COMMISSIONING OF ENERGY UPGRADED LINAC OF J-PARC

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Abstract

To realize a full potential of the J-PARC facility (1 MW at 3 GeV and 0.75 MW at 30 GeV), the J-PARC linac is upgraded from 181 MeV to 400 MeV by using an Annular-ring Coupled Structure linac (ACS). The ACS modules and peripheral system were installed and commissioned from summer of 2013. The results of beam commissioning and user operation are reported here.

INTRODUCTION

J-PARC, which stands for Japan Proton Accelerator Research Complex, consists of a 400 MeV linac, a 3 GeV rapid cycling synchrotron (RCS), a 30 GeV Main Ring synchrotron (MR) and related experimental facilities[1]. A proton beam from the RCS is injected to the Materials and Life Science Experimental Facility (MLF) for neutron and muon experiments. The MR has two beam extraction systems. One is a fast extraction for the neutrino beam line for the Tokai-to-Kamioka (T2K) experiment, and the other is a slow extraction for the Hadron Experimental Facility.

The goal of the J-PARC project is to deliver a 1 MW beam from the RCS and 0.75 MW beam from the MR. To achieve the goal, a step-by-step approach for the linac is taken: energy upgrades from 181 MeV to 400 MeV, and then, a peak current upgrades from 30 to 50 mA[2]. The energy upgrade project actually started in March 2009. The tunnel and the building had been designed and constructed for 400 MeV linac from the beginning of J-PARC project.

A radioactive material leak accident occurred at the Hadron facility in May 2013 and all the J-PARC operations were suspended[3]. As of April 2013, the beam power for MLF users was 300 kW and the maximum beam powers of the MR for the T2K experiment and the Hadron facility were 240 kW and 15 kW, respectively.

During the long shutdown period in summer of 2013, new accelerating modules and peripherals for the energy upgrade were installed, as scheduled before the accident, and beam commissioning started in December. The user operation for the MLF was resumed in February 2014.

LINAC SYSTEM

The configuration of the energy upgraded J-PARC linac is shown in Fig. 1. The linac consists of a negative hydrogen ion source, a 3 MeV RFQ (Radio Frequency Quadrupole linac), a 50 MeV DTL (Drift Tube Linac), a 191 MeV SDTL (Separated-type DTL) and a 400 MeV Annular-ring Coupled Structure linac (ACS). RF frequencies are 324 MHz for low β section (RFQ, DTL and SDTL) and 972 MHz for high β section (ACS), respectively.

By the time of the energy upgrade, after the SDTL section was a beam transport line. The last two SDTL cavities were installed in the beam line as debuncher cavities where no acceleration was expected. Therefore, the injection energy to the RCS was 181 MeV instead of 191 MeV.

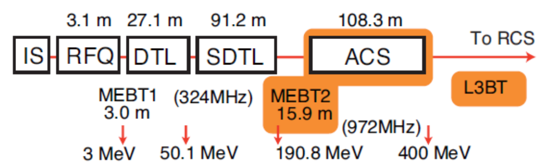

Figure 1: The configuration of the energy upgraded J-PARC linac.

ANNULAR-RING COUPLED STRUCTURE LINAC (ACS)

Development of ACS

The ACS is one of coupled cavity linacs, for example, a side-coupled structure (SCS), operated in a π/2 mode[4]. Comparing to the SCS, the ACS has an axial symmetry around a beam axis and has several advantages. It has a smaller transverse kick field component and can be obtained a smooth surface with an ultra-precision lathe machining. Shunt impedance and a coupling factor are comparable to those of the SCS.

Since the coupling cavity of the ACS is nearly coaxial, it has many modes above the coupling modes. This is one of the reasons why its development has not been succeeded. Improvement of the symmetry by increasing the number of coupling slots has solved the mixing of these modes to the coupling modes. In this way, the 1296 MHz ACS cavity for Japan Hadron Project at KEK was successfully developed and power tested[5]. The structure size of the 972 MHz ACS, which is used for the J-PARC linac, is much bigger based on a simple frequency ratio of 1.3, and it is very hard to machining and handling. We have successfully modified the cavity shape to reduce the size of the 972 MHz ACS to that of the 1296 MHz one[6].

Figure 2 shows an illustration of the ACS accelerating module. The ACS module consists of one lower bridge tank with 9 cells and two upper accelerating tanks with 17 cells. Focusing doublet Q magnets are placed between the accelerating tanks and also between the modules. Movable tuners for the frequency adjustment are attached in an excitation cell of the bridge tank. Twenty-one ACS

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modules accelerate an H^- beam from 191 MeV to 400 MeV. An average accelerating field, E_0, is 4.1 MV/m. In addition to the acceleration, two modules are installed in a matching section between the SDTL and the ACS (Medium Energy Beam Transport-2, MEBT2 in Fig. 1) as bunchers. One buncher consists of two accelerating tanks with 5 cells and a bridge tank with 5 cells. After the acceleration in the beam transport line (Linac-to-3 GeV RCS Beam Transport, L3BT in Fig. 1), two debunchers control the jitter and spread of momentum for the RCS injection.

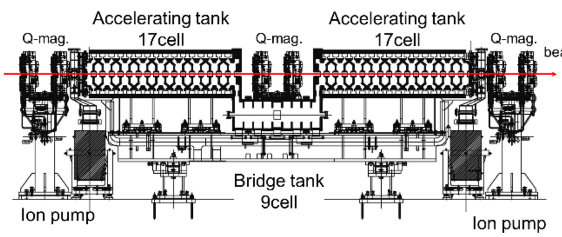

Figure 2: ACS Accelerating Module.

Manufacturing of ACS[7]

As mentioned above, the energy upgrade requires 21 accelerating modules, two bunchers and two debunchers. When the upgrade project started in March 2009, two bunchers and two accelerating modules had already been manufactured as a prototype of the ACS. All the other cavities had to be mass-produced within a three-year period. An ACS tank consists of many half-cell disks and is brazed as shown in Fig. 3. The estimated number of cell disks to be manufactured was approximately 1400, and it was thought to be tough schedule based on the prototype manufactured time span.

Because of a design that an accelerating cell is surrounded by a coupling cell, it is hard to tune an accelerating cell's frequency from the outside after assembling. We therefore need to tune the accelerating cell's frequency before assembling. It means that the tuning of the cell is essentially important. And also, because cell dimensions vary from a module to a module as changes in proton velocity, a tuning step is needed depending on a type of a cell. We have discussed the mass production plan with a manufacturer to complete the fabrication within a limited period. And also, reducing the labor cost for the frequency tuning is a key to save the cost.

The first modification was the simplification of the coupling slot machining, which was carried out with 5-axis processing in the prototype phase. We simplified the shape and the finishing process comparing the surface roughness and the machining time[8]. We confirmed the performance of the RF properties by a high power model and adopted in the mass production process.

The other is the coupling mode frequency tuning after the final brazing. In the prototype cavities, we had no tuning devices. We estimated a frequency shift before and after a brazing. And cells are machined to be a frequency goal including this frequency shift. But we found out from several brazing experiences that the frequency shifts before and after brazing were not easy to control within our specified range. That's why we changed the strategy to use tuners. These tunes were also implemented to the high power model and confirmed the performance before mass production.

All the half-cell pieces are machined and tuned by an ultra-precision lathe. The final machining of the equator is done for the precise frequency tuning. To do so, we need to know a coefficient of the frequency sensitivity as a function of radial machining depth. We have performed the series of test cell measurements and obtained consistent coefficients as a function of β beforehand[9]. As a result, the iteration of a frequency tuning could be reduced to only once while two or three times for the prototype modules. This process greatly saved the time.

In the middle of the mass-production, the Great East Japan Earthquake occurred in March 2011 and it severely damaged the linac facility. Our original plan was to perform a high power test for all ACS modules in the linac building before installing them to the beam line. However, conditioning of the modules was suspended since a test area was damaged. It took several months to recover existing linac components and one year for repair the building. As a result of the earthquake, the installation of energy upgrade components was postponed from summer of 2012 to 2013.

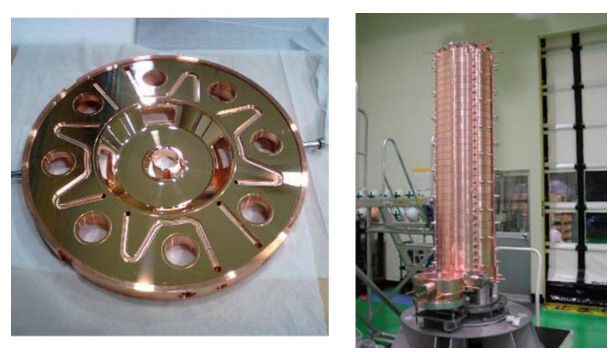

Figure 3: ACS half-cell disk (left) and stacked view of the disks before brazing (right).

Installation and Conditioning

Since a net allowed installation time of ACS modules is limited, approximately 3 months, we had a careful planning of the installation as well as the preparatory work[10]. Waveguides and cables were installed in summer shutdown periods of 2011 and 2012. In the first year of 2011, when the Great Earthquake occurred, the energy upgrade preparation was carried out in parallel with the recovery from the earthquake.

In the middle August of 2013, we started full-scale work. Before the installation of ACS modules, we removed beam ducts, vacuum pumps, etc. in the beam transport line for 181 MeV operation. It took half month. Then, the ACS modules were sequentially installed to the beam line. It took only one day as we planned for one ACS module to move from a stored ground floor to the beam line, which was 13 m underground level. For the completion of this work, it took about one month because we had 25 modules. Cable connection and installation of vacuum pumps, waveguides, cooling water pipes, diagnostics and beam ducts were carried out in parallel or sequentially. A vacuum leak test and precise alignment work followed the component level installation and test.

All the installation work was completed by the middle of November as shown in Fig. 4, being followed by the cavity high power conditioning[11]. This was the first conditioning for most of the modules because the restoration of the test area from the damage by the earthquake was delayed. A module was conditioned more than 2 MW with a short pulse length of 50 µs at first, and then it was powered from 0 to 2 MW with a long pulse length of 600 µs, which is the design pulse length of the ACS. The pulse repetition frequency was 25 Hz, which was constant through this conditioning. Conditioning time for each ACS module to achieve a specified power level is shown in Fig. 5. It's natural to have shorter time for bunchers (B1 and B2) and debunchers (D1 and D2), because required power levels are lower than accelerating modules of 2 MW. The average conditioning time is 149 hours for all the modules.

Figure 4: ACS section after installation.

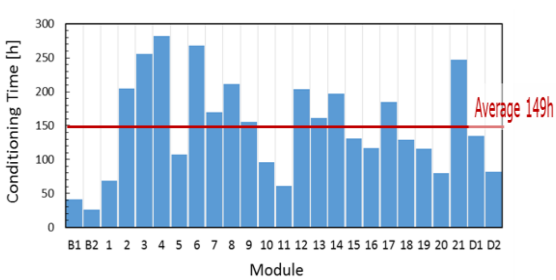

Figure 5: Conditioning time for each ACS module to achieve a specified power level at a pulse length of 600 µsec.

RF SOURCE

Klystron and Power Supply

In the upgraded J-PARC linac, twenty 324 MHz klystrons (Toshiba E3740A) and twenty-five 972 MHz klystrons (Toshiba E3766) are used as RF sources. Both klystrons have the common specifications: output power of 3 MW with a pulse duration of 0.7 ms at a repetition of 50 Hz. They have a triode-type electron gun and the same beam parameters and operate with an anode-modulating mode to reduce the cost of the power supply system.

A 972 MHz klystron was evaluated in 2001. The prototype klystron had strong oscillations by a drift tube oscillation. Therefore, we improved the RF structure with an asymmetric cavity, a short gap length and a reduced Q-value[12].

A 972 MHz klystron power supply is the similar system of the 324 MHz one[13]. One High Voltage DC power supply (HVDC) drives four klystrons. And one anode modulator drives one klystron to apply pulse power to the modulating-anode. Figure 6 shows the 972 MHz klystron station, though the HVDC is not shown here.

Figure 6: 972 MHz Klystron station. (From left to right) Disconnecting switch, m-anode modulator, klystron tank and circulator. A waveguide is disconnected for maintenance work.

Low Level RF Control

The field stabilization control of the ACS cavity is more difficult than that of the 324 MHz RF system because the RF frequency is three times higher and its loaded Q-value is about 8000; which is very low in comparison with that of the DTL and SDTL cavities, about 20000. Thus, we need some modifications or improvements for low level RF control system (LLRF) and RF reference distribution system[14-16].

Hardware of the LLRF control system for the 972 MHz system is basically the similar to the 324 MHz system except for the RF and IQ boards for different frequencies. The software has been developed as common for the two frequency systems for ease of the maintenance.

Stability is very sensitive to the temperature variation in the klystron gallery (27.0-28.6 deg-C). Then, more improvements have been carried out using temperature compensation. As a result, very good stability of the accelerating fields for beam operation has been successfully achieved about ±0.2% in amplitude and ±0.2 degree in phase, which is much better than the requirements of ±1% in amplitude and ±1 degree in phase.

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BEAM COMMISSIONING

The beam commissioning of the linac was started on December 16, 2013[17-19]. The main purposes of the beam commissioning are to achieve 400 MeV, to tune for the user operation condition (peak current of 15 mA) and to tune for high power demonstration (peak current of 25 mA)[20].

In the first step of the beam commissioning, we completed the tuning by the SDTL section. RF amplitudes and phases are determined by a phase scan method from upstream. Output energy is measured with an FCT (Fast Current Transformer) pair by a TOF (Time of Flight) method. An optimum setting is determined by comparison of the simulation results of PARMILA and IMPACT codes.

After tuning of the SDTL section, we checked the performance of beam monitors in the ACS section with 181 MeV beam. Since the FCTs in the ACS section are newly installed[21], these kinds of checking are important as well as the reproduction of the results at the existing beam transport section. After checking the FCTs, we carried out the phase and amplitude scan tuning for an ACS module by module from the upstream part.

The designed beam energy of 400 MeV was achieved on January 17, 2014. We confirmed the 400 MeV acceleration by two methods. The first one is a TOF with phase scan. The result of the last ACS module is shown in Fig. 7. But the TOF has a phase rotation ambiguity. The acceleration was checked by second method, a beam position measurement with dispersion in the 30 degree bending line. Detail beam commissioning results are described in [17].

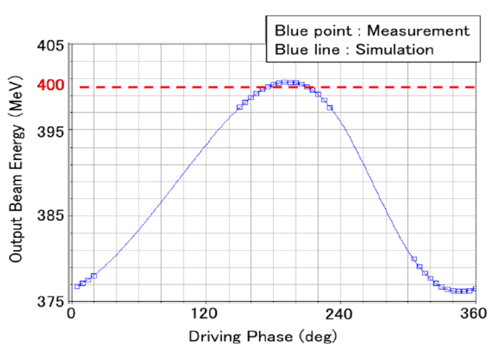

Figure 7: Phase scan result at the last ACS module.

After establishing the 400 MeV acceleration, we took additional tuning to suppress beam loss and to improve beam quality. One of the issues is a beam halo formation. Figure 8 shows the measured beam profiles at the entrance (191 MeV) and the exit (400 MeV) of the ACS. Significant beam halo formation was observed in the downstream of the ACS. The most probable cause is a longitudinal mismatch at the ACS section, which leads to transverse-longitudinal motion coupling through space charge.

After the commissioning of the linac, beam tuning of the RCS started for the upgraded injection energy of 400 MeV on January 30, 2014. The initial beam tuning was rapidly completed in 10 days. Then we performed a high intensity beam trial up to 550 kW using a 0.5 ms long linac pulse with a peak current of 24.6 mA[22]. Figure 9 shows the beam intensity in the RCS for 400 MeV and the 181 MeV injection cases. In both cases, injection conditions are the similar: the linac current of 25 mA and without painting injection. The beam loss at the injection clearly shows an advantage of the energy upgrade (30% beam loss at the 181 MeV and <1% at the 400 MeV injection). Although the painting injection at the RCS mitigates the beam loss at any rate, the energy upgrade has a great advantage to ramp-up the power to the 1 MW goal.

The user operation of the MLF was resumed on February 17, 2014 with the beam intensity of 300 kW after the nine months beam shutdown since the Hadron accident in May 2013.

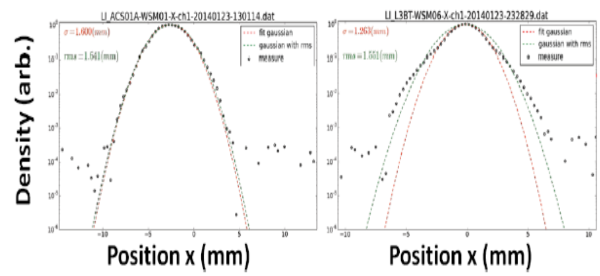

Figure 8: Measured and Gaussian fitted beam profiles at the entrance (left) and the exit (right) of the ACS (beam current of 25 mA).

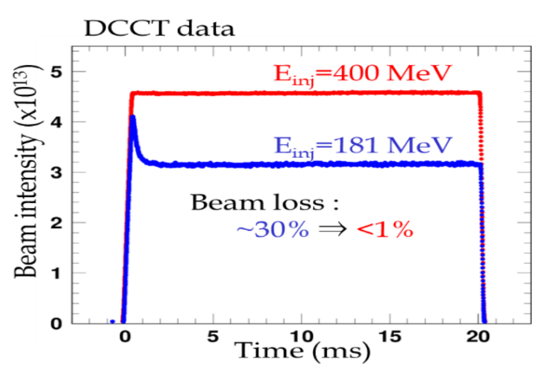

Figure 9: Beam intensity in the RCS for 400 MeV and 181 MeV injection cases (beam current 25 mA, no injection painting).

OPERATION EXPERIENCES

The 400 MeV linac has been successfully beam commissioned as planned, however, there remain several issues. Some of the new systems may need a debugging process, but we can emphasize that the ACS tanks are very stable after the proper conditioning.

After the ACS conditioning started in November 2013, we had discharge problems of some 972 MHz circulators. The reason was an imperfectness of an RF contact between a body and a post. We managed to modify ten circulators to meet the beam operation schedule. The rest of them are improved in a 2014 summer shutdown period.

At some part of the linac, Q magnets in the ACS section in particular, residual radioactivity is higher than others.

The beam bore of the current transformers at that position is slightly smaller. We need to reduce a beam halo and neutralization of an H^- beam. Mitigation of radioactivity is crucial to ramp-up the beam power.

In order to measure and mitigate the longitudinal mismatch to reduce halo components, installation of bunch shape monitors (BSM) is anticipated. We have three BSMs fabricated for the J-PARC linac at the Institute for Nuclear Research in Russia. The performance was tested in the beam line in 2012 but a vacuum pressure deterioration was observed[23]. We have baked the BSMs off-line to improve a vacuum condition.

One of six units of new 972 MHz klystron power supplies caused a big trouble. We had many discharges around a control circuit board, finding out that the circuit board and/or many devices were broken. This was one of main causes to decrease the beam availability after the energy upgrade. This problem was solved by fixing the potential at floating voltage points near the circuit board.

THE NEXT SCOPE

The next step after the energy upgrade is an intensity upgrade to perform 1 MW from the RCS. The peak beam current should increase from 30 mA to 50 mA and the linac beam power should be 133 kW. The upgrade involves the replacement of a front end, i.e. the ion source, the RFQ, and some parts of the MEBT1[24].

The 50 mA H^- ion source is one of the essential components for the intensity upgrade. A cesium seeded RF driven ion source has been developed and peak current of 70 mA has been achieved[25]. The RFQ for 50 mA operation has been constructed [26].

A front-end test stand was built to perform the RFQ high power and the beam test before the installation to the linac tunnel[27,28]. The 24-hour continuous beam test of the new ion source and the RFQ was performed for a month, in June 2014. Installation of the new front-end system is now on progress in the linac tunnel as shown in Fig. 10.

SUMMARY

Since beam users are eager to shorten the shutdown period, we established the work plan and commissioning scenario to meet the tight schedule. Thanks to all member's contributions, the energy upgraded 400 MeV linac has been successfully commissioned as planned and the following RCS achieved 3 GeV acceleration.

Figure 10: New ion source and RFQ in the linac tunnel. (August 2014)

The RCS demonstrated high intensity beam at 550 kW equivalent with lower beam loss, which confirmed advantages of the injection energy upgrade. The linac and RCS have been provided 300 kW beam to MLF users since February 2014.

Several issues remain in terms of beam stability and availability, since they are lower than those before the upgrade. Some of them are initial premature failures and require further improvements. The transverse beam profile at the ACS exit shows a significant beam halo. We anticipate installing the BPMs to mitigate a longitudinal mismatch. We have experienced certain machine activation due to uncontrolled beam losses and we need some mitigations for further ramping up the beam power.

The J-PARC linac is now on the way to replace the front-end to upgrade the peak current from 30 mA to 50 mA. It will be ready to realize a design beam power. The 1 MW equivalent beam tuning is planned in October 2014.

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