100 MeV HIGH-DUTY-FACTOR PROTON LINAC DEVELOPMENT AT KAERI*

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Abstract

The Proton Engineering Frontier Project (PEFP) is developing a 100MeV high-duty-factor proton linac, which consists of a 50keV proton injector, a 3MeV radio frequency quadrupole, a 20MeV drift tube linac, a 20MeV beam transport line, a 100MeV drift tube linac, and a 100MeV beam transport line. It will supply proton beams of 20MeV and 100MeV to users for proton beam applications with a beam duty factor of 24% and 8% respectively. A 20MeV front-end accelerator with CW RF systems has been constructed at KAERI Daejeon test stand, and the other part of the accelerator is being fabricated and it will be installed at the new site at Gyeongju City. The preliminary results of the 20MeV proton linac and the status of the 100MeV proton linac will be presented.

INTRODUCTION [1]

The project goals of PEFP are to construct a 100MeV proton linear accelerator, to develop technologies for beam utilizations and accelerator applications, and to promote industrial applications of the developed technologies. 20MeV and 100MeV beams will be extracted from one 100MeV linear accelerator and will be transported to user beam lines. In the user beam line, the beam will be shared to 5 users simultaneously by an AC switch magnet, which is a key component to increase beam utilization for many users. The shared beam will be used in many fields, such as radio-isotope production, power semiconductor production, developments of bio-technologies and space technologies etc, as shown in Figure 1. The end of the100MeV machine is open for the future project. We are considering a spallation neutron source with the extension of the superconducting linac.

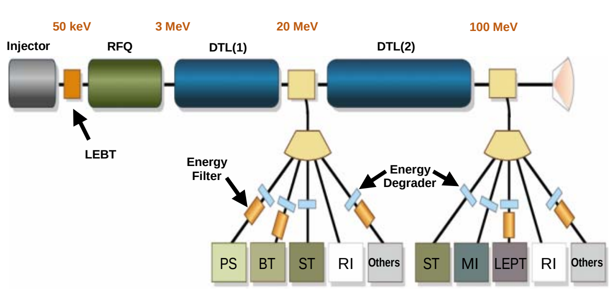

Figure 1: PEFP proton linac and user beam lines.

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PEFP PROTON LINAC

The beam requirements from PEFP beam users are summarized in Table 1.

Table 1: Beam Requirements

Particle	Proton	Proton
Energy	20MeV	100MeV
Energy Spread	<1%	<1%
Peak Current	1~20mA	1~20mA
Duty	Max. 24%	Max. 8%
Average Current	0.1~4.8mA	0.1~1.6mA
Pulse Width	0.1~2ms	0.1~1.33ms
Repetition Rate	Max. 120Hz	Max. 60Hz
Beam Power	Max. 96kW	Max. 160kW

In the beam requirements, 8% duty for 100MeV can be considered as an achievable duty, which is comparable with recent proton linear accelerators for other projects. But 24% duty for 20MeV is not easy to achieve easily. For this duty, at first we considered availability of MW class rf source. CW Klystrons are the only solution for this. We choose 350MHz 1.1MW CW Klystron from THALES for the rf source of our proton linac.

For the proton source, there are many types of ion sources, which can supply ~10mA DC proton beam. We choose the duoplasmatron because we already have many experiences and it has a low beam emittance. For 24% pulse operation, we use a high voltage DC power supply with a semiconductor switch because it is not easy to fabricate a 24% duty high voltage modulator.

For RFQ, the LEDA RFQ is the best example for high duty operation. It was tested with 100% duty successfully. We used many technologies, such as brazing, field stabilization, and tuning that had been developed for the LEDA RFQ. For DTL, it is not easy to handle a high duty rf because we should use many rf seals for complicated DTL structure and fabricate tanks with steel pipes which has poorer thermal conductivity than copper. We decided to reduce the accelerating gradient to reduce thermal load to tanks. Consequently the PEFP 20MeV DTL is longer than other DTLs such as SNS and J-PARC.

To meet the peak current requirement, 1 ~ 20mA, it requires variable quadrupole strength to control beam quality through DTL. But there is not enough room for a conventional electromagnet in a drift tube. We decided to use transformer wire for quadrupole winding and pool type cooling. For 3 ~ 20MeV DTL, radiation damage of insulation layer of winding is not critical. From 20MeV, there is enough space for a conventional hollow-conductor quadrupole in a drift tube. And we have a plant to use a hollow conductor for a DTL from 20MeV.

The 20MeV accelerator was fabricated and installed at KAERI Daejeon test stand as shown in Figure 2. The preliminary test for the 20MeV machine has been carried out to check the overall machine performance and tune the accelerator operating parameters. The test is being done at low duty, which is 50 μs beam pulse width and 0.1 Hz repetition rate, because of the improper radiation shielding for full beam power.

Figure 2: 20 MeV proton accelerator installed at KAERI test stand.

20 MeV Accelerator Test Stand in Daejeon [2]

The accelerator facilities at KAERI test stand are 20MeV accelerator itself, two sets of 1MW, 350MHz RF system, two sets of –100kV, 20A DC high voltage power supply for the klystron, two sets of 2MW cooling system for the cavity and RF system.

The ambient condition at KAERI test stand is not stabilized. Therefore the RF cavities should be stabilized against varying ambient conditions – especially ambient temperature. For this purpose, heater and heat shield were installed around the RFQ and DTL cavities. An 1kW heating power per RFQ and a DTL tank was used. The heater was controlled by PID mechanism of the SCR power unit. By using this method, the frequency could be stabilized within ± 1kHz.

The design duty of the 20MeV accelerator is 24% and two sets of 1MW, 350MHz klystron are used to drive a 20MeV accelerator, one is for RFQ and the other is for DTL. All the other ancillary facilities such as klystron power supply and cooling system were designed for 100% duty operation. During the low duty operation at KAERI test stand, the RF system is operating such that the electron beam of the klystron is CW whereas only the input RF signal is modulated for the low duty pulse operation.

Two sets of klystron power supply are used to drive two sets of 1MW klystron. As mentioned above, the design duty of 20MeV accelerator is 24%, therefore, not modulator, but DC high voltage power supply is used as a klystron power supply. During test, the klystron power supply is operating in CW mode.

Two sets of cooling system are operating, one is for RFQ, the other is for DTL. One set of the cooling system at KAERI test stand supplies cooling water both to the klystron and cavity simultaneously. With this cooling circuit configuration, the thermal load can be maintained nearly constant irrespective of the duty factor. Three-way valve is used to control the cooling water temperature during operation.

Proton Injector

The injector includes a duoplasmatron proton source and a low-energy beam transport (LEBT). The beam current extracted from the source reached up to 50mA. The extracted beam has a normalized emittance of 0.2 π mm-mrad from a 90% beam current, where the proton fraction is larger than 80%. To achieve pulsed operation, a high-voltage switch is installed in the high voltage power supply, whose rising and falling time is less than 50 ns. Figure 3 shows the beam signal measured with a Faraday cup. With the semiconductor switch, the pulse length and the repetition rate can be easily changed.

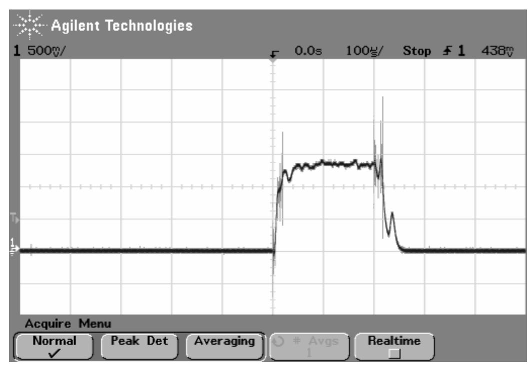

Figure 3: Beam signal at the LEBT exit (1mA/div., 200 μs pulse).

The LEBT consists of two solenoid magnets that can filter the H_2^+, and two steering magnets that can control the beam position at the entrance of the RFQ.

3 MeV RFQ [3]

PEFP RFQ is four vane type with 4 sections. They consist of a radial matching section, a shaper, a gentle buncher, an accelerator, and a fringe field region. The whole structure is separated into two segments which are resonantly coupled for the field stabilization. The RF power is fed into the cavity through two iris couplers in the third section. The main design parameters are given in Table 2. The vane voltage is constant along the RFQ structure. The aperture radius is slowly increasing after gentle buncher which helps the current independent beam matching into the following DTL. The beam dynamics is calculated by PARMTEQM code. The transmission rate is 98.3% by applying the matched beam for the RFQ.

Table 2: The PEFP RFQ Parameters

Frequency	350 MHz
Input / Output Energy	50 keV / 3 MeV
Transmission Rate	98.3 %
Total Length	326.64 cm
Peak Surface Field	1.8 Kilpatrick
Output emittance (normalized rms)	0.22 π mm-mrad 0.11 π deg-MeV
Type	4-vane type resonant coupling

High power rf conditionings for RFQ had been done up to 450kW peak power, 80μs pulse length, and 1Hz repetition rate. The time required for this conditioning is about 8 hours. The rf signals in Figure 4 are the signals after the conditioning, which are very stable.

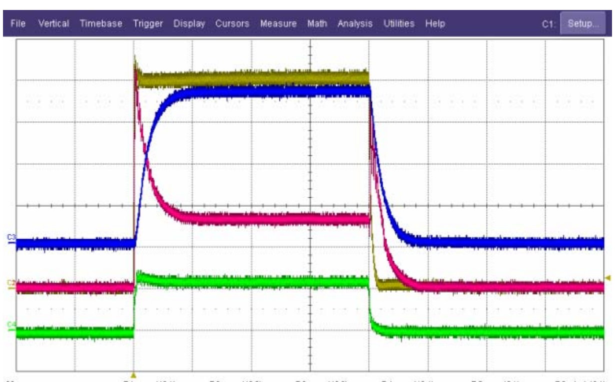

Figure 4: RF signals after high power rf conditioning (yellow : Forward, red : reverse, blue : cavity, green : klystron reverse).

A current transformer developed by Bergoz was installed at the exit of the RFQ to measure the beam current. The current transformer is tuned to the fundamental beam frequency, which is 350MHz and can catch the bunched beam signal component of 350MHz. The sensitivity of the current transformer is 2.5V/A. Because the peak beam current would range from a few tens μA to a few mA during initial beam test, it is difficult to directly measure the signal from the current transformer. Therefore two stage RF amplifiers were installed.

The output current through the RFQ was measured to set the RF operating point. The peak beam current during test was about 1 mA. The measured beam current and PARMTEQ simulation result are shown in Figure 5. During the test, the current transformer tuned to 350 MHz acted like a filter which could pick up the bunched beam signal, therefore the current transformer picked up the accelerated beam signal. From the test results, the operating point of the RF amplitude could be determined, which was about 10% higher than the design value.

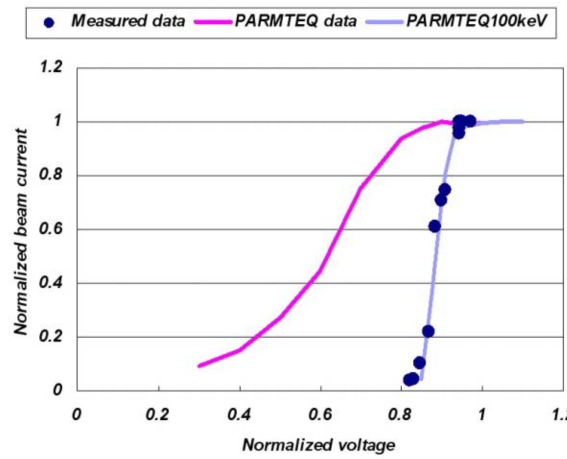

Figure 5: RFQ output current depending on RF field (Red line : total beam current, Blue line : accelerated beam current, Dot : measured beam current)

DTL[4]

The low energy part (3 MeV ~ 20 MeV) of PEFP DTL structures was designed for 24% beam duty. However PEFP decided to reduce the beam duty to 8% for the high energy part (20 MeV ~ 100 MeV) and the two different DTL structures are designed independently. Table 3 compares the design specifications of PEFP DTL1 and DTL2.

The differences between the design concepts of DTL1 and DTL2 are 1) accelerating gradient, 2) electromagnet type, 3) RF source operation mode, 4) RF system configuration.

First of all, the duty of DTL2 is 8%, therefore we can increase the accelerating gradient compared with DTL1. We investigated the effect of accelerating gradient of DTL2 on the overall parameters and decided to be 2.6 MV/m, which is about twice higher than that of DTL1. During design the DTL, we use the PARMILA code to simulate the proton beam going through the DTL structure. We used the simulated output beam of PEFP RFQ as the input beam of PEFP DTL. We decided the dimensions of the DTL tanks and drift tubes (DTs) by studying how the effective shunt impedance per unit length (ZTT) depends on the geometry. The sensitive geometrical parameters are the tank diameter, face angle, DT diameter and bore radius. For the efficient acceleration in DTL2, we increase the face angles of the drift tubes in DTL2 tanks compared with DTL1. Since the space for installing quadrupole magnets is limited in the initial part of DTL1, we used the pool type magnets for DTL1. In case of DTL2, we have enough space, the hollow conductors can be used for the quadrupole magnets in DTL2. The lattice is FFDD where the integrated field of the quadrupole magnets is 1.75 T.

The rf system of DTL1 was configured such that four tanks of DTL1 was driven by single klystron. Because the rf power required for each DTL1 tank is about 250 kW, and we can get a commercially available 1.1 MW CW klystron easily. In this case, we operate the klystron such that we only modulate the input rf signals whereas maintain DC electron beam power. About the rf system for DTL2, we have a plan to use a single klystron for each tank. The required peak power of each DTL2 tank is about 1.1 MW, and we can operate the existing TH2089F klystron up to 1.6MW with 9% duty with slight modification. For the klystron power supply of the DTL2 klystron, we will use a modulator compared to the DC high voltage power supply for DTL1 klystron.

Table 3: Summary of PEFP DTL1 and DTL2

Parameters	DTL1	DTL2
Resonant Frequency	350 MHz	
Klystron operation	DC	Pulse
Beam operation	Pulse	Pulse
Max. Peak Current	20 mA	
Max. Pulse Width	2 ms	1.33 ms
Max. Repetition Rate	120 Hz	60 Hz
Max. Beam Duty	24%	8%
Max. Average Current	4.8 mA	1.6 mA

As was stated earlier, the unique characteristic of PEFP 20MeV DTL is that one klystron drives four DTL tanks simultaneously. Also the cavity cooling circuits for four tanks are connected in parallel from one cooling system. For this multi-cavity driving concept, the tank wall temperature control mechanism with heater is installed, and mechanical phase shifters are also installed in each waveguide leg to the tank. By doing this, we can consider four independent tanks as one cavity. Therefore the resonant frequencies of each DTL tank were adjusted by controlling the wall temperature of each tank. During the test, the global operating condition was adjusted by controlling the coolant temperature.

To check and evaluate the system performance and tune the accelerator parameters, initial test was carried out at low duty factor. The main concern was to check the beam transmission through the DTL tanks. For this purpose, the current transformers were installed at the entrance of tank 1 and at the exit of tank 2, tank 3. Also a Faraday cup was installed at the exit of tank 4. During the test, the beam transmission through the DTL tanks was measured depending on the operating parameters using these beam diagnostic devices.

The LEBT parameters such as solenoid current and steering magnet current and rf parameters such as mechanical phase shifters were adjusted in advance. After that, beam steering was performed. The beam position monitor is not working yet at low current level, we determine the proper beam steering by measuring the beam transmission. Because the PEFP DTL has no steering magnet in the drift tubes, we move the tank itself for the beam steering. The minimum resolution that we can steer the tank was 30 µm. During the test, the position that the low energy side of the tank 1 was moved 1mm in the –x direction, high energy side of the tank 1 and all sides of tank 2 were moved 0.5mm in –x direction, and all the other tanks were not moved, is the best position for the 100 % beam transmission through the DTL. The rf field profile in each tank, DTL input beam current and output beam current profiles are shown in Figure 6 and Figure 7 respectively. During the test, the beam current was fluctuating because of the uncontrolled low level RF system and also the beam signals from the current transformer was decayed at some instance because of the improper cooling of the RF amplifier.

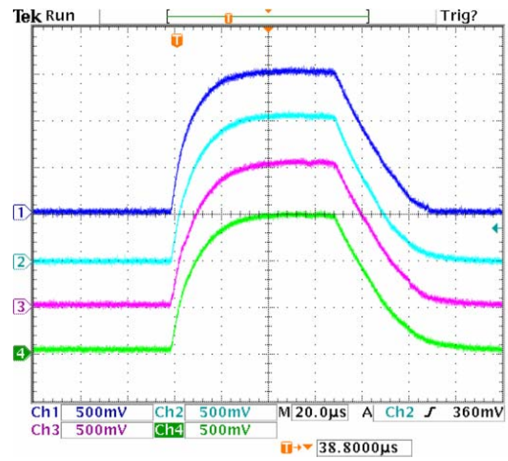

Figure 6: Field profiles in four tanks of DTL1 (blue : tank 1, jade : tank2, pink : tank3, green : tank4).

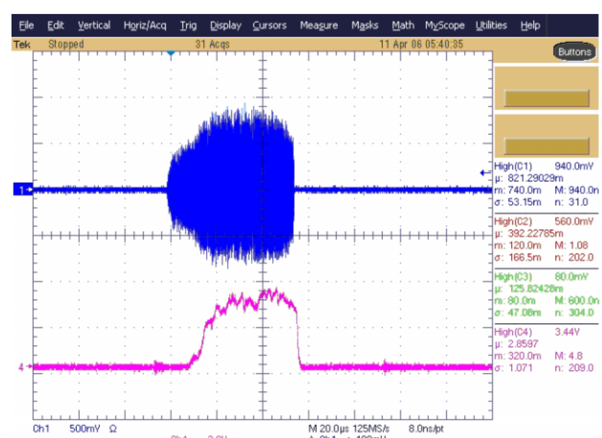

Figure 7: Beam signal of the 20 MeV DTL (CH1: ~1mA at RFQ exit, CH2: ~1mA at DTL exit).

The fabrication of 20MeV to 100MeV is under progress as shown in Figure 8. From 20MeV, we will use conventional hollow conductor for quadrupole windings because there is enough room for EQM in DT. The prototyping of the EQM is under progress. For the fabrication, because there is no technical problem, the schedule for DTL fabrication will depend on the budget profile.

Figure 8: Machined DTL2 tanks.

CONCLUSION

We have developed high duty proton linear accelerator technologies and constructed a 20MeV machine in KAERI Daejeon site. The machine has been tested with low duty to confirm the beam dynamics design and the rf design and the test of low duty was successful. But in this site, because there is not enough radiation shielding, we can not operate the accelerator at high duty. Fortunately, in this year, Gyeonju city hosted our project and will provide land and supporting facilities. In April 2007, the construction will be started and the 20MeV machine will be moved and installed in 2009. We hope that in 2009 we perform the full 24% duty operation of the 20MeV machine. The 100MeV machine will be completed in 2011 and the beams will be delivered to users from 2012.

Figure 9: Aerial view of Gyeonju site.

Figure 10: Bird's-eye-view for Gyeonju site.

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