CT System Course (SAM)

I. Image Acquisition Physics and Hardware
Baojun Li, PhD

II. Image Reconstruction and Artifact Reduction
Jiang Hsieh, PhD

III. Image Quality, Dose, and Clinical Applications
Frank F. Dong, PhD

CT System Course (SAM)

I. Image Acquisition Physics and Hardware

Baojun Li, PhD
Department of Radiology
Boston University Medical Center

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Acknowledgement

- Rolf Behling, Philips
- Jiang Hsieh, GE
- Brian Lounsberry, GE
- Peter Schardt, Siemens
- Aziz Ikhlef, FMI

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Learning Objective

- Understand the function of major components of x-ray tube.
- Understand the function of major components of CT detector.
- Understand the practical challenges, advanced technology to overcome the challenges, and the impacts on image quality when appropriate.

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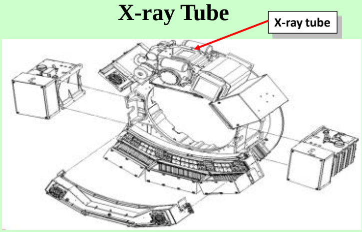
X-ray Tube



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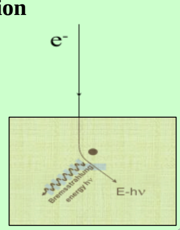
X-ray Generation

- How are X-rays produced?
  a) Take charged e^-,
  b) Accelerate them to high energy,
  c) Decelerate them very rapidly

  …and X-ray photons are produced!

  Brems-strahlung (Braking-radiation)



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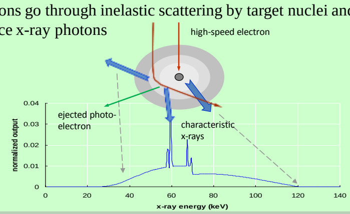
Bremsstrahlung

- Electrons go through inelastic scattering by target nuclei and produce x-ray photons



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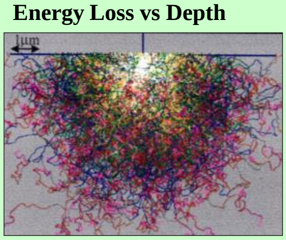
Energy Loss vs Depth

e- Energy (keV)

- 91-100
- 81-90
- 71-80
- 61-70
- 51-60
- 41-50
- 31-40
- 41-30
- <20



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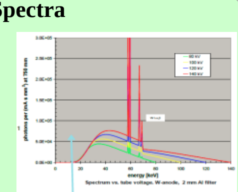
X-ray Spectra

- Continuum of frequencies
- Tube voltage defines spectrum
- Soft X-rays are preferentially absorbed
  - Inherent filtration from auto-filtration of target, beryllium window, and casing oil/window
  - Added filtration (FDA minimum 2.5 mm Al equivalent)
  - Skin dose further reduced by adding up to 1 mm Cu (“bowtie”)
  - Strong filtration requires powerful tube*



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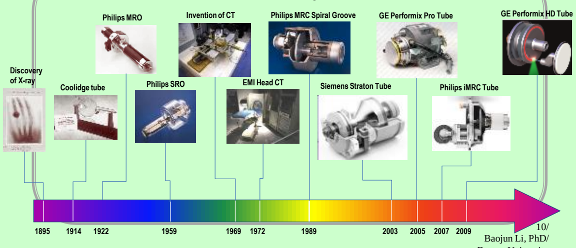
Modern X-ray Tubes



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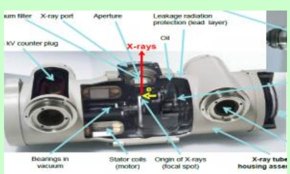
Tube Housing

- Made of cast steel & is lead lined
- Purpose:
  - Controls leakage radiation
  - Isolates high voltages
  - Cooling oil is sealed inside to cool the tube



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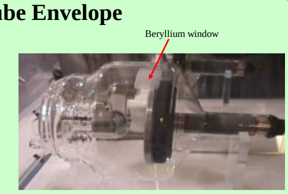
Tube Envelope

- Surrounds entire cathode & anode, except for the stator
- Conventional tube envelope made of layers of Pyrex & newer designs employ metal frames
- Purpose:
  - Maintains the vacuum environment inside the tube: ~10^{-5} Torr
  - Allows x-ray to exit through target window with less scatter & attenuation



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Cathode

- Made up of the filament(s) and a focusing mechanism
- Purpose:
  - Produces free electrons
  - Controls the focal spot on the anode
- Tube spits occurs when cathode discharges in the presence of impurities

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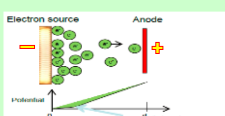
Space Charge

- Thermionic emission occurs when thermal energy overcomes the work function of W filament, which releases electrons (thermions)
- Thermionic emission follows Richardson's Law: $I \propto T^2$
- Electron clouds build up around the filament when no voltage is applied



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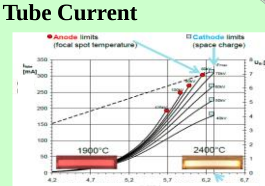
Limits of Tube Current

- **Cathode limited** - space charge cloud shields electric field, only a portion of the free electrons are accelerated to the anode, which limits the tube current regardless of the filament current
- **Anode limited** - when the voltage is higher enough to overcome the space charge cloud, tube current continues to increase till reaching the maximal anode operational temperature



Isowatt point - tube voltage where space charge limit = anode limit (75 kVp for the sample tube)

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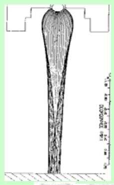
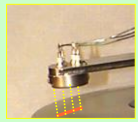
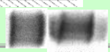
Focusing Mechanism

- Electrostatic focusing
  - Repels electrons away from the focusing cup
  - Shape of the focusing cup (electrostatic cylindrical lens)
  - Simpler design





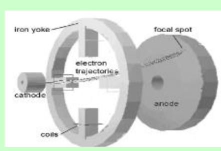
Normal focusing



Over-focusing

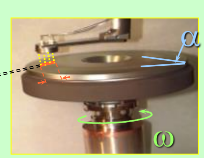
Focusing Mechanism

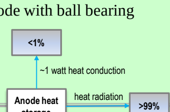
- Electromagnetic focusing
  - Electromagnetic quadrupoles
  - More effective & versatile
- Examples
  - Flying focal spot (Siemens Stratton Tube)
  - Focal spot wobble (GE Performix HD Tube)
  - Double quadruple magnetic deflection (Philips iMRC Tube)



Anode

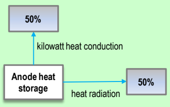
- A target and a rotating mechanism
- Tungsten-rhenium alloy placed on top of a large graphite (heat storage)
- Rotating mechanism - Rotating anode with ball bearing





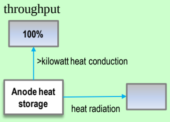
Anode

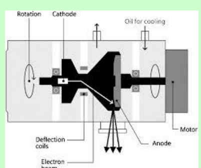
- Rotating mechanism – Rotating anode with liquid metal lubricated spiral groove bearing
  - Less cooling time = higher throughput



Anode

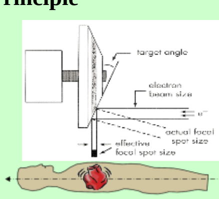
- Rotating mechanism - Rotating frame
  - Rotating tube envelope
  - Less cooling time = higher throughput





Line Focus Principle

- The larger target angle is, the larger the anatomical coverage (organ in a rotation)
- The larger target angle is, the less power (cardiac, large patient)
- The smaller target angle is, the smaller effective focal spot size (spatial resolution)
- Trade off between resolution, coverage, and power



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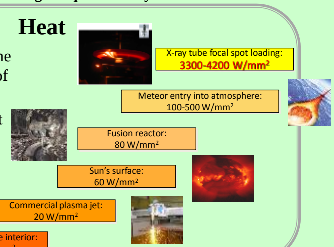
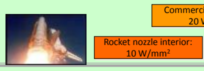
Heat

- Heat is conducted from the focal track into the bulk of the target
- Heat dissipation is almost entirely by thermal radiation thru the surface $\propto A\varepsilon T^4$





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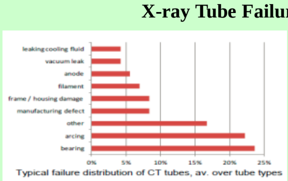
X-ray Tube Failures



Typical failure distribution of CT tubes, av. over tube types

- Bearing & arcing are the two most common failures

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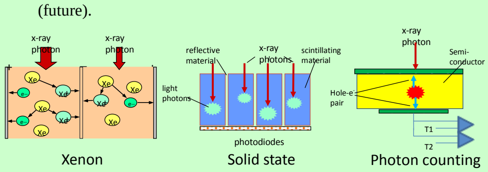
X-ray Detection

- Three types: Xenon (old), solid state, and photon counting (future).



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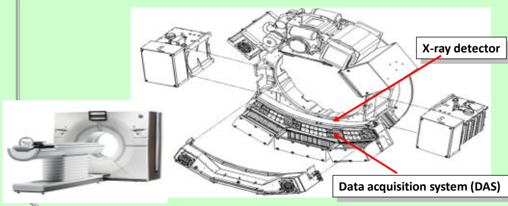
X-ray Detector



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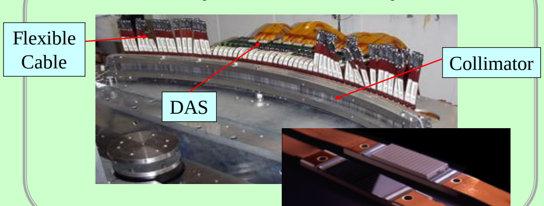
X-ray Detector Assembly



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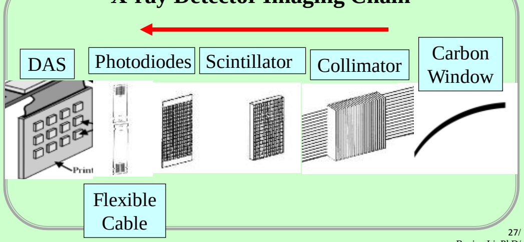
X-ray Detector Imaging Chain



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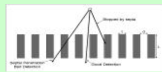
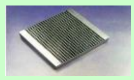
Collimator

- Placed immediately in front of the detector
- Made up of thin plates formed from lead or tungsten and a mounting rail
- Purpose:
  - Allows the X-rays traveling along a straight-line path
  - Rejects scattered X-rays
- Focused at the focal spot & generally located between detector columns (1-D) or between both columns and rows (2-D)
- Width: ~100µm±10µm





(Top) 1-d collimator
(Bottom) 2-d collimator

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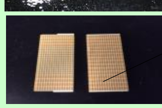
Scintillator

- Made of high purity (>99.99%) rare earth oxides
  - Gadolinium (Z=64) - absorption
  - Cadmium (Z=48) - absorption
  - Europium - activator
  - Praseodymium – quench afterglow
  - Cerium – quench afterglow
  - Calcium – reduce radiation damage
  - …
- Purpose:
  - X-ray absorption
  - Light emission
- Generally 2-3 mm thick to achieve high detection efficiency at quantum energy of 60+ keV: 20-60 photons per keV



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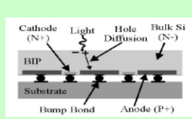
Photodiode

- Immediately behind the scintillator & illumination is from the front
- Conventional photodiodes are front lit & newer photodiodes are back lit
- Made of crystalline silicon, excellent linearity and temporal behavior
- Purpose:
  - Convert light from scintillator into electrical signals
- Photodiodes need to have low leakage current & low junction capacitance



Back lit photodiodes

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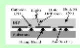
X-rays to CT Counts

X-ray photon ~ 70,000 eV

- Probability of absorption in 3 mm scintillator ~ 0.97
- Conversion efficiency of scintillator ~ 9.3 %
- Energy of emitted optical photon = 2.04 eV @ 610 nm

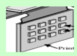
Number of optical photons ~ 3100

- Collection efficiency of optical photons ~ 0.38
- Quantum efficiency of the photodiode = 0.7



Number of electrons created ~ 824

- Integration time = 0.98 ms
- DAS gain = 1000 counts per pico-Amp



CT counts ~ 135 (0.135 pico-Amp)

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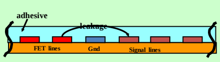
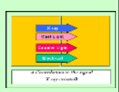
X-ray Detector Failures

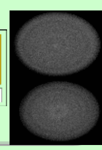


Leakage of the control lines to signal lines through the adhesive in the flex

Cracked pixel



Color reversal



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Learning Objective

- Understand the function of major components of x-ray tube.
- Understand the function of major components of CT detector.
- Understand the practical challenges, advanced technology to overcome the challenges, and the impacts on image quality when appropriate.

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Question 1

Assuming the filament length is constant, which one of the following statements regarding the anode angle of X-ray tube in CT is true?

1. Smaller anode angle provides better spatial resolution, larger field coverage, less heel effect, and higher power loading.
2. Smaller anode angle provides worse spatial resolution, smaller field coverage, stronger heel effect, and less power loading.
3. Larger anode angle provides better spatial resolution, larger field coverage, stronger heel effect, and higher power loading.
4. Larger anode angle provides worse spatial resolution, larger field coverage, less heel effect, and lower power loading.
5. None of above is correct.

Answer is 4. A smaller anode angle provides a smaller effective focal spot (hence better spatial resolution) for the same actual focal area. However, a smaller anode angle limits the size of usable x-ray field owning to cutoff of the beam. Smaller anode angle also can cause stronger heel effect because of the steeper intensity falloff across the beam. Finally, a larger anode angle reduces the actual focal area and results in poor power loading.

Reference: Reference: J. Bushberg, J. Seibert, E. Leidholdt, J. Boone, "The essential physics of medical imaging", Lippincott Williams & Wilkins.

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Question 2

The CT detector scintillator converts X-rays into?

1. Light
2. Electrons
3. Photons
4. Current
5. Gas

Answer is 1. An incident x-ray photon undergoes a photoelectric interaction with the scintillator…characteristic radiations are emitted in the visible or UV light spectrum.

Reference: J. Hsieh, "Computed Tomography: Principles, designs, artifacts, and recent advances", SPIE Press, Bellingham, WA.

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Question 3

The most likely artifact produced by a third-generation CT detector is a?

1. Doubloon
2. Ring
3. Vase
4. Statue
5. Shard

Answer is 2. With third-generation geometry in CT, each individual detector gives rise to an annulus (ring) of image information. When a detector becomes mis-calibrated, the tainted data can lead to ring artifacts in the reconstructed image.

Reference: J. Bushberg, J. Seibert, E. Leidholdt, J. Boone, "The essential physics of medical imaging", Lippincott Williams & Wilkins.

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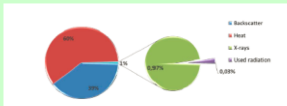
Efficiency of Bremsstrahlung



- Many electrons go through inelastic scattering and produce no or very little X-rays Conversion efficiency ~ 10^{-4}
- The wasted energy becomes heat

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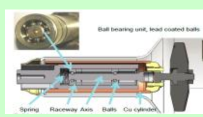
Rotating Anode Stator and Rotor

- Consists of two main parts:
- Rotor:
  - Located ***within*** the glass envelope
  - Made up of coper bars & ball bearing around a shaft
  - Ball bearings have limited life & deteriorate by high speed, load, and temperature
- Stator:
  - Located just ***outside*** the glass envelope
  - Made up of a series of magnets equally spaced around the neck of the tube
  - Induces rotation of the motor



Ball bearing system in a glass tube

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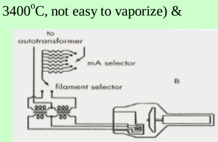
Filament

- Many X-ray tubes have dual filaments – dual focal spots
- Purpose:
  - Boil off electrons (thermionic emission aka Edison effect)
- Filaments need to withstand great amount of heat
- Made of Tungsten (A = 74, melts > 3400°C, not easy to vaporize) & Thorium is added to make the filaments last longer
- Vaporization of W is the main cause of tube arcing & ultimately tube failures



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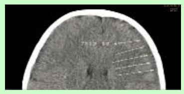
Off Focal Radiation

- Impact of back-scattered electrons
- ~10% off-focal
- Softer than primary
- Artifacts mimicking bleeding (stroke)
- Remedied by electron cup



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