# POWER UPGRADE OF J-PARC LINAC

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*Abstract*

The linac power upgrade program is now in progress, after a successful recovery from the earthquake disaster. The power upgrade includes an ion source, a RFQ, and a 400 MeV annular-ring coupled structure (ACS) linac. We started a full-scale development of a cesium-seeded RF-driven negative hydrogen ion source. The ion source extracted a beam current of more than 60 mA with a duty factor of 2.5 %, satisfying the requirement of the program. A new RFQ for 50 mA acceleration is under construction, on the basis of a RFQ fabrication process, which was previously built as a backup for the present RFQ. Mass production of the ACS modules has been completed.

## INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high-intensity proton accelerator facility that aims to realize 1 MW beam power [1]. The J-PARC accelerator consists of a linac, a 3 GeV synchrotron (rapid cycling synchrotron, RCS), and a main ring synchrotron (MR). The proton beam from the RCS is injected to the Materials and Life Science Experimental Facility (MLF) for neutron and muon experiments. The MR accelerates the beam up to 30 GeV. The accelerated beam is then injected to the hadron beam facility or the neutrino production facility.

Figure 1 shows the schematic configuration of the present and upgraded J-PARC linac, respectively. The J-PARC linac is currently operating with an output energy of 181 MeV and a designed peak current of 30 mA. Thereby, we can reach an RCS output beam power of 600 kW. The space charge effect in the RCS injection is increased with the beam intensity upgrade, and it could limit the obtainable beam power. To suppress the space-charge effects to a tolerable level, it is necessary to increase the injection energy. In this regard, the energy upgrade is essential for increasing the beam power of the J-PARC. To realize 1 MW beam power from RCS, we plan to upgrade both the energy and the intensity of the linac. For the intensity upgrade, we plan to replace the ion source and the radio frequency quadrupole linac (RFQ) to deliver a peak current of 50 mA. For the energy upgrade, the linac output energy is to be increased to 400 MeV by adding an annular-ring coupled structure linac (ACS) after the separated drift tube linac (SDTL). The ACS has an RF frequency of 972 MHz with a three-fold frequency jump from the SDTL.

In this paper, the status and the schedule of some of the main accelerator components being upgraded such as the ion source, the RFQ, the ACS cavity, the bunch shape monitor and the beam chopper system are presented.

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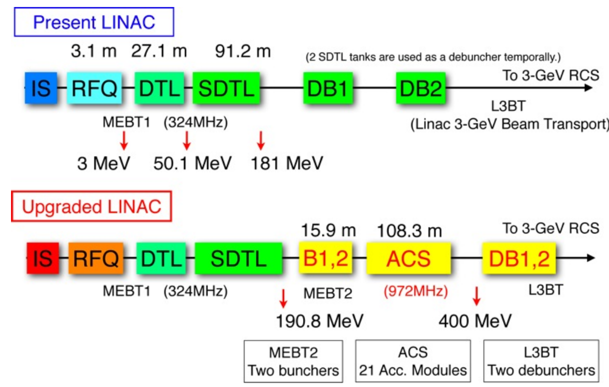


Figure 1: Schematic configuration of the present (upper) and upgraded (lower) J-PARC linac.

## STATUS OF COMPONENTS

### *Ion Source*

A cesium free $H^-$ ion source driven with a lanthanum hexaboride ($LaB_6$) filament is being operated at the J-PARC [2]. Although it satisfies the J-PARC initial stage requirements of an $H^-$ ion beam current of 30 mA, it was proven that the current did not increase by cesiation [3]. Although a J-PARC cesiated $H^-$ ion source driven with two tungsten (W) filaments successfully produced an $H^-$ ion beam current of 76 mA, it had insufficient lifetime and its high Cs consumption rate caused high rate of sparks, a few times per hour, at the beam extractor of the ion source. In order to satisfy the J-PARC upgrade requirements of an $H^-$ ion beam current of 60 mA and a lifetime of 50 days, a cesiated RF-driven $H^-$ ion source has been developed by modifying the J-PARC W-filament ion source [3]. The cross-sectional view of the J-PARC RF-driven $H^-$ ion source is shown in Figure 2.

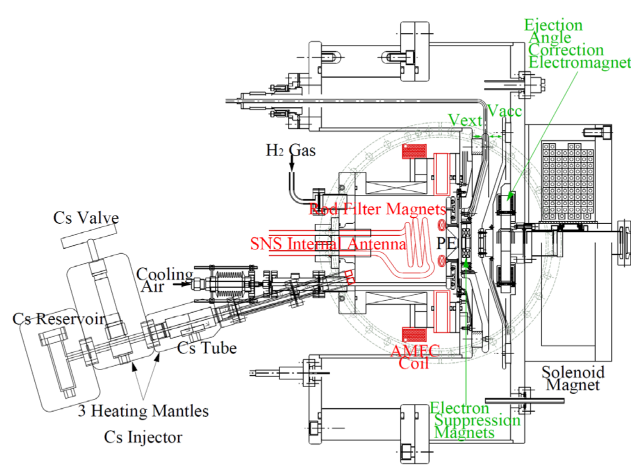


Figure 2: Cross-sectional views of the J-PARC RF-driven $H^-$ ion source.




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The ion source is driven with a 2MHz-RF using an internal-antenna, which is developed at the Spallation Neutron Source (SNS) [4]. The cesium vapor was introduced into the plasma chamber by using an oven.

Figure 3 shows the measured relationships between the $H^-$ ion beam current ($I_{H^-}$) and the RF power ($P_{2MHzRFnet}$) for the operation parameters of the pulse repetition and effective length of 25 Hz and 500 μs, and the hydrogen gas flow rate of 20 SCCM. The beam current increased with the RF power and reached 77 mA at the power of about 43 kW.

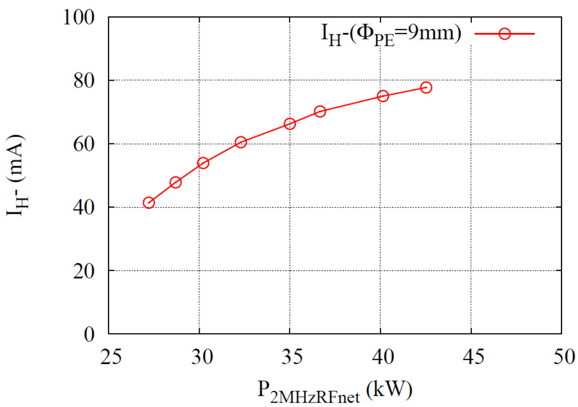


Figure 3: The measured relationships between the $H^-$ ion beam current ($I_{H^-}$) and the RF power ($P_{2MHzRFnet}$).

Figure 4 shows the measured emittance diagram in horizontal and vertical plane for the $H^-$ ion beam current of 77 mA, respectively. The ellipses drawn in Fig. 4 show a normalized emittance of 1.5 πmm.mrad, which gives a beam transmission rate of more than 90 % through the RFQ. The $H^-$ ion beam current inside of horizontal and vertical normalized emittances of 1.5 πmm.mrad is calculated to be more than 60 mA, satisfying the upgrade requirement.

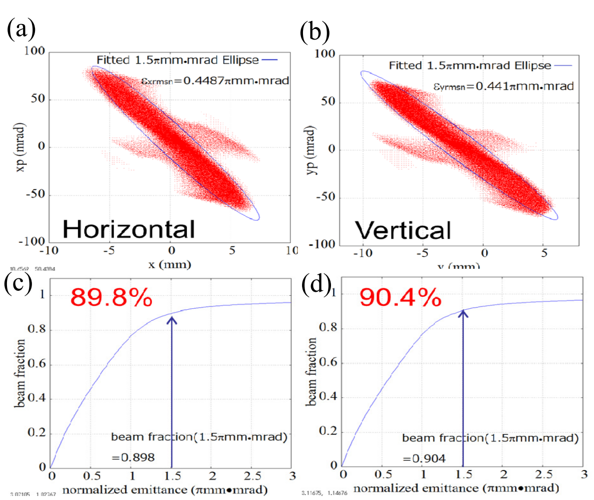


Figure 4: The measured horizontal (a) and vertical (b) emittances with the fitted normalized 1.5 πmm.mrad ellipses, and the relationships between the normalized emittances and the beam fractions in horizontal (c) and vertical (d) directions, respectively.

From the experimental result of a hundred hours continuous operation, the total cesium consumption for 50 days of operation at 60 mA is estimated to be 0.74 g [3]. The spark rate of less than once a day was observed at this consumption rate. The value is seemed to be acceptable because it is the same level as that of the current cesium-free ion source.

## *RFQ*

The commissioning of the J-PARC linac started in 2006 and entire accelerators started operation in 2009 using an RFQ with a design current of 30 mA (RFQ-I). Because a sparking problem occurred at the RFQ-I [5], we fabricated a new RFQ (RFQ-II) for spare. Moreover, to achieve the original design power of 1 MW, another RFQ with a design current of 50 mA is newly fabricated (RFQ-III) based on the same engineering design and the fabrication technologies as those of the RFQ-II.

Figure 5 shows the basic structure of RFQ-II or III. In designing these RFQs, fabrication methods were changed from the RFQ-I to increase the resistance to discharge. The major engineering change is in the design of the RF cavity structure. The RF cavity of RFQ-I is 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 RFQ-II and III. To this end, we adopted brazing for the assembly method.

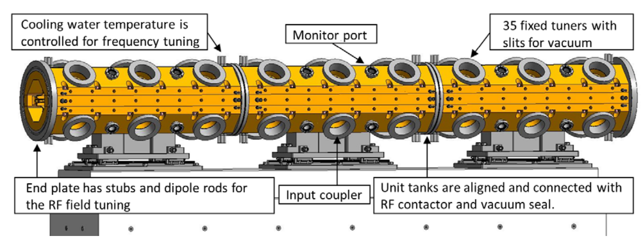


Figure 5: Basic structure of the J-PARC RFQ-II or III.

We conducted a high power test of the RFQ-II [6]. Figure 6 shows the conditioning history of the test. In Figure 6, the dashed and solid (black) lines represent the peak power ($P_{peak}$) at repetition rates of 25 and 50 Hz, respectively. The dotted line (blue) is the averaged power $P_{av}$, and the dash-dotted (red) line represents the vacuum pressure in the cavity. At first, the pulse width and repetition rate were set to be 30 μs and 25 Hz, respectively. After 15 hours of conditioning, the peak power reached 360 kW; this is 10 % higher than the nominal peak power of 330 kW. The pulse width was gradually broadened to 600 μs, and the repetition rate was increased to 50 Hz. After conditioning up to 390 kW, a 24 hours operation test was conducted at the nominal power. During the 24 hours of operation, trips occurred only 3 times, and the stable operation of RFQ-II was confirmed.

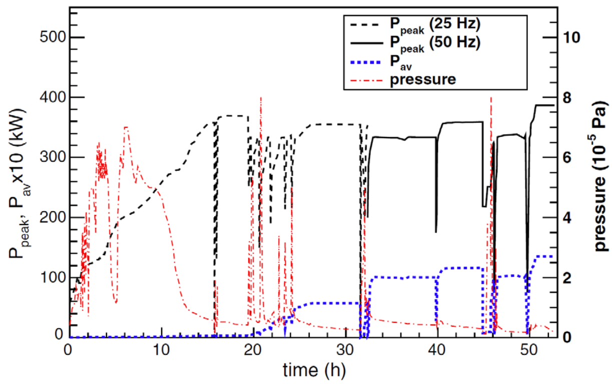


Figure 6: High power conditioning history of RFQ-II.

Such positive results of the RFQ-II encouraged us to develop the RFQ-III. The fabrication of the RFQ-III was completed in March 2013. All the mechanical and low power RF measurements and checks have been done. The results showed that the alignment precision, the field distribution and the vacuum characteristics are within the design goals [7].

A RFQ test stand (see Figure 7) was newly constructed to perform the beam acceleration test of the RFQ-III before the installation to the linac. The RF-driven $H^-$ ion source will be tested simultaneously to check the stability and reliability through the long term continuous operation. The conditioning of the ion source and the RFQ-III started individually in April, 2013. The RFQ beam acceleration test will start in the middle of May, 2013.

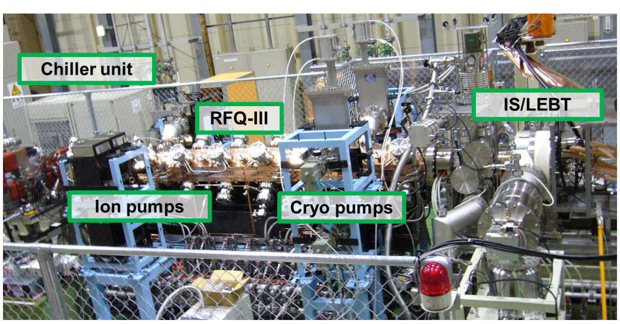


Figure 7: RFQ test stand for the beam acceleration test of the RFQ-III.

## *ACS Cavity*

Figure 8 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 acceleration. In addition, a 16-m long, beam-matching section (Medium Energy Beam Transport 2, MEBT2), where two ACS bunchers are installed for longitudinal matching, is inserted between the SDTL and the ACS. After the acceleration (before the RCS injection) two ACS debunchers are required to reduce the energy spread, since the energy acceptance of the RCS is relatively limited compared with the accumulator ring. To summarize, total twenty-five ACS modules are necessary.

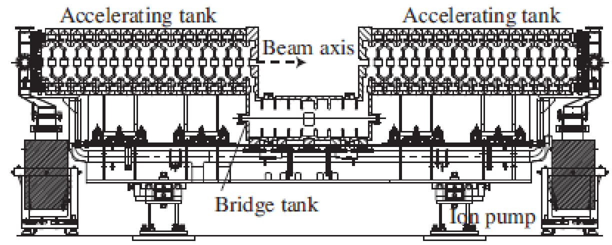


Figure 8: Configuration of the ACS accelerating module.

In the end of 2010, the first mass-produced ACS module was completed and its high-power test was performed [8]. Figure 9 shows the conditioning history of the high-power test. The conditioning time to reach the target power of 1.6 MW was 60 hours, which is an acceptable number for future conditioning of the mass-produced modules. The achieved vacuum pressure was $2.0 \times 10^{-6}$ Pa, under 1.6 MW operation after 240 hours of conditioning. This value is lower than the target vacuum pressure of $4{\times}10^{-6}$ Pa, which is a requirement to reduce the beam loss from residual gas to less than 0.1 W/m. However, the residual gas caused beam loss in the SDTL section, which is operated at less than this target pressure [9]. Therefore, further improvement in vacuum pressure is needed for the high intensity operation. We are measuring the vacuum pressure distribution in the ACS module precisely to examine how to improve the vacuum pressure using the stored module [10].

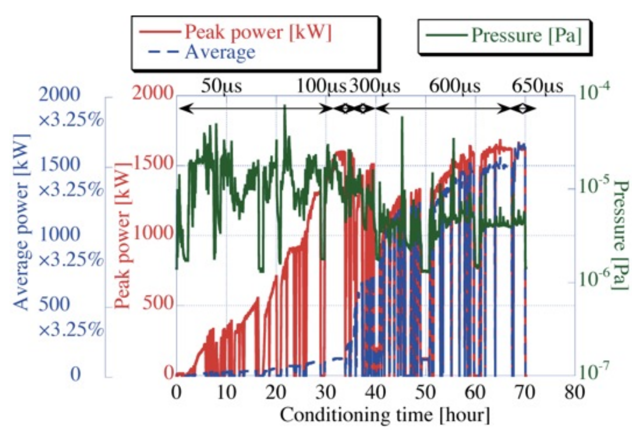


Figure 9: Conditioning history of the high-power test of the first mass-produced ACS module.

All ACS modules and 972 MHz klystrons have been fabricated and are stored in the J-PARC linac building (see Figure 10). In the original plan, the high power test would have been performed for all the ACS modules before installation onto the beam line. However, the test was suspended because the concrete floor of the test area was cracked and broken by the earthquake in 2011. The test area was restored in March 2013, and the test will be resumed in middle of May, 2013. However, at the most, only five modules can be tested before the installation, because of time constraints. The remaining modules,




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therefore, have to be conditioned after the installation at the beam line. Currently, the high power test of the 972MHz klystron is in progress. The test of all klystrons will be finished before the ACS cavity gets ready.

Figure 10: ACS cavities (upper) and 972MHz klystrons (lower) waiting for the installation.

### Bunch Shape Monitor

The bunch shape monitor (BSM) has been developed under collaboration with the INR (Institute for Nuclear Research: Russia) for the measurement of the longitudinal distribution. Three BSMs will be used in the beginning of ACS section in order to tune the longitudinal matching, because the acceleration frequency of 324 MHz at the end of SDTL jumps to 972 MHz for the ACS cavities.

The design of BSM was started in 2009 and the fabrication of three BSMs in 2010. In order to perform the test measurement, all three BSMs were installed and the commissioning was started in 2012. In the first commissioning for the BSM tuning with the 181 MeV beam, we successfully obtained the bunch profile of the $H^-$ beam at the end of the SDTL cavities (Figure 11). This was the first data acquisition of the J-PARC linac and the obtained data was rigorously compared with the beam simulation. The monitors were employed for the space charge driven transverse-longitudinal coupling resonance study. The results will be useful to the design of the beam operational parameters [11].

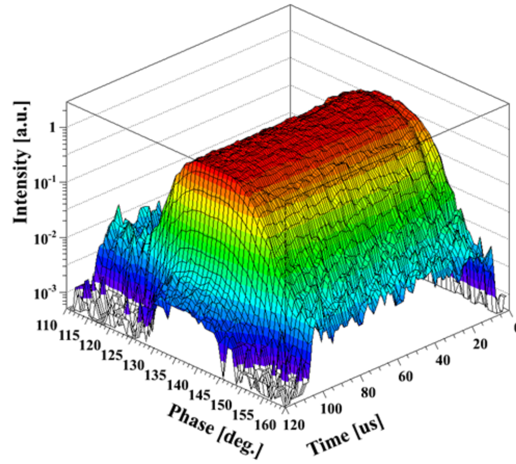


Figure 11: Example of bunch shape monitor measurement.

### Beam Chopper System

In order to form the medium pulse structure, a beam chopper system is used. The chopper system consists of an RF chopper cavity and a scraper [12]. Both of the components are installed in the beam line between the RFQ and DTL (MEBT1 section, see Figure 1). The RF chopper cavity is an RF deflector with a $TE_{11}$-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 present chopper system, which is designed with a beam current of 30 mA, works well with high extinction ratio of less than $10^{-6}$, and rapid rise and fall time of approximately 15 ns with the present user beam condition of approximately 15 mA. However, there are some issues with the 50 mA operation, and are as follows.

- Decrease in the extinction rate due to insufficient RF field in the RF cavity.
- Decrease in the beam transmission rate of the chopped beam due to narrow aperture.
- Decrease in the reliability of scraper under higher heat load.

To measure these issues, we established some upgrade plans for the RF chopper system. The 100 kW-class RF source will be used to compensate the insufficient RF field. We started the design work of new chopper cavity having similar geometry to the present one but wider aperture. The new cavity will be installed in 2014. An upgrade program for the scraper is under discussion. In order to find out if the CFC or another material can be used for the upgrade program, we have a plan to perform irradiation experiment for the material development of the scraper using the RFQ test stand in 2013.

## UPGRADE SCHEDULE

Figure 12 shows the preliminary ACS installation schedule in 2013. The installation work will be started in August, 2013. Due to the strong demand by users, the user operation have to be restarted after six months, which includes a usual summer shutdown (three months) and an additional shutdown (three months) for the energy upgrade. Consequently, all the installation works have to be completed until middle of November, 2013. The cavity conditioning and the linac beam commissioning will be performed by the end of December, 2013.

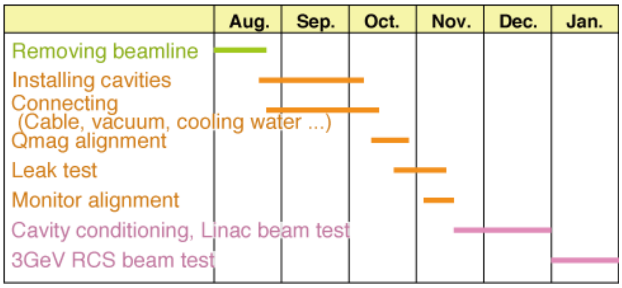


Figure 12: Preliminary ACS installation schedule in 2013.

The upgrade schedule of the front-end part of the RF-driven $H^-$ ion source and the RFQ-III is shown in Figure 13. In Figure 13, the original (upper table) and new (lower table) schedules are shown, respectively. In the original schedule, the new front-end part was to be installed at the same period as that of the ACS installation in 2013. In the new schedule, on the other hand, the installation is postponed till 2014 summer. This means that the user beam operation will be continued with the present front-end part, which consists of the cesium free $H^-$ ion source driven with a $LaB_6$ filament and the RFQ-I. The major advantage of the new schedule is that the term of the off-line beam test can be extended from three months to one year. We will be able to perform precise examination of the beam property, check the operation stability and debug the system during the off-line test. Moreover, the irradiation experiment for the material development of the chopper scraper can be conducted, too. The disadvantage of the new schedule, on the other hand, is that no high power demonstration run with more than 30 mA becomes possible until June 2014. However, since the projected power requirement in early 2014 does not require the peak beam current of 50 mA at end of linac, this disadvantage seems to be acceptable. We will decide on which option to choose soon.

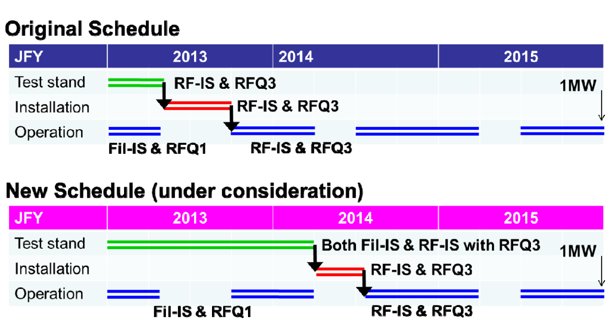


Figure 13: Original (upper table) and new (lower table) installation schedules of the upgraded front-end part.

## SUMMARY

The linac power upgrade program is now in progress. The new RF-driven $H^-$ ion source has satisfied the requirements, both in current and in emittance. The spark rate of the ion source was observed to be less than once a day. This value is seemed to be acceptable level for practical use. For the RFQ development, the RFQ-II has been successfully tested up to 118 % of the nominal power. The fabrication of the RFQ-III was completed in March, 2013, and the beam acceleration test will start in the middle of May, 2013 using the RFQ test stand. All ACS cavities have been fabricated, and the 5 cavities will be tested at high power before July, 2013. The fabrication of the 972 MHz klystron has been finished. The pre-conditioning of all klystrons will be accomplished before the ACS gets ready. All three bunch shape monitors were installed at the beam line and the commissioning was started in 2012. In the first commissioning, we successfully obtained the bunch profile of the $H^-$ beam at the end of the SDTL cavities. There are some issues for the present beam chopper system to be used for the 50 mA operation. An upgrade program of the RF chopper system is in progress. The installation work and the beam commissioning of the ACS cavities will be performed from August to December in 2013. The installation of the new front-end part may be postponed to 2014 because there would be some advantages in doing so.

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