The R&D Works on the High Intensity Proton Accelerator for Nuclear Waste Transmutation

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The R&D works of the 10MeV/10mA proton linear accelerator have been carried out for last four years. A high brightness hydrogen ion source, an RFQ and an RF power source have been developed and examined to achieve 2MeV proton beam. A DTL hot test model was also fabricated and a high power test has been carried out. The present status of the R&D works are described in this paper.

1. Introduction

A high intensity proton linear accelerator (ETA: the Engineering Test Accelerator) with an energy of 1.5 GeV and an average current of 10 mA has been proposed for the engineering test of the accelerator-driven nuclear waste transmutation system[1]. To achieve low emittance beam in the low energy portion, the Basic Technology Accelerator (BTA) with an energy of 10 MeV and an average current of 10 mA is planned to be built. Table 1 shows the fundamental specifications of the BTA.

Main accelerator components of a high brightness hydrogen ion source, a radio-frequency quadrupole (RFQ), a drift tube linac (DTL) and an RF power source have been developed as the R&D works for the BTA. The ion source, the RFQ, and the RF power source were fabricated successfully and 2 MeV beam tests have been performed with construction of a beam line. For the DTL development, the hot test model was fabricated and a high power test has been made by feeding RF power. This paper describes the present status of the R&D works.

2. Ion Source Development

Based on the design of the BTA, an ion source is needed to produce hydrogen beam of 100 keV with high current (120mA) and low emittance (0.5 πmm·mrad normalized 100%)[2]. The multicusp type ion source with two-stage beam extractor has been developed to obtain a high brightness beam.

Table 1 Fundamental Specifications of the BTA

Output energy	10 MeV
Ion source	100 keV
RFQ	2 MeV
DTL	10 MeV
Operation mode	pulse
Duty Factor	10 %
Average beam current	10 mA
Peak beam current	100 mA

Beam tests of the ion source have been carried out to confirm the performance[3]. The optimum beam currents providing minimum beam divergence were measured as a function of the extraction voltage; the results are shown in Fig. 1. As shown in the figure, beam current of 140 mA has been achieved at 100 kV, which exceeds the designed value of 120 mA. The normalized emittance was measured using a double slit emittance scanner and estimated to be about 0.5 πmm·mrad (90%). The proton ratio has been also measured to be 85 % at the current of 120 mA by the Doppler-shifted spectroscopy method. The impurities level has been also confirmed to be negligibly small (<1%). The details of the performance tests are presented in Ref.3.

After the performance tests, the ion source was connected with the RFQ through LEBT to carry out the RFQ beam test and has operated stably as an injector. More precise emittance measurements are scheduled to study the beam match for the RFQ.

3. RF Source Development

For the BTA, three sets of 201.25 MHz RF sources are required with output power of about 1 MW; one set with 640 kW (duty 12%) output for the RFQ and two sets with 760 kW (duty 20%) output for the DTL. Each RF power source consists of three-stage amplifier[4], i.e., 1 MW final stage amplifier with the tetrode tube 4CM2500KG (EIMAC), 60 kW intermediate amplifier with the tetrode tube RS2058CJ (SIEMENS) and 3 kW solid state amplifier.

In the R&D works, one set of the RF source has been

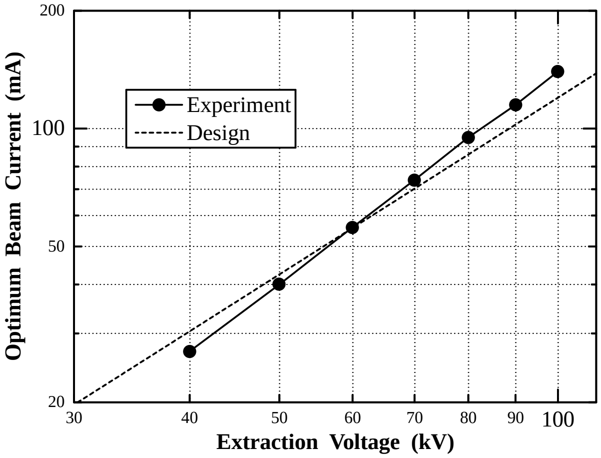

Fig. 1 Measured and designed optimum beam current from the ion source

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developed to provide RF power to the RFQ or the DTL hot test model. The high power test has been made successfully using a dummy load. RF power output of 1 MW was achieved at the duty factor of 0.6%, whereas the measured gain of the final stage amplifier is lower than the designed value. The power efficiency was measured to be 60 % which is in good agreement with the designed value of 62 %. At the high duty operation of 12 %, RF power of 830 kW was generated, which satisfies the requirements of the R&D studies for the RFQ and the DTL hot test model.

The low level controller of the RF system includes feedback circuits to compensate power loss and phase shift due to the beam loading. The performance of the feedback system was examined in the RFQ beam test. The amplitude change was remarkably small to be within 0.5 % even when the beam loading was 110 kW. On the other hand, the phase error was relatively large to be >5ß. The feedforward control system, which is also included in the RF system, will be examined to decrease the phase error.

The details of the design and the test are given in Ref. 4.

4. RFQ Development

A prototype RFQ has been developed in the R&D works of the BTA. Parameters of the RFQ are presented in table 2. The low-power tuning, the high-power conditioning and the first beam test were carried out successfully[5] at the test shop of Sumitomo Heavy Industries, Ltd. and the basic performance of the RFQ was obtained. To study further beam properties, the beam test has been made at Tokai site, JAERI since November, 1994.

The layout of the RFQ beam test is illustrated in Fig. 2. The hydrogen beam extracted from the ion source was focused by the two solenoids in the low energy beam transport (LEBT) to match the input beam emittance to the RFQ acceptance. Currents of the input and the output beam were measured by the Faraday cups of FC2 and FC3, respectively, and the RFQ transmission was deduced. The energy of the proton beam from the RFQ was measured by the compact magnetic energy analyzer (MEA) installed in the medium energy beam transport (MEBT) and was confirmed to be 2 MeV.

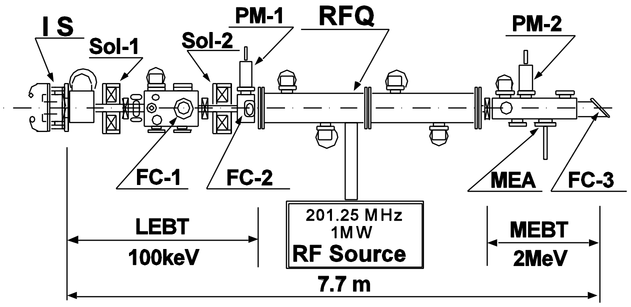

Fig. 2 Layout of the RFQ beam test
FC : Faraday cup
PM : Beam profile monitor
MEA : Magnetic energy analyzer

Figure 3 shows the RFQ output beam current as a function of the ion source extraction current, which includes H_2^+ and H_3^+ as well as H^+. In this beam test, the maximum RFQ output current is 70 mA at the ion source current of 155 mA as shown in Fig. 3. The ordinary RFQ operation with the current of 50 ~ 60 mA has been made at the ion source current of 125 ~ 135 mA to avoid over heat-loading of the ion source electrodes . The beam transmission of the RFQ has been estimated to be around 60%, although it is difficult to make the precise measurement because the net proton ratio of the beam coming into the RFQ is not clear due to the mass separation effects of the solenoids. The maximum duty factor of 5 % was achieved at the first beam test; it is limited by the over heat-loading of the RF contact between the tank and the vane. The improvement of the contact is required to achieve 10 % duty factor and the study is in progress.

Table 2 Parameters of the RFQ

Ion	Proton
Frequency	201.25 MHz
Input/Output energy	100 keV / 2.0 MeV
Beam current	100 mA (peak)
Duty factor	10 %
Number of cells	181
Vane length	334.8 cm
Cavity diameter	36.6 cm
Mean bore radius (r_0)	0.613 cm
Vane voltage	113 kV (1.68 Kilpatrick)
Q-value	9400 (71%Q)
Wall loss	360 kW (71%Q)

5. DTL Development

In the R&D works, a hot test model of the DTL with 9 cells, which is a mockup of the low energy portion of the BTA-DTL, has been fabricated to develop a hollow conductor type quadrupole magnet and to study the RF characteristics and the cooling capabilities[6]. Two electromagnetic quadrupoles have been fabricated successfully and installed in the hot test model. The cold test was made to investigate the RF characteristics.

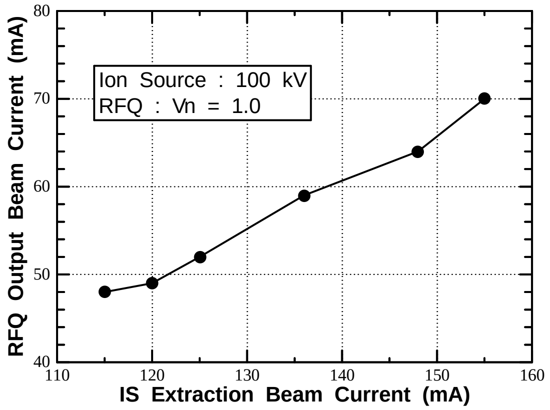

Fig. 3 Beam current accelerated by the RFQ as a function of the ion source extraction current. The ion source current includes H_2^+ and H_3^+ as well as H^+.

Parameters of the hot test model are listed in table 3.

The high power test was carried out with the RF power source. Prior to the cooling capability test, high power conditioning was made with monitoring RF signals from the pickup loop and the directional coupler, temperatures of the cooling water and the vacuum pressure. In the conditioning, the input RF power of 154 kW with duty factor of 12 % was fed to the hot test model, which exceeds the prescribed power of 130 kW as presented in table 3. Spectrum of the bremsstrahlung X-ray from the gap was also measured to estimate gap voltage. The gap voltage was measured to be 195 kV at the prescribed RF power of 130 kW, which was in good agreement with the calculated value of 197 kV by the SUPERFISH code.

As an example of the results of the cooling capability test, Fig.4 shows the power dissipation of the DTL hot test model. In the figure, histograms represent the calculated values by the SUPERFISH code and circles represent experimental results which were obtained from the calorimetric measurement (the temperature rise and flow rate of the cooling water flowing each path). The experimental results are in good agreement with the calculated values. Most of the Q-magnet heating around 7 kW was confirmed to be removed by the cooling water flowing in the hollow conductor, which satisfied our cooling design.

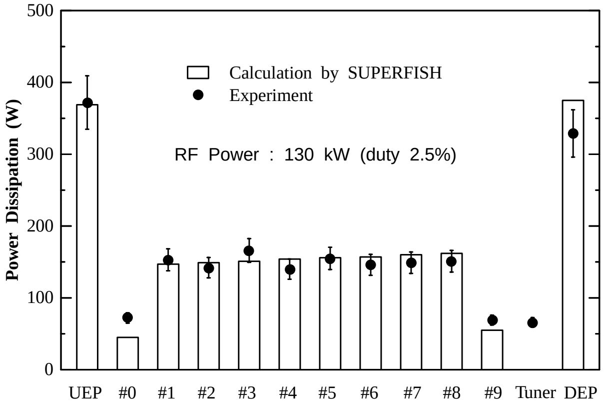

Fig. 4 Comparison of the RF power dissipation between the experimental results and the calculated values by the SUPERFISH code on the high power test of the DTL hot test model.

#0~9 : drift tube and stem
UEP : upstream end plate
DEP : downstream end plate

6. Summary

The R&D works with the design and the fabrication of the prototype accelerator components, i.e., the ion source, the RF source, the RFQ and the DTL, have been carried out. The good performance of the components has been confirmed, while some problems are remaining. For the RFQ, it is necessary to increase the duty factor and the transmission. To increase the duty factor, the improvement of the RF contact between the tank and the vane is being studied. For the increase of the transmission, the emittance measurements are being prepared to match the injected beam emittance to the RFQ acceptance. At the same time, the emittance of the RFQ output beam will be measured for the design of the BTA. For the DTL, the operation with the higher RF duty factor of 15~20% is required for the BTA and the high power test is being carried out with the higher duty factor. For the ion source, an examination of the negative hydrogen ion beam extraction is planed. These further R&D works will be performed in FY-1995 and the detailed design of the BTA has already started partly based on the results of the R&D works.

Table 3 Parameters of the DTL hot test model

Cavity	Frequency	:	201.25 MHz
	RF duty factor	:	12 %
	Average field strength	:	2 MV/m
	Number of cells	:	9
	Tank diameter	:	893 mm
	Tank length	:	1005.5 mm
	Q-value	:	42000 (83%Q)
	Wall loss (83%Q)	:	130 kW
Q magnet	Hollow conductor	:	5 ~ 5 mm^2
	Field gradient	:	80 T/m
	Excitation current	:	780 A (DC)
	Number of turn	:	5.5 Turns
	Pole & yoke	:	Fe-Co Alloy

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