COMMISSIONING OF THE J-PARC LINAC

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Abstract

The J-PARC (Japan Proton Accelerator Research Complex) is a multi purpose facility with 1 MW class proton beam power. The J-PARC comprises a linac, a 3 GeV rapid-cycling synchrotron (RCS), a 50 GeV main ring synchrotron (MR) and experimental facilities. The energy of the linac is reduced to 181 MeV for the time being, and it will be increased to 400 MeV in the near future. The 3 MeV RFQ, which is a front end of the linac, has been beam commissioned since November 2006, and we continue to work on the rest of the linac such as a 50 MeV DTL and a 181 MeV Separated-type DTL. The results and status of the J-PARC linac beam commissioning are presented.

INTRODUCTION

The High Intensity Proton Accelerator Project in Japan [1] is referred as "J-PARC Project", which stands for Japan Proton Accelerator Research Complex. This project is a joint one between the Japan Atomic Energy Agency (JAEA) and the High Energy Accelerator Research Organization (KEK). The facility is under construction at the JAEA/Tokai site as shown in Fig. 1. An H^- beam with a peak current of 50 mA and a pulse width of 500 μs is accelerated up to 400 MeV by a linac, and then injected to a 3 GeV Rapid Cycling Synchrotron (RCS) with a repetition rate of 25 Hz. The linac can be operated with a repetition rate of 50 Hz, the remaining half of the beam will be used for the basic study of the Accelerator Driven Nuclear Waste Transmutation System (ADS) in the future.

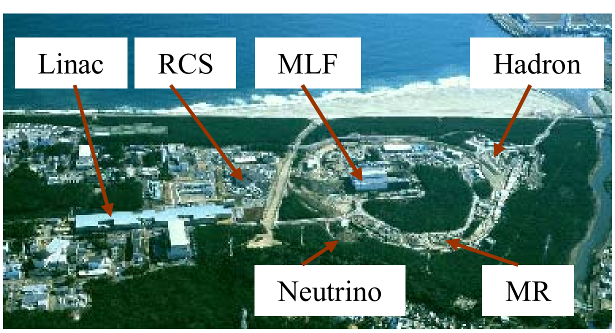

Figure 1: J-PARC facilities

The beam accelerated by the RCS with an average current of 333 μA and a beam power of 1 MW is fast extracted and transported to the Materials and Life science experimental Facility (MLF) most of the time. In the MLF, a muon and a neutron production targets are located in a series. About 10 % of the beam is used for the muon production. Every 3.5 second, the beam is transported to a 50 GeV Main Ring Synchrotron (MR) [2] and injected to it. The accelerated 50 GeV, 0.75 MW beam is slowly extracted to the Hadron Experimental Facility with duration of 1.6 sec. Kaon rare decay experiments, hyper nucleus experiments and so on will be conducted. The beam is fast extracted to a neutrino production target. Produced neutrinos are sent to the SUPERKAMIOKANDE detector located 300 km west for long base line experiments.

The J-PARC project is divided into two phases. The construction of the Phase I started from April 2001 and will be completed by 2008. The facilities in the Phase I comprises the linac, the RCS and the MR. The MLF is equipped with a full-power neutron production target. In the Phase I, however, the MR will be operated up to 40 GeV, since the fly-wheel electric power system will be equipped in the Phase II. The Neutrino Facility was originally in the Phase II, but it was forwarded to the Phase I in 2004. The half of the Hadron Experimental Facility building is in the Phase I, and the remaining half will be constructed in the Phase II. The superconducting proton linac from 400 to 600 MeV and the ADS experimental facilities are in the Phase II.

At the initial commissioning stage in the Phase I, the linac energy is decreased from 400 MeV to 181 MeV in order to compensate the budget overflow in the RCS and the linac. The lowering of the linac energy will reduce the RCS beam power from 1 MW to 0.6 MW and hence, the required peak current is 30 mA. The present building can accommodate the 400 MeV linac, and the energy recovery budget to 400 MeV is to be submitted to the funding agency.

At this point, the linac has been commissioned at full energy but lower than nominal power due to the limited beam dump capability. In this paper we report the latest results of the linac performance.

LINAC SYSTEM

The layout of the linac is shown in Fig. 2. The linac comprises a volume-production type H^- ion source, a 3 MeV Radio Frequency Quadrupole (RFQ), a 50 MeV Drift Tube Linac (DTL), a 191 MeV Separated-type DTL (SDTL), a 400 MeV Annular Coupled Structure linac (ACS) and a 600 MeV Superconducting Cavity Linac (SCL). Operation frequencies are 324 MHz for the RFQ, DTL and SDTL and 972 MHz for the ACS and SCL, respectively. As mentioned above, construction of the 191-400 MeV ACS linac is in the next step and it is replaced by a beam transport at the current stage. The last two SDTL tanks are installed in the beam line as debuncher cavities and no acceleration is expected.

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Therefore, the injection energy to the RCS is 181 MeV instead of 191 MeV.

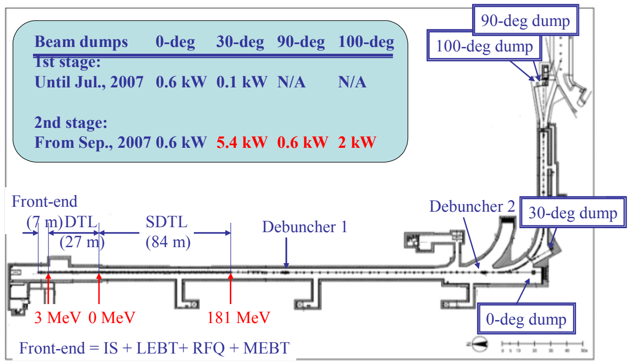

Figure 2: Layout of the J-PARC linac and commissioning stages

The required beam current for the RCS at 181 MeV injection is 30 mA at 0.5 msec, 25 Hz. The 0.5 msec long macro-pulses are chopped at the double of the RCS revolution frequency (because harmonic number is 2) into intermediate pulses of 636 ns duration with 428 nsec gaps. The RF chopper cavities in the Medium Energy Beam Transport (MEBT), which is between the RFQ and the DTL, chop the beam in the rise and fall times of 10 nsec.

The distinctive features of the J-PARC linac are arising from its multi-purpose concept; the realization of the high beam powers of MW in both several GeV and several tens of GeV region. The details of the accelerator design are reported in [3].

Since the 50 GeV synchrotron requires several-GeV injection beams, the accelerator scheme is based on the RCS in contrast to the scheme of a full-energy linac and a storage ring option as the SNS project.

The linac is required to provide the beam with low momentum spread ($\Delta p/p < \pm 0.1$ %) and with low transverse emittance (< 4 πmm.mrad). These values are necessary for the efficient painting and for the reduction of the beam loss in the RCS. In order to produce these high-quality beams, we designed and devised as follows;

- pi-mode stabilizing loops to eliminate any effects of the deflecting field in the RFQ,
- compact electro-qudrupole magnets contained in the drift tubes in the DTL in order to keep the flexible knobs for the transverse tuning,
- an RF deflecting chopper for fast chopping,
- an SDTL, comprised of short tank without post couplers and Q magnets are outside of the tank,
- an annular coupled structure (ACS) for its good axial symmetry,
- a debunching system in the beam transport line to control the momentum spread, and
- charge exchange scrapers in the beam transport line to scrape the beam outside of the transverse acceptance in the RCS.

The J-PARC is a pioneer of the proton linac with a frequency of 324 MHz. It is based on the design approaches of the 3 MeV ejection energy RFQ, the beam matching system including chopper, and the 3 MeV injection energy DTL with electro-quadrupoles. We have also developed a klystron and peripheral components. The same or the similar frequencies are adopted or considered at several facilities such as CSNS, ISIS-upgrade, GSI-FAIR and FNAL. Our 324 MHz operation experiences with 20 units of klystron system will provide a lot of information to accelerator community.

FRAMEWORK OF THE BEAM COMMISSIONING

Beam commissioning of the linac is divided into two stages as shown in Fig. 2 from the viewpoint of the beam dump availability. The linac has four beam dumps in the succeeding beam transport line, L3BT (Linac to 3 GeV synchrotron Bram Transport). In the first stage, the construction of the RCS has been continued in parallel with the linac beam commissioning. Thus the 90 deg and 100 deg beam dumps in the RCS side are not available and the maximum power of the 30 deg dump is limited to 100 W. In the second stage, from September 2007, the RCS is expected to be ready and all the dumps will be available and maximum power of the 30 deg dump will be 5.4 kW.

In the first stage, we have adopted a three to four weeks commissioning cycle, which consists of a two week beam commissioning run and a one or two week interval. Adjusting the terms of intervals to accommodate appropriate maintenance periods, eight beam commissioning cycles have been planned from November 2006 to June 2007. Detailed beam commissioning history and results by April 2006 are described in [4].

The purpose of the beam commissioning is to pass a government's inspection as a radiation facility, which is mandatory to proceed the next stage, which means RCS facility application. The next priority is to realize the beam conditions which are required to start the following RCS commissioning.

It is important to avoid a trial and error tuning, because even a temporal beam loss can cause a long term residual radiation. Therefore, a commissioning software system with accurate accelerator modelling is developed and performed [5-9].

FRONT END

The J-PARC uses a LaB_6-driven, Cs-free, multicusp H^- ion source. Two solenoid magnets are used to focus the beam into the RFQ that is 0.6 m downstream of the ion source extraction aperture. The beam from the ion source is accelerated to 3 MeV in the RFQ. The output energy was measured by a time-of-fight technique in the MEBT and found to be 2.96 MeV, compared with the nominal design energy of 3.0 MeV.

The MEBT is a complex beam transport line. It chops the beam and matches the beam for subsequent acceleration in the DTL. Eight quadrupole magnets and two buncher cavities provide the transverse and the

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longitudinal matching. The MEBT is equipped with a suit of beam diagnostics including beam current monitors, beam position monitors and wire scanners.

The maximum beam current from the ion source is 39 mA at the arc duty factor of 0.8 % (0.32 msec in pulse width and 25 Hz) and beam duty factor of 0.08 % (0.32 msec and 2.5 Hz). The filament life time is 644 hours as of June 17, 2007, and will be extended furthermore because we have not observed remarkable filament consumption yet.

Beam commissioning of the RFQ began in November 2006, with the beam successfully reaching the beam stop on the first day at 5 mA. The design peak current of 30 mA was achieved on the next day. The waveforms of beam current are shown in Fig. 3. The ion source acceleration voltage is modulated by 12.5 kV during the RFQ acceleration and extraction beam current increases.

The RF chopper at the MEBT was tested. The measured rise and falling times of the beam were 20 to 30 ns, which were slower than the results at KEK before. This implies that the system needs to be more tuning. The digitizer resolution does not allow an extinction ratio measurement to the design level of 10^{-4}.

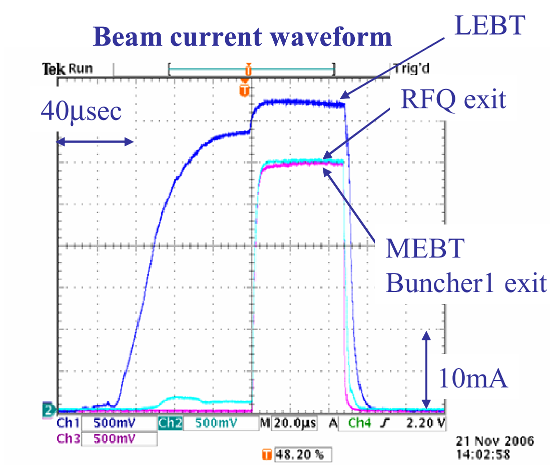

Figure 3: Beam current waveforms of 3MeV RFQ acceleration at 30 mA, 50 µsec, 5Hz.

DTL

The DTL consists of 3 tanks operating at 324 MHz with final output energy of 50 MeV. Each tank consists of three short unit tanks, which are about 3 m in length. The accelerating field is stabilized by post couplers. The transverse focusing is arranged in an FD lattice utilizing electro-magnet quadrupoles.

The first tank (DTL-1, 19.7 MeV) was commissioned at KEK by September 2004 [10]. These DTL tanks and assembled DTL and SDTL tanks had to be shipped to Tokai. In view of the severe cost and schedule constraint, lifting and shipping procedures against the dynamic load to JAEA-site was extensively reviewed and tested without disassembled condition. In order to prevent damages during shipping, we used a special trailer for satellite shipment and well balanced condition in the bed. Upon arrival, the low level RF measurements confirmed that the drift tubes were remained in the proper positions within the measurement accuracy.

After the high-power conditioning of the DTL was completed up to 1.2 times as high as the nominal power level [11], the beam commissioning of the DTL has been achieved in the second run, December 2006. The beam accelerated by the DTL-1 at the energy of 19.7 MeV was successfully delivered to the 0 deg dump at 300 m downstream. We didn't use any steering magnets to achieve nearly 100 % beam transmission efficiency through the 0 deg dump. This proved the precise alignment of the linac [12,13]. Then the tuning of the DTL-2 and 3 was carried out.

The principal method for determining RF phase and amplitude is the time-of-flight based phase scan [14]. In this method, the difference in beam arrival phase between two downstream fast current transformers (FCTs) is recorded as the cavity phase is scanned. The resulting phase scan curves are obtained for several tank amplitudes, and then compared to those from the modelling to determine the RF phase and amplitude. Figure 4 shows the experimental results as well as the simulated phase-scan curves obtained with PARMILA code. The experimental results show good agreement with the simulation. These results demonstrate that 1 % in amplitude and 1 degree in phase accuracies will be achievable.

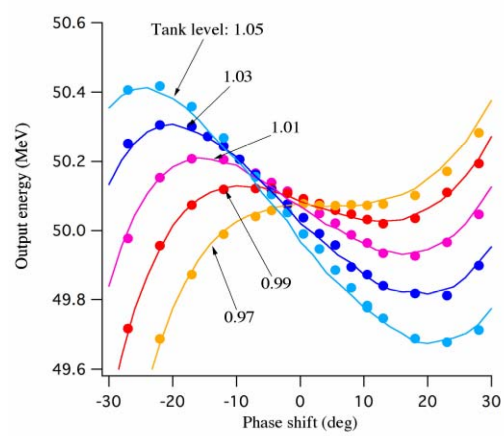

Figure 4: Phase scan curves for the DTL-1. Circles show measured beam energies and curves show results from the modelling.

SDTL

We have 32 SDTL tanks but two of them are used as debunchers. The inter-tank sections contain electromagnet quadrupole doublets with beam position monitors inside. Either steering magnet, wire scanner, or gate valve is arranged in between the doublet.

The two neighboring tanks are driven by one klystron. Since the RF phase and amplitude tuning is to be performed klystron by klystron, there are 15 units or modules to be tuned to achieve 181 MeV acceleration. We performed the RF tuning of SDTL with the phase scan

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method in a similar way to the DTL [15]. We have prepared two sets of FCT pairs for each SDTL module, namely, a short base-line pair and a long base-line pair. Short base-line pairs were prepared to avoid miscounting of the wave number between two FCTs in the corresponding long base-line pair. Though the RF tuning was rather rough, the 181 MeV acceleration had been achieved on January 24, 2007, without notable beam losses. This first acceleration was performed with the peak current of 5 mA, pulse width of 20 μs, and the repetition rate of 2.5 Hz. After achieving the 181 MeV acceleration, we have increased the pulse width to 50 μs, and have also achieved the beam delivery to 30 deg dump. Then we took the inspection and passed in February.

For the demonstration, a beam pulse of 25mA peak current, 50 μs pulse length at 2.5 Hz was achieved as shown in Fig. 5 within the allowed 0 deg beam dump power of 600 W (average power in one hour). Figure 6 shows the result of beam current stability measurement. Stability of 1 %, occasional beam stops and hourly gaps are observed. The beam was tripped by the machine protection system automatically. One of the main causes is breakdown in a cavity. To prevent the excess power of the allowed dump capacity limit, accumulated beam charge is carefully monitored and the beam was stopped manually several minutes before the hour sharp. And the beam was restarted on the hour sharp after the charge accumulation is reset.

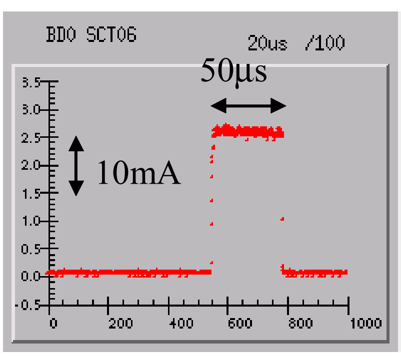

Figure 5: Beam current waveform at the 0 deg beam dump for high peak current of 25 mA at 181 MeV, 50 μs, 2.5Hz.

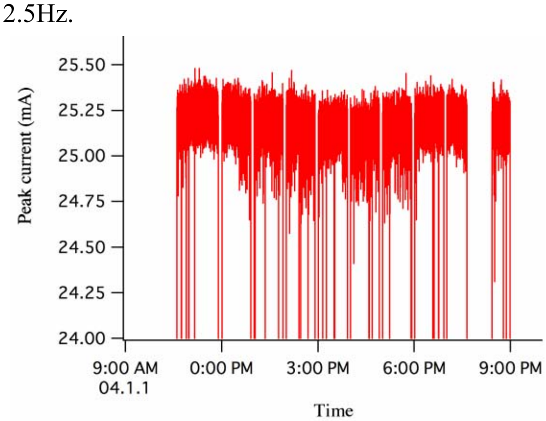

Figure 6: Beam current stability on May 24, 2007

BEAM MATCHING AND LOSS

Transverse matching has been performed for three matching sections, DTL exit, SDTL exit and at the end of the future ACS section. We have an array of four wire scanners at each matching section, and the matching was performed to have uniform beam widths with the wire scanners. Figure 7 shows the beam envelopes before and after the transverse matching at the SDTL exit.

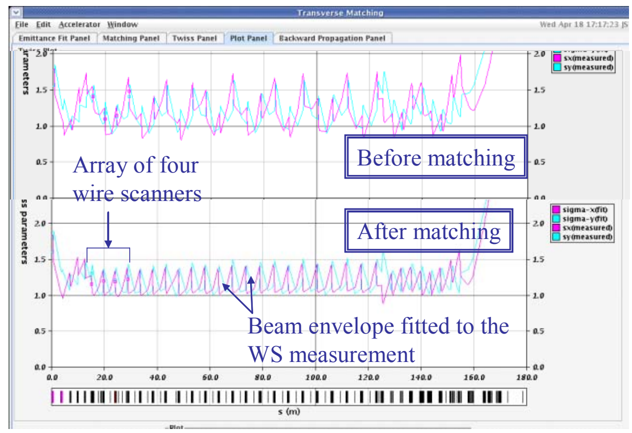

Figure 7: Transverse matching results at the SDTL exit

There is no reduction in beam current along the linac detectable by the beam current transformers. But beam loss monitors based on the ionization chambers detect a small amount of beam losses.

The localized residual radioactivity observed is due to losses in the beam window of the beam dump (10 mSv/h on contact). The local shield will be installed around it. Another loss points are at the SDTL tanks used as debunchers (40 – 100 μSv/h on contact), where the beam bore radius is smaller than the vacuum chamber aperture.

RF SYSTEM

Figure 8 shows the RF subsystem. Six HVDCPSs supply the pulsed power to the 20 klystrons with transmitter systems that control the klystrons and solid-state amplifiers to provide RF power to the structures.

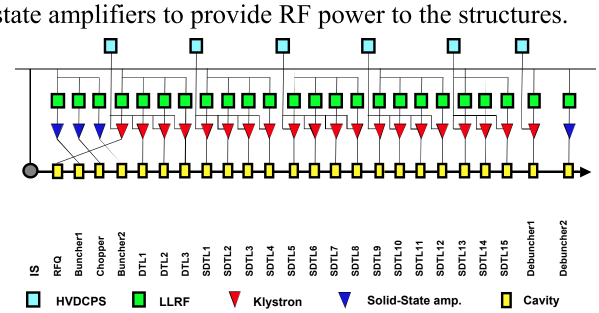

Figure 8: J-PARC linac RF system

The RFQ, DTL and SDTL have been RF conditioned and tested to full RF peak power level under LLRF closed loop control [16,17]. The RF conditioning is done by increasing peak power in short pulses at low duty factor to the maximum peak power and then by increasing the

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average power to the maximum duty factor. Most of the tanks are accepted at full duty factor RF, but some need still conditioning. Stabilization of the cavity fields is well performed with a feed-back and feed-forward control system. Test of the LLRF achieved field regulation specifications of ±1% and ±1degree in 0.2 ms. The beam loading ripple caused by a beam of 26 mA peak current and 50 μs duration in the DTL cavity is almost perfectly vanished with the feed-forward compensation as shown in Fig. 9.

We have totally 23 klystrons including 3 spares. Performance study was carried out for all the klystrons and it was found out that they met the required specifications. The hour meters are recording the high voltage on time and they show about 2,300 to 2,500 hours for all but spare klystrons as of June 19, 2007. We have no serious troubles in the klystron operation for the beam commissioning.

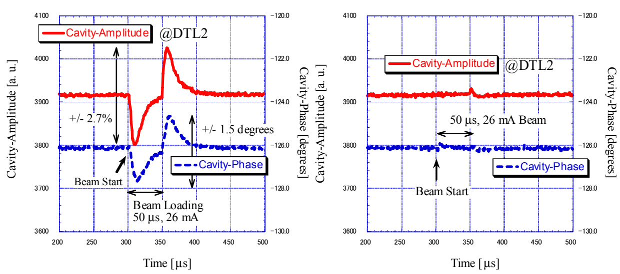

Figure 9: Feed-forward compensation in the DTL-2 at 26 mA, 50 μs. Without (left) and with (right) compensation.

ACS FOR ENERGY UPGRADE

Since the ACS has good axial symmetry which is desirable property for the linac structure, the J-PARC will use the ACS from 191 to 400 MeV. The 21 accelerating modules, 2 buncher modules and 2 debuncher modules will be used. We have succeeded in powering the first cavity of the J-PARC ACS which will be used as buncher at the transition between the 324 MHz SDTL and the 972 MHz ACS [18]. The conditioning has been completed without any troubles and maximum applied power was 1.2 times as high as the nominal level. Further characteristics analysis has been carried out [19] and test of the second buncher cavity will be performed in a few months.

SUMMARY

The J-PARC linac has been successfully commissioned. Acceleration to the design energy of 181 MeV of beam pulses with the peak current of 26 mA has been achieved. Tuning algorithms are well established and provide stable setting of RF phase and amplitude. In general, there is good agreement between the measured beam parameters and the design values. Our RF system will provide a lot of information to the accelerator community of 324 MHz klystrons and RF system. Chopper system was demonstrated, but further adjustment is needed to improve the rise/fall times. Beam losses are generally low, but some parts should be considered.

After the linac commissioning run in June, we will have a two month summer shutdown. The second stage will be started in September, and the downstream of the L3BT and the RCS will be beam commissioned. The high power operation of the linac using the 30 deg 5.4 kW beam dump is also to be performed.

REFERENCES

[1] "The Joint Project for High-Intensity Proton Accelerators", JAERI-Tech 99-056, KEK Report 99-4, and JHF-99-3 (1999).

[2] T. Koseki, "Status of J-PARC Main Ring Synchrotron", these proceedings, TUODKI01.

[3] "Accelerator Technical Design Report for High-intensity Proton Accelerator Facility Project, J-PARC", JAERI-Tech 2003-044, KEK Report 2002-13 (2003).

[4] M. Ikegami and A. Ueno, "Commissioning Experience and Plans for J-PARC Linac", ICANS-XVIII, April 2007, Dongguan, China.

[5] H Sako, et al., "Development of Commissioning Software System for J-PARC LINAC", these proceedings, MOPAN044.

[6] C. Allen et al., "XAL Online Model Enhancements for J-PARC Commissioning and Operation", these proceedings, MOPAN029.

[7] T. Ohkawa et al., "Comparison of Trajectory Between Modeling and Experiment for J-PARC Linac", these proceedings, THPAN043.

[8] S. Sato et al., "Beam Position Monitor and its Calibration in J-PARC Linac", these proceedings, FRPMN045.

[9] H. Akikawa et al., "Transverse Matching in J-PARC Linac", these proceedings, TUPAN039.

[10] Y. Kondo et al., "Beam Dynamics and Commissioning of the J-PARC Linac", ICFA-HB2004, Bensheim / Darmstadt, Germany (2004).

[11] T. Ito et al., "High Power Conditioning of the DTL for J-PARC", these proceedings, TUPAN058.

[12] T. Morishita et al., "The Precise Survey and the Alignment Results of the J-PARC Linac", these proceedings, TUPAN059.

[13] T. Morishita et al., "The DTL/SDTL Alignment of the J-PARC Linac", these proceedings, TUPAN060.

[14] M. Ikegami et al., "RF Amplitude and Phase Tuning of J-PARC DTL", these proceedings, TUPAN043.

[15] G. Shen et al., "RF Amplitude and Phase Tuning of J-PARC SDTL", these proceedings, TUPAN062.

[16] T. Kobayashi et al., "Performance of J-PARC Linac RF System", these proceedings, WEPMN039.

[17] Z. Fang et al., "RF Feedback Control Systems of the J-PARC Linac", these proceedings, WEPMN024.

[18] H. Ao et al., "First High-Power ACS Module for J-PARC Linac", 2006 Linac Conf., pp.725-727 (2006).

[19] H. Ao et al., "Fabrication Status of ACS Accelerating Modules of J-PARC Linac", these proceedings, TUPAN056.

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