Path to 1-MW at J-PARC Rapid Cycling Synchrotron

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Abstract The accelerator system at Japan Proton Accelerator Research Complex (J-PARC) has been operational since May 2008 and has mainly been used to perform physics experiments. The accelerator system consists of a Linac, a Rapid Cycling Synchrotron (RCS), and a Main Ring Synchrotron. The originally designed RCS injection energy is 400MeV, but the first operation started at 181MeV. New acceleration cavities were installed in J-PARC Linac during the summer shutdown of 2013, and user operation by the Material and Life science Facility (MLF) at the injection energy of 400MeV was started from February 2014. Post beam commissioning of 400MeV injection energy, beam loss was small enough, and we established 300kW continuous operation. Subsequently, the peak current of the Linac was increased from 30mA to 50mA. This upgrade enabled us to try 1-MW beam acceleration. Finally, after some additional improvements, we successfully accelerated 1-MW equivalent protons.

Keywords J-PARC, Proton Accelerator, High Intensity

1. Introduction

The Japan Proton Accelerator Research Complex (J-PARC) is a facility for performing various physics experiments. J-PARC facilities were constructed at the Tokai site of Japan Atomic Energy Agency (JAEA). The accelerator complex consists of a 400MeV Linac, a 3GeV Rapid-Cycling Synchrotron (RCS), and a Main Ring synchrotron (MR) [1]. The RCS delivers a 3GeV high-power proton beam to the Material and Life science Facility (MLF) and MR. Beam commissioning of the Linac started in November 2006 [2-4]. Construction of other accelerators and experimental facilities continued thereafter, and the RCS started to deliver a proton beam to the MLF in May 2008 [5]. User operation of MLF started in December 2008 [6], and beam power was increased gradually. However, the great east earthquake caused severe damage to all J-PARC facilities in March 2011. We completed the

recovery work in only nine months and restarted user operation [7]. After the earthquake, we smoothly increased the output power, and user operation at 300kW was started at the end of 2012 [8]. However, it was necessary to improve the Linac and the RCS to increase output power. Then, the acceleration energy of the Linac was raised to 400MeV by installing a new acceleration cavity in the summer of 2013. The injection system of the RCS was also upgraded simultaneously to accept 400MeV injection beam. In addition, the front end was replaced in the summer of 2014 to increase the beam current of 50mA to achieve 1-MW beam acceleration.

2. RCS Injection Energy Upgrade in 2013

2.1. Linac

To increase the output power of the RCS, the acceleration energy of the Linac was increased from 181MeV to 400MeV at the first set-out. This energy upgrade aims to mitigate the effect of space charge in the RCS injection process and to reduce beam loss. Therefore, the ACS (Annular-ring Coupled Structure) cavity was developed [9, 10]. Twenty-one ACS modules are used for the acceleration. In addition, two ACS bunchers are used for longitudinal matching before the ACS acceleration, and two ACS debunchers are used to reduce the energy spread before the RCS injection. To summarize, total twenty-five ACS modules are necessary. The ACS cavities were installed in the summer shutdown period of 2013 [11]. Figure 1 shows the Linac accelerator tunnel after installation of the ACS cavities. After installation of the ACS cavities, we started high-power conditioning of the ACS cavities. Figure 2 shows the typical conditioning history of the ACS cavity. In the conditioning sequence, we put short pulse RF (50US) up to 2MW at first. Thereafter, we put longer pulse RF (600US) up to 2MW. The average conditioning time for one ACS cavity is 149h. The detail conditioning sequence can be found in [12].

Figure 1. Linac accelerator tunnel after installation of ACS cavities

Figure 2. Typical conditioning history of ACS cavity [12]

2.2. RCS

In the RCS, the power supply for the injection shift bump magnets and the horizontal paint bump magnets was upgraded [13]. Those magnets traverse a painting orbit during injection [14]. A painting injection method is an ordinary way to reduce the space charge effect in a synchrotron [15-18]. The voltage of the power supply was increased by about twice according to increment of the Linac acceleration energy.

The shift bump power supply at the injection energy of 181 MeV is of the IGBT (Insulated Gate Bipolar Transistor) chopper type [19]. It is composed of multiple IGBT assemblies, and its synthetic frequency is 48 kHz. A chopper system has the advantage of flexibility in terms of output waveform, and a similar system is adopted in another accelerator system [20,21]. It can generate arbitrary waveform currents, and we could establish all required injection orbits by using this system in the early days of the RCS commissioning. However, one problem of this type of

power supply is its switching noise. The synthetic frequency of 48kHz and higher harmonics switching noises were observed on the output current monitor and also by means of search coils set inside the magnets. As a result, the beam orbit was shaken by the magnetic field distortion, and a 100kHz orbit ripple was observed by the beam position monitor. This ripple source was certainly originated from the power supply, but the magnets (a load of the power supply) also seemed to enhance the noise [22]. Therefore we developed a new, low-ripple shift bump power supply system considering replacement of the injection system with higher injection energy [23]. The new power supply was designed based on a capacitor bank scheme, and it has lower switching times to generate a trapezoidal current pattern. Thus, switching noise is suppressed well compared to old system. The maximum required current is 32 kV, and voltage is 14.4kV (± 7.2 kV), as defined based on the magnet inductance and the fast rise/fall time of 150 μ s [24].

The paint bump power supply is also of the same type as the old shift bump magnet, namely, IGBT chopper type. This IGBT chopper type is very suitable for generating arbitrary painting orbit patterns, and its required voltage is not as high as that of the shift bump. Therefore, noise is lower than that of the shift bump system and is at an acceptable level. Thus, the faster switching IGBT assembly is adopted continuously for the paint bump power supply [25]. Its synthetic frequency is 600kHz, and fast beam oscillation is not observed.

We checked the new shift bump power supply before continuous operation, and a malfunction was occurred. The diodes in the flattop unit, which works to keep the flatness of the waveform current, were frequently out of order. Owing to the defect of this unit, we were not able to keep the flatness of the waveform current and the flattop region of the shift bump current had a slope [26]. This induced beam orbit shift during injection. Figure 3 shows the magnetic field pattern defect of the shift bump magnet, and the orbit shift due to the defect is shown in figure 4.

Figure 3. Magnetic field pattern of shift bump magnet. When normal, the magnetic field during injection period should be flat. However, it has a slope and decreases 9.17% during injection period.

Figure 4. Orbit shift due to defect of shift bump field. Four shift bump magnets excite one power supply, and these magnetic fields cause the injection and the circulating orbits to merge. Due to slope of the magnetic field pattern, the injection and the circulating beams are separated from each other.

For the moment, we compensated for this orbit shift by using the other magnets. Four paint bump magnets (PBH1-4) were used to correct the shift of the circulating beam orbit, and two pulse steering magnets (PSTR1, 2) were used to correct the shift of the injection beam orbit respectively. Figure 5 shows the current waveforms of the injection magnets for compensation, and the injection orbits before and after correction are shown in figure 6. Owing to this countermeasure, we were able to start beam commissioning with 400MeV injection energy.

Figure 5. Current waveforms of injection magnets for orbit correction

Figure 6. Injection orbit shift before and after correction

2.3. Commissioning with 400MeV Linac

Beam commissioning with the new ACS cavities was carried out from December 2013 to January 2014. Thereafter, we achieved acceleration energy of 400MeV on January 17, 2014 [27]. Then, we started user operation at the acceleration energy of 400MeV, but we need additional study time to mitigate some issues. The first issue is halo formation in the ACS section. This halo causes beam loss in the RCS. Proper matching by means of additional longitudinal monitors is needed. The other issue is high radioactivity at some points in ACS section. To solve these issues, we continue the Linac beam study.

From the Laslett tune shift equation, the magnitude of space charge tune shift is proportional to $\beta^2\gamma^3$, where β and γ are the Lorentz factor [28]. This indicates that the amount of space charge tune shift with injection energy of 400MeV is considerably smaller than that with injection energy of 181MeV. We investigated the effect of injection energy upgrade, and the result demonstrated that beam loss due to space charge tune shift was reduced to an acceptable level [29]. We confirmed the effect of injection energy upgrade.

3. Ion Source Upgrade in Summer Shutdown 2014

3.1. Linac

In summer shutdown period of 2014, we improved many accelerator components of the Linac and RCS. The most important improvement in the Linac is replacement of the front-end system with one having a higher peak current. Figure 7 shows the new front end system. The front-end system consists of a new ion source, new Radio Frequency Quadrupole (RFQ), and some parts of a beam transport line between the new ion source and new RFQ. A cesium-free negative hydrogen ion source driven with a lanthanum

hexaboride filament had been used since the Linac operation began in 2006 [30]. Although it satisfied the initial stage requirement of 30mA in J-PARC, it was proven that this current level did not increase by cesiation. Thus, we have newly developed a cesiated RF-driven ion source to satisfy the Linac upgrade requirements of 50 mA [31]. In the ion source, the source plasma is produced by a 2MHz RF discharge using an internal antenna that was developed at Spallation Neutron Source (SNS) at Oak Ridge National Laboratory [32]. New RFQ is optimized for the beam current of 50mA [33].

The RF-driven H^- ion source and new RFQ were checked on a test bench, which was constructed in the J-PARC Linac building. We checked various parameters of the test bench [34], and we tried long-term continuous operation of this system [35]. Figure 8 shows the test results of long-term operation. Finally, we achieved 683h (about 1 month) of continuous operation. However, RFQ discharge occurred frequently during the long-term operation test. Therefore, we decided to install an additional pump in the

actual beam line and keep conditioning it as and when possible.

Figure 7. New front end system

Figure 8. Result of long-term operation test. There were some beam studies with low peak current during this long-term operation test.

3.2. RCS

The problem of shift bump power supply system was solved in the shutdown period of 2014, and we were able to keep the flat top of the magnetic field at an adequate level. The shift bump power supply used to trip frequently owing to overheating. To solve this issue, we installed additional cooling fans on the housing frame. Herewith, the inside of power supply housing was cooled and the system stabilized [36].

4. Commissioning Towards 1-MW Output Beam

We started beam commissioning of the Linac using the new front end system toward the end of September 2014 after maintenance work in the summer. The Linac beam commissioning progressed smoothly, and a 1-MW trial of the RCS was started in the middle of October.

In this trial, we chose the same parameters as those during user operation; betatron tune is (6.45, 6.42), and second harmonic RF is superimposed on the fundamental RF. Injection beam momentum is offset from synchronous momentum, and transverse painting area is $100 \pi \text{ mm mrad}$. The trial was started from the beam current of 380kW equivalent, and the current was increased gradually to 770kW equivalent. We could accelerate without remarkable losses under these conditions. However, the RF system tripped suddenly when we increased the current to 820kW equivalent (see figure 9). We investigated the cause of this trip and found that the required anode current surpassed the interlock level when the beam intensity was over 800kW [37]. In the RCS, the multi-harmonic feed-forward method ($h = 2, 4$, and 6) was employed for beam loading compensation [38]. Therefore, it was difficult to estimate the required anode current precisely. Figure 10 shows the required anode current of various conditions. The red dotted line in figure 10 corresponds to the interlock level for the anode current at this point, and the red circles denote the required anode current measured in the 1-MW trial. Thus, the required anode current exceeded the interlock level when the beam current was 820kW equivalent.

Since we were not able to accelerate to more than the 800kW equivalent beam in this situation, we decided to increase the resonant frequency of the RF cavity, which had been set to 1.7MHz. This is because impedance of the cavity becomes more inductive upon increasing the resonant frequency. At the higher resonant frequency (more inductive) cavity, the wake field caused by the beam current pushes up the acceleration voltage. Therefore, the required anode current to maintain the acceleration voltage is reduced. Thus, we removed the capacitors from the cavities and raised the resonant frequency from 1.7MHz to 2.1MHz. In addition, the interlock level was turned up to use the entire margin of anode power supply (from 110A to 125A).

The blue line in figure 10 is a new interlock level, and the blue squares show the required anode current of the 2.1MHz resonant frequency system. After these quick measures, we successfully achieved 1-MW beam acceleration in January, 2015 [39].

Figure 9. Beam survival of first trial [37]

Figure 10. Anode current dependence on beam power

5. Conclusions

To achieve 1-MW output power, improvements were made to the J-PARC Linac and the RCS. The acceleration energy of the Linac was raised to 400MeV by installing a new acceleration cavity in the summer of 2013, and the front end was replaced in the summer of 2014 to increase the peak Linac current to 50mA. The injection system of the RCS was upgraded simultaneously to accept a 400MeV injection beam. As a result, we successfully achieved 1-MW beam acceleration in January, 2015. Major components of beam loss in the RCS, which caused by the space charge effect, were well minimized by the injection energy upgrade and the injection painting scheme. For the

moment, the remaining beam loss is mainly from foil scattering during charge-exchange injection. To achieve stable 1-MW user operation, we continue to improve the accelerator system.

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