J-PARC ACCELERATOR: CONSTRUCTION STATUS AND MAINTENANCE SCENARIO

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J-PARC, the Japan Proton Accelerator Research Complex, is a joint project of the High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA). The J-PARC accelerator comprises an injector proton linac (181 MeV), a 3-GeV rapid cycling synchrotron (RCS, 25 Hz) and a 50-GeV synchrotron (MR, 0.3 Hz). The RCS supplies a 1-MW proton beam to the Materials and Life Science Experimental Facility (MLF) and about 5% of the output to the MR. The MR supplies a beam with an intensity of 750 kW to two experimental facilities after accelerating it to a maximum of 50 GeV. One is for fast extraction for the long baseline neutrino experiment (T2K), and the other for slow extraction for the Hadron experiment. At J-PARC, the proton linac started beam acceleration in January 2007. At the RCS and the MR, beam acceleration will start in September 2007 and May 2008, respectively. At these high-power accelerators, the maintenance of radioactive components will be a major concern. In the injection and extraction areas, semi-remote handling flanges, quick-detachment of cooling water tubes and cables, and linear motion guide rails for replacing activated components such as septum magnets are used.

I. INTRODUCTION

J-PARC, the Japan Proton Accelerator Research Complex, is a joint project of the High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA). Construction began in 2001 in Tokai-mura, Ibaraki Prefecture.[1] Fig. 1 (a) and (b) show the layout of J-PARC and its aerial view. The accelerator at J-PARC comprises a 181-MeV linac (400 MeV in the second step), a 3-GeV rapid cycling synchrotron (RCS) and a 50-GeV main ring (MR).

The RCS is operated at 25 Hz. A 3-GeV, 1-MW (600 kW in the first step) proton beam is introduced to a mercury target at the Materials and Life Science Experimental Facility (MLF), producing intense pulsed neutrons, which are used for various materials and life science experiments. About 5% of the output beam from the RCS is deflected by a pulse bend and is injected into the MR through the beam transport (BT) line. A 3-GeV beam is accelerated by the MR to a maximum of 50 GeV for neutrino experiments (the long baseline neutrino experiment T2K) and nucleus experiments (the Hadron experiment).

Construction of the facility is well underway. In the linac, an H^- ion beam was successfully accelerated to 181 MeV, the design target for the first step in Phase I of the J-PARC construction, on January 24, 2007. The linac energy will be increased to 400 MeV as the second step in Phase I of the construction. Currently, the linac beam is being fine-tuned. In the RCS, equipment installation and testing are underway toward beam injection in September 2007. In the MR, beam injection is scheduled for May 2008.

Beam loss and activation are significant issues for this high-power accelerator. It is very important to keep beam loss below a specified level and to maintain activated accelerator components as quickly as possible with limited radiation exposure.

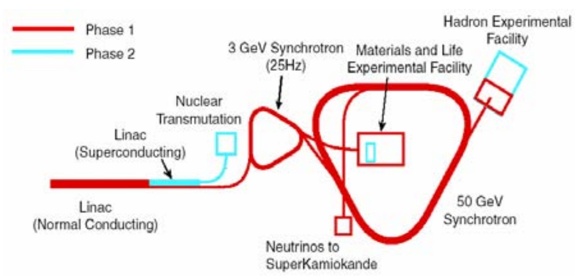

Fig. 1(a). Layout of J-PARC Accelerator.

Fig. 1(b). Recent aerial view of the J-PARC site. Almost all of buildings have been completed.

II. CONSTRUCTION STATUS

II.A. LINAC

II.A.1. Main Parameters

TABLE 1 shows the main parameters of the linac in step 1 of the construction phase 1. The total length of the tunnel is about 330 m. H^- ions from the ion source are accelerated at a frequency of 324 MHz RFQ (radio frequency quadrupole) to 3 MeV, and are accelerated to 50 MeV by three DTLs (drift tube linac) and to 180 MeV by 30 SDTLs (separate-type drift tube linac) driven by 15 klystrons. The current is 30 mA at maximum, with a pulse width of 500 μsec and a frequency of 25 Hz. The maximum current of 30 mA is decided by the present RFQ design.

Construction will take place in two phases. In the second step in Phase 1, the linac energy will be increased to 400 MeV by adding annular couple structures (ACS). After the increase in linac energy to 400 MeV and replacement of the RFQ, the maximum current will be increased to 50 mA.

TABLE 1. Main Parameters of LINAC

Accelerated particles	H^- (negative hydrogen)
Energy	181 MeV/400 MeV
Peak current	30 mA /50 mA
Repetition	25 Hz
Pulse width	500 μs

II.A.2. Klystron

324-MHz klystrons had been tested at the klystron gallery since October 2006, and all of the twenty klystrons used in step 1 were confirmed to meet the specifications. TABLE 2 shows the specifications of the klystrons (E3740A made by Toshiba).

TABLE 2. Main Parameters of Klystron

Peak power	2.5 (max. 3.0) MW
Frequency	324 MHz
Pulse width	650 μs
Repetition	50 Hz
μ–Perveance	1.37A/$V^{3/2}$
Gain	50 dB
Efficiency	55 %
Beam voltage	105 (max. 110) kV
Beam current	45 A
Mounting Position	Horizontal

II.A.3. Alignment

In high-power proton accelerators such as the J-PARC accelerator, precise alignment of accelerator components is critical in reducing uncontrolled beam loss and beam-quality deterioration. The J-PARC accelerator is located on a soft-soil site near the coast, and continuous settling of the tunnel was observed during the installation of linac components. In the final measurement, the displacement of +/- 2mm from the ideal straight line was found. This displacement might occur by the error of the floor markers and/or the deformation of the building. All the displacements from the ideal straight line were not corrected. Instead, the alignment was carried out to achieve smooth connection between components in close proximity to each other.[2] Fig. 2 shows the DTLs and SDTLs installed in the tunnel.

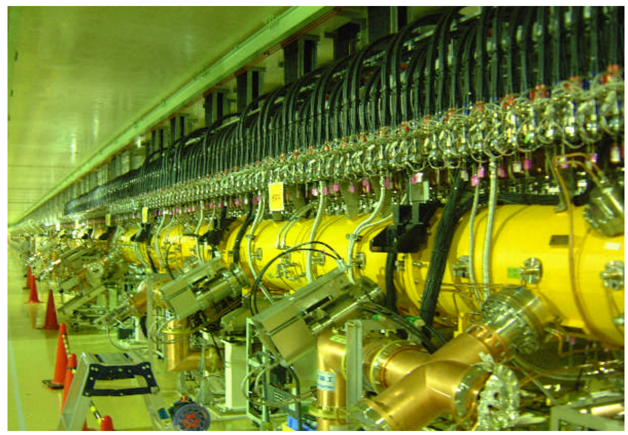

Fig. 2. All accelerator components are aligned to achieve smooth connection to each other.

II.A.4. Conditioning and Beam Commissioning

In the linac tunnel, the conditioning of the DTLs and the SDTLs using microwaves was started in October 2006. It took about one month to successfully supply the design microwave power to all the accelerating cavities, and this was achieved by gradually increasing the power while maintaining the vacuum in the accelerating cavities below the specified value. The conditioning of all of the accelerating cavities including 3 DTLs and 30 SDTLs used for acceleration and 2 SDTL cavities used as debunchers was completed in about one month, and then beam commissioning began in November 2006.

In this test, two different current of H^- beams, one with a beam current of 5 mA and the other with 30 mA, were accelerated using a pulse width of 50 μs and at a repetition rate of 5 Hz. In the first run, beam acceleration up to 3 MeV was performed with the RFQ accelerator. Subsequently, a beam energy of 19.7 MeV was obtained by acceleration using only DTL1 of the three DTLs. This beam was led to the 0-degree beam dump installed approximately 300 m downstream at a beam transmittance of 100% without orbit adjustment using steering magnets. This verifies the precise alignment of the linac accelerating cavities and the quadrupole electromagnets, as mentioned above.

The beam was adjusted as follows. First, a microwave was sequentially supplied from the upstream to the downstream accelerating cavity. Then, the relationship between the microwave phase and the beam energy was measured by scanning the phase as shown in Fig. 3 in which the line and circle show the simulated and measured values, respectively. The microwave power is set to the design value of 1 for five different microwave powers. Data is plotted on a graph by measuring the beam energy while changing the microwave phase at the power level. The energy of the H^- ion beam was measured using a time-of-flight method. The beam velocity was obtained from the relationship between the time lag and distance of the beam passing between a pair (or more) of high-speed current monitors, and converted into energy in MeV.

The relationship between the microwave power and phase and the beam energy was preliminarily obtained by calculation for each accelerating cavity, and the optimal phase and power were determined by comparison between the calculated and measured values. Since it is nearly impossible to obtain the microwave phase and power inside the accelerating cavities as absolute values with high precision, the optimal phase and power were determined by measuring the energy of the beam passing through the accelerating cavities. After the optimal phase and power for DTL1 were determined, the optimal phase for DTL2 was obtained by supplying a microwave to DTL2 to scan the phase of DTL2. Subsequently, the optimal phase and power were determined for the accelerating cavities one by one.[3]

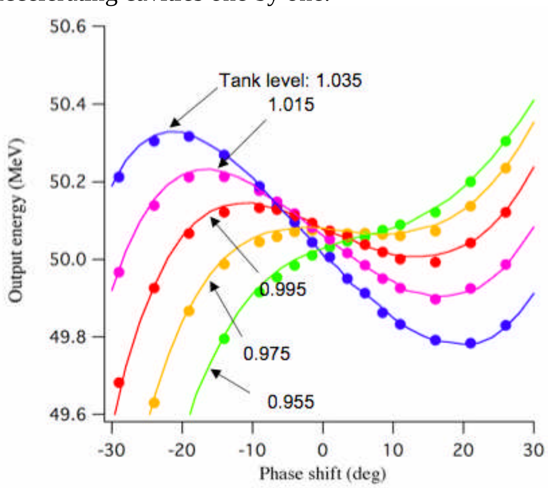

Fig. 3. Typical phase scan result is shown. Vertical: beam energy. Horizontal: phase shift of cavity. (Ref. 3)

The optimal phase for all the accelerating cavities was determined in this manner, and an H^- beam with the design energy of 181 MeV set for the first step in Phase 1 of the J-PARC construction was achieved in the test operation conducted on January 24, 2007.

In the beam commissioning, which continued until June 2007, transverse matching was carried out at the exits of the DTL and the SDTL as well as at the exit of the ACS section planned for the future using an array of four wire-scanner profile monitors. The long-term stability of the beam energy and orbit was also measured. It should be noted that chopped beam for single bunch acceleration in the RCS (harmonic number=2) was stably accelerated. This beam operation mode will be useful for beam study of the RCS. We must say that great interest is focused on residual radiation after beam operation. But we need more tuning time to discuss details of residual radiation issues.

II.B. Rapid Cycling Synchrotron: RCS

II .B.1. Main Parameters of RCS

The RCS is a rapid cycling synchrotron with a three-folding symmetry operated with a repetition rate of 25 Hz. TABLE 3 shows RCS main parameters. In the first step in Phase 1 of the construction, the injection energy, extraction energy and output beam power are 180 MeV, 3 GeV and 0.6 MW, respectively. In the second step, the injection energy will be increased to 400 MeV to achieve an output of 1 MW. The three linear sections are used for injection and beam collimation, extraction and acceleration.

TABLE 3. Main Parameters of RCS

Circumference	348.3 m
Injection Energy	181 MeV/400 MeV
Extraction Energy	3 GeV
Beam Power	600 kW/1 MW
Particle Per Pulse	$5x10^{13}/8.3x10^{13}$
Repetition Rate	25 Hz
Collimator Aperture	324 πmm-mrad
Physical Aperture	>486 πmm-mrad
Quantity of Bend. Magnet	24
Quantity of Q-magnet	60

II .B.2. Construction-Related Topics

This section describes some topics involved in the construction of the RCS. The first topic is the development of a large ceramic duct. The beam from the linac is painted in the vertical and horizontal directions to reduce the space charge force of a large-current beam. The horizontal paint area is 216 πmm-mrad. Consequently, the maximum bore of the quadrupole magnet is 410 mm. The largest ceramic duct for the quadrupole magnet has an inner diameter of 377 mm and has copper stripes on the surface and a high-frequency capacitor at the end.[4] The ceramic duct for the bending magnet is a 3.5-m long race track type as shown in Fig. 4. Stranded wire is used for the wound wire of the bending and quadrupole magnets to reduce the eddy current flowing in the wire and increase the Q value of the power supply network.[5]

Fig. 4. Ceramic duct for bending magnet is shown.

II .B.3. Installation and Hardware Commissioning

The installation of bending, quadrupole, sextupole and steering magnets began in 2006 and all of them were installed in the tunnel by the end of March 2007. A power supply to drive each of these magnets was installed in the respective power supply rooms. Cables to connect the power supplies to the magnets were all installed. Fig. 5 shows the bending and quadrupole magnets installed in the tunnel.

The RCS uses 60 quadrupole magnets of 7 families. A power supply test of the quadrupole magnets began in November 2006. The power supply of each family generates a direct current equivalent to the injection energy and a current with a sine waveform corresponding to the acceleration energy is superimposed. Each power supply is independently operated but all of the families must be operated at a repetition rate of 25 Hz in precise synchronization with each other.

Fig. 5. All magnets have been installed in the RCS tunnel.

The power supply test of all of the quadrupole magnets of 7 families was completed in 2006. Subsequently, the power supply to drive 24 bending magnets was adjusted. At the moment, the deviation from the ideal magnet current is still a little large, but is enough adequate for the initial stage of beam acceleration. Further tuning has been continued aiming 0.1% deviation.

II .B.4. RF Accelerating Cavities

The accelerating cavities are designed, using a magnetic alloy, to produce strong acceleration electric fields. The acceleration electric field gradient is about 25 kV/m. The accelerating cavities were developed in the expectation of significantly exceeding commonly used acceleration gradients. Many initial troubles occurred, as is commonly encountered when developing new technologies such as this. New technologies were also developed in connection with the accelerating cavities.[6] A particular challenge encountered in the development process was the melting of small spots that were produced on the surface of the core in the cavities after operation. After the process of manufacturing cores was reviewed and improved, all of the cores used were tested for 300 or 1,000 hours under actual operating conditions. In these tests, no melting spot was observed. Fig. 6 shows the accelerating cavities that were installed in the tunnel after the test.

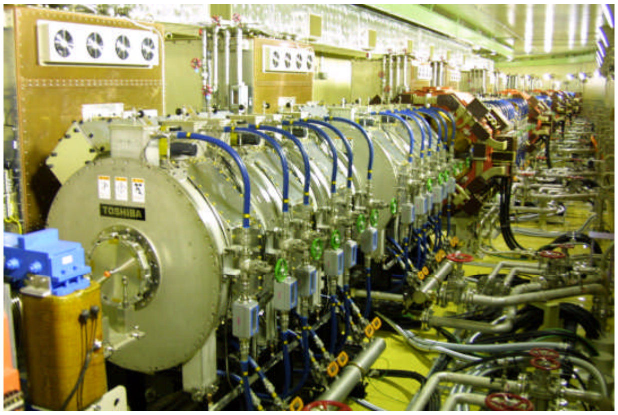

Fig. 6. Ten units of RF cavities have been installed in the RCS tunnel.

II .B.5. Injection Components

The injection components of the RCS have a very large aperture and many of them were difficult to design. Four shift bump magnets, four horizontal paint magnets, a charge stripper foil holder and other components are installed in close proximity to each other.

A charge stripper foil is a key component for a large current injection. A thin carbon foil or a diamond foil is commonly used, but these foils will have short lifetime at around 1800K due to large current. In order to overcome this problem, a new foil named HBC (Hybrid Boron mixed Carbon) foil was developed for use in the RCS. The HBC-foil showed a much longer life than those of a diamond foil and a commercial available foils.[7]

The shift bump magnets used in the injection section are required to turn the magnetic field intensity down rapidly in just 150 μsec after maintaining it at 1.6 Tesla for 500 μsec in order to improve beam performance and reduce thermal load on the charge stripper foil. A test was conducted to confirm that the magnets and the power supply met this performance requirement and then the shift bump magnet was installed in the tunnel.

A total of eight kicker magnets for extraction are used to deflect a beam by 17 mrad. All of the kicker magnets were tested for performance and then installed in the tunnel.

Off-beam hardware commissioning to check the operating performance of the RCS by operating almost all of the components at the rated power is underway and will complete in August 2007. The linac will start sending in an H^- beam to RCS in September 2007.

II .C. MR

The MR is a slow cycling synchrotron with a circumference of 1,568 m. In the base design, the repetition rate is about 0.3 Hz and the maximum beam output is 50 GeV, 750 kW. Higher repetition rate of 0.5 Hz is optional at 30 GeV operation. The main parameters of the MR are shown in TABLE 4. Magnetic field measurements of all of the bending, quadrupole and sextupole magnets were completed[8], and all of them were installed in the tunnel in March 2007 as shown in Fig. 7. The power supplies are now being installed at a rapid pace. RF cavities for the MR have been tested following the same procedure used in the RCS. Five sets of RF cavities are ready for installation. Wiring for the MR will be completed in November 2007, and hardware commissioning will begin in December 2007.

In parallel with the installation of magnets, almost all of the components used for injection and extraction are being tested on the Tsukuba campus. The injection and extraction components of the MR are required to generate very intense magnetic fields with a wide aperture to extract a high-energy, very high-output beam of 750 kW. Their manufacturing is a technological challenge. Operation experience of the 12 GeV proton synchrotron (KEK PS) at KEK indicates that the beam loss is concentrated at the injection and extraction sections. Furthermore, the injection and extraction components have lower reliability than the other components and require frequent maintenance resulting high radiation exposure, so it is necessary to check that they are sufficiently reliable. This will be done in off-line tests and necessary improvements will be made before the components are installed. Described below are examples of such improvements.

II .C.1. Pulse Bend Magnet

The pulse bend magnet to separate the output beam from the RCS into one for MR injection and the other for the MLF laboratory is required to start up at beam intervals (40 msec) of 25 Hz, to shut down at the same intervals after injecting 4 batches (8 pulses) to the MR, and not to affect the beam to the MLF. Magnetic field measurements of the magnet showed that the temporal flatness of the magnetic field after its startup was inadequate. The cause was found to be that the eddy current flowing through the magnet slowed the rise of the magnetic field. Improvements were made to compensate the reduced magnetic field intensity by slightly increasing the current at rising edge of the power supply. As a result, the flatness of the magnetic field met the requirement of 1×10^{-4} (Ref.9). A pulse bend was installed in the tunnel after the improvement.

TABLE 4. MAIM PARAMETERS OF MR

Circumference	1567.5
Injection energy	3 GeV
Extraction energy	50 GeV Max.
Beam power	750 kW
Particle per pulse	3.3×10^{14}

Repetition rate	0.3 Hz
Collimator aperture	54 πmm-mrad (variable)
Physical aperture	81 πmm-mrad
Bending Magnet	96 units
Q-magnet	216 units
Sextupole magnet	72 units
Steering magnet	186 units

Fig. 7. All magnets have been installed in the MR tunnel.

II .C.2. Kicker Magnet for Fast Extraction

The kicker magnet for fast extraction has an effective aperture of 100 × 100 mm and is of a distributed-constant type, with a characteristic impedance of 5 ohms, that generates a maximum current of 8 kA. It is 2.4 m long. This kicker magnet has a bipolar function: one is for fast extraction for neutrino experiment and the other is used to abort beams for machine protection.[10] Some problems were identified and corrected during testing.

The major improvements made are that the method of securing the electrodes was improved to prevent the movement of electrode when baking is repeated and that the electrodes were further rounded to reduce magnetic field intensity. The target extraction energy for Phase 1 is 30 GeV. Temporal flatness of a BL-product for the magnetic field intensity corresponding to 30 GeV is better than +/-0.5 %. Further efforts are required to enable reliable operation at higher energy levels.

II .C.3. Septum Magnet

There are ten septum magnets for fast extraction: four with a septum thickness of about 7 mm and weak magnetic fields, and six with a septum thickness of over 30 mm and strong magnetic fields. Magnetic field intensity measurements were carried out on the six magnets with strong magnetic fields, and all of them were confirmed to meet the specifications. For those with weak magnetic fields, ceramic sleeves to secure insulation of the electrodes broke during the test operation and are now being repaired. The cause may be that the ceramic sleeves were thin and not strong enough, and also that the electrodes behaved in an unexpected manner. The electrode behavior when patterned current is supplied is being observed to study a more reliable method of securing the electrodes.

If a component failure occurs after the facility commences operation, repairs will have to be carried out in a radioactive environment. Therefore, it is our policy to identify and correct design and manufacturing defects during testing. As described above, some problems were identified in injection and extraction components and corrected during testing, while other repairs are still underway. Improvements will be steadily made in steps to ensure adequate reliability of injection and extraction components.

III. MAINTENANCE SCENARIO

Beam loss is a significant factor determining the performance of a proton accelerator, and is allowed only within a maintainable range. In the linac, halo collimators will be installed before the injection section of the RCS to remove halos before they enter the RCS. In the RCS and MR, it is a principle for the J-PARC accelerator to reduce beam loss in locations other than the collimators by limiting the aperture with the collimators and to carry out hands-on maintenance. The beam loss in the normal section except for injection, extraction and collimators is expected to be 1 W/m in the RCS and 0.5 W/m in the MR, respectively. Beam simulation predicts very small beam loss at beam injection and extraction but operation experience of accelerators teaches us that unexpected beam loss will occur in these locations. Components will be activated by the proton beam lost, making their maintenance difficult. It is therefore very important in this accelerator to prepare a method of post-activation maintenance. This section describes a maintenance scenario for the MR.

In the MR, two beam collimators are installed, one in the beam transport line from the RCS and the other in the ring. The allowable beam loss is 450 W for both locations. Beam loss is expected to occur at three more locations, the injection section, fast-extraction section and slow-extraction section, in addition to the collimators, thus special maintenance is required for a total of five activated zones. Fig. 8 shows the potential high radiation zones to which maintenance scenario will be applied.

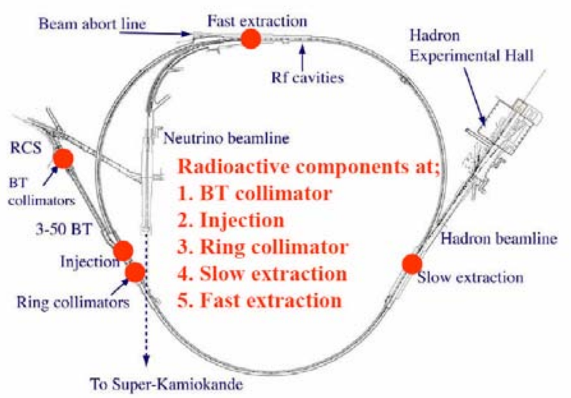

Fig. 8. Five potential hot zones in the MR: BT collimator, injection, ring collimator, slow extraction and fast extraction.

Experience in the PS at KEK shows that residual radiation at a worker's position must be below 0.5 mSv/h; maintenance work will be difficult if the residual radiation exceeds this limit. Needless to say, all work in a radioactive environment should be carried out following the ALARA (as low as reasonably achievable) principles. Measures to reduce radiation exposure are to reduce work time, to increase a worker's distance from a radiation source and to install radiation shielding. An analysis of the maintenance work for the PS shows that it will take many hours to remove a large, heavy component with an imbalance in weight distribution, such as septum magnets for injection and extraction, from the beam line, resulting in increased radiation exposure. Therefore, efforts should be focused on reducing the time for removing such large and heavy components.

It is also important to reduce the time for removing the vacuum flanges of these components. As a result of a study on how to maintain these components in the MR injection and extraction sections as quickly as possible, first, components for injection and extraction will be installed on the linear motion guide to allow them to be easily removed from the beam line. Second, the flanges on both ends of a component will be removed by semi-remote operation at some distance from the component. Third, if possible, radiation shielding will be installed between an activated component and workers.

III.A. Linear Motion Guide

If components are installed on the linear motion guide, the time for pulling out a failed component from the beam line can be reduced. Even if a component has an imbalance in weight distribution, a wide work area can be provided by pulling it out sufficiently away from the line.

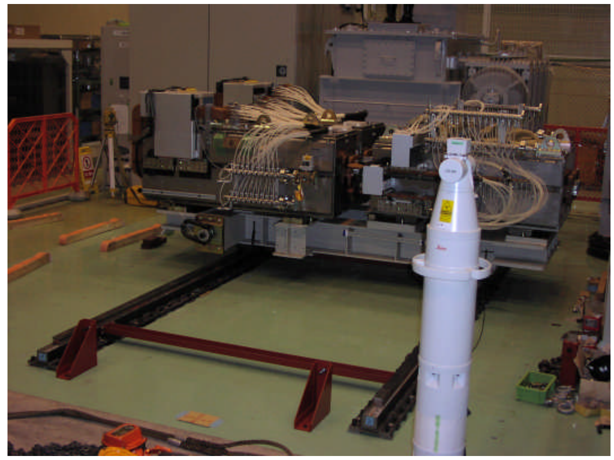

Fig. 9. Septum magnet installed on the linear motion guide.

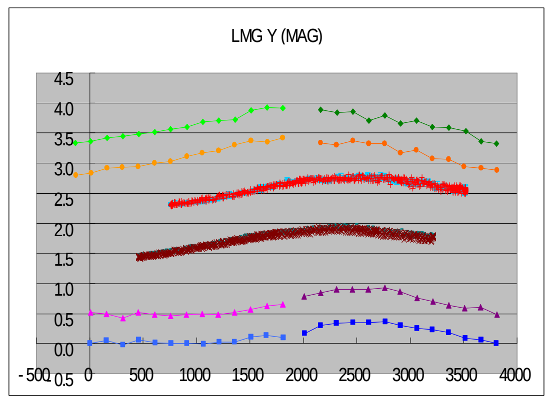

Fig. 10. Test result of reproducibility of the magnet position. Central 2 lines show position of septum magnet when the septum magnet was pulled-out and returned . Horizontal: 500mm/div. vertical: 0.5 mm/div. Width of the lines corresponds to the position deviation.

Fig. 9 shows the heaviest septum magnet in the MR installed on the linear guide rails. The reproducibility of the pulled-out and returned positions of this magnet was very good, with a deviation of about 100 microns. Test result of position reproducibility of the mounted septum magnet is shown in Fig. 10. (Ref. 12)

III.B. Semi-Remote Flange and Shielding

ISO 1609-compliant Cefilac vacuum flanges are used in the MR. Fig. 11 shows the device to semi-remotely connect/disconnect flanges, which was developed based on the Cefilac's remote handling clamp.[11] In the MR, semi-remote flanges in sizes of 180 to 450 mm will be used at 48 locations. As with the flanges, cables and coolant tubes will be able to be connected or disconnected in a quick motion to injection and extraction components.

When enough working space is available, radiation shielding installed between a radiation source and workers will reduce radiation exposure significantly. The lead glass that was used in detectors in physics experiments will be re-used as shield material between an activated component and workers. Lead glasses have enough radiation shielding ability and furthermore transparent to give a wide visual field.

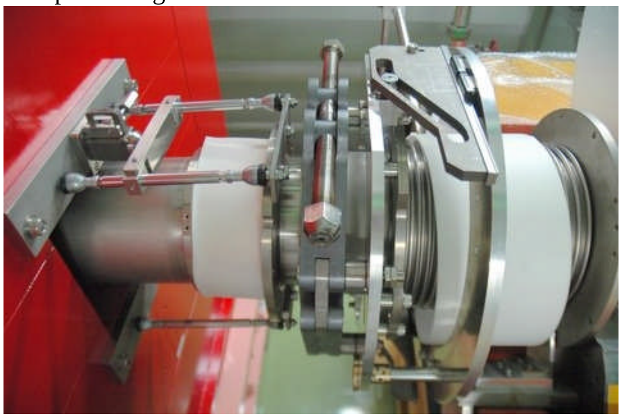

Fig. 11. Semi-remote flange installed at exit of the beam transport (BT) line collimator.

Ⅳ. CONCLUSIONS

At J-PARC, the first beam acceleration of the LINAC was carried out in January 2007. Construction of the facility is well underway on schedule. An RCS beam test will begin in September 2007, and an MR beam test in May 2008. At the Materials and Life Science Experimental Facility, a neutron production test will start in 2008. Beam supplies to the Hadron and neutrino facilities will commence in December 2008 and in April 2009, respectively. R&D for radiation maintenance is also being progressed.

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