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

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Contribute talk
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Outline

01 *Introduction*

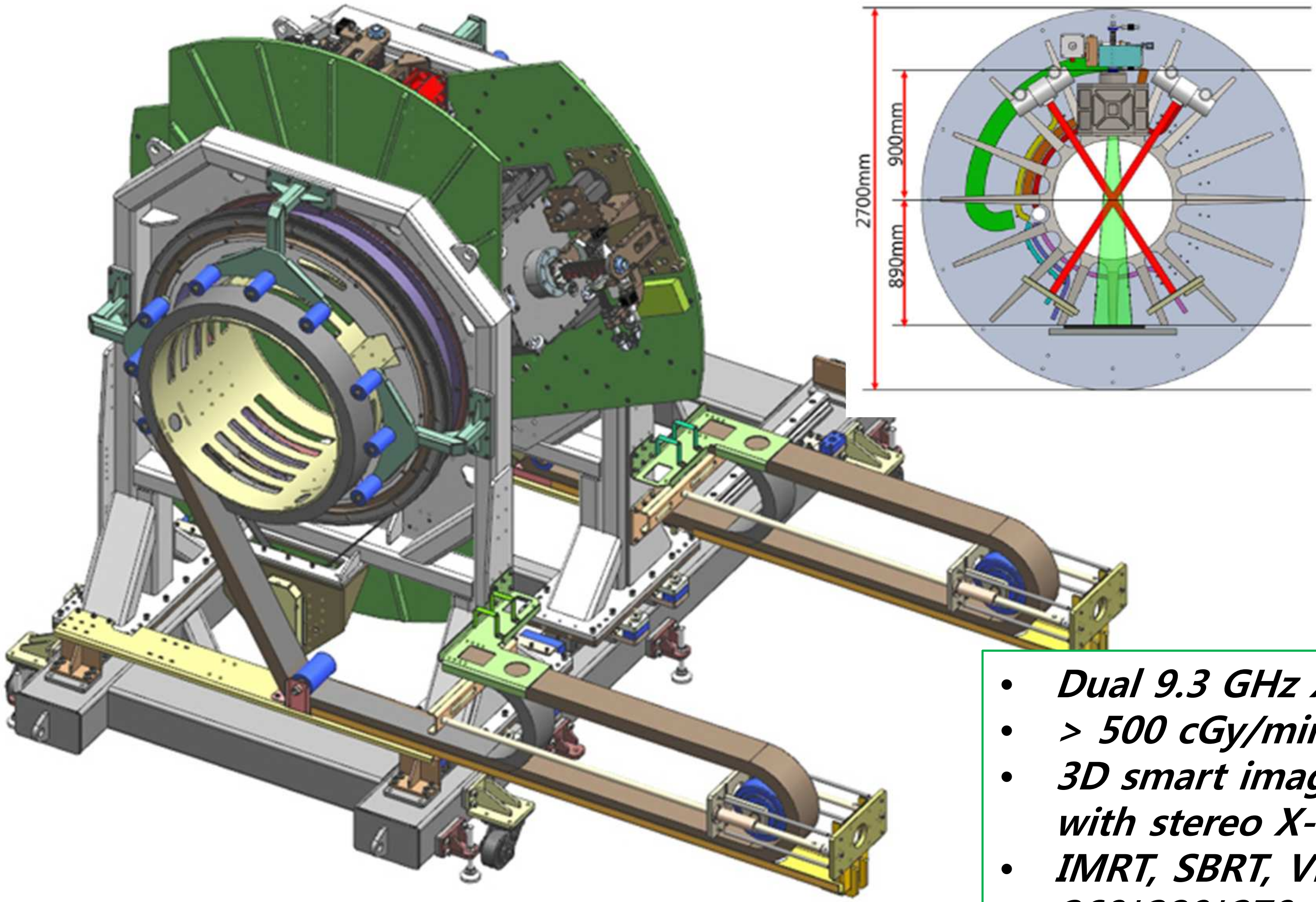
02 *X-band LINAC for radiation therapy*

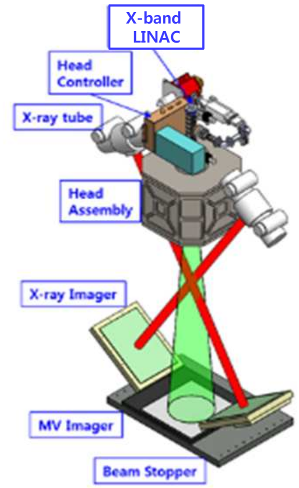
03 *Beam commissioning history*

04 *Experimental result and analysis*

05 *Conclusion*

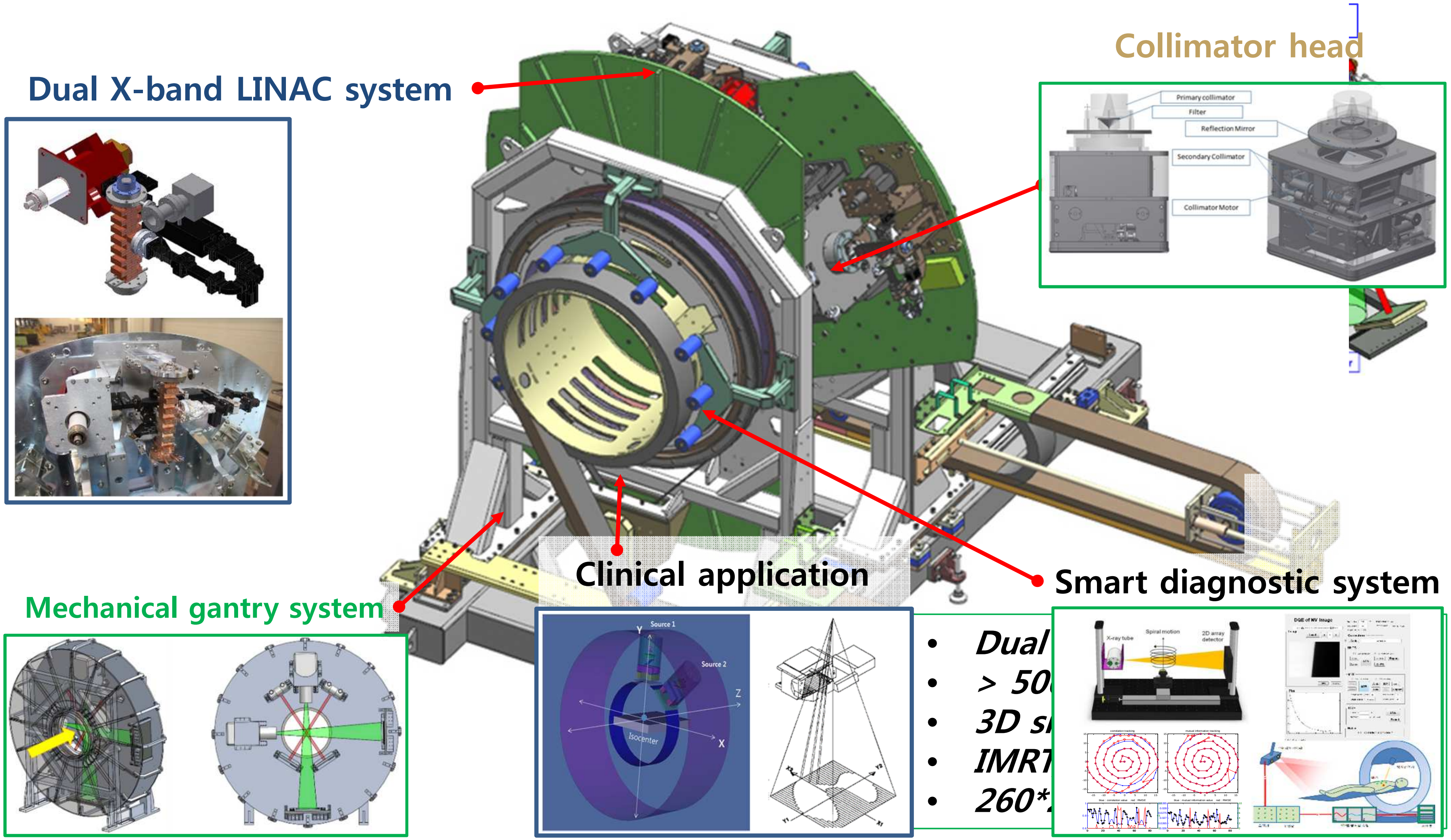
◆ Dual-head gantry system for Radiation therapy





- *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 cm^3*

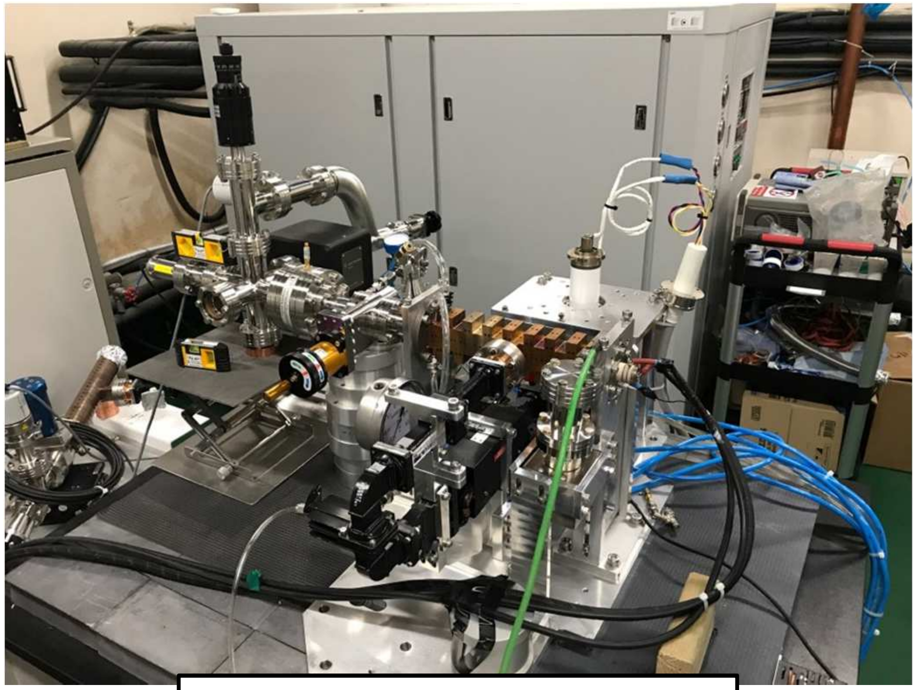
◆ Dual-head gantry system for Radiation therapy



- *Dual*
- *> 50*
- *3D s*
- *IMRT*
- *260**

◆ Research objective

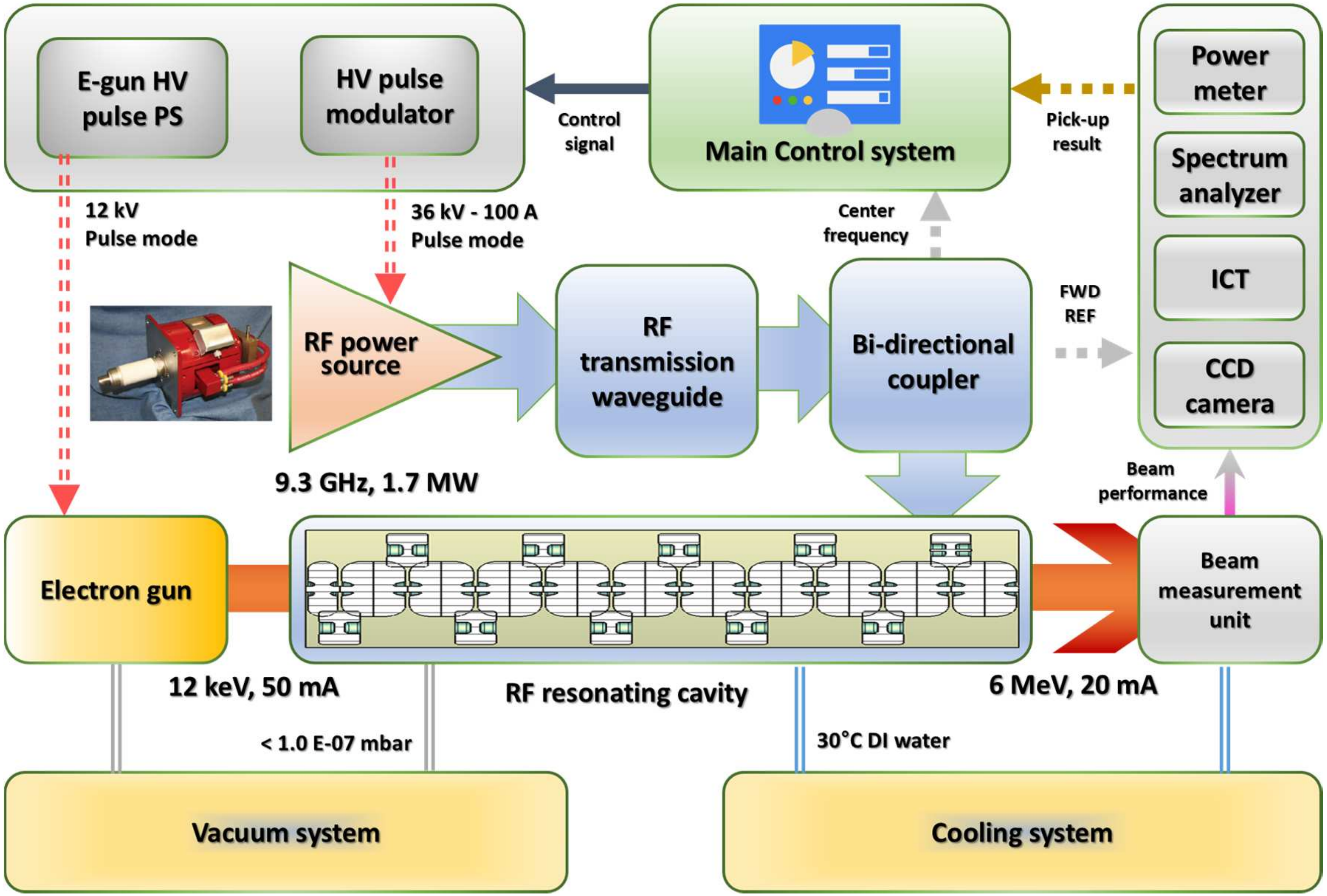
- Structure of **6 MeV X-band electron LINAC for dual-head gantry.**
- System implementation for beam commissioning test.
- Experiment test with RF power transmission and beam acceleration.
- Data analysis of performance result.



High-power test @ SKKU

Beam commissioning test @ KAERI

◆ X-band LINAC for dual-head gantry



◆ X-band LINAC for dual-head gantry – Design features

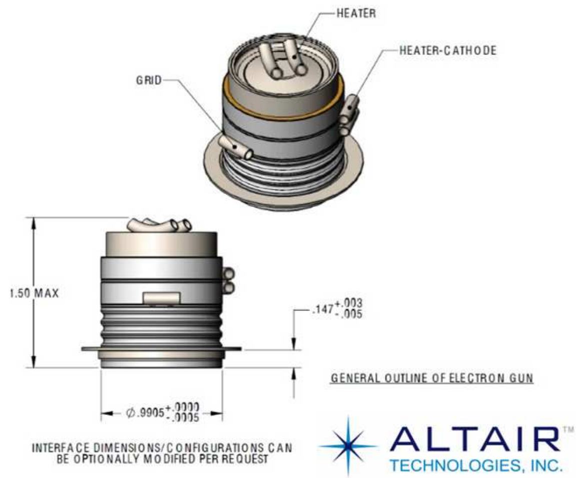
Parameters	*Value*
Beam energy	6 MeV
Peak beam current	20 mA
E-gun type	Dispenser triode E-gun
E-gun HV pulse	-12 kV
Grid voltage	+ 50 V for injection
RF resonating Frequency	9300 ± 30 MHz
RF accelerating cavity type	Side-coupled type, Pi/2 mode
Accelerating gradient per unit length	25 MV/m
Magnetron RF power (peak/average)	1.7 MW / 1.35 kW
Pulse width	4.0 ± 1.0 us
Duty factor	0.0008
Waveguide power durability	2.0 MW / 4 kW
Waveguide type	WR-112
Circulator type	4-port with 5 MW loader
Novel gas pressure	SF_6 novel gas in 35 psi
Cooling system	DI Water @ 30 ˚C

◆ Performance evaluation – Characteristic of X-band RF system [9]

	Parameter	Frequency dependence	Effects
Advantages	Wavelength	f_0	***Compactness***
	Effective shunt impedance per unit length ZT^2	$f_0^{1/2}$	***Acceleration efficiency***
	Maximum electric field strength E_{max} (Kilpatrick Criterion)	$f_0^{1/2}$	***Electric arching durability***
	Efficiency of acceleration per unit stored energy r/Q	f_0	***High-dose rate***
Disadvantages	Beam loading fluctuation	$f_0^{-1/2}$	***Stability***
	RF loss factor (Q-factor)	$f_0^{-1/2}$	***RF transmit efficiency***
	Power dissipation P	$f_0^{-1/2}$	

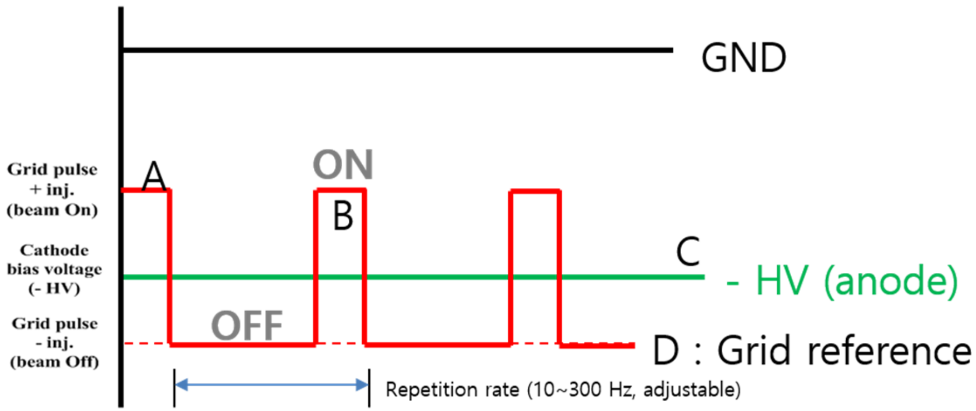
X-band LINAC for radiation therapy

◆ Triode electron gun



	NOMINAL	RANGE
Perveance	0.9 μpervs	.01 to >1.4 μpervs
Cutoff	Ek/Ec ≧ 110	-55V to -65V @ 12 kV
Ek	-12kV	up to -18kV
Grid Drive	1.2A Ik	+50V to +70V typical
Heater	Voltage: 5.0V (recommended MAX)	Current: 2.0A MAX
Cathode	Dispenser Type	
Coating	M-Type: 80% Os, 20% W	
Mix	5:3:2 with a molecular weight of 67.3%, BaO, 14.8% CaO, 17.9% Al_2O_3	
Optional Mix	3:1:1, 4:1:1, 6:1:2	
Beam Shape	Call for Beam Characteristics	
Leakage	Cathode to Ground: <100uA at 21 kV	

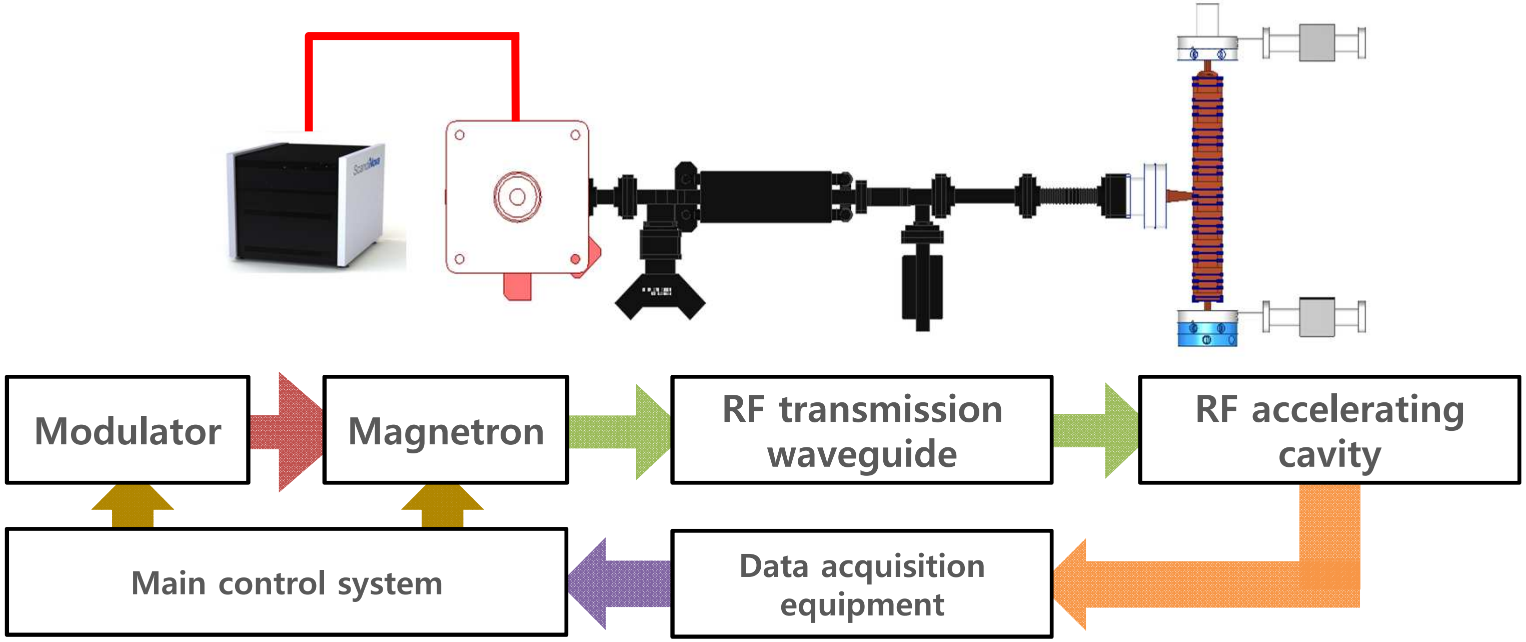
Parameters	Triode E-gun	Diode E-gun
(Relative) Size	Smaller	Bigger
Current density	Low	High
Grid existence	O	X
Precise current change	O	X
Normalized emittance (de-focusing)	Low	High
Price	High	Low



- Typical triode E-gun operation
  - Anode HV : - 12 kV DC
  - Repetition rate : ~ 400 Hz
  - Pulse width : 0 ~ 20 us

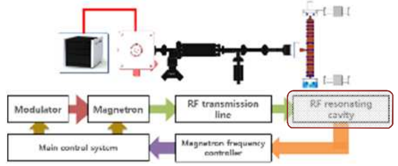
X-band LINAC for radiation therapy

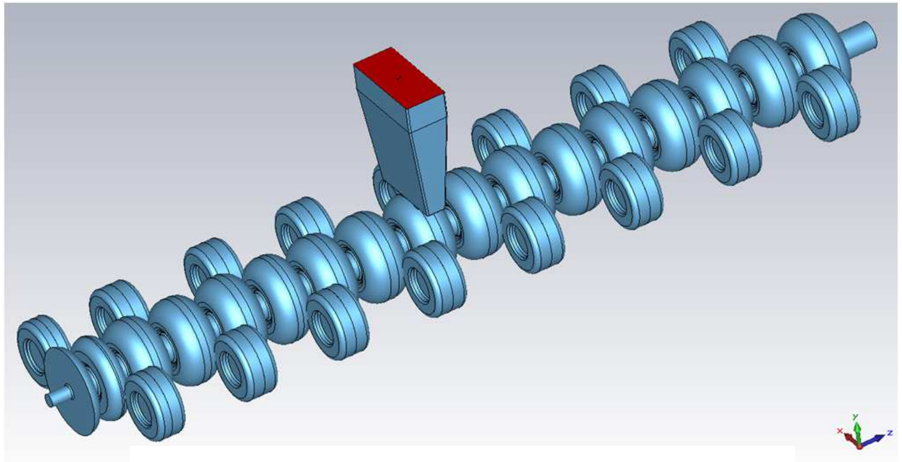
◆ RF system configuration



- 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.

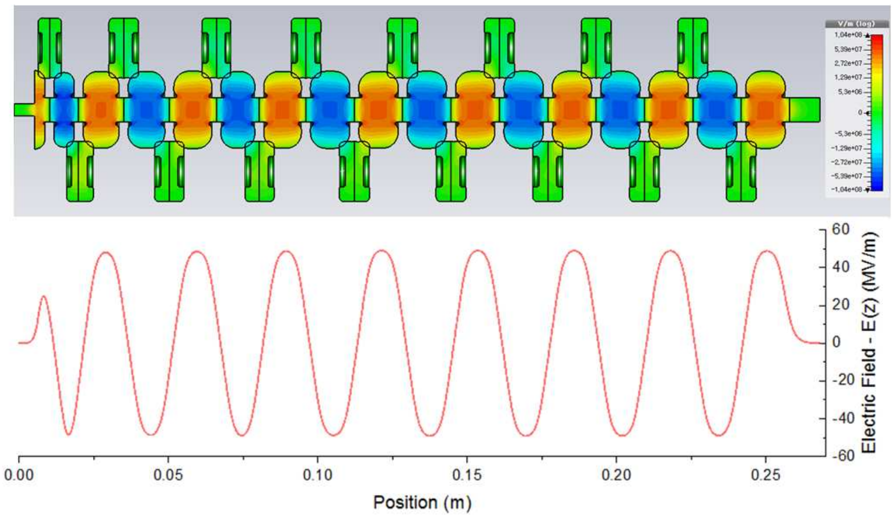
◆ X-band RF accelerating cavity



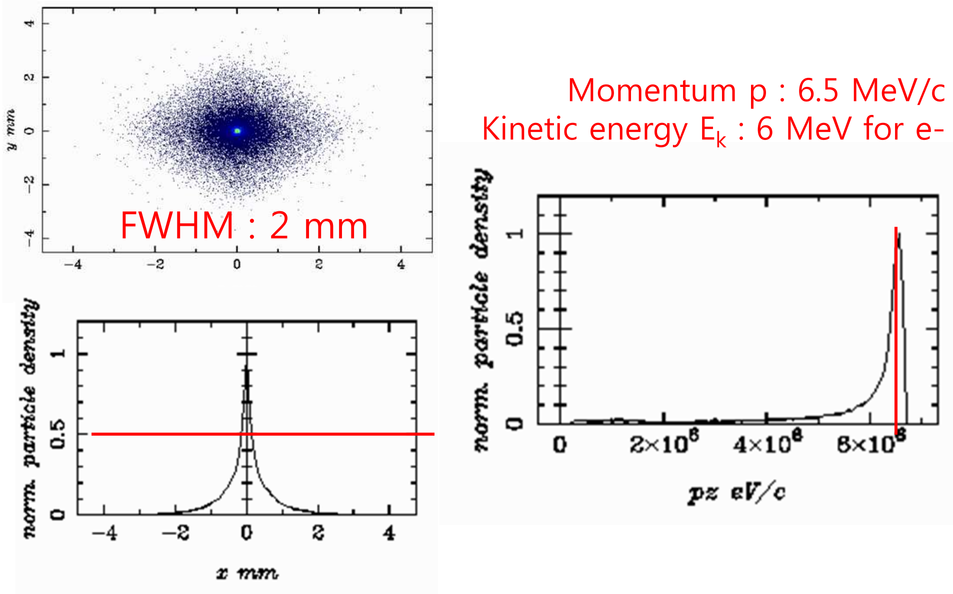


X-band RF cavity full-cell structure

- 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.



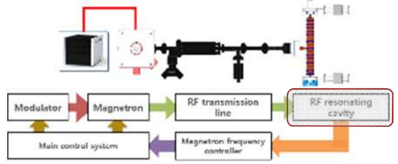
Electric field distribution (25 MV/m average)

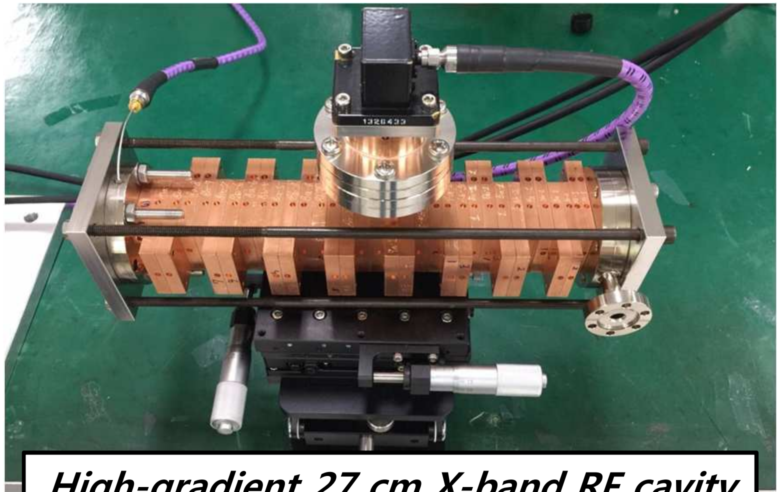


X-band LINAC for radiation therapy

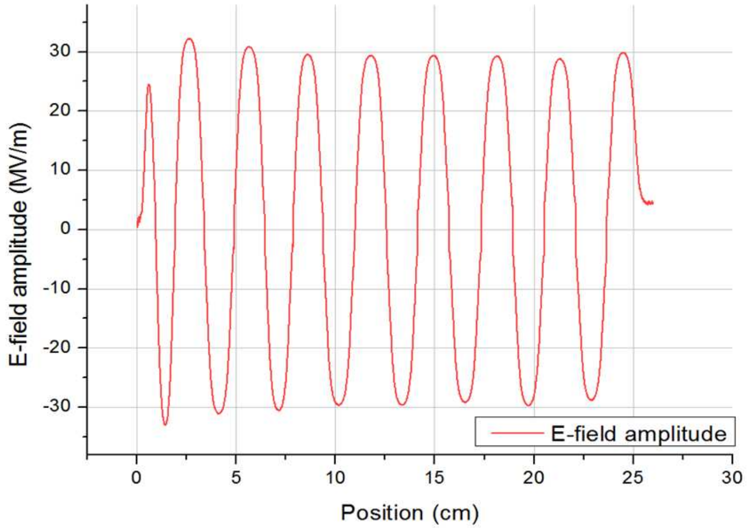
Unique Origin Unique Future

◆ X-band RF accelerating cavity





High-gradient 27 cm X-band RF cavity

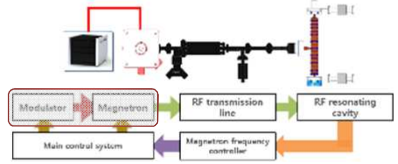


Bead-pull measurement of electric field distribution

- 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.**

Parameter	Design value	Measurement value
f_c	9.309 GHz	9.3069 GHz
S_{11}	-29.81 dB	-16.676 dB
Δf_{3dB}	220 kHz	350 kHz
External Q	11,000	8,500
VSWR	1.065	1.3436
Temperature	25℃	25℃

◆ RF source

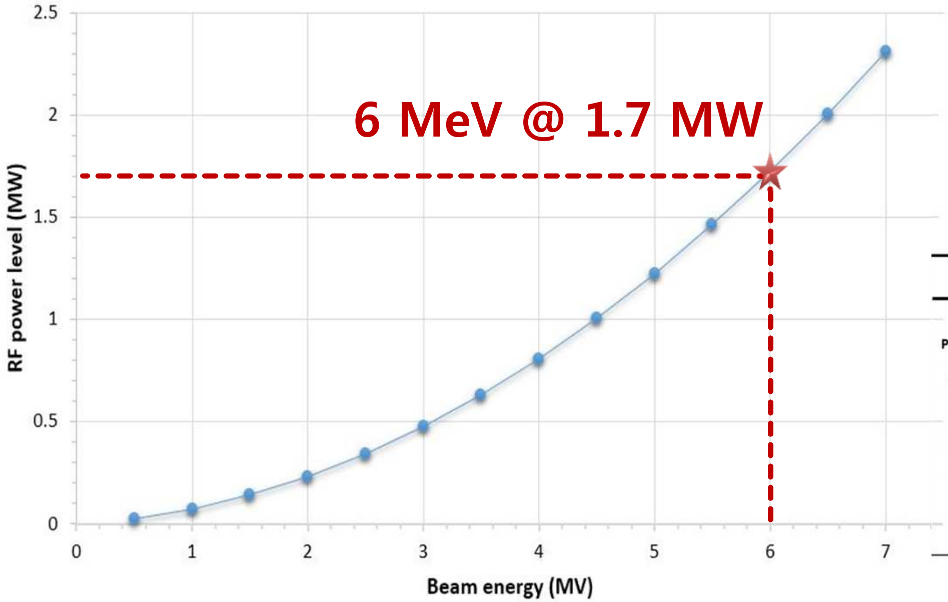


$$V_{gain} = \frac{2\sqrt{\beta_0}}{1+\beta_0} \cdot \sqrt{P_{rf} \cdot r_{sh} \cdot l} \cdot \cos(\omega t + \theta) \Leftrightarrow P_{diss} = \frac{V_{gain}^2}{R_{sh}} = \omega U\left(\frac{1}{Q_{ext}} + \frac{1}{Q_{unloaded}}\right)$$

$$P_{beam} = V_{gain} * I_{beam}$$

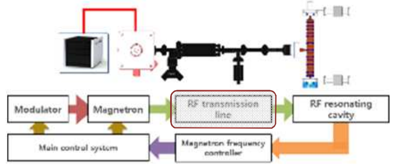
$$P_{total} = P_{diss} + P_{ref} + P_{beam}$$

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

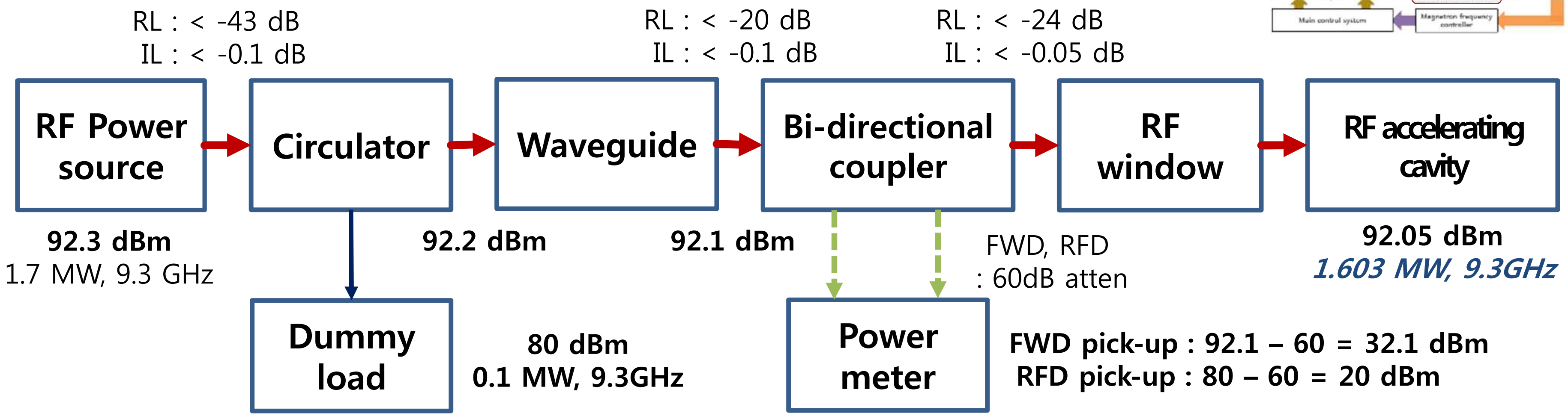


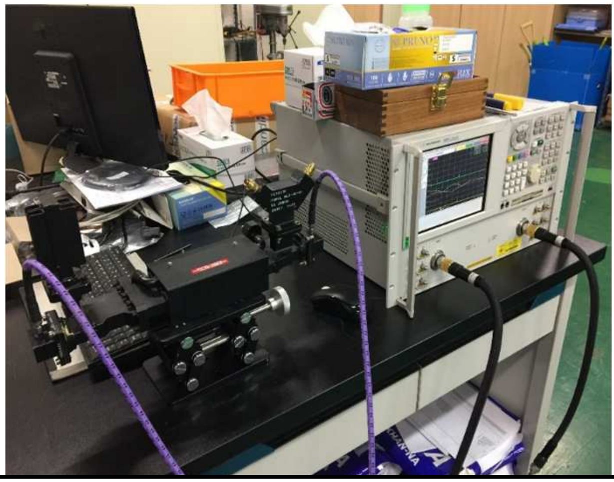
Parameter	L3 6170	CPI VMX3100HP
Frequency	9300 ± 25 MHz	9300 ± 30 MHz
Peak pulse power	1.7 MW	1.5 ~ 1.75 MW
Average power	1.36 kW	2.7 kW
Load VSWR	1.2:1 max	1.1 :1 max
Duty factor	0.0008	0.0018
Pulse width	4.0 us	5.0 ± 0.5 us
Peak anode voltage (kV)	34 ~ 38 kV	34 ~ 37 kV
Peak anode current (A	88 A	90 A

Parameter	ScandiNOVA M1 Mk4
Pulse power output (peak /avg)	4 MW / 8 kW
Top flatness	< 1%
Pulse rising time	< 10 ns
Pulse repetition rate	1 ~ 400 Hz
Max duty factor	0.003
Pulse width	0 ~ 5 us
Output peak voltage	0 ~ 40 kV
Output peak current	0 ~ 100 A



◆ Transmission waveguide



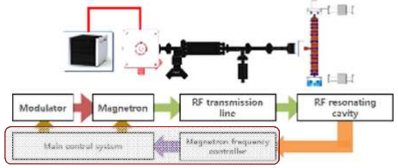


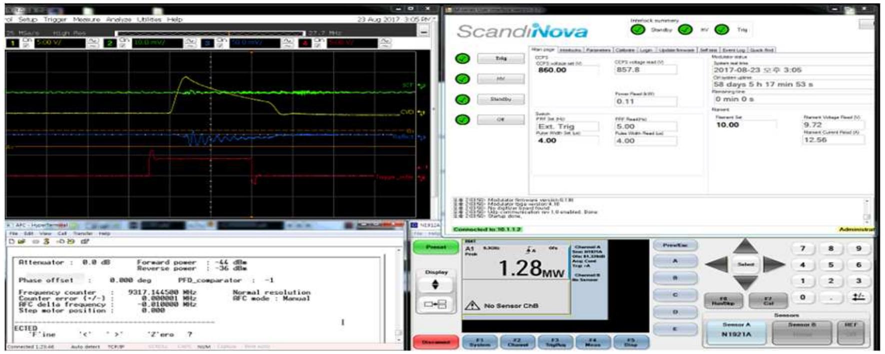
Component measurement using Network analyzer

Assembled RF transmission line	*Value*
Center freq. (GHz)	9.2979
Δf_{3dB} (MHz)	± 29
S_{11}, RL (dB)	-21.27
S_{21}, IL (dB)	-0.248
P.D (degree)	119.67
VSWR (:1)	1.188

X-band LINAC for radiation therapy

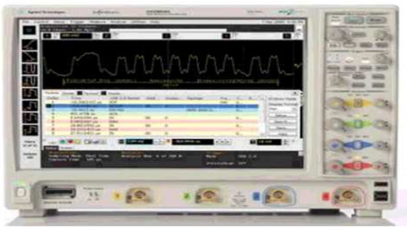
◆ Control system and data acquisition





Experiment process

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



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
1. Magnetron
2. Electron gun

7. Set trigger timing and duty cycle
1. Modulator
2. E-gun power supply

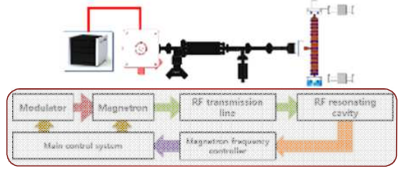
8. Modulator HV on
- 9.3 GHz, 1.7 MW RF power transmitting

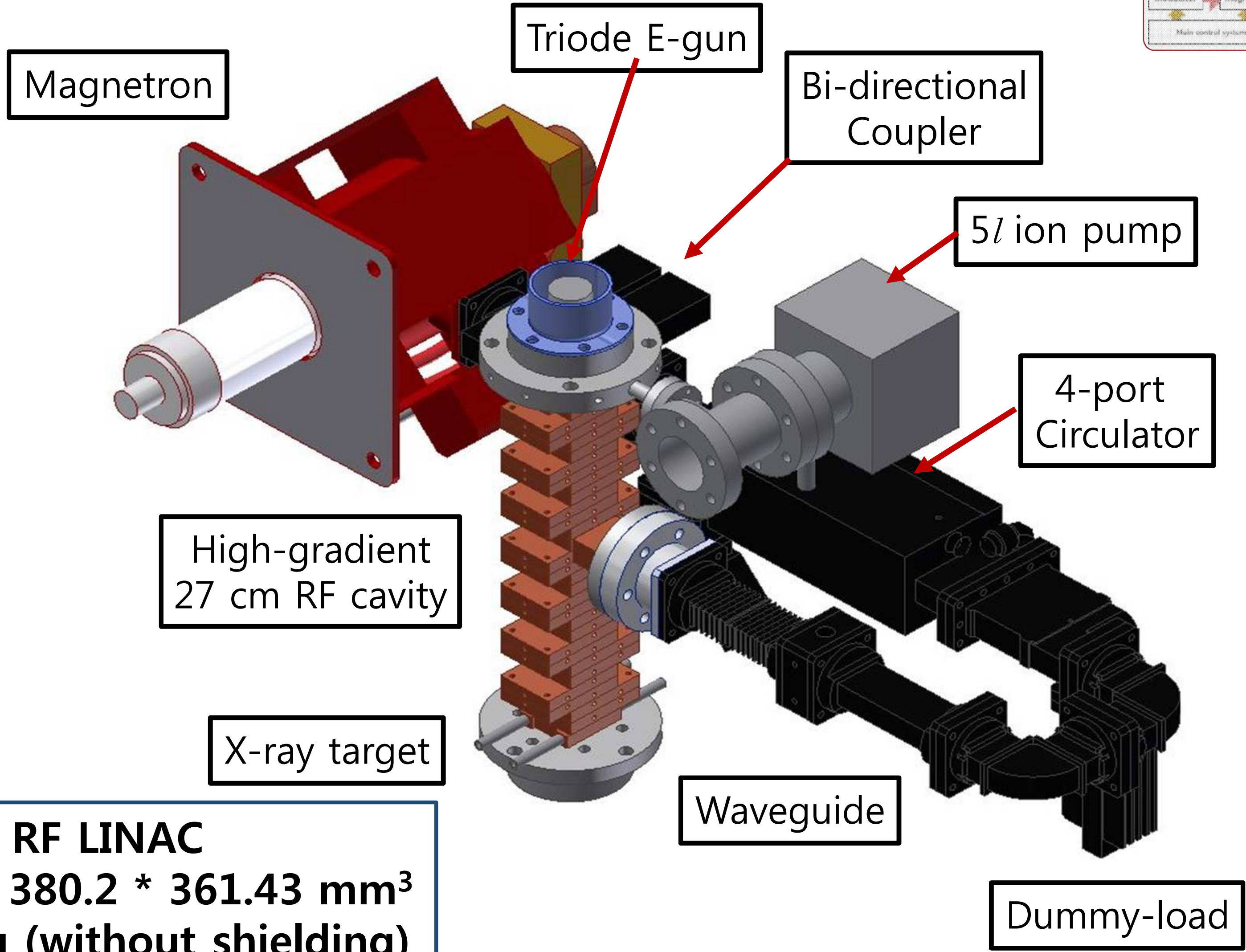
9. Set High Voltage
- 6 MeV, 20 mA pulse electron beam acceleration

10. Data acquisition
- RF power, beam performance

21. End of the procedure

◆ X-band LINAC system modeling





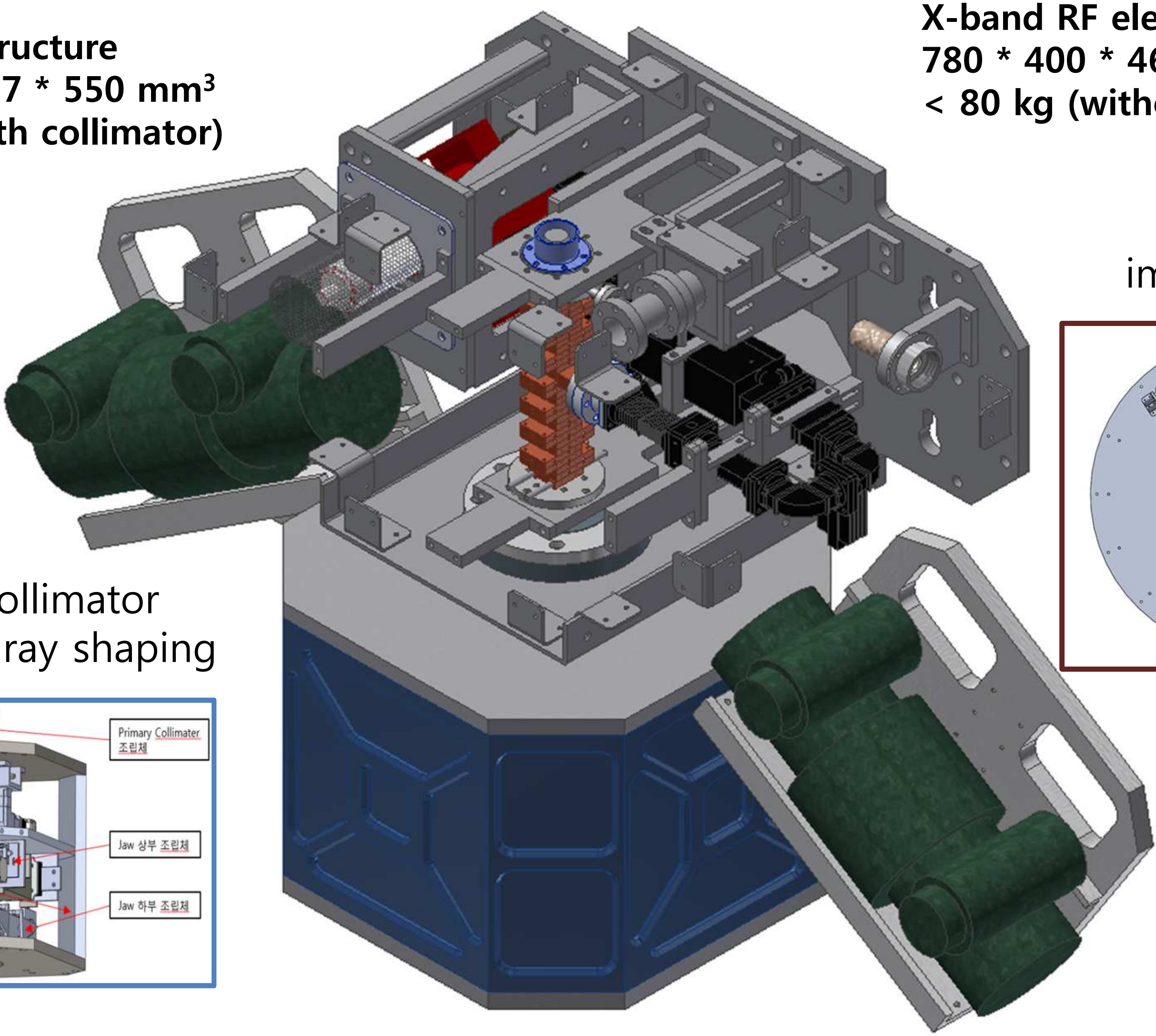
X-band RF LINAC
653.7 * 380.2 * 361.43 mm^3
< 80 kg (without shielding)

X-band LINAC for radiation therapy

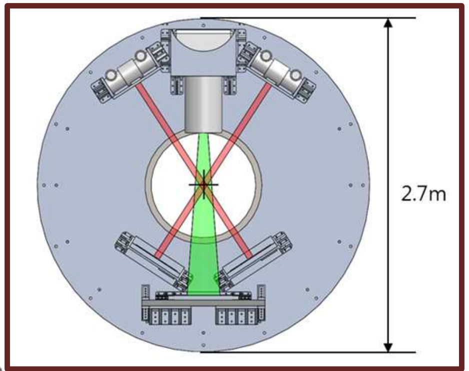
◆ X-band LINAC system modeling

Total head structure
1518.9 * 809.7 * 550 mm^3
< 350 kg (with collimator)

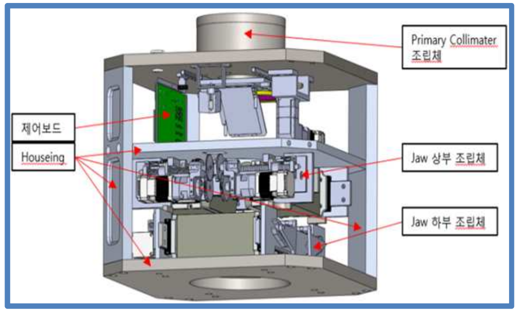
X-band RF electron LINAC
780 * 400 * 465 mm^3
< 80 kg (without shielding)



Stereo kV
imaging system



1st & 2nd Collimator
X-Y Jaw for X-ray shaping



Beam commissioning history

Unique Origin Unique Future

◆ Process of commissioning set-up

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

System implementation
- RF system installation
  - RF cavity, magnetron, modulator, and waveguide.
- Wire connection
  -electronics (380V)
- Ground check

Vacuum system configuration
- Pump installation
  - Rotary pump, TMP, ion pump (<1.0E-8 mbar)
- Leakage test
  - He detector

Cooling system configuration
- Cooling line installation
  - RF cavity, Magnetron, modulator, circulator, dummy-load with chiller
- Flow meter connection
  - Each component flow rate check

Magnetron filament heating
- Magnetron filament heating
  - Voltage, current, and resistor check
- First heating time during 5 hours
- Warm-up time : 30 min

RF pulse power transmission
- 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]

System implementation
- LINAC installation
  - E-gun, RF system, target, measurement unit, collimator.
- Wire connection
  -electronics (380V)
- Ground check

Vacuum system configuration
- Pump installation
  - Rotary pump, TMP, ion pump (<1.0E-8 mbar)
- Leakage test
  - He detector

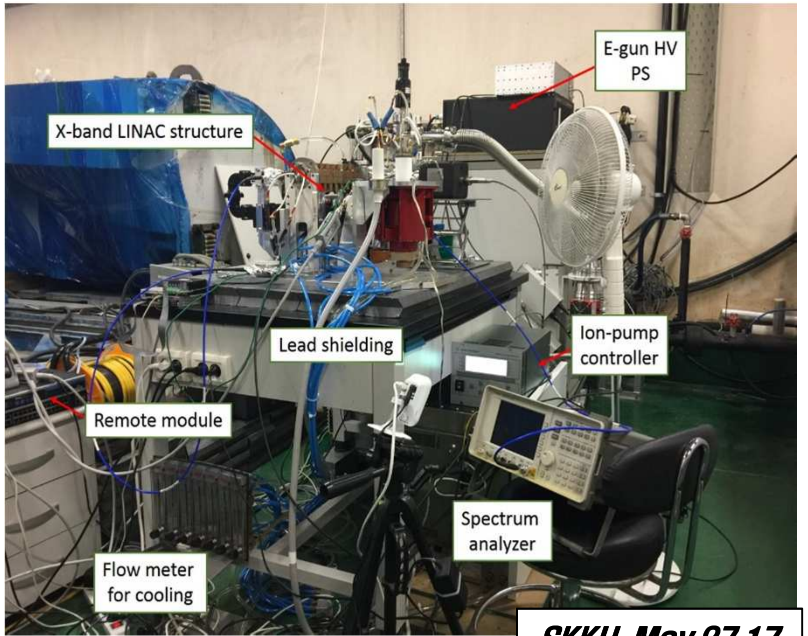
RF cavity heating
- Bake out
  - RF cavity, RF window, target, measurement system.
- Heating process
  - Up to 200℃ at 24 hours.
- Cool down slowly.

E-gun filament heating
- E-gun filament heating
  - Voltage, current, and resistor check
- First heating time during 10 hours
- Warm-up time : 1 hr

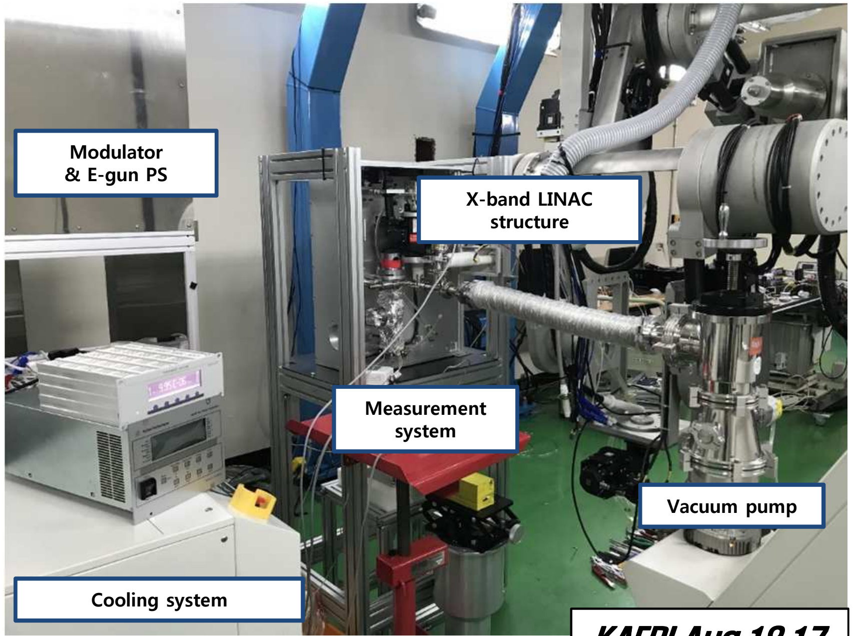
Beam acceleration
- Trigger timing check
- Increase HV pulse gradually
  - vacuum state check
- Beam acceleration check with CCD cam

Beam commissioning history

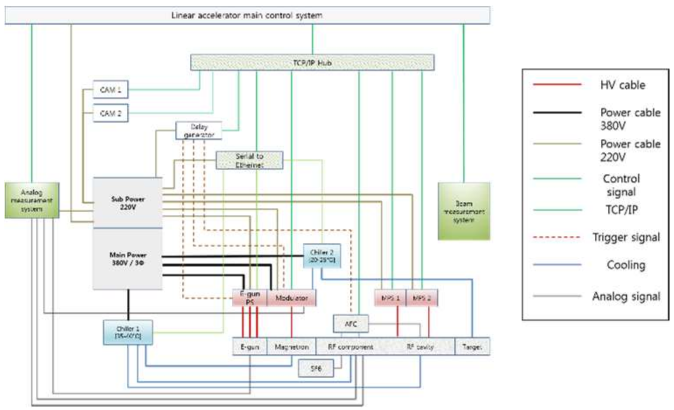
◆ System implementation



SKKU, May.27.17.



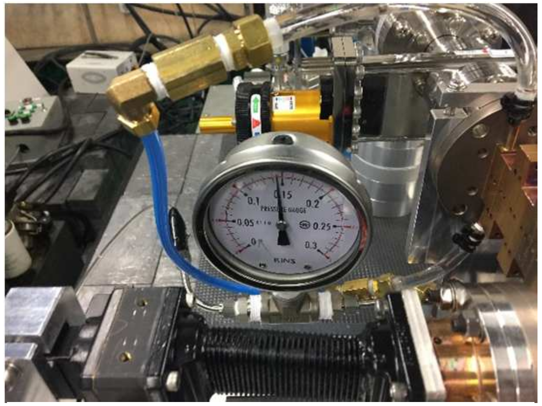
KAERI Aug.18.17.



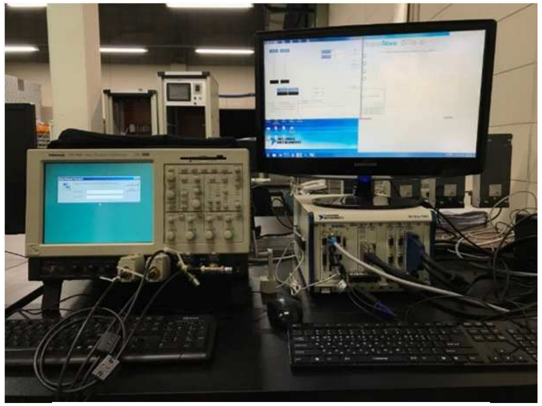
Beam commissioning history

Cooling system with 0.1℃ stability

Vacuum pump with ion pump controller

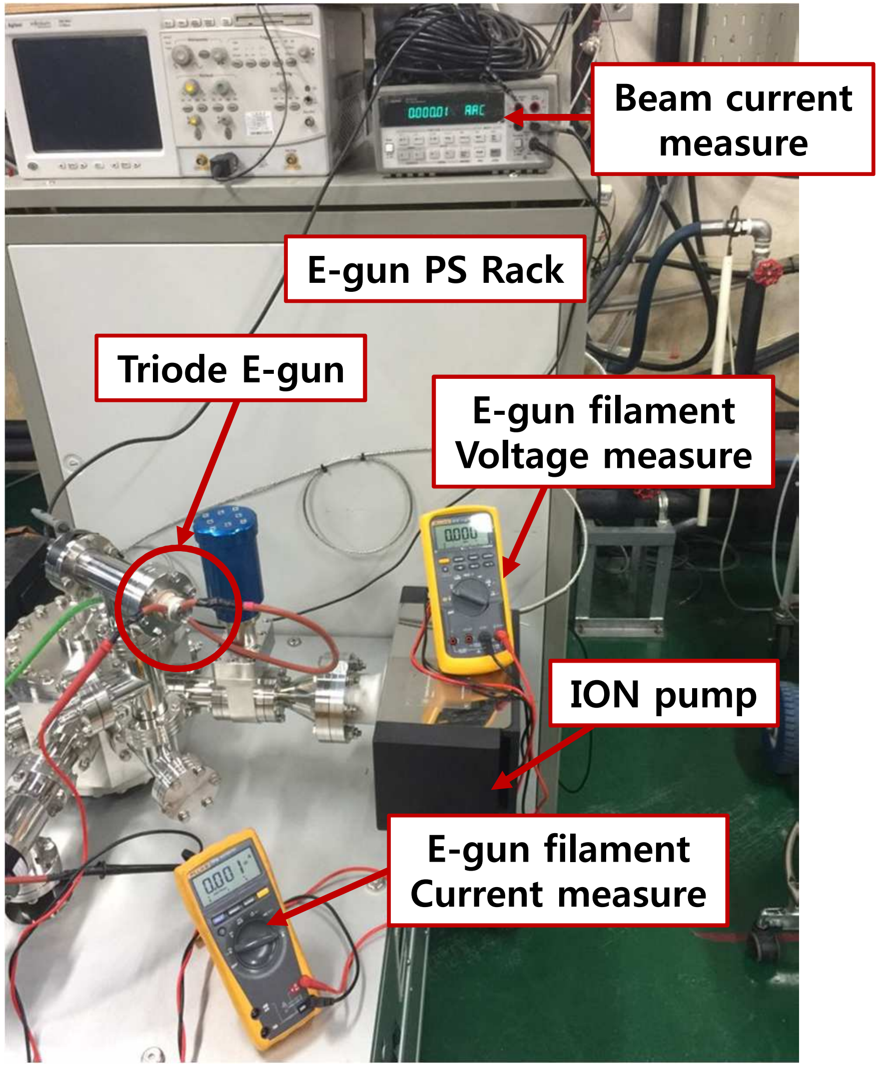


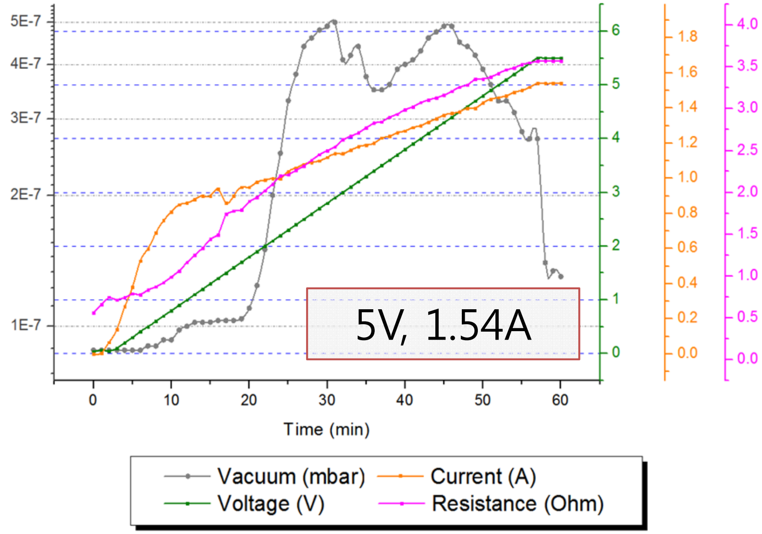
SF_6 dense meter (35 psi)

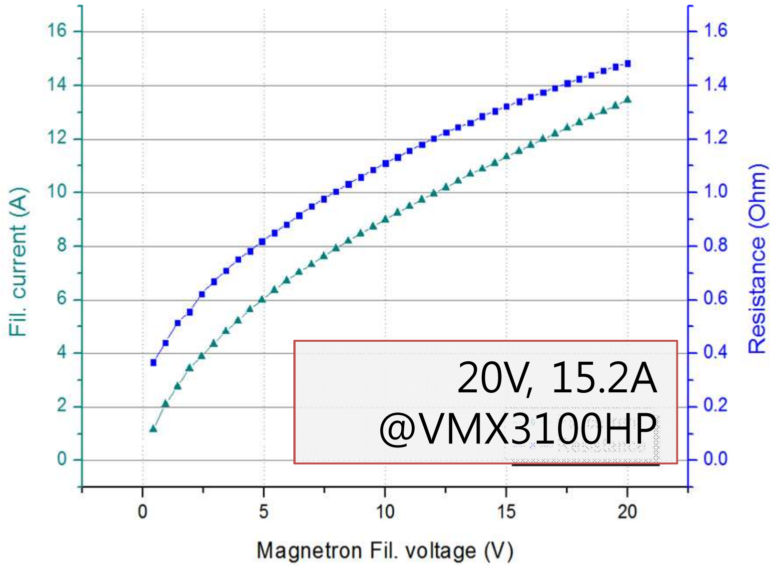


Main control system

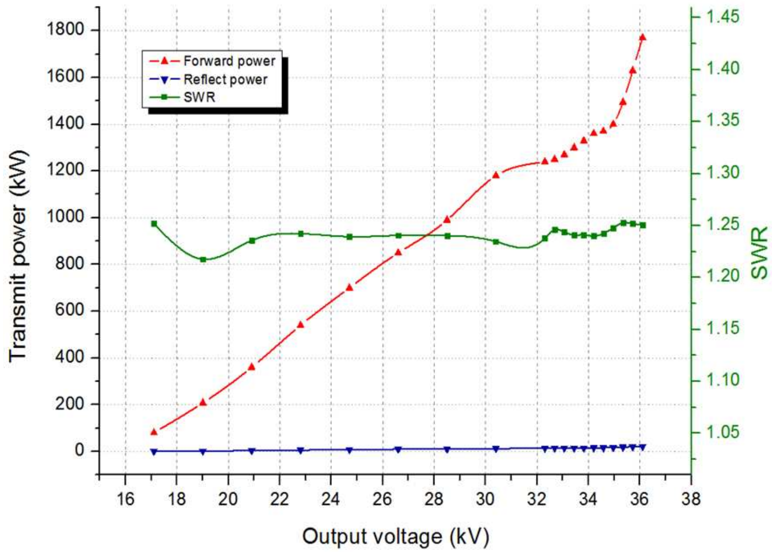
◆ Filament heating – E-gun & magnetron



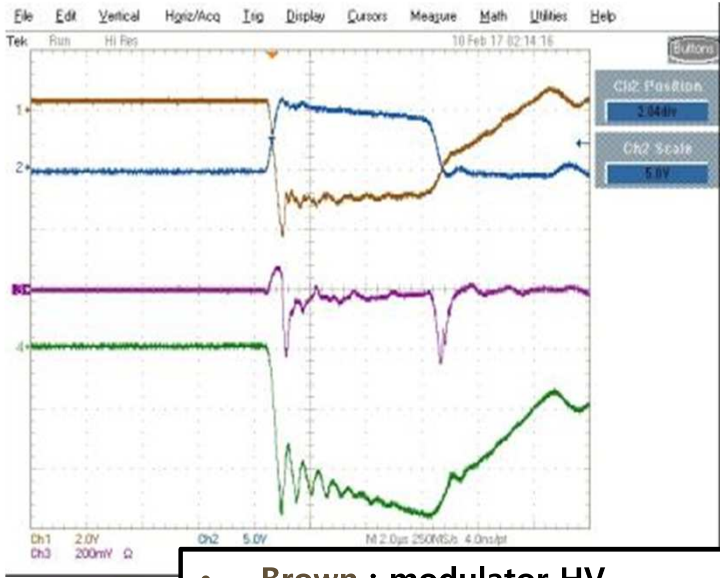




◆ RF commissioning test

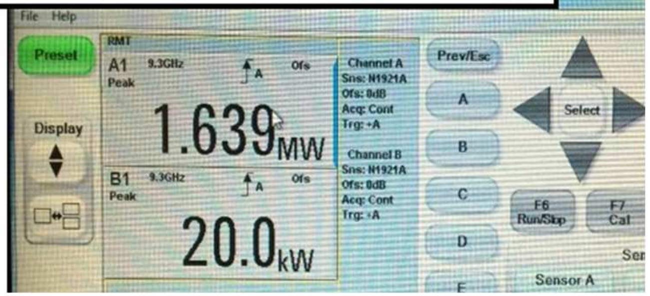


FWD 1.64 MW **RFD** 20 kW **SWR** 1.2 : 1
Repetition rate 120 Hz **Pulse width** 4.0 us

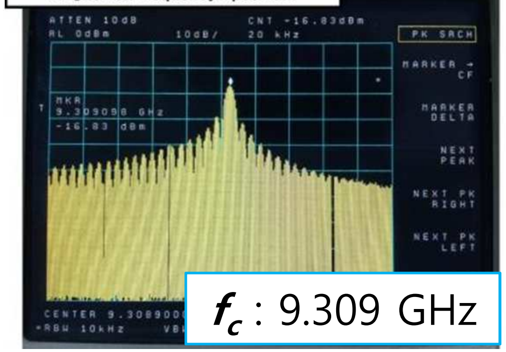


- **Brown : modulator HV**
- **Blue : modulator current**
- **Purple : Reflection power**
- **Green : HV measured 1:1000 probe**

Magnetron Power-meter level

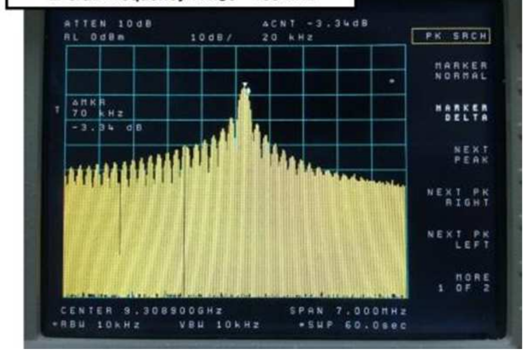


Magnetron frequency spectrum

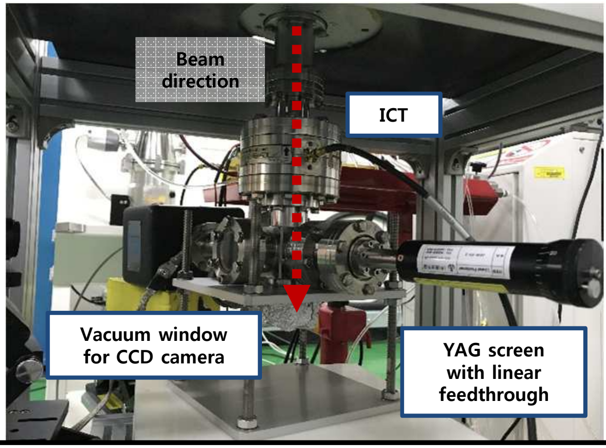


f_c : 9.309 GHz

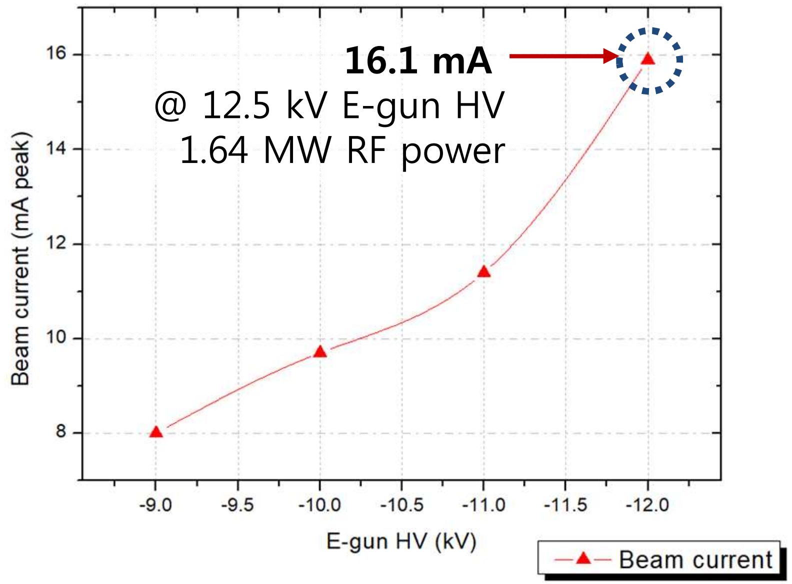
△ 3 dB frequency range : 135 kHz

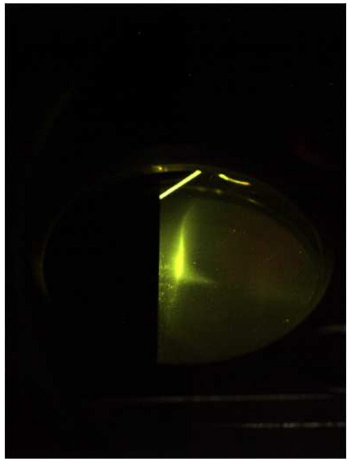


◆ Beam commissioning test – current & spot size

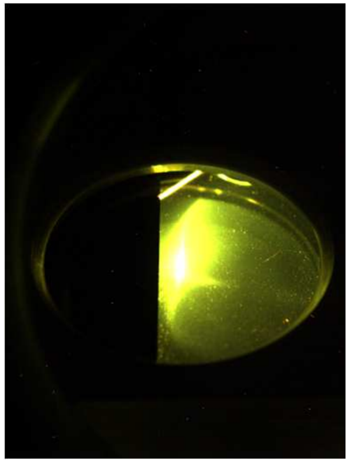


Beam measurement system implementation





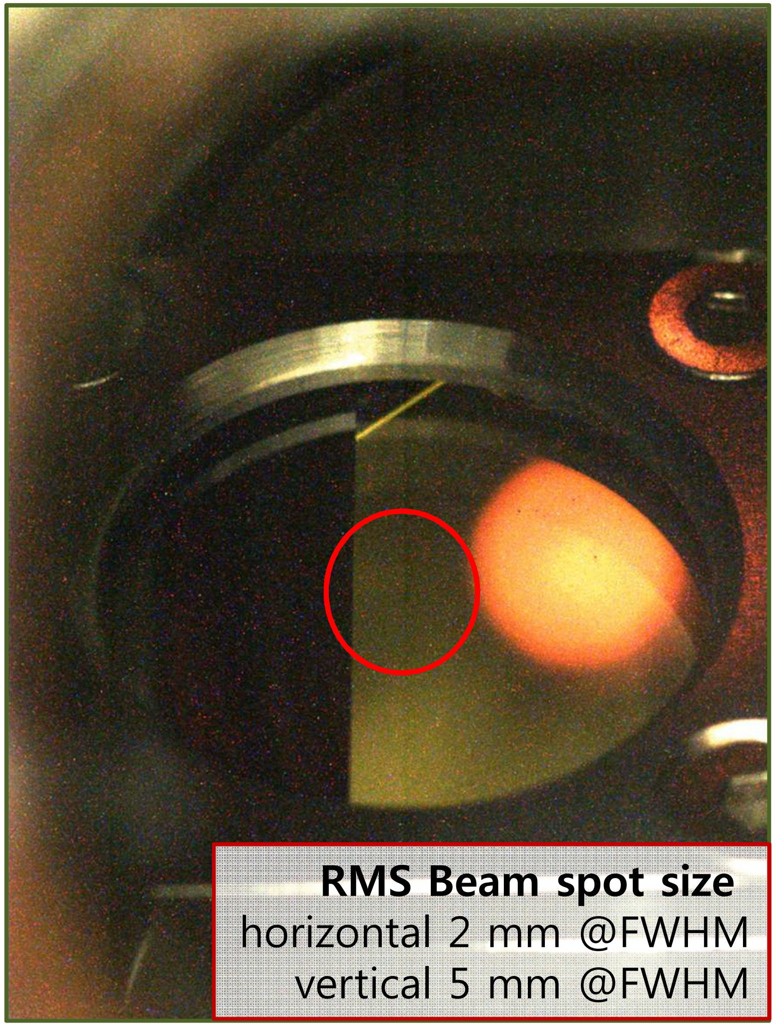
RF Power 1.05 MW (12.5kV -65 +55V)

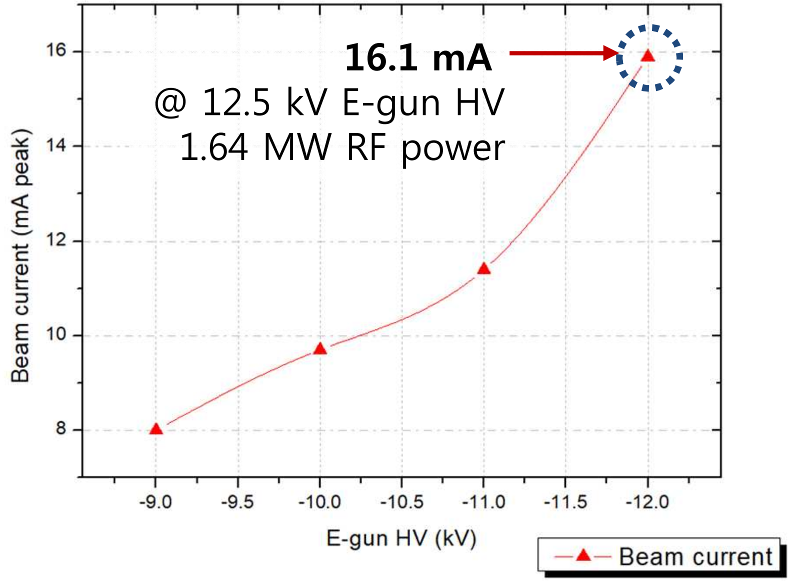


RF Power 1.64 MW (12.5kV -65 +55V)

E-gun HV voltage (kV)	*Beam current (mA) @ 1.64 MW*
< -9.0	-
- 9.0	8.0
- 10.0	9.7
- 11.0	11.4
- 12.5	**16.1**

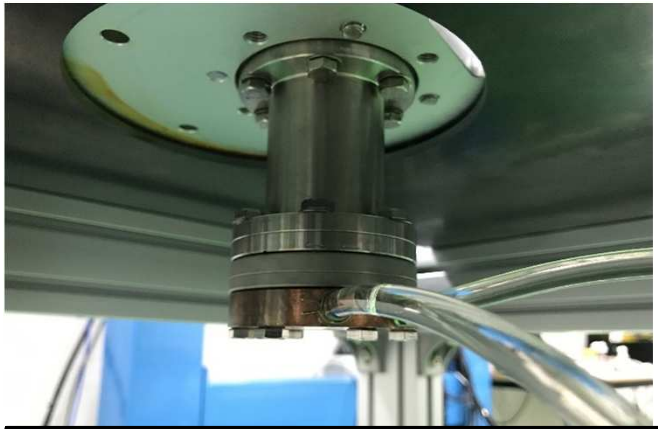
◆ Beam commissioning test – current & spot size



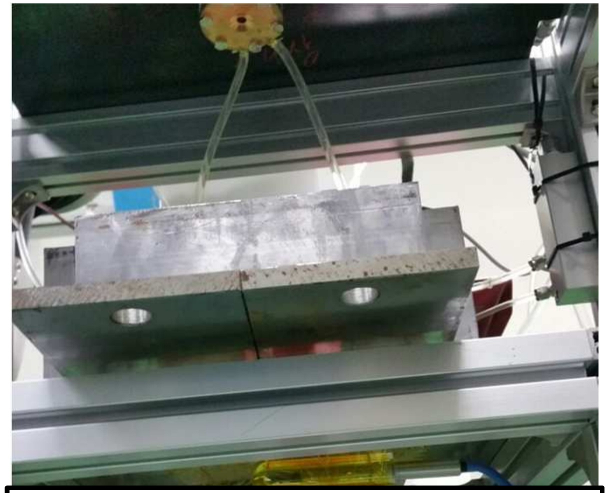


E-gun HV voltage (kV)	*Beam current (mA) @ 1.64 MW*
< -9.0	-
- 9.0	8.0
- 10.0	9.7
- 11.0	11.4
- 12.5	**16.1**

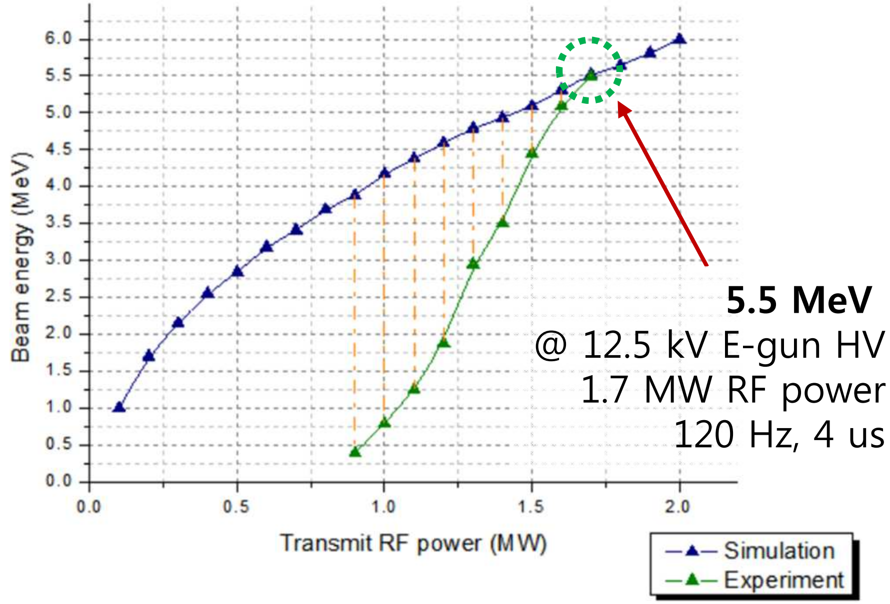
◆ Beam commissioning test – beam energy



e-γ tungsten target for X-ray irradiation



Steel plate for energy measurement by HVL method



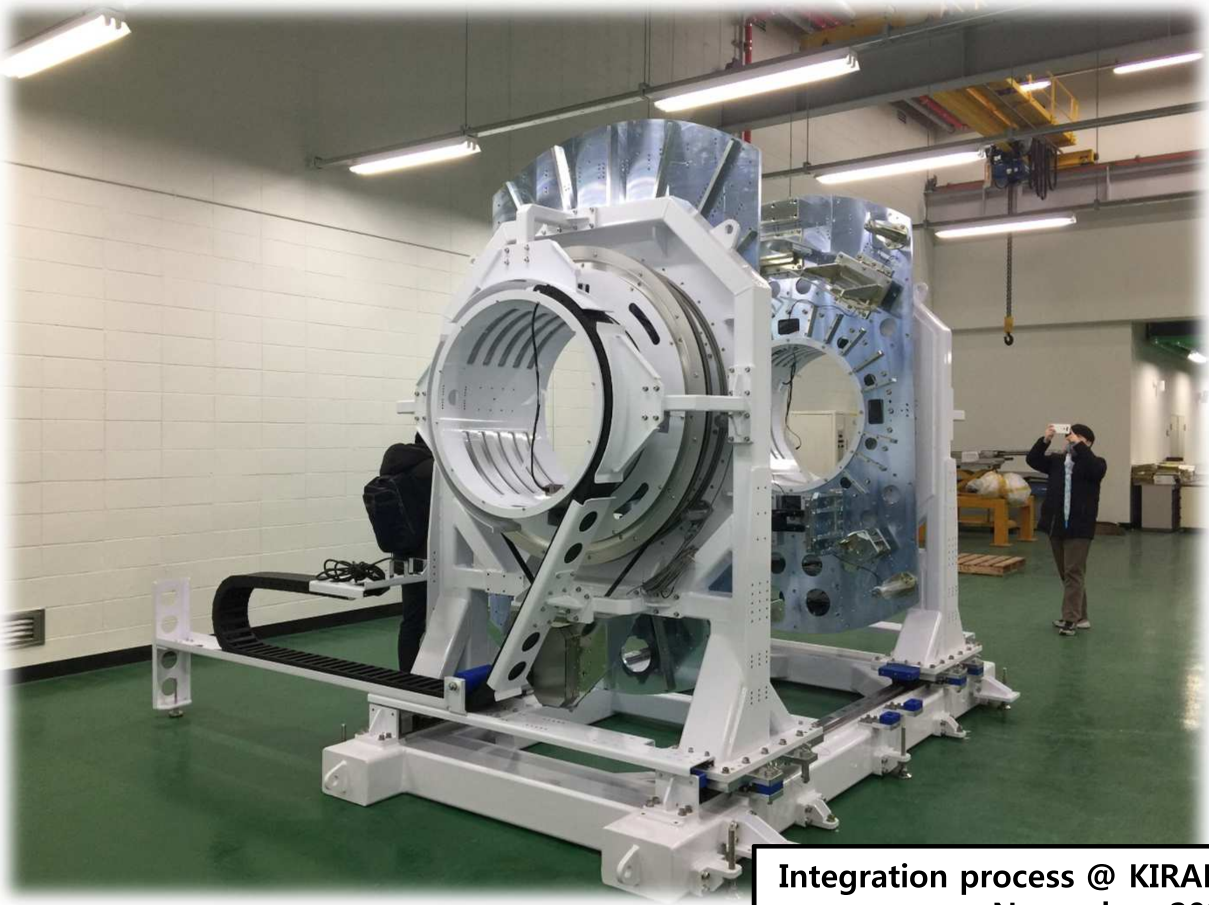
Transmitted power (MW)	*Beam energy (MeV)*
1.07	0.8
1.22	1.96
1.37	3.48
1.52	5.02
1.7	**5.5**

Experimental result and analysis

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

Conclusion

- 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 conducing 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
November. 2017.

Thanks for your attention

Back-up slide

Table 3. Overview of literature studies: comparison of treatment outcomes according to the radiation therapy schedule

Reference	Radiation dose (Gy) per fraction/# of fractions	No. of patients	Treatment outcome[a] (%)	Toxicity (%)
Boulware et al. [16]	10 Gy/#1	86	Bleeding (45), pain (42)	Acute (9.3)
	10 Gy/#2, 3–4 wk interval	55	Bleeding (85), pain (59)	Late (17.4)
	10 Gy/#3, 3–4 wk interval	20	Bleeding (100), pain (63)	
Hodson and Krepart [5]	10 Gy/#3, 4 wk interval	14	Bleeding (100), pain (100)	Late (14.3)
Halle et al. [6]	10 Gy/#1–3, at 4 wk interval or recurrence	42	Bleeding (90), pain (44)	Acute (6.7), severe late (11.9)
Patricio et al. [19]	6.5 Gy/#2 in 48 hr	56	Bleeding (94), pain (45)	Severe (16.3)[b]
Spanos et al. [20]	3.7 Gy/#4 in 48 hr, 2–4 wk interval, up to three cycles	61	Bleeding (76), pain (31)	Acute (3), late (7)
Onsrud et al. [14]	10 Gy/#1	11	Bleeding (90), pain (0)[c]	Acute (36.4)
	10 Gy/#2, 4 wk interval	51		Acute (45.3), severe late (9.4)
	10 Gy/#3, 4 wk interval	2		Acute (43.8), severe late (7.8)
Mishra et al. [15]	10 Gy/#1	100	Bleeding (74), pain (47)	Late (10)[c]
	10 Gy/#2, 4 wk interval	61	Bleeding (80), pain (59)	
	10 Gy/#3, 4 wk interval	33	Bleeding (100), pain (50)	
Present study	5 Gy/#4–5	17	Bleeding (93.8), pain (66.7)	Acute (47.1), late (23.5), severe late (0)

[a]Proportion of patients, which showed complete or partial (>50%) improvement of symptom. [b]Acute or late toxicity was not specified. [c]Treatment outcomes or toxicities according to number of fractions were not specified.

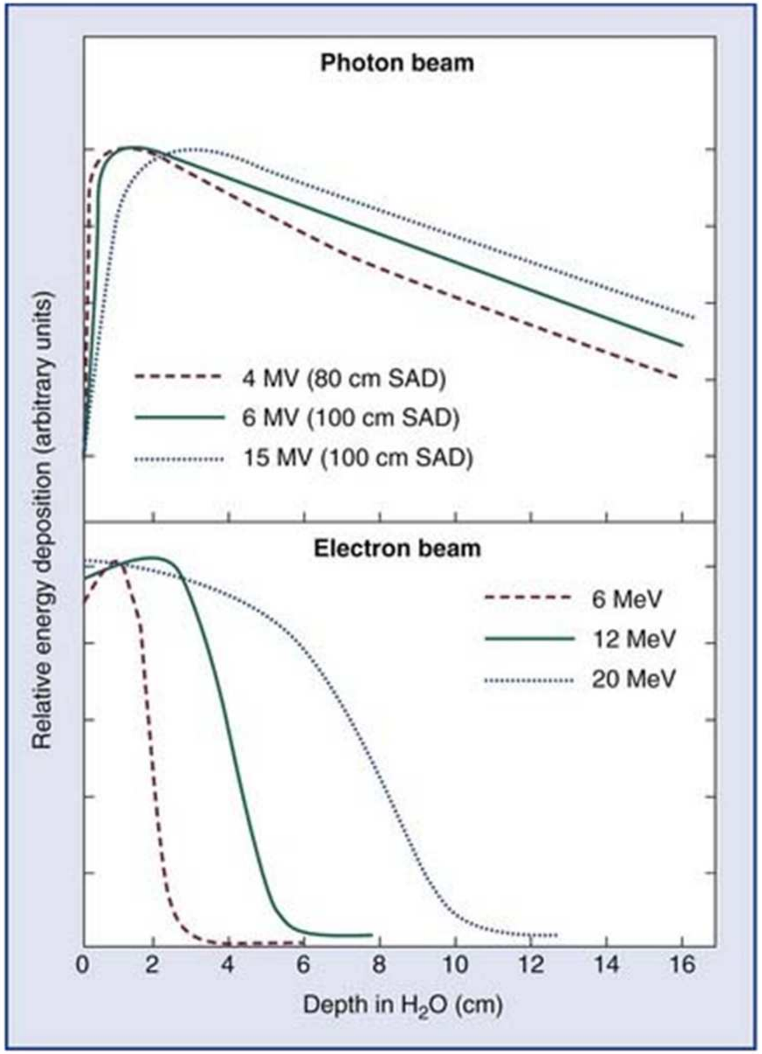
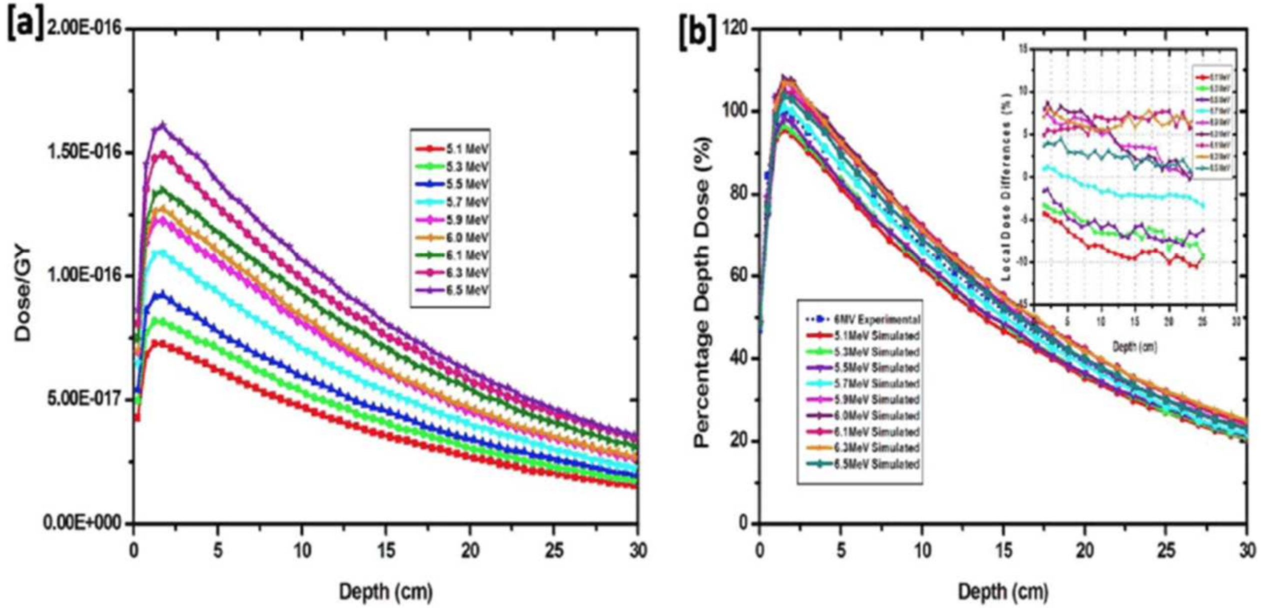
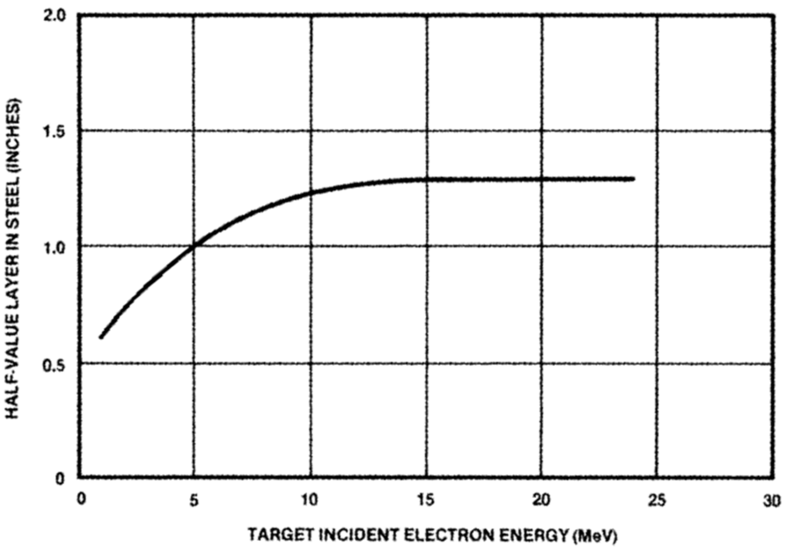


Figure 77-4. Typical depth-dose curves for megavoltage photon and electron beams commonly used in the therapy of head and neck cancers. The *upper panel* shows curves for 10 cm × 10 cm fields for a 4-megavolt (MV) (80-cm source axis distance [SAD]) linear accelerator *(dashed line)*, a 6-MV (100-cm SAD) 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 cm 2. 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 cm 2. The inset shows the local dose differences.



How to measure the energy of X-band LINAC



[전자빔 에너지 변화에 따른 철의 HVL 변화]

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(I_0). 초기 철판 두께보다 두껍게 하여 같은 양의 X-ray를 조사하여 방사선량을 측정한다(I). 철판의 두께를 두껍게 한 두께에서 초기 철판 두께를 빼준다(d). 아래의 공식을 이용하여 μ 값을 구한다.

$$I = I_0 e^{-\mu d} \text{ ------------ (1)}$$

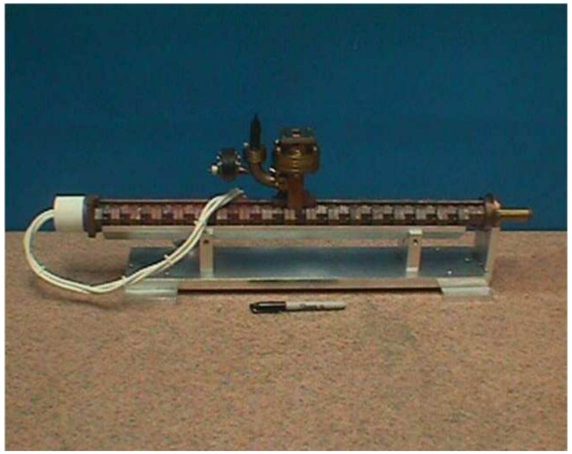
구한 값을 아래에 공식에 대입하여 반가층을 구한다.

$$HVL = 0.693/\mu \text{ ------- (2)}$$

전자빔 에너지 변화에 따른 철의 HVL (2.74 cm)은 실험을 통해 정해져 있다.

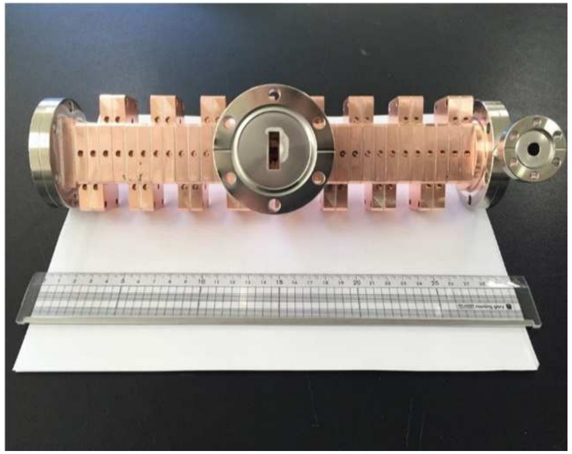
방사선 치료기에 사용 된 선형가속기 비교

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



Cyberknife

Tomotherapy



SKKU-KAERI Dual-head Gantry Therapy Machine