THE KEK/JAERI JOINT PROJECT;
STATUS OF DESIGN AND DEVELOPMENT

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Abstract

The Japan Hadron Facility of KEK and the Neutron Science Project of JAERI have been merged to one project; the KEK/JAERI Joint Project for high-intensity proton accelerator facility. The purpose of the Joint Project is to pursue frontier science and nuclear technology. The accelerator for the Joint Project comprises a normal- and super-conducting linac, a 3-GeV rapid cycling synchrotron and a 50-GeV synchrotron. The normal conducting linac provides a 400-MeV beam to the 3-GeV synchrotron at 25 Hz and to the superconducting linac at 25 Hz simultaneously. The superconducting linac provides a 600-MeV beam to an accelerator-driven nuclear waste transmutation system (ADS). The status of the linac design and the development work will be presented.

1 INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI) and the High Energy Accelerator Research Organization (KEK) are proposing “the Joint Project for high-intensity proton accelerator facility”[1] by merging their original Neutron Science Project (NSP)[2] and the Japan Hadron Facility Project[3]. The NSP was originally proposed for the accelerator driven nuclear waste transmutation system (ADS) based on the nuclear energy project OMEGA[4], but the project has been shifted to scientific orientation using a spallation neutron source. The accelerator complex of the NSP comprises a 1.5-GeV proton linac and storage rings. On the contrary, the JHF comprises a 50-GeV synchrotron, a 3-GeV rapid cycling synchrotron (RCS) and a 200-MeV linac[3]. The beam is used for fundamental particle physics, nuclear physics, materials science, life science and others. Since both projects have some common goals represented by a key word "high-intensity proton accelerators", the Government suggested a joint effort to one proton facility in Japan.

Figure 1 shows the schematic layout of the Joint Project. The facility will be constructed at the JAERI/Tokai site. The accelerator complex for the Joint Project consists of a 600-MeV linac, a 3-GeV RCS and a 50-GeV synchrotron. The linac plays two roles; one is to inject the beam to the RCS, and the other is to provide the beam to the ADS. The high-energy part of the 600-MeV linac uses superconducting (SC) cavities, which can be a prototype of the future CW accelerator for the ADS applications.

The 3-GeV, 1-MW beam is provided to the pulsed spallation neutron experiment. It is also used for muon science. The 50-GeV beam is used for particle and nuclear physics. It is also fast extracted for neutrino experiments, which are conducted at the SUPERKAMIOKANDE detector located 300 km from the Tokai site.

In this way, the high-intensity proton accelerators will intensively and efficiently promote a wide variety of science and engineering fields. The facility includes upgradability to a 5-MW neutron source, which is allocated to the second phase of the project.

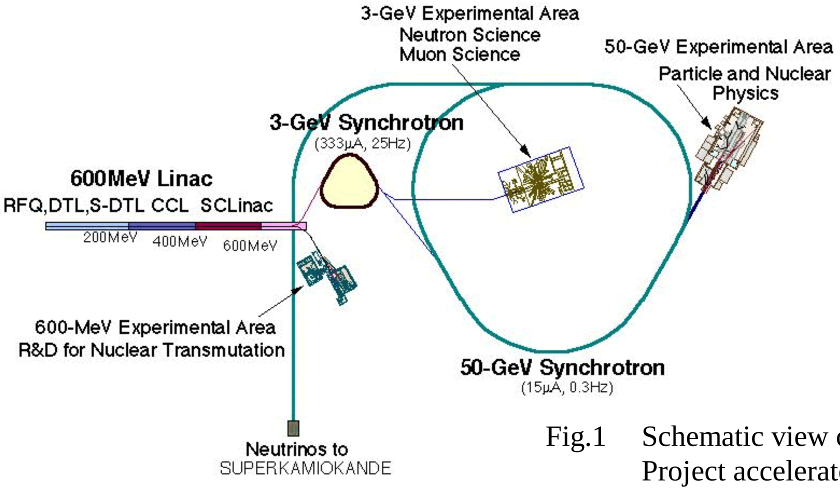

Fig.1 Schematic view of the Joint Project accelerator complex

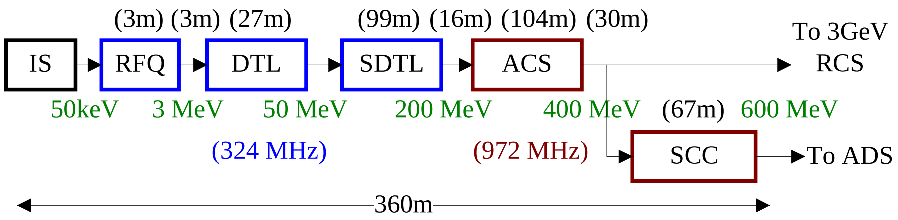

Fig. 2 Block diagram of the linac

2 LINAC DESIGN

Since the 50-GeV synchrotron requires several-GeV injection beams, the accelerator scheme is based on the RCS in contrast to the scheme of a full-energy linac and a storage ring option as the SNS or the ESS project. The H^- beam from the linac is injected to the RCS during 0.5 msec, which is limited by the flat bottom of the sinusoidally varying magnetic field of the 25 Hz RCS. The momentum spread of $\Delta p/p < \pm 0.1$ % is a key issue for the linac.

Figure 2 shows the block diagram of the linac. Key parameters are listed in Table 1. A peak current of 50 mA for H^- ion beam of 0.5 msec pulse duration is accelerated at a repetition rate of 50 Hz. The linac uses normal-conducting cavities up to 400 MeV. By using an AC switching magnet at 400 MeV, the half (25Hz) of the 400-MeV beam from the linac is injected to the RCS, while the other half is further accelerated up to 600 MeV by the SC linac simultaneously. An RF frequency of 324 MHz has been chosen for low-energy structures and 972 MHz for high-energy structures.

Particular attention has to be paid to suppress beam losses to minimize component activation and permit hands on maintenance.

2.1 Low Energy Linac

A negative hydrogen ion source is designed and will be examined to produce at least 60 mA peak current. 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 324 MHz is the highest-possible choice, for which an electromagnetic quadrupole magnet can be embedded in a drift tube at 3 MeV. The electromagnetic quadrupole system has much more tuning knobs against beam current and emittance variations than those of the permanent magnet system. Klystrons are available with the similar structures of 350 MHz ones.

In the negative ion source, the plasma confinement magnetic field is optimized by 3-dimensional analyses with a computer code TOSCA[5].

It's getting common to use an RFQ with higher ejection energy. This trend was initiated by the 3-MeV, 432-MHz RFQ linac at KEK[6]. Although this RFQ is approximately 4 times as long as its RF free-space wavelength, the good field uniformity is realized by inventing a new field stabilization method: pi-mode stabilizing loop (PISL)[7]. This RFQ successfully accelerated an H^- beam of 13 mA peak with a transmission efficiency of 82.5 %.

We have not yet had the accurate information on a 50-mA, 3-MeV beam from a 324-MHz RFQ. Therefore, we have prepared an injection beam in order to study the beam behavior of the following linac. The injected particles are generated randomly in a 6-dimensional ellipse.

The RFQ is followed by a medium energy beam transport (MEBT). The 3-m long MEBT consists of 8 quadrupole magnets and two bunchers[8]. In order to

Table 1 Key parameters of the linac

Parameter	RFQ	DTL	SDTL	ACS	SCC
Output energy (MeV)	3	50	200	400	600
Section length (m)	3.1	27.1	98.4	104.2	69.0
Structure length (m)	3.1	26.7	70.9	65.7	24.4
Frequency (MHz)	324	324	324	972	972
Accelerating field (MV/m),E0		2.5 ~ 2.9	2.5 ~ 3.7	4.3	12 ~ 13.5
Vane Voltage (kV)	82.9 (1.8Kilp)				
Number of cavities	1	3	34	44	30
Synchronous phase (deg)	-30	-30	-27	-30	-30
Copper RF power (MW)	0.34	3.3	16.5	27.6	
Total RF power (MW)@50mA	0.48	5.7	24.0	37.6	10
Number of klystrons	1	3	17	22	15
Aperture radius (mm)	3.7 (average)	6.5 ~ 13	18	20	30@Q, 45@Cav.
Number of cells	294	146	170	660	210

reduce beam losses after injection into the RCS, a fast beam chopper is required. The bunch length is 396 nsec in a period of 733 nsec. The chopping system is one of the most difficult items to be developed. A newly devised RF deflecting chopper[9] 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 transient time. According to the PARMILA simulations, 1.6 micro-bunches equivalent become unstable at the exit of the MEBT[9] for rising and falling time of 15 nsec. Since the intermediate pulse has 128 micro-pulses, the unstable particle beam is 1.2 % of the total beam. Some scrapers at the exit of the DTL tank-1 and tank-2 are effective to dump the unstable particles. In this case, the unstable particle ratio can be reduced to 0.08 % at the exit of the 50 MeV DTL[9].

The DTL accelerates 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[3]. Since the transverse beam size increases gradually along the linac, a bore radius of the drift tubes varies by three steps to take enough margin to the beam sizes; 6.5, 11 and 13 mm as shown in Fig. 3.

A new structure, an SDTL[10] 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:

(1) Simpler structures without quadrupole magnets in drift tubes: we can optimize the geometrical shapes of the drift tubes in order to maximize the shunt impedance.
(2) A stable accelerating field without post couplers.
(3) Easier alignment tolerance of drift tubes and tanks.
(4) Separation of the transition point in the transverse and the longitudinal motion: This scheme prevents an abrupt transition and degradation of beam qualities. For this linac, the transverse transition is at 50 MeV (before the SDTL) and the longitudinal transition is at 200 MeV (after the SDTL).

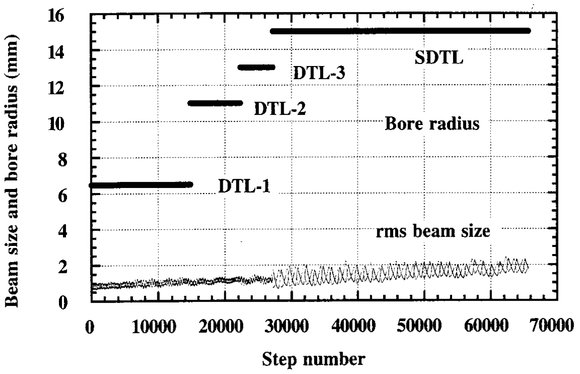

Fig. 3 Variation of RMS transverse beam size and bore radii along the DTL and the SDTL. One cell corresponds to 181 steps.

The effects of errors in RF fields in the DTL and SDTL are investigated[11]. The results obtained from the PARMILA simulations are as follows;

1) the longitudinal emittances as well as the energy spread increases as the field errors,
2) the beam loss increases as the field errors, which gives tolerances for the field errors,
3) the transverse emittances do no change much.

If we set the limit of the beam loss below 0.1 – 0.2 %, the allowable amplitude error for each cell is ±1%, for each tank ±3% and the phase error for each tank ±4%.

2.2 Medium Energy Linac

A coupled-cavity linac (CCL) is a natural choice from 200 MeV to 400 MeV, if we use normal conducting structures. Among the possible candidates in the CCLs, an annular coupled structure (ACS)[12] is a preferable choice owing to its axial symmetry, which may be important to minimize a halo formation. The tank has 15 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 (BT) line between the linac and the RCS is necessary. Considering the site boundary and arrangement of some target stations, there is no possibility to take optimum length from the linac to the RCS. The length of the BT line is approximately 300 m. The BT line 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 ±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 1.3 MV is required at 200 m. The debuncher is a kind of 324-MHz SDTL.

Another choice of this energy region is the SC linac. Detailed design and technology experiments are underway considering the pulse mode operation in particular.

2.3 High Energy SC Linac

In the first phase of the Project, the SC linac[13] has a role to accelerate from 400 to 600 MeV for the ADS experiments. The system design is conducted as the similar manner as the NSP design[14]. The SC linac consists of cryomodules containing two 7-cell 972-MHz niobium accelerating cavities. Quadrupole magnets provide focusing with a doublet lattice located in a room temperature region between cryomodules; these regions also contain beam diagnostics and vacuum systems. From the lengths in Table 1, the cavities are occupied only 35 % in the total length (24.4/69.0=0.35). There are two kinds of SC cavity shapes, and each type is designed for efficient acceleration and phase slips in a different velocity range; β=0.729 and β=0.771.

According to the quench condition experiments for the high-field SC cavities, the maximum accelerating field is determined by a multipacting referred to the magnetic field, not by a field emission or sparking referred to the electric field. In the current design, maximum magnetic field is set to be 525 Oe, which corresponds to the peak field of 30 MV/m. Total length and the number of the cryomodules are 69 and 15, respectively.

To reduce emittance growth, the lattice design is performed according to a nearly equipartitioned condition. Beam simulations are carried out using the PARMILA code. The 90-% emittances and RMS beam sizes along the SC linac are shown in Fig. 4. Since the equipartitioning scheme has applied in this design, emittance growth rates in the transverse and the longitudinal directions are as small as 6 % and –2 %, respectively. The beam sizes are nearly constant, because the energy range is not so wide in this SC linac. Ripples of the transverse beam sizes are due to the modulation of the doublet focusing system. The RMS beam size in transverse direction is 0.2 cm at the highest. The bore radius is 3 cm at the quadrupole magnets and 4.5 cm at the cavities. The ratio of bore radius to RMS beam size is greater than 15, which may be enough for the beam losses in the linac.

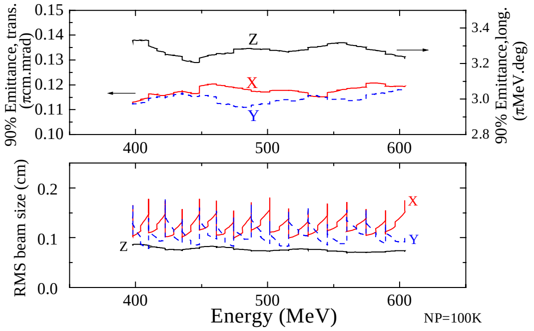

Fig. 4 90-% emittances and RMS beam sizes in the SC linac

One of the upgrade paths to increase beam power is to take the higher injection energy to the RCS. The RCS requires a linac beam with a momentum spread within ± 0.1 %, which refers to ±1MeV at 600 MeV. Effects of the RF phase and amplitude control errors to the momentum spread have been evaluated[15]. The phase and amplitude errors have been introduced randomly in the simulations. The 1000 cases of the calculations have been carried out and average output energies are evaluated statistically. As a result of the calculations, phase and amplitude errors within ±1 degree and ±1 % are required. After the momentum spread will meet the requirement, 600 MeV beam accelerated by the SCC will be injected to the RCS to upgrade the beam power.

3 R&D STATUS

The R&D programs have been formed for the JHF project and the NSP in order to overcome various difficulties associated with their high-intensity characteristics.

Construction of the 60-MeV linac started for the JHF at the KEK site in 1998. It includes the 324-MHz RFQ, the DTL and the first two tanks of the SDTL. The beam commissioning of the ion source has been started and of the RFQ linac will be scheduled in this fall. Since these two components were designed for a peak current of 30 mA, they will be replaced for the Project in the future. However, these components can be used for beam tests of the DTL and SDTL by that time. After construction and beam commissioning of the 60-MeV linac have been completed in collaboration between JAERI and KEK, the linac will be transferred to the Tokai site and used for the Joint Project. Details of the 60-MeV linac status are described in [16].

The work at JAERI has been performed for the 1.5-GeV linac of the NSP. The main feature of this linac is the high average current. In order to ensure the high-duty factor operation, the low frequency of 200 MHz has been chosen. The 2-MeV RFQ linac was tested for a proton peak current of 70 mA with duty factor of 10%[17]. The first 9-cell of the DTL was power-tested up to the duty factor of 20 % and 50 % with the field gradients of 2 MV/m and 1.7 MV/m, respectively. The R&D target at JAERI has been shifted to the Joint Project parameters.

3.1 Low Energy Linac

For the JHF at KEK, a volume-production type H^- ion source has been developed. It generates a peak current of 16 mA with a normalized 90 % emittance of 0.41 πmm.mrad without cesium[6]. For the NSP linac at JAERI, an H^- ion peak current of 40 mA was obtained at a duty factor of 5 % with cesium seeded[18]. The performance of the negative ion source is improved with the cesium insertion resulting in an increase of the beam current, improvement of the H^- and electron current ratio and flatness of the pulse shape. But the chemically active cesium vapor may cause a discharge problem in the RFQ. Further study is needed to evaluate the effects of cesium vapor insertion as well as improvement of a beam current.

The 3-MeV, 324-MHz RFQ[19] with PISLs is under construction at KEK. Since the RFQ is designed for the original JHF project, the peak current is limited to 30 mA. Design of a new RFQ for 50 mA is underway both at KEK and JAERI.

The construction of the 324-MHz DTL[20] has been started. The following items are highlighted: 1) A lining process using a new copper electroforming[21] 2) Quadrupole magnets with a hollow coil made by using the periodic reverse electroforming method[22]. High-power test of the components has been done by using a short model tank.

The ratings of 324-MHz klystrons have a maximum power of 3 MW, a pulse width of 650 μsec and repetition rate of 50 Hz. A prototype klystron has manufactured and tested up to an output power of nearly 3MW[23,24].

3.2 Medium Energy Linac

The fundamental RF issues concerning the ACS were solved and a high-power RF test using the 1296-MHz model cavity was successfully performed[12]. A machining test of the 972-MHz cavity piece, which is 1.5 times larger than the 1296-MHz one, using a superprecise lathe and milling machine has been completed. The test of the stacked cavity brazing in a vacuum furnace will be a next step.

3.3 High Energy SC Linac

The SC cavities for the proton linac have been intensively developed by the JAERI/NSP group in collaboration with KEK[13]. Vertical tests of single cell cavities have been successfully performed. The experiments on 5 cell cavities of β=0.5 and β=0.89 have been carried out with surface electric fields of 23 MV/m and 31 MV/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 has been developed and validity of the model has been confirmed by experiments[25].

Design of a prototype cryomodule, which includes two 5 cell cavities of β=0.60, is in progress. Performance test including RF control will be made in 2001

4 SUMMARY

The status of the linac design and the development work is described. To obtain better performances, new structures such as the SDTL, the ACS and the SCC are adopted. The system design of the linac is almost completed. The layout of the linac building and conventional facilities are designing.

According to the new law in Japan, big scientific projects must pass a third-party review committee organized by the Government. This project was assigned as a first example. According to the review report, the Project is very strongly supported by the committee. We hope that our project will be approved officially for construction start in JFY2001.

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