STATUS AND COMMISSIONING PLAN OF PEFP 100-MEV LINEAR ACCELERATOR*

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Abstract

One of the goals of the Proton Engineering Frontier Project (PEFP) is to develop a 100-MeV proton linear accelerator, which consists of 50-keV proton injector, 3-MeV radio frequency quadrupole (RFQ), 20-MeV / 100-MeV drift tube linac (DTL) and 20-MeV / 100-MeV beam lines. The 100-MeV linear accelerator and beam line components have been installed in the tunnel and experimental hall. After the completion of the utility commissioning, the commissioning of the accelerator starts with a goal of the beam delivery to the 100-MeV target room located at the end of the beam line. The proton beams will be supplied to users from March 2013. In this paper, the status and commissioning plan of the PEFP 100-MeV linear accelerator are presented.

INTRODUCTION

The PEFP was launched by the Korean Government at 2002 as a 21st century Frontier R&D program. It has three main objectives; to develop a high power proton linac, to develop proton beam utilization and accelerator application technology, to industrialize developed technologies.

The specifications and schematics of the 100-MeV, 20mA proton accelerator developed by PEFP are shown in Table 1 and Figure 1 respectively. The PEFP proton accelerator has its own characteristics; to supply high duty & high average current beam to users, to supply proton beam with wide range in beam energy and current, to supply proton beam into 3 beam lines simultaneously, and to supply beam with large area up to 300mm in diameter. The main application fields of the accelerator are such that; industrial field with ion cut, semiconductor switch application, radio isotope production, medical field with proton therapy research, biological field with mutation of plants & micro-organism, space technology field with research on radiation effect on materials, and basic science field with neutron application.

The project host city is Gyeongju who supplies land and supporting buildings such as main office building, regional cooperation centre and dormitory and so on. The main buildings for accelerator and experimental hall, utility and substation are provided by the central government. The construction of the main buildings will be completed in October, 2012.

The development of 100-MeV DTL was completed in 2010. The main accelerator components such as RFQ and DTL were designed by PEFP, fabricated by the 17 Korean domestic industries, assembled and tested by PEFP. As a front end, a 20-MeV linac was developed, installed and operated since 2007 at KAERI Daejeon site waiting for the PEFP site preparation at Gyeongju. [1][2] The operation of 20-MeV linac at Daejeon was finished at November 2011. Since then, the machine was disassembled and delivered to Gyeongju site at February 2012 when the accelerator tunnel was prepared. The 100-MeV accelerator and two beam lines were installed inside the accelerator tunnel and the experimental hall, respectively. The commissioning of the accelerator will start at the end of 2012 after the klystron gallery, modulator room and utility are prepared.

Table 1: Specifications of the PEFP Proton Accelerator

Parameter	DTL-I	DTL-II
Output Energy (MeV)	20	100
Max. Peak Beam Current (mA)	20	20
Max. Beam Duty (%)	24	8
Average Beam Current (mA)	4.8	1.6
Max. Pulse Length (ms)	2	1.33
Max. Repetition Rate (Hz)	120	60
Max. Avg. Beam Power (kW)	96	160

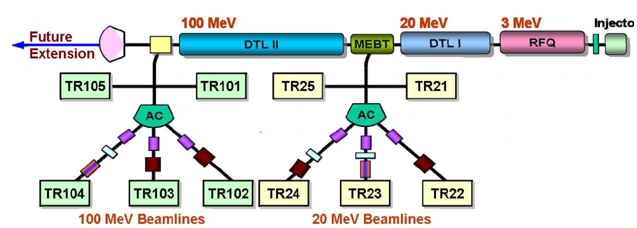

Figure 1: Schematic of the PEFP proton accelerator and beam lines

ACCELERATOR DEVELOPMENT

20-MeV Linac Operation

The 20-MeV linac was installed at Daejeon site temporarily in 2005 waiting for site preparation at Gyeongju. The 20-MeV linac got an operation license in 2007, since then the machine was used to study the machine itself and to test 100-MeV accelerator components in addition to supply proton beams to users. The key technologies developed during 20-MeV linac operation are as follows.

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The digital LLRF system was developed from the analogue system in 2007 and upgraded in 2010. The digital LLRF system utilized a commercially available control board with FPGA. The control algorithm with PI was developed by PEFP. The board can produce synchronized NCO output signal equipped in the board, therefore it does not need an analogue IQ modulator. By installing mixers at input and output section symmetrically, the LLRF system became more stable against the external reference signal perturbation. The delay of the system was measured to be less than 1us. The OPI interface of the LLRF system is GUI mode with EPICS. Various waveforms, such as RF forward power, RF reflected power and cavity field level can be monitored as well as the resonant frequency error measurement function. [3][4] The high power test results showed that the amplitude and phase were maintained within 1% and 1degree respectively. By using the digital LLRF system, the beam current could be stabilized during operation. [5]

The klystron power supply was changed from DC high voltage power supply to the high voltage converter modulator (HVCM) in 2009. The design duty of the 20-MeV machine is 24%. A CW klystron and DC high voltage power supply were used in the initial operation period. At that time, the electron beam of the klystron was operated in DC mode and only the RF operation was in pulse mode. Therefore the operation efficiency was very low because the machine could not be operated at high duty due to the insufficient radiation shielding, whereas the power consumption was 4MW to drive two CW klystrons. To increase the efficiency, the high voltage converter modulator was developed as a klystron power supply for 100-MeV linac. When the modulator was delivered, it was installed in 20-MeV linac RF system with the purpose of testing the modulator itself and driving the 20-MeV linac. The system efficiency of the 20-MeV linac could be increased by driving the klystron electron beam in pulse mode. In addition, several problems of the first modulator were identified and fixed. The debugging of the first delivered modulator was reflected on the successive procurements of the modulator. [6]

The ion source was changed from duoplasmatron type to microwave type in 2011. The main purpose of this change was to meet the ion source requirement of more than 100 hours continuous operation without maintenance. The former duoplasmatron type ion source satisfied all the requirements such as beam current, beam emittance and so on except the life time. Due to the filament, its life time was limited to 40 hours. But the life time of the ion source should be more than 100 hours based on the operation scenario of the 100-MeV linac. Therefore microwave ion source was developed because one of its advantages was long life time. The developed microwave ion source was tested for 100 hours at the test bench and it showed no degradation of the performance. After the test at the test bench, it was installed at 20-MeV linac and used as a proton injector. The microwave ion source had been operated for 243 hours without maintenance until the November, 2011. [7][8]

For beam diagnostic devices, the beam position monitors (BPM) for 100-MeV linac and the beam transfer line were developed and tested at the 20-MeV beam line in 2011. The beam test results showed that the BPM produced the expected signal and was good enough for the beam phase measurement. [9]

In addition to the technology development of each accelerator components, the integrated test of the accelerator was carried out.

The long-time operation was tried to check the pulse loss statistics. The total number of pulses was 14,400 and the total pulse loss rate was 0.56%. Among them, 0.01% was due to the spark at the ion source and 0.55% was due to the spark at the RFQ. The spark at the RFQ was the main cause of the beam pulse loss. [10] For the long-pulse operation test, it was not difficult to increase the beam pulse width up to 500us. The 500us beam pulse is shown in Figure 2. The high repetition rate test was also carried out. The RF system was operated at 20Hz and the repetition rate of the beam from the ion source was increased from 1Hz to 15Hz. The beam pulse at 15Hz is shown in Figure 3. All the system including low level RF and data acquisition system was operated without any problems. The radiation dose was measured at the target room fence which is 1m apart from the radiation shielding block. The neutron dose rate was 500uSv/hr at 15Hz and gamma ray dose rate was 150uSv/hr. We did not increase the duty because of the insufficient radiation shielding at Daejeon site. [11]

The beam parameters such as beam energy, beam profile, beam emittance and beam phase were measured in parallel with the machine study. The beam energy was measured with the time-of-flight method by using two BPMs installed at the 20-MeV beam line. The result was 20.2MeV and this was compared with other two methods; dose measurement and range measurement with the aluminium foil, Gafchromic film and ion chamber. Both results showed a good agreement within 1% with each other. To measure the beam profile, we used the wire scanner. The beam profiles depending on various operating conditions of the quadrupole triplet installed at the 20-MeV beam line were measured and the beam radius was compared with the PARMILA results.

The beam emittance at the upstream of the RFQ was measured by using the electric sweep scanner. The measured emittance was 0.35 π mm mrad in normalized rms value which showed higher than the design value of 0.2 π mm mrad. It is necessary to optimize the operation parameters of the ion source and LEBT. The beam emittance at the downstream of the 20-MeV DTL was also measured by using quad scan method. The last magnet in the triplet was used to change the transfer matrix. The measured emittance was 0.22 π mm mrad, which was well agreed with the design value. [8]

The BPM signals were utilized for the beam phase measurement, which is important at the commissioning stage of the 100-MeV linac because a phase scan method

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is considered as a tuning method of the RF amplitude and phase. The beam phase was measured at various amplitude and phase of the RFQ and DTL and the results were compared with the PARMILA results. Finally, we could establish the phase scan algorithm based on the measurement data. [12]

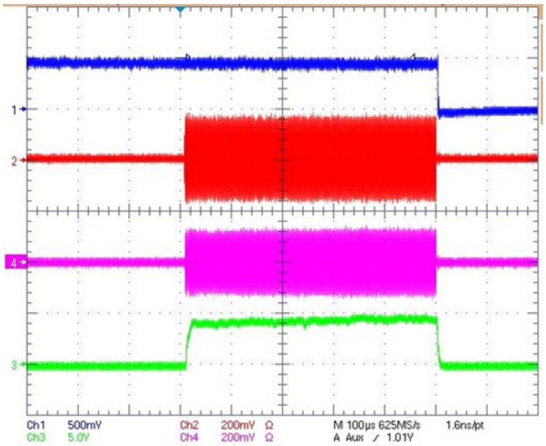

Figure 2: 500us beam operation (Time : 100us/div.)

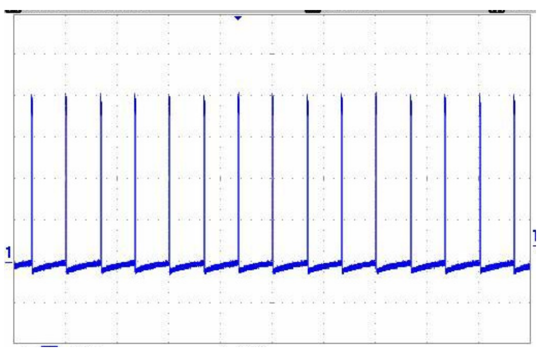

Figure 3: Beam pulse at 15Hz (Time span: 1s)

A 20-MeV beam was supplied to the users during the 20-MeV machine operation in Daejeon site. The users who want a beam service submit an application form through the Internet and the beam line operator contacts the users and discusses the irradiation conditions. After that, the beam line operator does the beam service by using the sample prepared by the users. During beam irradiation to the specimen, the beam line operator communicates with the linac operator through the control system which includes personal protection logics. The beam conditions were adjusted to the specific user demands however the typical operation conditions were 5mA peak current with 50us pulse width, 1Hz repetition rate during beam service. There were total 1603 samples irradiated by using 20-MeV linac for five years. The number of sample treatment increased from about 100 samples in 2007 to more than 680 in 2011 as shown in Figure 4. For five year beam service, most of the users (66%) come from the Research Institute, and the others come from the University (22%) and Industry (12%). The most frequent application field was Bio-Technology (60%) including the cancer cell irradiation and mutation study. The research and application field related to the Nano-Technology (17%) which included a nano-particle synthesis was next to Bio-Technology.

As mentioned above, the operation of 20-MeV linac at Daejeon site was finished at November 2011. Since then, the machine was disassembled and delivered to Gyeongju site at February 2012. The DTL tanks and klystrons were moved with the vibration free truck as shown in Figure 5. After the movement, the field profile of the DTL was measured and the difference was within 3% before and after the movement.

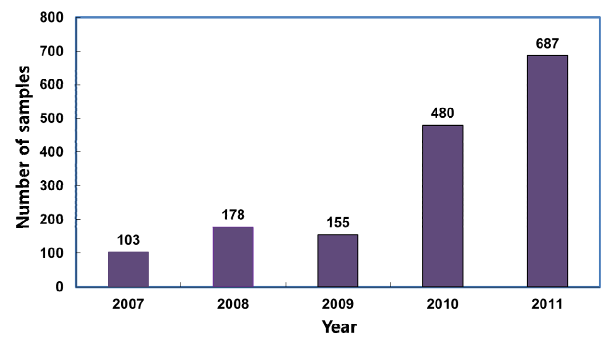

Figure 4: Number of samples depending on fiscal year

Figure 5: 20-MeV DTL tanks on the vibration free truck for the movement to Gyeongju site

100-MeV Linac Development

The fabrication of the 20-MeV ~ 100-MeV DTL tanks was completed at December 2010. It consists of seven tanks and total 163 ea. drift tubes. It has hollow type electromagnet for beam focusing whereas the 20-MeV DTL has a pool-type electromagnet. The length of each tank is 6.8m. The 100-MeV DTL tank has one klystron per one DTL tank and one Resonant Frequency Control Cooling System (RCCS) for each tank.

The fabrication of two Medium Beam Energy Transport (MEBT) tanks was also completed. MEBT tanks will be used as a longitudinal matching section between 20-MeV DTL and 100-MeV DTL because there is a long drift space between them for 20-MeV beam extraction. The MEBT tank is a kind of DTL tank with three gaps.

The 350MHz klystron is used as a RF amplifier for the PEFP linac. The specification of the klystron is 1.6MW peak power with 1.5ms pulse width, 60Hz repetition rate. It was modified from the TH2089F CW klystron to produce a higher peak power and reduced duty. There are

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total 7 klystrons for 20-MeV ~ 100-MeV DTL, and all the klystrons were delivered to Gyeongju site and waiting for installation.

The high voltage converter modulator is used to drive the klystron. The specification of the modulator is 5.8MW peak power with 1.5ms pulse width, 60Hz repetition rate. There are two distinct features in the PEFP modulator. One is to keep the pulse voltage droop less than 1% by the adjustment of the switching frequency. The other is to limit the load arc energy less than 20J spontaneously by the internal resonant characteristics, which means that the crowbar is not necessary in the modulator. One modulator drives two or three sets of the klystrons simultaneously. Total 4 sets of modulator are necessary for whole accelerator including 3-MeV RFQ, 20-MeV DTL and 100-MeV DTL and all of them were delivered. One of the modulators was used to drive the 20-MeV linac at Daejeon site for 3 years. The normal operation conditions was 2.8MW peak power with 1ms pulse width, 4Hz repetition rate. It was tested up to 30kW in average power.

A RCCS is used to control the resonance frequency of each DTL tank by supplying the temperature–controlled water to drift tubes. The maximum heat load is 94kW. It should cover large range of heat load from lowest heat load from the magnet only to the highest heat load from the full duty RF power in addition to the magnet heat load. The operating temperature range of the RCCS was designed from 21°C to 33°C to reduce the DTL tuning requirement. Within the above temperature range, the RCCS can maintain the temperature accuracy within ±0.1°C by using two sets of three-way valves. Also the RCCSs were ready to installation.

One of the most important interfaces between machine and building was the waveguide connecting accelerator located in first floor with the klystron located second floor. The waveguide was specially designed, fabricated and tested with care and embedded inside the ceiling of the tunnel during the building construction.

Beam Line Development

The important components of the beam line are AC magnet which distribute the proton beams into three beam lines pulse by pulse successively and 300mm aperture beam window to extract large area beam into the air for irradiation, in addition to the main dipole and quadrupole magnets. All the dipole and quadrupole magnets were fabricated. The magnetic properties of the magnet were measured and the geometrical fiducialization was also finished. Two AC magnets, one for 20-MeV beam, the other for 100-MeV beam were also fabricated. The sweep frequencies of the AC magnets are 15Hz for 20-MeV beam line and 7.5Hz for 100-MeV beam line. The maximum bending angle of the AC magnet is 20 degree. The AC magnet will be driven by the power supply with fast switch technology. The material of beam window is a 0.5mm thickness AlBeMat with concave geometry. The energy loss through the beam window is 0.6MeV for 100-MeV beam. The window will be forced air-cooled by using the blower.

COMMISSIONING PLAN

Each of the high power devices such as modulator and klystron will be commissioned after the commissioning of the all utilities is completed. The first devices to be on-site commissioned are 4 sets of modulator. The modulator will be tested at low power level of 2kW in average power with non-inductive resistor. The beam and RF test of the klystron will be done after the modulator tests are completed. Initial test of the klystron will be done without connection to the DTL tank and reflecting all the RF power to the dummy load by using a shorting plate installed one arm of the circulator. The on-line RF conditioning of the DTL tank will be done after the high power test of the klystron-modulator system finishes.

The beam commissioning goal of the accelerator is to deliver a 100-MeV, 1kW beam to the beam dump located at the end of the accelerator. The commissioning goal of the beam line is to deliver a 100-MeV, 1kW beam to the beam dump located in the TR103 target room.

An important step of the beam commissioning process is to determine the RF amplitude and phase of each DTL tank. We adopt a phase scan method [12][13]. For this purpose, a strip line BPMs will be used at the downstream of each DTL tank to pick up the beam phase signal. Then the signal is delivered to the commercially available control board. The control board treats both the LLRF control signals as mentioned above and beam phase signal because both signal needs RF reference. In addition to the hardware, software to treat the phase scan data was implemented in Matlab. An experimental data of the beam phase as a function of RF phase with the fixed relative amplitude A/A_0 is compared with the implemented PARMILA simulation results to generate a χ-value for each case of A/A_0. The quadratic fitting of the χ-values can determine the RF amplitude and phase.

INSTALLATION AND SCHEDULE

The 100-MeV linac was installed inside the tunnel as shown in Figure 6 after the survey of the tunnel was performed and the supporting structures were prepared at March 2012. The total length from the ion source to the beam dump is 93m. The magnets of the 20-MeV / 100-MeV beam line were also installed at May 2012 as shown in Figure 7. [14]

Based on the construction schedule, the klystron gallery and modulator room will be prepared in September 2012, and the utility commissioning will be finished in October 2012. Form September, the modulator will be delivered to the modulator room in 3rd floor and installation starts. Also all the RF components including klystron, RCCS and waveguides will be installed in the klystron gallery of 2nd floor. The accelerator commissioning starts from the modulator commissioning step by step after the utility commissioning is completed. The DTL conditioning will start in January 2013 and the beam acceleration into the beam dump is planned in February 2013. The construction status of the accelerator building is shown in Figure 8.

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Figure 6: The installed 100-MeV linac in the tunnel

Figure 7: The installed 20-MeV beam line magnets in the 20-MeV beam line hall

Figure 8: Construction of the accelerator building at Gyeongju project site

CONCLUSION

The PEFP launched by the Korean government in July 2002, is developing a 100-MeV proton linac and installing the facilities at Gyeongju project site. The 20-MeV part of the linac has been successfully developed, tested and operated for 5 years at Daejeon. After finishing operation at November 2011, it was moved to the project site at Gyeongju. The installation of the 100-MeV linac and beam line magnets were finished in March 2012. The modulators and klystrons will be installed from September 2012. The construction of the accelerator building including the commissioning of the conventional facility will be completed in October 2012. The commissioning of the accelerator starts from the modulator commissioning. The important milestones are to start the DTL tank conditioning in the tunnel in January 2013 and to deliver the 100-MeV proton beam into the beam dump in February 2013.

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