Industrial & Medical application of low energy electron LINACs

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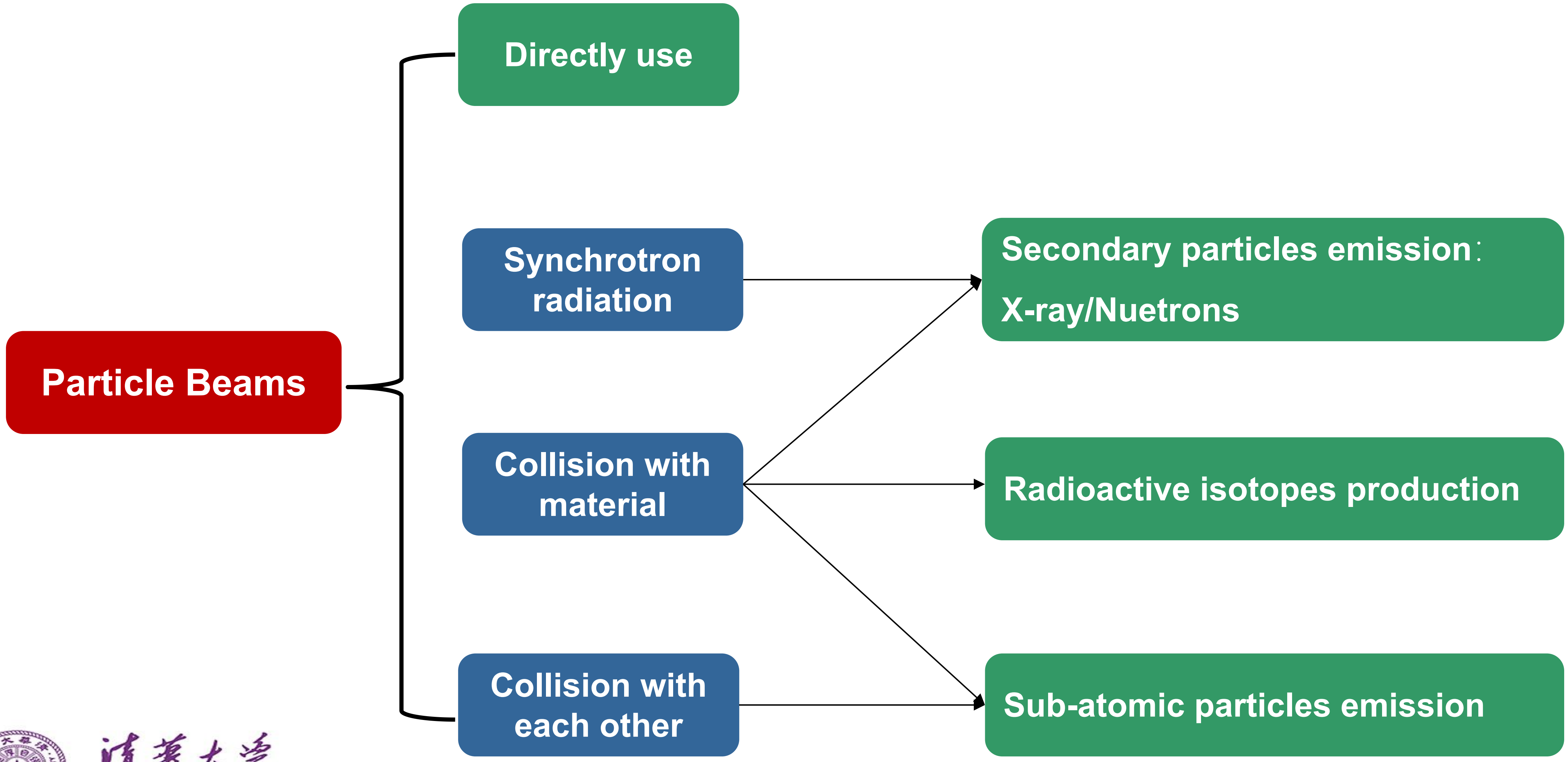
Outlines

- **Brief introduction**
- How to design a low energy electron LINAC?
- Application of LINACs in NDT
- Application of LINACs in radiation processing
- Application of LINACs in radiotherapy

How to use particle beams



Main force: low energy accelerators

- Over 90% of all operating particle accelerators are low energy types

Over 30’000 particle accelerators are in operation world-wide.

Only ~1% are used for fundamental research.

Medicine is the largest application with more than 1/3 of all accelerators.

Research		6%
	Particle Physics	0,5%
	Nuclear Physics, solid state, materials	0,2 - 0,9%
	Biology	5%
Medical Applications		**35%**
	Diagnostics/treatment with X-ray or electrons	33%
	Radio-isotope production	2%
	Proton or ion treatment	0,1%
Industrial Applications		**<60%**
	Ion implantation	34%
	Cutting and welding with electron beams	16%
	Polymerization	7%
	Neutron testing	3.5%
	Non destructive testing	2,3%

Mostly high energy

Low energy
Most of them
< 20 MeV

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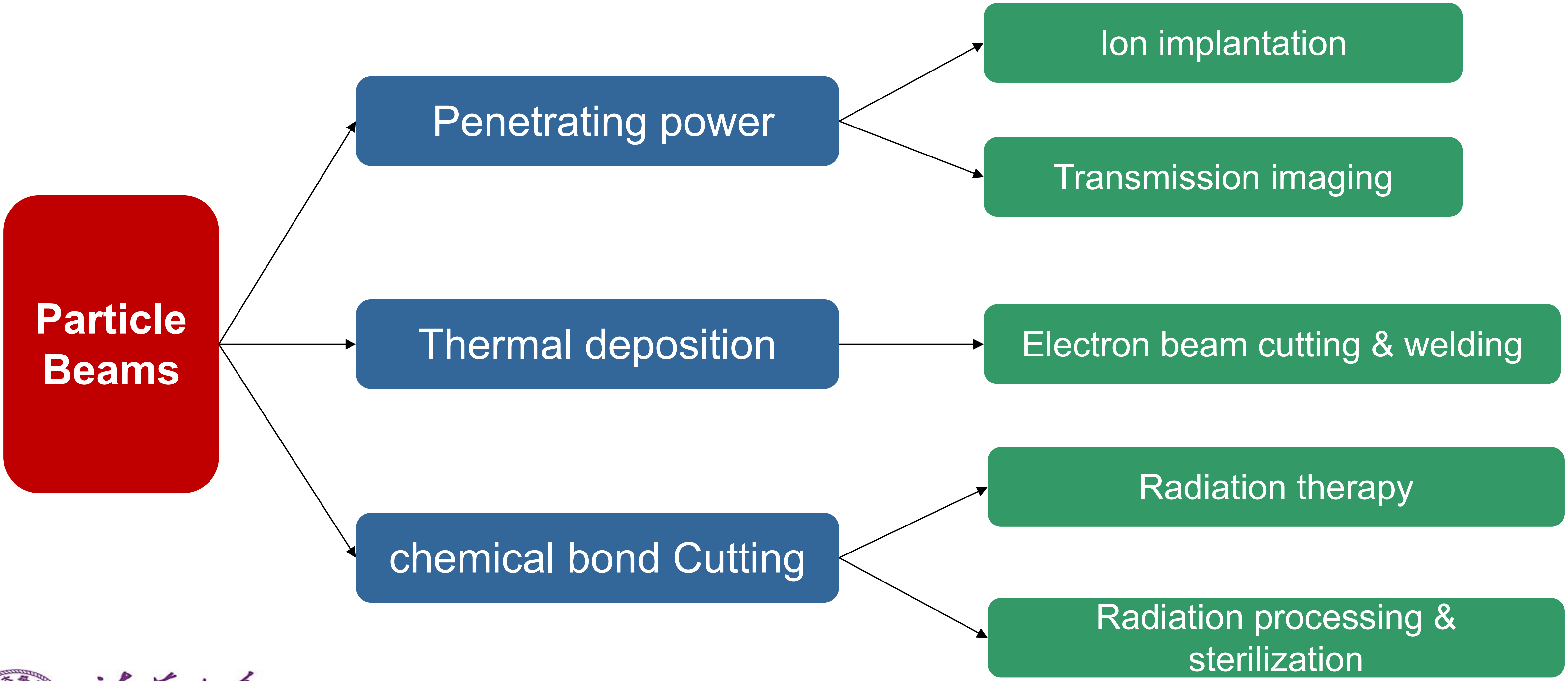
Courtesy of Maurizio Vretenar, CERN, Given in CERN School 2018

Application of particle beams



Compared with radioisotope source

- Radioisotope source (e.g. Cobalt-60): stable and cheap, but requires intensive safety protocols (also has significant risks)
- Accelerator-based source: easy to control, much higher dose rate
- No residual radiation if electron beam energy ≤ 10 MeV

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- Application of LINACs in NDT
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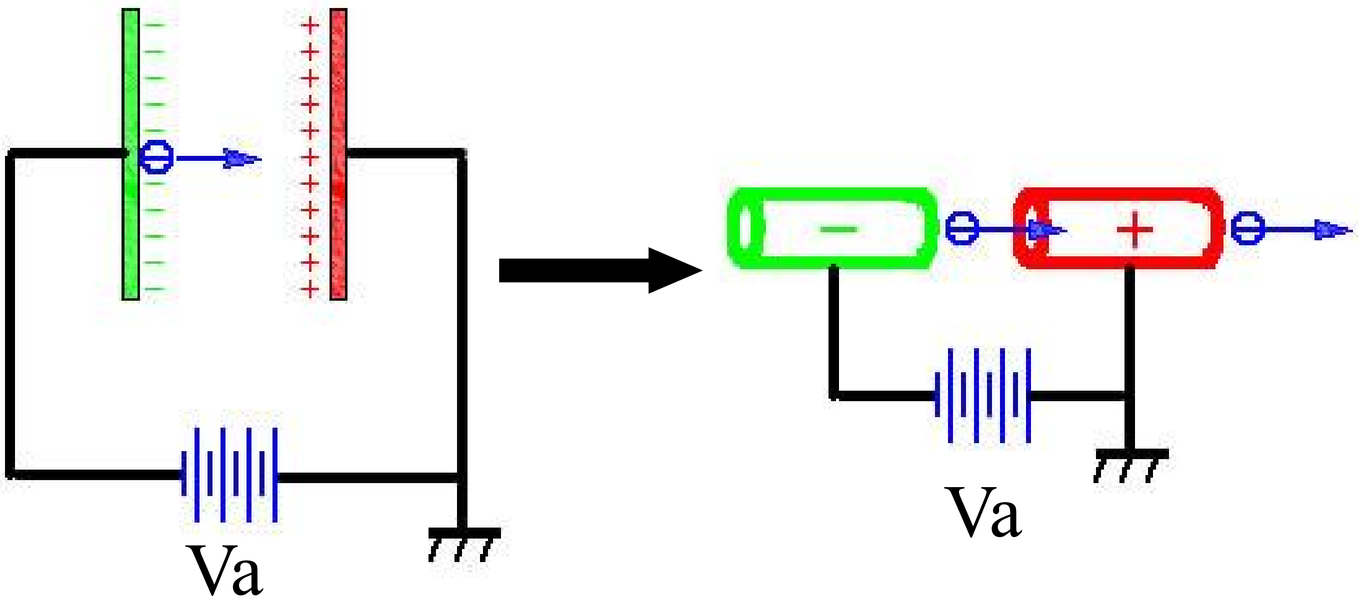
Simple linear accelerator

- Accelerators in early time had only two electrode, which generate the electrical field for electron acceleration
- However, electrons can be accelerated only once
- The energy is limited by the HV withstand



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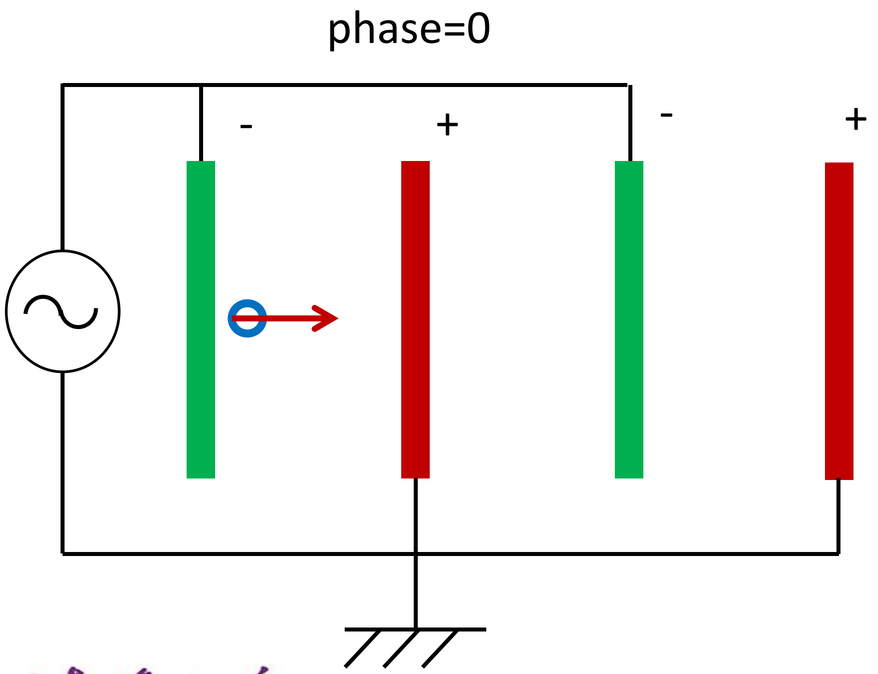
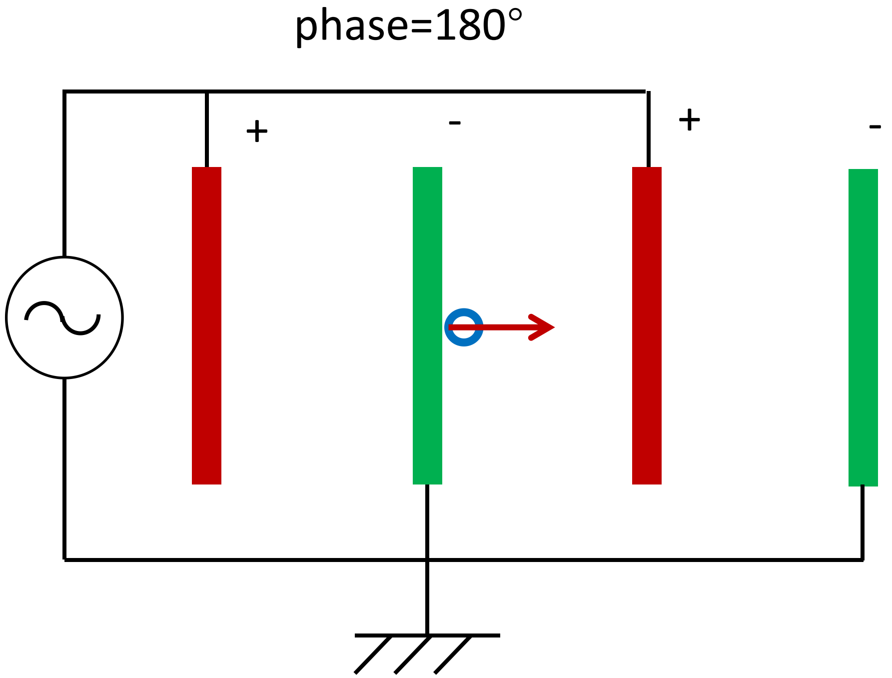
Principle of linear acceleration

- Similar to the cyclotron, particles could be continuously accelerated in the multiple electrons holding an alternating electrical (AC) field
- More electrodes = higher energy, infinitely scalable in principle



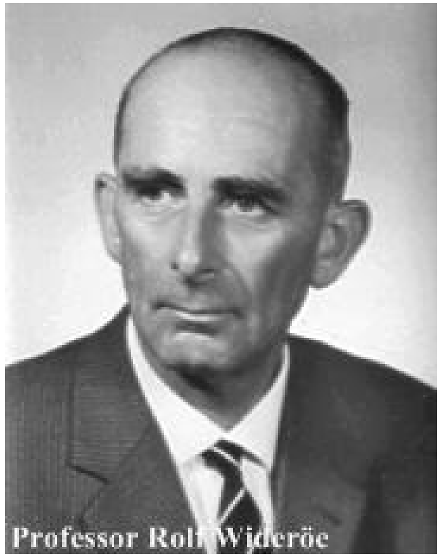


Birth of linear accelerator

Gustav Ising and Rolf Widerøe:

Introduced the linear accelerator principle based on cascaded alternating acceleration in 1920s

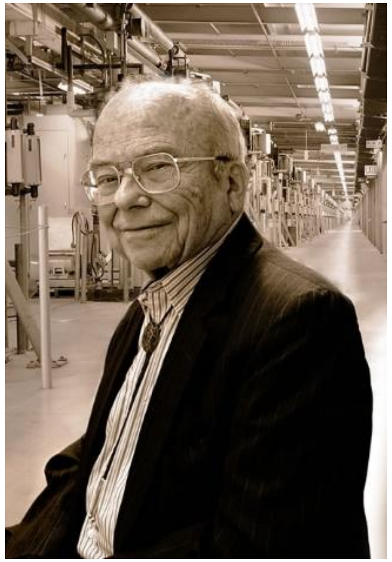
GUSTAF ISING



Wolfgang Panofsky (founding director of SLAC):

Build the first modern linear accelerator using radio-frequency cavities in 1950s

a 3-km linear collider



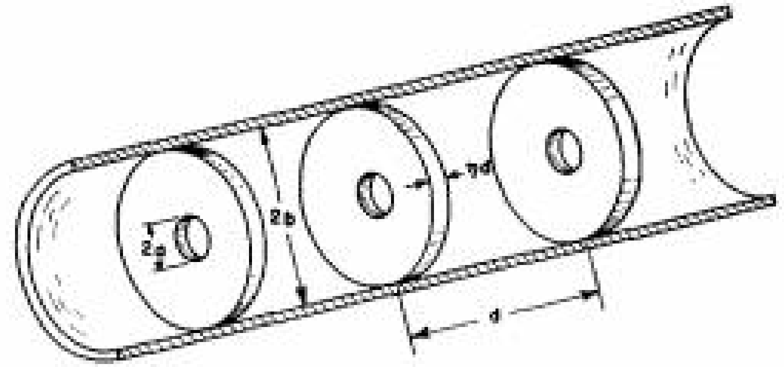
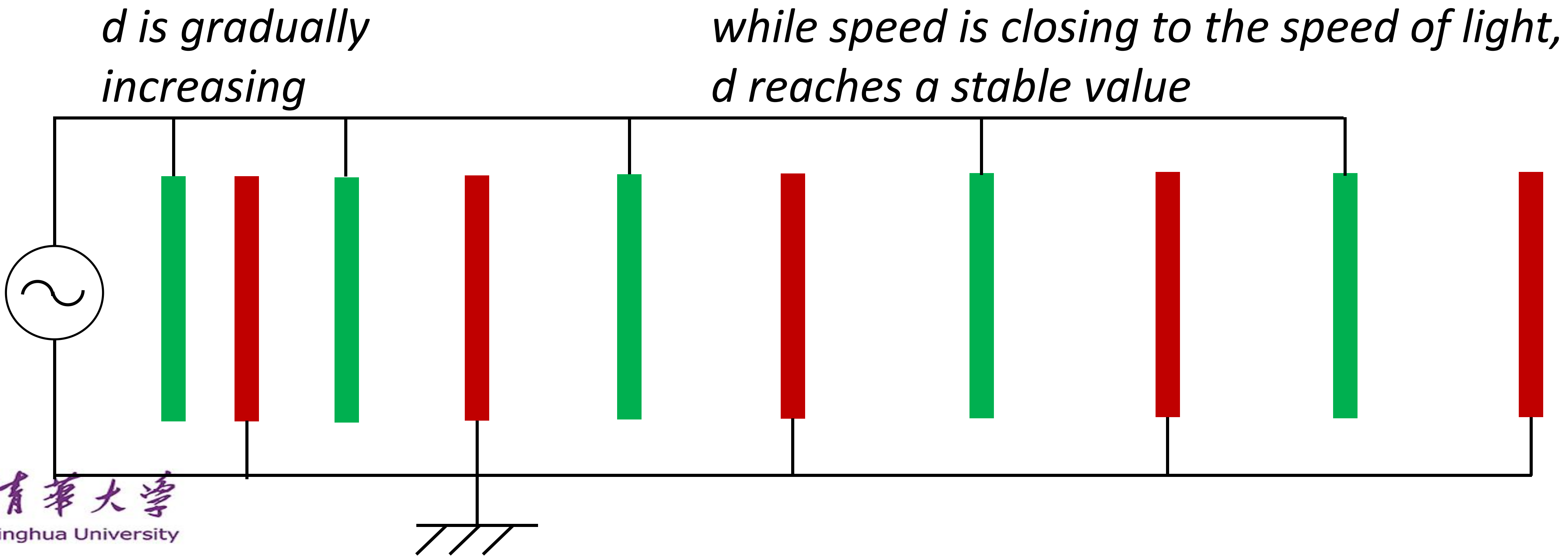


FIG. 1.2. Structure of disk-loaded accelerator showing important design dimensions.

Synchronization of beam and electrodes

- How to maintain synchronization between the alternating field phase and particle motion during acceleration?
- The electrode gap distance should be alternated simultaneously. And must meet the requirement of: d=[particle speed] * [AC period time]/2



Synchronization of beam and electrodes

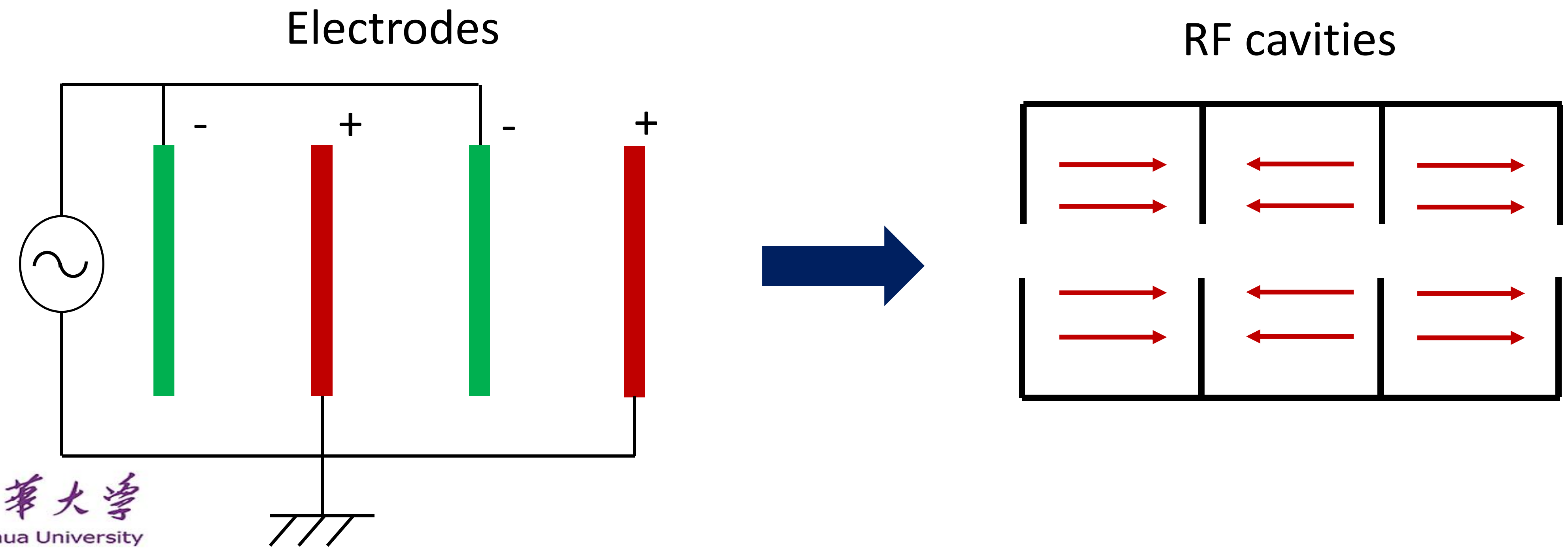
- In engineering practice, *d* cannot be too large or too small. 0.01~1 meter is a good choice → We need radio-frequency for AC field
- Electrons are very light, and easily to approach high speed → GHz is often selected.

Speed	0.99 c	0.1 c	0.01 c
Kinetic energy of electron	> 3 MeV	2.6 keV	25.6 eV
Kinetic energy of proton	> 6 GeV	4.7 MeV	4.7 keV
AC frequency	*d:* Distantce between neighbor electrodes		
1 kHz	150 km	15 km	1.5km
1 MHz	150 m	15 m	1.5 m
100 MHz	1.5 m	15 cm	1.5 cm
1 GHz	15 cm	1.5 cm	0.15 mm

Radio frequency (100 MHz – 1 GHz)

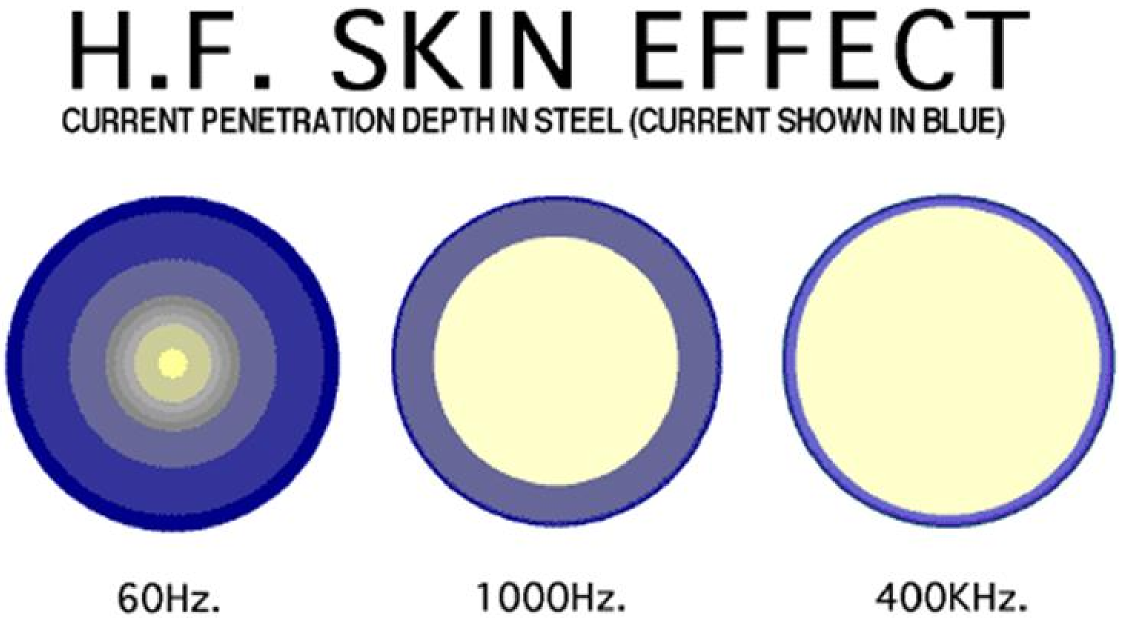
Radio frequency structure

- Power radiated outward ∝ [frequency] ^ 4
- Confinement of the EM field is needed to prevent the radiation loss
- Use enclosed structures, namely the resonate cavities



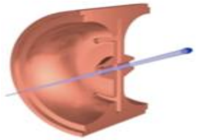
Ohmic loss of high frequency

- Skip effect: high frequency current is concentrated in the surface
- Surface resistance: ∝ [frequency] ^ 0.5
- Surface area/Volume: ∝ [frequency] ^ 1
- Total ohmic loss in the cavity: ∝ [frequency] ^ 1.5



$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \propto f^{1/2}$$

Ohmic loss calculation



- Power dissipated in the cavity wall: $P_{\mathrm{w}} = \frac{V^2}{R_s}$, where V is accelerating voltage, R_s is shunt impedance (usually proportional to structure length)

Typical value of normal conducting RF structures

Frequency band	Shunt impedance per 1 meter structure
S band (2998MHz)	50~100 MΩ/m
C band (5712MHz)	70~120 MΩ/m
X band (9300MHz)	100~150 MΩ/m

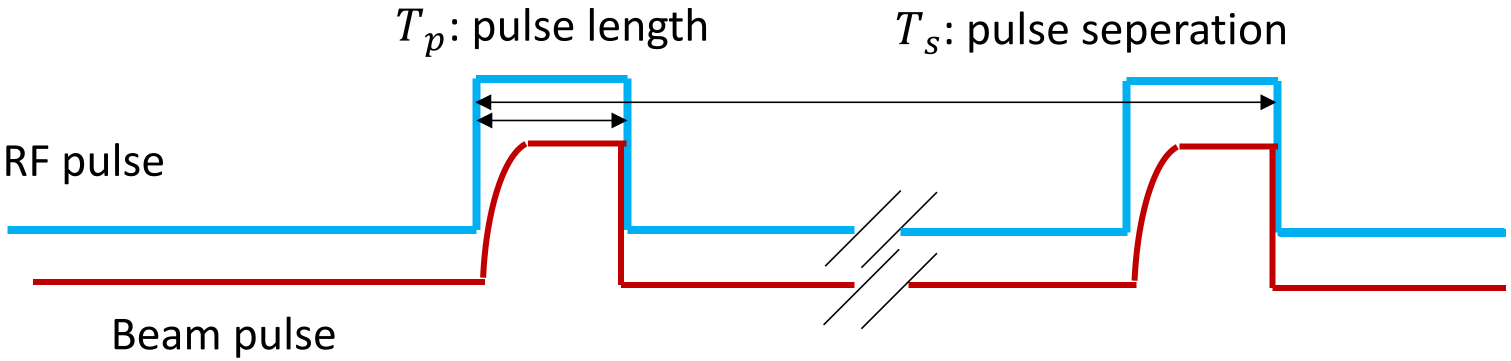
Example:

Dissipated power calculation for an accelerator tube with 1 meter length to have 10 MV acc voltage?

$$P_{\mathrm{w}} = \frac{V^2}{R_s} = \frac{(10\ \mathrm{MV})^2}{(100\ \mathrm{M\Omega})} = \mathbf{1\ MW}$$

Pulse operating mode

- Power dissipated (heat) of MW level is too huge, and it is almost impossible to cool down the structure with MW heat
- If LINAC is operated at pulse mode, then the average heat is reduced: [Average power] = [Peak power] * [Duty factor]
- Typical value of duty factor is 0.1%: MW → kW, reasonable

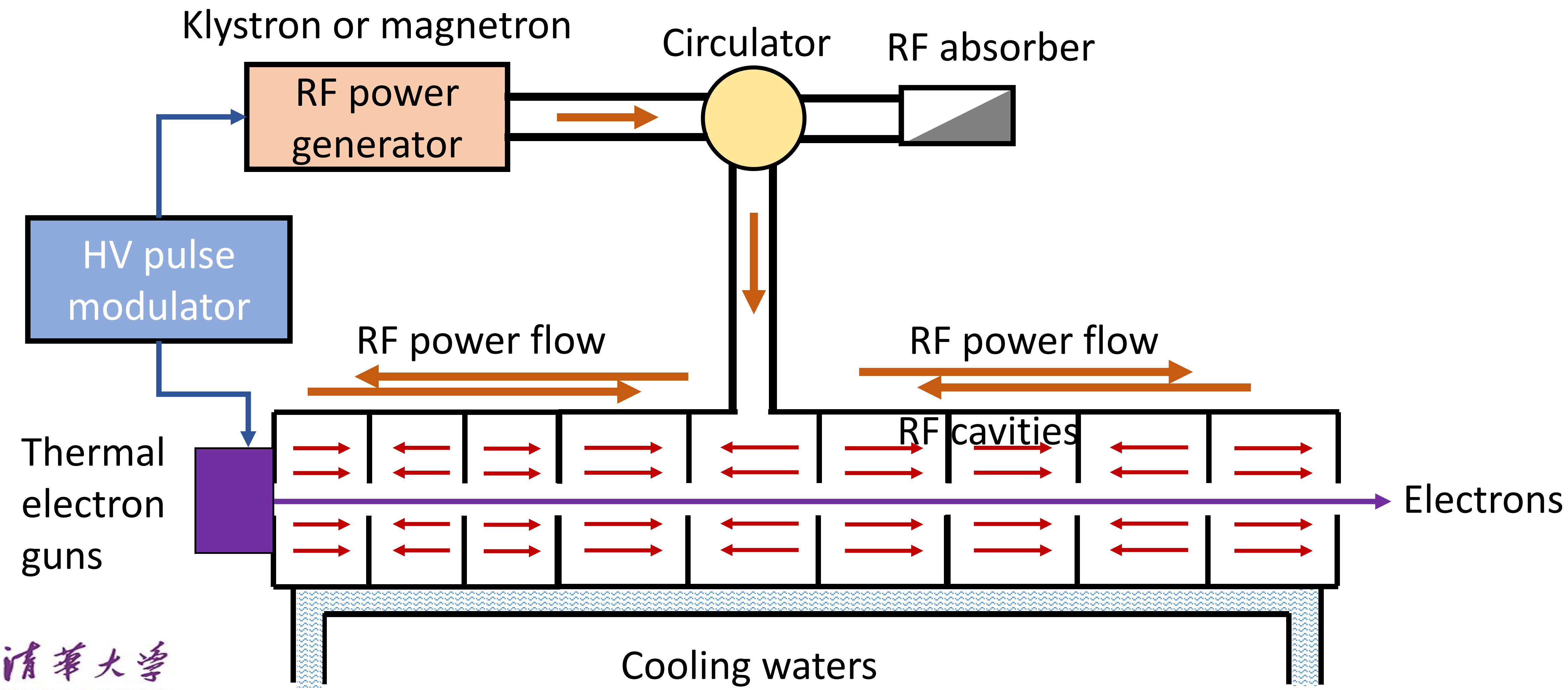


$$\text{Duty factor} = \frac{T_p}{T_s}$$

Example

- An S-band structure with 2.5 meter length and Rs per length is 50 MΩ/m.
  - Calculate the maximum accelerator voltage for 20 MW input power.
  - Calculate the accelerator voltage when beam current is 0.18 A.
  - Calculate the heat generation in the beam loaded case if duty factor is 0.1%
- Shunt impedance: Rs = 50 MΩ/m * 2.5 m = 125 MΩ
- Accelerating voltage: $\mathrm{V} = \sqrt{R_s P} = 50$ MV
- The beam current also consume power: $P = \frac{V^2}{R_s} + V * I$, which is a quadratic equation: $V^2 + 22.5V = 2500$ (Unit: MV). Solve it: $V =$ 40 MV
- Peak power dissipation is $P = \frac{V^2}{R_s}$ = 12.8 MW, so the heat is 12.8 kW

Layout of a typical LINAC



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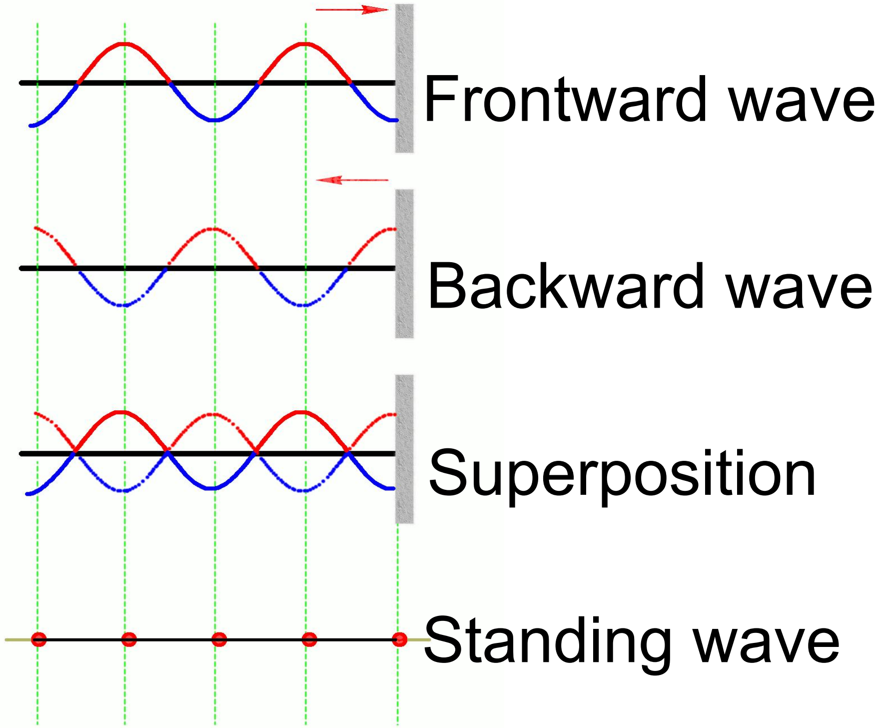
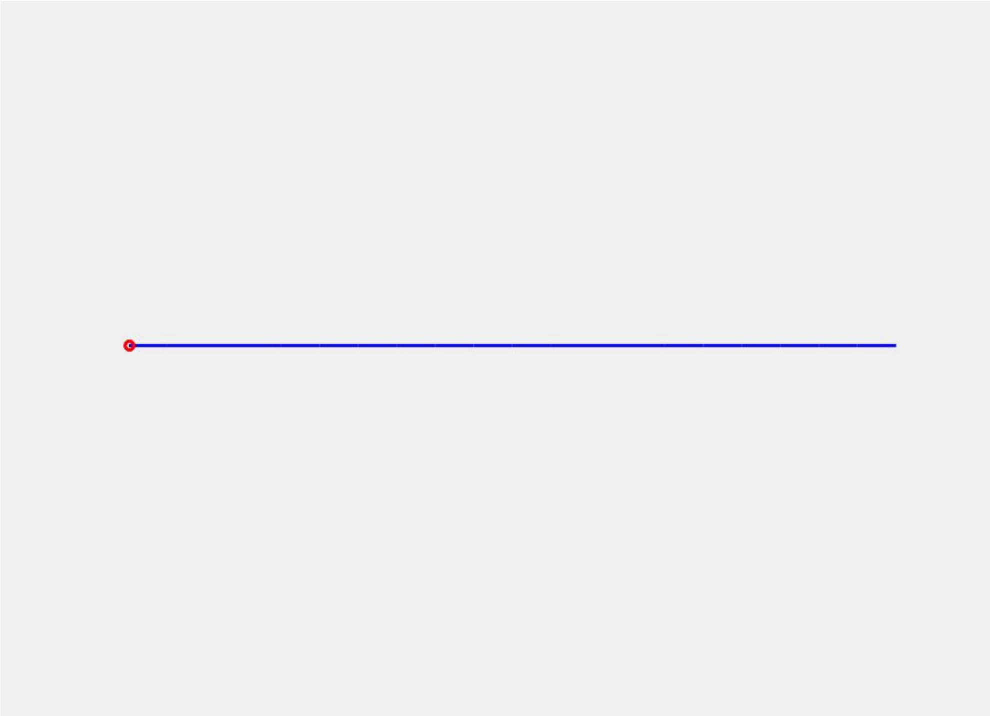
Principle of standing wave LINACs

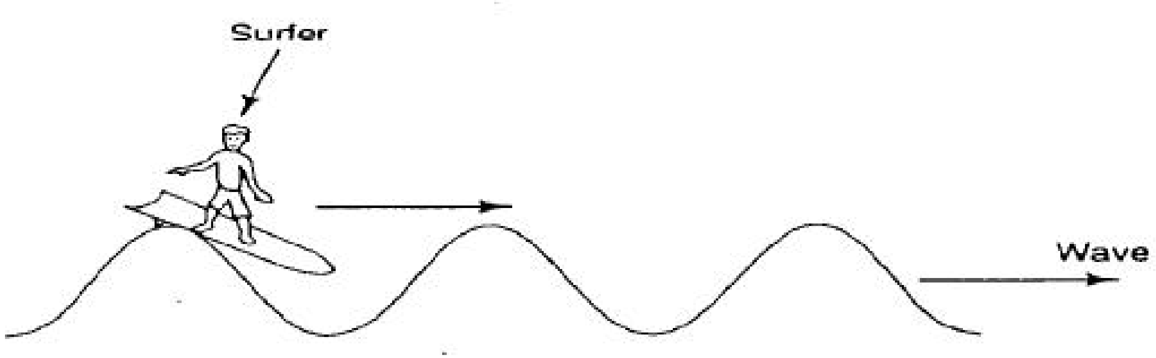
- The field in the structure is a standing wave, particle always see the accelerating field (not decelerating field)
- Usually case: phase advance per cavity = 180°, cavity length = wave length / 2



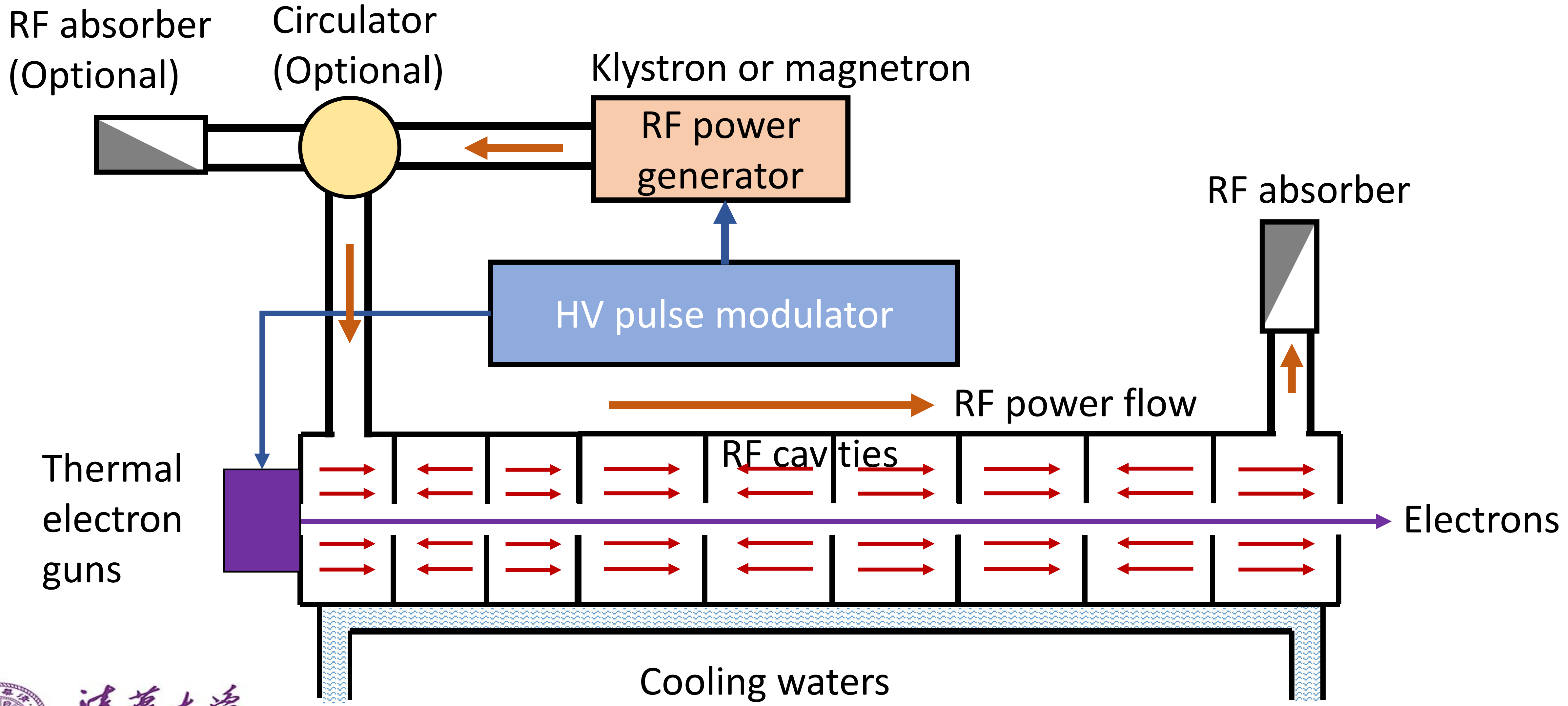


Travelling wave also wokrk

- Travelling wave moves in the same direction and speed with particles
- Phase advance per cavity is more flexible: 120°, 135°, 150° are the mostly used



Layout of a travelling wave LINAC



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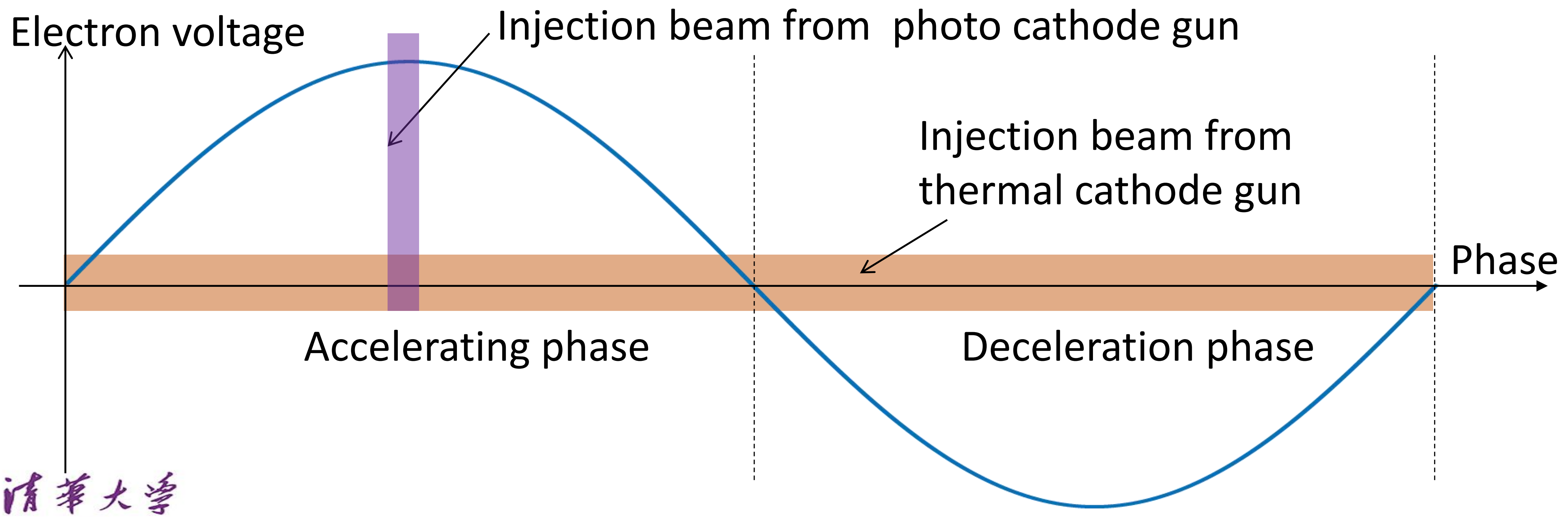
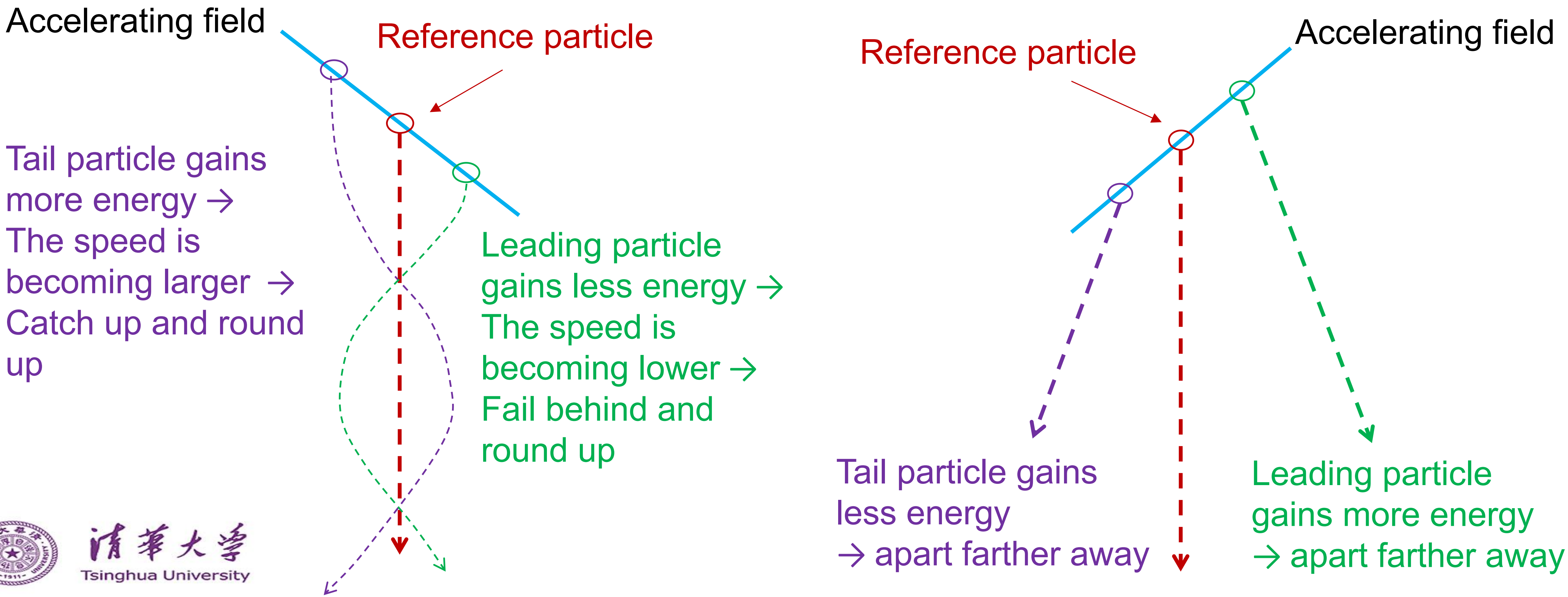
Injection beam fro gun

- Low energy LINACs often use thermionic cathode electron gun
- The injection of electrons for the thermal gun is continuous
- Only few electrons in a narrow phase range get full acceleration



Bunching issue

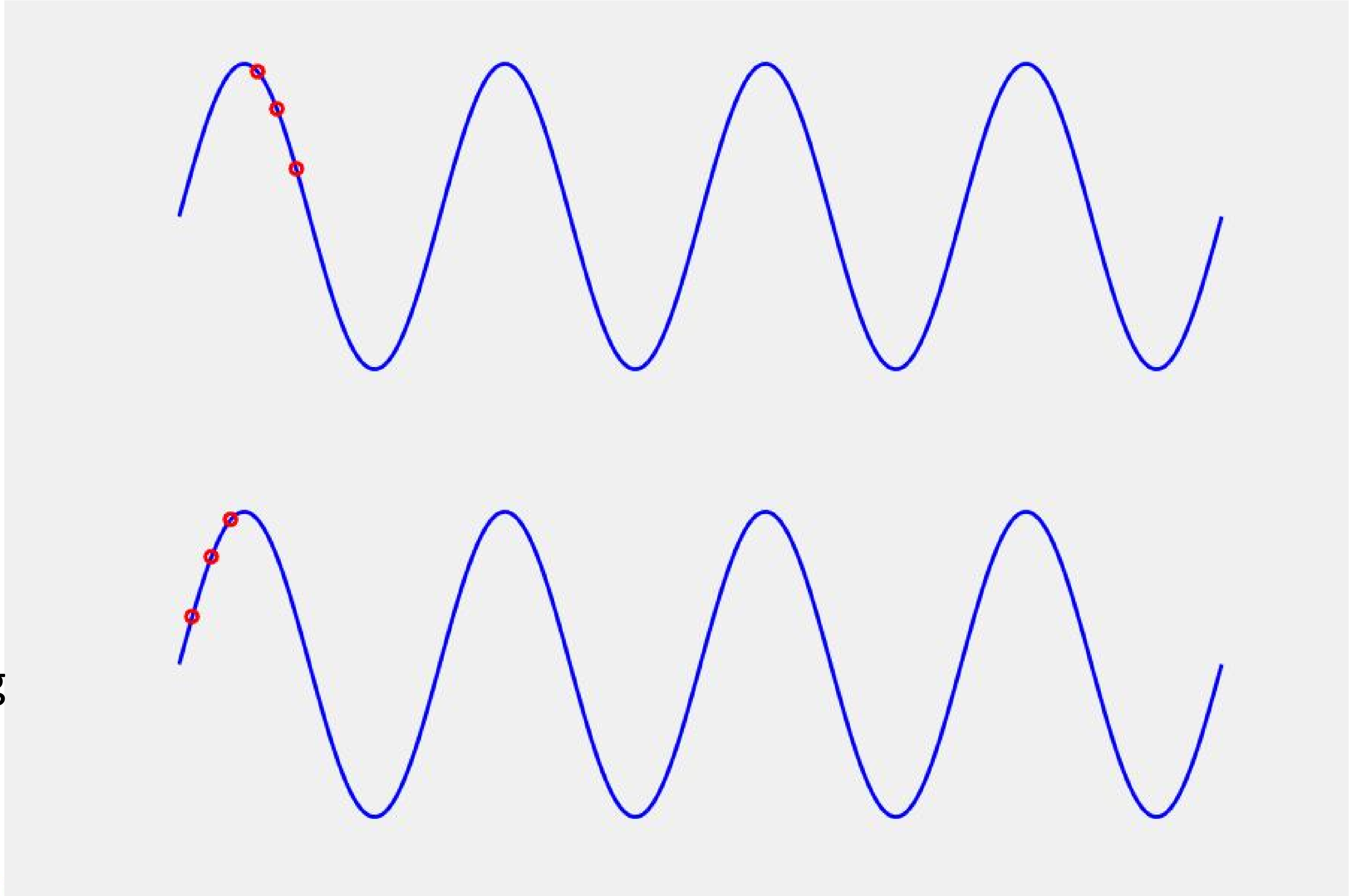
- Bunching is occurred when the slope of accelerating field versus phase is negative (versus time is positive)



Bunching issue

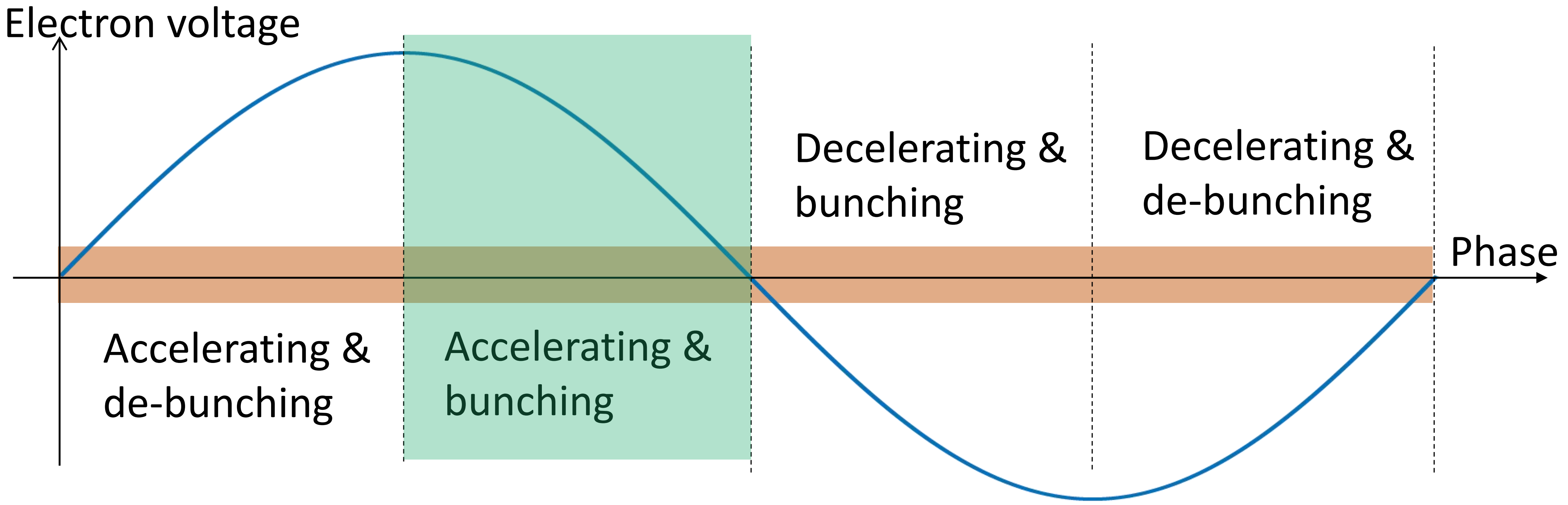
Bunching

De-bunching



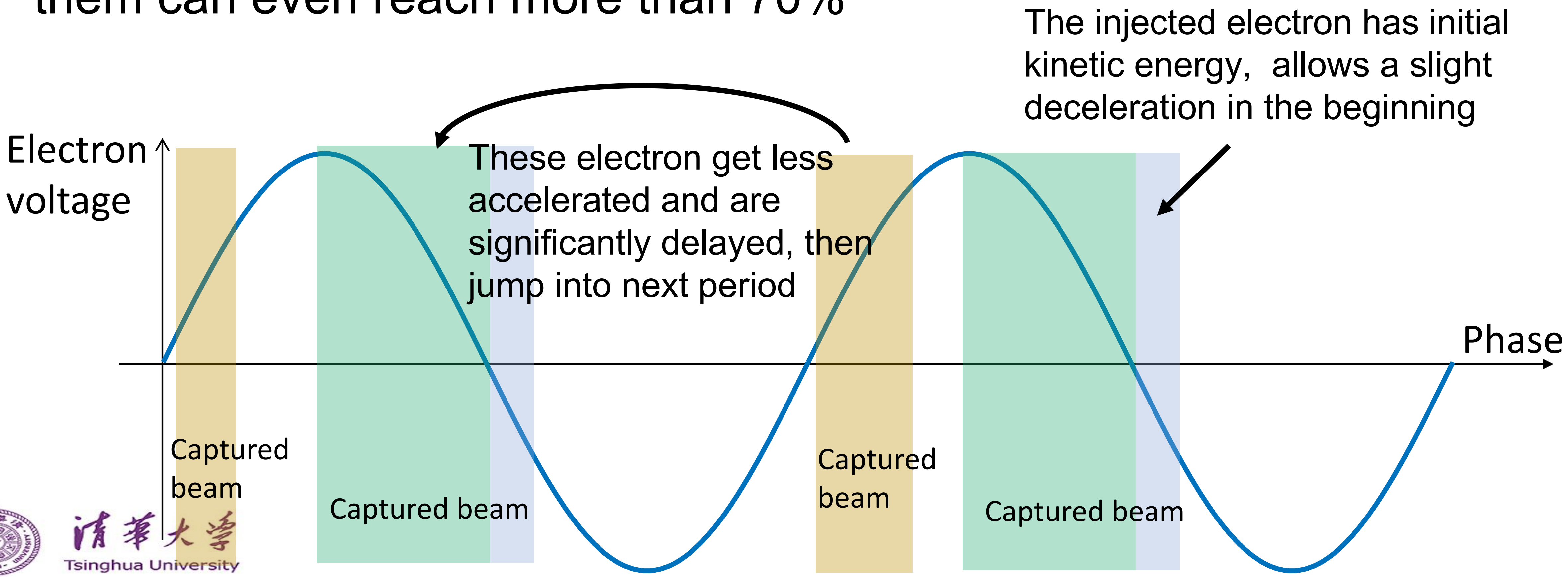
Bunching issue

- 1/4 of the phase range (90°~180°) is suitable for accelerating and bunching → at least 25% of the injected beam will be captured



Bunching issue

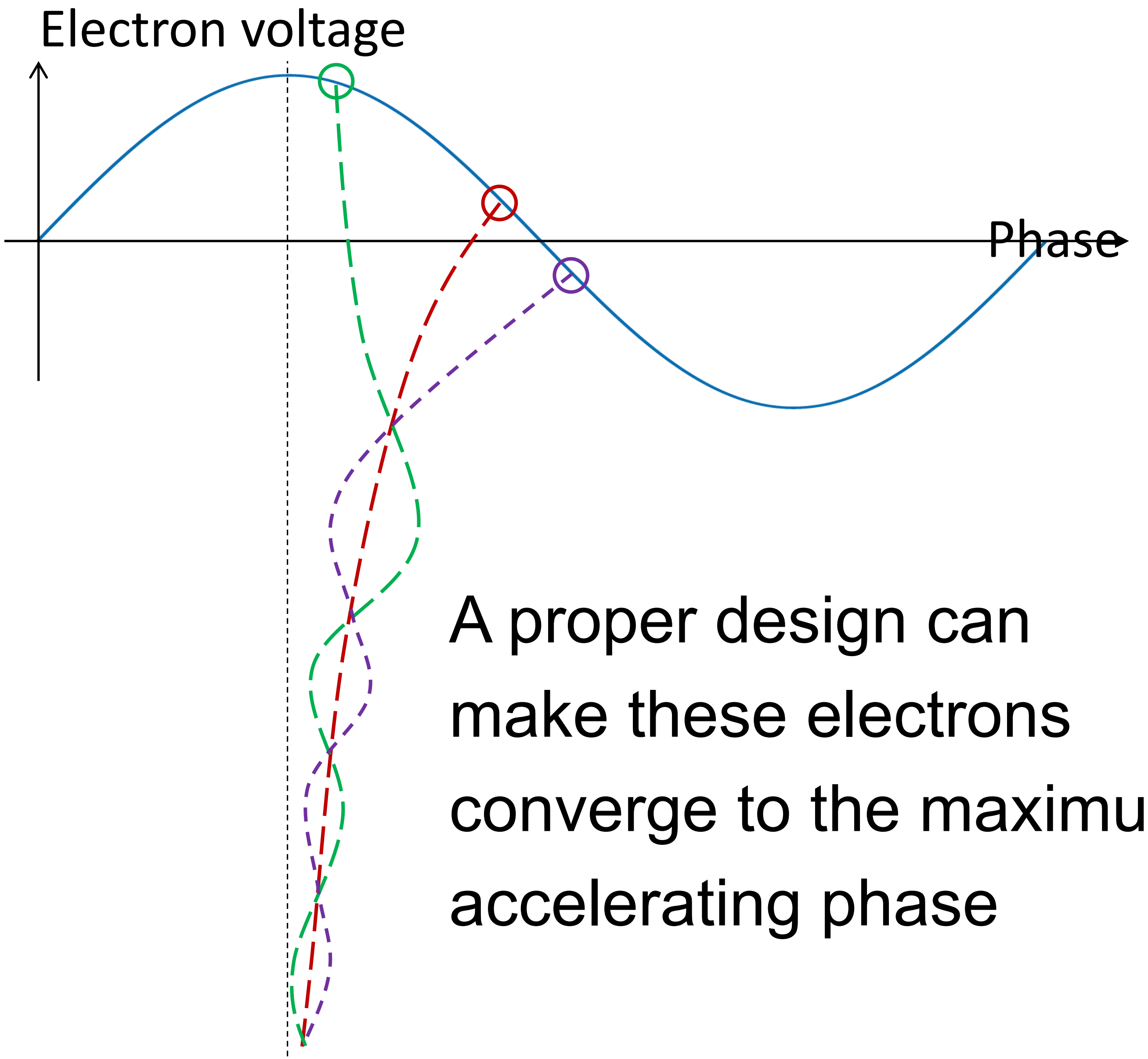
- Actually, the capture ratio could breakthrough limit of 25%
- Most of the LINACs have the capture ratio of 30%~40%, some of them can even reach more than 70%



Accelerating efficiency vs bunching

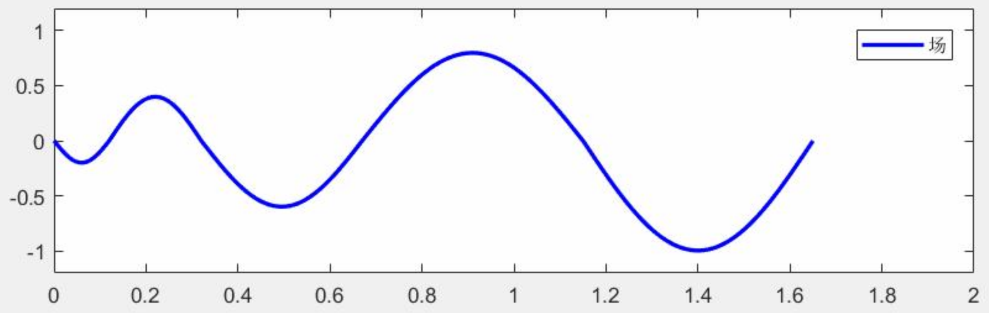
- The captured beam has a wide phase range → most of particles are not in the efficient accelerating phase

- As the beam energy goes up, the speed discrepancy of the beam gradually shrinks



A proper design can make these electrons converge to the maximum accelerating phase

An animation of beam capturing + accelerating



← Accelerating field

← Phases of sampled particles

← Energy of sampled particles

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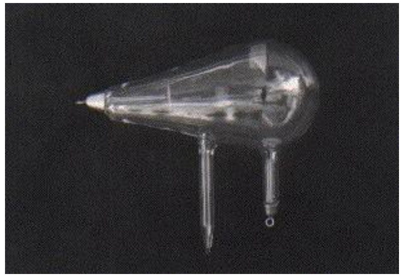
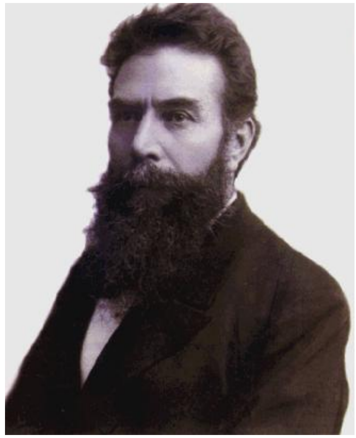
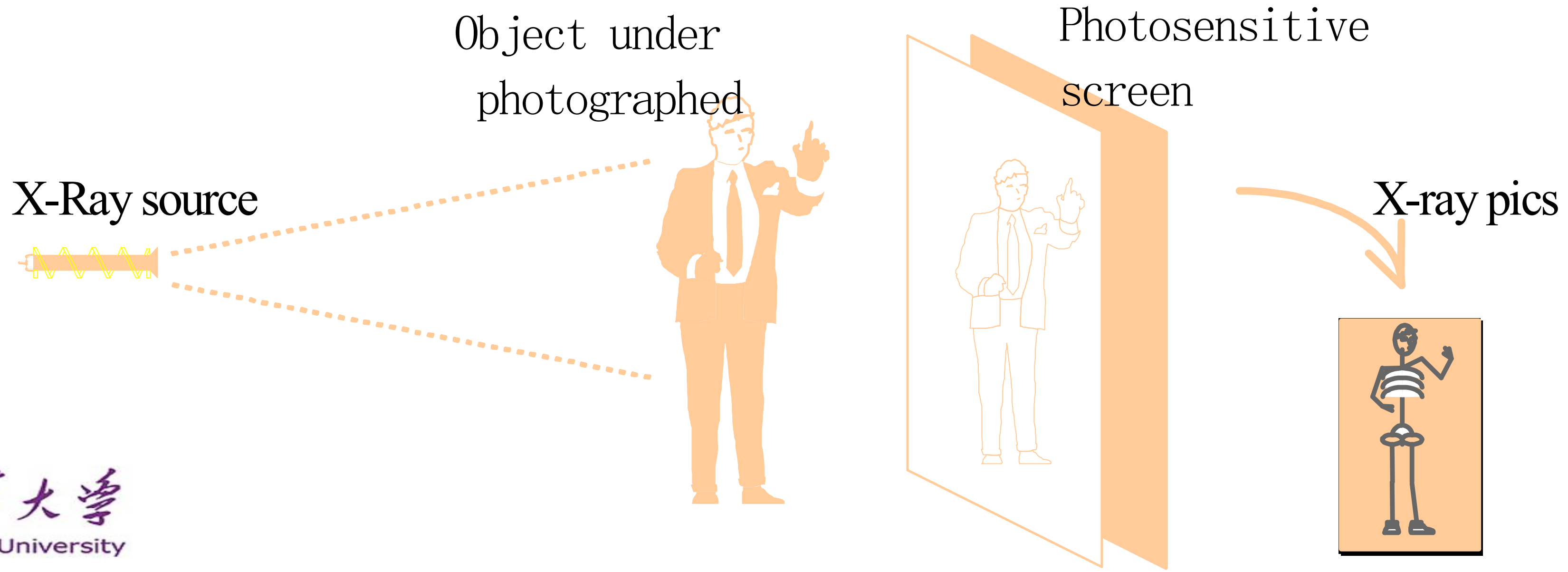
X-ray transmission imaging

- The first discovery of X-ray (1894) is due to its penetrability

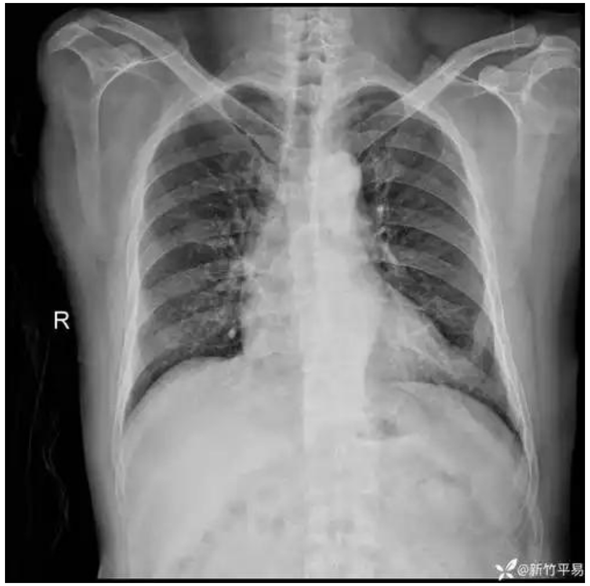


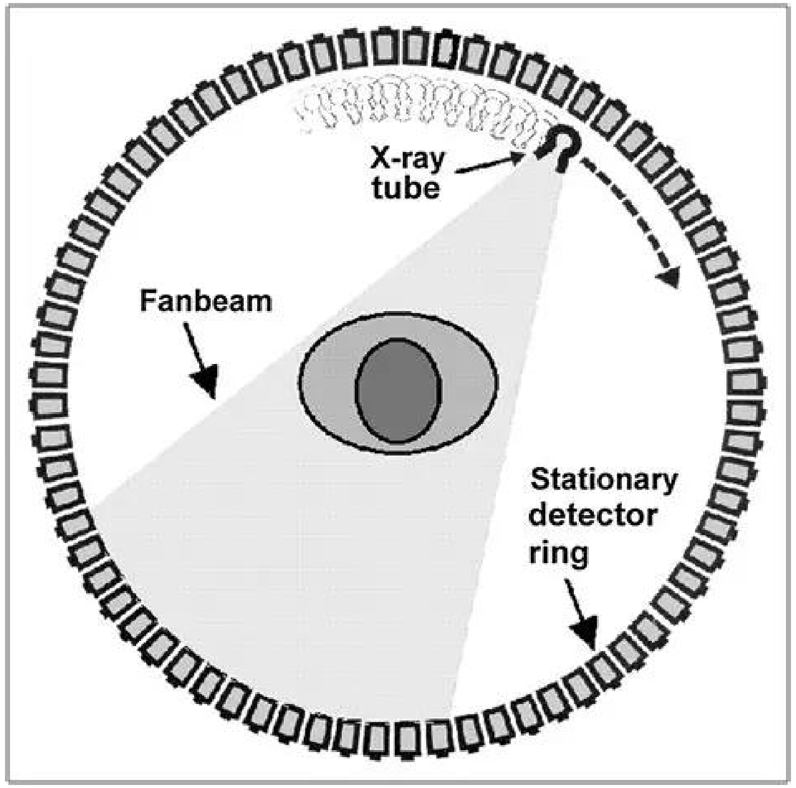
Computer Tomography

- Taking the transmission image from multiple directions, would provide more information and solve full 3D structure

DR: 2D imaging

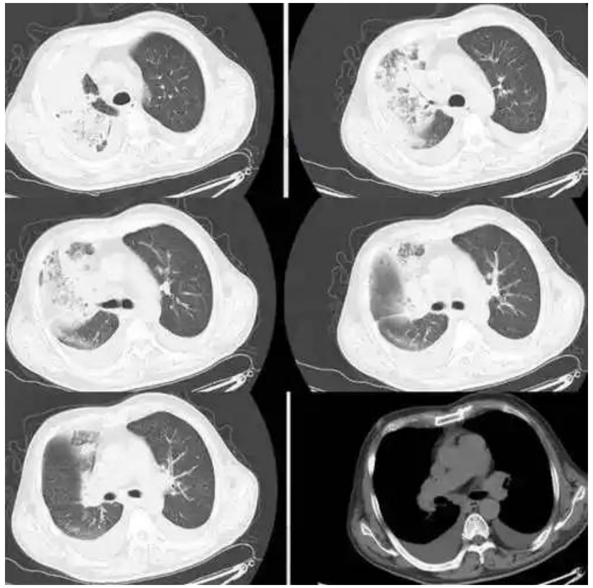


Many angles



Solve

CT: 3D imaging



Courtesy of Journal of Nuclear Medicine Technology

Principle of the imaging

- The attenuation factor of X-ray flux is depended on the material:
- Dense material: strong attenuation
- Light material: weak attenuation

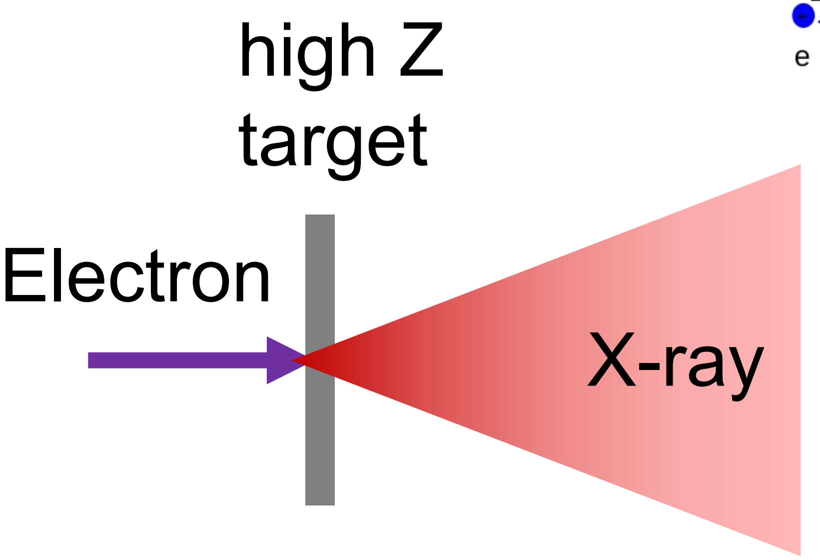
} Distinguish different materials

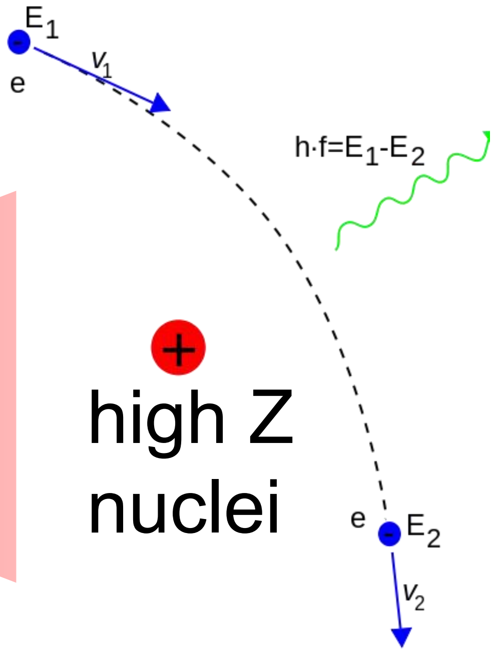
$$I = I_0 e^{-\mu x}$$

- I: X-ray flux after penetrated the object
- I_0: X-ray flux from source
- μ: linear attenuation coefficient
- x: Thickness of the object

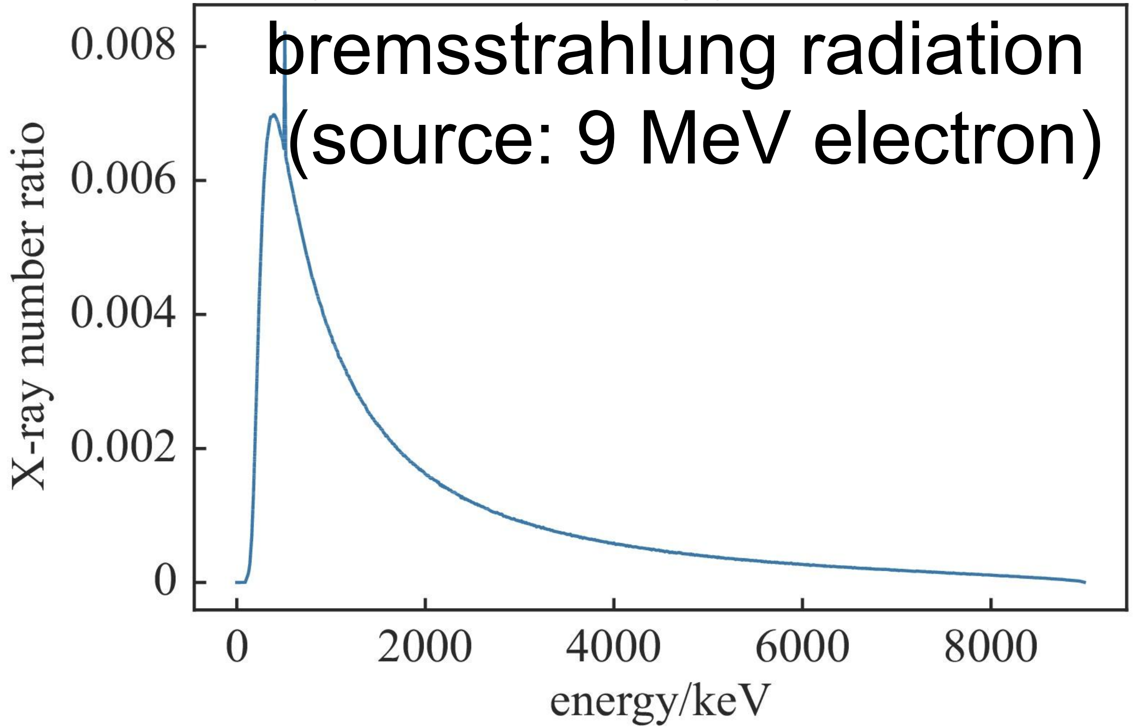
X-ray generation from electron beam

- The most common way to generate X-ray: bremsstrahlung radiation, which use electron beam to hit the high Z material (Tungsten)
- The energy of X-ray is depended on the energy of electron beam





Typical energy spectrum of bremsstrahlung radiation (source: 9 MeV electron)

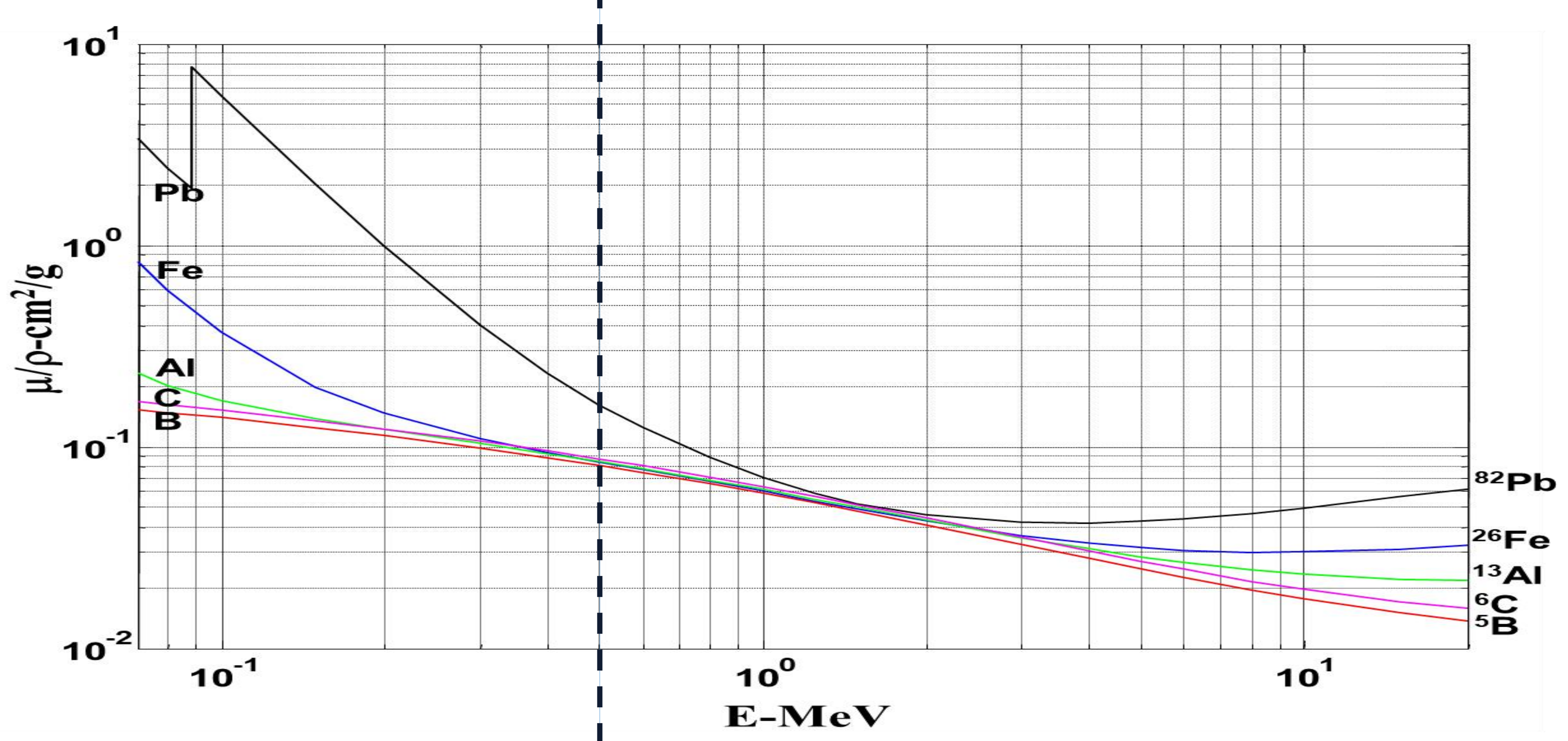


Choose the energy of X-ray

- Penetration ability of X-ray is depended on the energy

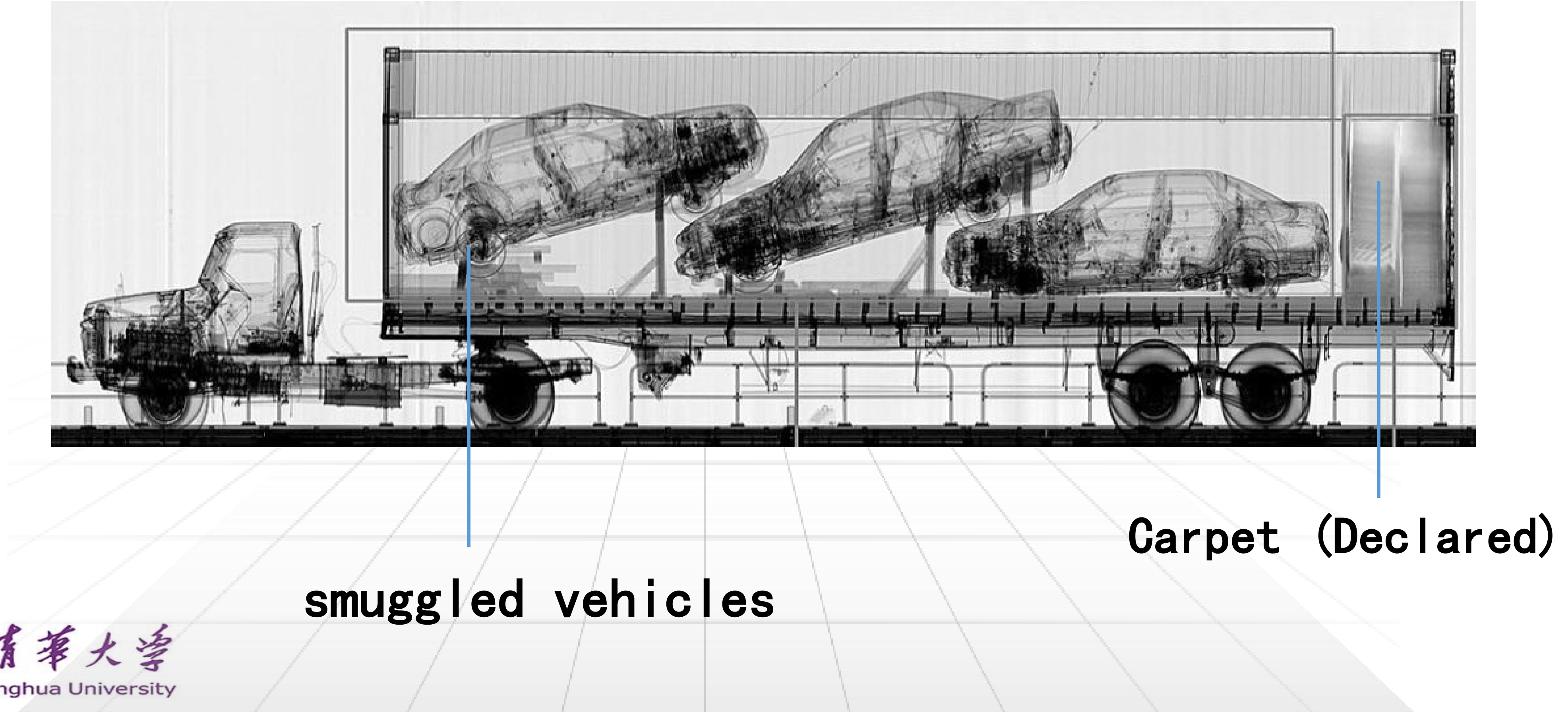
Low energy zone:
Small, light object

High energy zone:
Large, heavy object



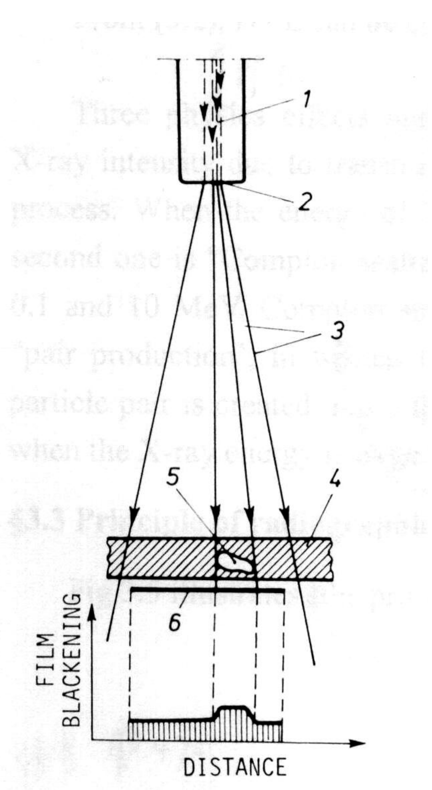
LINAC-based X-ray inspection

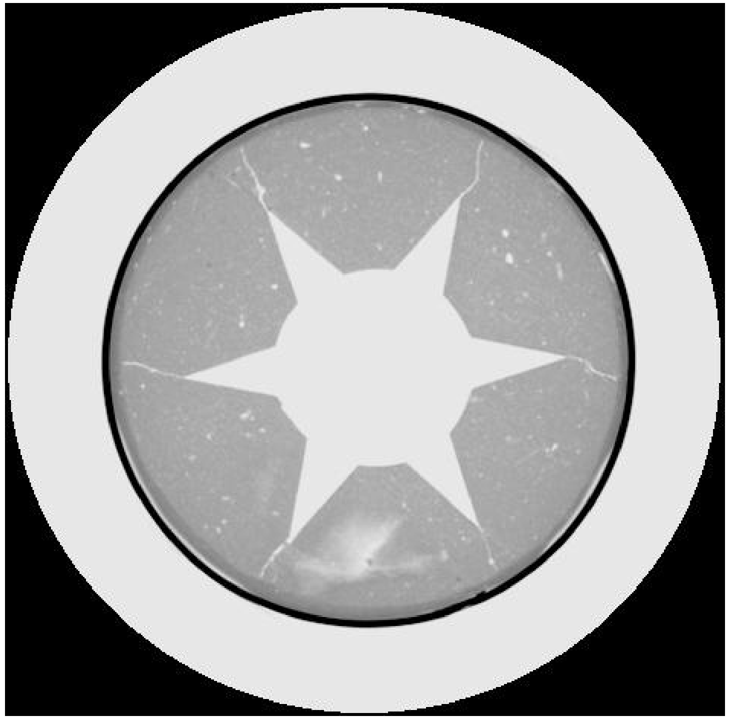
- LINAC could easily provide beam with MeV energy level (up to 20 MeV), and could penetrate very large object, like shipping containers



Inspection for large castings

- **No** **D**estructive **T**esting: didn't change the structure itself

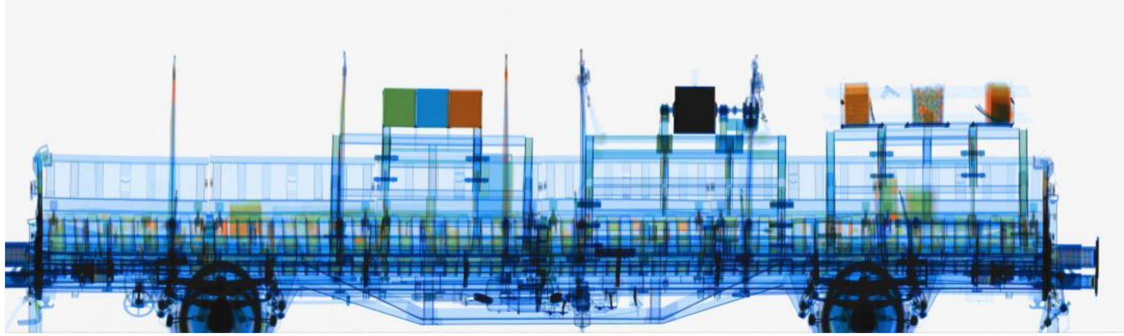




Rocket fuel testing

Crack inspection of high pressure chemical reaction vessel

Inspection for freight rail



Challenge: the train is moving fast, high time resolution is needed!

Inspection equipment

Mobile cargo inspector (6 MeV)

Combined type cargo inspector (6/9 MeV)

Mobile NDT inspector (15 MeV)

NUCTECH company

- NUCTECH company is originated from Tsinghua University
- It occupies ~50% of the whole world's market share

1500 accelerators are in operation at 160 counties

Dual-energy inspection

- X-rays image only reflects the product of attenuation factor and thickness, but can not determine both of them → not able to know what kind of material
- Dual-energy inspection could provide more information

$$I = I_0 e^{-\mu x}$$

We can calculated the product

What we really measure

μ=1, x=2 ??

μ=2, x=1 ? ?

μ=4, x=0.5 ? ?

Energy 1: $\mu_1 x = a$

Energy 2: $\mu_2 x = b$

$\frac{\mu_1}{\mu_2} = \frac{a}{b}$ → determines the material type

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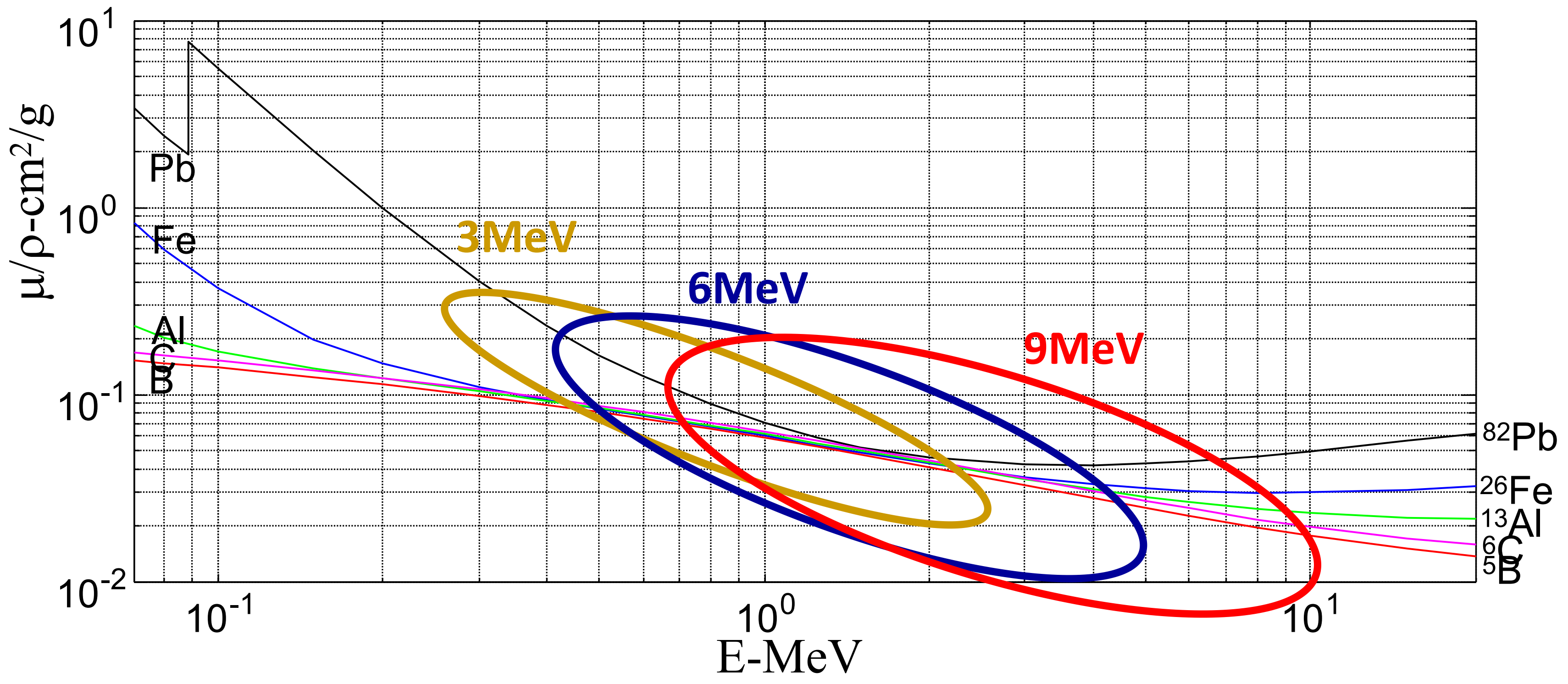
How to select the beam energy?

- Discrepancy among the linear attenuation factors is essential!
- Combination of 3/6 MeV is good, 6/9 MeV is also good
- But 3/9 MeV is not a good choice: attenuation factors are similar



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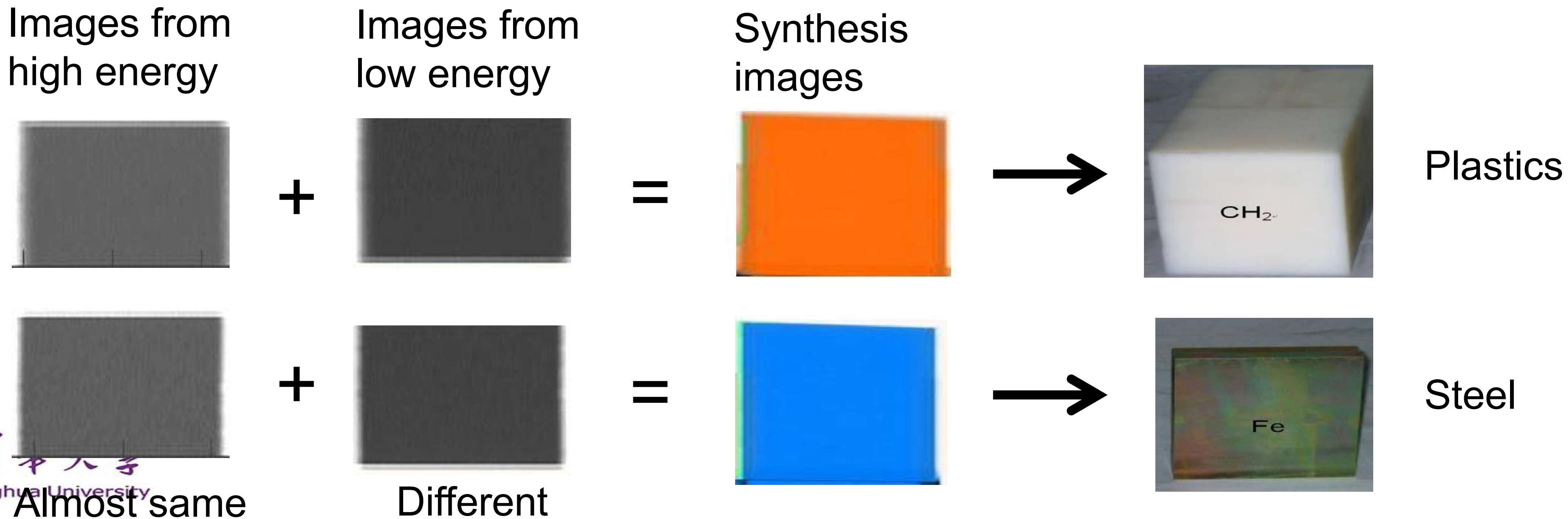
Effect of dual-energy inspection

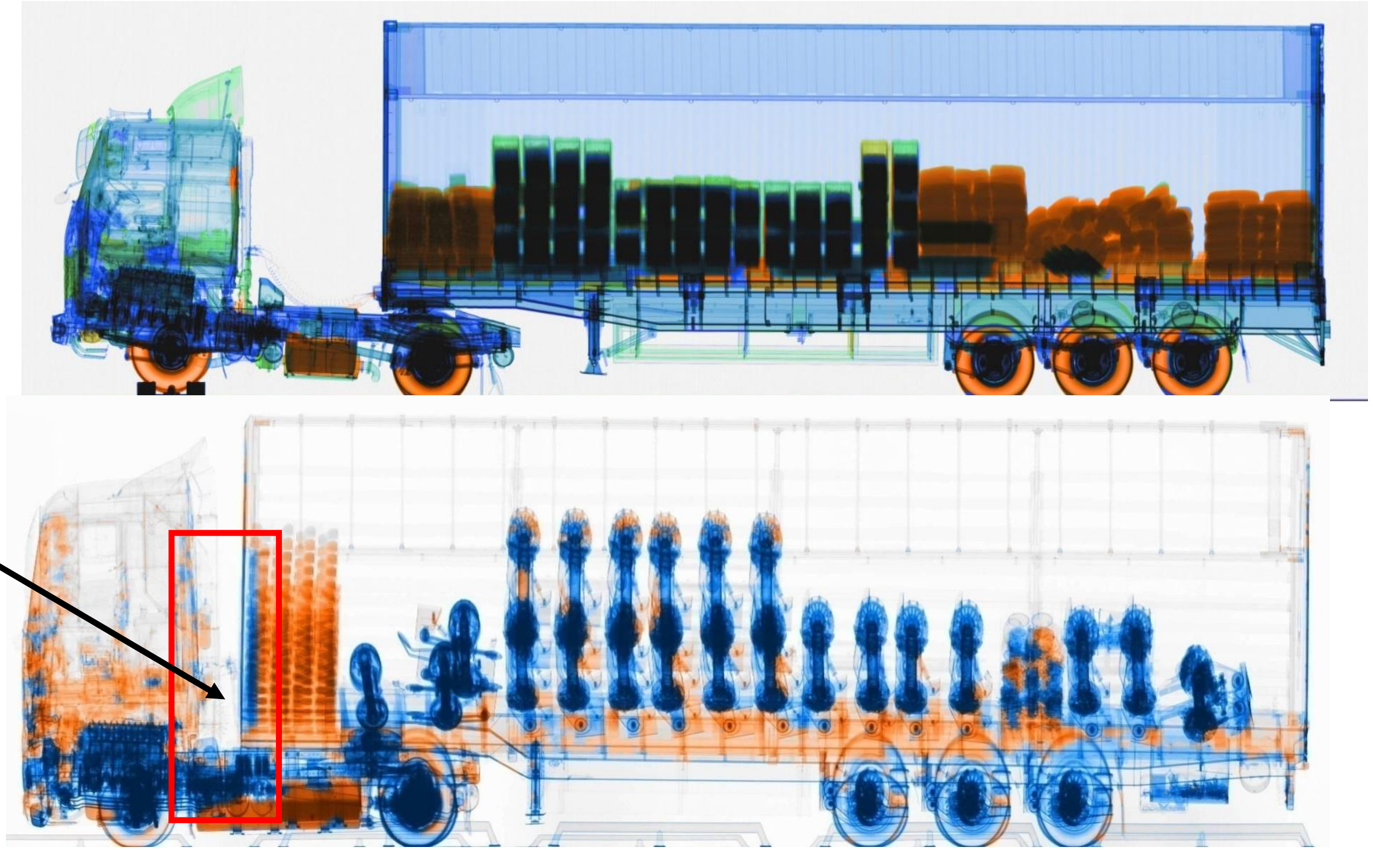
- Single-energy inspection: monochrome (grey) image
- Dual-energy inspection: extra dimension → coloured image
- In principle, more energies may further increase the accuracy. But in practice, it doesn't show much improvement vs dual-energy



Effect of dual-energy inspection

- Integrated with AI pattern recognition, the inspector could reach very high accuracy of identify objects (e.g. even know the brand of smuggled cigarette, wines or luxury watches, etc)

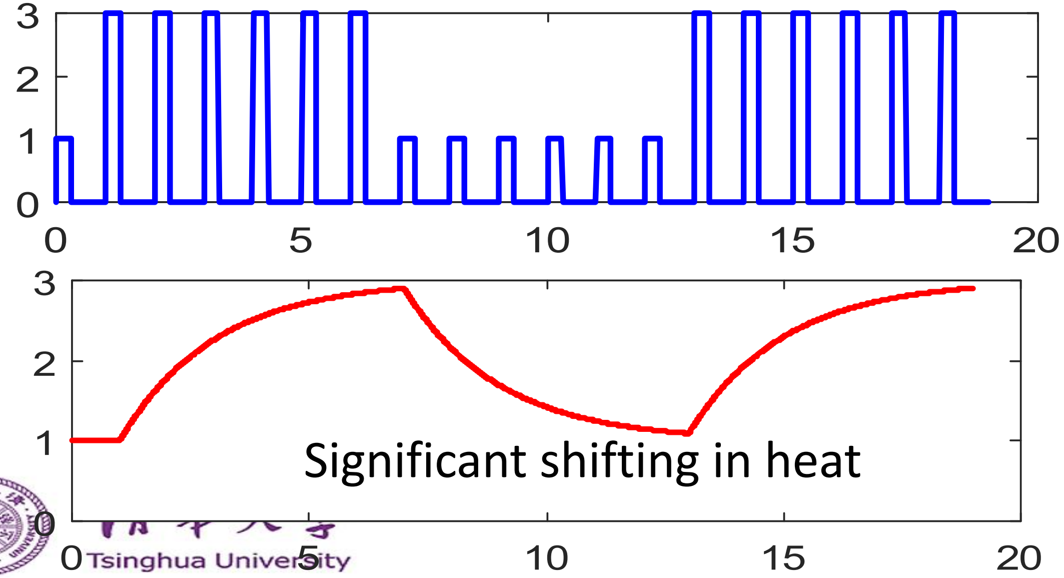
Undeclared red wine
Brand: ***
Origin: Finland



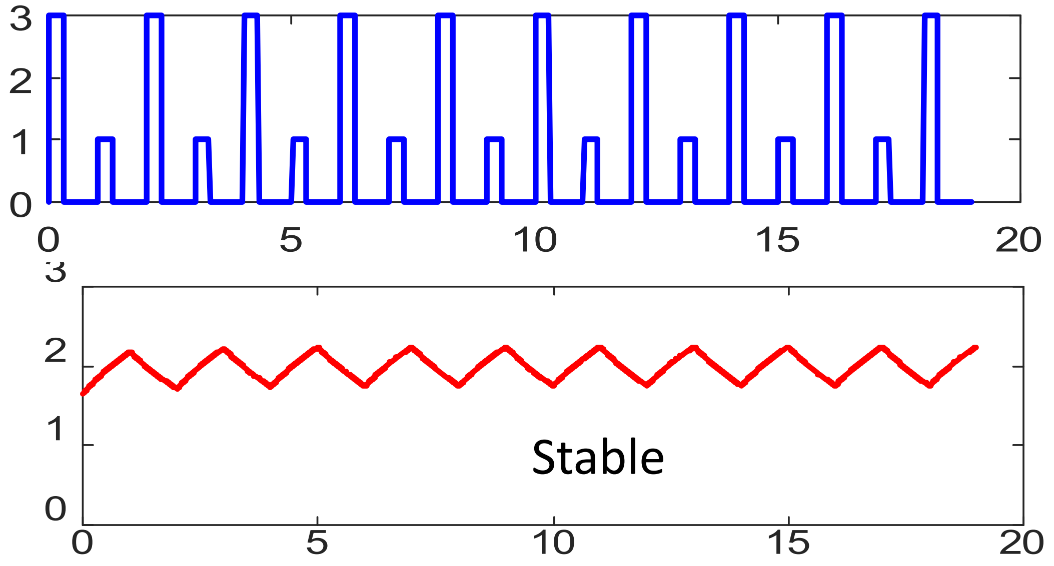
One challenge of dual-energy operation

- Switching the energy usually requires changing the RF power
- This approach brings operating instability: changing power dissipation level cause the resonant frequency shifting
- Solution: rapidly switching

Switch energy after every 6 pulses



Switch energy after every pulse



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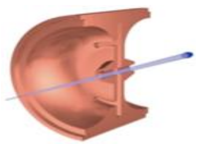
Principle of Radiation Processing

- Ionizing radiation could easily break chemical bonds:
  - Destruction of DNA and proteins: disinfection and sterilization
  - Degradation of large molecules: wastewater treatment
  - Chemical bond reconstruction: polymer hinges, material modification

Energy:	0.2 MeV	1 MeV	5 MeV	10 MeV	>15 MeV
Application:	Thin film	Waste water treatment	Cross-link	Sterilization	Activation

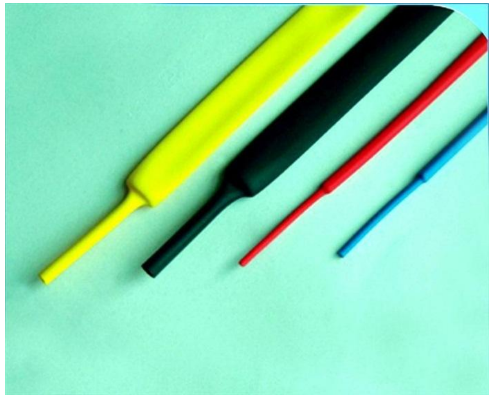
LINACs or radioisotope source?



Source	LINACs with 10MeV/20kW	Cobalt 60， 100 Cuires
Energy efficiency	~30% from plug to beam The rest is conversed into heat No offline power consumed	The emission of X-ray is isotropic, only ~20% of the energy would reach the target The emission is spontaneous, it is a totally waste if the equipment is off.
Processing speed	3 tons per hour	0.6 tons per hour
Penetration depth	10 cm (water equivalent value)	30 cm (water equivalent value)
Safety	No radiation when the equipment is off, easy maintenance	Hazardous
Cost	~1 RMB per kilogram	~2 RMB per kilogram

Crosslink

- Ionizing radiation breaks chemical bonds and force the recombination of these bonds, will improve some certain properties of materials
- Mostly used in polymer materials processing:
  - Increasing the strength of car tires, cables, heat shrink tubing
  - Increases insulation resistance and thermal protection



Material modification

- The recombination of chemical bonds also have some unexpected effect (pleasant aspect) :
  - Produce crystal defects, colorless to colored (gemstone processing)
  - Wood hardening, moisture resistance, increase its lifespan
  - Ink curing, Road hardening, etc.

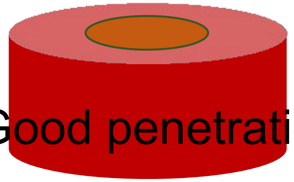
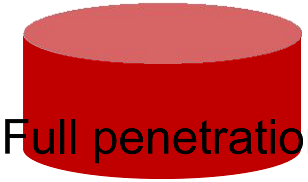
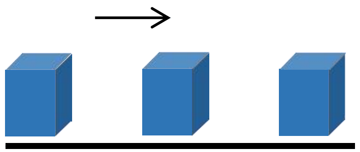
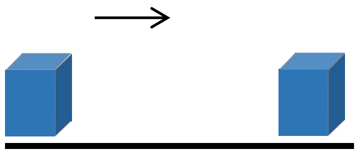
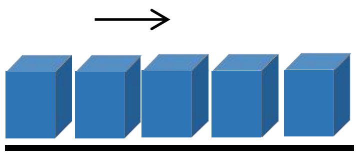





Application in environment protection

- Radiation could destruct the larger molecular chemical bonds and degrade them into small molecules :
  - Wasted water: degrade the organic matter
  - Waster gas: desulfurization (SO_2 → SO_3 → $CaSO_4$)

Advantage of radiation sterilization

	High temperature steam	Ethylene Oxide	Radiation
Capability	 Good penetration	 Only for surface	 Full penetration
Side effect	 High temperature may **damage something**	 Suitable for most items	 Suitable for most items
Processing speed	 **Fast**, but need time for heat up	 Need **long time** to evaporate the residual gas	 **Very Fast**, instantly killing all pathogens
Safety		 Flammable, Explosive, Toxic	 Radiation can be controlled

Application of radiation sterilization (1)

- A big advantage in food sterilization: cold processing, without damaging the nutrition and flavor of food
- Typical application: breading egg-shell sterilization (protect the yolk), flavored meat products (like sashimi), pickled products, high-end pet foods, sprout inhibition, etc




Application of radiation sterilization (2)

- 60% of medical production uses radiation sterilization: quick, thorough and clean: Played a significant role against COVID-19
- Potential application: medical waste processing





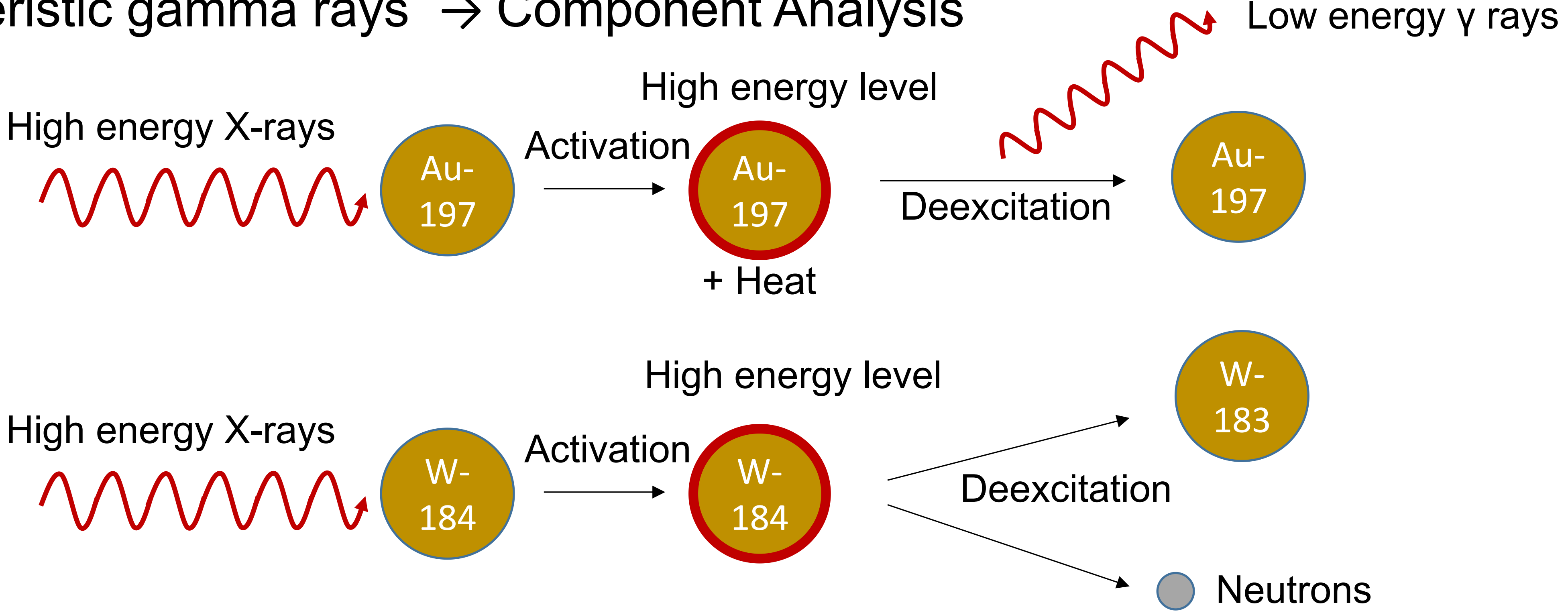

Application of radiation sterilization (3)

- Biologic safety is taking a very important place in national security:
- Terrorists may use letters and goods to transmit deadly pathogens
- Invasive alien species (hidden in import goods like woods) may damage the local ecology
- Radiation sterilization will provide a thorough solution



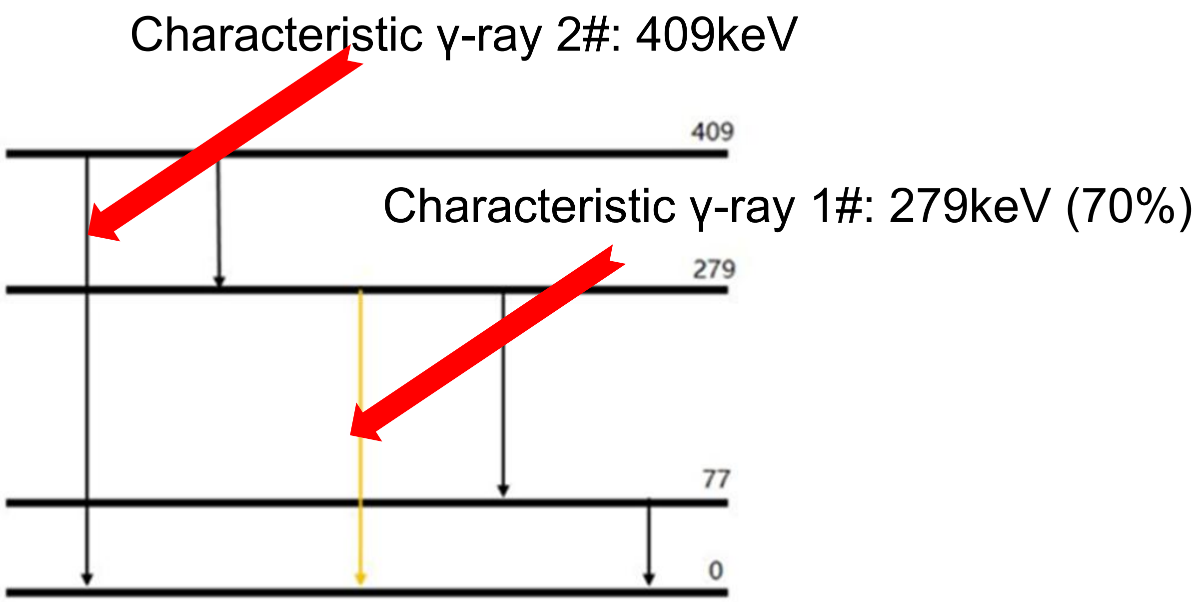
Activation

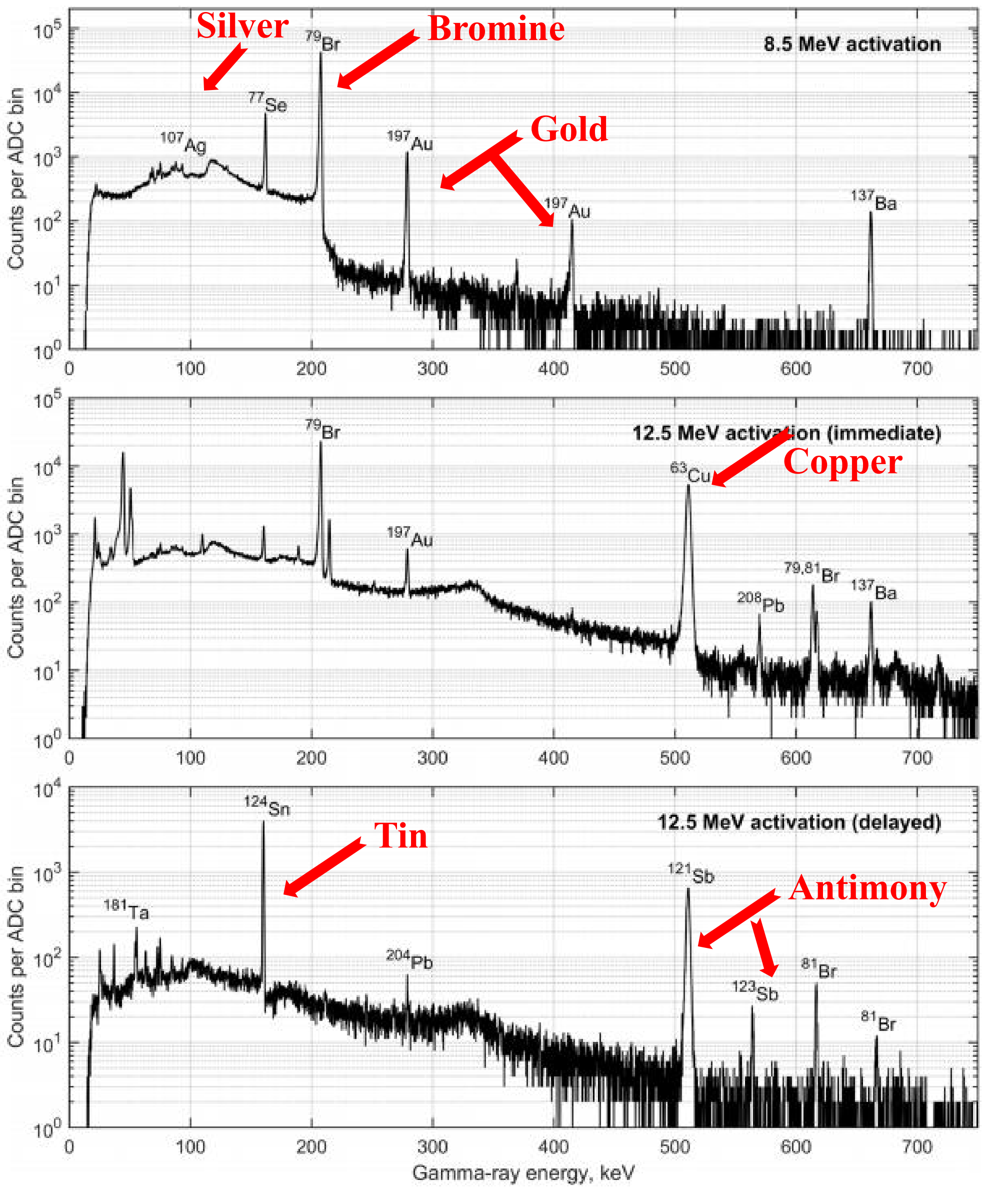
- High energy X-ray (> 9 MeV) may active nuclei of some elements
- The activated nuclei may release:
  - Neutrons → A compact neutron source
  - Characteristic gamma rays → Component Analysis



GAA: Gamma Activation Analysis

- GAA is capable of screening precious metal elements in minerals or wastes
- Example: Gold





Electron LINAC based neutron source

- Normally, generating neutron using proton hitting the Be-target is an efficient way: expensive, and strong residual radiation
- High energy electrons would also have a good efficient: every 200 electrons (energy = 30 MeV) could produce 1 neutron (lead target)
- Application: nuclear drug production, Boron neutron capture therapy (BNCT), pulsed neutron analysis instrument

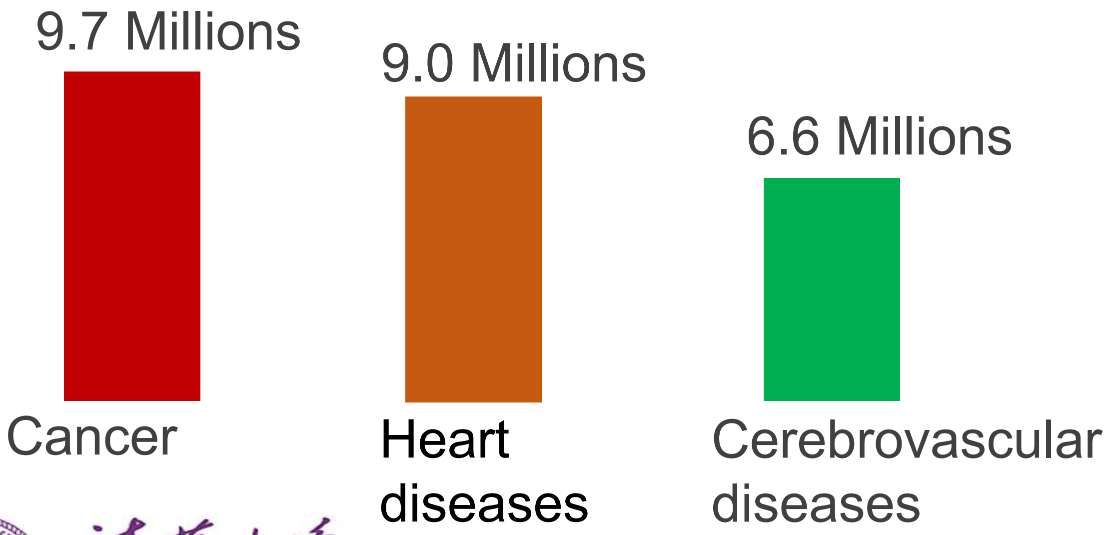
Outlines

- Brief introduction
- How to design a low energy electron LINAC?
- Application of LINACs in NDT
- Application of LINACs in radiation processing
- **Application of LINACs in radiotherapy**

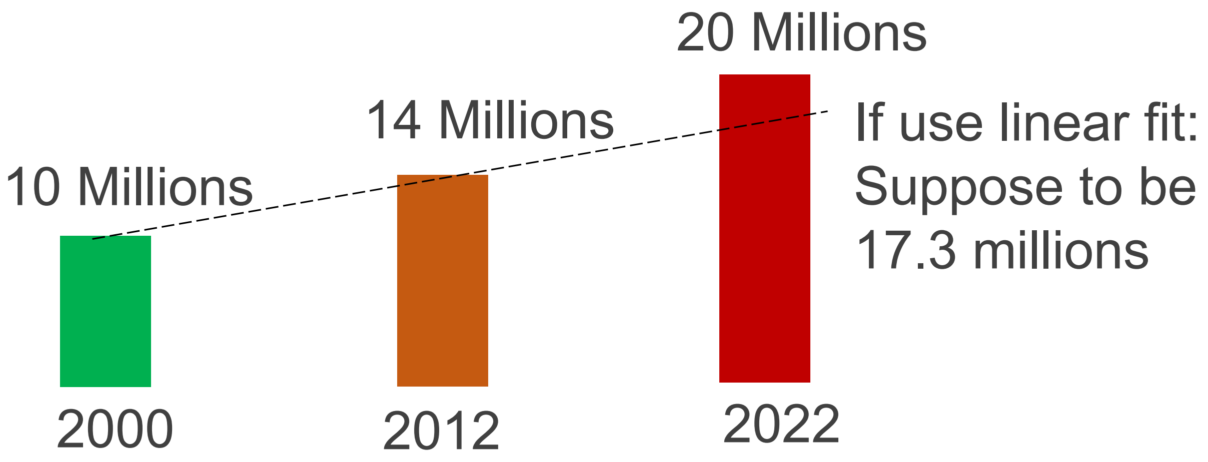
Cancer: first killer

- Since 2015, the number of people died with cancer already surpass the one of heart diseases
- However, incidence rate of cancer is still accelerating

2022 world wide cause of death



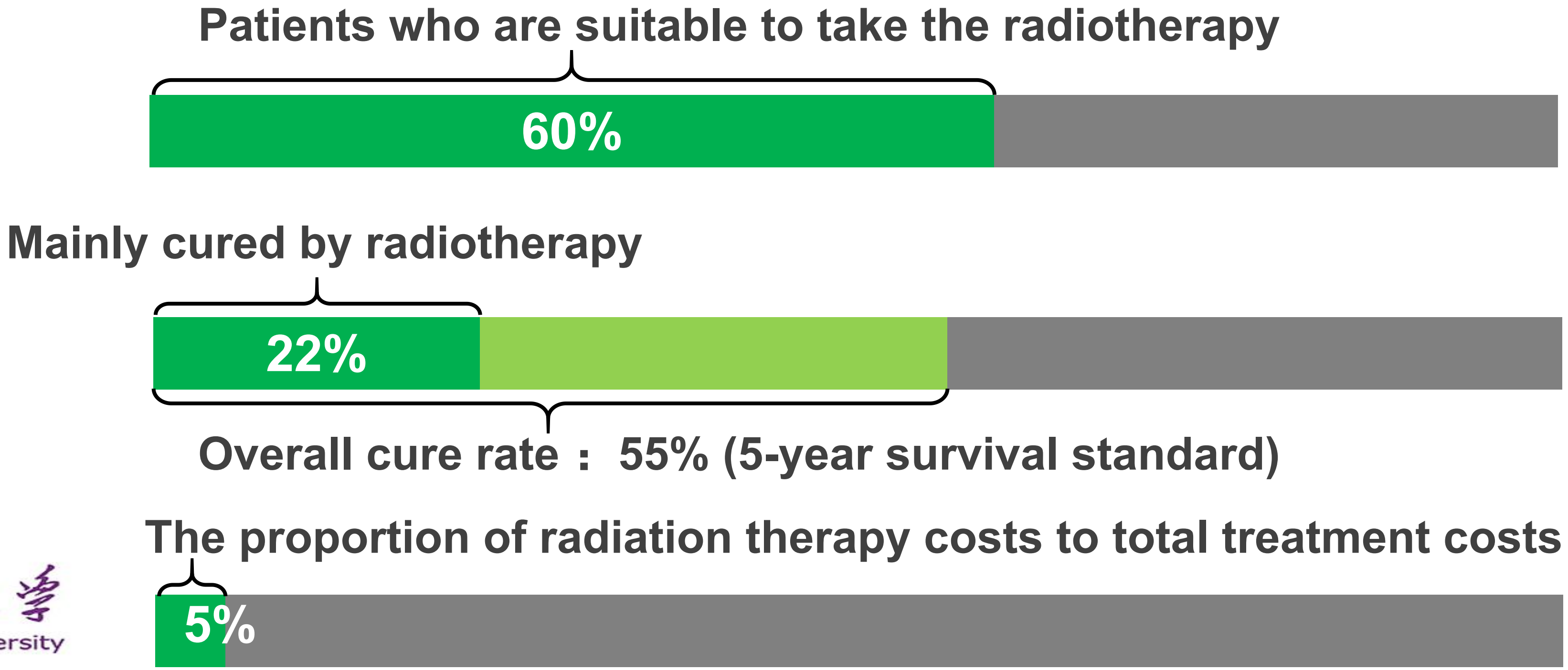
2022 world wide new cancer patients



Radiation therapy is an efficient treatment

- Surgery, radiation therapy, and chemotherapy are still the three main methods of cancer treatment at present.
- Radiation therapy has a very high efficacy/cost ratio.

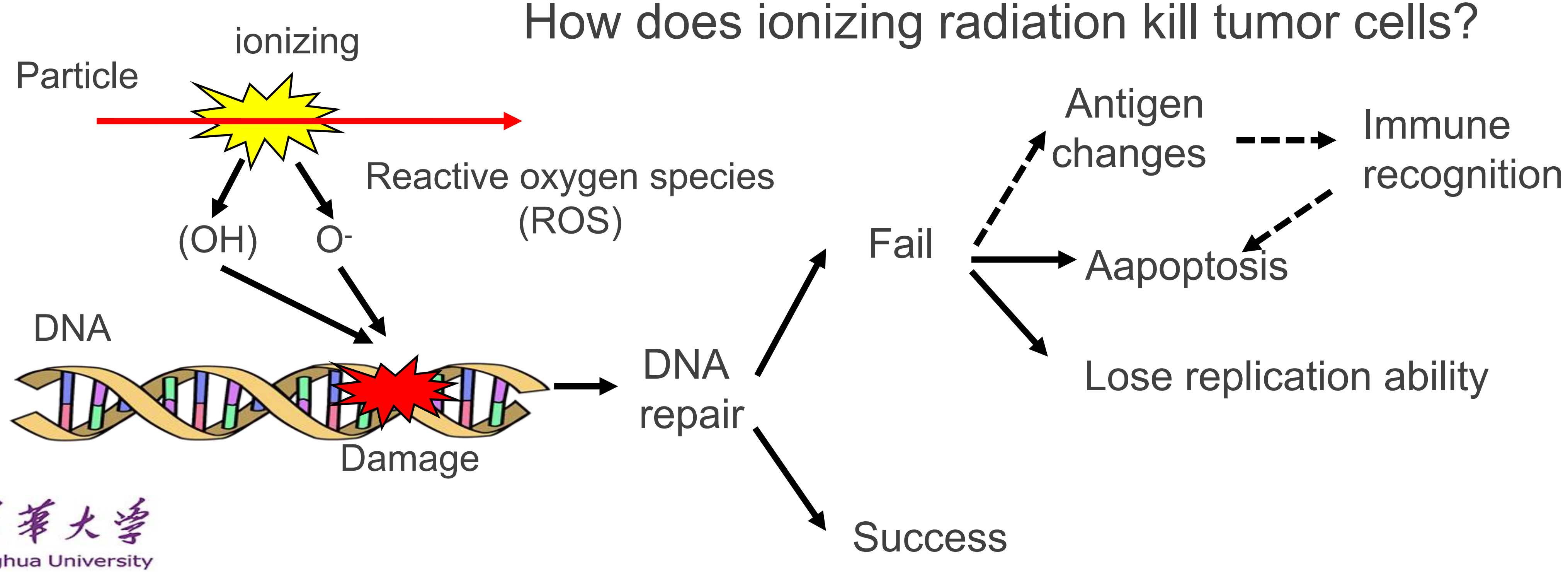
Statistics of radiotherapy (Average value for high income countries, 2020, IAEA)



Principle of radiotherapy

- Radiotherapy damages tumor cell DNA through ionizing radiation (while affecting normal cells, i.e. side effects)
- Compared to normal cells, tumor cells have lower tolerance to ionizing radiation (due to poor repair ability and more frequent replication)

How does ionizing radiation kill tumor cells?



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Radiotherapy for non cancer diseases

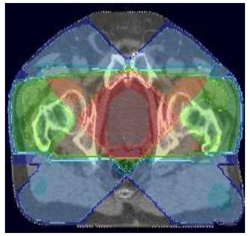
- Radiotherapy can also kill or regulate abnormal cell to curse some diseases:
- Cardiac arrhythmia: some cardiac cell generates abnormal discharge to cause the disorder of heat beat. It was very difficult to cure this problem. But now days radiotherapy can help (cure rate in a clinical trail: 99%)
- Neuralgia: some nerve cells generate abnormal discharge to cause a huge pain. Use radiotherapy to suppress the nerve cell and relieve the pain
- Alzheimer (Clinical trials in very early stage): a possible explanation is due to the chronic inflammation of brain cells. The radiotherapy may change the microenvironment and decrease inflammatory factors (IL series/TNF-α, etc)

History of radiotherapy

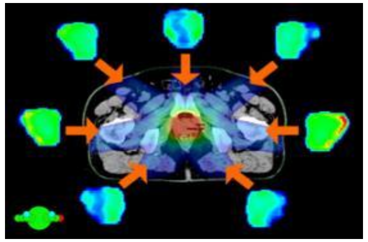
- Radiotherapy has always been developing towards obtaining a higher accuracy and reducing the side effects on normal tissues
- Only in this way can have the tumor to deliver a larger dose and strive for a chance of cure

X-ray discovery

LINAC



CRT



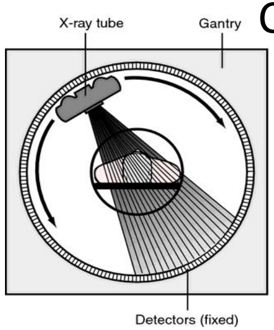
IMRT &VMAT

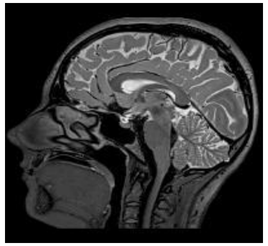
IGRT &SBRT

1895 … 1950 1960 1970 1980 1990 2000 2010 2020

ART
FLASH-RT
Proton/Heavy Ion
BNCT
……

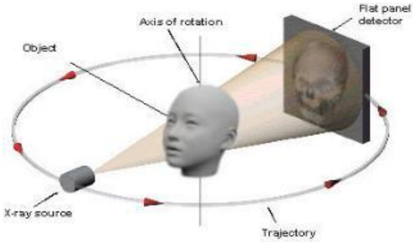
CT &MRI





MLC

CBCT



Pic from Wikipedia

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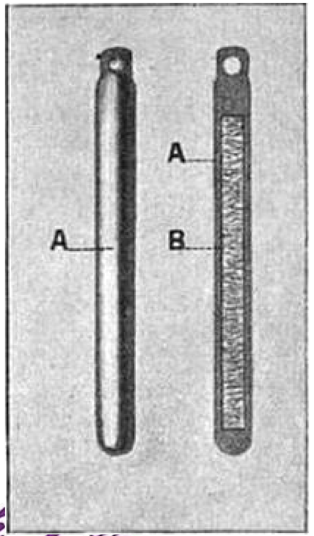
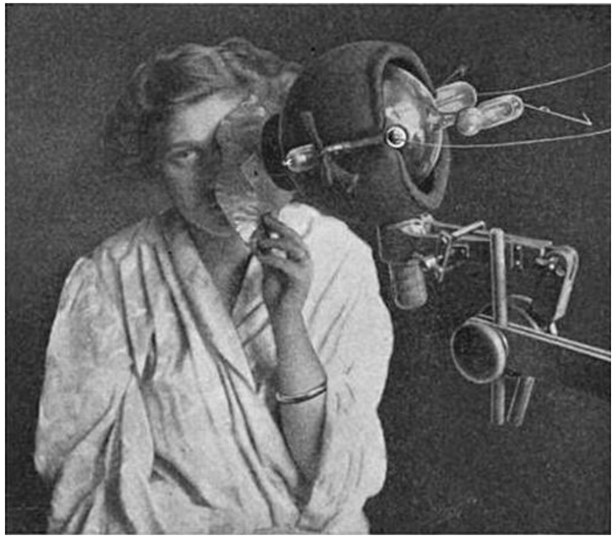
Radiotherapy in early time

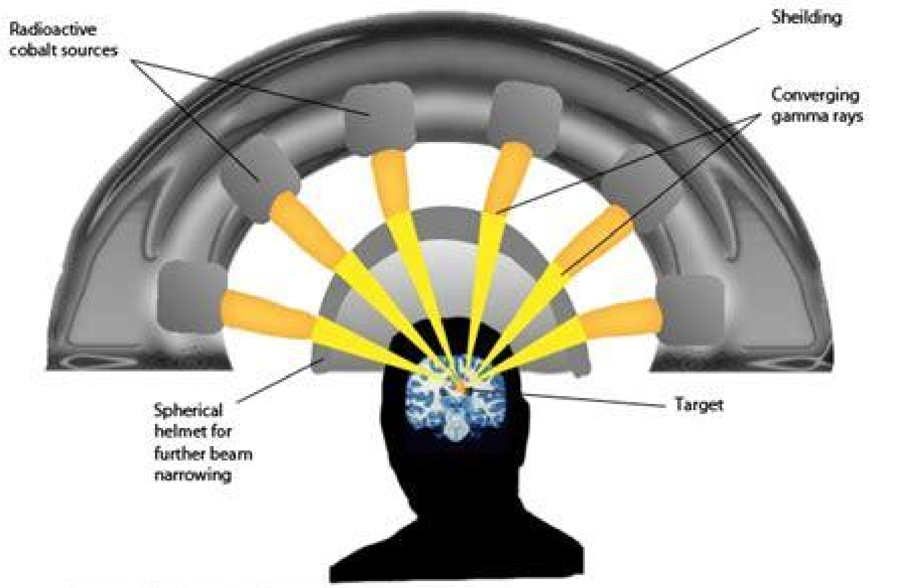
- In the early days, radium was used, and later it was mainly Co-60 therapy machines, these machines were gradually replaced by LINACs after 1950s
- But Gamma Knife is still widely used nowadays : focused irradiation method, especially suitable for head tumors

Radium rods used for radiotherapy



Device used to treat facial tumors in 1910



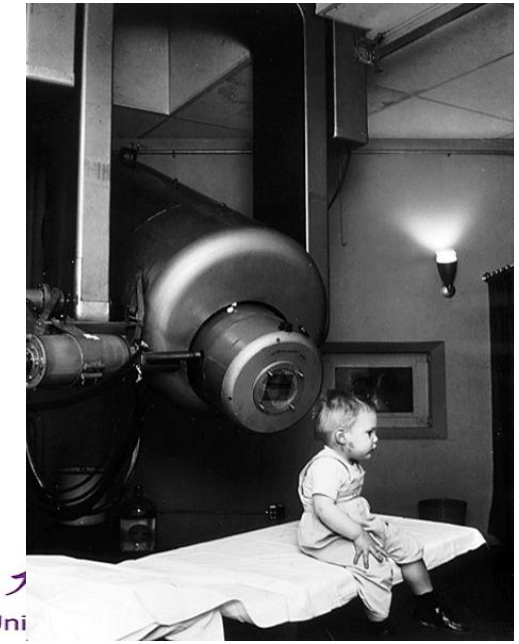


Stereotaxic Radiosurgery - Gamma Knife Concept
Multiple radiation beams converge on target tumor, delivering high-dose radiation to the tumor, but little to surrounding tissues. It is a single treatment and to ensure proper patient positioning and immobility, a positioning frame is secured to the patient's skull, then attached to the radiation source. Treatment lasts 45 to 60 minutes.

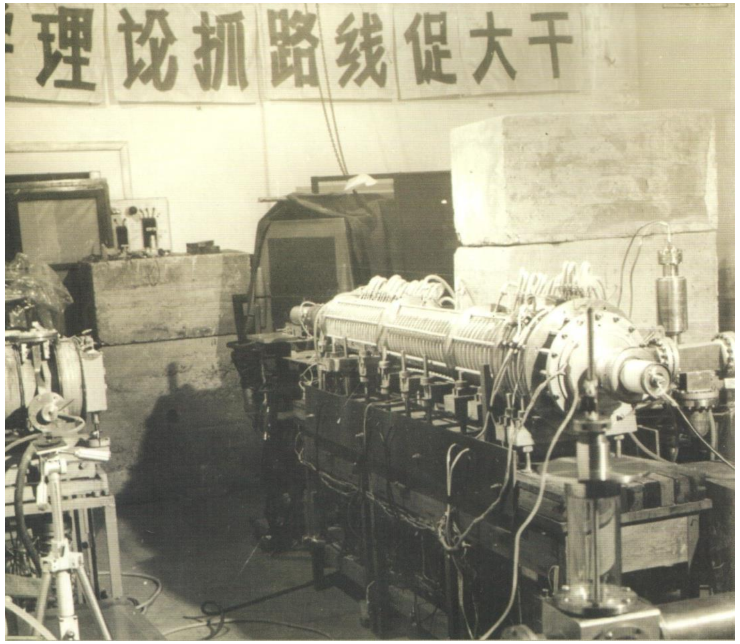
Evolution of LINAC radiotherapy

- RF-cavity based medical LINAC was first born in 1953
- The weight and dimension of LINAC are continuously decreased
- The progress brings many advanced radiotherapy techniques

1950s, First LINAC in Stanford Hospital

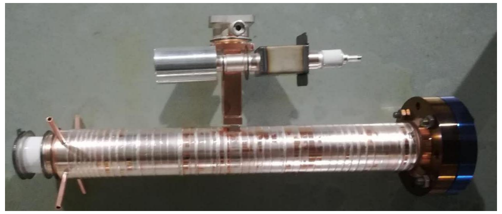


1974, China developed its first medical LINAC (9MeV) in Tsinghua University



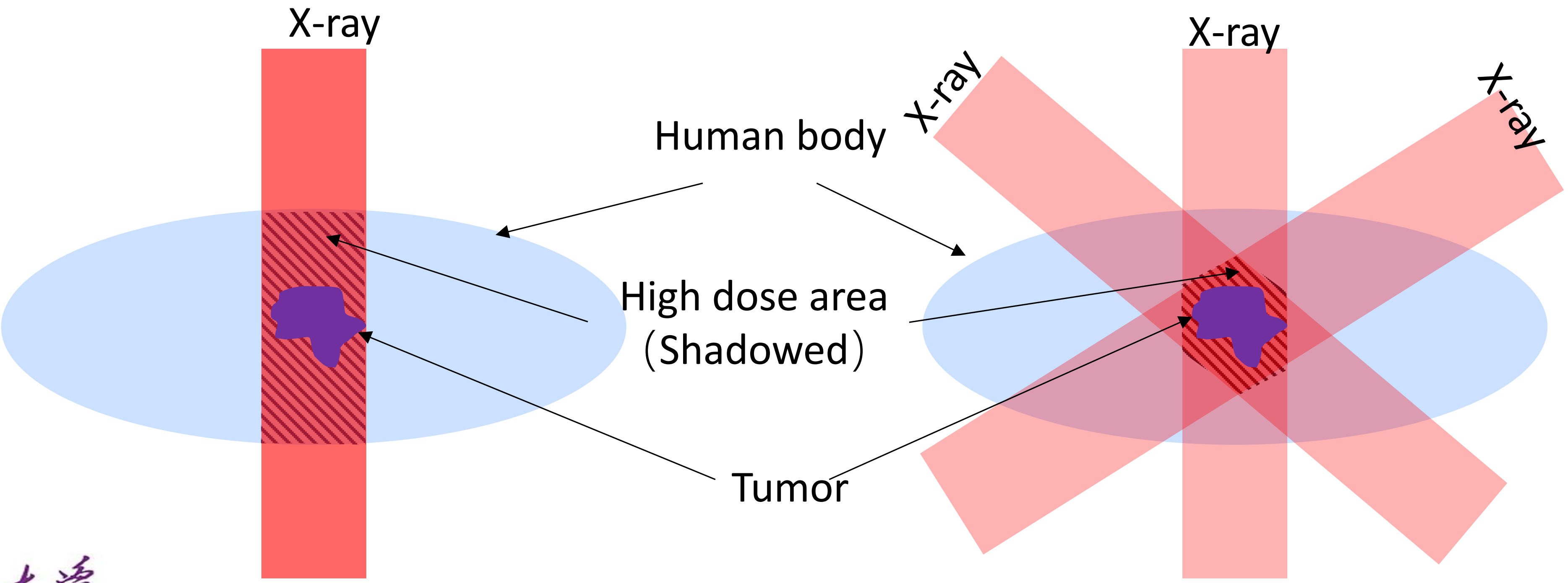
Compact C-band LINAC in Tsinghua University (2012)

Compact X-band LINAC in Tsinghua University (2019)



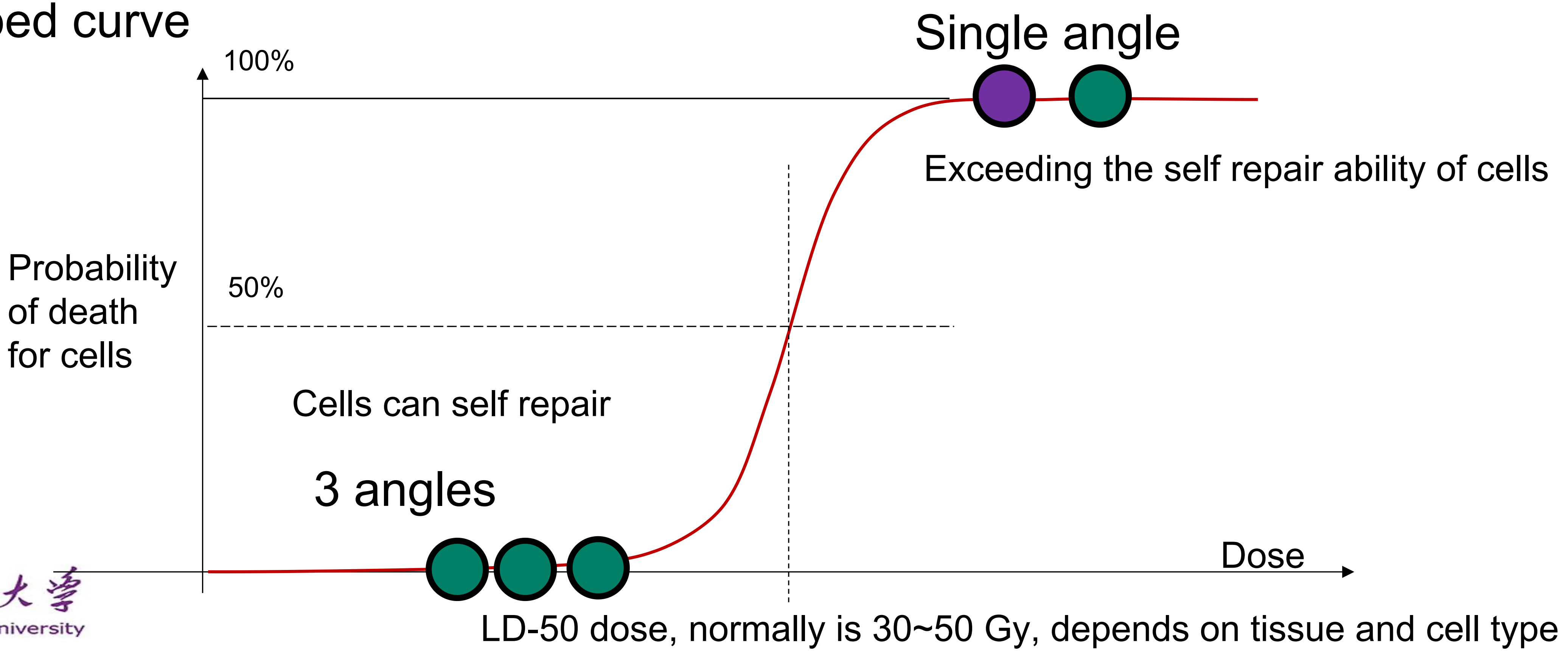
3D Therapy

- Lightweight LINACs allow the rotating gantry, irradiation at a single angle → multiple angles
- The radiation dose to normal tissues is spread out over a larger range



3D Therapy

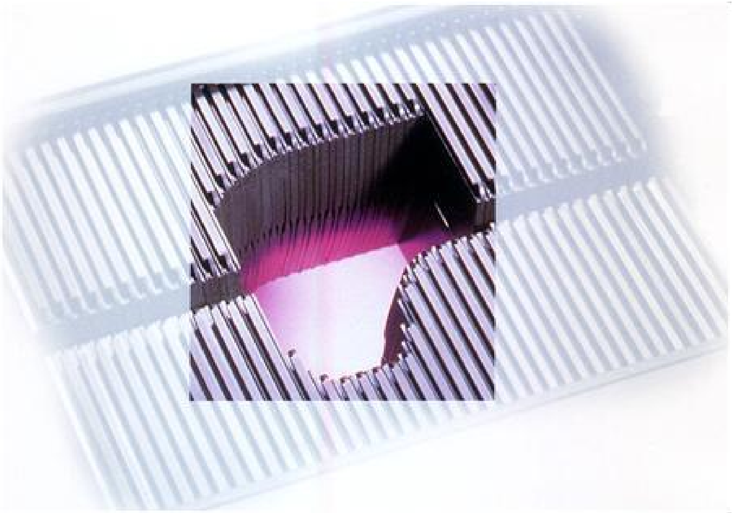
- Although multiple angles distribute radiation to more normal tissues, the total damage is still greatly reduced
- This is because the damage is not proportional to the dose , but rather follow an S-shaped curve



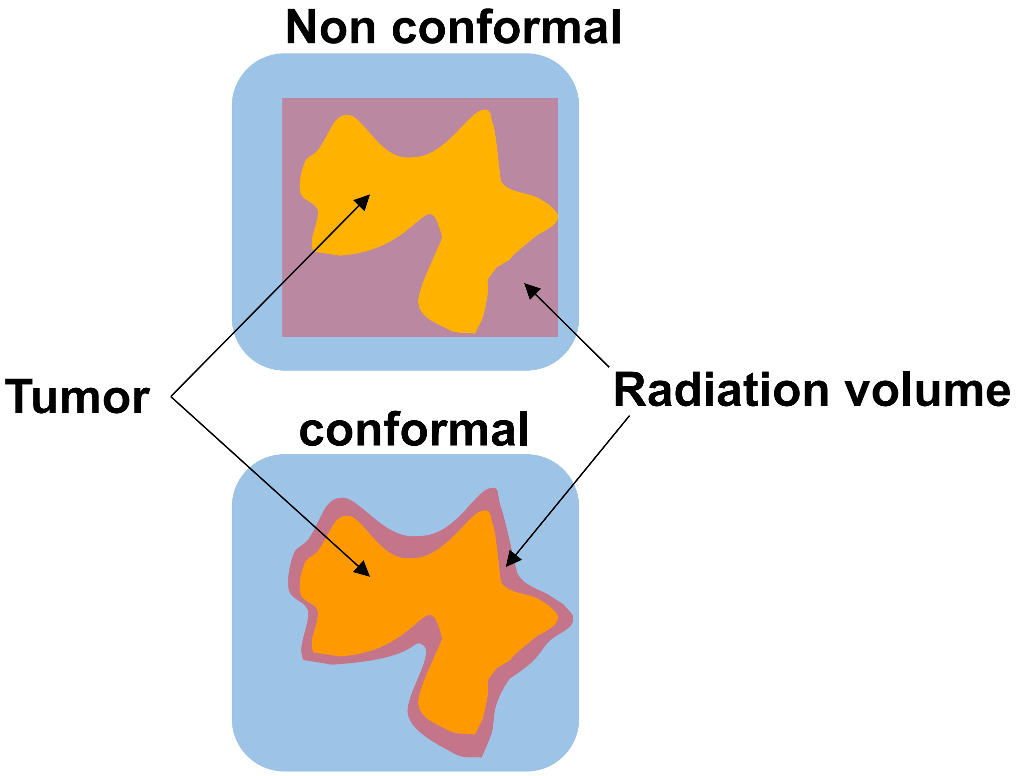
Conformal radiotherapy

- Multi leaf collimator (MLC) technology is a revolution in radiotherapy
- These leaves can be dynamically adjusted to the shape of the treatment area
- The dosage in non therapeutic areas can be significantly reduced;

Multiple Leaf Collimator



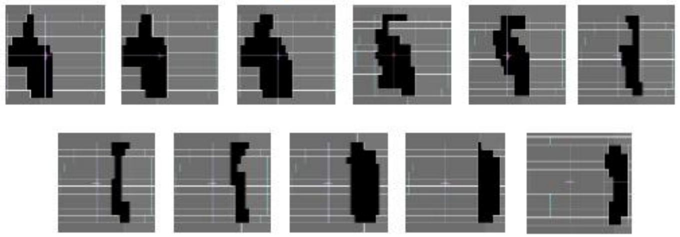
Courtesy of Jeff M. Michalski et al.Three-Dimensional Conformal Radiation Therapy (3DCRT) for Prostate Cancer

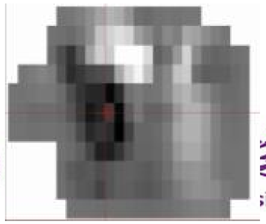


IMRT: Intense Modulate Radiotherapy

- By delivering different doses to different angles and irradiation shapes, the 3-D shape of the tumor can be reconstructed (like inverse process of CT)
- IMRT has ushered radiotherapy into the era of accurate therapy, and is currently the most mainstream radiotherapy mode
- Upgraded version: VMAT (Volume Modulate Arc Therapy)/ Tomotherapy

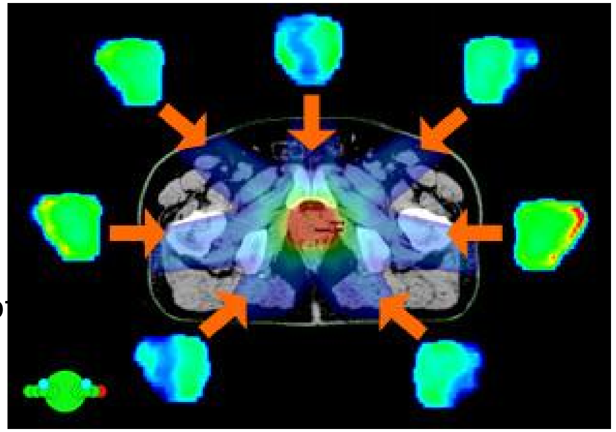
IMRT field decomposition



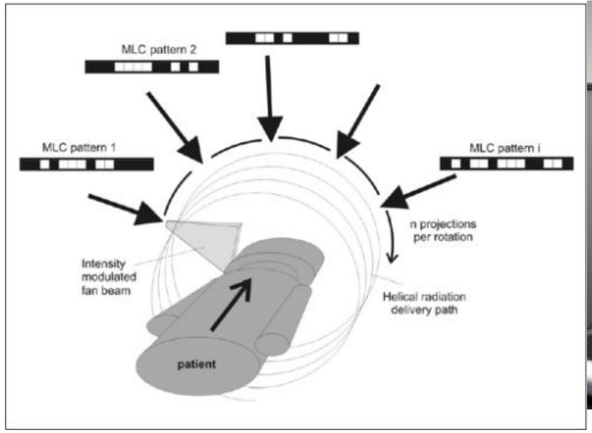


Courtesyof David Shepard, Overview of IMRT and Arc-Based Techniques.

IMRT



Tomotherapy

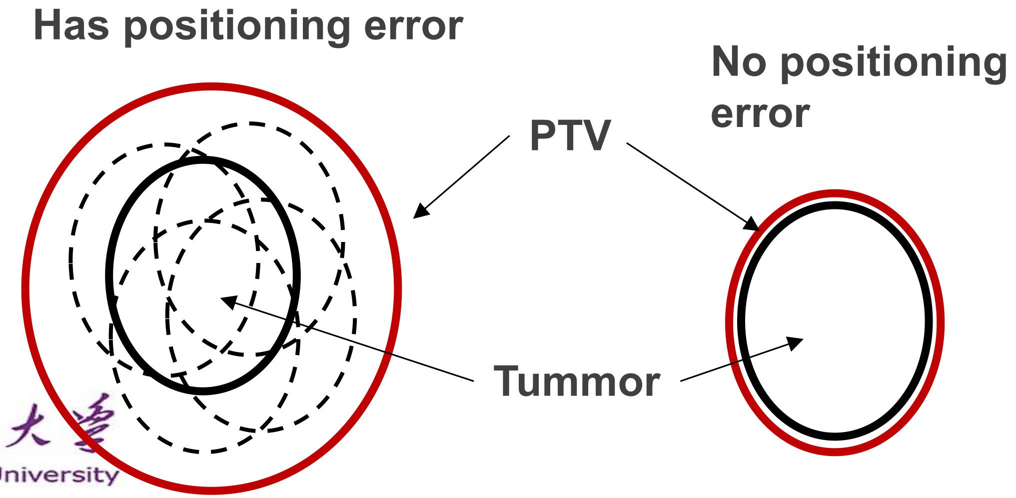


VMAT

IGRT: Image Guided Radiotherapy

- Errors in treatment:
  - Tumor shape error: During treatment, the shape and position of the tumor may change
  - Positioning error: After lying down, the patient's body is not in the predetermined position
  - Real time movement error: tumor displacement caused by breathing, heartbeat, etc
- IGRT is essential to reduce this error to the level of 1 mm, which will greatly reduce the irradiated volume of normal tissue

PTV：Planning Target Volume



Dp (PTV diameter) = Dt (Tumor size) + 5 x σ (RMS error)

When the Dt=3 cm, the volume of PTV is:

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

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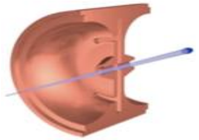
Future of radiotherapy



- Reducing side effect is always the main goal of developing radiotherapy, and several new biological effect found recently may help:
  - Immunotherapy wins Nobel Prize in 2018, it may fundamentally solve the problem of metastasis/recurrence of malignant tumors. Combination of radiotherapy and Immunotherapy is very promising, but it need a **large radiation dose** to trigger the immune effect
  - FLASH radiotherapy uses **ultra high dose rate** to trigger both stronger immune effect and less toxicity to the normal tissue, which is a attractive research highlights in RT area.
  - Both need **more powerful and accurate irradiations**: we need new LINACs

Developments of medical LINACs: SBRT

- SBRT (Stereotactic Body RT) or SABR (Stereotactic Ablation): use large dose per fraction to gains a much higher killing effect to the tumor (by enhance immune effect and vascular injury)
- But the side effect is also significantly increased
- Solution: more stereotactic angles, spread the dose to a larger volume

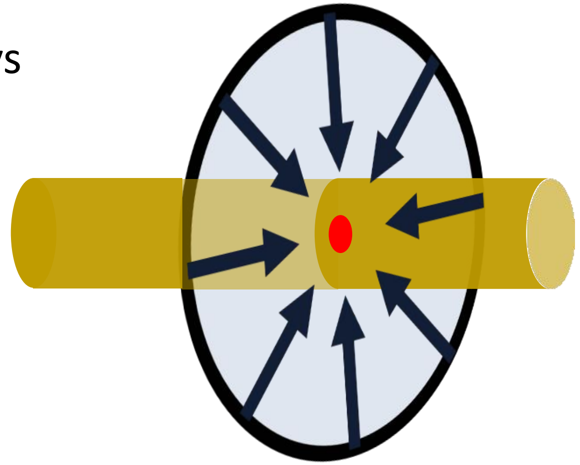
Conventional treatment：
2 Gy x 30 days

2 Gy	2 Gy	2 Gy
2 Gy	2 Gy	2 Gy
2 Gy	2 Gy	2 Gy
2 Gy	2 Gy	2 Gy

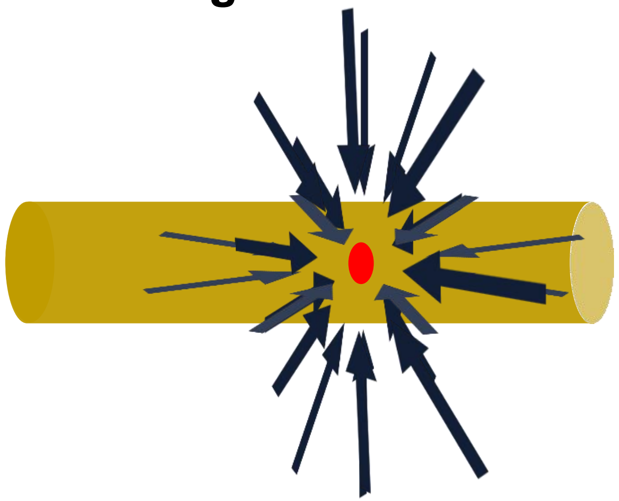
SBRT：
10 Gy x 4 days

10 Gy
10 Gy
10 Gy
10 Gy

Conventional treatment
The angles are in a same plane

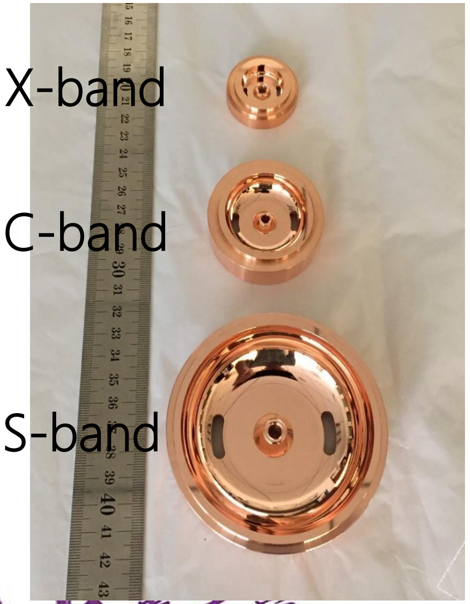


Stereotactic treatment:
More angles



Developments of medical LINACs: SBRT

- Implement of SBRT requires a more flexible gantry (robotic arm)
- It is necessary to choose a higher frequency band accelerator tube, which can significantly reduce weight
- Conventional LINAC (S-Band) → Lightweight version (X-Band)



Cyberknife Robotic RT

Developments of medical LINACs: FLASH-RT

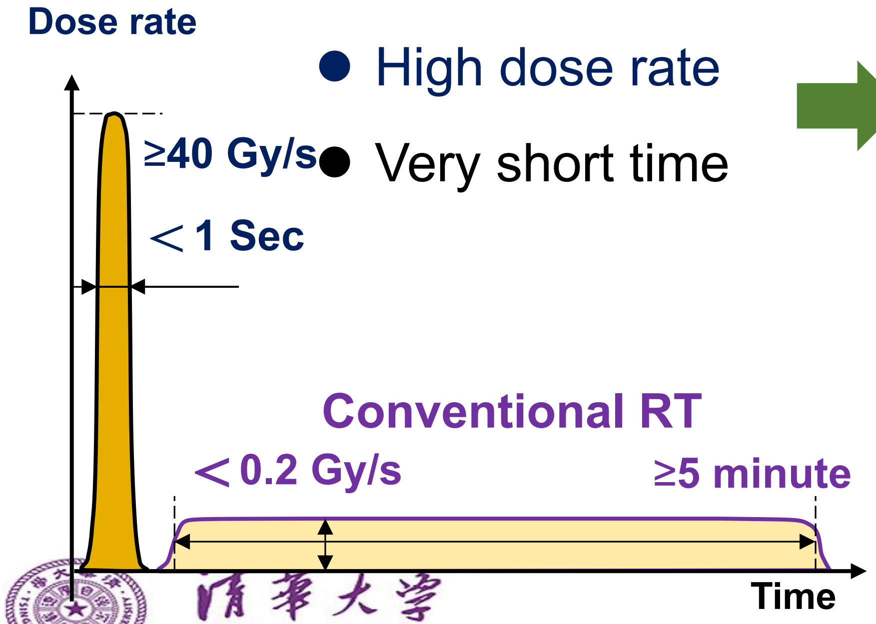
- Flash effect was first discovered in 2014 by Curie Institute, France

Ultra-high dose rate irradiation

(Physical concept)

FLASH Effect

(Biological Concepts)



- High dose rate
- Very short time

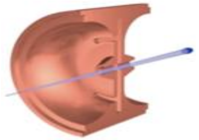
→

- Tumor control rate = Conv. RT
- Normal tissue damage < Conv. RT

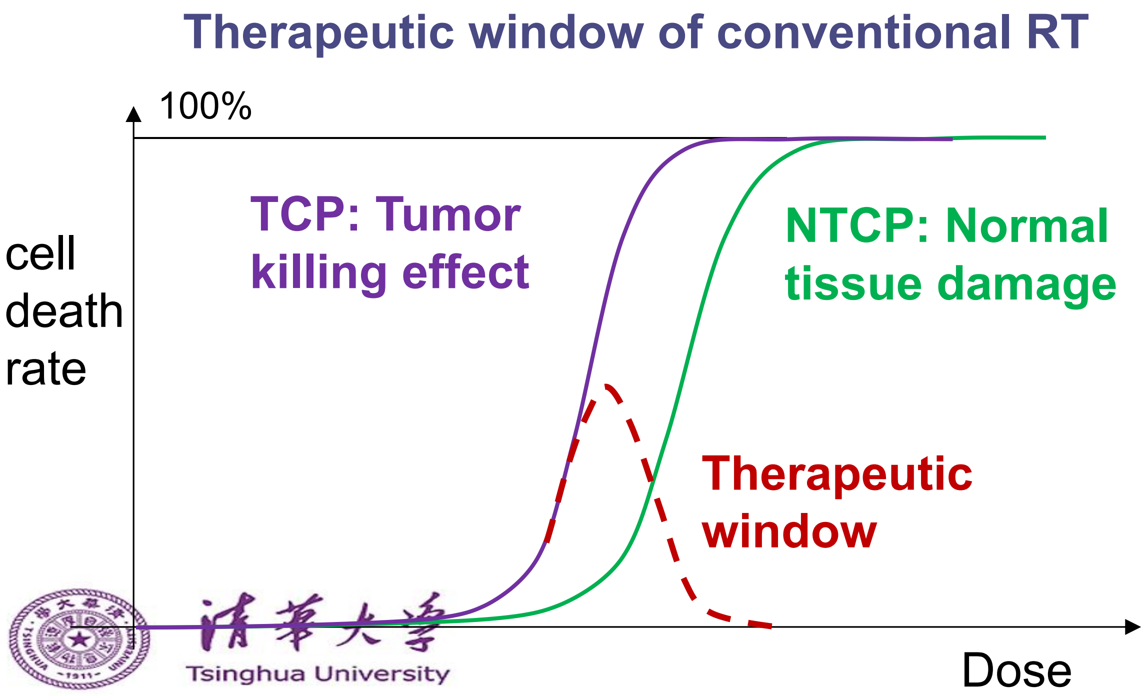
→

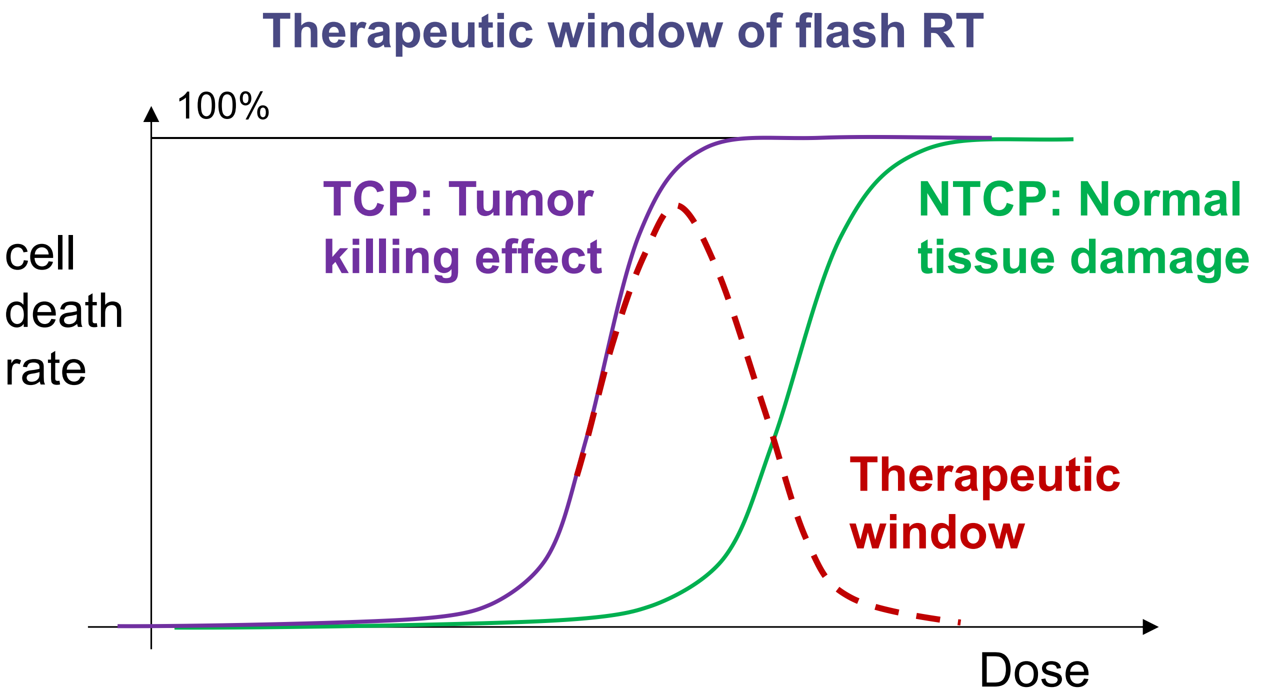
- Enhance therapeutic efficacy
- Widely applicable
- Freeze organ movement
- Less treatment time

Developments of medical LINACs: FLASH-RT



- Many experiments show that the FLASH effect may leads to a 20% to 40% increase in tolerated dose of normal tissue
- 20% tolerance increase is already very valuable: **palliative care** (50 Gy) could be upgraded to **curative treatment** (60 Gy)





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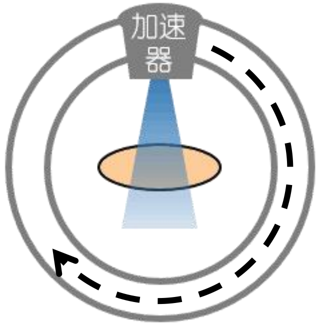
Developments of medical LINACs: FLASH-RT

- However, there is no machine could meet the standard of universal FLASH-RT
- There are few clinical trail, but only for superficial lesion or tumors in legs

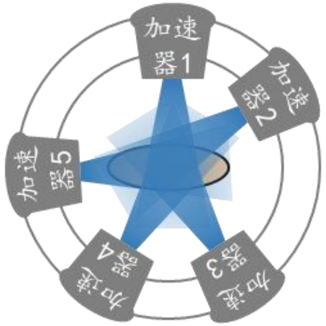
Lung?
Liver?
Breast?
Stomach?
Prostate?
Pancreas?

Universal X-ray FLASH-RT equipment

- Challenge①:
  - Current: 0.2 Gy/s
  - FLASH-RT: ≥40 Gy/s
  - Dose rate enhanced by 2~3 orders of magnitude
- Challenge ②:
  - Current: Rotating gantry



  - FLASH-RT: Need fast multiple-angle irradiation



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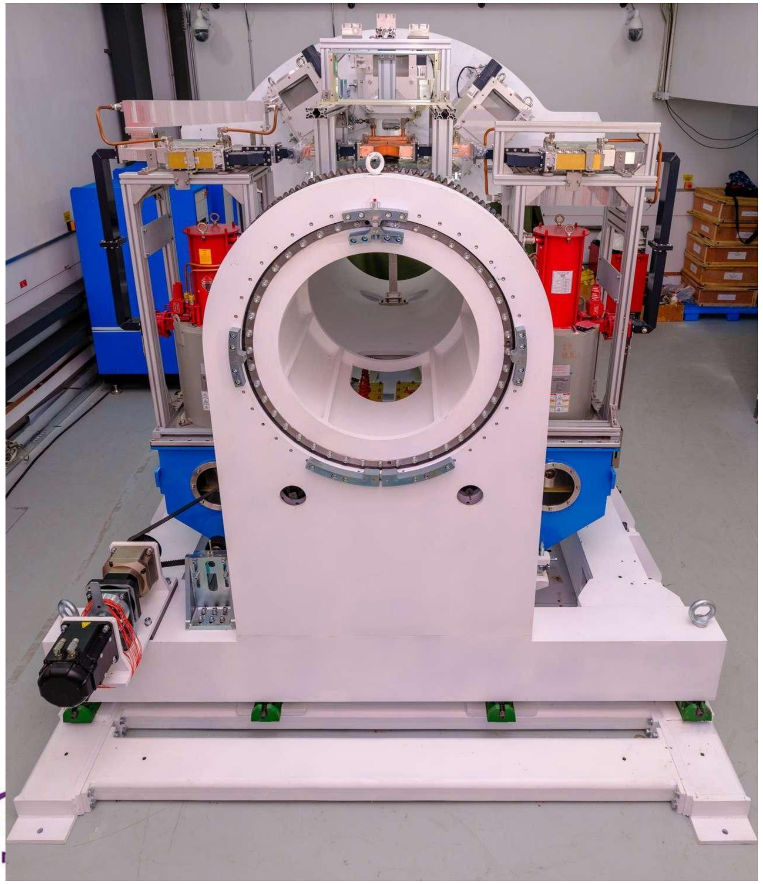
Developments of medical LINACs: FLASH-RT

- Tsinghua university made some breakthrough in this area

The world's first multiple-angle FLASH-RT prototype, dose rate = 50 Gy/s



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RADIOTHERAPY | RESEARCH UPDATE

Compact linac generates ultrahigh-dose-rate X-rays for clinical FLASH radiotherapy

27 Mar 2023 Tami Freeman

Tsinghua University team Hao Zha (second from right) and colleagues. (Courtesy: Haokun Wang)

Summary

- Low energy LINACs are the main force of accelerators, in terms of quantity
- Nowadays, LINACs use RF cavities to cascade the acceleration and get higher beam energy, but the a huge heat will be generated due to Ohmic loss. So the normal conducting LINACs are usually operated in pulse mode.
- Although thermal gun injects a continuous beam, LINACs could using bunching technology to capture many of them as well as get a good accelerating efficiency
- LINACs are widely used in:
  - In NDT for its good penetration in large objects, e.g. shipping containers, trains or large castings. Dual-energy helps to recognize the material in a higher accuracy
  - In Many radiation process: crosslink, waste water treatment, sterilization, activation
  - In radiation therapy: very important role in cancer treatment and have a bright future