清華大學
Tsinghua University

Electron linear accelerator for radiotherapy

Chuanxiang Tang/Hao Zha

Tsinghua University, Beijing 100084, China

At AFAD2018 (9th Asian Forum for Accelerators and Detectors), January 28 -31, 2018, Daejeon Convention Center, Daejeon, Korea

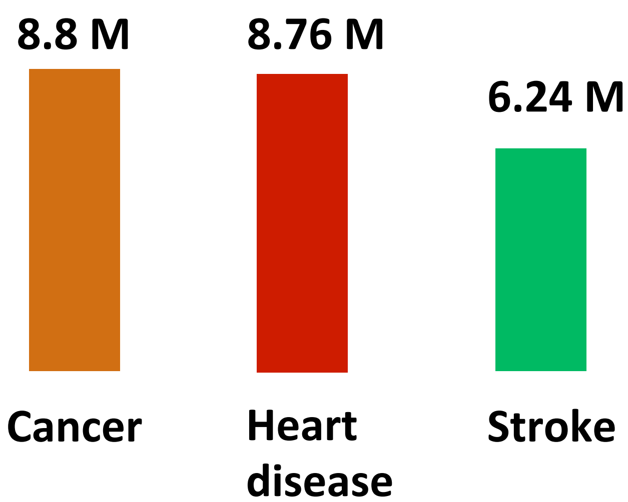
Outline

- **Brief overview of radiotherapy**
- Recent developments in medical electron linear accelerator
- Activities in Tsinghua University

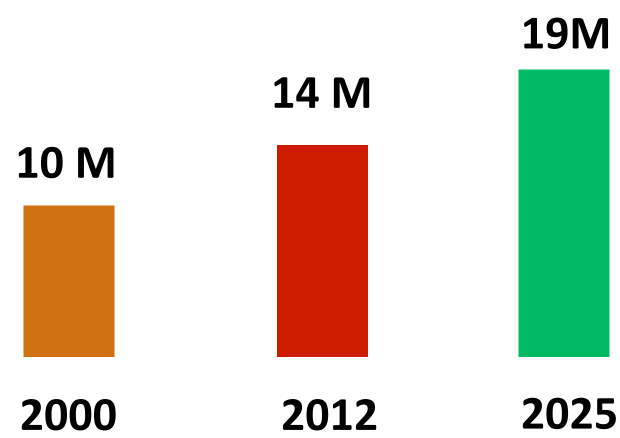
Cancer worldwide

- Cancer has been the first killer to human beings;
- Incidence of cancer is rising rapidly.

Top 3 causes of death worldwide, 2015
(Data from WHO)



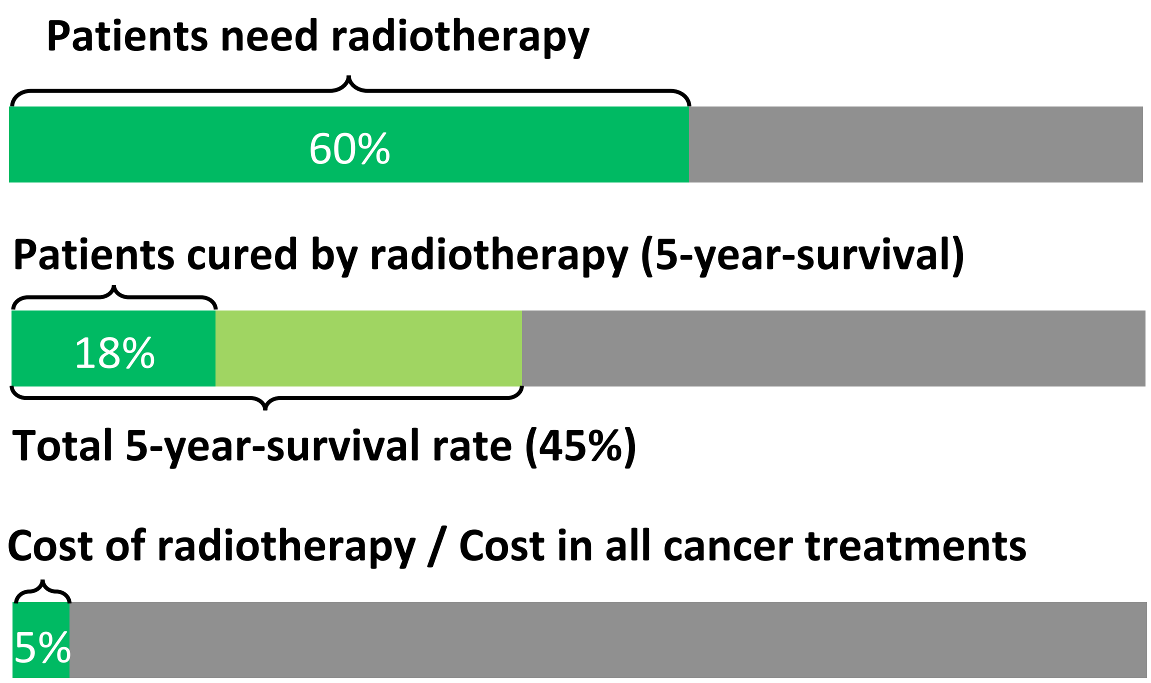
Annual cancer incident worldwide
(Data from WHO)



Radiotherapy

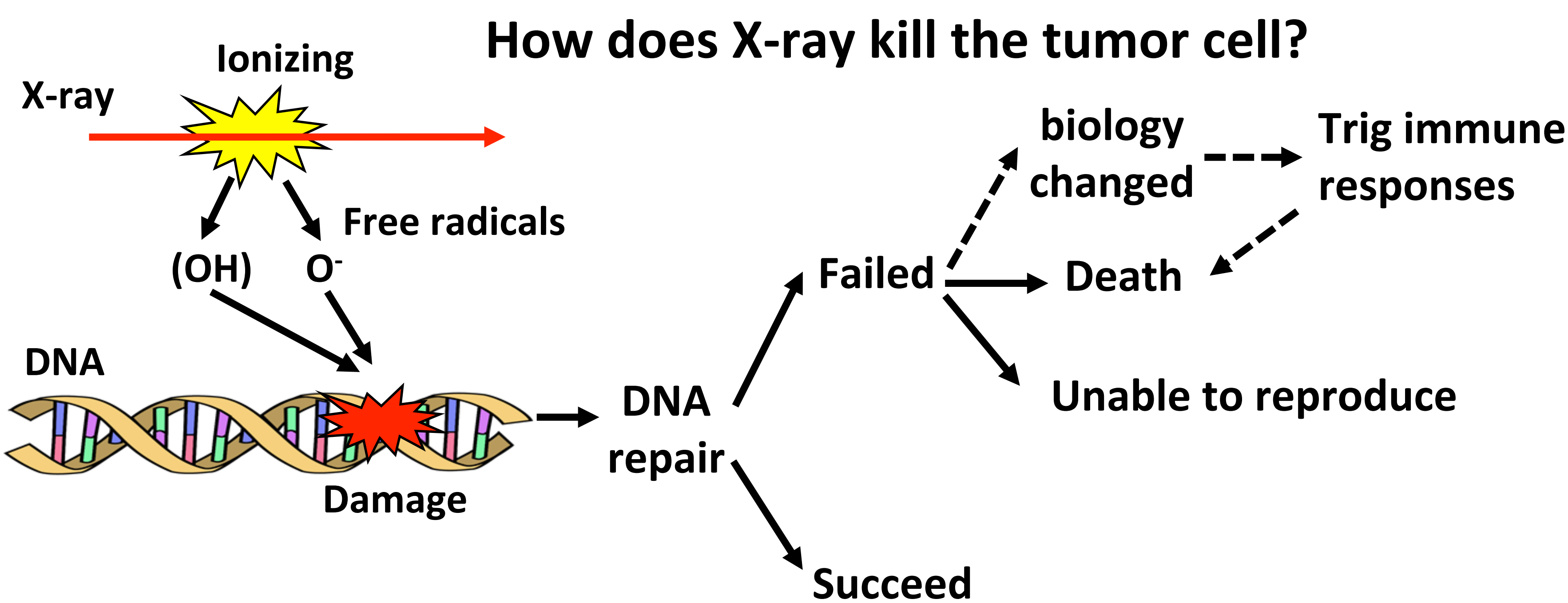
- Surgery, chemotherapy and radiotherapy are still the mostly used treatments of cancer .
- Radiotherapy (radiation therapy) has a high cost-effectiveness ratio.

Facts about radiotherapy (Data from high-income countries, 2012, IAEA)



How does radiotherapy kill the tumor cell?

- Radiotherapy use ionizing radiation to break the DNA of tumor cells (also harms the normal tissue, which is the side effect).
- Usually, a tumor cells has less ability to repair its DNA and thus is easier to be killed.

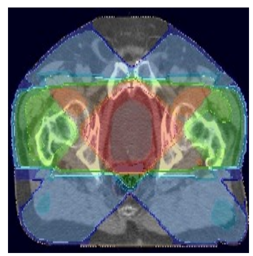


History of X-ray radiotherapy

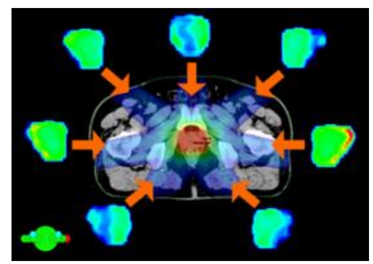
- X-ray was used to treat the cancel patient in 1896.
- After WW-II, hazards of ionizing radiation were more clearly understood. Many technologies were developed to reduce the radiation dose on normal tissues.

X-ray discovery

LINAC



CRT

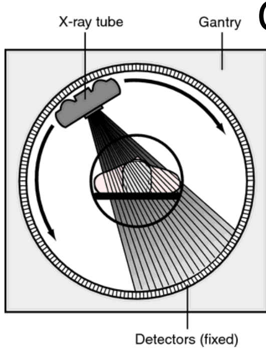


IMRT &VMAT

IGRT &SBRT

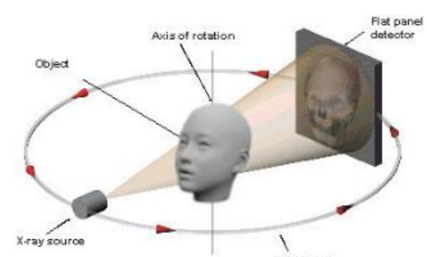
1895 … 1950 1960 1970 1980 1990 2000 2010

Pic from Wikipedia



CT &MRI

MLC



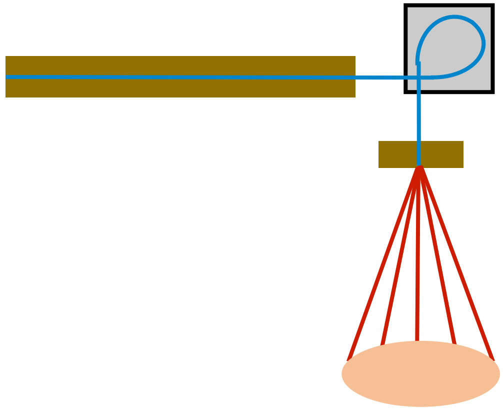
CBCT

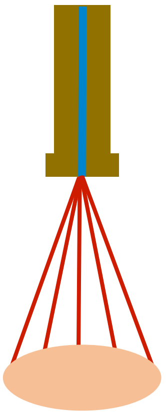
Electron LINAC in radiotherapy

- Electron LINACs were first used in radiotherapy since 1950s.
- Now most machines use Electron LINACs as the X-ray sources.
- 6 MV is the most-often choice of the LINAC voltage.

High-energy (e.g. 14 MV) machine:
Due to the diameter limitation, LINAC should be placed horizontally. And a magnet is used to bend the beam.

Low-energy machine:
LINAC is short and can be vertically placed.





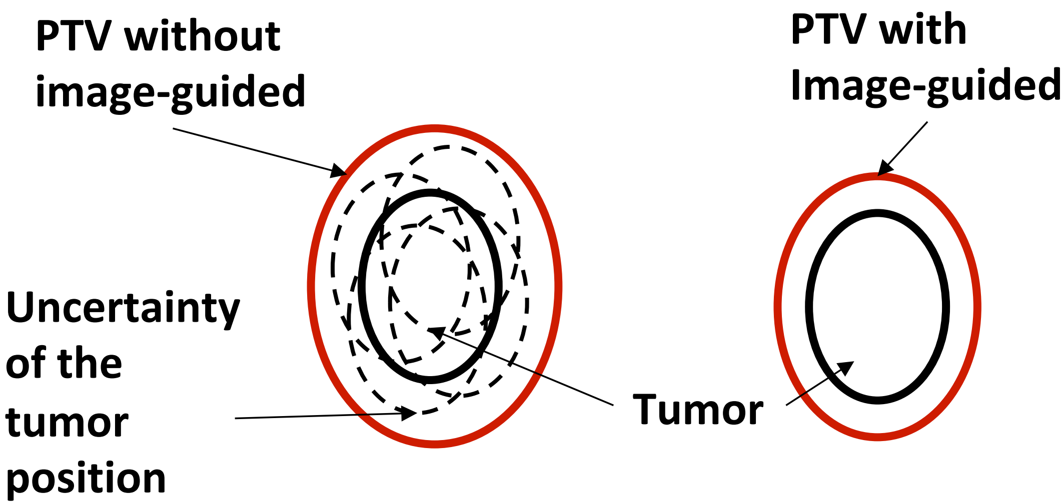
Outline

- Brief overview of radiotherapy
- **Recent developments in medical electron linear accelerator**
- Activities in Tsinghua University

Recent developments

- Spatial resolution (in positioning the tumor) is a crucial factor in radiotherapy.
- Higher resolution can bring:
  - Less side effect, increases the quality of life;
  - Able to deliver higher dose, increases the cure rate.

PTV: planning target volume



Dp (Dimension of PTV) =
Dt (Dimension of tumor) +
5 x σ (Spatial resolution, RMS)

If the size of a tumor = 3 cm:

σ	Dp	Volume of PTV/tumor
0.5 mm	3.25 cm	127%
1 mm	3.5 cm	159%
2 mm	4 cm	237%

IGRT: Image-guided radiotherapy

- **Sub-millimeter** accuracy is going to be needed in radiotherapy.
- IGRT:two functions (imaging, treatment) in one system/machine.

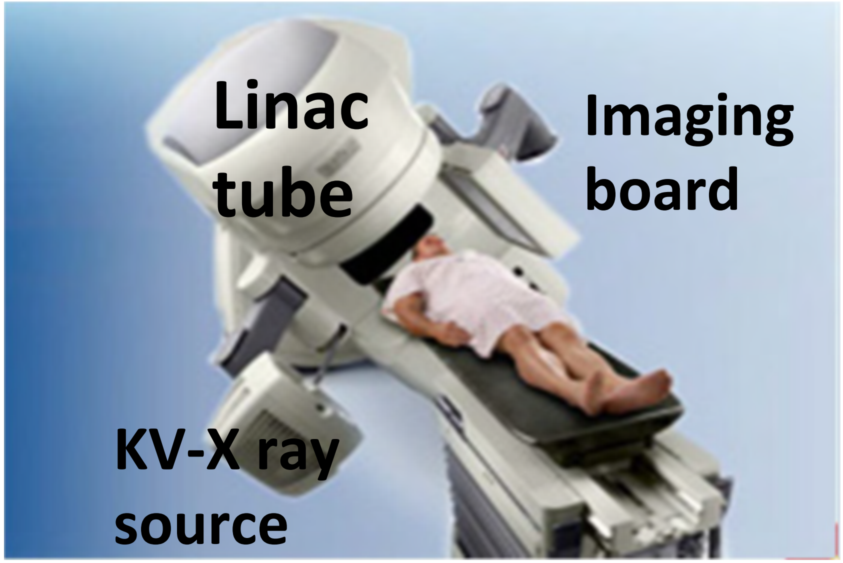
Scheme of imaging	**Precision**
Ultra-sound	**> 5 mm**
External marker (Optical)	**> 2 mm**
Internal marker (Magnetical)	**> 1 mm**
Fluoroscopy	**Unknown**
CT on rail	**1 mm**
PET	**Unknown**
KV X-ray/CBCT	**1-2 mm**
MRI	**< 2 mm**
Coaxial 2D X-ray	**< 2 mm**

Can determine position and volume of the target before delivering the dose (Offline IGRT)

Can track position and volume of the target during the dose delivery (Online/real-time IGRT)

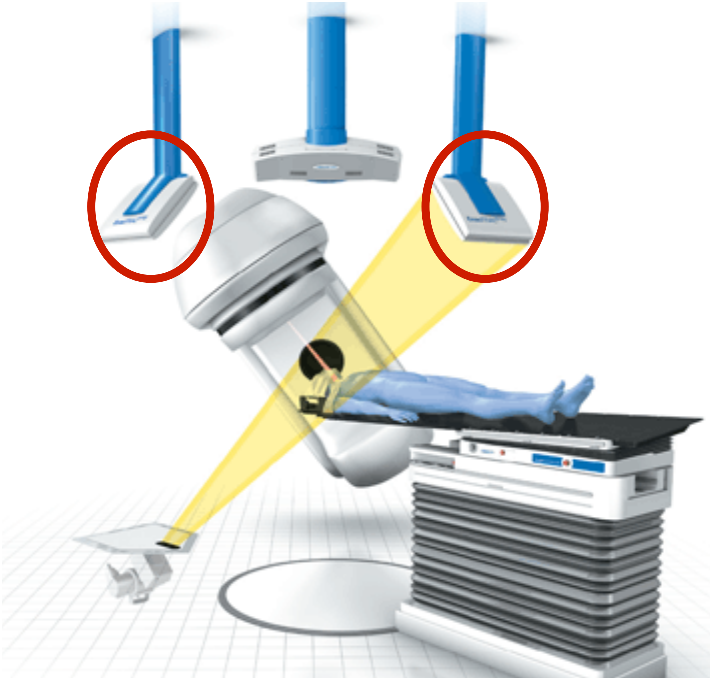
KV X-ray imaging

- Imaging system on the gantry. Rotate for CT imaging (Cone-Beam CT).
  - Higher resolution;
  - Large extra dose (of imaging);
  - Longer time;



Varian true beam

- Imaging system not on the gantry. Two orthogonal imaging devices:
  - Lower resolution;
  - Fast and less dose;
  - Real time tracking;

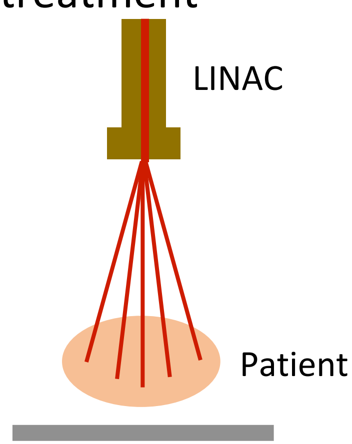


Pic from Stony brook cancer center

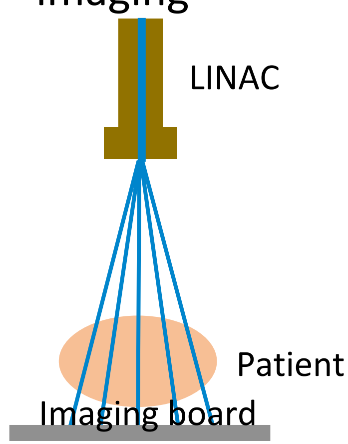
Coaxial imaging (Dual energy LINAC)

- If Imaging system and LINAC tube are in different coordinate system → Need transformation → Systematic error (~ 1 mm).
- If LINAC can do the imaging work, the systematic error could be eliminated.
- However, MV imaging has poor quality.
- KV/MV dual energy tube is under-developing.

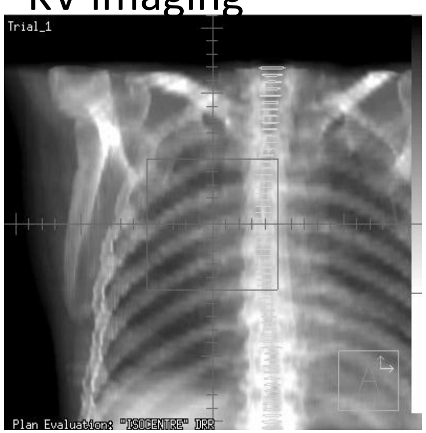
High energy for treatment



Low energy for imaging



KV imaging



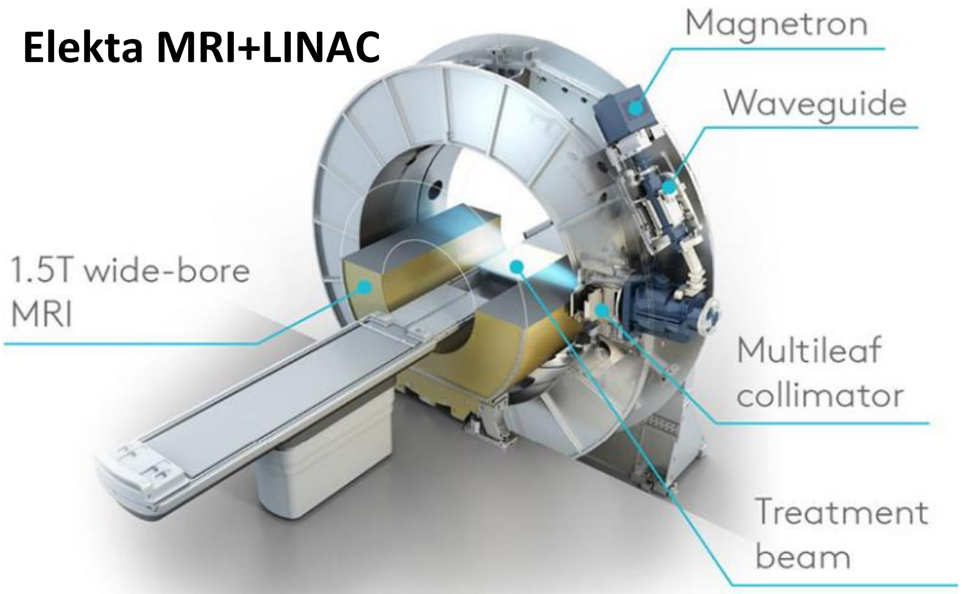
MV imaging

http://dx.doi.org/10.1155/2014/705604

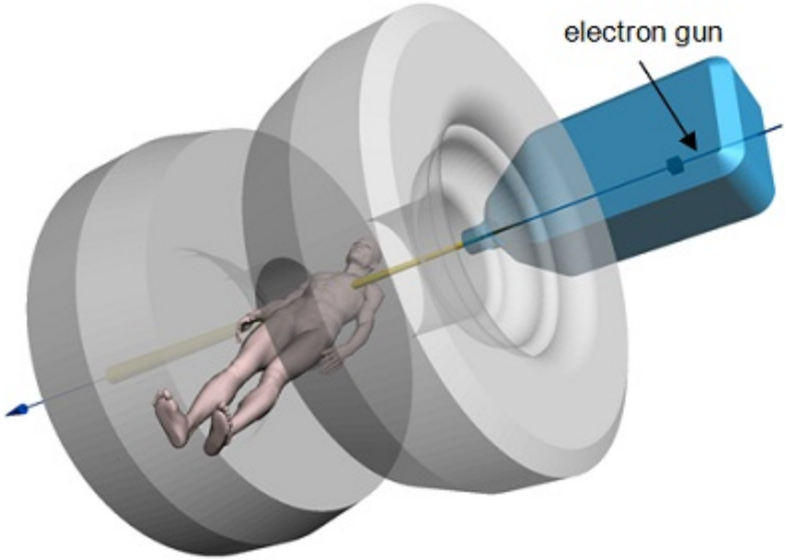
MRI+LINAC

- MRI could yield high quality imaging on soft tissue and with no extra dose.
- MRI+LINAC system is now under-developing.
- Difficulties:
  - Effect of strong alternating B-field on the linac tube;
  - Imaging time of MRI is quite long;

Elekta MRI+LINAC

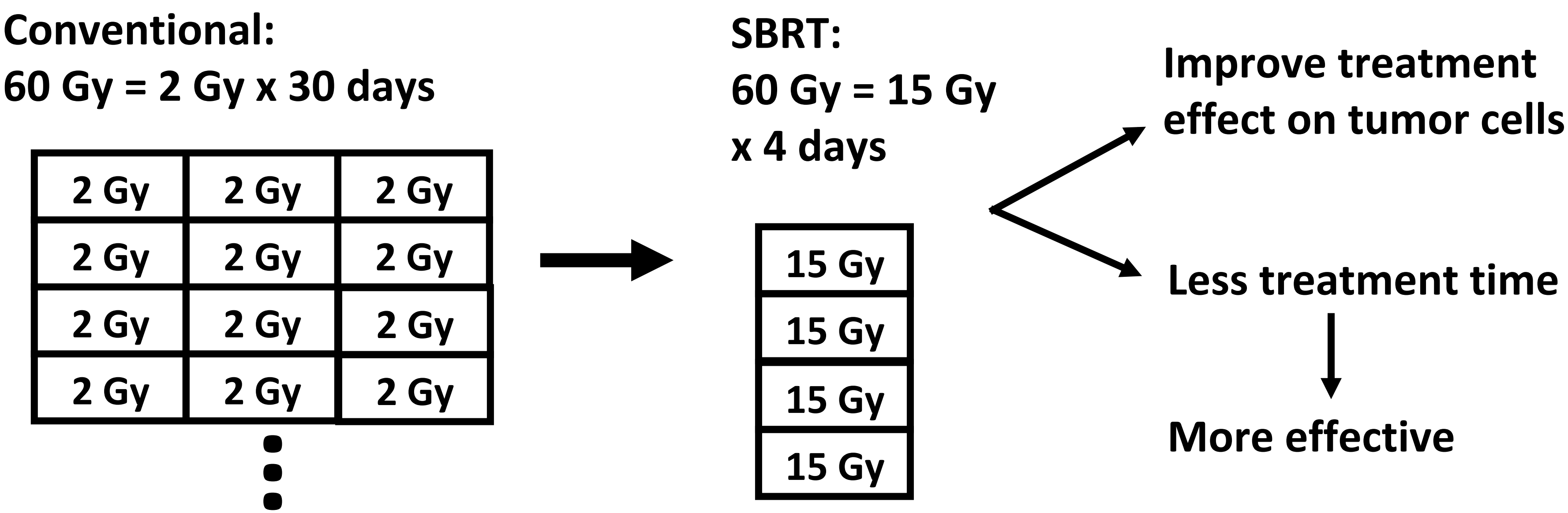


Robotic MRI+LINAC (Stanford Univ.)



SBRT: Stereotactic body radiotherapy.

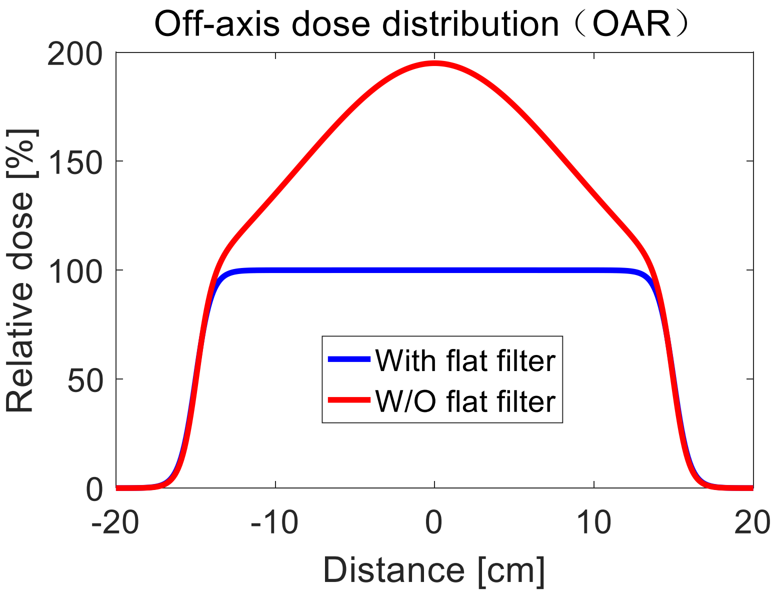
- Radiotherapy treatment is divided into many fractions:
    - let the normal tissue have time to recover (repair DNA);
    - Reduce the risk on normal tissue due to error in positioning.
- High resolution IGRT has a significantly less dose on normal tissue → allow higher dose per fraction (less fractions) → SBRT.



Higher dose rate

- SBRT need large dose per fraction → increasing the dose rate of the LINAC:
  - Higher power source (magnetron)/Optimizing on RF structure;
  - Work on flat-filter-free (FFF) mode → 2 times higher on-axial dose → TPS (dose-planning system) is more complex .

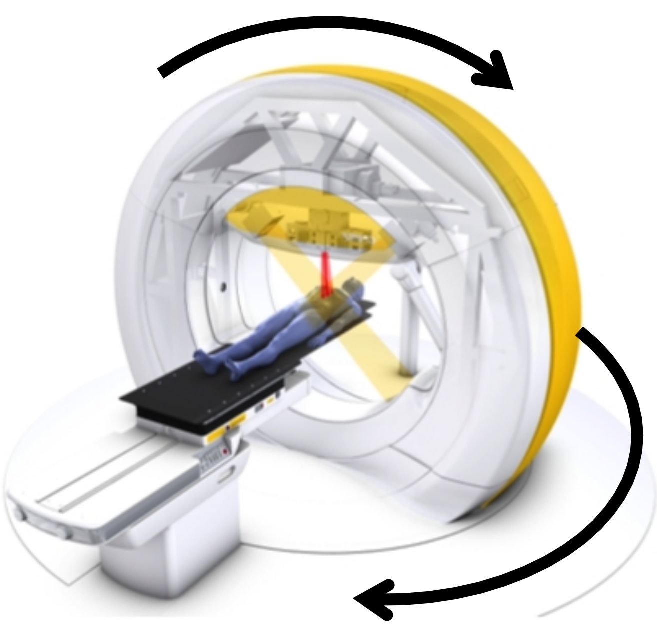
E2V MG7095 magnetron
Peak power: 3.1 MW



Flexible LINAC

- If patient receive radiotherapy from more directions, the maximum dose on normal tissue is reduced (less side effect).
- C-band/X-band LINAC has less weight →more flexible frame →provide more direction.
- less weight of LINAC → higher accuracy in positioning.

Vero SBRT: C-band



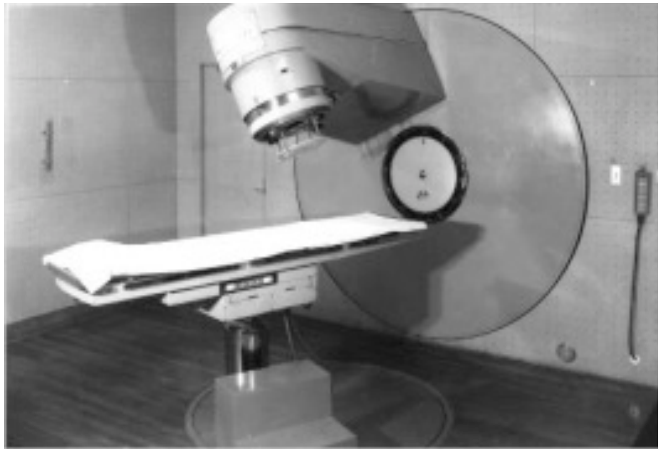
Cyberknife Robotic RT: X-band

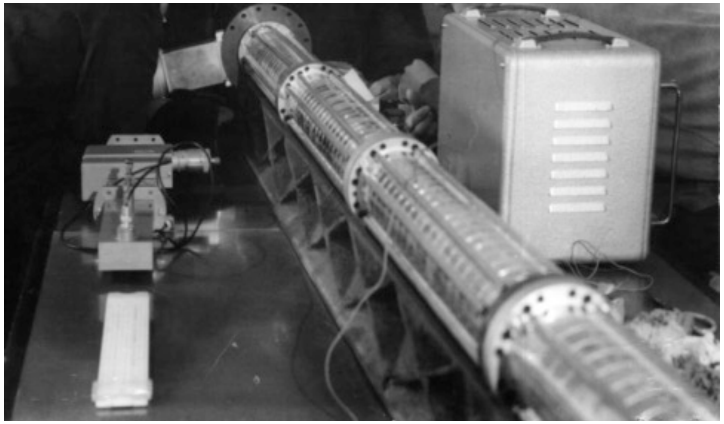
Outline

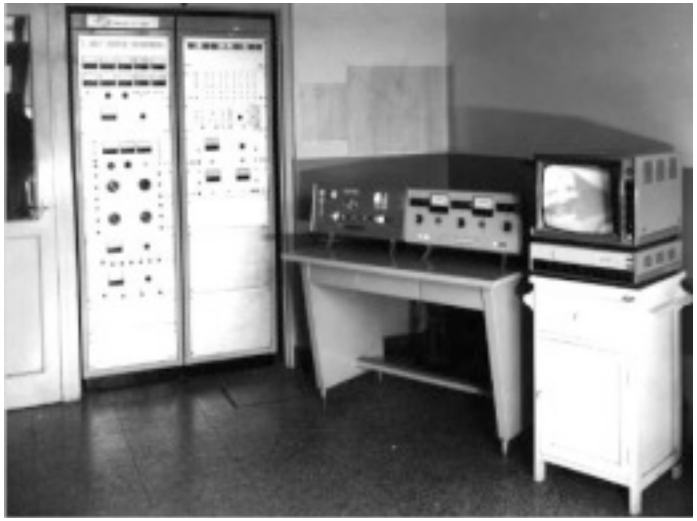
- Brief overview of radiotherapy
- Recent developments in medical electron linear accelerator
- **<u>Activities in Tsinghua University</u>**

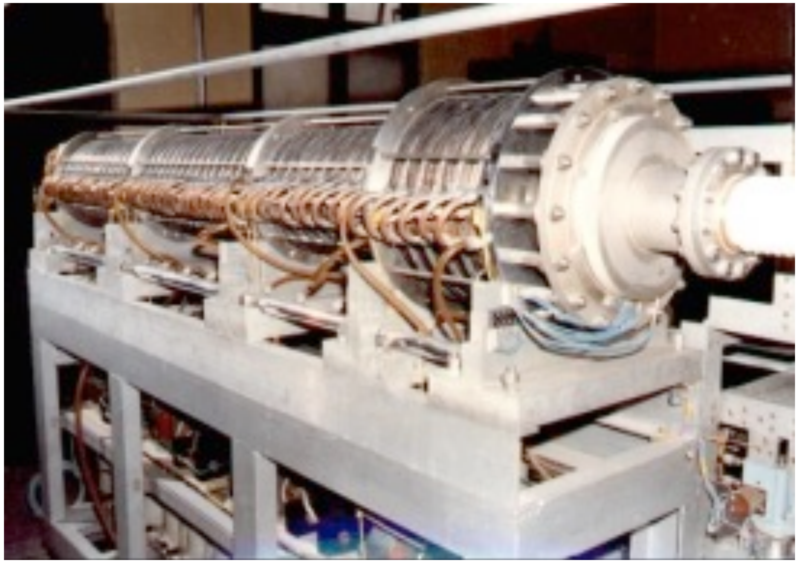
History in Tsinghua accelerator lab

- We built first medical LINAC in China: BJ10 (in 1970s)



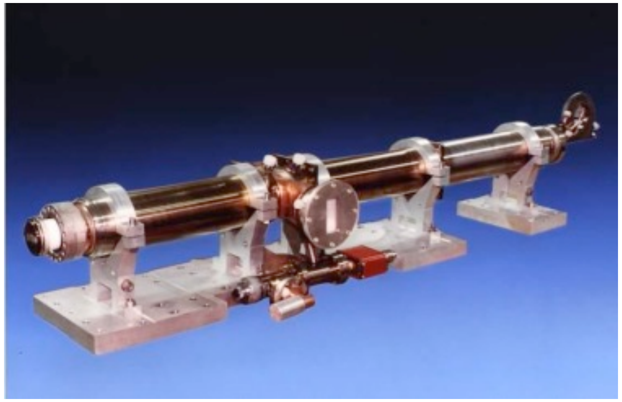


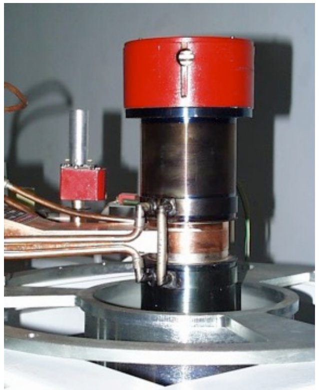




History in Tsinghua accelerator lab

- 1974 ✓ Convened a research group of more than 40 institutes to develop the first medical electron linac in China;
- 1977 ✓ BJ-10 travelling wave linac(10 MeV electron)
- 1987 ✓ 4 MeV axis-coupling linac
- 1993 ✓ 14 MeV linac
- 1998 ✓ Multi-energy linac (6~20 MeV)
- 2003 ✓ Dual-beam linac (X-ray/electron)
- 2006 ✓ Dual beam energy linac (kV/MV)
- 2009 ✓ Electron standing wave linac for IMRT
- 2012 ✓ C-band 6 MeV linac (1000 rad/min, 40 cm)
- 2016 ✓ High dose rate 6 MeV linac （1400 rad/min）
- 2018 ✓ X-band 6MeV linac (expected: 800 rad/min)

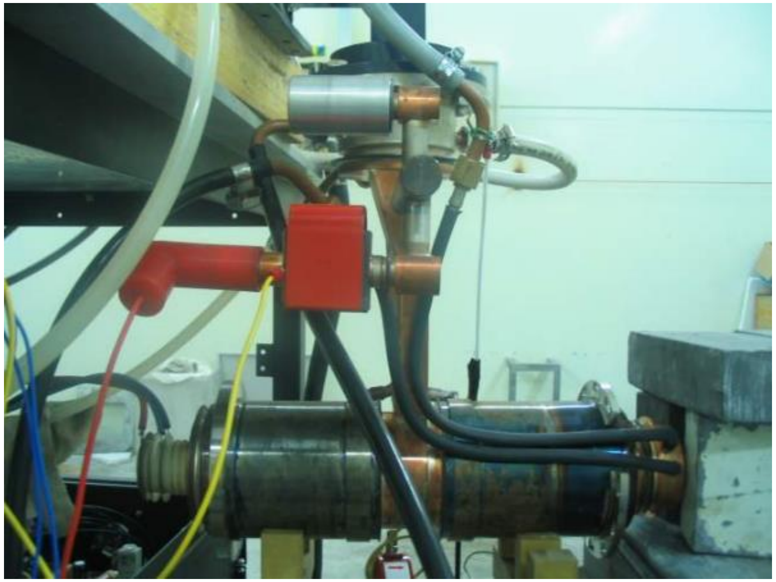




kV/MV coaxial LINAC

- We fabricated a prototype linac tube in 2007 and successfully demonstrated the energy switching (6 MV to 600 kV) . However, there are still some challenges:
  - Dose rate is not high (about 800 cGy/min @ 1 meter)
  - Linac tube is working not stably at low energy state (600 kV)

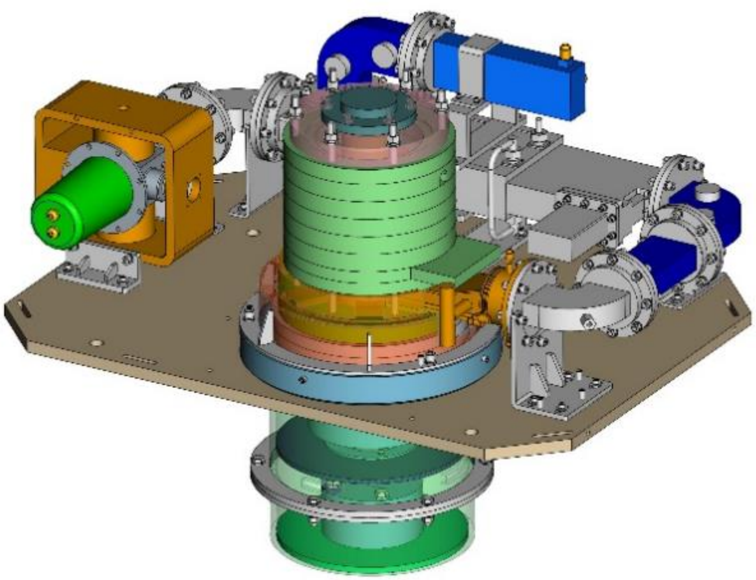
kV/MV Linac tube

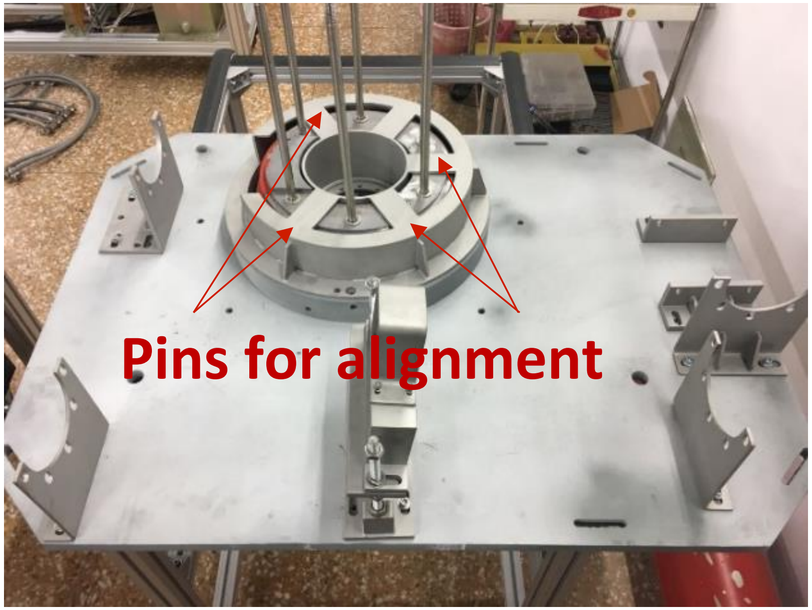


Full radiotherapy machine prototype (developed by NUCTECH. Inc, China)

S-band large dose-rate LINAC

- A full module of X-ray source: magnetron + waveguide + linac tube (with shielding) , weight = 500 kg.
  - Mechanically adapted for many kind of radiotherapy machines;
  - Control it like a step motor: trig→ try to deliver a dose unit (1 MU) → feedback the real dose;
  - Pins are reserved to aligned the linac tube (by twisting them).





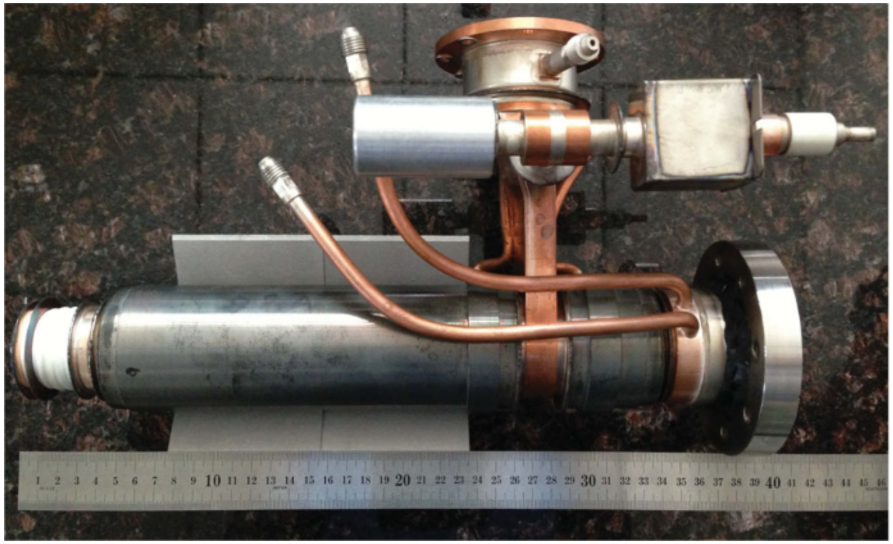
C-band medical LINAC

- We designed and tested a C-band 6 MeV LINAC in 2013.
- The dose rate is promising (1000 cGy/min@ 1m) .

Parameter of C-band medical linac design

Frequency	5712 MHz
Power	2.1 MW
Peak beam current	130 mA
Dose rate (at 1m with duty cycle is 0.1%)	1000 cGy/min
Capture ratio	32.8%
Spectrum FWHM	0.1 MeV (1.5%)
RMS spot size	1.4 mm
Accelerating Cell number.	13 cells
Acc. structure length	29 cm
Shunt impedance	130 MΩ/m

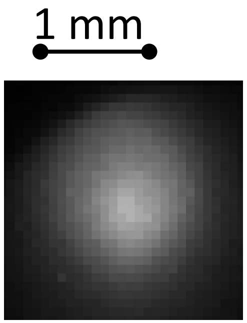
C-band medical linac tube
Total length : 40 cm
Weight of the tube : 7 kg

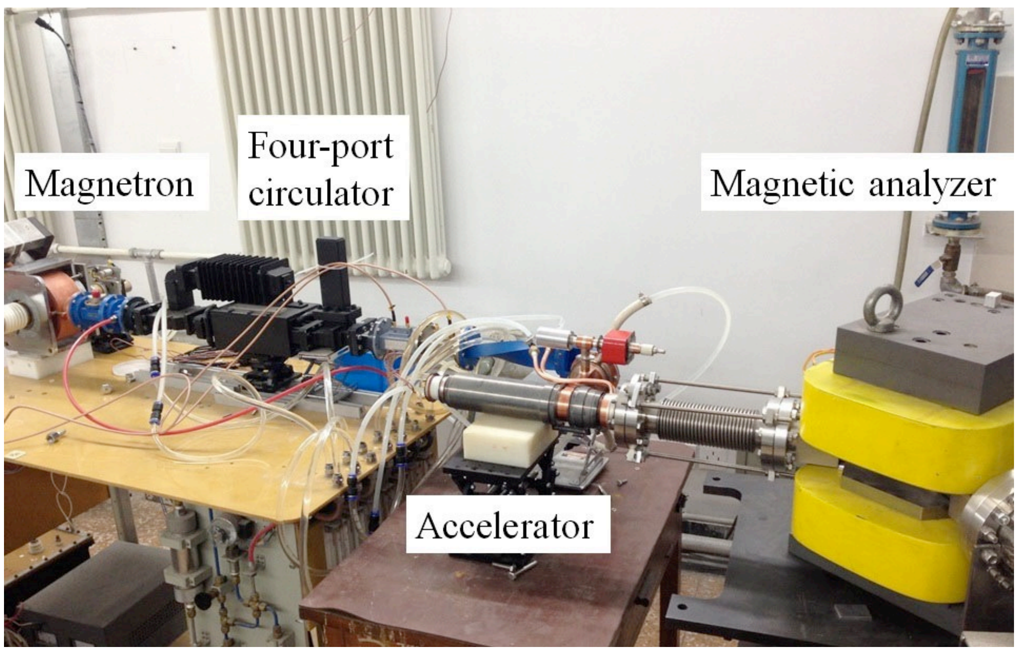


https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.16.090102

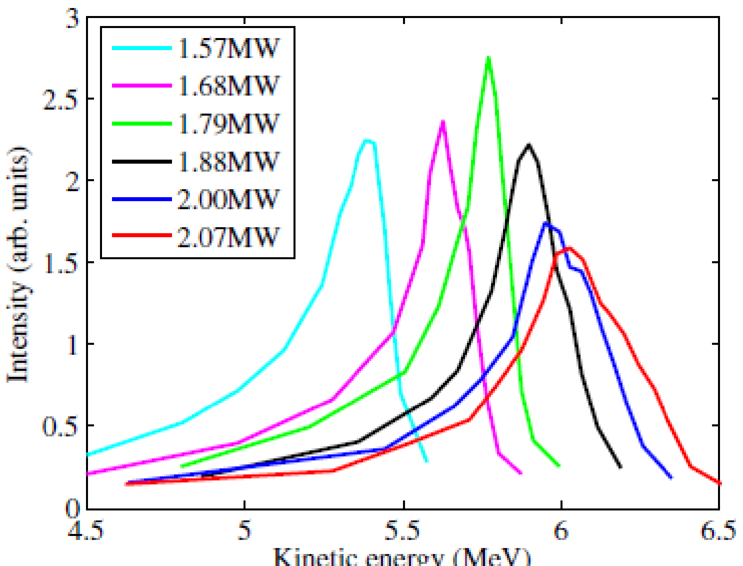
C-band medical LINAC

- The LINAC installed a titanium window at its end. So that we can measure parameters of the output electron beam:
  - Spot size: less than 1.5 mm ☺
  - Spectrum FWHM: 0.4 MeV ☹ (expected 0.1 MeV, may due to jitter in the power source)



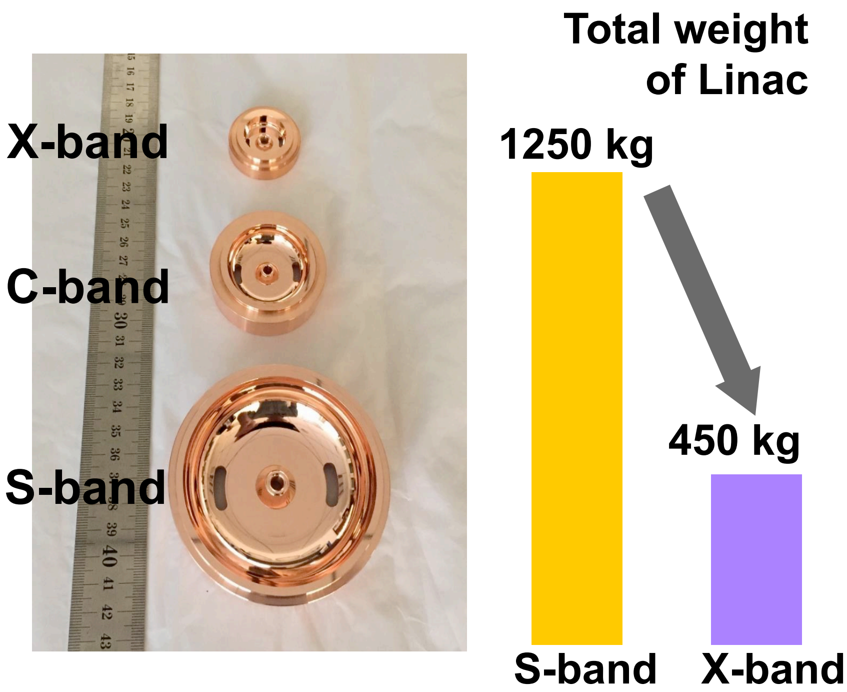


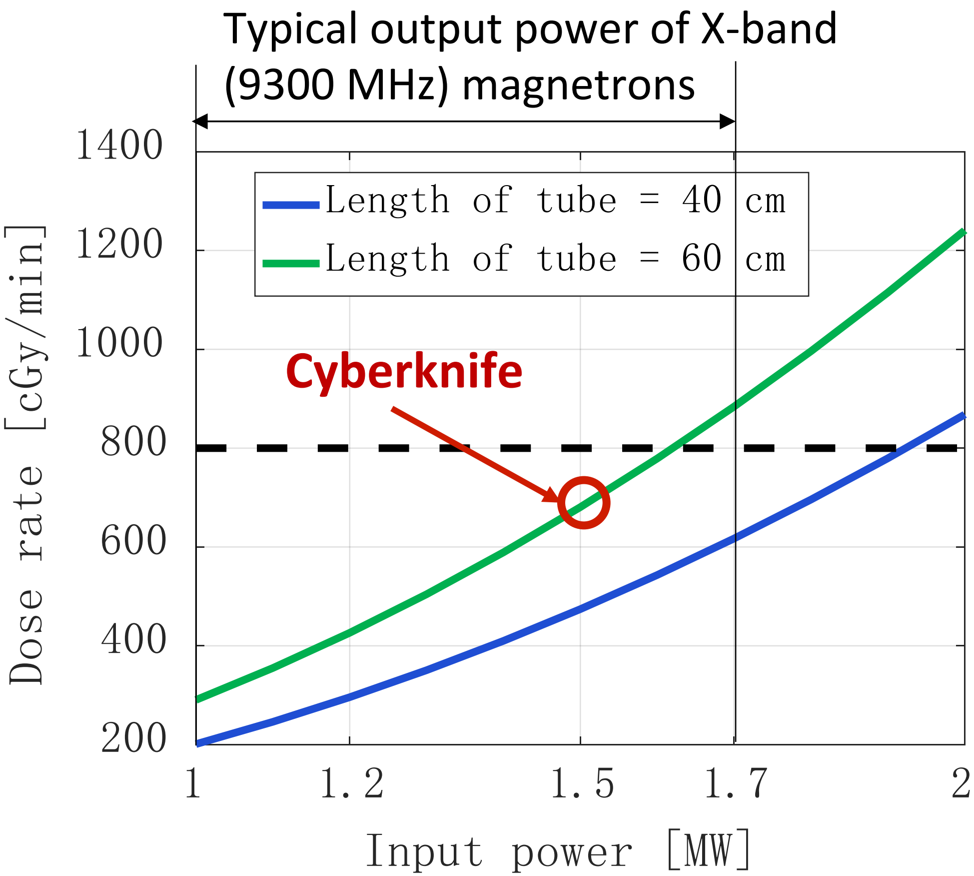
Spectrum vs power



X-band medical LINAC

- X-band medical LINAC is compact but has lower dose rate.
- We are developing a high dose rate X-band linac
  - 40 cm structure length
  - 800 cGy/min @ 1 meter

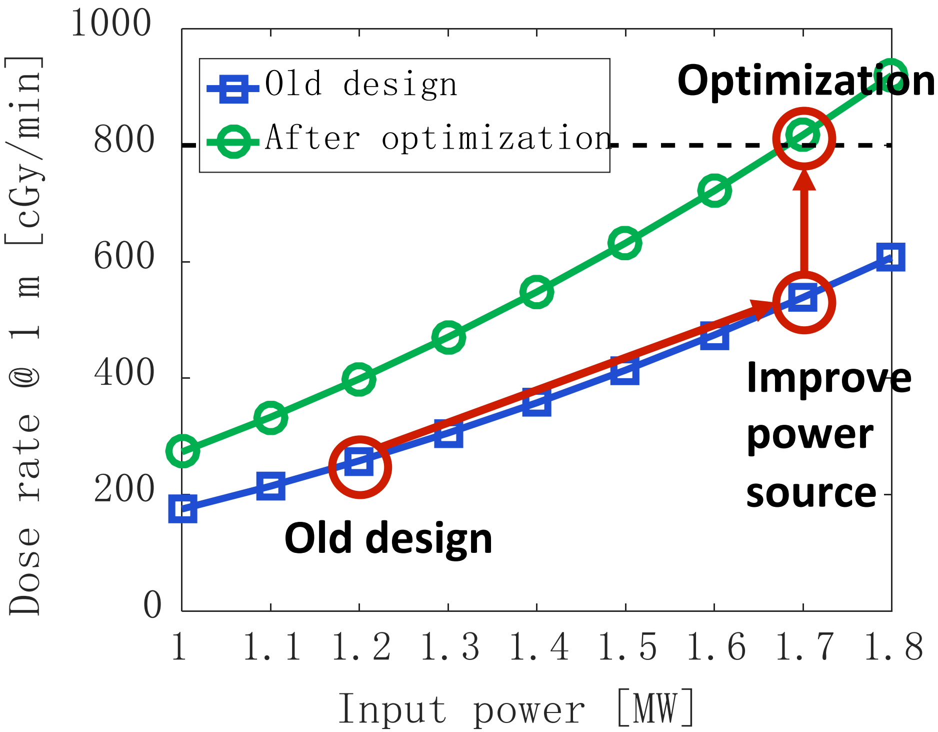




X-band medical LINAC

- We developed an X-band tube in the year 2000 (old design). The new X-band tube will improved :
  - More powerful source (expect 1.7 – 1.8 MW)
  - Increase the shunt impedance
  - Increase the capture ratio (less power absorbed by un-captured beam)
  - Optimize the beam spectrum.

Old design:
Input power = 1.2 MW
Dose rate = 300 cGy/min @ 1 m



清華大學

Tsinghua University

Thanks