

STATUS OF J-PARC LINAC ENERGY UPGRADE

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Abstract

The 400-MeV energy upgrade of the J-PARC linac started from March 2009. The linac beam energy is at present 181 MeV, limiting the beam power of the 3-GeV Rapid-Cycling Synchrotron (RCS) to 600 kW at most by the space-charge effect. The 400-MeV injection is therefore vital for its 1-MW operation. This energy upgrade requires 25 modules of Annular-ring Coupled Structure (ACS) in total, 25 high-power RF sources, low-level RF systems and beam monitors. In this paper, we report the development and fabrication status of these accelerator components, briefly summarizing their results.

INTRODUCTION

The energy upgrade project of the J-PARC linac from 181 MeV to 400 MeV started in March 2009, where J-PARC stands for Japan Proton Accelerator Research Complex [1]. Figure 1 shows its bird's eye view.

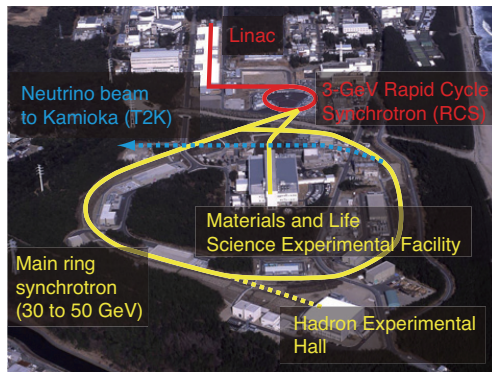


Figure 1: Bird's eye view of the J-PARC.

It is scheduled that all the accelerator components for this upgrade are installed by the end of the summer shut down in 2012. Here, the tunnel and the building had been completed for the 400-MeV linac from the beginning (main piping for cooling water system as well).

The J-PARC accelerator consists of a 400-MeV injector linac, a 3-GeV Rapid Cycling Synchrotron (RCS) and a 50-GeV main ring synchrotron. A high intensity proton beam is delivered to the materials and life science facility, the hadron experimental hall and the neutrino beam line.

The design parameters of the linac are as follows: a beam energy of 400 MeV (181 MeV at present), a peak current of 50 mA, a repetition of 50 Hz and a macro pulse length of 500 μ s. The linac H^- beam with a chopper beam-on

duty factor of 53% is injected to the RCS at a repetition of 25 Hz (the remaining half of the beam will be used for the accelerator driven nuclear waste transmutation system in future).

The linac energy upgrade to 400 MeV is vital for the designed 1 MW beam power of the RCS for the following reason. With the present 181-MeV injection the 300-kW RCS operation (a Lasslette tune shift of -0.16) was demonstrated for one hour [2] with a reasonable amount of beam loss (the beam power for the user run is at present limited to 120 kW by the performance of the neutron-production target which will be improved in fall 2010).

The $\beta^2\gamma^3$ scaling law of the space charge effect implies that the 300-kW operation with the 181-MeV injection is equivalent to the 1-MW operation with the 400-MeV injection [3]. Although the further optimization of the beam parameter may lead to the higher RCS beam power with the present injection energy, it seems extremely difficult to go beyond 600 kW [4]. This is the reason for the linac energy upgrade to the original design value of 400 MeV.

CONFIGURATION OF LINAC

Figure 2 shows the schematic configuration of the linac. The linac consists of the H^- ion source (IS), the radio-

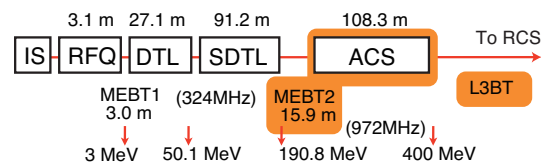


Figure 2: Schematic configuration of the linac.

frequency quadrupole linac (RFQ), the drift tube linac (DTL) and the 191-MeV separated-type DTL (SDTL). The injection energy to the RCS is reduced to 181 MeV, since the last two SDTL tanks are used as a debuncher. The Annular-ring Coupled Structure (ACS) was chosen for the acceleration from 191 MeV to 400 MeV. Figure 3 shows an ACS accelerating module. The frequency of ACS is 972 MHz, which is three times as high as that of the SDTL. The odd number of three rather than two or four was chosen for keeping the possibility of the simultaneous acceleration of both the H^- and H^+ beams for future use (if requested).

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, MEFT2), where two ACS bunchers are installed for longitudinal matching, is inserted between the SDTL and the ACS. After the accel-

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eration (before the RCS injection) two ACS debunchers are required for the energy compensation, since the energy acceptance of the RCS is relatively limited compared with the accumulator ring. To summarize, we need 25 ACS modules.

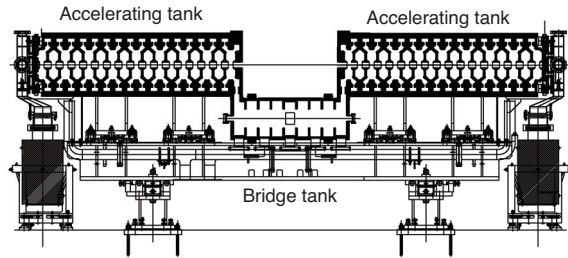


Figure 3: Layout of an ACS accelerating module. Two ACS tanks are coupled by one bridge tank.

STATUS OF COMPONENTS

ACS Cavity

Features of ACS The ACS is one type of bi-periodic structure (or sometimes referred to as Alternating-Periodic Structure, APS) [5]. Therefore, the ACS is keeping every advantage of the $\pi/2$ mode structure, electromagnetically. In other words, the structure is immune against the structure error and the beam loading. Topologically, it can be said that the ACS is an axially symmetric version of a Side-Coupled Structure (SCS). The axial symmetry has the following advantages over the SCS:

1. Negligibly small transverse kick field,
2. Possibility of precise machining by a lathe except for coupling slots,
3. Mechanical stability.

The four coupling slots are located every 90 degree around the beam axis. This arrangement eliminates any transverse electric field, which exists in the SCS (5% of the longitudinal field) [6]. The inner surface of the structure except for the coupling slots is machined by an ultra-precision lathe. The surface thus guarantees the high discharge limit, which is short conditioning time and stable operation by minimizing the discharge probability.

The shunt impedance and the coupling factor are comparable to the SCS. The ACS well satisfies the J-PARC operation with a duty factor of 3% and can meet the 15% operation if requested in future.

The 972-MHz J-PARC ACS has been developed on the basis of the 1296-MHz JHP ACS [6]. Here, the structure size was elaborately minimized (diameter of 460 mm) [7]. Figure 4 shows its exploded view. The ACS tank consists of many half-cell pieces. The four slots coupled the Accelerating Cell (AC) and the annular ring type Coupling Cell (CC) together.

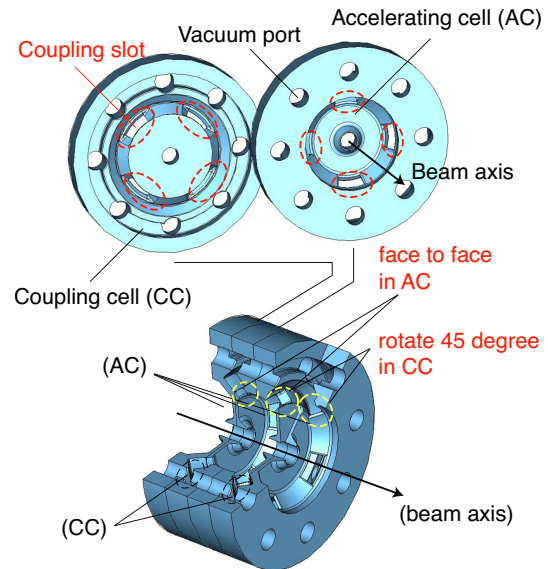


Figure 4: Exploded view of the J-PARC ACS.

Since the ACS should be operated at the $\pi/2$ -mode of a coupled cavity linac (CCL), the accelerating mode frequency should be confluent with the coupling mode frequency. The accelerating cell is surrounded by the coupling cell, thus it is hard to tune the accelerating cell frequency from the outside after assembling. We therefore need to tune the accelerating cell frequency before assembling.

Machining, Tuning and Fabrication Process An ACS accelerating tank is formed by silver-brazing all the half-cell pieces (Fig. 4) stacked in a vacuum furnace. Before the brazing all these half-cell pieces are precisely machined and tuned by an ultra-precision lathe. The following three processes are used for the machining and tuning.

1. After rough machining, the coupling slots, the water-cooling channels, and the vacuum ports are machined by a five-axis machining center, while the axial symmetric machining is done by a lathe.
2. Then, the ultra-precision lathe is used for the precise axial symmetric machining, but a small volume is left for the final machining at the equator.
3. The final machining of the equator is done for the precise tuning of the frequency.

For the process 3, we need to know the coefficient of df/dr , where f and r are the resonant frequency and radius, respectively.

Since we have already manufactured two bunchers and three accelerating modules, we need 18 accelerating modules and two debunchers. In order to manufacture 20 modules within three years, we had to shorten the period of the manufacturing and tuning, compared with the preceding modules.

For this purpose, we simplified the machining of the coupling slots and shortened the tuning time. The former shortened the process 1 from 1.5 day/piece to 1 day/piece [8].

The latter, that is, the process 3 is done just once. In general, the process 3 implies a risk of over-machining. For this reason, the process 3 so far had been further divided into three steps in order to avoid this risk. Step by step the frequency had approached the final goal. For saving the three steps to one, very careful determining of the coefficient df/dr is necessary.

Coefficient df/dr for the frequency tuning In reality, we need four kinds of half-cell pieces with respect to the orientation of the coupling slots and the resultant water-cooling channels. For this reason four kinds of test half-cell pieces were machined for each geometrical β .

The coefficient df/dr was experimentally evaluated by measuring the frequency variation df due to the machining depth dr . For safety, we did it twice. Figure 5 shows these two empirical results together with the evaluation by SUPERFISH (5 percent reduction included for approximately taking into account the coupling slot effect).

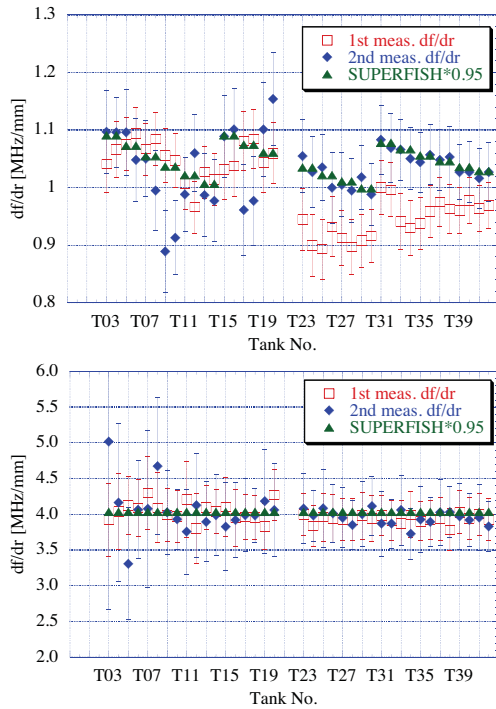


Figure 5: Measured coefficient df/dr for the frequency tuning. (Top: for the accelerating cell, Bottom: for the coupling cell.)

It can be seen that the value df/dr gradually decreases as β increases (the cavity volume increases) and that the value is suddenly recovered at two values of β . This is because the shape of the machining was adjusted twice in order to keep the coefficient around 1 MHz/mm. Every adjustment gives rise to the sudden increase in value of the df/dr .

Some systematic difference, which is slightly larger than the measurement error, is observed between the low- β group (up to T19) and the high- β group (from T23 and higher) where the second evaluation is always larger than

the first. The cause for this difference has not yet been elucidated. The dimension measurement after the tuning has just reconfirmed the correct machining. Finally we adopted the second evaluation. This is because the additional third measurement of the several cells corresponded with that of the second evaluation.

The coefficients were evaluated from these results to the exclusion of the wrong results regarded as the deviation from the trend of the β dependence and the calculated (SUPERFISH) values. This correction brought the accurate coefficients, which realized the precise frequency tuning, whose results will be discussed later. It was instructive to measure the coefficients df/dr systematically throughout the β range.

The coupling cell dimensions are constant not depending on the geometrical β , so that the df/dr of the coupling cell are almost constant around 4 MHz/mm.

Frequency tuning results The two accelerating tanks in one accelerating module have the same geometrical β . Thus the half-cell pieces of these two accelerating tank can be regrouped into two. For example, all the accelerating and coupling cells are numbered along the beam axis. Then the even-numbered cells are tuned at first and then the odd-numbered cells are tuned with reference to the tuned frequency of the even-numbered cell. This procedure prevents the concentration of the frequency error at one accelerating tank in one module. And it also aims to feed back to the coefficient df/dr of the second frequency tuning from the first tuning results.

So far, the cell frequencies have been tuned precisely in the first step on the basis of the coefficient summarized in Fig. 5. As a result, there was not any cells which required the feedback of df/dr in the second step. Table 1 summarizes the frequencies after the frequency tuning at this time. In the table 1, T03, T04... mean the accelerating tank number. One ACS module comprises two (odd and even numbered) accelerating tanks.

Table 1: Average Frequencies of the Accelerating Tank and the Standard Deviations After the Frequency Tuning (MHz)

	Accelerating cell	Coupling cell
T03	971.935 $\pm$ 0.008	976.559 $\pm$ 0.019
T04	971.932 $\pm$ 0.023	976.545 $\pm$ 0.017
T05	971.939 $\pm$ 0.019	976.085 $\pm$ 0.019
T06	971.938 $\pm$ 0.026	976.070 $\pm$ 0.030
T07	971.942 $\pm$ 0.016	975.711 $\pm$ 0.013
T08	971.938 $\pm$ 0.011	975.761 $\pm$ 0.060
T11	971.933 $\pm$ 0.003	975.164 $\pm$ 0.024
T12	971.932 $\pm$ 0.002	975.164 $\pm$ 0.024
T13	971.939 $\pm$ 0.009	974.885 $\pm$ 0.035
T14	971.942 $\pm$ 0.012	974.872 $\pm$ 0.022

The accelerating cell frequencies are in good agreement with the target of 971.93 $\pm$ 0.05 MHz. The coupling cell

frequencies whose target value depends on the geometrical β are also in good agreement within ± 0.05 MHz.

All the half-cell pieces are chromated in order to prevent the oxidation of the copper after the frequency tuning and then the accelerating tank is assembled with brazing. The frequencies of the accelerating tank, which is stacked many half-cell pieces are measured before and after brazing to find the frequency shift. The measurement setup before the brazing includes a brazing metal between the half-cell pieces. Figure 6 presents the results of the completed tanks up to this time.

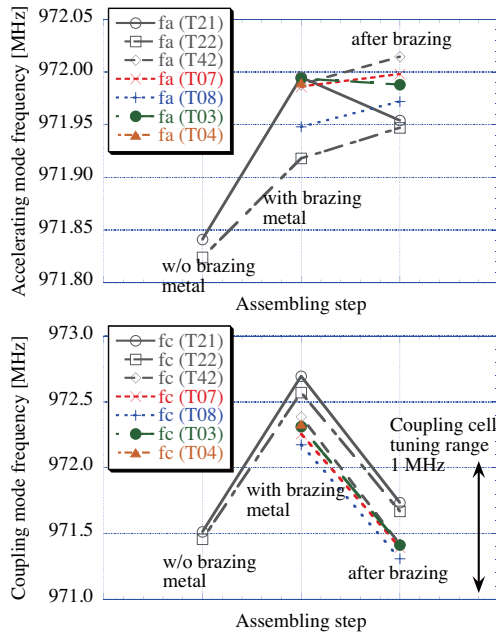


Figure 6: Frequency shift before and after the final brazing (Top: Accelerating mode, Bottom: Coupling mode). In these plots, the left, center, and right markers show the frequency of the stacked half-cell pieces without brazing metals, stacked pieces with brazing metals, and after the final brazing, respectively.

In these plots T21, 22, and 42 show the results of the prototype tanks. In the mass-production the setup without brazing metal is omitted to shorten the fabrication process. So far, T07, 08, 03, and 04 have been completed to the final brazing.

The result shows that the frequency shifts of the new tanks are within the expected range, compared with the prototype results. The accelerating mode frequency is expected to be within the tuning range of ± 0.3 MHz by a movable tuner on the bridge tank and the coupling mode frequency are within the tuning range of a fixed tuner (see "tuning range" in Fig. 6 bottom). The fixed tuners are attached on the outer circumference of the coupling cell [8].

The brazed accelerating tanks are assembled to the ACS accelerating module. The first module will be delivered to the J-PARC site in fall 2010 and then the high power test will be performed.

972-MHz Klystron and DC Power Supply

The developments of the 972-MHz klystron started from 2001. Although the prototype klystrons of #1 and #2 had the issue of oscillation caused by the higher mode of the second and third cavities, after that we improved the following points: i) anti-symmetrization of the higher mode distribution, ii) shortening of the gap length, and iii) reducing the cavity Q-value [9, 10]. Finally we achieved the design values in the #3 klystron whose parameters are summarized in Table 2.

Furthermore the #4 klystron was fabricated with a small collector and a high-purity of 99.7% alumina RF window. The power-test of #4 klystron confirmed good performance, thus the mass-production began from March 2009 on the basis of this design. The 16 klystrons were delivered or ordered.

Table 2: Parameters of the 972-MHz Klystron (#3)

Parameter	Design	Achieved
Output Power (MW)	> 3.0	3.1
Beam Voltage (kV)	< 110	106
Cathode Current (A)	< 50	45
Gain (dB)	> 50	51
Efficiency (%)	> 55	67
Band width at -3dB (MHz)	± 5	$> \pm 5$

One 972-MHz klystron power supply (KPS) drives four klystrons in the similar system of the 324 MHz.

The reliability of the 972-MHz KPS is improved on the basis of the operation experience of the 324-MHz KPS's. For an example, the high electric field region of the new 972-MHz KPS's is reduced with an electromagnetic simulation and a breakdown test in the anode modulator to prevent discharge (See Fig. 7). Furthermore we used insulation oil only without solid insulators. The preliminary result of the new KPS shows that the discharge incidence reduces from 4.3 times/day to 0.30 times/day [11].

Low-level RF

Accelerating field stability is one of the most important issues for a high intensity proton accelerator. The J-PARC Linac requires that the field stability should be less than $\pm 1\%$ in amplitude and ± 1 degree in phase.

To achieve these requirements the RF signals are controlled by the FPGA-based digital feedback control systems installed in a compact PCI (cPCI) for the 324-MHz and 972-MHz systems. The feed forward control is also used for a beam loading compensation. This control system consists of CPU, IO, DSP with FPGA, Mixer & IQ modulator, and RF & CLK boards. The hardware for the both systems is basically same except the RF board and Mixer & IQ board working for a different frequency. The software has been developed as the common software for the two frequency systems for the ease of maintenance.

This 324-MHz system have been operated from October

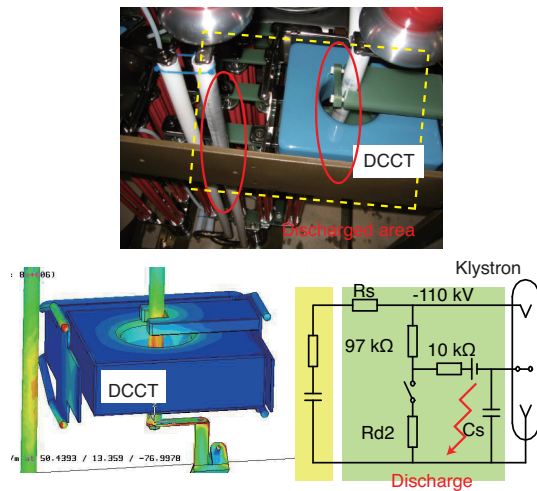


Figure 7: Discharge in the anode modulator. Top: discharge area around the DCCT. Bottom left: the simulation around the DCCT (yellow dashed box region in the top). Bottom right: discharge point in the circuit.

2006. The very good stability of the accelerating field was successfully achieved about $\pm 0.2\%$ in an amplitude and ± 0.2 degree in a phase. They are much better than the requirements of $\pm 1\%$ and ± 1 degree [12].

The new LLRF controller has been developed for the energy upgrade [13]. The 972-MHz system is required the chopped beam loading compensation because of the lower Q-value of the 972-MHz ACS cavity, compared with the 324-MHz cavities. The beam test of the chopped beam loading compensation was well performed with the present 324-MHz cavity system [14].

The debuncher #2 is located very far from the klystron (up to 110 m), then the feedback loop delay is about $1.5 \mu\text{s}$. We also studied the feedback control of the ACS cavity field including long loop delay and the effect of the chopped beam loading. The result shows that the maximum fluctuation is within $\pm 1\%$ in an amplitude and ± 1 degree in a phase [15].

Monitor

Figure 8 shows the monitor layout around the MEBT2 section including some ACS modules. Although Beam Position Monitors (BPM's) and Beam Loss Monitors (BLM's) are not shown in the Fig. 8, the BPM's are installed to each quadrupole doublet, and the BLM's are attached to each ACS module. Each ACS module has a Fast Current Transformer (FCT) at its exit for the beam phase measurement. The beam energy from the accelerating module is measured with the time-of-flight method utilizing two downstream FCT's. Each ACS module has also a Slow Current Transformer (SCT) at its exit for the beam current measurement.

Four Wire Scanner Monitors (WSM's) and three Bunch Shape Monitors (BSM's) are installed in the matching sec-

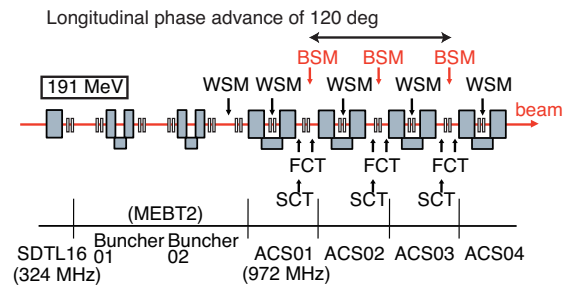


Figure 8: Monitor layout of the MEBT2 and the upstream of the ACS

tion from the SCTL (324 MHz) to the ACS (972 MHz). These BSM's are fabricated in collaboration with INR, Russia [16].

SUMMARY

The design of the ACS cavity varies according to the geometrical β , thus the mass-production of the ACS is not as simple as just making a copy. Keeping on schedule is therefore one of the greatest challenge for the mass-production of the ACS. Although there was minor trouble with machining, the fabrication is almost on schedule.

In the J-PARC site, the pre-installation began from summer 2009. The klystron power supplies, the LLRF system, and the most of cables are being installed in summer 2010.

Since beam users are eager to shorten the shutdown period of the energy upgrade, we should form the installation work plan and the conditioning scenario to meet the tight schedule in 2012.

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