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D.1.3. HIGH INTENSITY PROTON LINEAR ACCELERATOR DEVELOPMENT FOR NUCLEAR WASTE TRANSMUTATION

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D.1.3.1. INTRODUCTION

Design studies of accelerator-driven nuclear waste transmutation system have been carried out for the OMEGA project (Options Making Extra Gains of Actinides and Fission Products). The high-intensity proton linear accelerator (ETA: Engineering Test Accelerator) with an energy of 1.5 GeV and an average current of 10 mA has been proposed for various engineering tests for the transmutation system by JAERI. Nuclear spallation reactions with high energy proton beams will produce various intense beams that can also be utilized for other nuclear engineering applications. These include material science, radio isotope production, nuclear data measurements and other basic sciences with the proton, neutron and other secondary beams in addition to nuclear waste transmutation.

In the course of the accelerator development, the R&D work for the low energy portion of the accelerator (BTA: Basic Technology Accelerator), with an energy of 10 MeV and a current of 10 mA, has been made, because the maximum beam current and quality are mainly determined by this low energy portion. R&D for the main accelerator components such as the high current hydrogen ion source, radio-frequency quadrupole (RFQ), drift tune linac (DTL) and RF power source is in progress.

The conceptual and optimization studies for the high energy accelerator ETA have been performed simultaneously with regard to proper choice of operating frequency, high b structure, mechanical engineering considerations and RF source aspects in order to ensure low beam loss, hands-on maintenance and low construction cost.

D.1.3.2. ACCELERATOR DEVELOPMENT

The conceptual layout of the ETA is shown in Fig. 1. In the case of a high intensity accelerator, it is particularly important to maintain good beam quality (low emittance; small beam size and divergence) and minimize beam losses to avoid damage and activation of the accelerator structures. Because the beam quality and maximum current are mainly determined by the low energy portion of the accelerator, the accelerator (BTA) will be built as a first step in the ETA development [1]. The layout of BTA is shown in Fig. 2.

The basic specification of BTA is given in Table I. The beam dynamics design calculations for the BTA, which will consist of the ion source, RFQ and DTL including the beam transport system, have been made with the computer codes PARMTEQ and PARMILA [2]. Because of the high beam current and high duty factor, the problem of heat removal from the accelerator structure is also an important issue for the mechanical design. The electromagnetic field distribution, temperature distribution and thermal stresses are carefully studied with the three dimensional modelling codes, MAFIA and ABAQUS. The beam energy for the BTA is chosen to be 10 MeV in order to avoid proton induced reactions in accelerator structural materials where the Coulomb barriers are barely exceeded. The acceleration frequency of 201.25 MHz is selected both for RFQ and DTL mainly due to the large bore radius, manageable heat removal problem and the availability of an RF source

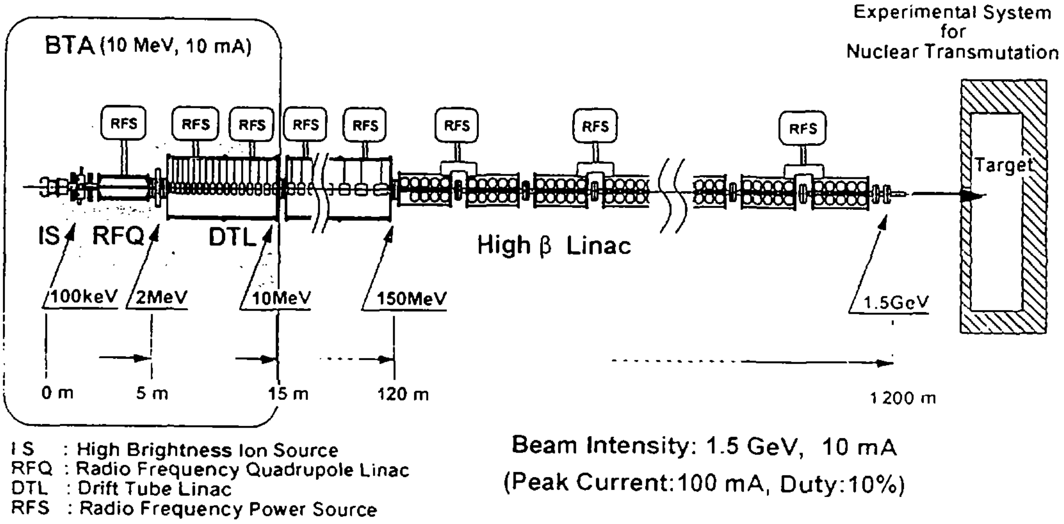


FIG. 1. A conceptual layout of the ETA

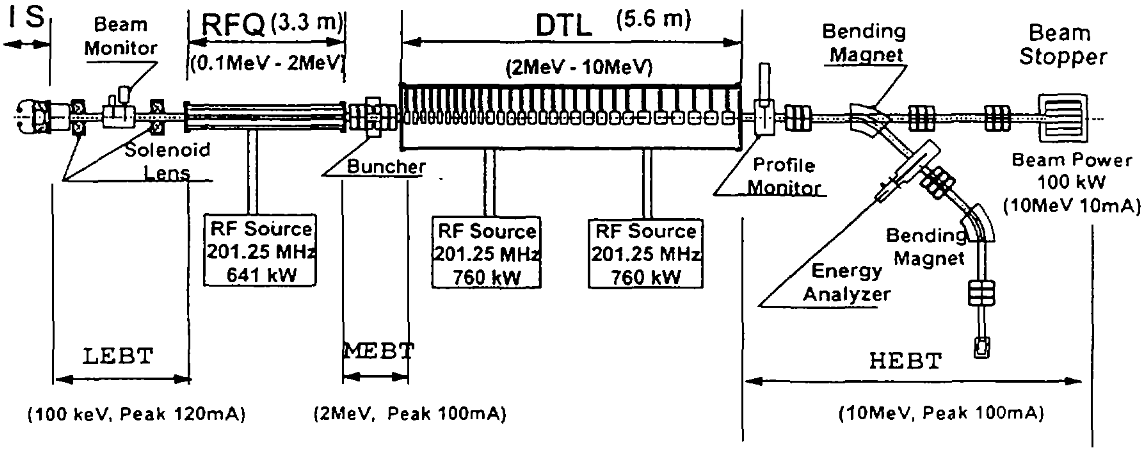


FIG. 2. A layout of the BTA.

D.1.3.2.1. Ion source

Figure 3 shows a prototype ion source which was constructed based on the experience from the NBI (Neutral Beam Injectors) for Fusion Research [3]. The ion source consists of a multicusp plasma type generator with four tungsten filaments and a two stage extractor. The dimension of the plasma chamber is 20 cm in diameter and

TABLE I. A BASIC SPECIFICATION OF BTA

Output energy	10 MeV
Operation mode	pulse
Duty factor	10 %
Average beam current	10 mA
Peak beam current	100 mA

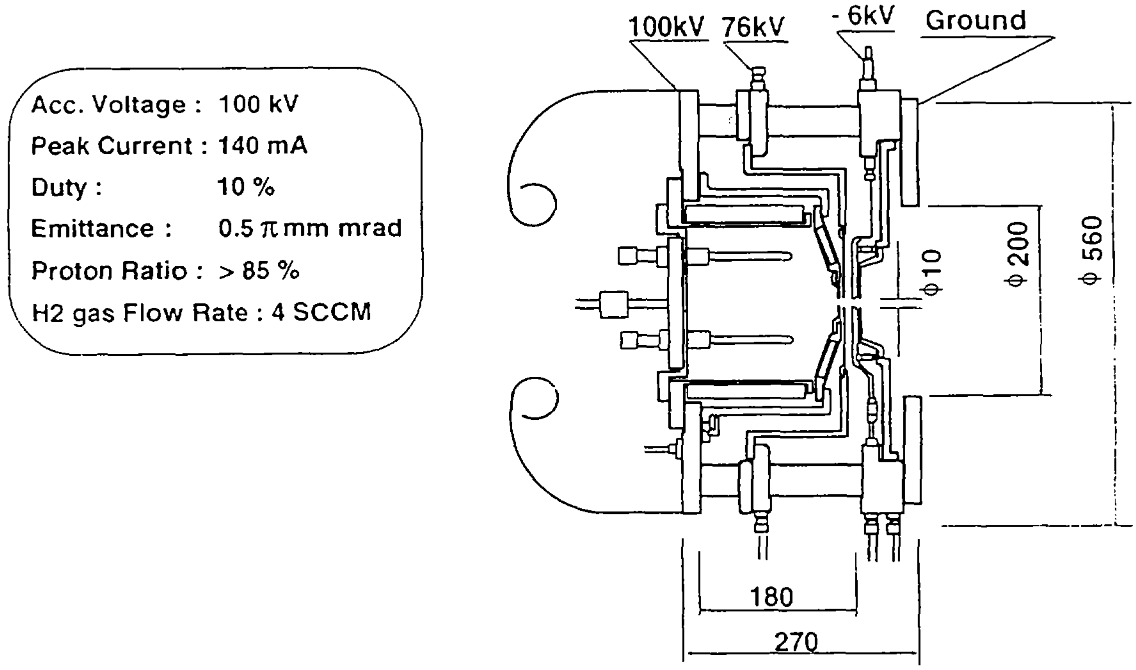


FIG. 3. A prototype of a high brightness ion source.

17cm in length. The chamber is surrounded by 10 columns of SmCo magnets with a field strength of about 0.2 T at the inner surface. The other basic specifications for the source are given in Table II.

The high brightness hydrogen ion beam of 140 mA was extracted using the 100 kV high voltage power supply. The beam profile was measured with a multi-channel calorimeter and the observed normalized emittance was about 0.45 pmm.mrad (90%). The proton ratio and impurity were found to be 80% and less than 1%, respectively, using a Doppler shifted spectroscopy method.

TABLE II. ION SOURCE

Energy	100 keV
Current	120 mA
Duty factor	CW
Emittance	0.5 pmm.mrad (normalized 100%)
Proton ratio	> 90%
Impurity	< 1%

D.1.3.2.2. RF source

Three sets of 201.25 MHz RF sources with about 1 MW peak amplifiers are needed for BTA (641 kW for RFQ and two 760 kW for DTL). The tetrode tube 4CM2500KG (EIMAC), which was originally developed for fusion plasma heating, is used with a multistage amplifier configuration [4]. The block diagram of the RF source is shown in Fig. 4. The RF source was designed and one set of amplifiers was manufactured. The high power amplifier (HPA) is driven by a 60 kW intermediate amplifier (IPA of RS2058CJ) which is fed by a master oscillator and a 3 kW solid state drive amplifier. The accelerator voltage and phase control loop with an accuracy of < 0.1% in amplitude and < 1 in phase were constructed. The high power test was successfully made with a peak power of 1 MW at 0.6% duty and 830 kW at 12%

duty obtained using a dummy load.

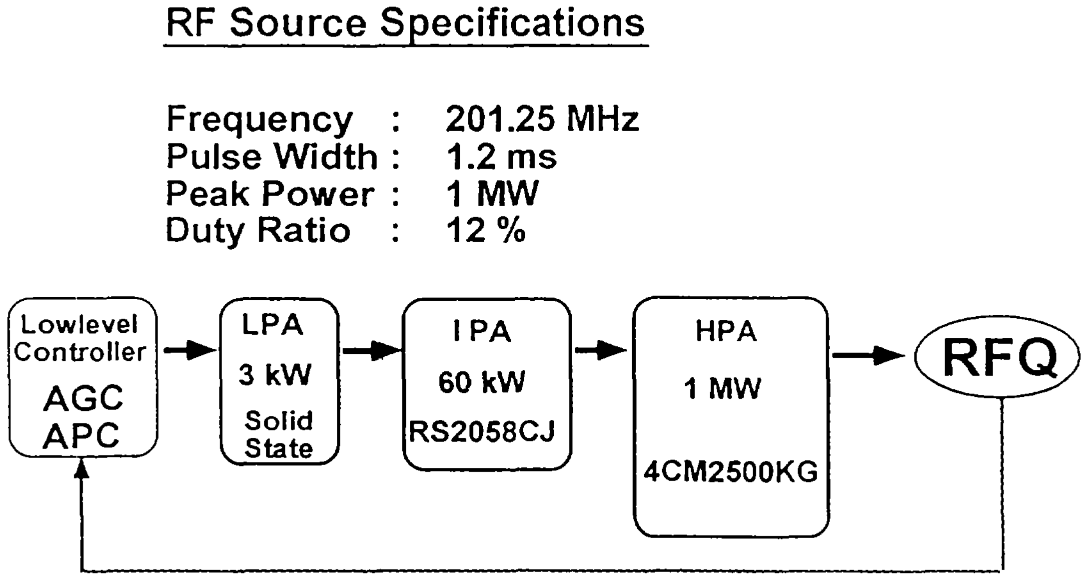
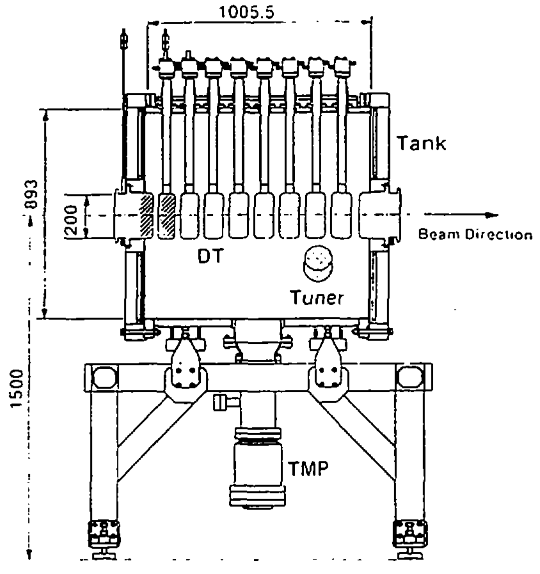


FIG. 4. A block diagram of the RF source.

D.1.3.2.3. DTL high power test

Design studies were made under various mechanical constraints for DTL such as the resonant frequency, magnetic field strength and the problem of heat removal. The DTL parameters are given in Table III. A hollow conductor type coil with 5*5 mm^2 was chosen for the electric quadrupole magnet. The configuration of this quadrupole magnet was optimized with conditions on the coolant water (temperature rise 25 K in the coil, pressure drop 50 N/cm^2 and velocity 3.4 m/s). The hot test model with 9 cells was fabricated with 8 drift tubes inside the DTL tank and 2 drift tubes in the end plates. The first drift tube and the one at the front end plate were installed with actual quadrupole magnets. The cross cut view of the DTL hot test model is shown in Fig. 5 [5].

The drift tube alignment was made with a laser telescope and an accurate longitudinal scale. Alignment errors in the transverse plane and the longitudinal direction were within 0.1 and 0.08 mm, respectively. The cold test was performed to examine the RF characteristics such as resonance frequency, Q value and electric field distribution on the beam axis. The resonant frequency of the TM01 mode was measured to be 201.178 MHZ when the tuner displacement was 100 mm. The measured frequency shifts were in good agreement with those predicted by calculation. The resonant frequency could be shifted with the tuner by about 200 kHz, which is enough to compensate the frequency change due to RF heating. The measured Q value was 42000 (83% of the SUPERFISH calculation). This result indicates that an RF power of 130 kW is required to obtain an average strength of 2 MV/m. The electric field distribution on the beam axis was measured by the bead perturbation method with an aluminum spherical bead of 7 mm in diameter. The average field strength over the whole region was deduced to be 2.03 MV/m which is in good agreement with the designed value of 2 MV/m. Deviation of the average field in each cell was within 2.3%. A high power test was carried out to examine the cooling capability. Various quantities were monitored during the high power conditioning; RF signals from a pickup loop and a directional coupler, temperature of the cooling water, total vacuum pressure using an ionization gauge, partial pressure using quadrupole mass spectrometer and bremsstrahlung X-ray spectrum. During the conditioning, an input RF power up to 154 kW with a duty factor of 12% was achieved in the DTL model, which exceeded the prescribed nominal power level of 130 kW. The relation between the input power from the RF monitor and the gap voltage from the X-ray spectrum agrees well with the calculation using the SUPERFISH code.



Item	BTA	R&D
Number of cells	36	9
Length of DTL tank	5649 mm	1005.5 mm
Number of DT	37	10
Number of Q mag	37	2

FIG. 5. A cross cut view of DTL hot test model.

TABLE III. DTL PARAMETERS

Frequency	201.25 MHz
Energy	2 - 10 MeV
Beam current	100 mA
Average field	2.0 MV/m
Tank diameter	89.3 cm
Tank length	564.9 cm
Cell length	9.86 - 21.55 cm
g/L	0.234 - 0.293
DT outer diameter	20 cm
DT inner diameter	2 cm
Synchronous phase	-30
DT cell number	36
Focus magnetic field	80 - 35 T/m
Q	69800
Wall loss	720 kW
Beam power	800 kW

A high power test was carried out to examine the cooling capability. Various quantities were monitored during the high power conditioning; RF signals from a pickup loop and a directional coupler, temperature of the cooling water, total vacuum pressure using an ionization gauge, partial pressure using quadrupole mass spectrometer and bremsstrahlung X-ray spectrum. During the conditioning, an input RF power up to 154 kW with a duty factor of 12% was achieved in the DTL model, which exceeded the prescribed nominal power level of 130 kW. The relation between the input power from the RF monitor and the gap voltage from the X-ray spectrum agrees well with the calculation using the SUPERFISH code.

The cooling capability was examined by feeding an RF power of 130 kW. To obtain the distribution of the power dissipation, the temperature rise and cooling water flow rate through each path were measured using platinum resistance thermometers and a flow meter, respectively. The experimental distribution of the power dissipation among the 9 drift tubes (including 2 in the end plates) is generally in good agreement with the SUPERFISH calculation.

D.1.3.2.4. RFQ beam test

The basic specification of the RFQ is given in Table IV. The first beam test with the ion source and RFQ was carried out at the test shop of Sumitomo Heavy Industries (SHI), Ltd. [6] in February, 1994. After this first beam test had been completed, the whole apparatus was transferred to Tokai, JAERI and reassembled. The beam test was restarted again in November, 1994 and various beam properties are being studied.

The layout of the 2 MeV RFQ beam test is shown in Fig. 6. The 100 keV H^+ beam was extracted by a multi-cusp type ion source to the RFQ. Two focusing solenoids in the low energy beam transport (LEBT) were used to match the ion source beam emittance to the RFQ acceptance. The transmission was deduced from the RFQ input and output currents measured with the two Faraday cups. The RFQ acceleration current as a function of the normalized vane voltage (a normalized vane voltage of unity corresponds to nominal gap voltage of 113 kV) is shown in Fig. 7. The results of the measured beam transmission were lower by 20 - 30% than the design values with PARMTEQ. The various causes of these lower transmissions are being investigated. The beam energy spectra from the RFQ were also measured using a compact magnetic energy analyzer (MEA), with a pole radius and gap length of 40mm and 6mm, respectively. The deflection angle was 25° and the energy resolution was assumed to be 5% for a 2 MeV proton beam. The 100 keV H^+, H^{2+} and H^{3+} beam from the ion source through the RFQ (without RF) was used as an energy calibration source for five vane voltages. The intervane voltage dependence of the proton energy spectra is shown in Fig. 8. As the intervane voltage was reduced, the energy spectrum shifted to lower energies with a prominent discrete energy distribution. This interesting phenomenon was well predicted by PARMTEQ as indicated in the figure.

TABLE IV. RFQ PARAMETERS

Frequency	201.25 MHz
Energy	0.1 - 2 MeV
Beam current	110 mA
Duty Factor	10 %
Synchronous phase	-90- -35
Vane voltage	0.113 MV
Focusing parameter B	7.114
Number of cell	181
Cavity diameter	36.6 cm
Vane length	334.8 cm
Quality factor (Q)	13000 (100% Q)
Wall loss power	432 kW (60% Q)
Beam power	209 kW

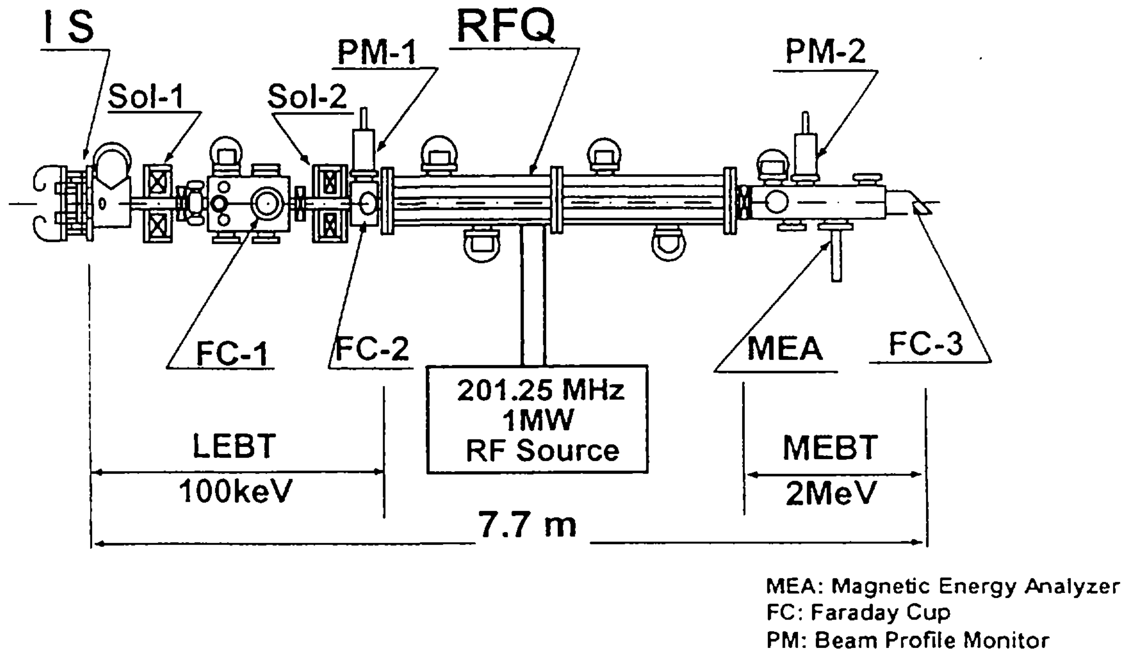


FIG. 6. A layout of the 2 MeV RFQ beam test.

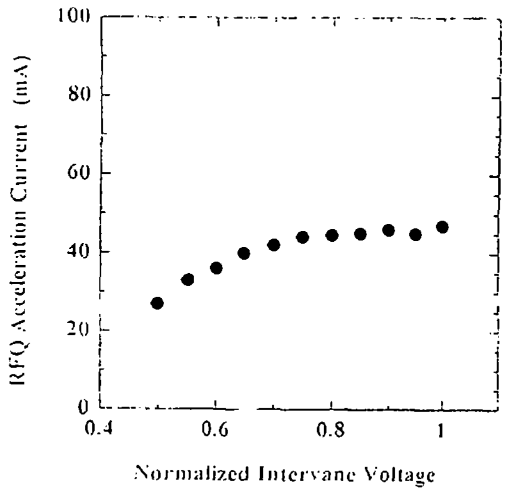


FIG. 7. Intervane voltage dependence of RFQ acceleration current.

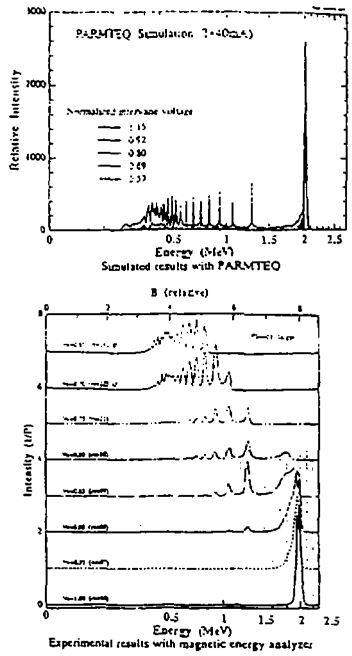


FIG. 8. Intervane voltage dependence of proton energy spectra from the RFQ.

D.1.3.3. SUMMARY

R&D work has been carried out on the design and construction of prototype accelerator structures (Ion source, RFQ, DTL and RF source). The low-power tests were made to study the RF characteristics for the RFQ and DTL accelerating structures and have verified the design prediction. The first 2 MeV beam test with the ion source and RFQ in combination with a single high power RF source unit was successfully carried out with a peak acceleration current of 52 mA (for the duty factor of 5%). For the DTL high power test, measurements of the electromagnetic characteristics were made satisfactorily. Problems of heat dissipation and heat removal in the structure were studied. Table V summarized the major results of the R&D work. The detailed design work for the BTA construction will follow in the next stage based on these R&D results. Further improvement is however still required to increase the average beam current (the goal is 10 mA) by improving the peak current and duty factor. More detailed studies of the beam properties are needed to improve transmission.

TABLE V. THE PRESENT STATUS OF THE PROTON LINAC DEVELOPMENT FOR THE JAERI OMEGA PROGRAM

(1) Ion source: Multi-cusp ion source	
High voltage	100 kV
Accelerating current	140 mA
Emittance	0.5 π mm.mrad (90%)
Proton ratio	> 80 %
(2) Radio frequency quadrupole (RFQ): 4 vane type	
Q	9,420 (71% Q)
Electromagnetic field distribution	
Field balance	< 2.5 %
Field flatness	< 7.1 %
(3) DTL: hollow conductor type DT	
Magnetic field center	< 30 μm
Temperature rise	< 25° C
Heat expansion	< 4 μm
Hot test model (9 cell)	
Q	42,000 (83% Q)
Electromagnetic field distribution	
Field flatness	< 2.3 %
High power test	154 kW (duty 12%)
(4) RF source	
Maximum power	830 kW (duty 12%)
	1 MW (duty 0.6%)
The RFQ beam test	
Methods	
Energy spectrum	Analyzing magnet
Vane voltage	X-ray detection with NaI and Ge detector
Profile	Profile monitor
Beam current & transmission	Faraday cup

	Present status	Goal
Current	52 mA	100 mA
Duty	5 %	10 %
Pulse width	1.0 ms	1.0 ms
Rep. rate	50 Hz	50 Hz

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