STATUS OF THE J-PARC LINAC, INITIAL RESULTS AND UPGRADE PLAN

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Abstract

The J-PARC linac comprises the voulume-production type negative hydrogen ion source, the 50-keV low-energy beam transport, the 3-MeV RFQ linac with π-mode stabilizing loop, the 50-MeV, 324-MHz Dift-Tube Linac (DTL) with electro quadrupole magnets therein, and 180-MeV separate-type DTL. The construction is on schedule for starting the beam commissioning in September, 2006. The first cavity of DTL already accelerated the beams up to 20 MeV in November, 2003. The beam study results are reported with the measured values of the emittances. The chopper installed to the medium-energy beam transport was already beam-tested with designed rise and falling times. Since the expected beam power of the 3-GeV rapid-cycling synchrotron is only 0.6 MW with an injection energy of 180 MeV, the construction budget for the linac energy recovery to 400 MeV will be immediately submitted to the funding agency after the completion of the present phase of the project. The further upgrade plans to several-MW neutron source and neutrino factory are also presented.

INTRODUCTION

The High-Intensity Proton Accelerator Facility in Japan [1-9], which is a joint project between JAERI (Japan Atomic Energy Research Institute) and KEK (High Energy Accelerator Research Orgainzation), has been referred to as J-PARC, which is the acronym of Japan Proton Accelerator Research Complex. The J-PARC project as agreed by JAERI and KEK comprises the 600-MeV linac, the 3-GeV rapid-cycling synchrotron (RCS), and the 50-GeV proton synchrotron (Main Ring, MR). The 400-MeV beams from the linac are injected to the RCS with a repetition rate of 25 Hz, while the beams are further accelerated up to 600 MeV by the superconducting (SC) linac to be used for the basic study of the Accelerator-Driven Nuclear Waste Transmutation System (ADS). The maximum average current is 333 μA for each of RCS and ADS. The 1-MW beams from the RCS are mostly extracted to the Materials and Life Science Experimental Facility (MLF), where the muon-production and neutron-production targets are located in a series. The 10 % of the beams are used for the muon production. Every 3.3 second, the beams are transported and injected to the MR four times. The ramping time is 1.9 s, while the deceleration takes 0.9 s. The accelerated beams are slowly extracted to the Nuclear and Fundamental Particle Physics Experimental Facility (NPF), and are fast extracted to produce the neutrino beams, which are sent to the SUPERKAMIOKANDE detector located 300-km west. The MR beam power is 0.75 MW at 50 GeV (15 μA). This is a full scope of the J-PARC project as agreed between JAERI and KEK.

When the project was funded to start in Japanese Fiscal Year (JFY) 2001 as a six-year project, the following facilities were shifted to the Phase II (the funded project is referred to as Phase I).

1) The Neutrino Facility
2) The ADS Facility
3) The SC linac from 400 MeV to 600 MeV
4) Half of the NPF Experimental Hall
5) The fly-wheel electric power generator for the MR, which means that the MR can be operated only up to 40 GeV with the above ramping time (if the ramping time is longer, the acceleration up to 50 GeV will be possible).

In the next section the project status and the overall schedule will be reported. Then, the linac scheme is summarized together with its reasoning. After the construction status is reported, the initial results of the beam commissioning up to the 20-MeV Drift-Tube Linac (DTL) are presented in detail. Finally, the upgrade plans proposed so far are described.

PROJECT STATUS

The following three major changes came into the project. First, the Neutrino Facility was approved for the construction starting from April 2004 to complete in March 2009, implying that the Neutrino Facility was moved up from Phase II to Phase I.

Second, the linac energy was decreased from 400 MeV to 180 MeV in order to compensate the budget overflow in the linac and RCS. Here, we will construct all the accelerating structures up to 190 MeV, but the two cavities, to accelerate the beams from 180 MeV to 190 Mev in future, will be used as debunchers rather than accelerators for the time being. Although the RCS beam power is reduced from 1 MW to 0.6 MW by this, the MR the same beam power may be kept as original by increasing the time duration of the injection from the RCS to the MR. The present building can accommodate the 400-MeV linac, and the energy recovery to 400 MeV will be submitted to the funding agency immediately after the completion of Phase I. Since it needs several-year beam operational experience to achieve the full performance of 0.6 MW, the 1-MW full power operation will not be delayed by recovering the linac energy to 400 MeV within a few years.

Third, the funding to the linac and the RCS was delayed by one year. The scheudule for the MR building had been delayed by more than one year for the archaeological investigation of the ancient salt pans. However, the delay in the beam commissioning schedule was managed to decrease to half a year. The updated construction schedule is shown in Fig. 1.

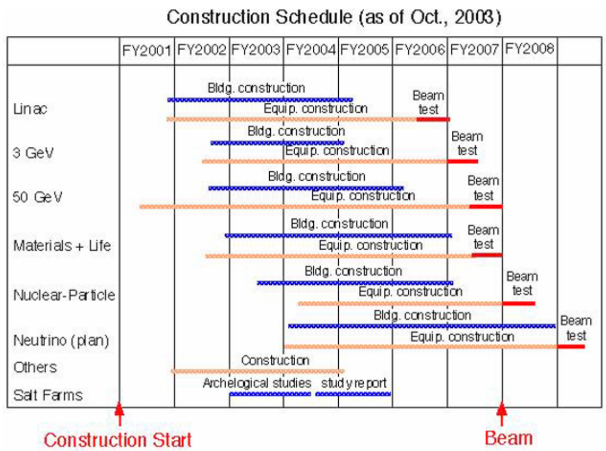

Figure 1: Construction Schedule Updated.

LINAC SHEME

The J-PARC linac scheme is summarized in Fig. 2. The volume-production type of the negative hydrogen ion source is followed by the 50-keV Low-Energy Beam Transport (LEBT), which uses the solenoid focusing. The Radio-Frequency Quadrupole (RFQ) linac accelerates the beams to 3 MeV, being equipped with the π-mode Stabilizing Loop (PISL) [10-12]. The 3-MeV Medium-Energy Beam Transport (MEBT) [13] comprises eight quadrupole magnets to transversely match the RFQ beams to the following DTL and two bunchers for longitudinal matching. In addition, the RF chopper [14] is installed in the MEBT. The 50-MeV DTL [15-21] comprises three cavities, being followed by the Separate type of DTL (SDTL) [22], which has no quadrupole magnets (QMís) inside. The shape of the Drift Tubes (DTís) can thus be adjusted for optimizing their shunt impedances. Since the QMís are installed outside the five-cell SDTLís, the transverse transition is located between DTL and SDTL systems. The 32 SDTL cavities accelerate the beams to 190 MeV, where the high-energy structure starts with an accelerating frequency three times as high as that of RFQ and DTL. Thus, the longitudinal transition is located there. The Annular-ring Coupled Structure (ACS) [23-32] was chosen for the high-energy structure. The ACS is also used for the bunchers located in the beam transport from the SDTL system to the ACS system, and for the debunchers in the beam transport (L3BT) [33] to the RCS.

The key issue of the parameter choices [34] is the RF accelerating frequency of the DTL. The higher frequency is preferable for increasing the beam current, since the larger number of the bunches can be accelerated per unit time. This choice is also advantageous, regarding the smaller sizes of the RF components. In particular, the feasibility to use the klystrons contributes to the stability and reliability of the RF system. On the other hand, the smaller size of the DTís do not accommodate the electro quadrupole magnets with hollow conductors. For this reason, the 432-MHz DTL was developed with the permanent QMís (PQMís) [35] for the Japan Hadron Project (JHP) [36]. Although the PQMís are very advantageous regarding their maintenance-free character, one has to lose the flexible knob for the focusing parameters. In particular, the matching between the beam emittance and the lattice parameters are important in order to reduce the emittance growth and the halo formation. The matching condition may be different from the designed one, depending upon the beam current or the ion source condition. Also, one has to avoid the unknown resonances, if they exist. For this reason, we decided to develop the water-cooled electromagnets with the minimum size. The water channels of the coils were formed by the electroforming technique, while the coils were machined out by means of wire-cutting technology [15]. In this way, the 324-MHz DTL starting from 3 MeV was realized, being powered by the klystron.

The DTL can start from 3 MeV rather than 2 or 2.5 MeV, since the long RFQ linac is made possible by the invention of the PISL [10]. The beams should be chopped at the MEBT in order to avoid the beam loss inherent to the adiabatic capture process for the ring injection. The beams with the energy much higher than 3 MeV are difficult to chop. This is the reason for the choice of the MEBT energy.

The RF chopper [14] is another invention for the J-PARC. The prechopper installed at the LEBT chops the beams with rather slow rise and falling times. The prechopper, based upon the FINEMET induction linac, decreases the injection energy to the RFQ linac, which was designed to work as a sharp energy filter. The RF chopper then chops the remaining beams with fast rise and falling times of 10 ns by the deflecting RF electric fields of TE111-like mode.

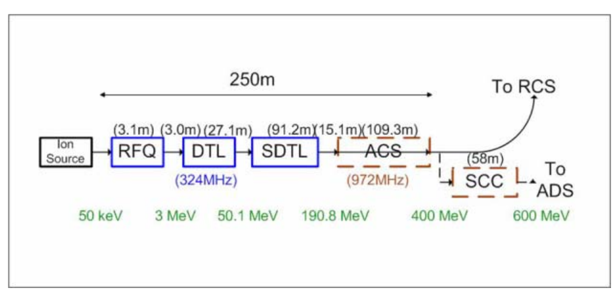

Figure 2: Scheme of J-PARC Linac.

ACCELERATOR STATUS

Ion Source

Three negative hydrogen ion sources are produced for the linac. All are of the volume production type. The first one is of the pure volume production type without cesium designed by KEK. Its filament is made of LaB_6. This is used for the beam test at present. The shortcoming of this ion source is a long rise time. The longest flat top so far obtained is 360 μs with a repetition of 25 Hz [37]. The second one was designed and tested by JAERI in order to study the parameter dependence of the ion source performance. With cesium, the peak current of 72 mA was obtained with a full duty factor [38]. Its filament is made of tugsten, the life time of which could be elongated to 258 hours by optimising the filament shape. Since this is specialized for the study of the ion production mechanisms and for the parameter search with adjustable cusp fields, the ion source cannot be used for injecting the beams to an RFQ linac. The third one was produced for the use in the real machine with improved design for the stability of the beam current. This is now under test without cesium. The peak current of 28 mA has been already obtained and is increasing (a pulse length of 600 μs and a repetition of 10 Hz, at present). The use of the RF fields are planned for the arc excitation rather than the filament in collaboration with the SNS ion source group.

LEBT, RFQ, MEBT, Choppers and DTL1

These components are already under beam-commisioning to be detailed in the next section.

DTL2, DTL3 and SDTL

The low-power tuning of the DTL2 has been finished with field uniformity better than 1 %, while that of the DTL3 is under way. The components of all the SDTL cavities will be completed by the end of this year. The seven cavities have been assembled, while the three were power-tested.

RF Power Sources

Among twenty klystrons for RFQ, DTL and SDTLís the sixteen have been assembled, while the seven were power-tested. All the twenty anode-modulators and the five cathode power supplies were ready.

BT to RCS

Most of the Beam Transport (BT) components from the linac to the RCS will be completed by March, 2005, while some will be finished one year later.

Building, Installation and Alignment

The linac building will be completed by October, when the electricity and the air conditioning system start to be installed. Everything will become ready by May, 2005, for the installation of accelerator, although some installation will begin much earlier. Most of the linac components are tested and stored in the KEK site. Thus, their shipping to Tokai is an issue, in particular, for the DTL cavities with long DT stems delicately aligned. The laser tracker will be fully used for the alignment [39] rather than the laser-beam alignment first planned.

INITIAL RESULTS

The beam test of the RFQ linac and the MEBT has been conducted in the KEK site from 2002 to March, 2003. The results of the emittance measurements and the beam chopper tests were reported in Refs. [13,14]. The DTL1 was then installed to the tunnel and the RF power was fed in the DTL1 cavity. The detail of the DTL is reported in Refs. [15-21]. The photograph of the DTL1 being used for the beam study is shown in Fig. 3.

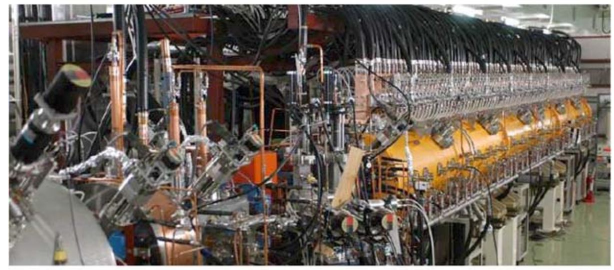

Figure 3: The DTL1 and MEBT ready for the beam study.

The beam commissioning of the DTL1 started on October 30th, 2003, when the peak current of 5 mA was accelerated. On the second day (November 6th) of the beam commissioning, the peak current of 30 mA was obtained with a transmission of 100 % (the accuracy of the used current transformer is typically a few per cent). The beam pulse length is 20 μs with a repetition rate of 12.5 Hz. The duty factor is limited by the radiation shielding capacity of the beam dump (in the case of the 3-MeV MEBT the pulse length of 250 μs with a repetition rate of 25 Hz was tested).

Just after this beam test, the turbo-molecular vacuum pump installed to the downstream of the DTL1 was broken, resulting in the serious damage on the nearby vacuum chamber. After the repair of the damaged components the beam study restarted in February 2004. Until May, the beam has been mainly used for the basic test and study of the beam monitors installed to the MEBT. In June, the improved emittance monitor was installed at the downstream of the DTL1. The emittance measurement then started.

At the 2782-mm down stream from the end plate of the DTL1 the first slit for the emittance measurement was located. The distance between the two slits is 340 mm. The slits are 0.1-mm wide and 5-mm thick. The beam current was measured by both the slow current transformer (SCT) just after the DTL1 and the Faraday Cup (FC) just after the second slit. The beam energy was measured by the time-of-flight method between the Fast Current Transformer (FCT) and the Beam Position Monitor (BPM2) 1.1-m apart.

The preliminary results of the emittance measurements [40] are shown in Table 1 together with the simulation result by PARMILA for comparison. It is seen that the measured emittances are 1.5-times as high as the calculated ones. In order to eliminate the space-charge effect, the emittance measurements were also performed at the peak current of 5 mA. The horizontal emittance became close to the simulated one, while the vertical one was still larger.

Table 1: Measured and Calculated Emittances (normalized rms in π mm mrad)

	Horizontal	Vertical
After MEBT[a)] (Measured at 29 mA)	0.25	0.21
After DTL1 (Measured at 30 mA)	0.39	0.49
After DTL1 (calculated)	0.25	0.27
After DTL1 (Measured at 5 mA)	0.26	0.37

a) Ref. [13]. This is in reasonable agreement with the simulation result by IMPACT [41].

Since the phase and amplitude tuning of the DTL1 is essential for the results, the phase scan method was tested to obtain the best tuning. The tuning thus obtained was close to that which was used to minimize the emittances. The further investigation is ongoing to find the reason of the observed emittance growth.

LINAC ENERGY RECOVERY PLAN AND HIGH-ENERGY STRUCTURE

It is agreed among the two institutes, the user community and the ministry that the linac energy recovery to 400 MeV should be done at first as mentioned in the previous section. The two ACS cavities are already under construction to be used from 190 MeV to 400 MeV. The two ACS bunchers are also under production for the beam transport from the 190-MeV SDTL to the ACS. The three klystrons have been ordered, while the two is under power test.

The ACS first appeared in Ref. [23] had been long useless for its Q degradation, although its advantage regarding the axial symmetry has been realized [34]. The 1300-MHz ACS was developed for JHP [36] in KEK, with deep insight to the RF characteristics of the structure [24]. The prototype of the ACS with two five-cell cavities bridged by a five-cell bridge coupler was first power-tested up to more than designed field with a pulse length of 600 μs and a repetition of 50 Hz [25-27]. Afterwards a few ACS cavities were fabricated and power-tested with different β values and different coupling slots [28].

After the J-PARC project started, the new 972-MHz ACS cavity [29-32] was developed in order to keep the same size as that of 1300-MHz ACS in close collaboration with Institute for Nuclear Research (INR), Moscow, and Tokyo Institute of Technology. One disadvantage of the ACS cavity is its big size, since the ACS can be formed by rotating the side-coupled structure around the beam axis, geometrically speaking. This disadvantage is partly compensated by this new structure. The present version of the ACS is the one thus developed.

FUTURE UPGRADE PLAN

The future upgrade plan may be divided into two categories. The first one is the Phase II of the J-PARC project, which has been already agreed between the two institutes. The second one comprises facilities proposed by the J-PARC users as extensions of the present J-PARC facilities.

Phase II of J-PARC Project

As mentioned in the introduction, several facilities originally included in the J-PARC project were moved to the Phase II except for the neutrino facility. For the future extension to the 600-MeV linac, the present linac beam dump and the shielding there were built removable. In particular, the removable shielding concrete blocks surround the beam dump, since the activated soil cannot be removed later.

The development of the SC linac is in progress by the budget for the ADS development outside the J-PARC budget. One cryomodule comprising two nine-cell cavities for β = 0.725 was fabricated and low-power tested at 2°K in June [42, 43]. The high-power test is planned in this fall.

On the other hand, a branch tunnel was built from the present linac tunnel in order to extract the 400-MeV beams to the ADS facility. In this way, the ADS experiment can use the 400-MeV beams before the construction of the 600-MeV SC linac.

Upgrade Plan in Letter of Intent

Among thirty Letters of Intent (LoIís) [44] collected for the use of NPF, six letters proposed additional rings which accelerate or store the secondary beams produced by the MR beams, including the neutrino factory. The fast extraction system was made bi-polar in order to extract the beams either inside or outside the ring. The former is for the long base-line neutrino experiment, while the latter is for the future upgrade (for the abort at present). The present beam abort dump and the shielding can be removed by the same means as described in the above subsection.

Neutron Source Upgrade Plan

The scientific community for the pulsed spallation neutron source has been requesting the more powerful source beyond 1 MW. Until the J-PARC project was agreed between the two institutes, JAERI had been promoting the Neutron Science Project (NSP) including GeV-class linac. The present 180-MeV linac can be extended to the 1-GeV linac outside the MR area. Since the 1-GeV beam line is straightly extended through the shielding concrete wall of the MR tunnel, the wall was built so as to have the beam transport tunnel in order to keep the future upgradability. Inside the MR area the additional RCS or the compressor ring can be built together with an experimental facility building. The high-power RCS technology will be fully developed by realizing the present RCS. The 1-GeV injection to the

RCS will make possible a several-MW pulsed neutron source.

One of the serious problems for the future upgrade plan is that some plans in the LoIís do not seem geologically compatible with the several-MW neutron source. Some new methods such as extremely deep tunnels are necessary for solving this problem.

CONCLUSION

The J-PARC linac is under construction for the beam commissioning starting in September, 2006, at Tokai site. In general, the construction is on schedule. The beam study for the front end up to 20 MeV is in progress at KEK site.

The other topics, including the control and beam diagnostics, cannot be mentioned in this report for the limited space. These are detailed in Refs. [45-52].

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