THE KOREAN PROTON ENGINEERING FRONTIER PROJECT*

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Abstract

The proton engineering frontier project (PEFP) is the first high power proton linac development project in Korea. The main purposes are developing 100-MeV proton linac and supplying 20-MeV and 100-MeV proton beams to user groups. The 20-MeV part of the linac with 24% beam duty has been successfully installed and tested at the KAERI site. Now we are supplying 20-MeV proton beams to users in a restricted beam condition. The fabrication of the remaining part of the DTL with the beam duty of 8% is in progress. The PEFP user facilities include 5 beam lines for 20-MeV and 100-MeV beams, respectively. The results of beam utilization surveys are used to determine the main purpose and beam requirement for each beam line. The characteristics of the PEFP beam supplying system are using AC magnets in order to distribute proton beams into several beam lines. At the same time, the PEFP concentrates on developing the potential user group of the high intensity proton beams. Several beam utilization programs are under way for this purpose. The civil construction is scheduled to start in spring 2009. The present status and progress of the project are summarized in detail.

INTRODUCTION

The proton engineering frontier project (PEFP) was approved and launched by the Korean government in July 2002. The final goals of the project are constructing a proton linear accelerator with the final energy of 100 MeV and the peak beam current of 20 mA, developing technologies for the proton beam utilizations and the accelerator applications, and promoting industrial applications with the developed technologies.

A high power proton accelerator can produce high-intensity beams of protons and secondary particles including neutrons, radionuclei, mesons, neutrinos, etc. Such intense beams can be used to understand and manipulate the properties of materials on the molecular and atomic scales for both academic and industrial purposes. As shown in Figure 1, proton beams can be used in various fields of interest and have potential application area with a wide range of energy and current. In the low energy region less than 10MeV, high-current proton beams are useful in industrial and defence application, such as ion-cutting, power semiconductors, mine detection, boron neutron capture therapy, and neutron radiography. In the medium energy region between 10 and 250 MeV, low current proton beams are useful in biological and medical research, for example, in studies on mutations in plants and microorganisms, in neutron and proton therapy, and in radioisotope production. High-power proton beams with energies around 1 GeV have great potential as spallation neutron sources, radioactive nuclei beams, uses in nuclear physics experiments, and in accelerator-driven systems. In the higher energy region, main application area is a basic science such as nuclear physics and high-energy physics.

The primary goal of PEFP is to develop a 100-MeV, 20mA proton linear accelerator and to supply 20-MeV and 100-MeV proton beams. This proton driver can be applied to various applications in the low- to medium-energy range, or can be an injector for a high-energy proton machine in the next stage of development.

This brief report summarizes the present status of the PEFP, including the progress in accelerator development, the construction of the utilization facilities, and the development of user programs.

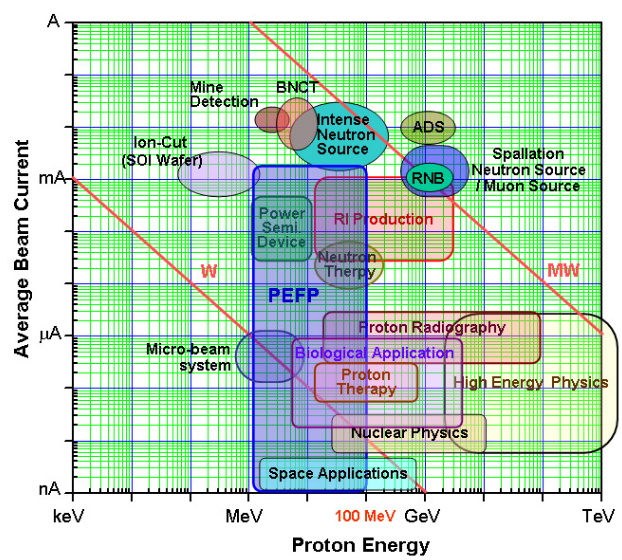

Figure 1: Utilization and application of proton beams depending on energy and current: the PEFP linac can cover the shaded (blue) region.

ACCELERATOR DEVELOPMENT

The PEFP proton linear accelerator consists of two parts. The low energy part includes an ion source, a low energy beam transport (LEBT), a 3-MeV radio frequency quadrupole (RFQ), and a 20-MeV drift tube linac (DTL) [1]. The high energy part consists of seven DTL tanks which accelerator proton beams from 20 MeV to 100 MeV. The 20-MeV linac system has been successfully installed and tested at the KAERI site. The remaining DTL tanks are under fabrication and test. A medium energy beam transport (MEBT) system will be installed after the 20-MeV DTL. It includes a 45-degree

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bending magnet in order to extract 20-MeV proton beams. 100-MeV proton beam will be guided into beam lines by another 45-degree dipole magnet which is located after the last DTL tank. The schematic plot of the PEFP linac and beam lines is given in Figure 2. The basic parameters of the linac are summarized in Table 1.

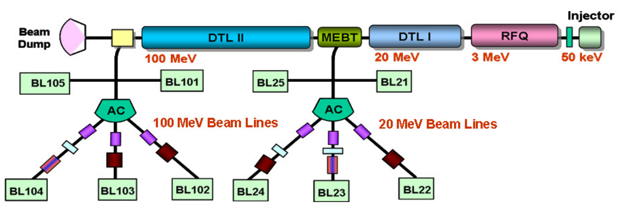

Figure 2: Schematic plot of the PEFP linac and beam lines.

Table 1: Basic parameters of PEFP linac

Parameter	Value
Particle	Proton
Beam Energy	100 MeV
Operation Mode	Pulsed
Max. Peak Current	20 mA
Pulse Width	<1.33 ms (< 2.0 ms up to 20 MeV)
Max. Beam Duty	8% (24% up to 20 MeV)

Injector

The injector part of the PEFP linac includes a duoplasmatron H^+ ion source, and an LEBT as shown in Figure 3. The beam extraction system of the ion source has been tested up to 60 kV when the pressure of the vacuum chamber was less than 2×10^{-6} torr. The beam current extracted from the source reached up to 50 mA at a voltage of 50 kV using a 150 V, 10 A arc power. 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 15 Hz pulsed operation, a high-voltage switch will be installed in the LEBT system, whose rising and falling times are less than 50 ns. The LEBT consists of two solenoid magnets and a 211 cm diameter beam line. The estimated transmission efficiency is 92%, with a variable beam current from 10 to 50 mA.

RFQ

The PEFP RFQ is designed to accelerate 20 mA proton beams from 50 keV to 3 MeV. It is the usual four-vane type. The entire structure with four sections is separated into two segments that are resonantly coupled for the field stabilization. The RF power is fed into the cavity through two iris couplers in the third section as shown in Figure 4. The main design parameters of the PEFP RFQ are summarized in Table 2.

20-MeV DTL

The PEFP 20 MeV DTL consists of four tanks that accelerate 20 mA proton beams from 3 MeV to 20 MeV as shown in Figure 5. The total length of the DTL is about 20 m. A 1 MW klystron supplies RF power into the four tanks. The FFDD lattice configuration has a magnetic field gradient of 5 kG/cm, and an effective field length of 3.5 cm. The DTL parameters are given in Table 3.

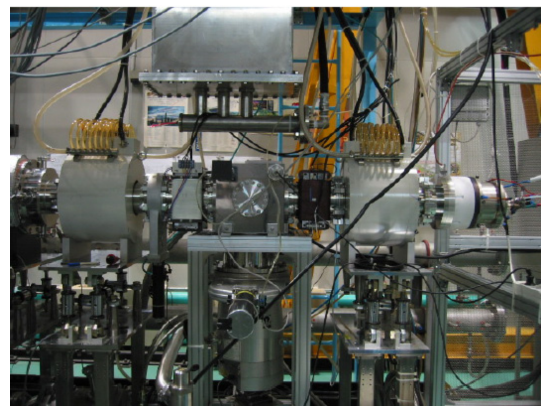

Figure 3: PEFP injector system including an ion source and a low energy beam transport.

Table 2: PEFP RFQ parameters

Parameters	Values
Frequency	350 MHz
Input / Output Energy	21 mA / 20 mA
Input / Output Current	50 keV / 3 MeV
Peak Surface Electric Field	1.8 Kilpatrick
Power	465 kW Cu =400 kW, Beam = 65 kW
Transmission Rate (design)	98.3%
Length	325 cm

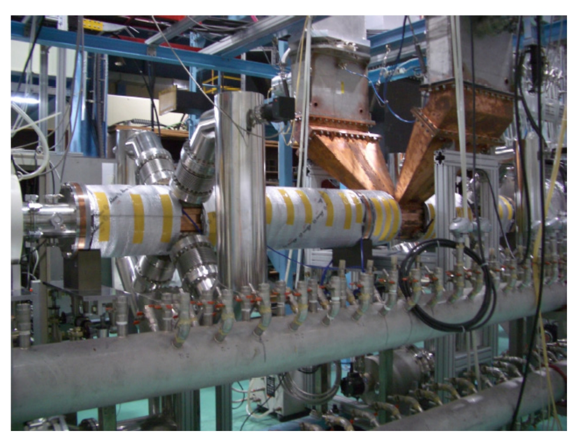

Figure 4: PEFP 3-MeV RFQ.

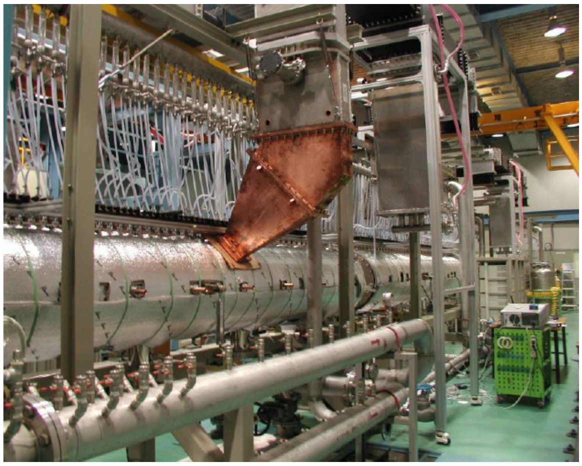

Figure 5: PEFP 20-MeV DTL.

Table 3: PEFP 20-MeV DTL parameters

Parameter	Values
Frequency	350 MHz
Input / Output Energy	3 MeV / 20 MeV
Peak Current	20 mA
Length	4.44 ~ 4.78 m
Input / Output Emittance	
Transverse:	0.23 / 0.23 π mm-mrad
Longitudinal:	0.11 / 0.15 deg-MeV

Beam Experiment

In order to study 20-MeV proton beam properties, a small target station was installed at the end of 20-MeV DTL tanks as shown in Figure 6. Under the local shielding around the room, the allowed average beam current is 1.0 µA with the repetition rate of 1 Hz and the pulse width of 50 µs. The target station includes triplet quadrupole magnet for beam manipulation. Figure 7 shows the beam current signals measured at the ends of the 3-MeV RFQ and the 20-MeV DTL. The peak beam currents are 20.2 mA which is slightly larger than the design values.

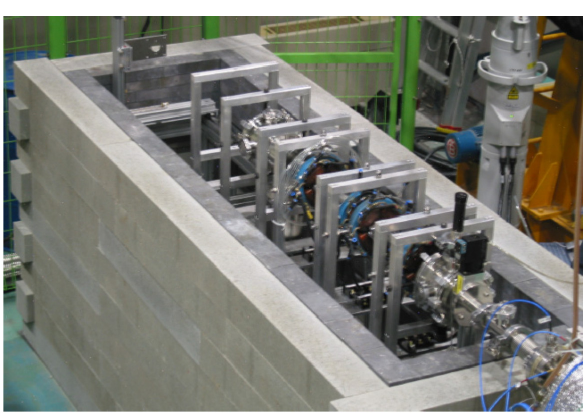

Figure 6: Target station for 20-MeV proton beam test.

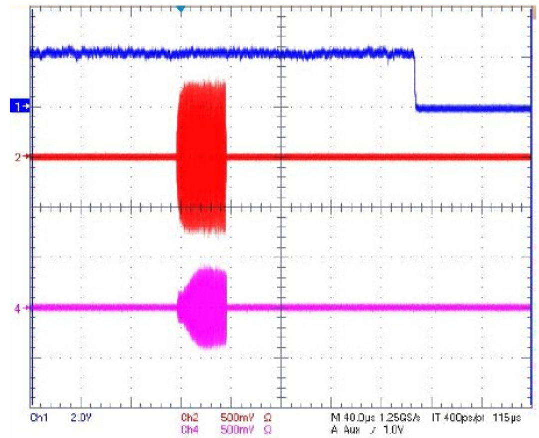

Figure 7: Beam current at the ends of the 3-MeV RFQ (middle, red) and the 20-MeVDTL (low, pink): peak beam current of 20.2 mA.

Development of 100-MeV DTL [2]

The PEFP 100-MeV DTL consists of seven tanks which accelerates proton beams form 20 MeV to 100 MeV. The beam duty is 8% in the 100-MeV DTL and a 1.6 MW pulsed klystron drives one tank. Each tank separated into 3 sections for easy assembling. The length of each tank is about 6.7 m. The lattice structure is FFDD and the integrated field is 1.75 T for a quadrupole magnet in the tanks. The hollow conductor is used for the quadrupole magnets. On the other hand the 20-MeV DTL uses pool-type magnets. Figure 8 shows the drift tube and the quadrupole magnet which were installed in the first 100-MeV DTL tank. In the field measurement by using rotating coil the design value of the qudrupole filed can be achieved at the current of 412A. Until March 2008, two DTL tanks were fabricated and assembled as shown in Figure 9. In order to align drift tubes into DTL tanks, two laser trackers are used and temperature is controlled. The allowed value of the alignment errors is 50 µm in transverse direction and achieved value was 40 µm. In the tuning process using slug tuners and post couplers, the field flatness of 1.5 % was achieved. The target value is was 2 %. Figure 10 shows the normalized field values before and after tuning process.

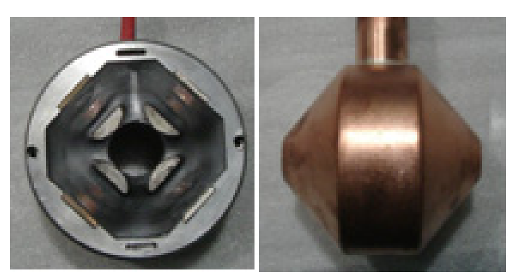

Figure 8: Quadrupole magnet and drift tube installed in the 100-MeV DTL tank.

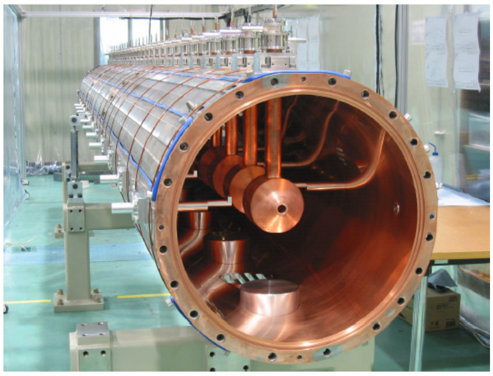

Figure 9: 100-MeV DTL tanks which is assembled at the KAERI site.

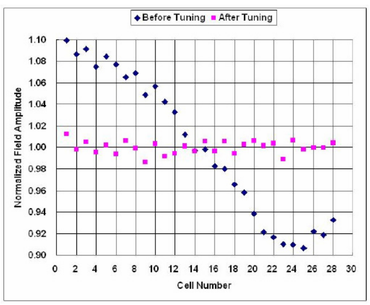

Figure 10: Normalized electric fields before and after tuning.

PEFP BEAM LINES

The PEFP user facilities include 20-MeV and 100-MeV beam lines as shown in Figure 11 [3]. The extracted proton beams are distributed into 5 target rooms, respectively. The main characteristics of PEFP beam lines is using AC magnets to distribute proton beams into 3 target rooms in both 20-MeV and 100-MeV beam lines.

A user survey of domestic demand for proton beams shows that many users require proton beams with a wide range of energy, current, and pulse widths to control the irradiation depth, dosage, and temperature. To meet these requirements, beam lines in the user facility have to include a degrader for beam energy control, a collimator for flux control, and scanning magnets to ensure uniform irradiation. The main purposes of the target rooms were determined by the user survey. They are a radio-isotope (RI) production, a detector and space technology, a fuel cell and nano technology, a biological application, and a semi-conductor for the 20-MeV beam lines and an RI production, a low energy proton therapy, a nano-particle production, a detector and space technology, and a neutron source for the 100-MeV beam lines.

In the beam lines, two types of quadrupole magnets are used: effective length of 200 mm and 400 mm. Their integrated field values are 1 T and 2 T, respectively. The bending angles of the dipole magnets are 90, 45, and 25 degrees. The AC magnets bend proton beams into ±20 degrees. Their operating frequencies are 15 Hz and 7.5 Hz for 20-MeV and 100-MeV beam lines, respectively. In the beam optics calculation, we used an achromatic condition between first two 45-degree bending magnets, and between the AC and the next 25-degree bending magnets. The fabrication of the quadrupole magnets is in progress at the IHEP, China as shown in Figure 12.

The diameter of the beam window is 300 mm in order to meet the beam requirement. The AlBeMet (Al 38% and Be 62%) was adopted as the basic material for the beam window. The thermal and structure analysis are in progress.

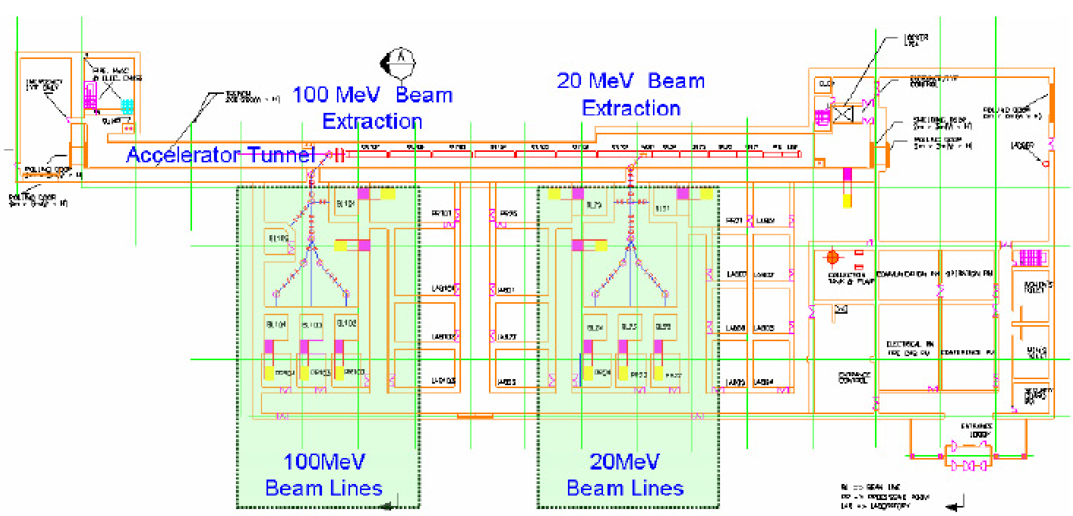

Figure 11: PEFP 20-MeV and 100-MeV beam lines.

PROTON BEAM UTILIZATION

An important goal of the project is to extend the application area of proton beams. The project is developing user programs to achieve this purpose. The goals are to develop new fields using proton beams, to promote basic research on proton beam utilization, to reflect the user demands of the PEFP facility design, and to expand the beam user group in Korea. The project has identified and supported a lot of basic research projects using proton or neutron beams since the project was launched. As a part of the program, workshops and technical meetings are held three or four times per year to exchange information on beam utilization technology. The work also includes construction of a user network, advertisement of the PEFP to foreign scientists at international conferences, and cooperation with foreign institutions in the user development program and beam utilization technologies.

The project is supporting several subprojects in the study and development of beam utilization and applications of protons at low and medium energies as shown in Table 4. These projects are presently using the available proton facilities including PEFP 20-MeV target station in domestic or foreign institutions. The important results of this program are as follows.

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 and IGBT were improved by more than five times.

Protons are useful for cutting hard materials into very thin films on the nanoscale. When a constant energy proton beam is irradiated onto a silicon wafer, the particles penetrate the silicon, and stop within a certain range in a high concentration. The resulting weak layer in the material can be easily split into a very thin film. This ion cut method can be used to make silicon-on-insulator or GaAs-on-insulator wafers.

The structure of DNA can be changed by proton beam irradiation through energy transfer processes. New genetic resources will 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 is concerned with mutations of microorganisms, such as *Escherichia coli* for producing bio-degradable plastics, such as polyhydroxybutyrate.

The low energy proton therapy (LEPT) is very effective way to treat eye melanoma and age-related macular degeneration. The system can be also a basic research tool to develop a proton therapy technologies. The project is developing an LEPT system using 70~100 MeV proton beams. The prototype was developed and installed at the MC-50 cyclotron beam line at KIRAMS.

Proton beams of moderate energy can reproduce the radiation environment in space and then are used to study the radiation effects on silicon-based electric 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 hardness of the CNT under widely varying radiation conditions [4]. A user program discovered a key mechanism of the ferromagnetism in graphite by irradiating high energy proton beams [5].

Proton beam irradiation and subsequent annealing process modify the optical properties of gemstones such as diamond and ruby. For example, the diamond color is changed from white to purple and the ruby is decolorized by the irradiation process. The mechanism should be related with the interaction of impurities and defects.

Table 4: User development program

Research Fields	Sub-categories
Nano technology	Ion-cutting, Nano-particle shaping & fabrication, Carbon nano-tube, Nano-machining
Information technology	High power semiconductor, Semiconductor manufacturing R&D, Proton beam lithography
Space technology	Radiation hard electronic device, Radiation effect on materials
Bio technology	Mutations of plants & micro-organisms
Medical research	Low energy proton therapy study, Biocompatible material, Biological radiation effects, New RI production R&D
Material science	Proton irradiation effects with various materials Gemstone coloration
Environment & energy	Bio-ethanol production study, New micro-organism development for bio fuel, New material for fuel cell ; electrolyte, nano catalyst, organic solar cell
Nuclear & particle physics	Detector R&D, Nuclear data, Thin Layer Activation

CIVIL CONSTRUCTION

Gyeongju city which is located in the south-eastern part of Korea hosted the project in January 2006. The geological surveys of the site and the site-dependent plan such as the facility layout and access road have been completed for the civil construction. The general arrangement of the accelerator and beam utilization buildings and conventional buildings are also completed. Figure 12 shows the bird's eye view of the PEFP accelerator center. Now the engineering design of each building is in progress.

Figure 12: Bird's eye view of the PEFP accelerator center.

The local government has a plan to provide conventional facilities for electric power, water, and other kinds of utilities in cooperation with PEFP. The construction schedule is summarized in Figure 13. The ground breaking is schedules in April 2009.

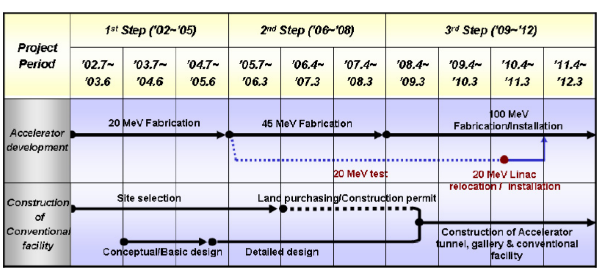

Figure 13: Construction schedule of the accelerator center.

THE EXTENSION PLANS

For future extension plans of PEFP, we are studying two options: a superconducting linac (SCL) and a rapid cycling synchrotron (RCS).

The 100-MeV proton linac can be an injector of an RCS whose extraction energy is 1-2 GeV [6]. The main purpose is a spallation neutron source with a fast extraction system. The RCS includes a slow extraction option which is used for radioisotope production, medical application, and basic science.

An SCL should be an optimal solution for extending the linac energy. We are now studying an elliptical cavity with the design beta of 0.42 [7]. It can be used to accelerate proton beams from 100 MeV to 200 MeV. The prototype of the copper cavity has been successfully fabricated and tested as shown in Figure 14.

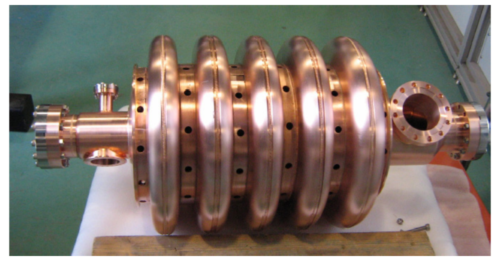

Figure 14: Copper model of PEFP low beta cavity.

CONCLUSIONS

The goals of PEFP launched by the Korean government in July 2002 are developing an 100-MeV proton linac and user programs for its utilization and application. The 20-MeV part of the linac has been successfully developed and tested at the KAERI site. The higher energy part (20~100 MeV) of the linac are under development. The PEFP user facilities include 20-MeV and 100-MeV beam lines. The magnets for the beam lines are under fabrication. The project also focus on the user program in order to increase the beam user group in Korea. Some programs have produced promising results which show a great potential of utilization and applications with proton beam irradiation. In cooperation with Gyeongju city, the site preparation and construction works are in progress. The design of the accelerator building and conventional facilities are under way.

REFERENCES

[1] Y.S. Cho, et. al, "The PEFP 20-MeV Protn Linear Accelerator", Journal of Korean Physical Society, 52 (2008) 721.

[2] Y.H. Kim, et. al., "Design and Fabrication of the PEFP DTL II", PAC'07, Albuquerque, TUPAN78, p. 1553 (2007); http://www.JACoW.org.

[3] I.S. Hong, et. al., "Conceptual Design of the PEFP Beam Line", EPAC'08, Genoa, THPP093, p. 3581 (2008); http://www.JACoW.org.

[4] W.K. Lee, et. al., Nanotechnology, 17 (2006) 5675.

[5] K.W. Lee and C.E. Lee, Phys. Rev. Lett., 97 (2006) 137206.

[6] B. Chung, et. al., "Conceptual Design of the PEFP Rapid Cycling Synchrotron", PAC'07, Albuquerque, THPMN046, p. 2817 (2007); http://www.JACoW.org.

[7] S. An, et. al., "Status of the PEFP Superconducting RF project", EPAC'08, Genoa, MOPP112, p. 820 (2008); http://www.JACoW.org.