Status of the PEFP:
A High Duty Proton Linac and Its Application

Byung-Ho Choi
on behalf of the Proton Engineering Frontier Project

* Supported by the Ministry of Education, Science and Technology of Korea.
I. Overview

II. Accelerator Development & Construction

III. Beam Utilization & Applications

IV. Activities for the Future Extension

V. Summary
Overview

- **Project: Proton Engineering Frontier Project (PEFP)**
  21C Frontier R&D Program, MEST, Republic of Korea

- **Objectives:**
  - To develop a High Power Proton Linac (100MeV, 20mA)
  - To develop Proton Beam Utilization & Accelerator Application Technologies
  - To support R&D Programs and industrialize Developed Technologies

- **Period:** July 2002 – March 2012 (10 years)

- **Budget:** 128.6 B KRW (Gov. 115.7 B, Private 12.9 B)
  (Gyeongju City: Land, Buildings & Supporting Facilities)
Schematics of PEFP Accelerator & Beamlines

Future Extension

100 MeV

DTL II

MEBT

DTL I

RFQ

Injector

TR105

TR101

TR25

TR21

AC

AC

TR104

TR103

TR102

TR24

TR23

TR22

100 MeV Beamlines

20 MeV Beamlines

Features of the PEFP linac

• 50 keV Injector (Ion Source + LEBT)
• 3 MeV RFQ (4-vane type)
• 20 & 100 MeV DTL
• RF Frequency : 350 MHz
• Beam Extractions at 20 or 100 MeV
• 5 Beamlines for 20 MeV & 100 MeV
  - Beam to be distributed to 3 BL via AC

<table>
<thead>
<tr>
<th>Feature</th>
<th>20 MeV</th>
<th>100 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Energy (MeV)</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Peak Beam Current (mA)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Max. Beam Duty (%)</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>Avg. Beam Current (mA)</td>
<td>4.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Pulse Length (ms)</td>
<td>2</td>
<td>1.33</td>
</tr>
<tr>
<td>Max. Repetition Rate (Hz)</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>Max. Avg. Beam Power (kW)</td>
<td>96</td>
<td>160</td>
</tr>
</tbody>
</table>
Layout of Accelerator Tunnel & Experimental Hall

1: RI Processing Lab
2: Bioengineering Lab
3: Biocell Analysis Lab
4: Activation Analysis Lab
5: Basic Science Lab
6: Radio-Medical Lab
7: Semiconductor Processing Lab
8: Material Analysis Lab
9: Nano-processing Lab
10: Detector R&D Lab
11: SRF Lab
12: RCS Lab
Status of Accelerator Development

- 20MeV: fully developed & installed and under routine operation
- 6 tanks up to 91 MeV: fabricated, partly tested & prepared
- 1 tank (91~102 MeV): under fabrication
 RFQ Design & Fabrication

- 350 MHz, 4 vane structure, 85kV constant voltage (1.8 Kilpatrick)
- 3.25 m long with resonant coupling and dipole stabilizer rods
- Established a full fabrication process with domestic companies

Design ➔ Vane machining ➔ Tuning before Brazing ➔ Brazing

Leak test (< 1e-9torr/l/s) ➔ Tuning

- Frequency : 349.931 MHz
- Q field : < ± 2%
- D field : < ± 5% of Q
3MeV RFQ Test

Set up for Test of RFQ

Remarks of RFQ test

- RFQ have been fabricated and tuned. (Aug., 2005)
- Full Peak Power RF test has been done. (Oct., 2005)
- Beam test up to 20mA has been done. (Mar., 2008)
- Routinely used for the beam acceleration. (Now)
### DTL Design

<table>
<thead>
<tr>
<th></th>
<th>DTL I</th>
<th>DTL II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (MeV)</td>
<td>3 → 20</td>
<td>20 → 100</td>
</tr>
<tr>
<td>Max. Beam Duty (%)</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>Max. Repetition Rate (Hz)</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>RF Frequency (MHz)</td>
<td>350</td>
<td></td>
</tr>
</tbody>
</table>

#### Beam Dynamics (PARMILA)

- **DTL I**
- **MEBT**
- **DTL II**

#### Emittance

- Transverse
- Longitudinal

#### Output Beam (PARMILA)

<table>
<thead>
<tr>
<th>Tank</th>
<th>E [MeV]</th>
<th>Cells</th>
<th>Length [m]</th>
<th>E0 [MV/m]</th>
<th>RF [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTL I</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>101</td>
</tr>
<tr>
<td>DTL II</td>
<td>7.18</td>
<td>11.50</td>
<td>15.80</td>
<td>20.00</td>
<td>33.1</td>
</tr>
</tbody>
</table>
• Established a full fabrication process; from design to field tuning, and RF test

Design of DTL
Machining (Acc <100 μm)
Copper Plating (Thickness < 100 μm)
Tank Assembling (Tolerance < ±100 μm)

DT alignment < 40 μm

Field Tuning < ±1.5 %
PEFP 20 MeV Linac Performance

- 20 MeV of front-end of 100 MeV was completed in 2005
- Extracted first beam (July 2005)
- Obtained operation license (June 2007)
- Started beam service (July 2007)
- Temporary service for users before moving to Gyeongju

Beam Current
- Designed: 20 mA (08.5.24)

Beam Energy: 20.33 MeV

Beam Range: 2.18 mm (10% position of peak)

Irradiated Samples
- 2007: 103
- 2008: 178
- 2009: 145

Refer to MOPD 050 & MOPE 036
MEBT (Medium Energy Beam Transport)

- **For 20 MeV Beam Extraction,**
  - ⇒ A Long Drift Space between DTL-1 and DTL-2 to place a bending magnet
  - ⇒ Beam phase matching issue
- **Solution:** 2 buncher cavities of 3 cells with 4 QMs
  - ⇒ QM for transverse matching, and RF for longitudinal matching

### MEBT tank parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell number</td>
<td>3</td>
</tr>
<tr>
<td>Cell Length</td>
<td>174.0 mm</td>
</tr>
<tr>
<td>Gap Length</td>
<td>35.5 mm</td>
</tr>
<tr>
<td>Tank Length</td>
<td>522.1 mm</td>
</tr>
<tr>
<td>Synchronous Phase</td>
<td>-90 deg.</td>
</tr>
<tr>
<td>Power for tank1</td>
<td>33 kW</td>
</tr>
<tr>
<td>Power for tank2</td>
<td>14 kW</td>
</tr>
</tbody>
</table>

### MEBT Tank Design
Beamline Development

• Completed design of beamlines by reflecting user’s requirement
• Different conditions; beam current, size, vacuum/external, hor./ver.
• Developed components (BM, QM, ACM & beam instruments)

<table>
<thead>
<tr>
<th>Beam Line</th>
<th>Application Field</th>
<th>Rep. Rate</th>
<th>Avg. Current</th>
<th>Irradiation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR21</td>
<td>Semiconductor</td>
<td>60Hz</td>
<td>0.6mA</td>
<td>Hor. Ext. 300mmØ</td>
</tr>
<tr>
<td>TR22</td>
<td>Bio-Medical Application</td>
<td>15Hz</td>
<td>60μA</td>
<td>Hor. Ext. 300mmØ</td>
</tr>
<tr>
<td>TR23</td>
<td>Materials, Energy &amp; Environment</td>
<td>30Hz</td>
<td>0.6mA</td>
<td>Hor. Ext. 300mmØ</td>
</tr>
<tr>
<td>TR24</td>
<td>Basic Science</td>
<td>15Hz</td>
<td>60μA</td>
<td>Hor. Ext. 100mmØ</td>
</tr>
<tr>
<td>TR25</td>
<td>Radio Isotopes</td>
<td>60Hz</td>
<td>1.2mA</td>
<td>Hor. Vac. 100mmØ</td>
</tr>
</tbody>
</table>

100 MeV Beamlines

<table>
<thead>
<tr>
<th>Beam Line</th>
<th>Application Field</th>
<th>Rep. Rate</th>
<th>Avg. Current</th>
<th>Irradiation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR101</td>
<td>Radio Isotopes</td>
<td>60Hz</td>
<td>0.6mA</td>
<td>Hor. Ext. 100mmØ</td>
</tr>
<tr>
<td>TR102</td>
<td>Medical Research (Proton therapy)</td>
<td>7.5Hz</td>
<td>10μA</td>
<td>Hor. Ext. 300mmØ</td>
</tr>
<tr>
<td>TR103</td>
<td>Materials, Energy &amp; Environment</td>
<td>15Hz</td>
<td>0.3mA</td>
<td>Hor. Ext. 300mmØ</td>
</tr>
<tr>
<td>TR104</td>
<td>Basic Science Aero-Space tech.</td>
<td>7.5Hz</td>
<td>10μA</td>
<td>Hor. Ext. 100mmØ</td>
</tr>
<tr>
<td>TR105</td>
<td>Neutron Source</td>
<td>60Hz</td>
<td>1.6mA</td>
<td>Ver. Vac. 100mmØ</td>
</tr>
</tbody>
</table>
Details of Beam Lines

- AC magnet with 7.5 Hz can distribute beam pulses to 3 beamlines successively
- 3 targets can provide beam simultaneously
 Beamline Key Components: AC Magnet & Programmable PS

AC Magnet for Beam Distribution

Programmable Power Supply

Specifications

<table>
<thead>
<tr>
<th></th>
<th>±20°</th>
<th>75</th>
<th>0.436</th>
<th>507</th>
<th>217.7</th>
<th>501.8</th>
<th>15</th>
<th>7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending angle</td>
<td>±20°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pole gap (mm)</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. B field (T)</td>
<td>0.436</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eff. length (mm)</td>
<td>507</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Current (A)</td>
<td>217.7</td>
<td>501.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Op. freq (Hz)</td>
<td>15</td>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

for 20 MeV for 100 MeV

Waveform of Power Supply
Beamline Key Components: Large Beam Window

**Beam Window**

- Concave type
- AlBeMet (38% Al, 62% Be)
- Diameter: 300 mm
- Thickness: 0.5 mm

**Vacuum Protection**
from window breaking
- Fast closing valve
- Closing time: 15ms
- Max. pressure rising: 3.8E-1torr@ 20m length
- 4.2E-2torr@ before accelerator
- Shock wave velocity: ~1km/s

**Frequency of beam pulse**: 15 Hz
**Duration of beam pulse**: 2ms

**Thermal Analysis**

- **Sensor module 1**
- **Sensor module 2**
- **Valve module**
- **Control module**

**Window breaking tool (1kg)**

- **Vacuum sensor 1**
- **Low pressure Gauge**
- **FCV**
- **Rotary Pump**
- **Angle valve**

**CH1 CH2**

**Specification**

- Concave type
- AlBeMet (38% Al, 62% Be)
- Diameter: 300 mm
- Thickness: 0.5 mm

**Controller**

- **Sensor module 1**
- **Sensor module 2**
- **Valve module**
- **Control module**
Target System Development

- **Target system for radioisotope production for high current & power beam**
  - Targeted RI: Sr-82, Cu-67, Ge-68 (target material: RbCl, ZnO, Ga)

- **Proton beam irradiation system with very large area**
  - Large & uniform beam (300mm dia.), In-situ beam monitoring, remote operation

Refer to MOPEA 070
Site Plan and Preparation for the PEFP

Proton Accelerator Research Center
Location: Gyeongju
Area: 44,000m²
Ground Breaking(’09.5) Completion(’12.3)

1 Accelerator Building
2 Experimental Hall
3 Ion Beam Facility
4 Utility Building
5 Substation
6 Cooling Tower
7 Water Storages
8 Main Office Building
9 Regional Cooperation Center
10 Dormitory
11 Information Center
12 Sewage Plant

Express Railway (Under construction)
Gyeong-bu Freeway
Application Fields with Proton Beams

- **Industrial applications**: ion-cut, power semiconductor devices
- **Medical applications**: BNCT, RI production, proton therapy
- **Biological applications**: mutation of plants and microorganisms, micro-beam system, etc.
- **Space applications**: radiation tests of space components and radiation effects, etc.
- **Defense applications**: mine detection, proton & neutron radiography
- **Intense neutron source**: radiation damage study, nuclear materials, target & modulator development, etc.
- **MW beam utilization areas**: - Spallation Neutron Sources - Muon Source - Radioactive Nuclei Beams - High Energy Physics (mesons, neutrinos)
### R&D Program using Proton Beam

### User Program Development (2003 ~)

<table>
<thead>
<tr>
<th>Research Fields</th>
<th>Sub-categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano Technology</td>
<td>Ion-cutting, Nano-particle fabrication, Carbon nano-tube, Nano-machining</td>
</tr>
<tr>
<td>Information Technology</td>
<td>High power semiconductor, Semiconductor manufacturing R&amp;D, etc.</td>
</tr>
<tr>
<td>Space Technology</td>
<td>Radiation hard electronic device, Radiation effect on materials</td>
</tr>
<tr>
<td>Bio-Technology</td>
<td>Mutations of plants and micro-organisms</td>
</tr>
<tr>
<td>Medical research</td>
<td>RI production, Low energy proton therapy study, Biological radiation effects, etc.</td>
</tr>
<tr>
<td>Materials Science</td>
<td>Proton irradiation effects with various materials, Gemstone colouring</td>
</tr>
<tr>
<td>Energy &amp; Environment</td>
<td>New materials for fuel cell, nano catalyst, organic solar cell, New μ-organism (bio fuel)</td>
</tr>
<tr>
<td>Nuclear &amp; Particle Physics</td>
<td>Detector R&amp;D, Nuclear data, TLA (Thin Layer Activation)</td>
</tr>
</tbody>
</table>

- **20 MeV Beam Facility @ KAERI**
  - Lead shielding
  - Concrete Shielding
  - QM (triplet)
  - DTI
  - Target

- **45 MeV beam facility @ KIRAMS**
  - Faraday Cup
  - BPM
  - Degrader
  - Scatterer
  - SOBP Modulator
  - Stage
Status of PEFP User Program

- Goals for the user program:
  - Build up a strong community of proton beam users
  - Diversify R&D fields by using proton beams

No. of Proton Beam Users

User Distribution (R&D Fields)

User Distribution (138 Institutions)

Irradiated Samples
(20 MeV Linac, MC-50 @ KIRAMS)
R&D Activities (I) – Nano

- Fabrication of metallic nano-particles; Gold, Platinum, Silver etc
- Fabrication of Hybrid Nano-Logic Device - n-type nanowire + p-type nanotube

- Silver nano particle (SEM Images)

- Silver nano crystal (Flower) formation

Refer to MOPEA 069
R&D Activities (II) - Medical

Medical RI Production

- Medical RI production using high energy (100MeV) and high current proton beam
- Mass production of many kinds of RI
- Substitution for imported RI

RI products and their applications

Medical RI available

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>RI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low energy (&lt;20MeV)</td>
<td>F-18, C-11, O-15, N-13, Pd-103</td>
</tr>
<tr>
<td>Medium Energy (30~100MeV)</td>
<td>TI-201, Ga-67, I-123, I-124, In-111, Co-57</td>
</tr>
<tr>
<td>High Energy (&gt;100MeV)</td>
<td>Al-26, Mg-28, Si-32, Be-7, Na-22, Ge-68, Sr-82, Tc-95, Cu-67</td>
</tr>
</tbody>
</table>

Low Energy Proton Therapy

- Proton therapy machine & technology
- Basic study of proton therapy
- Facility for radiation biological R&D
- Study of proton therapy for eye tumors

Principle of Eye therapy

Refer to MOPEA 018
R&D Activities (III) – Bio

**Biodegradable Plastic**
- Mutant breeding of microorganism
- PHB production using E-coli

- Yield: 85 g/L PHB
- 99% PHB content
- 80% autolysis

**Mutation Studies**
- Mutant Breeding of Vegetables
- Plant breeding of Flowering Tree

- Technology transfer was performed at 2008

- Chinese cabbage transferred to company
- Mutants of radish (M3)
- **Lagerstroemia indica**
R&D Activities (IV) – Semiconductor

**Power Semiconductor**
- Control of minority carrier lifetime
- High power & speed power semiconductor
- FRD, IGBT, BJT etc.

**Ion-cut Technology**
- Development of Ion-cut technology
- Manufacture SOI and GOI wafers
- Thin layer of compound semiconductor

**Minority Carrier Lifetime (1/35)**

<table>
<thead>
<tr>
<th>Ion-cut Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Irradiation</td>
</tr>
<tr>
<td>FRD (Fast Recovery Diode)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Semiconductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minority Carrier Lifetime (1/35)</td>
</tr>
<tr>
<td>T_{rr} = 6000 ns</td>
</tr>
<tr>
<td>T_{rr} = 170 ns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ion-cut Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIBOND® process Flow</td>
</tr>
<tr>
<td>Initial Silicon</td>
</tr>
<tr>
<td>Oxidation</td>
</tr>
<tr>
<td>Smart Cut® Implantation</td>
</tr>
<tr>
<td>Cleaning &amp; Bonding</td>
</tr>
<tr>
<td>Smart Cut® anneal &lt; 600 °C</td>
</tr>
<tr>
<td>Annealing 1100°C &amp; CMP Polish</td>
</tr>
<tr>
<td>Wafer A becomes B</td>
</tr>
<tr>
<td>SI bulk</td>
</tr>
<tr>
<td>SCI wafer</td>
</tr>
<tr>
<td>New A</td>
</tr>
<tr>
<td>New B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Semiconductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT (600V, 5A)</td>
</tr>
<tr>
<td>And Power IGBT</td>
</tr>
</tbody>
</table>

288nm
646nm
1110nm
R&D Activities (V) – Space & Others

- **Space Radiation Test**
  - Radiation hardness test of semiconductor devices for space crafts
  - Total Dose Effect, Single Event Effect, etc.

- **TLA (Thin Layer Activation)**
  - Thin Layer Difference Method
  - Concentration

- **Gemstones Coloration**
  - Optical property modifications of gemstones by irradiation & heat treatment

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Space environment of MACSAT with 5mm Al shielding
  - total radiation dose 400 rad for 3 years
  - 1000% margin -> 4 krad

Refer to MOPEA 037
Activities for the Future

Two Extension Options of the PEFP
Proposed by Science & TEchnology Policy Institute (Feb, 2009)

: in a research report on “Long-term Planning for Proton Engineering Frontier Project”

Primary Proton Beam ➔ Secondary Neutron Beam

Option 1
- 1 GeV SC Linac + Accumulation Ring
  ⇒ 2 MW Spallation Neutron Source
  ⇒ 250, 400 Proton Beam

Option 2
- 200 MeV SC Linac + 2 GeV RCS
  ⇒ 0.5 MW Spallation Neutron Source
  ⇒ 250 MeV Proton Beam
- 400 MeV SC Linac + 8 GeV PS
  ⇒ 8 GeV Proton Beam
Superconducting Linac Development

- $\beta=0.42$, RF: 700 MHz
- SC Cavity, RF coupler, Tuner, Vacuum Vessel, etc.
- Fabricated & tested a warm module (Cu Cavity)
- Fabricated and tested a 2-cell cold module (Nb Cavity)

5-cell Cu cavity

E-field tuning

Field flatness $< 1.43\%$

2-cell Nb cavity

E-field tuning

Field flatness: 1.8%
Requirement: $< 8\%$

Eacc $\sim 1.8$ MV/m
(Available RF power limit)
Q0 $\sim 3.7E7$

Refer to WEPEC 044
Activities for the Future

- Rapid Cycling Synchrotron

- Injection Energy: 100 (200) MeV
- Extraction Energy: 1 (2) GeV
- Injection: Charge Exchange
- Fast Extraction: Spallation neutron source
- Slow Extraction (~450 MeV): Medical application

- 4-Fold Symmetry (20 Cells)
- FODO Lattice
- 4 Dispersion Free Sections
- 4 Arc Straight Sections
- $Q_x, Q_y = 4.39, 4.29$
- Harmonics: 2
- Circumference: 204.45 m

- Upgrade Path

<table>
<thead>
<tr>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>0.1</td>
<td>1.0</td>
<td>15</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Upgrade #1</td>
<td>0.1</td>
<td>1.0</td>
<td>30</td>
<td>140</td>
<td>120</td>
</tr>
<tr>
<td>Upgrade #2</td>
<td>0.1</td>
<td>2.0</td>
<td>30</td>
<td>260</td>
<td>250</td>
</tr>
<tr>
<td>Upgrade #3</td>
<td>0.2</td>
<td>2.0</td>
<td>30</td>
<td>250</td>
<td>500</td>
</tr>
</tbody>
</table>

- Lattice Design

Refer to MOPD 005
Summary

- **100 MeV, 20 mA Proton Linac & Beamlines**
  - **20 MeV Linac**:
    - Completed & in beam service
    - Achieved designed beam energy & current
  - **Higher energy part**:
    - 20~91 MeV DTL: fabricated and tested
    - 91-100 MeV DTL: under fabrication
  - To relocate the 20 MeV linac to the site from April 2011
  - To complete the 100 MeV linac & beamlines by March 2012

- **Construction Work**
  - Under site preparation; leveling along with excavation
  - To start construction work in July 2010, accelerator buildings to be completed by June 2011

- **Beam Utilization & Applications**
  - Cultivated and fostered user programs in the wide range of research fields
  - Produced promising outcomes including some industrialized

- **Activities for the Future (a Spallation Neutron Source)**
  - R&D in SCL, RCS, RF Power Source, Spallation Neutron Target, and Beam Sharing
Thank you very much for your attention