STATUS OF THE HIGH INTENSITY PROTON LINEAR ACCELERATOR DEVELOPMENT IN JAERI

J. Kusano, M. Mizumoto, K. Hasegawa, N. Ito, H. Oguri,
K. Mukugi, Y. Touchi and H. Ino

Proton Accelerator Laboratory
Japan Atomic Energy Research Institute (JAERI)
2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken, 319-11 Japan

Abstract

JAERI has been proposed a high intensity proton linear accelerator to be utilized in future accelerator-driven Partitioning and Transmutation (P&T) system. The R&D of the high intensity proton accelerator was started in 1991 as one of the approaches for the OMEGA program in Japan. The first phase of the R&D has been made successfully on the components of the front-end part of the accelerator i.e., an ion source and RFQ, resulting in the peak current of 70 mA with duty factor of 7~10 % operation was obtained at the energy of 2MeV after the RFQ acceleration.

In these years, JAERI has been planned the Neutron Science Research Program (NSRP) for exploring basic researches and nuclear waste transmutation technology based on a next generation spallation neutron source driven by the high intensity proton linac. The conceptual design of the high intensity proton accelerator is rearranged slightly to achieve various operation modes in the NSRP. The second phase R&D has been started for the study of whole accelerator system with 1.5GeV and 10mA, beam power of about 15 MW. This report describes the summary of the first phase R&D and the present status of the second phase development of the high intensity proton linear accelerator.

Introduction

A progress of the technology in the field of charged particle accelerator gave a possibility of high intensity neutron source by nuclear spallation reaction. In 1980's research activities have been made for high intensity proton linacs to be applied to the nuclear fuel breeding and high-level long-lived radioactive waste transmutation. One of the approaches for the OMEGA program in Japan, JAERI has been carrying out the design study of an accelerator-driven nuclear transmutation system of minor actinides. The required beam current to drive a subcritical nuclear reactor for Partitioning and Transmutation (P&T) system is more than 40mA by preliminary evaluation. The initial concept of the high intensity proton accelerator to be used for the OMEGA program is a pulsed linear accelerator with an energy of 1.5GeV and an average current of 10mA (peak current of 100mA with 10% duty factor).

The average proton beam current of 10mA with the energy of above 600MeV is much higher than those for the present operating machines in the world. Most important issue in the proton accelerator is the handling of an intense beam with lower beam loss rate. The velocity of the accelerated proton is changed along with the beam energy. When the energy reaches at 1.5GeV, the velocity still does not get to the light speed. Acceleration method and accelerator structure must be changes to match an effective acceleration and in particular to keep low beam loss rate. In addition, the beam current and the beam quality of the high intensity accelerator are mainly determined by the low energy part of the accelerator because of the space charge effect. The stepwise development for the high intensity proton accelerator has been planned in JAERI. The first phase development was assigned to develop a low energy part components such as a high current and a low emittance ion source, a high peak current RFQ, a DTL hot test model and a high power RF source with a frequency of 200MHz.

To make the best use of the high intensity proton accelerator, JAERI has been proposing the Neutron Science Research Program (NSRP) in these years aiming at the exploring basic researches and nuclear waste transmutation technology by means of the proton accelerator application. The second phase R&D of the high intensity proton accelerator has been started to associate the accelerator design and the NSRP issues[1]. The various proton beam conditions are required such as high peak current, variable intensity, short pulse (less than μs), long pulse (2~3 ms) or continuous wave (CW) beam to realize the experiments in the NSRP. Figure 1 shows a conceptual layout of the accelerator for the NSRP.

The conceptual profiles of the accelerator are; 1) energy and current of the accelerator are 1.5GeV and about 10mA respectively, 2) positive and negative ion beam are simultaneous accelerated with a peak currents of 30 mA,

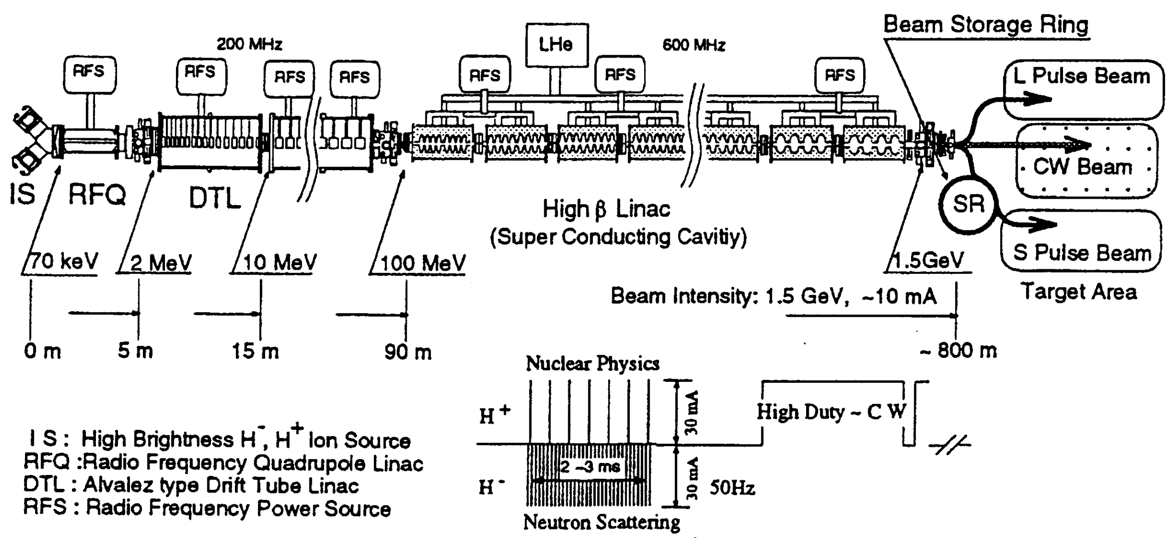

Fig. 1 A Condeptual layout of the Accelerator for the JAERI NSRP

3) main option of the high energy accelerating structure above 100MeV region is a superconducting cavity system, 4) a beam storage ring is used to make an intense short pulse neutron and 5) the development for CW proton accelerator is kept in mind to apply a driver of future transmutation system. Preliminary parameters for the NSRP accelerator are given in Table 1.

Table 1 A preliminary specification for the JAERI NSRP accelerator

Energy	1.5 GeV
Accelerated particle	Negative and positive hydrogen ion
Average current	1st stage: 1 mA 2nd stage: 10 mA maximum
Peak current	Nominal 30 mA
Low energy part	Normalconducting linac / 200 MHz
High energy part	Superconducting linac / 600 MHz
Beam operation mode	1st stage: Pulse mode operation 2nd stage: CW / Pulse mode operation
Repetition rate	50Hz maximum
Macro-pulse width	2 ms (at 1mA operation) to CW maximum
Intermediate pulse width	400 ns (interval 270 ns)
Chopping factor	60 %

The development of the technologies for the nuclear waste transmutation system is one of the major subjects of the NSRP. In the scale of the NSRP, the R&D experiment for a P&T target system, cross section measurement of minor actinide (MA) nucleus and basic reactor physics experiments with MA fuel subcritical reactor will be made by using the high intensity proton accelerator.

General Aspects of the R&D

The low energy accelerator components have been developed since 1991 for the R&D to study the front end of the accelerator. An ion source, an RFQ, and an RF source for 10 % duty factor operation were fabricated and 2MeV beam tests have been performed[2]. The characteristics of the RFQ such as beam current, energy spectra and emittance have been studied. The layout of the RFQ beam test is illustrated in Fig 2. To demonstrate the RF characteristics and the cooling capability at the high duty factor operation, a DTL hot test model with 9 cells was fabricated and high power tests were carried out.

The present activity of the second phase R&D attempts a high current negative hydrogen ion source development, high duty factor (up to CW mode) component development in the low energy portion (for RFQ and DTL), superconducting accelerating cavity development and evaluation of high current proton beam dynamics for the conceptual accelerator design.

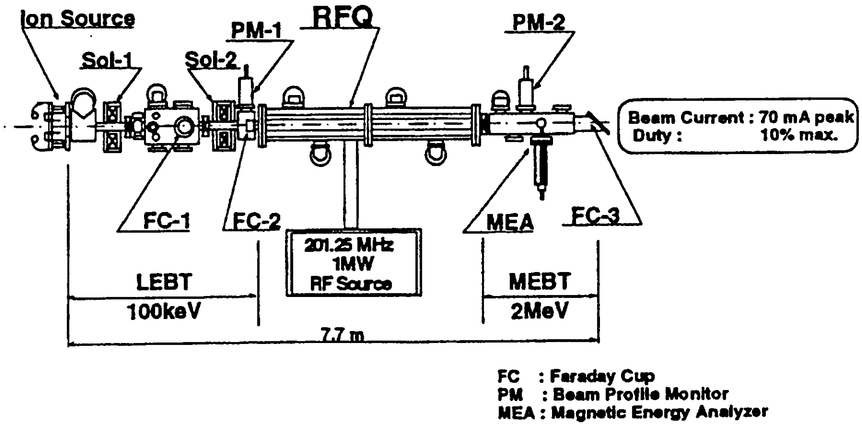

Fig. 2 A Schematic Layout of 2 MeV RFQ Beam Test Line

Ion Source

A multicusp type hydrogen ion source with two-stage extractor has been developed to obtain a high brightness proton beam. The ion source has been operated successfully with more than the designed current of 140 mA at 100 keV[3]. Normally, the ion source is operated by pulsed mode with a duty factor of 10 % to inject into the R&D 2MeV RFQ. Fundamental capability of the ion source allows an operation with a CW mode. This work was carried out in collaboration with the JT-60 NBI group of JAERI. A typical beam extraction characteristic of the ion source is shown in Fig. 3

To inject the beam into a beam storage ring at a beam energy of 1.5 GeV for applications of the basic researches, a high brightness negative hydrogen ion source is required. The development of the negative ion source has been started[4]. The structure of the negative ion source is based upon the multicusp type hydrogen ion source and the first beam test of the negative ion source coupled with the R&D RFQ is scheduled at the beginning of 1997.

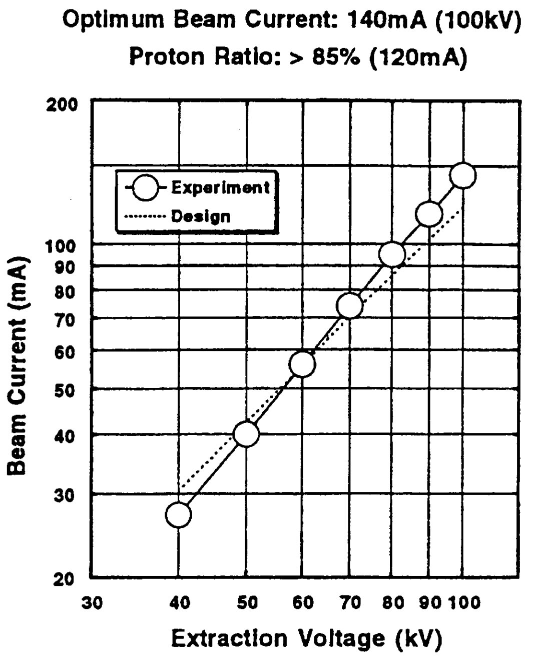

Fig. 3 A Proton Beam Extraction Characteristics of the Multi-cusp Ion Source

RFQ

The R&D RFQ is a four-vane type and its frequency is 201.25 MHz. It is designed to accelerate 100 mA (peak) of protons to 2 MeV with a duty factor of 10 %. After the low power tuning and the high power conditioning, the beam tests have been made at JAERI since November 1994. The maximum RFQ output current was 80 mA at the ion source extraction current of 155 mA. The energy of the proton beam from the RFQ was measured by a compact magnetic energy analyzer installed in the Medium Energy Beam Transport (MEBT). The energy resolution is assumed to be 5 % for 2 MeV proton beam. The RFQ beam emittance has been measured by the conventional double-slit type monitor. Typical value of the normalized rms emittance for the RFQ beam were X-X' = 0.62 πmm-mrad and Y-Y' = 0.76πmm-mrad at 80 cm downstream of the RFQ.

At the beginning of the beam test in JAERI, the maximum duty factor was limited to less than 2 % due to the partial burn out of the RF contact at the RFQ. A silver plated spiral type RF contact, which is made of beryllium copper alloy, was used between the tank and the vane. The diameter of the contact was 3.2 mm and the thicknesses of the base beryllium copper alloy and the silver plate were 100μm and 30 μm, respectively. To improve the heat transfer properties, the RF contact was replaced by a 100μm thickness silver-plated type. In addition to the contact replacement, copper blocks were installed to cover the open space between the vane and the tank to reduce the heat dissipation at the vane end region. As a result of these modifications, steady operations with 7 % duty factor, and short-duration operation at 10 % duty factor can be achieved at the beam current of 70 mA.

A high power test model of CW-RFQ of 50cm in length is fabricated and tested in 1996 to demonstrate the manufacturing technique and the RF characteristics.

RF Power Source System

A 201.25 MHz RF system was designed and manufactured for the RFQ beam tests and the DTL high power tests. A tetrode, 4CM2500KG (EIMAC), is used in a final-stage amplifier[5]. Dummy load tests were completed resulting in a peak RF power output of 1 MW was achieved at a duty factor of 0.6 % and high duty operation of 12 % with an RF power of 830 kW was generated, which satisfied the requirement for the tests in the R&D. The power efficiency was 60 %, which is in good agreement with the designed value of 62 %.

The voltage and the phase stability during the beam acceleration should be controlled within ± 0.5 % and ±1 degree, respectively. To satisfy these specifications, the RF control system has a feedforward-circuit combined with a feedback-circuit. The performance of the feedback-circuit was examined in the RFQ beam tests. The amplitude and the phase errors were on the order of 0.5 % and 5 degree, respectively, during 100μs period after the beam injection when the beam loading was 110 kW.

DTL

A high power test model of DTL with 9 cells, which is a mock-up of the low energy portion of the DTL, has been fabricated to study the RF characteristics and the cooling requirements. A DC excited electromagnetic quadrupole using a hollow conductor (5 mm x 5 mm) was developed successfully for the focusing magnet, of which field gradient is 80 T/m with 5.5 turns at 780 amperes. The high power tests were carried out with the RF power source[6]. Fig. 4 shows the schematic layout of the test. At first, the duty factor had been limited to less than several percent due to the RF contact problem at the end plate. After an improvement of the RF contact structure, RF power of 128 kW with a duty factor of 20 % was fed to the model without any troubles, this power corresponds to the average axial field of 2 MeV/m. The gap voltage was estimated to be 195 kV at an RF power of 128 kW by a spectrum measurement of Bremsstrahlung X-ray from the model, which was in good agreement with the calculated value of 197 kV by the SUPERFISH code. The measured RF power dissipation in the each drift tube and the end plates was in good agreement with the calculation. The calculations were performed with the combination of the thermal defomation from the ABAQUS FEM code and the frequency shift from the SUPERFISH code. These high power test results have confirmed the heat dissipation calculation and the cooling design of the DTL.

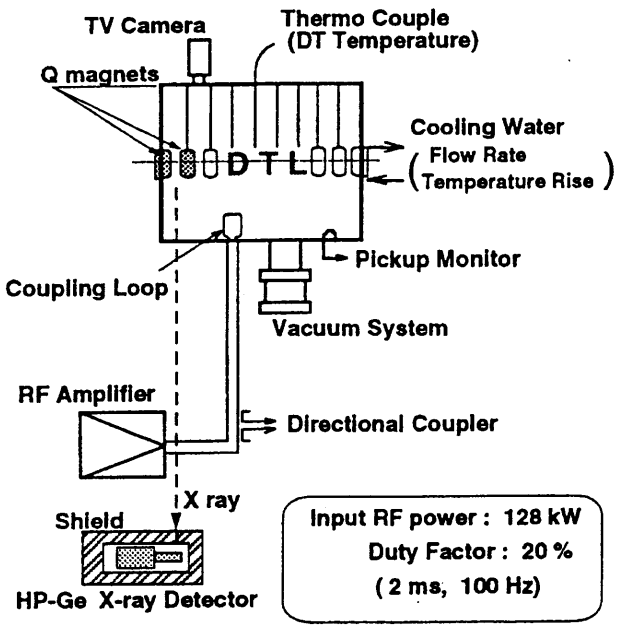

Fig. 4 Schematic Layout of the DTL High Power Test

To extend the capability of CW operation based upon the previous DTL design parameters, a cold model of CW-DTL will be fabricated in 1996 to examine RF characteristics. Accelerating gradient of the CW-DTL may be lowered to be 1.5 MeV/m in order to reduce the RF consumption and the RF heating. The end point energy for the DTL is 100 MeV which will be determined from the beam dynamics and mechanical consideration of the high energy structure.

Superconducting Cavity

Superconducting (SC) cavity is a main option for high energy portion of the accelerator. Resulting with basic studies for the structure of high energy part of the accelerator, several favorable characteristics were pointed out with SC option in comparison with normal conducting cavity option. There are a high electrical field gradient for beam acceleration of 10 to 25 MeV/m, high quality factor of ~10^9 and acceptable wide beam tube aperture of 100 to 180 mm.

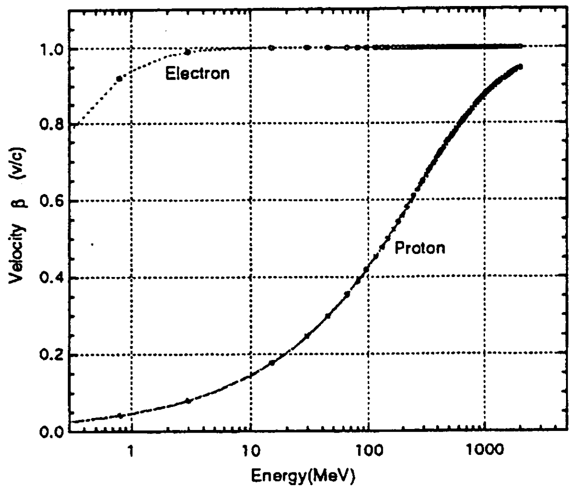

Fig. 5 Accelerating Particle Velocity

In the CW electron accelerator, technologies of SC accelerators are established. The experiences of design, manufacturing and operation for the electron SC accelerator are accumulated for years such as KEK-TRISTAN and other many laboratories[7], [8]. The high energy part of these electron SC accelerator operates single velocity of light speed. This condition leads uniform cavity shape and uniform cryomodule design for all accelerating cavity structure. In the proton accelerator, however, velocity varies sequentially from 100MeV to 1.5GeV. Fig. 5 illustrates the velocity changes in accelerating electron and proton. Accordingly, the length of the cavity also changes. Main concern is the mechanical strength of the cavity under the vacuum load for the energy range of 100 to 200MeV because of the more flatter shape than electron accelerator's one.

The R&D work for SC accelerator has been started since 1995 in collaboration with KEK SC group[9]. The mechanical structure calculations with the ABAQUS code have been done to determine the cavity shape parameters as well as electromagnetic ones with the SUPERFISH code. The schematic drawing of the JAERI SC accelerator cryomodule is shown in Fig. 6. Niobium superconducting test cavity for the 150MeV region will be fabricated and

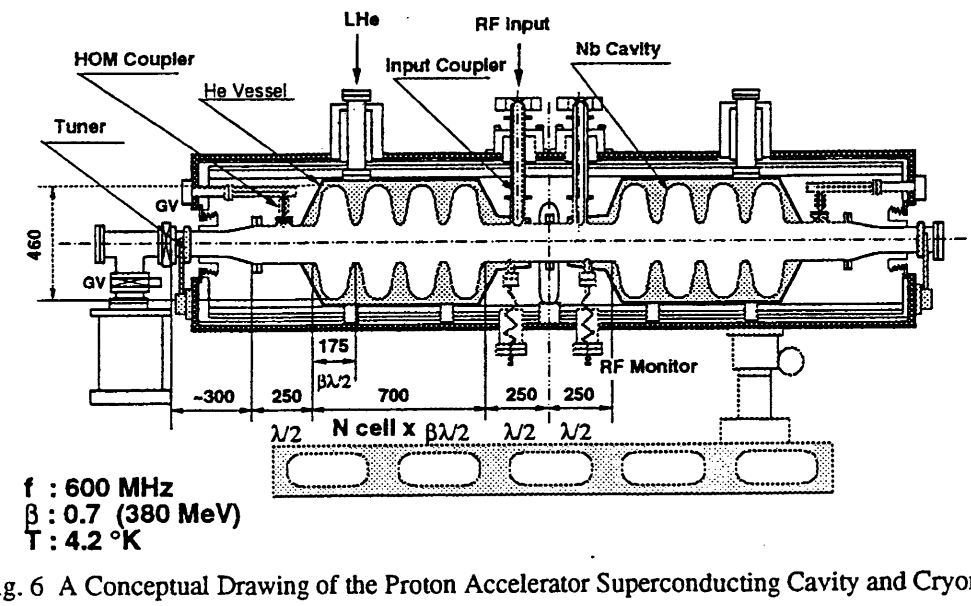

Fig. 6 A Conceptual Drawing of the Proton Accelerator Superconducting Cavity and Cryomodule

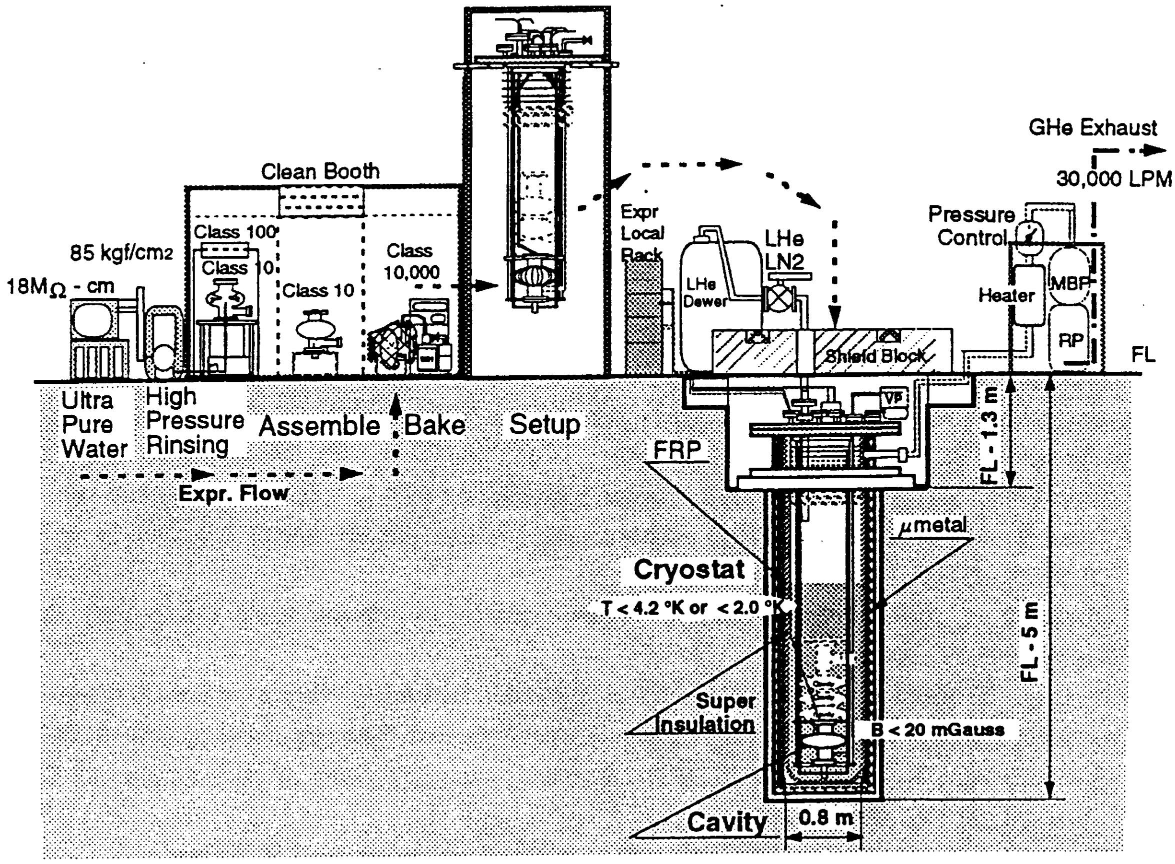

Fig. 7 An Image view of a Superconducting Cavity Vertical Test

examined in 1996 according to the preliminary design. A test stand for the vertical tests of 600MHz cavities has been installed at JAERI with a cryostat of 80 cm in diameter and 350 cm in depth.

The temperature of the vertical test for SC cavity experiments can be adjusted at 2 °K or 4 °K by evacuating the liquid helium vessel. A clean room of class 10 to prepare the clean surface of a test SC cavity with an ultra pure water of 18 MΩ-cm generating system, a high pressure of 8.5 MPa water rinsing system and an oil-free ultra high vacuum of 10^{-9} Pa pumping system was installed. An image view of the SC cavity preparation work and the vertical test set-up are shown in Fig. 7.

Summary

The first phase R&D with the design and the fabrication of the prototype accelerator structures (ion source, RFQ, RF source and DTL) have been carried out. The good performance of the components has been confirmed. In the RFQ beam tests, acceleration current of 70 mA with a duty factor of 7 to 10 % has been achieved.

Since 1995, the basic specification for the accelerator has been changed to match the NSRP in JAERI such as negative and positive ion simultaneous acceleration, variable beam intensity, SC cavity option and storage ring. The second phase R&D work has been started. For the injector of the SC cavities, much longer duty factor or CW beam operation will be required. Design work on the RFQ and DTL for the CW operation is being performed. Negative hydrogen ion source beam acceleration test coupled with 2MeV RFQ beam line is planned in 1997. SC cavity development has been started to establish mechanical property and electromagnetic performance for energy range of 100 MeV to 1.5 GeV with a frequency of 600MHz.

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