THE JAERI/KEK JOINT PROJECT FOR HIGH-INTENSITY PROTON ACCELERATORS

Y. Yamazaki
JAERI, Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan
KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan

Abstract

The Phase I of the high-intensity proton accelerator facility project in Japan comprising a 600-MeV linac, a 3-GeV, a 1-MW rapid-cycling synchrotron (RCS), and a 0.75-MW, 50-GeV synchrotron was approved for the construction. The RCS scheme is chosen for producing the pulsed spallation neutrons and the muons. The 50-GeV synchrotron is used for the nuclear and particle physics experiments, including the long-base line neutrino experiment.

1 INTRODUCTION-ORGANIZATION, SCHEDULE

The purpose of the high-intensity proton accelerator facility project in Japan is to promote a variety of scientific and engineering fields, by making the full use of the secondary beams, such as the neutrons, the muons, the Kaons, the neutrinos, and so forth, which can be efficiently produced by the proton beams[1]. The facility comprises a 600-MeV linac, a 3-GeV rapid-cycling synchrotron (RCS), and a 50-GeV synchrotron (MR) [2-4] as shown in Fig. 1. A half of the 400-MeV beams from the normal-conducting (NC, that is, room-temperature) linac are injected to the RCS, while the other half are further accelerated up to 600 MeV by the superconducting (SC) linac. The RCS provides a beam power of 1 MW (333 μA) to the Materials and Life Science Experimental Area with a repetition rate of 25 Hz. Here, the muon-production target and the neutron-production one are located in a series. The 50-GeV MR provides a beam current of 15 μA with a repetition rate of 0.3 Hz to either the Nuclear and Particle Physics Experimental Area or the neutrino production target. The beams are slowly extracted to the former, while they are fast extracted to the latter. The former is used for the experiments of the hypernuclei, the Kaon rare decay, or others. The neutrinos produced in the latter will be sent to SUPERKAMIONKANDE detector located 300-km far from the accelerator in order to do the long-base line experiment. The 600-MeV beams from the SC linac are transported to the experimental area for the Accelerator-Driven nuclear waste transmutation System (ADS), where the basic study of the ADS will be conducted.

The facility will be constructed as a joint project of Japan Atomic Energy Research Institute (JAERI) and High Energy Accelerator Research Organization (KEK). The location of the facility is JAERI/Tokai site. The project has evolved from Neutron Science Project (NSP) [5, 6] of JAERI and Japan Hadron Facility (JHF) Project [7-10] of KEK. The JHF project itself has evolved from Japan Hadron Project (JHP) [11].

The phase I of the project was approved for the construction starting from April, 2001 and being completed by March, 2007. In the Phase I the linac will be constructed only for the RCS injection (400 MeV). The 50-GeV MR will be operated with an energy of 40 GeV. The neutrino production target area is not included in the Phase I, either. However, the full power system will be completed for the pulsed spallation neutron source. The effort will be immediately started for the approval of the Phase II: the neutrino experiment and the ADS.

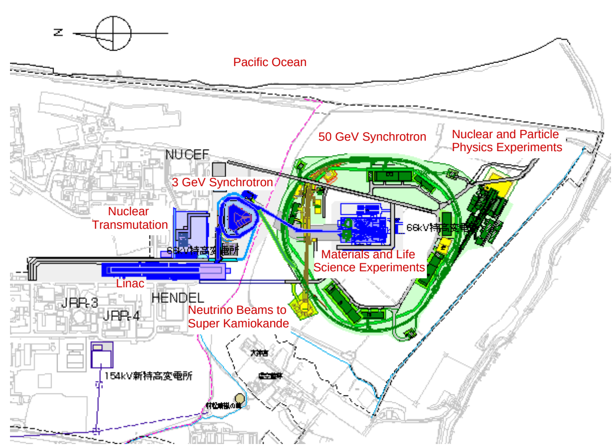

Figure 1: Plan view of the facility

In order to make full use of resources of both the institutes the Project Team was formed under the agreement between them. The Project Team will do all the works for the construction of the facility and the research and development necessary for the project under the single Project Director. Approximately 300 staffs were assigned from the staff members of the two institutes as the Project Team (approximately half of them have other duties in their institutes). The Project Director placed the team members into the eight groups, including the accelerator group.

Since the number of accelerator staffs (109 including 5 postdoctoral fellows, and 29 staffs with other duties) are quite limited, the accelerator team was organized for the highest efficiency as the following mesh structure. One grouping system is based upon their expertise: RF, vacuum, magnet, and so on. For example, the RF group is responsible for both the RF system of the RCS and that of the MR. The vacuum group is responsible for all the vacuum systems of the linac, the RCS and the MR. On the other hand, some works should be done within a framework of each machine. Thus, each staff is also belonging to one of three accelerator groups: linac, RCS, and MR.

The construction of the low-energy front 60-MeV linac [12] was already started in KEK by the JFY (Japanese Fiscal Year starting from April) 1998 supplementary budget for the JHF. From 2000 on, JAERI has been supporting this by both its budget and manpower. Then, some of the remaining components for the linac were funded by the JFY2000 supplementary budget to JAERI. All the contracts for the remaining components of the 200-MeV linac was completed by the end of JFY2001 as *four-year contacts, while those from 200 MeV to 400 MeV by the end of JFY2002, being funded to JAERI.

The contracts of the major components for the MR funded to KEK have been done by the end of JFY2001, including the bending magnets, the quadrupole magnets, the power supplies for these magnets, some of the RF systems, and so forth. On the other hand, major components for the RCS (funded to JAERI) will be contracted in JFY2002 and later. The basic design for the RCS, including the lattice design, has been drastically changed last year (2001). For these reasons, the designs of some components for the RCS are still in progress.

2 ACCELERATOR SCHEME

In order to produce the intense secondary beams, the beam power should be as high as possible, while the beam energy should sufficiently exceed the thresholds for the efficient production of the secondary beams. The time structure of the proton beams is another important factor in order to conduct the fruitful experiment [13]. The major requirements for the accelerator can be summarized as follows.

1) The accelerator complex should provide the 1-MW beam with a repetition rate of 25 Hz and a pulse length less than 1 μs to the full use of pulsed spallation neutrons. For efficiently producing the spallation neutrons the beam energy should be higher than several hundred MeV and lower than several GeV.
2) It should also provide the several ten GeV beams with a beam power of 0.75 MW for nuclear and particle physics experiments, being extracted both slowly and fast.

In order to meet the requirement 2) the cascade system is most suitable. For the power up, one has to increase the beam energies for both the extraction and the injection. The former is for the beam power itself, while the latter is for increasing the beam current by reducing the space charge effect at injection. The extraction energy of the MR is chosen 50 GeV, while the injection energy is 3 GeV. The extraction energy is perhaps optimized by taking into account various factors including the full use of the site area, the cost performance for the scientific outputs, the ratio of the extraction energy to the injection one, and so forth. If the ratio is too large, the repetition will be decreased, since the ramping speed is limited by the affordable magnet supply power, the eddy current effect, and others. The injection energy, that is, the extraction energy of the booster RCS, is chosen for efficient production of the spallation neutrons, which starts to be decreased at this proton energy.

The RCS can also be used to produce the high-power pulsed beams for the neutron source. The requirement 1) is thus fulfilled. The Spallation Neutron Source (SNS) in US [14] or the European Spallation Neutron Source (ESS) [15] are using another scheme, which comprises the full-energy linac and the compressor accumulator ring (AR). The advantages and disadvantages of the RCS scheme versus the AR scheme are discussed in detail in Ref. [13]. It is still controversial which scheme is more promising for producing the MW beam power. The further powerful sources may be realized by combining the RCS with the high-energy linac. In this case, the powerful RCS developed in this project will contribute a lot to the future accelerator technology in order to go beyond several MW.

The H^- beams are chopped with a chopping rate of 56 %. The two buckets in the RCS are waiting for the beam injection. The injection continues for 500 μs, while the magnet system of the RCS is sinusoidally oscillating. The RCS beams are fast extracted for most of times to the muon and neutron production targets. Every 3.33 seconds, on the other hand, the beams are extracted to the MR. The two buckets among the nine buckets in the MR accept the two bunches from the RCS at a time. This is repeated four times. After the last two bunches are injected, the ramping is immediately started. The beams are slowly extracted for 0.7 s to the Nuclear and Particle Physics Experimental Area in one case. In the other case, the beams are fast extracted to the neutrino production target.

3 LINAC FEATURES

The linac comprises a volume-production type of H^- ion source, a 50-keV low-energy beam transport (LEBT), a 3-MeV, 324-MHz Radio-Frequency Quadrupole (RFQ) linac, a 50-MeV, 324-MHz Drift-Tube Linac (DTL), a 200-MeV, 324-MHz Separated DTL (SDTL), and a 400-MeV, 972-MHz high-energy linac [12,16,17]. The 400-MeV beam further accelerated to 600MeV is used for the ADS.

We have the following conflicting requirements for the linac design [13]. The higher accelerating frequency is preferable, since the lower bunch current and the short focusing period arising from the higher frequency are both advantageous regarding the space charge effect. Also, the higher frequency is also advantageous regarding the discharge limit of the electric field gradient, the shunt impedance, and the size of the RF components including that of the klystrons. All imply the better cost performance. On the other hand, the electromagnet system is preferable in order to keep the flexible knob. Either the equipartitioning or constant phase advance can be realized in this case. The possibly dangerous parametric resonance can also be avoided. However, the large size of the drift tube is necessary in order to contain the quadrupole electromagnets. Then, the frequency must be decreased for the large drift tube.

We have developed the smallest-possible quadrupole electromagnets [18]. The electromagnet coils are produced by fully using the electroforming method and the wire cutting. In this way, it becomes possible to use a frequency of 324 MHz for the DTL starting from 3 MeV. Definitely, the klystrons can be used for this frequency. However, the huge power feeding system is necessary for exciting these electromagnets.

Another problem arising from the high accelerating frequency was that the accelerating energy of the RFQ linac was quite limited (2 ~ 2.5 MeV for ~400MHz), since the four-vane type of the RFQ could not exceed four times as long as the free-space wave length. This problem has been solved by the invention of the π-mode stabilizing loop (PISL) [19], which is also used for the SNS. The PISL's eliminate any effect of the deflecting field, resulting in the high quality of the accelerating and focusing fields.

Another feature of the linac design is that the longitudinal transition at 200 MeV from SDTL to the high-energy linac is separated from the transverse transition at 50 MeV from DTL to SDTL [16]. It is well known that the beam loss and beam quality degradation arise at the transitions. The separation of the two transitions give us more flexibility in order to avoid the mismatching at the transition, which gives rise to the halo formation.

It should be emphasized that the linac is an injector to the RCS. The most stringent requirement for this purpose is the accuracy of the beam momentum ($\Delta p/p(100\%) = \pm 0.1\%$). Both the 1% amplitude control and the 1˚ phase control should be realized for this requirement. Also, the 99 % emittance (normalized) should be 3~5 π mm mrad. Then, the alignment of 0.05 ~ 0.1 mm is necessary for the quadrupole magnets.

In order to reduce the halo formation, the axial symmetry [20] is perhaps important. This is one of the reasons for developing the Annular-Ring Coupled Structure (ACS) [21] for the high-energy linac structure. The axial symmetry also imply the easy manufacturing and the mechanical stability of the structure.

The medium-energy beam transport (MEBT) is another important component in the proton linac, in particular, for the injector linac. First of all, the beam from the RFQ should be matched to the DTL both longitudinally and transversely. Second, this is the place where one can chop the beam, which the ring RF separatrix cannot accept for its phase. The chopping is very difficult to do, since the chopping field should rise and fall, respectively, in between the two bunches. Otherwise, the beams partly deflected by the chopper would be accelerated, eventually giving rise to the high-energy beam loss. The RF chopper has been devised, and developed for this[22]. Another difficulty in the chopper is that any scraper or stopper cannot stand the beam loss of all the chopped beams. The beams will be partly chopped before entering the RFQ linac, by decelerating the beam below the energy acceptance of the RFQ.

We are developing the ion sources both with and without caesium. At first we attempted the ion source without caesium [23], that is, purely volume production, since we prefer caesium-free ion source in order to avoid the possible decrease in the discharge limit of the following RFQ. However, the peak beam current of the caesium-free ion source is limited to 23 mA so far. Further improvement of the caesium-free ion source is under way. On the other hand, the caesium-seeded ion source being developed as a back up (of course, useless, if the RFQ cannot allow the use of the caesium) has already produced a peak beam current of 70 mA (above the required value) with an aperture size of 8 mmϕ [24]. The emittance measured is small enough. At present the effort is concentrated on the increase in its lifetime, which is at present one half of the required value.

The commissioning of the 3-MeV RFQ linac has been started last March. The beam transmission through the RFQ was in agreement with the designed value.

Finally, we will discuss about the choice between the SC linac and the NC linac. The obtainable field gradient in SC cavities has been recently improved, mainly owing to the state-of-art surface electropolishing technique[25]. Then, one can decrease the linac length for the same energy by using the SC linac. In addition, the higher field gradient implies the larger longitudinal acceptance or the stronger longitudinal focusing, being more immune against the effect of the space charge. For these reasons we have again seriously evaluated the feasibility of the use of the SC linac from 200 MeV to 400 MeV.

The required phase and amplitude accuracy of each cell and each tank (0.1˚ and 0.1 % to 1˚ and 1 %, respectively, being dependent upon the kind of the errors) is much severer for the RCS injection than required just for the ADS as mentioned above. Therefore, the Lorentz detuning which becomes dynamic under the pulse operation should be accurately compensated. The SCC has been recently power-tested with the same pulse mode as required [26]. The detuning is periodic from pulse to pulse. The amount of the static detuning was in agreement with the simulation [26] within a few percent.

This detuning will be accurately compensated, if one uses a system of one SC cavity per one klystron. However, a system of two SC cavities per one klystron is only competitive in cost with the NC system from 200 MeV to 400 MeV. Therefore, the feasibility of the 400-MeV SC linac as an RCS injector is dependent upon how similar the detunings of the two cavities are to each other.

It is recently realized that the high field gradient imposes further severe phase-amplitude control for the same deviation of the beam energy. For the same reason as the larger acceptance expected in the high-filed operation, the random kick or walk and the synchrotron oscillation during the course of the acceleration through the higher field gradient cavities becomes larger in the direction of the $\Delta p/p$ in the longitudinal phase space. Under the presence of the Lorentz detuning the field control of the SC linac is obviously much harder than the NC linac. For this reason, we have finally decided to use the NC linac up to 400 MeV.

4 RCS FEATURES

We have chosen the lattice with three-folding symmetry. We need three long straight sections. One is dedicated to the long RF acceleration section, another to the injection and collimation, and the other to the extraction. The latter two sections will suffer from a lot of radioactivity, in particular, the injection/collimation section. It is preferable to keep the RF section apart from these radioactive sections, since the maintenance of the RF components are usually required more frequently than other components.

The circumference of the RCS is limited by the following two factors. One is the beam pulse length of less than 1 μs for the neutron production, and the other is the circumference of the MR. As seen from Fig. 1, the present circumference for the MR is perhaps the maximum, if one attempts to keep the MR within the campus. If one increases the circumference of the RCS, the number of the beam transfer from the RCS to the MR must be decreased, resulting in the decrease in the beam current of the MR.

Once the circumference of the RCS is thus limited, the three-folding symmetry should be taken in order to keep one long straight section for the sufficient RF acceleration. The lattice with the three-folding symmetry is geometrically matched to the landform rather than that with the four-folding symmetry.

The measure of the space charge effect is represented by the incoherent Laslett tune shift (spread). The value of the tune shift for the beam power of 1 MW is 0.24 with a bunching factor of 0.27, while it will come down to 0.16, if the bunching factor is improved to 0.41 by introducing the second harmonics into the RF accelerating field. Although the emittance growth should be carefully estimated on the basis of the beam simulation, the tune shift of 0.16 looks reasonable for keeping the emittance growth within 1.5 times. Taking all of these features into the lattice design, we have seven families of magnet power supplies. The precise tracking of each of a large number of families is one of the most difficult technical issues to solve.

Another difficult problem inherent to the high-energy RCS was solved by the innovative development of the accelerating cavity loaded with magnetic alloy(MA) [27], one of which is FINEMET. This cavity can generate the field gradient of over 50 kV/m (potentially over 100 kV/m) which is several times as high as conventional ferrite-loaded cavities. For this reason the RF system becomes a reasonable size even for the high-energy RCS. Further power test and beam test of the MA-loaded cavities are being continued after several successful experiments.

As an injector the RCS has to match its beam longitudinally for the injection to the MR. In order to realize this, keeping the controllably high RF voltage, the transition gamma should be much higher than 3 GeV, although the ring circumference becomes longer than the low transition gamma lattice. In addition the beam should be elongated in order to avoid a fast blow up just after the injection to the MR.

5 MR FEATURES

The striking feature of the MR lattice is the choice of the imaginary transition gamma. This is realized by the missing bend method, in which the beta modulation is relatively small. The missing bend structure generates the negative dispersion at bending magnets, resulting in the imaginary transition gamma. Similarly to the RCS, we make the dispersionless straight section including the RF section in order to avoid the synchro-betatron coupling.

The slow extraction scheme is most difficult issue to solve for this kind of high-intensity, high-energy proton synchrotron. Only the one percent beam loss is allowed during the slow extraction process. An electrostatic septum (80 μmϕ tungsten wires with rhenium) is being developed for this purpose. The voltage of 230 kV, which is higher than the necessary value of 170 kV, has been already supplied to the electrodes. Although the beam simulation results satisfy the above requirement, the further improvement in the beam loss simulation will be necessary for increasing the margin, which is needed for this kind of the beam loss/radioactivity mitigation.

The RF system of the MR will also use cavities loaded with the same MA as that of the 3-GeV ring. However, the Q value will be optimized for the MR. The adjustability of the Q value by cutting the MA core [27], which is also developed for this project, is another important advantage of the MA-loaded cavity.

6 CONCLUSION

The accelerator scheme for the high-intensity proton accelerator facility project in Japan is unique as follows. First of all, the RCS scheme is chosen for the MW proton machine producing the pulsed spallation neutrons. Second, the MR is attempting to realize the MW proton machine also for the several ten GeV region. If successful, 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. Together with the success of the SNS and/or ESS projects, this project will contribute a lot to the future several or ten MW accelerators, which are really required for the 21st century science and technology, including the biology, the nuclear and particle physics, the energy development, the environmental science/technology and so forth.

For this purpose, there is no other way than challenging. On the other hand, we have to be careful and conservative, where we can.

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