Fundamentals of X-ray Computed Tomography

Tomography: chụp cắt lớp

Part I : the very very basics

Part II : components and physics

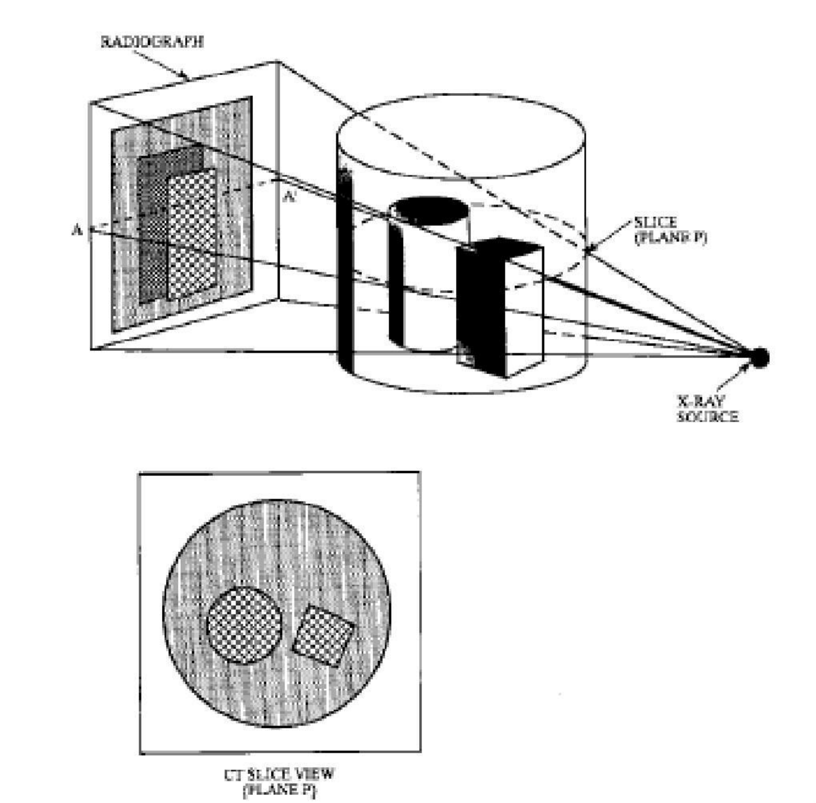
Part III : recent advances in CT

Part IV : some images

CT: Computed Tomography
CAT: Computerized Axial Tomography
CAT: Computer Assisted Tomography

- Pass x-rays through patient
- Detect on the other side
- Repeat from all angles surrounding patient
- Reconstruct cross sectional images
- Pixel values represent attenuation of tissue

tomography < τομος – γραφειν

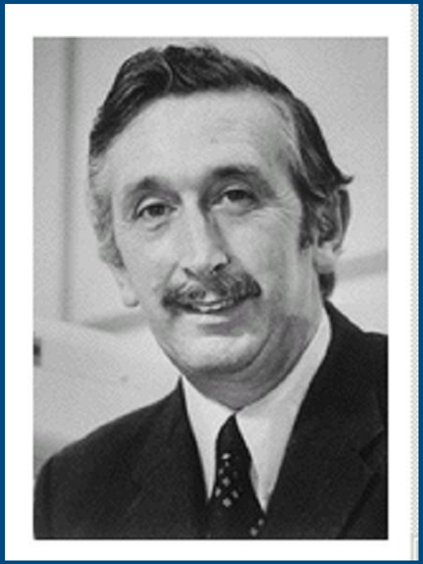


Courtesy of Bruno De Man, GE Global Research
< Courtesy of ??? >

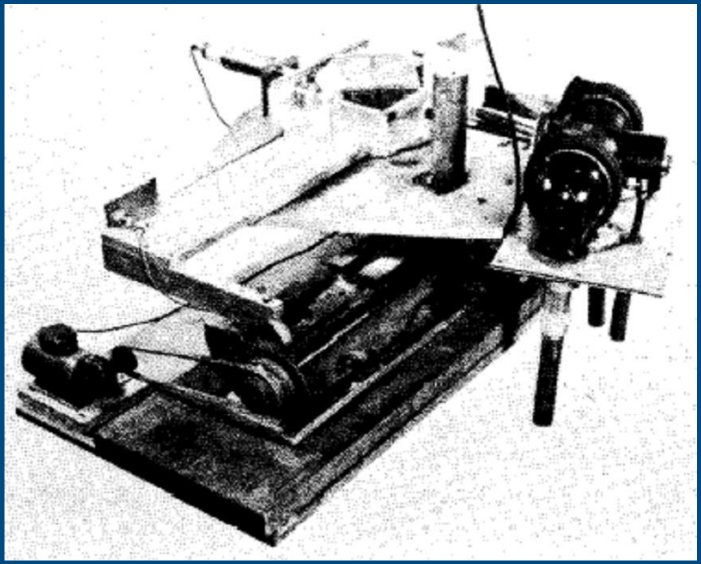
imagination at work

Sir Godfrey N. Hounsfield (1971)

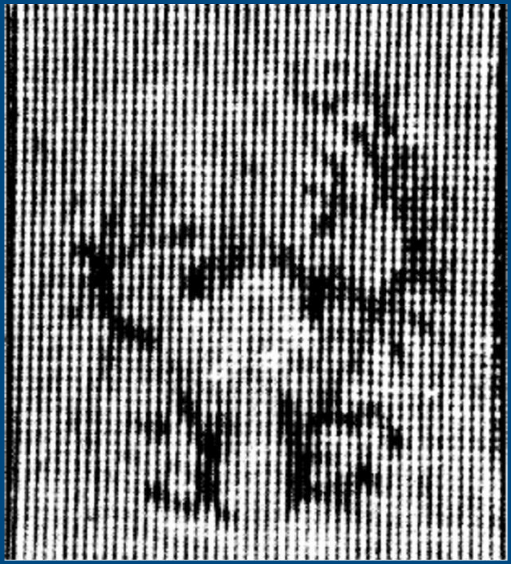
G. N. Hounsfield



Laboratory CT device



Brain image



http://www.nobel.se/medicine/laureates/1979/hounsfield-lecture.pdf

Courtesy of Bruno De Man, GE Global Research

< Courtesy of ??? >

Over 30 years of advances in CT

5 min	*Scan time/image*	0.5 sec
80x80	*Image size*	512x512
3 lp/cm	*Spatial resolution*	15 lp/cm
5mm/5HU/50 mGy	*Contrast resolution*	3mm/3HU/30 mGy
A few	*Slices to review*	100 - 1000
I Can See Clearly Now (Johnny Nash)	*Hit song*	Can't Get You Out Of My Head (Kylie Minogue)

Courtesy of Bruno De Man, GE Global Research
< Courtesy of Tom Toth (GE Healthcare) >

2014: CT Revolution

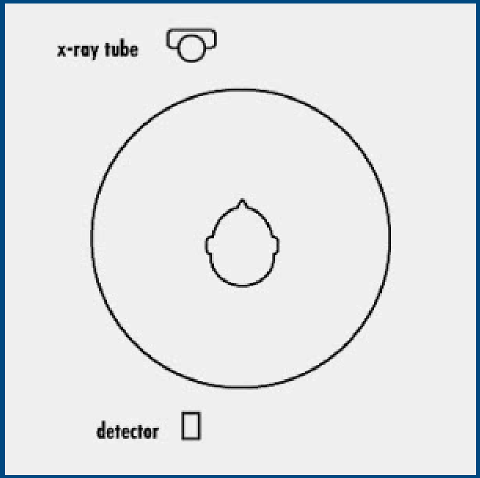
Introduction

Cardiac application

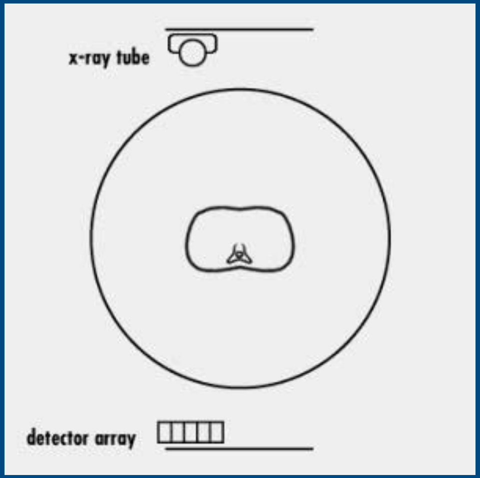
Courtesy of Bruno De Man, GE Global Research

CT scanner generations

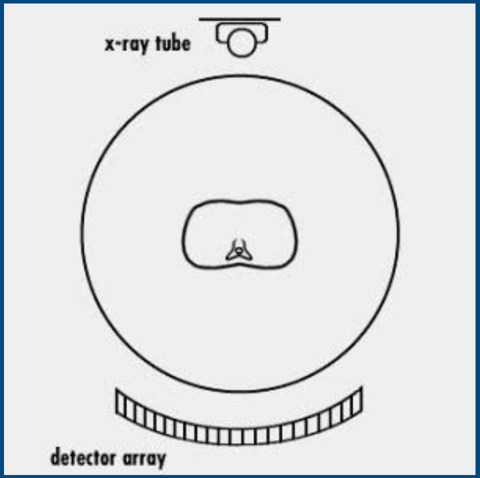
1st generation



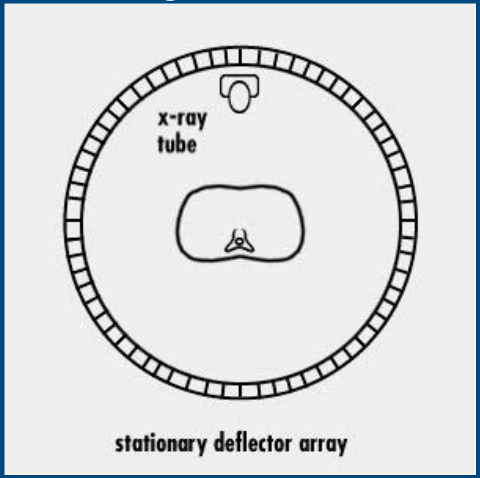
2nd generation



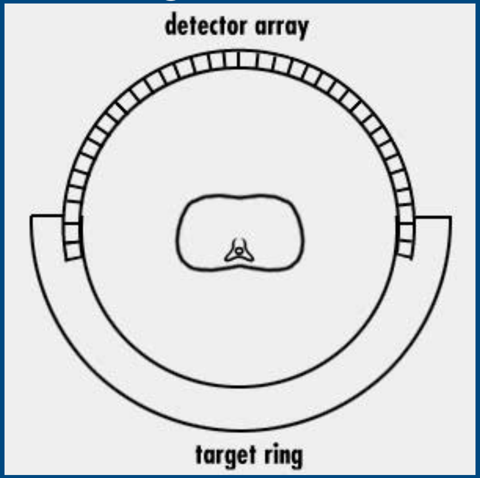
3rd generation



4th generation



5th generation

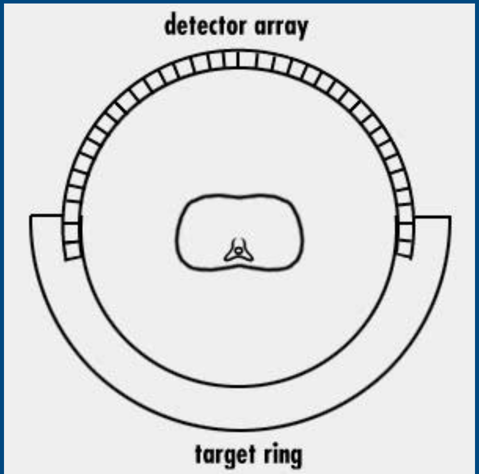


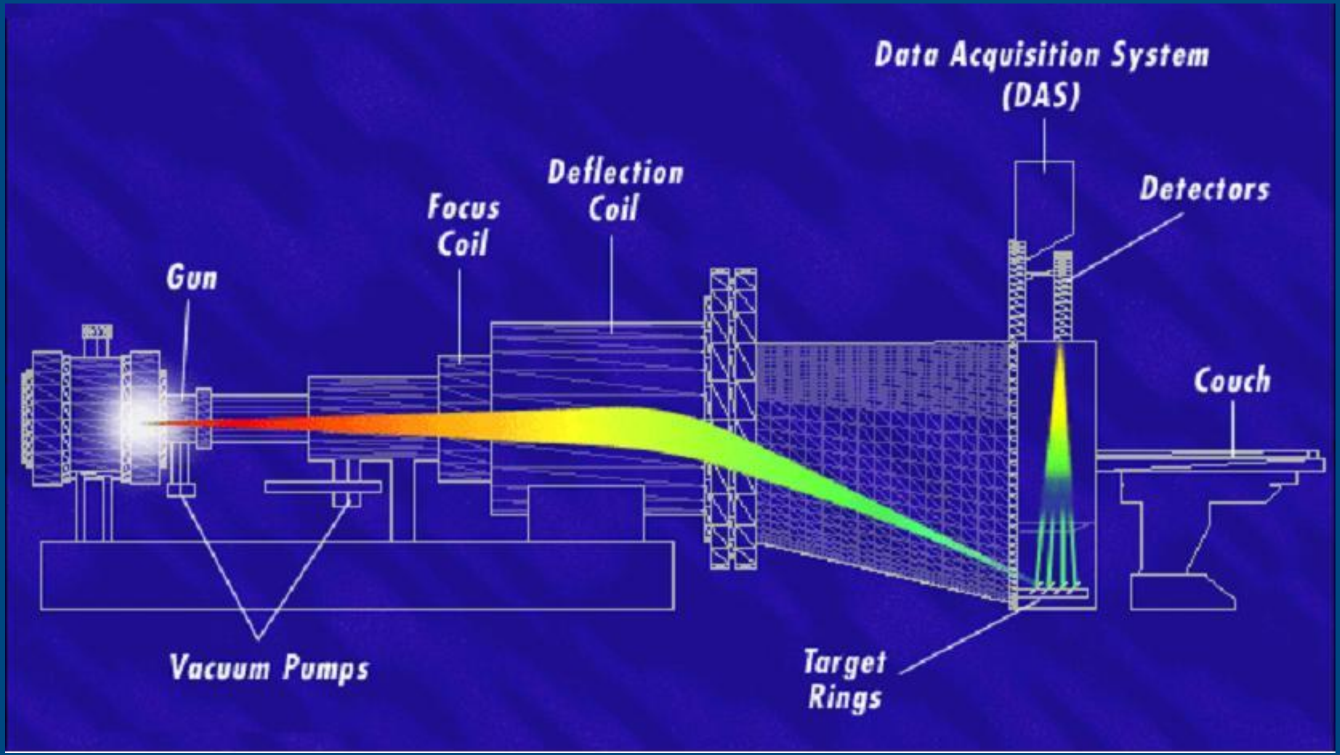
Hiện tại tất cả đang dùng 3rd generation
4th generation và 5th rất là đắt

Courtesy of Bruno De Man, GE Global Research
< Courtesy of ??? >

Electron beam tomography / e-Speed

5th generation





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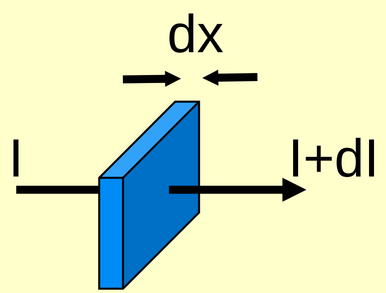
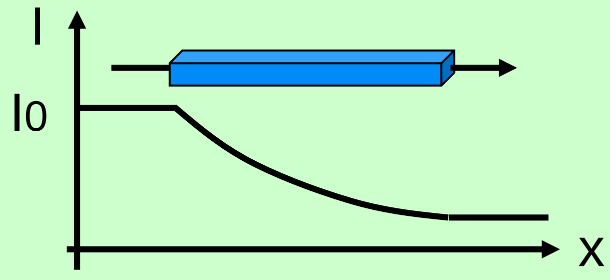
< Courtesy of ??? >

Beer's law



"Linear attenuation coefficient"

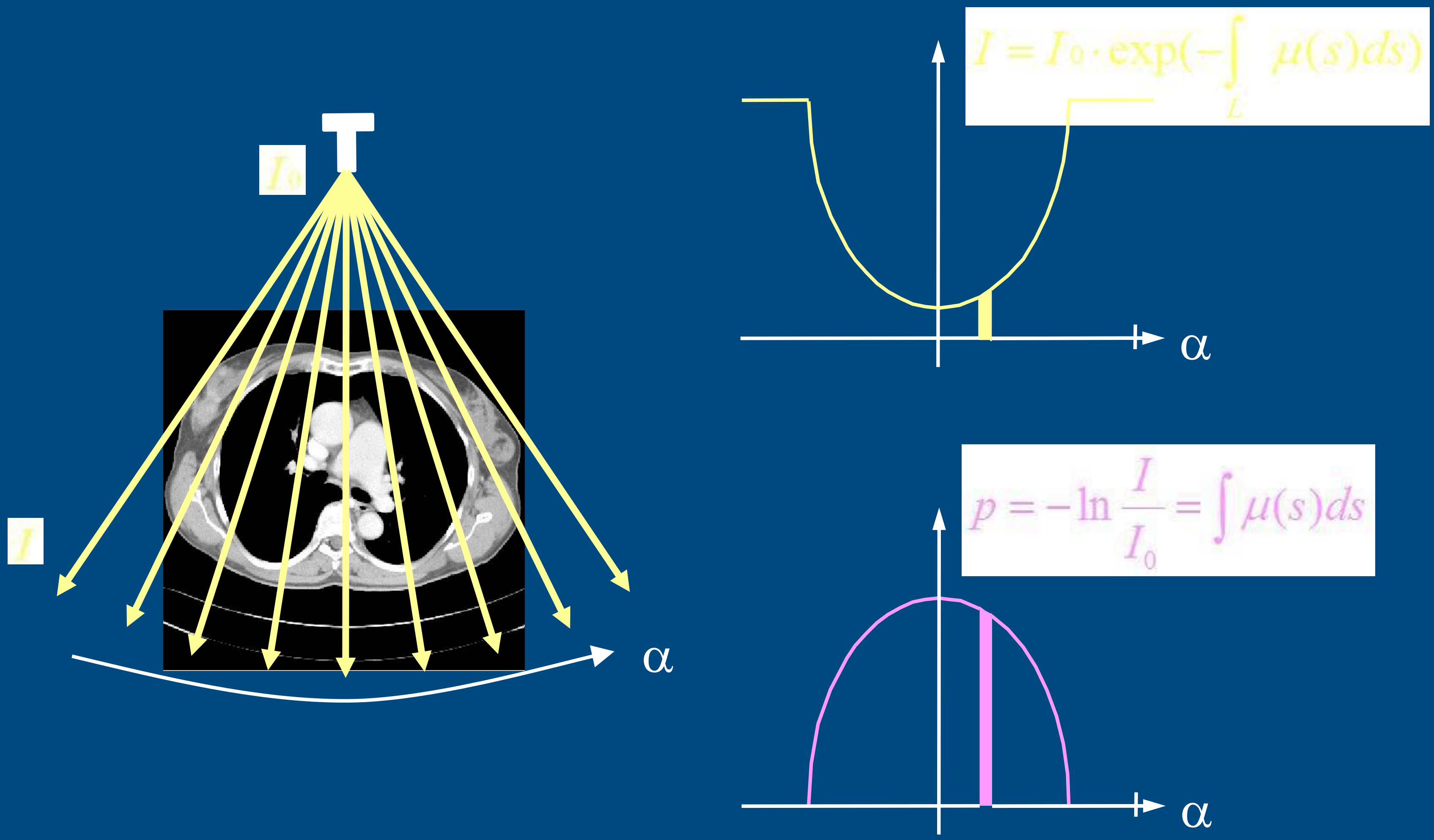
$$\mu = -\frac{\partial I / \partial x}{I}$$



"Beer's law"

$$I(x) = I(0) \cdot \exp\left(-\int_0^x \mu(t)dt \right)$$

Measuring attenuation line integrals

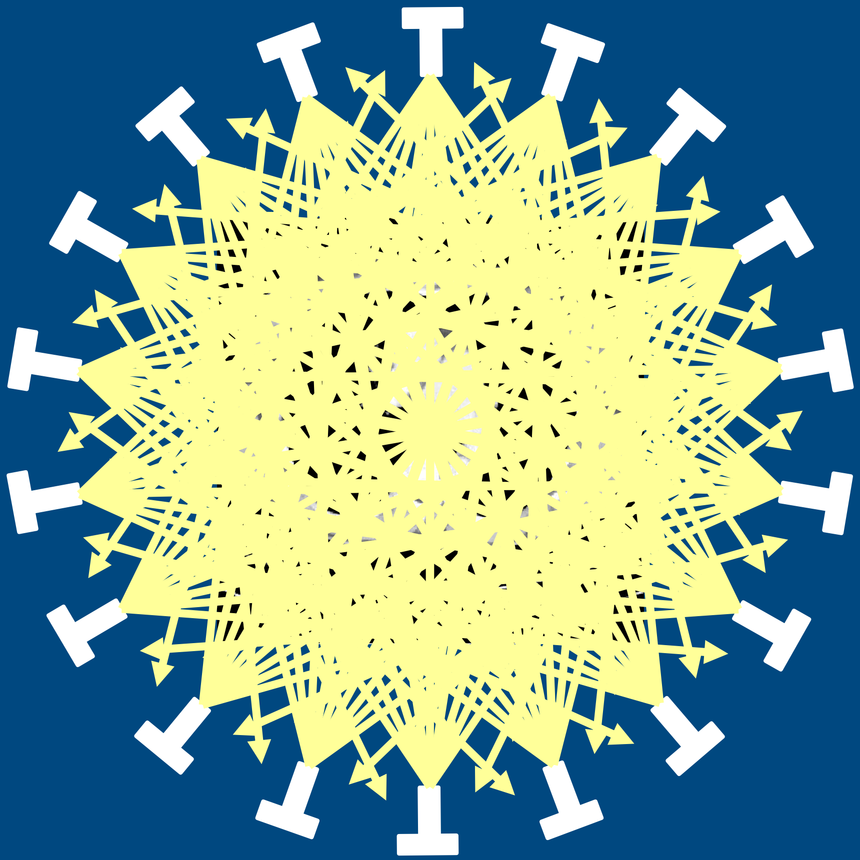


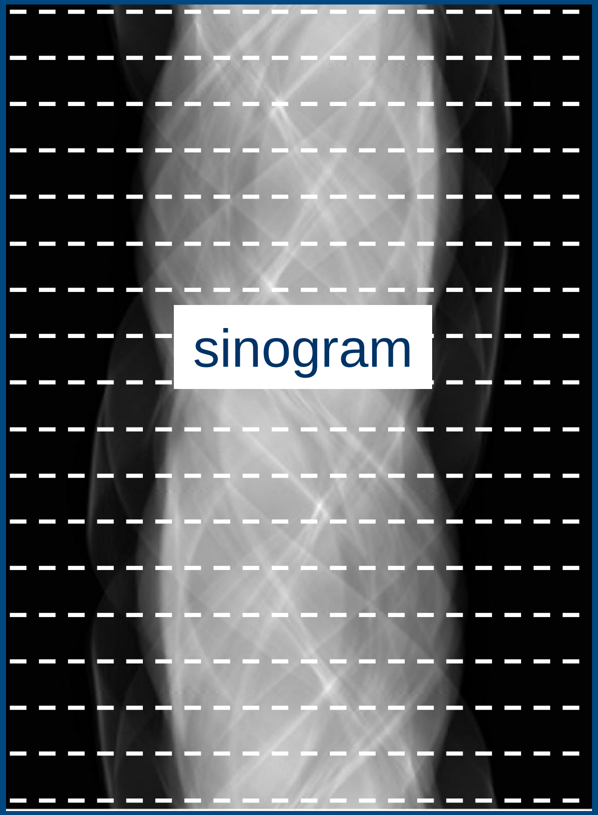
“view” or “projection”

Courtesy of Bruno De Man, GE Global Research

I là mật độ suy hao còn lại từ Io ban đầu

Sinogram



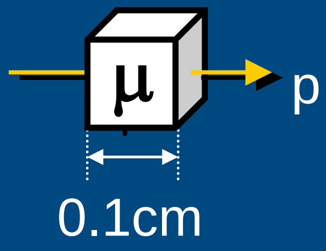


Courtesy of Bruno De Man, GE Global Research

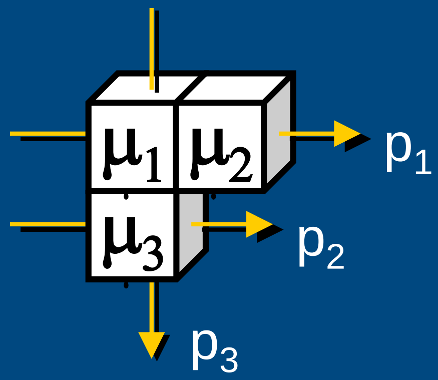
nombre de ligne est le nombre des images
nombre de colone est le nombre de pixel

mu commme la densité/surface

Image reconstruction



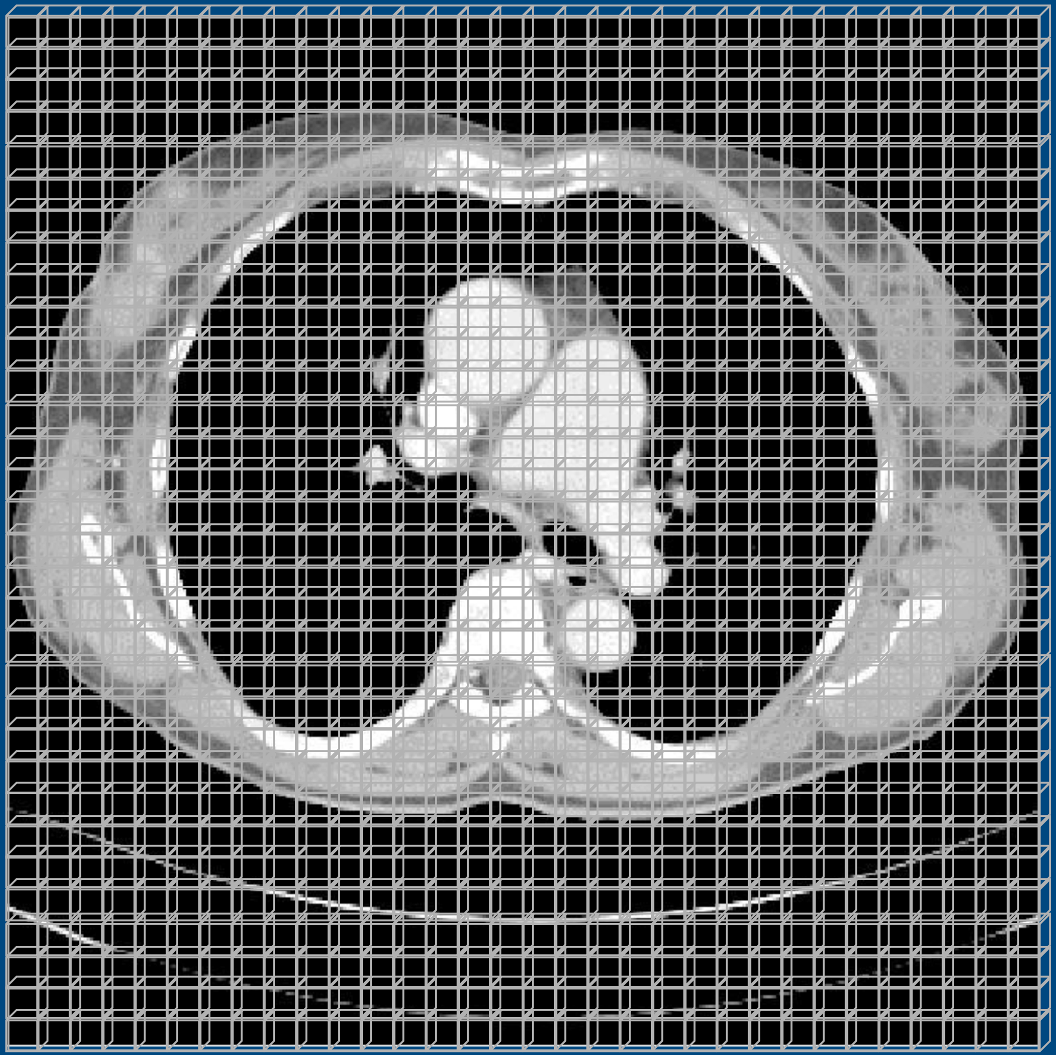
$p = 0.02 \rightarrow \mu_1 \cdot 0.1\text{cm} = 0.02 \rightarrow \mu_1 = 0.2\text{cm}^{-1}$



$$\begin{array}{l} p_1 = 0.06 \\ p_2 = 0.01 \\ p_3 = 0.03 \end{array} \rightarrow \begin{array}{l} (\mu_1+\mu_2)\cdot 0.1\text{cm} = 0.06 \\ \mu_3 \cdot 0.1\text{cm} = 0.01 \\ (\mu_1+\mu_3)\cdot 0.1\text{cm} = 0.03 \end{array} \rightarrow \begin{array}{l} \mu_1 = 0.2\text{cm}^{-1} \\ \mu_2 = 0.4\text{cm}^{-1} \\ \mu_3 = 0.1\text{cm}^{-1} \end{array}$$

Courtesy of Bruno De Man, GE Global Research

Image reconstruction



512x512 pixels
~1000 detector channels
~1000 views

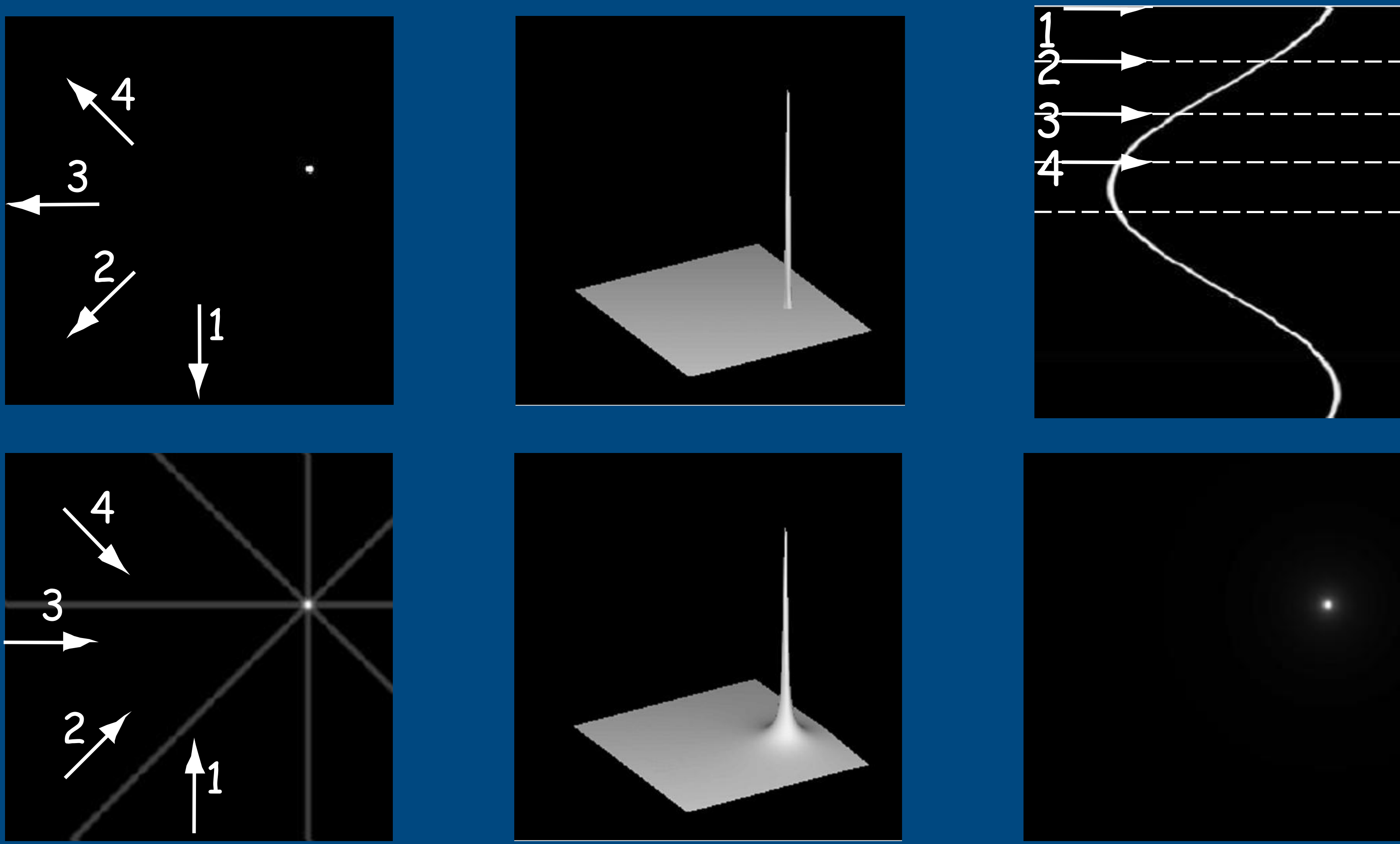
250.000 unknowns
1.000.000 equations

→

need practical algorithm

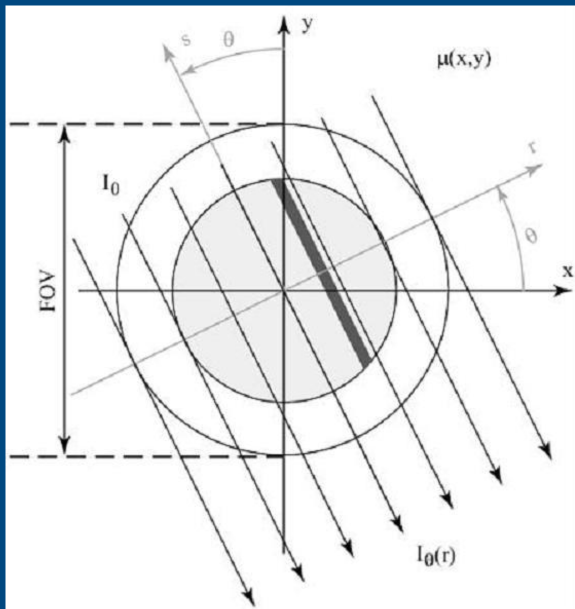
Courtesy of Bruno De Man, GE Global Research

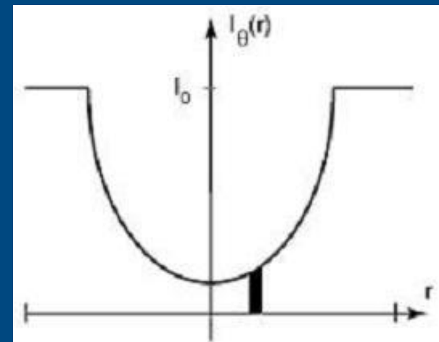
Backprojection

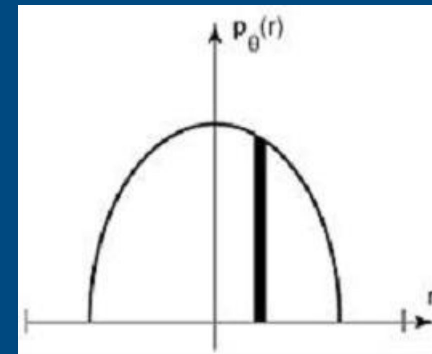


Courtesy of Bruno De Man, GE Global Research

Fourier slice theorem







$$P(k,\theta) = \int_{-\infty}^{\infty} p(r,\theta)\, e^{-2\pi i (k \cdot r)}\, dr$$

$$F(k_x,k_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\, e^{-2\pi i (k_x x + k_y y)}\, dx\, dy$$

$$P(k,\theta) = F(k_x,k_y)$$

with $\begin{cases} k_x = k \cdot \cos\theta \\ k_y = k \cdot \sin\theta . \end{cases}$

Fourier slice theorem

Courtesy of Bruno De Man, GE Global Research

k la coordonnee dans la transforme fourrier: k = squrt(kx^2 + ky^2)

Filtered backprojection

Direct Fourier inversion

(1) for all θ_m (varying from 0 to π), calculate the 1D discrete FT $\mathcal{F}_1$ of $p(r_n, \theta_m)$ with respect to r_n:

$$\mathcal{F}_1\{p(r_n, \theta_m)\} = P(k_{n'}, \theta_m), \tag{2.25}$$

(2) for every θ_m, put the values of $P(k_{n'}, \theta_m)$ on a polar grid,

(3) Calculate $F(k_{x_{i'}}, k_{y_{j'}})$ (sampled on a Cartesian grid) from $P(k_{n'}, \theta_m)$, using bilinear interpolation,

(4) and calculate the 2D inverse discrete FT $\mathcal{F}_2^{-1}$ of $F(k_{x_{i'}}, k_{y_{j'}})$:

$$\mathcal{F}_2^{-1}\{F(k_{x_{i'}}, k_{y_{j'}})\} = f(x_i, y_j). \tag{2.26}$$

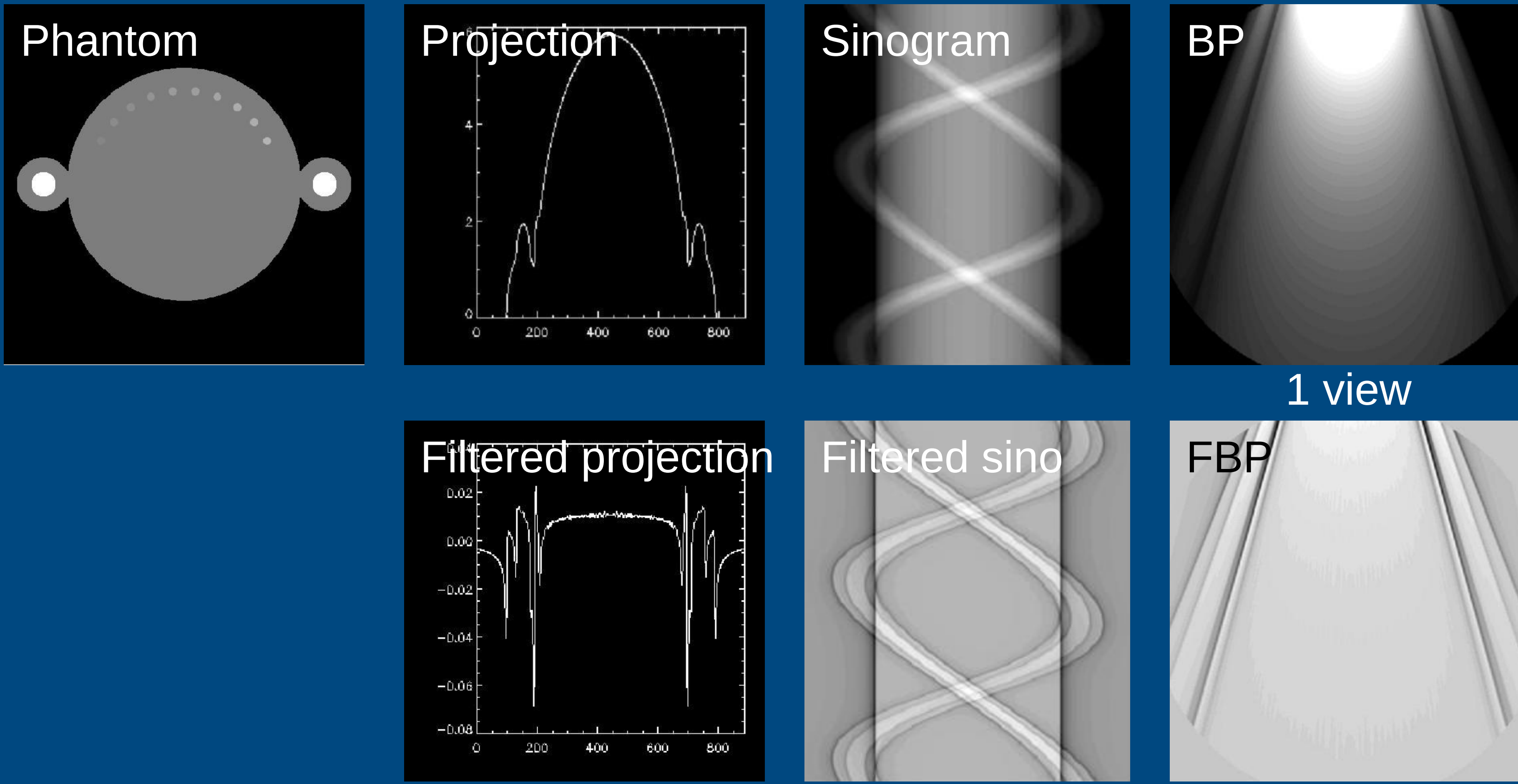
Filtered backprojection (FBP)

$$f(x,y) = \int_0^{\pi} \int_{-\infty}^{\infty} P(k,\theta)\ |k|\ e^{i2\pi kr}\ dk\ d\theta, \quad \text{with } r = x\cos\theta + y\sin\theta$$

Filtre HPF
Fixer theta: r coordonner linaire en l'angle theta (l'est alpha)
k: la frequent correspond à coordonne r de petit p
à grand P

f(t) -> F(nu
F(nu) = integrale(-inf, +inf) f(t)exp(-2*pi*i*nu)dt

Backprojection - Filtered Backprojection

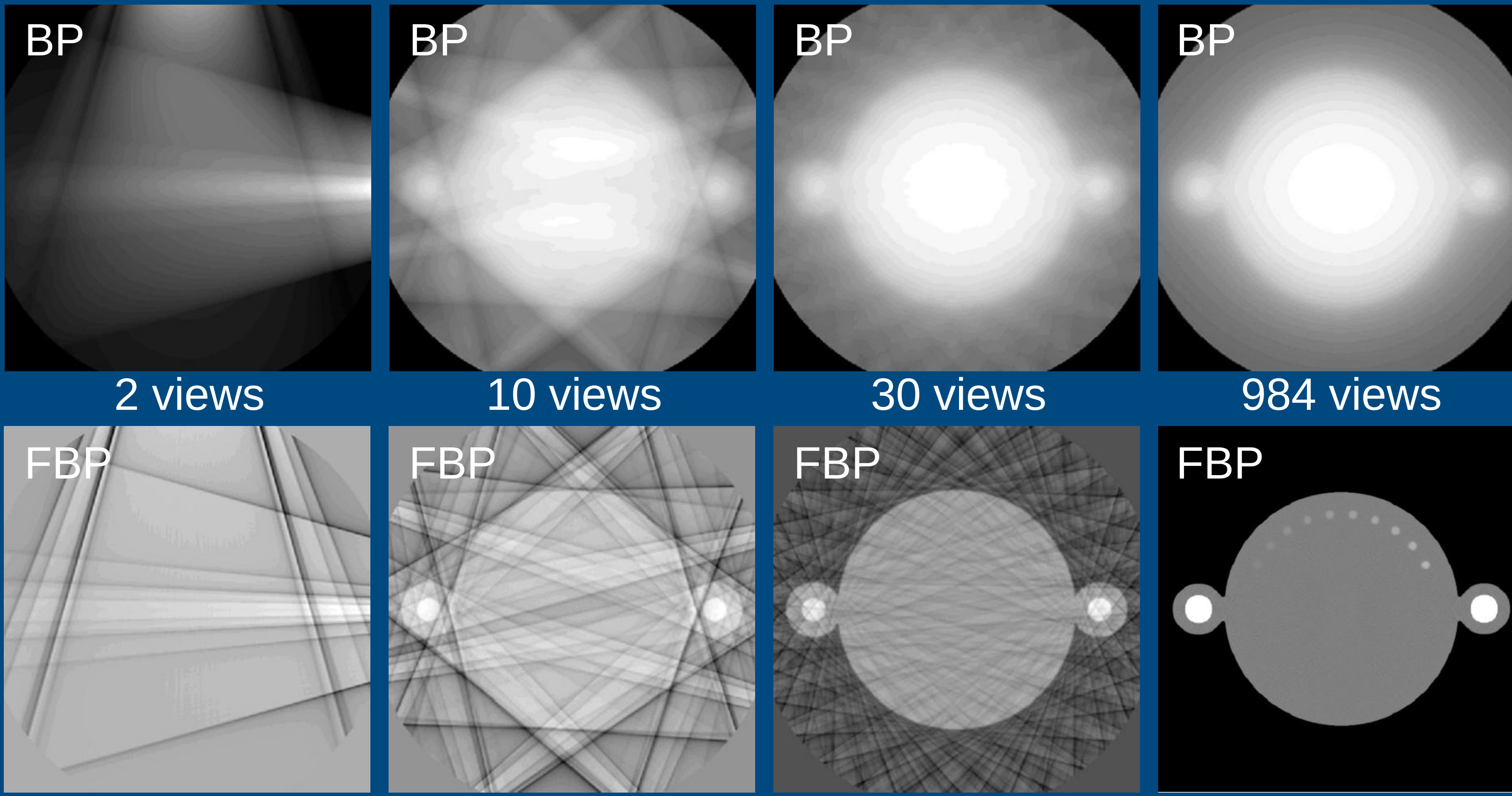


BP: Backprojection
FBP: Filtre Backprojection
HPF and Ramp PF ; filtre est necessaire pour ameliorer les images

Courtesy of Bruno De Man, GE Global Research

P(K,theta) = integrale(-inf,+inf)p_theta*exp(-2*pi*r*k)dr

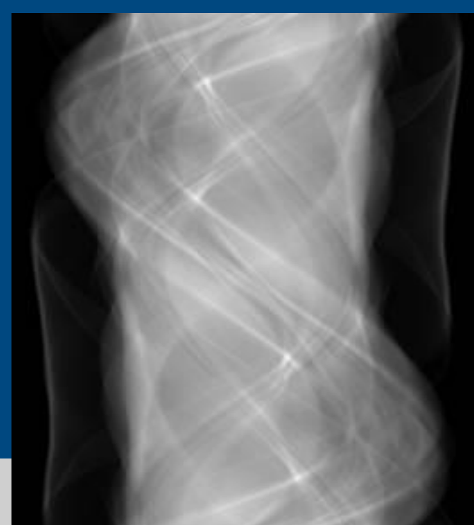
Backprojection - Filtered Backprojection



Courtesy of Bruno De Man, GE Global Research

Filtered Back-projecgtion

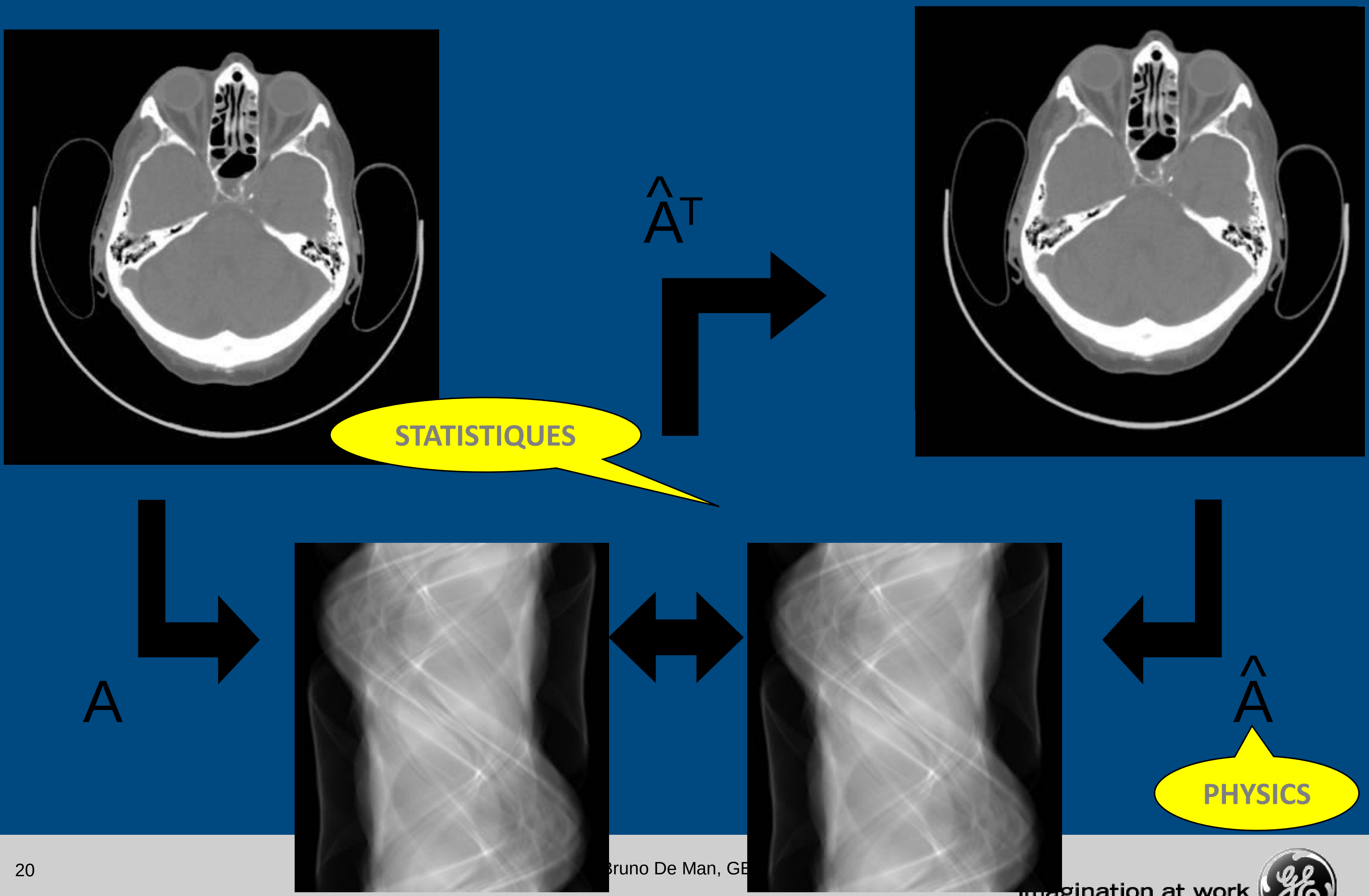
A



$\hat{A}^{-1}$

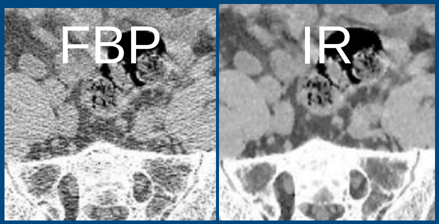
< Courtesy of Bruno DeMan (GE GRC) >

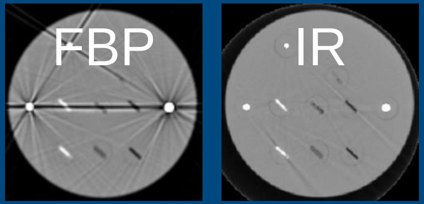
Iterative reconstruction

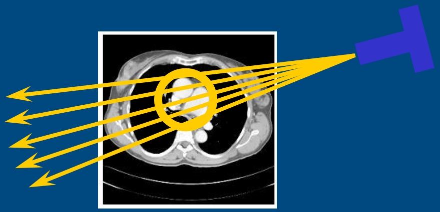


Why iterative reconstruction ?

- Dose/noise reduction
- Prior information
- Missing data
  - MAR
  - Detector gaps
  - Truncation
  - Local ROI
  - Under-sampling
- Incorporate physics
- Flexibility
  - Cone-beam
  - New geometries







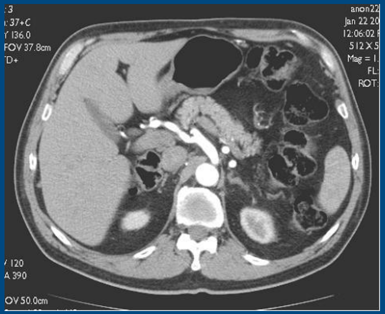
dynamique image: 0...1023 (10bit)
dynamique ecran: 0...255 (8bit)
window width:largeur de l'image voulant voir sur l'écran
window level:100

0,...,75 (100-50/2) -> 0
125(100+50/2) -> 255

Courtesy of Bruno De Man, GE Global Research

CT number - Hounsfield Units

$$\text{CT number} = 1000 * (mu - mu_{H20}) / mu_{H20}$$

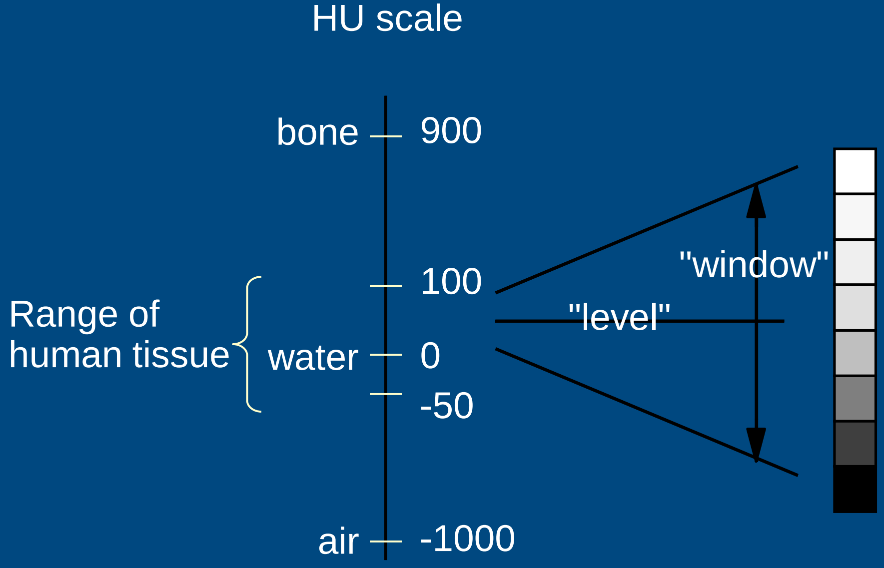


Air = -1000 HU

Water = 0 HU

Human tissue ~ 0 HU

Bone ~ 1000HU

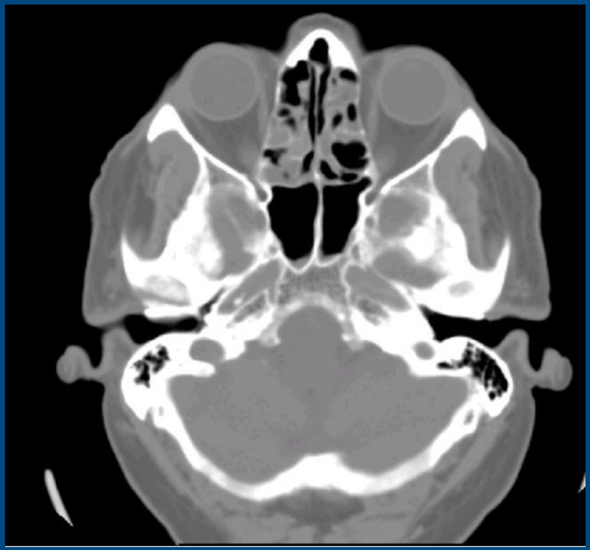


Courtesy of Bruno De Man, GE Global Research
< Courtesy of Tom Toth (GE Healthcare) >

Window - level

W100, L 20

Soft tissue contrast visible



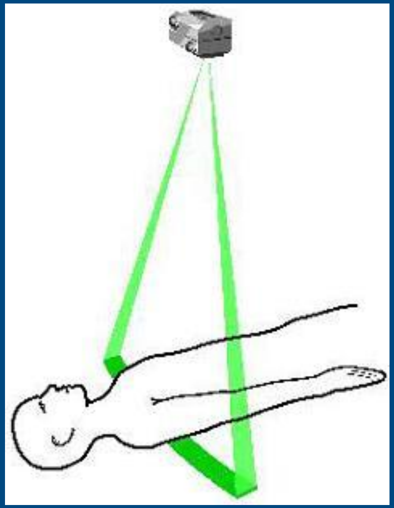
W1000, L 0

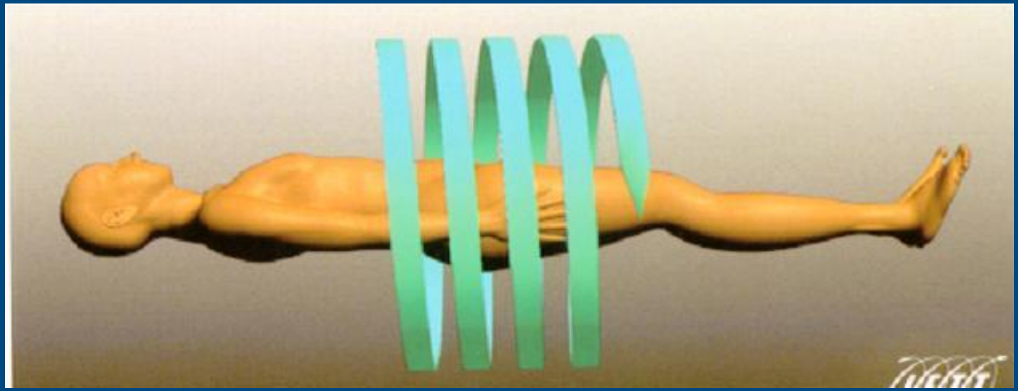
Bone structure visible

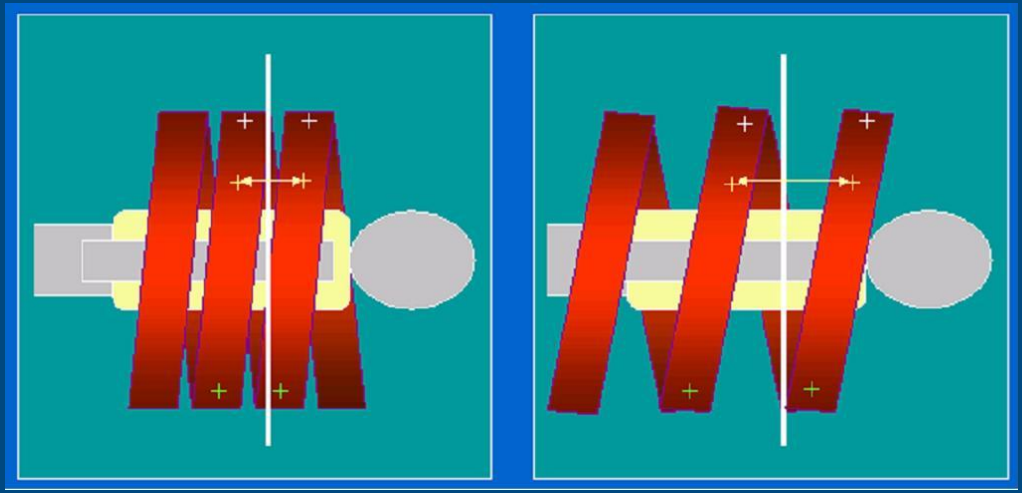
Courtesy of Bruno De Man, GE Global Research

< Courtesy of Tom Toth (GE Healthcare) >

Spiral CT or Helical CT

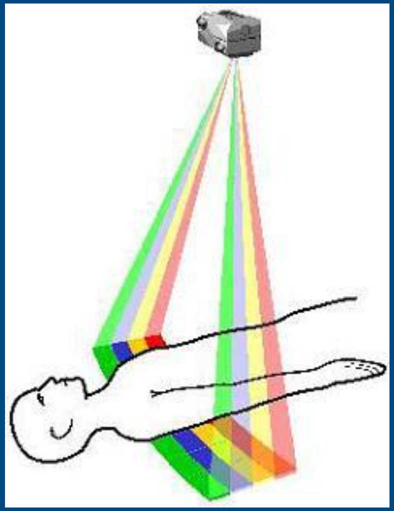


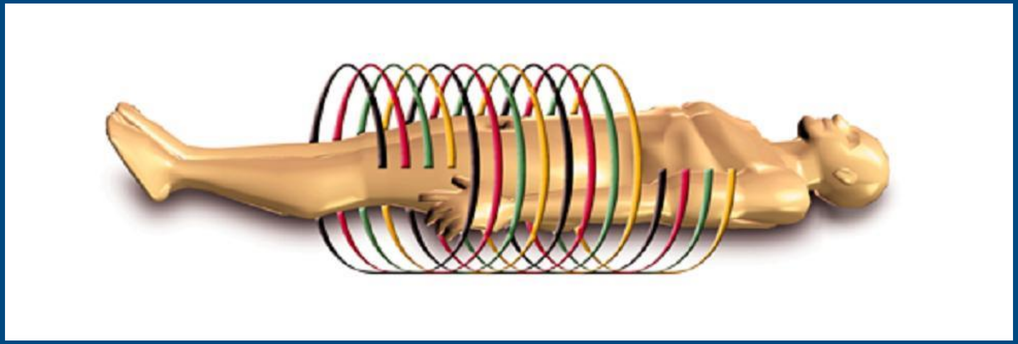




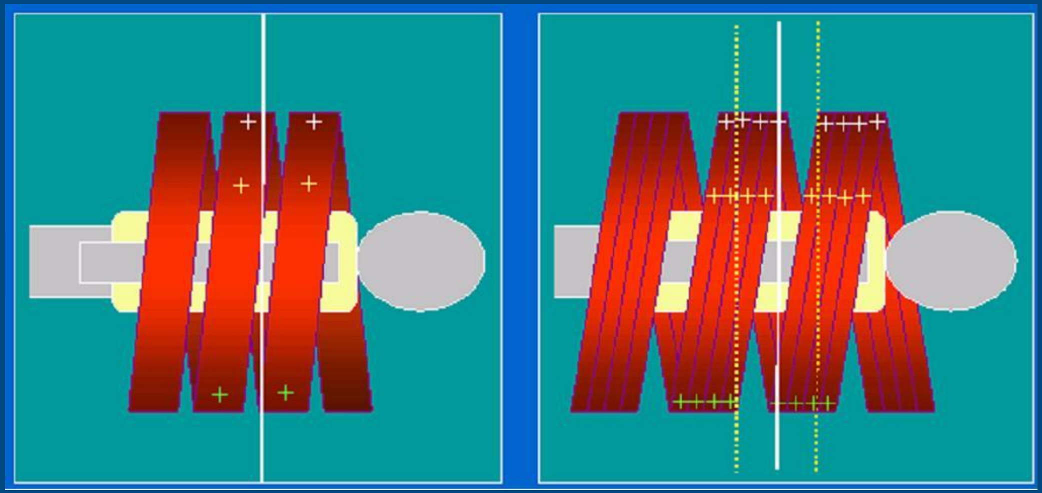
Courtesy of Bruno De Man, GE Global Research
< Courtesy of ImPACT >

Multi-slice CT or Multi-detector CT



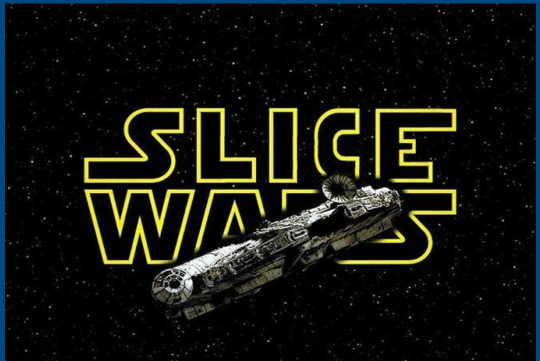


Higher resolution – Larger coverage – Faster scanning



Courtesy of Bruno De Man, GE Global Research
< Courtesy of ImPACT >

Slice wars



Courtesy of N. Pelc (Stanford University)

Manufacturer	GE	Philips	Siemens	Toshiba
CT scanner	Lightspeed 64	Brilliance 64	Sensation 64	Aquilion 64
# detector rows	64	64	32	64
row size (@iso)	0.625mm	0.625mm	0.6mm	0.5mm
total coverage (@iso)	40mm	40mm	20mm	32mm
# slices per rotation	64	64	64	64

Courtesy of Bruno De Man, GE Global Research

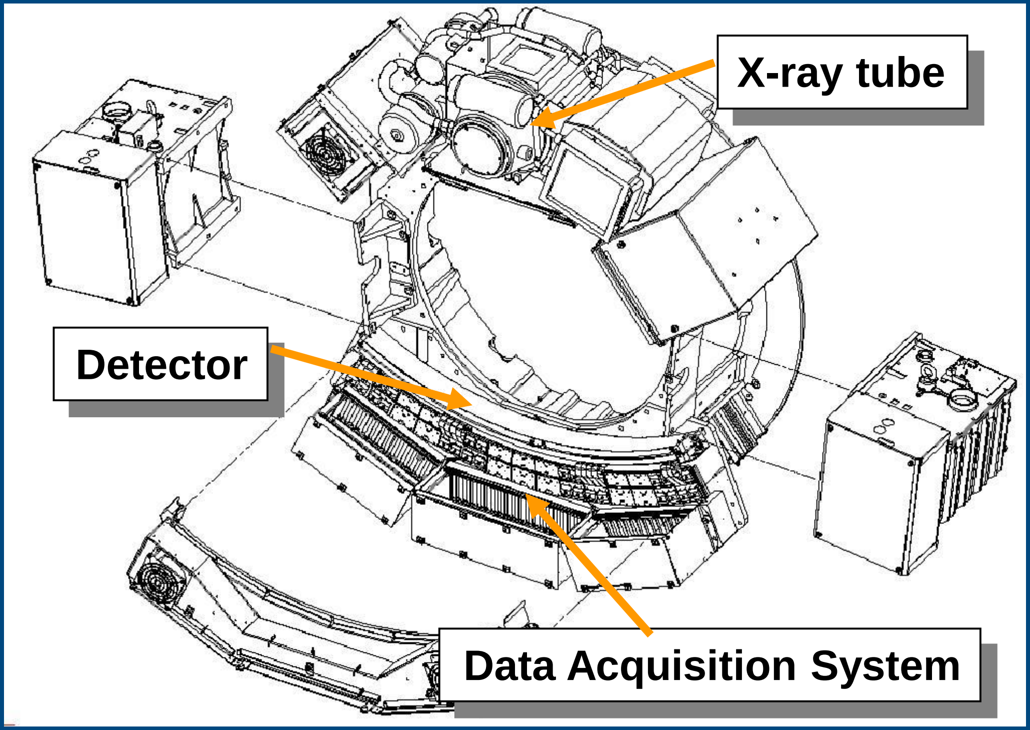
Part I : the very very basics

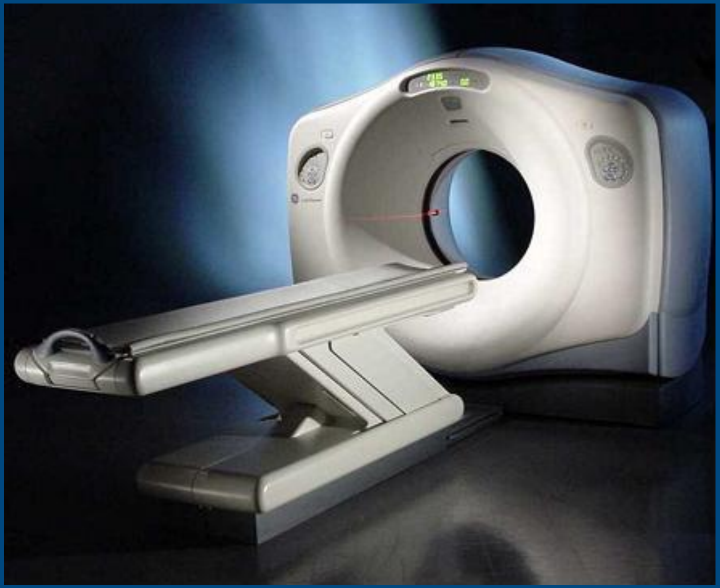
Part II : components and physics

Part III : recent advances in CT

Part IV : some images

CT system and components





Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

X-ray tube

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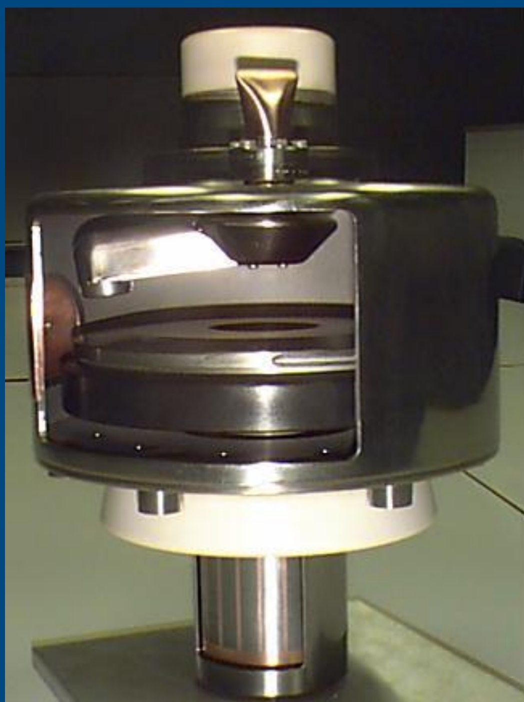
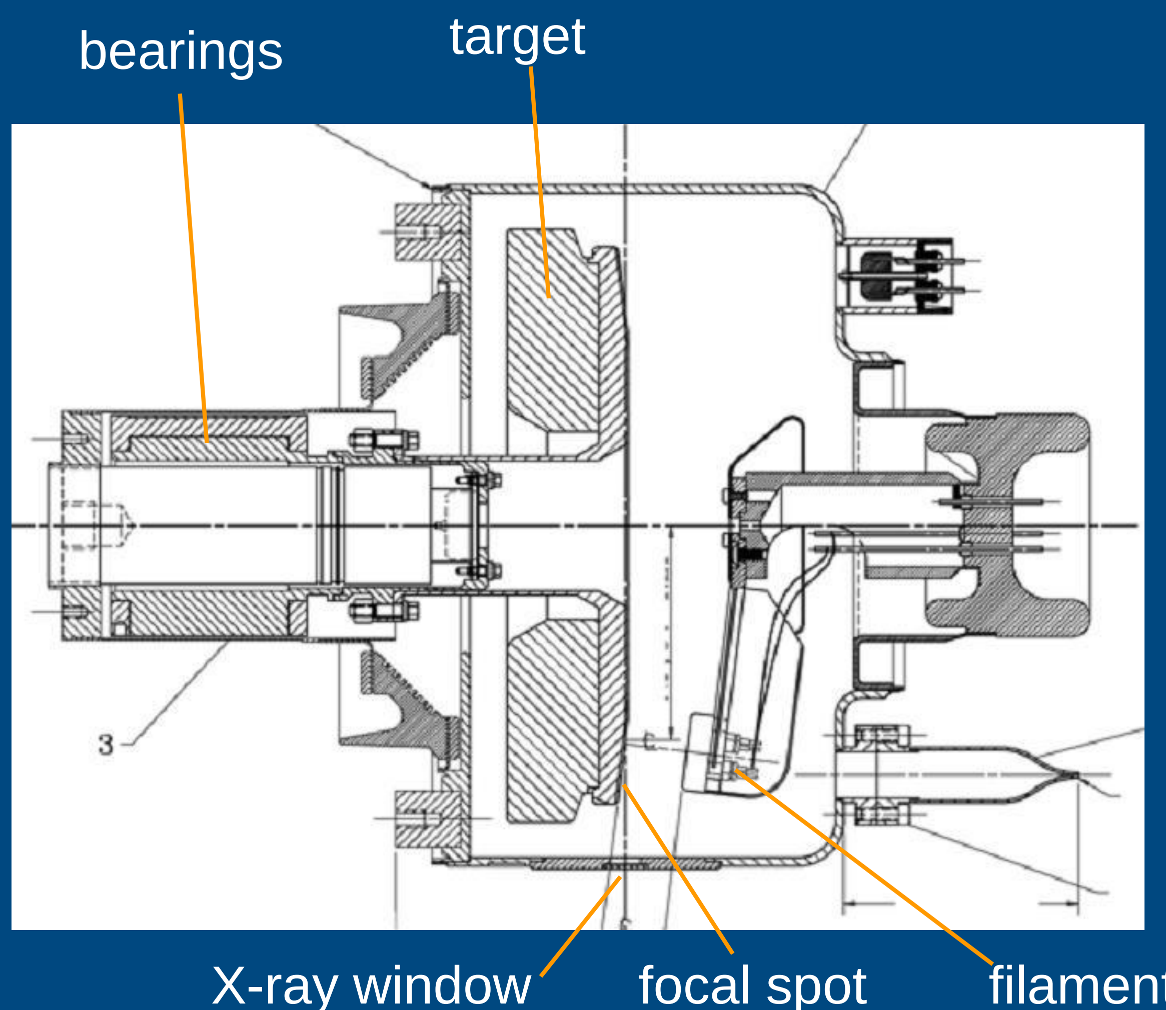
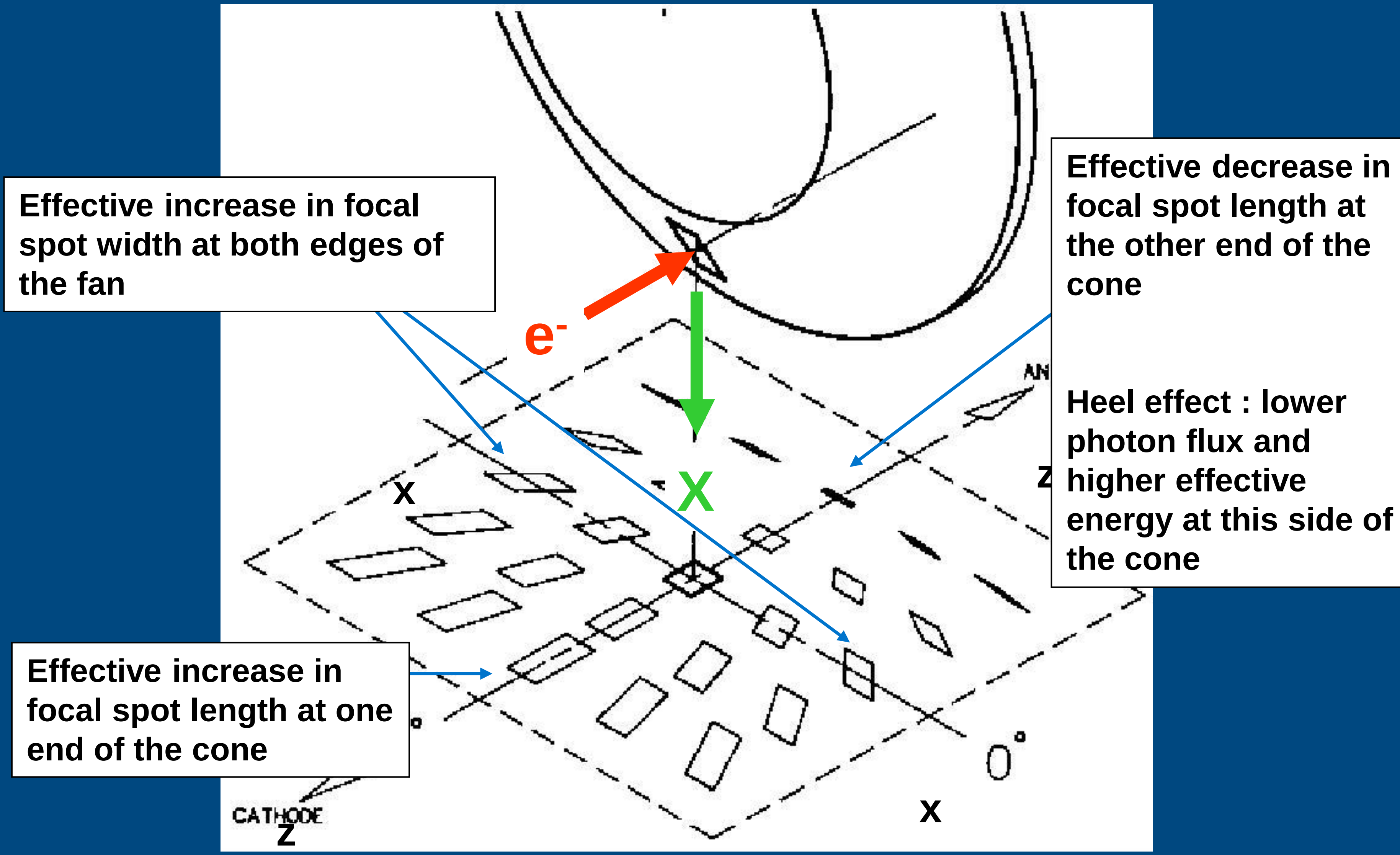




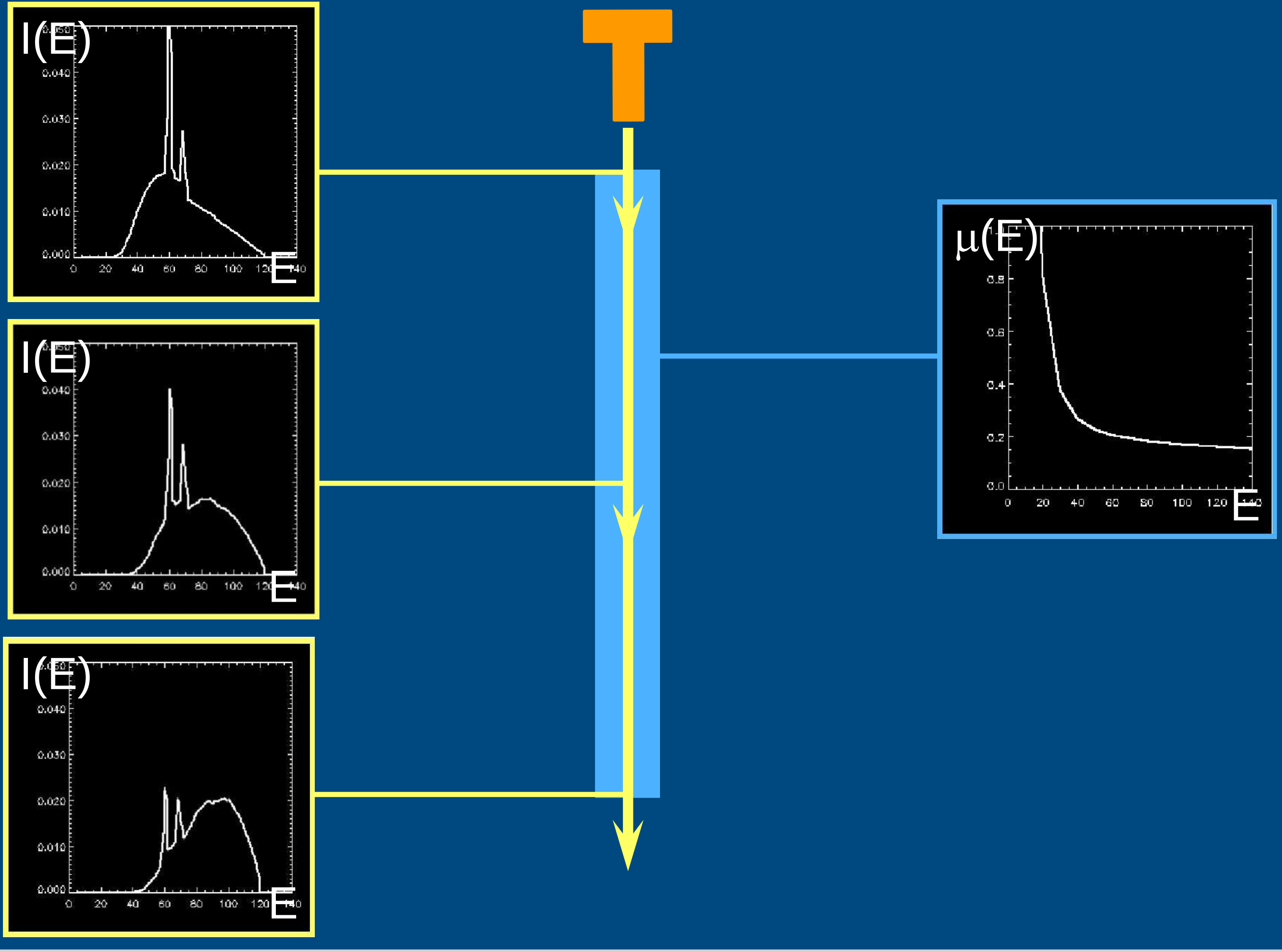
Courtesy of Bruno De Man, GE Global Research
< Courtesy of Brian Lounsberry (GE Healthcare) >

Apparent focal spot size



Courtesy of Bruno De Man, GE Global Research
< Courtesy of Brian Lounsberry (GE Healthcare) >

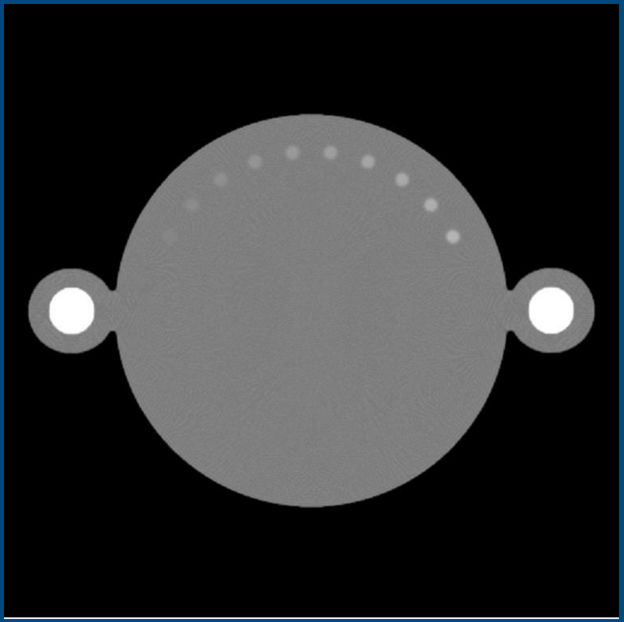
Beam hardening

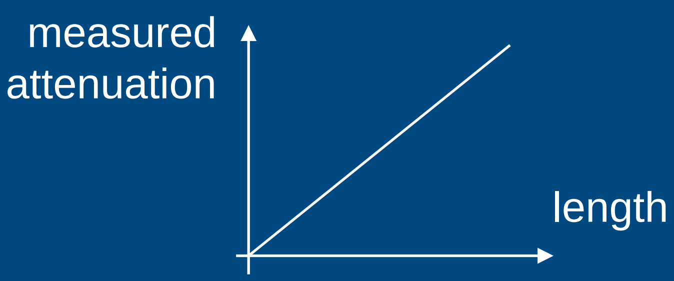


Courtesy of Bruno De Man, GE Global Research

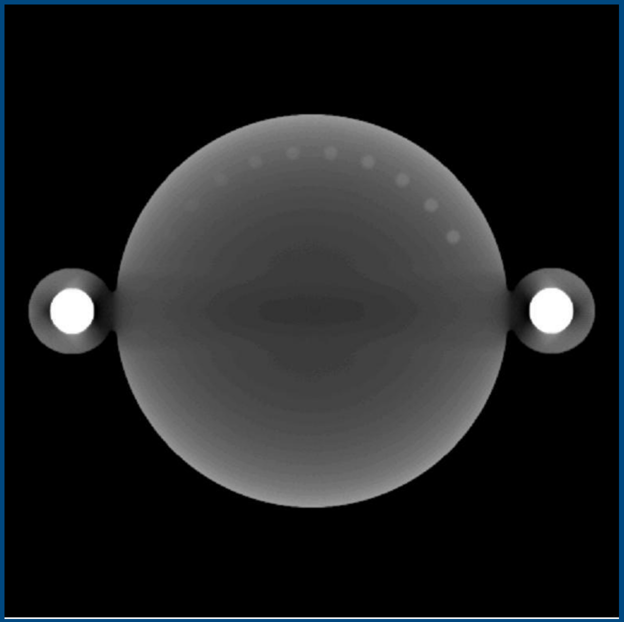
Beam hardening

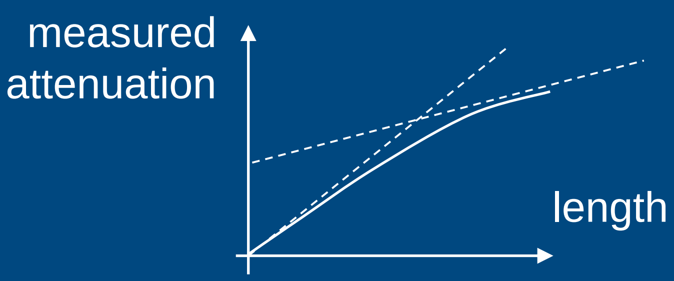
Monochromatic





Polychromatic





Courtesy of Bruno De Man, GE Global Research

X-ray detectors

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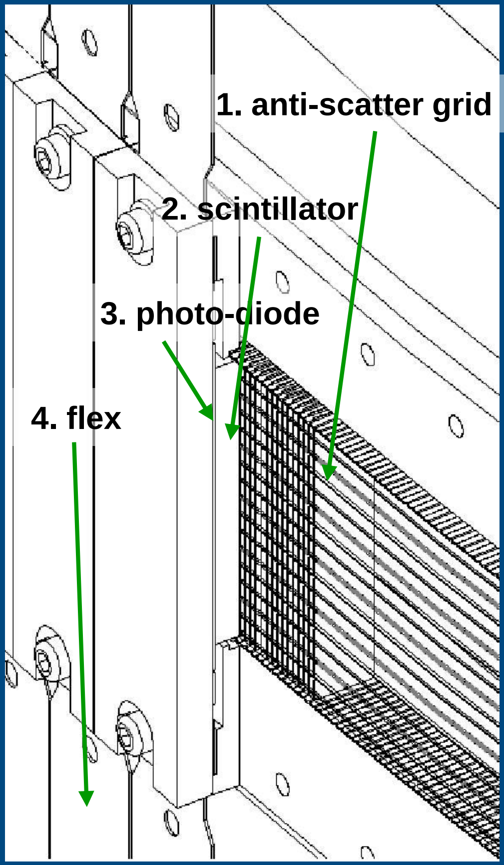
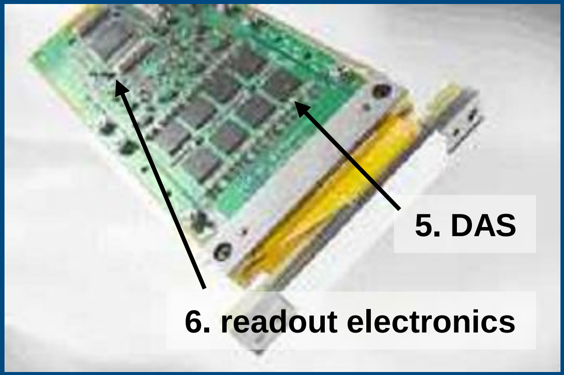
Lightspeed 16 (2002)



Lightspeed 16 (2002)

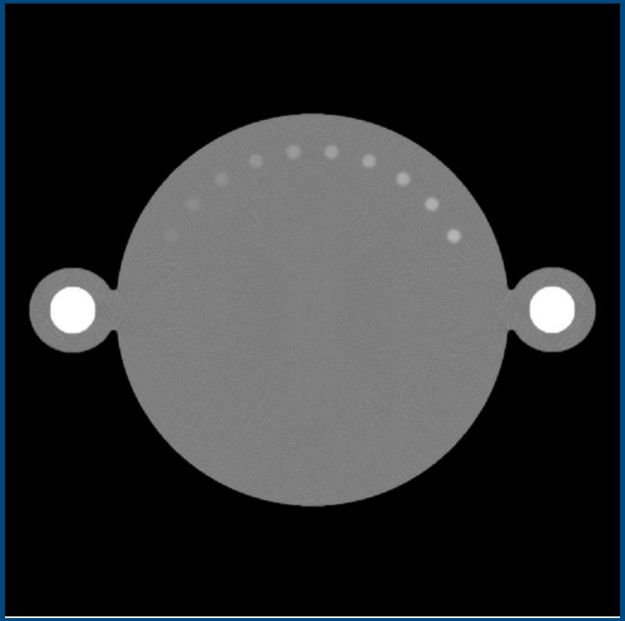


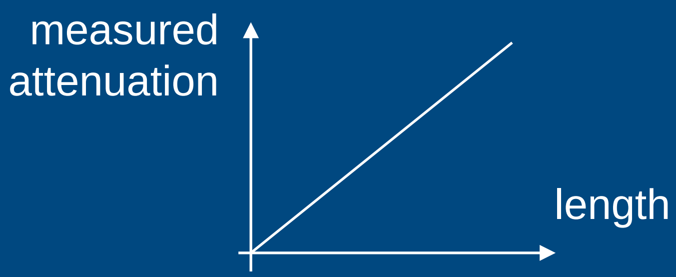
Lightspeed VCT (2004)

Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

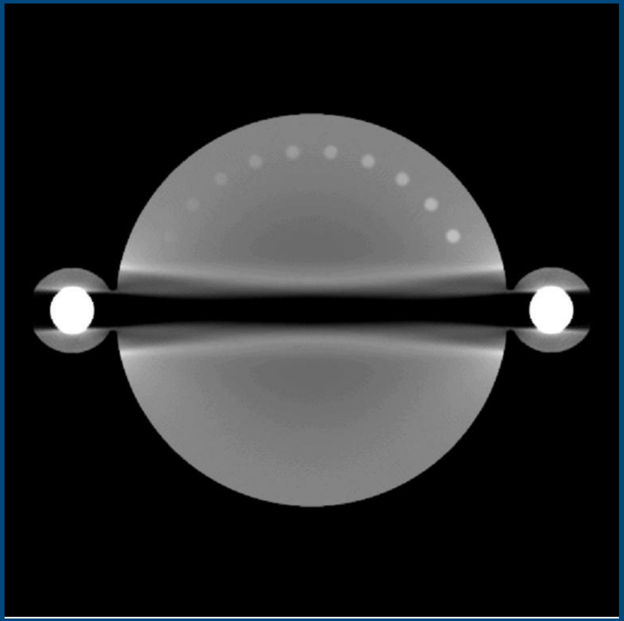
Scatter

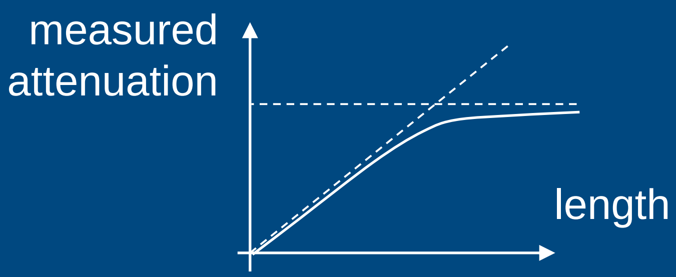
Without scatter





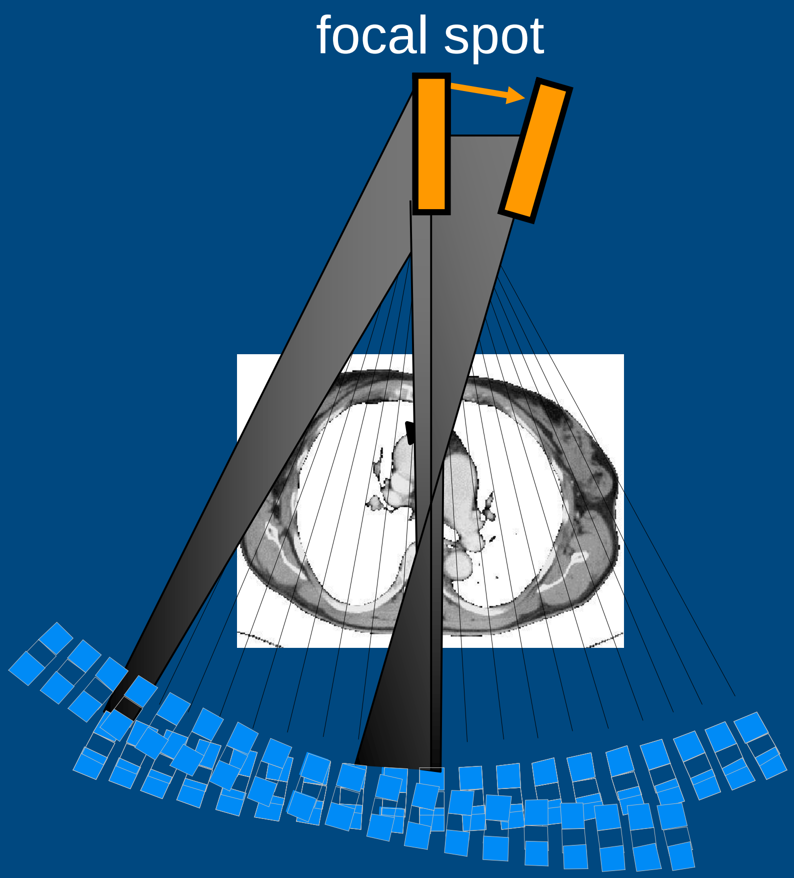
With scatter





Courtesy of Bruno De Man, GE Global Research

Spatial resolution



<u>Increase</u> spatial resolution by :
-smaller detector
-smaller focal spot
-smaller detector cross-talk
-comb colimator (dose penalty!)

<u>Uniform</u> spatial resolution by :
-shorter focal spot
-higher number of views

<u>Boost</u> spatial resolution and reduce <u>aliasing artifacts</u> by :
-improved interpolation / recon
-boost kernels / deconvolution
-quarter detector offset
-focal spot wobble (FFS)

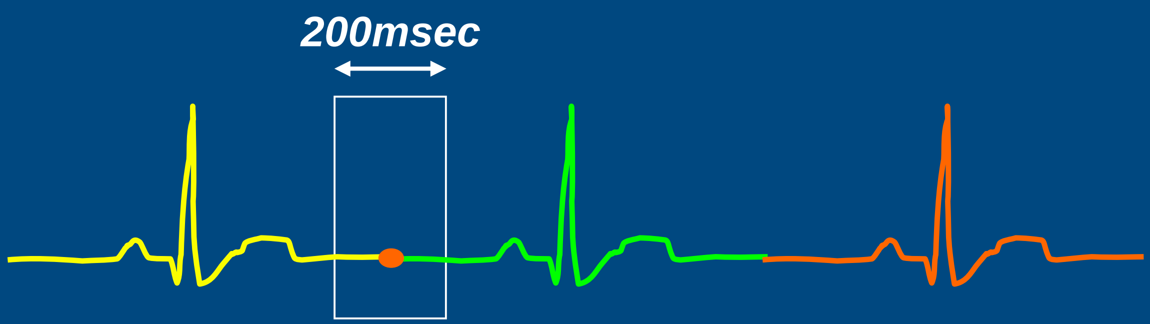
Courtesy of Bruno De Man, GE Global Research

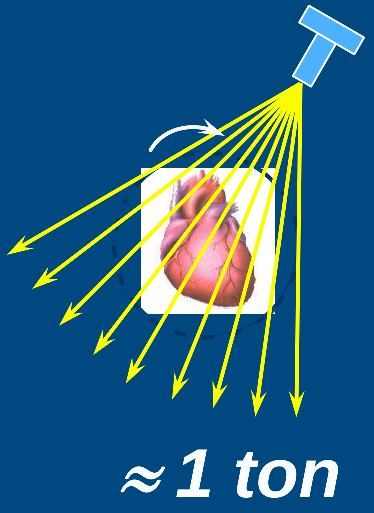
Temporal resolution (cardiac CT)

rotation period : 0.35s

full-scan = 360° → half-scan ≈ 230°

temporal resolution : 200ms

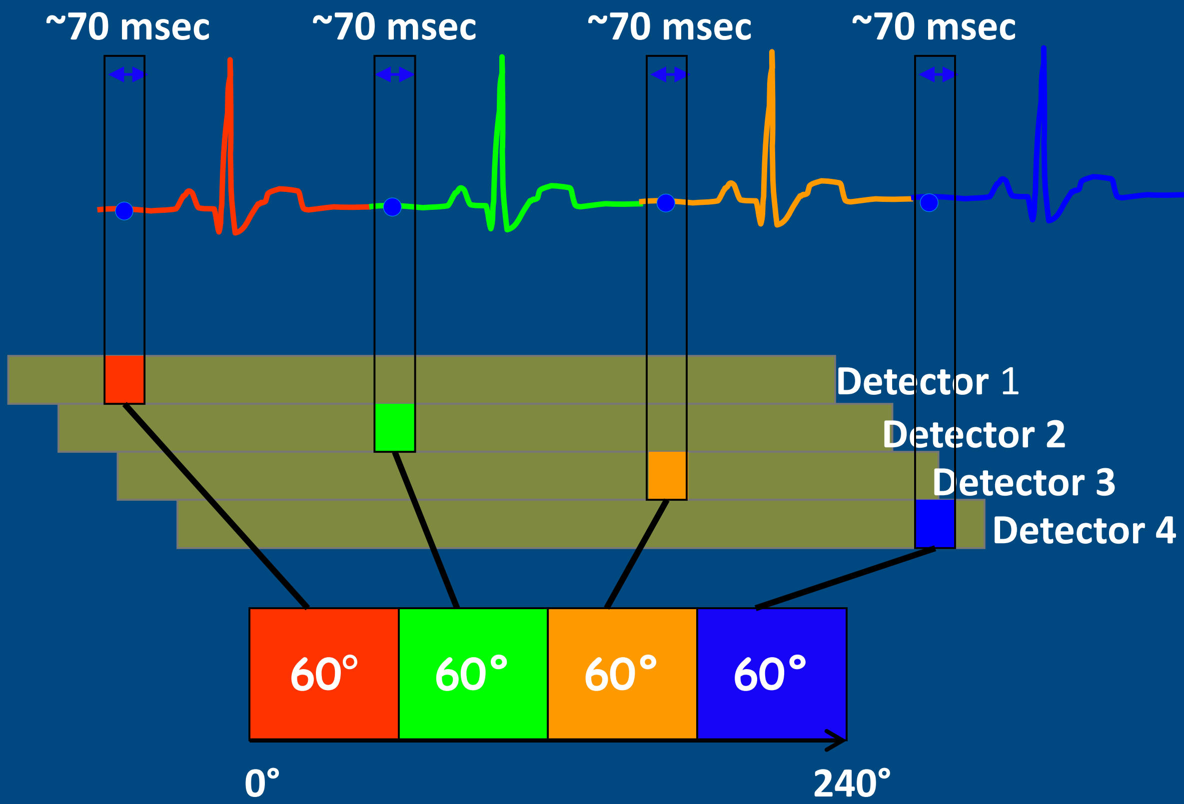


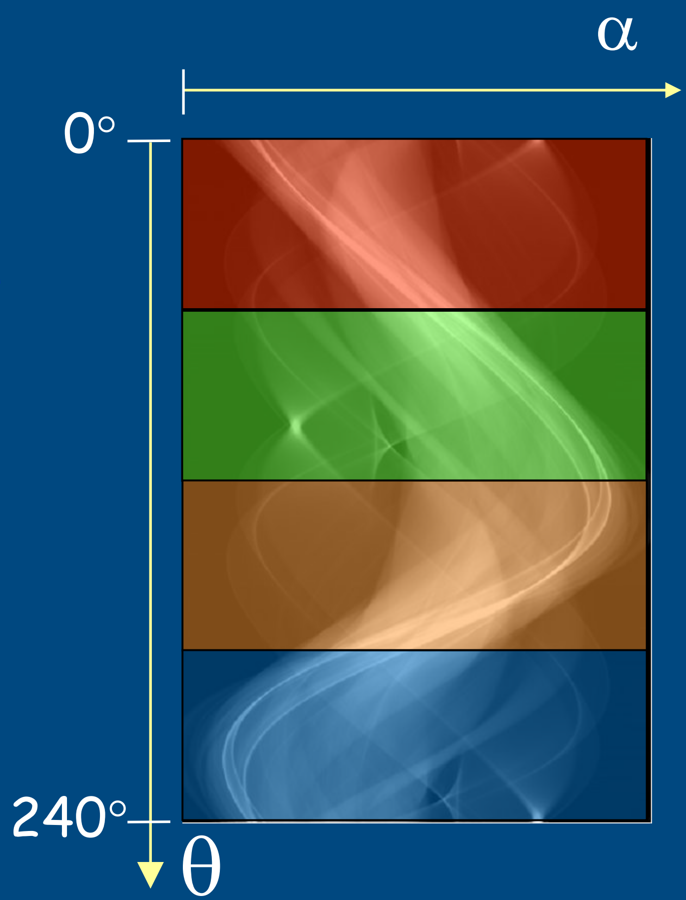


Tai sao k 180 mà 230? Utilise
pas parallel mais connique (hình nón)

Courtesy of Bruno De Man, GE Global Research

Cardiac CT: multi-sector recon

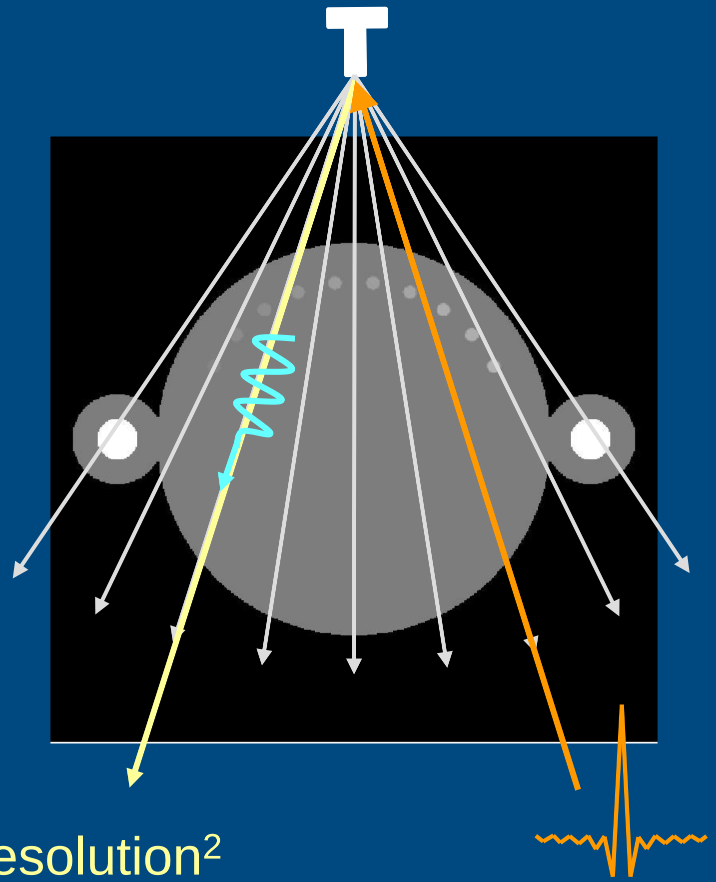




Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

Image noise

Sources :
- quantum noise
  (X-rays)
- electronic noise
  (detector)



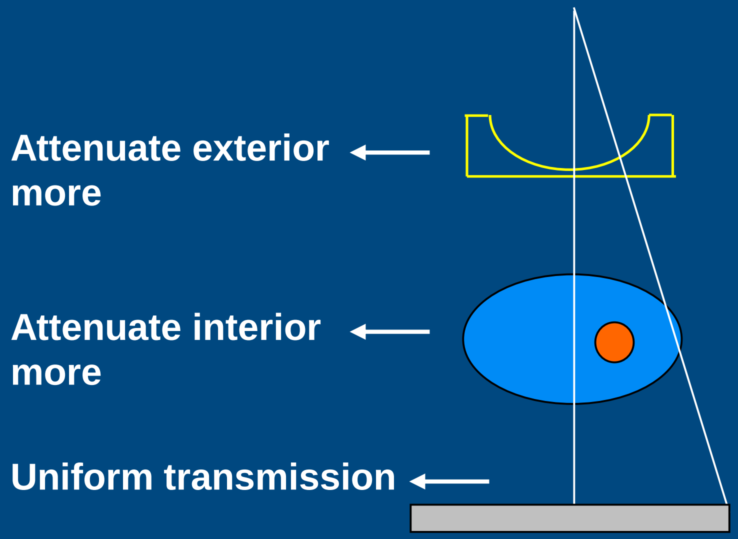
$$\sigma_p \sim \exp(p/2) \,/\, \mathrm{sqrt}(I_0) \cdot \mathrm{resolution}^2$$

Courtesy of Bruno De Man, GE Global Research

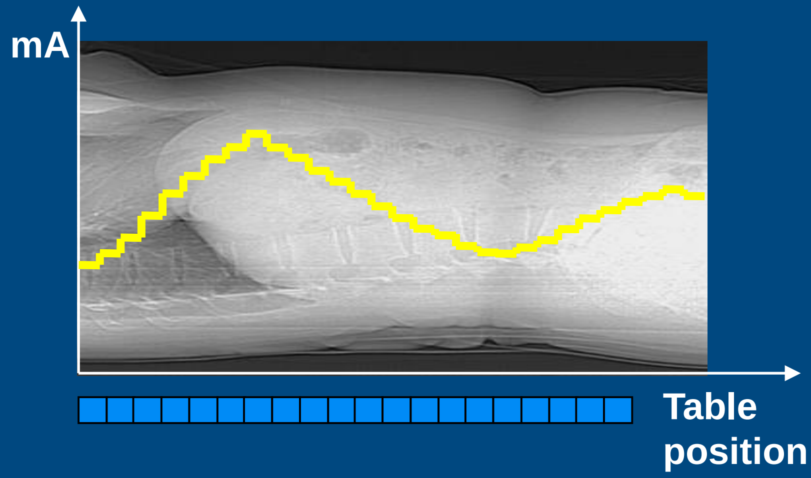
filtre papillon pas papillon

Optimizing dose-efficiency

Bow-tie filter



Tube current modulation (auto-mA)



Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

Part I : the very very basics

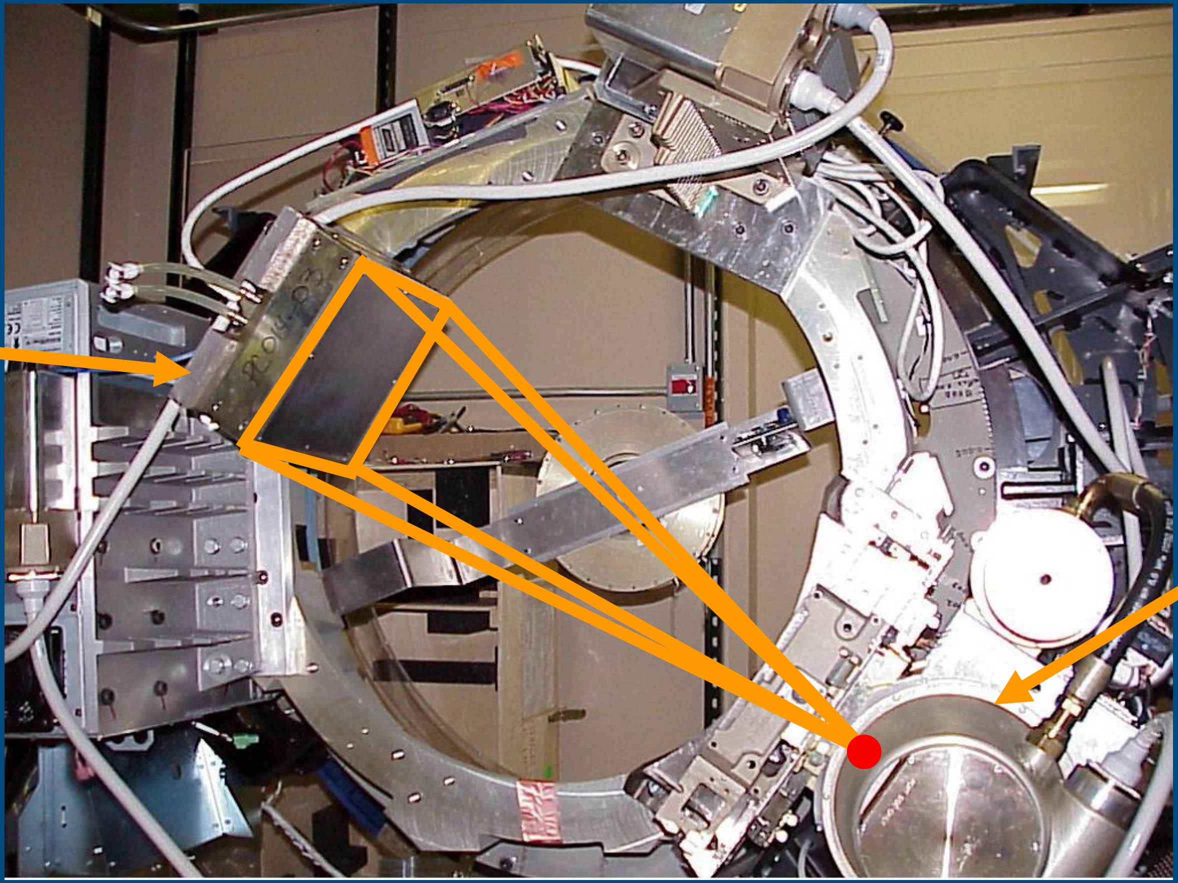
Part II : components and physics

Part III : recent advances in CT

Part IV : some images

Flat-panel hi-res VCT

flat-panel detector : 1024x360 channels



x-ray tube

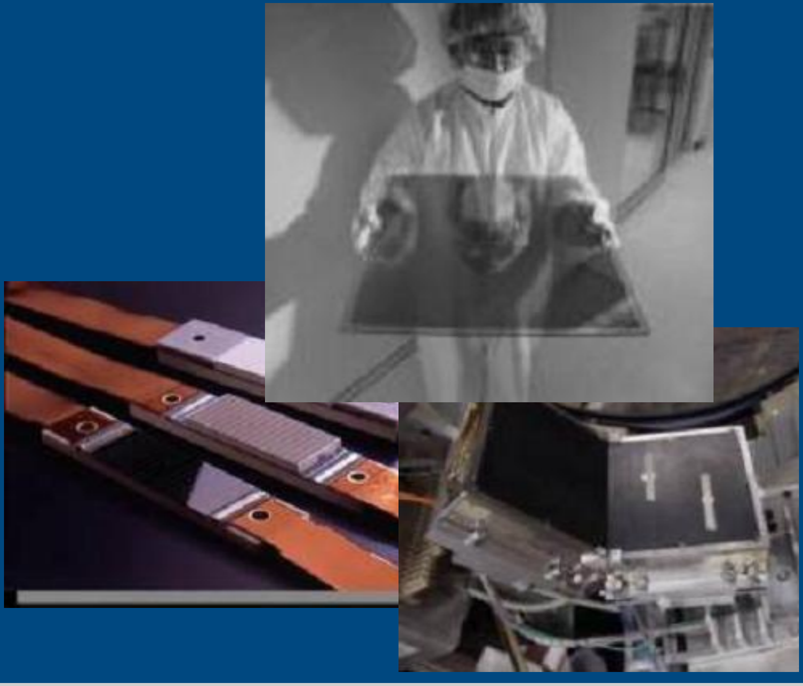
Courtesy of Bruno De Man, GE Global Research

<Courtesy of W. Ross (GE Global Research)>

Flat-panel hi-res VCT

2001	2002	2003	2004

• 1-panel sys
• Hi-res
• Limited FOV
• Algorithm Investigatio n
	• 2-panel sys
	• Hi-res
	• Extended FOV
	• Further Algorithm Investigation
		• 3 Units
		  • MD Anderson
		  • U Giessen
		  • Goettingen U
		• 500+ Studies
		• Apps Research
			• 4-panel sys
			• Large FOV

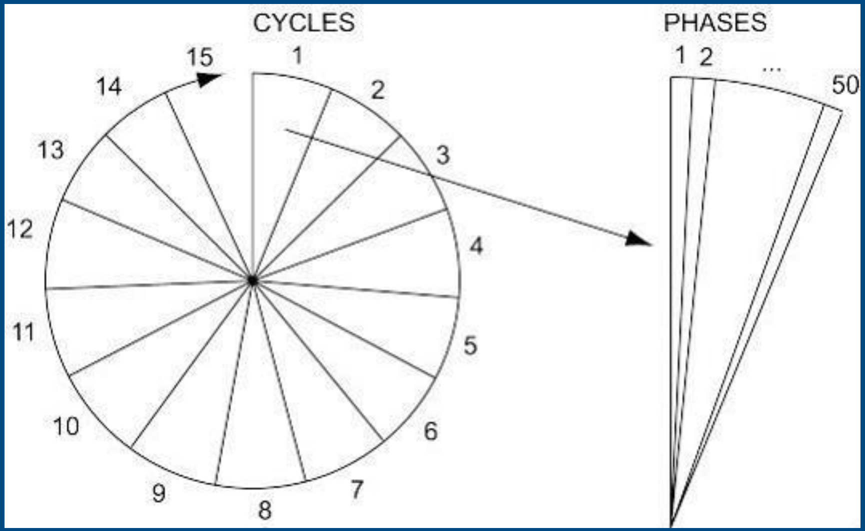


Courtesy of Bruno De Man, GE Global Research

<Courtesy of W. Ross (GE Global Research)>

Slow-gantry cardiac CT

- 1 full rotation
- 18s acquisition
- 1500 views
- 180bpm (rabbit heart)
- 1 heart cycle = 1/3sec
- 54 heart cycles
- 28 phases / cycle
- temp.res. ~ 12ms

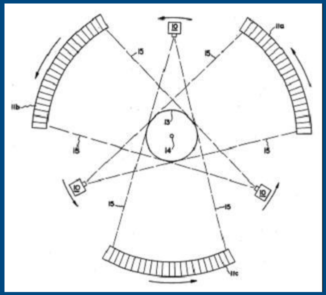


Courtesy of Bruno De Man, GE Global Research

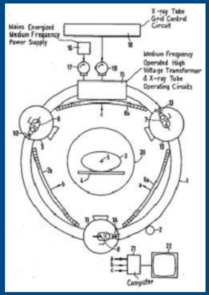
Slow-gantry cardiac CT

Courtesy of Bruno De Man, GE Global Research

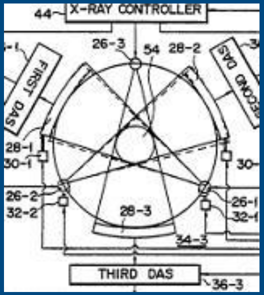
Multi-tube multi-detector CT



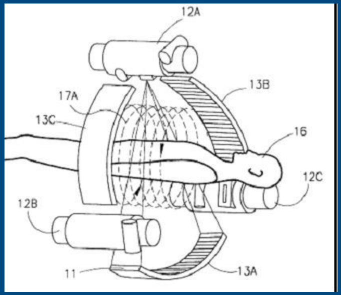
GE 1980



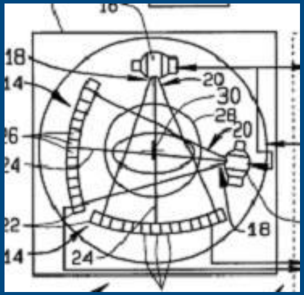
Siemens 1983



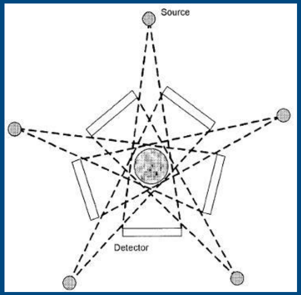
Toshiba 1991



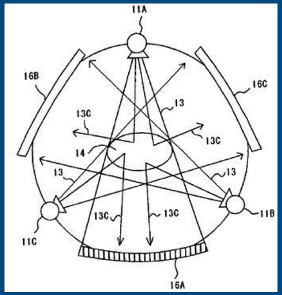
Picker 1999



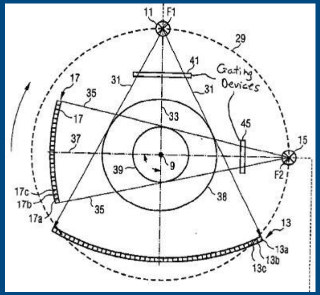
GE 2002



Wang 2002

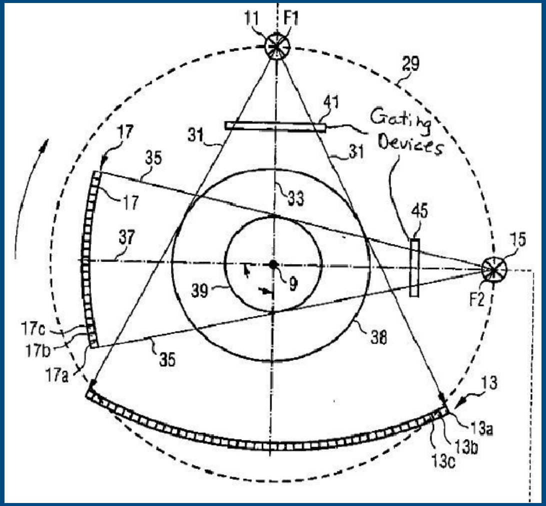


Toshiba 2004



Siemens 2004

Multi-tube multi-detector CT



Benefit :
- 120° half-scan (i.s.o. 210°)

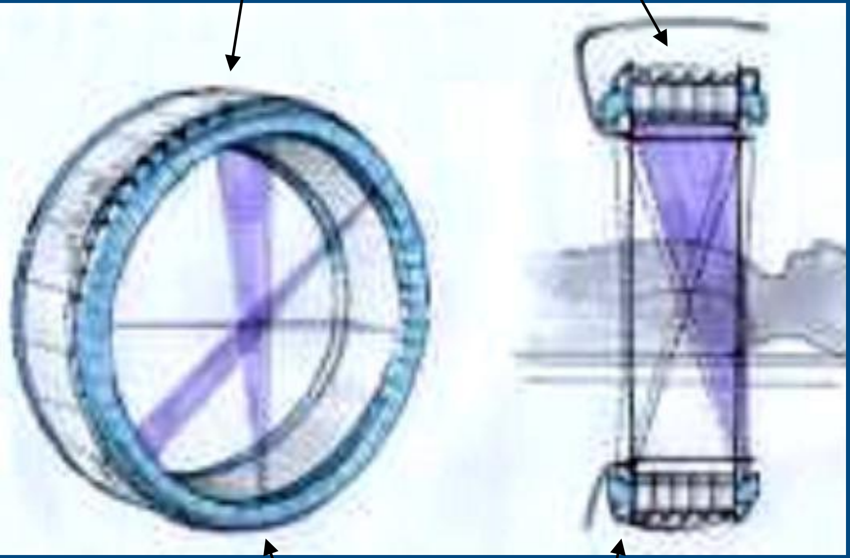
Challenges :
- Cross-scatter
- Size / weight / cost

	2 x 50kW tube 2 x 20mm detector	1 x 100kW tube 1 x 40mm detector
Coverage	20mm	40mm
Temporal res	120° or 210°	210°
Power	50kW or 100kW	100kW
Dual kVp	50kW @ 1 rot.	100kW @ 2 rot.
Scatter	↑↑↑	=

Courtesy of Bruno De Man, GE Global Research

Stationary CT (a.k.a. sCT)

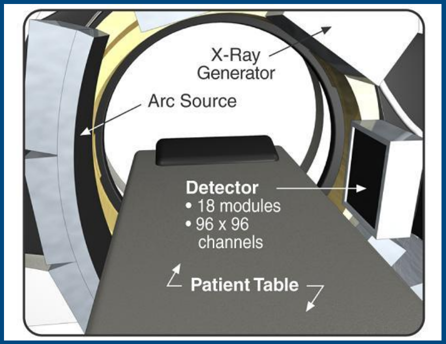
360° detector ring



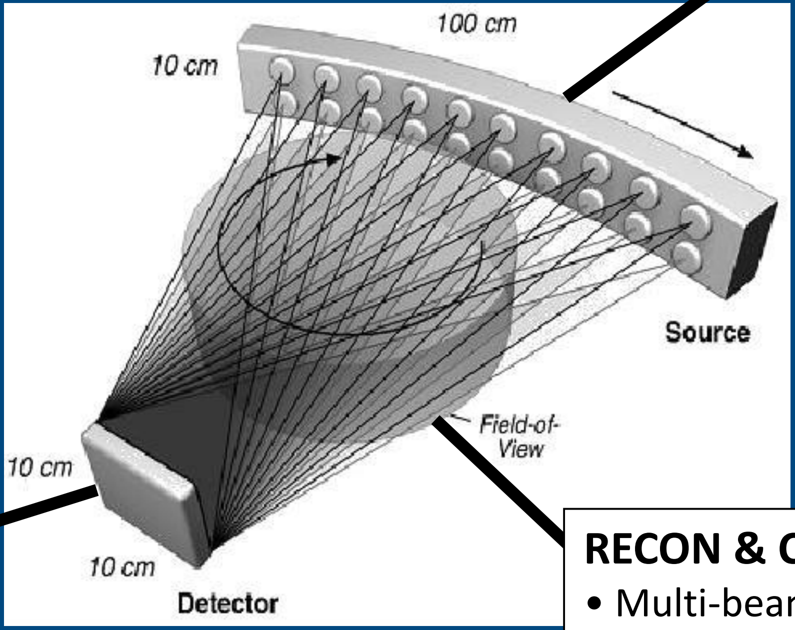
360° distributed source ring

Courtesy of Bruno De Man, GE Global Research

Multi-source inverse-geometry CT



X-RAY SOURCE
- 1 vacuum vessel
- multiple spots in-plane
- multiple spots in z
- solid-state e^--emitters
- fast sequencing
- small fan-angles
- mA modulation



DETECTOR
- small flat-panel
- high frame rate
- photon-counting
- small cell size
- no scatter grid

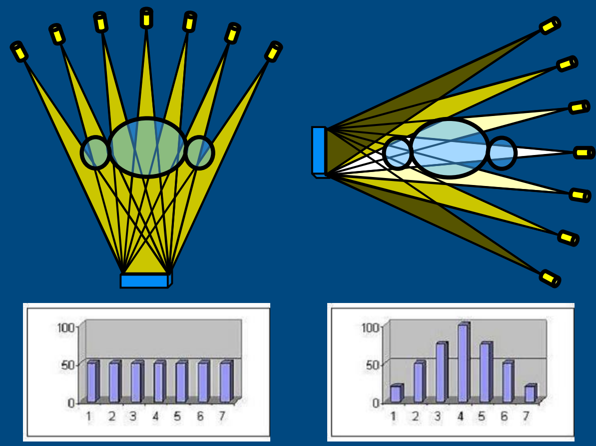
RECON & CAL
- Multi-beam rebinning
- Multi-axial cone-beam recon
- Low-dose statistical recon
- Multi-beam calibration

Courtesy of Bruno De Man, GE Global Research

Virtual bowtie

Conventional bowtie

- absorbs large x-ray fraction
- shape fixed

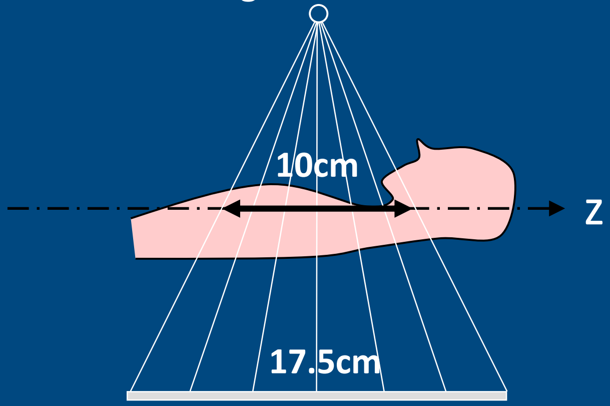


- reduced dose @ fixed noise
- reduced noise @ fixed dose
- improved (?) noise structure

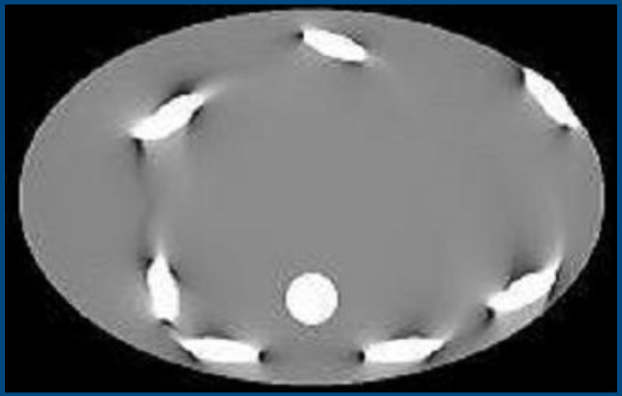
Courtesy of Bruno De Man, GE Global Research

Volumetric coverage & cone-beam artifacts

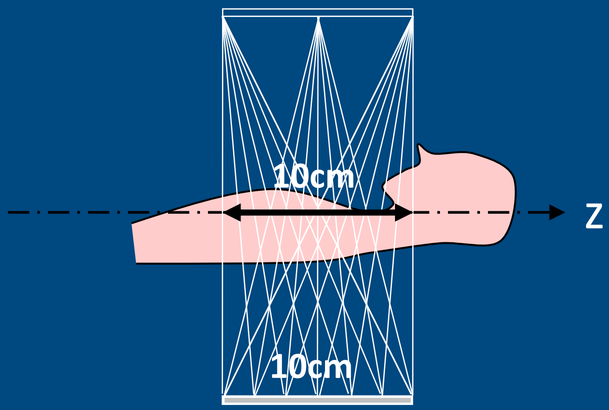
3rd generation CT



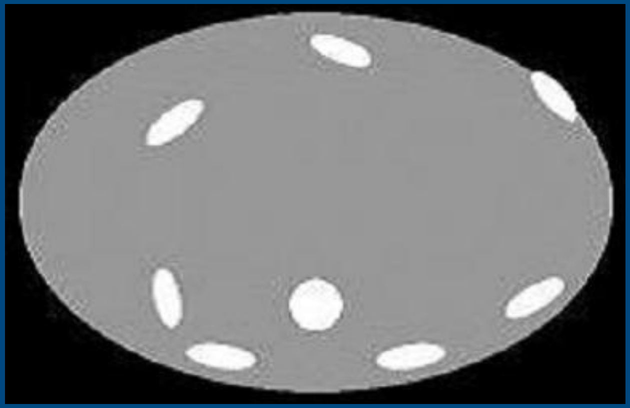
10cm - 3rd generation CT



Multi-source CT



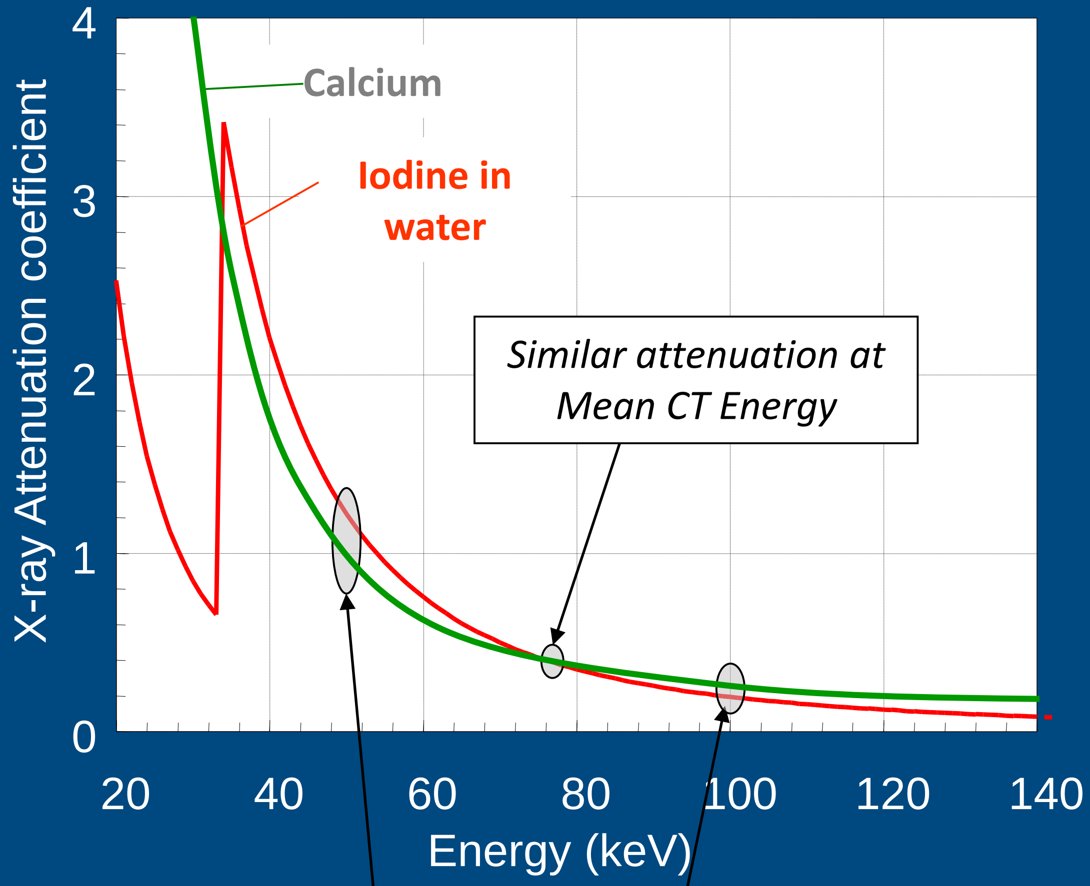
10cm - Multi-source CT



Courtesy of Bruno De Man, GE Global Research

Spectral CT

- *Photon-coun* <This slide may contain GE Proprietary information>
- *Dual kVp (short-term)*
- *Dual layer (worst --> Philips)*



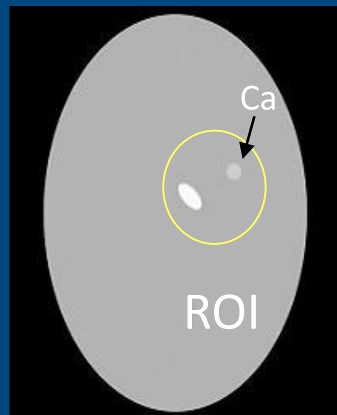
Differentiate materials through the energy dependence of the attenuation curve

Courtesy of Bruno De Man, GE Global Research

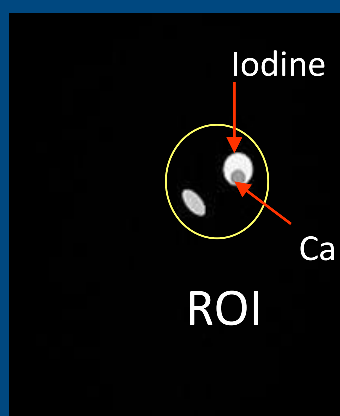
<Courtesy of J. LeBlanc (GE Global Research)>

Dual kVp CT

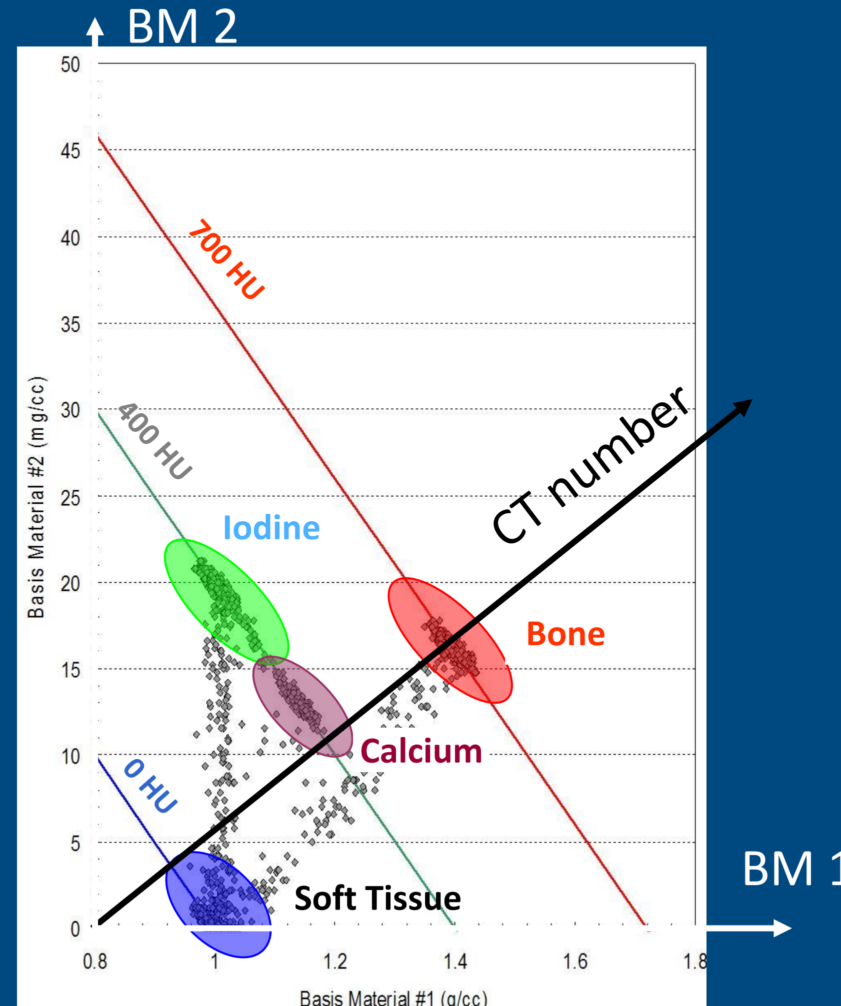
“Soft Tissue” Image
(“Basis Material #1”)



Dual kVp acquisition and reconstruction



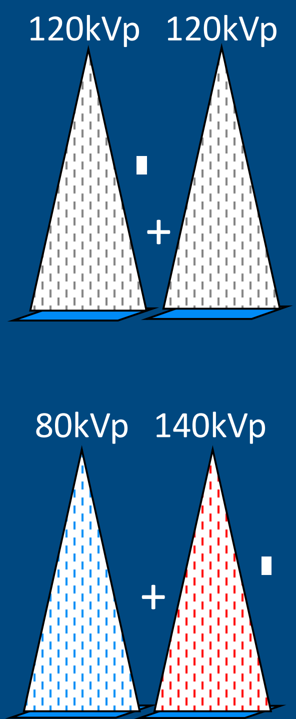
“Iodine” Image
(“Basis Material #2”)

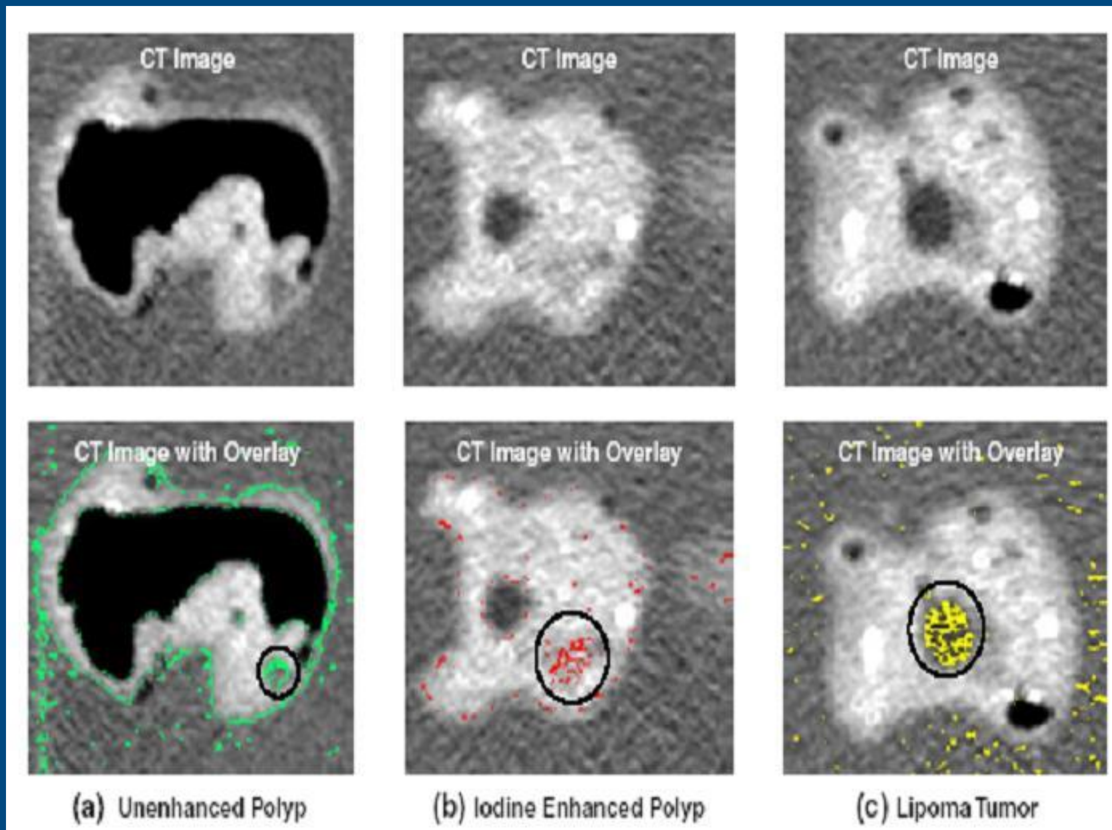


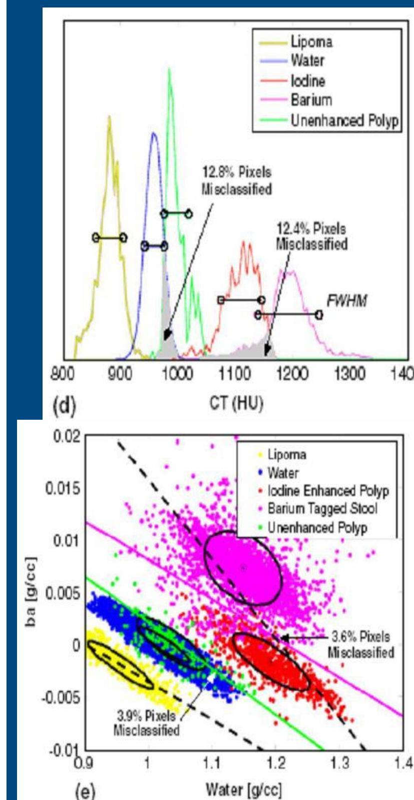
Courtesy of Bruno De Man, GE Global Research
<Courtesy of J. LeBlanc (GE Global Research)>

Dual kVp CT : virtual colonoscopy

<This slide may contain GE Proprietary information>







Part I : the very very basics

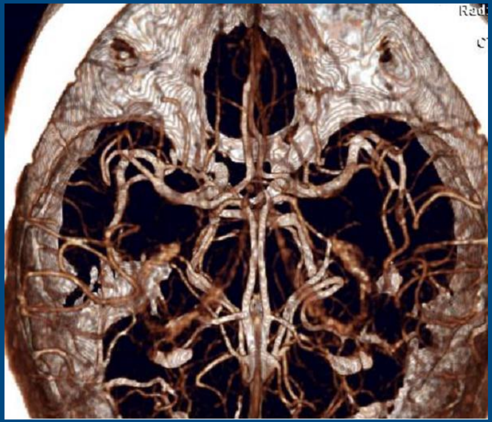
Part II : components and physics

Part III : recent advances in CT

Part IV : some images

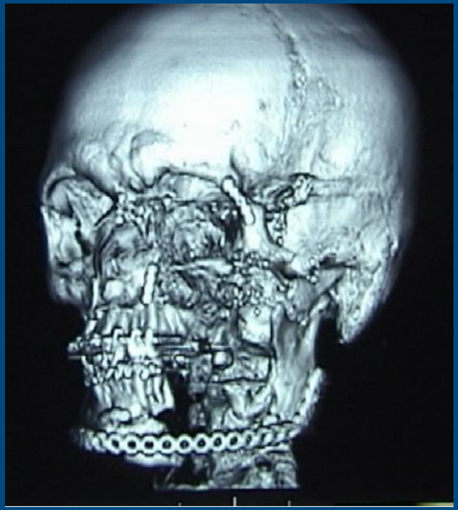
Clinical applications : head

Routine head
Perfusion (stroke)



Circle of Willis

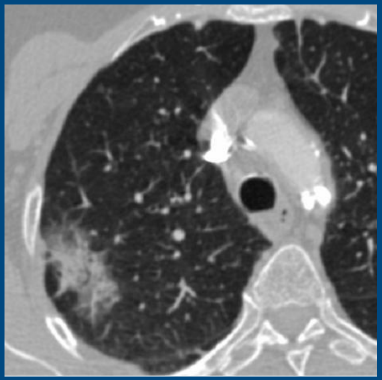
Sinuses

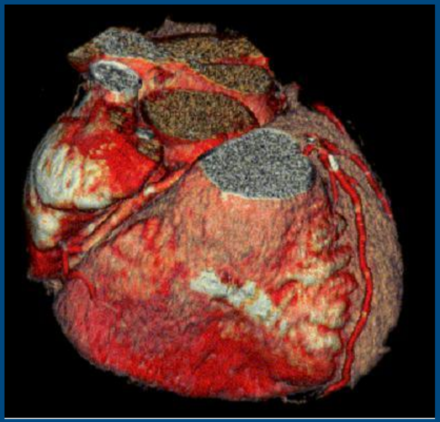


Trauma
temporal bone
Facial bones

Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

Clinical applications : oncology & cardiac

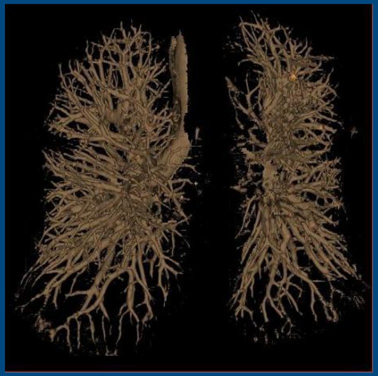


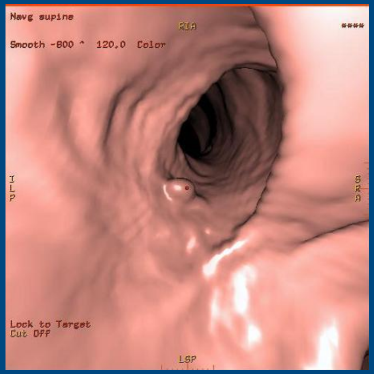


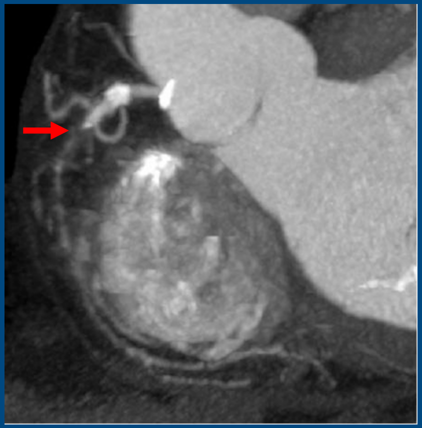
Lung nodules
Diffuse lung disease

CT Colonography for
Cancer detection

Stenosis / re-stenosis
Calcium scoring



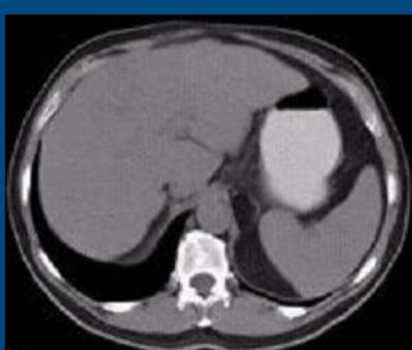




Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

Clinical applications : abdominal

- Dual or tri phase liver
- Pancreas
- Kidney studies
- Adrenals
- Pelvis
- Trauma
- Advanced Apps: Perfusion, colonography



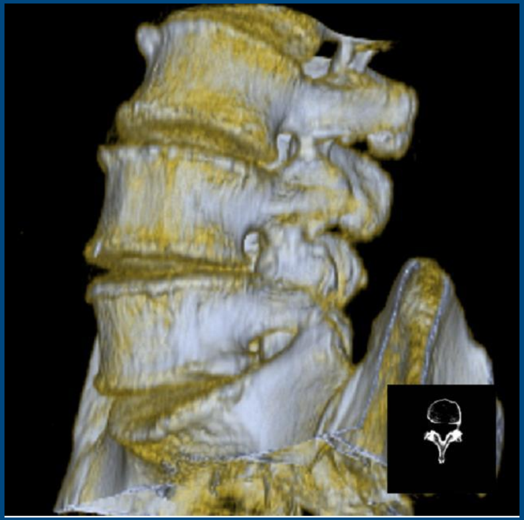
Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

Clinical applications : orthopedics

Knees

Extremities

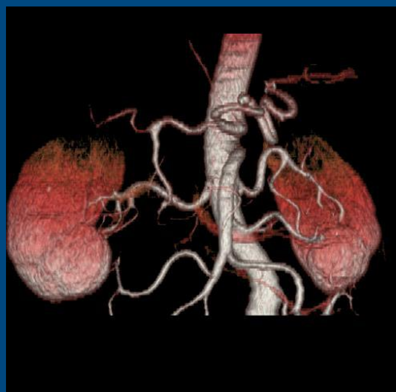
Spine



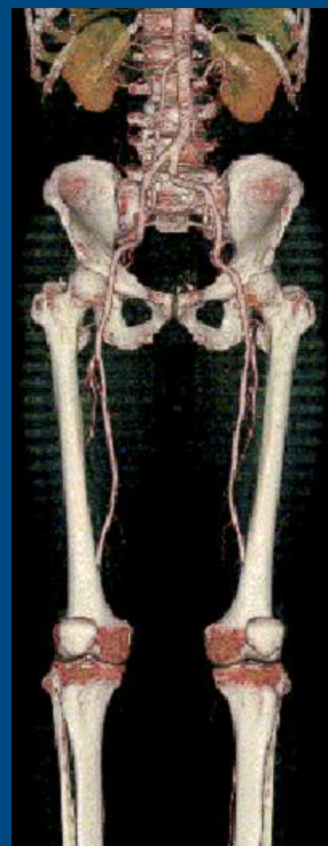
Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

Clinical applications : angiography

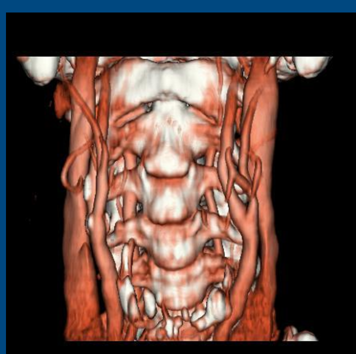
Renal agnio



Lower run offs

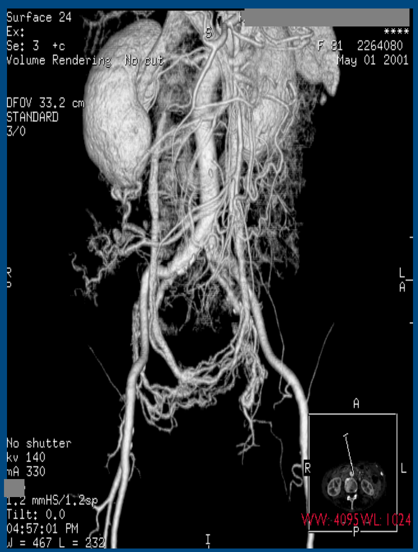


Carotids



Abdominal aorta
Stent sizing

MIP image



Surface rendering

Courtesy of Bruno De Man, GE Global Research
< Courtesy of GE Healthcare >

The End