HIGH POWER PROTON ACCELERATOR IN KOREA*

Byung-Ho Choi, Jun Yeon Kim, Kye Ryung Kim, Hyeok-Jung Kwon, Ji-Ho Jang, Kui Young Kim, Jae Won Park, Sun An, Byungchul Chung, Yong Young Lee and Yong-Sub Cho#
PEFP, Korea Atomic Energy Research Institute
P.O.Box 105, Yueong, Daejeon 305-353, Republic of Korea

Abstract

A high power proton accelerator project, Proton Engineering Frontier Project (PEFP), as one of the 21C Frontier Projects promoted by Korean Government, has the goals to develop a 100 MeV high current proton linear accelerator and the user programs for its beam utilization and industrial applications. The upstream part of the 100 MeV linac, the 20 MeV linac, was successfully developed and tested. The rest part of the accelerator and beam lines and user facilities are under development, and also the site preparation and construction works are in progress. In parallel, proton beam utilizations and accelerator application technologies have been extensively studied and developed. In this paper, the status and the future plan of the project, including beam test results of the 20 MeV linac, site preparation and construction works, and development of proton beam utilization and user program are presented.

INTRODUCTION

A high-power proton accelerator (HPPA) can produce intense beams of protons and secondary particles, such as neutrons, radioisotopes, mesons, and neutrinos. Such intense beams provide us with the practical and efficient means to realize quantum engineering. High-current proton beams with low energy (< 10 MeV) are useful in industrial and defense applications, such as ion-cutting, power semiconductors, mine detection, boron neutron capture therapy, and neutron radiography. Low-current proton beams with moderate energy (10–250 MeV) are valuable in biological and medical researches and applications, for example, mutations of plants and micro-organisms, proton and neutron therapy, and radioisotope production. High-power proton beams with energies around 1 GeV are widely utilized in spallation neutron sources, radioisotope beam facilities, nuclear and high-energy physics experiments, and accelerator-driven systems.

The PEFP was launched by the Korean government in 2002 to realize potential applications of the intense proton beams. Its primary goal in the first stage is to develop a high-current proton linear accelerator to supply 100 MeV, 20 mA proton beams and to construct beam line facilities, with which the users can access the proton beams with wide ranges of energies and currents for their research and development programs [1]. In addition, the PEFP accelerator can be exploited as a proton driver for various applications in the low- to medium-energy range, or an injector for a high-energy proton machine in the next stage of development.

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# choys@kaeri.re.kr

ACCELERATOR DEVELOPMENT

We have successfully developed a 20 MeV proton linac in the first phase of the project, which consists of a 50 keV proton injector, a 3 MeV RFQ, and a 20 MeV drift tube linac (DTL). In the second phase, we will develop the high energy part of the PEFP 100 MeV linac and beam line facilities which supply the users with the low and medium energy proton beams. Two user facilities are to be installed to utilize the 20 MeV and 100 MeV proton beams at the end of the 20 MeV and 100 MeV accelerating structures, respectively. The schematics of the PEFP linac and beam line facilities are illustrated in Fig. 1. Some characteristic parameters of the accelerator are given in Table 1 [2].

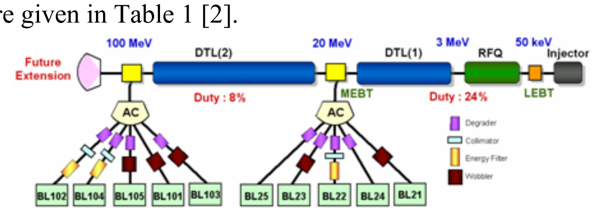

Figure 1: Schematics of the PEFP 100 MeV linac and beam line facilities.

Table 1: Characteristics of the PEFP accelerator.

Energy (MeV)	20	100
Energy spread (%)	< 1%	< 1%
Peak current (mA)	1~20	1~20
Max. beam duty (%)	24	8
Average beam current (mA)	0.1~4.8	0.1~1.6
Pulse width (ms)	0.1~2	0.1~1.33
Max. repetition rate (Hz)	120	60
Max. beam power (kW)	96	160

The injector consists of a duoplasmatron H^+ ion source and a low-energy beam transport (LEBT). The extracted beam current from the source reached up to 50 mA at a voltage of 50 kV. The extracted beam has the normalized emittance of 0.2 π mm-mrad with the proton fraction more than 80%. To achieve a pulsed operation, a high-voltage switch is installed, of which rising and falling times are less than 50 ns, respectively [3]. The LEBT consists of two solenoid magnets, which focus the protons and filter the H_2^+ ions, and two steering magnets which control the beam position at the entrance of the RFQ.

The PEFP RFQ is designed to accelerate the proton beam from 50 keV to 3 MeV with the 4 vane structure [4]. The entire 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. Some design specifications of the PEFP RFQ are summarized in Table 2.

Table 2: Characteristics of the PEFP 3 MeV RFQ.

Frequency	350 MHz
Input / Output energy	50 keV / 3 MeV
Transmission rate	98.3 %
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

Figure 2: The PEFP 3 MeV RFQ.

The PEFP RFQ (see Fig. 2) was successfully fabricated and tuned. The high-power RF test shows that the stable power level reaches about 440 kW, 110% of the required level after baking its RF window and modifying the power coupler. Figure 3 shows a beam test result with the peak current of 3 mA, measured by a current transformer at the RFQ exit. The transmission rate was measured to be more than 98%.

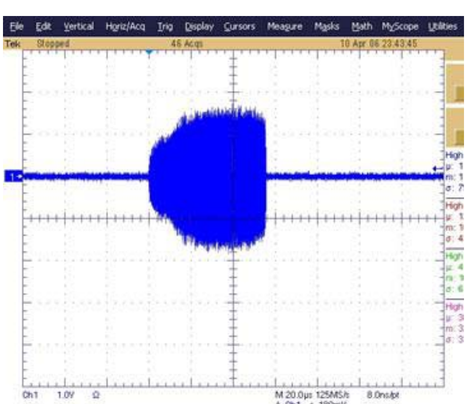

Figure 3: The output beam current of the PEFP RFQ. The horizontal scale is 1 μs/div. and the vertical is 2 mA/div.

Figure 4:The PEFP 20 MeV DTL.

The PEFP 20 MeV DTL, shown in Fig. 4, consisting of four tanks, is designed and fabricated to accelerate the proton beam from 3 MeV to 20 MeV with the maximum peak current of 20 mA and the maximum duty of 24% to meet the user demands. One of its unique design features is that a klystron supplies the RF power into the four tanks to efficiently utilize a 1 MW CW klystron [5]. The RF system for the 20 MeV DTL, including a klystron, circulator, and power dividers, was constructed and tested. The klystron was tested up to 600 kW power. Figure 5 shows a beam test result with 1 mA peak current measured by the current transformers at the entrance and the exit of the 20 MeV DTL. The beam transmission rate was measured to be nearly 100% [6].

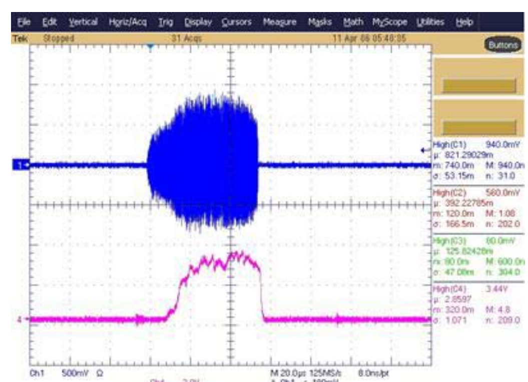

Figure 5: The beam currents measured at the entrance (upper plot) and the exit (bottom plot) of the 20 MeV DTL. The vertical scale is 0.5 mA/div. and the horizontal is 20 μs/div.).

By far, we have performed a limited beam test with low beam currents and short pulses simply because of the inadequate radiation shielding environment. We are planning to perform the full power test, and measure the energy and the emittance of the output beam as soon as the national radiation safety authority licenses the full power operation.

We have redesigned the high energy part of the PEFP 100 MeV accelerator by reducing the maximum beam duty to 8% from 24% in consideration of the user demands. Therefore, the PEFP 100 MeV accelerator has two largely different DTL structures and operation conditions: the low energy part (up to 20 MeV) is called as DTL-1 and the high energy part covering from 20 MeV to 100 MeV is called DTL-2. Table 3 compares the design specifications of DTL-1 and DTL-2. The noticeable differences are the accelerating field gradients, electromagnet types, RF operation modes, and RF system configurations. The fabrication of DTL-2 tanks is in progress [6]. The design of electromagnetic quadrupole magnet using a hollow conducting copper coil is completed and prototyping is in progress.

Table 3: Specifications of the PEFP DTL-1 and DTL-2.

Parameters	DTL-1	DTL-2
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

BEAM LINES AND USER FACILITIES

One of the important goals of the project is to develop the beam lines and user facilities. To meet the user demands as much as possible, the PEFP focuses on efficient utilizations of the proton beams, to supply various protons with different conditions, to provide multi-users with the plenty of protons, and to achieve cheaper proton beams compared to other facilities such as cyclotrons and synchrotrons.

In order to provide wide ranges of beam energies, currents and beam time, it is essential to extract a low energy beam of 20 MeV and a medium energy beam of 100 MeV, and to distribute the beams to the multi beam lines simultaneously. Figure 6 shows the schematics of the PEFP 20 MeV beam lines and user facilities, in which the proton beams are extracted by using a 45° bending magnets and transported through a common beam line up to a beam distribution system with a programmable AC magnet which distributes the proton beams into maximum five individual beam lines. The 100 MeV beam lines and user facilities have the similar structure. Each beam line has a degrading and filtering system to control beam energy, a collimator to control flux, and a scanning system to make a uniform irradiation possible for large area applications.

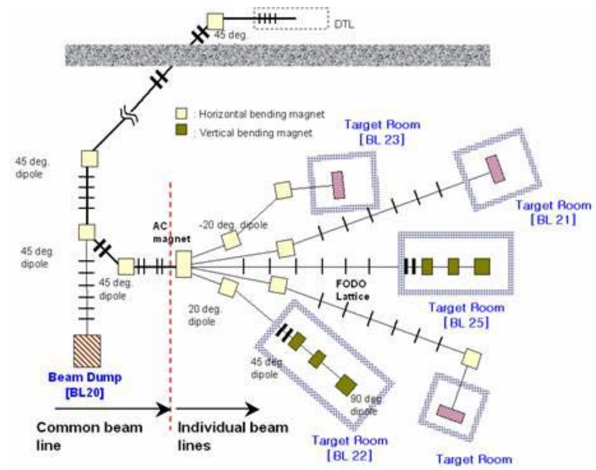

Figure 6: The PEFP 20 MeV beam line facility.

Implementing the 20 MeV beam extraction magnet requires relatively large space between the DTL-1 and DTL-2, which raise the beam matching issue between them. To resolve the problem, we implement a medium energy beam transport (MEBT) system with two small buncher cavities between which the beam extraction magnet is placed. Each cavity has three cells with four quadrupole magnets [7]. The quadrupole magnets in the cavity are used for transverse matching and RF for the longitudinal matching between the DTL-1 and DTL-2. Figure 7 shows the schematic plot of the MEBT and the matching calculated by TRACE-3D [8].

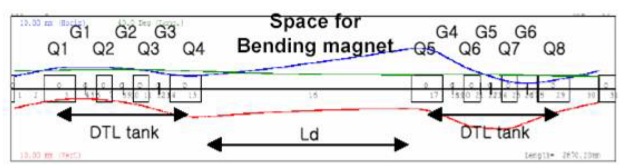

Figure 7: Beam matching in the PEFP MEBT system.

Figure 8: 45 MeV proton beam line at KIRAMS.

To support on-going user programs, and to develop and test the beam line components, a test beam line has been developed and installed in the MC-50 cyclotron located at KIRAMS as shown in Fig. 8. The test beam line currently supports a wide range of user programs.

CONSTRUCTION WORKS

The project host site was selected, in January 2006, to be *Gyeongju* city located in the south-eastern part of Korea. Since then, detailed geological surveys of the site and site plan have been completed. Based upon these, facility layout, site improvement and access road are under engineering.

General arrangements of the accelerator and beam application buildings are completed along with setting up interface requirements for utility design of conventional facilities as shown in Figure 9. The architectural works of conventional facilities are under way.

Figure 9: Bird's eye view of the PEFP research center.

This work is to build up facilities to supply the research center with electric power, water and other kinds of utilities from outward sources. Gyeongju local government is planning for this in cooperation with the PEFP. The construction schedule of the PEFP research center is given in Figure 10.

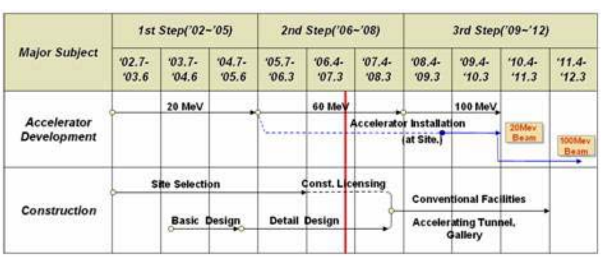

Figure 10: Projected construction schedule of the accelerator center.

THE USER PROGRAMS

The PEFP has supported its user programs to develop new research fields using proton beams, to promote basic researches on proton beam utilization, to reflect the user demands of the PEFP facility design, and to expand the beam user community in Korea. The PEFP user program supports five subprograms in the study and development of utilization and applications of the proton beams at low and medium energies using the available domestic and foreign proton facilities in the U.S.A., Japan, and EU. Under the programs, there are 23 basic research projects using proton or neutron beams in the wide range of leading research fields as summarized in Table 4.

Some of the user programs have produced promising results. One useful industrial application of low-energy proton beams is to produce power semiconductors with fast switching characteristics through charge carrier lifetime control. This can be realized by proton beam irradiation of the p-n junctions of power semiconductors. After proton beam irradiation, the switching speed of a fast recovery diode improves by more than five times.

Table 4: Active research fields by using proton beams.

Nano-technology	Ion-cutting, Nano-particle shaping & fabrication, Carbon nano-tube, Nano-machining
Bio-technology	Mutations of plants, Mutations of micro-organisms
Space-technology	Radiation hard electronic device, Radiation effect on materials
Information technology	High power semiconductor, Semiconductor manufacturing R&D, Proton beam lithography
Medical research	Low energy proton therapy, Biological radiation effects, New RI production R&D
Material science	Proton irradiation effects, Gemstone coloring
Nuclear & particle physics	Detector R&D, Nuclear data

Proton beams are useful for cutting hard materials into thin films on the nanoscale. When a constant energy proton beam is irradiated onto a silicon wafer, they penetrate the silicon wafer and are deposited within a certain range, creating a weak layer in silicon which can be easily split into a very thin film. This can be an effective method to fabricate silicon-on-insulator wafers.

The structure of DNA can be changed by the proton beam irradiation through energy transfer processes. New genetic resources can be formed by such mutations. Two application studies are under way: one is concerned with the mutation of plants, such as vegetables and flowers, and the other with of micro-organisms, such as escherichia coli for producing plastics, such as polyhydroxybutyrate.

Protons beams of moderate energy can reproduce the radiation environment in space and then are used to study the radiation effects on silicon-based electronic device and materials of a spacecraft. We have several projects investigating the radiation effects on the silicon-based electronic components. A project recently discovered a very interesting property of CNT-based transistor via proton irradiation experiments, which shows a consistent radiation harness of the CNT under wildly varying the radiation conditions [9]. Recently, a user program discovered a key mechanism of the ferromagnetism of graphite by irradiating high energy proton beams [10].

Proton beam irradiation and subsequent annealing modify the optical properties of gemstones, such as diamond and ruby; for examples, such processing changed the diamond color from white to purple and decolorized ruby by probably interacting the impurities and the defects.

THE EXTENSION PLANS

We are drawing a post-PEFP plan to extend the accelerator capability and its utilization scopes in reflection of user demands and future trends of HPPA. Active research fields in Korea, which require a HPPA, are nuclear and high-energy physics facility, spallation neutron source, radioisotopes and medical research facility, accelerator driven system research facility, etc. As an option study, we have focused on radioisotope production and medical research facility, and spallation neutron source.

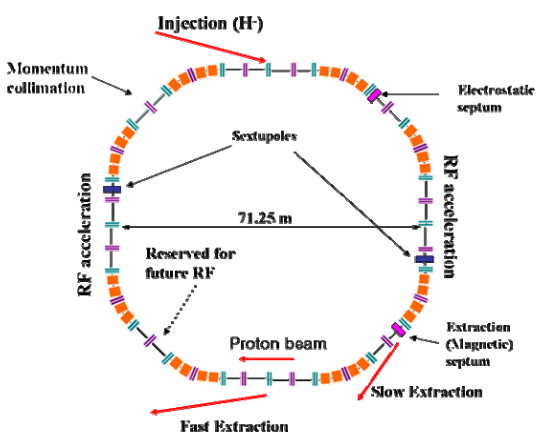

Figure 11: Conceptual design of the proposed RCS.

Table 5: Proposed machine parameters

Rapid cycling synchrotron	
Beam power	44-800 kW
Injection energy	0.1-0.2 GeV
Extraction energy	1-2 GeV
Repetition rate	15-60 Hz
Injector	
Beam energy	100-200 MeV
Beam current	20-40 mA
Duty	8-10 %

A rapid cycling synchrotron (RCS) with the extraction energy 1-2 GeV and injection energy 0.1-0.2 GeV would be an optimal machine to support both the spallation neutron source and radioisotope production and medical research facility. We have designed an RCS, as shown in Fig. 11, with some parameters summarized Table 5. The proposed machine has unique features of the fast extraction for the spallation neutron source application and the slow extraction for the radioisotope productions and medical applications. In addition, the RCS is designed to have upgrade option of the beam power from 44 kW to 800 kW step by step. A superconducting cavity linac is considered as an option for the high energy part of the 200 MeV injector of the RCS [11].

CONCLUSIONS

The PEFP launched by the Korean government in 2002 has the goals to develop a 100 MeV proton linear accelerator and the user programs to utilize the proton beams. A 20 MeV linac, the upstream part of the PEFP 100 MeV proton linac, has been successfully developed and integrated, including its low level RF control and beam diagnostic systems. The high energy part the accelerator, beam lines and user facilities are under development.

The site preparation and construction works are in progress in cooperation with the local government of Gyeongju city to start the ground-breaking and construction in 2007. The design of the accelerator building and conventional facilities are under way.

In parallel, the PEFP user program supports 23 projects to foster and widen the proton beam utilization and application. A beam line facility with a 50 MeV cyclotron at KIRAMS was set up to support the on-going user programs. Some of the user programs have produced promising results which show a great potential of utilizations and applications with proton beam irradiation.

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