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.
Synchrotron Radiation

• Charged particles emit light when they are bent in the accelerator. This high energy light can be used to explore and modify the surface structure of matter. Charged particles crossing a magnetic field are accelerated and therefore emit photons. This effect was first observed in synchrotron accelerators and was called synchrotron radiation. The sharper the bend and the larger the energy of the particle, the larger is the loss of energy due to synchrotron radiation. This is often a large problem when designing a very high energy accelerator. However, the synchrotron radiation is an excellent probe of the surface structures of matter and a tool in producing modern microelectronics. Now the annoying energy loss in circular accelerators has been developed into a dynamic field of research and technical development.

From Nobel e-musium web.
There are about 13,000 accelerators in use around the world:

**General industrial use:**
Sterilisation, imaging

**Research accelerators:**
Particles, synchrotron light used in biomedical, physics, chemistry, biology, material research

**Radiotherapy:**
Cancer treatment with X-rays, protons and other particles

**Ion implantation, surface modifications:**
Controlled semiconductor doping; Changing properties of surfaces

**Radioisotope production:**
Cancer treatment; Imaging organs for medical use
K. Berghe plot, modified by U. Amaldi
Content

1. Basic knowledge
2. Radiotherapy
3. Radiography
4. Irradiation
1.1 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 ion beam: cyclotron, synchrotron, linac

• Imaging
  – PET (Positron Emission Tomography): low energy cyclotron
  – X-ray imaging: x-ray tube, electron linac, betatron, microtron
  – Proton imaging: synchrotron
  – Neutron imaging: nuclear reactor, linac, synchrotron

• Irradiation
  – High Voltage Accelerator (>100kW, <MeV)
  – Electron Linac (<80kW, >5MeV)
  – Others: Rhodotron, LIU, Ridgetron, Fantron
Kinds of Rays

THE ELECTROMAGNETIC SPECTRUM

- **Wavelength (in meters)**: 10^3, 10^2, 10^1, 1, 10^-1, 10^-2, 10^-3, 10^-4, 10^-5, 10^-6, 10^-7, 10^-8, 10^-9, 10^-10, 10^-11, 10^-12
- **Size of a wavelength**: longer, shorter
- **Common name of wave**: Radio waves, infrared, visible, ultraviolet, "soft" X rays, "hard" X rays, gamma rays
- **Sources**: AM radio, FM radio, microwave oven, radar, people, light bulb, the ALS, X-ray machines, radioactive elements
- **Frequency (waves per second)**: lower, higher
- **Energy of one photon (electron volts)**: 10^-9, 10^-8, 10^-7, 10^-6, 10^-5, 10^-4, 10^-3, 10^-2, 10^-1, 1, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6

- **Electron**
- **Proton**
- **Neutron**

- **Optic light**
- **Microwave and RF radiation**

- **Kinds of Rays**
γ-rays:

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

\[
E = h\nu \quad \text{(from few – keV to few – MeV)}
\]

\[
= \frac{hc}{\lambda} = \frac{12.4 \text{ keV} \cdot A}{\lambda}
\]

\[
h = 6.626 \times 10^{-34} \text{ J s} \quad \text{(1 keV = 1.6 \times 10^{-16} J)}
\]

\[
= 4.136 \times 10^{-18} \text{ keV s}
\]

\[c = 3 \times 10^{-8} \text{ m}
\]

\[A \text{ (Angstrom)} = 10^{-10} \text{ m}
\]
**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

Relative Intensity per Energy Interval

Unfiltered

Characteristic Radiation

Excitation Voltage

65 kv

100 kv

150 kv

200 kv

Photon Energy (kev)
Range of x-ray energies:

- 20 – 120 kV: diagnostic x-rays (CT, simulator)
- 120 – 300 kV: orthovoltage x-rays
- 300 kV – 1 MV: intermediate energy x-rays
- 1 MV – 25 MV: Megavoltage x-rays
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.

<table>
<thead>
<tr>
<th>Type of interaction</th>
<th>Photoelectric effect ($\tau$)</th>
<th>Scattering</th>
<th>Pair production ($\kappa$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outgoing particles</td>
<td>1 electron, characteristic x-rays or auger electrons</td>
<td>1 photon</td>
<td>1 positron, 1 electron</td>
</tr>
<tr>
<td>Remarks</td>
<td>Dominant event for diagnostic applications</td>
<td>No energy loss, small angle scattering</td>
<td>Dominant event for therapeutic applications</td>
</tr>
</tbody>
</table>

\[ \mu = \tau + \sigma_{coh} + \sigma_{inc} + \kappa \]
Photoelectric Effect

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

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 $E_K - E_L - E_M$. 
Photoelectric Effect (cont’d)

 Photon energy (MeV)

<table>
<thead>
<tr>
<th>Photon energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>10</td>
</tr>
</tbody>
</table>

Photoelectric mass attenuation coefficient

\[
\frac{\tau}{\rho} \propto \frac{1}{E^3}
\]

\[
\frac{\tau}{\rho} \propto Z^{3\sim4}
\]

L-shell binding energy \(~15\) keV

K-shell binding energy \(~88\) keV

\[\frac{E}{Z} \propto \frac{\rho}{\tau}\]

\[\frac{\tau}{\rho} \propto Z^{3\sim4}/E^3\]
Compton Effect (Dependence on Energy)

Compton effect decreases with increasing photon 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⁺).

\[ h\nu > 1.022 \text{ MeV} \]

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 \((h\nu - 1.022)\) MeV.
Pair Production – cross section

The atomic attenuation coefficient (cm²/atom):
\[ a\kappa \propto Z^2 \]

The mass attenuation coefficient (cm²/g):
\[ \kappa/\rho = a\kappa N_A/A \]
\[ \propto Z^2/A \]
\[ \propto Z \]

Pair production coefficient increases with photon energy.
Relative Importance of Various Types of Interactions

- **Photon energy (MeV)**
  - 0.01
  - 0.1
  - 1
  - 10
  - 100

- **Mass attenuation coefficient (cm²/g)**
  - 100
  - 10
  - 1
  - 0.1
  - 0.01
  - 0.001

- **K-shell binding energy ~88 keV**

- **L-shell binding energy ~15 keV**

- **Lead**

- **Water**

- **3 MeV**

- **~50 MeV**
Electrons:

If negative in charge, they are called ‘electrons’.

If positive in charge, they are called ‘positrons’.

If emitted from a nucleus, they are referred to as β–rays.

If emitted from an atom resulting from a charged-particle collision, they are referred to as δ–rays.

High energy electron beams (6 to 50-MeV for clinical applications) can be produced by linacs, betatrons and microtrons.
Heavy charged particles: **has more favorable depth dose distribution** due to the ‘Bragg’ peak and greater LET (linear energy transfer).

Protons: up to 250-MeV.
Carbon ions: carbon atoms stripped of some electrons.

**Neutrons:** Epithermal neutrons *used in Boron Neutron Capture Therapy (BNCT).*
Energy Loss to the Medium

**Ionization**: The energy lost by the incident particle is sufficiently large to remove an electron from the atom, resulting in an ion pair (negative charged electron & positive charged atom).

**Excitation**: The energy lost by the incident particle is insufficient to cause ionization, but leaving the atom in an excited state.
**Directly ionizing radiation:** charged particles (electrons, protons, $\alpha$-particles) produce large amount of ionization in its energy loss to the medium. (Example: it takes approx. 34 eV to produce 1 ion pair in air. Thus, for an electron to lose 1 MeV of its energy, approx. 30,000 ion pairs are produced.)

**Indirectly ionizing radiation:** neutral particles (photons, neutrons) themselves produce very little ion pairs. Instead, they eject directly ionizing particles from the medium. These charged particles then lose energy to the medium. This is called a two-step process. (Example: a 2-MeV photon, upon interacting with the medium, loses about 1-MeV of its energy, but producing only 1 pair of ions.)
2.1 放射治疗原理

・电离辐射的治疗作用是电离辐射作用于人体后发生一系列物理、化学和生物反应的结果。
・X射线及γ射线作用于物质的原子，发生光电效应、康普顿效应和电子对效应，产生光电子、反冲电子、散射光子、正负电子和电离效应。
・主要与细胞的关键靶（主要是DNA）中的原子作用。
电离辐射对DNA的直接和间接作用
辐射作用的时相阶段

直接作用

物理阶段

化学阶段

生物分子中的能量吸收

激发和电离的分子

重排

原初损伤

分子内能量传递

生物自由基

继发反应

分子的变化

间接作用

环境中的能量吸收

激发和电离的分子

重排

扩散自由基

和生物分子相反应

与生物分子反应
辐射作用的时相阶段（续I）

生物阶段

分子的变化

代谢

突变

代谢

代谢

生化变化

亚显微损伤

可见损伤

细胞死亡

机体死亡

辐射晚期损伤

（辐射诱发癌、白血病、早衰等）
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。
Dose

组织损伤率

肿瘤对放疗敏感

肿瘤对放疗不敏感

肿瘤控制率

组织损伤率

Dose

TCP (%)  NTCP (%)
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
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）

\[ LET = \frac{dE}{dl} \text{ (KeV/μm)} \]

◆ The radiation with a LET value less than 10 KeV/μm is called low LET radiation.

\[ LET_{200KV \ x - rays} = 3 KeV/\mu m \]

\[ LET_{1\sim16,000MeV, \ helium \ to \ Uranium} = 10 \ to \ 10,000 KeV/\mu m \]
相对生物效应（RBE）

- 描述不同性质射线，对同一种细胞作用产生相同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。

$$OER = \frac{D_{\text{乏氧}}}{D_{\text{含氧}}}$$

- 低LET射线  OER=2.5～3.0
- 高LET射线  OER=1.0～1.8
Dependence of RBE and OER on LET
我国医用加速器增长状况
2.2 History of Radiotherapy

- 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)
View of a medical betatron mfd by Brown Bover (Switzerland)
The Era of RF Linear Accelerators

- 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

The total number of medical electron linear Accelerators (linacs) is 7,000~8,000
2.3 Radiotherapy by X-ray and electrons

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
3. Precision of the Delivered Dose
±2%

4. Radiation Field Size

- X-rays: $2 \times 2 \text{cm}^2 \sim 40 \times 40 \text{cm}^2$
- Electron beams:
  $2 \times 2 \text{cm}^2 \sim 25 \times 25 \text{cm}^2$

5. Dose Distribution Flatness:

- X-rays: $\leq \pm 3\%$
- Electron beams: $\leq \pm 5\%$

Dose distribution flatness
Medical Linac Fundamental Systems

Medical TW linac
Medical SW Linac (clinac 18, Varian)
Standing-wave (SW) medical linac
---side-coupled SW accelerating structure
---on-axis coupled SW accelerating structure
Idea of side-coupled SW structure
High Energy SW acceleration tube with an "energy switch"
The principle of “energy switch”
RF Power Source and Transport System

- The type of RF power source
  - ☺ Klystron \((f = 2856\ \text{MHz})\)
  - ☷ Magnetron \((f = 2856;\ 2998\ \text{MHz})\)

- Peak power, pulse width
  - \(-\-2\sim5\ \text{MW, 4}\ \mu s ,\ 250\ \text{PPS}\)

- 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
Domestic RF Electron Linacs for Conventional Therapy in Mainland China

- The urgent need for radiation therapy spurred the development of domestic electron linacs for medical application.

- From 1972 to 1977, four groups from the Shanghai, Beijing, Nanjing, and Sichuan areas started to develop medical linacs.

  - Tsinghua University and Beijing Medical Equipment Institute (BMEI) completed an 8~10MeV TW medical linac (BJ-10) in July, 1977.

  - Institute of High Energy Physics (IHEP) and Shanghai Medical Nuclear Instrument Factory (SMNIF) constructed another 8~10MeV TW machine (ZJ-10) in Dec. 1977.
2.4 质子及重离子放射治疗

Depth dose in water for 190MeV deuterons and 187MeV protons
Ernest Orlando Lawrence

Nobel prize in Physics 1939 for the invention of cyclotron
Physical characteristics of proton beams

Protons have excellent physical properties for radiation therapy which permit one to control very precisely the shape of the dose distribution inside the patient's body. The dose delivered by a proton beam is well localized in space, not only in the lateral direction, but also very precisely in depth, due to the presence of the characteristic BRAGG peak.
Proton Therapy

Left: A liver cancer of 5 cm diameter indicated by arrows was inoperable because of renal dysfunction.

Right: The cancer disappeared after proton beam irradiation.
Irradiation of a mediastinal tumor with a proton beam

(a) depth-dose for $^{60}\text{Co}$ γ-rays
(b) depth-dose for monoenergetic protons
(c) depth-dose for multienergetic protons
图 4-39  Loma Linda 大学质子治疗中心设备平面图
図 3 日本重粒子治療装置 HIMAC
2.5 放射治疗中的新技术

- 适形与调强
- 美国 Accvray公司
  - Cyberknife 定向放射外科手术刀
- 美国 Intraop Inc公司
  - Mobetron 移动式术中放疗专用加速器
  - 机器人+X波段加速器（只出电子）
- 美国 威斯康星大学
  - TOMOTherapy 断层放疗装置
- 日本 三菱
  - C形臂X刀系统
适形与调强
三种适形放疗

1、静态适形放疗（State Conformal Radiotherapy）
6-9个固定辐射野在某机架角度用某种挡块（或手动调节MLC）照射下个机架角度前换挡块

2、分段适形放疗（Segmetal Conformal Radiotherapy）
自动实现各次静态治疗之间的调整操作员在各次变换时不需进机房，需要电动MLC

3、动态适形放疗（Dynamic Conformal Radiotherapy）
照射是在机架、MLC的准直器、床等运动进行的。
调强放疗

• 调强放疗（IMRT）
• IMRT使靶区内剂量处处相等
• 概念的由来：CT发射强度均匀的X线，穿过人体后形成强度分布正比于组织厚度和密度的乘积，形成影像。如果强度分布类似于CT影像，适形分布的X线去穿过人体就能实现形状适应，强度均匀的照射野。
External beam radiation therapy
Intensity Modulated Radiation Therapy (IMRT) : prostate plan
Delivery of IMRT with a Multileaf Collimator (MLC)
• 设备操作过程

1）进行放射手术前，医生首先会经CT或MRI扫描出来的病灶点图像储存在一个计算机内，而追踪病人头部的移动，则利用一套整合的X线影像处理系统（Image Process System, IPS），其中包括两个矩形的X线摄像机。X线摄像机可制造一对传输图像，这些图像由一对荧光屏幕、影像增强器及CCD摄像机摄取。高速度的计算机便可依靠分析这些图像数据，来计算出病灶点的位置。
设备操作过程

• 2）当手术进行时，X线追踪系统会不断把术中所拍摄出来的低剂量骨骼剖析图像（Bony Anatomy）与先前储存在计算机内的病灶点图像相互比较，以便决定肿瘤的正确位置，再把这些数据输送至机械臂，使其可对准病灶点。

3）治疗计划系统（TPS）通过所获取的脑部组织的三维图像，计算出病灶点需承受的放射剂量。放射光束从不同的方向聚焦至病灶点，使病灶点承受高剂量的放射，减少对周围的组织的放射。
术中放疗专用加速器

- 移动式术中放疗专用加速器
- 美国Intraop Inc公司，Mobetron移动式
- 机器人+X波段加速器（只出电子）
- X波段驻波加速器管，电子束最高能量12MeV用1.2MW磁控管
- 只出电子，束流负载很轻，调制器功率也小。
- 不出X线，所以防护简单，照射头小，配不同尺寸限光筒。
- 无旋转机架，用可调节旋转臂式结构，可以移动。
Mobetron
X-band Linac
断层放疗装置

- 断层放疗装置（Tomotherapy）
- 美国威斯康星大学研制
- 将CT与加速器合二为一，在CT该放X球管的地方放一根6MV驻波加速管。用MV X线探测器代替kV级探测器。
- CT成像→计划→摆位→验证→治疗。在用一台设备上完成，也可以适形调强。
螺旋扫描式断层治疗机结构示意图

(a) 断层治疗机 (tomotherapy unit); (b) 螺旋扫描示意 [60]。
Research Prototype: Not Available For Commercial Sale
注：Δ表示 M_φ 和 M_ψ 在垂直纸面的转矩分量
Positron Emission Tomography (PET)
PET Image: Breast Cancer

Image showing malignant breast mass that was not revealed by conventional imaging techniques such as CT, MRI, and mammogram.

Image of same patient with enlarged left axillary lymph nodes (indicated by arrows), which through biopsy were found to be metastatic (spread from another location). The whole body scan reveals a mass in the left breast (indicated by arrow), that was malignant and subsequently removed.
PET Scan of Lung Tumor
Boron Neutron Capture Therapy

Thermal neutron

Li-7

$E_{\text{Li-7}} = 0.84 \text{ MeV}$

B-10

$E_{\alpha} = 1.47 \text{ MeV}$

$\alpha$-particle

$\gamma$-ray
Roentgen discovered the X-ray in 1895 and used the ray to radiate his wife’s hand to make a film.
射线成像的形式

- 射线照相
- 实时成象
- CT成象

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
3.1 射线成象物理基础

• 3.1.1 X射线的产生
电子束的描述

- 电子能量:
  - $1\text{eV} = 1.6 \times 10^{-19} \text{Joule}$
  - $1\text{KeV} = 10^3 \text{eV}$
  - $1\text{MeV} = 10^6 \text{eV}$
  - $1\text{GeV} = 10^9 \text{eV}$

- 流强
  - 脉冲流强
  - 平均流强

- 靶点：焦点
- 脉冲宽度：$\tau$
- 重复频率：$F = 1/T$
- 占空比：$\text{Duty} = \frac{\tau}{T} = \tau \times F$
X射线的剂量

- 剂量：Gy = 1 Joule/kg
- 剂量率：Gy/min
- 1 Gy = 100 cGy = 100 Rad
韧致辐射X射线

- 打靶电子的速度越高，打靶产生的X射线的能量也越高。
- 打靶电子的数目越多，产生的X射线的强度越大。
$J_x = \eta \cdot I_b \cdot E_e^n$

Where

$I_b$ -- the electron beam currents ($\mu A$)

$E_e$ -- Electron energy (MeV)

$n = 2.6 \sim 3$
- NCRP51
- 电子束打高Z厚靶产生X射线的曲线
X射线的空间分布

电子束打靶产生X射线
3.1.2 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，强度的衰减值$dJ$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
- \( \mu \) —— 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

- $\mu$——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 射线成象原理
3.2.1 射线照相

图中的$\Delta D$, $U$ 和$\sigma_D$ 就是影像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)。
不同透照电压的射线照相厚度宽容度

• 黑度 $D$

![图示](image)
增感

相对增感因子

1 MeV
2 MeV
4-6 MeV
8-9 MeV
16 MeV

前铅屏厚度 / mm
3.2.2 实时成像

- 射线 → 可见光

图 3 荧光屏实时成像检验系统
1. 射线源  2. 工件  3. 荧光屏  4. 光学系统
5. 摄象管  6. 显示器
图 6 半导体检测器阵列实时成像检验系统
1. 射线源  2. 工件  3. 半导体检测器阵列
4. 转换电路  5. 显示器

射线→电子
图4 直线阵列型电视-荧屏检测系统

图6 X射线调制传递函数
3.2.3 工业 CT

- \( X_1 + X_2 = Y_1 \)
- \( X_1 + X_3 = Y_2 \)
- \( X_2 + X_3 = Y_3 \)
- \( X_2 + X_4 = Y_4 \)

\[
X_1 = \frac{1}{2} [Y_1 + Y_2 - Y_3]
\]
\[
X_2 = \frac{1}{2} [Y_1 - Y_2 + Y_3]
\]
\[
X_3 = \frac{1}{2} [Y_2 - Y_1 + Y_3]
\]
\[
X_4 = Y_4 - \frac{1}{2} [Y_1 - Y_2 + Y_3]
\]
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
(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
被检测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
空间分辨率

空间分辨率
- 也称几何分辨率，是指从CT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 (1p/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
密度分辨率

- 密度分辨率
  - 又称对比度分辨率，是利用图象的灰度分辨被检物材质的基本方法。
  - 表示方法：通常以可分辨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
ICT与普通射线成象
表 9-1 三种射线检测技术的特点比较

<table>
<thead>
<tr>
<th>射线检测技术</th>
<th>射线吸收率/%</th>
<th>空间分辨力</th>
<th>动态范围</th>
<th>数字图象处理能力</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>keV</td>
<td>keV</td>
<td>MeV</td>
<td>Lp/mm</td>
</tr>
<tr>
<td>胶片照相</td>
<td>≈ 5</td>
<td>≈ 2</td>
<td>≈ 0.5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>实时成像</td>
<td>≈ 20</td>
<td>≈ 8</td>
<td>≈ 2</td>
<td>≈ 25</td>
</tr>
<tr>
<td>CT技术</td>
<td>≈ 99</td>
<td>≈ 95</td>
<td>≈ 80</td>
<td>0.2 ~ 4.5</td>
</tr>
</tbody>
</table>
3.3 加速器在射线成像中的应用

• 对加速器的要求
  – 剂量率：单脉冲剂量越大越好，平均剂量率要求不同
  – 焦点：越小越好，1mm
  – 剂量率稳定性：剂量率上升时间，长期稳定性
  – 电子能量：根据应用确定
  – 漏剂量：0.1%
加速器的类型

- 电子直线加速器为主：美国Varian, 中国-自动化研究所, 中国原子能研究院, 中国工程物理研究院, 清华大学及同方威视, 德国Siemens, 日本Mitsubishi, 俄罗斯D.V. Yefremov Institute.

- 电子感应加速器

- 电子回旋加速器
直线加速器工作原理

380V AC → Modulator → Pulse transformer → Magnetron

Electron gun

10kV Electron gun

Microwave pulse

11kV

44kV

X-ray

Electron bunch

Target

Electron Accelerator Tube
<table>
<thead>
<tr>
<th>Model</th>
<th>Linatron200</th>
<th>Linatron400</th>
<th>Linatron3000A</th>
<th>Linatron6000</th>
<th>Linatron6000H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max.beam Energy (MeV)</td>
<td>2</td>
<td>4</td>
<td>9</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>X-ray output (cGy/min, at 1m)</td>
<td>200</td>
<td>400</td>
<td>3000</td>
<td>6000</td>
<td>20000</td>
</tr>
<tr>
<td>Max.focus spot (mm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>HVL (mm)</td>
<td>20.0</td>
<td>25.0</td>
<td>31.0</td>
<td>33.0</td>
<td>33.0</td>
</tr>
</tbody>
</table>
VARIAN

MINI

LINATRON300
9MeV Linac
The ICT images of a vessel and an exhaust manifold provided by the ARACOR Company, CA., U.S.A.
3.4 大型集装箱及其他货物
检查系统
Mobile Cargo Inspection System
With X-band or S-band linacs of 2~6MeV

Relocatable Cargo Inspection System
With S-band linacs of 6~9MeV
Typical Pictures
Smuggling Cars

3 sets of smuggling car

Declaration Goods: Carpets
smuggling ivory
cannabis
Heroin
Stowaway
3.5 Introduction of 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

\[
P(E_e, E', t_m, Z) = P_0(E_e, E') \cdot e^{-\frac{\mu(E', Z)}{\rho} t_m}
\]
Photoelectric effect/ Scattering/ Pair production

- L-shell binding energy ≈ 15 keV
- K-shell binding energy ≈ 88 keV
- Mass attenuation coefficient (cm²/g)
- Photon energy (MeV)
- 3 MeV
- Lead
- Water
- ~50 MeV
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
Material Discrimination Coordinate

- Transparency Ratio (Higher/Lower)
- Transparency (Higher-Energy X-ray)

- $^{82}$Pb
- $^{26}$Fe
- $^{13}$Al
- $^{6}$C
X-ray Source-The Dual Energy Linac

- Interlaced Dual Energy

\[ V = a \sqrt{P} - BI \]
Dual Energy X-ray

Diagram showing the differences between Low Energy X-ray and High Energy X-ray with respect to Photon Energy in MeV.

- Low Energy X-ray
- High Energy X-ray
Image Example and Photo Grey Image of a Van with Different Tested Samples

Pure material samples include lead, iron, aluminum and polythene with different masses in grams per square centimeter: 60, 50, 40, 30g/cm².
Image Example and Photo Dual-Energy Color Image of a Van with Different Tested Samples
国内市场分布图

同方威视®安全检查系统国内业绩图

- 装备中国海关集装箱/车辆检查系统：42 套
- 装备中国海关铁路货物/车辆检查系统：1 套
- 装备中国铁路的集装箱/车辆检查系统：19 套

（数据截至：2006 年 2 月）
4 Radiation Processing

4.1 Basic Concepts

Dose and Dose Rates

- Dose Unit:

1 Gy = 1 Joule / kg

- Dose Rate Unit:

1 KGy/sec. or 1 KGy/min

Electron Range

- Electron range in water (cm) $\propto$ electron energy/2 (MeV).
- Electron range is inversely proportional to the density of the Irradiated material.
- For example, 10 mm Al (2.79 g/cm$^3$) $\Rightarrow$ 27 mm H$_2$O.
Irradiation Methods

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

Figure 2.5 (a) figure-of-eight method  (b) parallel-wire method
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
Irradiation Efficiency ($\eta$)

- 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
4.2 Wire and Cable Processing

- It is the most extensive use.
- The wires and cables cross-linked by electron radiation possesses very good electrical properties, high resistance to the heat of soldering irons (95~105°C → 135°C) low abradability, resistance to organic solvents and nonflammability
Production of Packaging Materials

- Cross-linked polyethylene possesses elastic memory.
- We can get heat-shrinkable foil.
Curing Coatings

- The main advantages of electron curing of coatings are lower electricity consumption, and the absence of solvents released during drying.
- The curing process is very rapid, taking only 0.1~1 sec. It is not accompanied by the release of heat.
Radiation-induced Degradation

- Degradation of teflon waste by irradiation with accelerated electron beams can be carried out under normal air pressure.

- The resulting product can be used in the production of aerosol lubricants (懸浮狀潤滑劑).
Processing of Semiconductors

- The irradiation of accelerated high energy electrons (5~14MeV) can induce the defective energy levels on the semiconductor, forming recombination centers to reduce the life time of minority carrier and improve the electronic characteristics considerably.

- By this technique, the switching velocity of the thyristors and transistors are obviously increased.
The following devices are good candidates for EB processing:
• Fast Recovery Diodes
• Power Rectifiers
• Silicon Controlled Rectifiers (SCRs)
• Bipolar Junction Transistors (BJTs)
• Insulated Gate Bipolar Transistors (IGBTs)
• Gate Turn-Off Thyristors (GTOs)

**Effects of Annealing after EB Processing (1800V Diodes)**

Removing $\text{SO}_2$ and $\text{NO}_x$ From Flue Gas

- The emission of coal-fired boiler flue gas containing large amounts of $\text{SO}_2$ and $\text{NO}_x$ is a serious air pollution problem.

- With the irradiation of electron-beams, $\text{SO}_2$ and $\text{NO}_x$ can be removed from flue gas. The technique is called electron-beam flue gas treatment (EFGT).

- Figure 2.4 shows a view of a pilot plant constructed by China Academy of Engineering Physics for removing $\text{SO}_2$ and $\text{NO}_x$ in Mianyang, Sichuan, China.
Figure 2.4  The principle of EFGT’s technique
A pilot plant constructed by CAEP for removing SO$_2$ and NO$_x$ in Mianyang, China
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

<table>
<thead>
<tr>
<th>Type of food</th>
<th>Effect of irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat, poultry, fish as <em>Salmonella</em>, <em>Clostridium botulinum</em>, and <em>Trichinae</em></td>
<td>Destroys pathogenic organisms, such as Salmonella, Clostridium botulinum, and Trichinae</td>
</tr>
<tr>
<td>Perishable foods</td>
<td>Delays spoilage; retards mold growth; reduces number of microorganisms</td>
</tr>
<tr>
<td>Grain, fruit, vegetables, dehydrated fruit, spices and seasonings</td>
<td>Controls insect infestation</td>
</tr>
<tr>
<td>Onions, carrots, potatoes, garlic, ginger</td>
<td>Inhibits sprouting</td>
</tr>
<tr>
<td>Product</td>
<td>Dose Permitted (kGy)</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Wheat, Wheat Flour</td>
<td>0.2-0.5</td>
</tr>
<tr>
<td>White Potatoes</td>
<td>0.05-0.15</td>
</tr>
<tr>
<td>Pork</td>
<td>0.3-1</td>
</tr>
<tr>
<td>Dried Enzymes</td>
<td>10 (max.)</td>
</tr>
<tr>
<td>Fruit</td>
<td>1 max.</td>
</tr>
<tr>
<td>Vegetables</td>
<td>1 max.</td>
</tr>
<tr>
<td>Herbs &amp; Spices</td>
<td>30.max</td>
</tr>
<tr>
<td>Vegetable seasonings</td>
<td>30 max.</td>
</tr>
<tr>
<td>Poultry</td>
<td>3 max.</td>
</tr>
<tr>
<td>Frozen, packaged meat for use in space program</td>
<td>44 min.</td>
</tr>
<tr>
<td>Animal feed &amp; pet food</td>
<td>2-25</td>
</tr>
<tr>
<td>Meat, uncooked, chilled</td>
<td>4.5 max.</td>
</tr>
<tr>
<td>Meat, uncooked, frozen</td>
<td>7.0</td>
</tr>
</tbody>
</table>

食品辐照过程

**Figure 3: Electron beam irradiation**


**Figure 2: Schematic of an irradiation facility**

“...activists groups called for a ban on all food products containing plants developed by induced mutation via irradiation”

SOURCE: Reuters, “Mono-cultured: potentially more dangerous than biotech foods” May 10, 2001

“I always thought the plants we eat every day came from Mother Nature”

Charles Margulis, Greenpeace USA
4.3 辐照加速器

• 高压加速器：功率大，能量低
  - （高压闪络放电）
• 电子直线加速器：能量高，功率小
  - （大脉冲功率与平均功率的高频功率源）
Dynamitron

- The dynamitron operating Principle is shown in the following figure.
- The accelerating chamber is installed inside the HV tank, which is filled with SF6.
- Usually, the max. accelerating voltage is 2~4MeV, the max. beam power being in the tens of kW.
Insulating-Core Transformers (ICT)

- The core of ICT is divided into sections separated by a thin insulating space. The core is excited through the primary winding in a three-phase system.
- Usually, the max. accelerating voltage is about 1.2MeV, the max. beam power being about ten kW.
Installation, testing & commissioning of GJ 2 Accelerator
电子直线加速器

380V市电 
升压、整流、滤波 
脉冲调制器 
微波功率器件：速调管、磁控管、四极管 
加速结构 
电子束
大功率高能电子束

- 射频加速
- 选择高平均功率的微波产生器件
- 多次加速
  - 频率：100MHz ~ 200MHz
  - 功率：MW

- 几种解决方案
  - 俄罗斯
  - 法国IEA，比利时IBA
  - 韩国
  - 日本
### ILU accelerators produced by BINP.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ILU-8</th>
<th>ILU-6</th>
<th>ILU-6M</th>
<th>ILU-10</th>
<th>ILU-10M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range, MeV</td>
<td>0.5-1</td>
<td>1-2.5</td>
<td>1-2.5</td>
<td>3-5</td>
<td>2.5-4</td>
</tr>
<tr>
<td>Maximum beam power, kW</td>
<td>20</td>
<td>20</td>
<td>50</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Average beam current, mA</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Maximum consumed power, kW</td>
<td>100</td>
<td>100</td>
<td>150</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Weight, tons Accelerator</td>
<td>0.6</td>
<td>2.2</td>
<td>2.2</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Local shielding</td>
<td>76</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
ILU

Energy – 2.5-5 MeV
Average beam power – up to 60 kW
Operating frequency – 176 MHz
Shunt impedance of the accelerating structure – 13.4 MOhm/m
Duty factor – 2.5%
RF Power 0.6MW

Figure 4: Accelerator design with on axis situated coupling cavities.
Rewinding system is installed in local shield for work with 4-window extraction device allows 4-side irradiation. Design of rewinder exceptions twist of product. Production line has 2 modes:

- 2 line mode for 2-sided irradiation
- 1 line mode for 4-sided irradiation

This facility can irradiate tubes with diameter up to 30 mm and wires up to 5 mm.
Accelerator ILU-6 for sterilization of medical goods
(upstairs part)

Energy 1-2.5 MeV
Power up to 20kW
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.

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

Bending Magnet  Coaxial Cavity

Electron Gun  Beam Extraction

Figure 1. Operating principle of Fantron-I
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)

Fig. 1. The schematic drawing of the Ridgetron prototype. G: electron gun; L: solenoid lens; M: deflector magnet; R: hollow ridge; E: electric field.
Thanks!
Roentgen discovered the X-ray in 1895 and used the ray to radiate his wife’s hand to make a film.
射线成像的形式

- 射线照相
- 实时成象
- CT成象

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
3.1 射线成象物理基础

• 3.1.1 X射线的产生
电子束的描述

- 电子能量:
  - $1\text{eV} = 1.6 \times 10^{-19} \text{Joule}$
  - $1\text{KeV} = 10^3 \text{eV}$
  - $1\text{MeV} = 10^6 \text{eV}$
  - $1\text{GeV} = 10^9 \text{eV}$

- 脉冲流强
- 平均流强

- 靶点: 焦点

- 脉冲宽度: $\tau$

- 重复频率: $F = 1/T$

- 占空比: Duty = $\tau/T = \tau \cdot F$
X射线的剂量

- 剂量：Gy = 1 Joule/kg
- 剂量率：Gy/min
- 1 Gy = 100 cGy = 100 Rad
韧致辐射X射线

• 打靶电子的速度越高，打靶产生的X射线的能量也越高。
• 打靶电子的数目越多，产生的X射线的强度越大。
出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 (\( \mu A \))

\( E_e \) -- Electron energy (MeV)

\( n = 2.6 \sim 3 \)

Photon conversion \( \eta \)
• NCRP51
• 电子束打高Z厚靶产生X射线的曲线
X射线的空间分布

电子束打靶产生X射线
3.1.2 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

\( \mu \) —— 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

$\mu$——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)

$J_0$  \[ \frac{1}{2} J_0 \]  

HVL

Half-value layer of steel as function of radiation energy (Varian Ass.)
3.2 射线成象原理
3.2.1 射线照相

图中的$\Delta D, U$ 和 $\sigma_D$ 就是影像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)
不同透照电压的射线照相厚度宽容度

・黑度 $D$

透照厚度

120kV  200kV

$D=3.0$  $D=3.0$

$D=1.5$  $D=1.5$
均整

Relative Dose Rate

Angle (degree)

Unflattened
Flattened by Fe
增感
3.2.2 实时成象

- 射线→可见光

图 3 荧光屏实时成像检验系统
1. 射线源  2. 工件  3. 荧光屏  4. 光学系统
5. 摄象管  6. 显示器
射线→电子

图 6 半导体检测器阵列实时成象检验系统
1. 射线源   2. 工件   3. 半导体检测器阵列
4. 转换电路   5. 显示器
图4 直线阵列型电视 荧屏检测系统

图6 X射线调制传递函数
3.2.3 工业 CT

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

$$X_1 = \frac{1}{2} [Y_1 + Y_2 - Y_3]$$
$$X_2 = \frac{1}{2} [Y_1 - Y_2 + Y_3]$$
$$X_3 = \frac{1}{2} [Y_2 - Y_1 + Y_3]$$
$$X_4 = Y_4 - \frac{1}{2} [Y_1 - Y_2 + Y_3]$$
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
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
图 3 ICT 结构工作原理简图
空间分辨率

- **空间分辨率**
  - 也称几何分辨率，是指从CT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 (1p/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
密度分辨率

• 密度分辨率
  - 又称对比度分辨率，是利用图象的灰度分辨被检物材质的基本方法。
  - 表示方法：通常以可分辨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
ICT与普通射线成象
表 9-1 三种射线检测技术的特点比较

<table>
<thead>
<tr>
<th>射线检测技术</th>
<th>射线吸收率/%</th>
<th>空间分辨力</th>
<th>动态范围</th>
<th>数字图象处理能力</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>keV</td>
<td>keV</td>
<td>M eV</td>
<td>Lp/mm</td>
</tr>
<tr>
<td>胶片照相</td>
<td>≈ 5</td>
<td>≈ 2</td>
<td>≈ 0.5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>实时成象</td>
<td>≈ 20</td>
<td>≈ 8</td>
<td>≈ 2</td>
<td>≈ 25</td>
</tr>
<tr>
<td>CT 技术</td>
<td>≈ 99</td>
<td>≈ 95</td>
<td>≈ 80</td>
<td>0.2~4.5</td>
</tr>
</tbody>
</table>

需胶片扫描器。典型为 8bit 数据。
3.3 加速器在射线成像中的应用

- 对加速器的要求
  - 剂量率：单脉冲剂量越大越好，平均剂量率要求不同
  - 焦点：越小越好，1mm
  - 剂量率稳定性：剂量率上升时间，长期稳定性
  - 电子能量：根据应用确定
  - 漏剂量：0.1%
加速器的类型

- 电子直线加速器为主：美国Varian，中国－自动化研究所，中国原子能研究院，中国工程物理研究院，清华大学及同方威视，德国Siemens, 日本Mitsubishi，俄罗斯D.V. Yefremov Institute.
- 电子感应加速器
- 电子回旋加速器
直线加速器工作原理

380V AC → Modulator → Pulse transformer → Magnetron

11kV → 44kV

10kV Electron gun

Electron bunch

Target

Microwave pulse

X-ray

Electron Accelerator Tube
### Varian电子直线加速器

<table>
<thead>
<tr>
<th>Model</th>
<th>Linatron200</th>
<th>Linatron400</th>
<th>Linatron3000A</th>
<th>Linatron6000</th>
<th>Linatron6000H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max.beam Energy(MeV)</td>
<td>2</td>
<td>4</td>
<td>9</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>X-ray output (cGy/min, at 1m)</td>
<td>200</td>
<td>400</td>
<td>3000</td>
<td>6000</td>
<td>20000</td>
</tr>
<tr>
<td>Max.focus spot(mm)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>HVL (mm)</td>
<td>20.0</td>
<td>25.0</td>
<td>31.0</td>
<td>33.0</td>
<td>33.0</td>
</tr>
</tbody>
</table>
VARIAN

MINI

LINATRON300
9MeV Linac
The ICT images of a vessel and an exhaust manifold provided by the ARACOR Company, CA., U.S.A.
3.4 大型集装箱及其他货物检查系统
Relocatable Cargo Inspection System
With S-band linacs of 6~9MeV

Mobile Cargo Inspection System
With X-band or S-band linacs of 2~6MeV
Typical Pictures
Smuggling Cars
smuggling ivory
cannabis
Heroin
Stowaway
3.5 Introduction of 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

\[
P(E_e, E', t_m, Z) = P_0(E_e, E') \cdot e^{\frac{-\mu(E', Z) \cdot t_m}{\rho}}
\]
Photoelectric effect/ Scattering/ Pair production

L-shell binding energy
~15 keV

K-shell binding energy
~88 keV

Mass attenuation coefficient (cm$^2$/g)

Photon energy (MeV)

lead

water

3 MeV

~50 MeV
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
Material Discrimination Coordinate

![Graph showing the relationship between Transparency Ratio (Higher/Lower) and Transparency (Higher-Energy X-ray). The graph includes curves for different materials: $^{82}\text{Pb}$, $^{26}\text{Fe}$, $^{13}\text{Al}$, and $^{6}\text{C}$.]
Heavy Metal
The diagram shows a scatter plot with density (g/cm³) on the x-axis and atomic number on the y-axis. There are different categories of materials represented:

- **Nuclear Material**: Elements like Pb and W are shown near the top of the graph.
- **Inorganic Material**: Includes elements like Copper (Cu) and Iron (Fe).
- **Light Metal**: Elements like PVC, Black Powder, Salt (NaCl), Glass, and Aluminum (Al) are shown.
- **Organic Material**: Shows various substances such as Cocaine, Heroin, Book, Water, Sugar, Leather, Nylon, Cotton, Wool, Alcohol, Plastic, Ammonium Nitrate, Composition C-4, DETASHEET HMX, RDX, Composition B, TNT, and Composition C-3.

The density values range from 0.5 to 20 g/cm³, and the atomic numbers range from 5 to 100.
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

Photon Energy MeV
清华大学
Tsinghua University
Image Example and Photo Grey Image of a Van with Different Tested Samples

Pure material samples include lead, iron, aluminum and polythene with different masses, each of 60, 50, 40, 30 g/cm².
Image Example and Photo Dual-Energy Color Image of a Van with Different Tested Samples
国内市场分布图

同方威视®安全检查系统国内业绩图

- 装备中国海关集装箱 / 车辆检查系统：42 套
- 装备中国海关铁路货物 / 车辆检查系统：1 套
- 装备中国铁路的集装箱 / 车辆检查系统：19 套
（数据截至：2006 年 2 月）
4 Radiation Processing

4.1 Basic Concepts

Dose and Dose Rates

- Dose Unit:
  \[ 1 \text{ Gy} = 1 \text{ Joule} / \text{ kg} \]

- Dose Rate Unit:
  \[ 1 \text{ K Gy/ sec. or 1 K Gy/ min} \]

Electron Range

- Electron range in water (cm) \( \propto \) electron energy/2 (MeV).
- Electron range is inversely proportional to the density of the Irradiated material.
- For example, 10 mm Al (2.79g/cm³) \( \Rightarrow \) 27 mm H₂O.
Irradiation Methods

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

Figure 2.5 (a) figure-of-eight method  (b) parallel-wire method
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
Irradiation Efficiency (\( \eta \))

- 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
4.2 Wire and Cable Processing

- It is the most extensive use.
- The wires and cables cross-linked by electron radiation possesses very good electrical properties, high resistance to the heat of soldering irons (95~105°C $\rightarrow$ 135°C) low abradability, resistance to organic solvents and nonflammability
Production of Packaging Materials

- Cross-linked polyethylene possesses elastic memory.
- We can get heat-shrinkable foil.
Curing Coatings

- The main advantages of electron curing of coatings are lower electricity consumption, and the absence of solvents released during drying.

- The curing process is very rapid, taking only 0.1~1 sec. It is not accompanied by the release of heat.
Radiation-induced Degradation

- Degradation of teflon waste by irradiation with accelerated electron beams can be carried out under normal air pressure.

- The resulting product can be used in the production of aerosol lubricants (懸浮狀潤滑劑).
Processing of Semiconductors

- The irradiation of accelerated high energy electrons (5~14MeV) can induce the defective energy levels on the semiconductor, forming recombination centers to reduce the life time of minority carrier and improve the electronic characteristics considerably.

- By this technique, the switching velocity of the thyristors and transistors are obviously increased.
The following devices are good candidates for EB processing:

- Fast Recovery Diodes
- Power Rectifiers
- Silicon Controlled Rectifiers (SCRs)
- Bipolar Junction Transistors (BJTs)
- Insulated Gate Bipolar Transistors (IGBTs)
- GateTurn-Off Thyristors (GTOs)

**Effects of Annealing after EB Processing (1800V Diodes)**

Removing SO$_2$ and NO$_x$ From Flue Gas

- The emission of coal-fired boiler flue gas containing large amounts of SO$_2$ and NO$_x$ is a serious air pollution problem.

- With the irradiation of electron-beams, SO$_2$ and NO$_x$ can be removed from flue gas. The technique is called electron-beam flue gas treatment (EFGT).

- Figure 2.4 shows a view of a pilot plant constructed by China Academy of Engineering Physics for removing SO$_2$ and NO$_x$ in Mianyang, Sichuan, China.
Figure 2.4 The principle of EFGT’s technique
A pilot plant constructed by CAEP for removing SO$_2$ and NO$_x$ in Mianyang, China
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.
<table>
<thead>
<tr>
<th>Type of food</th>
<th>Effect of irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat, poultry, fish as <em>Salmonella</em></td>
<td>Destroys pathogenic organisms, such as <em>Salmonella</em>,</td>
</tr>
<tr>
<td><em>Clostridium botulinum</em>, and <em>Trichinae</em></td>
<td></td>
</tr>
<tr>
<td>Perishable foods</td>
<td>Delays spoilage; retards mold growth; reduces number</td>
</tr>
<tr>
<td></td>
<td>of microorganisms</td>
</tr>
<tr>
<td>Grain, fruit, vegetables, dehydrated fruit,</td>
<td>Controls insect infestation</td>
</tr>
<tr>
<td>spices and seasonings</td>
<td></td>
</tr>
<tr>
<td>Onions, carrots, potatoes, garlic, ginger</td>
<td>Inhibits sprouting</td>
</tr>
<tr>
<td>Product</td>
<td>Dose Permitted (kGy)</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Wheat, Wheat Flour</td>
<td>0.2-0.5</td>
</tr>
<tr>
<td>White Potatoes</td>
<td>0.05-0.15</td>
</tr>
<tr>
<td>Pork</td>
<td>0.3-1</td>
</tr>
<tr>
<td>Dried Enzymes</td>
<td>10 (max.)</td>
</tr>
<tr>
<td>Fruit</td>
<td>1 max.</td>
</tr>
<tr>
<td>Vegetables</td>
<td>1 max.</td>
</tr>
<tr>
<td>Herbs &amp; Spices</td>
<td>30.max</td>
</tr>
<tr>
<td>Vegetable seasonings</td>
<td>30 max.</td>
</tr>
<tr>
<td>Poultry</td>
<td>3 max.</td>
</tr>
<tr>
<td>Frozen, packaged meat for use in space program</td>
<td>44 min.</td>
</tr>
<tr>
<td>Animal feed &amp; pet food</td>
<td>2-25</td>
</tr>
<tr>
<td>Meat, uncooked, chilled</td>
<td>4.5 max.</td>
</tr>
<tr>
<td>Meat, uncooked, frozen</td>
<td>7.0</td>
</tr>
</tbody>
</table>

食品辐照过程

Figure 2: Schematic of an irradiation facility


Figure 3: Electron beam irradiation

“...activists groups called for a ban on all food products containing plants developed by induced mutation via irradiation”

SOURCE: Reuters, “Monsanto plants potentially more dangerous than bio-foods,” May 10, 2001

“I always thought the plants we eat every day came from Mother Nature”

Charles Margulis, Greenpeace USA
4.3 辐照加速器

- 高压加速器：功率大，能量低
  - （高压闪络放电）
- 电子直线加速器：能量高，功率小
  - （大脉冲功率与平均功率的高频功率源）
The dynamitron operating principle is shown in the following figure.

The accelerating chamber is installed inside the HV tank, which is filled with SF6.

Usually, the max. accelerating voltage is 2~4 MeV, the max. beam power being in the tens of kW.
Insulating-Core Transformers (ICT)

- The core of ICT is divided into sections separated by a thin insulating space. The core is excited through the primary winding in a three-phase system.
- Usually, the max. accelerating voltage is about 1.2MeV, the max. beam power being about ten kW.
电子直线加速器

380V市电

升压、整流、滤波

脉冲调制器

微波功率器件：速调管、磁控管、四极管

加速结构

电子束
大功率高能电子束

- 射频加速
- 选择高平均功率的微波产生器件
- 多次加速
  - 频率: 100MHz ~ 200MHz
  - 功率: MW

- 几种解决方案
  - 俄罗斯: ILU
  - 法国IEA, 比利时IBA
  - 韩国
  - 日本: Rhodotron, Fantron, Ridgetron
# ILU accelerators produced by BINP.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ILU-8</th>
<th>ILU-6</th>
<th>ILU-6M</th>
<th>ILU-10</th>
<th>ILU-10M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range, MeV</td>
<td>0.5-1</td>
<td>1-2.5</td>
<td>1-2.5</td>
<td>3-5</td>
<td>2.5-4</td>
</tr>
<tr>
<td>Maximum beam power, kW</td>
<td>20</td>
<td>20</td>
<td>50</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Average beam current, mA</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Maximum consumed power, kW</td>
<td>100</td>
<td>100</td>
<td>150</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Weight, tons</td>
<td>0.6</td>
<td>2.2</td>
<td>2.2</td>
<td>2.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Accelerator</td>
<td>76</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Local shielding</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
ILU

Energy – 2.5-5 MeV
Average beam power – up to 60 kW
Operating frequency – 176 MHz
Shunt impedance of the accelerating structure – 13.4 MOhm/m
Duty factor – 2.5%
RF Power 0.6MW

Figure 4: Accelerator design with on axis situated coupling cavities.
REWINDING SYSTEM IS INSTALLED IN LOCAL SHIELD FOR WORK WITH 4-WINDOW EXTRACTION DEVICE ALLOWS 4-SIDE IRRADIATION. DESIGN OF Rewinder exceptions twist of product. Production line has 2 modes:

- 2 line mode for 2-sided irradiation
- 1 line mode for 4-sided irradiation

This facility can irradiate tubes with diameter up to 30 mm and wires up to 5 mm.
Accelerator ILU-6 for sterilization of medical goods (upstairs part)

Energy 1-2.5 MeV
Power up to 20kW
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.

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

Bending Magnet  Coaxial Cavity

Electron Gun  Beam Extraction

Figure 1. Operating principle of Fantron-I
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)

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