A PROTON ACCELERATOR FOR NEUTRON SCIENCE PROJECT AT JAERI

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Abstract

The high-intensity proton accelerator with an energy of 1.5GeV and a beam power of 8MW has been proposed for the Neutron Science Project (NSP) at JAERI. The NSP is aiming at exploring nuclear technologies for nuclear waste transmutation based on a proton induced spallation neutrons. The proposed accelerator facilities will be also used in the various basic research fields such as condensed matter physics in combination with a high intensity proton storage ring. The conceptual design and R&D work has been carried out for the components of the front-end of the proton accelerator. For the high energy portion above 100MeV, superconducting (SC) linac has been designed and developed as a major option. The proton storage ring has been studied to produce high intensity pulsed beam.

1 INTRODUCTION

Japan Atomic Energy Research Institute, JAERI, has been proposing the Neutron Science Project (NSP) which is composed of research facilities based on a proton accelerator with an energy of 1.5GeV and an average current of 5.3mA.

One of the most important issues with nuclear energy is the management of high-level radioactive waste arising from the reprocessing spent fuels. The Japan Atomic Energy Commission (AEC) proposed the partitioning and transmutation research program for high level radioactive nuclear wastes, OMEGA, in 1988. After this proposal, JAERI started an intensive work to study the accelerator-driven transmutation system of minor actinides as one of the attractive options. The JAERI's activities cover development of a high intensity proton accelerator as well as various developments of partitioning process of the high level radioactive waste, design study of the actinide target and accelerator driven hybrid system[1].

In recent years there has been a growing interest in new intense neutron sources for advanced fields of basic research and many engineering applications. Many of previous neutron experiments have been carried out at high-flux fission reactors. High-flux reactors are, however, over subscribed by two or three times more proposals than they can accept, so that there is an increasing demand for additional neutron sources. Furthermore high flux reactors are presently operated at the upper technical limit which is determined by the overall heat deposition released in the fission process. In recent years, an alternative technology for generating neutrons based on the intense proton accelerator started to attract the strong interest in this field. The use of time-of-flight instruments in this field has led to an increasing desire for higher peak fluxes. These fluxes cannot be achieved from steady state fission reactors. Proposals and their specifications can be found for many intense neutron sources based on the accelerators in various institutions.

In addition to development of such new basic neutron researches and nuclear energy related technologies on material science, neutron irradiation, neutron physics and nuclear waste transmutation, many potential applications for applying the intense accelerator have been also

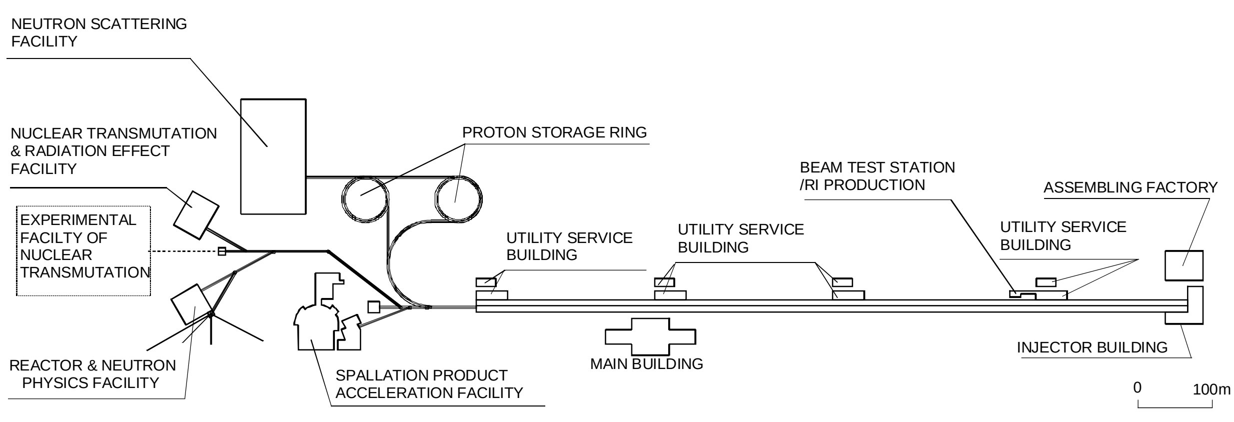

Fig. 1 A Conceptual Layout for Neutron Science Project

discussed, which include meson/muon production and spallation RI beam (mainly for nuclear physics studies) and radio isotope production. An idea of research complex composed of the variety of the research facilities Neutron Science Project (NSP) have been proposed with such versatile purposes. The conceptual layout of the accelerator for the NSP is shown in Fig. 1.

CW-DTL. 3) the SC cavity development with the KEK electron SC group, 4) the high intensity proton storage ring and 5) high power RF source development.

A specification for the NSP LINAC is given in Table 1. Neutron scattering facility will require more strict pulse time structure. The beam chopping capability with about 1μs intermediate pulse length will be needed to compress the beam width by the storage ring.

Table 1. A specification of the JAERI NSP-LINAC

Energy		1.5GeV
Accelerated particle		Negative and positive hydrogen ion
Beam current:	1st stage;	Pulse average 1mA, peak 16.7mA (duration 2ms, repetition rate 50Hz)
	2nd stage;	CW maximum 5.3mA Pulse average 5.3mA, peak 30mA
Low energy part		RFQ, DTL/SDTL Normal-conducting linac: 200MHz
High energy part		Super-conducting linac: 600MHz
Intermediate pulse width		400ns (interval 270ns)
Chopping factor		60%

JAERI had originally planned to build the pulsed linac with an energy of 1.5GeV and a peak current of 100mA with 10% duty factor. The design study has been intended to obtain the technical validity to accelerate high peak current with high duty operation from the beam dynamics point of view under the OMEGA program. In this accelerator development, the R&D work has been performed on high brightness ion source, radio frequency quadrupole linac (RFQ), drift tube linac (DTL) and RF source, as well as the conceptual design of the whole accelerator components.

JAERI has modified the original plan by proposing an option of superconducting (SC) linac to meet requirements for a variety of basic research fields mentioned above and an ultimate goal for waste transmutation[2]. This SC linac will be operated in pulse as a first stage for the spallation neutron source and upgraded in CW for engineering test as a second stage. These two operational modes, pulse and CW operation, will be realized with time sharing manner, not simultaneously, and is the most challenging technical issues for the accelerator development. The SC linacs have several favorable characteristics as follows; the large bore radius results in low beam loss, the length of the linac can be reduced, and high duty and CW operation can be made for engineering purposes. The possibility to inexpensive operation cost may be also expected in comparison with normal conducting (NC) option.

Several R&D items are studied for the high intensity accelerator development; 1) the beam dynamic calculation including the high β linac. 2) the development of the negative ion source and the fabrication of high power test models for CW-RFQ and

2 LOW ENERGY ACCELERATOR PART

2.1 Beam tests of the 2MeV R&D-RFQ

In the case of a high intensity accelerator, it is particularly important to maintain the good beam quality (low emittance; small beam size and divergence) and minimize beam losses to avoid damage and activation of the accelerator structures. The R&D work for the low energy portion has been made as a first step in the NSP-LINAC development. The R&D-RFQ is a four-vane type and designed to accelerate 100mA (peak) of protons to 2MeV with a duty factor of 10%. The low power tuning, the high power conditioning and the beam tests were carried out[3]. The proton beam from the 100keV ion source was focused by the two solenoids to match the RFQ acceptance. The maximum RFQ output current, which was currently achieved, was 80mA at the ion source extraction current of 155mA with 10% duty factor. The transmission in the low energy beam transport (LEBT) from the ion source to the RFQ was about 60% - 70% with the proton fraction of about 80% in the ion source beam. The estimated transmission rate through the RFQ was 75% - 90% depending on the ion source condition.

2.2 Low energy part for the NSP-linac

In order to realize the short pulse with the proton storage ring and the final CW operation, R&D's are being carried out including negative ion source and CW-RFQ/

DTL in addition to the SC linac development. At the high energy part of DTL, the SDTL (separated type of DTL) proposed by Kato[4], KEK, has been studied. The SDTL, which has higher shunt impedance and simpler mechanical structure than DTL, is an attractive option for CW operation in the energy region of 50 - 100MeV where SC linac can not be applicable.

Ion Source

A negative ion beam is required for basic research to inject the beam into the storage ring which produce 1 μs pulse. Table 2 gives the specification of the negative ion source. The beam extractor of the existing positive ion source used for previous beam experiment was modified to produce negative ion beams from source ion plasma by providing the transverse magnetic field. The characteristics of the negative ion beam have been examined with the maximum observed beam current of 10mA at an arc discharge power of 38kW[5].

Table 2 Specification of Negative Ion Source

Accelerated particle	H^-
Energy	70keV
Current	50mA
Emittance(rms)	0.1πmm.mrad
Type	Single/multi-aperture Volume type

RFQ for Pulse and CW operation

The low energy part should be capable for the CW mode operation with a current of 5.3mA as well as the pulse mode with 30mA, because the SC linac has been selected.. The scheme to prepare two independent RFQs together with ion sources for pulse and CW operation is considered to meet these two different operational conditions[6]. Table 3 gives the specifications of the RFQs.

Because the most important problem for the R&D-RFQ was found to be the RF contact between vane and tank, the RFQ will be made as integrated type by brazing between vane and tank.

Table 3 Specifications of the RFQ

	Pulse	CW
Energy	0.07 – 2MeV	0.07 – 2MeV
Current	20 - 40mA	-7mA
Frequency	200MHz	200MHz
Peak field	1.65Ek	1.5Ek
Length	3.58m	3.91m
Pulse width	6ms	CW
Synchronize phase	-30°	-30°
Wall loss(60%Q)	325kW	300kW

CW-DTL/SDTL

The parameters for the CW-DTL are also re-evaluated to match the CW operation for the SC linac design concept. The SDTL concept has been also adopted to improve the performance for CW operation. Relatively low accelerator gradient of 1.5MeV/m is taken in order to reduce the RF power consumption and the RF heating. The expected maximum magnetic field gradient for the focusing magnet is about 50T/m using the hollow conductor type Q-magnet. The end point energy for the SDTL is 100MeV which is determined from the beam dynamics and mechanical consideration of the high β structure.

The beam dynamics study is conducted to obtain the optimized parameters for each accelerator structure. An equipartitioned design approach is taken for the DTL/SDTL to maintain the good beam quality and to prevent emittance growth causing beam losses. Table 4 gives the specifications of the CW-DTL and SDTL.

Table 4 Preliminary Specifications of CW-DTL/SDTL

	DTL	SDTL
Energy	2-50MeV	50-100MeV
Current	30mA	30mA
Frequency	200MHz	200MHz
Accelerating gradient	1.5MV/m	1.5MV/m
Synchronize phase	-55° - -30°	-30°
Number of cells	179	85
Length	50.2m	47.8,
Focus gradient	50.8-5.0T/m	8.5-7.9T/m
Total wall loss(70%Q)	3.6MW	2MW

3 HIGH ENERGY ACCELERATOR PART

3.1 The layout of the superconducting linac

In the SC linac part, the proton velocities β gradually change from 0.43 to 0.92 corresponding to the energies for 100MeV and 1.5GeV. Accordingly, the length of the cavity is also changed. Main concern is the strength of the cavity under the vacuum load for the low β (β<0.7) region. The mechanical structure calculations with the ABAQUS code have been made to determine the cavity shape parameters as well as electromagnetic ones with the SUPERFISH code.

In order to determine the layout of the SC accelerating structure, the case of the SC linac, which is composed of 8 different β sections has been studied[7]. The cavities in each β section will be made with identical

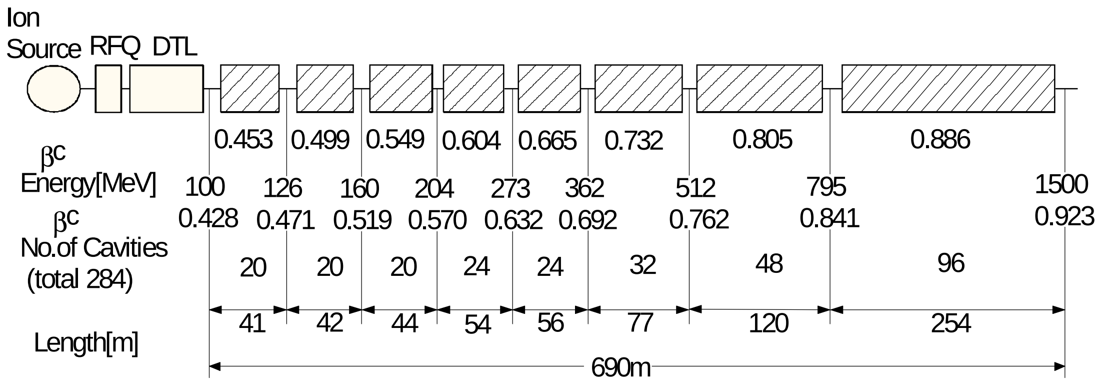

Fig. 2 Basic Parameters for Superconducting (SC) Accelerator

5 cells and designed at the specific beam energy but also can be operated at slightly different beam energy with lower efficiency. The conceptual layout of the superconducting linac is shown in Fig. 2. The structure of the cryomodule, input/HOM couplers and tuning devices etc. are being designed based on the KEK-TRISTAN (high energy e+, e- colliding machine) experiences. Using these parameters, calculations for the beam dynamics have been made with the modified PARMILA code. The equipartitioned design approach is also taken for the SC linac with the data given in Fig. 2.

3.2 Fabrication and test of a superconducting cavity

The test stand for a superconducting cavity development with the cryostat 80cm dia. x 350cm long and a clean room has been constructed. Two sets of single SC test cavities have been fabricated for β =0.5 which corresponds to the proton energy of 145MeV. Fabrication process such as cold rolling and press of pure Niobium metallic sheet, electron beam welding, surface treatment (barrel polishing, electro-polishing and high pressure water rinsing, etc.) has been performed based on the KEK experiences for 500MHz TRISTAN cavity. Vertical tests have been conducted to examine the RF and mechanical properties. The maximum surface peak field strength of 24MV/m at 4.2K and 44MV/m at 2.1K have been successfully obtained for the first time as proton SC accelerator cavity[8]. This test result has satisfied the specification for the conceptual layout of the superconducting linac.

4 RF sources

The RF sources are main components to determine the availability and reliability, and most costly parts for the accelerator system. Two frequency choices, 200MHz and 600MHz, have been selected in the conceptual study for low energy and high energy part, respectively, where total peak RF powers of about 300kW for RFQ, 9MW for DTL/SDTL and 29MW for SC linac are required for pulse operation. Due to the different two mode operations and gradual upgrade path, optimization for RF configuration is one of the most important technical issues. An RF system based on the Grid tube (Tetrode) and Klystron has been carried out[9]. As an example, Fig. 3 shows RF power requirements for 8 different β sections for each operating condition in the SC linac.

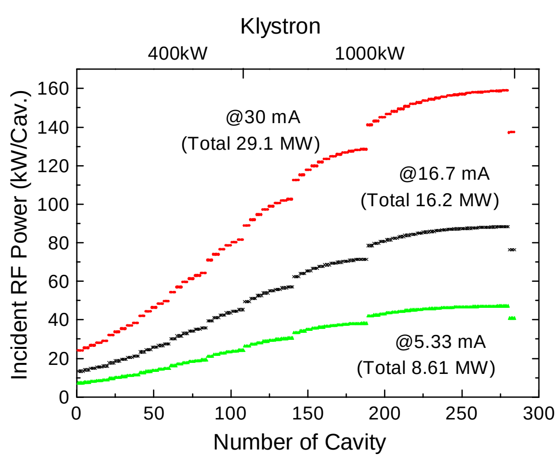

Fig. 3 Peak RF Power Requirement for the SC Linac

5 PROTON STORAGE RING

In the beam storage ring, the pulsed beam from the linac is accumulated, and high intensity pulsed beam is produced for the neutron scattering experiment. The linac beam is chopped to 670ns bunch width with 60% duty cycle at 50Hz. The 1.5GeV H^- linac beam is compressed by means of a multi-turn charge exchange injection. When a harmonic number of the ring is 1, a circumference and a revolution frequency are 185m and 1.49MHz, respectively. The single bunch in the ring is contained by RF resonant cavity. To achieve a beam power of 5MW with this beam structure, it is necessary to accumulate 4.17×10^{14} protons with one ring.

Because the average current circulating in one ring scheme becomes about 100A, in such a high average current, a beam loss of even a very small fraction makes a very high radioactivity around the ring. It is necessary to examine reduction and localization of the beam loss with sufficient consideration of the divergence of the beam by the space charge force, the resonance phenomena by the tune shift, longitudinal instability. It is, therefore, considered to prepare two separate rings for 2.5MW and combine them to obtain the 5MW beam. The pulse structure of the beam from the linac and preliminary parameters of the storage ring are given in Table 5[10]. A new attractive method, which is in preliminary physics design stage, is proposed using the wiggler magnet and high intensity laser to eliminate a beam stripper foil which is subject to a high temperature rise and causes large beam losses[11].

Table 5 Parameters for two 2.5MW ring scheme

Kinetic energy	1.5 GeV
Repetition frequency	50 Hz
Harmonic number	1
Revolution frequency	1.49 MHz
Circumference	185.4 m
Magnetic rigidity	7.51 Tm
Circulating current	99.5 A
Number of circulating protons	2.08×10^{14} protons

6 SUMMARY

The R&D work for the prototype linac structures has been performed. The good performances of the components such as ion source, 2MeV-RFQ, RF-source have been achieved. The test stand for the SC cavities was constructed. The vertical SC cavity test has been successfully conducted resulting in the satisfactory maximum surface electric field strength for SC proton accelerator. The design work on the RFQ and DTL/SDTL as well as SC cavities for the CW operation is performed. The preliminary design study for the high intensity storage ring is carried out.

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