Imaging using ionizing radiations

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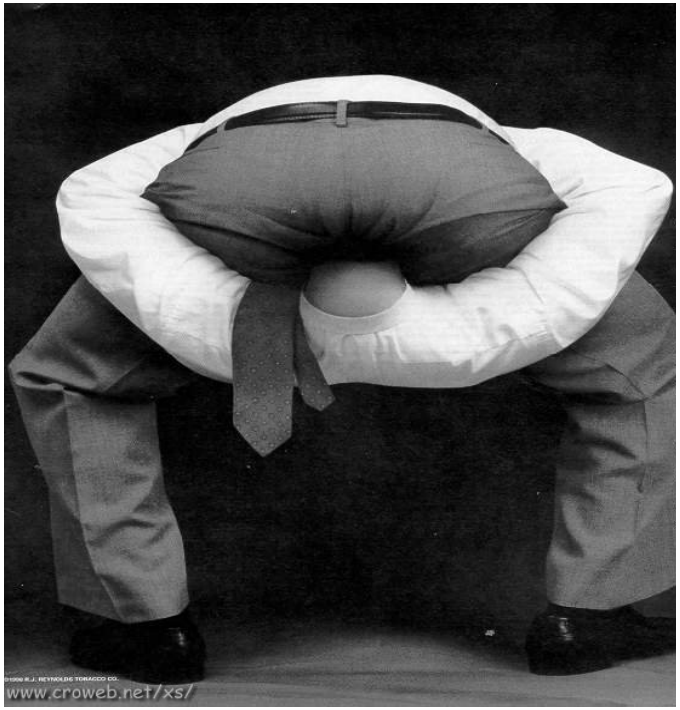
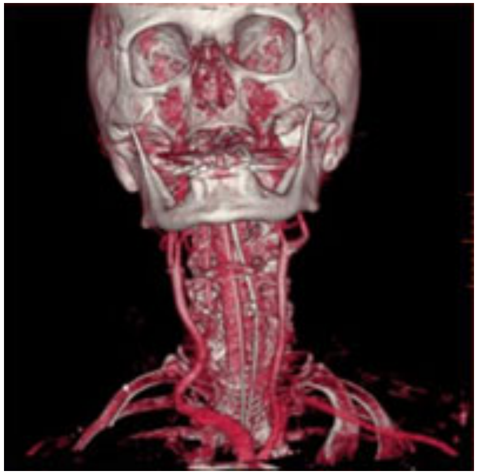
ESIPAP, March 2017

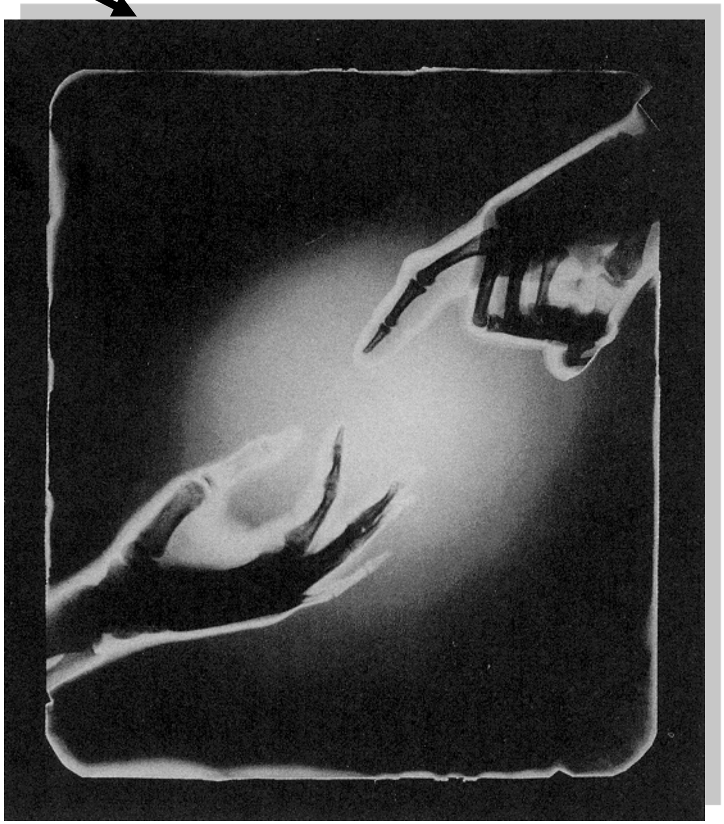
Slides are courtesy of David Brasse

Curious to know how
we are made inside ?



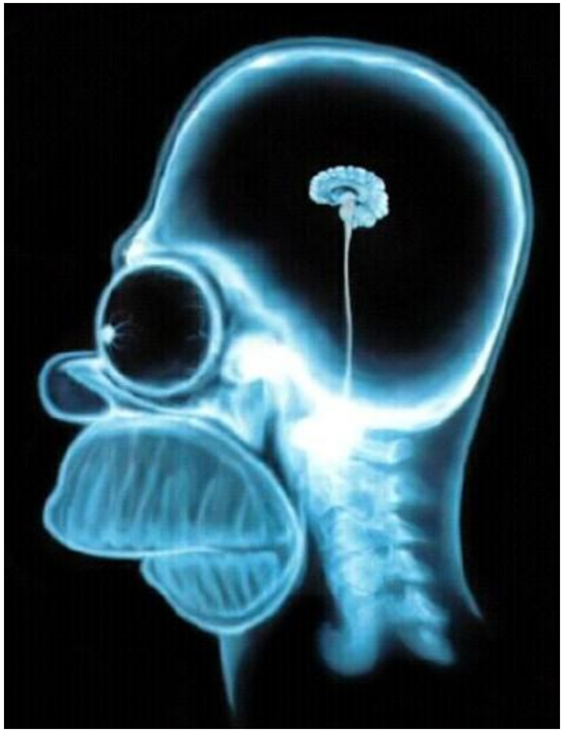
…however, without being sacrificed !

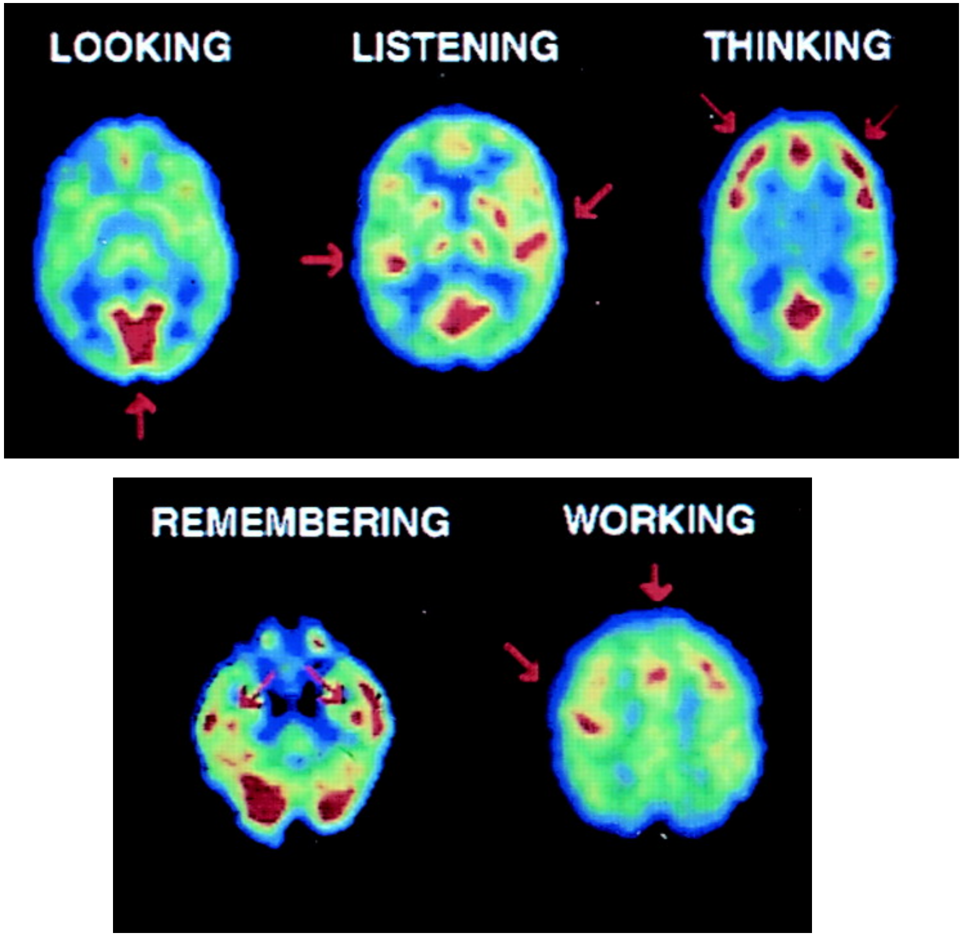




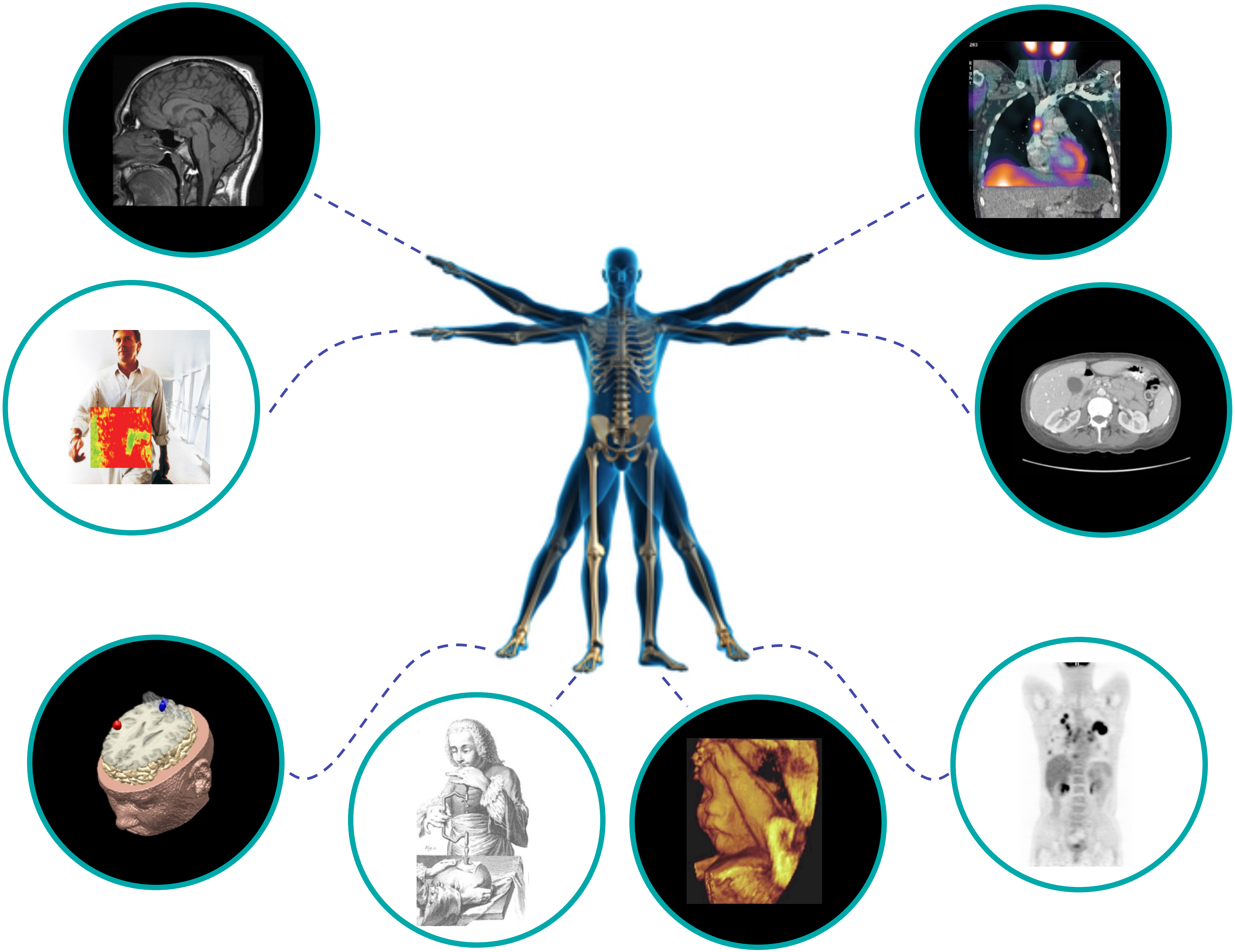
David Teplica, Birth of man with homage to Michelangelo (1987)

We are also curious to know how …





…do our organs function?



Morphology vs Functional

Emission vs Transmission

Real time vs Integration

Modality using X Rays or gamma rays

- Radiology (X rays)
  - *Standard radiology, mammography*
  - *Angiography*
  - *Computer Tomography (CT scanner)*
- Nuclear medicine
  - *Scintigraphy*
  - *Emission tomography*
    - *Simple photons*
    - *Positons*
- Radiotherapy

Nuclear Medicine

Science that contributes

to the *treatment* and

to the *diagnosis* of human disease (illness)

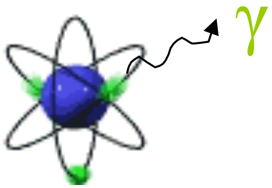
using rays emitted by nucleus of radioactive atoms

Commonly used isotops

Isotop	Energy	Period
γ emitters		
Technetium 99m	140 keV *(89%)*	6,02 hours
Iodine 123	27 *(71%)* 159 keV *(83%)*	13,2 hours
Thallium 201	71 keV *(47%)*	73 hours
β+ emitters		
Oxygene 15	1738 keV	2,1 minutes
Carbon 11	960 keV	20,4 minutes
Fluor 18	634 keV	109,8 minutes
Brome 76	3980 keV	972 minutes

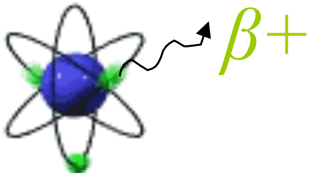
Associated imaging techniques

Emitters γ

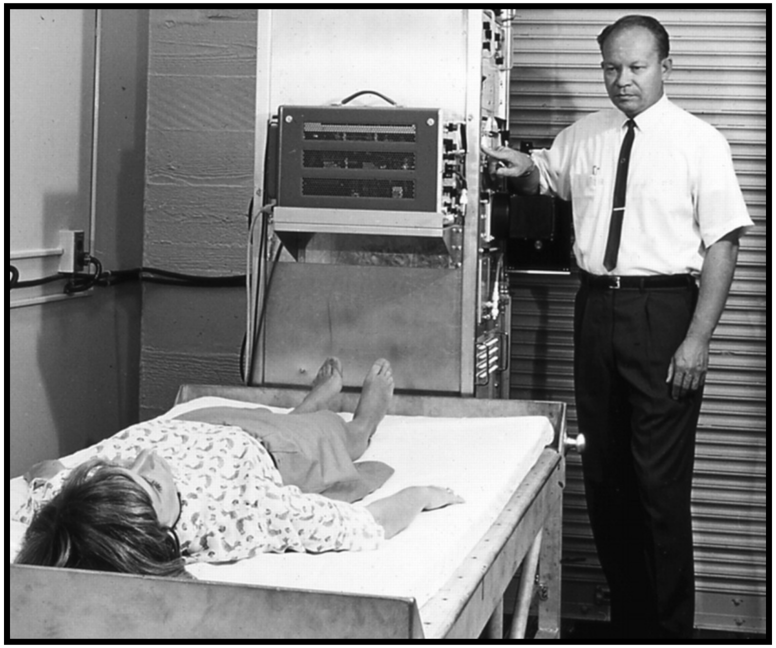


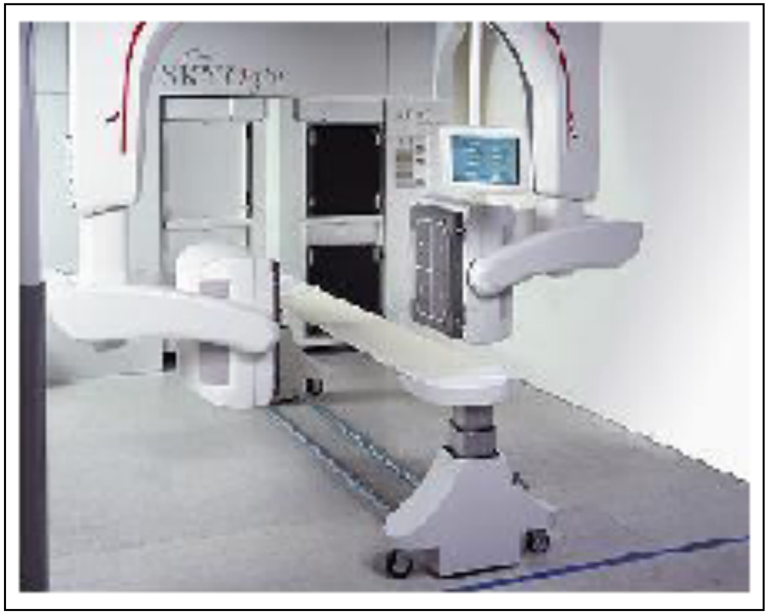
Single Photon Emission Computed Tomography (SPECT)

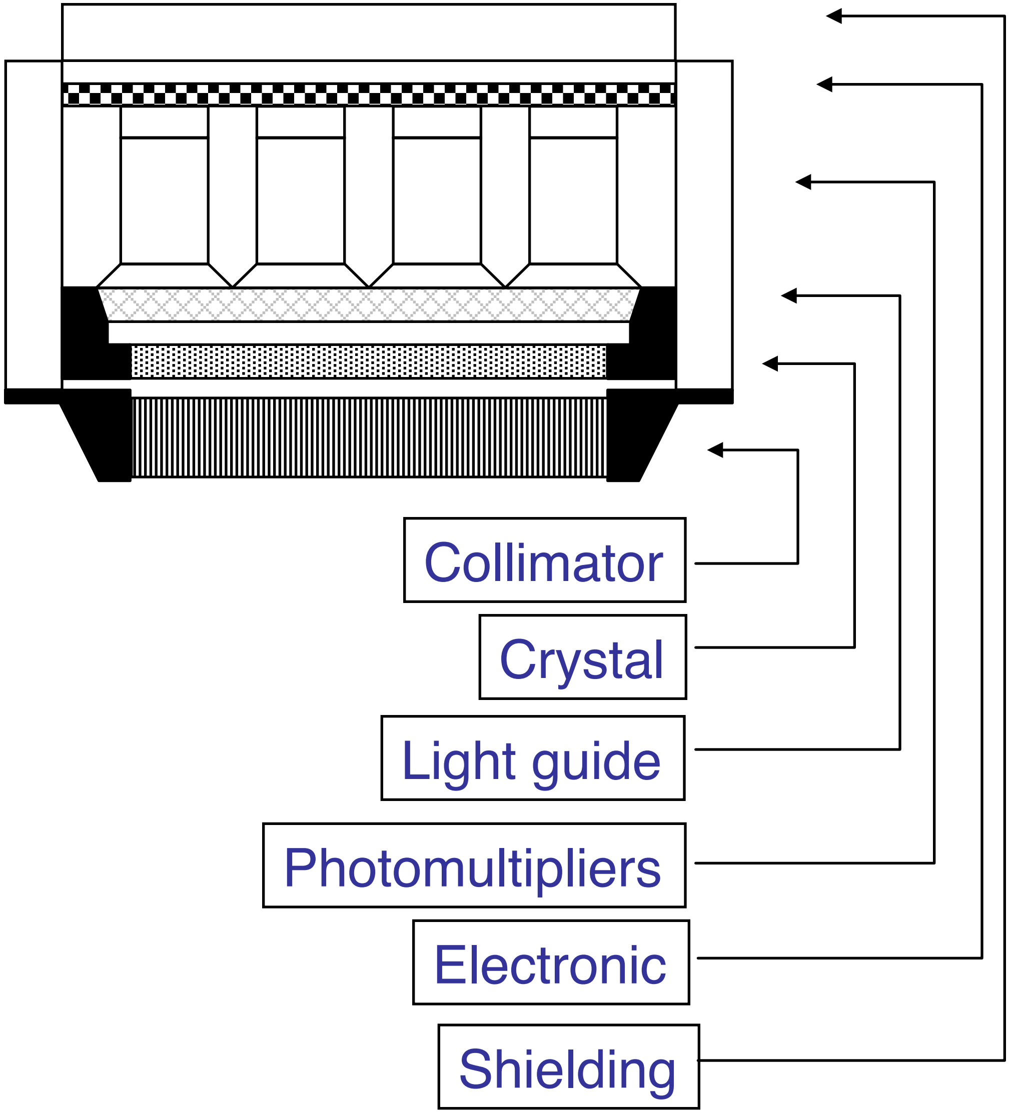
Emitteurs β+



Positon Emission Tomography (PET)







Collimator

Crystal

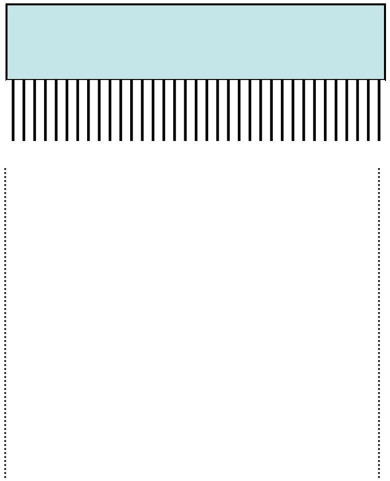
Light guide

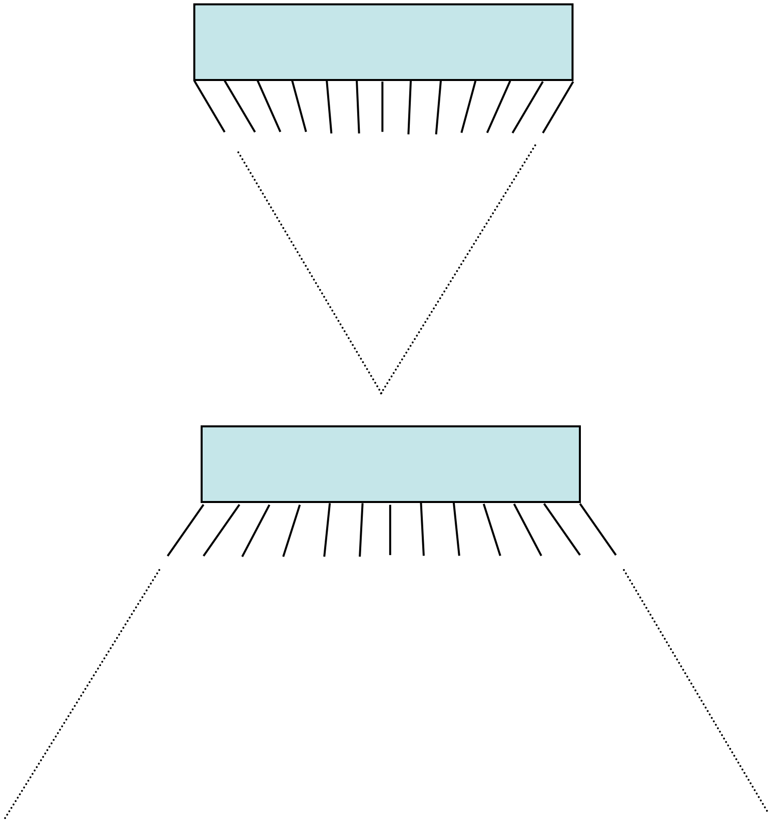
Photomultipliers

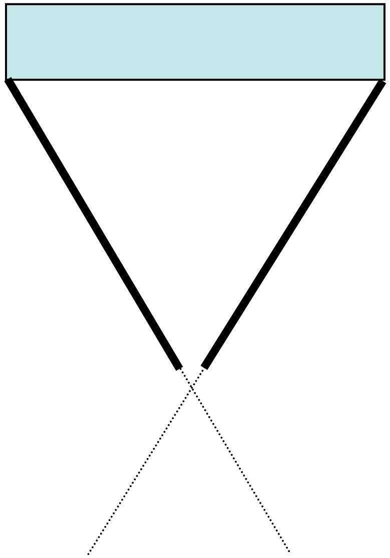
Electronic

Shielding

The collimator

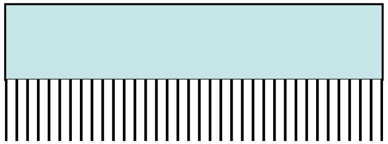

Parallel


Fan beam


pinhole

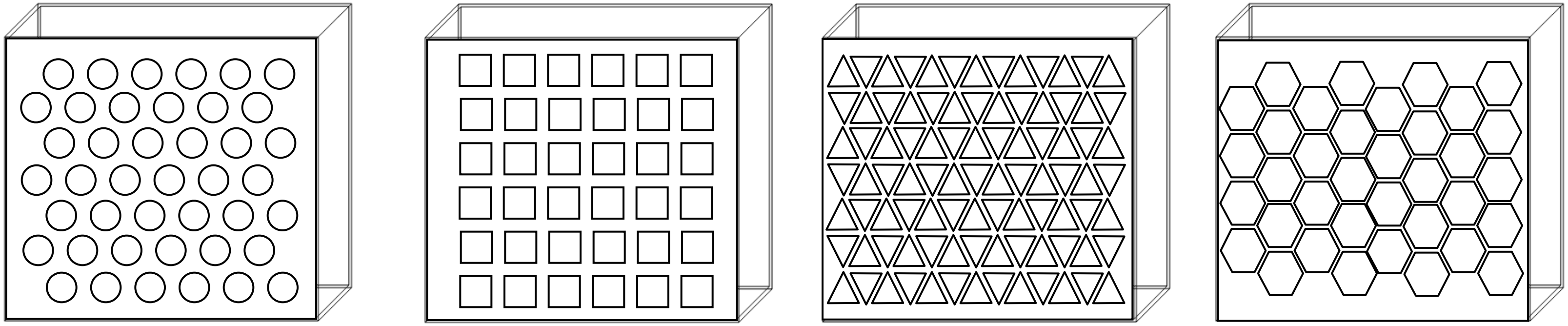
Determine the distribution of photons in the crystal

Parallel collimator



Thichness varies from 25 to 80 mm
Contains betwenn 3.10^4 and 9.10^4 holes

Different geometrial shapes of holes

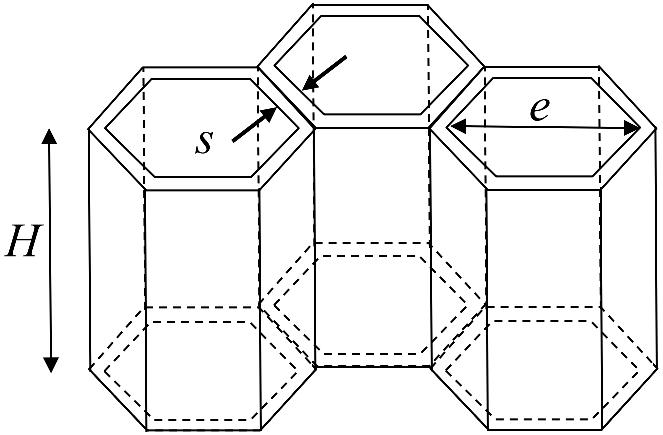


Two conception modes : « foil or cast »

Septa = Material between holes

Holes are organized in a way that optimizes the exposition of the crystal
Hexagonal arrangement presents the best compromise
Hexagone, cylindre, square, rectangle offer the same septal thickness which is not the case of the circle

Minimum septum thickness is determined by the energy of the photons



$$s = \frac{2ep}{H - p} \quad \textit{with } p = \text{minimum crossed distance}$$

If we tolerate 5% of penetration,

What should be the lower limit of s ?

$$\text{transmission} = e^{-\mu p} \leq 0{,}05$$

$$e^{-\mu p} \leq e^{-3}$$

$$\boxed{s \geq \frac{6e}{\mu H - 3}}$$

Example

Energy: 150 keV

Material: Lead

ρ = 11,35 g/cm^3

μ/ρ = 2,014 cm^2/g

μ = 22,86 cm^{-1}

Material: Tungsten

ρ = 19,3 g/cm^3

μ/ρ = 1,581 cm^2/g

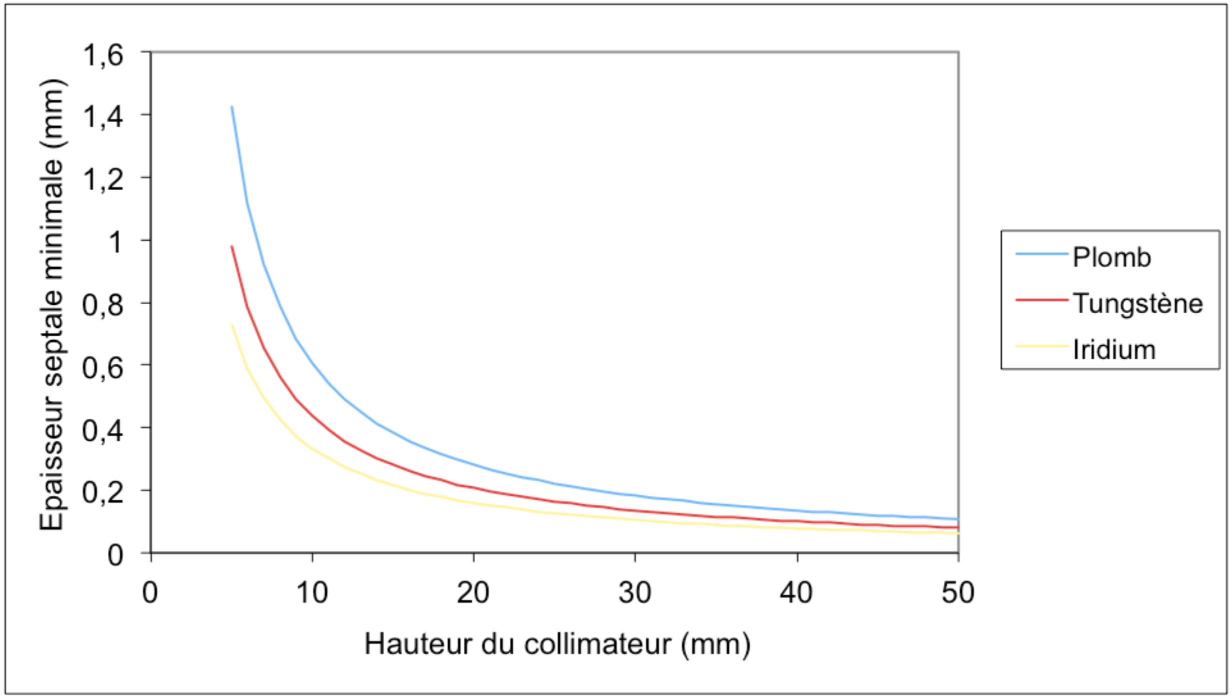
μ = 30,51 cm^{-1}

Material: Iridium

ρ = 22,42 g/cm^3

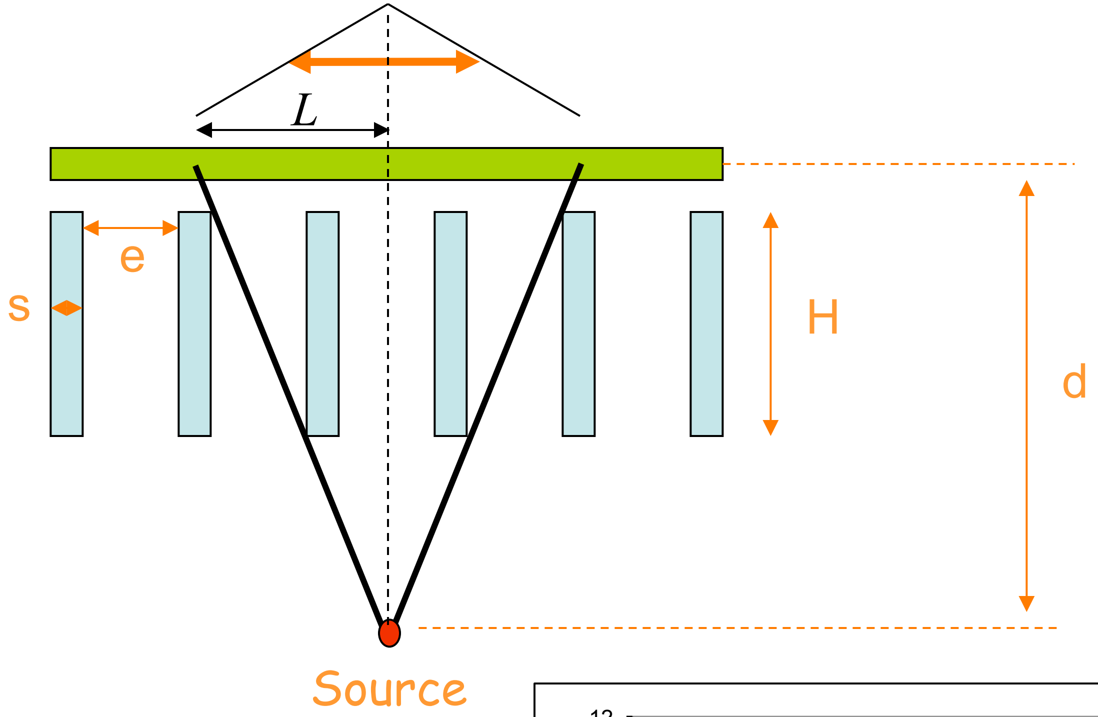
μ/ρ = 1,74 cm^2/g

μ = 39,01 cm^{-1}



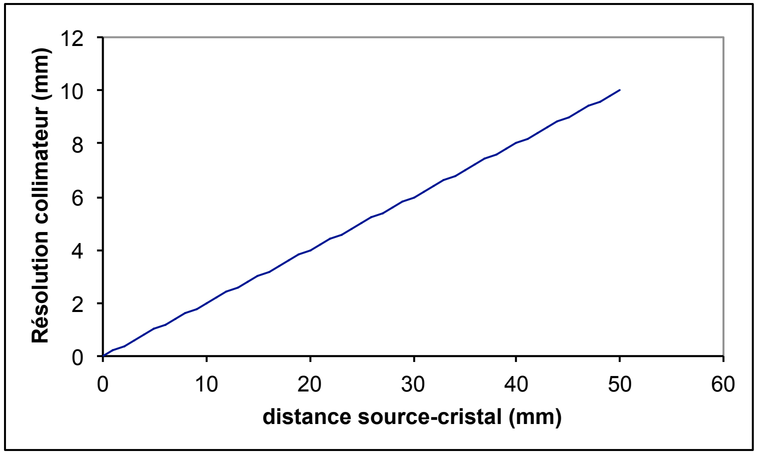
Calculate *s min* for an energy of 365 keV

Spatial resolution



Hit: $\tan\alpha = \frac{L}{d} = \frac{e}{H}$

$$R_p = \frac{d \cdot e}{H}$$



Geometrical detection efficiency

Proportion of photons emitted from a point source and
Transmitted through the collimator

$$S_p \approx k \frac{e^4}{H^2 (e+s)^2}$$

k is determined by the geometrical shape of the holes

Circulars	0,06
Hexagonals	0,07
Squares	0,08

Independant of source-collimateur distance
Two effects compensate one another:

- Hole efficiency decreases as $1/d^2$
- Number of holes is proportional to d^2

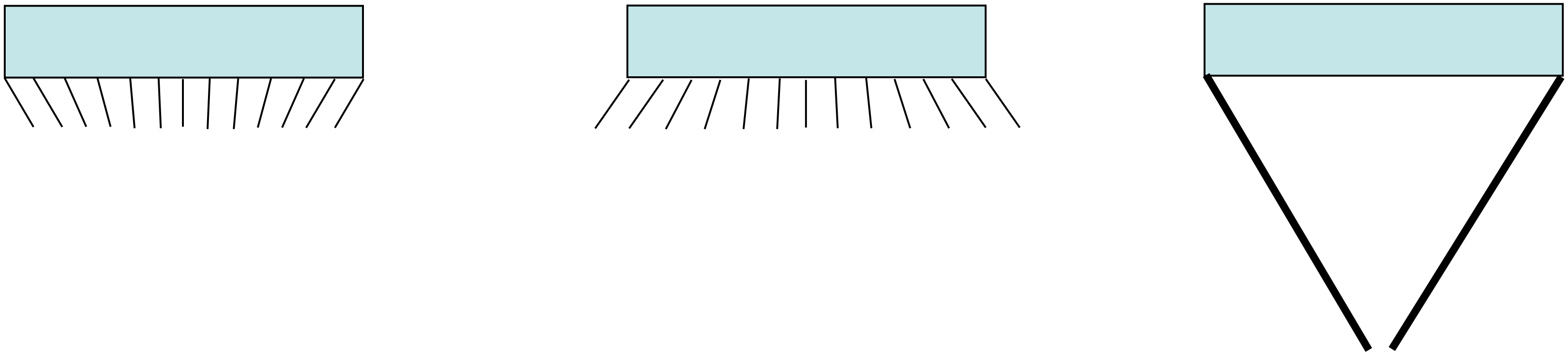
Hole effective height

Modification due to septal penetration

$$H = H_r - \frac{2}{\mu}$$

Real height

Non parallel collimator



The field of view varies as function of the magnification factor

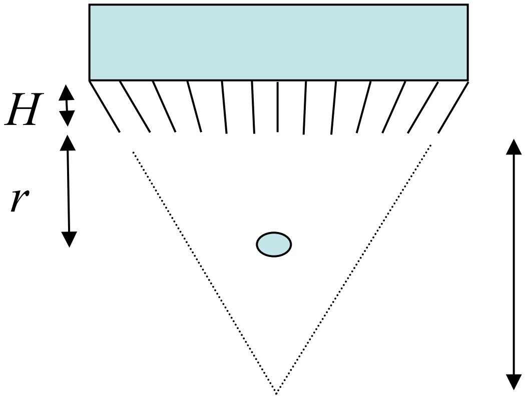
$$F_M = \frac{F}{M}$$

Total field of view of the camera

Magnification factor

$$R_s = \sqrt{R_c^2 + \left(\frac{R_i}{M}\right)^2}$$

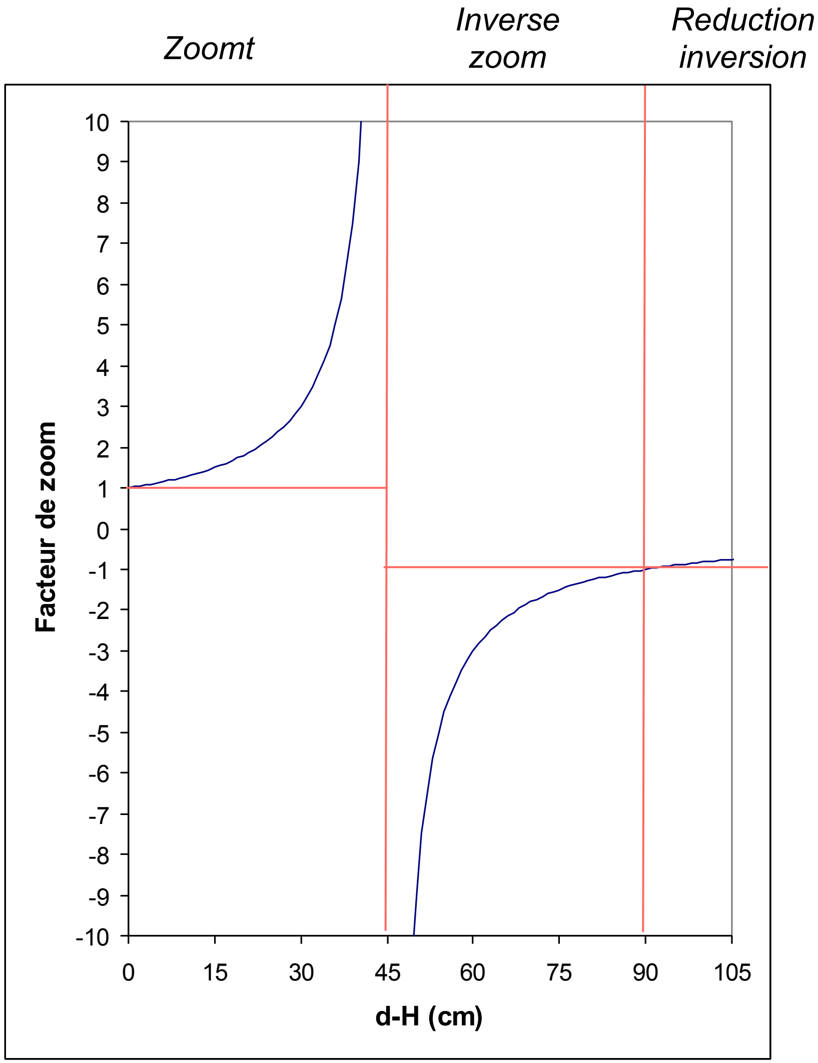
Collimateur convergent



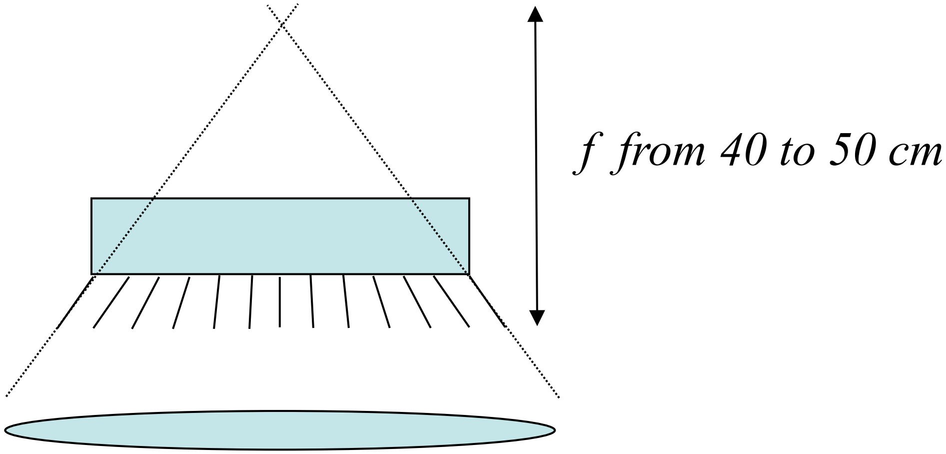
f de 40 à 50 cm

$$M = \frac{H + f}{H + f - r}$$

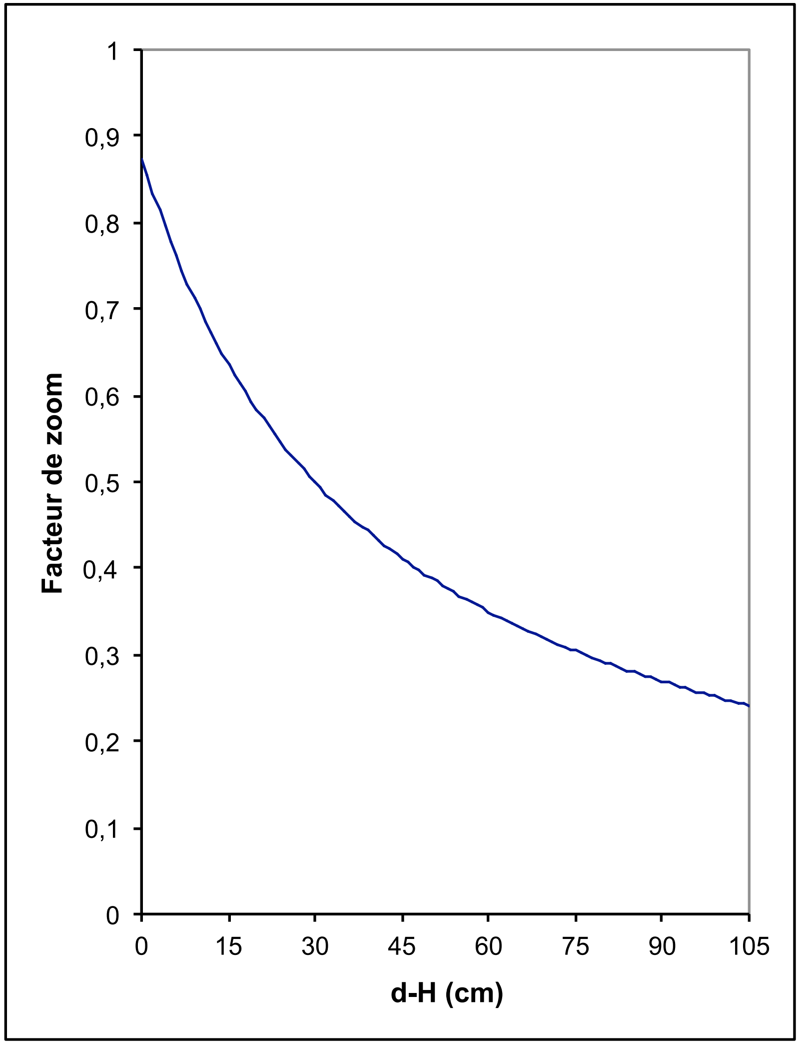
Special case: *fan beam*



Fan beam collimator

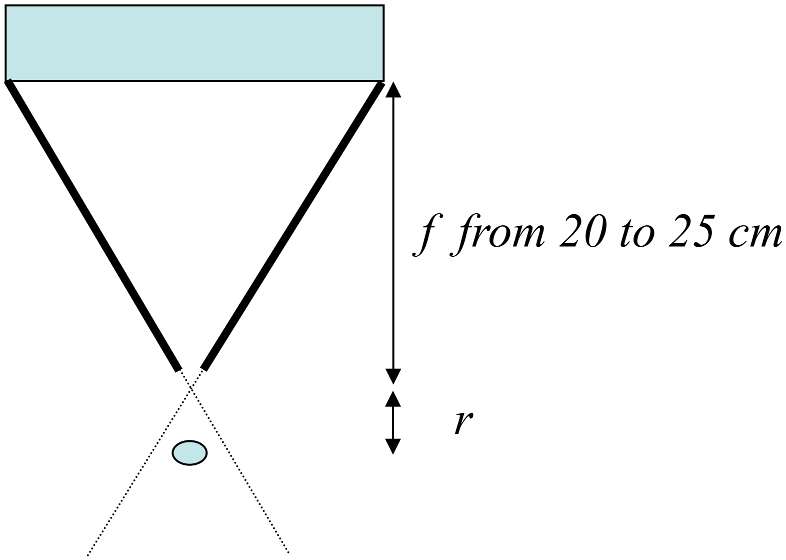


$$M = \frac{f - H}{f + r}$$

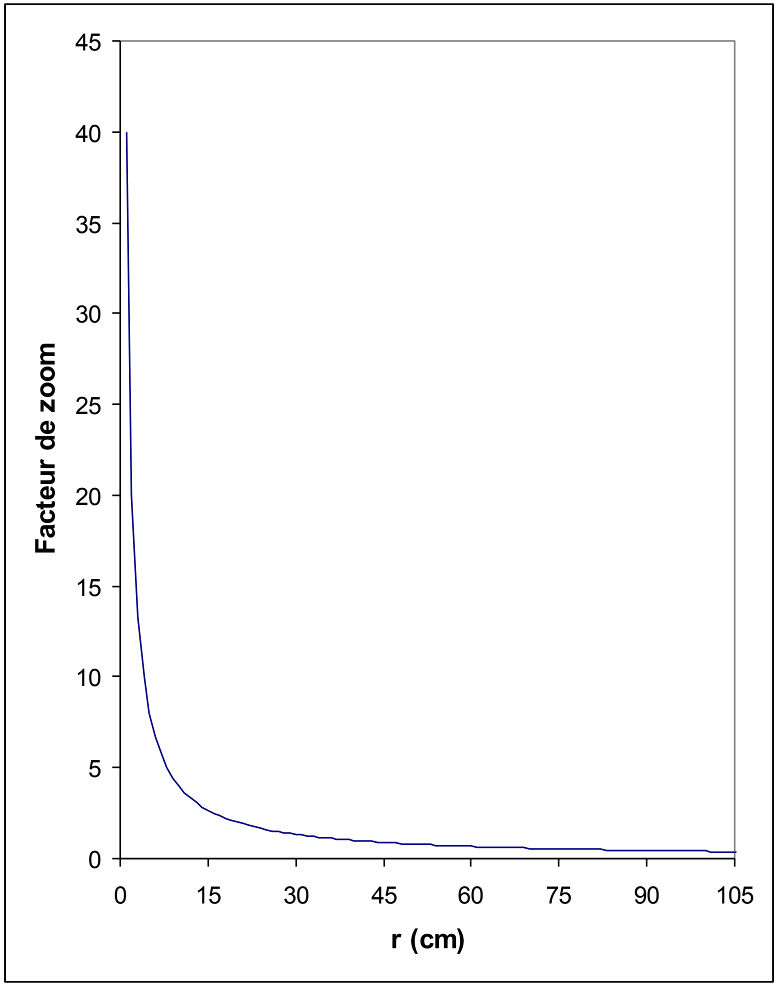


Special case: *fishtail*

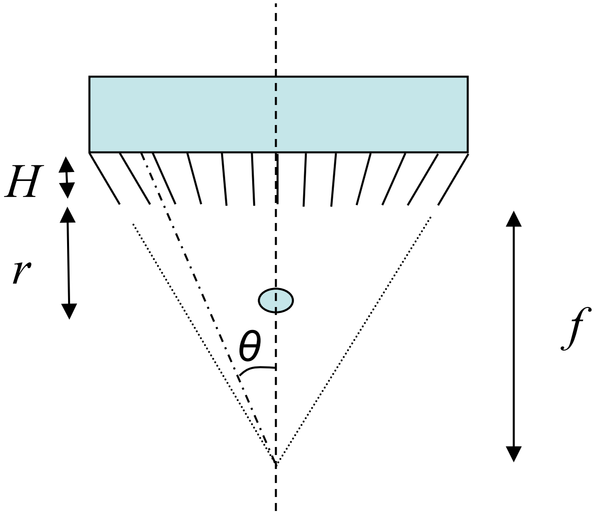
Pinhole collimator



$$M = \frac{f}{r}$$

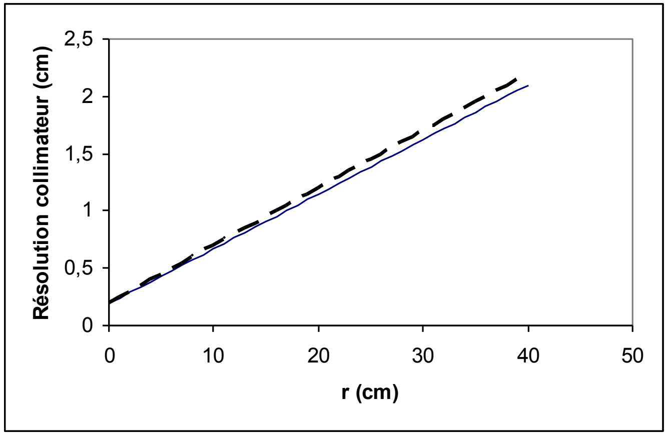


Spatial resolution
Detection efficiency

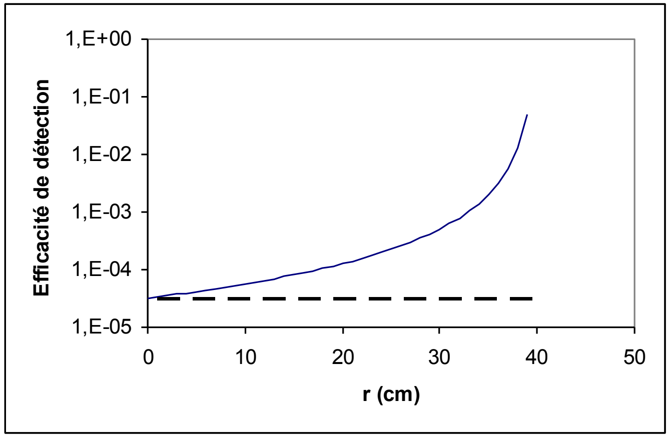


Convergent collimator

$$R_c \approx \frac{R_p}{\cos\theta}\left(1-\frac{H}{2(f+H)}\right) \qquad S_g \approx S_p \cos^2\theta \frac{f^2}{(f-r)^2}$$

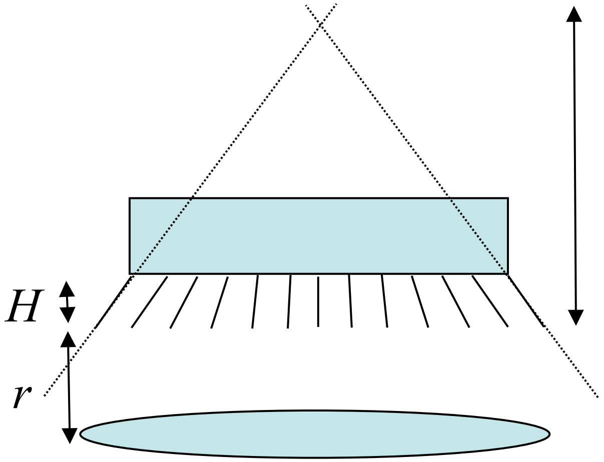


H = 4 cm
f = 40 cm
e = 0,2 cm
s = 0,02 cm
θ =0°



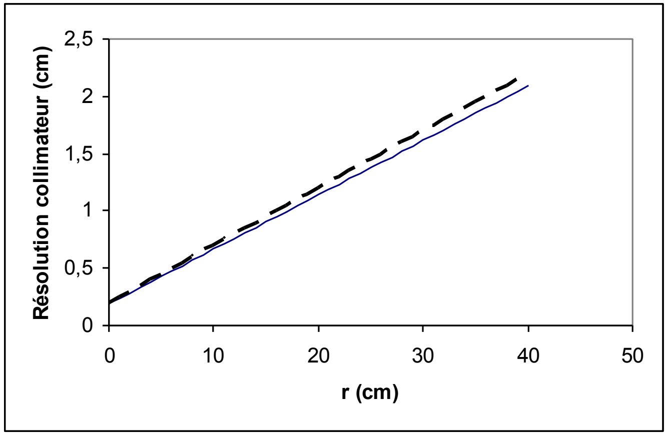
Spatial resolution and detection efficieny vary in the field of view
Maximum for *θ=0*

Spatial resolution
Detection efficiency

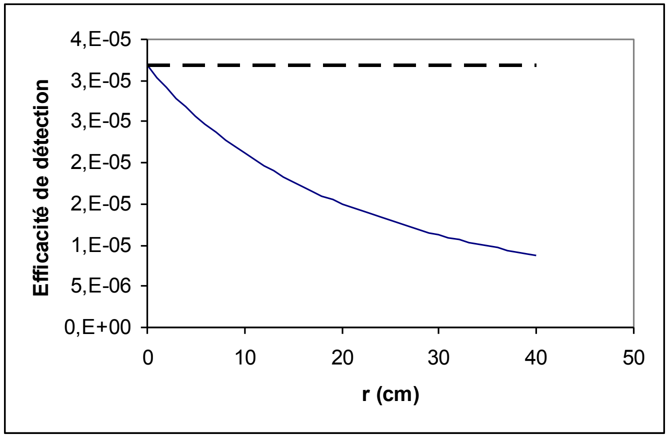


Divergent Collimator

$$R_c \approx \frac{R_p}{\cos\theta}\left(1+\frac{H}{2f}\right) \quad S_g \approx S_p \cos^2\theta \, \frac{(f+H)^2}{(f+H+r)^2}$$

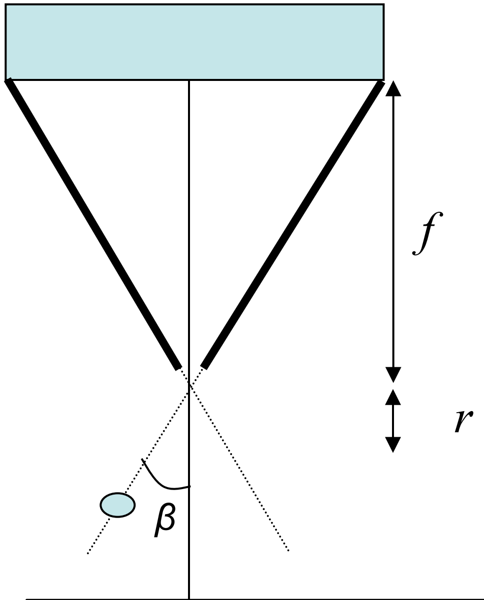


$H = 4$ cm
$f = 40$ cm
$e = 0{,}2$ cm
$s = 0{,}02$ cm
$\theta = 0°$



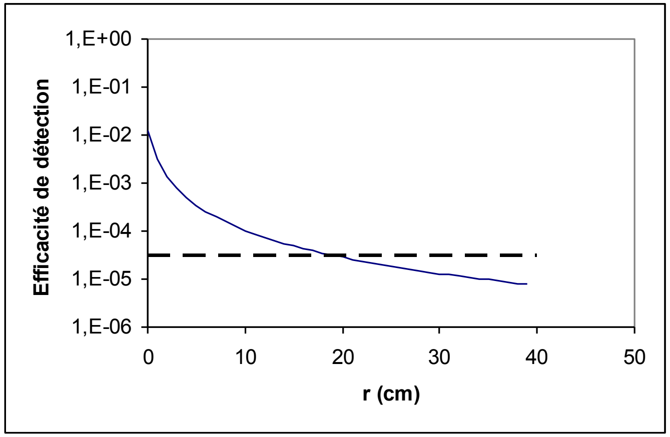
Spatial resolution
Detection efficiency

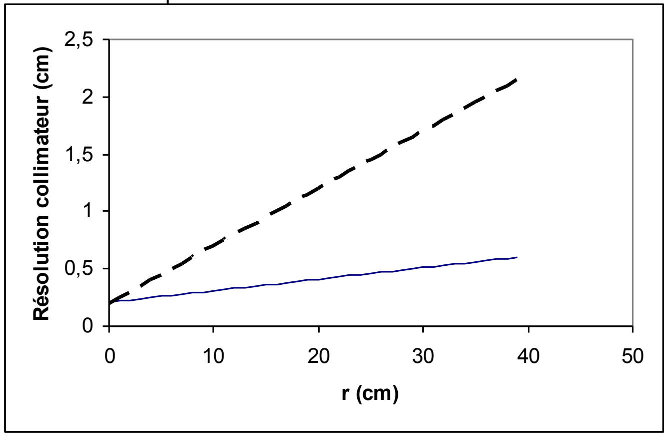
Pinhole collimator



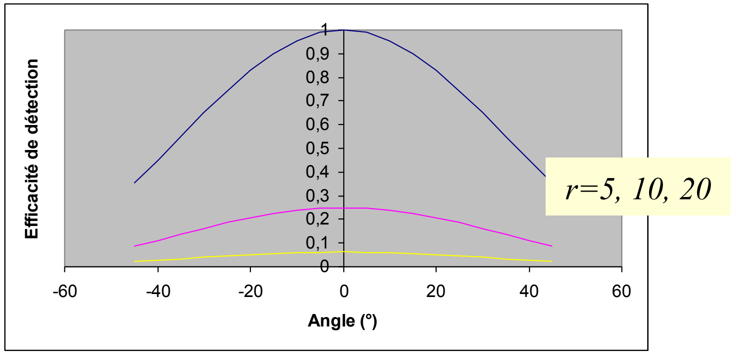
$$R_c = e + e\frac{r}{f}$$

$$S_g \approx \frac{e^2 \cos^3 \beta}{16 r^2}$$



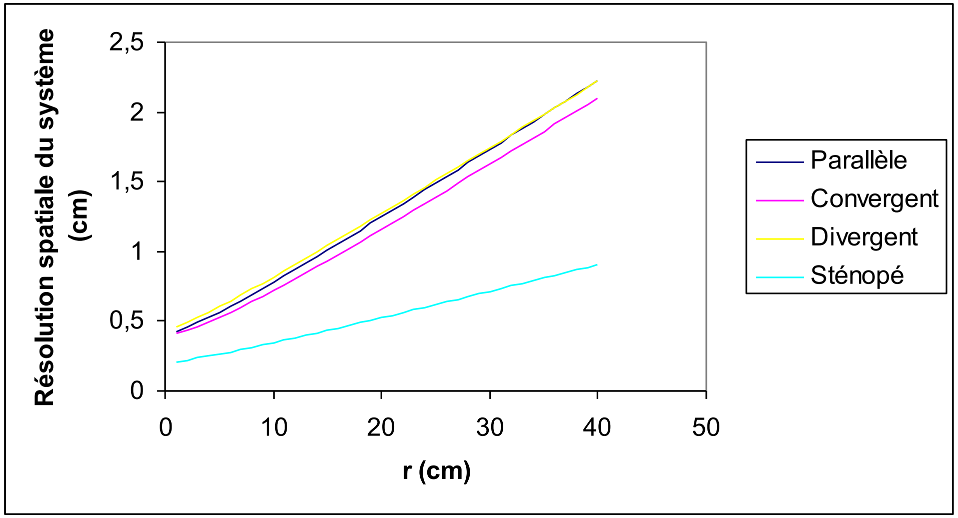


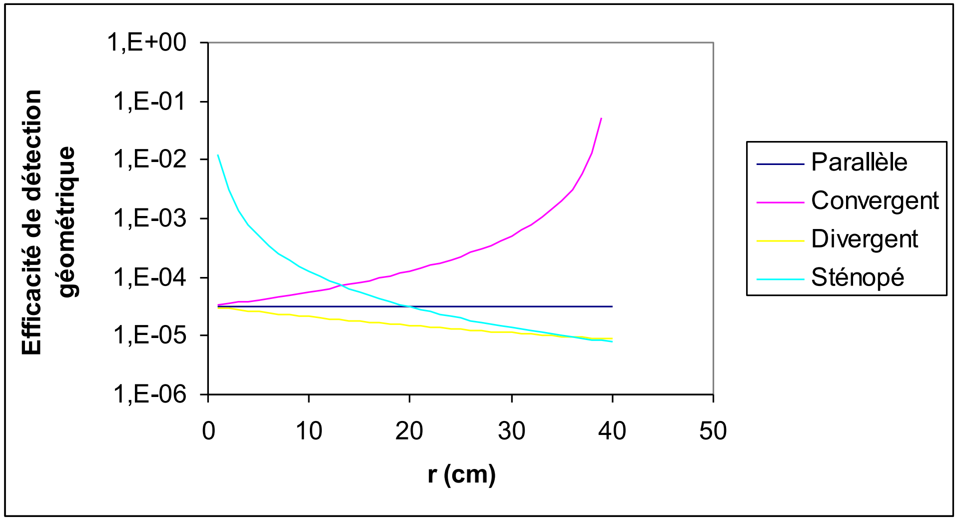
f = 20 cm
e = 0,2 cm
β =0°



Comparison

Ri = 0,34 cm
H = 4 cm
f = 40 cm
e = 0,2 cm
s = 0,02 cm
θ =0°





Paper study

D Lowe et al, ’’Optimisation of the design of round-hole parallel collimators for ultra-compact nuclear medicine imaging,’’ NIM A488 (2002) 428-440.

Scintillating crystal

The crystal dimension determines the geometrical field of view of the camera

At the beginning,
The field of view was circular with small diameter
Actually,
Rectangular going to 590 x 390 mm²
Requiring crystal dimension of 600 x 450 mm²

Its thickness determines the detection efficiency
As ^{99m}Tc is the main used isotope
Crystal thickness was optimized for 140 keV
Generally, NaI(Tl) 9,5 mm (84% @140 keV)

Luminescence effect by fluorescence

incidents $\gamma \rightarrow N_0^*$ excited states

$$N^*(t) = N_0^* e^{-t/\tau_0}$$

Number of optical photons:

Energy deposit in the crystal

Fluorescence decay constant

$$N_{h\nu} = \frac{\Delta E}{h\nu}\varepsilon = N_0^* - N^*(t) = N_0^*\left(1 - e^{-t/\tau_0}\right)$$

Efficiency of the crystal

Crystals characteristics

	YAP:Ce	$LaBr_3$:Ce	$LaCl_3$:Ce	NaI:Tl
Density($g.cm^{-3}$)	5.35	5.29	3,9	3,7
$1/\mu$ (mm) [à 140keV]	6,7	3,6	4,5	4,9
Yield (ph/MeV)	18000	63000	50000	38000
λ_{max} (nm)	370	380	350	415
Refraction index	1.93	1.9	1,9	1,85
Resolution (%) [@ 140keV]	20	6	10	9
Photoelectric proportion (%) [@ 140keV]	50	79	80	84
Decay time (ns)	27	25	20	230
Hygroscopic	Non	Oui	Oui	Oui

Limit on the decay time

Depends on the free electrons/holes velocity from the ionisation band to the luminescence center

Depends on the life-time of the emission state of the activators

Limit on the light yield

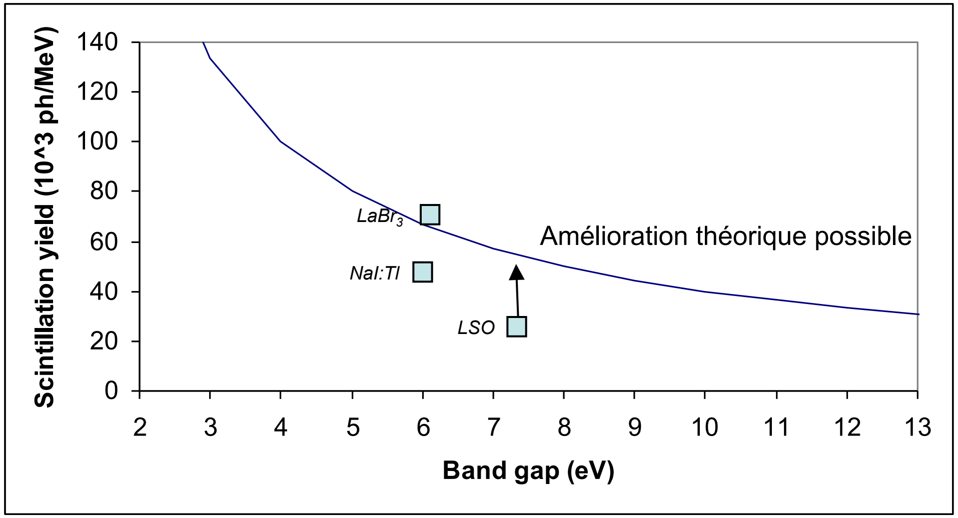
Determined by the number of electrons/holes pairs created in the ionization band

$$n_{ph} = \frac{E_\gamma}{\beta E_g}$$

Photon energy

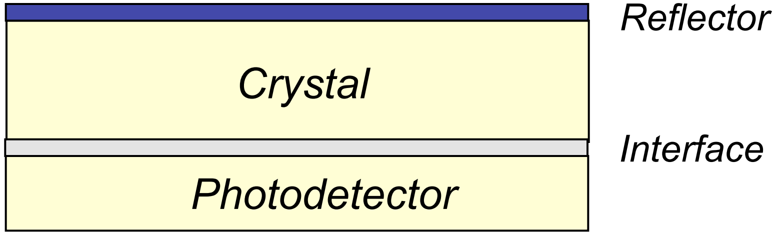
About 2,5

Energy gap of the media



Coupling: optimization

Optimize surface treatment



The choice of the reflector:

Specular reflector:

reflexion angle = incidence angle -> not ideal

Lambertian reflector:

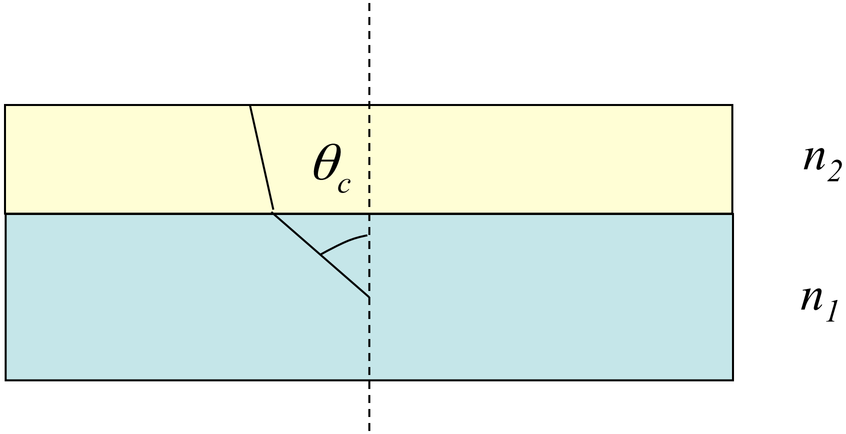
$R(\theta_r)=\cos\theta_i$, almost normal to the crystal reflexion -> better

Reduces the light spread

Treatment surfaces:
Avoid/Reduce total reflexion

Total reflexion critical angle :

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$



Example:
NaI:Tl n=1,85
Optical diffusor: n=1,5

$$\theta_c = 54°$$

Intrinsic resolution

Crystal / PMT coupling

Barycenter approach

Valid for a uniform crystal coupled to several cells of the photodetector

Number of photoelectrons

$$R_i = 2{,}35\left(\frac{\left(\sum s_i^2 n_i\right)^{1/2}}{\sum s_i\left(dn_i / dx\right)}\right)$$

Linear coordinates

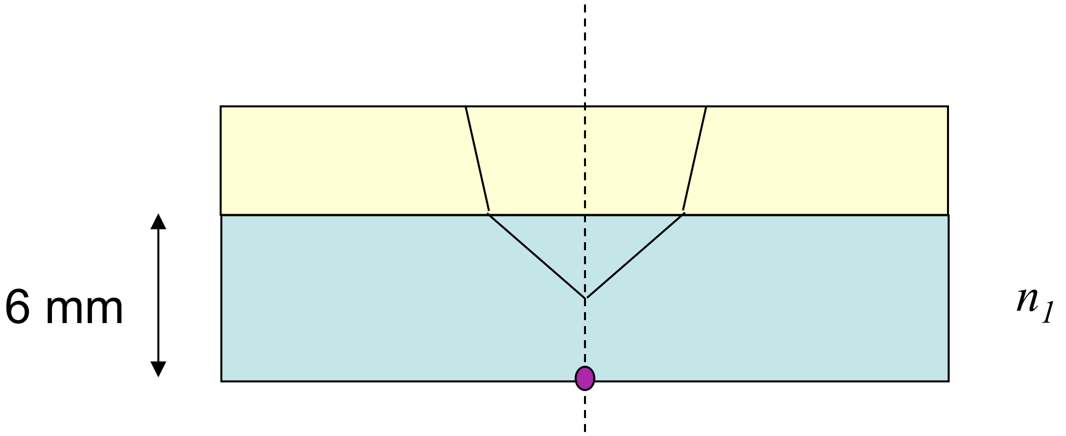
PMT weight factor

Limit resolution research
Minimize R with respect to s

Reducing the dimension of the photodetector cell

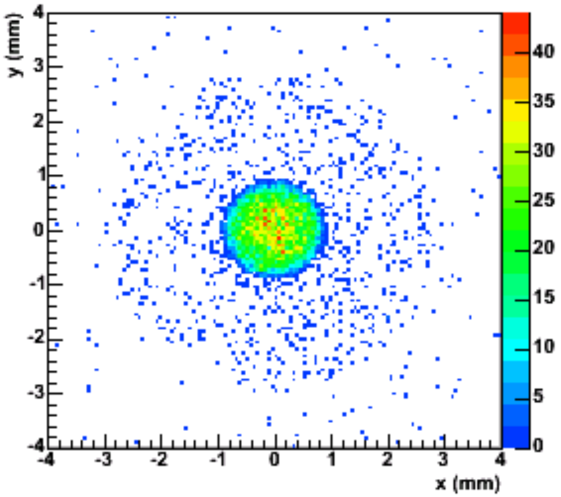
$$R_i = 2{,}35\left(\sum \frac{\left(dn_i/dx\right)^2}{n_i}\right)^{1/2}$$

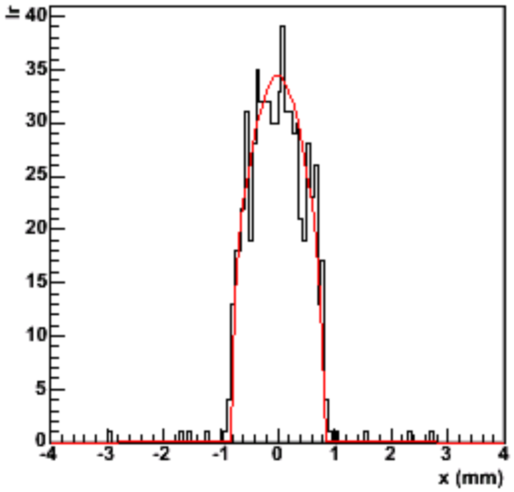
Resolution improvement due to a high number of photoelectrons



For NaI:Tl, If the scintillation occured at the edge, the light spot spread is 16 mm
If scintillation occurs in the center, the light spot spread is 8 mm
If the diffusion media is « AIR », the light spot spread will be 4 mm

Geant4 simulation
Crystal YAP (n=1,93)
Thickness 3mm
Scintillation in the center





Photomultiplier Tube

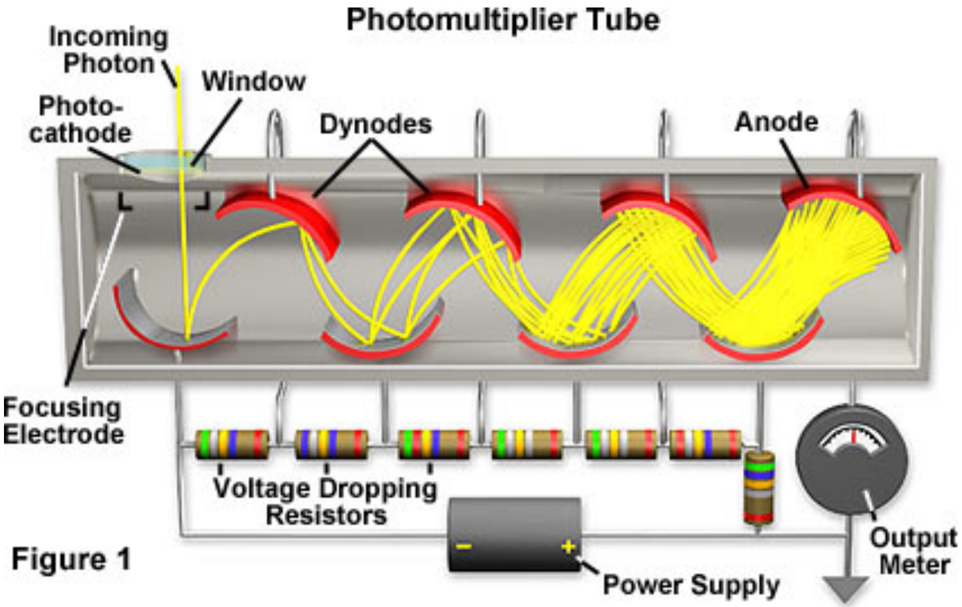


Figure 1

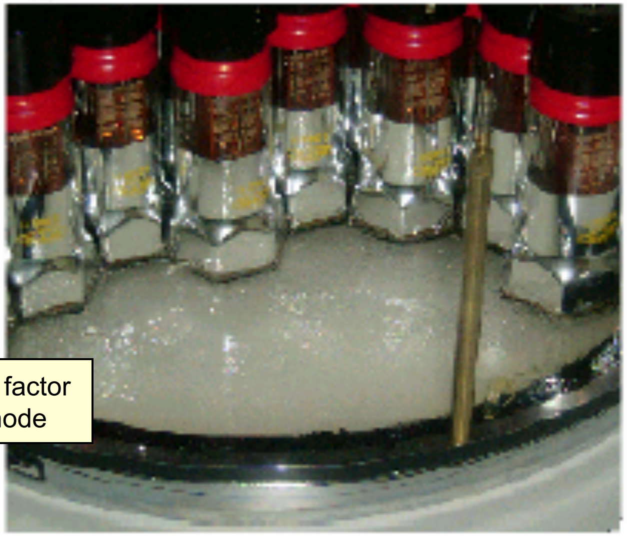
Nb of e⁻ collected at the anode

Nb of primary e⁻

$$n_a = n_k \prod_N g_i$$

Amplification factor
Of each anode

Nb ofdynodes



http://www.olympusmicro.com/primer/digitalimaging/concepts/photomultipliers.html

La charge $Q = Ne$

N

=

$N_{h\nu}$	Number of optical photons emitted by the scintillator
$\Omega(\lambda)$	Optical yield of the photocathode
$\sigma(\lambda)$	Quantum yield of the photocathode
C	Collection yield of the optical entry
G	Global gain of the PM

$$N_{h\nu} = \frac{\Delta E}{h\nu}\varepsilon$$

et

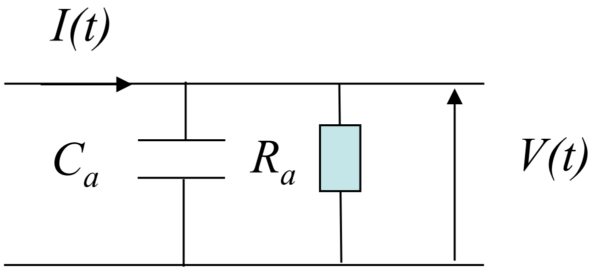
$$\Gamma = \frac{\varepsilon}{h\nu}\Omega(\lambda)\sigma(\lambda)C$$

Total conversion coefficient

$$\boxed{Q = \Gamma \Delta E G e}$$

with $G=K \text{ x } HT^{\alpha d}$

Output Voltage



R_a= 50 Ω
C_a=10 pF
τ_0=25 ns
Q_1=1,6 10-13 C
Q_2=0.8 10-13 C

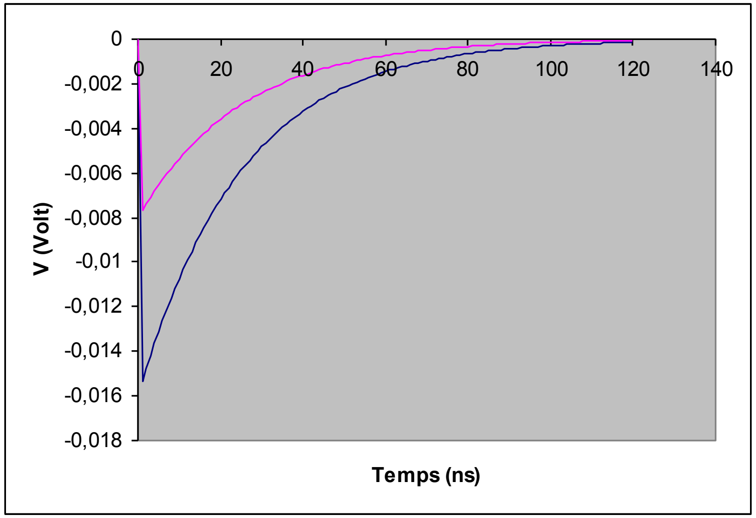
$$I(t) = \frac{dQ}{dt} \propto \frac{Q}{\tau_0} e^{-\frac{t}{\tau_0}}$$

$$I(t) = C_a \frac{dV(t)}{dt} + \frac{V(t)}{R_a} = \frac{dQ}{dt}$$

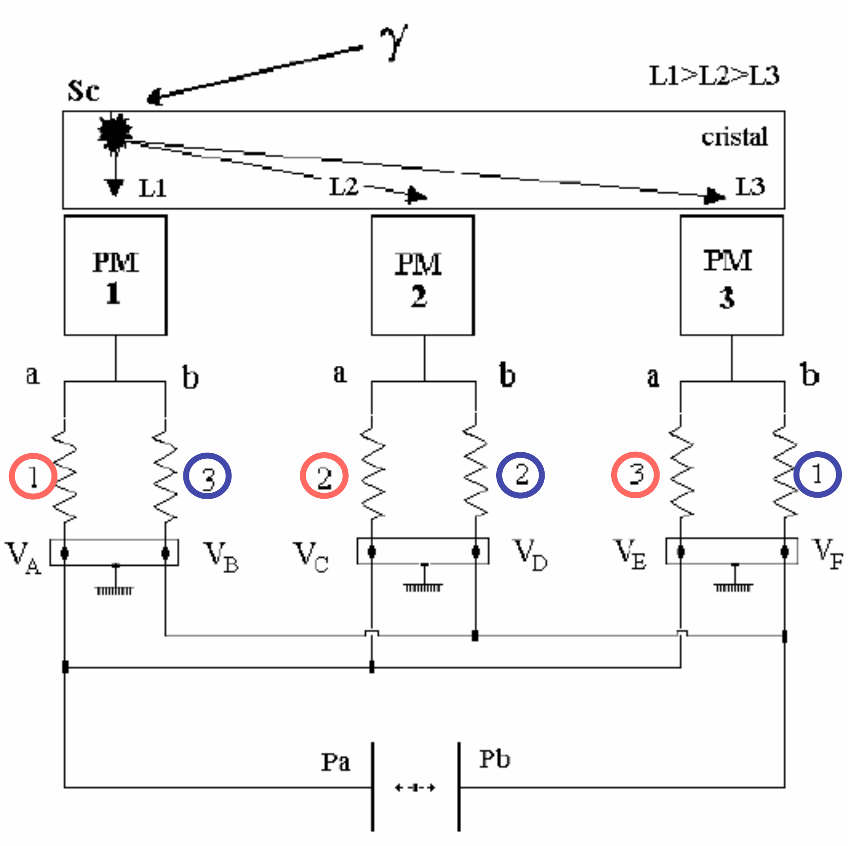
$$\frac{dV(t)}{dt} + \frac{1}{R_a C_a} V(t) = \frac{Q}{C_a \tau_0} e^{-\frac{t}{\tau_0}}$$

$$with \quad \tau_a = R_a C_a$$

$$V(t) = \frac{Q}{C_a} \frac{\tau_0}{\tau_0 - \tau_a} \left(e^{-\frac{t}{\tau_0}} - e^{-\frac{t}{\tau_a}} \right)$$



Scintillation localization

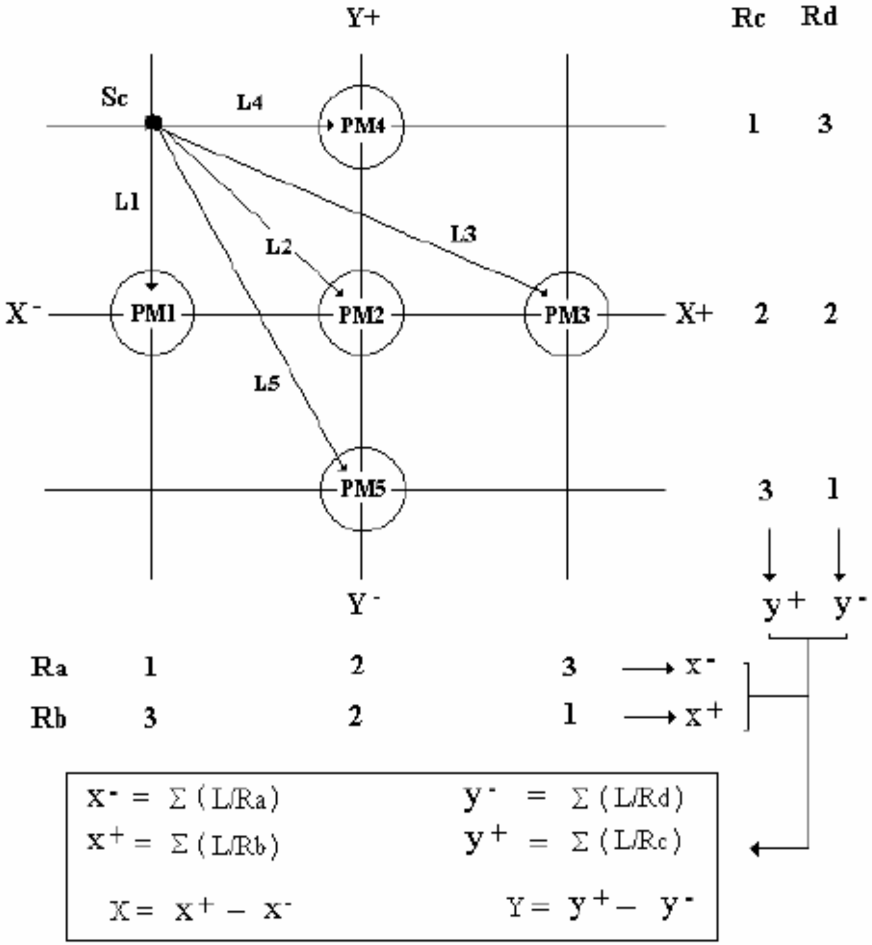


Each PM anode is connected to two separated circuits
(« a » and « b »)
yielding to vertical layers
(Layers of horizontal deviation) of an oscilloscope
« Pa » et « Pb ».

Arbitrary:
L1=12
L2=10
L3=6
with V~L/R

Pb-Pa=(Vb+Vd+Vf)-(Va+Vc+Ve)=(12/3+10/2+6/1) – (12/1+10/2+6/3) = 15-19 = -4

Displacement to the left of the light spot !!



$x^- = \Sigma(L/Ra)$

$x^+ = \Sigma(L/Rb)$

$X = x^+ - x^-$

$y^- = \Sigma(L/Rd)$

$y^+ = \Sigma(L/Rc)$

$Y = y^+ - y^-$

$$X = \frac{X^+ - X^-}{X^+ + X^-}$$

$$Y = \frac{Y^+ - Y^-}{Y^+ + Y^-}$$

$$W = X^+ + X^- + Y^+ + Y^-$$

New approaches

Crystals segmentation

Advantages:

Light confinement
The spatial resolution is given by the crystal size: choice of the resolution
Almost-independent count rate
Possible rejection of scattered

Drawbacks:

Dead zone due to segmentation
Increase of pixel numbers
Degradation of light collection with thin crystals
Adaptation of the collimator holes shape
Pixellization artifcats
Price

Photodetectors

PM multi anodes / sensitive to the position
Solid detector

Performances' evaluation

Characterized by 6 parameters

Energy resolution
Spatial linearity
Uniformity
Spatial resolution
Detection efficiency
Count rate

Usually, these parameters are correlated

Performances very in the field of view
Three regions:
FFOV: Full field of view
UFOV: Useful field of view 95% de FFOV
CFOV: Central field of view 75% de FFOV

Energy resolution

coupling with a PMT

N	
=	
$N_{h\nu}$	Number of optical photons emitted by the scintillator
$\Omega(\lambda)$	Optical yield of the photocathode
$\sigma(\lambda)$	Quantum yield of the photocathode
C	Collection yield of the optical entry
G	Global gain of the PM

$$\overline{N} = \overline{N}_{h\upsilon}\,\overline{\Omega}\,\overline{\sigma}\,\overline{C}\,\overline{G}$$

with $\upsilon_x = \dfrac{\sigma_x^2}{\overline{x}^2}$ Relative variance

$$\upsilon_N = \upsilon_{N_{h\upsilon}} + \frac{\upsilon_\Omega}{\overline{N}_{h\upsilon}} + \frac{\upsilon_\sigma}{\overline{N}_{h\upsilon}\overline{\Omega}} + \frac{\upsilon_C}{\overline{N}_{h\upsilon}\overline{\Omega}\,\overline{\sigma}} + \frac{\upsilon_G}{\overline{N}_{h\upsilon}\overline{\Omega}\,\overline{\sigma}\,\overline{C}}$$

Random variable	Distribution law	Relative variance
$N_{h\upsilon}$	poissonienne	$\upsilon_{N_{h\upsilon}} = \dfrac{1}{\overline{N}_{h\upsilon}}$
Ω	binomiale	$\upsilon_\Omega = \dfrac{1-\overline{\Omega}}{\overline{\Omega}}$
σ	binomiale	$\upsilon_\sigma = \dfrac{1-\overline{\sigma}}{\overline{\sigma}}$
C	binomiale	$\upsilon_C = \dfrac{1-\overline{C}}{\overline{C}}$

$$\upsilon_N = \frac{1+\upsilon_G}{\overline{\Omega}\,\overline{\sigma}\overline{C}\overline{N}_{h\upsilon}}$$

To this, we add the Noise Equivalent Count (NEC)

NEC : *Required input signal so that the output signal has an amplitude equal to the effective value of the output signal generated by the electronic noise*

Entre 0,1 et 0,2

$$R_e = \frac{\Delta E}{E_\gamma} = 2,35\sqrt{\frac{1+\upsilon_G}{\overline{\Omega}\,\overline{\sigma}\overline{C}\overline{N}_{ph}} + \left(\frac{NEC}{\overline{\Omega}\,\overline{\sigma}\overline{C}\overline{N}_{ph}\overline{G}}\right)^2}$$

To this we add,
Crystal homogeneities
Light transport with the crystal

Spatial linearity

Capability of an imaging instrument to provide an image consistent with the object, without geometric distorsion

The spatial linearity of a gamma camera is determined by analyzing the induced distorsions in the scintigraphic image of radioactive source with a know geometry

A distorsion can be corrected at the scintillations positionning matrix

Uniformity

A camera response to small object of a given acitivity is more or less
independent of the object position in the field of view

This quality is to be examined in two cases:

There is no collimator
Intrinsic uniformity
because it is a property of base of the γ camera

There is a collimator
System uniformity
because this property is related to particular use cases

Case of uniform irradiation

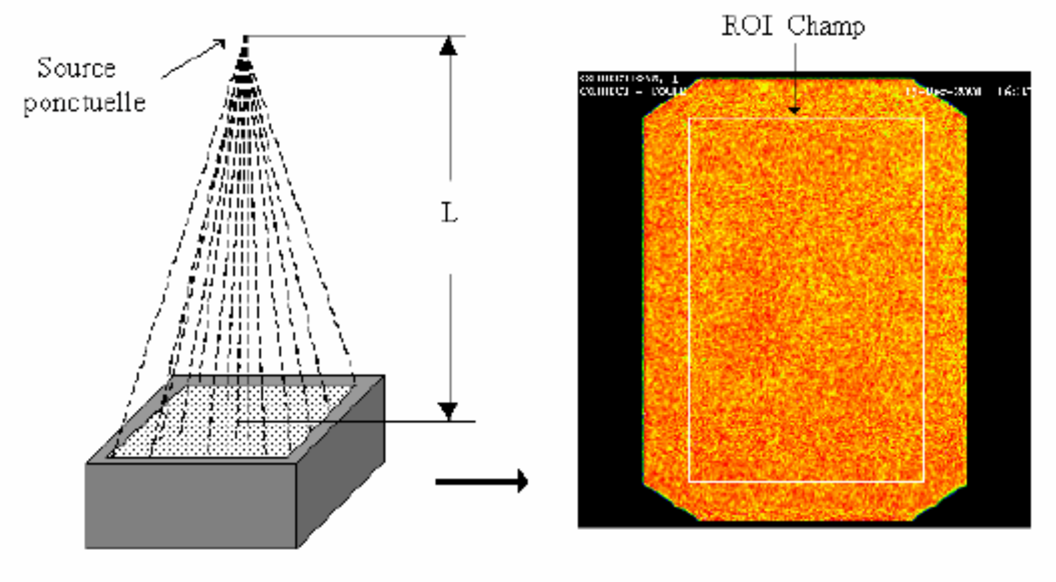
Integrale uniformity Ui

within a large ROI (Region Of Interest)
that limits the studied field (UFOV ou CFOV)
Ui = (Cmax – Cmin) / (Cmax + Cmin) en %

Differential uniformity Ud

largest local variation between two pixels,
in the ROI limiting the studied field
The localization is arbitrary defined by a group of 25 pixels centered around a non zero pixel
Ud = $(C_{hi} – C_{low}) / (C_{hi} + C_{low})$ en %

Intrinsic uniformity

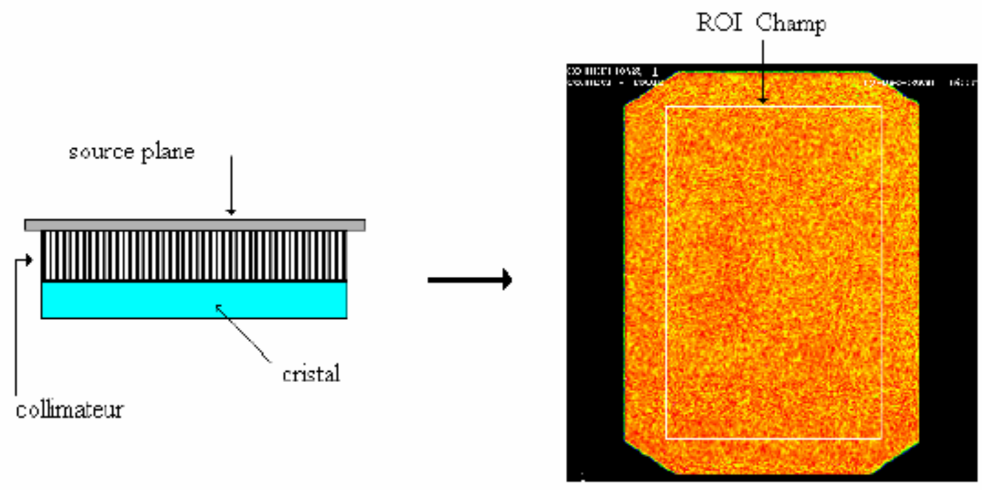


Source ponctuelle de 10 MBq **L > 5 fois dimension maximale du champ**

Integral uniformity		Differential uniformity	
CFOV	UFOV	CFOV	UFOV
2,5	3,0	1,5	2,0

^{99m}Tc

System uniformity



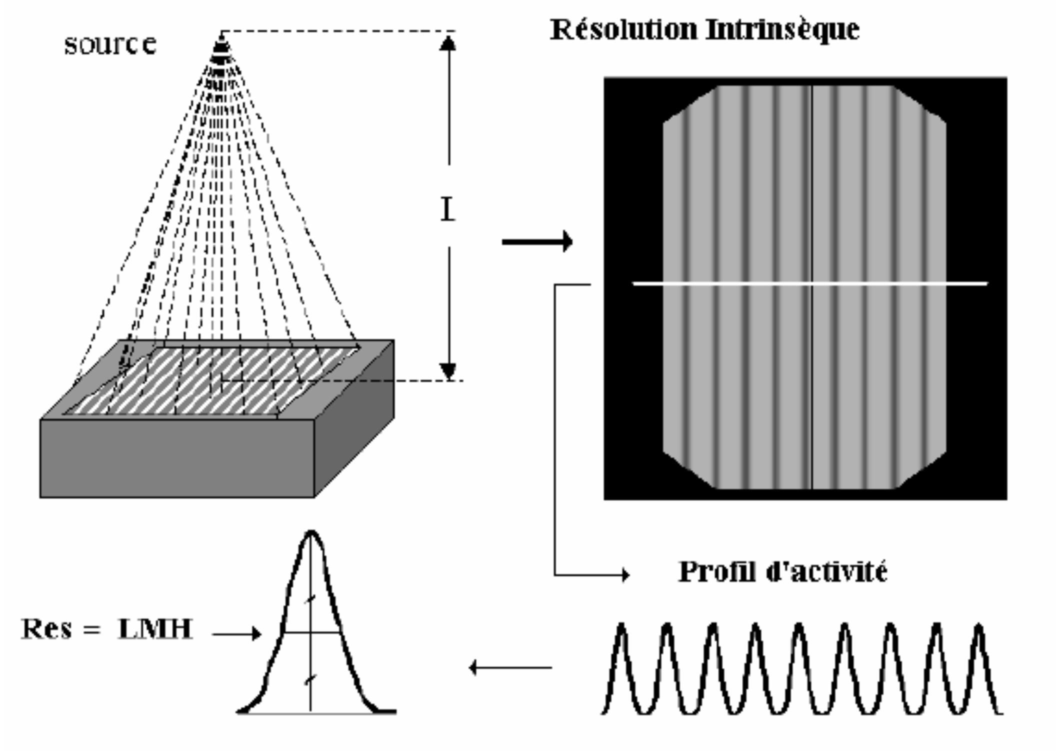
Source plane uniforme de 57 Co ~ 370 MBq

Integral uniformity		Differential uniformity	
CFOV	UFOV	CFOV	UFOV
4,0	5,1	2,5	3,0

^{57}Co

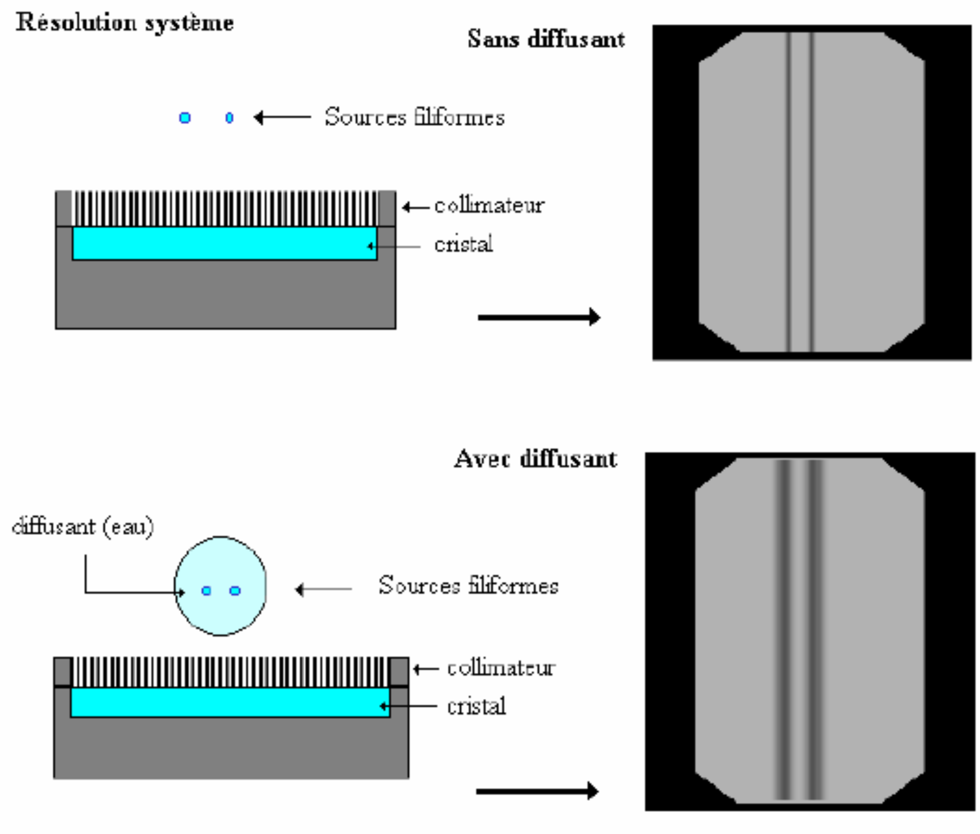
Spatial resolution

Intrinsic spatial resolution



Spatial resolution

Spatial resolution of the system



Other method: calculate the FTM (Full Width tenth measurement)

Detection efficiency or *sensitivity*

Probability of detecting an incident photon
Quantified as the count rate with a planar source

System = intrinsic (S_i)+ collimator (S_c)
With $S_i >> S_c$

S_i crystal dependent
S_c collimator dependent

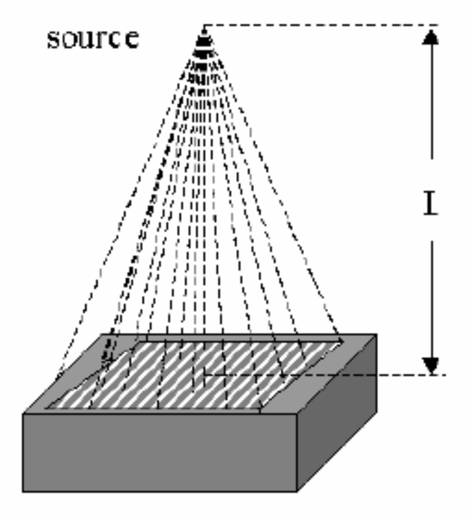
Current value, collimator LEHR: 130 cps/MBq

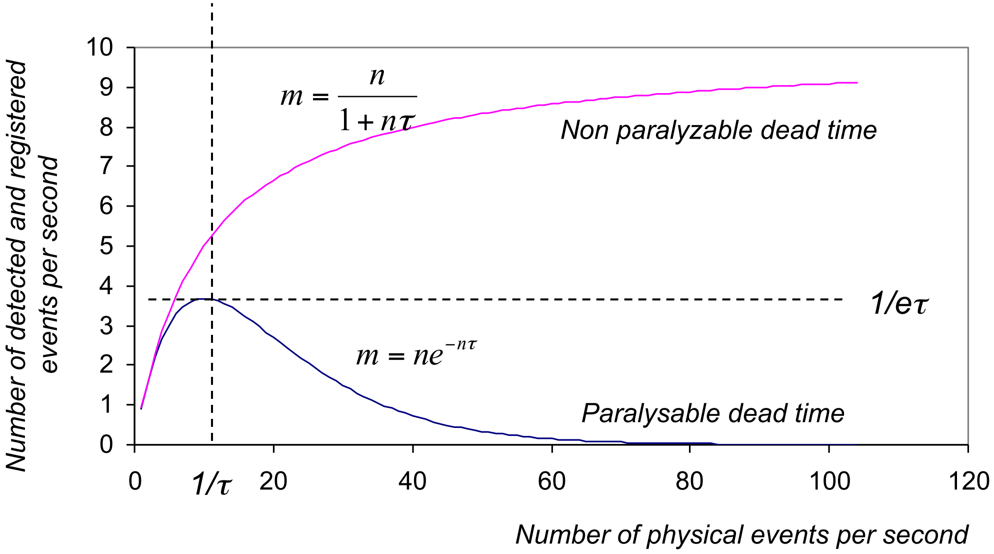
Count rate

With the increase of the activity,
the count rate has two components:

The linearity of the observed count rate
The accuracy of the positionning of the registered event

Source activity variation





Clinical procedures

The power of nuclear medicine is that it offers the possibility of acquiring images of a physiological function

Planar imaging : integration of a volume

One big advantage is the capability of the activity follow-up upon time

Installation

Image optimization requires a well controlled envionment

Variation of ambient temperature: 3-5°C / hour with collimator
-> 1°C/ hour at crystal level

Conclusion: The collimator protects the crystal

Knowing of backgroune noise

Acquisition consideration

Patient movement

« Macroscopic and microscopic »

Choice of the collimator

resolution, efficiency, energy…

Size of the image matrix

pixel = LTMH/3, Magnification usage

Partial volume effect

Object size < 2xLTMH

Energy window

Compromise between contrast and efficiency
Typically: 20% around the peak of interest

Count rate

Injected activity in order to reduce the loss in counts (<10%)

Contrast in the image

Object contrast

$$C_O = \frac{A_a - A_n}{A_n} \qquad C_O = \frac{A_a - A_n}{A_a + A_n}$$

Normal activity

Abnormal activity

n = background count

n+Δn = counting in the ROI

Δn > 10% of n (for 2σ)

$$\sigma_n = \sqrt{n}$$

$$\sigma_a = \sqrt{n + \Delta n}$$

$$\sigma = \sqrt{\sigma_n^2 + \sigma_a^2}$$

$$\text{si } \Delta n << n, \quad \sigma \approx \sqrt{2n}$$

$$2\sigma = 95{,}5\% = 2\sqrt{2n}$$

$$2\sqrt{2n} \geq 0{,}1n$$

Different types of acquisitions

Static

Radiopharmaceutical distribution should remain unchanged during all the acquisition period

Dynamic

Set of static images (time)
Stop point: count rate or measurement time

Hole body

Set of static images (space)

Synchronized

Set of static images (time) synchronized with a physiological rythm

List mode

Quality control

Tedious procedure: Standardization

Satisfy two requirements:

Perfomances comparison before the purchase
Detect performances « degradation » during the utilization

Constructors' dedicated procedures
NEMA and IEC

Users' dedicated procedures
AAPM, IAEA, IPSM, IPEM

Quality control

Installation

Control of the stability of the high voltage delivered to the instrument (24h)
Electric protection: inverter
Control of the temperature and humidity
Protection against magnetic field

Acquisition condition

Follow the constructor instruction
Check the photoelectric peak position
Adjust the energy window
The count rate should be less than ~$2x10^4$ cps (< 10% of loss)
No magnification acquisition
The position of the camera should be well known
In case of a multi-head camera, the measurements should be performed on each detector
Protect the detector from leakage and schock

Quality control

Source

If possible, realize the test with ^{99m}Tc
Optimize the point source located at 5xFOV
Check the uniformity of planar source

Phantom

The phantom size should correspond to the system resolution
The LTMH = 1,75 x size of the smallest object

Mechanical system

Collimator (lead…)
Collimator charging
System rotation
Check there is no eventual collision

Quality control

Different tests proposed for the procedures:

Energy calibration: find the photoelectric peak and center the energy window
Perform a background couting: test contamination
Unifomity
Detection efficiency
Energy resolution
Spatial linearity
Spatial resolution
Collimator: Holes' orientation
Count rate