Nuclear Medicine Physics

Lecture 4
Gamma Cameras

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References :
- RSNA/AAPM Physics Modules
http://www.rsna.org/RSNA/AAPM_Online_Physics_Modules_.aspx
- Physics in Nuclear medicine, 4th ed. by Cherry et al.
- Essentials of Nuclear Medicine Physics and Instrumentation, 3rd ed. by Powsner

General purpose systems

Dual-Head gamma camera

Triple-Head gamma camera

Detector size ~ 30 – 50 cm

Dedicated systems

Cardiac system

brain system

Breast-Specific Gamma Imaging (BSGI)

Gamma emitting radionuclides for NM imaging

- Must be able to pass through the body
- Must be detectable

Radionuclide	Energy (keV)	Tracers (2014)
Tc-99m	140	17
Tl-201	71, 167, 135	1
In-111	245, 171	5
Ga-67	184, 300	1
I-123	159	3
I-131	364	2
Xe-133	81	1

Workhorse of NM

80-85% of all NM imaging procedures

Energy range
70 ~ 360 keV

Scintillation Crystal

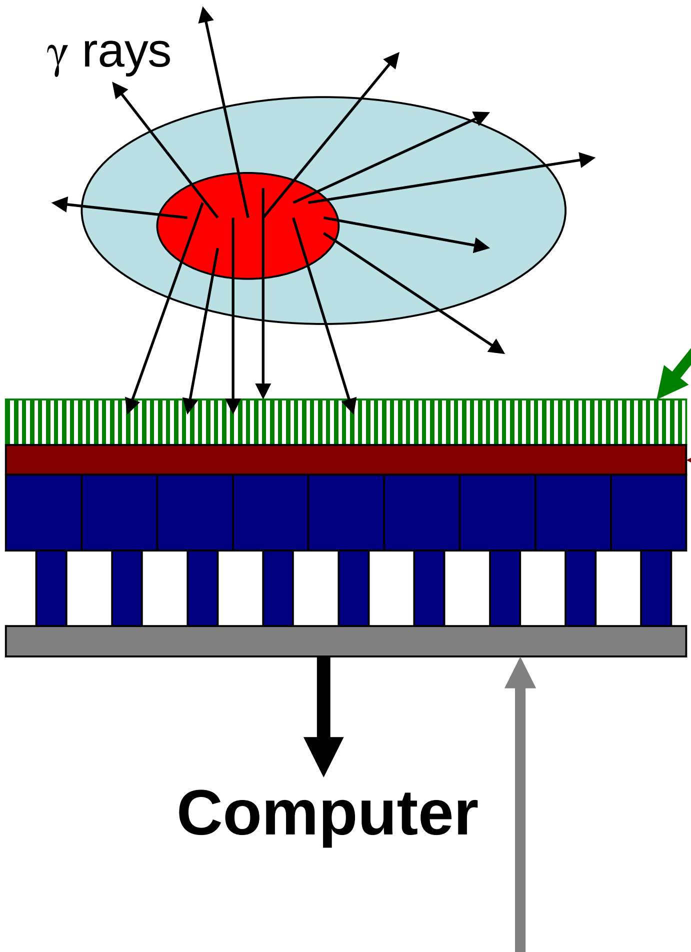
<u>General purpose Gamma ray detector,</u>

- Must have good detection efficiency
- the detector of choice for radionuclides with γ ray emissions in the energy range, 70-360 keV
- Nearly all nuclear imaging devices in routine clinical use utilize Thallium doped Sodium Iodide, NaI (Tl),
- a scintillator
- Typical detector thickness : ~ 0.95 cm (3/8 inch)
- Large area crystal with a field of view ~ 50 x 40 cm

<u>Other detectors in NM</u>: Small field of view camera using CZT (Cadmium zinc telluride, CdZnTe) **<u>semiconductor</u>** detectors had been developed.

(dedicated cardiac or breast imaging system)

Camera Design



Collimator Define the direction of the detected γ rays. Major component affecting resolution and efficiency.

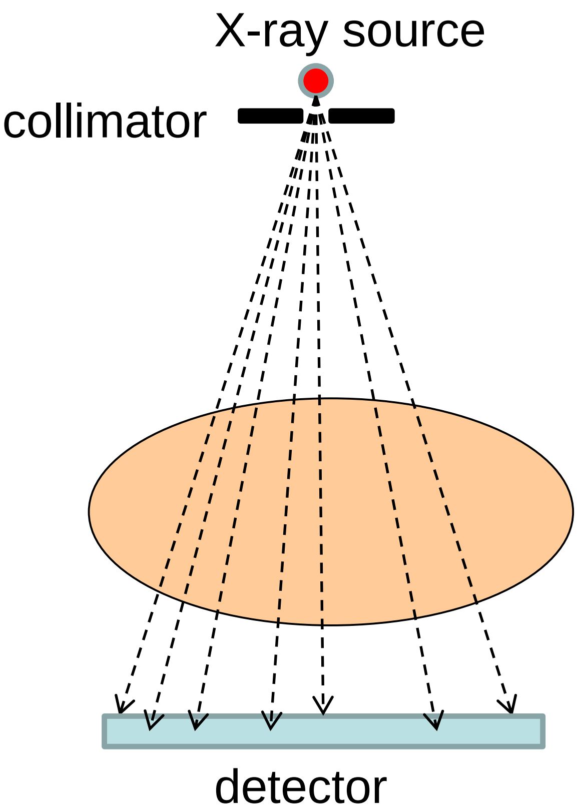
scintillation crystal γ ray detector. Emits light photons after deposition of high energy γ rays.

Photomultiplier tube (PMT) Each tube converts a light signal to an electrical signal and amplifies it.

Preamplifier, Positioning circuit & pulse height analyzer
Determines the location of each scintillation event. Rejects non-photopeak events.

Collimator

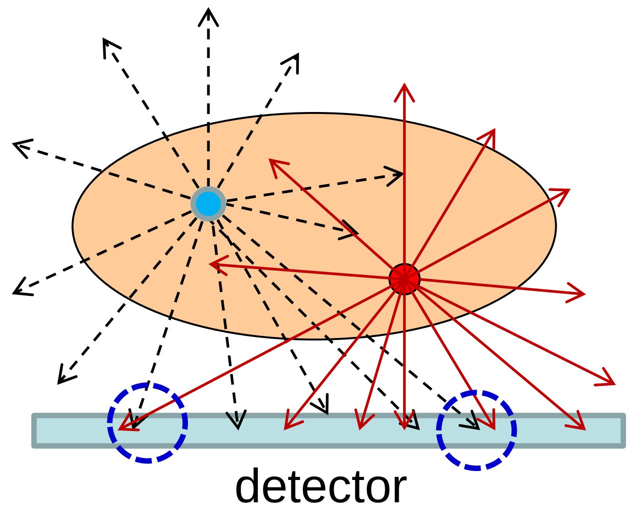
Transmission imaging



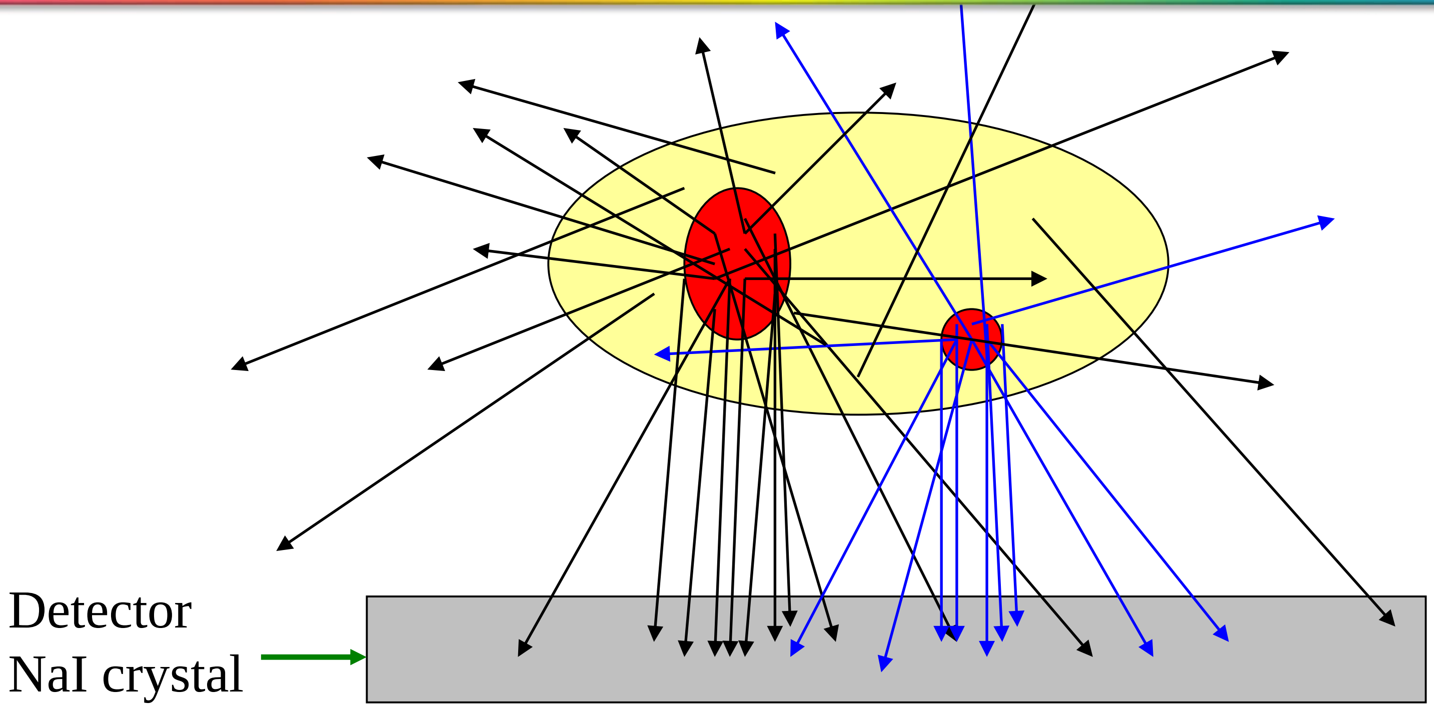
Primary photons travel known paths diverging radially from the focal spot

Emission imaging using a gamma camera

Photons in each volume element of a patient are emitted isotropically (equally in all directions)

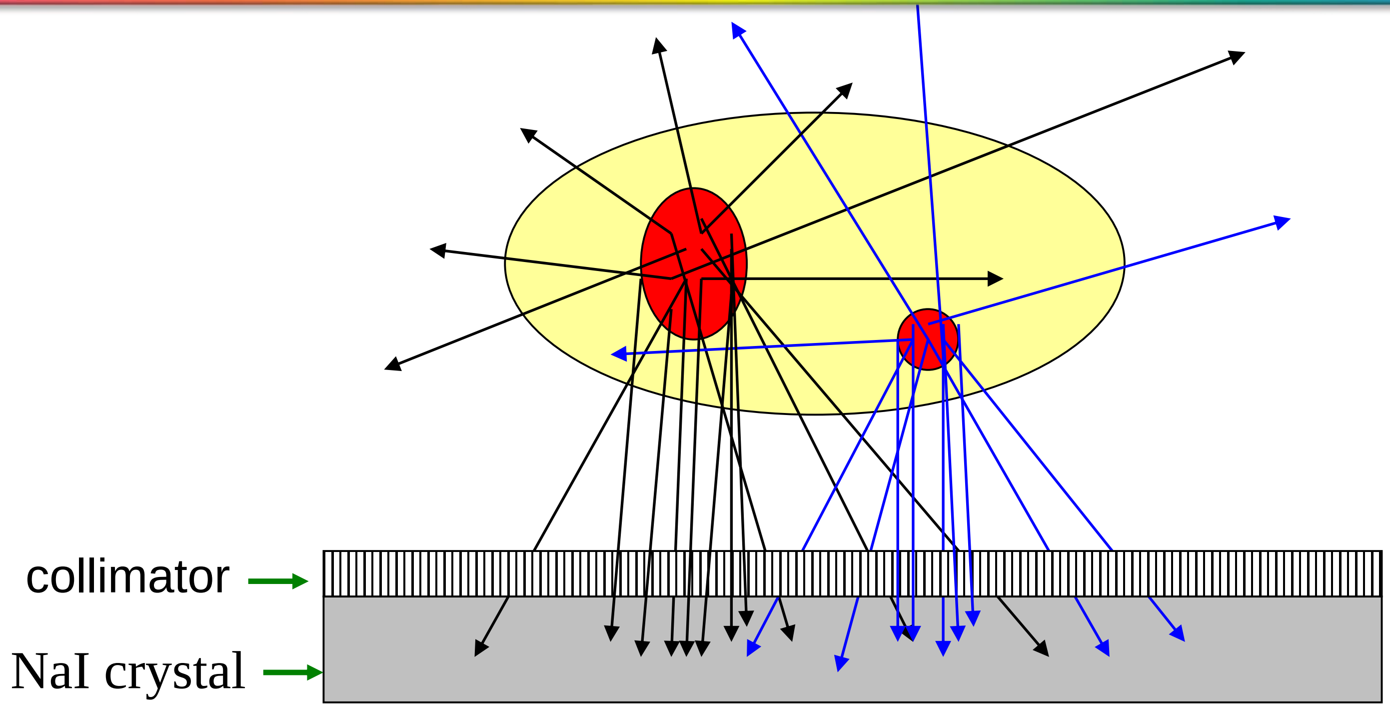


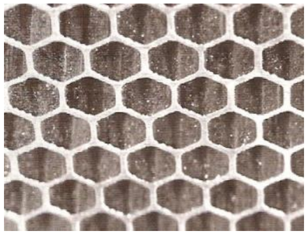
Collimator



- Gamma rays are emitted to all directions
- The detected gamma rays can come from any locations in the body

Collimator





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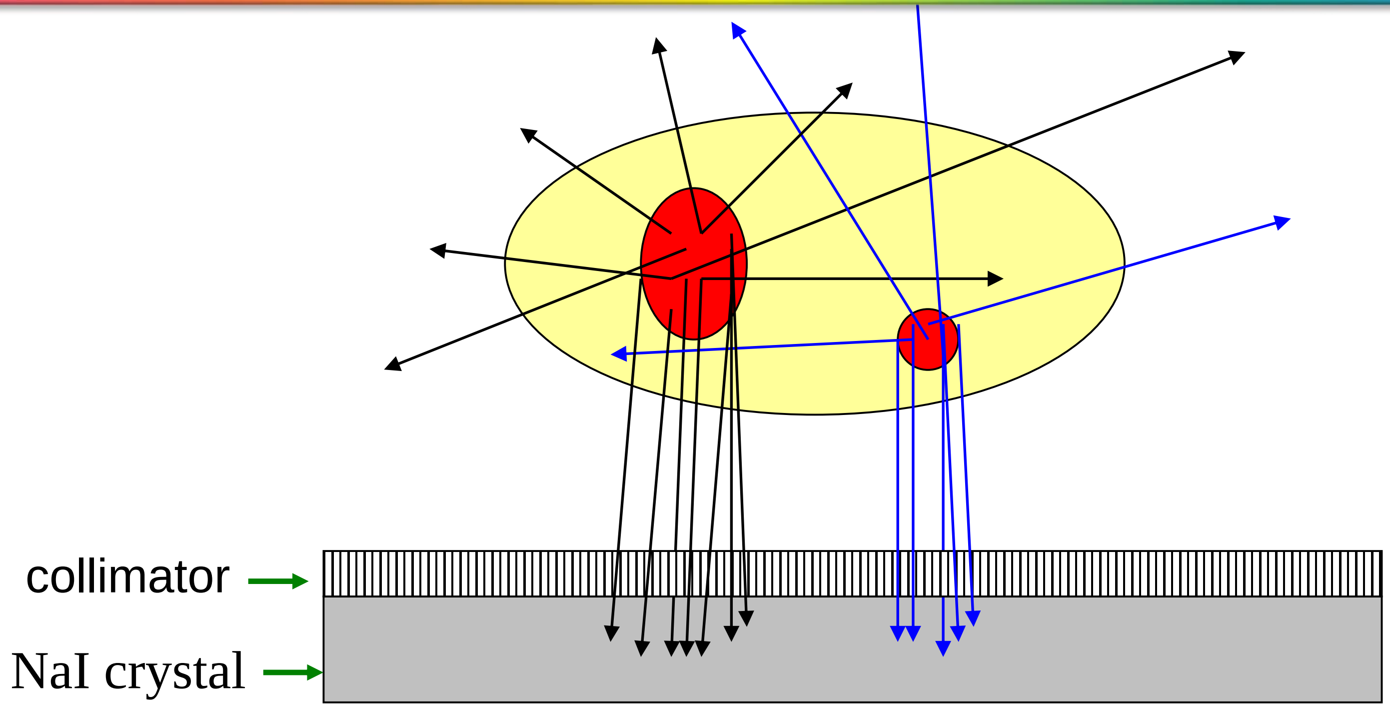
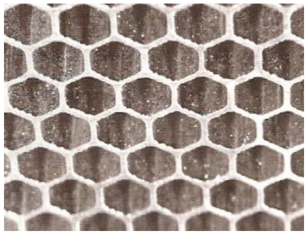
Collimator

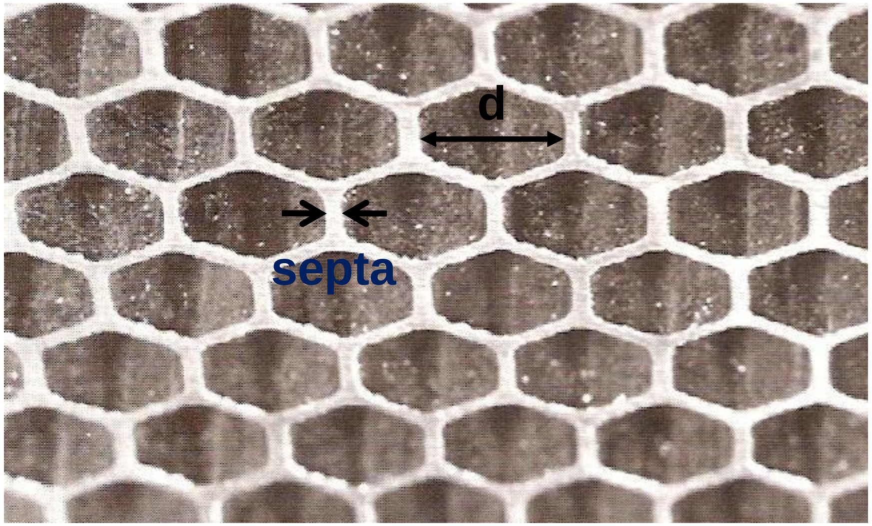




- The collimator allows those gamma rays traveling along certain directions to reach the detector
- The collimator establishes a one-to one correspondence between locations on the detector and those within the organ.

Collimator

- Made of gamma ray absorbing material, usually lead or tungsten
- Round, square, hexagonal hole shape
- Collimator selection requires consideration of the imaged object's location and size, energy of gamma rays, and desired resolution and sensitivity.
- <u>Usually more than 99.95 % of incident γ rays are absorbed (not detected!!!).</u>

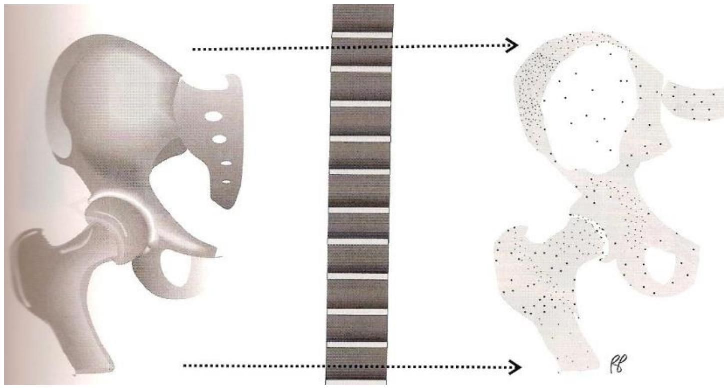


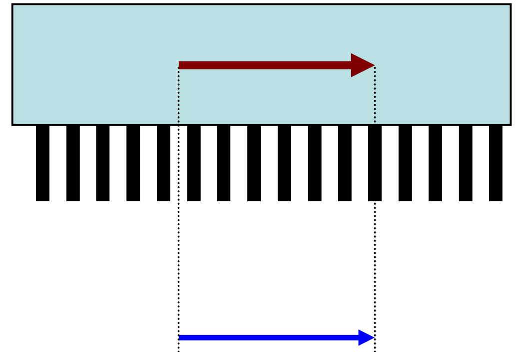
Cherry, p. 220 Fig.13-8

Half value layer (HVL) of lead for 140 keV (Tc-99m) ~ 0.3 mm

Types of Collimators

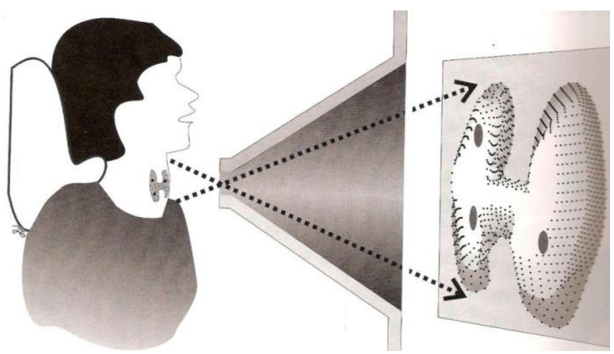
Parallel-hole collimator

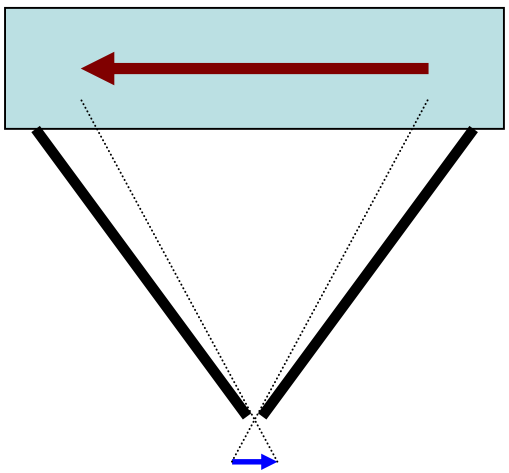




Workhorse collimator
Image size = object size

Pinhole collimator



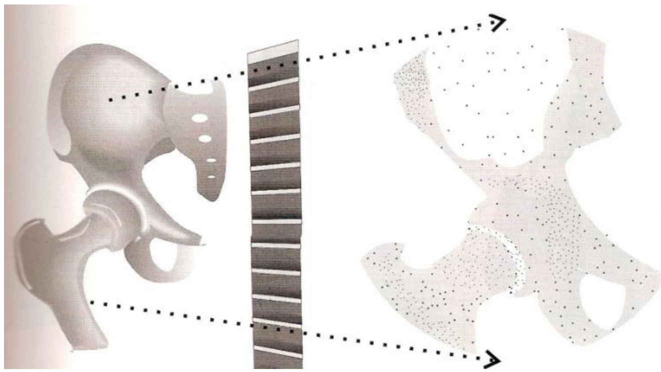


Inverted and magnified images. For small organs, thyroid, joint, pediatric imaging.

Powsner, p. 89-90.

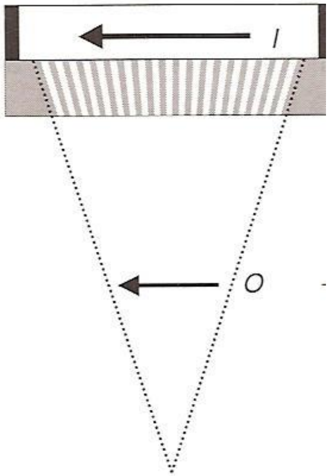
Types of Collimators

Converging collimator

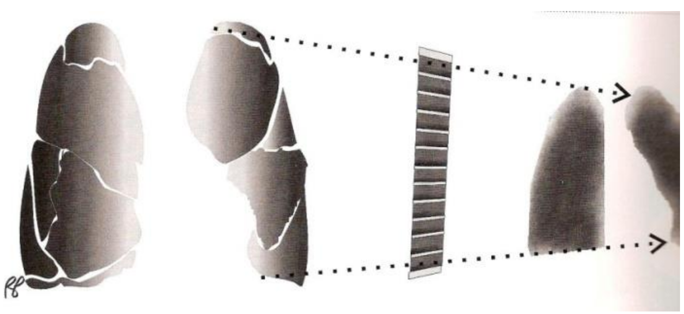


Magnified image

Imaging small or medium size organs with a large detector

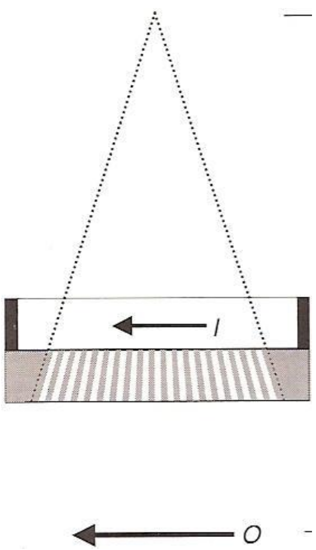


Diverging collimator



Minified image

Imaging large organ with smaller detector

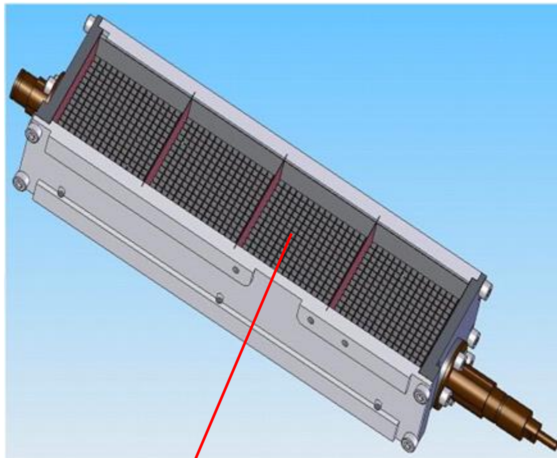


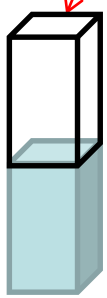
Types of Collimators

Parallel-hole collimator

Pin-hole collimator

For Gamma cameras with pixelated semiconductor detector

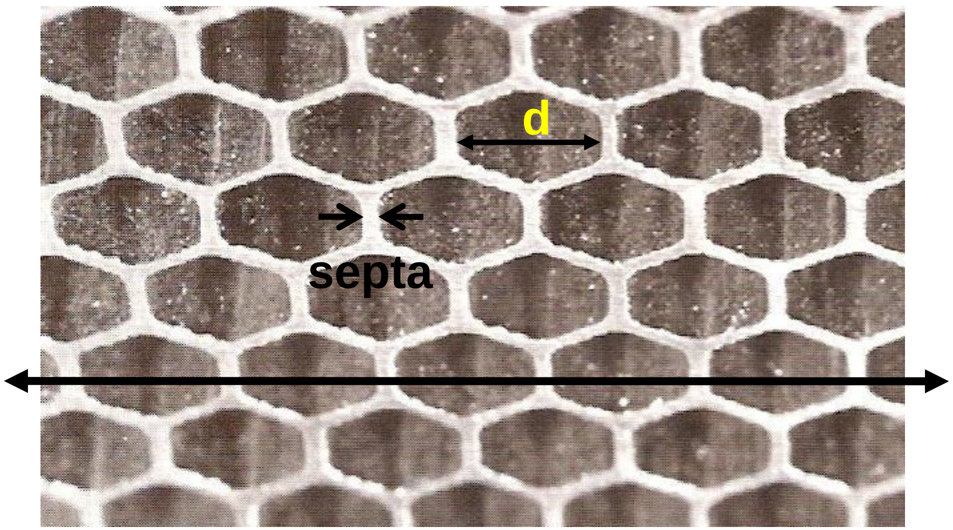


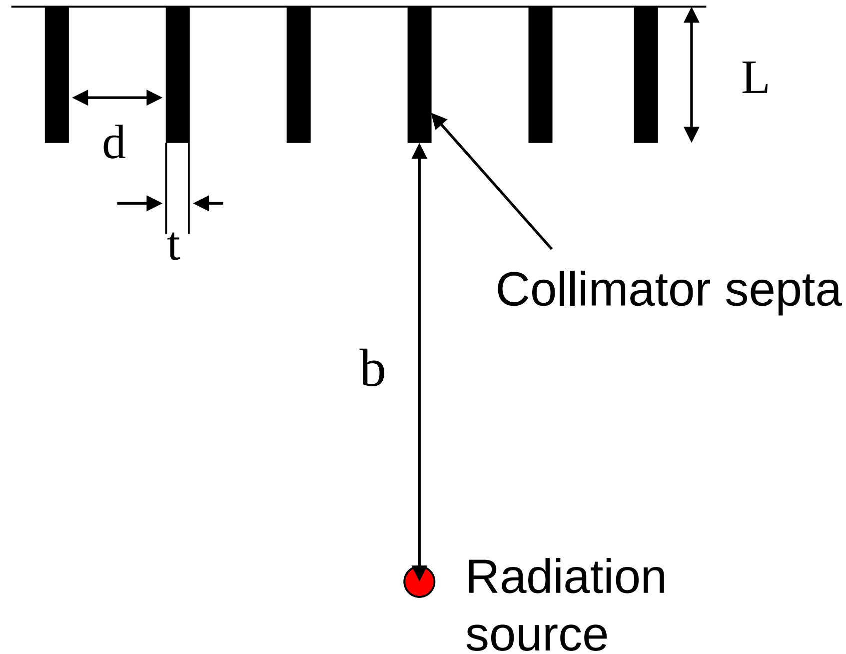


Each element, 2.5 x 2.5 x 5mm
with matching collimator (tungsten) ~ 2.2cm long

D-SPECT cardiac system and detector-head configuration. Sanjiv S. Gambhir et al. J Nucl Med 2009;50:635-643

Parallel-hole Collimator





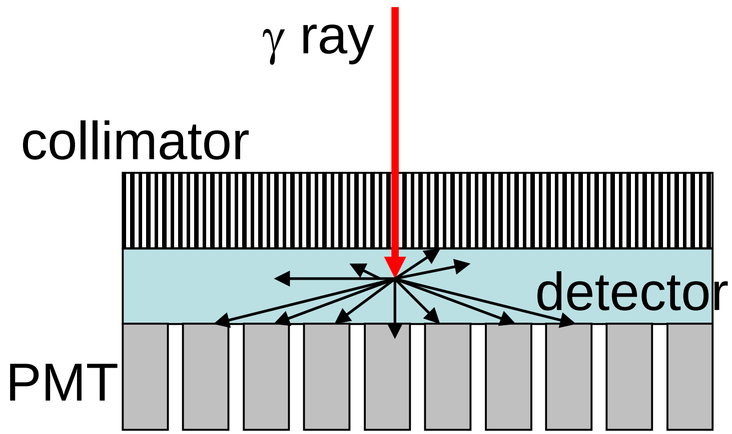
Three adjustable parameters (typical range)

L : hole length (2 - 4 cm)
d : hole diameter (1 - 3 mm)
t : septal thickness (0.1 – 0.3 mm)

➡ All contribute to image quality

b: distance from the collimator to the source

Scintillation Crystal



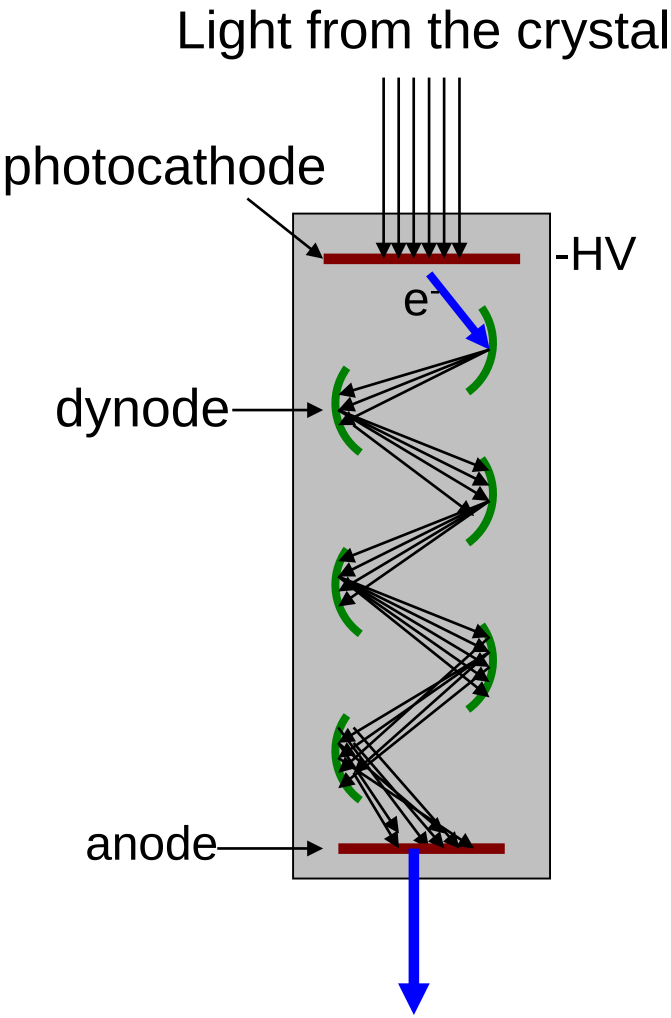
1. The gamma ray photon interacts with the scintillation detector through the <u>Photoelectric Effect</u> or <u>Compton</u> scattering primarily with the iodide ions of the crystal. → This interaction releases an electron .

2. The electrons interact with the crystal lattice (Tl) to produce **<u>light</u>** in a process known as **<u>scintillation</u>.**

3. A flash of light triggers nearby photomultipliers tube (PMT)

Scintillation crystal (detector) converts the gamma ray to visible light!

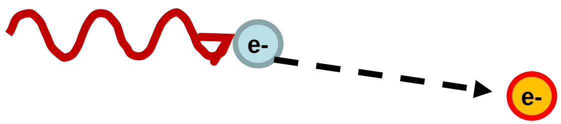
Photomultiplier tube (PMT)



Electric current pulse to electronics board for positioning and summing circuits

PMT turns those visible light photons into an electrical signal

1. photocathode will emit electrons by <u>photoelectric effect</u>, after absorbing light photons.



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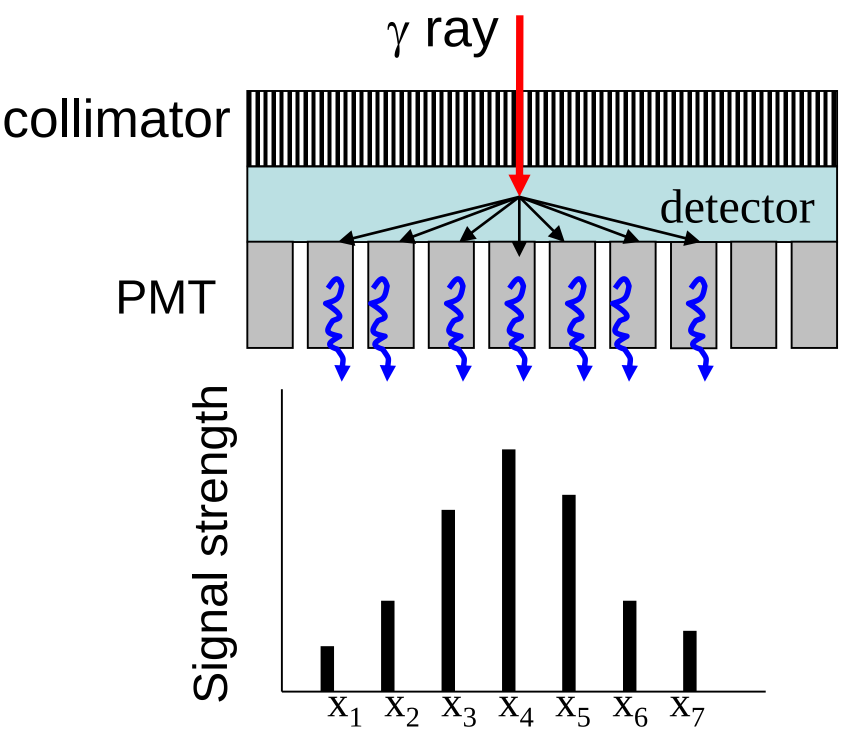
2. The electron multiplier (amplifier), called a dynode, emits several secondary electrons for each incident electron. ~10 - 14 multiplication steps (number of dynodes).

3. Total electrons ~ (#electron amplified)$^{\#dynode}$

4. For each electron liberated from the photocathode, ~10^6 electrons reach the anode, depending on the number of dynodes

Spatial Localization

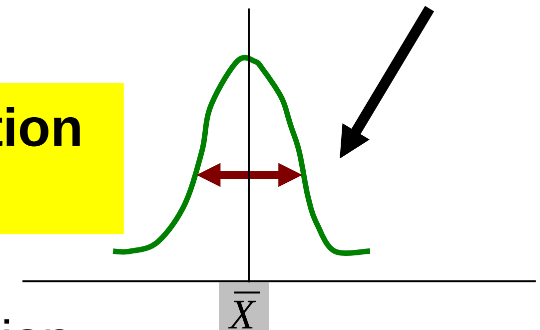


Weighted sum for positioning the primary interaction

$$\hat{X} = \frac{\sum_{i=1}^{7} x_i S_i}{\sum_{i=1}^{7} S_i}$$

This allows the position circuits to determine where each scintillation event occurred in the detector crystal.

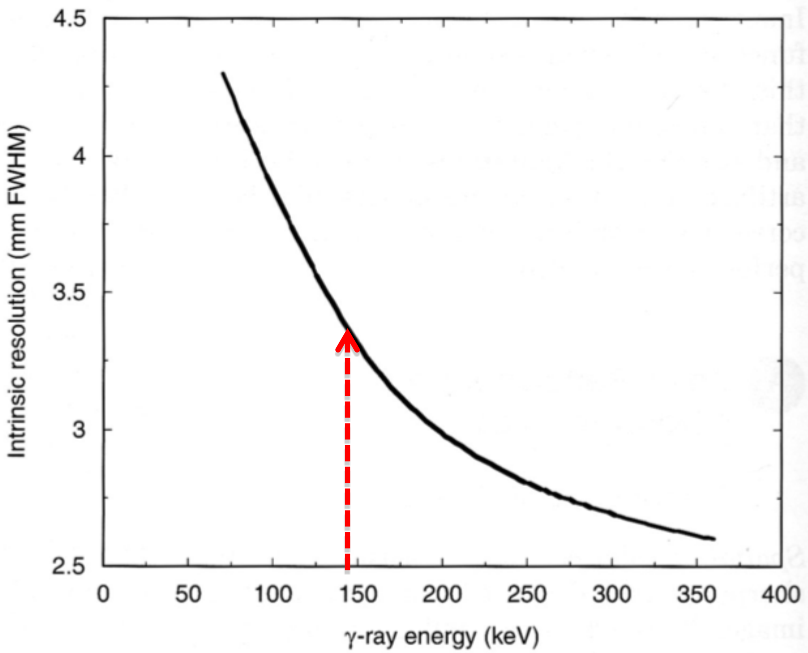
intrinsic resolution (FWHM)



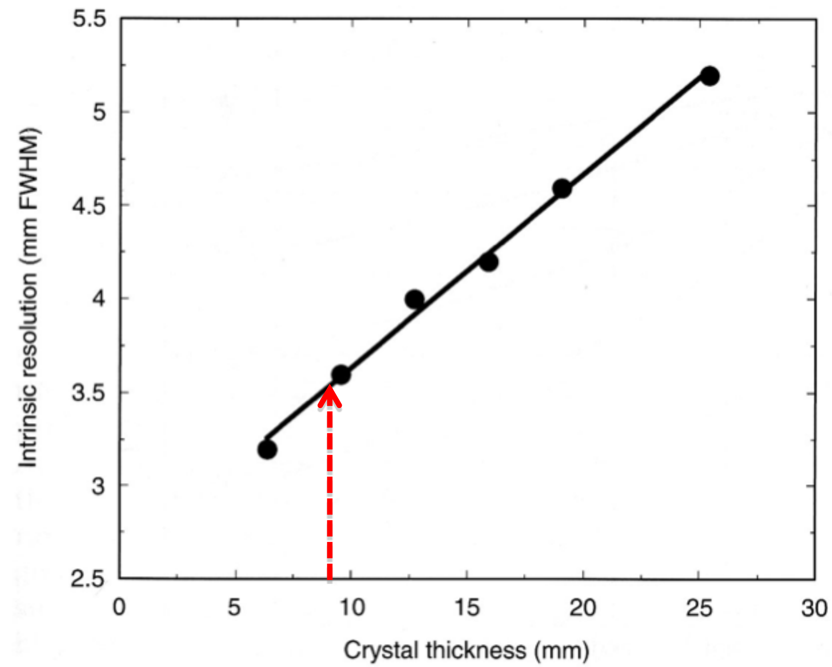
Error in the calculation of the position

Intrinsic spatial resolution

Number of scintillation light photon is roughly proportional to E.
At low E ➔ less photons → statistical fluctuation → blurring



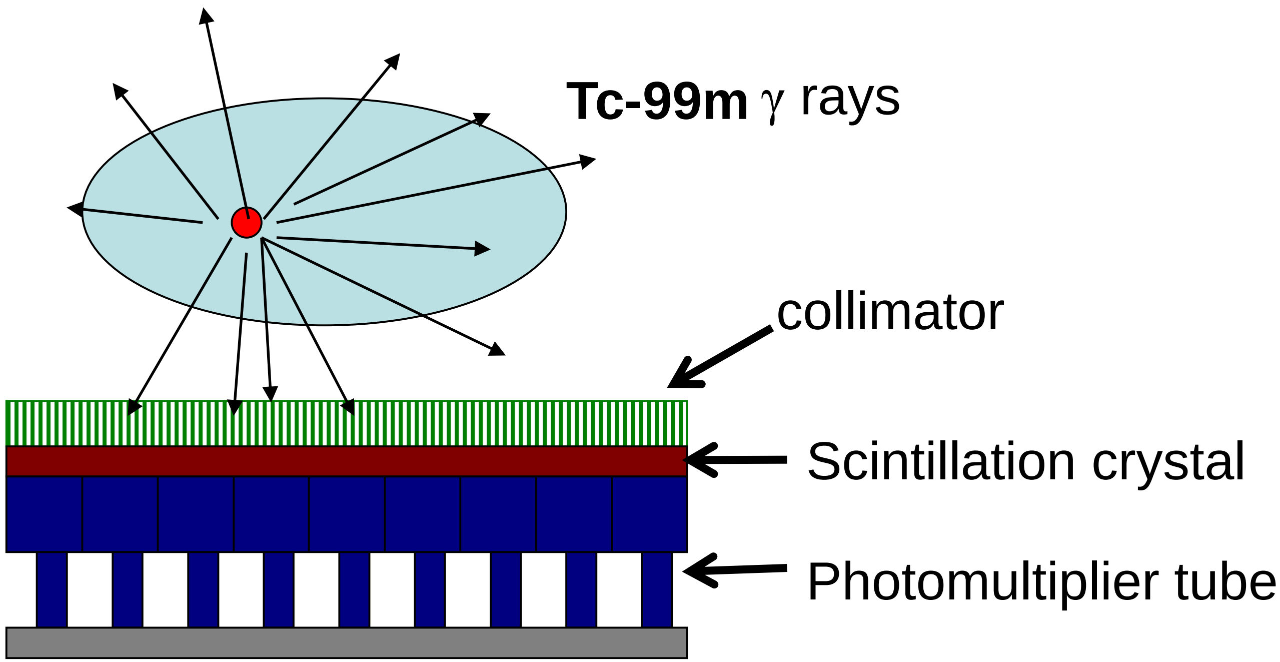
Thicker crystal →
greater spreading of light

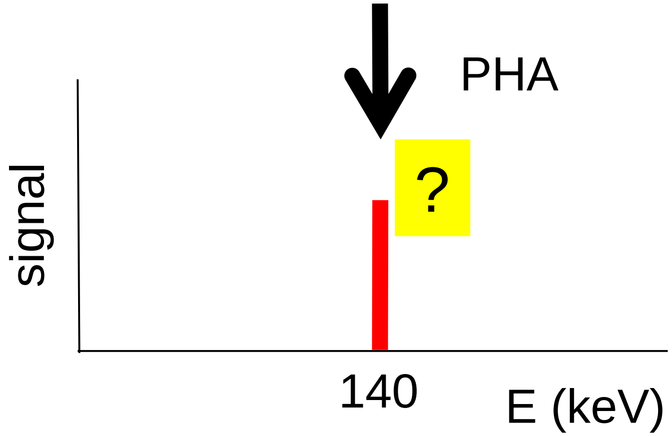


Intrinsic resolution for a large field of view gamma camera, ~ 3.5 mm FWHM at 140 keV (Tc-99m). (**3/8in=9.5mm thick NaI**)

Cherry, p. 228-229

Pulse-height analyzer : Energy Discrimination





Summing the signals from the individual PMT & produce an energy signal

→ proportional to total energy deposited in the crystal

→ Send to energy discrimination circuit

Individual events are analyzed for energy by pulse-height analyzer circuit

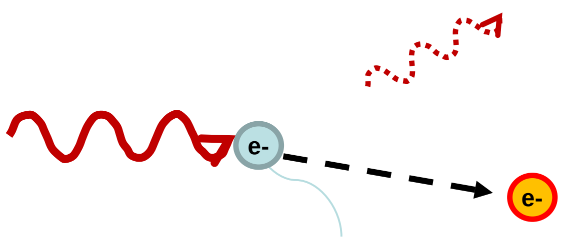
Energy Discrimination

Compton scattering process : photon gives some energy to electrons

- change direction with reduced energy
- Position information has been lost

→ contribute to noise and reduce contrast

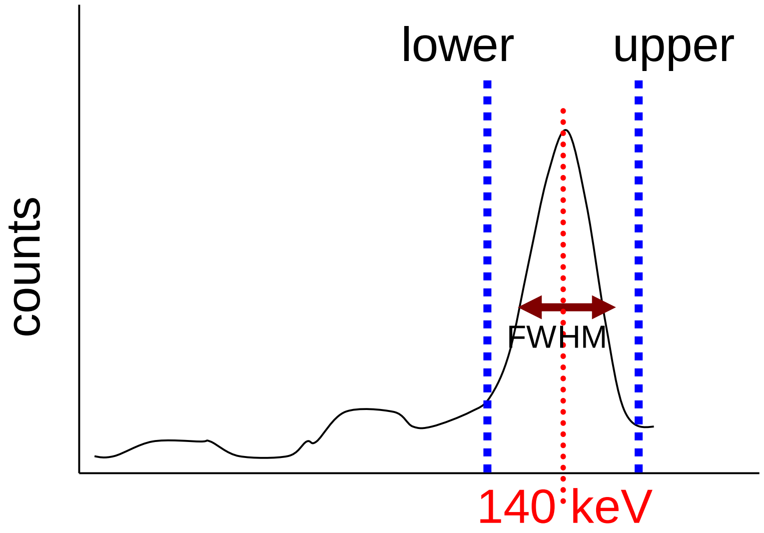
→ Need to get rid of these scattered photons from our final dataset



Scattered photons have reduced energy compared to original emission energy!

➔ set gamma camera to accept events that deposit energy close to the photopeak energy

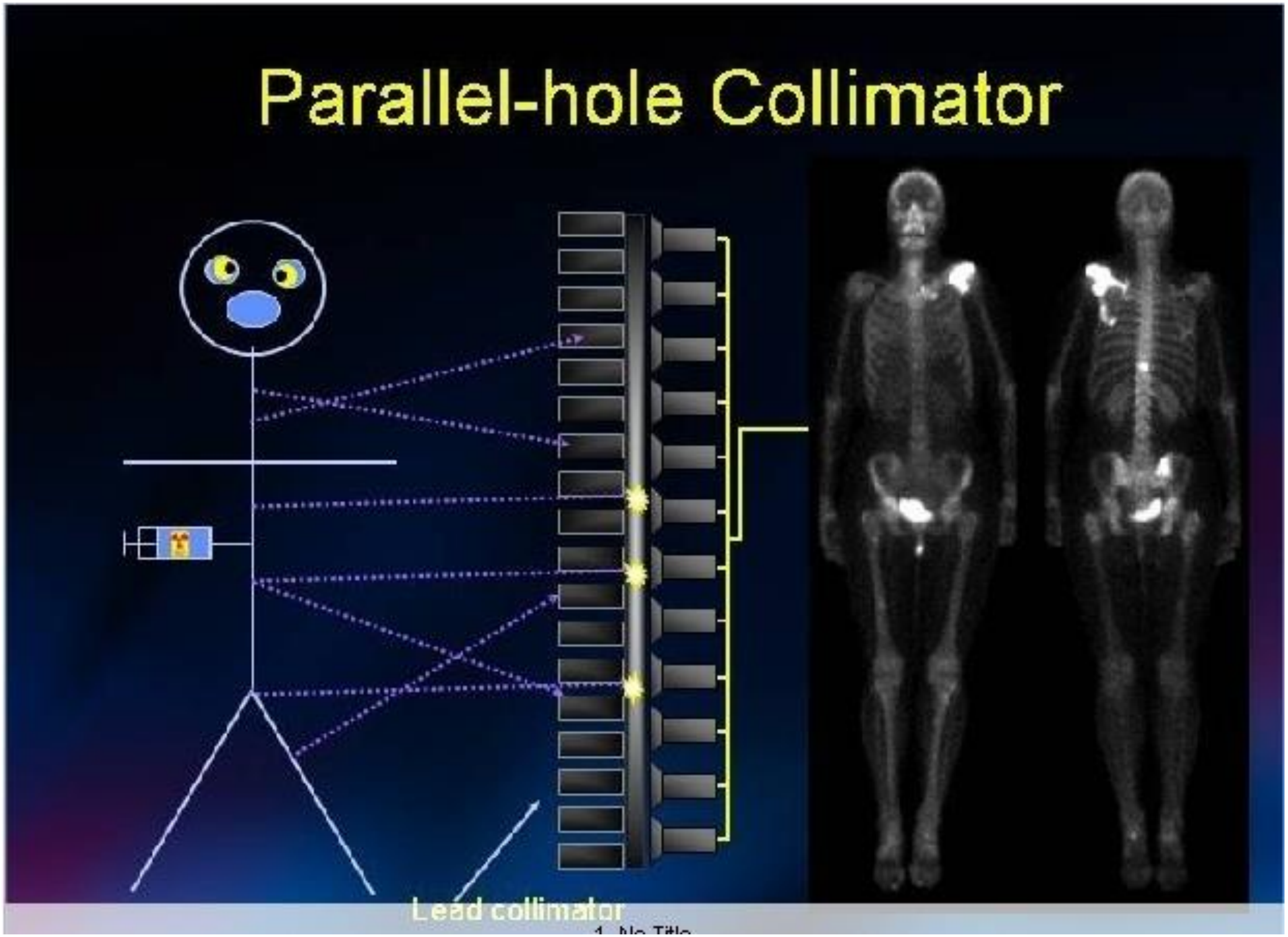
Energy Window



Typical window for Tc-99m is 15-20%

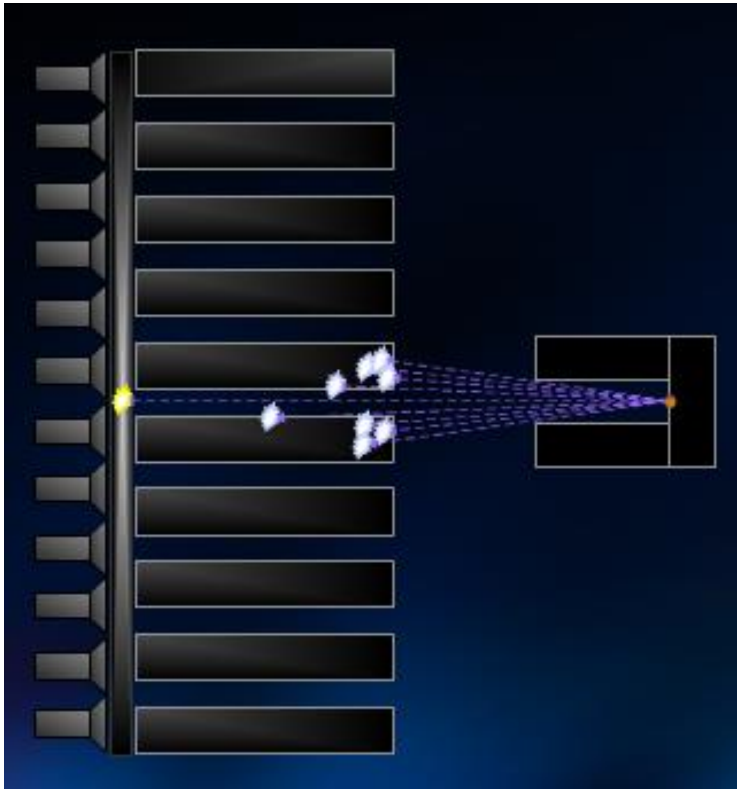
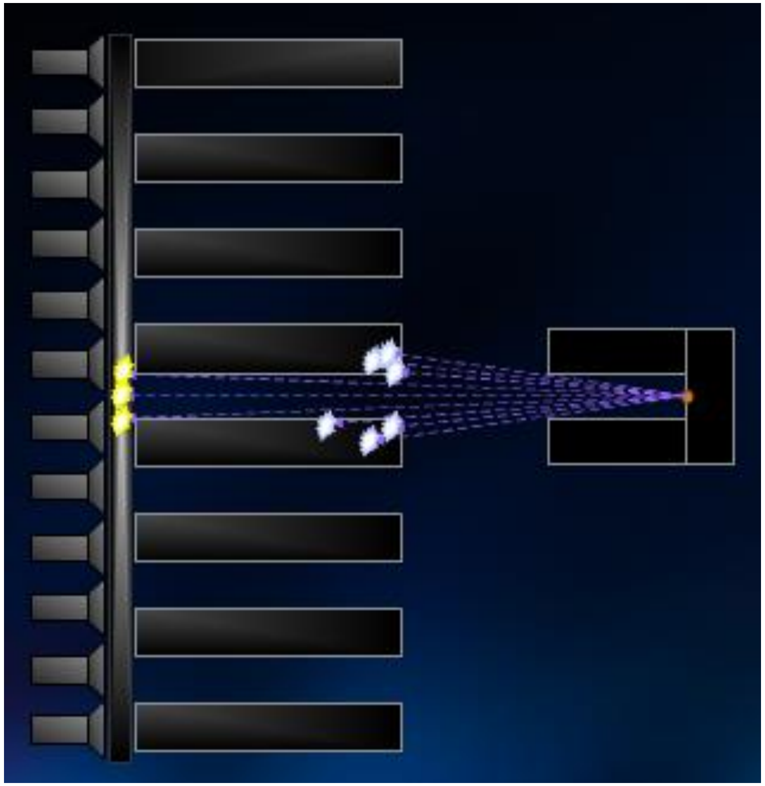
15 % window : 139.5 keV ~ 150.5 keV
20 % window : 133 keV ~ 157 keV

Collimator Characteristics

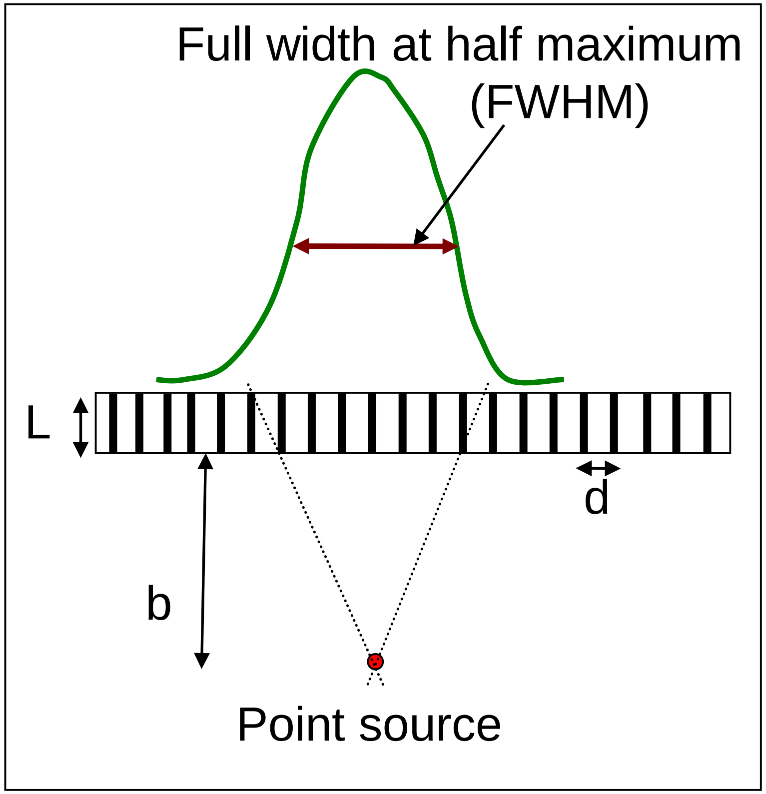


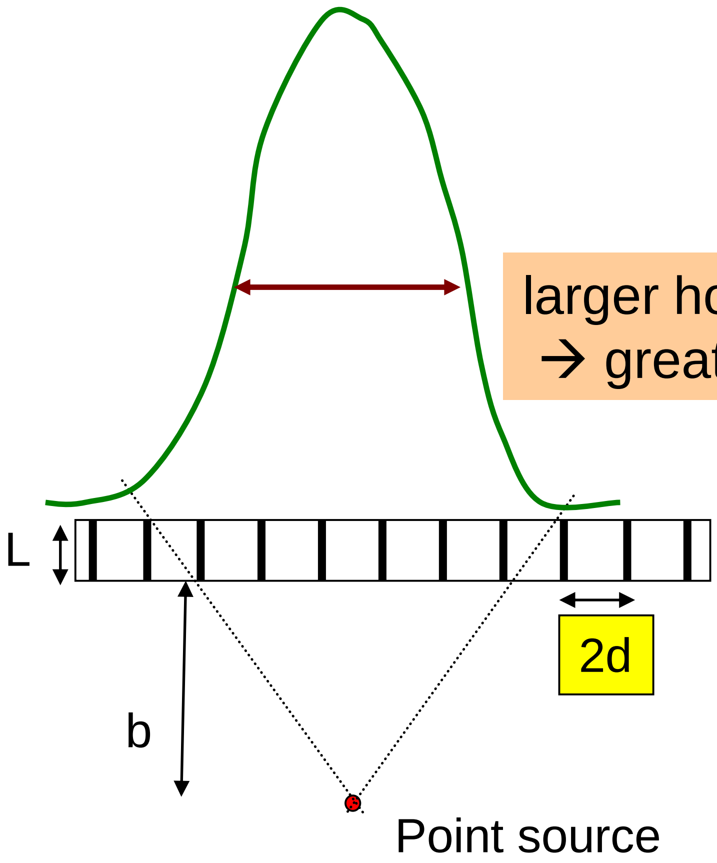
dual-head gamma camera, AP planar bone scan

Collimator Characteristics : Hole diameter

Small hole diameter	Large hole diameter
	
Better spatial resolution Low sensitivity	Worse spatial resolution High sensitivity

Collimator Characteristics : Hole diameter



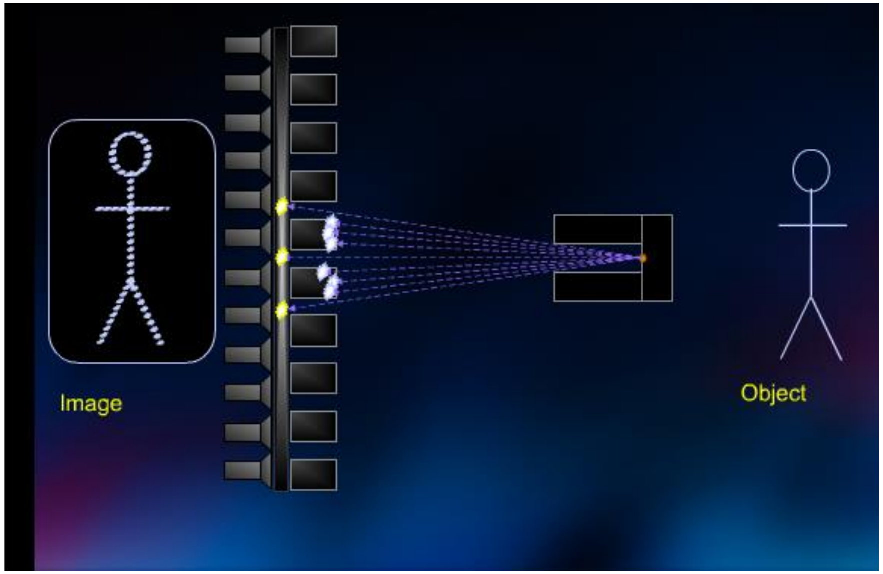


larger hole size
→ greater FWHM

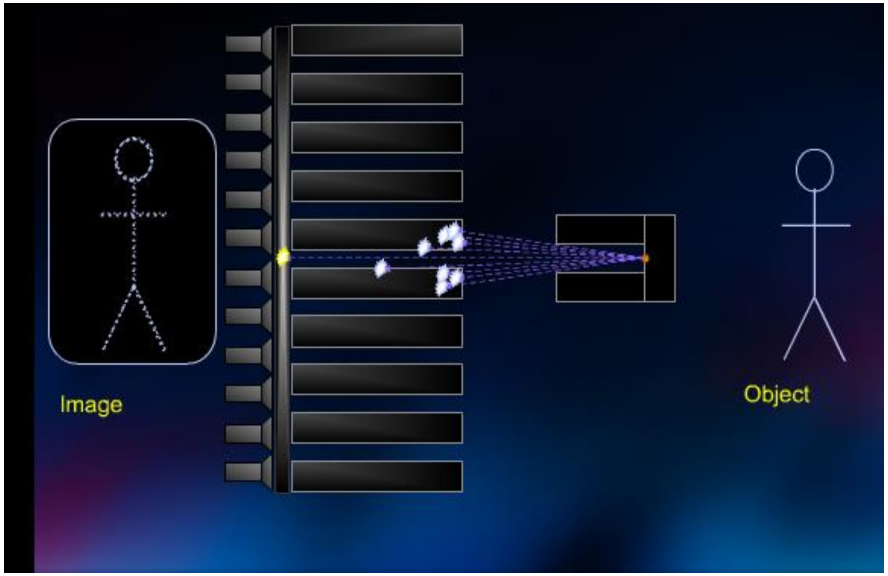
Projected radiation profile (point-spread function)

Collimator Characteristics : Septal length (hole length)

Short septa



long septa

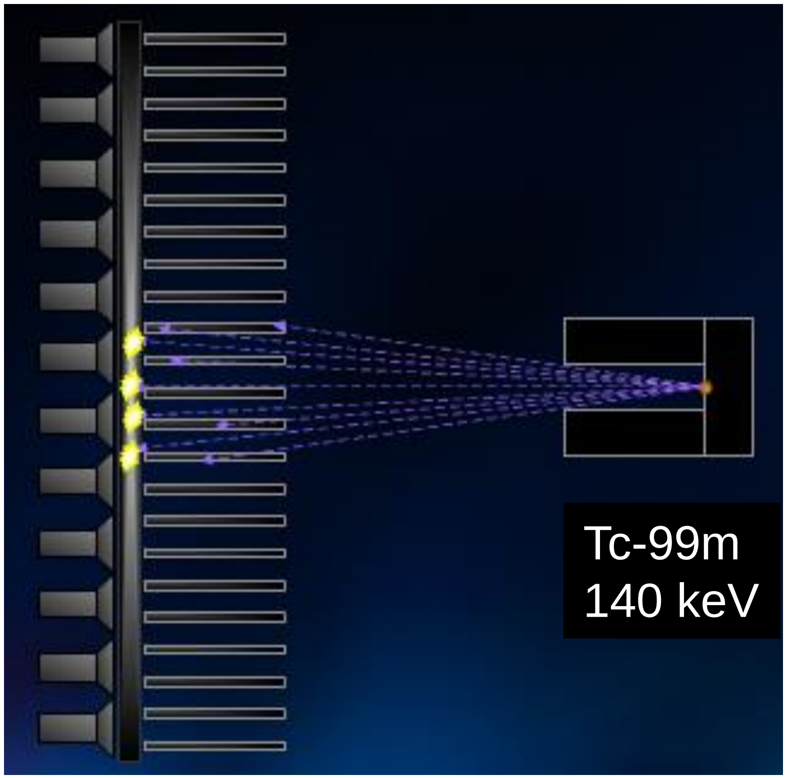


Low spatial resolution
high sensitivity

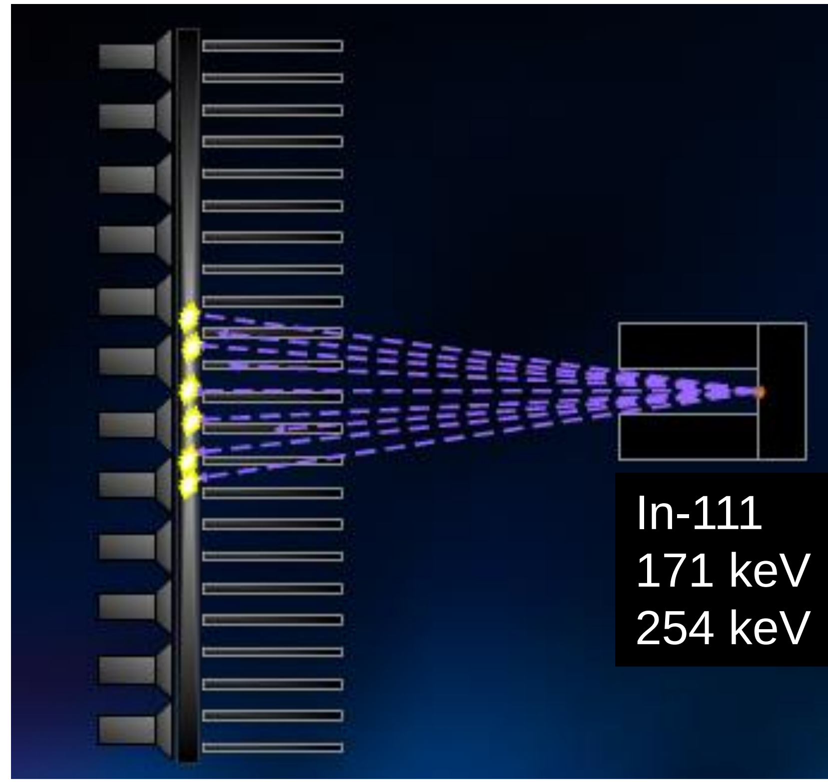
high spatial resolution
Low sensitivity

Collimator Characteristics : Septal thickness

Low energy, Tc99m



Medium energy, In-111



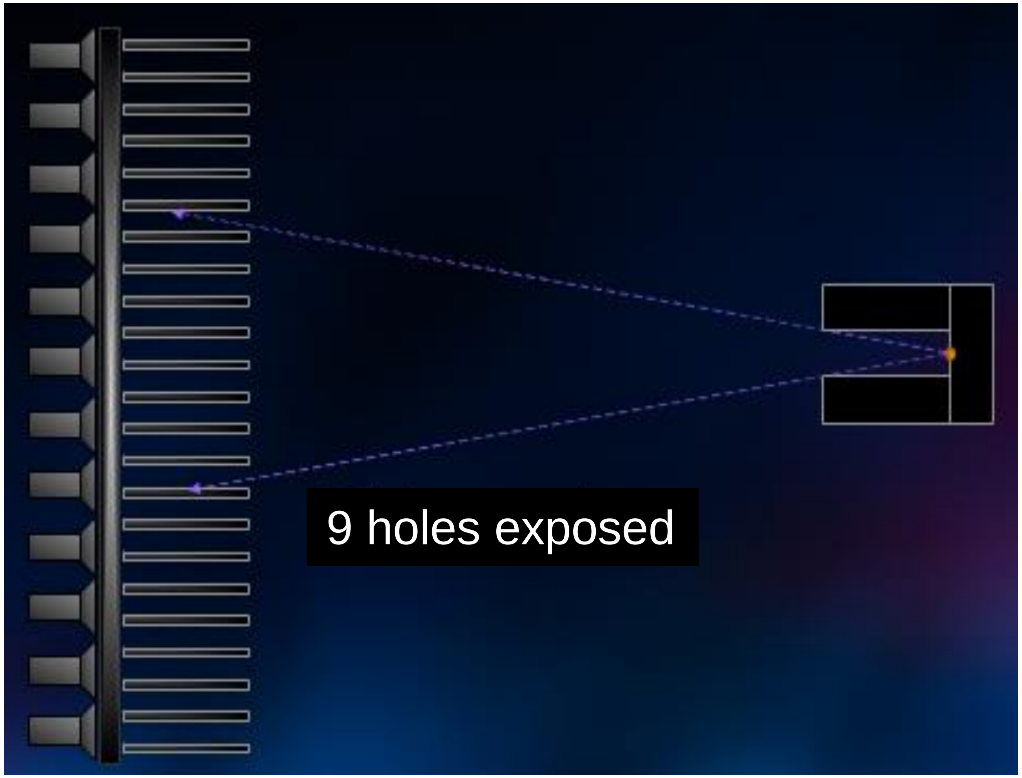
septal penetration : degrade spatial resolution
Thicker septa is used for medium and high energy gamma rays

Collimator Characteristics : collimator-object distance

Closer to the collimator

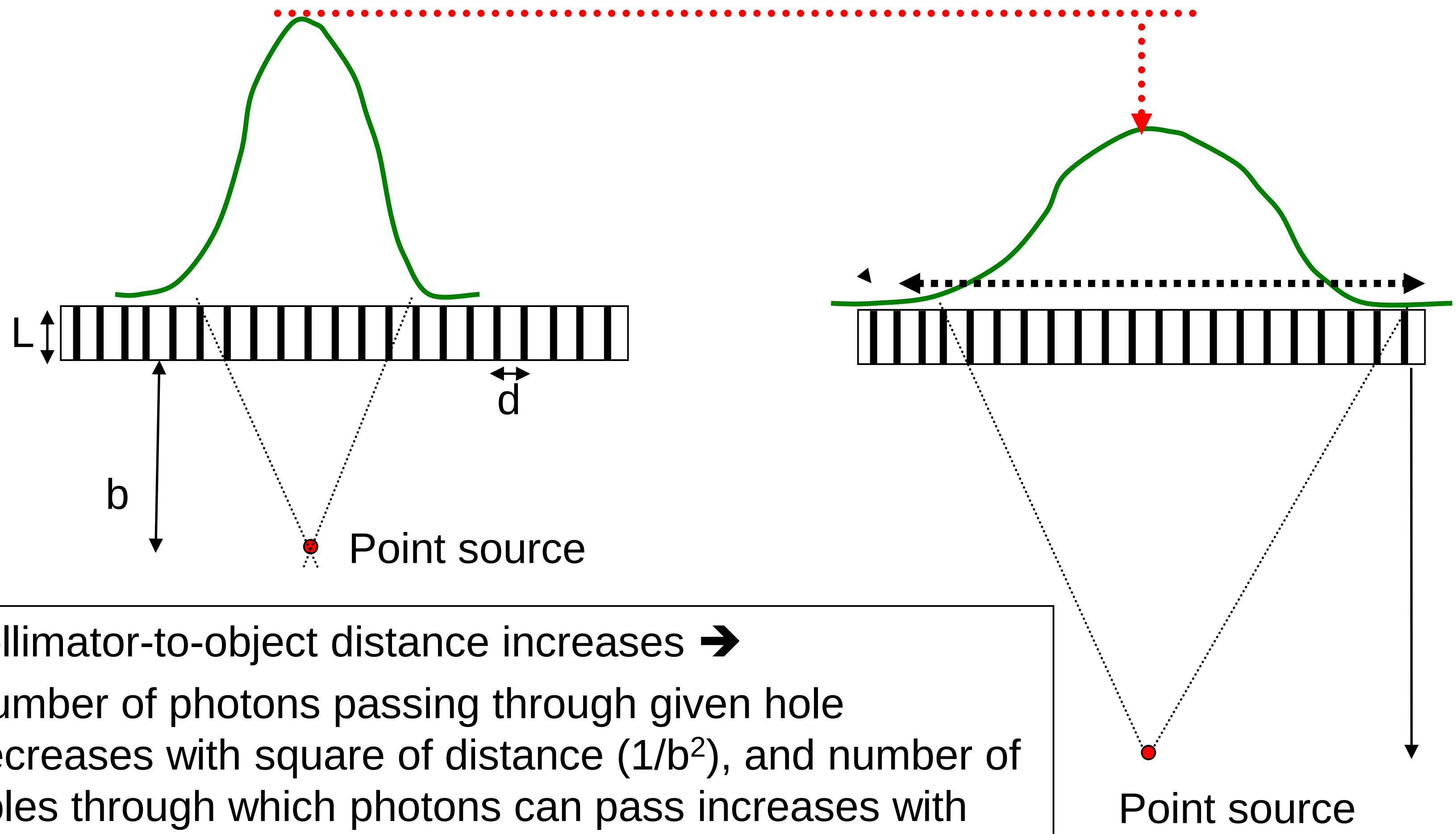
High resolution

Far from the collimator



low resolution

Collimator Characteristics : collimator-object distance

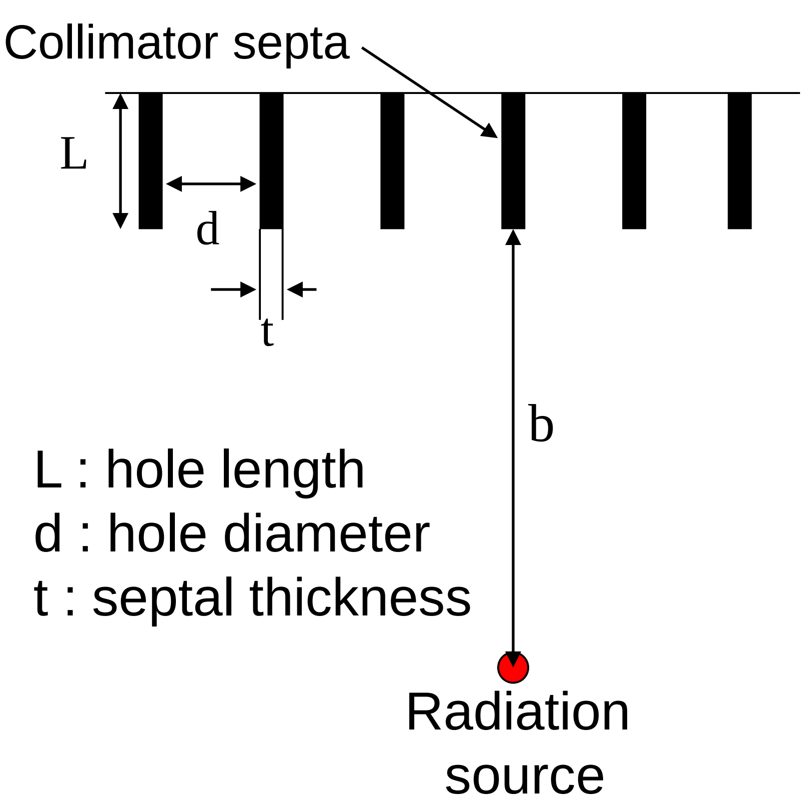


collimator-to-object distance increases ➔

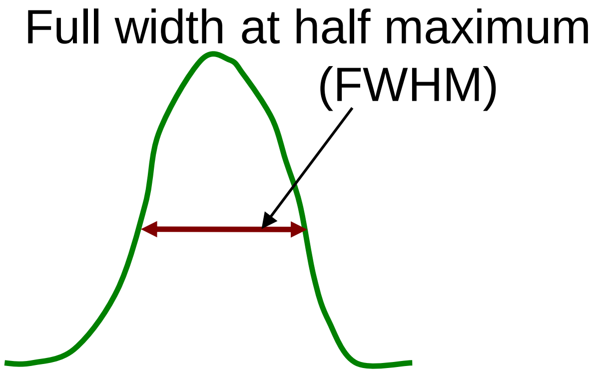
Number of photons passing through given hole decreases with square of distance ($1/b^2$), and number of holes through which photons can pass increases with square of distance (b^2).

Efficiency of a parallel-hole collimator is constant over the collimator-to-object distances

Collimator resolution



L : hole length
d : hole diameter
t : septal thickness



Full width at half maximum (FWHM) of the radiation profile from a point or line source projected by the collimator onto the detector

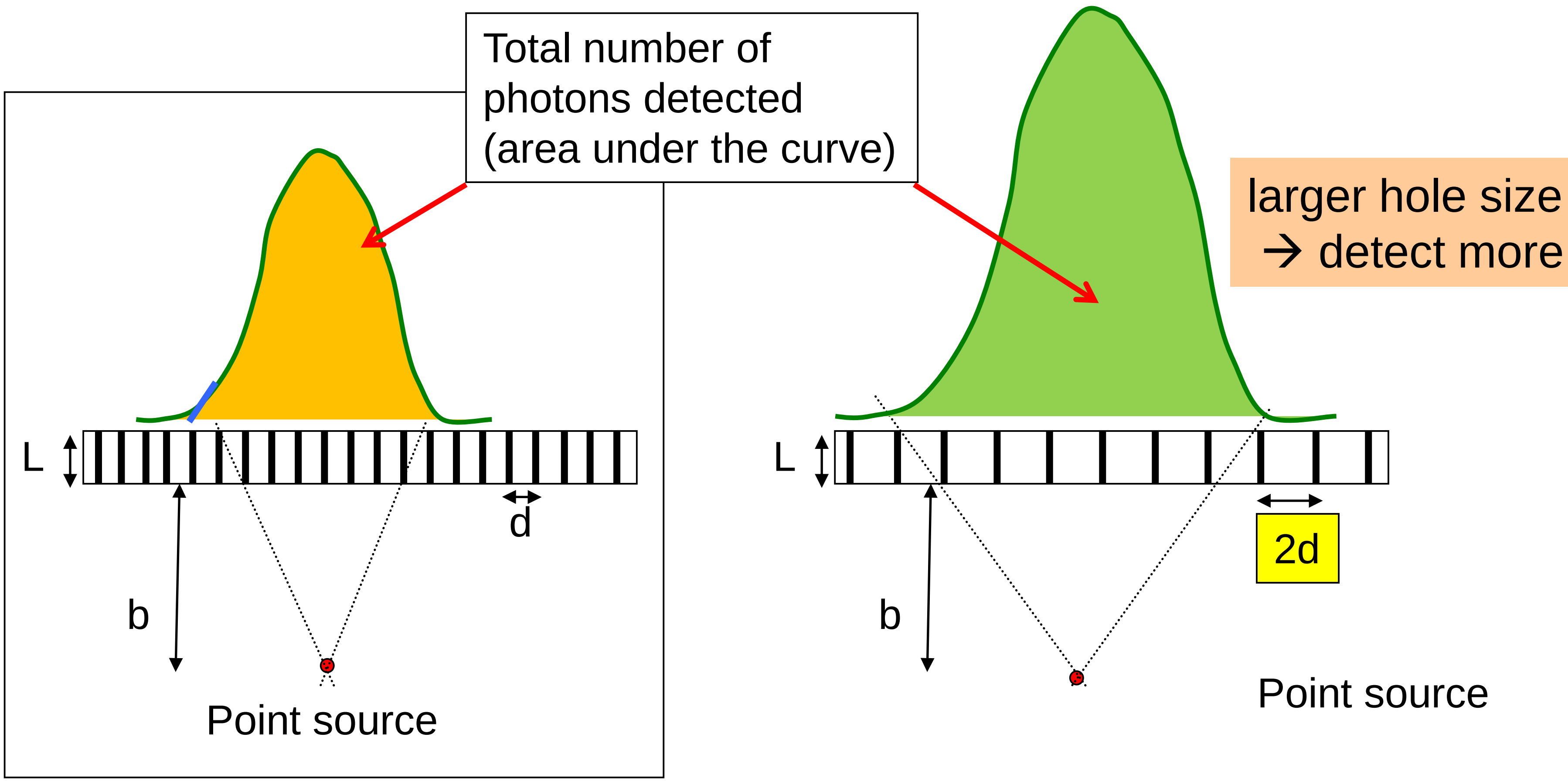
$$R_{coll} \approx \frac{d(L+b)}{L}$$

<u>Example</u> : Collimator parameters, d=0.25cm, L=2.5cm, t=0.03cm

a. Source at b=2cm, R ≈ 0.25 (2.5+2)/2.5 = 0.45 cm
b. Source at b=10cm, R ≈ 0.25 (2.5+10)/2.5 = 1.25 cm

Improvement in resolution means smaller R_{coll}

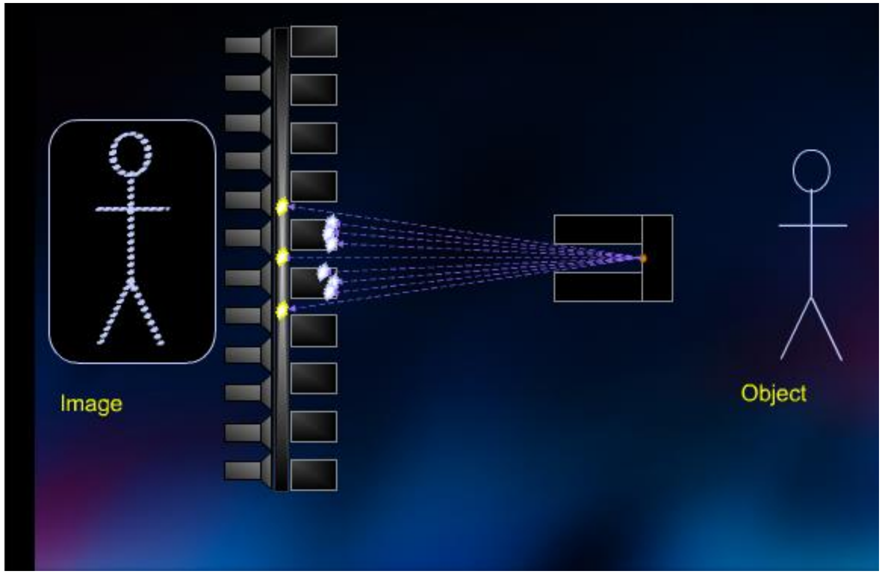
Collimator Characteristics : Geometric sensitivity



Projected radiation profile (point-spread function)

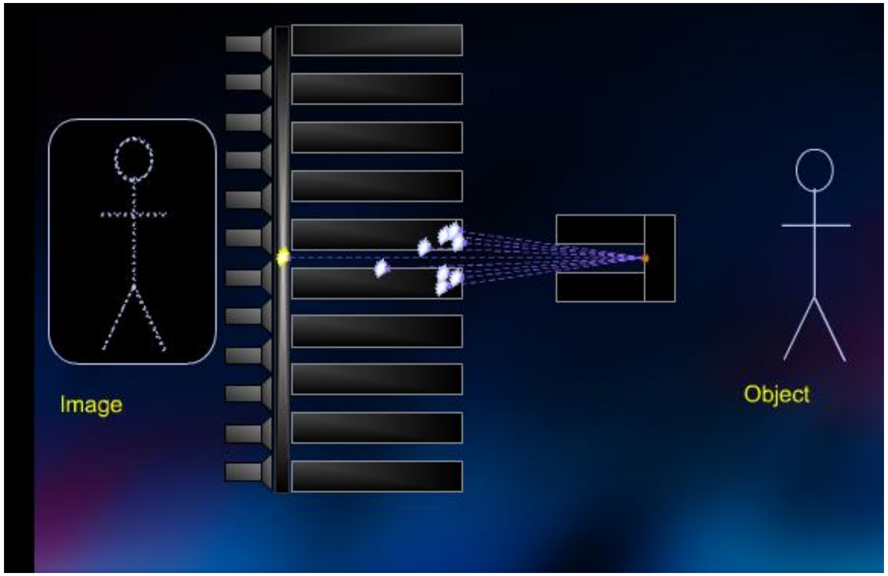
Collimator Characteristics : Septal length

Short septa



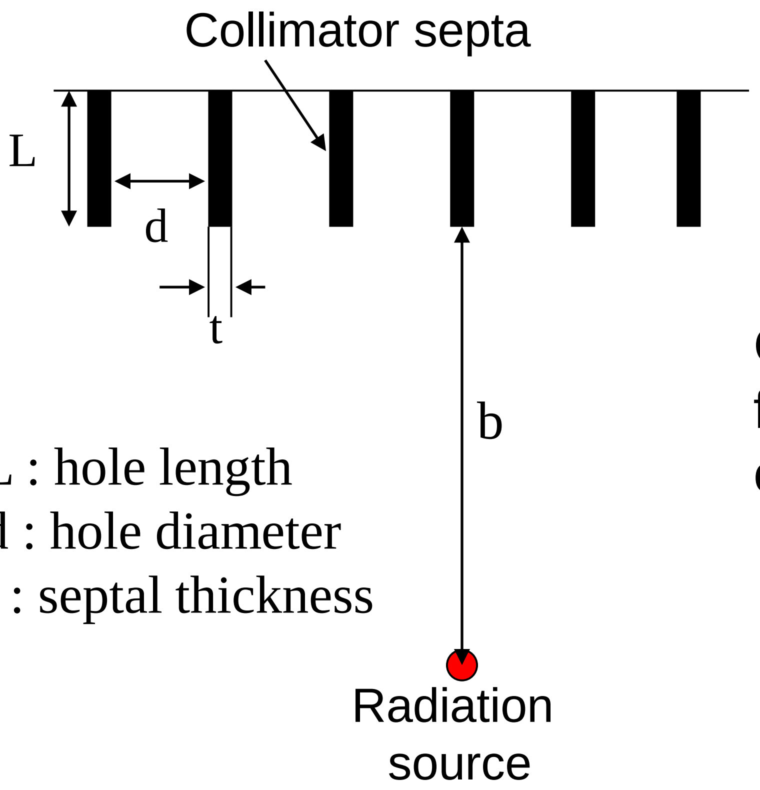
More photons

long septa

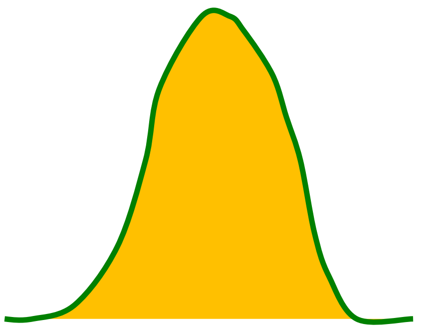


Less photons

Collimator geometric sensitivity



L : hole length
d : hole diameter
t : septal thickness



Geometric sensitivity (efficiency) is the fraction of γ rays passing through the collimator per γ rays emitted by the source

$$g_{coll} \approx K^2 \left(\frac{d}{L}\right)^2 \left[\frac{d^2}{(d+t)^2}\right]$$

No "b"

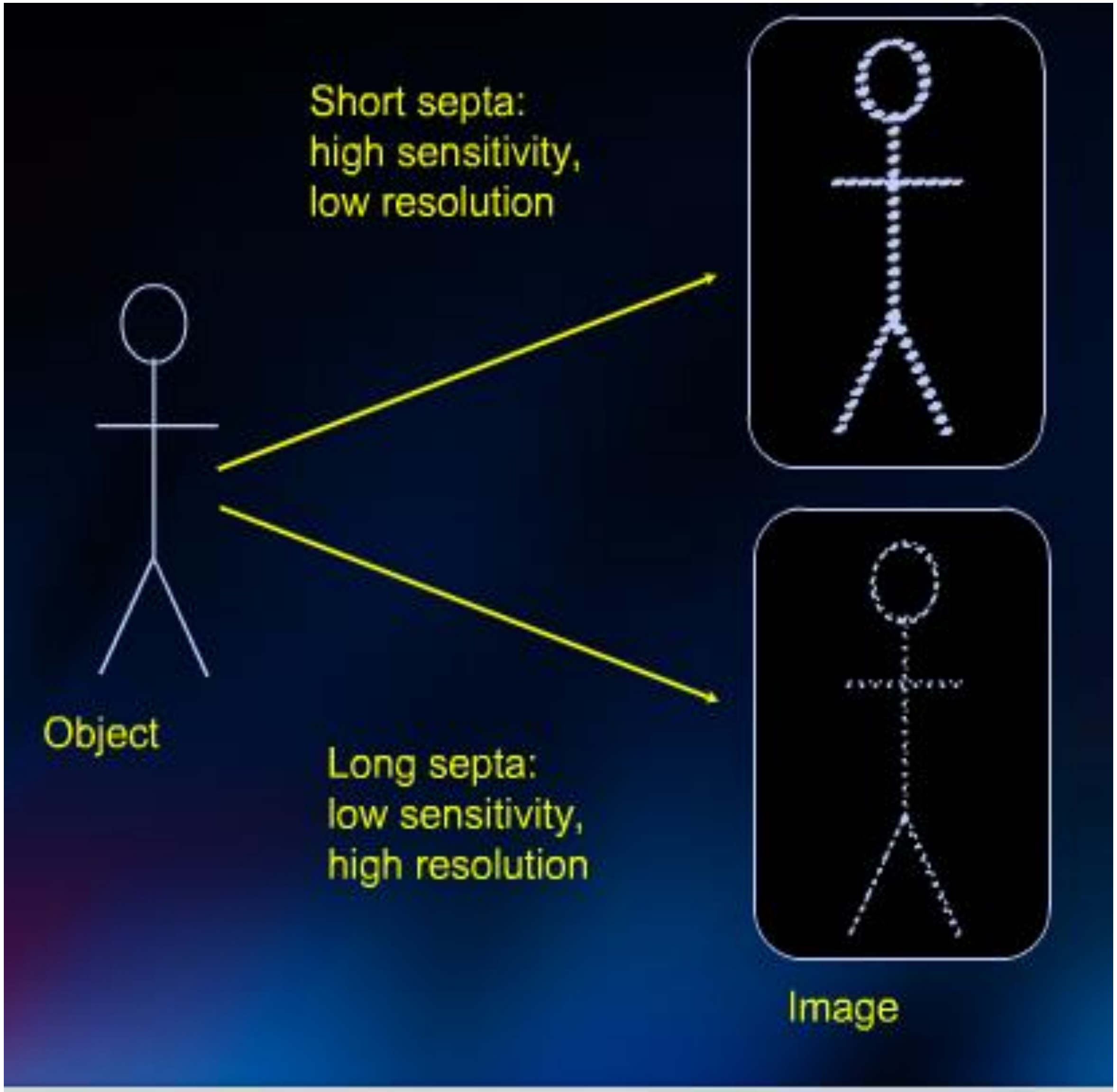
K~0.26 for hexagonal hole & array

<u>Example</u> : d=0.25cm, L=2.5cm, t=0.03cm, and a source at 10 cm.

$g \approx 0.26^2\ (0.25 / 2.5)^2\ [0.25 / (0.25+0.03)^2] = 5.4 \times 10^{-4}$

5 out of 10,000 photons are detected!!!

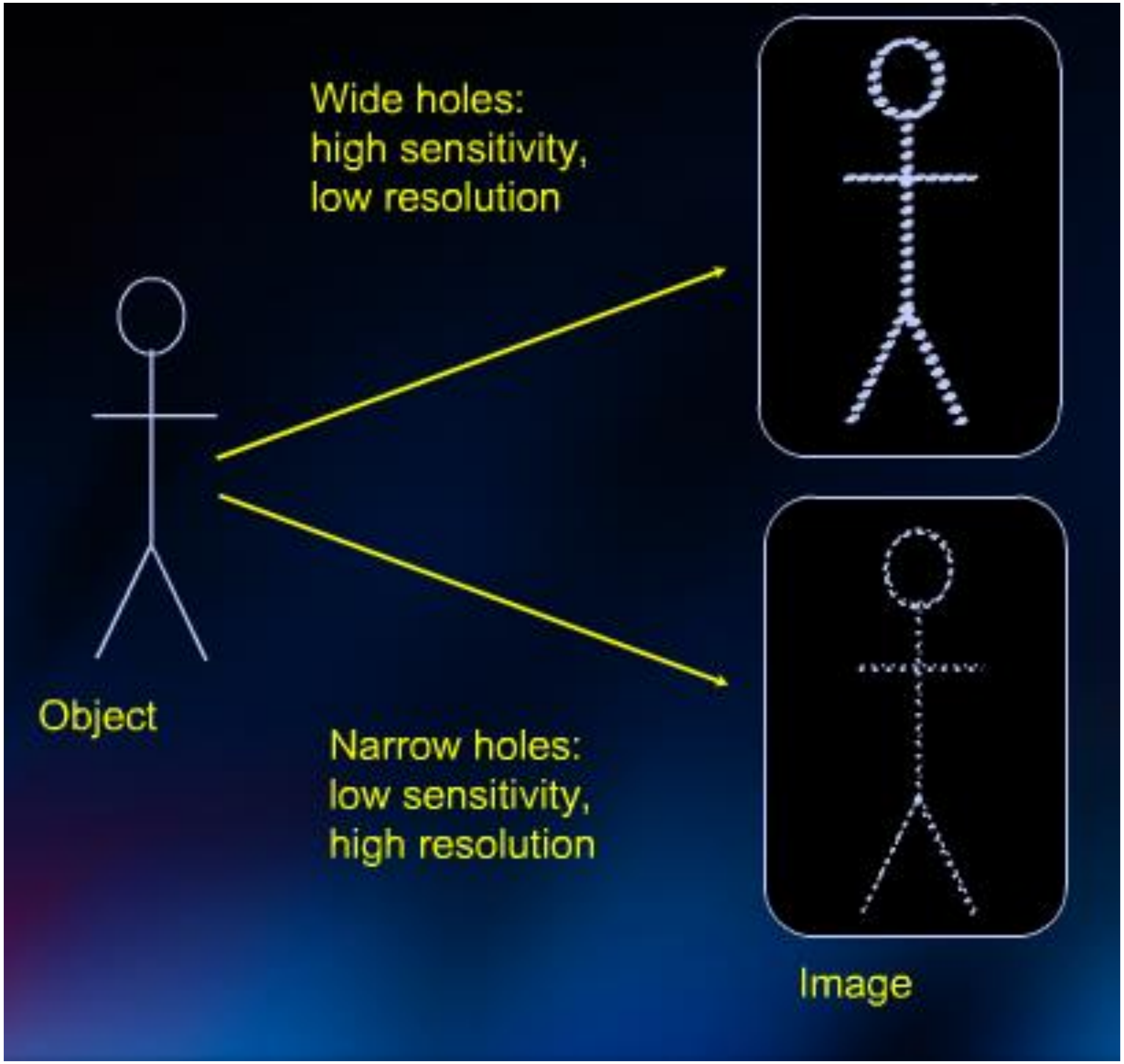
Resolution-Sensitivity trade-off : hole (septa) length, L



High counts
BUT not all in the right place

Counts are in the right place
BUT not many are detected

Resolution-Sensitivity trade-off : hole diameter, d



High counts
BUT not all in the right place

Counts are in the right place
BUT not many are detected

Summary of Collimator Characteristics

Collimator selection requires consideration of imaging object's location and size, energy of gamma rays, and desired resolution and sensitivity.

- Energy : low energy collimator (Tc-99m, Tl-201)
  medium energy collimator (Ga-67, In-111),
  high energy collimator (I-131)
  → Thicker septa to reduce septal penetration
- Resolution : Low-energy high resolution (LEHR)
  Low-energy Ultra-high resolution (LEUHR)
- Sensitivity : Medium- or Low-energy general-purpose collimator (MEGP, LEGP) → poor resolution, high sensitivity

Which of the following best completes the sentence.

1. “Photomultiplier tubes primarily detect __________________”.

A) gamma radiation
B) x-rays
C) beta radiation
D) alpha radiation
E) visible light

2. “Using a low energy collimator for a high energy radionuclide ___”

A) Allows faster scans
B) Reduces the sensitivity of the detector
C) Causes the image to be inverted
D) Increases the field of view but minifies the image
E) Results in septal penetration

3. Which of the following statements regarding parallel-hole collimators is **correct**?

A. parallel-hole collimator is placed between the crystal and the PMTs to channel the radiation

B. A parallel-hole collimator efficiently attenuates the photons colliding with its septa

C. Septa for Tc-99m imaging must be thicker than that for In-111 imaging

D. An image made using a parallel hole collimator is magnified with respect to the object

System Resolution

System resolution determined the sharpness of images.

- intrinsic resolution
- Collimator resolution

$$R_{sys} = \sqrt{R_{\text{int}}^2 + R_{coll}^2}$$

<u>Example</u> R_{coll}=1.25cm (at 10cm from the collimator) and R_{int}=0.3cm

$$R_{sys} = \sqrt{R_{\text{int}}^2 + R_{coll}^2} = \sqrt{1.25^2 + 0.3^3} = 1.29cm$$

determined primarily by collimator resolution

System Sensitivity (efficiency)

- The fraction of gamma rays emitted by a source that produces counts in the image

- Product of
  - collimator efficiency (Ec) ,
  - intrinsic efficiency of the crystal (Ei), and
  - fraction of interacting photons accepted by the pulse-height analyzer (f).

- Intrinsic efficiency is the fraction of photons passing through the collimator that interact with the crystal.

System Efficiency = Ec * Ei * f

Ec ~ 0.05 %
Ei ~ 85 %
f : 0 ~1

Performance Parameters

Important step for the highest image quality

- **Extrinsic (system)** : measures of the performance **with** the collimator
- **Intrinsic** : measures of the performance **without** the collimator

measure of camera response to uniform irradiation of the detector surface

Intrinsic Uniformity

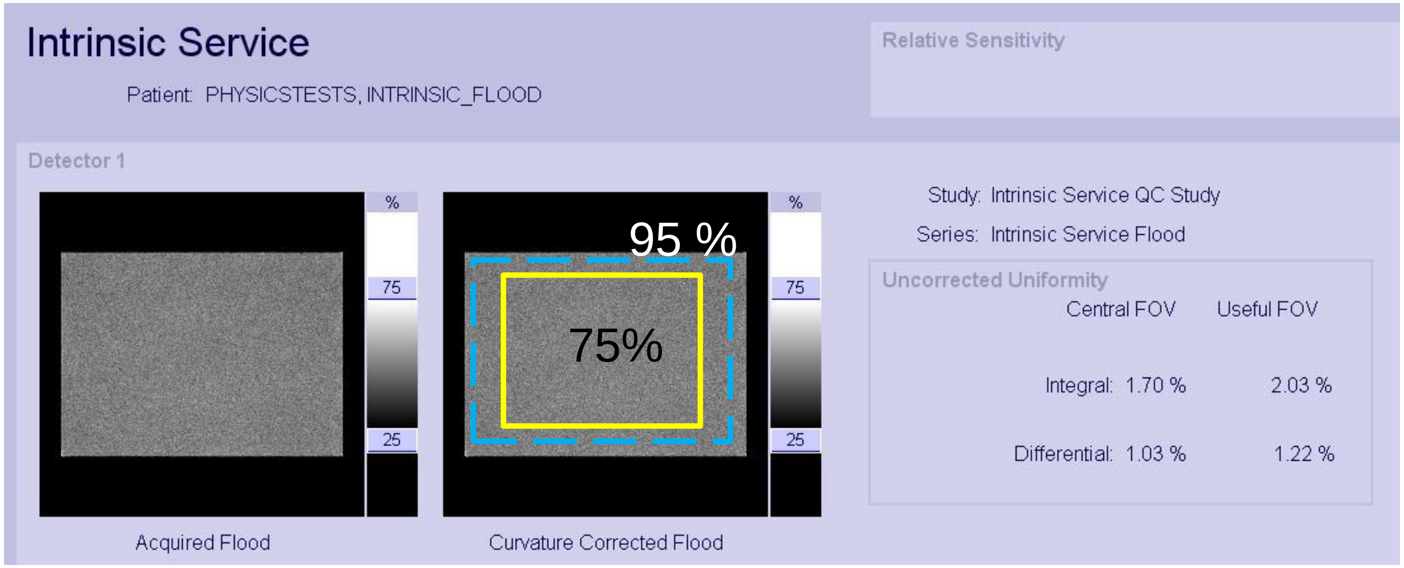
A syringe source placed at 4-5 times the largest side of the detector (~150 µCi Tc-99m)

Extrinsic Uniformity

Daily QC

Uniformity

Daily : > 2 Mcnts (before patient imaging)
Monthly > 30 Mcnts (used for correction)



< 4-6 %

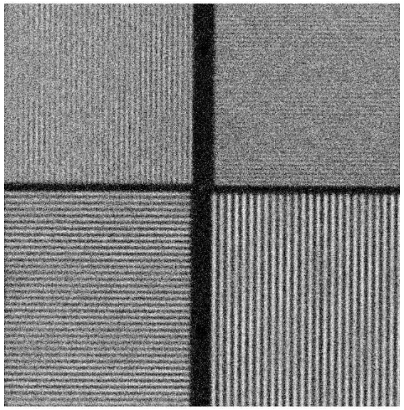
Monthly Uniformity correction

- Integral uniformity searches the entire flood to find the max and min pixel values

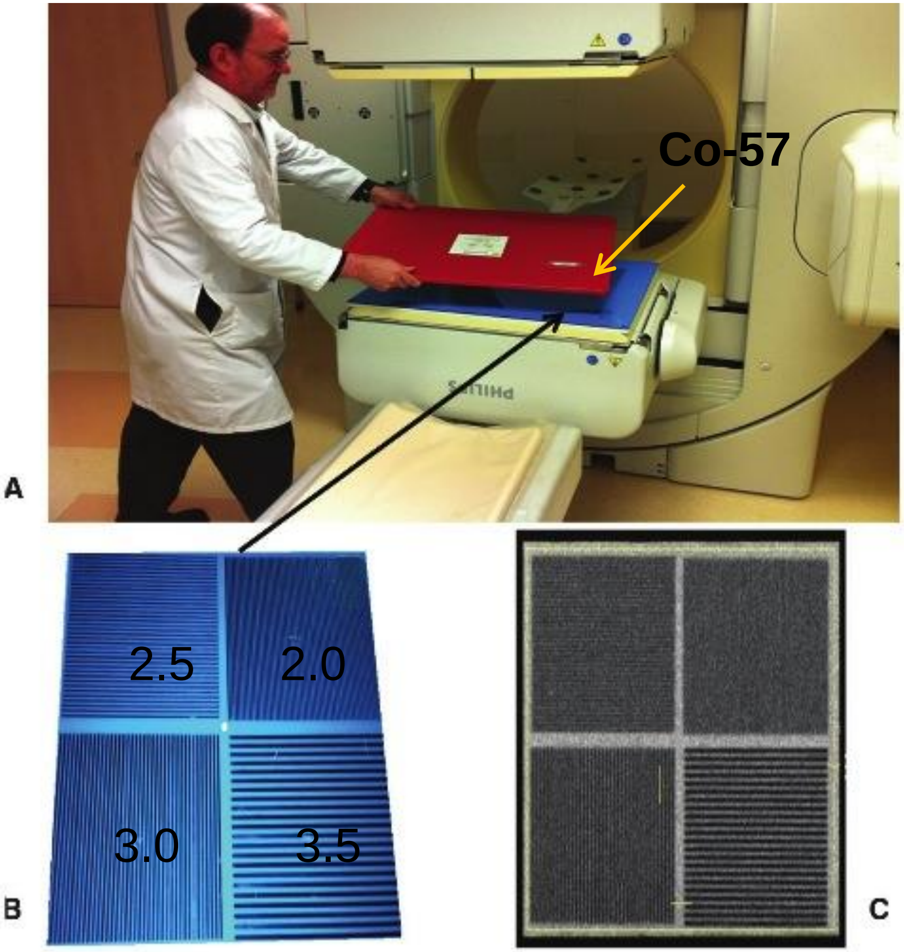
- Differential uniformity looks at changes in pixel values over short segments of the flood (find the highest & lowest pixel values within a five-pixel segment)

Spatial resolution

Intrinsic



extrinsic



Bar phantom

Acquired image

3.0mm bars visible → 1.7 x 3.0 = 5.1 mm

Weekly QC

Some of 2 mm bars visible → 1.7 x 2.2 = 3.7 mm

Count Sensitivity (efficiency)

Fraction of gamma rays emitted by a source that produces counts in the image

System efficiency (Es) = (Ec) * (Ei) * (f)

Ec : collimator efficiency
Ei : intrinsic efficiency
f : fraction of accepted by the energy discrimination circuits

- 150-200 µCi Tc-99m layer in flask.
- Acquire for 2min and obtain the total counts (after background subtraction)

~200 CPM / µCi per detector (LEHR, Tc-99m)

3.3 counts for ~ 37,000 decays
~ detect 1 in 10,000 emitted gammas