System brand name) is high-precision image-guided radiotherapy equipment that was developed with a concept of sophisticatedly integrating beam delivery technologies and imaging technologies. The most distinguishingly unique features are the design of the entire structure, the configuration and the sub-devices mounted on the Vero4DRT, which are intended to realize dynamic tracking radiotherapy to deliver beams to tumors moving inside the body because of factors such as respiration.

The Vero4DRT is equipped with our original ultra-compact C-band standing-wave accelerator, which delivers therapeutic beams (one-third the size of traditional accelerators and is being used in medical equipment for the first time anywhere in the world). The Vero4DRT also has an "irradiation head" containing accelerator mentioned above and a multi-leaf collimator (MLC) by which the X-ray beam is adjusted to fit the shape of the target tumor, and the irradiation head is mounted on a gimbal mechanism that can be swung. Thus, it has become possible to correct extremely small displacements of the irradiating direction and perform tracking radiation therapy onto a tumor moving by breathing.

3.2 Applications

The Vero4DRT has been installed at more than 18 domestic and overseas hospitals, producing many clinically satisfied outcomes for cancer treatment.

3.3 Production technologies, configuration and capabilities

In radiation therapy equipment, the accuracy of delivering radiation concentrated to the location of the cancer while avoiding irradiation to the healthy cells determines the accuracy of treatment. It is necessary to precisely align the diseased region with the precisely controlled irradiation area. To realize a mechanical accuracy of ±0.1 mm, which is the top level in industry, we combined the basic technologies we have accumulated through developments of various products including (1) micro-positioning technologies (as used in machine tools), (2) image-processing technologies (printing machines), (3) system control technologies (iron-making machines) and (4) ultra-compact accelerating structure technologies to generate X-rays.

The equipment is comprised of a highly-rigid O-ring structure (a gantry) approximately 3.3 m in diameter, an irradiation head mounted on the swing mechanism (a gimbal), two perpendicular pairs of X-ray imaging systems (each consists of a kV X-ray generator and a flat-panel detector), and the patient's bed (a couch) movable in five axial directions (**Figure 5**).

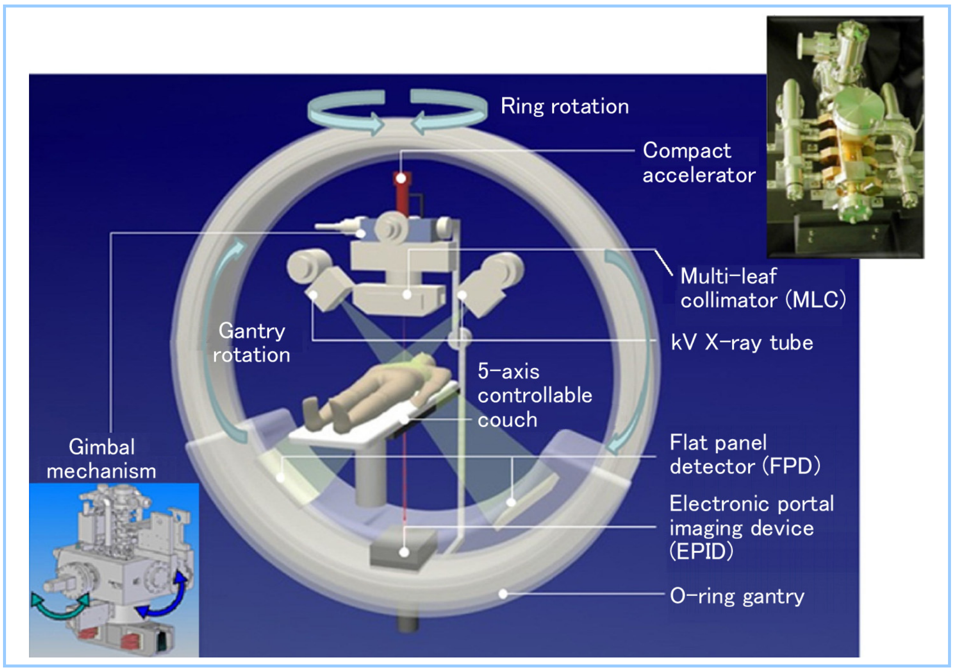

Figure 5 Mechanical configuration of Vero4DRT

In image-guided radiation therapy, the imaging systems installed on the rotatable gantry along horizontal axis enable the three-dimensional capturing of a tumor from any direction, whereby exact alignment can be performed quickly. The rotation of the gantry along vertical axis allows mechanical movements that had not been possible with conventional equipment, enabling non-planar irradiation without moving/rotating the couch. Not only does this reduce the patient's burden caused by couch rotation in existing equipment, but it also eliminates the patient's positional deviation and maintains the accuracy of patient positioning, which is vital for high-precision irradiation. Research for new treatment methods using this innovative gantry rotation technology is under way.

Using its dynamic tracking irradiation function, the Vero4DRT can capture the movement of a tumor in real time through the imaging systems and track the tumor using the swing mechanism of the interlocking irradiation head with the system. Irradiation can also be performed in combination with intensity-modulated radiation therapy (**Figure 6**). This functionality has been developed with the financial support of the Japan Society for the Promotion of Science, based on the Funding Program for World-Leading Innovative R&D on Science and Technology systemized by the Council for Science and Technology Policy. Clinical support has been provided by Kyoto University and the Institute of Biomedical Research and Innovation.

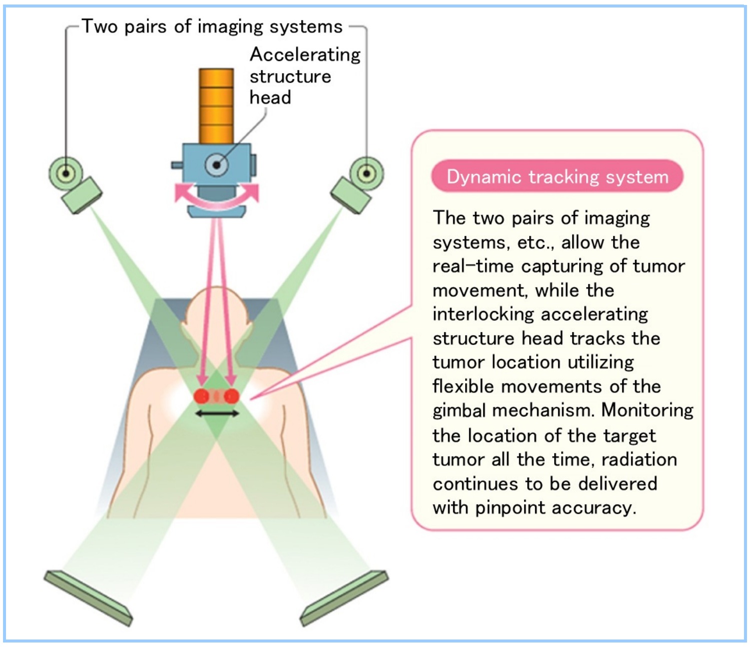

Figure 6 Conceptual diagram of dynamic tracking system