J-PARC PROGRESS AND CHALLENGES OF PROTON SYNCHROTRONS

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Abstract

On October 31st, 2007, the Rapid-Cycling Synchrotron (RCS) successfully accelerated a proton beam to the design energy of 3 GeV and extracted it to a 4 kW beam dump at Japan Proton Accelerator Research Complex (J-PARC). This is an important step for the joint project between High Energy Accelerator Research Organization (KEK) and Japan Atomic Energy Agency (JAEA). This goal was obtained a few months earlier than scheduled. The successful start of the beam commissioning of the J-PARC RCS made the RCS option very promising to achieve the high proton beam power. This presentation will concentrate itself on the outcome of the J-PARC RCS commissioning program, including the discussion on the challenges of the high-power proton synchrotrons.

INTRODUCTION

The High-Intensity Proton Accelerator Project in Japan[1] is referred to as “J-PARC Project”, which stands for Japan Proton Accelerator Research Complex. The facility is under construction as a joint project between High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA) at Tokai site of JAEA as shown in Fig. 1. An H^- beam with a peak current of 50 mA and a pulse width of 500 μs is accelerated up to 400 MeV by a linac, and then injected to a 3 GeV Rapid Cycling Synchrotron (RCS) with a repetition rate of 25 Hz. The linac can be operated with a repetition rate of 50 Hz; the remaining half of the beam will be used for the basic study of the Accelerator Driven Nuclear Waste Transmutation System (ADS) in future.

The beam accelerated by the RCS with an average current of 333 μA and a beam power of 1 MW is fast extracted and transported to the Materials and Life Science Facility (MLF) most of the time. In the MLF, a muon and a neutron production targets are located in a series. About 10 % of the beam is used for the muon production. Every 3.64 second, the beam is transported to a 50 GeV Main Ring Synchrotron (MR) and injected to it. The accelerated 50 GeV, 0.75 MW beam is slowly extracted to the Hadron Experimental Facility with a duration of 1.6 sec. Kaon-rare decay experiments, hyper-nuclei experiments and so forth will be conducted there. The beam is fast extracted to a neutrino production target also. The neutrinos thus produced are sent to the SUPERKAMIOKANDE detector located 300 km west for the long base-line experiments. The 400 MeV linac beam will be further accelerated to 600 MeV by the superconducting linac and will be used for the basic research on the ADS.

This is a full scope of the J-PARC project. However, the project was divided into two phases, and only the Phase I was funded for construction. The ADS and nearly a half of the Hadron Facility were shifted to the Phase II, and the MR energy was limited to 40 GeV on the Phase I. Also, the linac energy will be 181 MeV at the beginning, although the linac building can house the 400 MeV linac. The beam power of the RCS will be at most 0.6 MW until the linac energy becomes 400 MeV. Every effort is under way in order to start the linac energy upgrade to 400 MeV, just after the completion of the Phase I construction, that is, next fiscal year.

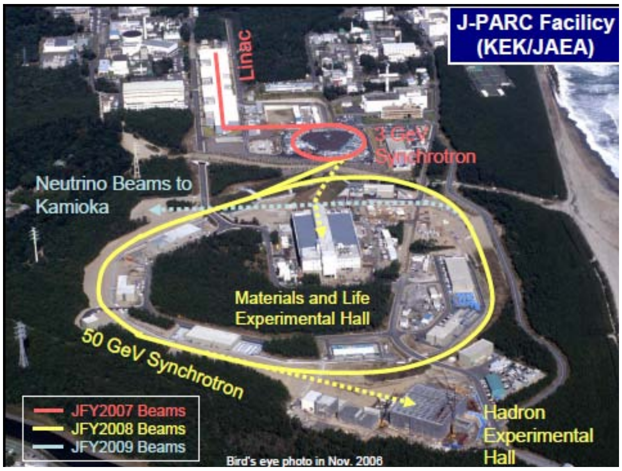

Figure 1: J-PARC facilities.

The linac beam commissioning has started in December, 2006, and the RCS beam commissioning in September, 2007. On January 24th, 2007 the linac accelerated the H^- beam up to the energy of 181 MeV which is the design value [2], and we accelerated the 181 MeV beam injected from the linac to the designed beam energy of 3 GeV via the RCS, and extracted it to the beam transport (referred to as 3NBT) to the muon and neutron production targets on October 31st, 2007. Afterwards, the measurement of the radiation levels has been carried out by the authority on November 28th and December 20th at the beam dumps for the extracted beam at 3 GeV and the H0 beam at 180 MeV, respectively. The latter dump is used in the case of a failure to strip two electrons from a negative hydrogen ion at the first charge exchange foil. Both the beam dumps can accept beams up to 4 kW and the inspections were conducted at a quarter of the beam power, that is, 0.8 kW. Note that the inspections have been successfully passed with very stable operation of the linac and the RCS for several hours. This implied that we obtained the official permission to operate the RCS and was an important step towards the beam commissioning of the MLF and the MR, which has started from this May.

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CHALLENGES AND ISSUES

The distinctive features of the J-PARC accelerator are arising from its multi-purpose concept; the realization of the MW beam powers in both several GeV and several tens of GeV region. Since the 50 GeV synchrotron requires the several-GeV beam injection at a rapid cycle, the accelerator scheme based upon the RCS has been chosen to provide the pulsed-neutron target with a MW beam. The details of the accelerator design are reported in Ref. [1]. Although it is quite common to use the Accumulator Ring (AR) system with a full-energy linac for pulsed-neutron source like SNS, the RCS system may be more powerful than the AR system for the following reason.

A linac is easy to design, to build and to operate, since the beam automatically goes straight. A ring is also easy, since it has the stability arising from its high periodicity. On the other hand, the beam is forced to inject into, and to extract from the ring. These are very difficult processes to manage. Then, if one manages to inject the beam, why not accelerate? One can easily increase the beam power.

In other words, the RCS scheme is advantageous over the AR scheme regarding the lower beam current and the lower injection energy for the same beam power. The higher beam loss is allowed during the injection process, into which most of the beam loss is concentrated among all. If one increases the beam energy by a factor of 7.5 like the J-PARC case, the allowed beam loss during the injection is 7.5 times as high as that for the AR with the same beam power. These points are discussed in more detail in Ref. [3]. For these reasons, we decided to develop the high-power, high-energy RCS and has challenged to solve many issues for realizing the high power proton beam as follows,

The Rapid-accelerating System with High Field Gradient Cavities

In order to realize a high-power, rapid-cycling proton synchrotron, we need the rapid acceleration. For the rapid acceleration we need the high field gradient in the accelerating cavity. The high field gradient at the accelerating gap can be induced only by high RF magnetic flux in the magnetic core. The ferrite which has been conventionally used in proton synchrotrons has a problem that the μQf value, which is proportional to the shunt impedance, rapidly decreases, as one attempts to generate the field typically beyond 10 or 20 kV/m. On the other hand, the μQf value of the magnetic alloy (MA) core has most flat response to the magnetic flux which produces the electric field gradient up to an order of 100 kV/m. Therefore, the high field gradient is potentially feasible by using the MA core [4, 5, 6].

The long-run, high-power operation test of the MA-loaded cavity has started from 2005. Then, we found one core was damaged on the surface around 50 hours. This core was installed the nearest to the acceleration gap, being loaded with the highest transverse electric field. This was the start point to grapple with the MA core development. We decided to check all the cores before their installation in the cavity. Each cavity was operated up to 300 hours, since the problem at the initial stage usually happened during the first 50 hours operation. During the course of this RF cavity testing, we learned that the poor electric insulation has something to do with the damage [7]. The MA core is formed by winding the MA tapes 35 mm wide, 18 μm thick with 2 μm silica insulator on one side. Some damaged MA cores had already revealed the low resistance between the MA layers prior to the high-power test. This indicates that the damage occurred at the poor insulation between the MA layers, when powered. We improved the manufacturing process of the MA cores in such a way that the thin silica insulators can keep the good insulation throughout the winding process and others. Afterwards the test results have been drastically improved.

This is truly the innovative development of the accelerating cavity loaded with magnetic alloy (MA). Ten RF cavities loaded with MA cores, which passed more than 300 hours operational test, were installed in the RCS tunnel as shown in Fig. 2. All the cavities have been in operation at the maximum acceleration gap voltage of 40kV/cavity without any problem more than 1000 hours [8, 9].

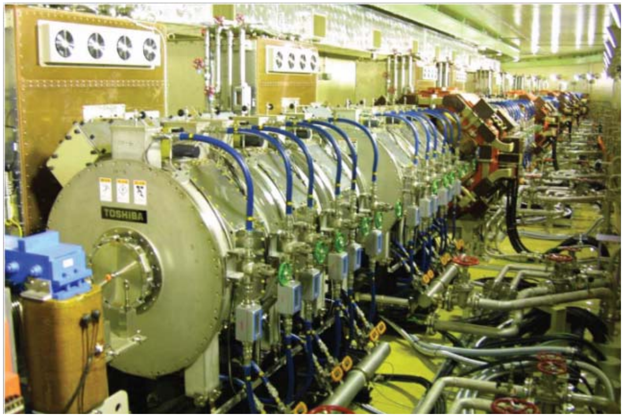

Figure 2: High field gradient RF cavities loaded with MA cores.

Large Aperture Magnet with Little Eddy Current Effect due to Rapidly Changing Magnetic Field

We had to develop large aperture, radiation-hard magnets with little eddy current effect arising from the rapidly changing magnetic field [10]. The RCS main magnet system comprises 25 dipoles (1 monitor magnet included), 60 quadrupoles and 18 sextupoles. The coils for these main magnets are made of aluminum-stranded conductors which consists of many electrically-isolated thin wires wrapped around a stainless-steel water-cooling pipe and is isolated by polyimide resin whose resistance for radiation is more than 10 MGy [11].

In order to keep the sufficient acceptance for the low energy beam injection all the magnets must have the large physical apertures. As a result, most of the quadrupole magnets are quite short with the large apertures, and are located very close to each other. This is partly because the ring circumference was limited, partly because the frequent focusing is necessary for mitigating the space charge defocusing effect. We worried that the fringing field effects are substantial for these magnets, and the interference between the fields of the two neighbouring magnets is not negligible. In addition, the saturation effects should be taken into account at the core ends. These effects altogether might give rise to large higher multi-pole components in their fields, resulting in the small dynamic aperture. Fortunately, the dynamic aperture was still sufficiently large, when the magnetic fields measured for the actual magnet layouts were taken into account in the beam simulation.

Figure 3: Large aperture quadrupole magnet.

Precise Magnetic Field Tracking

Magnets are formed to some resonant networks and excited by a current with DC-biased sinusoidal waveform. Resonant networks are generally configuration in either parallel or series resonance. In parallel resonance the AC and DC power supplies are separated, but in series resonance the AC and DC components can be combined and supplied with one power supply. By carefully investigating the peak current, circuit simplicity, current controllability, and state of the art of power electronics, parallel resonance was adopted for dipole magnet network and series resonance for the quadruple magnets networks. Since the quadruple magnets were grouped into 7 kinds, totally 8 independent resonance circuit should be excited. All the circuits are driven by IGBT (IGBT: Insulated Gate Bipolar Transistor) based power supplies, because lower harmonic components and fast response could be obtained by using IGBT power supplies. The precise control is necessary for tracking all the eight families of the magnets, in particular, in the present case that each family of the magnets has its own saturation effect. For this purpose, the IGBT devices are ideal by its fast switching characteristics. On the other hand, the fast switching implies that care should be taken of even very high-frequency components of the electromagnetic power. The components of the eight resonant circuits are driven by the power supplies with the very high frequency components. From the beginning it was foreseen that the electromagnetic compatibility issue would be hard to solve. For this reason, we scheduled nearly one year for powering and controlling tests in-situ. In fact, the circuit systems altogether form distributed three-dimensional circuit systems coupled with each other. Even some chassis or some grounds revealed several hundred volts at some frequency components. After nearly one year painstaking effort almost all the electromagnetic issues have been solved, except for the shift-bump system. Figure 4 shows the deviation of dipole magnetic field from the ideal sinusoidal field. The quadrupole magnets are operated with sinusoidal. In our system, magnetic field tracking of less than 10^{-3} has been performing during beam operation. Together with these magnet-excitation tests the in-situ efforts were exerted to improve the signal-to-noise ratios of almost all the beam diagnostics systems, by means of filtering the noises.

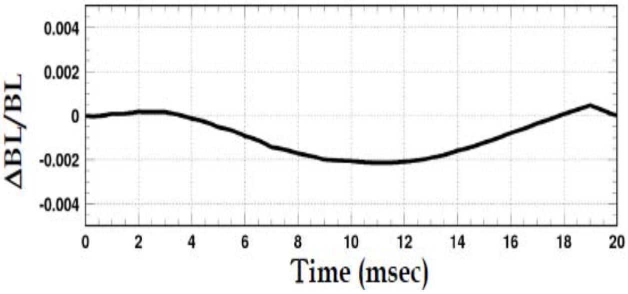

Figure 4: Magnetic field tracking of dipole magnet. Deviation of dipole magnetic field from the ideal sinusoidal curve.

Low-impedance Ceramics Vacuum Chamber

For mitigating the eddy current effect, all the vacuum chambers exposed to the fast varying magnetic fields have been manufactured of the alumina ceramics. To use a ceramic chamber, some electrically conductive layer is necessary on the ceramics so that the wall impedance is reduced and thus the beam is stabilized. The RF shield is designed as a high frequency pass filter, where eddy current cannot be generated [12].

In order to keep the large aperture with the reasonable cost for the bending magnet (BM), we decided to choose the cross section of the race-track shape for the BM vacuum chambers as shown in Fig. 5. In addition, the special shapes (rectangular and racket-shape cross sections) of vacuum chambers have been produced for the injection section.

The 99.7% alumina ceramics chambers of sub-meter in length, having racetrack and circular cross-sections were sintered and jointed by braze. Several chambers of rectangular and racket-shape cross sections were also produced. The alumina ceramics chambers have copper stripes on the outside surface of the ducts to reduce the impedance. One of the ends of each stripe is connected to a titanium flange by way of a capacitor so to interrupt an eddy current circuit. The copper stripes are produced by an electroforming method in which a stripe pattern formed by Mo-Mn metallization is first sintered on the exterior surface and then overlaid by PR-electroformed copper (Periodic current Reversal electroforming method). In order to reduce emission of secondary electrons when protons or electrons strike the surface, TiN film is coated on the inside surface of the ducts [13].

Since the development and/or the mass production of the ceramics vacuum chambers, in particular, with the special shapes, took much longer time than expected, some chambers were delivered to the J-PARC site just in time [14].

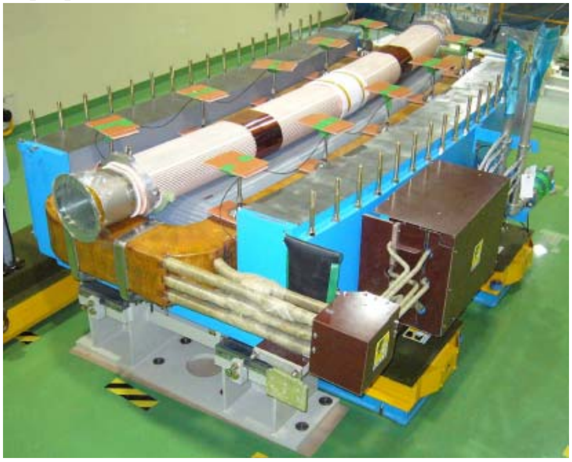

Figure 5: Ceramics vacuum chamber installed in BM

Injection and Extraction

The injection and extraction devices for the large aperture of the beams were another challenge to develop and manufacture. The injection scheme is hard to design for the large beam aperture [15, 16]. A beam collimation system is prepared to localize the loss for blow-up beams [17]. Leakage of the magnetic field is evaluating and the magnetic shield is carefully designing [18]. The large aperture magnets and powerful power supplies were developed [19]. In particular, the injection bump magnets, comprising the shift bump and the painting bump, have still some issues arising from the fast switching of the IGBT and others, since the decay of these magnetic fields should be faster than 100 μs for reducing the number of hitting of the circulating beams on the charge-exchange foil [20]. The capacitors installed to the ceramics vacuum chamber, through which the mirror current passes, were damaged by this fast falling field.

Transition Free Lattice

Both the RCS and the MR are designed on the base of the lattices with low and negative momentum compaction factors, respectively, which implies no transition crossing during acceleration. The beam loss inherent to the transition crossing will be thus avoided.

In the case of high power operation which was 1.07 x10^{13} protons were accelerated and extracted, the beam loss observed at the beam collimator was about 6.5 %. Figure 5 shows beam survival rate during beam operation [21]. Here, note that almost all of the beam loss occurred during the beam injection. In the conventional lattice design, the beam inevitably passes through the transition energy during the acceleration. At the transition energy, no stabilizing mechanism works for the longitudinal degree of freedom in such a way that the synchrotron frequency becomes zero at the transition, inevitably giving rise to the beam loss. In the J-PARC RCS lattice design, the transition energy was raised to 9 GeV, which is far above the operational energy, by choosing the missing bend lattice. This can be the reason why no beam loss was observed during the acceleration.

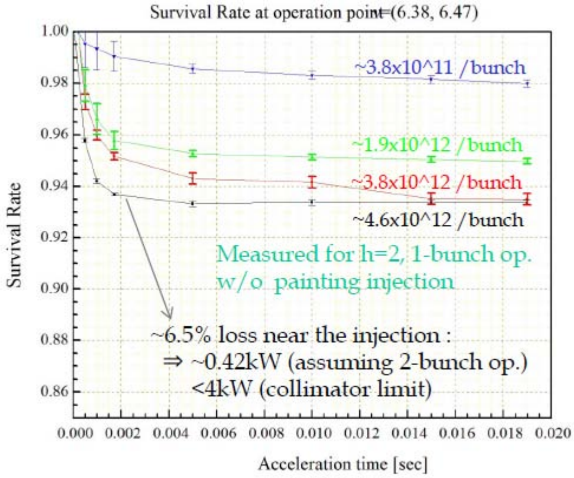

Figure 6: Beam survival rate during beam operation. Operation condition; harmonic number: 2, bunch number: 1, w/o injection painting

The technical issues for the RCS have been solved in this way. The challenge in developments and mass productions of the technically difficult components have been successful, all the components working well.

BEAM COMMISSIONING STATUS

On October 31st, we accelerated the 181 MeV beam injected from the linac to the designed beam energy of 3 GeV via the RCS, and extracted it to the beam transport (referred to as 3NBT) to the muon and neutron production targets. Just after the extraction we had the 4 kW beam dump, to which the beam was transported until the targets were ready. Exactly as scheduled, we started the beam commissioning of the RCS in the run starting September 10th after the long summer shutdown. The linac was again in operation and the beam was successfully transported from the linac to the RCS on October 2nd. Then, the H^- beam was transported to the H^0 dump located at the injection section of the RCS on October 4th without the charge exchange foil, well simulating the behavior of the H^- beam, for which the charge stripping would be failed. Then, the charge exchange foil was installed during the scheduled two week shutdown. On October 25th, the proton beams produced by stripping two electrons of the H^- ion beam via the foil was transported through one arc of the RCS and extracted to the beam dump at the 3NBT. Next day, the beam was successfully circulated in the RCS, was captured in the RF separatrix, and was extracted to the 3NBT. Finally, at 2:03 pm on October 31st, we could accelerate the beam to the designed beam energy of 3 GeV and extract it to the 3NBT dump via the kicker system [22].

At the end of October we had a successful acceleration in the RCS. Four months later, at the end of February of 2008, the beam study result was demonstrated as follows. First, 4.4x10^{12} protons were extracted from the RCS over 4 minutes at the energy of 3 GeV and a repetition rate of 25 Hz. This corresponded to the beam power of approximately 50 kW (note that the designed number of protons accelerated and extracted is 8.3 x10^{13} at the designed repetition rate of 25 Hz and at the designed energy of 3 GeV, corresponding to the beam power of 1 MW). The operation was terminated here, since the beam dump at the extraction could only accept the beam power of 4 kW averaged for one hour. In this case, only one bucket was filled rather than two available buckets. Second, the two buckets were filled out to form two bunches in the RCS. In this way, 1.07 x10^{13} protons were accelerated and extracted just once, although all the accelerator components were in operation at a full repetition rate of 25 Hz. This corresponded to a beam power of 130 kW, if the beam is injected at the designed repetition rate of 25 Hz. In both cases, the linac beam with the emittance of approximately a few π mm mrad was directly injected to the RCS without any painting, which was designed over the available RCS aperture of 324π mm mrad to mitigate the space charge effect. Even under this condition, the beam loss observed at the beam collimator was only 6.5 %, corresponding to 0.5 kW, which was well below the designed capacity of 4 kW for the beam collimator. Here, note that almost all of the beam loss occurred during the beam injection and they were disposed in the beam collimator located at injection area. The demonstrated result indicates that the beam power of 130 kW is promising on the neutron production target, if operated at 25 Hz, and that more beam power is promising, if the beam is painted over the available RCS aperture.

Importance of LINAC Stability for RCS

A role of the injector linac is very important to inject the high intensity proton beams to a ring. The stable, low emittance beams should be prepared. In particular, the stability of the beam energy is most important. For this reason we have also been concentrating our effort into building the high quality linac.

In order to minimize the radio activation of the accelerator components, the above beam commissioning was done with one shot of the linac beam. The usual process of the beam study was as follows. One shot of the linac beam was injected and data as many as possible were taken by use of this one shot of the beam. After the data was analyzed, the new ring parameters were chosen and then next shot of the beam was injected. Sometimes, the latter shot was injected one hour after the former shot. Even that time, the linac beam was injected to the exactly same position with the exactly same momentum as those of the former, as far as the RCS monitors could detect. Therefore, we could accumulate the sensible beam data shot by shot with a minimum amount of the radio activation on the accelerator components. If the integration of the data was necessary for improving the signal-to-noise ratio, the number of shots was increased until the S/N ration was improved to the required level. In this case, the injection repetition was 1 Hz. One of the reasons for the early accomplishment of the 3GeV acceleration was the extremely stable beam from the linac.

CONCLUSION

Almost all the technical issues for the RCS have been solved to some extent. In contrast to the expectation, the RCS reached the pretty high power level within the first four-month period, after the injection, the acceleration and the extraction of the RCS beams successfully started at 3 GeV. This implies that the RCS is quite easy to operate, once its technical difficulties were overcome. The successful start of the beam commissioning of the J-PARC RCS made the RCS option very promising to achieve the high proton beam power.

REFERENCES

[1] KEK Report 99-4 and JAERI-Tech 99-056 (1999).
[2] K. Hasegawa, PAC'07, 2169(2007).
[3] Y. Yamazaki, EPAC'08, THPP084.
[4] M.Yoshii et al., EPAC2002, 2181(2002).
[5] T. Uesugi et al., PAC2003, 1234(2003).
[6] C. Ohmori et al., EPAC2004, 123(2004).
[7] M. Ymamoto et al., EPAC2006, TUPCH131.
[8] M. Ymamoto et al., PAC'07, TUPAN063.
[9] M.Yoshii et al., EPAC'08, MOPC134.
[10] N. Tani et al., IEEE Tran. On Applicated superconductivity, Vol.14 N02, (2004) 409-412.
[11] N. Tani et al., to be published in IEEE Tran. On Applicated superconductivity, (2008) .
[12] M.Kinsho et al., J.Vac.Sci.Technol. A20 (2002) 829.
[13] M.Kinsho et al., Vacuum 81 (2007) 808-811.
[14] Y.Saito et al., J.of Phys. conference series 100(2008).
[15] M.Yamamoto et al., EPAC2006, 1765(2006).
[16] J.Kamiya et al., EPAC'08, THPP097.
[17] M.Yamamoto et al., PAC2005, WPAE013.
[18] M.Yoshimoto et al., EPAC'08, THPP112.
[19] M.Watanabe et al., EPAC'08, THPP134.
[20] T.Takayanagi et al., EPAC'08, TUPD016.
[21] M.Yamamoto EPAC'08, MOPC133.
[22] P.Saha et al., EPAC'08, THPP105.