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APPROACHES TO HIGH POWER OPERATION OF J-PARC ACCELERATOR

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Abstract

The J-PARC linac started beam operation with an energy of 181 MeV in 2006. To realize the nominal performance of 1 MW at a 3 GeV Rapid Cycling Synchrotron (RCS) and 0.75 MW at a Main Ring synchrotron (MR), the linac beam energy was increased to 400 MeV and the beam current was also increased from 30 to 50 mA. After the upgrade, the RCS demonstrated 1 MW equivalent beam operation and currently operates 500 kW for the Material and Life Science Facility. The MR beam power is also increasing and it recently achieved the beam operation of 490 kW for the Neutrino experiment and 51 kW for the Hadron experiment, respectively. At present, we are considering two further upgrade plans increasing the RCS beam power to 1.5 MW and duplation the linac repetition rate to 50 Hz for the planned Transmutation Experimental Facility. To achieve 1.5 MW from the RCS, it is necessary to increase both the beam current and the pulse length about 20% at the linac.

INTRODUCTION

A layout of the J-PARC facilities is shown in Fig. 1. The J-PARC facilities consist of the linac, the 3-GeV Rapid Cycling Synchrotron (RCS), the Main ring Synchrotron (MR) and three experimental facilities of the Material and Life Science Facility (MLF), the Hadron Experimental Facility (HD) and the Neutrino Facility (NU). Construction of a Transmutation Experimental Facility (TEF) is planned in phase-II in the near future. The goal of the J-PARC project in phase-I is to achieve a 1-MW beam power at the RCS and a 0.75-MW beam power at the MR [1].

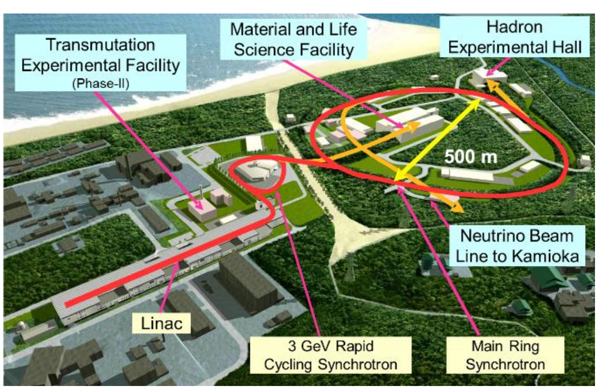

Figure 1: A layout of J-PARC facilities.

In 2006, the J-PARC linac started beam operation with an output energy of 181 MeV and a designed peak current of 30 mA. Thereby, we could reach an RCS output beam power of 600 kW in principle. The space charge effect in the RCS injection is increased with the beam intensity upgrade, and it limits the obtainable beam power. To suppress the space-charge effect to a tolerable level, it was necessary to increase the injection energy. Therefore, we conducted both the energy and the intensity upgrade of the linac. For the intensity upgrade, we replaced a front-end system, which consists of an ion source, a radio frequency quadrupole linac (RFQ) and a beam chopper system to deliver a peak current of 50 mA. For the energy upgrade, the linac output energy was increased to 400 MeV by adding an annular-ring coupled structure linac (ACS) after the separated drift tube linac (SDTL). A layout of the linac before and after upgraded is shown in Fig. 2.

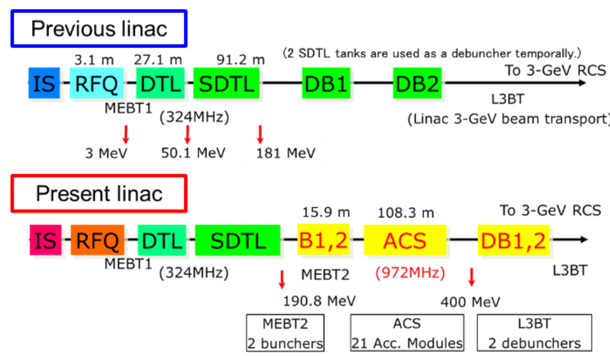

Figure 2: A layout of previous and present linac.

Two further upgrade plans of 1.5-MW beam power at the RCS and construction of the TEF are now in consideration. To achieve the 1.5-MW beam, it is necessary to increase both the peak beam current and the beam pulse length about 20% at the linac. For the TEF, duplation the linac repetition rate to 50 Hz is necessary. The detail process in the past upgrade and the possibility for further upgrade at the linac are presented in this paper.

BEAM INTENSITY UPGRADE

High Intensity Negative Hydrogen Ion Source

A cesium-free negative hydrogen ion source driven with a lanthanum hexaboride (LaB_6) filament was used since linac operation started in 2006 [2]. Although it satisfied the J-PARC's initial stage requirements of 30 mA, it was confirmed that the current level did not increase by cesiation and the life time of the filament of approximately 500 h was insufficient for the desired life of 2000 h at least. In order to satisfy linac upgrade requirements, a cesiated RF-driven negative hydrogen ion source has been developed. A schematic of the RF-driven ion source is shown in Fig. 3. An internal antenna that was developed at Spallation Neutron Source at Oak Ridge National Laboratory [3] is used for the source of plasma. The RF-driven ion source was tested on an off-line test stand for about five years, and it was found to satisfy the requirements. The RF-driven ion source was installed in the summer of 2014.

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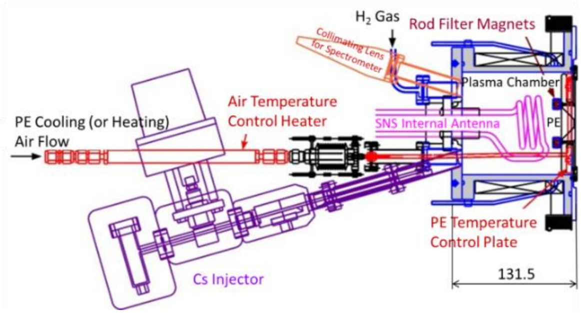

Figure 3: A schematic of the RF-driven ion source.

The operation history of the ion source from October 2014 is shown in Fig. 4. The user operation was started with the beam current of 33 mA from the ion source. The RF source has been successfully providing the required beam to the accelerator with almost no serious problem except for the RF antenna failure caused by the excess cesium due to a misoperation in October, 2014 [4]. From January, 2016, the ion source beam current increased to approximately 45 mA. We gradually increased continuous operation times of the ion source. In spring, 2018, approximately 2,200 hours continuous operation was achieved with the typical beam current, pulse length and repetition rate of 47 mA, 300 μs and 25 Hz, respectively [5]. Based on the result, we decided to change the operation duration of a single RUN cycle from 1.5 to 3 months.

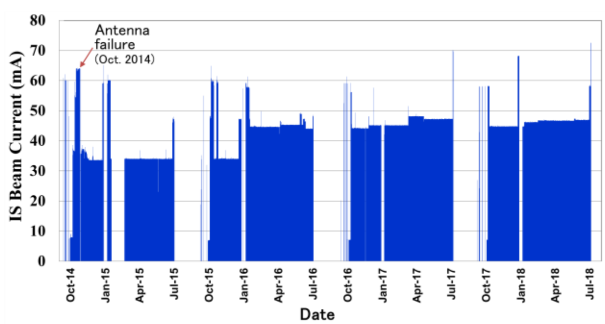

Figure 4: Operation history of the RF-driven ion source.

High Intensity RFQ

At the beginning of the J-PARC linac operation, the RFQ which was fabricated for the Japan Hadron Facility project (we call it "RFQ-I") was used. The design peak beam current of the RFQ-I was 30 mA. To achieve 1 MW, an RFQ with a design current of 50 mA (we call it "RFQ-III") was newly developed and replaced. In the design, we adopted a modified conventional design, that is both the average-bore radius and intervane voltage are constant along the RFQ. The beam is also held equipartitioned through the gentle buncher section. As the result of the simuration, the beam transmission, transverse and longitudinal emittance of 98.5%, 0.21 πmm.mrad and 0.11 πMeV.deg are obtained for the input beam condition of 60 mA and the transverse emittance of 0.20 π mm.mrad [6]. This result satisfies the requirement for the upgraded RFQ.

In designing RFQ-III, fabrication methods were changed from the RFQ-I to increase the resistance to discharge [7] which was the main issue of J-PARC linac at the beginning of the operation. The major engineering change is in the design of the RF cavity structure. The RF cavity of the RFQ-I was installed in a large vacuum vessel. Because the surface area of this type is very large, it is difficult to obtain good vacuum quality. Therefore, a vacuum-tight cavity structure is adopted for the RFQ-III. For this purpose, we adopted brazing for the assembly method. Many vacuum pumps of three 2700-L/s cryopumps, four 400-L/s ion pumps and two 1000-L/s non-evaporable getter (NEG) pumps are equipped. A B-A gauge and a residual gas analyzer are also installed for monitoring the vacuum. The longitudinal distribution of these devices is shown in Fig. 5. The fabrication of the RFQ-III was completed in March 2013. After the off-line beam test, the RFQ was installed in the summer of 2014 as the same time of the ion source.

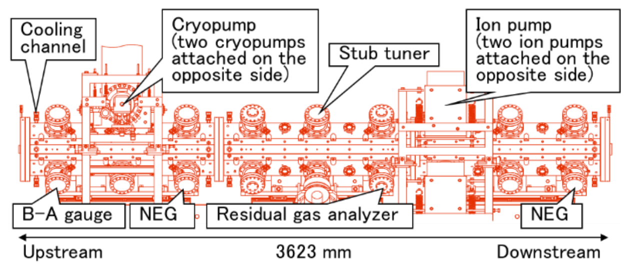

Figure 5: View of the RFQ vacuum devices.

The RFQ has been successfully operated without any serious trouble. Figure 6 shows the operation time variation of number of the RFQ RF-trip. The trip at the beginning of the operation was typically about 20 times per day. The number of trip decreased gradually and almost saturated at about 15 times a day. These trip events reduce the beam availability by approximetaly 1%. We supposed the origin of the trip is the sparking between vane tips, which had been contaminated by the carbon-related contaminants [8]. Inprovement of the evacuation performance and performing the high power conditionign are planned to clean up the inner surface of the RFQ.

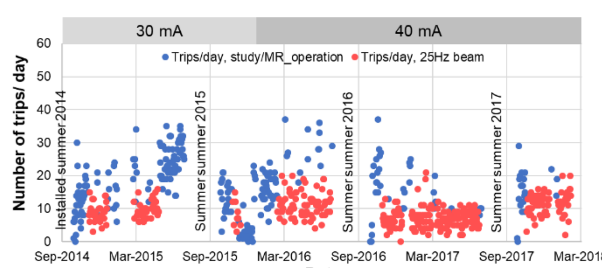

Figure 6: Time variation of number of RFQ RF-trip.

Beam Chopper System

In order to form the intermediate-pulse structure, a beam chopper system is used. The chopper system consists of an RF chopper cavity and a scraper. Both of the components are installed in the beam line between the RFQ and the

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DTL. The RF chopper cavity is an RF deflector with a TE_{111}-like mode with the same RF frequency as the RFQ. While the RF chopper cavity is on, the beam is deflected horizontally to be absorbed by a scraper. The scraper is made of carbon fiber composition (CFC).

The original chopper system, which was designed with a beam current of 30 mA, worked well. For the intensity up-drade, the chopper cavity was replaced with a newly fabricated one, which has a larger aperture and longer gap length between electrodes to decrease beam loss in the cavity in 2014 [9]. Until 2016 summer, the cavities were connected in series with a coaxial line and powered by one RF power system. The large ringing on the RF falling of the intermediate-pulse appeared due to the reflected wave from the downstream cavity, and it caused beam loss at the RCS. The ringing problem was solved by supplying the RF power to the two cavities independently by installing an additional RF power system, as shown in Fig. 7.

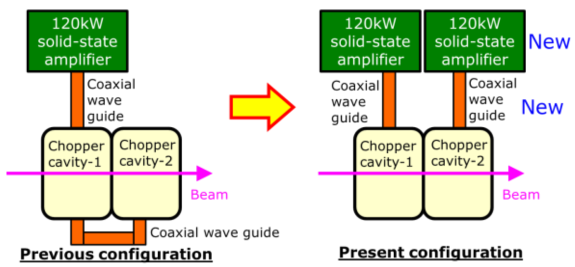

Figure 7: Beam chopper cavity configuration.

Recently, the 300-400 kW user operation with single-bunch was conducted at the RCS. In the 400 kW and single-bunch operation, the scraper received the heat flux approximately 1.3 times larger than that at the 1 MW double-bunch operation (our goal). The measured surface temperature of the scraper is shown in Fig. 8 as the function of the operation time. At 400 kW and single-bunch operation, the temperature reaches and saturates about 1800 °C, which is sufficiently lower than the tolerable temperature of 2900 °C [10].

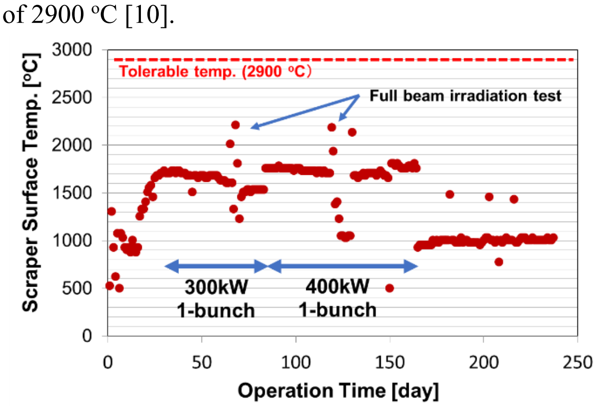

Figure 8: Time variation of the temperature on the scraper on the scraper surface.

After 237-hours operation, we removed the used scraper from the beam line and measured the depth of damaeged part using the laser microscope. Shallow crater of approximately 0.7 mm in depth was observed [10]. In case of 1-MW operation, the depth of damaged part is estimated to be approximetaly 1 mm. The damage level is sufficiently permissible because the beam axial thickness of the scraper material is 40 mm. These results shows the present scaper is saticfied with our requirement.

BEAM ENERGY UPGRADE

As the space charge effect in the RCS injection is increased with the beam intensity, it limits the obtainable beam power. To suppress the space-charge effect to a tolerable level, the beam energy was increased from 181 MeV to 400 MeV, which is the original design energy, by adding ACS cavities after the SDTL [11].

ACS Cavity

Figure 9 shows the configuration of the ACS accelerating module. One ACS module consists of two accelerating tanks and one bridge tank. Twenty-one ACS modules in total are installed for the beam acceleration. In addition, two ACS bunchers are installed between the SDTL and the ACS for longitudinal matching. After the acceleration cavities (before the RCS injection), two ACS debunchers are installed to reduce the energy spread, since the energy acceptance of the RCS is relatively limited compared with the accumulator ring.

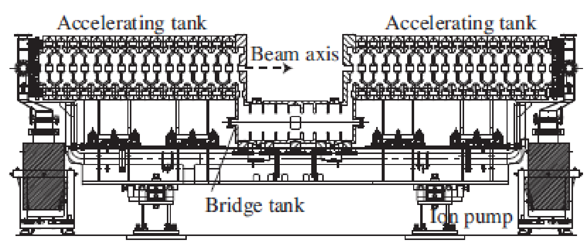

Figure 9: Configuration of ACS accelerating module.

In the end of 2010, the first mass-produced ACS module was completed and its high-power test was performed [12]. In the original plan, the high power test would have been conducted for all the ACS modules before installation at the beam line. However, the test was suspended because the test area was broken by the earthquake in 2011. The test was resumed in May, 2013, however only five modules could be tested before the installation because of time constraints. In the middle of August 2013, we started to install the ACS modules to the beam line. It took one day to complete the transportation and the alignment for one ACS cavity [13]. After completing the installation work in the middle of November, we performed the high-power conditioning of all the ACS cavities. The modules were conditioned more than 2 MW with a short pulse length of 50 μs, and then they were powered to 2 MW with a long pulse length of 600 μs, which is the design pulse length of the ACS. An average conditioning time is 149 hours for all the modules. The beam commissioning of the linac was started in the middle of December, then the designed beam energy of 400 MeV was achieved in January 2014 [14-17].

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The ACS cavities have been successfully operated without any serious troubles. The operation time variation of the RF trip rate per day for all ACS cavities is shown in Fig. 10. The trip rate decreases with the time to an acceptable value of approximately 0.3 times per day.

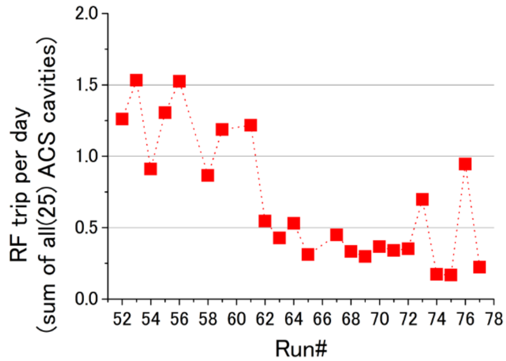

Figure 10: Time variation of number of ACS RF-trip.

972-MHz RF System

The 972-MHz klystron for the ACS cavity was evaluated using an own test-stand in 2001. The prototype of the klystron had strong oscillations due to a drift tube oscillation. Therefore, we improved the RF structure with an asymmetric cavity, a short gap length and a reduced Q value [18]. After the evaluation of the prototypes, mass production of the klystron was started. Four 972-MHz klystrons are driven by a High Voltage DC power supply (HVDC), which is the same system of the 324-MHz one [19]. Figure 11 shows the 972-MHz klystron station. After the ACS conditioning started in November 2013, we had discharge problems at ten circulators due to the malfunction of an RF contact between a body and a post. Because we replaced the RF contact with improved one after the conditioning completed promptly, this trouble did not affect the beam operation schedule.

Figure 11: 972-MHz klystron station.

The LLRF control systems for both the 324-MHz and 972-MHz stations are basically the same. However, many improvements of the 972-MHz-LLRF control systems have been carried out [20-22]. The reference 12-MHz signal delay settings for the feed-back control systems have been optimized using 12-MHz delay modules. The stability performances of the 972-MHz RF&Clock and the Mixer & IQ-modulator) boards have been improved using temperature-compensation techniques. Owing to the improvement, very good stability of the accelerating fields for beam operation was achieved about ±0.2% in amplitude and ±0.2° in phase, which is much better than the requirements of ±1% and ±1°, respectively [23]. However, it has become difficult to keep such a good stability with increasing the beam current. Therefore, we started to use the new beam loading compensation method which the feed-forward (FF) system is operated by assuming the shape of the intermediate pulse [24].

OPERATION STATUS AFTER URGRADES

At present, the linac is being operated successfully with high availability of approximately 90% [25]. After the beam current upgrade work, the linac was started to operate with the beam current of 30 mA. From January, 2016, the beam current was increased to 40 mA. At present, the RCS operates 500 kW for the MLF user operation. The MR beam power is gradually increasing and becomes 490 kW at the NU and 51 kW at the HD, respectively. Beam studies have been conducted at the interval of the user operation. In January, 2015, the RCS successfully demonstrated the beam acceleration and extraction of 1MW-equivalent with a single-shot operation mode [26]. At that time, the ion source kept the peak beam current of 60 mA because the peak beam current of 50 mA is necessary at the end of the linac. We have already demonstrated this condition in a few days duration and up to 2.5 Hz repetition rate. Further beam loss is studied to reduce residual radioactivity for long time user operation.

FUTURE UPGRADE PLAN

We are considering two upgrade plans that increasing the RCS beam power from 1 MW to 1.5 MW and duplation the linac repetition rate to 50 Hz for the TEF which is planned in the near future. In order to reach 1.5 MW at the RCS, the beam current and the beam pulse length are needed to increase to 60 mA and 600 μs respectively, it corresponds to increase by 20% than the present design values.

60-mA Operation Plan

The ion source is the key component to realize the 1.5 MW upgrade plan. We have been performed the R&D work of the ion source at an off-line test-stand. Figure 12 shows the waveforms of the ion source output current (cyan) and input RF power (blue) without (a) and with (b) impurities ventilation system [27]. The beam current of 66 mA had previously been demonstrated. However, we observed the approximately 10% current droop. Recent R&D has shown that the constant current without droop, a 10 % smaller emittance and the reduction of the required RF power from 40.6 kW to only 24.6 kW are achieved by removing N_2 & Ar impurities in the plasma [27].

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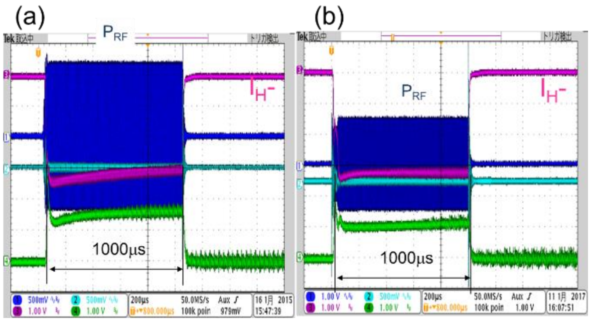

Figure 12: Waveforms of the H- beam current (cyan) and input RF power (blue) without (a) and with (b) impurities ventilation system.

Trial beam study with 60 mA was started in July 2017 just before the longer accelerator shutdown. The first 400-MeV and 56-mA beam at the linac exit was demonstrated in December, 2017, as shown in Fig.13 [28].

We were concerning that a significant beam loss occurs at the DTL1 section, because the alignment of DTs in DTL1 was deformed by the huge earthquake in 2011 so that the actual aperture was reduced. However, no significant beam loss was observed during the beam study. Therefore, the shift of the DT alignment is not probably fatal to the 60-mA operation.

The beam study showed that issues of the linac are the transmission in the RFQ and the MEBT1 scraper. The RFQ transmission is about 6 % lower than that of nominal 40 mA. On the other hand, a drop of the transmission of MEBT-1 happened for 60 mA by the scraper. In order to avoid the decrease of the beam transmission, we have the plan for increasing the RFQ tank level, re-optimization of the MEBT1 lattice and adjustment of the scraper gap at the next trail study. As the result of the beam simulation, reduction of the beam halo from the ion source is effective to improve the beam transmission at the RFQ. We will continue the R&D work of the ion source in the future.

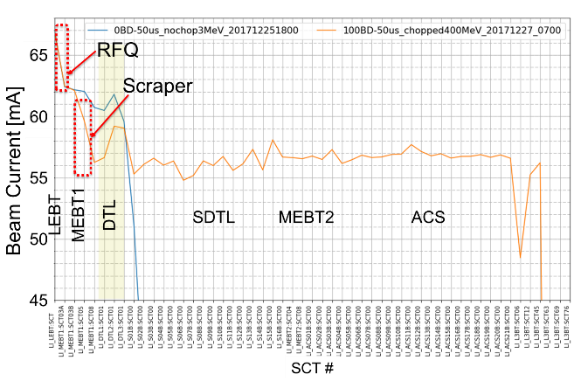

Figure 13: Transmission measured 60-mA trial beam study in December 2017.

600-µs Operation Plan

To obtain a 600-µs pulsed beam, approximately 750-µs RF pulse from the klystrons is necessary. Figure 14 shows the simulation result in case of 800-µs operation. The result shows the cathode voltage drops from 110 kV to 103 kV, corresponding to the output power from 2.47 MW to 2.22 MW across the pulse due to the capacitor bank droop. The reduction is not fatal because the maximum power required from a klystron at 60 mA beam current is 1.89 MW [29].

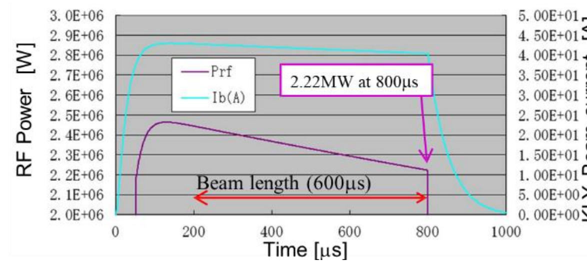

Figure 14: Simulation result of klystron power in case of 800 µs operation.

50-Hz Operation Plan

Because the TEF will use 400 MeV beam with 25 Hz from the linac, alternating 50 Hz pulses from the linac are sent to both RCS and TEF using a separator [30]. The main issues for the 50 Hz operation are insufficiency of the klystron AC power, that of the water-cooling system capacity and the increase of the beam loss. The klystron high voltage transformer is rated at 1000 kVA but 1154 kVA is necessary for 50-Hz and 600-µs operation. Therefore, it is planned to add auxiliary power supplies. For the 50-Hz and 600-µs operation, increase the cooling water system is also necessary because the capacity of the present system has little redundancy. Although some hardware upgrades are required to fix the issues described above, the issues are not so serious except for beam loss. For the mitigation of beam loss, the beam simulation and experiment are ongoing.

CONCLUSION

In 2006, the J-PARC linac started beam operation with the energy of 181 MeV and the design peak beam current of 30 mA. To realize the nominal performance of 1 MW at RCS and 0.75 MW at a MR, the beam intensity and energy upgrade were performed. The upgrades were completed in 2014. At present, the linac is operated with the beam current of 40 mA and high availability of approximately 90%. The beam current will be increased to 50 mA after 2018 summer shutdown. We are considering two upgrade plans that increasing the RCS beam power 1.5 MW and duplation the linac repetition rate to 50 Hz for construction of the TEF. We started trial beam studies with 60 mA in July 2017. 400 MeV and 56 mA beam at the linac exit was demonstrated in December, 2017. Further trial beam studies are planned to demonstrate 1.5 MW-equivalent beam at the RCS.

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