The Proton Engineering Frontier Project [1]

K. Y. KIM [1], Y. S. CHO [1], B. H. CHOI [1], J. Y. KIM [1], K. R. KIM [1], J. W. PARK [1]

[1] Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

Email contact of main author: ky@kaeri.re.kr

Abstract. The Proton Engineering Frontier Project was launched, in 2002, to establish an advanced research facility based on a high power 100 MeV, 20 mA proton linac, and to cultivate and expedite core scientific and industrial R&D programs by utilizing high quality proton beams. The upstream part of the proton linac, up to 20 MeV, has been developed and commissioned to meet the designed performance in beam energy and peak beam current. The high energy portion of the linac is under development and the full system is to be completed by 2012. Besides developing the proton linac, a dedicated user program has been developed to nurture and foster scientific and industrial R&D by utilizing proton beams, and made promising progresses in the wide range of R&D fields, from basic science to industrial applications. The paper reports the status of the proton linac development and progresses made by the user program. In addition, the future expansion options and related R&D activities is briefly described.

1. Introduction

Various proton accelerators have been developed and utilized as sources of proton beams or secondary particles, such as neutrons, radioisotopes, photons, muons, or neutrinos, which have been used as practical and efficient means to probe or manipulate the substructure or underlying phenomena of materials on the atomic or smaller scale. High current proton accelerators, with energy around 10 MeV, are beneficial in practical applications, such as ion-cutting, power semiconductor fabrication, mine detection, boron neutron capture therapy, and neutron radiography. Low current proton accelerators with moderate energy from 10 to 250 MeV are effectively used in biological and medical researches and applications, for example, mutations of plants or micro-organisms, proton therapy, and radioisotope production. High power proton accelerators with energy around a few GeV are widely utilized in spallation neutron sources, radioisotope beam facilities, and accelerator-driven systems. Even higher energy proton accelerators are employed in nuclear and high energy physics to probe the fundamental phenomena and to understand the origin and evolution of the universe.

Korean government launched the Proton Engineering Frontier Project (PEFP), in 2002, to realize potential applications of the high intensity proton beams in the wide range of research fields to secure the cutting-edge technologies and develop advanced materials required to maintain her competitiveness in science and technology. The primary goal of the project is to develop a high power 100 MeV, 20 mA proton linac and beam facilities, with which users can access the proton beams with wide ranges of energies and currents for their research and development projects. In addition, the PEFP accelerator can be exploited as a proton driver for various applications in the low to medium energy range, or as an injector for a high energy proton accelerator in the future.

2. The PEFP Proton Accelerator

The PEFP proton accelerator consists of a 50 keV injector, a 3 MeV radio frequency quadrupole (RFQ) linac, and a 100 MeV drift tube linac (DTL), as schematically shown in

[1] Supported by Ministry of Education, Science and Technology, Republic of Korea.

Figure 1. The 100 MeV DTL is designed to have two separated parts: the low energy part, called as DTL-I which consists of four tanks, accelerates the 3 MeV proton beam to 20 MeV with the maximum beam duty of 24%, and the high energy part, called as DTL-II which consists of seven tanks, boosts the 20 MeV proton beam up to 100 MeV with the nominal beam duty of 8%. In between DTL-I and DTL-II, a medium energy beam transport (MEBT) system is implement in order to extract the 20 MeV proton beams and to match the 20 MeV proton beams to the DTL-II. Table I summarizes some major specifications of the PEFP proton accelerator [1].

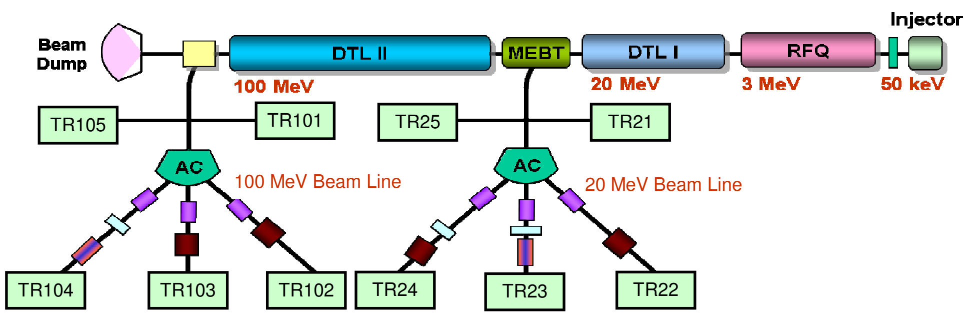

FIG. 1. Schematics of the PEFP 100 MeV linac and beamline facilities.

TABLE I. SPECIFICATIONS OF THE PEFP PROTON LINAC.

Parameters	**RFQ**	**DTL-I**	**DTL-II**
Operation Frequency (MHz)	350	350	350
Output Energy (MeV)	3	20	100
Max. Peak Current (mA)	20	20	20
Max. Beam Duty (%)	24	24	8
Max. Average Beam Current (mA)	4.8	4.8	1.6
Max. Pulse width (ms)	2	2	1.33
Max. Repetition Rate (Hz)	120	120	60
Max. Beam Power (kW)	14.4	96	160

We have developed the 50 keV injector, 3 MeV RFQ, and 20 MeV DTL, which have been successfully integrated and installed at Korea Atomic Energy Research Institute, as shown in Figure 2. Licensed its operation in 2007 with the limited conditions simply because of the inadequate radiation shielding, we have performed test and commissioning operations, and achieved its performance goals in beam energy and peak beam current, as shown in Figure 3 [2]. To meet increasing demands of the proton beams, we have installed a target station at the end of the 20 MeV accelerator and supplied the proton beams to the users while performing test and commissioning operations. With improving radiation shielding, we have revised the operation conditions and provided the users with the proton beams to perform hundreds of irradiation experiments annually.

The fabrication of the high energy part of the PEFP 100 MeV accelerator is in progress. We have fabricated and assembled three DTL tanks, corresponding to the accelerating energy range from 20 to 57 MeV, and performed low power RF tests for those DTL tanks. The remaining parts are also being fabricated as scheduled [3].

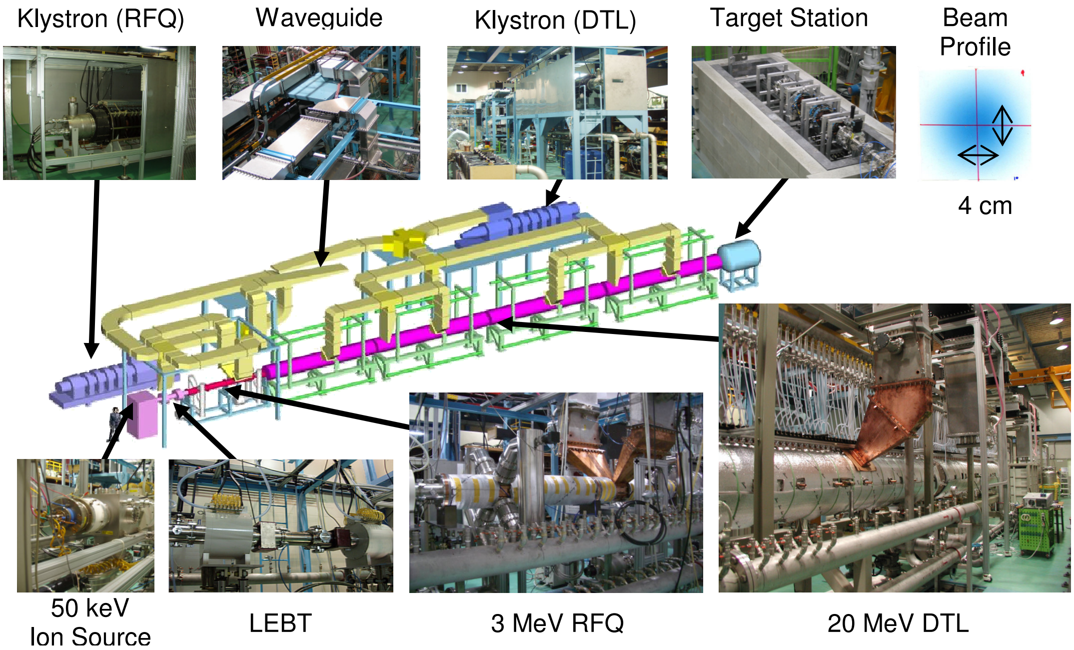

FIG. 2. The PEFP 20 MeV proton accelerator installed at KAERI.

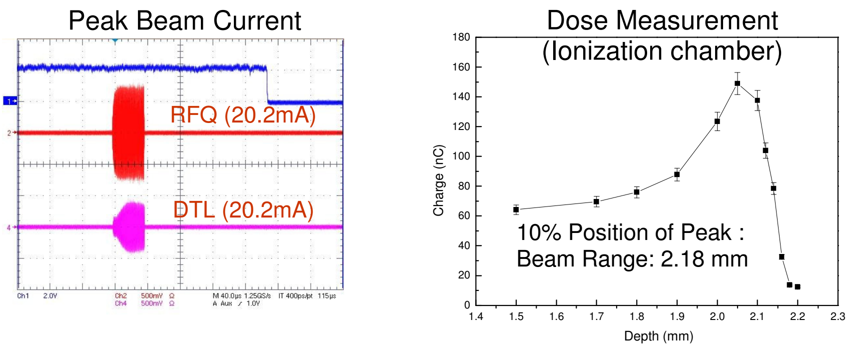

FIG. 3. Beam currents measured at the end of the RFQ and DTL (left), and beam energy measured at the end of DTL-1(right).

3. Beamlines and User Facilities

One of the main goals of the project is to develop the beamlines and user facilities. To meet the user demands as much as possible, the PEFP focuses on efficient utilizations of the proton beams, to supply protons with different conditions, to provide multi-users with the high quality of proton beams. To provide proton beams with the wide range of beam energies, currents and beam time, it is essential to extract a low energy beam of 20 MeV and a high energy beam of 100 MeV, and to distribute the beams to the multiple beamlines. Figure 4 shows the 3-D design of the PEFP beamlines [4]. Either 20 MeV or 100 MeV proton beam is delivered to five target rooms with dedicated beam conditions in beam currents, repetition rates, irradiation methods, and so on, as listed in Table II. The nominal beam conditions of each beamline have been determined by categorizing the accumulated requirements by the proton beam users in the wide range of research fields supported by the PEFP user programs.

The beamline components and instruments have been designed and the quadrupole magnets and beam distribution magnets have been fabricated.

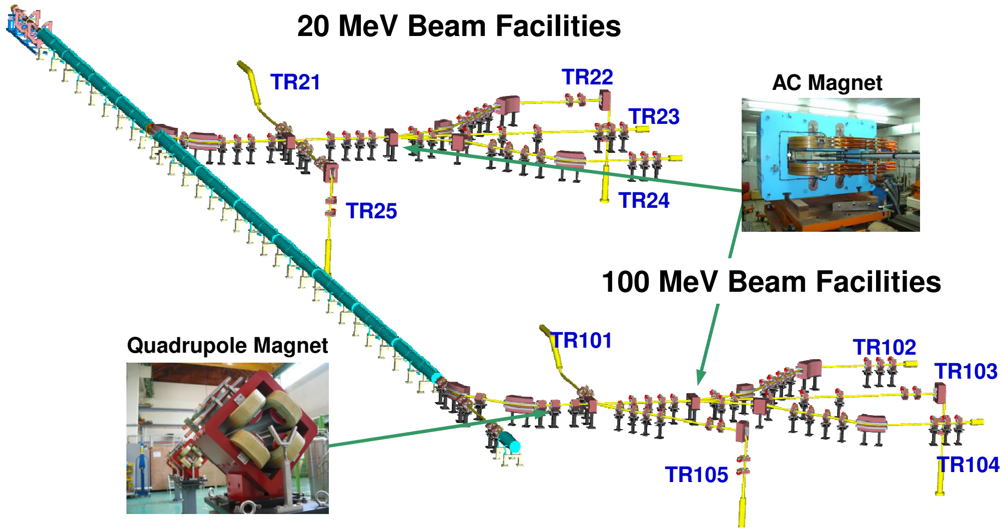

FIG. 4. The PEFP 20 and 100 MeV beam facilities.

TABLE II. SPECIFICATIONS OF THE PEFP 20 MeV AND 100 MeV BEAM FACILITIES.

Target Room	Application Fields	Rep. Rate (Hz)	Max Avg. Current (mA)	Ref. Target
TR21	Semiconductor Fabrication	60	0.6	Si
TR22	Biotech, Medical Application	15	0.06	H_2O
TR23	Materials, Energy & Environment	30	0.6	Si
TR24	Basic Science	15	0.06	Si
TR25	Radio Isotopes Production	60	1.2	H_2O(Liquid)
TR101	Radio Isotopes Production	60	0.6	Ag (Solid)
TR102	Medical App.(Proton therapy)	7.5	0.01	H_2O
TR103	Materials, Energy & Environment	15	0.3	Si
TR104	Basic Science, Aero-Space Tech.	7.5	0.01	Si
TR105	Neutron Source, Irradiation Test	60	1.6	W

4. Construction Works

The project host site was selected, in January 2006, to be *Gyeongju* city located in the south-eastern part of Korea. Since completing detailed geological surveys and site plan, facility layout, site improvement and access road are under engineering. General arrangements of the accelerator tunnel and beam experiment buildings have been completed along with setting up interface requirements for utility of conventional facilities as shown in Figure 5. The architectural designs of conventional facilities to supply utilities have been completed. Gyeongju municipal government is planning for construction works in close cooperation with the PEFP. The ground breaking is planned to be in May 2009.

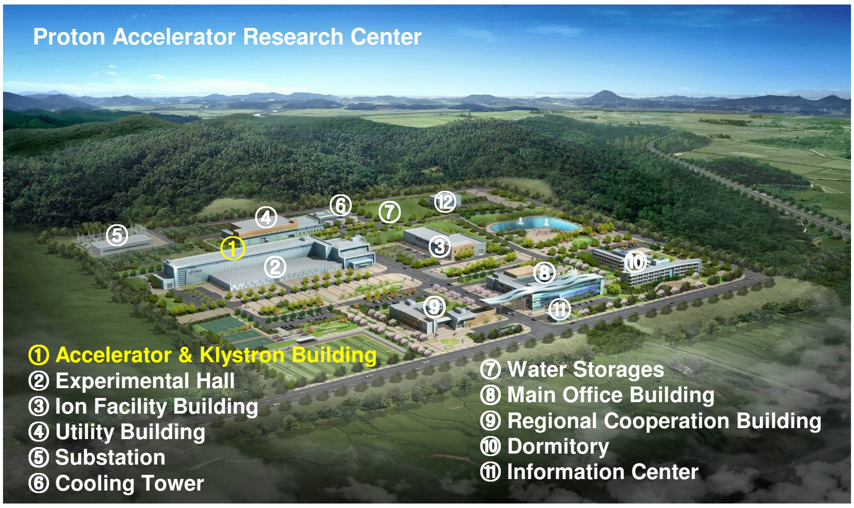

FIG. 5 Bird's eye view of the Proton Accelerator Research Center.

5. Beam Utilization and Applications

The PEFP has developed its user programs to pioneer new research fields by using proton beams, to promote basic researches on proton beam utilization, to reflect the user demands to the PEFP facility design, and to foster the user community in Korea. The PEFP has formulated a network of domestic and abroad beam facilities to support user programs with low to medium energy proton beams. To develop and test the beamline instruments, we have developed a 45 MeV beam facility at the MC-50 cyclotron at Korea Institute of Radiological and Medical Science (KIRAMS) [5], which has severed a majority of the researches performed through the user programs for several years. To meet the increased demands of high intensity proton beams, we has developed and installed a target station at the end of the PEFP 20 MeV proton accelerator. With the two beam facilities, shown in Figure 6, the users perform about 1,500 irradiation experiments annually in the wide range of research fields.

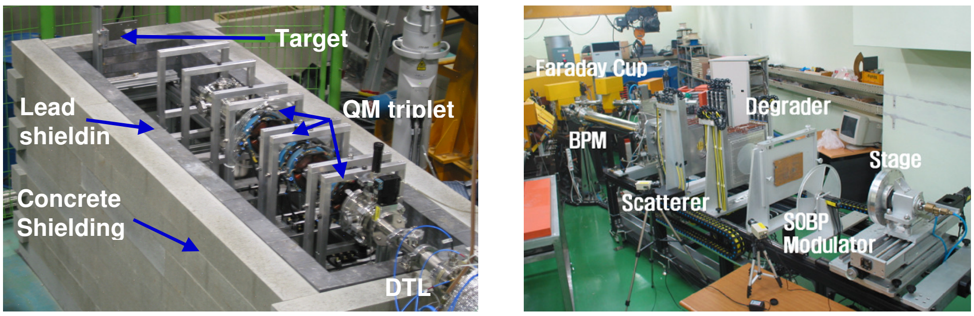

FIG. 6. The 20 MeV beam facility installed at the PEFP 20 MeV accelerator (left) and the 45 MeV proton beam facility at KIRAMS (right).

Listed in Table III are on-going activities in the leading research fields, which have produced promising results. In nano sector, the proton beam with the fine energy and does control is an effective means to fabricate Si-on-insulator (SOI) and GaAs-on-insulator (GOI) wafers [6]. We have developed a technology to stack multiple SOI layers, which can be used in fabricating the next generation display device such as SiLM. We have intensive research programs focusing on the fabrication of nano-particles, such as gold, silver and platinum, and development of advanced materials to be used in nano-logic elements by proton beam irradiation [7]. In information sector, we have observed that the proton irradiation can control the charge carrier lifetime of semiconductors. With irradiating proton beams, the switching speed of a fast recovery diode was improved by more than a factor of five.

TABLE III. ACTIVE RESEARCH FIELDS BY USING PROTON BEAMS.

Nano technology	SOI & GOI wafer fabrication, Nano particle fabrication, Nano logic element fabrication
Information technology	High power semiconductor, Semiconductor manufacturing R&D
Bio technology	Mutations of micro-organisms and plants
Medical application	Low energy proton therapy, Biological radiation effects, Radioisotope production R&D
Energy & Environment	Fuel cell membrane & Solar cell materials, Preprocessing of biomass
Advanced materials	Functional materials, Gemstone coloring
Space technology	Radiation durability test of space components, Simulation of space radiation environments
Nuclear & particle physics	Detector R&D, Nuclear data

In bio sector, we have started to run a special program, in cooperation with Korea Research Institute of Bioscience and Biotechnology, to study the mutation mechanism of microorganism by proton beam irradiation and to set up a research hub for proton beam induced mutagenesis. In medical applications, we have developed an *in-vivo* facility to perform a systematic study of the low energy proton therapy. In addition, we have supported a program to develop new radio isotopes, to be used in medial applications, by the intense high energy proton beam.

Protons beams of moderate energy effectively reproduce the space radiation environment and then are used to study the radiation effects on silicon-based electronic device and materials of a spacecraft. A project recently discovered a very interesting property of CNT-based transistor via proton irradiation experiments, revealing a consistent radiation harness of the CNT under the harsh radiation conditions [8]. Recently, a user program discovered a key mechanism of the ferromagnetism of graphite by irradiating high energy proton beams [9].

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.

6. Expansion options of the PEFP Accelerator

We are drawing a post-PEFP plan to expand the accelerator capability and its utilization scopes by reflecting the user demands. Active research fields in Korea, which require a high power proton accelerator, are nuclear and high energy physics facility, spallation neutron source, radioisotopes and medical research facility, accelerator driven system research facility, and so on. As an option, we have focused on radioisotope production and medical research facility, and spallation neutron source.

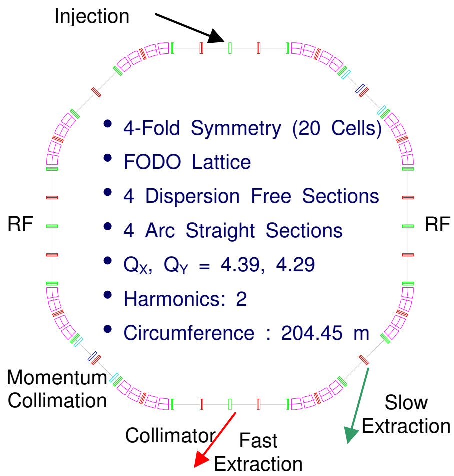

FIG. 7. Conceptual design of the proposed RCS.

TABLE IV. PROPOSED MACHINE PARAMETERS.

Beam power	60 - 500 kW
Injection energy	0.1 - 0.2 GeV
Extraction energy	1 - 2 GeV
Repetition rate	15 - 60 Hz

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 a spallation neutron source and radioisotope production and medical research facility. We have designed an RCS, as shown in Figure 7, with some parameters summarized Table IV [10], to have both a fast extraction system for a spallation neutron source and a slow extraction for a radioisotope production medical application facility. The proposed RCS has an upgrade option of the beam power from 60 kW to 500 kW step by step. In addition, we have active R&D programs to develop a superconducting RF linac [11], a high power RF source [12], and a spallation target in cooperation with MEGAPI at PSI, and made remarkable progresses.

7. Concluding Remarks

The PEFP, launched by the Korean government in 2002, has the goals to develop a 100 MeV proton linac 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, beamlines and user facilities are under development.

The site preparation and construction works are in progress in cooperation with the municipal government of Gyeongju city to start the ground-breaking and construction in 2009. The design of the accelerator building, beam experimental hall and conventional facilities has been completed.

The PEFP user program has supported numerous projects to foster and diversify the proton beam utilization and applications, and has produced promising results, realizing great potentials of practical and industrial utilization and applications of the proton beams.

8. References

[1] Y. S. Cho, et al., “The PEFP 20-MeV Proton Linear Accelerator,” J. of Korean Phys. Soc., **52** (2008) 721.

[2] Hyeok-Jung Kwon, et al., “Beam Test Results of the PEFP 20 MeV Proton Accelerator at KAERI Site,” XXIV Linear Accelerator Conference, Victoria, Canada (2008).

[3] H. S. Kim, et al., “Fabrication Status of PEFP DTL II,” EPAC’08, Genoa, Italy (2008).

[4] In-suk Hong, et al., “Conceptual Design of the PEFP Beamline,” EPAC’08, Genoa, Italy (2008).

[5] S. P. Yun, et al., “Development of the Proton Beam Monitoring System at the 45-MeV Proton Irradiation Test Facility,” J. of Korean Phys. Soc., 52 (2008) 783.

[6] H. J. Woo, et al., “Development of Ion-Beam Nano-Structuring Techniques in KIGAM,” J. of Korean Phys. Soc., **52** (2008) 743.

[7] T. H. Lee, et. Al., “Piezoelectric Effect on the Electronic Transport Characteristics of ZnO Nanowire Field Effect Transistors on Bent Flexible Substrates,” Advanced Materials, **20** (2008) 4557.

[8] Woong-Ki Lee, et al., Nanotechnology, 17 (2006) 5675.

[9] Kyu Won Lee and Cheol Eui Lee, Phys. Rev. Lett., **97** (2006) 137206.

[10] Ji-Ho Jang, et al., “Beam Optics Design of the PEFP RCS,” The 12th International Workshop on Accelerator and Beam Utilization, Gyeongju, Republic of Korea (2008).

[11] Sun An, Y. S. Cho and B. H. Choi, “Status of the PEFP Superconducting RF Project,” EPAC’08, Genoa, Italy (2008).

[12] Bo-Hyun Chung, et al., “A CW K-Klystron of 700 MHz and 1 MW for PEFP,” J. of Korean Phys. Soc., **52** (2008) 761.