COMMISSIONING OF THE J-PARC LINAC

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Abstract

The beam commissioning of the J-PARC linac will start in December, 2006. All the components have been installed in the linac tunnel and the klystron gallery, respectively. The preparation for the beam commissioning is under way as scheduled, except for the air-pressure control system, which delayed the powering of the cavities by one month. If no more serious trouble, the beam commissioning will start on schedule. The J-PARC linac comprises the 3-MeV, 324-MHz RFQ linac, the 50-MeV DTL, and the 181-MeV SDTL and the 400-MeV, 972-MHz ACS. It is unique by making use of many newly developed or invented accelerator technologies.

INTRODUCTION

The J-PARC (Japan Proton Accelerator Research Complex) is the joint project between High Energy Accelerator Research Organization (KEK) and Japan Atomic Energy Agency (JAEA) to construct and operate the high-intensity proton accelerator facility at Tokai site [1-12]. The J-PARC comprises the 600-MeV linac, the 3-GeV Rapid-Cycling Synchrotron (RCS), and the 50-GeV Main Ring (MR) Synchrotron. The 400-MeV negative hydrogen beams are injected to the RCS with a repetition rate of 25 Hz, a pulse length of 500 μs, and a peak current of 50 mA. Since the beams are chopped to 53 percent, the average beam current becomes 333 μA. The 400-MeV beams further accelerated to 600 MeV by the superconducting (SC) linac are used for the fundamental study of the Accelerator-Driven nuclear waste transmutation System (ADS). The 1-MW beams accelerated to 3 GeV by the RCS are extracted mostly to the Materials and Life science experimental Facility (MLF), where the muon-production target and neutron production target are located in series. Every 3.3 second, the RCS beams are switched to the MR four times. In other words, the average beam current of 15 μA is accelerated by the MR to 50 GeV to produce the beam power of 0.75 MW. The MR beam is slowly extracted to the Hadron Experimental Facility, while it is fast extracted to the Neutrino Experimental Facility. In the MLF, the pulsed muons and pulsed spallation neutrons are used for the materials and life science. The industrial use of the neutrons are especially encouraged. For this purpose, the local government funded three neutron beam lines. In the Hadron Facility, the Kaon rare decay and hyper nuclei with strangeness will be studied. In the Neutrino Facility, the neutrino beams produced will be sent to Super Kamiokande detector located about 300-km west.

When the project was approved for construction starting from JFY2001 (JFY stands for Japanese Fiscal Year starting from April), the following facilities were not funded, being referred to as Phase II: Neutrino Facility, ADS, SC linac, half of the Hadron Facility building, and the electric power facility which enables the MR in 50-GeV operation (therefore, at present, the MR energy is at highest 40-GeV). Among them, the Neutrino Facility was approved for construction starting from JFY2004 to be completed in JFY2009. In other words, the Neutrino Facility is now in Phase I. On the other hand, the linac energy had to be reduced to 181 MeV for the time being in order to have more margin for realizing the design beam power by increasing the RCS aperture and so forth, when the linac beam energy is increased to 400 MeV as originally desigen. We are going to submit the request for funding the upgrade of the linac energy up to 400 MeV just after the completion of the funded facilities, that is, JFY2009. Until the linac energy increase is accomplished, the beam power of the RCS is around 0.6 MW at most. In this case, the peak current of the linac is 30 mA.

The above project status was already reported in the last Linac Conference. Afterwards, the project funding was delayed more, that is, by two years. We managed to reduce the delay by one year and one month as shown in Fig. 1.

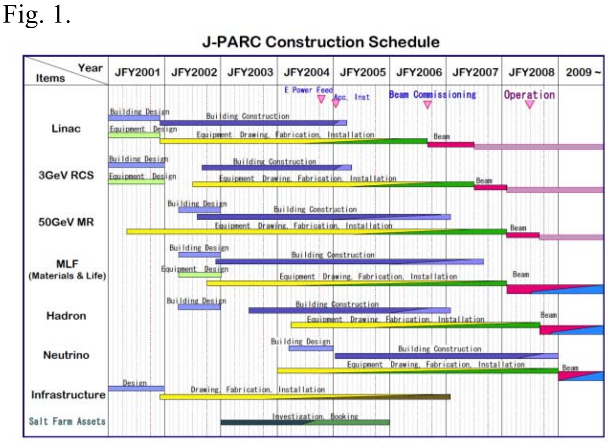

Figure 1: Construction Schedule Updated

The project milestones are as follows.

1. Start the linac beam commissioning in December, 2006.
2. Start the RCS beam commissioning in September, 2007.
3. Start the beam commissioning of the MR and MLF in May, 2008.
4. Start the experiments at both MLF and Hadron Facility in December, 2008.

5. Start the beam commissioning of the Neutrino Facility in April, 2009.

Figure 2 shows the present bird view of the J-PARC facilities. In the next section, we will briefly describe the characteristic features of the J-PARC linac. Then, the present status of the linac will be presented, emphasizing the progress after the last LINAC conference [10] and the preparation for the linac beam commissioning.

Figure 2: The present bird view of the J-PARC site

LINAC SCHEME AND CHARACTERISTIC FEATURES

The linac scheme is shown in Fig. 3. The volume-production type of the negative hydrogen ion source is used for producing a peak current of 50-mA with a pulse length of 500 μs and a repetition rate of 50 Hz. The beam is injected to and accelerated by the 324-MHz Radio-Frequency Quadruple (RFQ) Linac from 50 keV to 3 MeV [13-15]. The Low-Energy Beam Transport (LEBT) is based upon solenoid focusing, which allows one to make use of the space charge neutralization. The LEBT is equipped with a prechopper, although the fast chopper [16] is installed to the Medium Energy Beam Transport (MEBT) [17], since the stopper there cannot stand the chopped beam power. The prechopper is a small induction linac which decelerates the beam below the energy acceptance of the RFQ by taking use of the Magnetic Alloy (MA). The RFQ has been designed so as to work as an energy filter for this purpose. The present RFQ Linac has been designed and built for the JHF project which required the peak current of 30 mA. In order to increase the peak beam current to 50 mA, we have to build another RFQ linac which can accelerate the peak current of 50 mA. One third of this RFQ has already been built as detailed in Ref. [18].

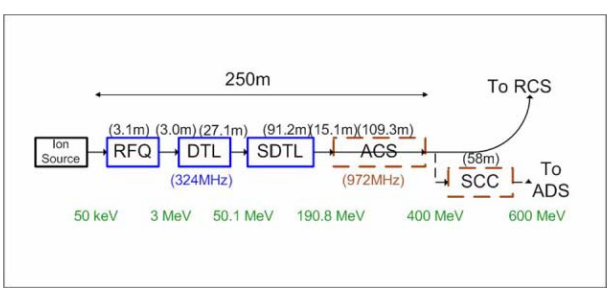

Figure 3: Scheme of J-PARC Linac

The choice of the RFQ energy of 3 MeV and the accelerating frequency of 324 MHz is a result of the trade off of the following factors [19]. The RFQ energy is the same as those of the MEBT and the first cell of the Drift-Tube Linac (DTL), while the RFQ frequency is the same as that of DTL (theoretically one can choose a multiple of 324 MHz). One wishes to increase the RFQ energy in order to decrease the emittance growth, since the RFQ is ideal for that. Although there had been a serious problem to build a long RFQ, the π-mode Stabilizing Loop (PISL) [13] invented by KEK could solve the problem. In this way, the high-energy, high-frequency RFQ became feasible. The first cell of DTL also prefers the higher energy, since the low β means very short period implying very dense mechanical structure. Also the high magnetic field is required for the first cell to cope with the strongest space charge force. For this, more space is required. However, the MEBT should play an important role to chop the beam with very fast rising and falling times. This is the most difficult device to develop, to design and to manufacture. The higher-energy beam is the more difficult to chop (if the beam energy is too low, the fast chopping will be difficult again, since the velocity of the beam is too slow). The 3 MeV is thus the result of trade off, which is also related to the choice of the frequency.

The high frequency is more preferable, since the stable, powerful RF power source of klystron can be utilized, and since the system is more advantageous regarding the space charge force. The latter is a little controversial, and sometimes sounds paradoxical. However, the higher frequency implies more bunches, resulting in the lower bunch current. Also, the shorter focusing period implies the stronger focusing against the space-charge repulsive force. On the other hand, the size of the drift tube becomes smaller, disbling the use of the quadruple electromagnets in drift tubes. Thus, the permanent magnets are used for SNS. We strongly stuck to the flexible knob, in particular, for matching the beams under space charge force between the MEBT and DTL. Thus, we have concentrated ourselves on the development of the extremely compact water-cooled quadrupole electromagnets by making a full use of electroforming technique and wire-cutting [20, 21]. Even so, the frequency of 324 MHz is the highest possible one for the DTL starting from 3 MeV. Thus, we requested the klystron vendor to newly develop the 324-MHz, 3-MW klystron with the J-PARC pulse length and repetition. Both the developments were successful. Also, one should note that both the frequencies of 432 MHz (for Japan Hadron Project, JHP) [22] and 324 MHz are very close to the measures of the L-band (1300 MHz) which will be used for the International Linear Collider (ILC).

The concept of the separated DTL is also a new attempt [23]. At medium energy like several ten MeV, the frequent focusing is no more necessary. Thus, the quadruple magnets in the DTL have been taken outside the DTL tank. In this way, we can optimize the shunt impedance of the SDTL by eliminating the size restriction arising from accommodation of the quadrupole magnets.

Also, the drift tubes with the magnets therein are more expensive than those without. In addition, since the transverse focusing of the SDTL region can be the same as or similar to that of the high-energy structure region, the transverse focusing transition is located between the DTL and the SDTL, while the longitudinal focusing transition between the 324-MHz SDTL and the 972-MHz high-energy structure. The emittance growth and thus the beam loss usually arise from the mismatchings at these kind of transitions. The simultaneous matching both transverse and longitudinal are difficult, while those are easier if separated. This is another advantage of the SDTL concept.

We have chosen the Annular-ring Coupled Structure (ACS) [24-34] for the high-energy structure. It is noted that the use of the axially symmetric structure of ACS may reduce the halo formation at the high-energy region compared with the asymmetric structure of the SCS. The detail will be discussed in the ACS section below.

COMMISSIONING STATUS

Ion Source

As reported last conference [10], three negative hydrogen ion sources have been developed. All are of so-called volume-production type, where “so-called” implies that there are some experimental results indicating the surface ionization even in the “so-called” volume-production ion source. The first one, which makes use of cesium vapour, has generated a peak current of 72 mA [35]. The life time of the tungsten filament amounted to five hundred hours with an arc power of 30 to 40 kW turned on. However, the discharge at the extraction region occurred every hour. Although the frequency of the discharge could be significantly reduced by eliminating the use of cesium, the maximum peak current has decreased to 16 mA. The second one [36] and the third one are of “so-called” pure volume-production type without cesium. The second one makes use of LaB_6 filament, while the third one tungsten. The second one could generate a peak current of 38 mA, while the third one 30 mA. Both are sufficient for the RCS beam power of 0.6 MW. The second one needs a large-scaled power supply in order to provide a sufficiently high voltage for igniting the arching and to keep a flat beam current throughout the beam pulse of 600 μs. Third one thus seemed most promising. However, we have encountered one serious shortcoming in this ion source. The peak current decreases from 30 mA to 16 mA within one hour. It seems that the tungsten is sputtered on the plasma electrode. This situation means that we have the ion sources for the RCS beam power of 0.1 or 0.2 MW, but we need more intensive development for stable operation beyond 0.5 MW. We are now attempting to improve the second one, adding a low-power constant-current power supply to the constant-voltage power supply which has been so far used for the third one. By this we are hoping the significant improvement of the second source performance.

Beam Study of Front End (LEBT, RFQ, MEBT, Choppers and 20-MeV DTL1)

As reported in LINAC2004 [10], the beam commissioning and beam study of the ion source, LEBT, RFQ and the 20-MeV DTL (the first DTL cavity, DTL1) has been conducted from October 30th, 2003 through the end of 2004 in KEK Tsukuba Campus, since the linac test area had been built for JHF. The peak current of 30 mA, which meets the requirement of the beam power of 0.6 MW at the first stage, has been accelerated with a transmission of 100 percent (the measurement accuracy is a few percent) on November 6th. In that report [10], we presented the problem of the emittance growth with more than 50 percent. Afterwards, we have finally obtained the reasonable agreement between the measurements and the theoretical calculations on the beam emittances as shown in Table 1. This is the result of the finer adjustment and tuning together with the improvement in the slit sizes of emittance monitors [37].

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)	0.30	0.29
After DTL1 (calculated)	0.25	0.26

a) This is in reasonable agreement with the simulation result.

DTL and SDTL

All the three DTL cavities and thirty two SDTL cavities [20, 21, 38-45] were assembled and tuned in KEK Tsukuba Campus. Among them, one DTL cavity was high-power tested and beam tested as reported above. The twelve SDTL cavities were also high-power tested there. The high-power test has been done for the first seven cavities (low-β side), the highest-β and the second highest-β cavities manufactured at the end, and three sampled cavities. Since the J-PARC Linac building was completed in May, 2005 including the electricity and air conditioning, all the linac components have been shipped from KEK Tsukuba Campus to JAEA Tokai site in the summer, 2005. Special efforts were necessary for the shipping of the DTL, since the heavy focusing magnets are suspended by the stems in the DTL cavity as detailed in Ref. [45]. All the DTL and SDTL cavities have been installed in the J-PARC linac tunnel as shown in Fig. 4 [43]. The final accurate alignment of all the cavities and magnets is on-going right now. The laser tracker is fully used as mentioned in the last LINAC conference [10, 46].

Figure 4: The SDTL's installed.

RF Power Sources

All the twenty klystrons were power-tested as shown in Fig. 5, while all the twenty anode-modulators and the five cathode power supplies are ready in situ.

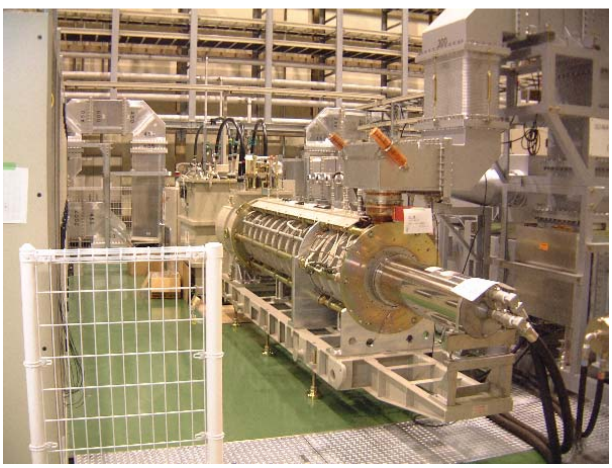

Figure 5: The klystron under high-power test

Beam Commissioning Scenario

Both the Low-Level RF system and the beam monitoring system for the J-PARC Linac are ready as detailed in Ref. [47] and Ref. [48, 49], respectively. The beam tuning method for the beam transport from the linac to the RCS has been intensively explored [50-51].

Bottle Neck for the Beam Commissioning

As described above, all the linac components have been installed in the J-PARC linac tunnel, klystron galleries and so forth, respectively. Right now, the starting date of the powering of the cavities is determined by the completion of the air pressure control system for the tunnel and sub-tunnel. The tunnel, where the air will be radioactive, will be pumped out to keep the air pressure slightly lower than those outside. The lower pressure of the linac tunnel prevents the radioactive air from leaking out of the tunnel. Therefore, the system test is one of the important items inspected by the authority to issue the permit for setting the radiation-control area and starting the beam acceleration. The air pressure control system could be fully tested only after all the cablings between the klystron gallery and the linac tunnel including the beam transport tunnel to the RCS have been completed and the openings for these cables and waveguides were hermetically sealed. The test done early summer showed unstable behaviour of the air pressure: sometimes the air pressure in the tunnel exceeds those outside. It takes some time to fully repair the system. As a result the high power test of the system can start mid October, since the radiation-control area has been set on both the klystron gallery (this is only for x ray) and linac tunnel. This schedule is delayed almost by one month, which was a margin for keeping more time than expected for the high-power test and commissioning of all the system. In other words, if any serious problem which takes some time to fix does not occur, we can start the beam commissioning as scheduled.

DEVELOPMENTS FOR THE 400-MEV LINAC

The high energy structure to be used for accelerating the beam from 190 MeV to 400 MeV is ACS [24-34], which may be considered as an axially symmetric version of the Side-Coupled Structure (SCS), geometrically speaking. The axial symmetry around the beam axis keeps the electric field therein from kicking the beam transversely. Although the geometrical structure of the ACS can be obtained by rotating the SCS around the beam axis, its resonant frequency spectra are totally different from those for SCS. Since the coupling cavity of the ACS is coaxial, it has many modes above the coupling mode. This is the reason why its development has not been successful long time after the structure was proposed. In order to eliminate the mixing of these modes to the coupling modes we improve the symmetry by increasing the number of the coupling slots to four rather than two. The ACS cavity thus developed for JHP was successfully power-tested. The resonant frequency of the ACS for JHP was 1296 MHz. When we design the J-PARC linac, we have reduced the frequency for the ACS to 972 MHz, resulting in much larger size of the structure. We have attempted to reduce the size of the 972-MHz ACS to that of the 1296-MHz one. The present version was thus developed. As detailed in Ref. [34], we have finally succeeded in powering the first cavity of J-PARC ACS which will be used for the buncher to be installed at the transition between the 324-MHz SDTL and the 972-MHz ACS. In order to do the high-power test, we needed the 1296-MHz klystron, which has been already developed. Therefore, the high energy side of the 400-MeV linac was technically ready.

The purpose for upgrading the linac energy is to inject more beam to the ring. For this purpose, we are developing the RFQ which can accelerate the peak current of 50 mA. We actually fabricated and tuned the first one third part of the real RFQ as detailed in Ref. [18].

CONCLUSTION

The J-PARC linac is ready for the beam commissioning starting from December, 2006, except for some problem regarding the air pressure control system of the linac tunnel. If the problem is solved on schedule, the commissioning of all the system including the powering of all the cavities in the tunnel will start mid-October in time for the scheduled beam commissioning.

Since the J-PARC linac makes use of many newly developed technologies including the 324-MHz powerful klystrons, the success of its beam commissioning and the beam power increase will give rise to a significant impact on the future proton linac design.

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