ACTIVITIES OF HITACHI RELATING TO CONSTRUCTION OF J-PARC ACCELERATOR

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Abstract

The Japan Proton Accelerator Research Complex (J-PARC) consists of a 330-m-long linac, a 3-GeV rapid cycle synchrotron with a circumference of 350 m, and a 50-GeV synchrotron with a circumference of 1,570 m. Owing to a collaboration between the Japan Atomic Energy Agency (JAEA) and the High Energy Accelerator Research Organization (KEK), the accelerators will be commencing operations at the site of JAEA Tokai Research and Development Center. The beam commissioning of the entire accelerator system is planned to take place before the end of 2008. Along with the JAEA and KEK, Hitachi has contributed to the construction of the system by manufacturing some major equipment with specifications that are of the highest level in the world.

INTRODUCTION

J-PARC [1,2] will shortly be commencing operations, and it is expected to lead to new research trends in the fields of nuclear and particle physics, materials and life sciences, and nuclear engineering. The complex has three accelerators for generating high-power MW-class proton beams—a 181-MeV linac (linear accelerator), a 3-GeV synchrotron, and a 50-GeV synchrotron. This paper describes the contribution of Hitachi Ltd. through the manufacture of equipment for the J-PARC accelerators and related technological developments.

LINAC

RFQ

The linac generates negatively charged hydrogen ions, accelerates and injects them into the 3-GeV synchrotron. Hitachi has manufactured the radio frequency quadrupole (RFQ) linac for the first stage (Fig. 1). The RFQ linac accelerates the ions up to an energy of 3-MeV. Its electrodes have been machined with a precision of the order of several tens of micrometers.

Klystron Power Supply System for Linac

The pulsed power supply system for klystrons has been manufactured by Hitachi. It comprises six high-voltage (110 kV) DC power supplies and 21 modulators to supply 93-kV signals on control electrodes that are known as modulation anodes.

The signal from the modulator supplies a maximum power of 3 MW per klystron at a repetition rate of 50 Hz and a pulse width of 600 μs. The cathode voltage fluctuation has been confirmed to be below 0.2%. This power supply system has commenced operations along with the RFQ linac.

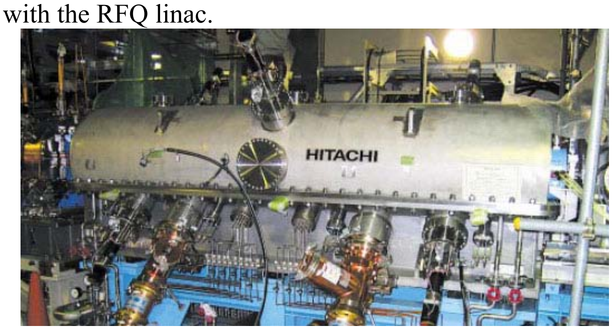

Figure 1: RFQ linac for the first-stage of the accelerator.

3-GeV SYNCHROTRON

The 3-GeV synchrotron operates with a rapid cycle of 25 Hz. Hitachi has manufactured the magnets, resonant power supply system, and the injection bump magnet system (Table 1).

Magnets

The magnets used in the 3-GeV synchrotron are listed in Table 1. The important specifications of the magnets are as follows: (1) AC loss reduction withstanding 25 Hz operation and (2) reliable coils in a radiation environment with a dose of 100 MGy.

Table 1: Magnets and Power Supply System of the 3-GeV Synchrotron Fabricated by Hitachi

Name of Magnet		Number of Units	Waveform	Power Supply
Main magnet	Bending BM	25	Sinusoidal	Resonant
	Quadrupole QM	60	Sinusoidal	
	Sextupole	18	Sinusoidal	---
Injection bump magnet		10	Pulse	Pulse

In order to reduce the AC loss, the following design was employed. Al-stranded conductors were developed for the coil by adopting the technology used in the manufacture of Al transmission lines, and the slits at the ends of the iron core were formed with Rogowski shapes. The slit optimization procedures are discussed in another presentation in this conference [4]. For enhancing the reliability of the coil in the presence of radiation, insulation with high resistance to radiation was used.

The bending magnets (BMs) are the world's largest class and have 210-mm gaps between their magnetic poles; they have a length of 3.4 m and a mass of 40 ton.

Before the installation of the magnets, their magnetic fields were measured by the JAEA team. Fig. 2 shows the setup for a quadrupole magnet (QM).

Figure 2: A QM during magnetic field measurements.

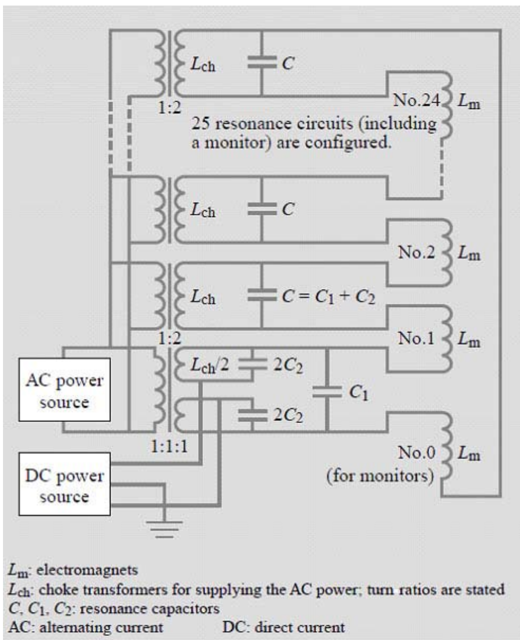

Figure 3: Power supply system for the BMs

Resonant Power Supply [3]

The power supply system for the 3-GeV synchrotron comprises one power supply for BMs and seven power supplies for QMs. The former power supply excites 25 BMs, including one standard magnet. The latter power supplies excite 60 QMs that are divided into seven groups

The magnets are excited by a DC-biased 25 Hz AC current. In the case of the BMs, the AC component is 1,002 A and the DC component is 1,667 A and a resonant power supply system has been adopted, which is world largest class, and is shown schematically in Fig. 3. The resonant power supply works

The beam acceleration must be stable when the eight power supplies are used. Therefore, 0.01%-class stability and accuracy are assured by means of a whole-power-supply control system controlled by a computer, thereby maintaining the degree of freedom in the control.

Injection Bump Magnet System

The electrons of the negatively charged hydrogen ions (H^-) in the beam obtained from the linac are stripped off and injected into the 3-GeV synchrotron as protons (H^+). The injection system has been designed so as to form an injection bump orbit and perform paint injection to increase the beam intensity. The magnets used are injection bump magnets, which generate short magnetic field pulses with a width of roughly 1 ms at 25 Hz.

Among the injection bump magnets, there are ten magnets classified into three types (4 horizontal shift, 4 horizontal paint, and 2 vertical paint magnets). Laminated electric steel sheets with a thickness of either 0.1 mm or 0.15 mm are used as the iron cores to obtain rapid magnetic field responses. In particular, the 0.1-mm-thick sheets are used for the first time on large-scale magnets, and therefore, considerable attention has been paid to the precision during their manufacture.

There are three types of power supplies (7 supplies). One type is used for the four horizontal shift bump magnets connected in series. The second and third type of power supplies are for the horizontal paint and vertical shift bump magnets respectively. Each magnet of horizontal paint and vertical shift has a power supply.

The final specification for the power supply of the horizontal shift bump magnets will be 320 MVA, 10 kV, and 32 kA peak capability. The power supplies of the horizontal paint bump magnets will provide large current pulses up to 29 kA at 1.2 kV in the final specification. However, at present, the injection bump system has been constructed with rated currents at 60% of the abovementioned final specifications.

We have introduced feed-forward control to obtain good control performance. The supplied currents can trace the reference waveforms with a precision of ±1% for rise times of several hundred microseconds.

Eddy Current Analyses in Magnets

The magnets were to be operated at 25 Hz, and therefore, eddy current generation and temperature rise were of significant concern during the designs. Dynamic electromagnetic (EM) analyses and thermal analyses were carried out for the cores in all the magnets. For the injection bump magnets, the analyses were carried out for the conductors as well as the cores. The techniques for these analyses are discussed in papers [4,5].

An example result of the dynamic EM analyses is shown in Fig. 4; the figure shows the eddy current distribution in a bump magnet. The computational model is a one-fourth model.

In the core, the eddy currents are concentrated in the end region; however, they bypass the slits. With regard to the coil conductor, the current is supplied from a power supply and the eddy currents distort the current distribution.

The validity of the dynamic EM analyses was confirmed by the magnetic field data obtained during the performance tests carried out by the JAEA team. The magnetic field uniformity distribution in a pulse is shown in Fig. 5. The distribution obtained from the dynamic analysis is in good agreement with that obtained from the experimental one, while static analysis failed to explain the distribution.

The depth and position of the slits on the iron core were optimized to reduce the heat generation without affecting the magnetic field. The position of the conductor relative to the core and the cross-sectional shape of the conductor were also optimized to reduce the heat generation. Furthermore, partial water cooling was introduced to mitigate increases in the temperature.

After discussions so far, detailed magnet designs were performed. Currently, the magnets are stable and are being successfully operated.

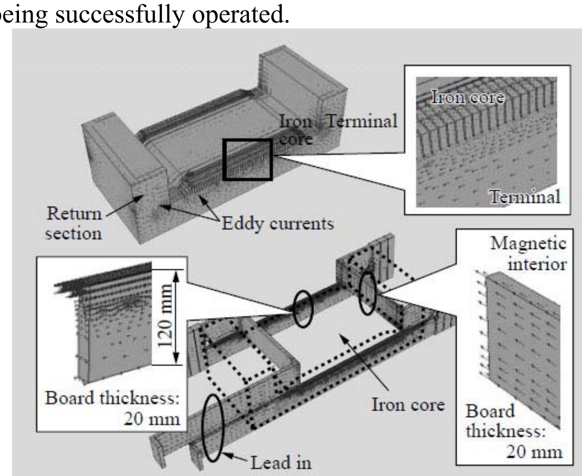

Figure 4: Eddy current distribution obtained from the electromagnetic analyses of a horizontal shift bump magnet.

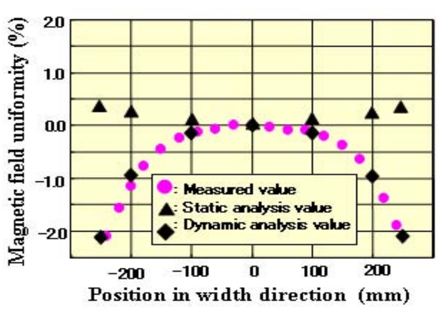

Figure 5: Magnetic field uniformity in the case of a horizontal shift bump magnet.

50-GEV SYNCHROTRON

The 50-GeV synchrotron has 96 BMs, 216 QMs, 80 sextupole magnets, 8 magnets for resonant extraction, and 186 correction magnets. Hitachi has manufactured all ~~the~~ BMs and QMs. The specifications for these magnets are listed in Table 2. The BMs are the world largest class magnet and possess a laminated core. From the viewpoint of improving the packing factor in the iron core, a fairly thick (0.65 mm) electric steel sheet is used. The end plates are made of stainless steel (Japanese Industrial Standard SUS304) to reduce the eddy currents, in contrast to the conventional carbon steel end plates.

The large sizes of the BMs and QMs made it difficult to manufacture them with precision. However, magnetic measurements performed by KEK at Hitachi's Futo plant confirmed that the desired magnetic field performance had been attained.

Table 2: 50-GeV Synchrotron Magnet Specifications

Item	BM	QM
Core length	Approx. 5.85m	1.86 m (maximum)
Gap between poles Bore diameter	106 mm	140 mm (maximum)
Magnetic flux density	1.9 T	18 T/m
Weight	Approx.33 t	Approx. 12 t
Operation frequency	0.3 Hz	

Figure 6: Magnets in the 50-GeV synchrotron tunnel.

CONCLUSIONS

This paper describes the contribution of Hitachi Ltd. in the construction of the J-PARC proton accelerator. The operation of all the accelerators in a series is planned for the Japanese Fiscal Year 2008, and the operation of the linac will commence first; this will be followed by the operation of the 3-GeV to 50-GeV synchrotrons. The beam has reached the last 50-GeV accelerator, proving that the RFQ linac, 3-GeV synchrotron magnets, and their power supplies can be operated at the designed specifications. It can be expected that this technology, developed through the construction, will be applied to future large-scale accelerators.

ACKNOWLEDHEMENTS

Authors would like to express their thanks to all those concerned with the construction, and special thanks to Drs M. Yoshioka, K. Niki, T. Oogoe, S. Takeda of KEK and M. Kinsho, T. Takayanagi, N. Tani of JAEA for their guidance and cooperation.

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