FROM KEK-PS TO J-PARC

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Abstract

The user experiments at J-PARC have just started. JPARC, which stands for Japan Proton Accelerator Research Complex, comprises a 400-MeV linac (at present: 180 MeV, being upgraded), a 3-GeV rapid-cycling synchrotron (RCS), and a 50-GeV main ring (MR) synchrotron, which is now in operation at 30 GeV. The RCS will provide the muon-production target and the spallation-neutron-production target with a beam power of 1 MW (at present: 120 kW) at a repetition rate of 25 Hz. The muons and neutrons thus generated will be used in materials science, life science, and others, including industrial applications. The beams that are fast extracted from the MR generate neutrinos to be sent to the Super Kamiokande detector located 300-km west of the J-PARC site. The slowly extracted beams generate kaons for hypernuclei experements, kaon rare decay experiments, and so forth. This unique accelerator scheme and its usage scheme both originate from those of KEK-PS. It can be said that the J-PARC is an upgraded version of KEK-PS in both the beam energy and beam power. It is detailed how the world-class machine of J-PARC has been developed from KEK-PS.

INTRODUCTION

This paper reports on how KEK-PS has developed to JPARC [1] and then the recent progress in J-PARC, which has already started user runs. Here, KEK stands for National Laboratory for High Energy Physics (originally), which right now is High Energy Accelerator Research Organization, while PS stands for proton synchrotron. JPARC is the acronym of Japan Proton Accelerator Research Complex. It will be seen that many aspects, making J-PARC unique among accelerator projects in the world, originate from KEK-PS. The linac features and ring features are then presented, including the newly developed ring RF systems. Throughout this report, the relation and the comparison between KEK-PS and JPARC will be shown at many places.

ACCELERATOR SCHEMES OF KEK-PS AND J-PARC

J-PARC was built in Tokai, Ibaraki, as a joint project between KEK and Japan Atomic Energy Agency (JAEA). The 330-m long linac accelerates a negative hydrogen beam to 181 MeV at present (right now, we are upgrading it to 400 MeV) to be injected to the rapid-cycling synchrotron (RCS), where the beam is ramped up to 3 GeV with a repetition rate of 25 Hz. It is fast extracted to Materials and Life Science Experimental Facility, where the muon-production target and the neutron-production target are located in series. Every 3 s or so, depending upon the usage of the main ring (MR), the beam is extracted from the RCS to be injected to the MR. Here, it is ramped up to 30 GeV at present and slowly extracted to Hadron Experimental Hall, where the kaon-production target is located. The experiments using the kaons are conducted there. Sometimes, it is fast extracted to produce the neutrinos, which are sent to the Super Kamiokande detector, which is located 295-km west of the J-PARC site. In the future, we are conceiving the possibility of constructing a test facility for an accelerator-driven nuclear waste transmutation system, which was shifted to Phase II. We are trying every effort to get funding for this facility.

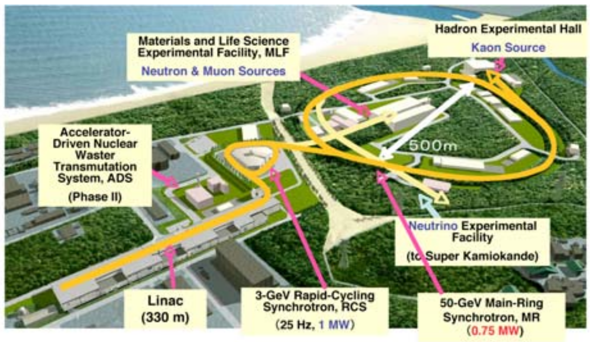

Figure 1: Bird's eye view image of J-PARC.

Figure 2 shows the J-PARC accelerator scheme. It is noted that this scheme is essentially the same as that of KEK-PS, which Yoshitaka Kimura presented in his lecture [2]. In other words, it can be said that the J-PARC accelerator is an upgrade version of KEK-PS by approximately several times in energy and by twenty-times in beam intensity, that is, by two orders of magnitude in beam power.

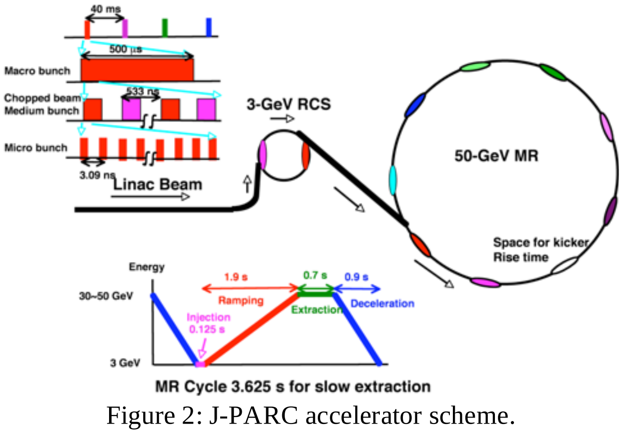

Figure 2: J-PARC accelerator scheme.

It is also noted that KEK-PS already placed the booster RCS in between the injector linac and the high-energy synchrotron MR. At that time, it was a very new idea, which was proposed by T. Kitagaki for KEK-PS. Perhaps, this was also proposed by others independently, because Fermi National Accelerator Laboratory (FNAL) began to use this scheme almost at the same time. Now this scheme is employed everywhere for high-energy accelerators and is a kind of global standard.

The booster synchrotron is idle after injecting its beams to the MR until the next injection. It was KEK-PS which used this period for the first time in order to produce spallation neutrons and muons. These two secondary particles thus produced have been very useful tools for materials and life science. The ISIS followed this RCS scheme, but increased the beam power much further, and it was the world's highest power sources for neutrons and muons, until the spallation neutron source (SNS) [3] achieved higher beam power.

BRIEF HISTORY OF JAPANESE HIGH ENERGY ACCELERATORS

Figure 3 shows a brief history of the high-energy proton and electron accelerators in Japan for discussing KEK-PS and J-PARC. In the previous papers, the authors mentioned Ernest O. Lawrence's visit to Japan, which had a big impact on starting the accelerator project in Japan. In 1955, the Institute for Nuclear Study (INS), University of Tokyo, was founded and an electron synchrotron was built there. Immediately after that, Japanese scientists began to make a plan to have a high-energy proton accelerator because CERN-PS and BNL-AGS started their operations. However, the construction of KEK-PS was delayed for quite a long time until KEK was founded and its construction started in 1971. During that time, radio-frequency quadrupole (RFQ) linac was invented and Los Alamos Meson Physics Facility (LAMPF) began its beam operation as shown in Fig. 3.

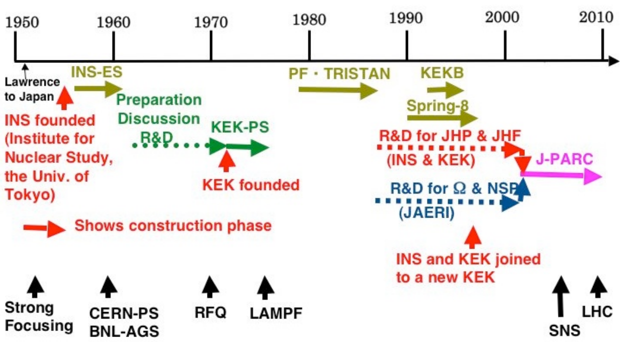

Figure 3: Brief history of high-energy accelerators in Japan.

After KEK-PS started its operation at 12 GeV in 1976, the long period was again needed to start the next-generation proton synchrotron. Although INS was joined together with KEK in 1997 for starting Japan Hadron Project (JHP) [4] or Japan Hadron Facility (JHF) [5], another effort was still necessary. Finally in 2001, we could start the construction of J-PARC by joining the JHF project of KEK and the Neutron Science Project (NSP) [6] of JAERI. Here, JAERI stands for Japan Atomic Energy Research Institute, which was joined with Japan Cycle Organization (JCO) to form JAEA in 2005. The joint project could take advantage of the R&D results, for a period of more than ten years, of both KEK and JAERI. During this long R&D period, many young accelerator scientists have been brought up in both the institutes. This is one of the reasons why we could start the pretty challenging project immediately after the funding. During the course of the construction, SNS in US started the beam commissioning and the user run. In 2009, Large Hadron Collider (LHC) [7] started the beam commissioning. These are the historical background for KEK-PS and J-PARC.

PROGRESS FROM KEK-PS LINAC TO J-PARC LINAC

As mentioned above, during the time period between KEK-PS and J-PARC, the RFQ linac was invented. Therefore, J-PARC could take benefit of using a compact RFQ linac rather than a gigantic Cockcroft-Walton electrostatic injector. One may see from Fig. 4 how these sizes are different, where the J-PARC 3-MeV RFQ linac is compared with the KEK-PS 750-keV Cockcroft-Walton electrostatic injector.

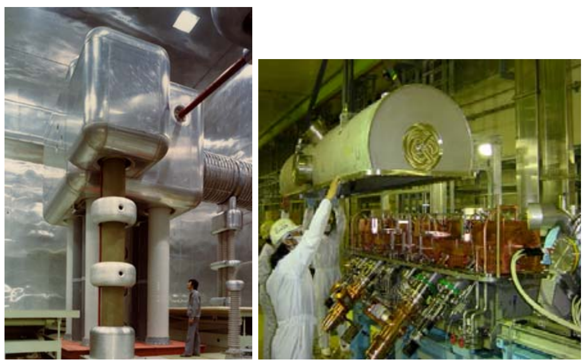

Figure 4: Cockcroft-Walton Electrostatic Accelerator for KEK-PS (left) by courtesy of KEK Archives Office and J-PARC RFQ linac (right). Compare the sizes of people there.

In addition, the RFQ linac is doing the adiabatic bunching before the acceleration, guaranteeing ideal bunching. For this reason, it does not give rise to any whisker shaped particle distribution in the longitudinal phase space ($\Delta p/p$ and the longitudinal distribution), which is inevitable in the case of the conventional buncher system. The ideal bunching contributes a lot to the minimization of beam loss downstream, in particular, in the ring injection. This is a very important progress for high-intensity accelerators, where one has to minimize the beam loss, which would otherwise give rise to high radioactivity. The radioactivity prevents people from hands-on maintenance, which is indispensable for accelerator components. Since an RFQ can transversely focus the particles frequently, the transverse emittance growth is suppressed well. For this reason, it is preferable to accelerate the beams up to the energy as high as possible by an RFQ linac. This can also ease the design and manufacturing of the drift tube linac (DTL) following the RFQ. The low-energy drift tubes (DTs), housing the focusing/defocusing quadrupole magnets with water cooling, are difficult to design and manufacture because of their small sizes. The beam energy of the J-PARC RFQ was set at 3 MeV by inventing the π-mode stabilizing loop (PISL) [8] which will be detailed in the following section.

In contrast to the RFQ, the J-PARC 50-MeV DTL is not so different from the KEK-PS 40-MeV DTL, but the accelerating frequency was increased by more than 1.5 times (200 MHz to 324 MHz, Figs. 5-6). This makes it possible to use klystrons, which are much more stable RF power sources than are vacuum tubes like triodes, which have been conventionally used.

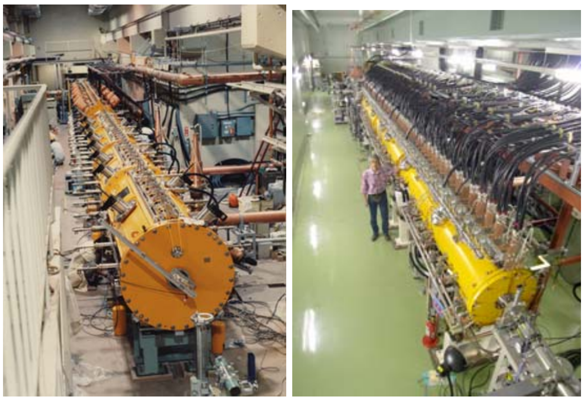

Figure 5: KEK-PS DTL (left) by courtesy of KEK Archives Office and J-PARC DTL (right).

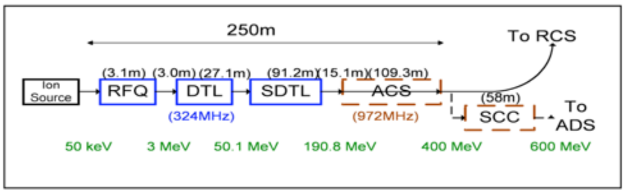

Figure 6: Scheme of J-PARC linac.

The J-PARC DTL was followed by a 180-MeV separated DTL (SDTL), while the KEK-PS linac energy was 40 MeV. Recently, upgrade to 400 MeV was funded for construction. Annular-ring coupled structure (ACS) [9, 10] is now under mass production for upgrade. Geometrically speaking, the ACS is an axially symmetric version of the side-coupled structure, which is commonly used everywhere. As Y. Kimura mentioned [2], it is our heritage or tradition to use or to stick to the axial symmetry, since we believe that it is very important for the quality of the beam. In this way, the scheme of the J-PARC linac was formed, as shown in Fig. 6.

COMPARISON BETWEEN KEK-PS AND J-PARC RINGS IN TERMS OF SPACE–CHARGE FORCE

In the above section, the differences between the KEK-PS linac and the J-PARC linac are presented. For those in rings, some preliminary introduction is necessary regarding the space–charge effect. In a ring, particles exert betatron oscillations, both horizontally and vertically, around the equilibrium closed orbit during the course of the circulation. The space–charge force depressed the numbers of the oscillations per cycle, referred to as the tunes in the accelerator field, since it is a repulsive Coulomb force against the focusing function of the quadrupole magnets. In general, the tunes are set far from any integer numbers and any dangerous resonances, which give rise to emittance growth and/or the beam loss. The space–charge force shifts and/or spreads the tunes thus set, ultimately pushing them close to these resonances. It is understood that this is the mechanism to limit the beam intensity in a ring. This tune shift, which has a negative sign for its defocusing character, is sometimes represented by “Lasslette Tune Shift” defined as follows:

$$\Delta\nu_y = -\frac{N r_p}{\pi \varepsilon_y \left(1+\sqrt{\frac{\varepsilon_x}{\varepsilon_y}}\right)\beta^2\gamma^3}\frac{F}{B_f}$$

where N is the number of protons; ε_y, the vertical emittance; ε_x, the horizontal emittance; r_p, the classical proton radius; F, the form factor; B_f, the bunching factor; β, v/c, and γ, the relativistic mass divided by the rest mass. It is not insisted here that the Lasslette tune shift can be used for the detailed discussion on the space–charge force. Instead, we are quoting these values as a useful measure or a scaling law regarding the space–charge force. In particular, it is noted that the tune shift is inversely proportional to β^2 and γ^3 for the following reason. In general, the beam generates a magnetic field, which cancels the repulsive force between the charges. In addition, if the beam is accelerated, the mass is increased, making the space–charge force less effective. This inverse proportionality to $\beta^2\gamma^3$ is the reason why one increases the injection energy for upgrading the beam intensity. The large emittances and the large bunching factor respectively imply less-dense charge distribution transversely and longitudinally. The form factor and the bunching factor are respectively introduced to represent the deviation from the uniform distribution transversely and longitudinally.

Table I and Table II show the comparisons between the

RCSs and MRs, respectively, of KEK-PS and J-PARC. Figures 7 and 8 show the photographs of these machines. First of all, the energy of the injector linac is increased by a factor of 10 from KEK-PS to J-PARC. In addition, the circumference of J-PARC RCS is about ten times as long as that of KEK-PS booster. As a result, the extraction energy of the RCS is increased by a factor of 6 from KEK-PS to J-PARC. The repetition rates are about the same. Another big difference exists at their apertures in such a way that the aperture of J-PARC RCS is about four times as wide as that of KEK-PS Booster. In the case of the MRs, however, the difference is not so much (1.8 times). Here is some difficulty in J-PARC MR, if one tries to maximize the beam power. The circumference of J-PARC MR is five times that of the KEK-PS MR to accelerate the beam to 30–50 GeV, which is several times as high as that of KEK-PS MR.

Table I Comparison between KEK-PS booster RCS and J-PARC RCS.

Parameters	KEK-PS (Achieved)	J-PARC (Designed)	J-PARC (Achieved)
Ring Circumference, m	38	348	-
Repetition, Hz	20	25	25
Beam Stored Energy per pulse, kJ	0.2	40	12
Number of protons per pulse, 10^{13}	0.25	8.3	2.5
Beam Energy, GeV	0.5	3	3
Beam power, MW	0.004	1	0.3
Beam current, μA	8	333	100
Injection energy, GeV	0.04	0.4	0.18
$\beta^2\gamma^3$ at injection	0.0908	1.475	0.505
Beam emittance after painting, π mm mrad		216	150
Beam aperture, π mm mrad	79[a)]	324	
Lasslette tune shift	- 0.312 [b)]	- 0.16	- 0.20

a) Effective values estimated by taking into account the difference between the horizontal apertures of 248 and vertical ones of 49.
b) By assuming that the beam emittance is two thirds as high as the aperture.

In order to understand how J-PARC is a world-class machine, it is useful to classify the world-class machines into two categories. The first one is easy to understand, that is, the beam-energy front, exemplified by the International Linear Collider (ILC) [11], which will be detailed by the following paper by Marc Ross, and the Large Hadron Collider (LHC) [7], which would be and has been built, respectively, to find Higgs particles and explore beyond the standard model. The second one is referred to as the beam power front, which J-PARC belongs to. The beam energies (V; horizontal axis) and the beam currents (A; vertical axis) are shown in Fig. 9 for major high-energy proton accelerators in the world. The product of the beam current and the beam energy is a beam power (W), the front of which can be represented by the tilted lines in the figure. The reason why the beam power is considered as a figure of merit is as follows. In most of these machines, the secondary particles like neutrons, muons, kaons, neutrinos and so forth, generated by bombarding the proton beams into targets made of heavy elements, are made use of for a variety of sciences. The numbers of the secondary particles thus produced are proportional to the beam energies, that is, the beam powers.

Table II Comparison between KEK-PS MR and J-PARC MR.

Parameters	KEK-PS (Achieved)	J-PARC (Designed)	J-PARC (Achieved)
Ring Circumference, m	339	1568	-
Repetition, s	2	2.9	3.25
Beam Stored Energy per pulse, kJ	1.5	2,175	228
Number of protons per pulse, 10^{13}	0.8	48 to 29	5
Beam Energy, GeV	12	30 to 50	30
Beam power, kW	0.7	750	70
Beam current, μA	0.6	25 to 15	2.3
Injection energy, GeV	0.5	3	3
$\beta^2\gamma^3$ at injection	2.07	69.8	69.8
Beam emittance after painting, π mm mrad		216	150
Beam aperture, π mm mrad	30[a)]	54	54
Lasslette tune shift	- 0.30 [b)]	- 0.30 to - 0.18	

a) Effective values estimated by taking into account the difference between the horizontal apertures of 82 and vertical ones of 20.
b) By assuming that the beam emittance is two thirds as high as the aperture.

Figure 7: KEK-PS booster RCS (left) by courtesy of KEK Archives Office and J-PARC RCS (right).

Figure 8: KEK-PS MR (left) by courtesy of KEK Archives Office and J-PARC MR (right).

Another important factor is the time structures of the beams, for example, the pulse length (say, microsecond-long or millisecond-long) and repetition rate. The scientific accomplishments are significantly dependent upon how these requirements are fulfilled. On the other hand, the difficulty to build and to operate the machines are dependent upon these parameters.

It is very interesting to see in Fig. 9 that one can make power-front lines throughout the whole range of the beam energy, except for PSI and TRIUMF, which are different (CW) from the other machines (pulsed ones) like SNS and J-PARC. This is not accidental, since the radioactivity is proportional to the power of the beam loss. In order to keep the radioactivity to allow the hands-on maintenance, one should control the power of the beam loss below some level. The two lines indicate where the world levels were in the past and are at present, respectively. The line was approximately located along the beam-power of 100 kW, before SNS and J-PARC were beam-commissioned. The SNS project has already pushed and the J-PARC project is trying to push the line to that of 1 MW, respectively. In order to push the beam power front from 100 kW to 1 MW, we have to solve the beam loss problem; in other words, we have to reduce the beam loss rate by factor of 10. That was and is a big challenge in SNS and J-PARC, respectively.

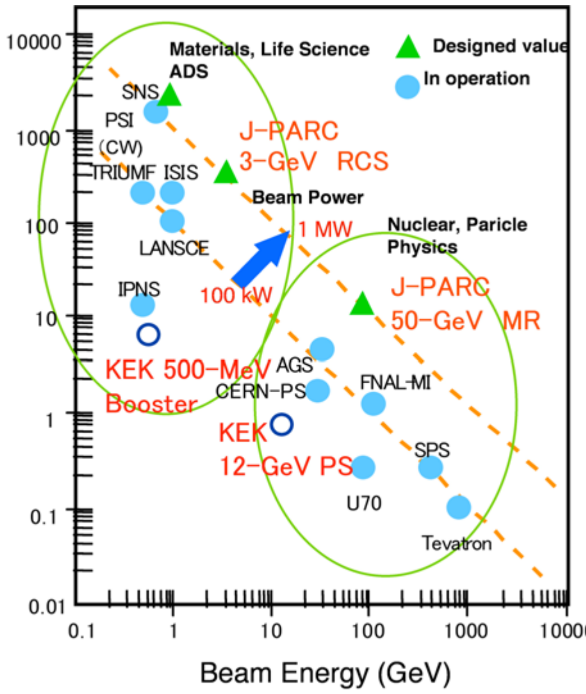

Figure 9: Beam currents and beam energies of the major proton accelerators in the world.

It should be also mentioned that the accelerator scheme used for J-PARC and ISIS is quite different from that for SNS and LANSCE in US. The former is RCS-based, while the latter is based upon a combination of the full-energy linac and an accumulator ring (AR), that is, no acceleration in a ring. It is very interesting to see [12, 13] which is more promising for the beam power between the RCS scheme and the AR scheme.

It can be also seen from Fig. 9 that J-PARC is a world-class machine being located at the beam-power front in both the beam-energy ranges of several gigaelectronvolts and several tens of gigaelectronvolts. J-PARC would be thus an international center for many fields of science. One field is of course materials and life science, which uses the pulsed spallation neutrons and muons. For this, J-PARC will be one of the three centers together with ISIS and SNS. The European Spallation Source (ESS) is about to be funded for construction. For hadron physics, a long time ago, TRIUMF was trying to build the Kaon Factory. About the same time, the Institute for Nuclear Research (INR) in Russia, having a 600-MeV proton linac (Moscow Meson Factory, MMF), tried to get funding, but was not successful. Therefore, now, as a kaon factory, J-PARC is at a unique situation. For neutrino physics, again one of three competitive world-leading centers competing with each other; FNAL is conducting the project NOvA, while CERN is conducting the OPERA experiment.

RECENT J-PARC PROGRESS

The J-PARC accelerator started its construction in April 2001. On January 24th, 2007, we succeeded in accelerating the beam up to the designed value of 181 MeV. On October 31st of the same year, we accelerated the beam up to 3 GeV by the RCS. In both the cases, it took only one month or so (exceptionally short periods compared with other similar-size machines) for the successful accelerations after the start of the beam commissioning. These are partly because of the excellent alignment of the linac components and the new ring RF systems, respectively, which will be detailed later. These also promised the future beam-power performance.

On May 30th, 2008, the beam thus accelerated was transported to the neutron target, producing the neutron beam. Here, it is worthwhile to note that the neutron beams from the J-PARC target have shown extremely sharp energy distribution (by nearly a factor of three better than the KENS target of the KEK-PS, eliminating the tails by nearly two orders of magnitudes), thereby promising fruitful scientific outcomes. This is one example of the synergy effects between KEK neutron-target technology and JAEA nuclear-reactor one. The neutron beam produced by the high-energy protons should be cooled down by the moderator in order to generate thermal neutrons or cold neutrons. For this purpose, we use the liquid hydrogen entirely covered by the AIC Decouplers, where AIC stands for silver-indium-cadmium alloy. The excellent energy distribution is the result of the AIC technology, which is common to the nuclear reactor technology, combined together with the KEK neutron target one.

Following the neutron production, the muons were guided to the experimental area in the MLF on September 26th and was immediately used for the muon spin rotation (μSR) experiment. Finally, towards the end of 2009, we started the MR beam commissioning. The MR beam was accelerated to 30 GeV on December 23rd, 2008, and, immediately after that, the beam was slowly extracted to the Hadron Experimental Facility on January 27th, 2009. At the end, the MR beam was fast extracted to produce the mu-neutrinos ν_μ on April 23rd, and finally the first neutrino event was observed by the Super Kamiokande (SK) Detector on February 24th, 2010. The purpose of the experiment is to observe the electron-neutrino ν_e to be converted from ν_μ during the course of its flight from the J-PARC site to SK.

As such, the J-PARC project is now at the stage for user runs. In parallel, we are making every effort for bringing the beam power up to the design value of each component accelerator. Also, we have been encountering the problems associated with its high-intensity character, which we had never foreseen until the long-term beam operation started. For example, we had a big trouble with the RFQ linac, whose remedy took one year to find (in fall, 2009). The discharge rate of the RFQ linac had been gradually increased during the course of beam operation, until it could not be powered any more after a typically three-day beam operation. We have made every effort to improve the vacuum pressure in the RFQ, including the installation of the orifice to the low-energy beam transport between the ion source and the RFQ, the increase in the number of the high-speed vacuum pumps, the painstaking baking to a temperature as high as possible (the RFQ was not designed for the proper baking), and so forth.

J-PARC LINAC FEATURES

In the preceding sections, it was noted that all the three J-PARC accelerators have successfully accomplished their first goals of the beam acceleration in surprisingly short periods. None of these is an accidental incident. Rather, they have the following reasons and promise excellent performance in the near future.

It is emphasized here that the importance of the injector linac has been overlooked in many cases by over-concentrating the attention to the highest-energy ring. In reality, however, all that the rings can do is to just wait for the high-quality beams from the injector linac, preparing their apertures as wide as possible. Here, the high quality beam implies the low-emittance, stable beam both longitudinally and transversely with the minimum amount of halos and tails. The low-emittances, stability, and reliability are three key factors for both efficient beam commissioning and fruitful scientific outcomes.

Regarding these purposes, it is preferable to choose the higher accelerating frequency (300–400 MHz at the linac energy front) than conventional (nearly 200 MHz). First of all, the higher accelerating frequency implies short focusing periods both longitudinal and transverse. Here, longitudinal focusing is provided by acceleration. The frequent focusing, that is, with a short focusing period, is vital for the immunity against the space–charge effect. Even further important is to enable the use of klystrons, which are very stable high-power RF sources, with a reasonable size by increasing the frequency.

On the other hand, this means that everything has a smaller size, making it difficult to house the quadrupole magnets within the DTs. In many cases, the permanent quadrupole magnets have been developed for coping with the small DTs. Then, one loses the flexible knobs, which could empirically optimize the beam optics parameters and/or keep the parameters from any unpredictable resonances. For this reason, we have concentrated our effort on developing the DTs with water-cooled electromagnetic quadrupoles therein. Making full use of electroforming and wire-cutting technologies, we have finally succeeded in manufacturing a very compact electromagnetic coil with a water cooling channel. By that, we could produce the 324-MHz DTL. This is based on the heritage of the collaboration between the Japanese industries and KEK, in particular, for the electroplating, electroforming and electropolishing technology, which was mentioned by Kimura in a preceding paper [2]. We took a big advantage of this kind of tradition.

It is preferable to accelerate the beam up to the highest-possible energy by using an RFQ linac, since the RFQ can frequently and strongly focus the beam in both transverse and longitudinal directions. However, it had been said that the RFQ linac longer than four wavelengths of free space (that is, with a frequency of 300 to 400 MHz and an acceleration energy higher than around 2.5 MeV) is almost impossible to tune. During the course of the development of a 3-MeV, 432-MHz RFQ linac for JHP, we found the reason for this saying. By elongating the RFQ to this region, the degenerate resonant frequency of the two second-lowest dipole modes (deflecting modes) is lowered down, getting close to the operational quadrupole mode. As a result, these modes are mixed with each other, giving rise to complicated field distributions, which cannot be used for operation. We have invented the π-mode stabilizing loop (PISL) [8] shown in Fig. 10 to increase the dipole-mode frequencies far beyond the operating frequency, eliminating the mode mixings. As a result, long RFQ linacs, that is, high-energy RFQ linacs beyond around 3 MeV, have become possible to manufacture. By that technology, we have marked the world record (3 MeV) of the beam energy of a proton RFQ linac at that time [14].

For the stability and reliability of the linac performance, the high-power RF amplifiers and high-voltage converter modulator (HVCM) are two most important components. For the former, we developed klystrons in collaboration with a vendor. We have a long history for the collaboration, starting from KEK Photon Factory. The 3-MW, 324-MHz klystrons are most powerful for a repetition of 25 Hz or 50 Hz and a pulse length of 600 μs. Perhaps because the klystrons were in reliable, stable operation at the J-PARC linac, the frequency itself now becomes a kind of global standard (FNAL Project X, ISIS future project, China Spallation Neutron Source, GSI-FAIR project, and so forth).

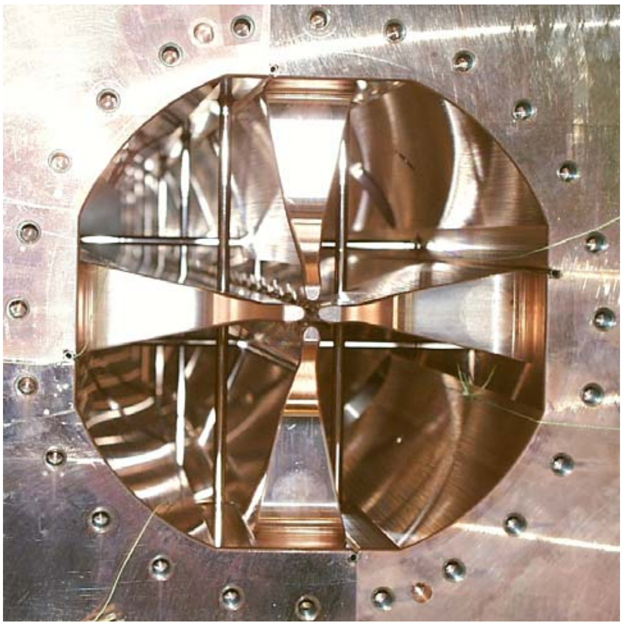

Figure 10: Inside view of the J-PARC linac. Bar-like objects are PISLs.

This fact may be for the following additional reasons. First, the frequency of 325 MHz is a quarter of the L-band frequency of 1300 MHz, which will be used for future ILC. If one chooses 325 MHz for the front end, one can choose the L band for the high-energy part, for which the Superconducting Cavities (SCC) would be a choice. In this case, one may take a full benefit from a world-wide ILC effort. Second, the 324-MHz system is actually working in the J-PARC linac as an example with a designed emittance and so forth. This is a very important factor since one might have found some serious difficulty during the course of the detailed design, construction, and operation, if one chooses a new parameter. In fact, the medium-energy beam transport (MEBT) between the RFQ and DTL was very difficult to design, fabricate, and install since the MEBT is through a very busy area including many components like bunchers (that is, longitudinal matcher), choppers, and transverse matchers. Now, here is a working example at the J-PARC.

Another important decision to make is a choice of the pulse-modulation scheme of the HVCM. In general, there are two major schemes: anode modulation and cathode modulation. One system of the former scheme comprises one high-power, big DC power supply with several low-current, pulsed-anode modulators, each of which is installed to a klystron. The latter is just a high-power, pulsed-cathode modulator, in which, it is difficult to manage the noise issue and reliability. The former provides several klystrons with power, while the latter provides just one klystron. As far as the HVCM concerned, the former is much advantageous regarding both cost and reliability. However, the former scheme requires klystrons with modulation anodes, which perhaps limit the klystron power to nearly 3 MW for the J-PARC duty specification. On the other hand, the latter scheme requires no modulation anode, simplifying the structure of the klystron. As a result, the highest-possible power would be more than 3 MW. In the J-PARC case, and in the other cases such as SNS and the proposed future project, one RF system to be driven by one klystron does not require the RF power beyond 3 MW. Also, the vendor has successfully developed the anode-modulated klystron; with an RF power of 3 MW, an RF pulse length of 1 ms, and a repetition of 50 Hz. The choice of the anode modulation is one of the most important reasons for the reliability and stability of the J-PARC linac.

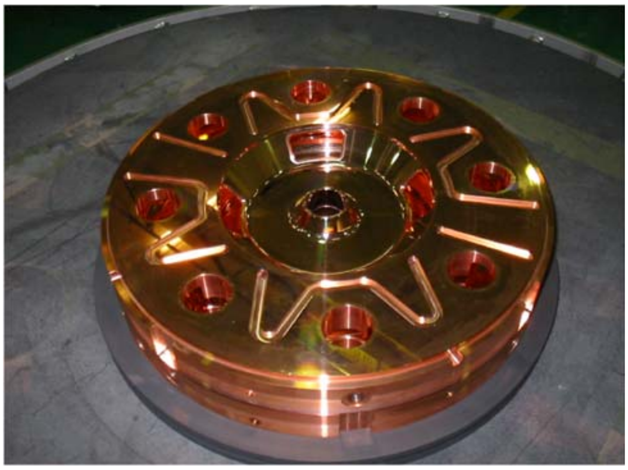

Figure 11: A half cell of the J-PARC ACS. The view is from the accelerating cavity side.

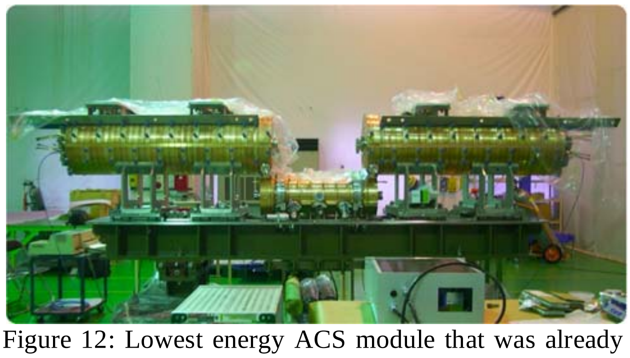

Figure 12: Lowest energy ACS module that was already powered.

It is noted that we are going to use the axially symmetric accelerating structure, ACS, for the high-energy part of the J-PARC linac as previously mentioned. This is the result of the 15-year collaboration with the Moscow Meson Factory (MMF), Institute for Nuclear Research (INR), Russian Academy of Science (RAS).

The ACS had been proposed by a Russian physicist [9], who invented the famous disk-and-washer (DAW) structure. Afterwards, the ACS had not been enabled to practical use for its parasitic mode problem inherent to its coaxial structure of coupling cavities. We could solve this problem [10] by increasing the number of slots to connect the coupling cavity with the accelerating one from two to four (see Fig. 11), when we were developing the linac for JHP. Since the frequency of the J-PARC linac is three-fourths of that of the JHP one, the size of the J-PARC ACS would have been four-thirds of that of the JHP one just by scaling. The collaboration with the MMF managed to reduce the size of the J-PARC ACS to that of the JHP one and made the detailed RF design. The five-cell, buncher cavities and the eighteen-cell, lowest-energy cavity (Fig. 12) was powered well above their design values. At present, the ACS cavities are under mass production for the energy upgrade, as previously mentioned. The collaboration with the MMF is continuing, since the MMF people, who once planned the Kaon Factory, are very enthusiastic about J-PARC, which includes the Kaon Factory.

J-PARC RING FEATURES

The linac beam that cannot be accepted by the ring RF is eliminated at the linac MEBT. The RF chopper devised by T. Kato [15], deflects the beam during the period of the operation with the same frequency as that of the acceleration. No beam was observed during the chopped period (world's best performance) in contrast to the Meandor-type chopper being used everywhere.

Separated-function scheme of bending magnets and focusing magnets were invented by T. Kitagaki (Ref. [16] published in 1953) for strong focusing lattice, and they were used in KEK-PS MR. Here, the focusing and defocusing functions of the quadrupole magnets are separated from the bending function of the bending magnets, being in contrast to the combined-function lattice, which had been commonly used before this invention. Nowadays, the separated-function scheme is so common that people do not recognize who invented this.

In addition, the transition energy of J-PARC MR is imaginary for eliminating the beam loss inherent at the transition. In the case of the normal FODO lattice that is commonly used for the proton synchrotrons, the proton beams pass the transition energy during the course of their acceleration. Here, the transition energy means that the frequency of the synchrotron oscillation vanishes, that is, the beams lose the restoring force for both the energy and phase deviation from their equilibrium values. The beam loss is inevitable here. The imaginary transition energy means no transition energy in the real world.

Figure 13 shows one of the very early stage results of the KEK-PS MR acceleration for comparison with that of the J-PARC MR. After nine-times injection from the KEK-PS booster to the MR, the bending magnets were ramped up for acceleration, but the beam was lost at the transition. In contrast, the J-PARC MR result showed no beam loss observed during acceleration. This is one distinguished example of the progress in the accelerator technology, during the period of about more than 30 years from 1977 to 2010.

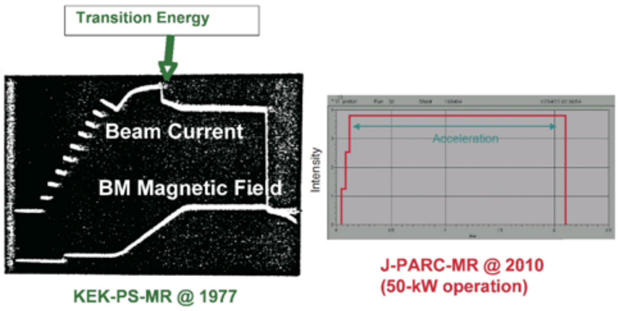

Figure 13: Beam current variation patterns during the injection and the energy ramping. The left is that of the KEK-PS MR (courtesy of KEK Archives Office), while the right is that of J-PARC MR. The original data points of the right figure were too thin to see. So, the data points were traced in a thick curve.

The J-PARC RCS has the transition energy, but it is beyond the acceleration energy, eliminating the beam loss again. The lattice for this case is referred to as a high-transition energy lattice. Figure 14 shows the result of 300-kW beam delivery of the RCS. At the injection, we have some beam loss in some cases. But, if we make very good adjustment of the parameters, the beam loss at the injection is almost eliminated. During the course of acceleration, no beam loss was observed at all.

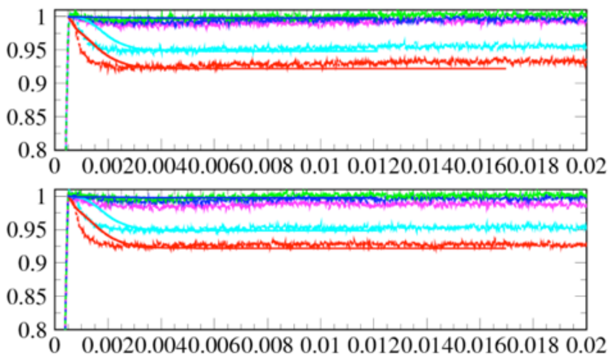

Figure 14: The beam current variation patterns of the J-PARC RCS, which delivered a beam power of 300 kW to the neutron-production target. Experimental data points and theoretical curves are shown for various injection conditions. The upper figure is as measured by DC-current transformer (DCCT), while the lower one by slow-current transformer (SCT). The horizontal axis is the time duration in seconds. Thus, the left-most corresponds to the start of the injection, while the right-most corresponds to the extraction. The beam loss is concentrated on the injection period.

In addition to the transition-free lattice, we have many innovations of the accelerator technologies like ceramics vacuum chamber, MA-loaded accelerating cavities, and so forth, where MA stands for magnetic alloy. The J-PARC RCS uses many ceramics vacuum chambers, as shown in Fig. 15. Ceramics technology was vital for the RCS, which should keep the system from any effect of the eddy current to be otherwise induced by rapid-cycling magnetic field.

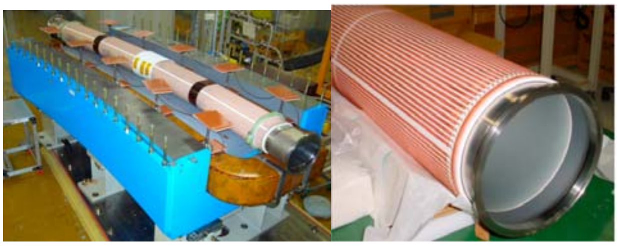

Figure 15: Ceramics chambers used for the J-PARC RCS. The left is for the bending magnet, while the right for the quadrupole magnets.

The MA-loaded cavity could generate the very-high field gradient, which is 2.5 times as high as that of the conventional one. By that, we could realize the world's most rapid acceleration, that is, 2.82 GeV with a repetition of 25 Hz. Note that the rapid acceleration requires the high field gradient. The MA-loaded cavity has another advantage regarding the cure of the beam instability. The quality value of the cavity is extremely low, enabling the powering with both the fundamental accelerating frequency and the second-harmonics one. The latter can be used to elongate the beam bunch for easing the space–charge effect. Conventionally, additional cavity system to the accelerating one would have been necessary for that purpose. Finally, we need no complicated tuning system for the cavities, since the Q value is very low. The cavity tuning system is conventionally complicated by applying the magnetic field to the ferrites to vary the resonant frequency. The use of the MA-loaded cavities significantly simplifies the RF control system, easing the beam commissioning a lot.

BEAM POWER DEVELOPMENT FROM KEK-PS TO J-PARC

Main parameters of both KEK-PS and J-PARC are compared in Tables I and II. The designed Lasslette tune shift, which is a measure of the space–charge force, is -0.16 for the J-PARC RCS. However, it is noted that the tune shift of the KEK-PS booster achieved -0.31, and that of the KEK-PS MR -0.30. This shows how skilful the KEK-PS people were achieved in beam operation.

Figure 16 shows an expectation of how the beam power of the J-PARC RCS would be developed. This was just an expectation or prediction, maybe, optimistic one. Immediately after this was shown, the J-PARC users took it as promise, since they were and are very anxious to have the high beam power for their science outputs. This kind of pressure has been very important and useful for the accelerator progress. Fortunately, the powers realized so far for one pulse, for 1 min, and 1 h, exceeded the expected values. However, for the user runs, it is a little lower. This is mainly because the neutron-production target needs development and testing in order to accept the 300-kW beam power. The J-PARC performance is a challenge not only for accelerator technology, but also for target technology.

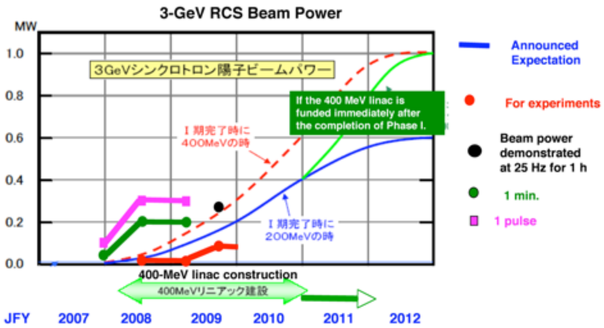

Figure 16: An expectation of the beam-power improvement as compared with the realized.

SUMMARY

The J-PARC accelerator technology largely originated from that developed for KEK-PS. It is also based on the developments starting in 1986 for JHP and JHF in KEK and for Omega Project and NSP in JAERI. It took 22 years. During that time, there has been the progress in the technology and young scientists have grown up. This is the reason for the on-schedule, successful beam commissioning of the J-PARC accelerator. However, we need further effort to overcome some technological issues. In this way, the developments and the operational experiences in J-PARC will contribute a lot to the worldwide technological advance in the accelerator field for several-megawatt neutron sources in the future, neutrino factories, and so forth.

Needless to say, J-PARC has been built for its scientific outputs. As mentioned at the beginning, J-PARC will be useful not only for materials and life sciences, but also for high-energy physics and nuclear physics. In the KEK roadmap for the high-energy physics, three important projects are listed: J-PARC, ILC, and Super B Factory. J-PARC is required for the lepton number or lepton physics, including the already-started neutrino experiment, and the future muon g-2 and ultra-cold neutron experiments. Therefore, many of you are invited to join us for enjoying the J-PARC world at present and in the future.

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