Activities of Hitachi Regarding Construction of the J-PARC Accelerator

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OVERVIEW: The accelerator at J-PARC is composed of a 330-m-long linac (linear accelerator), a 3-GeV rapid cycling synchrotron with a circumference of 350 m, and a 50-GeV synchrotron with a circumference of 1,570 m. Through cooperation between JAEA and KEK, the accelerator is currently under construction at JAEA Tokai Research and Development Center, and beam commissioning of the whole accelerator system is targeted for 2008. Along with JAEA and KEK, Hitachi is advancing technical developments based on its accumulated know-how on electromagnet and power-supply technologies and has constructed some of the main equipment at J-PARC — whose required specifications are the highest level in the world today.

INTRODUCTION

SET up for performing cutting-edge research in the fields of nuclear and particle physics, materials and life sciences, and nuclear engineering, J-PARC (Japan Proton Accelerator Research Complex) — which has a group of proton accelerators (with the world's highest grade proton beam) and various experimental measurement facilities — is under construction. The proton-accelerators are composed of a linac (linear accelerator) for injection, a 3-GeV synchrotron, and a 50-GeV synchrotron. They can produce a high-intensity proton beam with a power in the order of megawatts.

This report describes Hitachi, Ltd.'s contributions regarding the main equipment of the J-PARC accelerators and their related technological developments (see Fig. 1).

Aerial photo provided by Japan Atomic Energy Agency

Fig. 1—A Photo of the 50-GeV Electromagnet Installed in a Tunnel (Left) and Birds-eye View of Construction of J-PARC (Right).
J-PARC (Japan Proton Accelerator Research Complex) under construction at the Tokai Research and Development Center of Japan Atomic Energy Agency (an independent administrative agency) in Tokai-mura, Ibaraki Prefecture, Japan (facing the Pacific Ocean) is shown. Construction of the building housing the 3-GeV synchrotron and linac has finished, and construction of a 50-GeV synchrotron, materials and life science facilities, a hadron laboratory, and a neutrino beam line is continuing. Moreover, as for the indoor construction, installation and trial runs of equipment, starting with the electromagnet, are continuing.

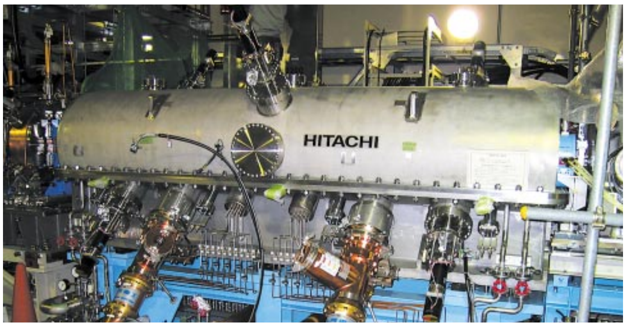

Fig. 2—RFQ Installed at the Linac Wing.
An accelerated beam produced by a RFQ (radio-frequency quadrupole linac) is further accelerated by a DTL (drift-tube linac) and injected into the 3-GeV synchrotron.

TABLE 1. Electromagnets and Power Supply System of 3-GeV Synchrotron Fabricated by Hitachi
24 bending magnets are installed in the synchrotron, and one is for the magnetic-field-monitor.

Electromagnet name		Number of units	Power-turn-on waveform	Power-supply system
Main electromagnet	Bending magnet	25	Sinusoidal wave	Resonant power supply
	Quadrupole magnet	60	Sinusoidal wave	
	Sextupole magnet	18	Sinusoidal wave	—
Injection bump electromagnet		10	Pulse	Pulse power supply

LINAC

RFQ

The linac of the J-PARC generates negatively charged hydrogen ions and injects them into the 3-GeV synchrotron. Hitachi fabricated the RFQ (radio-frequency quadrupole linac) of the first-stage accelerator (see Fig. 2). The RFQ accelerates an ion beam by microwaves, and accelerated beam energy is 3 MeV. Its electrodes were processed with precision in the order of several tens of micrometers.

Klystron Power Supply System for Linac

A high-voltage pulse power supply system for supplying the power to klystrons (which generate the microwaves used in the particle-acceleration process) is used. It is composed of six boards for a high-voltage (110 kV) direct-current power source, and 21 modulators for adding a 93-kV signal to a control electrode (known as a “modulation anode”).

A maximum power of 3 MW per klystron is supplied by means of a repetition at 600-μs width and 50 Hz by the signal from the modulators. It was confirmed that cathode-voltage fluctuation is suppressed below 0.2%. This power supply system is already being used for beam-acceleration experiments using the RFQ.

3-GEV SYNCHROTRON

The 3-GeV synchrotron is rapid cycling synchrotron. Its operating frequency is 25 Hz. Hitachi fabricated the main electromagnets, the resonant power supply system, and the injection-bump system of the synchrotron (see Table 1).

Main Electromagnet

The characteristic specifications of the main electromagnet of the 3-GeV synchrotron consist of (1) AC (alternating current)-loss reduction for 25-Hz sinusoidal-wave current excitation, and (2) a coil for withstanding a radiation dose of 100 MGy.

As features, in regards to the AC-loss reduction [(1) above], an aluminum-stranded conductor (utilizing technology used in aluminum transmission lines) was developed, and the iron-core terminals were formed as a Rogowski shape with slits. As for the coil [(2) above], highly radiation resistant insulation was used for insulating the coil.

As one of the top class electromagnets in the world, the bending magnets have a gap between magnetic poles of 210 mm, a total length of 3.4 m, and a weight of 40 t.

After the electromagnets were completed, it was subjected to electric-field measurements by Japan

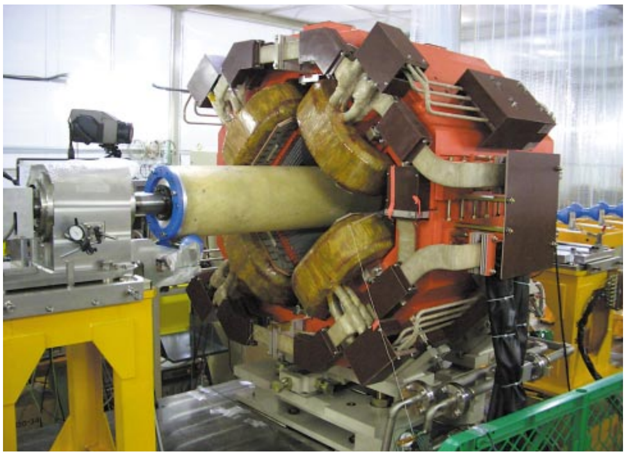

Fig. 3—3-GeV Quadrupole Magnet during Magnetic-field Measurement.
The magnetic field is measured by a cylinder (called a harmonic coil), and effective magnetic-field length and the center of the magnetic field is obtained.

Atomic Energy Agency (JAEA, an independent administrative agency), as shown in Fig. 3, and installed in the main tunnel of 3-GeV synchrotron.

Resonant Power Supply System for Exciting Main Electromagnets(3)

The power supply system is configured as one supply for the bending magnet (which excites 25 units of bending magnets including one monitor) and seven supplies for exciting quadrupole magnets (60 magnets divided into seven groups).

Each magnet group is excited by an alternating current of 25 Hz with a biasing direct current. In the case of the bending magnets, the alternating current is 1,002 A and the direct current is 1,667 A. As for all 25 units of bending magnets, an alternating voltage of about 250 kV is needed. Accordingly, a power-source system applying resonance was adopted. This resonant power supply — of world-class grade — is shown schematically in Fig. 4.

A beam must be stably accelerated by a total of eight power supplies; therefore, while 0.01%-class stability and accuracy are assured by means of a whole-power-supply control system controlled by a computer, the degrees of freedom of control are also assured.

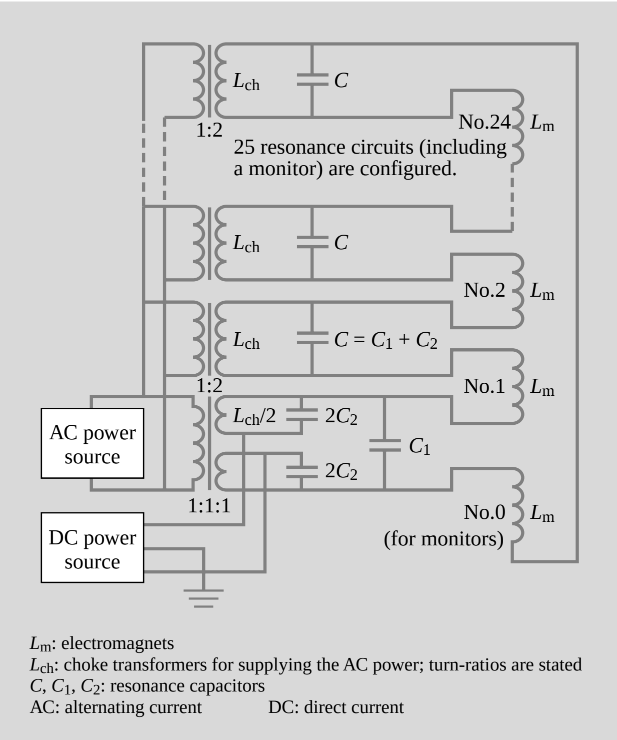

Fig. 4—Power-supply System for Excitation of the Bending Magnets of 3 GeV.
The direct-current source supplies a biasing current of 1,667 A. The alternating-current source utilizes resonance to supply an alternating current of 1,002 A at 25 Hz.

Injection-bump System

At J-PARC, negatively charged hydrogen ions accelerated by the linac are charge converted in the injection section of the 3-GeV synchrotron and become protons. An injection-bump system was designed in such a manner as to create an injection-bump track and perform paint injection for increasing beam intensity. With this system, a 1-ms-pulse magnetic field with a cycle of 40 ms is generated.

The injection-bump electromagnets are composed of ten electromagnets consisting of three types (four horizontal-shift bumps, four horizontal paint-bump units, and two vertical-paint units). Electromagnetic steel sheet with thickness of either 0.1 or 0.15 mm is applied to the iron-core materials to improve high-frequency characteristics. In particular, the 0.1-mm-thick electromagnetic steel sheet is applied for the first time to a large-scale electromagnet, so attention was paid to fabrication precision.

The power supplies are composed of three parts: one horizontal-shift-bump electromagnet power supply for exciting four electromagnets in series, four horizontal paint-bump electromagnet power supplies for exciting each electromagnet one by one, and two vertical-paint electromagnet power supplies.

The horizontal-shift-bump electromagnet power supply has a maximum capacity that becomes 320 MVA, 10 kV, and 32-kA peak in the final specification. The horizontal paint-bump electromagnet power supplies provide large current pulses that become a 29-kA peak at 1.2 kV as maximum values in the final specification. At present, the injection-bump system is constructed with a rated current of 60% of the above-stated specifications. By combined use of feed-forward control, high-speed control performance for tracking at precision of ±1% in correspondence with the large current pulse patterns (which vary at a rate of several hundred microseconds) is satisfied.

Eddy Current Analysis in Electromagnets

The electromagnets are operated at 25 Hz, so eddy-current generation and temperature rise were evaluated. As for the main electromagnet, only the iron core was subjected to dynamic electromagnetic analysis and thermal analysis; on the other hand, as for the bump electromagnet, the iron core including the conductor was subjected to these analyses.

(1) Electromagnetic analysis

In the analysis, eddy-current heating and hysteresis heating were calculated from the measured B-H characteristic, taking into account the directionality of electro-conductivity in the core of the laminated electrical steel sheets. As for the bump electromagnet, current distribution and generated heat in the sheet-copper coil conductor were obtained. An example of the results from dynamic electromagnetic analysis is shown in Fig. 5 in the form of an eddy-current distribution. The analysis range is shown in one-fourth full. In the core, the eddy currents bypass the slits, and in the coil conductor, it can be seen that the current distribution is biased. The results of performance-evaluation tests performed by JAEA are presented in Fig. 6. It is clear that the analysis results are in good agreement with the experimental measurements.

(2) Thermal analysis

Natural convection cooling of surfaces and heating determined by electromagnetic-field analysis as well as heat conduction in the iron core were taken into account (in terms of design proportions of steel sheet and air as well as insulation coating), and temperature rise was evaluated. The depth and position of the slits in the iron core were aligned in the region that does not affect the electromagnetic-field distribution, and heat generation was reduced. As for the conductor of the bump electromagnet, partial water cooling was assumed, its position in relation to the core was optimized, and temperature rise was alleviated. Through above-described discussion, the prospect of achieving thermally stable operation was obtained, and detailed design of the equipment was performed.

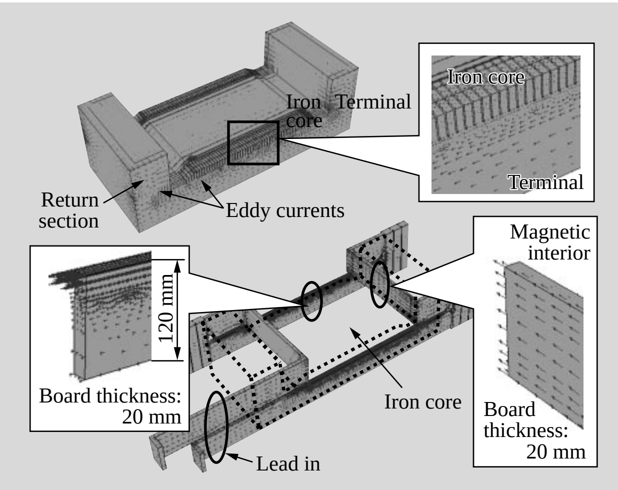

Fig. 5—Electromagnetic-analysis Results for Horizontal-shift Bump Electromagnet (Eddy-current Distribution).
A quarter part was analyzed under a symmetrical assumption. The eddy-current distribution when maximum current is attained is shown by arrows.

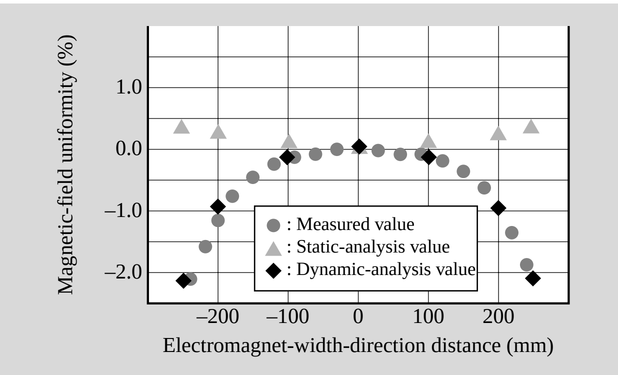

Fig. 6—Magnetic-field Uniformity of Horizontal-shift Bump Electromagnet.
Magnetic-field distribution in the width direction during pulse-current application is expressed as the line integral (beam-line, BL, product) in the beam direction. The dynamic-analysis value taking account of eddy currents is in good agreement with the experimentally measured values.

50-GEV SYNCHROTRON

The 50-GeV synchrotron is composed of 96 bending magnets, 216 quadrupole magnets, 80 sextupole magnets (including eight magnets for resonant extraction), and 186 correction magnets. Hitachi fabricated the bending magnets and the quadrupole magnets. The specifications for these two kinds of magnets are given in Table 2.

As laminated core magnets, the bending magnets are world-class in terms of both size and magnetic induction.

From the viewpoint of packing-factor improvement in the iron core, magnetic steel sheet with thickness of 0.65 mm was utilized. As regards the side plate (using conventional carbon steel), the influence of eddy currents due to high magnetic induction cannot be ignored, so Japanese standard SUS304 (stainless steel) is applied for the bending magnet.

As for both the bending and quadrupole magnets,

TABLE 2. 50-GeV Synchrotron Electromagnet Specifications
The quadrupole magnet is classified in terms of seven core lengths and three bore diameters, making a total of 11 varieties.

Item	Bending magnet	Quadrupole magnet
Core length	About 5.85 m	1.86 m (maximum)
Gap between poles/ bore diameter	106 mm	Maximum diameter 140 mm
Magnetic flux density	1.9 T	18 T/m (maximum)
Mass	About 33 t	About 12 t (maximum)
Operation frequency	0.3 Hz	

assuring fabrication precision is extremely difficult as a consequence of their size. However, magnetic measurements done by Inter-University Research Institute Corporation High Energy Accelerator Research Organization (KEK) operating at Hitachi's Futo Plant confirmed that designated magnetic-field performance is attained.

CONCLUSIONS

In regard to the equipment that configures the proton accelerator group at J-PARC, this report describes the main equipment and related technical developments taken charge of by Hitachi. Aiming to start operating in 2008, J-PARC has reached the final stage of construction, and it is expected that it will become an accelerator of primary importance for ground-breaking science in the 21st century. It is considered that this technology, developed and established through equipment construction, will be applied to large-scale accelerator projects from now onwards.

ACKNOWLEDGMENTS

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