High Power Proton Accelerator Development at KAERI and its Vacuum System*

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The Proton Engineering Frontier Project (PEFP), approved and launched by the Korean government in July 2002, includes a 100 MeV proton linear accelerator (linac) development and programs for its utilization and application. The main goals in the first phase of the project, spanning from 2002 to 2005, were the design of a 100 MeV proton linac and the development of a 20 MeV linac consisting of a 50 keV proton injector, a 3 MeV radio frequency quadrupole (RFQ), and a 20 MeV drift tube linac (DTL). The 50 keV injector and 3 MeV RFQ have been installed and tested, and the 20 MeV DTL is being assembled, tuned and under a beam test. At the same time, the utilization programs using the proton beam have been planned, and some are now under way. The vacuum system of the 20 MeV proton linac and its related issues, especially in operation with a high duty, are discussed in detail.

1. Introduction

In the 21st century, science and technology will require detailed understandings of the quantum behaviour of materials on the molecular and atomic scales. Particle beams can provide manipulative and visual tools to probe and fabricate nano-scale materials. High-power proton accelerators (HPPAs) can produce high-intensity beams of protons and also secondary particles, such as neutrons, mesons, neutrinos, and radioisotopes. Such intense beams provide practical and efficient means to realize quantum engineering.

Figure 1 shows various fields of utilizations and potential applications of the proton beams with a wide range of energy, current, and beam power. High-current proton beams with low energy (<10 MeV) are useful in industrial, medical and defence applications, such as ion-cutting, power semiconductors, mine detection, boron neutron capture therapy, and neutron radiography. Low-current proton beams with medium energy (10–250 MeV) are valuable in biological and medical researches, for example, in studies and applications on mutations in plants and micro-organisms, in neutron and proton therapy, and even in radioisotope production. High power proton beams with energies around 1 GeV have many uses in spallation neutron sources, in production of radioisotope beams and in high energy physics experiments and great potential in accelerator-driven systems.

The Proton Engineering Frontier Project (PEFP) was launched by the Korean government in 2002 to realize utilizations and applications of high-intensity proton beams. Its primary goal is to develop a high current proton linear accelerator to supply 100 MeV, 20 mA proton beams. It can be used as a proton provider for various

Fig. 1 Utilization and applications of proton beams.

applications in the low to medium energy range and also a proton driver of a high energy proton machine for the future extension.

In parallel, the design of buildings and conventional facilities for the 100 MeV proton linac is under way with architectural engineering works as shown in **Fig. 2**.

2. Accelerator Development

The accelerator system for the 20 MeV proton beam had been developed in the first phase of the project, which was completed in 2005. It consists of a 50 keV proton injector, a 3 MeV RFQ, and a 20 MeV DTL. In the second phase, it is extended to a 100 MeV accelerator with a DTL or a superconducting linac to supply proton beams with low to medium energies. To supply proton beams with low to medium energies two beam lines will be located at the positions of energies of 20 MeV and 100 MeV. **Fig. 3** shows a schematic drawing of the PEFP

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Fig. 2 Accelerator building and experimental hall.

Fig. 3 Schematic drawing of the PEFP linac and beam lines.

Table 1 Basic parameters of the PEFP accelerator.

Parameter	Value
Particle	Proton
Beam Energy	100 MeV
Operation Mode	Pulsed
Max. Peak Current	20 mA
Repetition Rate	15 Hz (max. 120 Hz)
Pulse Width	< 1 ms (max. 2 ms)
Max. Beam Duty	24%

linac system and beam lines. The basic parameters of the accelerator are listed in Table 1.

2.1 Injector¹⁾

The front part of the PEFP linac consists of a duoplasmatron ion source to produce a high current proton beam (Fig. 4), and a low energy beam transport (LEBT) to separate protons from the hydrogen ions. The LEBT has also other function to focus protons for a good RFQ acceptance. The maximum beam current extracted from the source reaches more than 50 mA at an extraction voltage of 50 kV with a 10 A arc current. The extracted beam has a normalized emittance of $0.2 \pi \text{ mm-mrad}$ from a 90% beam current, where the proton fraction in the beam is up to 80%. To achieve a pulsed operation of 15 Hz, a high-voltage switch is installed in the injector, whose rising and falling time is less than $50 \text{ ns}^{1)}$ as shown in Fig. 5. The LEBT (Fig. 4) consists of two solenoid magnets. The transmission efficiency of protons is about 92% with a variable beam current from 10 to 50 mA. The injector and the LEBT are evacuated with a turbo molecular pump of 2,000 l/s and the normal operating pressure is less than 5×10^{-6} torr, which depends on the operational conditions of the ion source.

Fig. 4 The PEFP proton injector.

Fig. 5 Pulsed proton beam from injector (1 ms, 10 Hz). In the plot, the x-axis is the pulse length in 0.2 ms/division, and y-axis is the pulse beam current in 10 mA/division.

2.2 RFQ^{2,3)}

The PEFP RFQ is designed to accelerate the 20 mA proton beam from 50 keV to 3 MeV. The entire structure consists of 4 sections. It is separated into two segments that are resonantly coupled to make the easy field stabilization. The RF power is fed into the RFQ cavity through two iris couplers in the third section. The main design parameters of the RFQ are summarized in Table 2.

The RFQ has been fabricated and tuned (Fig. 5). High power RF test has been performed with a great progress, and the beam test is under way. The stable input RF power of the RFQ reaches about 400 kW as much as the design value. It corresponds to peak surface electric field

Table 2 PEFP RFQ parameters.

Parameters	Values
Frequency	350 MHz
Input/Output Current	21 mA/20 mA
Input/Output Energy	50 keV/3 MeV
Peak Surface Electric Field	1.8 Kilpatrick
Power	465 kW
	Cu = 400 kW, Beam = 65 kW
Transmission Rate	98.3%
Length	329 cm

Fig. 6 The PEFP RFQ and test stand.

of 1.8 Kilpatrick.

2.3 DTL⁴⁻⁶⁾

The 20 MeV DTL consists of 4 tanks that accelerate the 20 mA proton beam from 3 MeV to 20 MeV. The total length of the DTL is about 20 m. A 1 MW klystron supplies the RF power into the four tanks. The quadrupole magnet in each drift tube of the FFDD lattice configuration has the magnetic field gradient of 5 kG/cm and effective field length of 3.5 cm. The DTL parameters are given in **Table 3** and its layout are shown in **Fig. 7**. The drift tube installation with a high precision of $\pm 50 \mu\text{m}$ in the 20 m length and field tuning of 4 tanks were completed (**Fig. 8**). The 20 MeV DTL RF system with a 1 MW klystron has been installed and tested up to the power of 800 kW.

The tuning goals for the DTL have been achieved for two key parameters, the frequency deviation less than ± 5 kHz from the design value and the field fluctuation less than $\pm 2\%$ throughout the tank with the tilt sensitivity against the perturbation less than 100%/MHz. The results of the high power RF test of each cavity reaches successfully to the required peak power of 150 kW per tank after several hour conditioning. **Fig. 10** shows the test results of the 4 tanks.

Recently, we have started beam tests to check system integration of the 20 MeV accelerator. With adjusting the RF phase of RFQ and DTL, and the quadrupole strengths of the drift tubes, 3 MeV beam extracted from RFQ was injected into the 20 MeV DTL. **Figure 11**

Table 3 PEFP DTL parameters.

Parameter	Values
Frequency	350 MHz
Input/Output Energy	3 MeV/20 MeV
Peak Current	20 mA
Beam Duty	24%
Input/Output Emittance	
Transverse	0.23/0.23 π mm-mrad
Longitudinal	0.11/0.15 deg-MeV

Fig. 7 The layout of the PEFP 20 MeV proton linac. **Fig. 8** The DTL after DT installation. **Fig. 9** Installed DTL tank and power coupler.

shows the proton beam signal measured with a faraday cup at the end of the 20 MeV DTL.

Fig. 10 RF power to the 4 DTL tanks (150 kW/tank, 50 μ s, 1 Hz). The x-axis is RF pulse width in 10 μ s/division and y-axis is the RF power in 75 kW/division.

Fig. 11 A beam signal at the exit of the 20 MeV DTL (20 μ A peak). The x-axis is the pulse width of the proton beam in 10 μ s/division and y-axis is the beam current in 5 μ A/division.

3. Vacuum System

3.1 RFQ Vacuum System

The required vacuum pressure to prevent an RF break down and neutralization of the beam in the RFQ is lower than 5×10^{-7} torr. The pumping efficiency of the PEFP RFQ with 4 vanes is poor because of the low conductance with a small accelerating space, the high outgassing rate with a large surface area and the high rate of beam loss. The PEFP RFQ consists of 4 sections and each section is bolted with fluorocarbon sealants (Viton O-rings). The oxygen free high conductive (OFHC) copper was machined and brazed to shape the 4 vane cavities, and the helium leak rates of each brazed joints except the O-ring parts are measured to be below 1×10^{-9} torr l/s. In order to secure enough conductance of the vacuum, we designed 8 vacuum grills at each quadrant of the section 1 and section 4, and large pumping ducts made of stainless steel pipe of 25 cm in diameter.

During the operation the dominant gas loaded in the cavity, especially in section 1, is hydrogen. From simulation studies, we found that only 10% of H_2^+ beam ex-

Fig. 12 The RFQ Pumping system.

tracted from the injector is transmitted to the RFQ through LEBT due to separation of ion species by two solenoids, and that more than 90% of the H_2^+ transmitted into RFQ is lost in the RFQ. It can make a gas load in the RFQ cavity. The expected gas loads is estimated as follows, in which we use the typical outgassing of 1×10^{-10} torr l/s/cm² for polished copper.

- Outgassing (cavity surface area of 41,500 cm²):
 4×10^{-6} torr l/s
- Joint leaks: 3×10^{-6} torr l/s
- Beam loss (H_2^+ , 4 mA, 24% Duty): 2×10^{-5} torr l/s
- Gas load from LEBT: 5×10^{-5} torr l/s

We choose the cryo-pump as the main pump of the RFQ. The pumping system consists of two 3,000 l/s cryopumps for cavity and two 300 l/s turbo molecular pumps (TMP) for the rf windows. **Fig. 12** shows the schematics of the RFQ pumping system. The normal operation pressure is 2×10^{-7} torr for RFQ cavity and 4×10^{-7} torr for windows, which are higher than the expected values but sufficient for the operation. We consider that small leaks are main factor for these pressures.

3.2 DTL Vacuum System

The 20 MeV DTL is composed of 4 tanks and 150 drift tubes. A DTL tank is fabricated with two seamless copper-plated carbon steel cylinders of 54 cm in diameter which are bolted together with Viton seals. The cavity structure of DTL consists of drift tubes, post couplers, slug tuners, and pick-ups. All vacuum facing surfaces, except for the electro-polished stainless steel pump spool pieces and gate valves, are made of OFHC copper. The estimated gas load due to the surface outgassing per tank applying these values for copper and stainless steel is about 1.2×10^{-5} torr l/s. We have tested vacuum characteristic for the plating sample of I.D. 150 mm and L 750 mm cylinder. The measured outgassing rate without RF conditioning of the copper plating is 3×10^{-10} torr l/s cm².

We finally decided the pumping configuration of the 4 DTL tanks as shown in **Fig. 13**. We will use 2 TMPs and 2 Sputter Ion Pumps (SIP) in parallel to evacuate the tank during the initial beam operation. The SIPs have several merits but they have cathode limitation. All vacuum ports have RF shields of the slot type grill jointed with the tank with RF seal and Viton O-ring. The grill was made of OFHC copper jointed with stainless steel flange. The grill was specially designed to have high gas

Fig. 13 The DTL pumping system.

conductance and low RF attenuation. Calculated conductance of the grill is 857 l/s for N₂ gas. The required pressure of the tank is less than 5×10^{-7} torr, and the estimated gas load per tank is 5.42×10^{-5} torr l/s. Each tank is evacuated with two 300 l/s TMPs and each window per tank is evacuated with a 1,000 l/s non-evaporable getter (NEG) pump. The normal operation pressure is 4×10^{-7} torr for tanks, and 6×10^{-8} torr for windows, which are slightly higher than the estimated values, 1×10^{-7} torr for tanks, and 1×10^{-8} torr but sufficient for the operation.

4. Summary

The Proton Engineering Frontier Project launched by

the Korean government in 2002 includes a 100 MeV proton linear accelerator development and construction, and also its utilization and application programs. A 20 MeV proton linear accelerator has been integrated. The beam test through a system conditioning is under way. The full beam test will be done in this year. For the vacuum system of the proton linear accelerator, we considered many possible cases to induce vacuum issues and resolve the problems systematically. Thus far we have no serious problem on this subject. However, for the high duty operation, the gas load due to the beam loss should be considered in the initial design phase.

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