PRESENT STATUS OF HIGH-INTENSITY PROTON ACCELERATOR FACILITY IN JAPAN

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Abstract

The construction of the Project for High-intensity Proton Accelerator Facility(Figure 1). in Japan has been started this year. The Japan Hadron Facility of KEK[1] and the Neutron Science Project of JAERI[2] merged to this project. The purpose of this Joint Project is to pursue frontier science in particle physics, nuclear physics, materials science, life science and nuclear technology. Accelerators for this project comprises a 600-MeV linac, a 3-GeV rapid cycling synchrotron(RCS) and a 50-GeV main ring. 600-MeV beam of the linac is transported to the accelerator-driven nuclear waste transmutation system (ADS). Material and Life-science Facility(MLF) that receives the beam from the RCS is used in neutron beam experiment and muon experiment. High-energy beam of 50-GeV main ring is used for elementary particle experiment and neutrino oscillation experiment.

In this paper, the status of this project is described, and accelerator design is mainly presented.

1 INTRODUCTION

This facility will be used for wide area purpose from elementary particle physics to material science and neutron application engineering. The constitution of this facility is as follows, to correspond to these wide area application field. The 600-MeV linac outputs the beam toward the accelerator driven nuclear waste transmutation system (ADS) and 400-MeV beam of the linac send to the RCS simultaneously. RCS accelerates the beam to 3-GeV, and outputs the beam toward MLF and the 50-GeV main ring simultaneously. 50-GeV main ring outputs the beam to the elementary particle experiment station and the neutrino oscillation experiment station.

This project is divided to two phases. The 400-MeV linac of the normal-conducting cavities is built, the 3-GeV RCS is fully completed, and the 50-GeV main ring is temporarily equipped the power supply corresponding to 30-GeV at phase-1. MLF and several beam lines will be built, and the meson experiment arena will be installed to 50-GeV main ring. The construction of phase-1 begins this year from the part of the linac, and completion of phase-1 is 2006 years. Phase-1 of this plan costs 133.5 billion yen.

Phase-2 will be delayed several years to phase-1, and now we prepares the budget demand. At phase-2, the linac will be upgrade to 600-MeV of the super-conducting cavities, and the fly-wheel power supply for the 50-GeV synchrotron will be additionally installed. The budget for the neutrino experiment separates with the main budget and may be demanded. When phase-2 is included, it totally costs 185 billion yen.

2 ACCELERATORS

Three accelerators are designed to provide beam power of 1-MW at phase-1. And future utilization of this facility should be extended, we are planning to upgrade to 5-MW for spallation neutrons and others. The phase-1 accelerator complex has some parts common with JHF accelerator design[1]. The main difference is the linac which ensures more flexibility for the upgrade towards the phase-2.

2.1 LINAC

The normal conducting linac provides a 400-MeV beam to the 3-GeV RCS at 25Hz and to the super conducting linac at 25Hz simultaneously. The super conducting linac provides a 600-MeV beam to ADS. The main parameters of the linac are listed in Table 1.

A negative hydrogen ion source is designed to produce at least 60-mA peak current, and 70-mA, 0.15 πmm mrad has achieved this summer. The plasma chamber is volume production type, and cesium is infused. Although it is trade-off of quantity emission and life time, the research will be carried out aiming at two demand, long life time over three weeks and high-current over 70-mA consistently.

An RFQ linac accelerates the beam up to 3-MeV, a DTL up to 50-MeV, and a Separated type DTL(SDTL) up to 200 MeV. The frequency of 342MHz is the highest-possible choice, for which an electromagnetic quadrupole magnet can be embedded in a drift tube at 3-MeV. We have not yet had the accurate information on a 50-mA, 3-MeV beam from a 324MHz RFQ. Therefore, we have prepared an injection beam in order to study te beam behaviour of the following linac.

The RFQ is followed by a medium energy beam transport (MEBT). The 3-m long MEBT consists of 8 quadrupole magnets and two bunchers. In order to reduce beam losses after injection into RCS, a fast beam chopper is required. The bunch length is 396ns in a period of 733ns. The chopping system is one of the most difficult items to be developed. A newly devised RF deflecting chopper is used in the MEBT. Fast rising and falling times in a deflecting field are required to prevent beam losses. it is noted that the beam will not totally become unstable particles during

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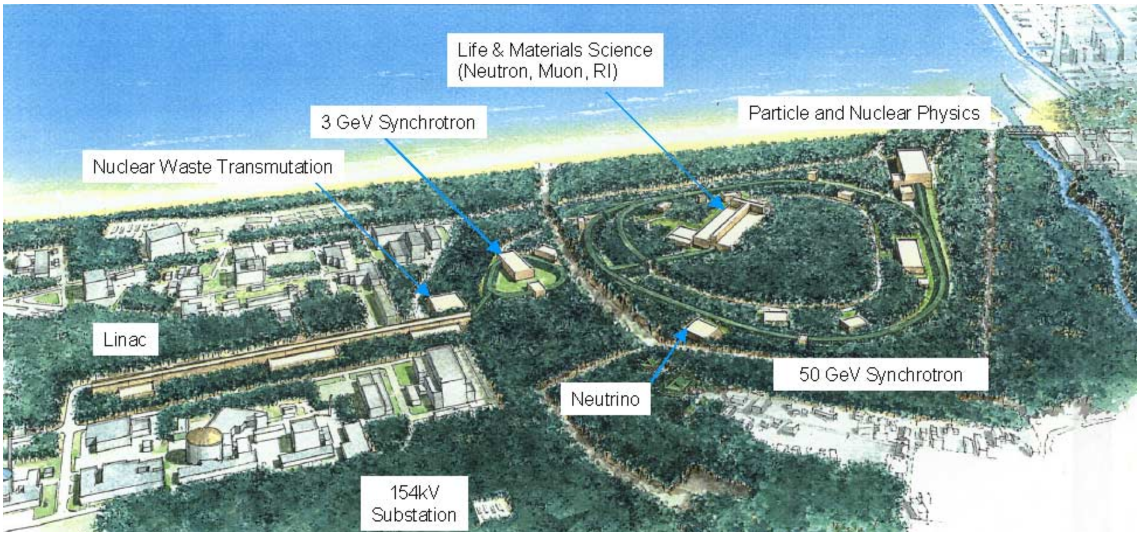

Figure 1: Birds view of the site.

transient time. Some scrapers at the exit of the DTL are effective to dump the unstable particles.

The DTL accelerator the beam from 3 to 50-MeV. Each tank is stabilized with post couplers. The maximum electric field on the surface of drift tubes is less than the Kilpatrick limit (17.8MV/m). The coupled envelope equations and the equipartitioning theory are used for the focusing design[1].

A new structure, and SDTL[2] has been chosen after 50-MeV. The SDTL has very similar principle of the conventional DTL, but it uses shorter tank with several cell structures. Its idea is based on the fact that quadrupole magnets are not necessary in every drift tube at higher energy. The SDTL has some advantages to the DTL, simpler, stable, easier alignment and decoupled motion of transverse and longitudinal. We set the limit of the beam loss below 0.1 %, the allowable amplitude error for each cell is ±1%, for each tank ±3% and the phase error for each tank ±4%.

Annular coupled structure(ACS) accelerates from 200-MeV to 400-MeV. ACS is a preferable choice owing to its axial symmetry, which may be important to minimize a halo formation. The tank has 16 cells and two tanks are coupled via a bridge coupler. The bridge coupler is a disk-loaded structure and has an input iris port at the middle cell. Transverse focusing is provided with the doublet quadrupole magnets. Detailed design work is underway.

In order to satisfy the requirement of the momentum spread, a debunching system placed in the beam transport(L3BT) line between the linac and the RCS is necessary. Because of limitation of site boundary, the length of L3BT is not enough. L3BT consists of a matching section from the previous doublet lattice to an FODO section, a transport line, an achromatic bending system with emittance and momentum scrapers and matching section to the RCS. A full energy spread of $\pm 0.07 - MeV$ is obtained at a debuncher voltage of 4.0-MV, located at a distance of 50 m from the ACS. Since the energy spread becomes larger again due to the space charge, another debuncher of 1.3MV is required at 200 m. The debuncher is a kind of 324MHz SDTL.

Super-conducting linac accelerates from 400 to 600-MeV for the ADS experiments. The system design is conducted as the similar manner as the NSP design[3]. The SC linac consists of cryomodules containing two 7-cell 972MHz niobium accelerating cavities. Quadrupole magnets provide focusing with a doublet lattice located in a room temperature region between cryomodules; there regions also contain beam diagnostics and vacuum systems. The cavities are occupied only 35 % in the length. The experiments of 5 cell cavities of $\beta = 0.5$ and $\beta = 0.89$ have been carried out with surface electric fields of 23MV/m and 31MV/m, respectively, at 2K. The cavity performance is not good compared with the single cell cavities, which reached constantly to more than 40 MV/m. The reasons for these results are considered to be the insufficient surface treatment. Further studies will be performed to meet the requirement with the peak field more than 30 MV/m. The most serious issue is how to overcome the problems associated with the pulse mode operation related to the microphonic vibration. A model describing dynamic Lorentz detuning is developed and validity of the model was confirmed by experiments by a prototype cryomodule, which includes two 5 cell cavities of $\beta = 0.60$.

2.2 RCS

The main parameters of the 3-GeV RCS are listed in Table 2. The lattice has been designed with the following considerations. First, sufficiently long straight sections are necessary to accommodate an extraction system, and injection system, and RF cavities. Among them, the extraction of 3-GeV beams requires at least 9-m long free space. Space for RF cavities, on the other hand, is only

Table 1: LINAC specifications

Energy	600 MeV
Repetition	50 Hz
Beam Pulse Length	500 μs
Chopping Rate	56 %
RFQ, DTL, SDTL Frequency	324 MHz
ACS, SCC Frequency	648 MHz
Peak Current	50 mA
Linac Average Current	1.25 μA
Average Current after chopping	700 μA
Total Length	350 m (393 m with a debuncher)
H- Ion Source	
Type	Volume-Production Type
Peak Current	53 mA
Normalized Emittance (90%)	1.5 π mm mrad
Extraction Energy	50 kV
RFQ	
Energy	3 MeV
Frequency	324 MHz
DTL	
Enegy	50 MeV
Frequency	324 MHz
Focusing Quadrupole Magnet	Electromagnet
Total Length	27 m
The Number of Tanks	3
SDTL	
Energy	191 MeV
Frequency	324 MHz
Total Length	91 m
The Number of Tanks	32
The Number of Klystrons	16
ACS	
Energy	400 MeV
Frequency	972 MHz
Total Length	108 m
The number of Tanks	46
The Number of Klystrons	23
SCC	
Energy	600 MeV
Frequency	972 MHz
The number of cells in one tank	7
Tne number of tanks per cryomodule	2
The total number of cryomodules	21
Total Length of cryomodules	110 m

Table 2: RCS specifications

Energy	3 GeV
Beam Intensity	8.3 x 10^{13} ppp
Repetition	25 Hz
Average Beam Current	333 μA
Beam Power	1.0 MW
Circumference	313.5 m
Magnetic Rigidity	3.18 ~ 12.76 Tm
Lattice Cell Structure	(3-Cell FODO x 2module arc + 3-Cell Straight) x 3
Typical Tune	(7.35, 5.8)
Momentum Compaction Factor	0.012 (no transition below 3 GeV)
Total Number of Cells	27
The Number of Bending Magnets	24
Magnetic Field	0.27 ~ 1.1 T
The Number of Quadrupoles	60
Maximum Field Gradient	4.6 T/m
Harmonic Number	2
RF Frequency	1.36 ~ 1.86 MHz
Average Circulating Beam Current	9 ~ 12.4 A
RF Voltage	420 kV
RF Voltage per Cavity	42 kV (14 kV/gap)
The Number of RF Cavities	10
Beam Emittance at Injection	144 π mm.mrad
Collimator Acceptance	216 π mm.mrad
Beam Emittance at Extraction	54 π mm.mrad

about 10-m because of the recent development of a high gradient cavity with magnetic alloy. Second, the maximum strength of bending magnets should be at most 1-T because of fast ramping. For the same reason, the maximum gradient of quadrupole magnets is 8-T/m at most. Third, the momentum compaction factor is adjusted in order to obtain the transition energy far from the extraction energy. It eases longitudinal matching between RCS and the main ring without reducing RF voltage just before extraction in the RCS. The lattice we designed has three-fold symmetry. The are section consists of three modules of three FODO cells with two missing bends in the middle cell. This arrangement of the magnets makes the momentum compaction factor tunable. There are three long straight sections are for the extraction, the RF cavities, and the injection/ beam-collimation, respectively. The phase advance is also kept below 90 degrees. The tunability is again an important feature of the present lattice, ensuring tunes adjustable within $\pm$0.5 around the nominal values of ν_x=7.35 and ν_y=7.3, respectively. A momentum compaction factor of 0.005 is realized in order to make the transition energy above 6-GeV.

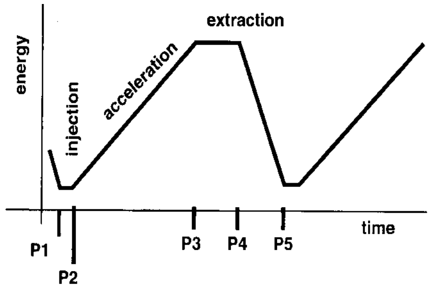

Figure 2: Typical machine cycle of 50-GeV main ring. P1-P2(injcection):0.12s, P2-P3(acceleration):1.9s, P3-P4(extraction):0.7s, P4-P5:0.7s, total:3.42s. Slow extraction of 50-GeV, duty factor:0.20, average current:15.6μA.

2.3 MAIN RING

50-GeV main ring accepts the beam from RCS, and accelerates. Two bunches from RCS are injected four times into the main ring when the main ring stays at low field. Then, 8 buckets out of 10 are filled with beams, and the main ring starts acceleration while other facilities start to use. The typical machine cycle structure is illustrated in Figure 2.

After 0.12s injection the beam energy is ramped up to 50-GeV for 1.9s, and thenthe beam will be extracted slowly during a time of 0.7s. The ramping cycle is to be completed in 3.42s, including the falling time of 0.7s.

The main parameters are listed in Table 3. Its lattice has been designed in order to meet the following requirements. First, one 100-m long straight section is necessary for slow extraction to the Particle and Nuclear Physics Experimental Hall. The other 100-m long straight section is used for fast extraction to the neutrino experiment and for RF acceleration. The two 44-m long straight sections are for injection and beam collimation. Second, the imaginary transition(γ_T), that is, negative-momentum compaction factor(α), should be realized in order to make the ring free of the transition. Third, the phase advance has been chosen to be below 90 degrees in order to avoid any strong resonance of the self space-charge force coupled with the beam-envelope modulation. Forth, the maximum tunability is guaranteed: the momentum compaction factor(α), which is nominally -0.001, is adjustable from $1/\nu_x$ to -0.01, while both horizontal and vertical tunes are adjustable within ± 1 (nominally 21.8 and 16.3, respectively).

3 RESEARCH FACILITIES

This project of accelerator complex has several facilities to adapt various purpose for modern and future science. some of them uses directly proton beam, and other uses various secondary particles from targets. Many users make experiment using neutron beam as a microscopic probe. There are three facilities (as follows), and beam line for neutrino oscillation experiment.

Table 3: 50-GeV main ring specifications

Energy	50 GeV
Beam Intensity	3.3 x 10^{14} ppp
Repetition	0.29 Hz
Average Beam Current	15.6 μA
Beam Power	0.78 MW
Circumference	1567.5 m
Magnetic Rigidity	12.8 ~ 170 Tm
Lattice Cell Structure	Arc(3-Cell DOFO x 8 module) + Insertion(2-matching cell + 3-Straight Cell + 2-matching cell)
Typical Horizontal Tune	22.3
Typical Vertical Tune	17.3-22.3
Momentum Compaction Factor	-0.001 (imaginary γ_T)
Number of Bending Magnets	96 (5.85 m)
Magnetic Field	0.135 ~ 1.8 T
Total Number of Quadrupoles	192 (0.86,1.26, 1.56, 1.66, 1.86, 1.96 m)
Number of Quadrupole Family	11
Maximum Field Gradient	18 T/m
Harmonic Number	10
RF Frequency	1.86 ~ 1.91 MHz
Average Circulating Beam Current	9.9 ~ 10.2 A
RF Voltage	280 kV
RF Voltage per Cavity	40 kV (13.3 kV/gap)
Number of RF Cavities	7
Beam Emittance at Injection	54 π mm mrad
Beam Emittance at Extractin	6.1 π mm mrad

3.1 MLF

This facility utilize a pulsed spallation neutron source and high-intensity muon beams based on the high-power 3-GeV RCS. Neutron and Muon beams will provide for innovative research in material and life science. One of the important features of this facility is its variety of subjects, which are super-conducting materials, battery anode, magnets, structures of the earth core, liquids, polymers, proteins, medicines, etc.

By measuring scattered neutrons from various materials, we can study atomic structures and their vibrational modes in microscopic level which characterize their macroscopic properties. For example, the mechanism of super conductivity, magnetic structure of magnetic thin films, electro-chemical cell reactions, structure of polymer micelles, designs of the new therapeutic drugs and so on.

Muon beams ranging from ultra-slow muon(KeV) to fast muons(100KeV) will allow new and frontier muon science. For example, surface science with ultra-slow muons, the study of muonic atoms and molecules, each consisting of a muaon and nuclei, muon catalyzed fusion, the mysteries of the muon as an elementary particle, and even more.

3.2 Particle and Nuclear Physics Facility

The 50-GeV Proton Synchrotron is a long-awaited wish for the Japanese hadron physics community, both from particle and nuclear physics. Existing machines are low intensity, it is not easy to carry out further extensive physics programs that are competitve with the best ones in the world. The users have been requesting a higher-inteisity proton machine with higher energy, and this Joint Project is a realization of their dream. Physics programs at the 50-GeV main ring cover a broad range of topics in particle and nuclear physics. Topics can not be mentioned, since more detailed reports are available else where.[4].

3.3 ADS

Conceptual design studies have been carried out for accelerator-driven transmutation systems[5]. The current design aims at supporting about 10 units of large-scale light water reactor with an electric power of 1000-MW. This corresponds to around 800-MW thermal power of a transmutation systems.

At phase-2, we will be the subcritical reactor-physics experiments and fundamental demonstration of the feasibility of the ADS concept. It will demonstrate the sustained stable integral operation of a spallation target and a subcritical core driven by a proton beam at a low power level ~ kWt. The first phase of ADS will include experiments to test ot instumentation and control system, to test the effects of beam trips for drawing up the restart sequence, to test the maintainability and replaceability of accelerator-interface hardware, to test the possible power oscillation, and to test the accuracy of design data and methods. The first phase program will also provide experience in design, construction, and operation of the ADS as the technology base for the second and third phase program. The proton beam required is 600-MeV in energy and 0.01 ˜ 0.08 mA in average current, operated in pulsed mode with 25Hz repetition rate.

4 CONCLUSION

These are the accelerators without the precedence that should suppress the radiation sufficiently and require a high accuracy and a high stability beam control. Although the construction began such a change that the examination of the details is carried out continually and make a better accelerator is carried out at any time. This facility will be opened the world. We are expecting many experimental proposal, and resonable collaboration proposal will be accepted.

5 REFERENCES

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