Accelerator Applications

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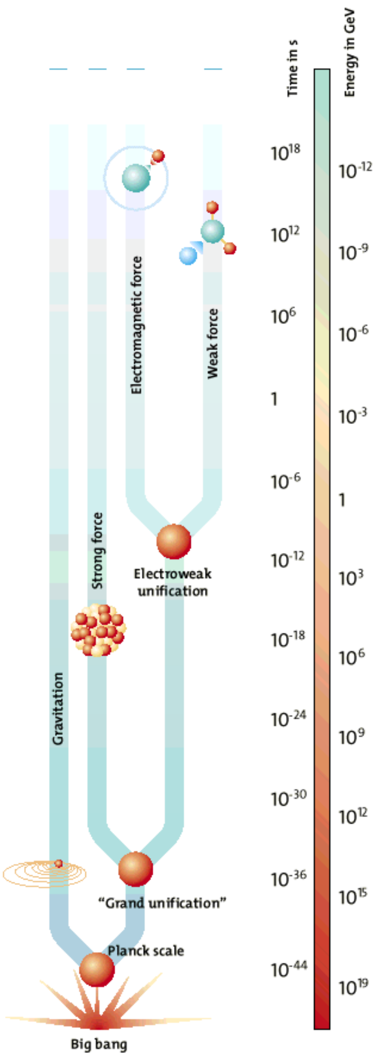
Accelerator
—The largest tool to explore the world



- While exploring the interior of matter accelerators are used as tools, either as energy transformers or as super microscopes.

In particle collisions the energy of the colliding particles can be transformed to mass.

The accelerator can be used as a super microscope to "see" quarks

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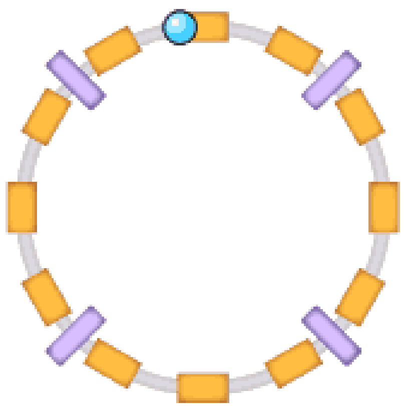
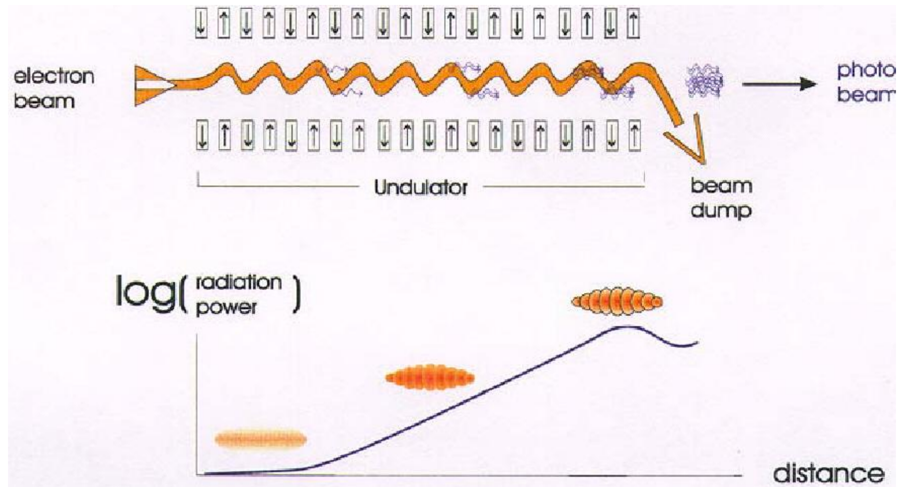
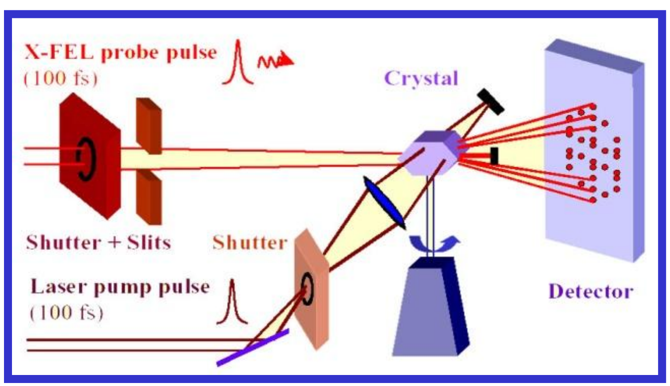
Light Sources based on Accelerators

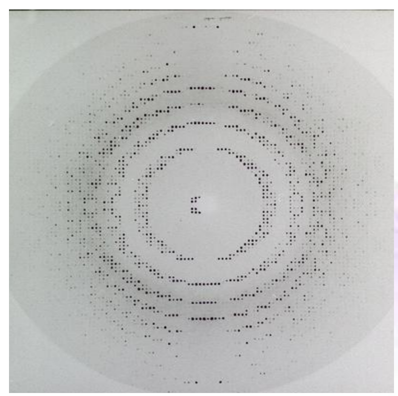


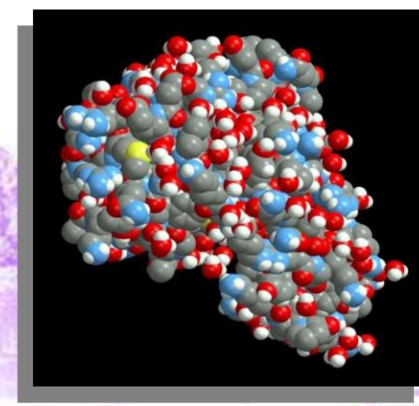
Synchrotron Radiation



Free Electron Laser

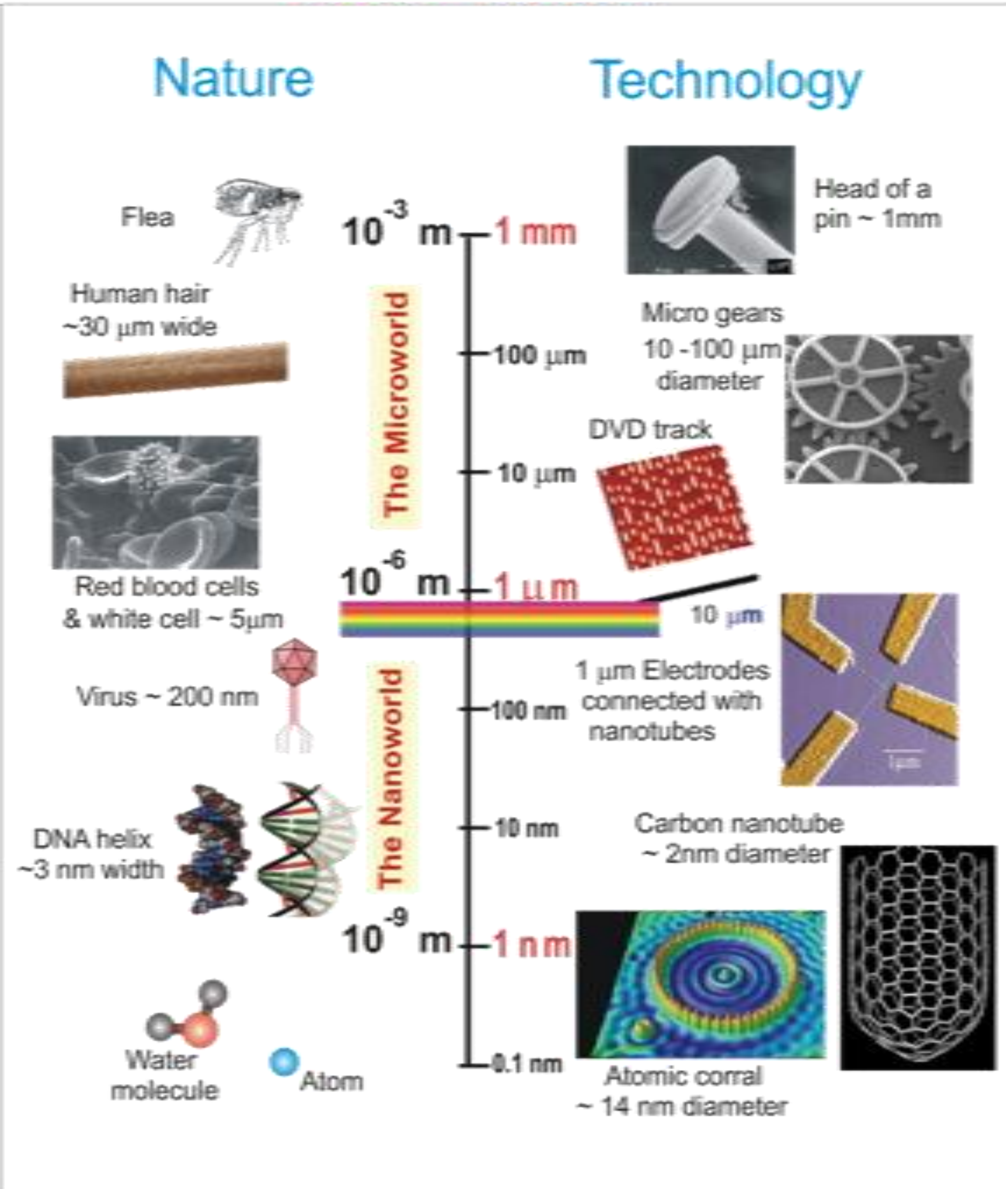




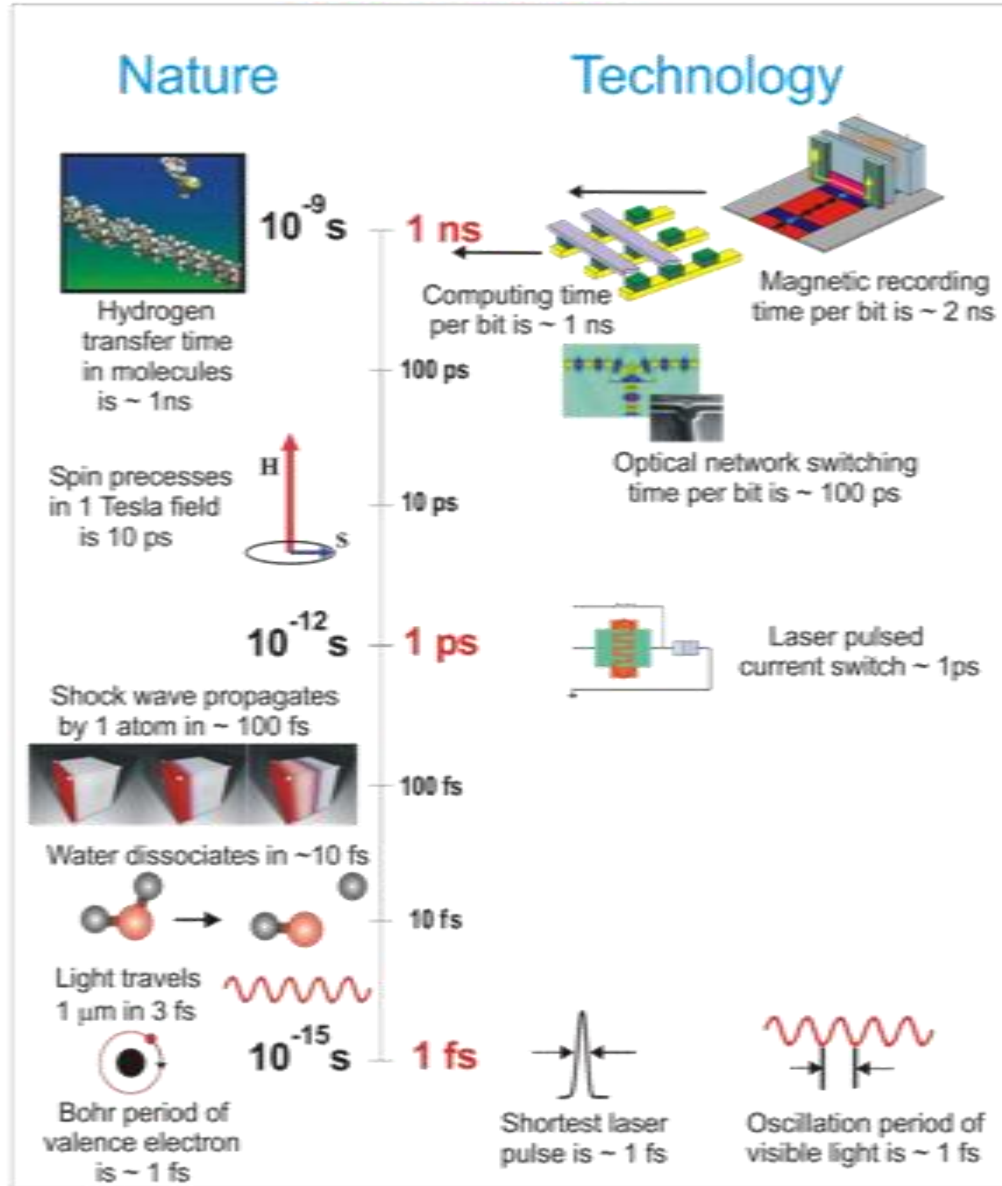


X-Rays have opened the Ultra-Small World
X-FELs open the Ultra-Small and Ultra-Fast Worlds

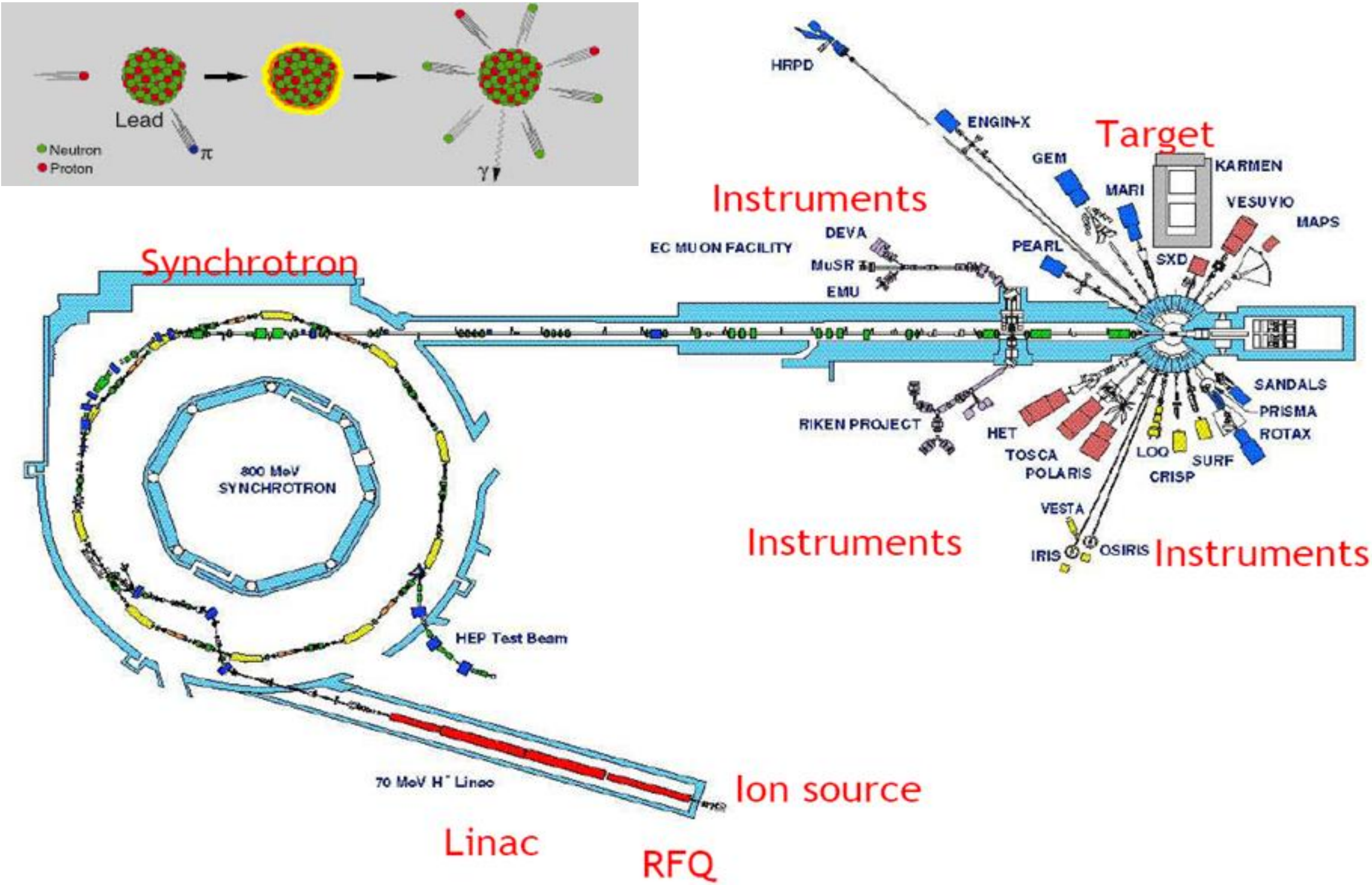
Ultra-Small



Ultra-Fast

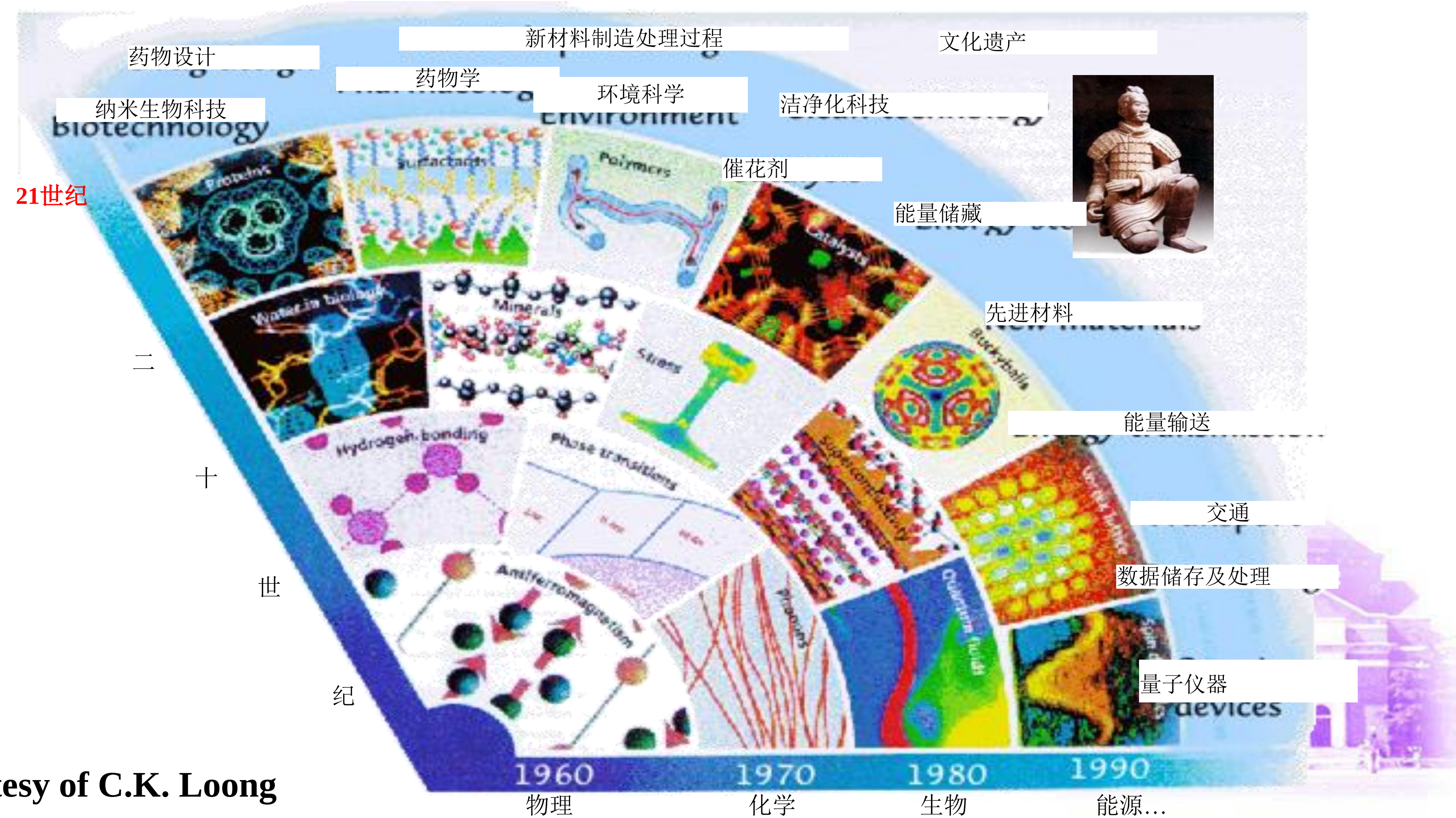


Neutron Sources based on Accelerators

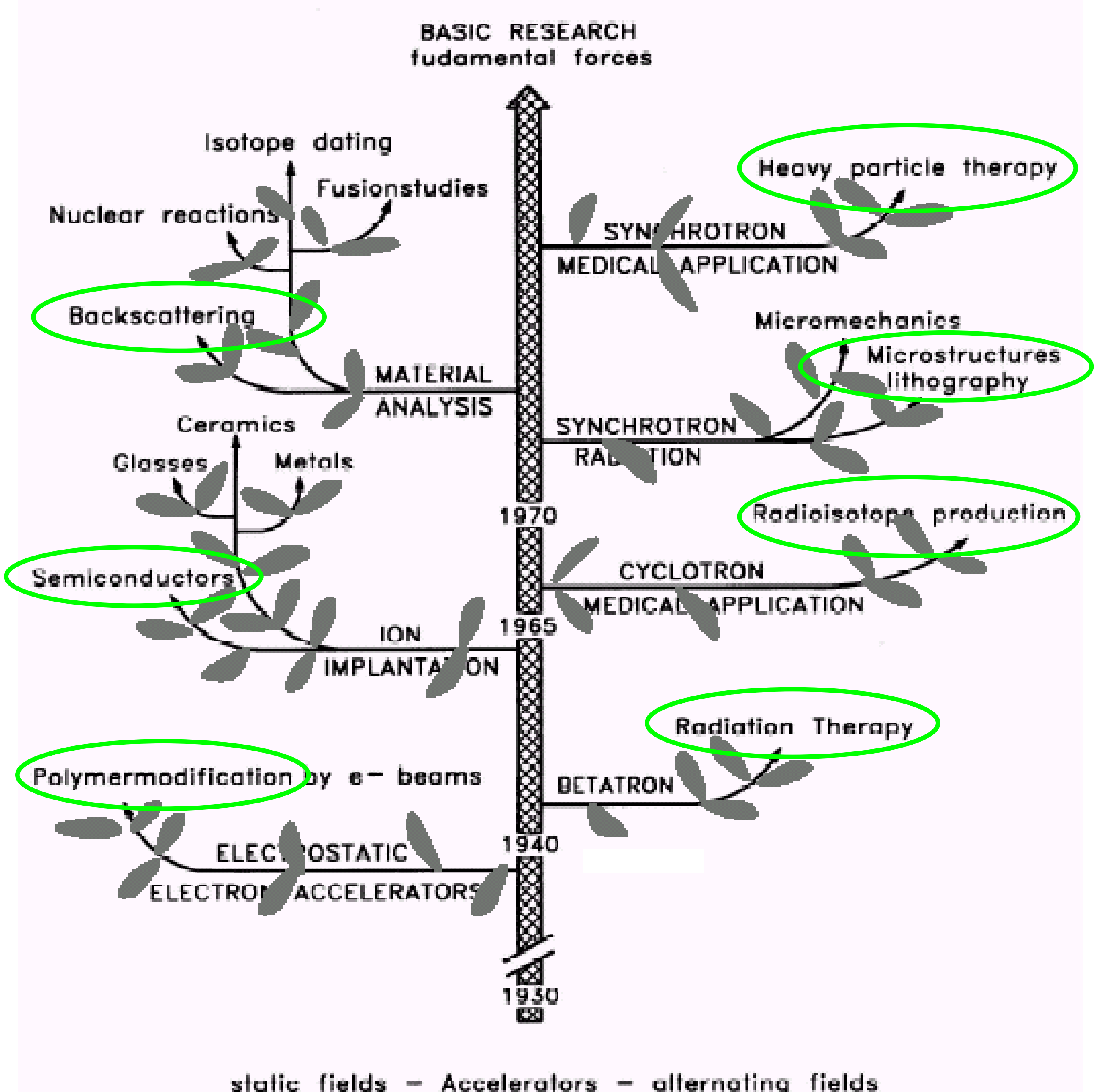


Applications of Neutron

中子散射技术的应用领域



Courtesy of C.K. Loong



K. Betghe plot, modified by U. Amaldi

We will only discuss the applications of low energy accelerators here.

Outline

- 1. Basic knowledge
- 2. Radiotherapy
- 3. Radiography
- 4. Irradiation

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1. Introduction

- Applications of low energy accelerators
  - Particles directly from accelerators：electron,proton,ions .
  - Secondary particles：x-ray or neutron.
- Radiotherapy
  - X-ray or electron beam: electron linac, microtron, betatron
  - Proton or heavy ion beam: cyclotron, synchrotron, linac, FFAG
- Imaging
  - X-ray imaging: x-ray tube, electron linac, betatron, microtron
  - Proton imaging: synchrotron or cyclotron
  - Neutron imaging: nuclear reactor, linac, synchrotron, cyclotron
  - PET (Positron Emission Tomography) : low energy cyclotron
- Irradiation
  - DC High Voltage Accelerator (>100kW, <5 MeV)
  - Electron Linac (<80kW, >5MeV)
  - Others: Rhodotron, LIU, Ridgetron, Fantron

Kinds of Rays

- Particle
  - Electron
  - Proton
  - Ion
  - Neutron
- Eletromagnetic Radiation
  - X-ray， γ-ray
  - Optic light
  - Microwave and RF radiation

γ-rays:

Photons emitted from a nucleus or in annihilation between a matter (electron) and an antimatter (positron).

$$E = h\upsilon \quad (\,from\ \ few - keV\ to\ \ few - MeV\,)$$

$$= \frac{hc}{\lambda} = \frac{12.4\,keV \bullet A}{\lambda}$$

$$h = 6.626\times10^{-34}\,J\ \ s \quad (1keV = 1.6\times10^{-16}\,J)$$

$$= 4.136\times10^{-18}\,keV\ s$$

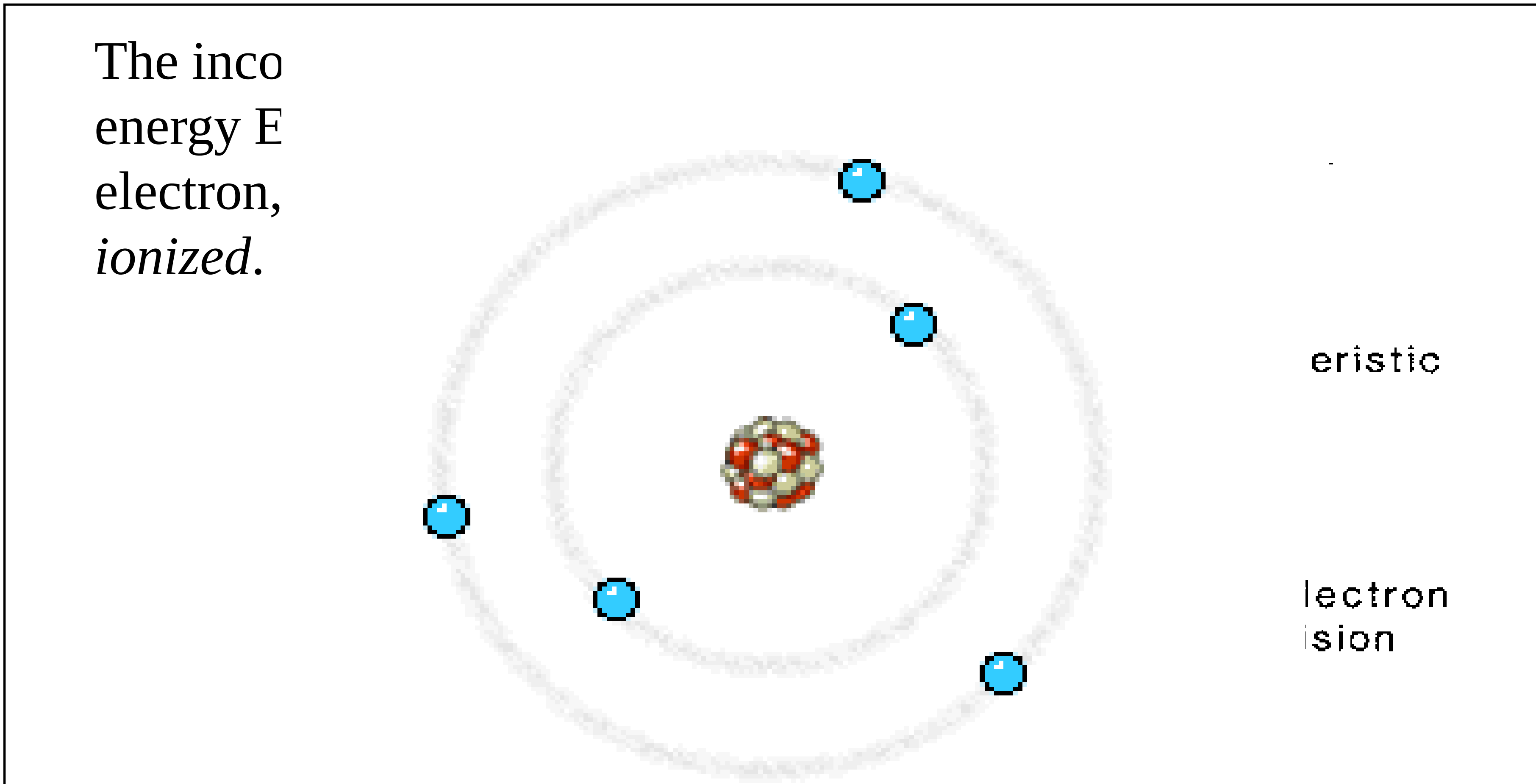
$$c = 3\times10^{-8}\,m$$

$$A\,(Angstrom) = 10^{-10}\,m$$

*Some following slides are from Prof. Xu's lectures given at Tsinghua U. Summer of 2002

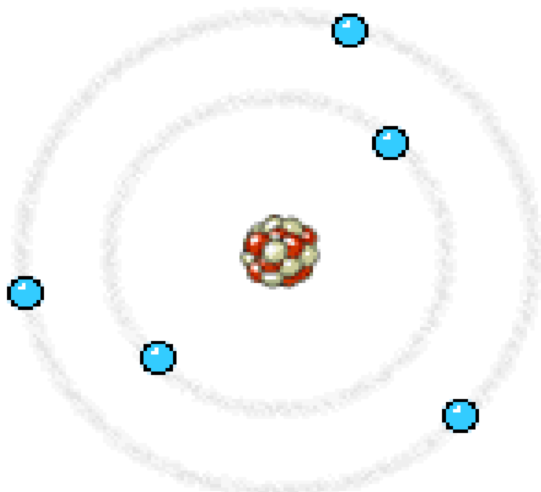
x-rays: (*characteristic or fluorescent x-rays*)

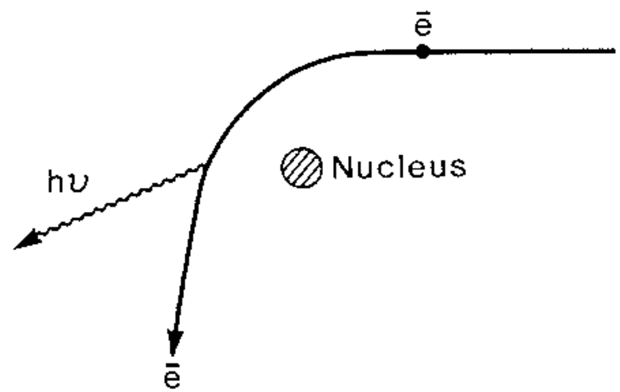
Photons emitted by electrons falling from a higher-energy level to a lower-energy level in an atom.



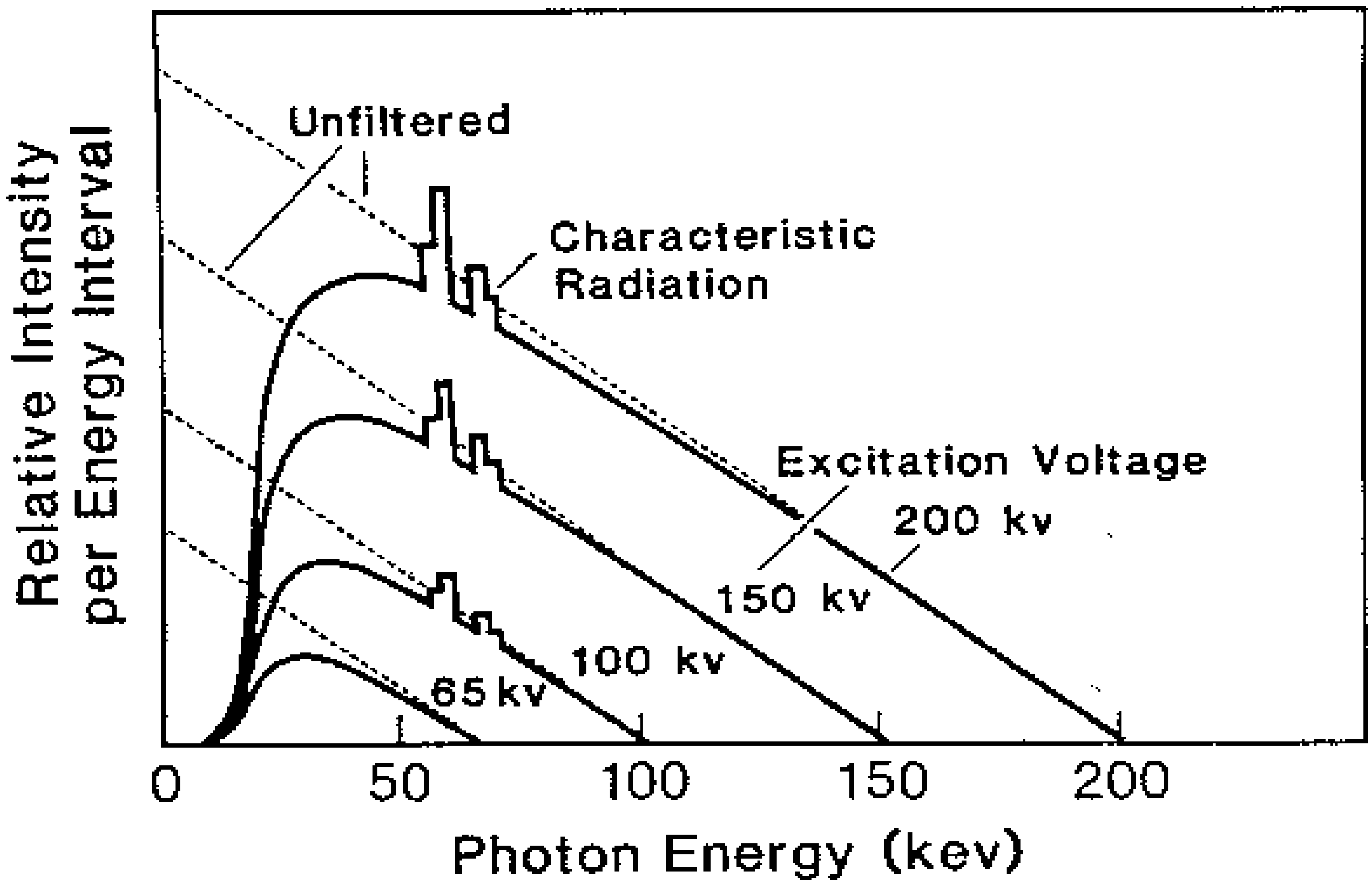
x-rays: (*continuous or bremsstrahlung x-rays*)

Photons emitted by electrons deflected and slowing down in a Coulomb force field near a nucleus.





A typical x-ray energy spectrum



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The Interaction of Photons with Matter

In radiological physics, the range of energies of interest is from 1 keV to ~50 MeV. Within this range, the following types of interaction with matter are relevant.

Type of interaction	Photoelectric effect (τ)	Scattering		Pair production (κ)
		Coherent (σ_{coh})	Compton (σ_{inc})	
Outgoing particles	1 electron, characteristic x-rays or auger electrons	1 photon	1 electron, 1 photon (reduced energy)	1 positron, 1 electron
Remarks	Dominant event for diagnostic applications	No energy loss, small angle scattering	Dominant event for therapeutic applications	Only important for high-Z materials

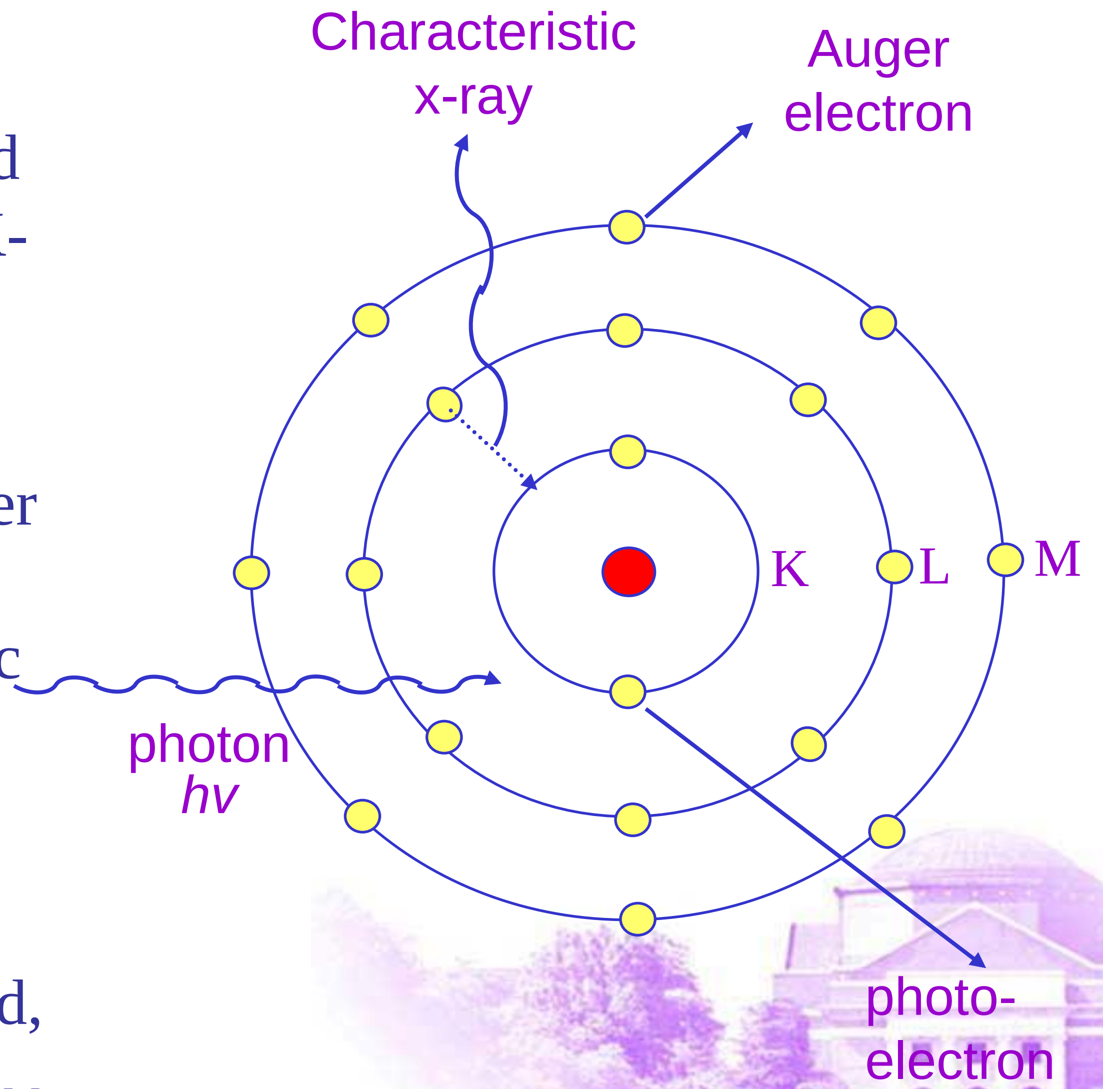
$$\mu = \tau + \sigma_{coh} + \sigma_{inc} + \kappa$$

Photoelectric Effect

The incident photon is absorbed by the atom, an electron (e.g. K-shell) is ejected with a kinetic energy equal to $h\nu - E_K$.

The vacancy is filled by an outer shell electron (e.g. L-shell), thereby emitting a characteristic x-ray with energy E_K-E_L.

Alternatively, instead of the characteristic x-ray, an Auger electron (e.g. M-shell) is ejected, with kinetic energy of E_K-E_L -E_M.



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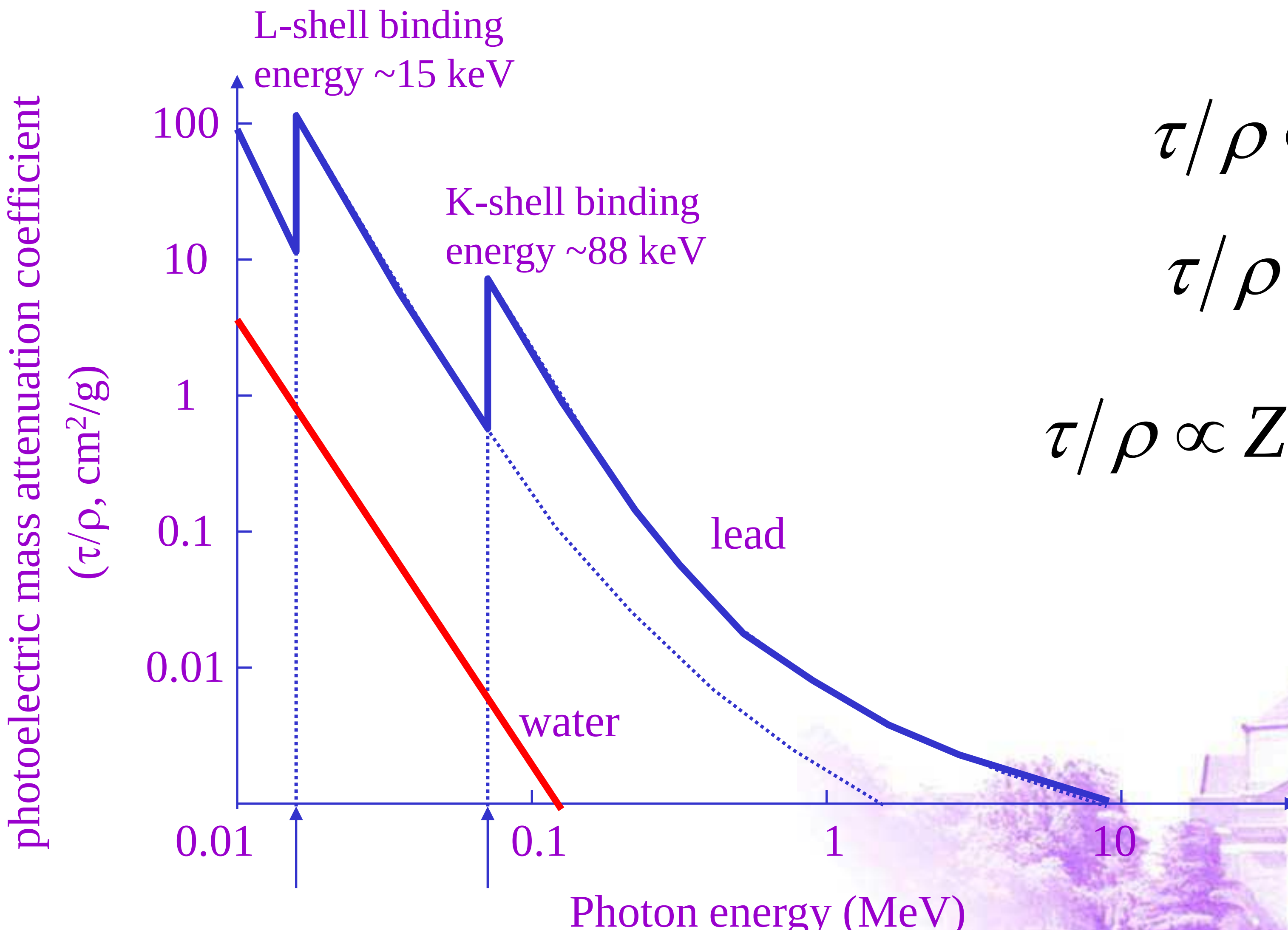
Photoelectric Effect (cont'd)

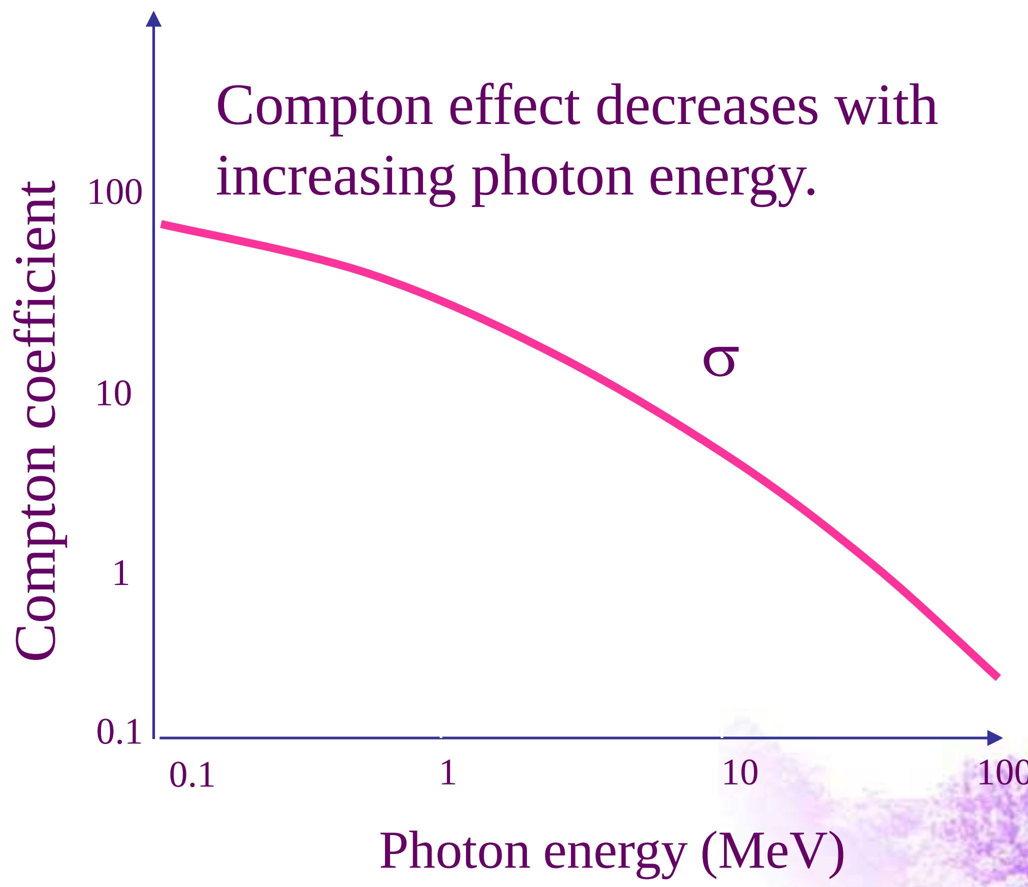


$$\tau/\rho \propto 1/E^3$$

$$\tau/\rho \propto Z^{3\sim4}$$

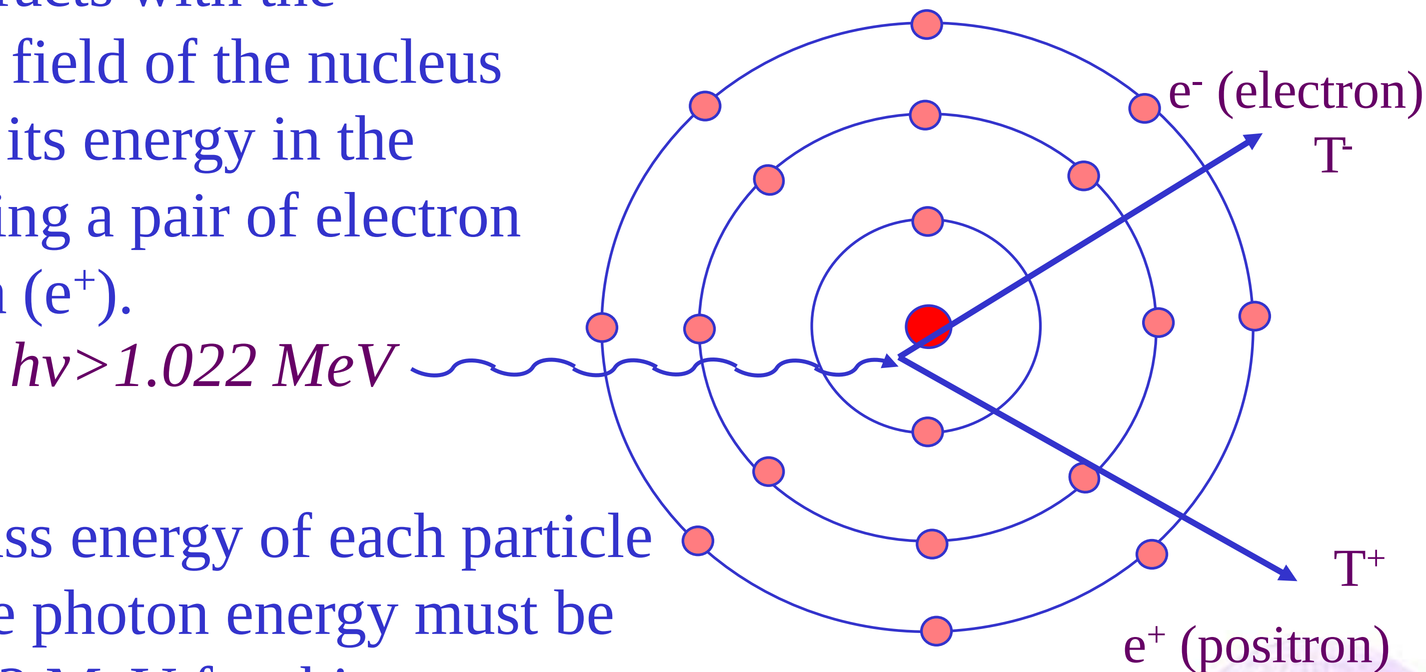
$$\tau/\rho \propto Z^{3\sim4}/E^3$$

Compton Effect (Dependence on Energy)



Pair Production in the Nuclear Field

The photon interacts with the electromagnetic field of the nucleus and gives up all its energy in the process of creating a pair of electron (e^-) and positron (e^+).



Since the rest mass energy of each particle is 0.511 MeV, the photon energy must be greater than 1.022 MeV for this interaction to happen. The total kinetic energy carried by the pair is (*hv* – 1.022) MeV.

Pair Production – cross section

The atomic attenuation coefficient (cm^2/atom):

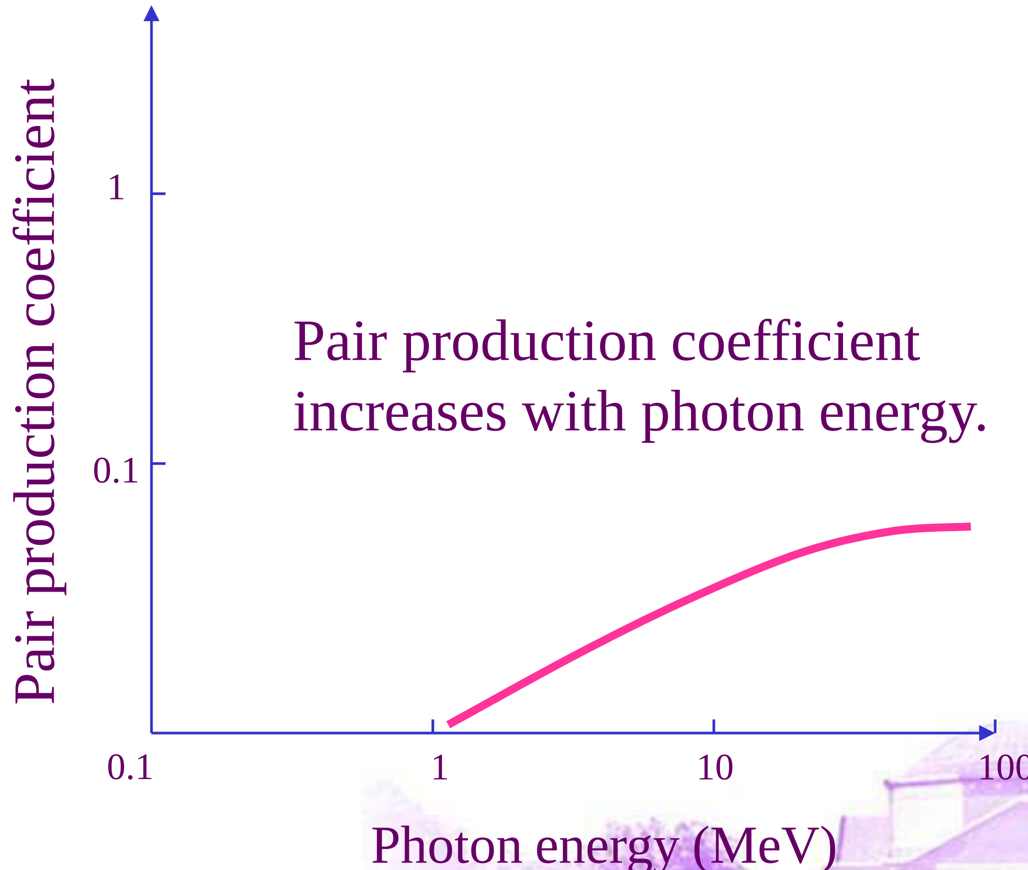
$${}_a\kappa \propto Z^2$$

The mass attenuation coefficient (cm^2/g):

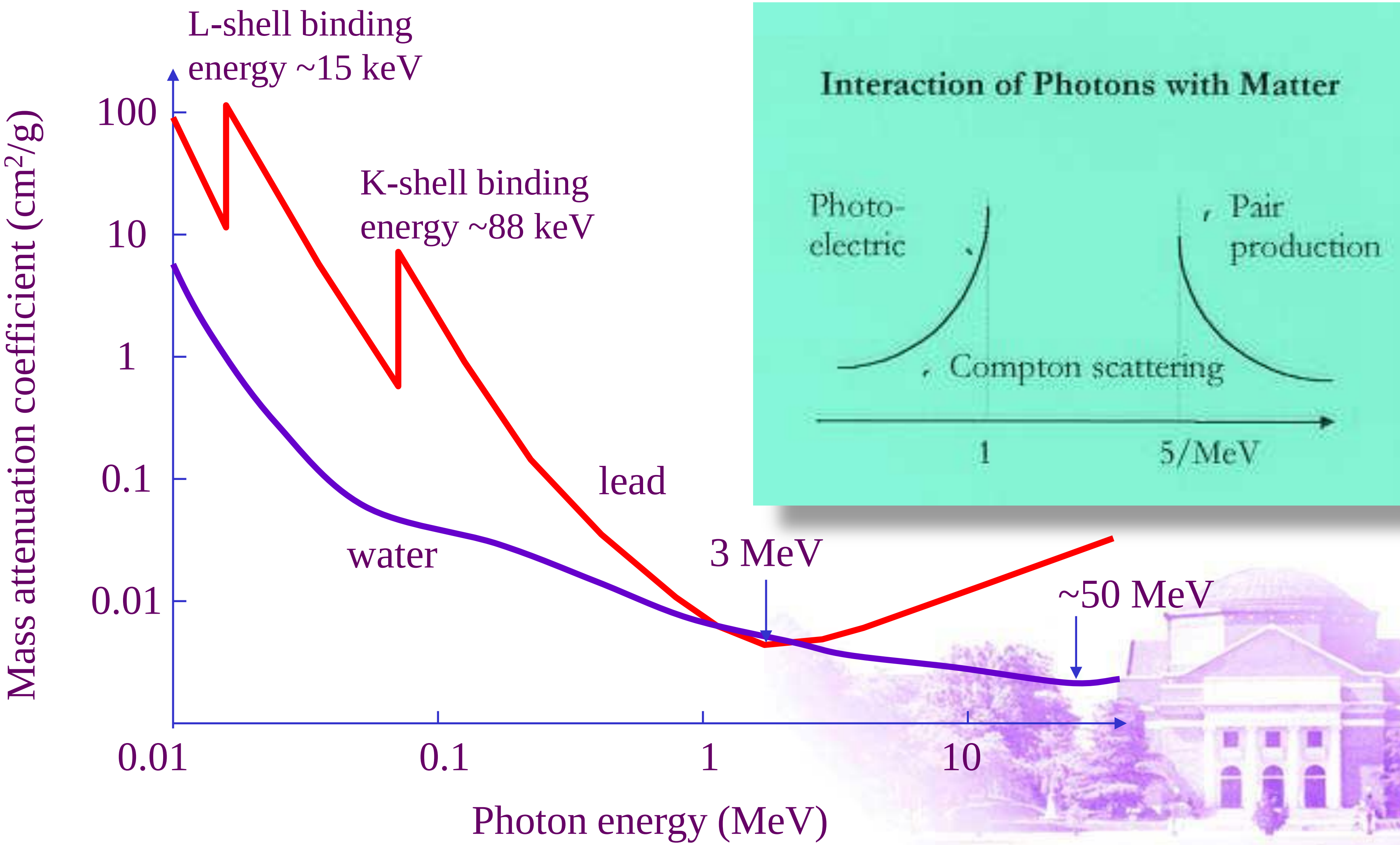
$$\kappa/\rho = {}_a\kappa N_A/A$$

$$\propto Z^2/A$$

$$\propto Z$$

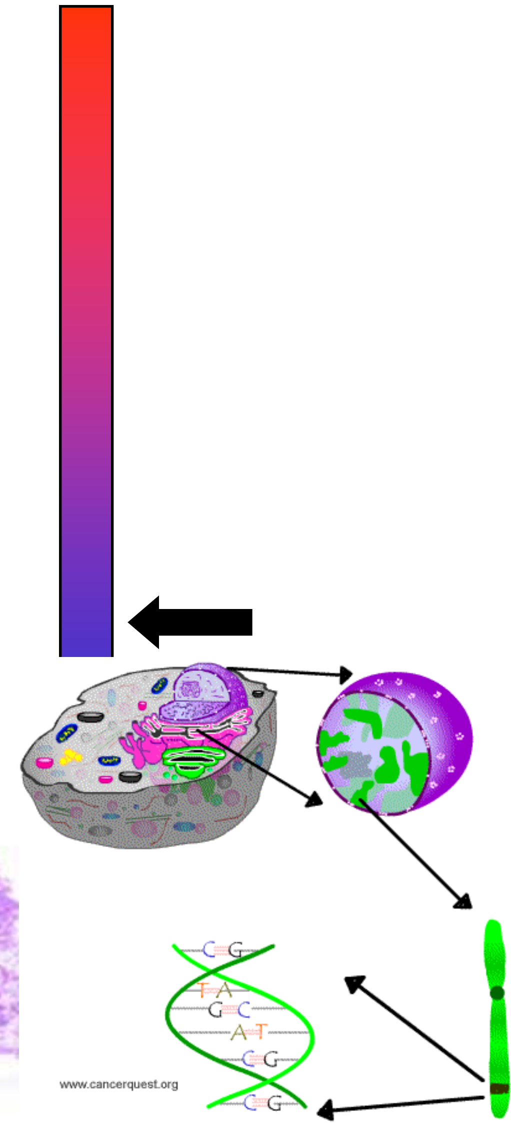


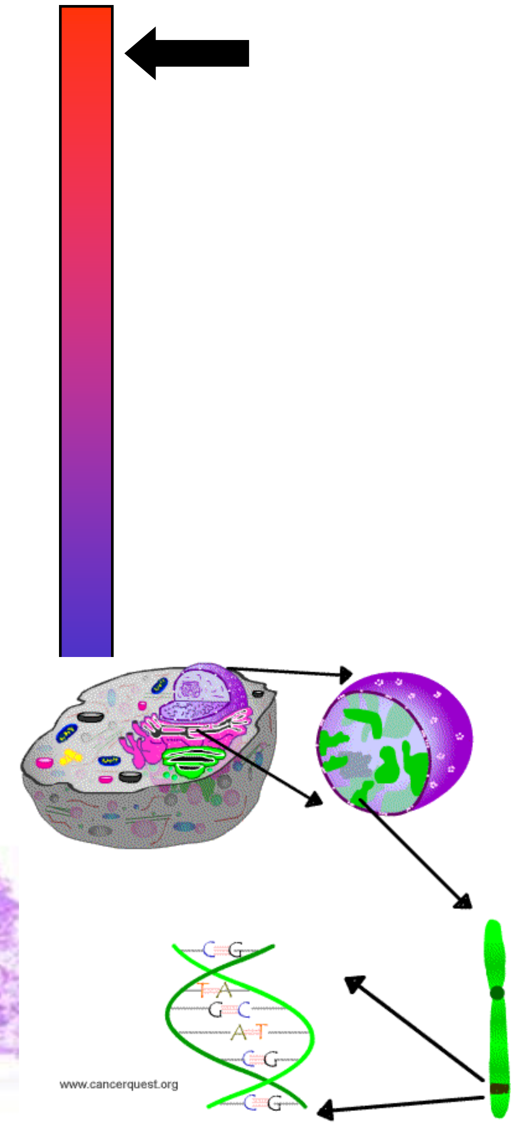
Relative Importance of Various Types of Interactions



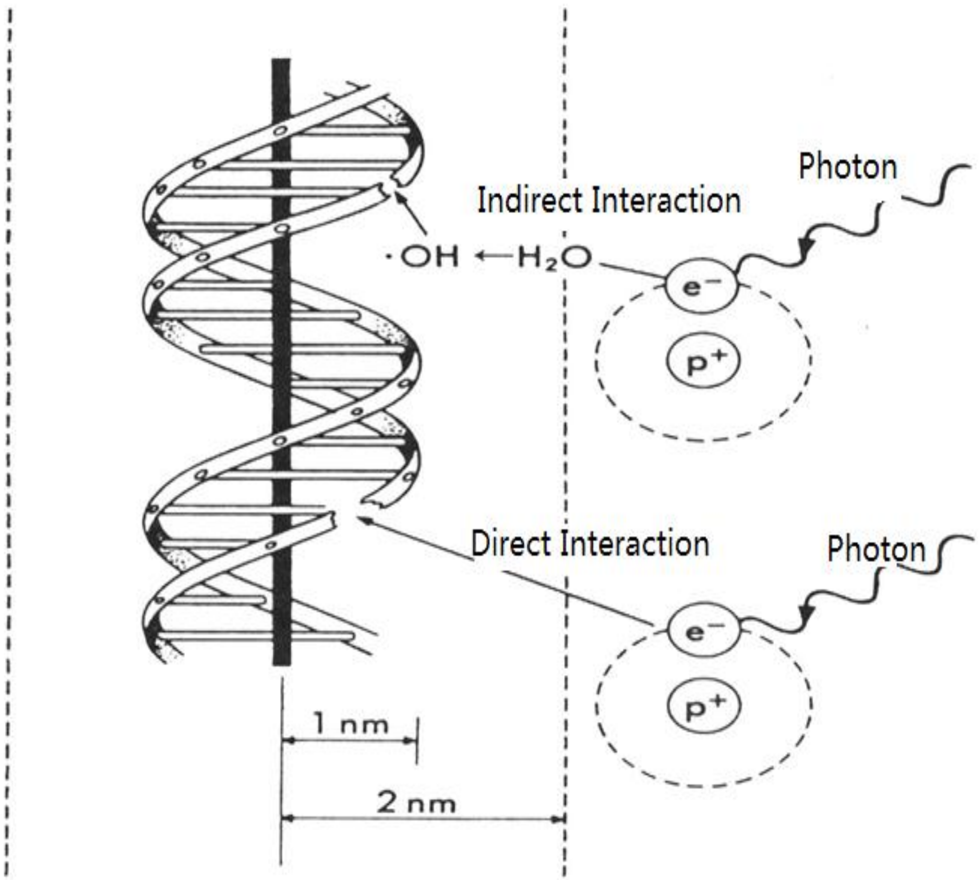
2.1 Introduction to Radiotherapy

- Radiotherapy, is the treatment of cancer and other diseases with ionizing radiation. Ionizing radiation deposits energy that injures or destroys cells in the area being treated (the "target tissue") by damaging their genetic material, making it impossible for these cells to continue to grow. Although radiation damages both cancer cells and normal cells, the latter are able to repair themselves and function properly.
  - External radiotherapy, where radiotherapy is given from outside the body using X-rays, electrons or, in rare cases, other particles such as protons.
  - Internal radiotherapy, where radiotherapy is given from within the body, either by drinking a liquid that is absorbed by the cancerous cells or by putting radioactive material into or close to the tumour.


www.cancerquest.org

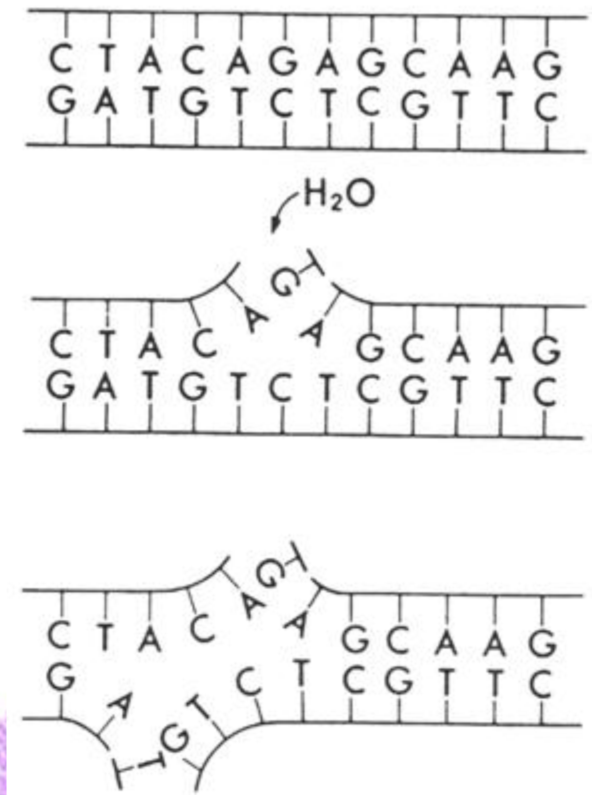

www.cancerquest.org

Ionizing Radiation Damage to DNA



Single strand breaks

Double strand breaks



Radiotherapy

- X-ray or γ-ray
- Electron
- Proton
- Heavy ion (carbon)
- Neutron (BNCT)

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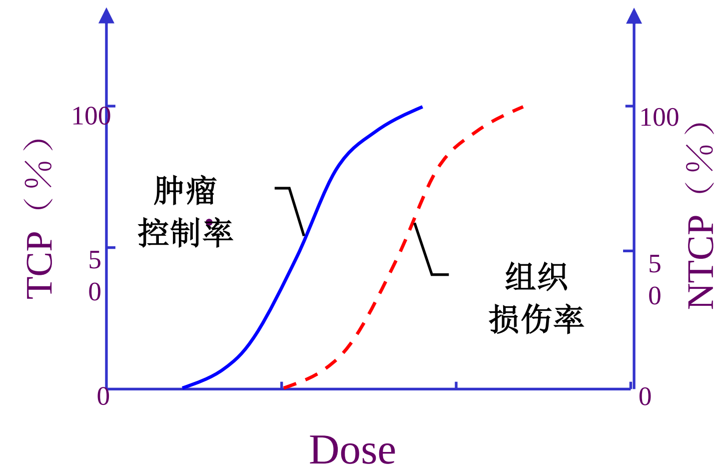
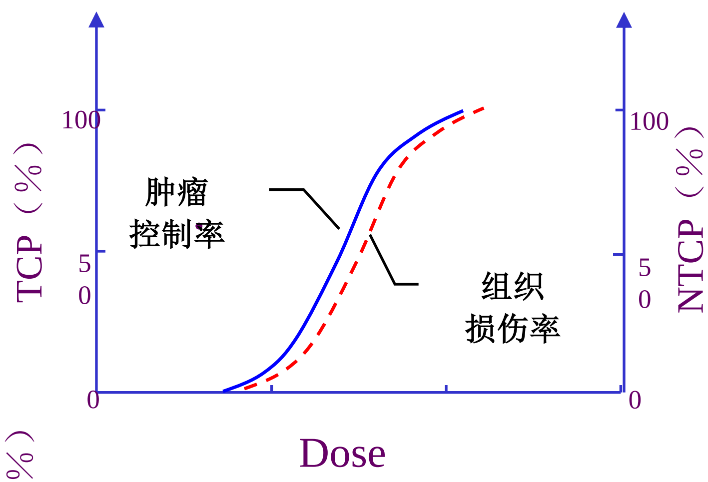
细胞的放射敏感性

- **细胞核的放射敏感性比细胞质高100倍以上。**
- **提高肿瘤治疗的局部控制率TCP（Tumor Control Probability），尽量减小并发症发生率NTCP（Normal Tissue Complication Probability）**
- **“细胞的放射敏感性高低和细胞增长速率成正比而和细胞的分化程度成反比”，在大多数情况下正确。（Bergonie, Tribondeau, 1906年）**
- **大多数恶性肿瘤组织和同类正常组织比较，对电离辐射更为敏感。**

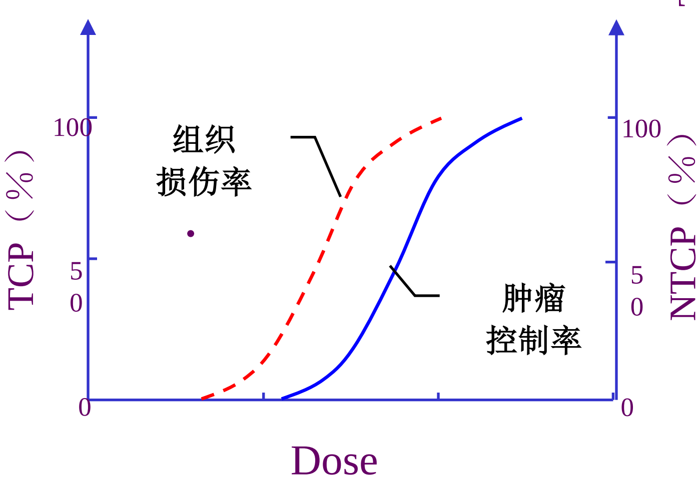
肿瘤对放疗敏感



肿瘤对放疗不敏感

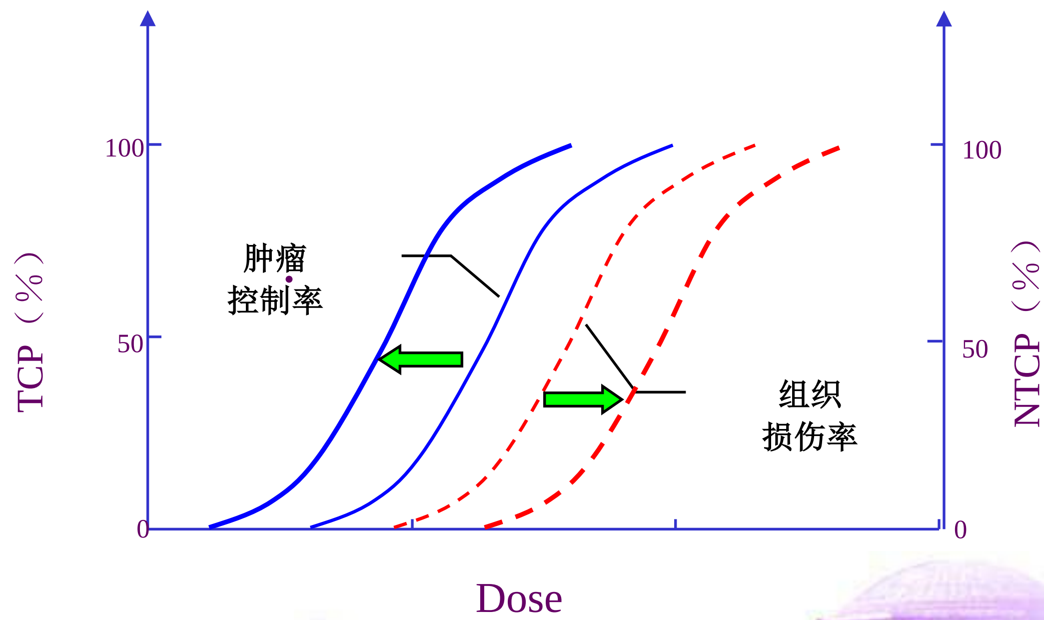


肿瘤对放疗抗拒



肿瘤放疗增敏及正常组织保护

- 增敏
  - 高压氧
  - 加温
  - 增敏药物
- 保护
  - 低氧放疗
- 超分次放疗



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传能线密度
（Linear energy transfer LET）

- 射线在组织中，在单位长度上（ μ ）由于碰撞造成的平均能量损失（keV）

$$LET = \frac{dE}{dl} \quad (KeV/\mu m)$$

◆ The radiation with a LET value less than 10 $KeV/\mu m$ is called low LET radiation.

$$LET_{200KV\ X-rays} = 3\,KeV/\mu m$$

$$LET_{1\sim16{,}000\,MeV,\ helium\ \ to\ \ Uranium} = 10\ to\ 10{,}000\,KeV/\mu m$$

相对生物效应（RBE）

- 描写不同性质射线，对同一种细胞作用产生相同的生物效应所需的剂量比值。

$$RBE = \frac{250kVX\text{线剂量}}{\text{该射线所需剂量}}$$

氧增强比（OER）

- 表示某种射线的放射敏感性对细胞含氧状态的依赖关系的物理量。定义为：乏氧细胞和有氧细胞产生同样生物效应所需的剂量之比。

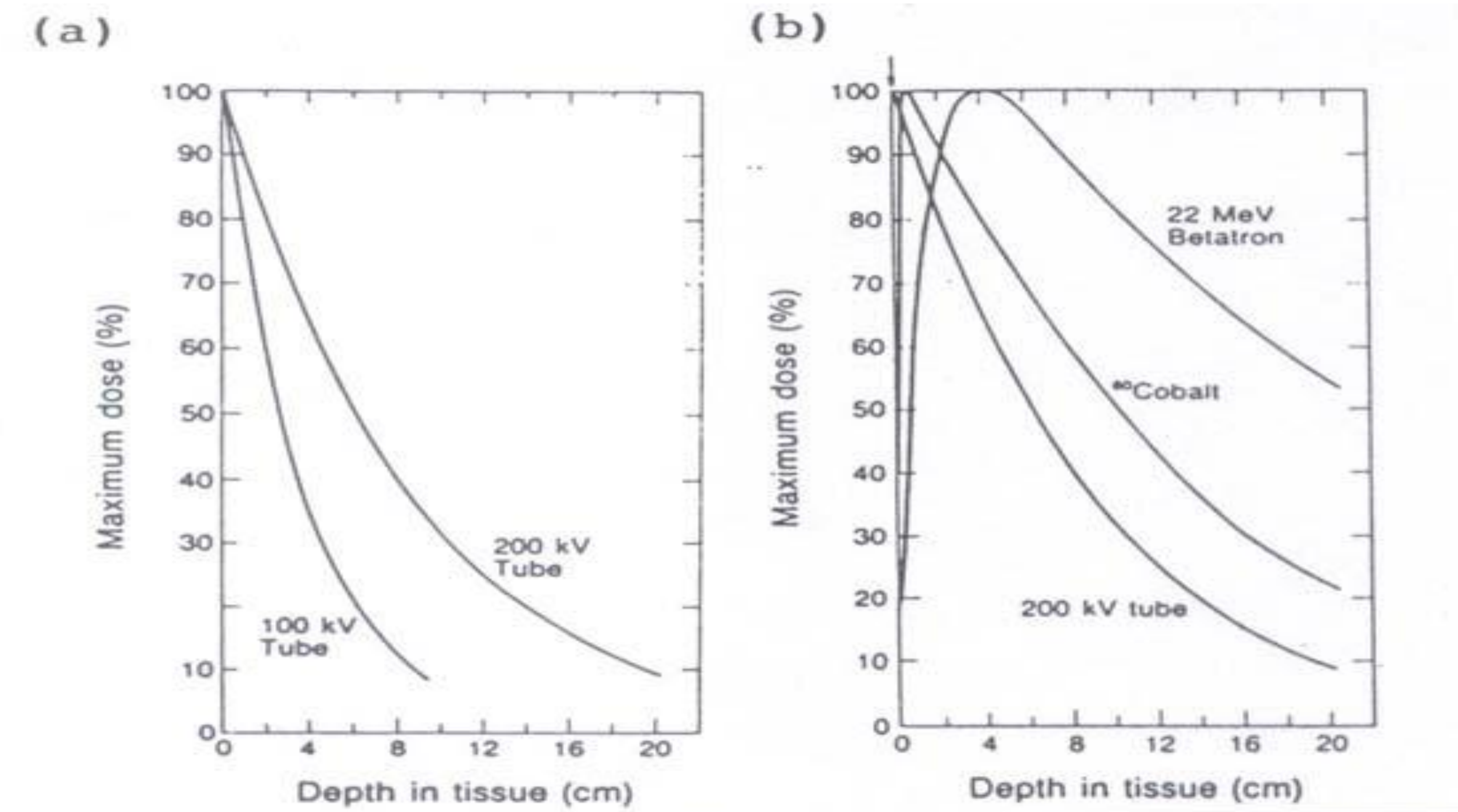
$$OER = \frac{D_{乏氧}}{D_{含氧}}$$

•低LET射线 OER=2.5～3.0

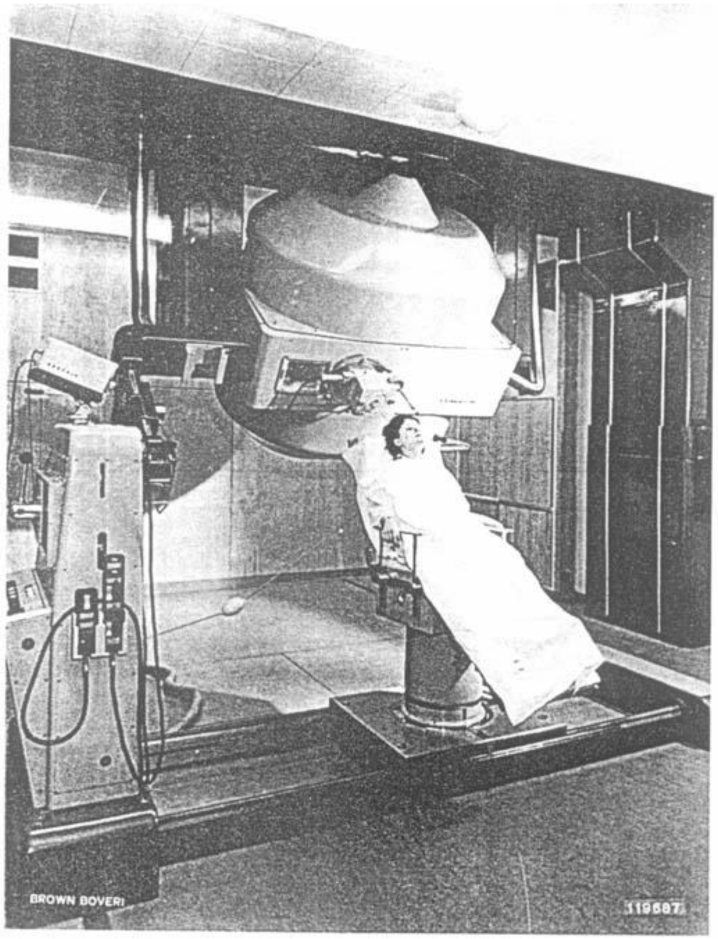
•高LET射线 OER=1.0～1.8

2.2 Radiotherapy with x/γ ray and electron beam

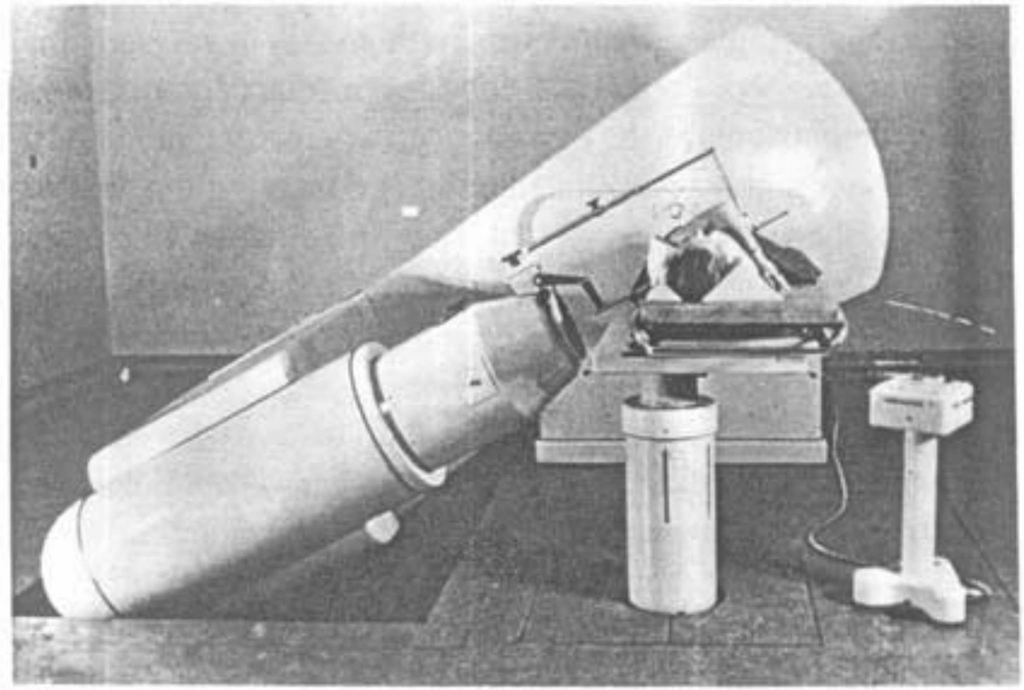
- ❑ The Era of X-ray Tube Machines (150~400 KeV)
- ❑ The Era of ^{60}Co. (1.17 MeV and 1.33 MeV) (in 1950s)
- ❑ The Era of Betatrons (in the 1950s and 1960s)



Early time of x-ray and electron therapy

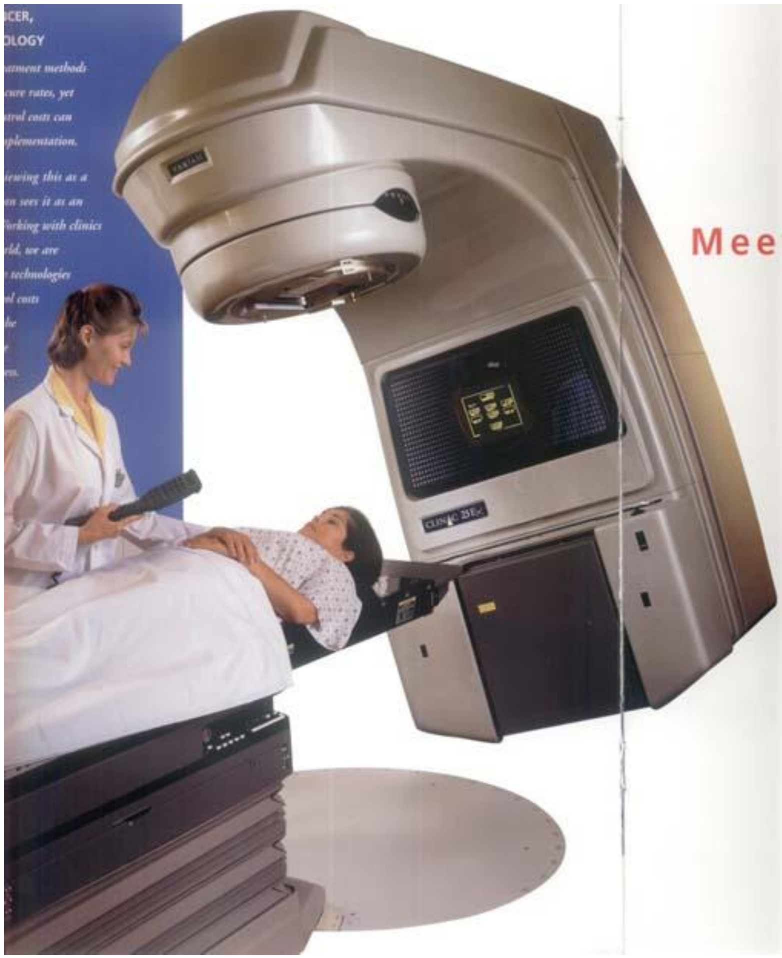


View of a medical betatron mfd by Brown Bover (Switzerland)



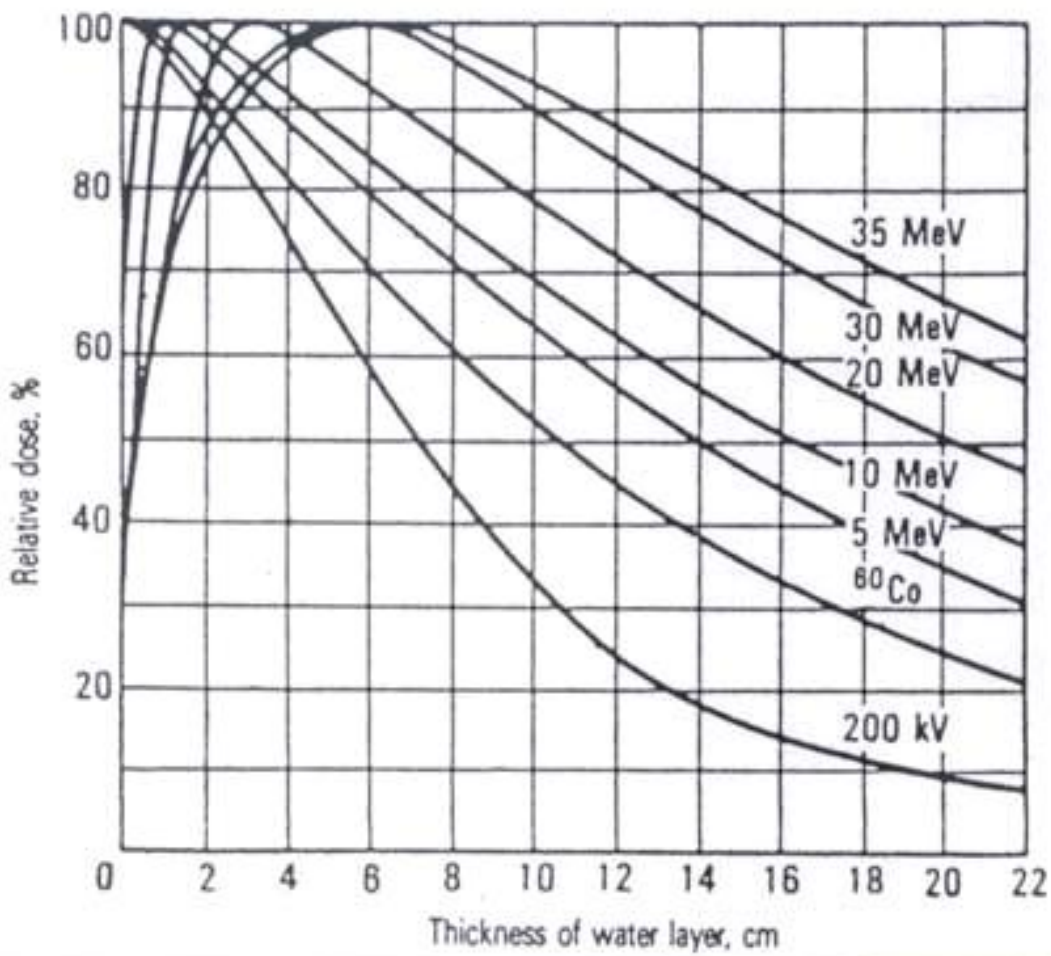
- ☺ The first linear electron accelerator was installed at Hammersmith Hospital, England, in 1952, (8MeV)
- ☺ First orientable linear accelerator—the orthotron (1954, 4MeV)

☺Varian Associates clinac machine



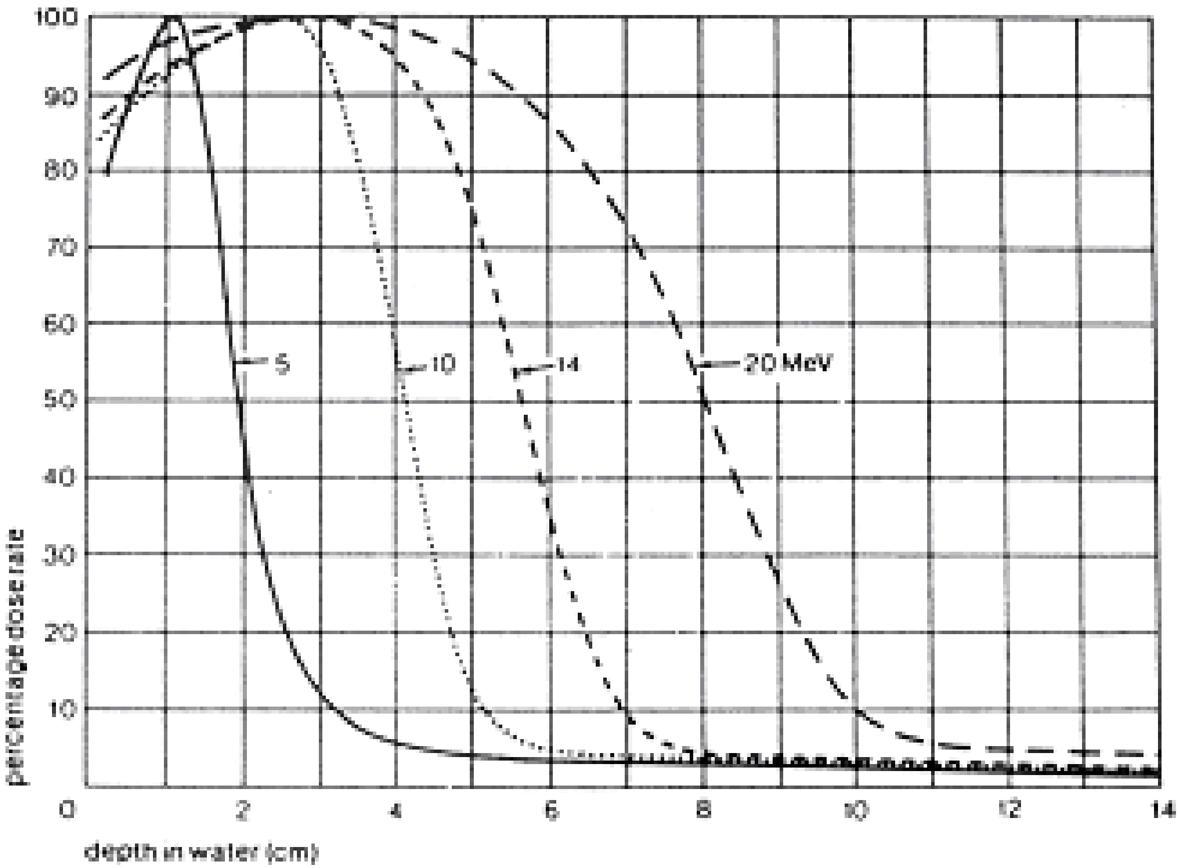
XHA600C of SHINVA

X-ray Radiotherapy



Depth-dose as a function of thickness of water layer for X-rays with energies of 5, 10, 20, 30 and 35 MeV

Electron Radiotherapy



Depth-dose distribution in a water phantom for electron beams

RF Electron Linear Accelerators for Conventional Therapy

- In most conventional therapies the RF linear accelerator (Linac) serves as the radiation source.

- Clinical Requirements

1. Radiation Energy Range
   - ☺ Low energy 4~6MeV
   - ☺ Middle energy 8~14MeV
   - ☺ High energy 15~25MeV
2. Dose Rate
   - ☺X-rays: 100~600 cGy/min at 1 m
   - ☺Electron beams: 100~1000 cGy/min at 1 m

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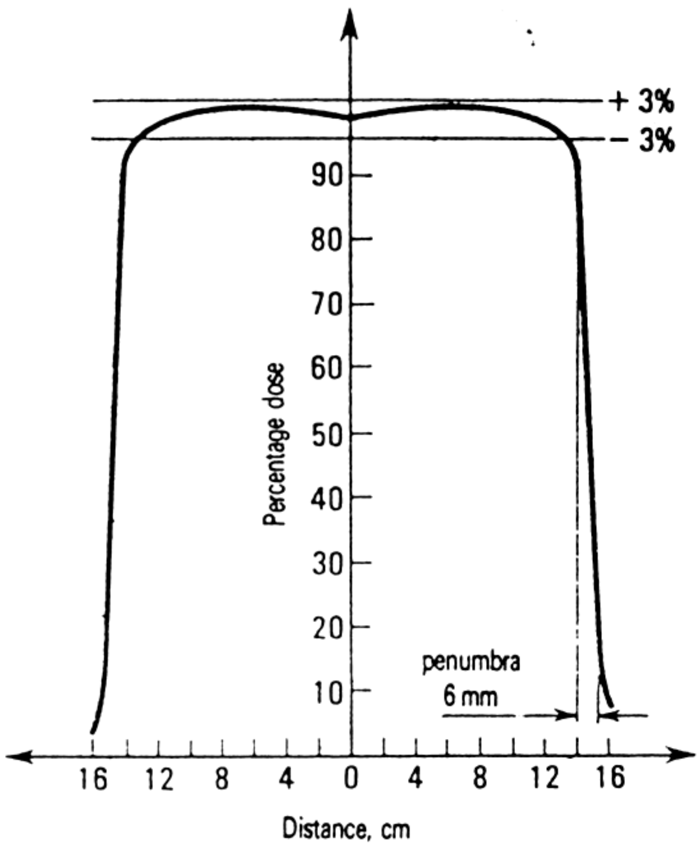


Dose distribution flatness

3. Precision of the Delivered Dose

   ±2%

4. Radiation Field Size

   ☺X-rays: 2×2cm²~40×40cm²

   ☺Electron beams:

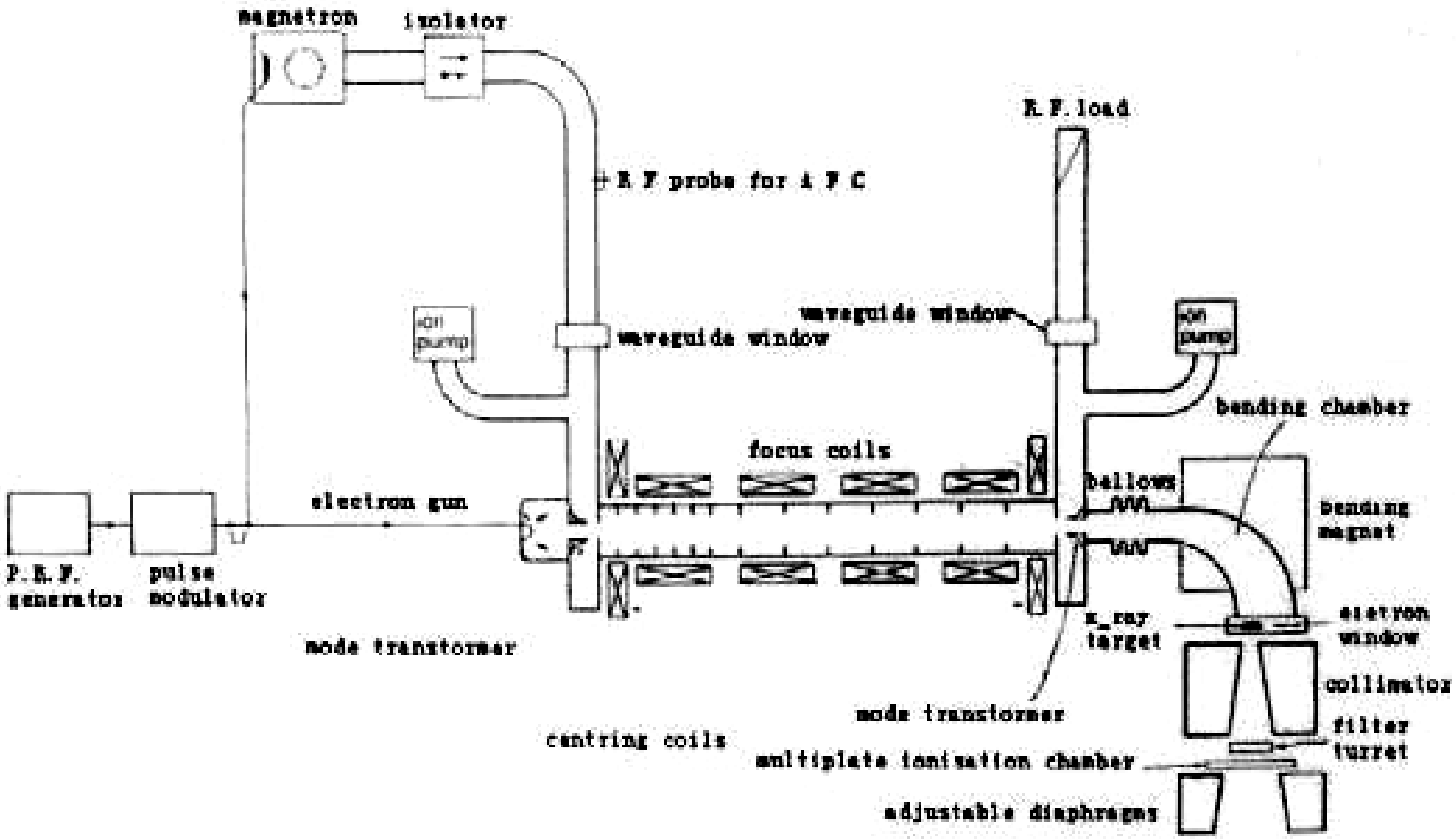
   2×2cm²~25×25cm²

5. Dose Distribution Flatness:

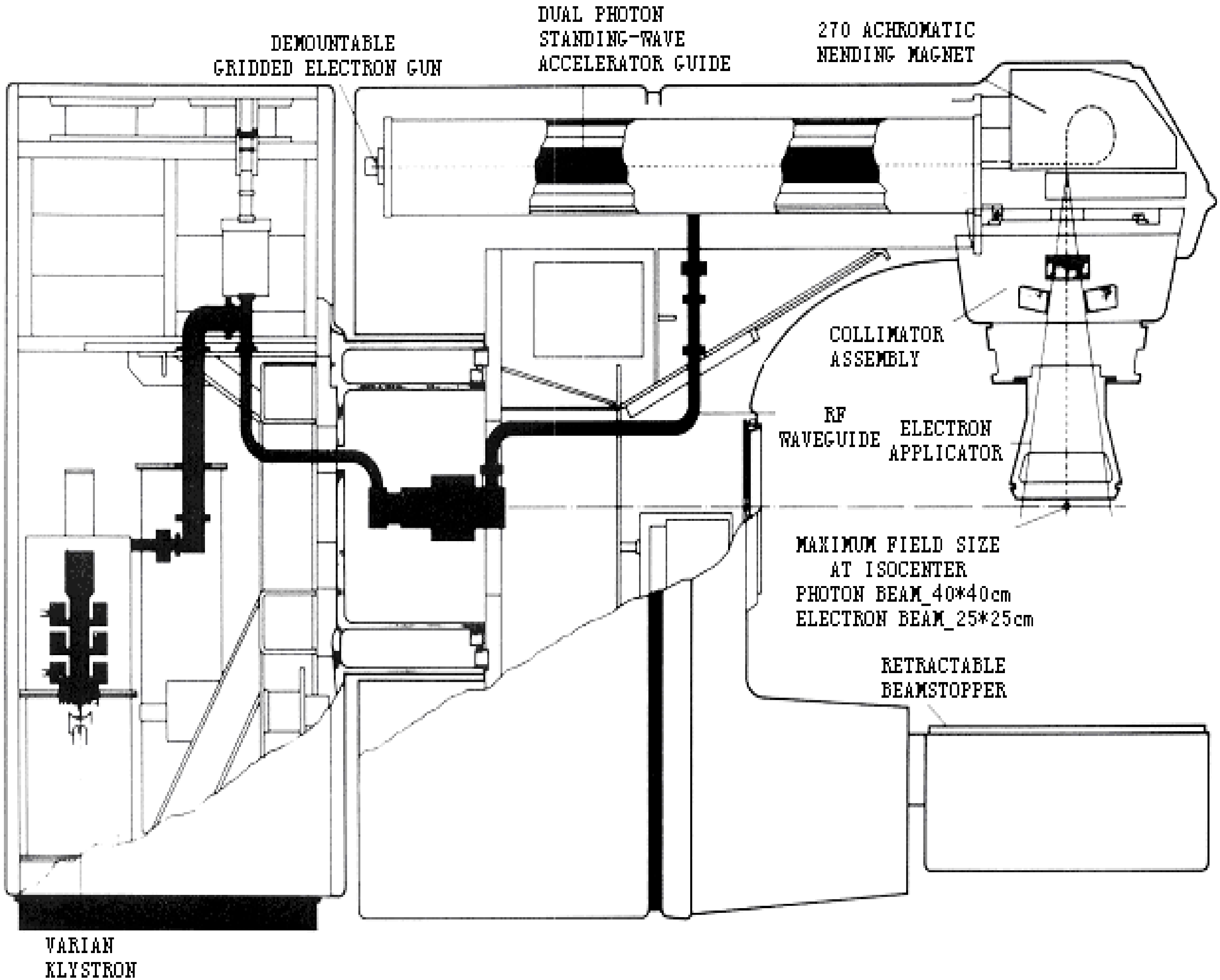
   ☺X-rays: ≤ ± 3%

   ☺Electron beams: ≤ ±5%

Medical Linac Fundamental Systems



Medical TW linac



Medical SW Linac (clinac 18, Varian)

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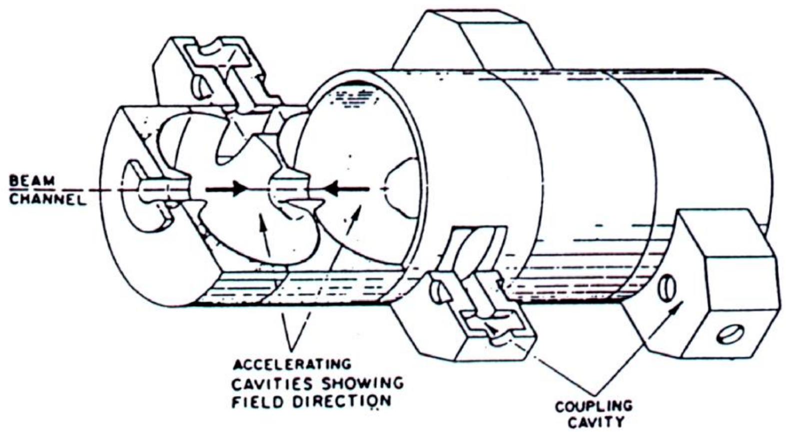
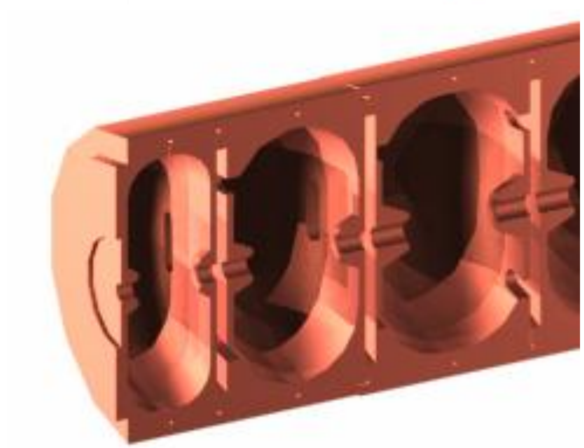
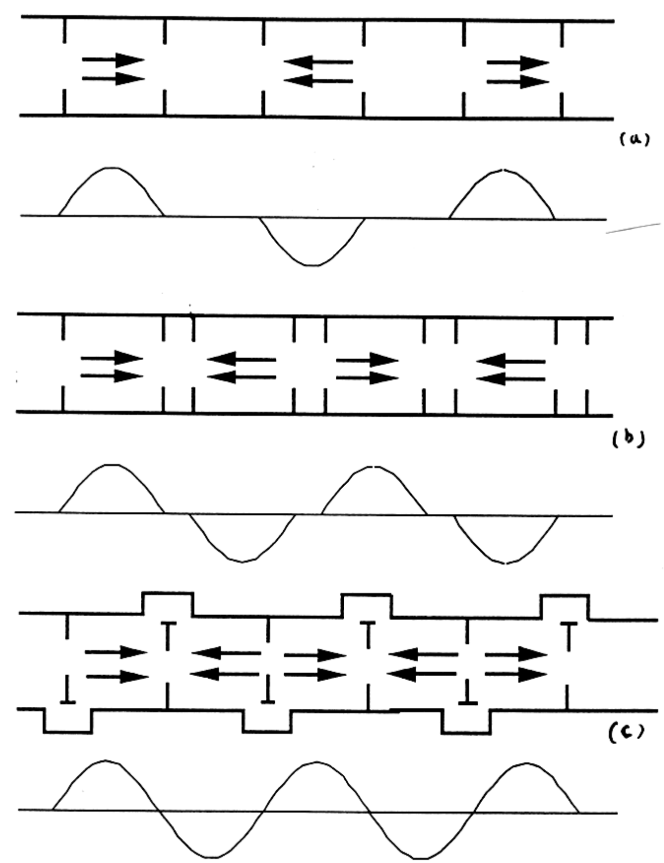
◆Standing-wave (SW) medical linac

---side-coupled SW accelerating structure

---on-axis coupled SW accelerating structure







RF Power Source and Transport System

- The type of RF power source

  ☺Klystron (f = 2856 MHZ)

  ☺Magnetron (f = 2856; 2998 MHZ)

- Peak power, pulse width

  ----2~5 MW, 4 μs , 250 PPS

- If a klystron is employed, the klystron is housed in a separate stationary cabinet

Beam transport, Bending System and Gantry

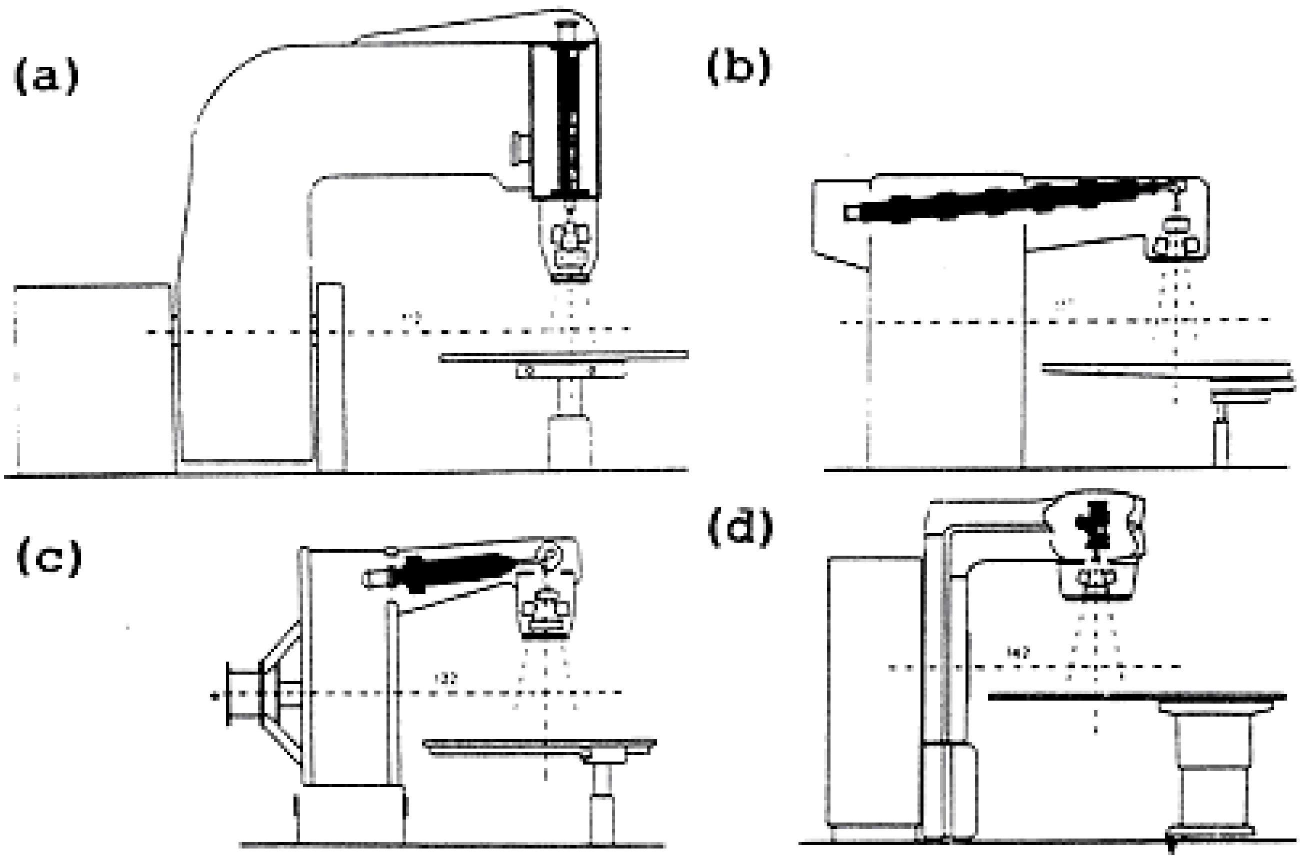


Figure 1.19

Treatment heads

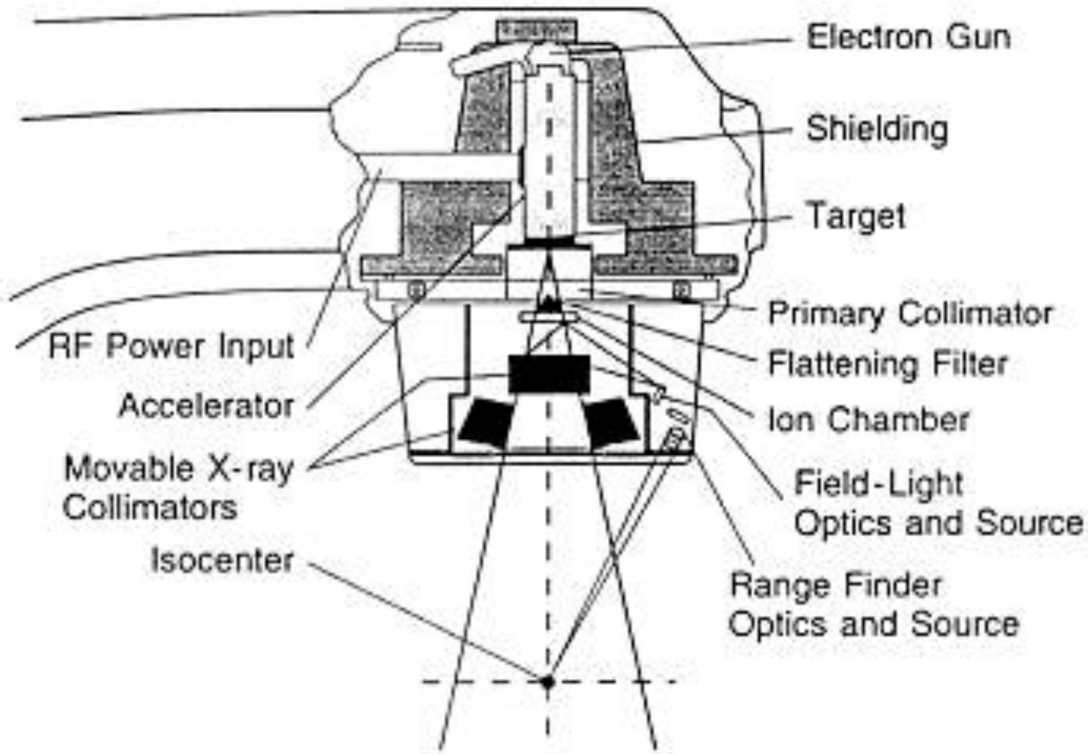
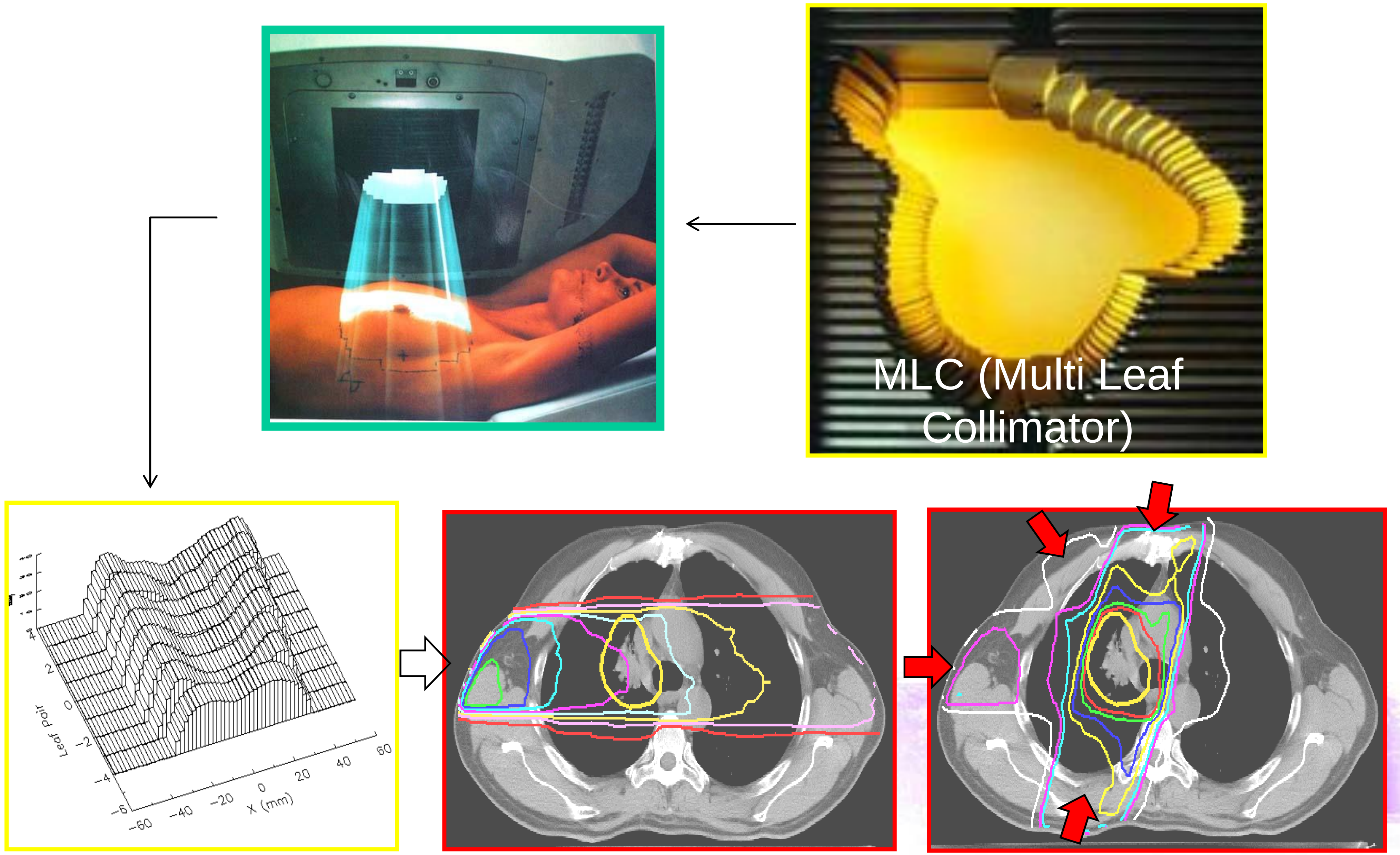


Figure 1.20 Schematic of a treatment head of Varian clinac 6/100 accelerator for X-ray therapy


VARIAN
4
6
5
3
2
1
8
7

IMRT(Intensity Modulated RadioTherapy)



Intensity Modulated Radiation Therapy (IMRT)

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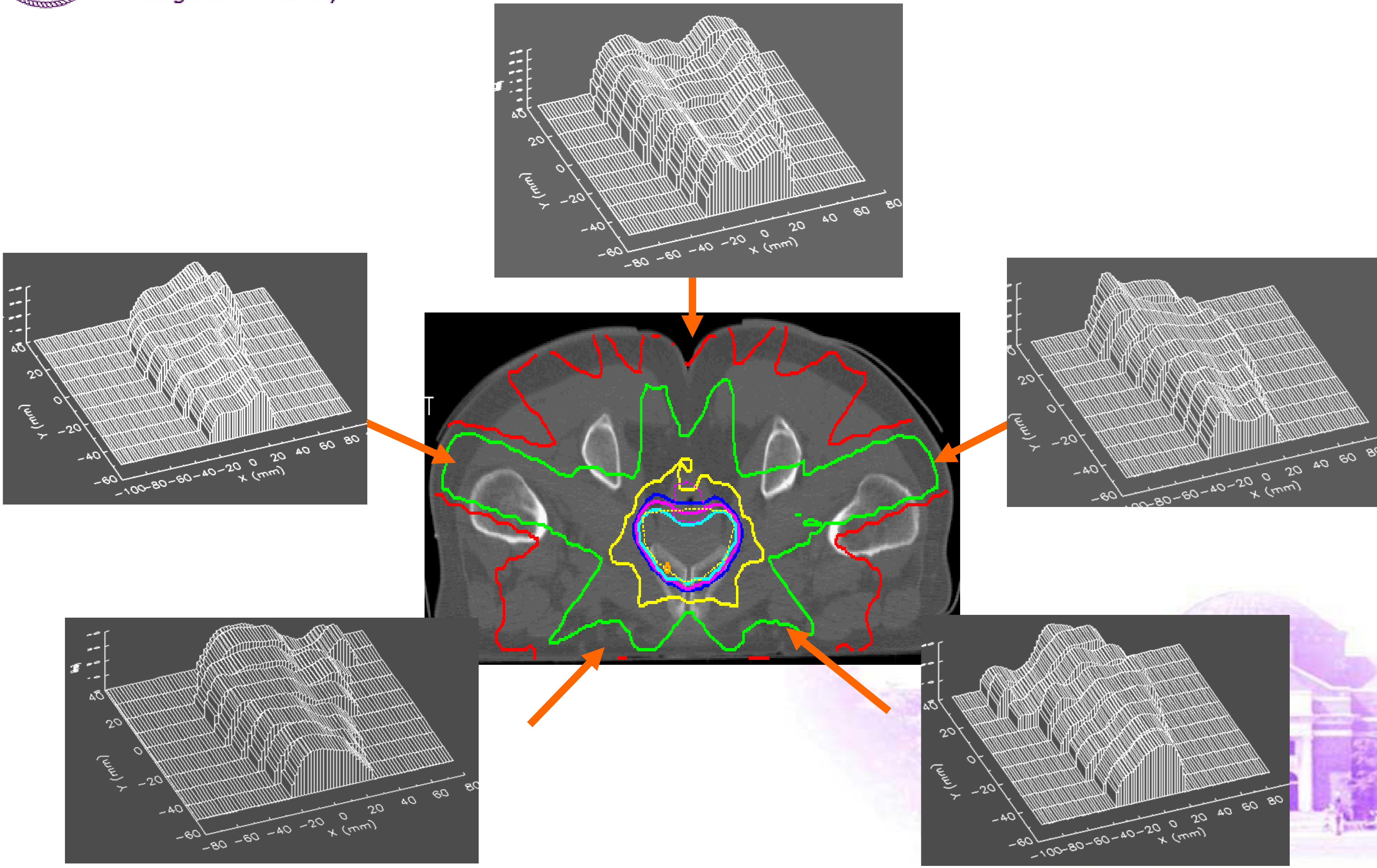
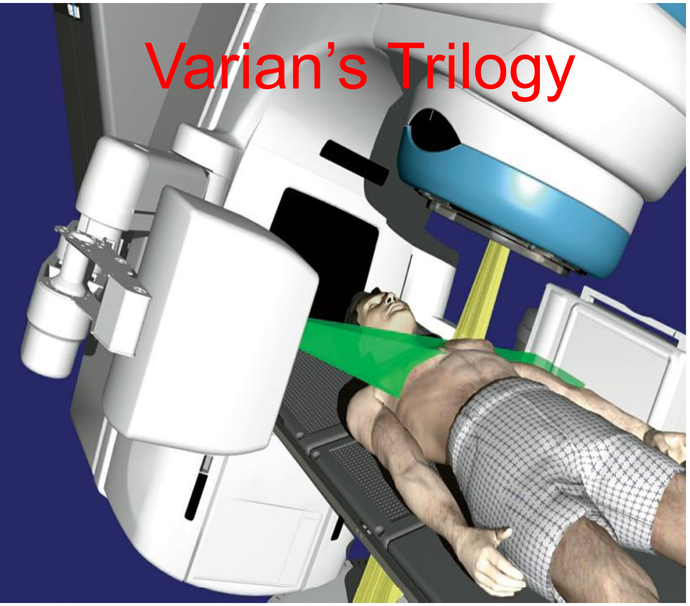


IGRT(Image Guided Radio Therapy)



•利用附加的KV级Ｘ光系统成像获得3Ｄ影像，采用两个射线源和两块成像板。

• 具有很好的影像质量并可提供治疗中实时影像.

• 射线与影像系统与治疗射线不同源（方向正交），实时影像并非真实反映治疗照射部位情况。

•加速器MV级X线相垂直的轴线方向上装了一个KV级X线影像系统。利用Ｘ光机成像方法获得3Ｄ影像。

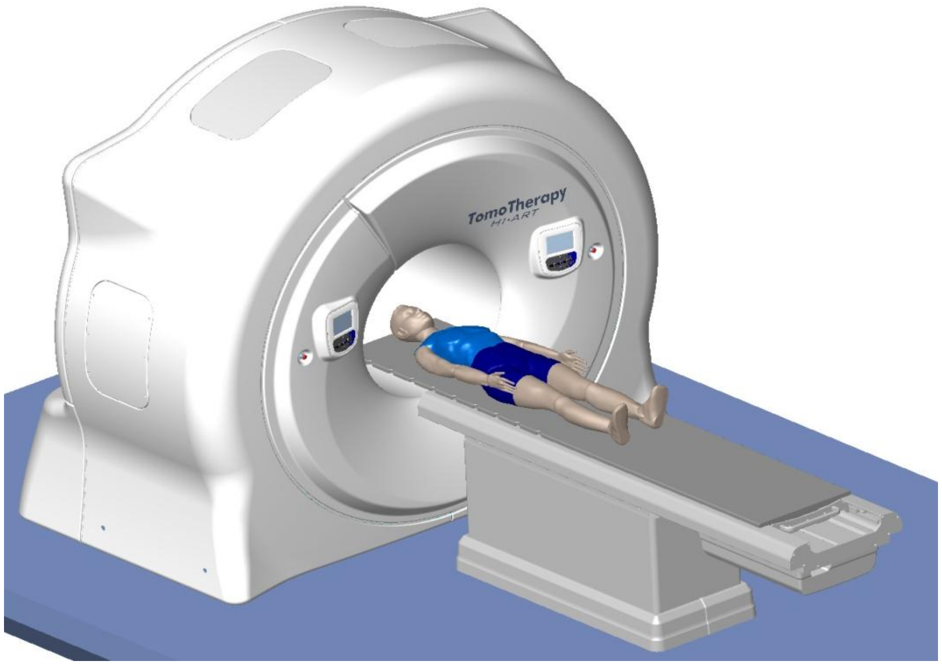
• 采用两个射线源和两块成像板的方法。

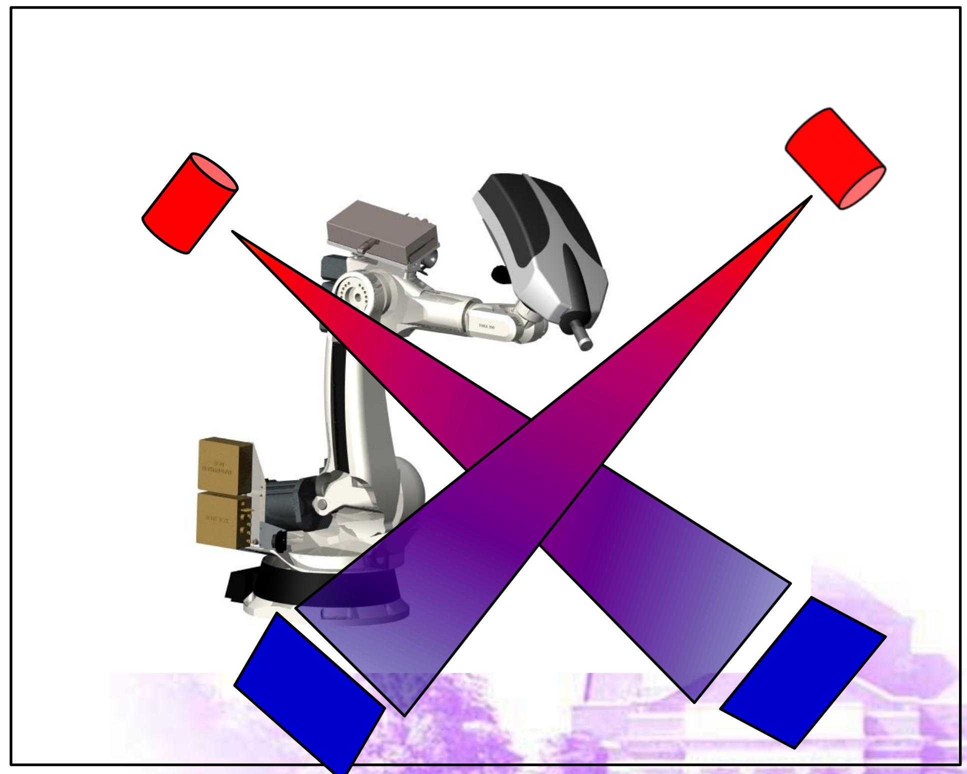
•用加速器产生的MV级 X射线与EPID影像板作 CBCT三维和治疗照射成像;

•与治疗射线同源可以准确反映治疗部位情况。

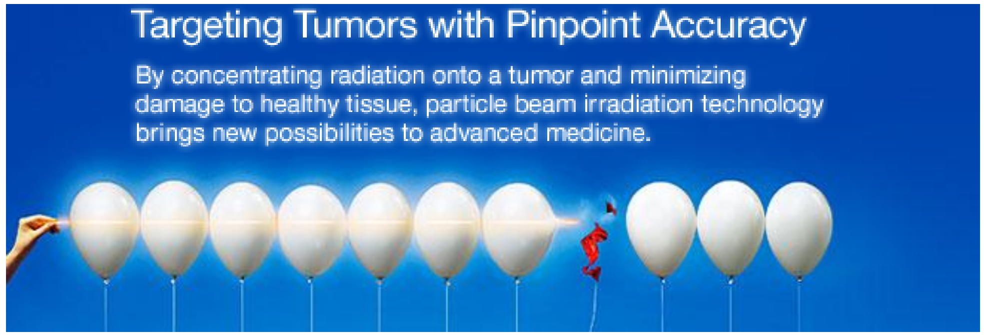
•MV能级X线成像质量差,且患者接受剂量较大。

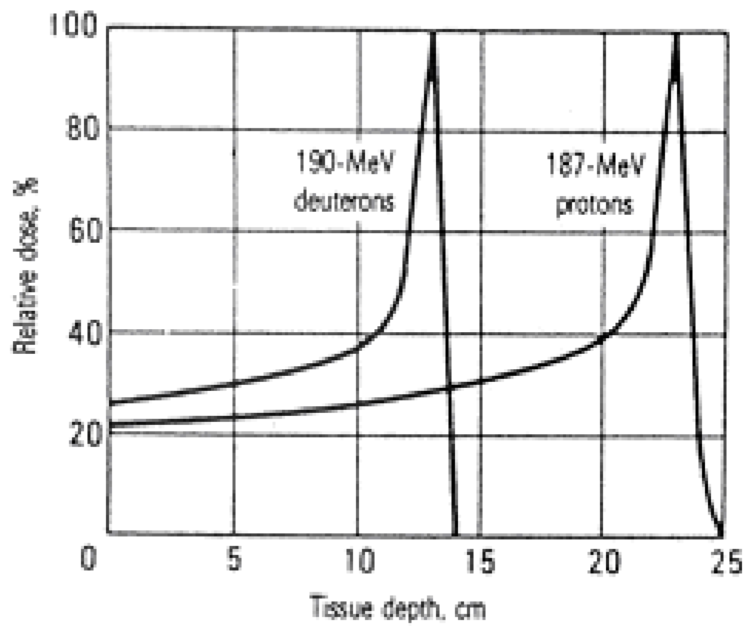
IGRT
Tomotherapy and Cyberknife





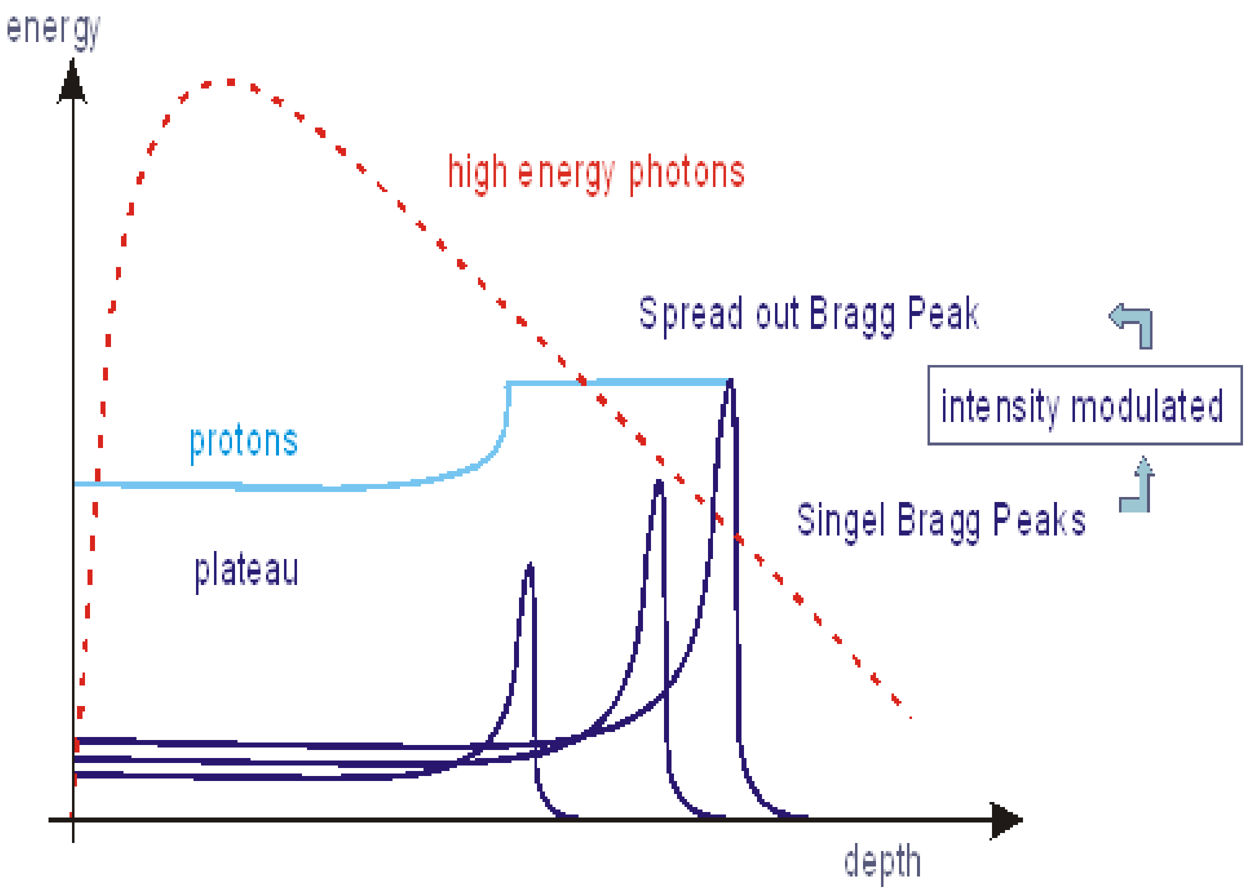
2.3 Proton/Ion Radiotherapy



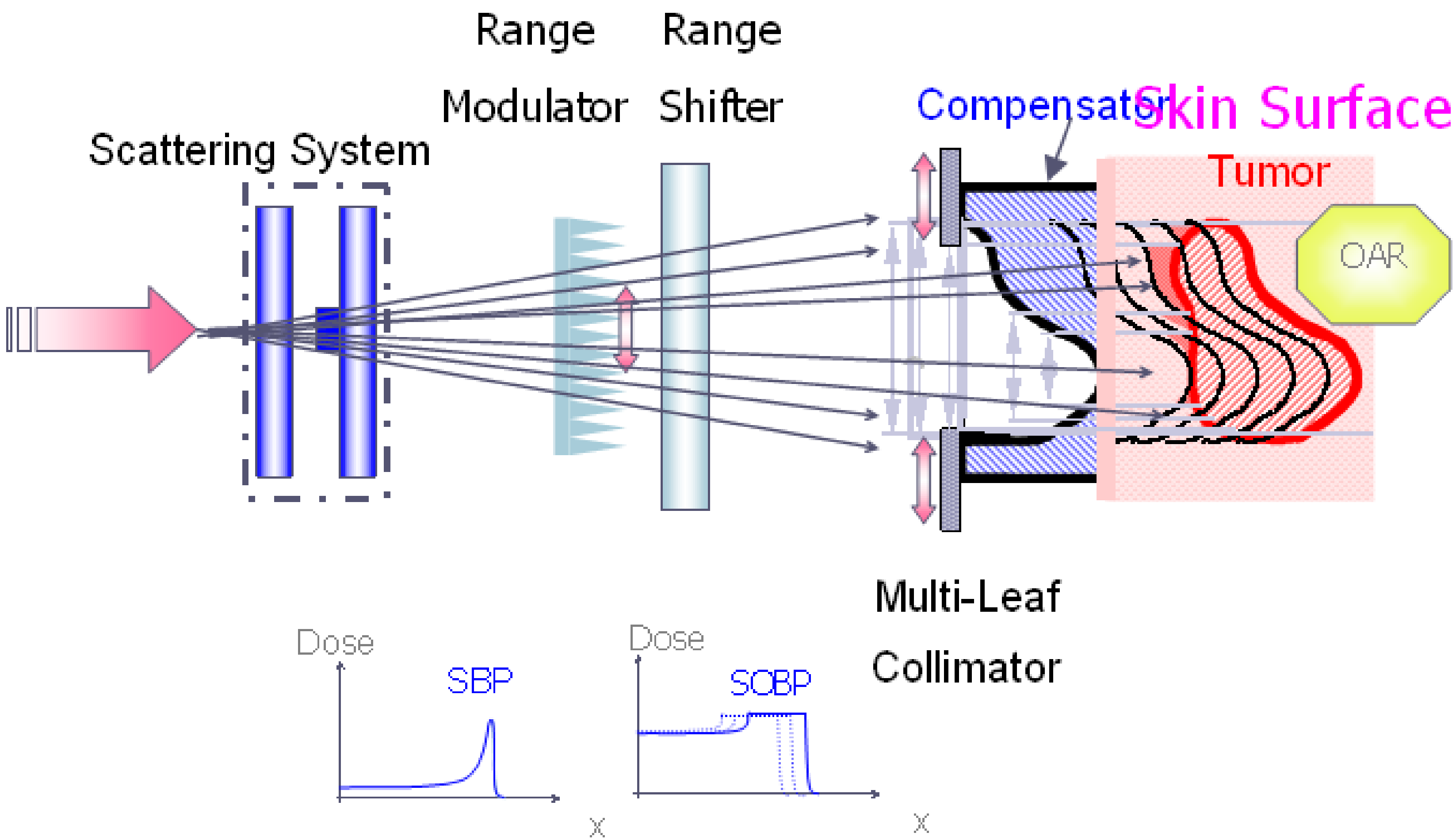


Depth dose in water for 190MeV deuterons and 187MeV protons

Deep direction-Spread Out Bragg Peak



Transverse distribution



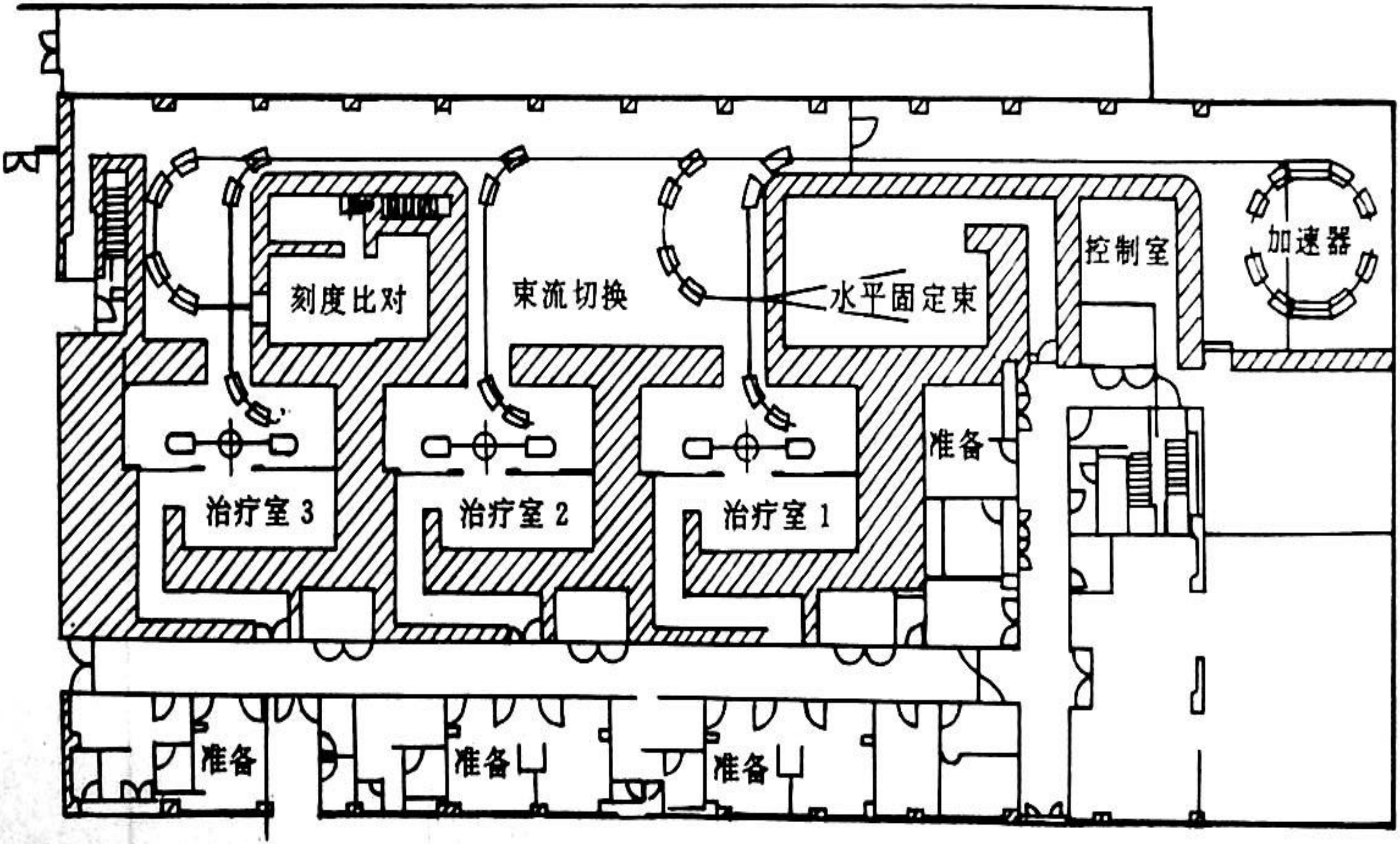


图 4-39 Loma Linda 大学质子治疗中心设备平面图

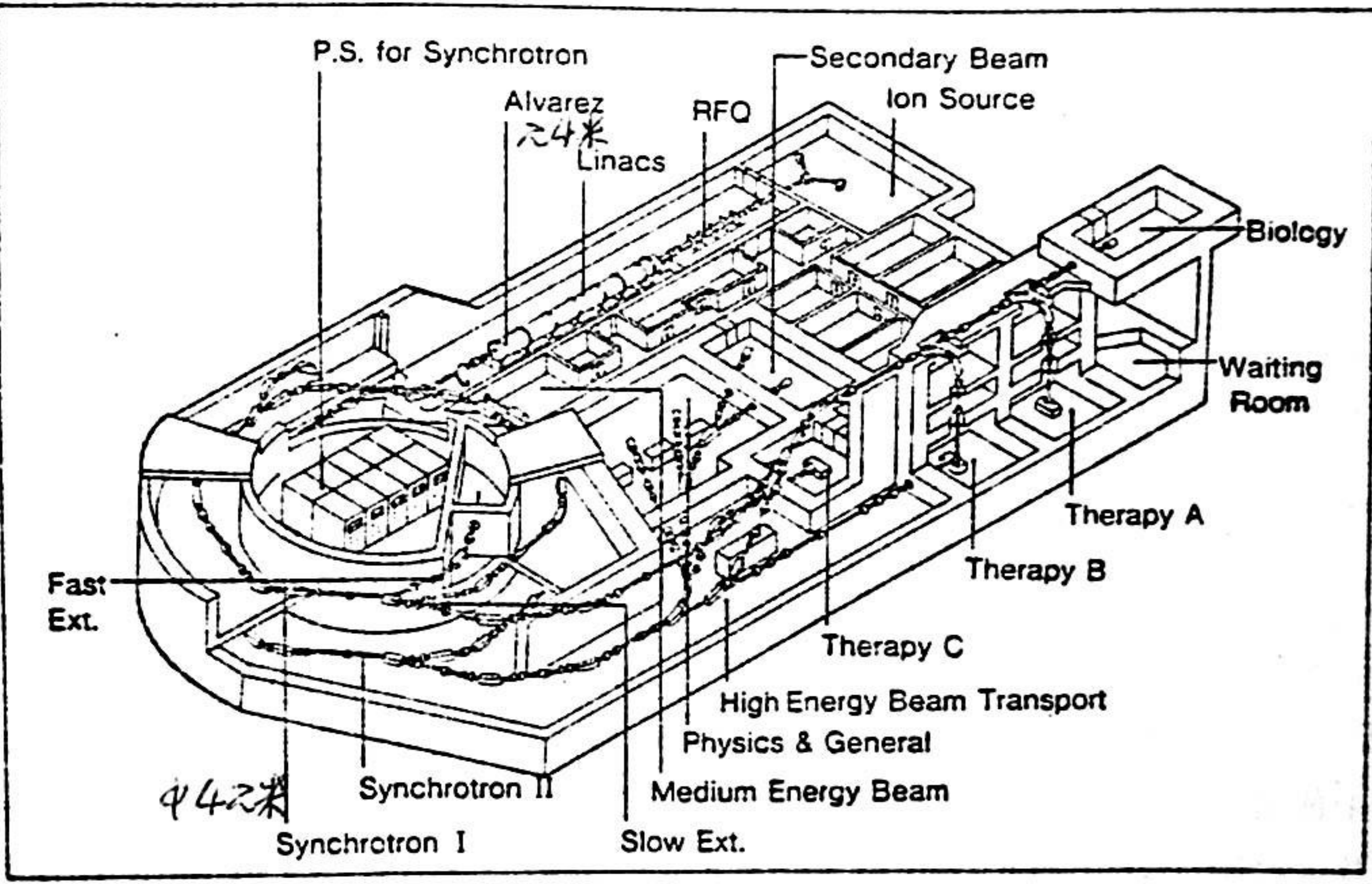
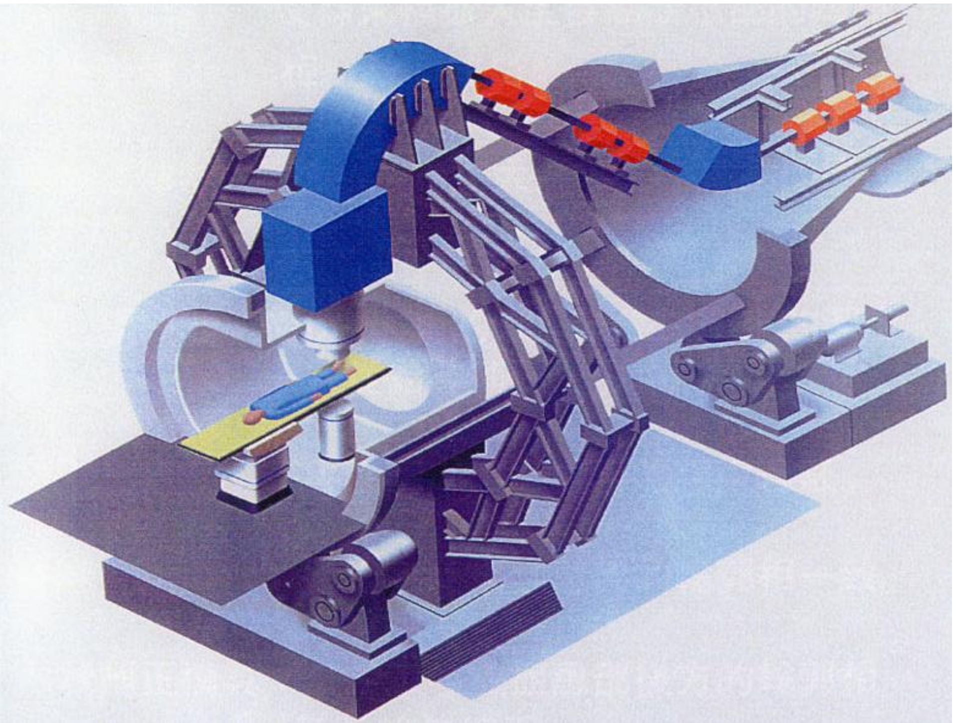


图 3 日本重粒子治疗装置 HIMAC

Gantry



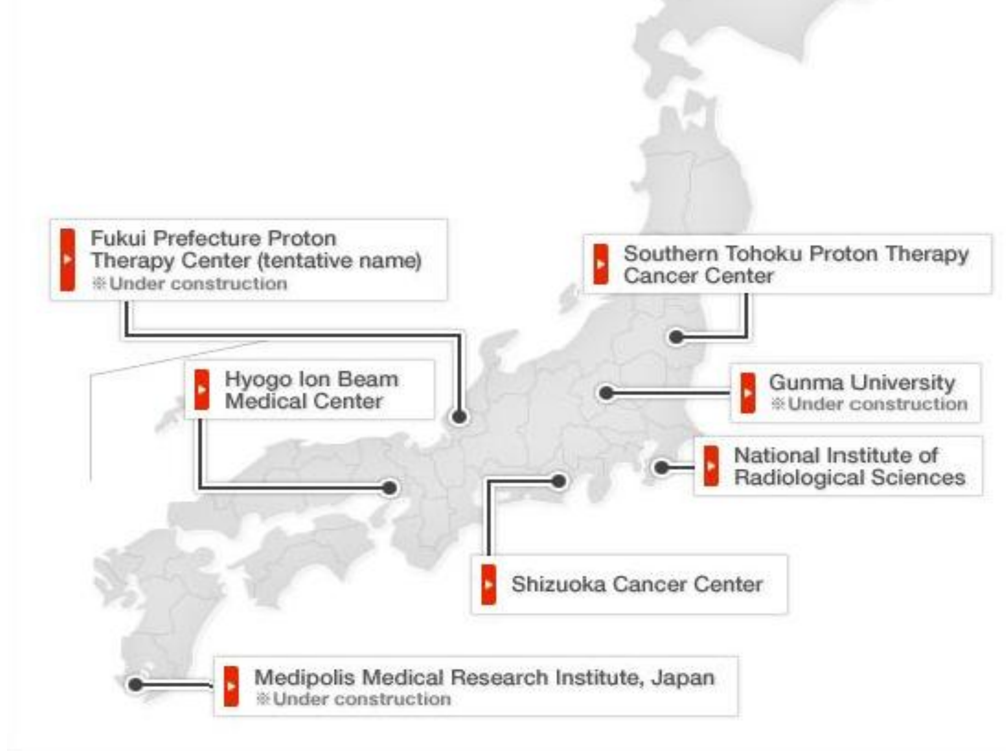
Beam position precision 1mm

20 m long, diameter of 13 m, total weight of 670 tons. @HIT

Mitsubishi Electric

- Synchrotron therapy systems
  - Proton type (70 - 250 MeV)
  - Proton (70 - 250 MeV) /carbon (70 - 380 MeV/u) type.

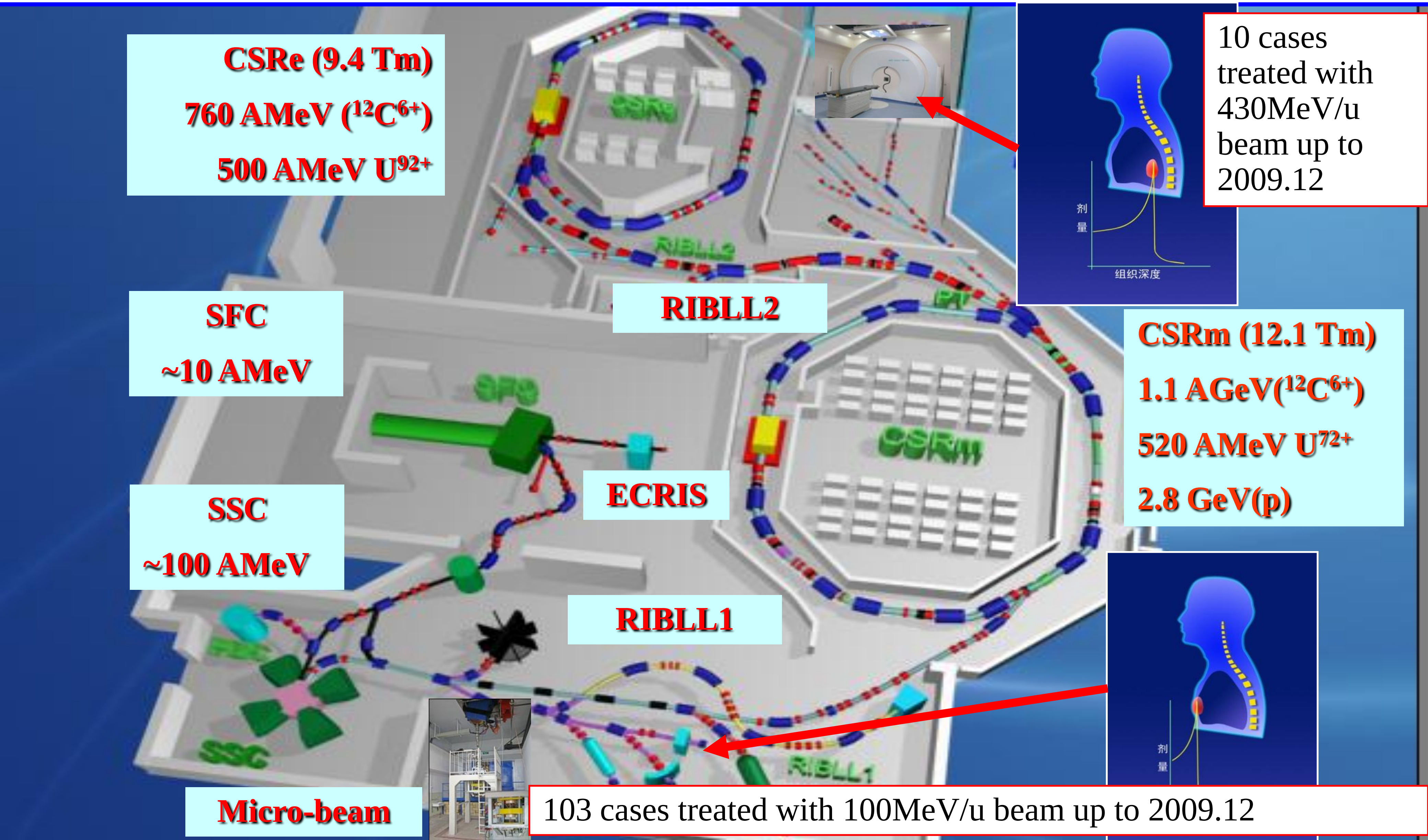
From 1994, four systems manufactured by Mitsubishi have been installed and another three systems under construction



http://global.mitsubishielectric.com/ , (2010).

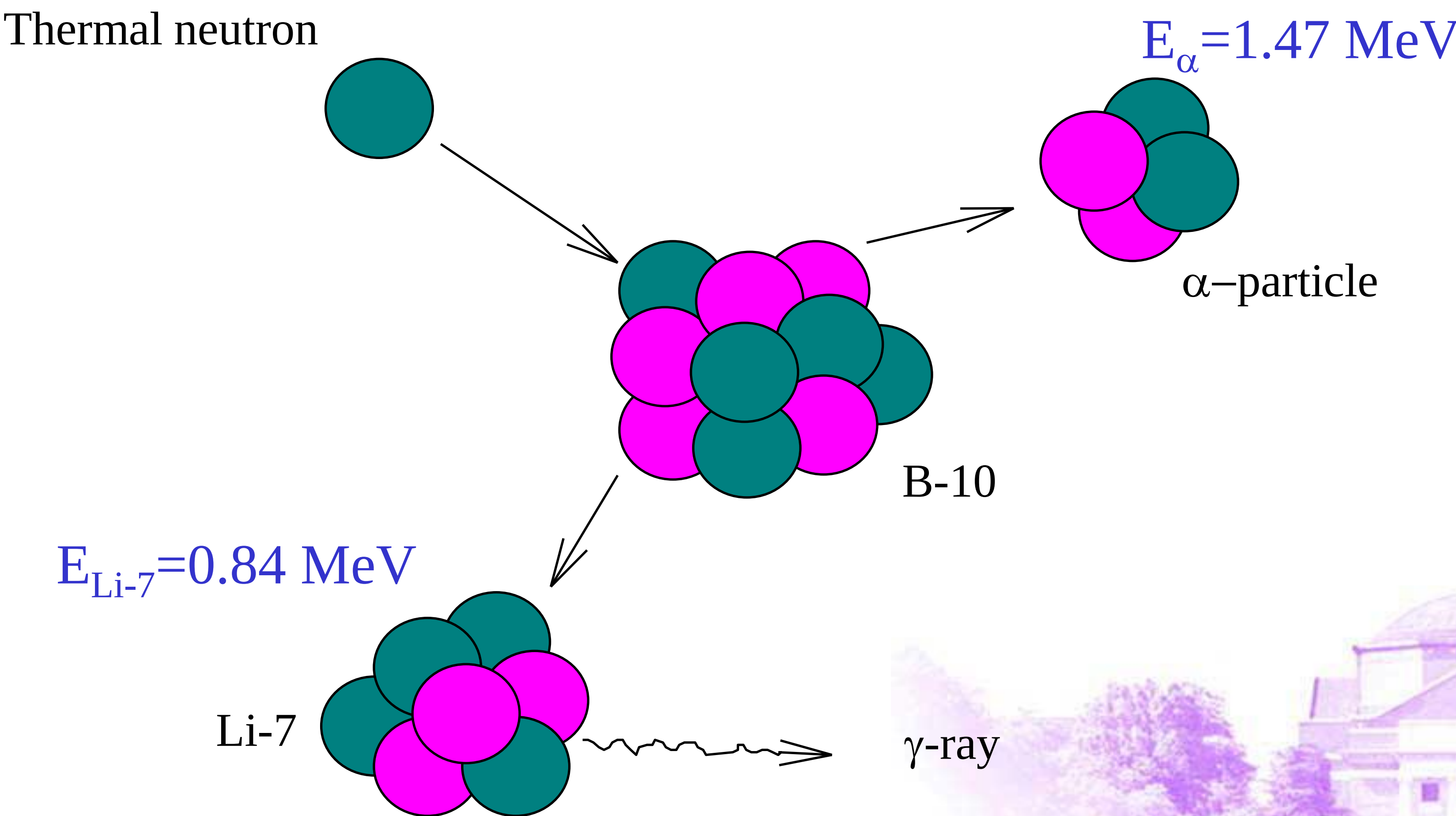
HIRFL-CSR at IMP

Courtesy of Mingtao Song

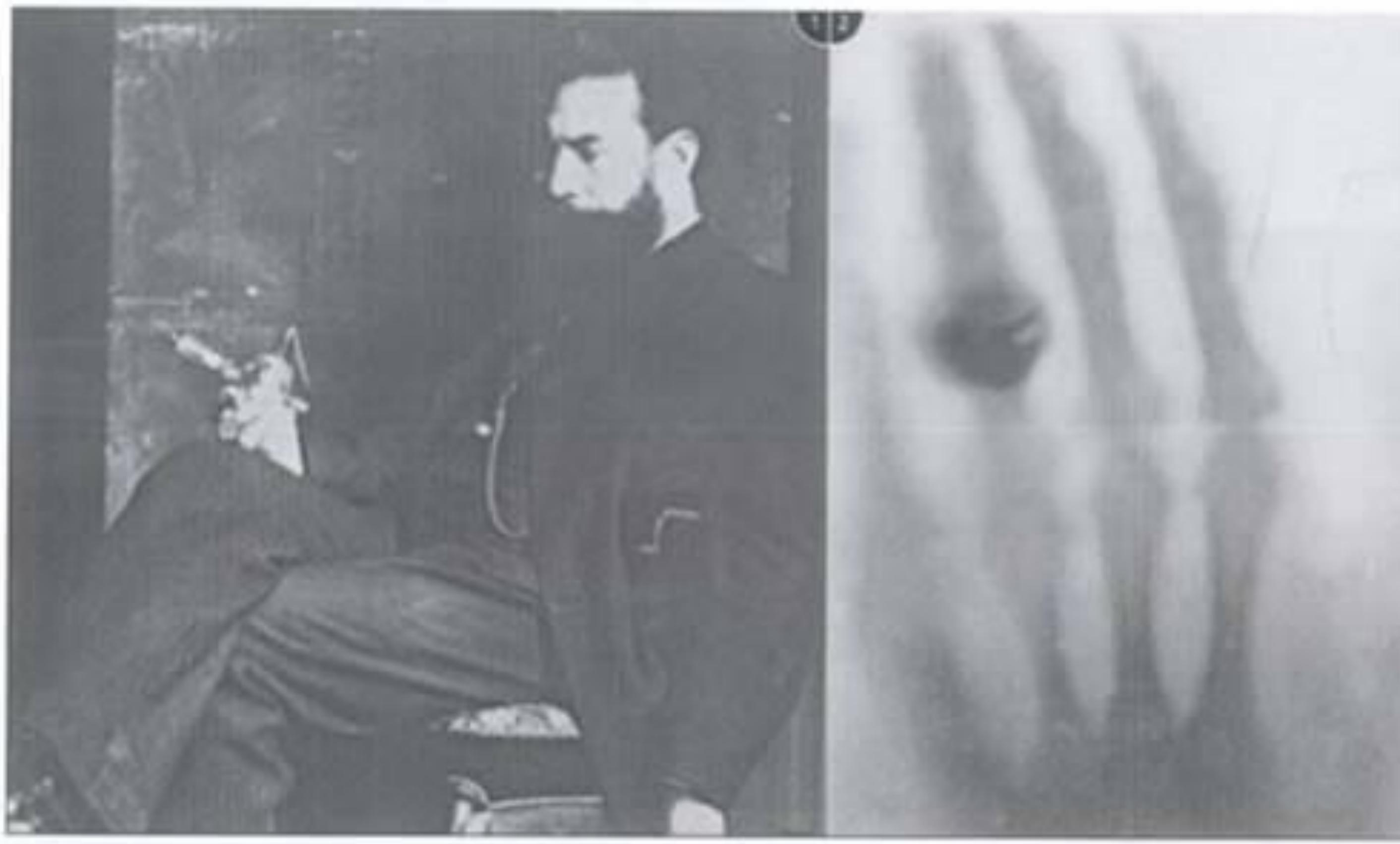


BNCT

(Boron Neutron Capture Therapy)



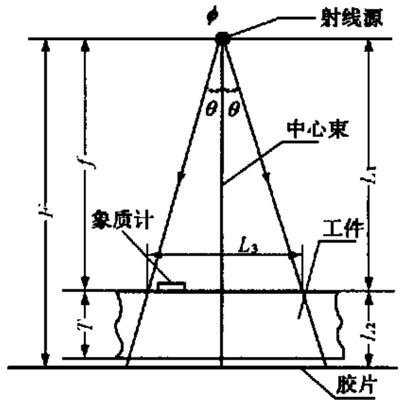
3 Radiography



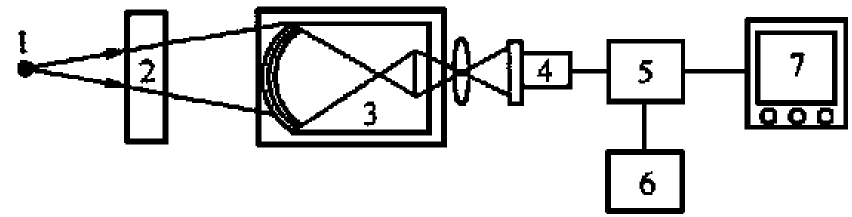
Roentgen discovered the X-ray in 1895 and used the ray to radiate his wife's hand to make a film.

3.1 X-ray radiography

- 射线照相
  (Photography)



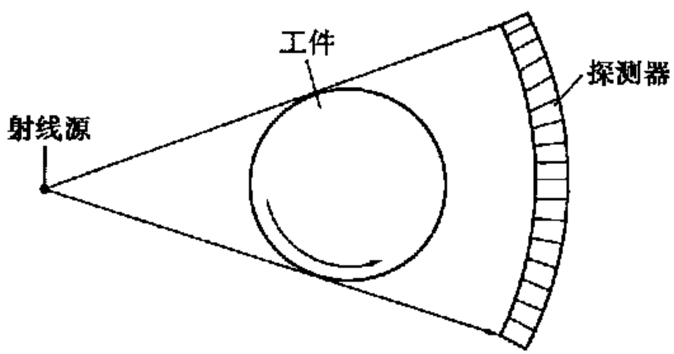
- 实时成象
  (DR)



1. 射线源2. **工件与机械驱动系统**3. **图象增强器**

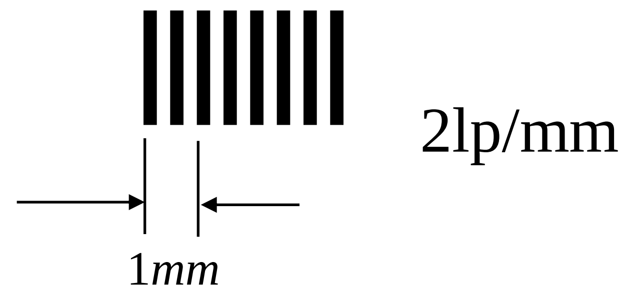
4. **摄象机**　5. **图象处理器**　6. **计算机**　7. **显示器**

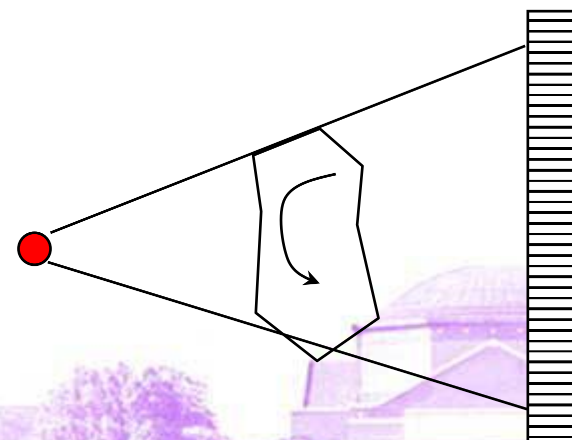
- CT成象



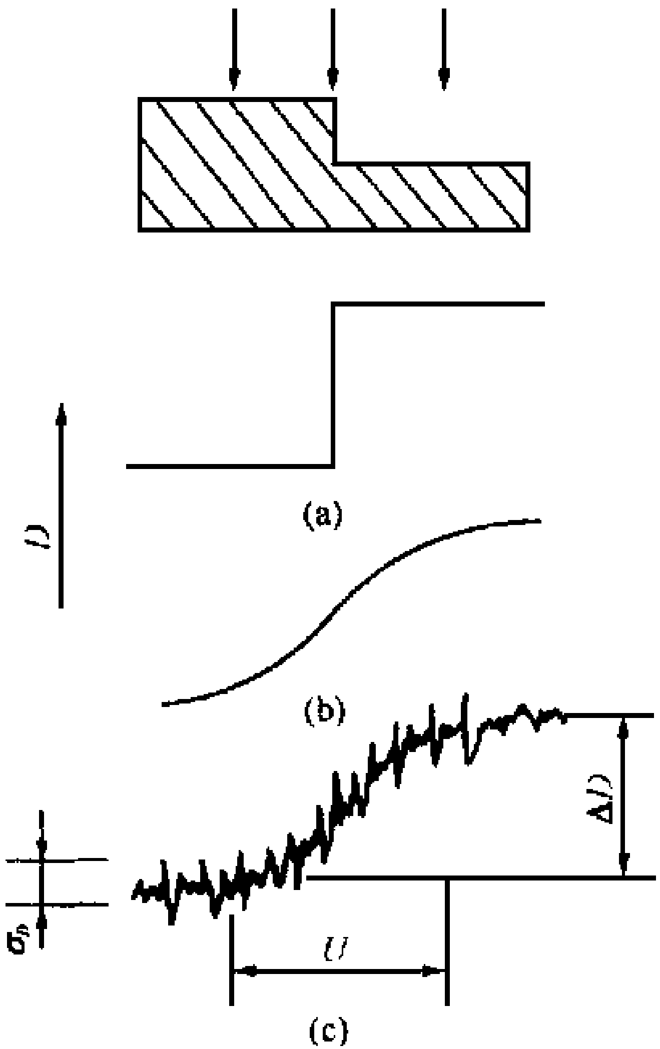
空间分辨率(Spatial Resolution)

- 空间分辨率
  - 也称几何分辨率，是指从图象中能够辨别最小物体的能力。
  - 表示方式：等间距圆孔测试卡，多少mm的小孔；等间距条形实物，每mm的线对数(lp/mm)
  - 影响因素：扫描矩阵大小，探测器准直孔宽度，被检物采样点对应的距离，扫描机械精度，X射线焦点，图象数据校正与图象重建算法是否得当等

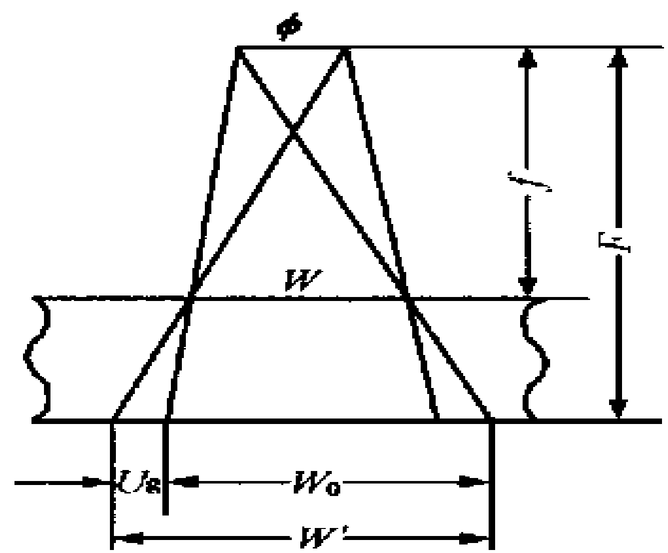




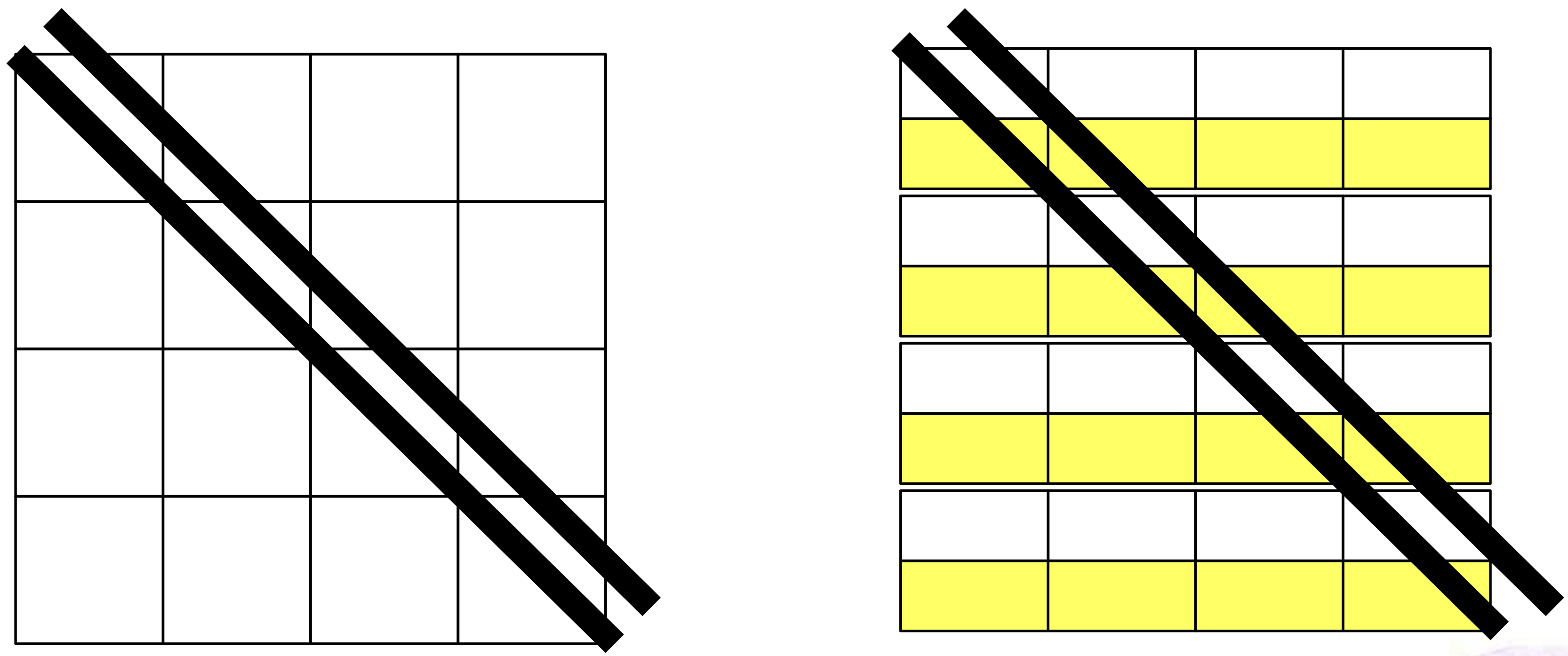
成像质量



图中的ΔD ,U 和σ_D 就是影象质量的三个基本因素，即对比度(衬度)、不清晰度和颗粒度(或噪声)

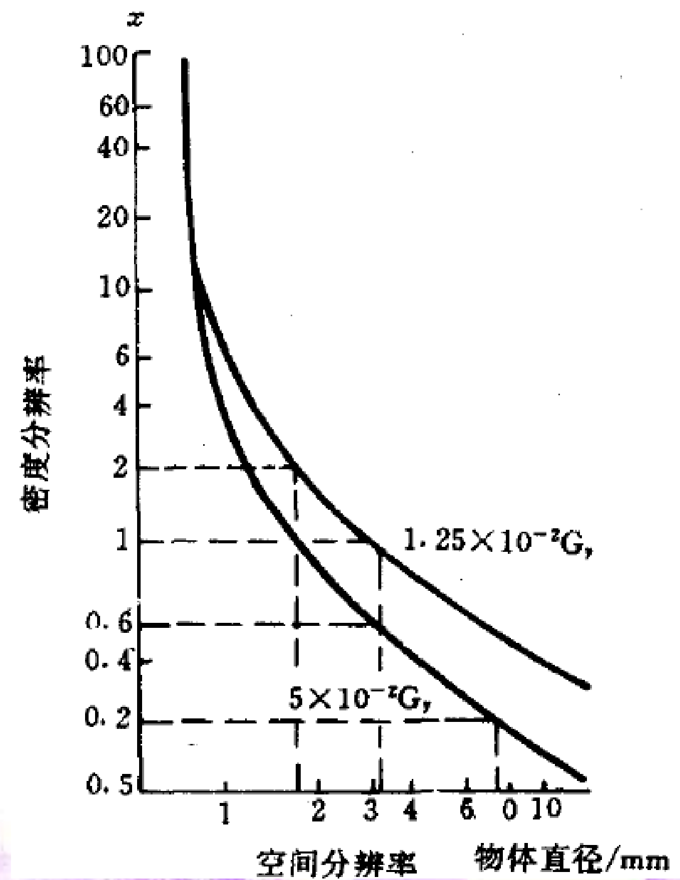


探测器对图像质量的影响



密度分辨率(Density Resolution)

- 密度分辨率
  - 又称对比度分辨率，是利用图象的灰度分辩被检物材质的基本方法（ICT）。
  - 表示方法：通常以可分辩的密度变化的百分比（％）表示。
  - 影响因素：信噪比（放射源的量子噪声、电子元件噪声及重建算法造成的反映在图象上的噪声等）
  - 目前的ICT，1％～0.1％



在辐射剂量一定的情况下，空间分辨率与密度分辨率相矛盾

X射线的产生与电子束参数的关系

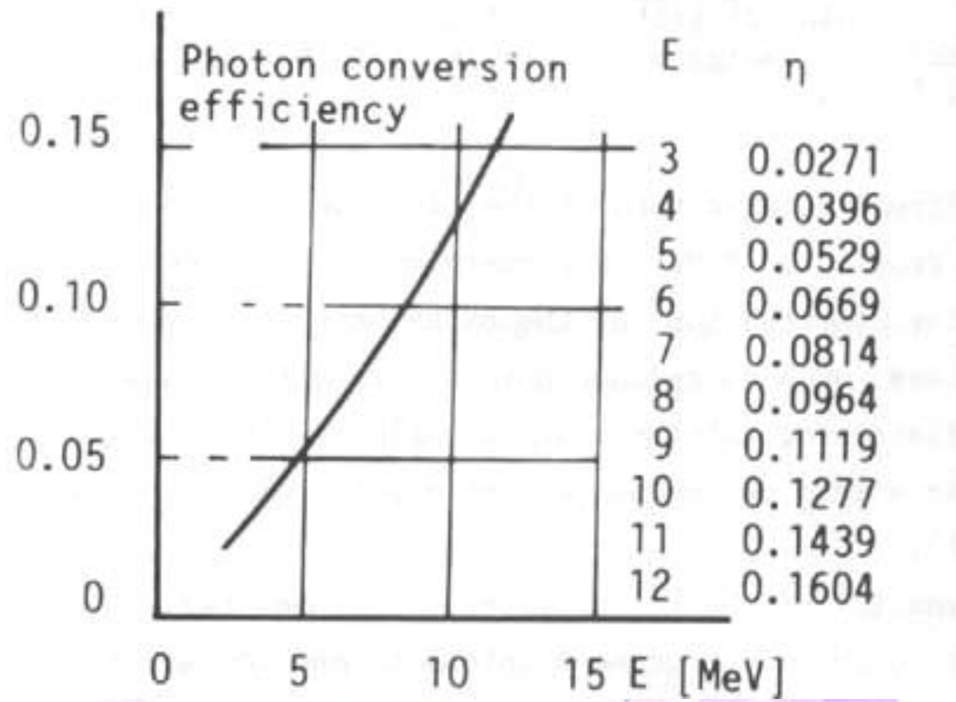
$$J_x = \eta \cdot I_b \cdot E_e^{\,n}$$

Where

I_b-- the electron beam currents (μA)

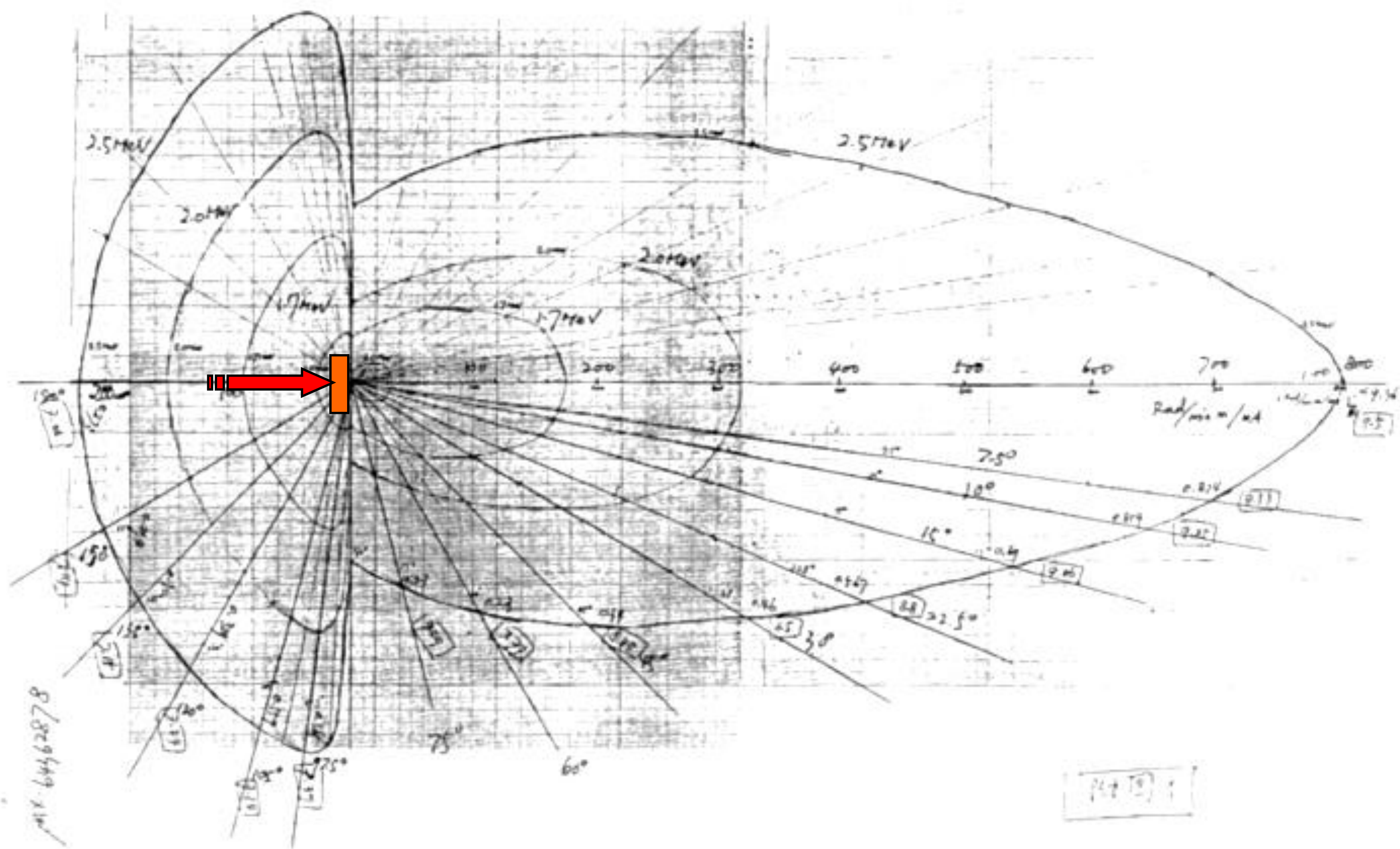
E_e-- Electron energy (MeV)

n=2.6~3



Photon conversion η

X射线的空间分布



电子束打靶产生X射线

X射线在物质中的衰减

- 射线穿透物体时其强度的衰减与吸收体(射线入射的物体) 的性质、厚度及射线光量子的能量相关。
- 实验表明, 对于一束射线, 在均匀媒质中, 在无限小的厚度范围dx 内, 强度的衰减量dJ 正比于入射射线强度和穿透物体的厚度x。这种关系可以写为

$$dJ = -J\mu dx$$

射线衰减规律

$$J = J_0 e^{-\mu x}$$

式中

J ——透射线强度

J_0 ——无吸收体时的入射线强度

μ ——物体的线衰减系数, cm - 1

宽束

- 在实际射线探伤中，一般都是宽束射线情况，这时透射射线强度应为一次射线和散射射线强度之和，透射的一次射线一般记为J_D，透射的散射线一般记为J_S，这样有

$$J = J_D + J_S$$

$$J = (1 + n)\, I_0 e^{-\mu x}$$

式中

μ——等效能量的线衰减系数

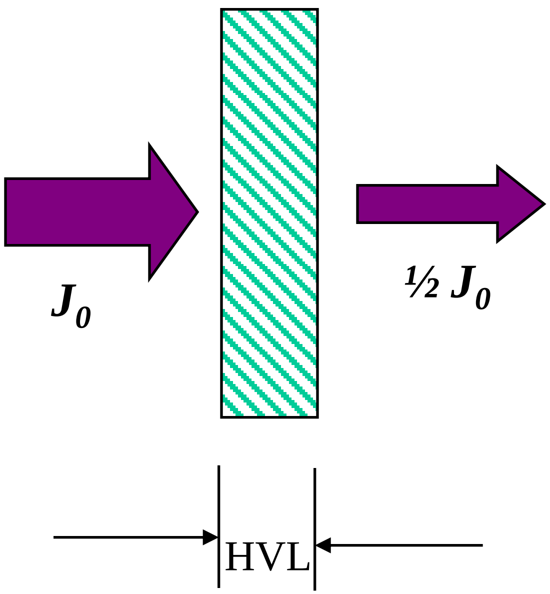
$n = J_S / J_D$

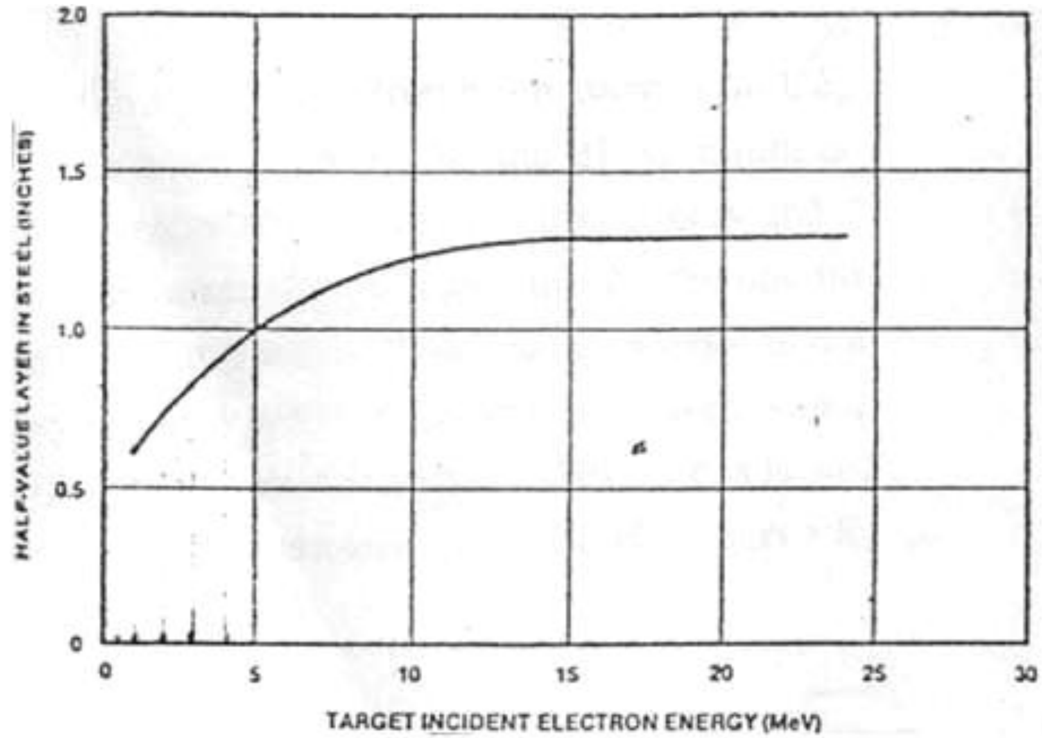
- 引入积累因子B，即

$$B = 1 + n$$

$$J = B\, J_0 e^{-\mu x}$$

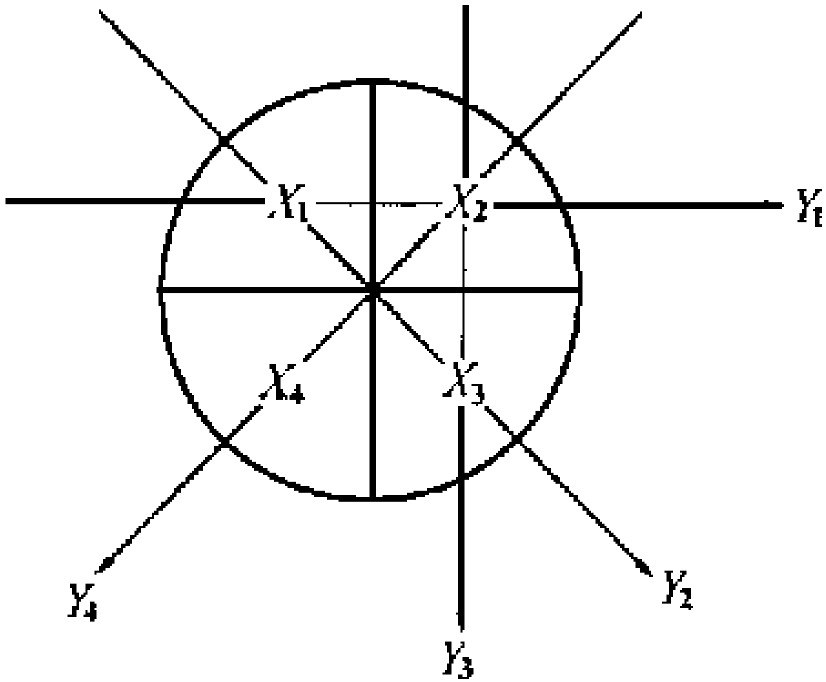
半价层 half-value layer (HVL)





Half-value layer of steel as function of radiation energy (Varian Ass.)

3.2 工业CT （ICT）



- $X_1+X_2=Y_1$
- $X_1+X_3=Y_2$
- $X_2+X_3=Y_3$
- $X_2+X_4=Y_4$

$$X_1 = \frac{1}{2}[Y_1 + Y_2 - Y_3]$$

$$X_2 = \frac{1}{2}[Y_1 - Y_2 + Y_3]$$

$$X_3 = \frac{1}{2}[Y_2 - Y_1 + Y_3]$$

$$X_4 = Y_4 - \frac{1}{2}[Y_1 - Y_2 + Y_3]$$

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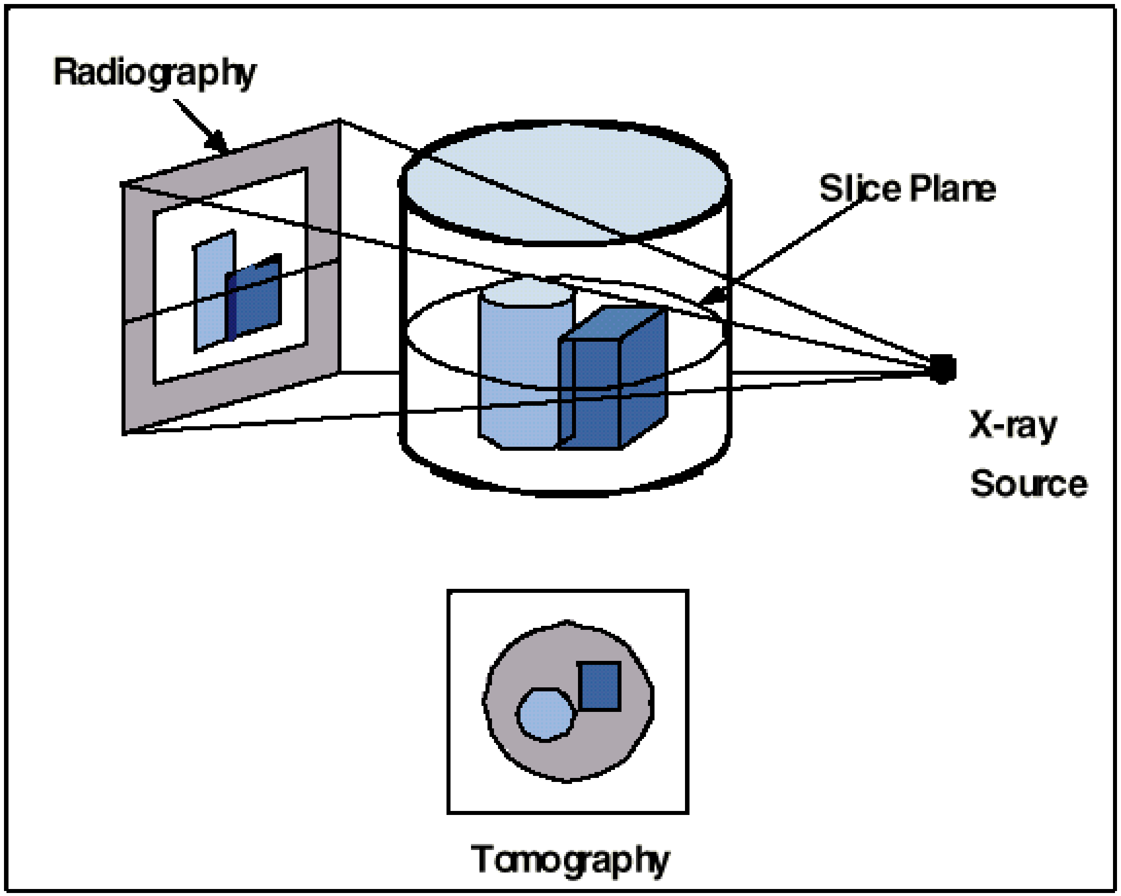
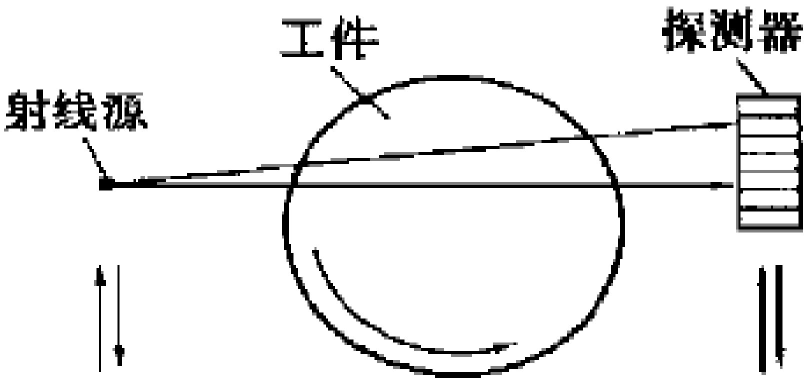
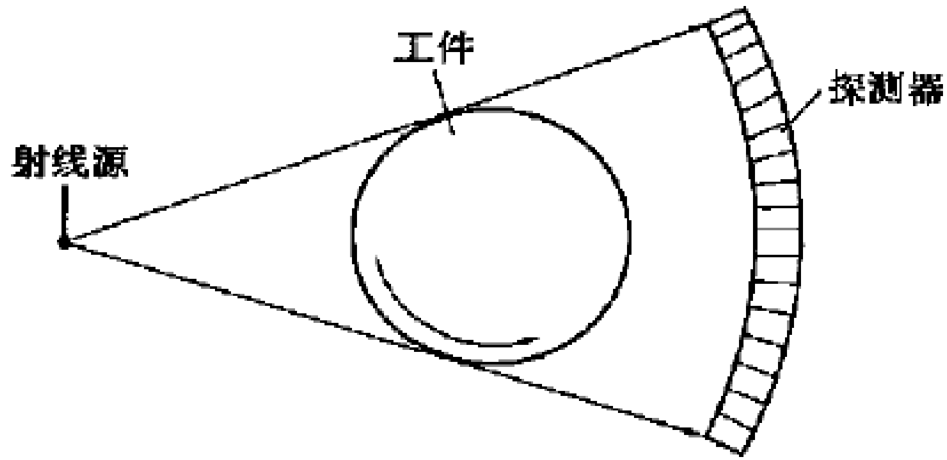
ICT与普通射线成象



CT 扫描方式



(a) 单源、小扇角平移加旋转扫描系统



(b) 单源、大扇角单旋转扫描系统

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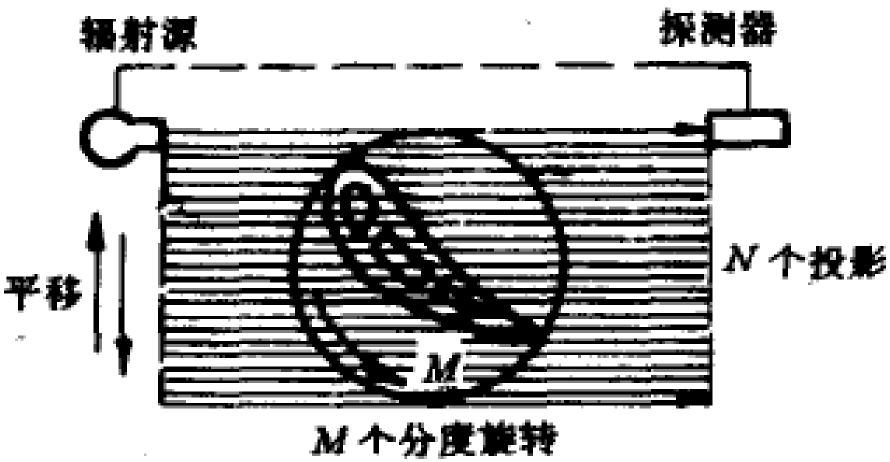
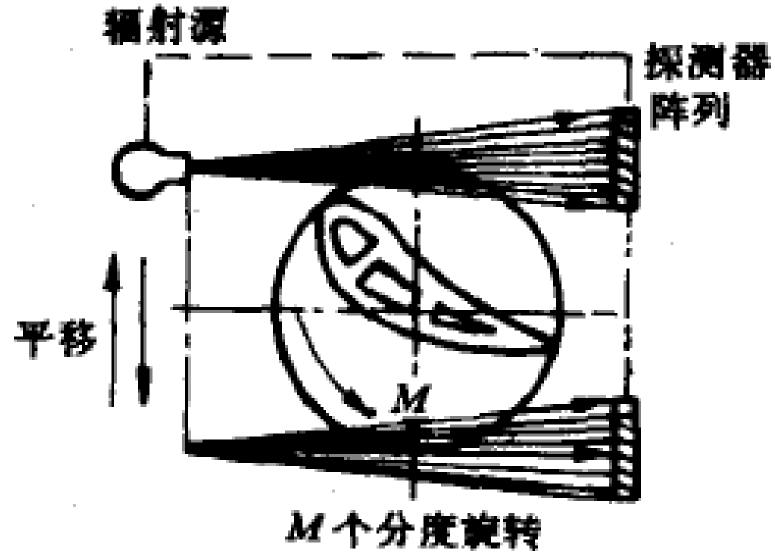
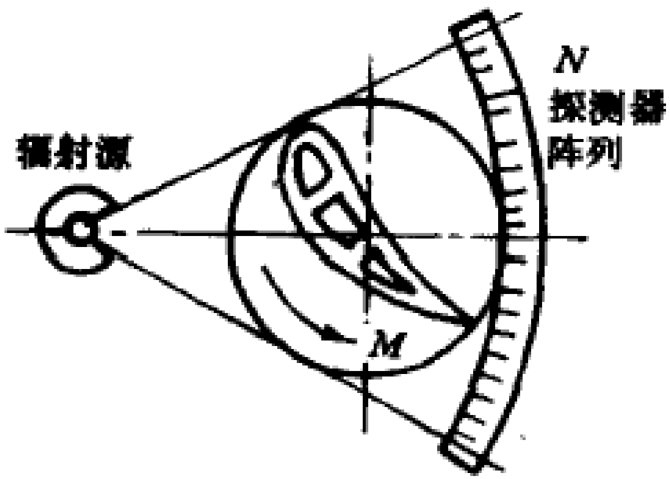


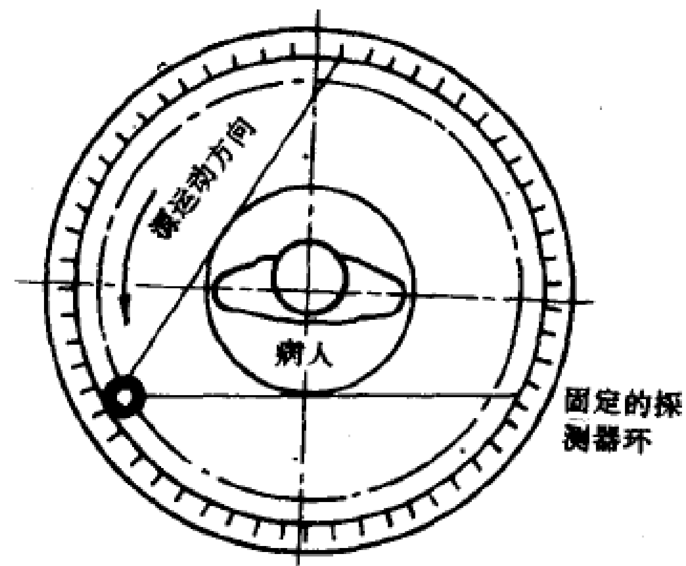
(a)第一代 CT 扫描方式



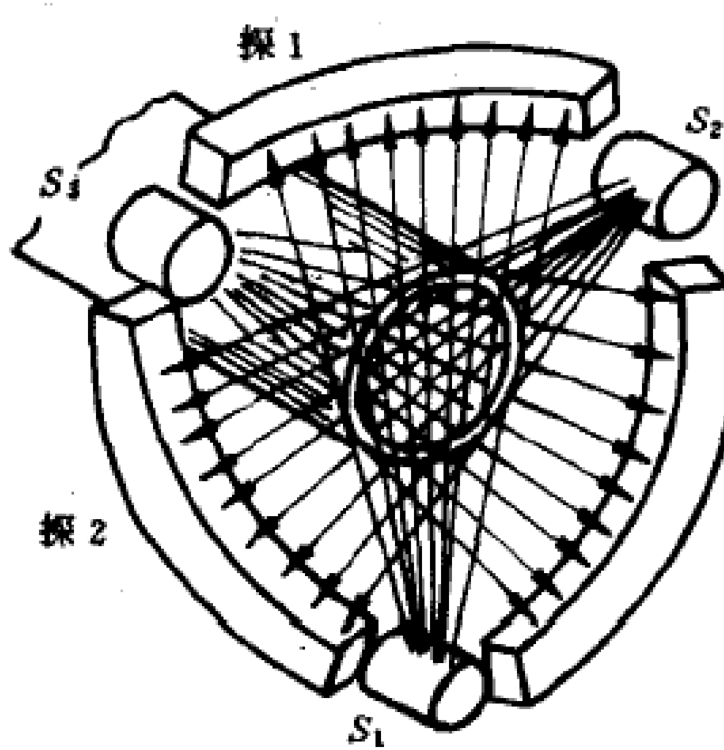
(b)第二代 CT 扫描方式



(c)第三代 CT 扫描方式



(d)第四代 CT 扫描方式



有按 120°分布的三个辐射源和三个探测器阵列
被检物只作沿轴向旋转运动
(e)第五代 CT 扫描方式

ICT工作原理

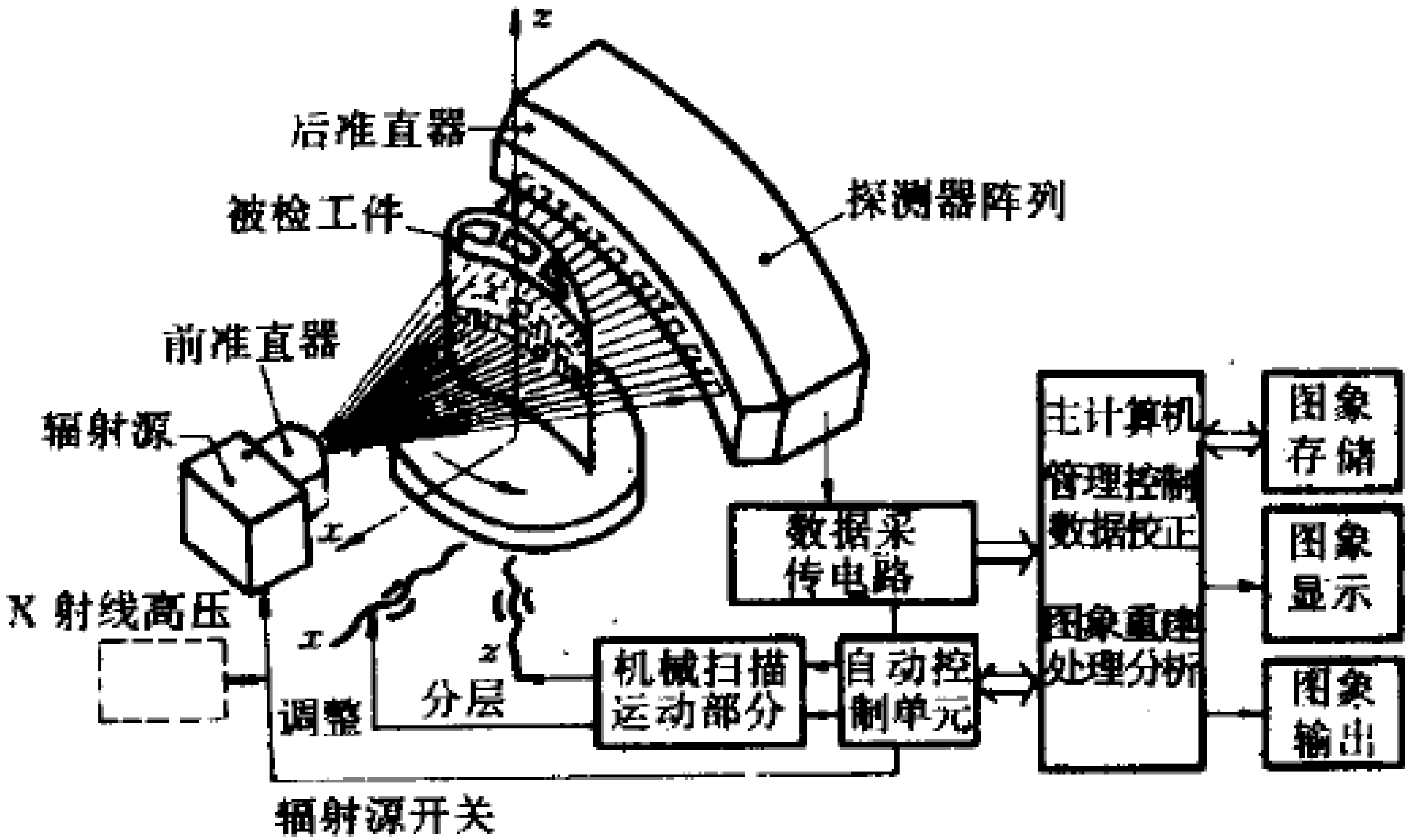
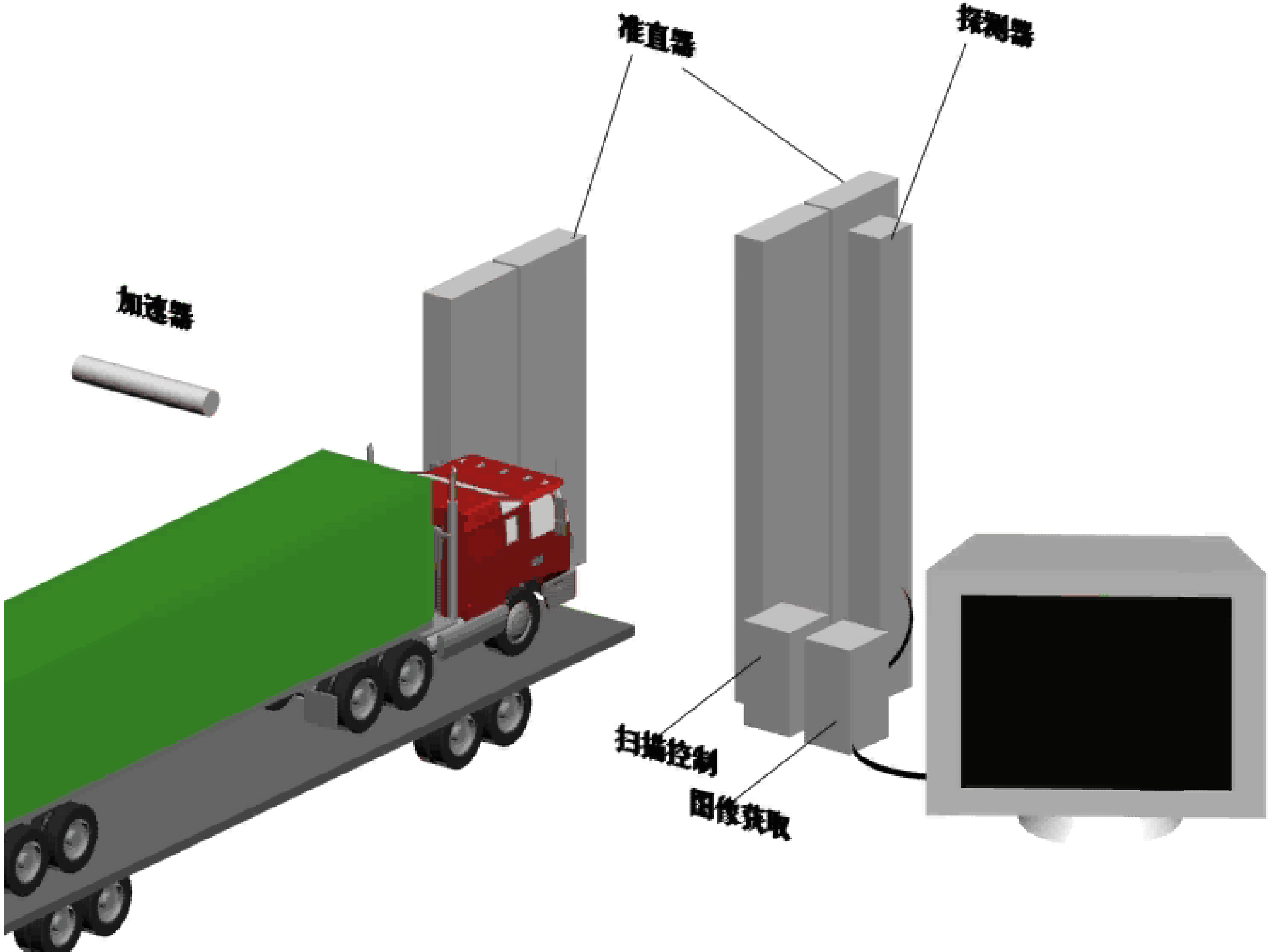


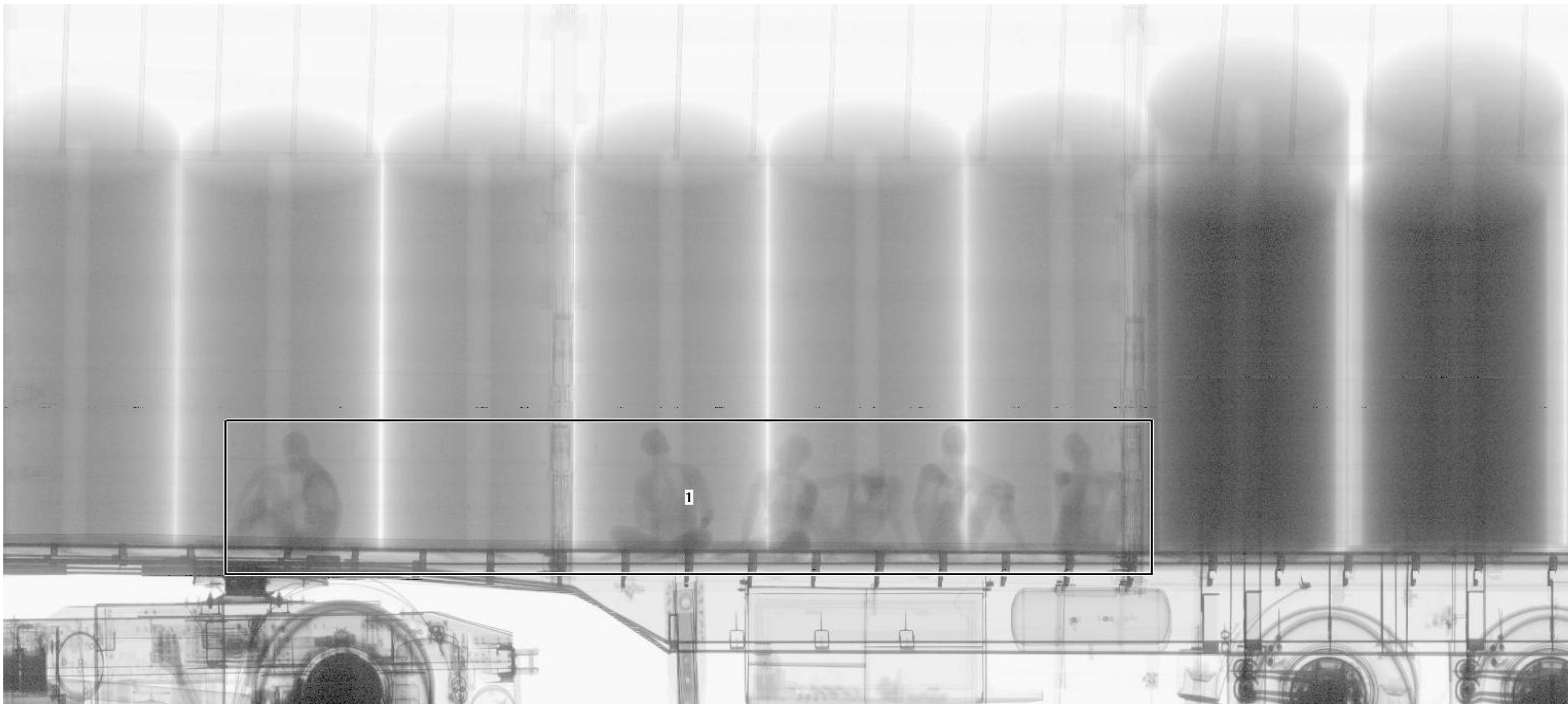
图 3 ICT 结构工作原理简图

- The ICT images of a vessel and an exhaust manifold provided by the ARACOR Company, CA., U.S.A.

3.3 Cargo Inspection System



Stowaway



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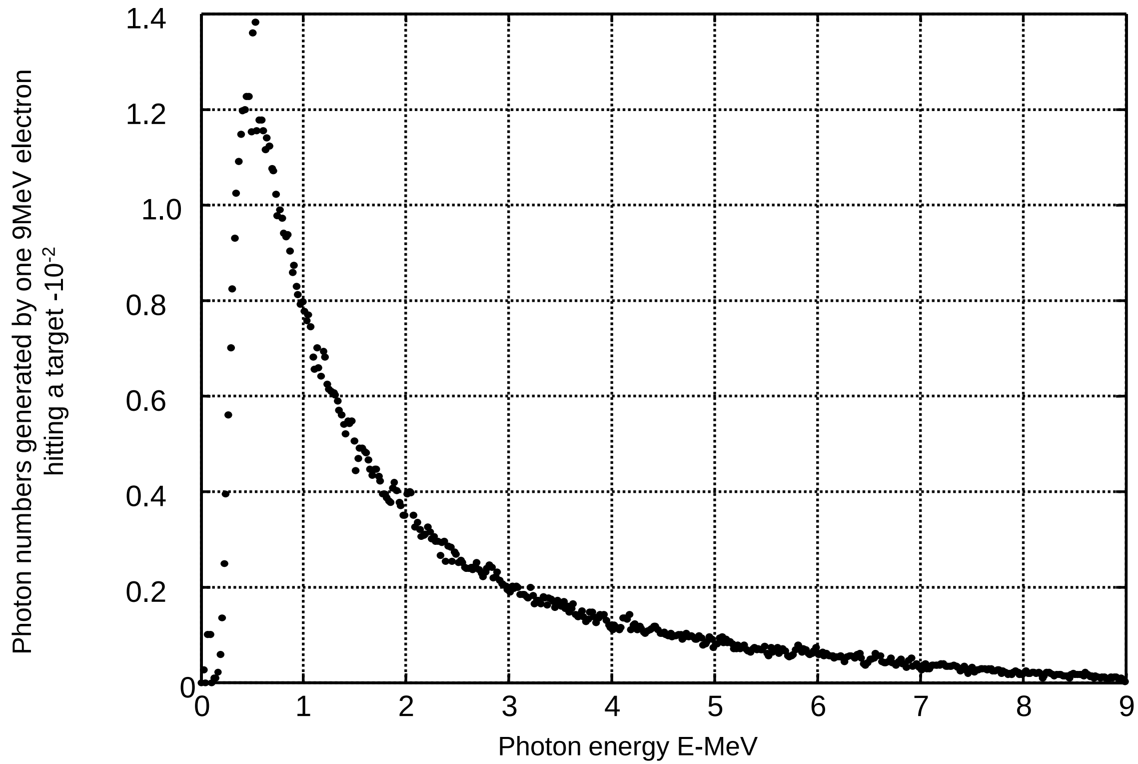
Material Identification in High Energy Dual-Energy X-ray Imaging Technology

- Aim of Inspection：Identify threat and dangerous cargo
- Material Discrimination Function of Dual-Energy X-ray Imaging Technology
  - Application：Container or Vehicle and other large-scaled cargo
  - Principle：Dual-Energy X-ray Image, calculate atomic number (Z) of the scanned object and marked by different colors
  - Purpose：Differentiate organic material and inorganic material

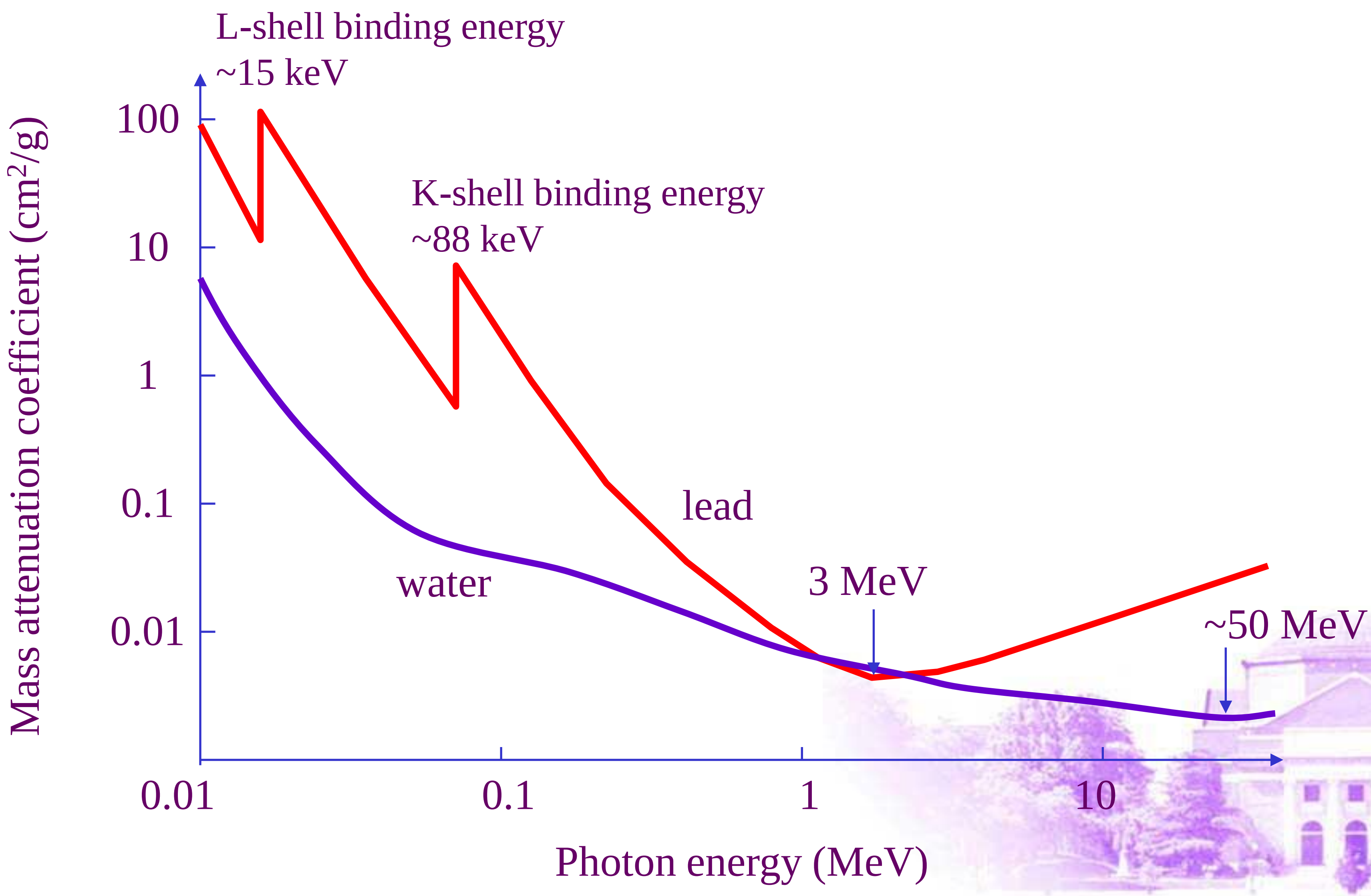
Technology Principle

- Physics Basis
  - Different Energy X-ray pass through different material, the attenuation is different



$$P(E_e, E', t_m, Z) = P_0(E_e, E') \cdot e^{-\frac{\mu(E',Z)}{\rho} \cdot t_m}$$

Photoelectric effect/ Scattering/ Pair production



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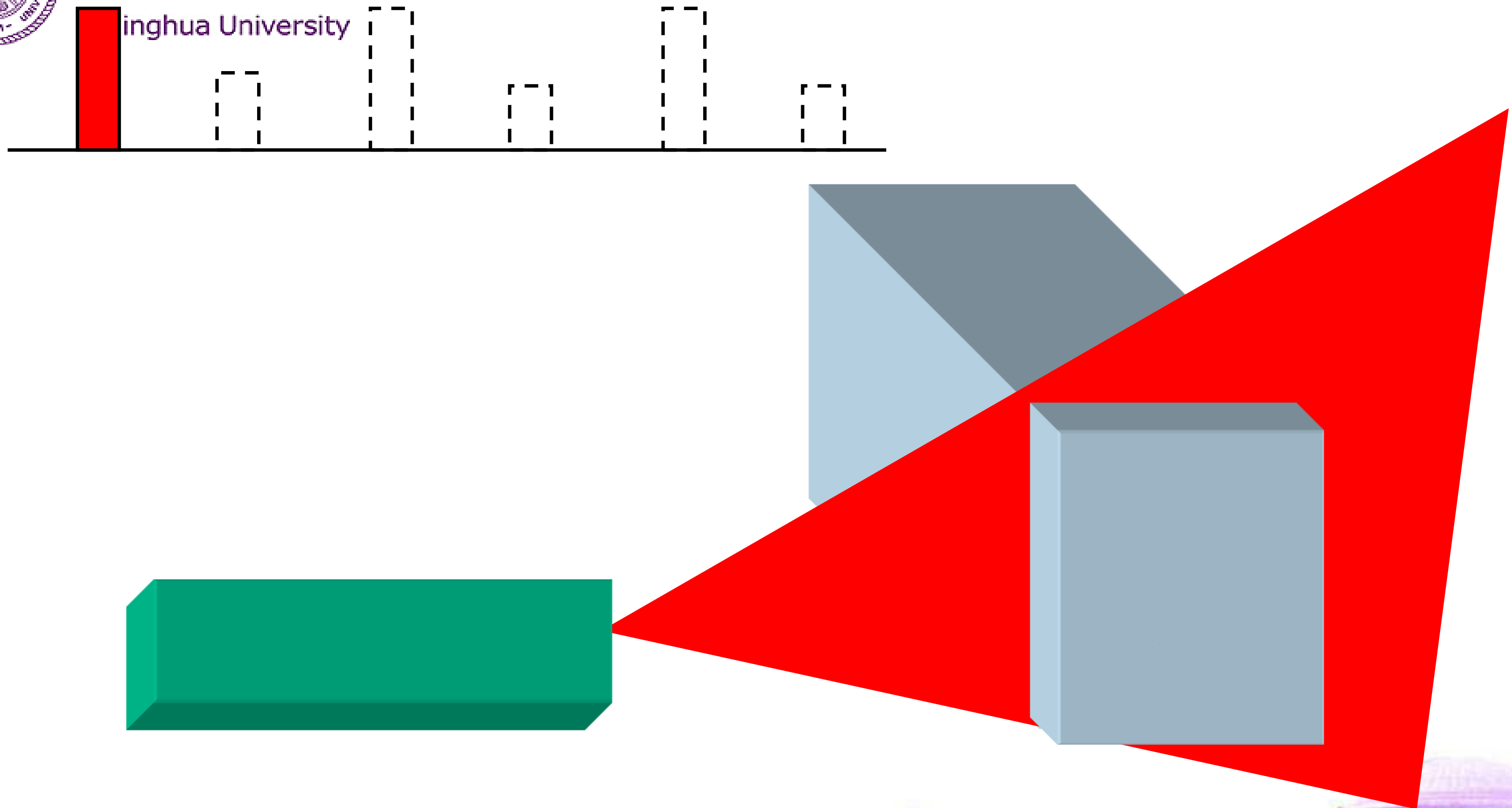
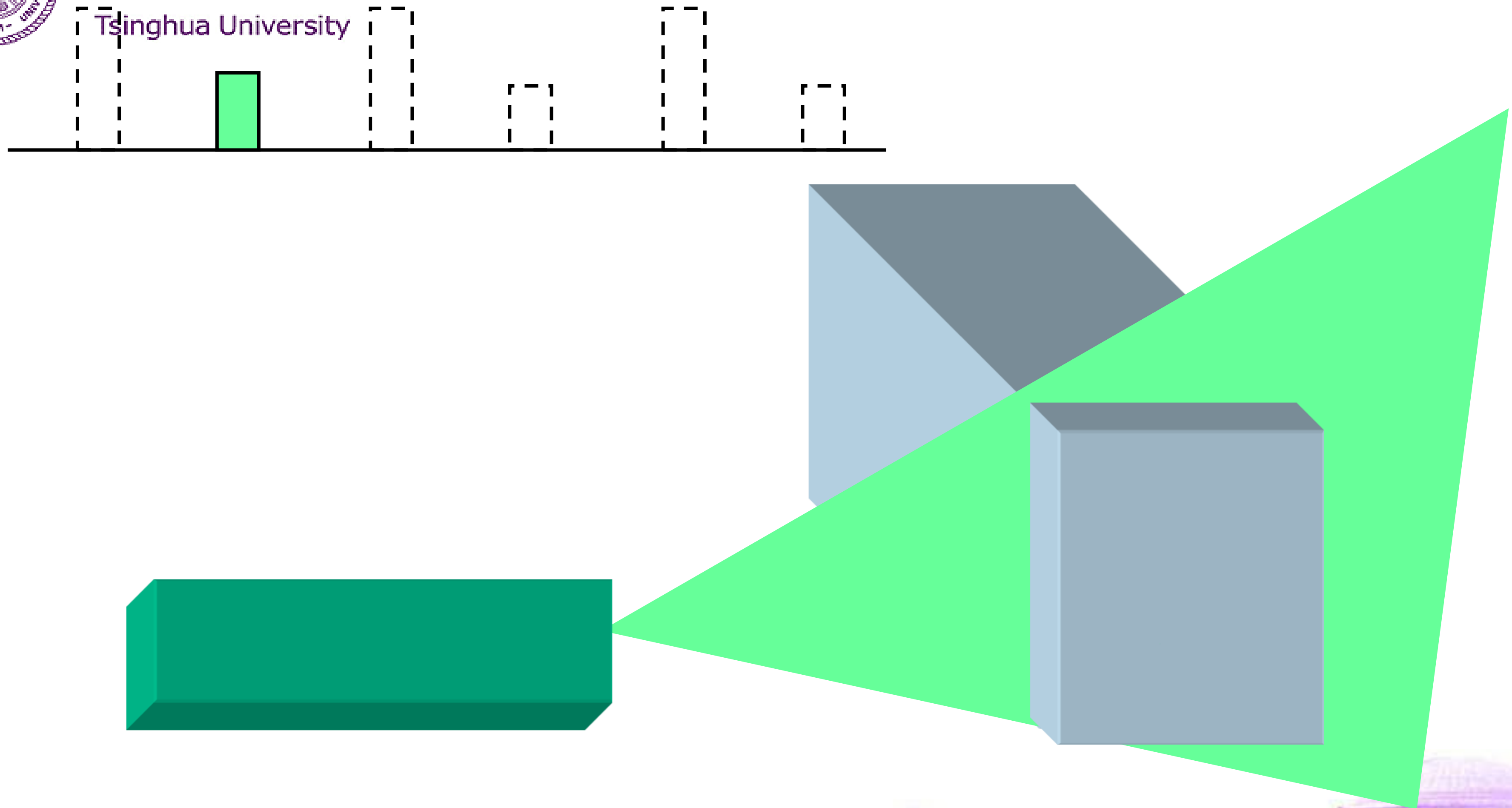
Realization method

- Using two different energy level X-ray to scan the container
- Using special algorithm of material discrimination to process these two X-ray signals, obtain the atomic number (Z) of the scanned object, differentiate organic material and inorganic material
- Using different colors to mark different material





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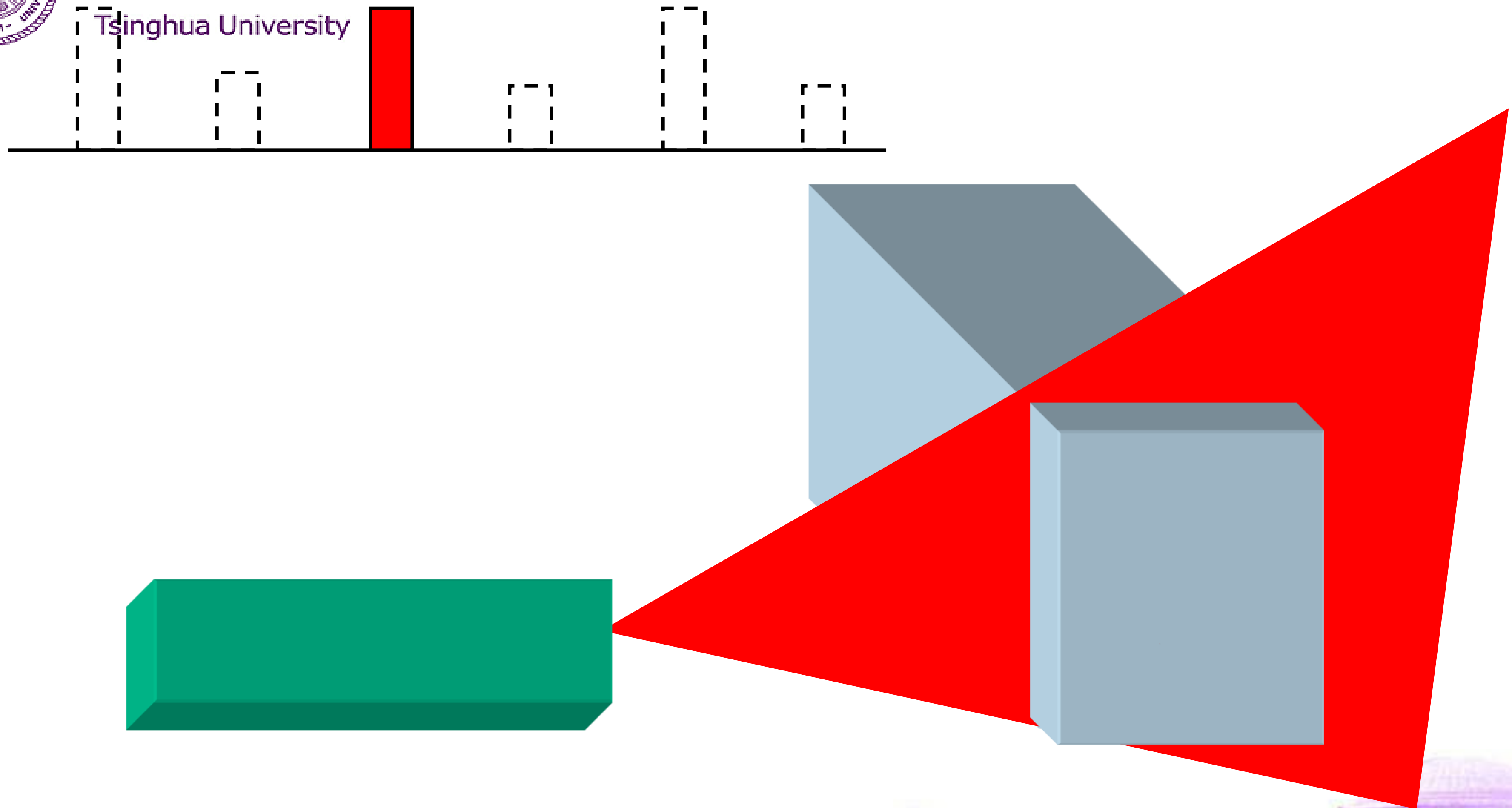
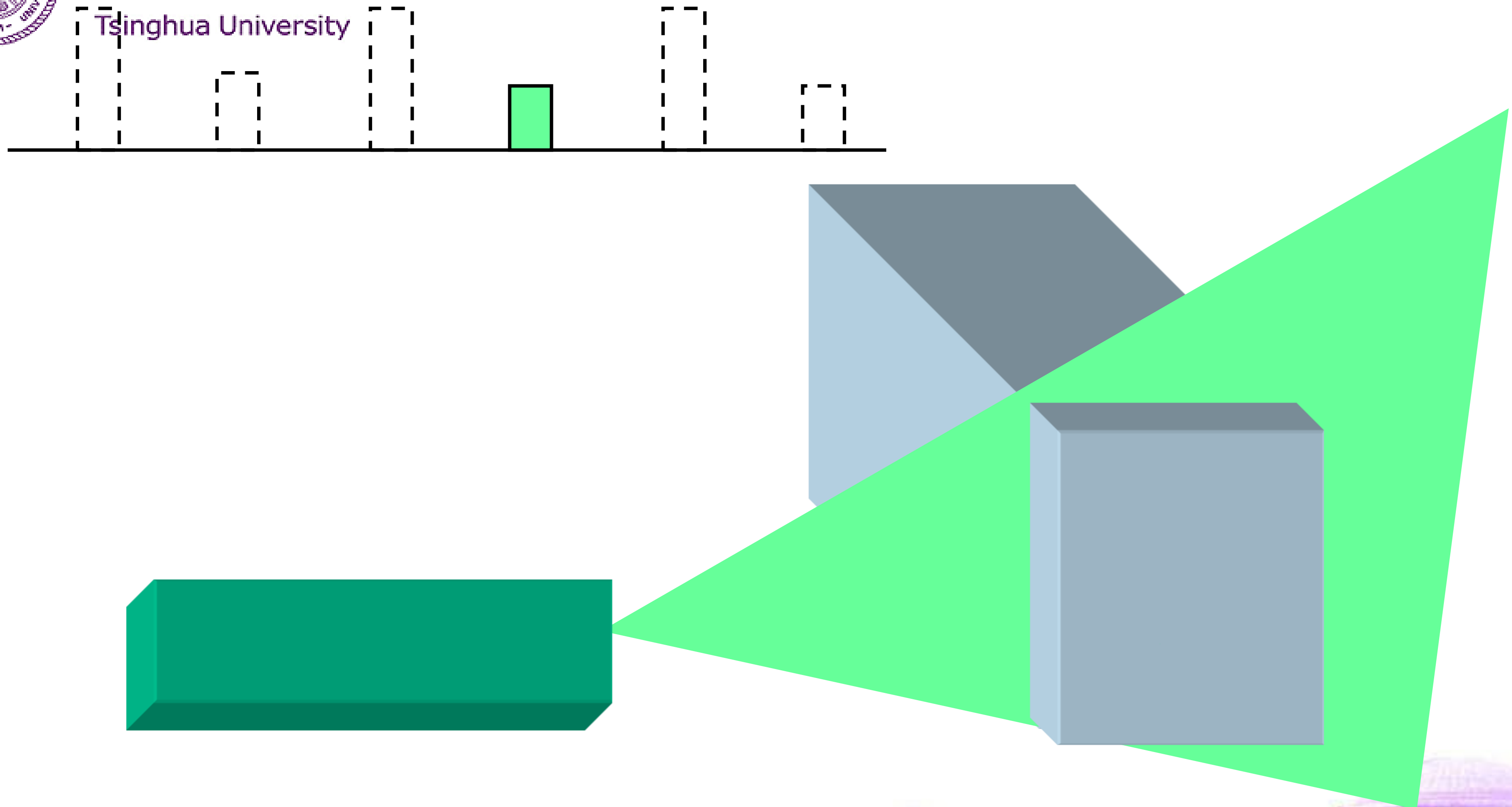
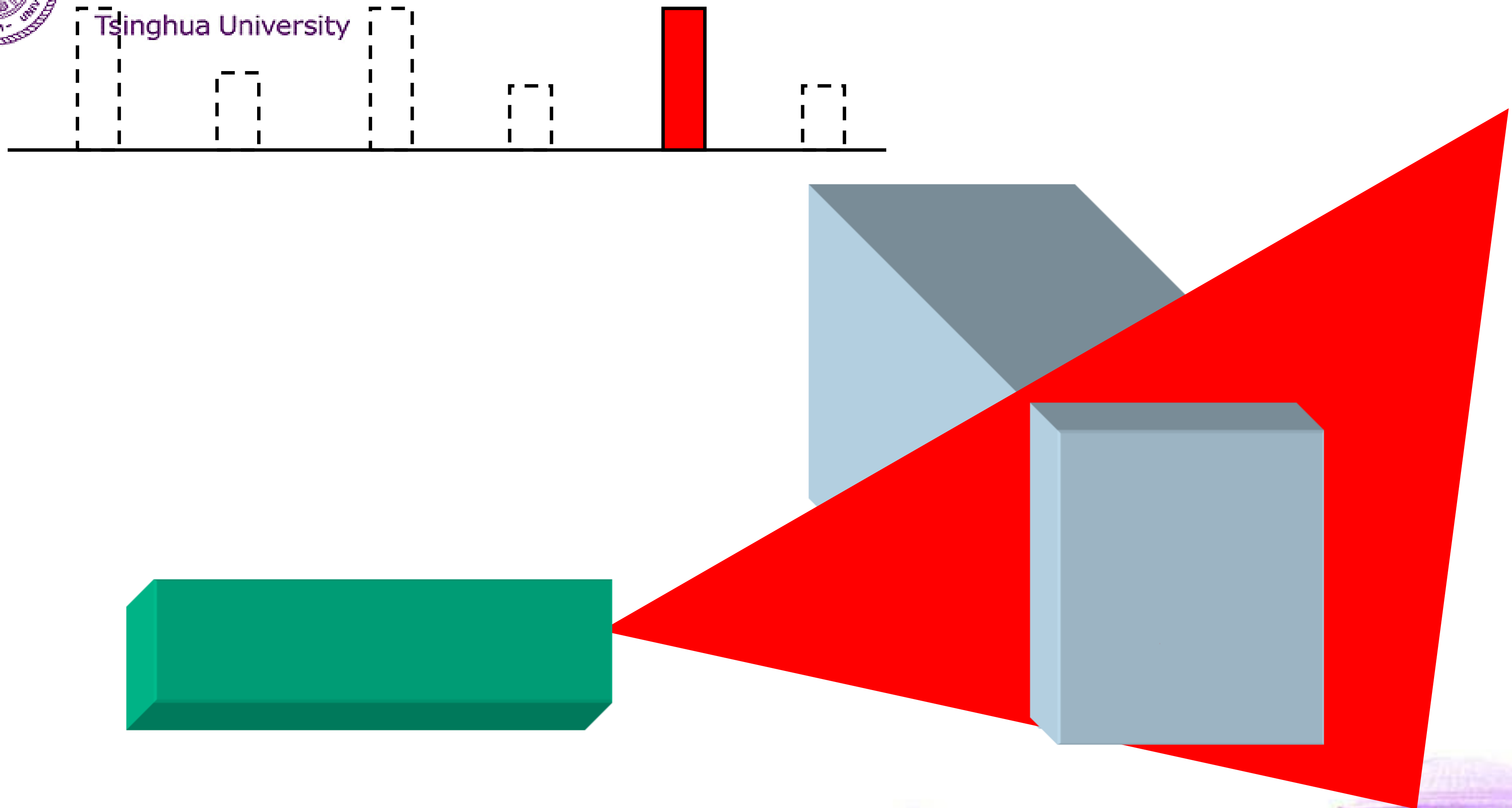
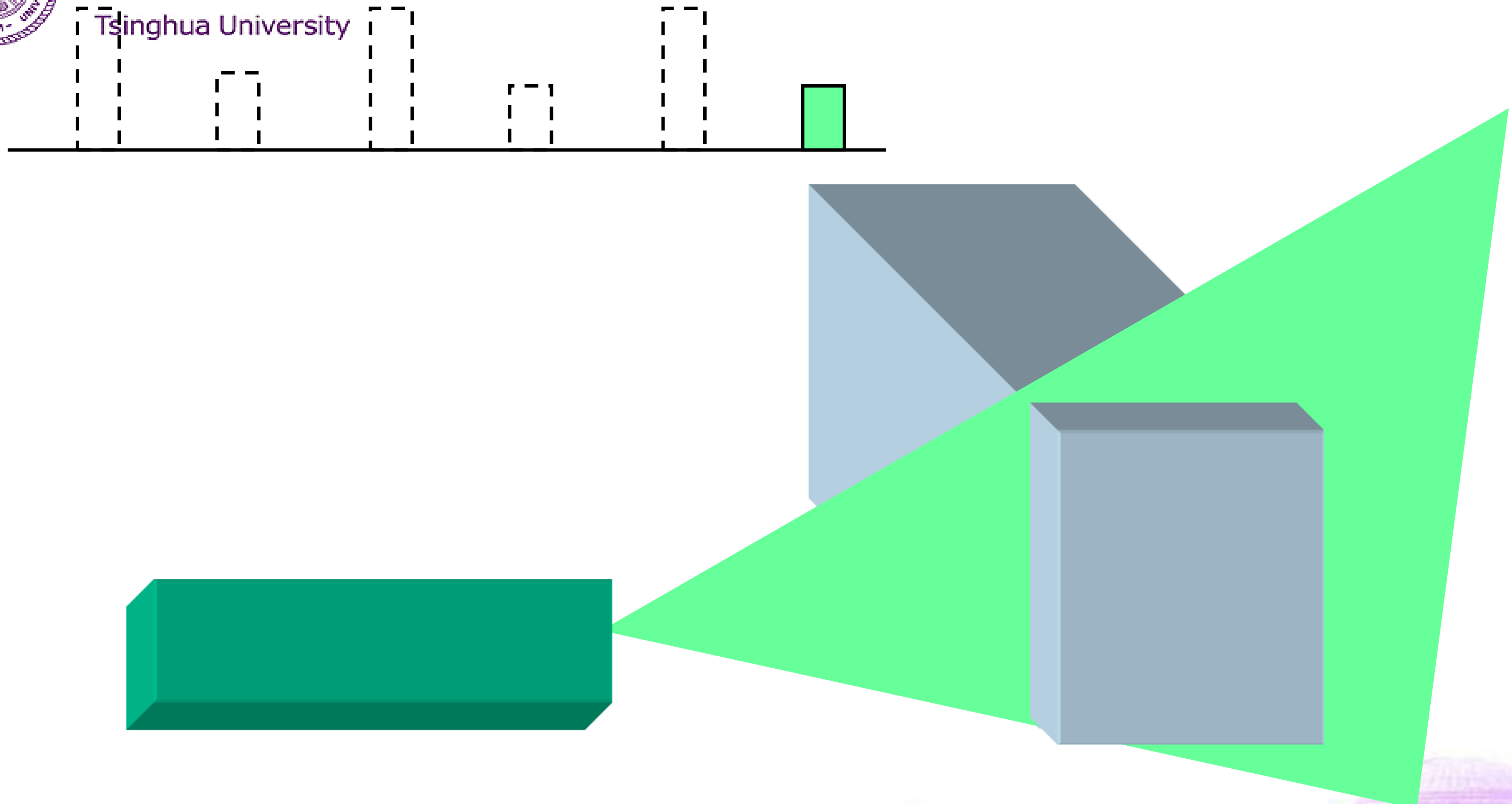
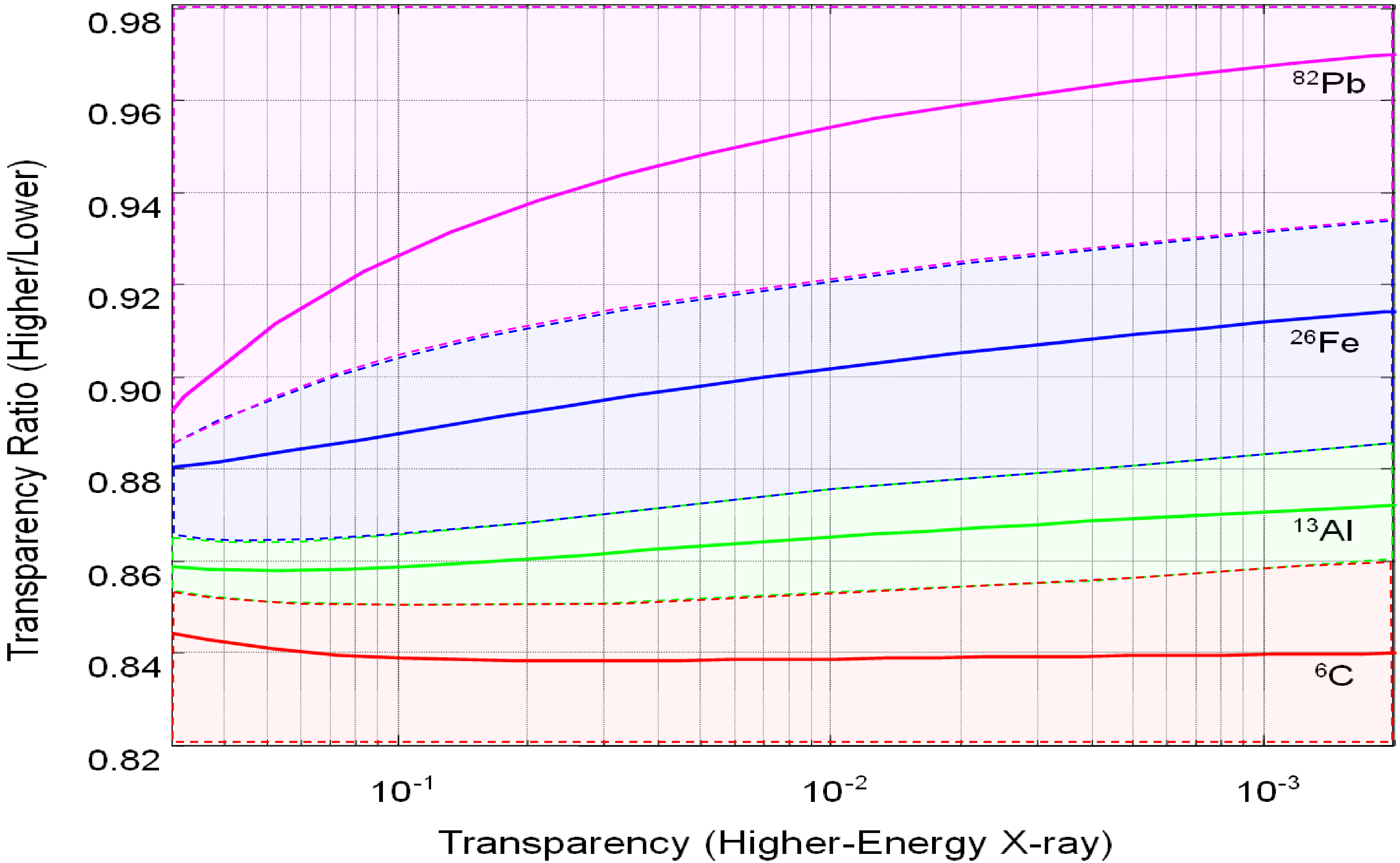


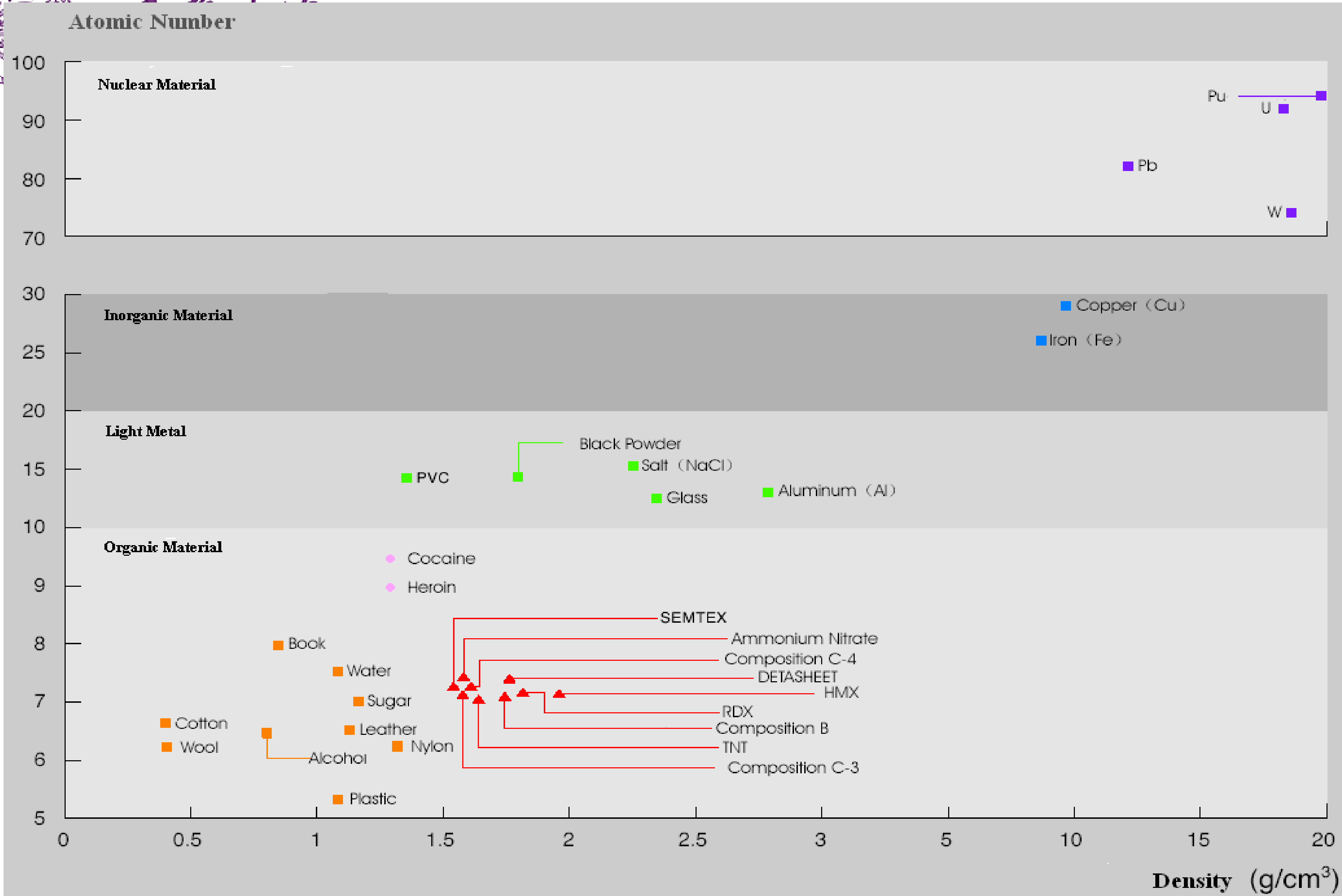






Material Discrimination Coordinate

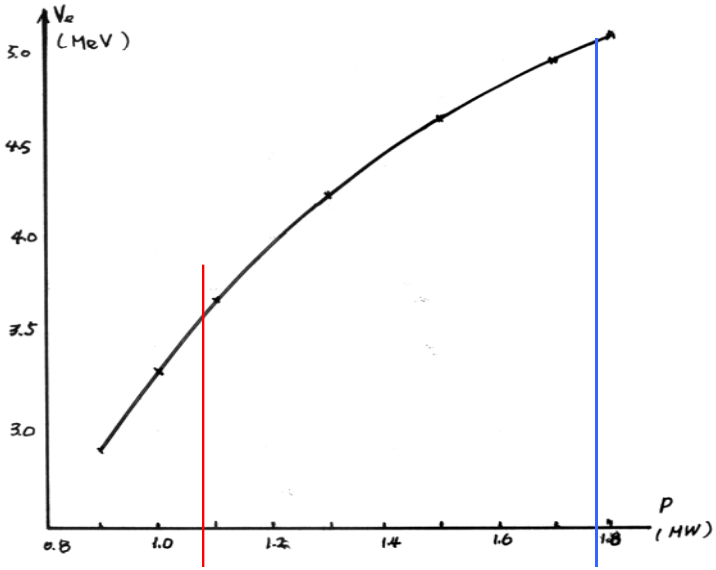


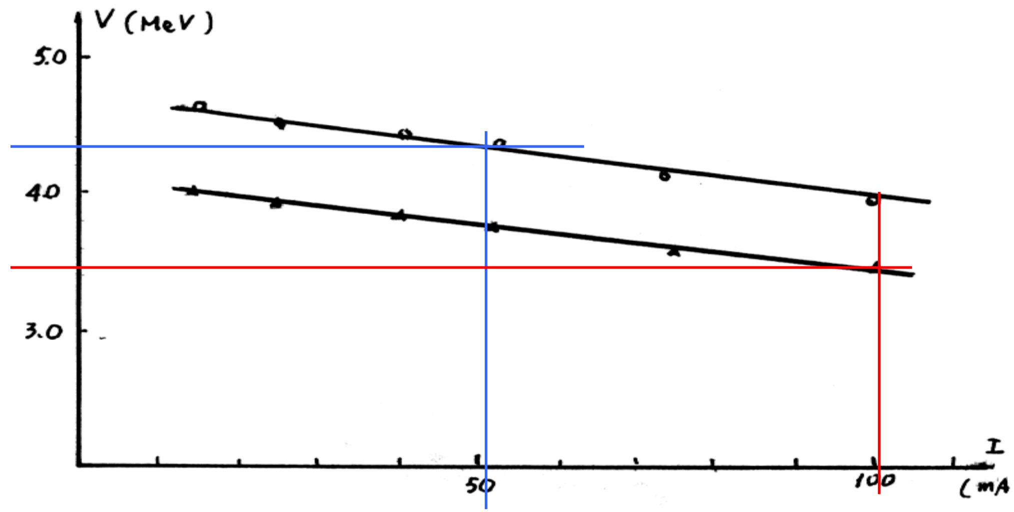


Atomic Number
Nuclear Material
Pu
U
Pb
W
Inorganic Material
Copper（Cu）
Iron（Fe）
Light Metal
Black Powder
Salt（NaCl）
PVC
Glass
Aluminum（Al）
Organic Material
Cocaine
Heroin
SEMTEX
Ammonium Nitrate
Composition C-4
DETASHEET
HMX
RDX
Composition B
TNT
Composition C-3
Book
Water
Sugar
Cotton
Leather
Wool
Alcohol
Nylon
Plastic
100
90
80
70
30
25
20
15
10
9
8
7
6
5
0
0.5
1
1.5
2
2.5
3
5
10
15
20
Density (g/cm3)

X-ray Source-The Dual Energy Linac

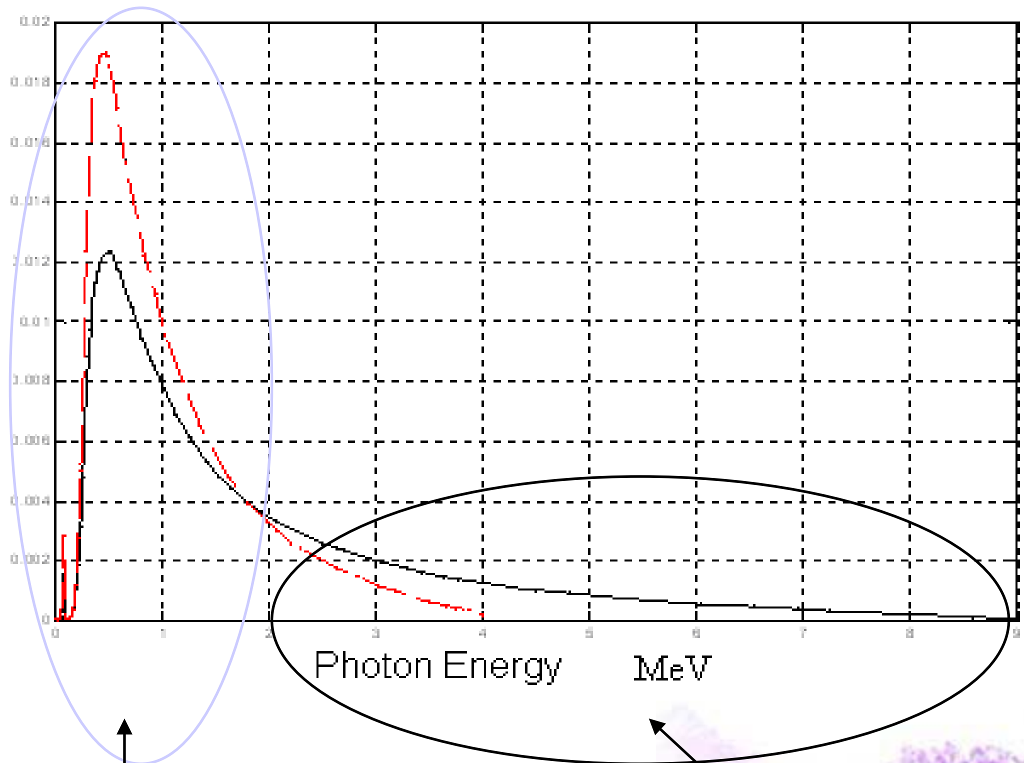
- Interlaced Dual Energy





$$V = a\sqrt{P} - BI$$

Dual Energy X-ray



Low Energy X-ray

High Energy X-ray

Image Example and Photo Grey Image of a Van with Different Tested Samples

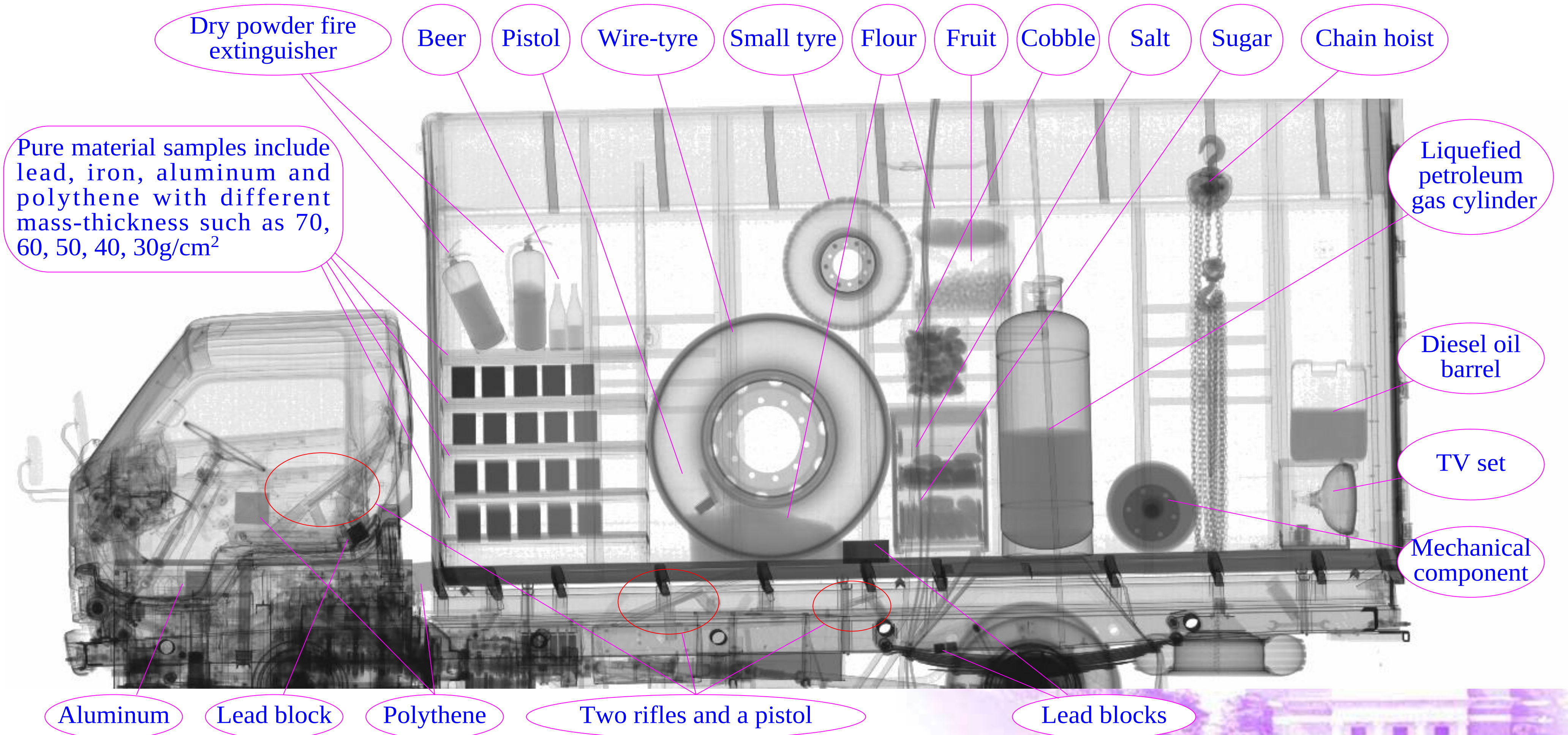
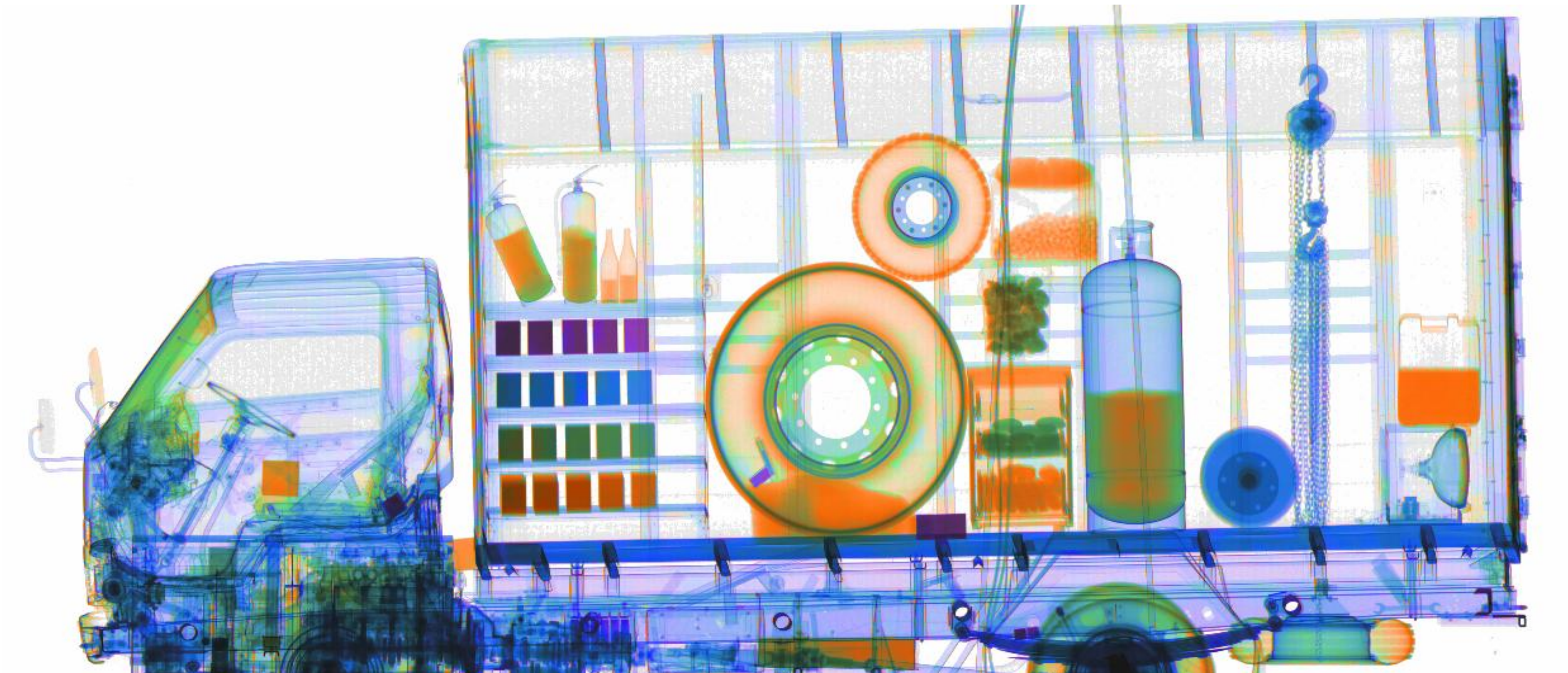


Image Example and Photo Dual-Energy Color Image of a Van with Different Tested Samples



Dual-Energy Color Image: obtained by processing of dual-energy material discrimination algorithm according to effective atomic number

3.4 X-RAY PHASE CONTRAST IMAGING (PCI)

From
Haisheng Xu

X射线 → 照射 → 物体 → 接收数据 → 成像

相互作用

复折射率 n=1-δ+iβ

$$\tilde{E}(z) = E_0 e^{iknz}$$

$$\tilde{E}(z) = E_0 e^{-k\beta z} e^{ik(1-\delta)z}$$

振幅变化 → 光强差别 → 探测器

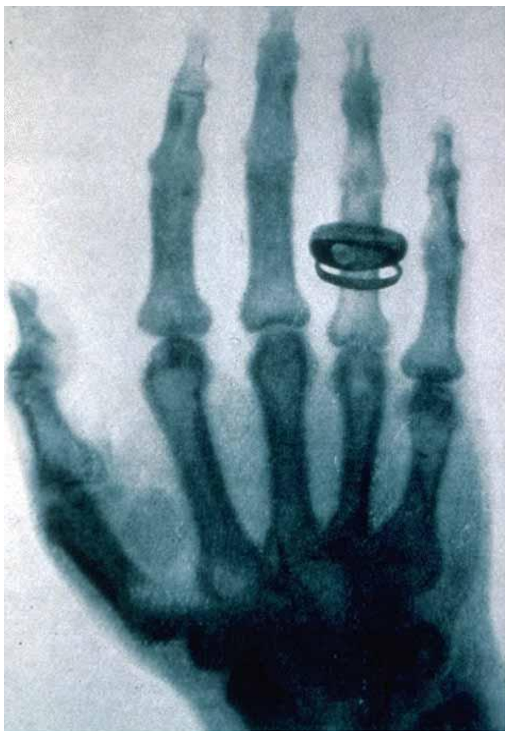
相位变化 → 光强差别 → 探测器

干涉法

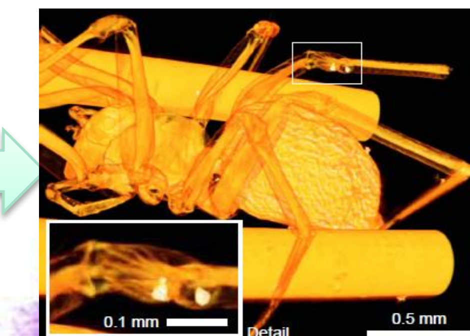
衍射增强法

类同轴全息法

光栅成像法



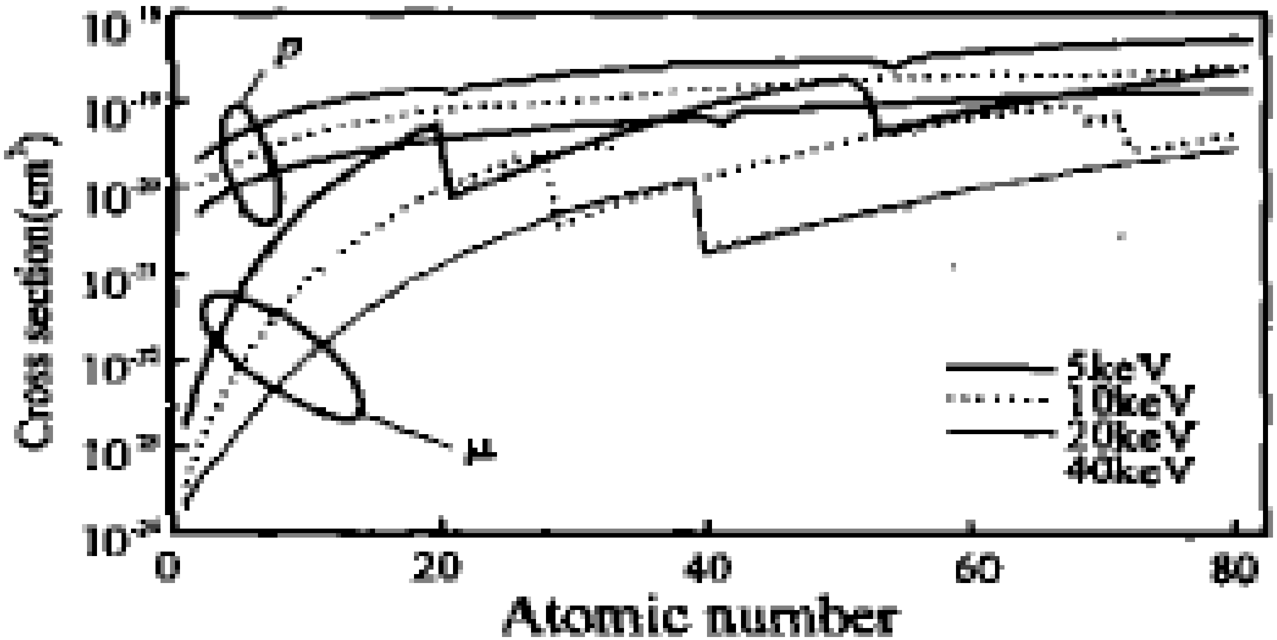
http://zh.wikipedia.org/zh-cn/X%E5%B0%84%E7%BA%BF



Timm Weitkamp et. al, OPTICS EXPRESS, Vol. 13, No. 16,8 August 2005,P6296-P6305

X 射线相衬成像物理基础

From Haisheng Xu



不同原子序数及x射线能量，x射线吸收和相移的相互作用截面的比较图

$$n=1-\delta+i\beta$$

$$\beta=\frac{\lambda}{4\pi}\sum_k N_k \mu_k$$

$$\delta=\frac{\lambda}{2\pi}\sum_k N_k P_k$$

相移截面大！

$$\beta(E)\approx O(E^{-4})$$

$$\delta(E)\approx O(E^{-2})$$

随能量提高相移截面减小速度慢！

生物、医学中研究的样品大多原子序数较低 → 传统吸收成像衬度低 → 相衬成像！

- ✓ 更适用于低原子序数 的物质组成的物体成像！
- ✓ 更适用于原子序数相近的物质组成的物体成像！

例 当x射线能量为20keV时，水对x射线的吸收项 β=6E-10， 相移项 δ=5.8E-7

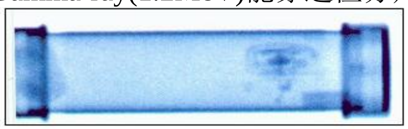
陈建文 等，x射线相衬成像，物理学进展，Vol25（2），2005

中子照相、动态成像和断层摄影术：与X光技术互补

可见光只看外表

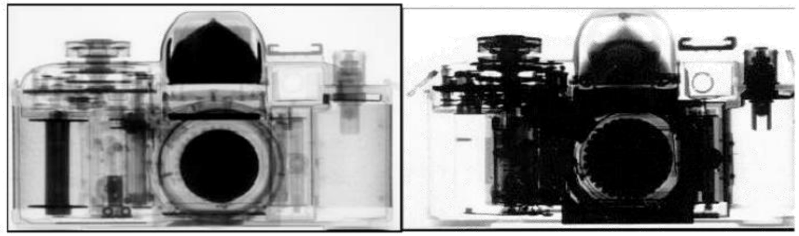
X-光(150keV)不能看穿

Gamma-ray(1.2MeV)能穿透但分辩力差

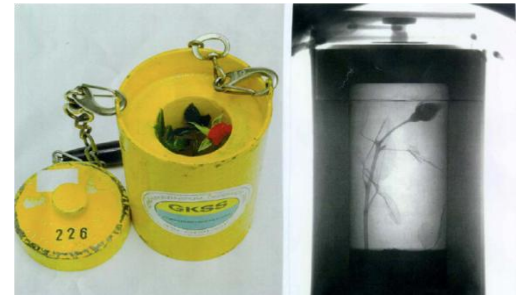


中子(25meV)能穿又能见

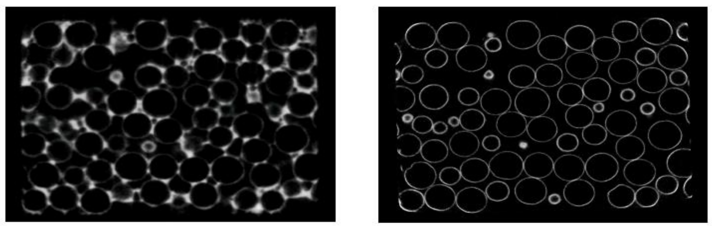
中子(左）黑色的是含氢组件（如胶卷）
X-光(右）看到的是金属部分，看不见胶卷



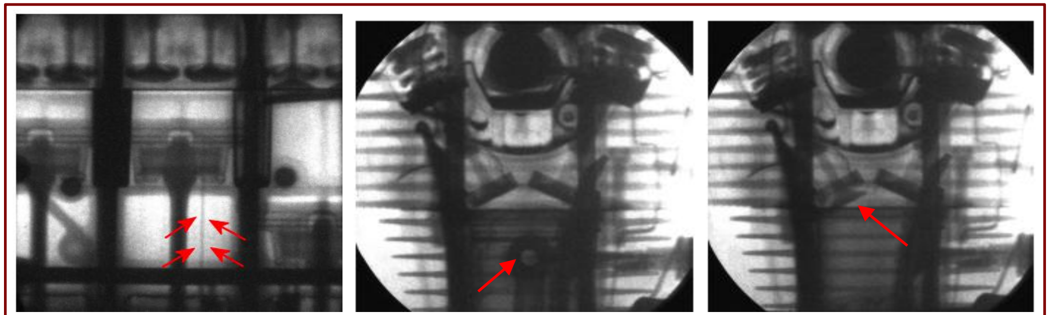
中子可穿透厚金属看见里面的有机物质



断层摄影
中子(左）看到球与球之间的粘胶
X-光(右）只看到空的金属球

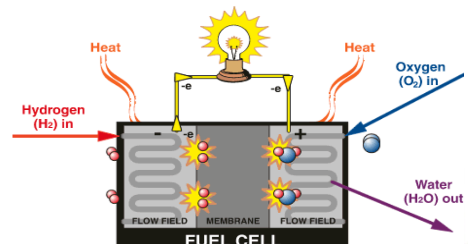


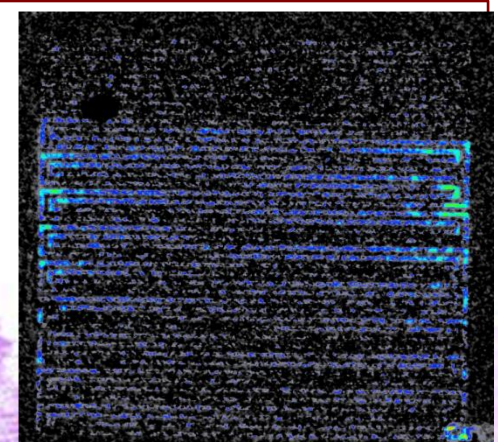
普通照相(左）只看到车门外表
中子照相(右）看到内部粘口、焊接、或裂缝、被腐蚀的位置等等



脉冲中子源特别善于动力照相。左上图：中子照相看到汽车引擎开动时的某一瞬间油丝从活塞渗出。右上图看到活塞活门不同时刻的位置情况。

Courtesy of M. Arif (NIS)





燃料电池操作时(左上电影）水必须在细密的管道流通。
中子动态成像(右电影）可看见水的流动情况，探出与电池性能的关系。

Courtesy of C.K. Loong

4 Irradiation

4.1 Basic Concepts

Dose and Dose Rates

- Dose Unit:

$$1\ \mathrm{Gy} = 1\ \mathrm{Joule} / \mathrm{kg}$$

- Dose Rate Unit:

$$1\ \mathrm{KGy/sec.}\ \text{or}\ 1\ \mathrm{KGy/min}$$

Electron Range

- Electron range in water (cm) ≌electron energy/2 (MeV).
- Electron range is inversely proportional to the density of the Irradiated material.
- For example, 10 mm Al (2.79g/cm^3) =>**27** mm H_2O.

Irradiation Efficiency (η)

- Cross-linking of polyethylene roads

$$\eta = 60 \sim 70\%$$

- Cross-linking of cable

$$\eta = 15 \sim 50\%$$

Processing capacity, W (*Kg/hr*)

$$W = 3600 \times \frac{P}{D} \times \frac{\eta}{100}$$

Where P is the beam power (*kW*)

D is the required dose

辐照加工技术简介

From
Chen Li

- What is irradiation?

Irradiation is the process to change molecular structure of an item, which is exposed to radiation.

In common usage it refers specifically to ionizing radiation, and to a level of radiation that will serve specific purpose.

Ray species: *X-rays, gamma rays, electron beam*

Classification
- *Food irradiation*
- *Sterilization for medical devices*
- ***Industrial irradiation***

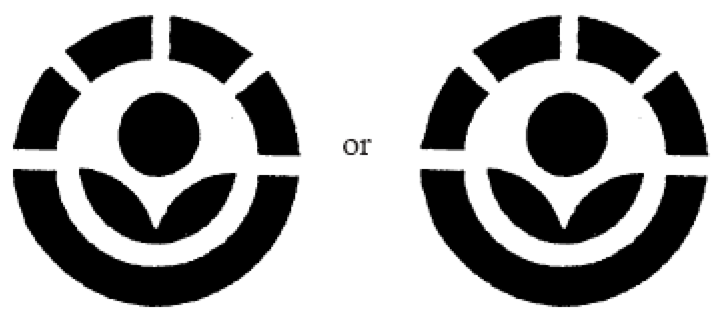
食品辐照 Food Irradiation

- The radiation of interest in food preservation is ionizing radiation, also known as irradiation. These shorter wavelengths are capable of damaging microorganisms such as those that contaminate food or cause food spoilage and deterioration.

- **Two things are needed for the irradiation process.**

  1) A source of radiant energy, and

  2) a way to confine that energy.



Treated with irradiation   Treated by irradiation

Potential food irradiation uses

Type of food	Effect of irradiation
Meat, poultry, fish	Destroys pathogenic organisms, such as *Salmonella*, *Clostridium botulinum*, and Trichinae
Perishable foods	Delays spoilage; retards mold growth; reduces number of microorganisms
Grain, fruit, vegetables, dehydrated fruit, spices and seasonings	Controls insect infestation
Onions, carrots, potatoes, garlic, ginger	Inhibits sprouting
Bananas, mangos, avocados, papayas, guavas, other non-citrus fruits	Delays ripening
Grain, dehydrated vegetables	Reduces rehydration time

Table 1: *Food approved for irradiation*

Product	Dose Permitted (kGy)	Date	Purpose
Wheat, Wheat Flour	0.2-0.5	1963	Insect Disinfestation
White Potatoes	0.05-0.15	1964	Sprout Inhibition
Pork	0.3-1	1985	*Trichinella spiralis* control
Dried Enzymes	10 (max.)	1986	Microbial control
Fruit	1 max.	1986	Delay ripening, insect disinfestation
Vegetables	1 max.	1986	Disinfestation
Herbs & Spices	30.max	1986	Microbial control
Vegetable seasonings	30 max.	1986	Microbial control
Poultry	3 max.	1990	Microbial control
Frozen , packaged meat for use in space program	44 min.	1995	Sterilization
Animal feed & pet food	2-25	1995	*Salmonella* control
Meat, uncooked, chilled	4.5 max.	1997	Microbial control
Meat, uncooked, frozen	7.0	1997	Microbial control

Source: Olson, D.G. Food Technology, 52(1), 1998.

From
Chen Li

- Industrial irradiation

Vulcanization of rubber , e.g. cross-link

Pollution Control , e.g. NOx and SO_x

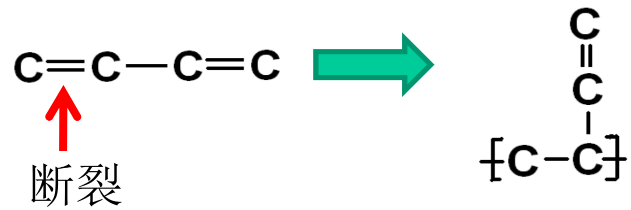
Material modification , e.g. carbon-fiber or semiconductor

Surface processing , e.g. Gem & Glass

辐照交联技术基本原理

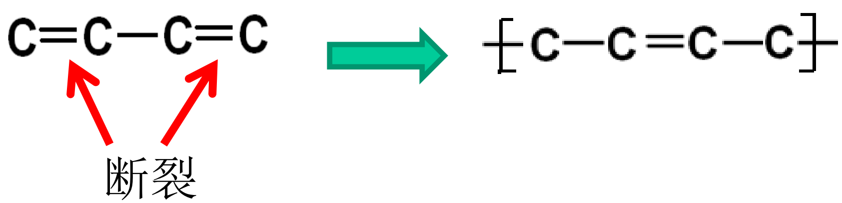
From
Chen Li

1-2加成



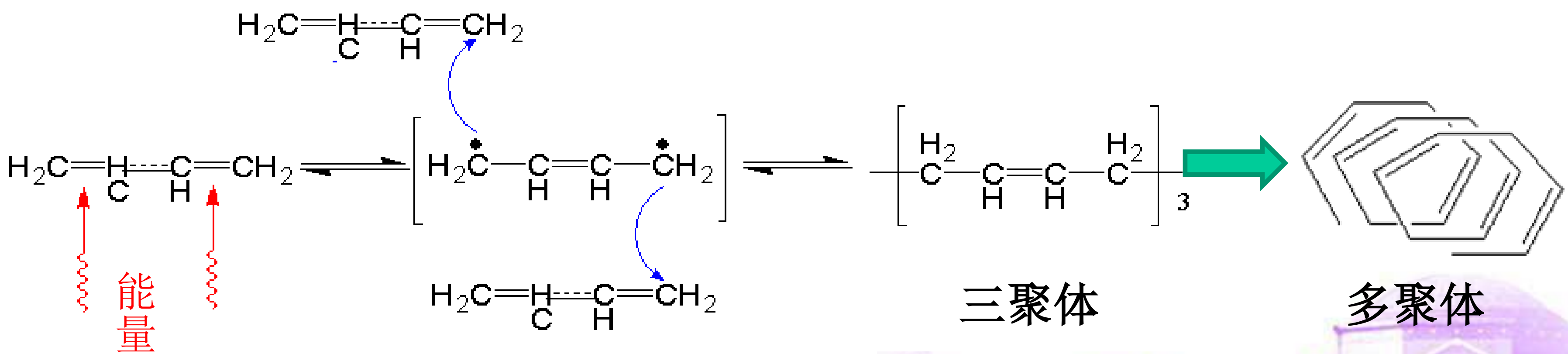
化学活性强

1-4加成



稳定性强

加成的选择性？
键能不同



单体　　交联

不同的剂量可以控制交联度，
韧性与刚性

Irradiation Methods

- Two-sided irradiation of insulation of wires and cables.

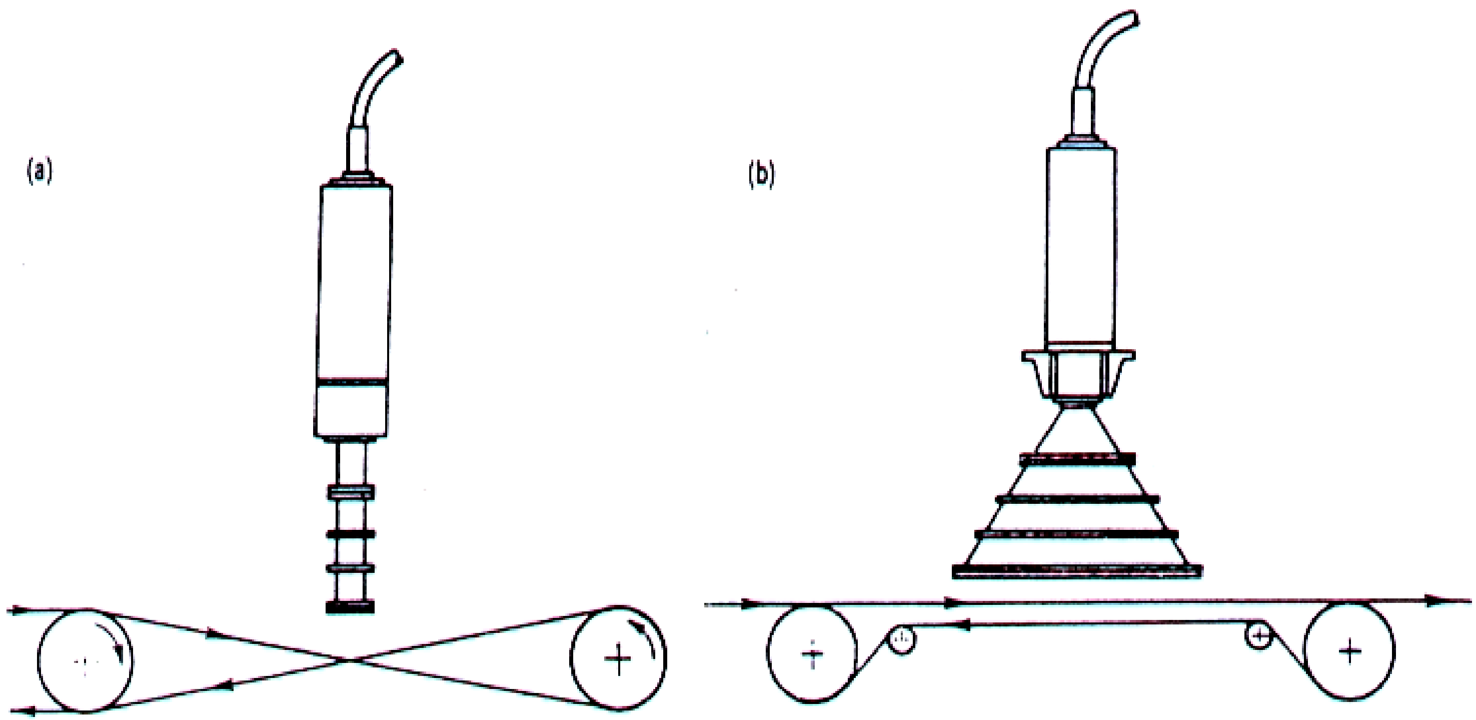


Figure 2.5 (a) figure-of-eight method (b) parallel-wire method

Tsinghua University

◆ Two-sided irradiation of thin foil and arrangement for irradiation of liquid.

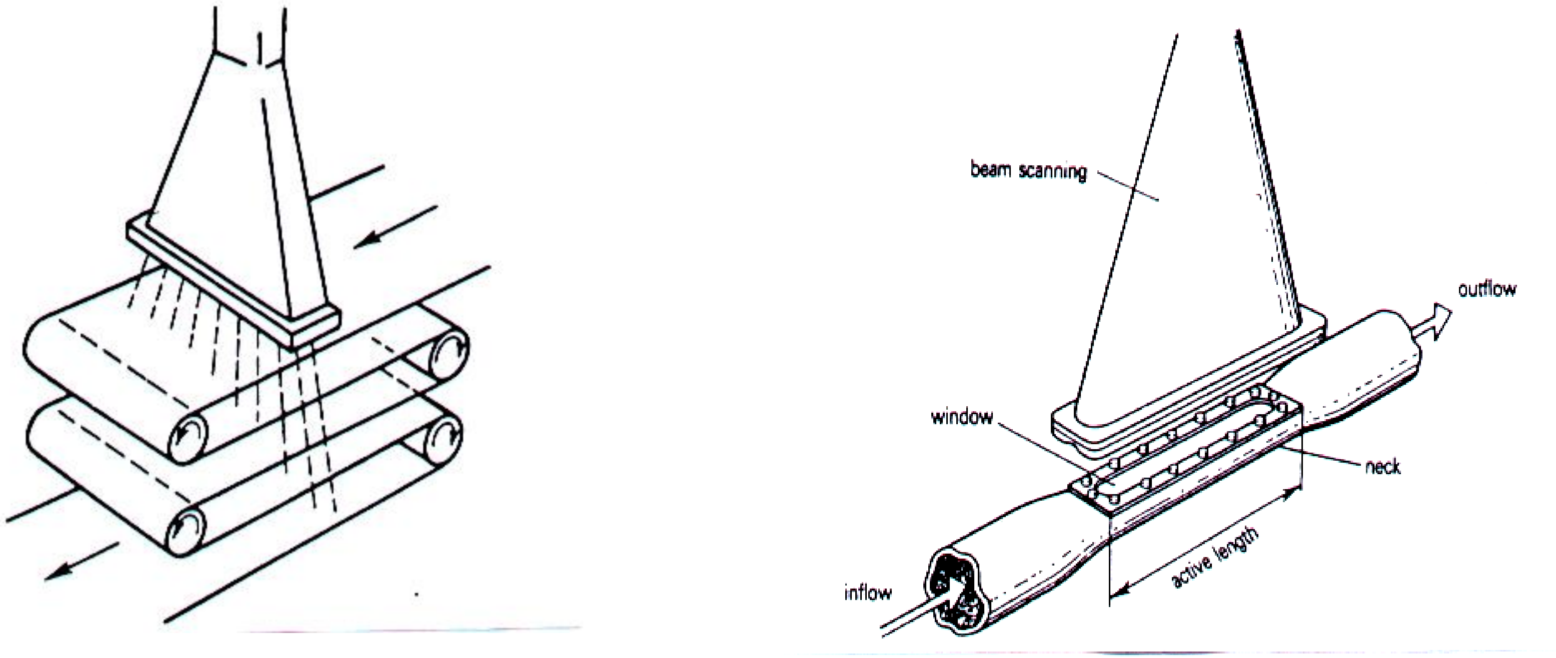


Figure 2.6 (a)Two-sided irradiation of thin foil (b) Arrangement for irradiation of liquid

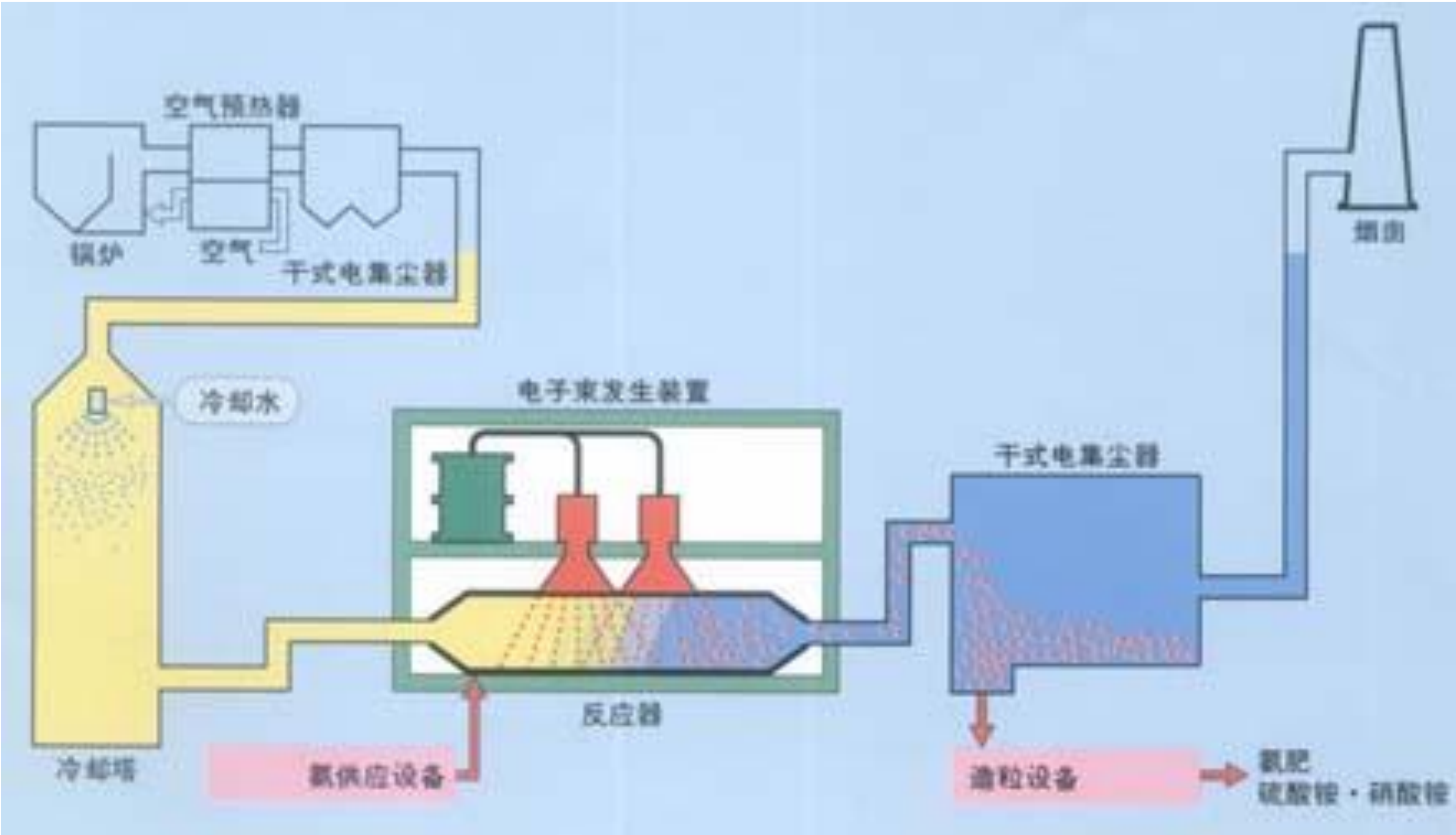


Figure 2.4 The principle of EFGT's technique

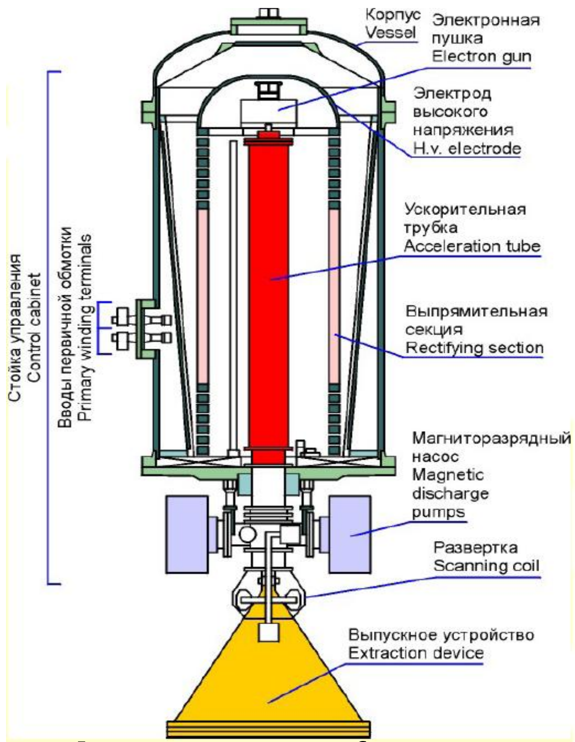
EB Irradiation

- Electron RF Linacs (S-band, L-band)
  – Easy to get high electron energy
  – Hard to get very high electron beam power (<60kW)
- DC High Voltage Accelerators
  – Easy to get high electron beam power
  – Hard to get high electron energy (<5MeV)
- RF High Power Accelerators-Rhodotron, ILU
  – Can be suitable for both high energy and high power

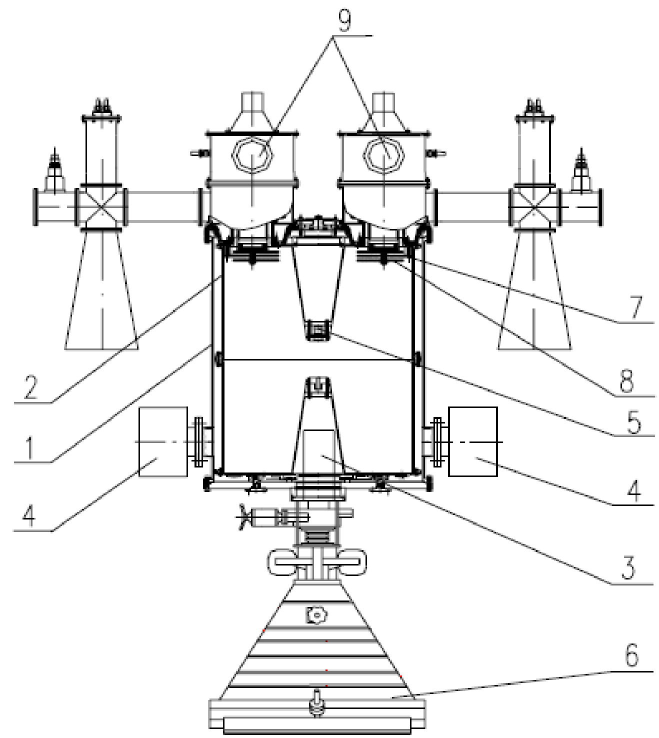
清華大学 Tsinghua University

ELV and ILU developed by BINP

Two kinds of widely used irradiation accelerators in Asia: ELV-DC high voltage type, and ILU based on RF acceleration.



The electron beam power of ELV-12 can reach 400kW with electron energy of 0.6-0.9MeV, and the electron energy of ELV-8 can be 1.0-2.5MeV with beam power of 90kW .



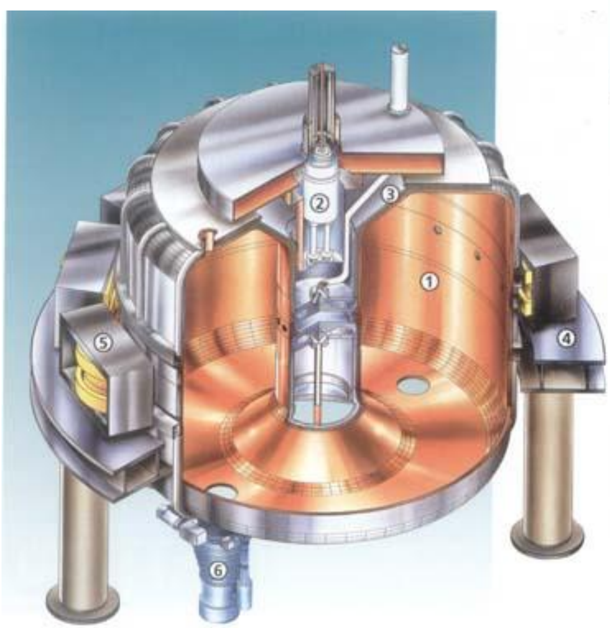
ILU covers the energy range from 0.6MeV to 5 MeV, and the maximum beam power is 50 kW. A 5MeV/300kW ILU accelerator is developing now.

Yu.I. Golubenko, et al, “Electron Accelerator of ELV-Type And Their Worldwide Application”, APAC2007,THPMA118.
V.L. Auslender, et al, “Industrial High Energy Electron Accelerators Type ILU”, Proceedings of RuPAC 2008, P367(2008).

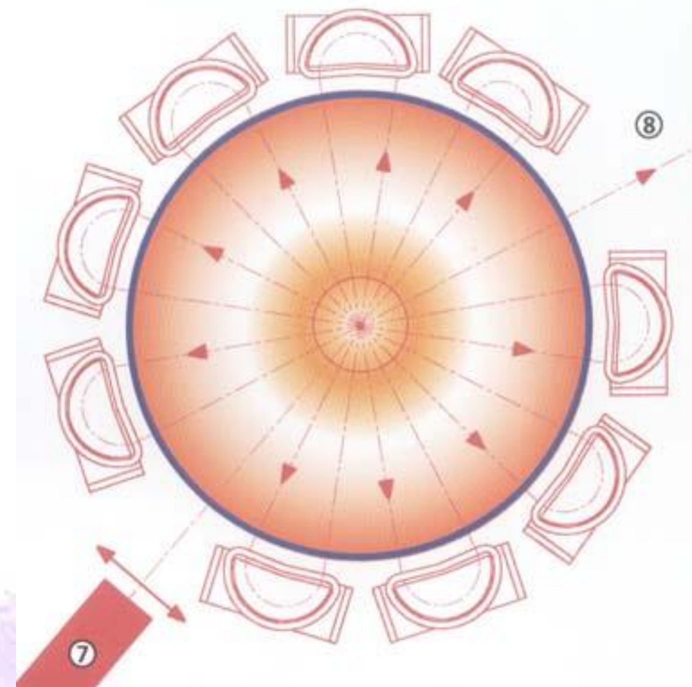
Rhodotron

- Rhodotron is an IBA company's patent product. Its operating principle is shown in the following figures.

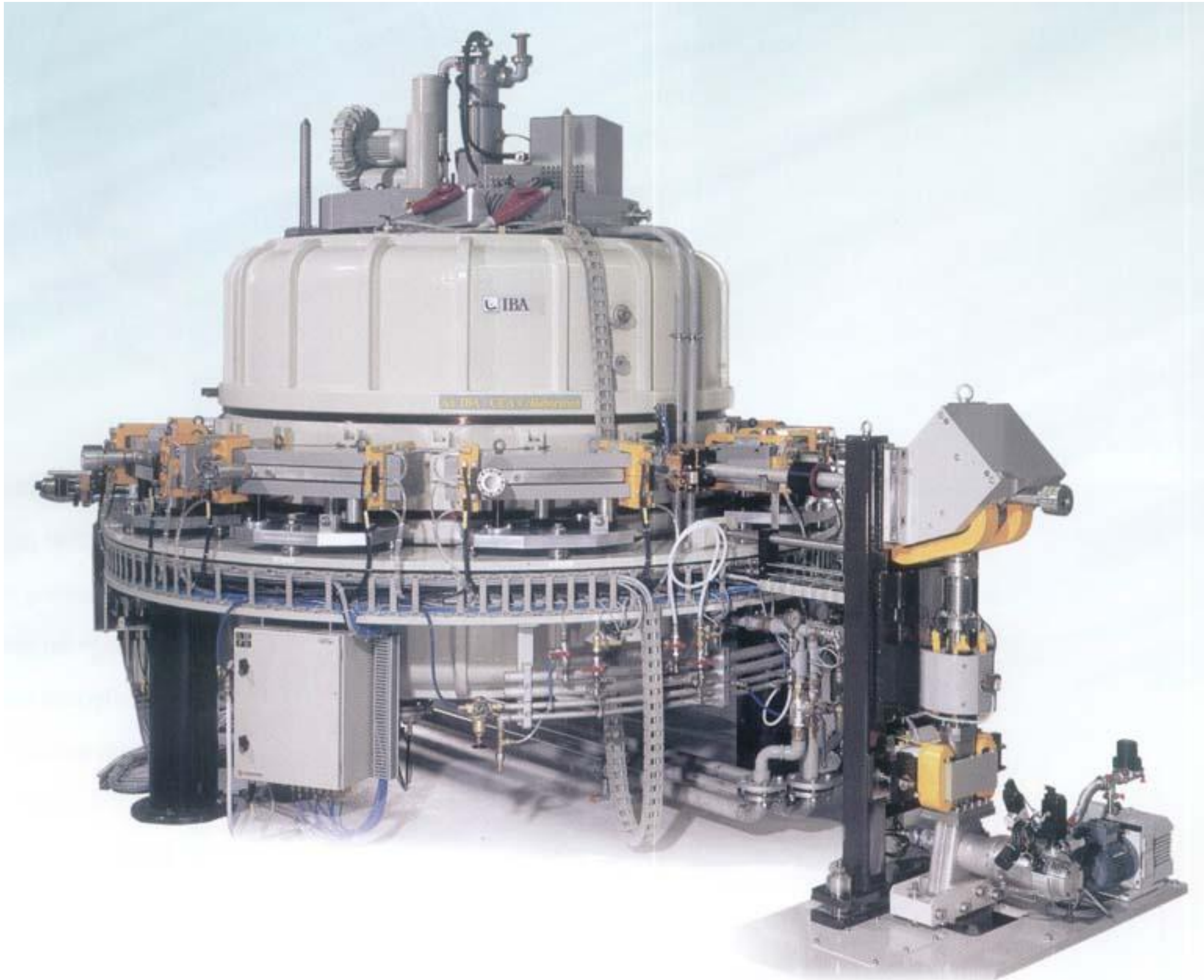
The electrical field is radial and oscillates at a frequency of either 107.5 or 215 MHZ.



1. Coaxial cavity
Final stage RF amplifier (tetrode)
3. Cooling system
4. Supporting rings for magnets
5. Beam deflection magnets
6. High vacuum pump
7. Electron gun
8. Exit port for 10 MeV beam



- Its beam power can reach 150 kW (10MeV).


IBA

Fantron

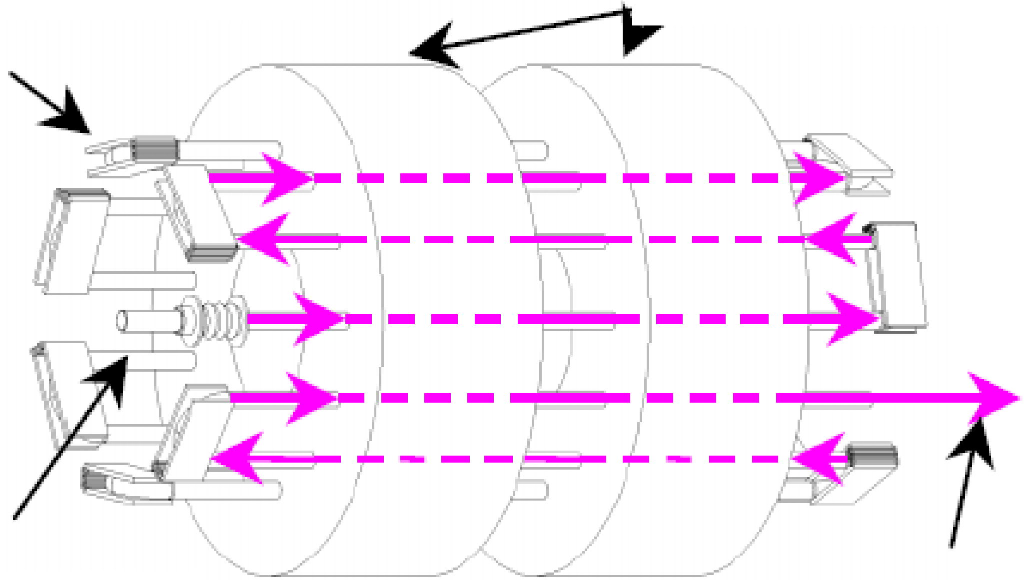


Figure 1. Operating principle of Fantron-I

Hyeok-jung Kwon，Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

Tsinghua University 清華大学

Ridgetron

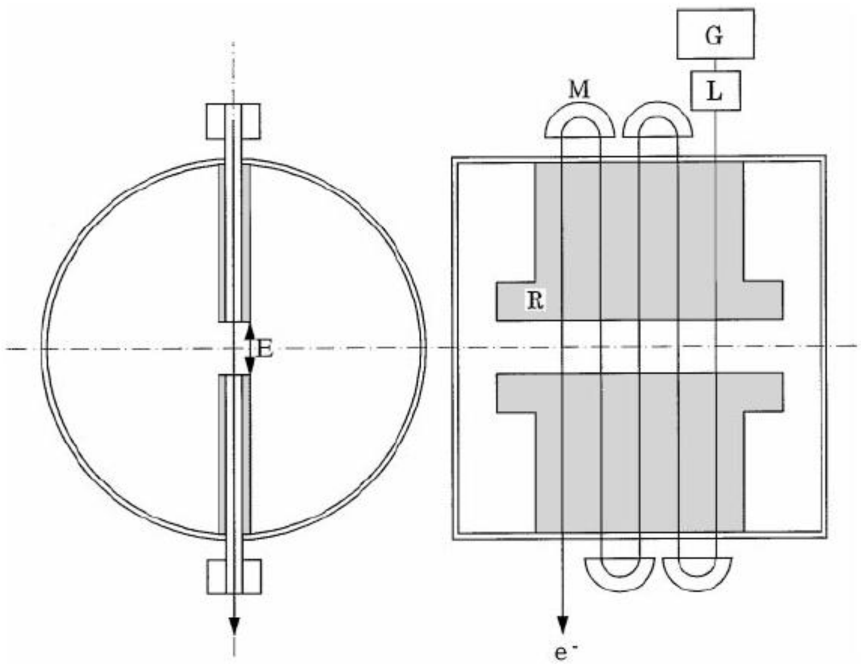


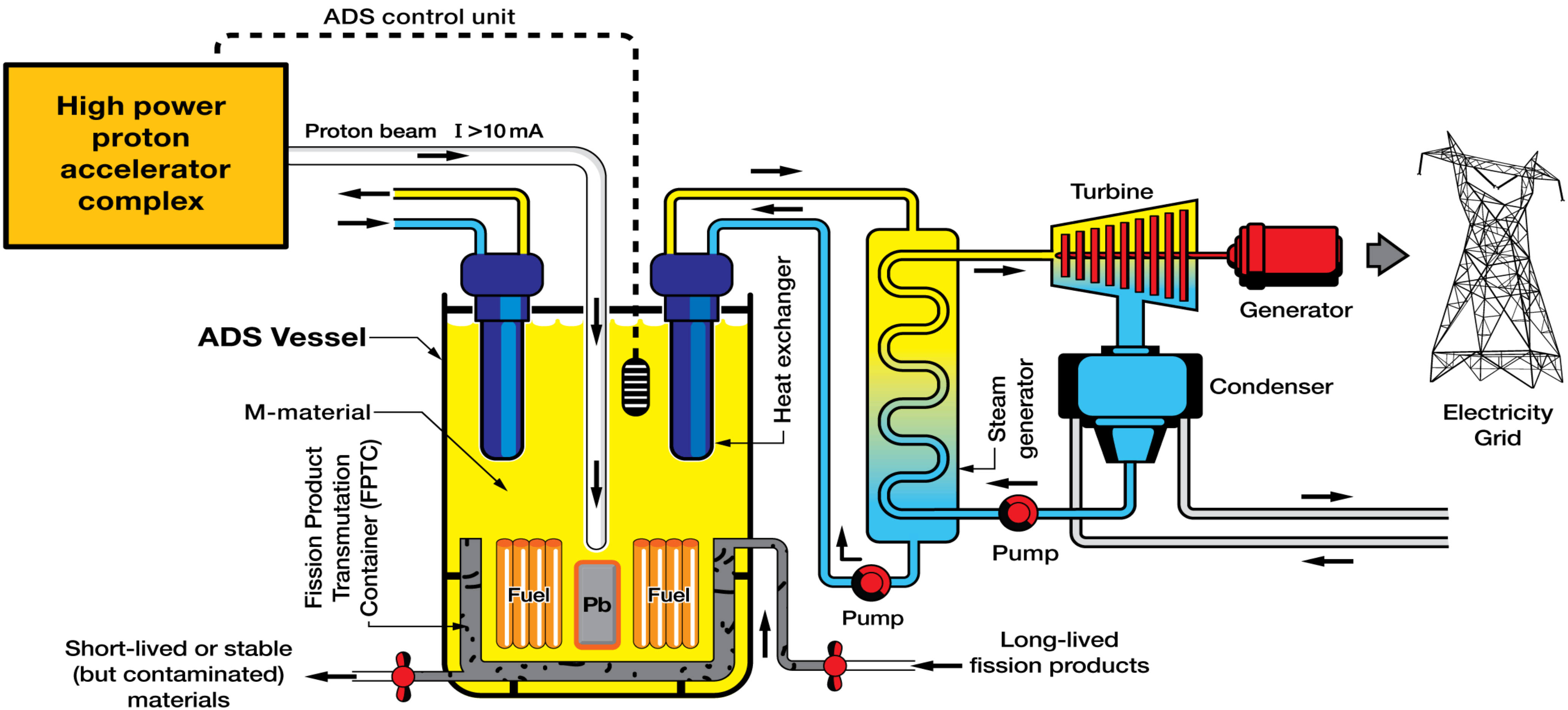
Fig. 1. The schematic drawing of the Ridgetron prototype. G: electron gun; L: solenoid lens; M: deflector magnet; R: hollow ridge; E: electric field.

The design parameters of the Ridgetron prototype

Operating frequency	100 (MHz)
Input energy	0.02 (MeV)
Output energy	2.5 (MeV)
Beam power	6.5 (kW)
Maximum gap voltage	0.5 (MV)
Cavity inner diameter	964 (mm)
Cavity inner length	940 (mm)
Gap length	140 (mm)
Ridge width	80 (mm)
Quality factor	27 000
Shunt impedance	5.9 (M))
RF power loss	42 (kW)

N. Hayashizaki et al. / Nuclear Instruments and Methods in Physics Research A 427 (1999) 28～32

能源-ADS


ADS control unit
High power proton accelerator complex
Proton beam I >10 mA
ADS Vessel
M-material
Fission Product Transmutation Container (FPTC)
Heat exchanger
Fuel
Pb
Fuel
Turbine
Generator
Condenser
Steam generator
Pump
Pump
Electricity Grid
Short-lived or stable (but contaminated) materials
Long-lived fission products

清華大學

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THANK YOU!