Beam commissioning of a 6 MeV X-band Electron Linear Accelerator for radiation therapy

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Contribute talk
November 16, 2017
HICO, Gyeongju, Korea
Introduction

Dual-head gantry system for Radiation therapy

- Dual 9.3 GHz X-band LINAC
- > 500 cGy/min * 2 LINACs
- 3D smart imaging system with stereo X-ray imager
- IMRT, SBRT, VMAT and more
- 260*280*270 cm³
Introduction

◆ Dual-head gantry system for Radiation therapy

- Dual X-band LINAC system
- Mechanical gantry system
- Smart diagnostic system
- Collimator head

Clinical application

- Dual-9.3 GHz X-band LINAC
- > 500 cGy/min * 2 LINACs
- 3D smart imaging system
- IMRT, SBRT, VMAT and more
- 260*280*270 cm
X-band LINAC for radiation therapy

◆ Research objective

- Structure of 6 MeV X-band electron LINAC for dual-head gantry.
- System implementation for beam commissioning test.
- Experiment test with RF power transmission and beam acceleration.
- Data analysis of performance result.

*High-power test @ SKKU*

*Beam commissioning test @ KAERI*
X-band LINAC for radiation therapy

◆ X-band LINAC for dual-head gantry

- E-gun HV pulse PS
- HV pulse modulator
- Main Control system
- RF power source
- RF transmission waveguide
- Bi-directional coupler
- Power meter
- Spectrum analyzer
- ICT
- CCD camera
- Beam measurement unit

Electron gun

- 9.3 GHz, 1.7 MW
- 12 kV, 50 mA
- < 1.0 x 10^-7 mbar

Vacuum system

- RF resonating cavity
- 6 MeV, 20 mA
- 30°C DI water

Cooling system
### X-band LINAC for dual-head gantry – Design features

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>6 MeV</td>
</tr>
<tr>
<td>Peak beam current</td>
<td>20 mA</td>
</tr>
<tr>
<td>E-gun type</td>
<td>Dispenser triode E-gun</td>
</tr>
<tr>
<td>E-gun HV pulse</td>
<td>-12 kV</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>+ 50 V for injection</td>
</tr>
<tr>
<td>RF resonating Frequency</td>
<td>9300 ± 30 MHz</td>
</tr>
<tr>
<td>RF accelerating cavity type</td>
<td>Side-coupled type, Pi/2 mode</td>
</tr>
<tr>
<td>Accelerating gradient per unit length</td>
<td>25 MV/m</td>
</tr>
<tr>
<td>Magnetron RF power (peak/average)</td>
<td>1.7 MW / 1.35 kW</td>
</tr>
<tr>
<td>Pulse width</td>
<td>4.0 ± 1.0 us</td>
</tr>
<tr>
<td>Duty factor</td>
<td>0.0008</td>
</tr>
<tr>
<td>Waveguide power durability</td>
<td>2.0 MW / 4 kW</td>
</tr>
<tr>
<td>Waveguide type</td>
<td>WR-112</td>
</tr>
<tr>
<td>Circulator type</td>
<td>4-port with 5 MW loader</td>
</tr>
<tr>
<td>Novel gas pressure</td>
<td>SF₆ novel gas in 35 psi</td>
</tr>
<tr>
<td>Cooling system</td>
<td>DI Water @ 30 °C</td>
</tr>
</tbody>
</table>
## Performance evaluation – Characteristic of X-band RF system [9]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency dependence</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>$f_0$</td>
<td>Compactness</td>
</tr>
<tr>
<td>Effective shunt impedance per unit length $ZT^2$</td>
<td>$f_0^{1/2}$</td>
<td>Acceleration efficiency</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum electric field strength $E_{\text{max}}$ (Kilpatrick Criterion)</td>
<td>$f_0^{1/2}$</td>
<td>Electric arching durability</td>
</tr>
<tr>
<td>Efficiency of acceleration per unit stored energy $r/Q$</td>
<td>$f_0$</td>
<td>High-dose rate</td>
</tr>
<tr>
<td>Beam loading fluctuation</td>
<td>$f_0^{-1/2}$</td>
<td>Stability</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF loss factor (Q-factor)</td>
<td>$f_0^{-1/2}$</td>
<td>RF transmit efficiency</td>
</tr>
<tr>
<td>Power dissipation $P$</td>
<td>$f_0^{-1/2}$</td>
<td></td>
</tr>
</tbody>
</table>
◆ Triode electron gun

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Triode E-gun</th>
<th>Diode E-gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Relative) Size</td>
<td>Smaller</td>
<td>Bigger</td>
</tr>
<tr>
<td>Current density</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Grid existence</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Precise current change</td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td>Normalized emittance (de-focusing)</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Price</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

- **Typical triode E-gun operation**
  - Anode HV: -12 kV DC
  - Repetition rate: ~400 Hz
  - Pulse width: 0 ~ 20 μs
RF system configuration

- RF system consists of RF accelerating cavity, magnetron, modulator, data acquisition equipment, and main control system.

- Characteristic parameters as beam energy, beam current and dose rate are defined by the correlation between RF cavity and RF power source containing magnetron and modulator.

- Main control system adjusts the output parameters by using HV pulse power suppliers according to the results obtained.
X-band RF accelerating cavity

- High-frequency electromagnetic field simulation was performed using CST Microwave studio (MWS) for X-band RF accelerating cavity.
- Using electric field distribution data, electron beam dynamics simulation was performed using ASTRA code.

Momentum $p : 6.5$ MeV/c
Kinetic energy $E_k : 6$ MeV for e-

FWHM : 2 mm

Electric field distribution (25 MV/m average)
X-band RF accelerating cavity

- X-band RF accelerating cavity with π/2 mode with a side-coupled structure.
- 27 cm length for high accelerating gradient with 25 MV/m electric field.
- 7 bunching cells, and 10 accelerating cells: 353 kV/cell.
- 104 MΩ/m of effective shunt impedance.
- **Manufactured in Korea.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
<th>Measurement value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$</td>
<td>9.309 GHz</td>
<td>9.3069 GHz</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>-29.81 dB</td>
<td>-16.676 dB</td>
</tr>
<tr>
<td>$\Delta f_{3dB}$</td>
<td>220 kHz</td>
<td>350 kHz</td>
</tr>
<tr>
<td>External Q</td>
<td>11,000</td>
<td>8,500</td>
</tr>
<tr>
<td>VSWR</td>
<td>1.065</td>
<td>1.3436</td>
</tr>
<tr>
<td>Temperature</td>
<td>25°C</td>
<td>25°C</td>
</tr>
</tbody>
</table>
**X-band LINAC for radiation therapy**

**RF source**

\[ V_{\text{gain}} = \frac{2\sqrt{\beta_0}}{1 + \beta_0} \cdot \sqrt{P_{rf} \cdot r_{sh} \cdot l} \cdot \cos(\omega t + \theta) \]

\[ P_{\text{diss}} = \frac{V_{\text{gain}}^2}{R_{sh}} = \omega U \left( \frac{1}{Q_{\text{ext}}} + \frac{1}{Q_{\text{unloaded}}} \right) \]

\[ P_{\text{beam}} = V_{\text{gain}} \times I_{\text{beam}} \]

\[ P_{\text{total}} = P_{\text{diss}} + P_{\text{ref}} + P_{\text{beam}} \]

- Effective length of RF cavity \((l)\): 251.5 mm
- Effective shunt impedance \((r_{sh})\): 104 MΩ/m
- Beam energy \((V_{\text{gain}}) / current (I_{\text{beam}})\): 6 MeV / 20 mA peak
- Transient time factor \((TTF)\) with phase difference: > 0.7
- Return loss \((\propto P_{\text{ref}})\): < 5%

---

**6 MeV @ 1.7 MW**

**Graph:**

- **Parameter**
  - L3 6170
  - CPI VMX3100HP
  - Scandynova M1 Mk4

- **Frequency**
  - 9300 ± 25 MHz
  - 9300 ± 30 MHz

- **Peak pulse power**
  - 1.7 MW
  - 1.5 – 1.75 MW

- **Average power**
  - 1.36 kW
  - 2.7 kW

- **Load VSWR**
  - 1.21 max
  - 1.1 : 1 max

- **Duty factor**
  - 0.0008
  - 0.0016

- **Pulse width**
  - 40 μs
  - 50 ± 5 μs

- **Peak anode voltage (kV)**
  - 34 – 36 kV
  - 34 – 37 kV

- **Peak anode current (A)**
  - 68 A
  - 90 A

- **Pulse power output (peak / avg)**
  - 4 MW / 8 kW

- **Top flatness**
  - < 1%

- **Pulse rising time**
  - < 10 ms

- **Pulse repetition rate**
  - 1 – 400 Hz

- **Max duty factor**
  - 0.003

- **Pulse width**
  - 0 – 5 μs

- **Output peak voltage**
  - 0 – 40 kV

- **Output peak current**
  - 0 – 100 A
X-band LINAC for radiation therapy

**Transmission waveguide**

- **RF Power source**: 92.3 dBm, 1.7 MW, 9.3 GHz
- **Circulator**: 92.2 dBm
- **Waveguide**: 92.1 dBm
- **Bi-directional coupler**: RL : < -43 dB, IL : < -0.1 dB
- **RF window**: FWD, RFD : 60 dB atten
- **RF accelerating cavity**: 92.05 dBm, 1.603 MW, 9.3 GHz

**Component measurement using Network analyzer**

<table>
<thead>
<tr>
<th>Assembled RF transmission line</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center freq. (GHz)</td>
<td>9.2979</td>
</tr>
<tr>
<td>$\Delta f_{3\text{dB}}$ (MHz)</td>
<td>± 29</td>
</tr>
<tr>
<td>$S_{11}$, RL (dB)</td>
<td>-21.27</td>
</tr>
<tr>
<td>$S_{21}$, IL (dB)</td>
<td>-0.248</td>
</tr>
<tr>
<td>P.D (degree)</td>
<td>119.67</td>
</tr>
<tr>
<td>VSWR (:1)</td>
<td>1.188</td>
</tr>
</tbody>
</table>
Control system and data acquisition

1. Turn on & setting Measurement equipment
   - Spectrum analyzer
   - Power meter
   - Oscillator

2. Communication check

3. Turn on cooling system

4. Checking vacuum level (< 1.0E-8 mbar)

5. Checking SF6 gas pressure

6. Heat on filament during 30 min
   - Magnetron
   - Electron gun

7. Set trigger timing and duty cycle

8. Modulator HV on

9. Set High Voltage

10. Data acquisition
    - RF power, beam performance

11. RF power transmitting
    - 9.3 GHz, 1.7 MW

12. 6 MeV, 20 mA pulse electron beam acceleration

21. End of the procedure
X-band LINAC for radiation therapy

**X-band LINAC system modeling**

- Magnetron
- Triode E-gun
- Bi-directional Coupler
- 4-port Circulator
- 5l ion pump
- Waveguide
- Dummy-load
- X-ray target
- High-gradient 27 cm RF cavity

**X-band RF LINAC**
- $653.7 \times 380.2 \times 361.43 \text{ mm}^3$
- < 80 kg (without shielding)
**X-band LINAC system modeling**

Total head structure
- $1518.9 \times 809.7 \times 550 \text{ mm}^3$
- < 350 kg (with collimator)

X-band RF electron LINAC
- $780 \times 400 \times 465 \text{ mm}^3$
- < 80 kg (without shielding)

1\textsuperscript{st} & 2\textsuperscript{nd} Collimator
X-Y Jaw for X-ray shaping

Stereo kV imaging system
**Beam commissioning history**

◆ **Process of commissioning set-up**

**RF commissioning @ SKKU [Jan. 2. 2017 ~ Mar. 31. 2017, 216 hrs]**

<table>
<thead>
<tr>
<th>System implementation</th>
<th>Vacuum system configuration</th>
<th>Cooling system configuration</th>
<th>Magnetron filament heating</th>
<th>RF pulse power transmission</th>
</tr>
</thead>
</table>
| • RF system installation  
  - RF cavity, magnetron, modulator, and waveguide  
  • Wire connection -electronics (380V)  
  • Ground check | • Pump installation  
  - Rotary pump, TMP, ion pump (<1E-8 mbar)  
  • Leakage test - He detector | • Cooling line installation  
  - RF cavity, Magnetron, modulator, circulator, dummy-load with chiller  
  • Flow meter connection - Each component flow rate check | • Magnetron filament heating  
  - Voltage, current, and resistor check  
  • First heating time during 5 hours  
  • Warm-up time: 30 min | • Trigger timing check  
  • Increase HV pulse gradually  
  - vacuum state check  
  • Full -power transmission with low reflection power |

**Beam commissioning @ KAERI [Jul. 31. 2017 ~ Oct. 20. 2017, 554 hrs]**

<table>
<thead>
<tr>
<th>System implementation</th>
<th>Vacuum system configuration</th>
<th>RF cavity heating</th>
<th>E-gun filament heating</th>
<th>Beam acceleration</th>
</tr>
</thead>
</table>
| • LINAC installation  
  - E-gun, RF system, target, measurement unit, collimator.  
  • Wire connection -electronics (380V)  
  • Ground check | • Pump installation  
  - Rotary pump, TMP, ion pump (<1E-8 mbar)  
  • Leakage test - He detector | • Bake out  
  - RF cavity, RF window, target, measurement system  
  • Heating process - Up to 200°C at 24 hours.  
  • Cool down slowly. | • E-gun filament heating  
  - Voltage, current, and resistor check  
  • First heating time during 10 hours  
  • Warm-up time: 1 hr | • Trigger timing check  
  • Increase HV pulse gradually  
  - vacuum state check  
  • Beam acceleration check with CCD cam |
Beam commissioning history

**System implementation**

- X-band LINAC structure
- Lead shielding
- Ion-pump controller
- Remote module
- Flow meter for cooling
- Spectrum analyzer

**SKKU, May 27, 2017.**

- E-gun HV PS
- Modulator & E-gun PS
- Measurement system
- Cooling system
- Vacuum pump

**KAERI Aug 18, 2017.**

Measurement system
Beam commissioning history

- Cooling system with 0.1°C stability
- Vacuum pump with ion pump controller
- SF₆ dense meter (35 psi)
- Main control system
Beam commissioning history

- Filament heating – E-gun & magnetron

![Image of equipment setup with labels for E-gun PS Rack, Triode E-gun, E-gun filament Voltage measure, ION pump, E-gun filament Current measure, Beam current measure.]

Graph showing measurements:
- Voltage: 5V, 1.54A
- Voltage: 20V, 15.2A @ VMX3100HP
Experimental result and analysis

◆ RF commissioning test

- FWD 1.64 MW  RFD 20 kW  SWR 1.2 : 1
- Repetition rate 120 Hz  Pulse width 4.0 us

- $f_c : 9.309 \text{ GHz}$

- Brown : modulator HV
- Blue : modulator current
- Purple : Reflection power
- Green : HV measured 1:1000 probe
**Beam commissioning test – current & spot size**

- RF Power 1.05 MW (12.5kV -65 +55V)
- RF Power 1.64 MW (12.5kV -65 +55V)

### Experimental result and analysis

**Beam measurement system implementation**

- **Vacuum window for CCD camera**
- **ICT**
- **YAG screen with linear feedthrough**

<table>
<thead>
<tr>
<th>E-gun HV voltage (kV)</th>
<th>Beam current (mA) @ 1.64 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -9.0</td>
<td>-</td>
</tr>
<tr>
<td>- 9.0</td>
<td>8.0</td>
</tr>
<tr>
<td>- 10.0</td>
<td>9.7</td>
</tr>
<tr>
<td>- 11.0</td>
<td>11.4</td>
</tr>
<tr>
<td>- 12.5</td>
<td>16.1</td>
</tr>
</tbody>
</table>
**RMS Beam spot size**

horizontal 2 mm @FWHM
vertical 5 mm @FWHM

**Beam commissioning test** – current & spot size

![Image of beam spot size](image.png)

<table>
<thead>
<tr>
<th>E-gun HV voltage (kV)</th>
<th>Beam current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -9.0</td>
<td>-</td>
</tr>
<tr>
<td>- 9.0</td>
<td>8.0</td>
</tr>
<tr>
<td>- 10.0</td>
<td>9.7</td>
</tr>
<tr>
<td>- 11.0</td>
<td>11.4</td>
</tr>
<tr>
<td>- 12.5</td>
<td>16.1</td>
</tr>
</tbody>
</table>

16.1 mA
@ 12.5 kV E-gun HV
1.64 MW RF power

Experimental result and analysis
Experimental result and analysis

- **Beam commissioning test** – beam energy

<table>
<thead>
<tr>
<th>Transmitted power (MW)</th>
<th>Beam energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07</td>
<td>0.8</td>
</tr>
<tr>
<td>1.22</td>
<td>1.96</td>
</tr>
<tr>
<td>1.37</td>
<td>3.48</td>
</tr>
<tr>
<td>1.52</td>
<td>5.02</td>
</tr>
<tr>
<td>1.7</td>
<td>5.5</td>
</tr>
</tbody>
</table>
### Experimental result and analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>X-band electron LINAC system for dual-head RT</th>
<th>Cyberknife® M6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>9.309 GHz</td>
<td>9.3 GHz</td>
</tr>
<tr>
<td>Maximum beam energy</td>
<td>5.5 MeV</td>
<td>6 MeV</td>
</tr>
<tr>
<td>Beam peak current</td>
<td>16 mA</td>
<td>30 ~ 40 mA</td>
</tr>
<tr>
<td>Length of cavity</td>
<td>27 cm</td>
<td>~ 40 cm</td>
</tr>
<tr>
<td>MeV/cm</td>
<td>0.2222</td>
<td>0.15</td>
</tr>
<tr>
<td>Maximum forward RF power</td>
<td>1.639 MW</td>
<td>2.0 MW</td>
</tr>
<tr>
<td>Duty factor</td>
<td>0.0008</td>
<td>0.001</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>108 MΩ/m</td>
<td>&lt; 80 MΩ/m</td>
</tr>
<tr>
<td>VSWR max</td>
<td>1.3</td>
<td>-</td>
</tr>
<tr>
<td>Power stability</td>
<td>&lt; 1%</td>
<td>-</td>
</tr>
<tr>
<td>E-gun type</td>
<td>Triode E-gun (Diode E-gun)</td>
<td>Triode E-gun</td>
</tr>
<tr>
<td>E-gun pulse HV / grid</td>
<td>-12 kV / 100 V</td>
<td>-</td>
</tr>
<tr>
<td>Dose rate</td>
<td>&gt; 500 cGy/min * 2</td>
<td>1,000 cGy/min</td>
</tr>
<tr>
<td>Vacuum</td>
<td>&lt; 1E-07 mbar</td>
<td>-</td>
</tr>
</tbody>
</table>
• In accordance trend of radiation therapy, we have been developing X-band electron LINAC for dual-head radiation therapy since 2012.

• The X-band electron LINAC system was designed, fabricated and experimented of beam commissioning test.

• Based on the design structure, X-band electron LINAC test-bench was constructed for commissioning test.

• Before performing beam commissioning test, RF commissioning test was conducted to measure resonant frequency and peak RF power level in SKKU.

• Beam commissioning experiments have been conducting to find acceleration beam performance in KAERI.

• In order to achieve the final goal, we will continue to carry on beam commissioning test for 6 MV – 500 cGy X-ray generation and accumulate experimental data.
Integration process @ KIRAMS

Thanks for your attention
Back-up slide
### Table 3. Overview of literature studies: comparison of treatment outcomes according to the radiation therapy schedule

<table>
<thead>
<tr>
<th>Reference</th>
<th>Radiation dose (Gy) per fraction/# of fractions</th>
<th>No. of patients</th>
<th>Treatment outcome&lt;sup&gt;a&lt;/sup&gt; (%)</th>
<th>Toxicity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulware et al. [16]</td>
<td>10 Gy/#1</td>
<td>86</td>
<td>Bleeding (45), pain (42)</td>
<td>Acute (9.3)</td>
</tr>
<tr>
<td></td>
<td>10 Gy/#2, 3–4 wk interval</td>
<td>55</td>
<td>Bleeding (85), pain (59)</td>
<td>Late (17.4)</td>
</tr>
<tr>
<td></td>
<td>10 Gy/#3, 3–4 wk interval</td>
<td>20</td>
<td>Bleeding (100), pain (63)</td>
<td></td>
</tr>
<tr>
<td>Hodson and Kepart [5]</td>
<td>10 Gy/#3, 4 wk interval</td>
<td>14</td>
<td>Bleeding (100), pain (100)</td>
<td>Late (14.3)</td>
</tr>
<tr>
<td>Halle et al. [6]</td>
<td>10 Gy/#1-3, at 4 wk interval or recurrence</td>
<td>42</td>
<td>Bleeding (90), pain (44)</td>
<td>Acute (6.7), severe late (11.9)</td>
</tr>
<tr>
<td>Patricio et al. [19]</td>
<td>6.5 Gy/#2 in 48 hr</td>
<td>56</td>
<td>Bleeding (94), pain (45)</td>
<td>Severe (16.3)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Spanos et al. [20]</td>
<td>3.7 Gy/#4 in 48 hr, 2–4 wk interval, up to three cycles</td>
<td>61</td>
<td>Bleeding (76), pain (31)</td>
<td>Acute (3), late (7)</td>
</tr>
<tr>
<td>Onsrud et al. [14]</td>
<td>10 Gy/#1</td>
<td>11</td>
<td>Bleeding (90), pain (0)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Acute (36.4)</td>
</tr>
<tr>
<td></td>
<td>10 Gy/#2, 4 wk interval</td>
<td>51</td>
<td></td>
<td>Acute (45.3), severe late (9.4)</td>
</tr>
<tr>
<td></td>
<td>10 Gy/#3, 4 wk interval</td>
<td>2</td>
<td></td>
<td>Acute (43.8), severe late (7.8)</td>
</tr>
<tr>
<td>Mishra et al. [15]</td>
<td>10 Gy/#1</td>
<td>100</td>
<td>Bleeding (74), pain (47)</td>
<td>Late (10)&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>10 Gy/#2, 4 wk interval</td>
<td>61</td>
<td>Bleeding (80), pain (59)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 Gy/#3, 4 wk interval</td>
<td>33</td>
<td>Bleeding (100), pain (50)</td>
<td></td>
</tr>
<tr>
<td>Present study</td>
<td>5 Gy/#4-5</td>
<td>17</td>
<td>Bleeding (33.8), pain (66.7)</td>
<td>Acute (47.1), late (23.5), severe late (0)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Proportion of patients, which showed complete or partial (>50%) improvement of symptom. <sup>b</sup>Acute or late toxicity was not specified. <sup>c</sup>Treatment outcomes or toxicities according to number of fractions were not specified.
Figure 11.4. Typical depth-dose curves for megavoltage photon and electron beams commonly used in the therapy of head and neck cancers. The upper panel shows curves for 10 cm × 10 cm fields for a 4-megavolt (MV) (80-cm source axis distance [SAD]) linear accelerator (dashed line), a 6-MV (100-cm SAD) linear accelerator (solid line), and a 15-MV (100-cm SAD) linear accelerator (dotted line). The lower panel shows depth-dose curves for 10 cm × 10 cm fields for 6-megaelectron volt (MeV) (dashed line), 12-MeV (solid line), and 20-MeV (dotted line) electron energies.
Fig. 4. [a] MC simulated Depth Dose values for various incident beam energies for 6 MV photon beams for the field size of 10×10 cm². The top line of the curve denotes the higher energy of 6.5 MeV whereas the bottom line of the curve denotes the lower energy of 5.1 MeV. [b] Comparison of MC simulated and measured PDD curves for various incident beam energies for 6 MV photon beams for the field size of 10×10 cm². The inset shows the local dose differences.
How to measure the energy of X-band LINAC

철에 X-ray 반가층(Half Value Layer)을 측정하여 전자빔 에너지를 측정하는 방법이다.

X-ray가 나오는 타겟 1m 떨어진 곳에 방사선량을 측정 할 수 있는 도시메터를 설치한다. 타겟과 도시메터 사이에 철판의 두께를 변화하여 방사선량을 측정한다. 이 때, 타겟에서 나오는 X-ray 양은 일정해야 한다. HVL 측정하기 위해 초기 철판 두께를 정하고 X-ray를 조사하여 방사선량을 측정한다($t_0$). 초기 철판 두께보다 두께가 하여 같은 양의 X-ray를 조사하여 방사선량을 측정한다($t$). 철판의 두께를 두께가 한 두께에서 초기 철판 두께를 빼준다($d$). 아래의 공식을 이용하여 $\mu$ 값을 구한다.

\[ I = I_0 e^{-\mu d} \quad (1) \]

구한 값을 아래에 공식에 대입하여 반가층을 구한다.

\[ HVL = 0.693/\mu \quad (2) \]

전자빔 에너지 변화에 따른 철의 HVL 변화(2.74 cm)은 실험을 통해 정해져 있다.
## 방사선 치료기에 사용 된 선형가속기 비교

<table>
<thead>
<tr>
<th></th>
<th>Cyberknife</th>
<th>Tomography</th>
<th>Dual-head Gantry Therapy Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>작동 주파수</td>
<td>9.4 GHz</td>
<td>2.856 GHz</td>
<td>9.3 GHz</td>
</tr>
<tr>
<td>가속관에 적용 된 기술</td>
<td>X-band RF Technology</td>
<td>S-band RF Technology</td>
<td>X-band RF Technology</td>
</tr>
<tr>
<td>전자빔 에너지</td>
<td>6 MeV</td>
<td>6 MeV</td>
<td>6 MeV</td>
</tr>
<tr>
<td>가속관 길이</td>
<td>58 cm</td>
<td>30 cm</td>
<td>27 cm</td>
</tr>
<tr>
<td>가속관 종류</td>
<td>Standing Wave, Pi/2 Side-coupled type</td>
<td>Standing Wave, Pi/2 Side-coupled type</td>
<td>Standing Wave, Pi/2 Side-coupled type</td>
</tr>
<tr>
<td>Dose Rate</td>
<td>800 cGy/min</td>
<td>850 cGy/min</td>
<td>500 cGy/min</td>
</tr>
<tr>
<td>가속관 시스템 무게 (방사선 차폐체 포함)</td>
<td>285 lb (~ 130 kg)</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

![Cyberknife](image1.jpg)  
![Tomotherapy](image2.jpg)  
![SKKU-KAERI Dual-head Gantry Therapy Machine](image3.jpg)