Approach to a Very High Intensity Beam at J-PARC

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Abstract

The high-intensity, high-energy proton accelerator project, J-PARC, comprises the 400-MeV proton linac, the 3-GeV, 1-MW Rapid-Cycling Synchrotron (RCS) and the 50-GeV Main Ring (MR) Synchrotron. The secondary particles such as neutrons, muons, Kaons, neutrinos and so forth will be fully made use of for materials science, life science, nuclear physics, and particle physics. Even the industrial use of the neutrons and the nuclear energy application are incorporated in the project. The rationale for choosing the accelerator schemes are presented together with the present status of the project and research and development for the high-intensity, high-energy proton accelerators J-PARC. The development of the high-field gradient RF cavity system making use of the magnetic alloy (MA), which is really necessary for the future development of the high-power proton accelerators, is reported in detail.

INTRODUCTION

The J-PARC is the acronym of Japan Proton Accelerator Research Complex [1-12], which is the joint project between High Energy Accelerator Research Organization (KEK) and Japan Atomic Energy Agency (JAEA). The project is to construct and operate the high-intensity proton accelerator facility at Tokai site (Fig. 1). The linac accelerates the H^- beam to 400 MeV, which is injected to the Rapid-Cycling Synchrotron (RCS) via charge stripping. The beams accelerated there to 3 GeV with a repetition of 25 Hz (the beam power is 1 MW) are mostly extracted to the Materials and Life Science Experimental Facility (MLF), where the muon production target and the neutron production target are located in series. Every three second, the beams are extracted four times to the main ring (MR), which accelerates them to 50 GeV. Then, the beams are either fast extracted to neutrino production target or slowly extracted to the Hadron Experimental Facility. The neutrinos thus produced are sent to the Super KAMIOKANDE detector which is located 300-km west. At the Hadron Facility, the experiments making full use of the strangeness will be conducted in such a way as the Kaon rare decay experiment, the Hypernuclei experiment and so forth. The 400-MeV linac beams will be further accelerated to 600 MeV by the superconducting linac and will be used for the basic research on the Accelerator-Driven Nuclear Waste Transmutation System (ADS).

This is a full scope of the J-PARC project. However, the project was divided into two phases, and only the Phase I was funded for construction. The ADS and nearly a half of the Hadron Facility were shifted to the Phase II, and the MR energy was limited to 40 GeV in the Phase I. Also, the linac energy will be 181 MeV at the beginning, although the linac building can accommodate the 400-MeV linac. The beam power of the RCS will be at most 0.6 MW until the linac energy becomes 400 MeV. Every effort is under way in order to start the linac energy upgrade to 400 MeV, just after the completion of the Phase I construction.

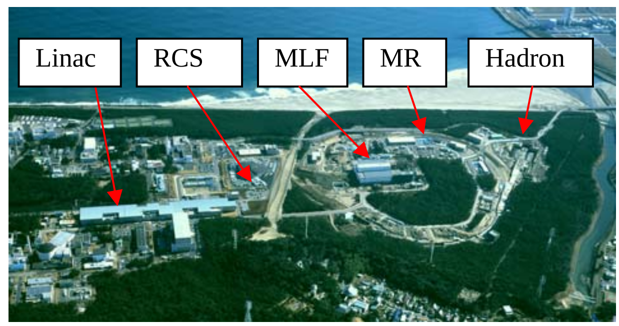

Figure 1: The bird-view photograph of the J-PARC site

The updated construction schedule is shown in Fig. 2. The linac beam commissioning will start in December, 2006, the RCS beam commissioning in September, 2007, the beam commissioning of the MR and MLF in May, 2008, the experiments at both MLF and Hadron Facility in December, 2008, and the beam commissioning of the Neutrino Facility in April, 2009.

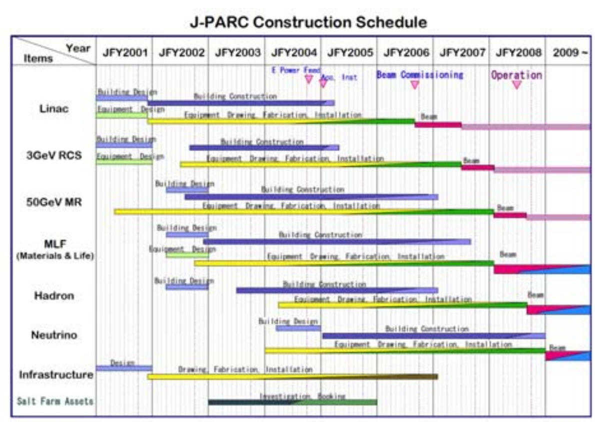

Figure 2: Construction Schedule Updated

DISTINCTIVE FEATURES OF THE J-PARC ACCELERATOR

The J-PARC accelerator is designed for providing the beams with an energy of several ten GeV and a beam power of 0.75 MW. The slow and fast extractions should be possible for the Hadron Facility and the Neutrino Facility, respectively. Simultaneously, the accelerator complex should provide the beams with an energy of a few GeV, a beam power of 1 MW, a pulse length shorter than 1 μs, and a repetition rate of around 25 Hz for the spallation neutron source.

It is noted that the cascade system is suitable for the several-ten GeV machine. The prototype is the KEK-PS, which has been recently shut down to be replaced by the J-PARC. The booster RCS can then be used for the Neutron Souce. The present project is a kind of scale up of the KEK-PS by a factor of nearly ten in both the beam energy and the beam current. Although it is natural to use Accumulator Ring (AR) system with a full-energy linac for the Pulsed Neutron Source like SNS at ORNL, the RCS system may be more powerful than the AR system for the following reason.

The following naïve reasoning is quite persuasive. A linac is easy to design, to build and to operate, since the beam automatically goes straight. A ring is easy, since it has a high periodicity with the stability. On the other hand, the beam is forced to inject into, and to extract from the ring. These are very difficult processes to manage. Then, if one manages to inject the beam, why not accelerate? One can easily increase the beam power.

In other words, the RCS scheme is advantageous over the AR scheme regarding the lower beam current and the lower injection energy for the same beam power. The higher beam loss is allowed during the injection process, into which most of the beam loss is concentrated among all. (If one increases the beam energy by a factor of 7.5 times as the J-PARC case, the allowed beam loss during the injection is 7.5 times as high as that for AR with the same beam power.)

As a matter of course, there are many reasons for the SNS and ESS to have chosen the AR scheme rather than the RCS scheme. First, the lower injection energy in turn implies higher space charge effect. Large aperture magnets as shown in Fig. 3 are required, giving rise to large fringing fields. Second, ceramics vacuum chambers (Fig. 4) have to be used with RF shielding to avoid the eddy current effect. Third, the magnet coils should be stranded (Fig. 5) to overcome the eddy current effect on the magnet coils. Fourth, the beam injection into the RCS is difficult to make large aperture beam and its extraction are hard to manage. Fifth, the precise magnet field tacking is necessary for each family of magnets. Sixth and perhaps most difficult is the high-field gradient RF accelerating system for the rapid acceleration.

All the challenging developments and the mass production of these components have been successful as seen from Fig. 3-5, except for the high-field gradient RF system, which is detailed in the next section.

MAGNET ALLOY (MA) LOADED CAVITY

In order to accelerate the beams rapidly, we need the high field gradient in the accelerating cavity. The high field gradient at the accelerating gap can be produced only by the high RF magnetic flux in the magnetic core. The ferrite which has been conventionally used in proton synchrotrons has a problem that the μQf value, which is proportional to the shunt impedance, rapidly decreases, as one tries to generate the field gradient typically beyond 10 or 20 kV/m. On the other hand, the μQf value of the magnetic alloy (MA) core [13, 14] has almost flat response to the magnetic flux which produces the electric field gradient up to an order of 100 kV/m. Therefore, higher field gradient is potentially feasible by using MA core.

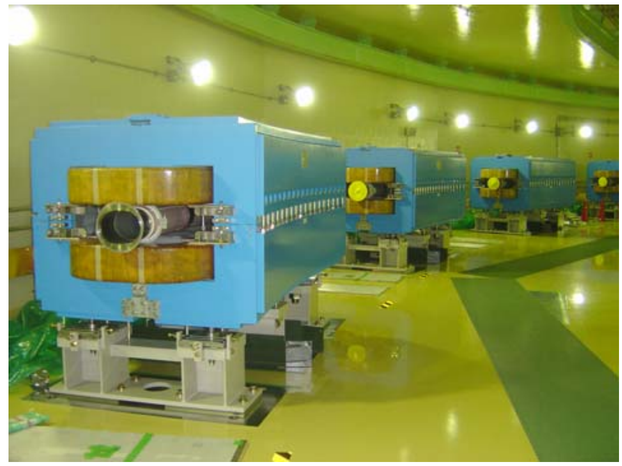

Figure 3: The bending magnets installed to the J-PARC RCS tunnel

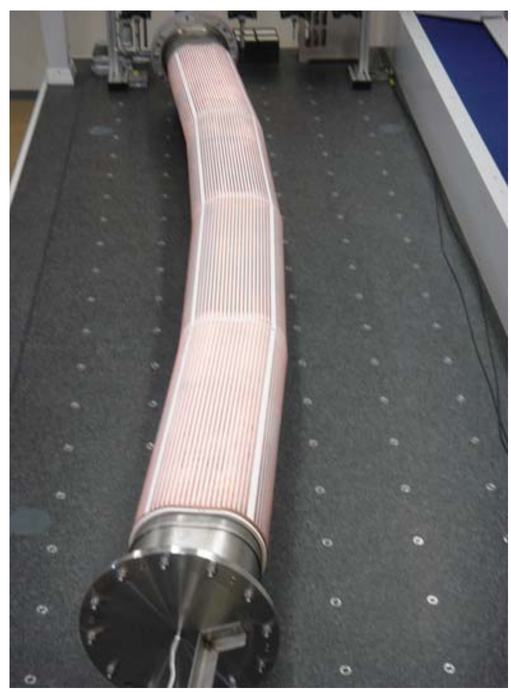

Figure 4: The ceramics vacuum chamber for the J-PARC RCS bending magnets

In addition, its extremely low Q-value (a value of less than one is possible) drastically simplifies the RF system by eliminating any tuning system. On the other hand, its high R/Q (low stored energy) with the low Q value requires the wide-band beam loading compensation via feed-forward control. As a result, even the high power system should be wide-band.

Figure 5: The cut-away view of the stranded coil used for the bending magnet

In order to minimize the band width necessary for the compensation, the Q-value is optimized by adjusting the gap between the MA cores radially cut under the condition of no tuning system. The Q values thus optimized are 2.9 (1.5-mm gap) [2 (1-mm gap) for 180-MeV injection] and 10 (10-mm gap) for the RCS and the MR, respectively.

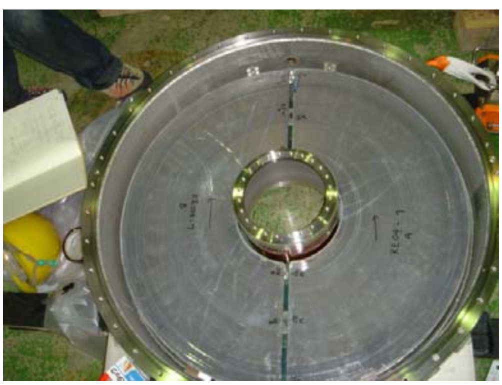

Figure 6: Cut MA cores for the J-PARC

The cut cores, however, was seriously damaged under the high RF power loading. During the course of the development, it was proposed that the Q value and the resonant frequency of the RCS cavity with uncut cores can be adjusted by adding the inductance in parallel to the cavity. In this way, the RCS RF system can meet the requirement for the full beam power. The preliminary power test was successful in demonstrating its feasibility. The full-fledged test of this system is planned in this summer. We thus decided to use the uncut cores for the RCS RF system, since the time limit is coming close to the final decision of the RCS RF system, the beam commissioning of which will start in September, 2007.

The MR RF system is such that both the Q value and resonant frequency of the MR system are higher than those of RCS system. Thus, the inductance becomes too big in practice. Since we have by 8 months more time for development than the RCS system, we decided to continue the development of the cutting technique of the MA cores for the MR system, including the diamond polishing of the cut surface.

The 30 uncut cores have been high-power tested at a full field gradient (1.3 times as high as the full average power) for 300 hours. Then, the six were damaged. All the damaged cores were located on the side of the accelerating gaps. (Six of the 10 cores located on the accelerating gap sides were damaged.) All the damages appeared on the surface to the accelerating gap except for one slight color change (brown). It is reasonable to assume that the electric field, thus the current by this, damaged the rare shorts between the MA layers sandwiching the thin (2 micron, typically) silica insulator layer.

The impedances of all the damaged cores, as measured in the simulated transverse electric field, were significantly (by 10 to 15 %) lower than those of the others. The damaged cores belong to a production lot of the cores manufactured at the beginning of the mass production, when the silica insulations were badly damaged during the manufacturing process. Now the manufacturer has developed the mass production technique free of the damage of the insulation. We are proving that the newly developed measurement method of the core impedances can sort the good cores out of all the cores.

We are perhaps solving the problems of MA-loaded cavity system which appear during the several hundred hour operation. Another new problems might appear at several thousand hour operation and at several ten thousand hours. It is reasonable to assume that all these difficulties are arising from the high accelerating gradient (typically 15 kV/gap, 25 kV/m) and high average power. We are thus considering to use lower field gradient, like 12 kV/gap or less, at the beginning of the beam commissioning, and to gradually increase the field gradient together with the increase in the beam power. During the course of the beam power increase, we will develop more robust cores. In order to expect and solve the problems which might appear during several thousand or several ten thousand hour operation, we need deeper understanding of the MA system together with the interaction of the cooling water and resins on them on the basis of the materials science. For this we may need to organize a team for this kind of study including the outside research institute like universities.

LINAC AND MR

A role of the injector linac is very important to inject the high intensity proton beams to a ring. The stable, low emittance beams should be prepared. In particular, the stability of the beam energy is most important. For this reason we have also been concentrating our effort into building the high quality linac.

The J-PARC linac comprises the volume-production type of H^- ion source [15, 16], the 50-keV Low Energy Beam Transport (LEBT), the 3-MeV, 324-MHz Radio-Frequency Quadrupole (RFQ) linac [17-19], the 3-MeV Medium Energy Beam Transport (MEBT) [20] with a 324-MHz RF chopper [21] and bunchers, the 50-MeV, 324-MHz Drift-Tube Linac (DTL) [22-26], the 190-MeV, 324-MHz Separated DTL (SDTL) [27], and the 400-MeV, 972-MHz Annular-Ring Coupled Structure (ACS) linac [28-36].

In designing the high-intensity, high-energy proton linac, there are two conflicting requirements [37]. On one hand, the higher accelerating frequency is preferable for the reasons of lower bunch current and shorter focusing period. More importantly, the klystrons feasible for stable operation can be used. On the other hand, electro quadrupole magnet system is preferable in order to keep the flexible knob. If one finds some harmful resonances like the parametric resonance, one may avoid it by using this flexibility. Electroquadrupole magnets with a water cooling channel usually require some space, resulting in the large drift tubes, that is, the lower frequency. In order to produce the smallest-possible electroquadrupole magnets we fully made use of the electroforming technique together with wire cutting (Fig. 7) [38, 39]. At last, we have successfully produced the 324-MHz DTL with electroquadrupole magnets therein to accelerate the 3-MeV beam to 50 MeV.

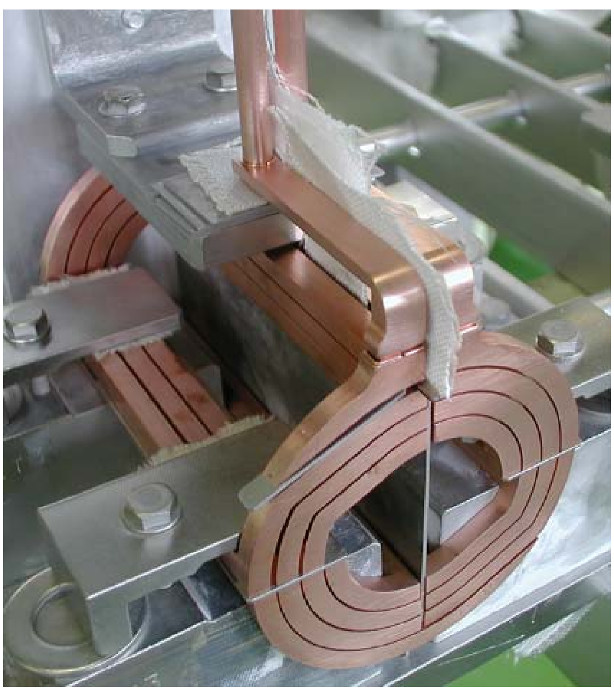

Figure 7: Electromagnetic coil produced with the electroforming technique and the wire-cutting. Water cooling channels therein.

We made the extensive study for optimizing the parameters of the MEBT with respect to many factors like mechanical design of the magnets, monitors, spaces, space-charge effects and so forth. Our conclusion is the 3-MeV MEBT with a 324-MHz chopper and bunchers. For this purpose we successfully developed the 3-MeV, 324-MHz RFQ by inventing the π-mode Stabilizing Loop (PISL). When we accelerated the H^- beam with the 432-MHz PISL-loaded RFQ linac for the first time in world, the acceleration energy by the RFQ was world highest.

For these DTL and RFQ, we have developed the 324-MHz, 3-MW klystrons with a repetition of 50 Hz and a pulse length of 600 μs in collaboration with Toshiba as shown in Fig. 8. Since we demonstrated the reasonably low emittance, the high intensity beams (a peak current of 30 mA) from the 20-MeV DTL (Fig. 9) and its stable operation [40], the frequency of 324 MHz and the MEBT energy of 3 MeV are becoming one of world standard for the future project. This is partly because the 324 or 325 MHz is one quarter of L band, which will be used for superconducing International Linear Collider (ILC). If one considers the future upgrade to several GeV proton linac, one can make full use of the superconducting cavity technology to be developed by the world-wide ILC collaboration.

For the MR, we are using the optics of the imaginary transition gamma in order to avoid the transition, where the beam loss is indispensable. The typical view in the MR tunnel is shown in Fig. 10.

Figure 8: 324-MHz, 3-MW klystron with a repetition of 50 Hz and a pulse length of 600 μs

CONCLUSTION

The J-PARC accelerator, comprising the 400-MeV linac, the 3-GeV RCS, and the 50-GeV MR, is based upon many newly developed technologies. Most of the developments were successful except for the RF system.

The J-PARC accelerator scheme is unique as follows. The RCS scheme is chosen for the MW proton machine producing the pulsed spallation neutrons. The MR is attempting to realize the MW proton machine also for the several ten GeV region. Not only for the scientific and engineering output, but this accelerator complex will also open up the new era for the field of the accelerator technology. We believe that the RCS system is really necessary for realizing several MW pulsed spallation neutron source or more in future. Increase in the injection energy to 1 GeV results in this. Many future projects like neutrino factories also requires the high power RCS with the high field gradient acceleration. However, the development of the high power proton RCS is very challenging as you see in our development of the high field RF system, which is necessary for rapid acceleration (25 kV/m here in contrast to typical field gradient of around 10 kV/m for the ferrite-loaded cavity). We are really challenging right now. Proposals to help us are coming from many institutes world-wide.

Figure 9: 324-MHz, 20-MeV DTL for J-PARC

Figure 10: Typical Arc Section in the MR tunnel

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