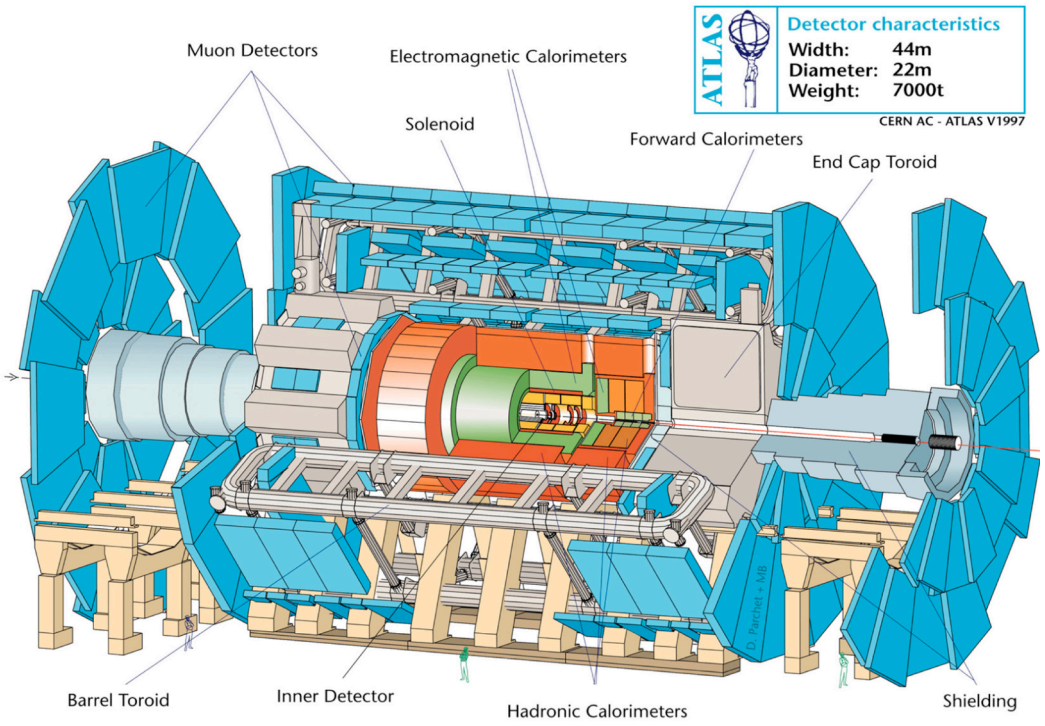
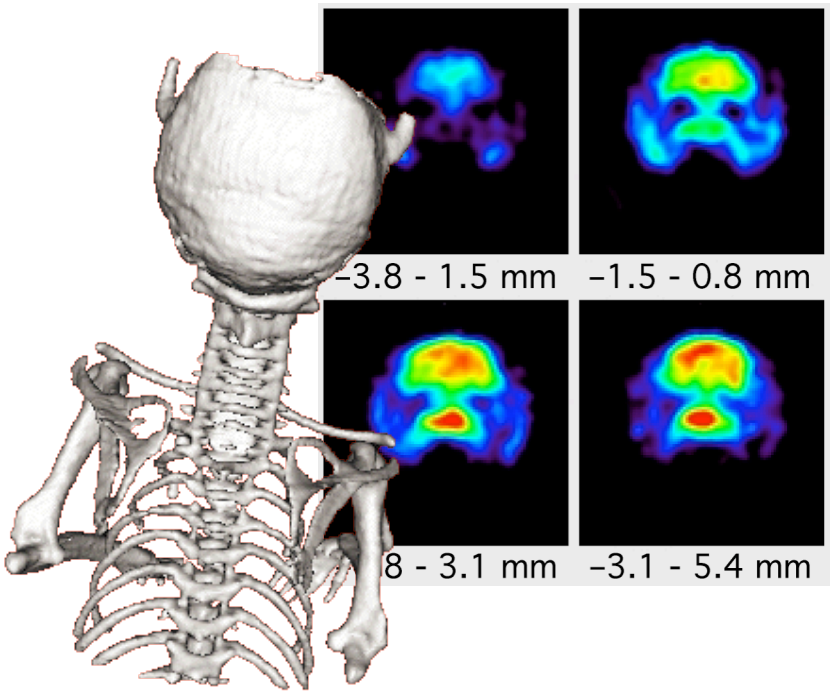
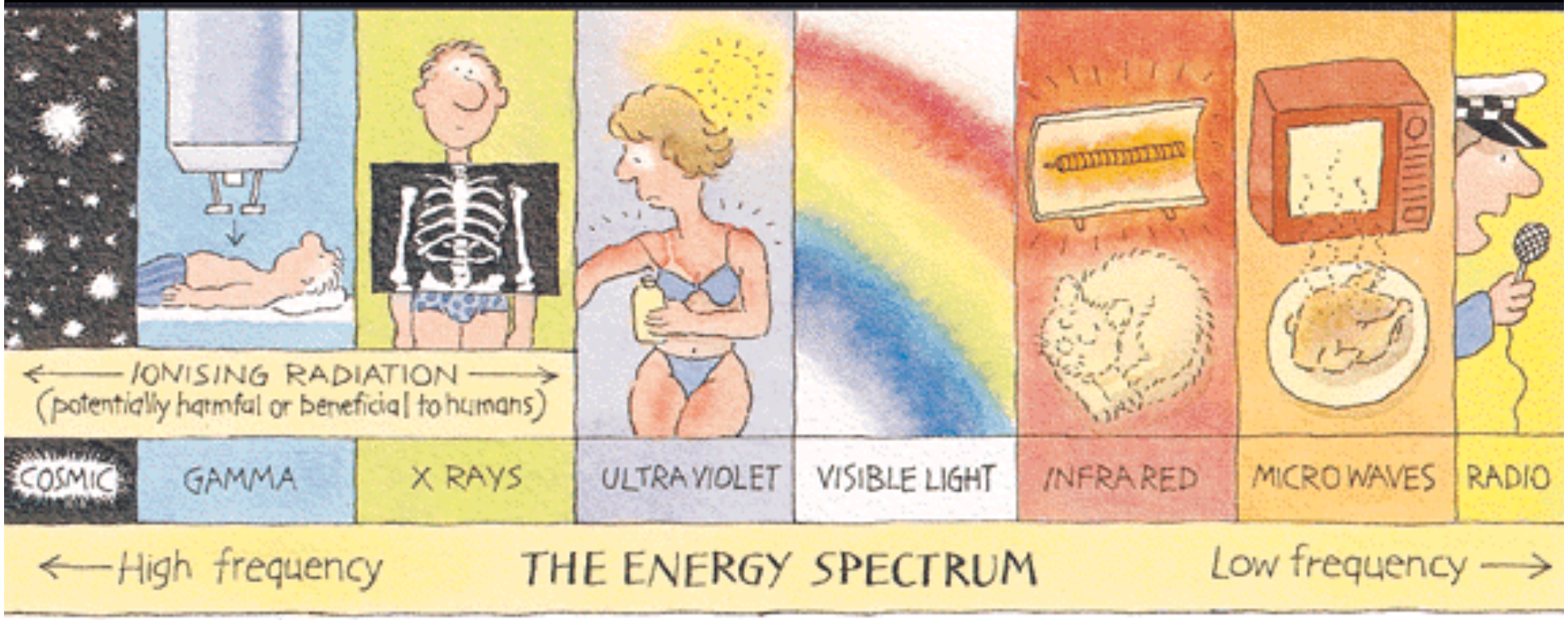
Pr Christian MOREL

Le scanner X : le passage du noir et blanc à la couleur pour bientôt, grâce aux pixels hybrides

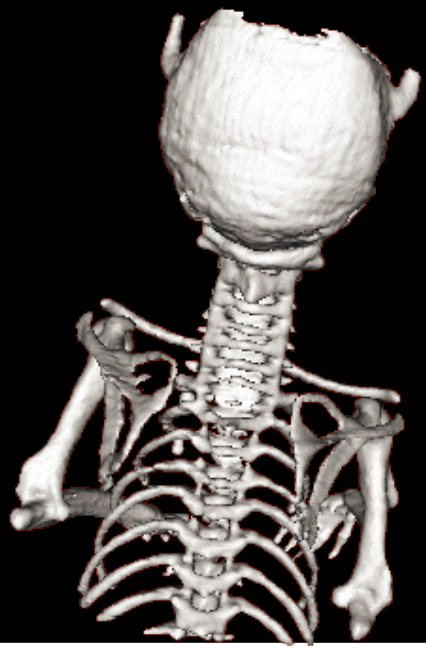




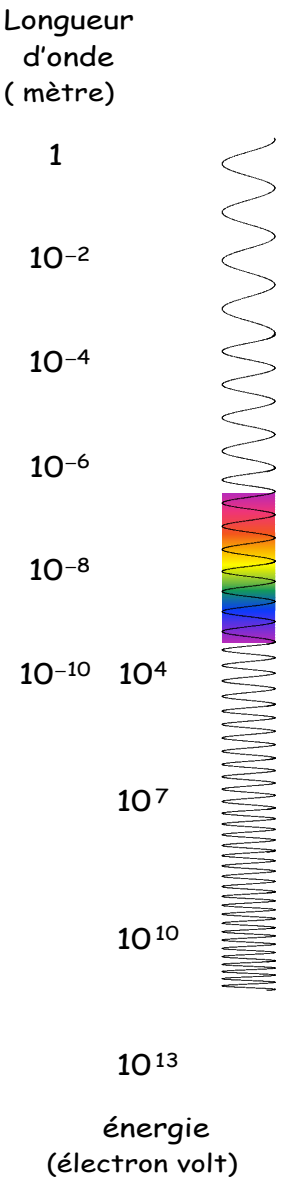
Le scanner X : le passage du noir et blanc à la couleur pour bientôt, grâce aux pixels hybrides

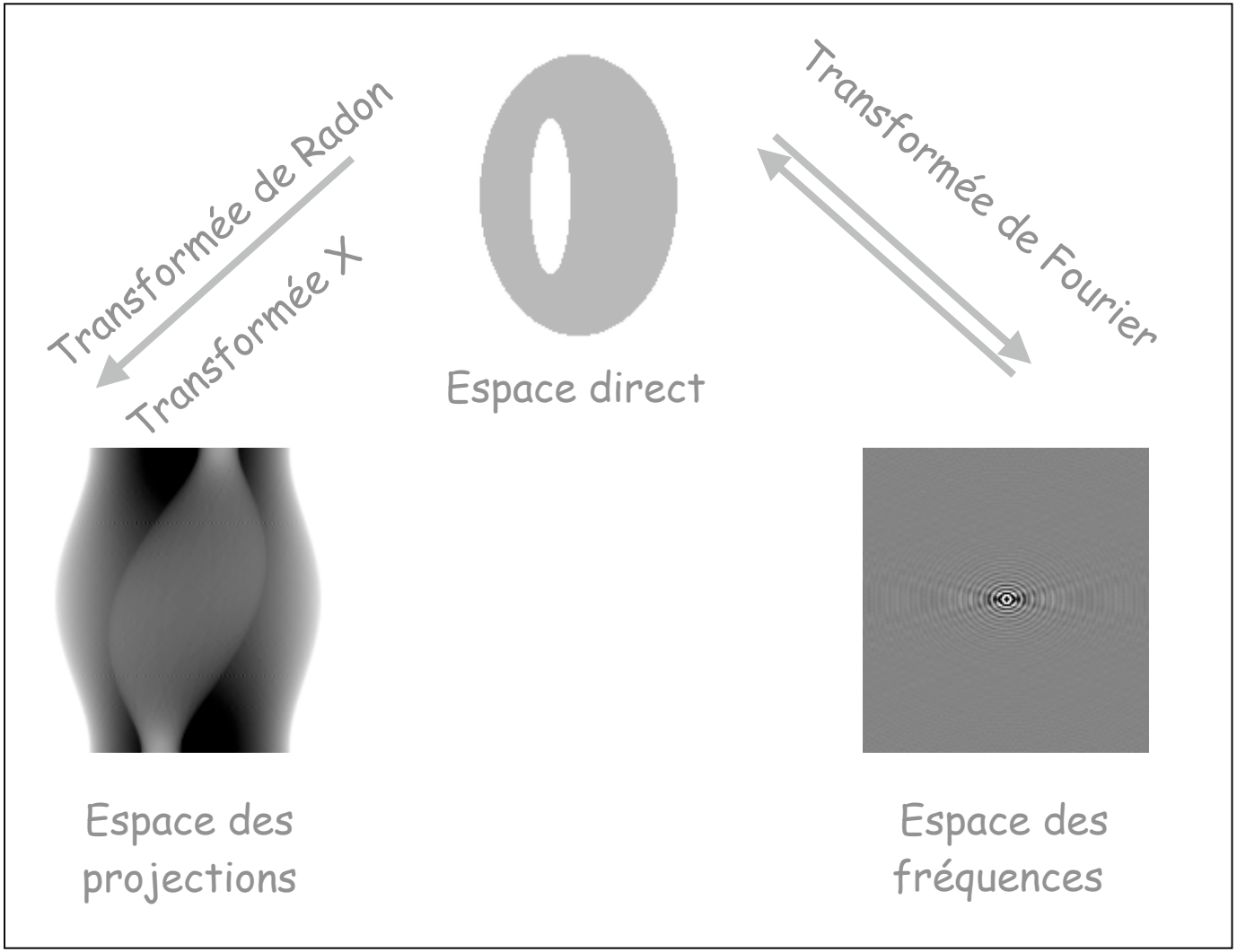


Le scanner X : le passage du noir et blanc à la couleur pour bientôt, grâce aux pixels hybrides



Principe de reconstruction tomographique

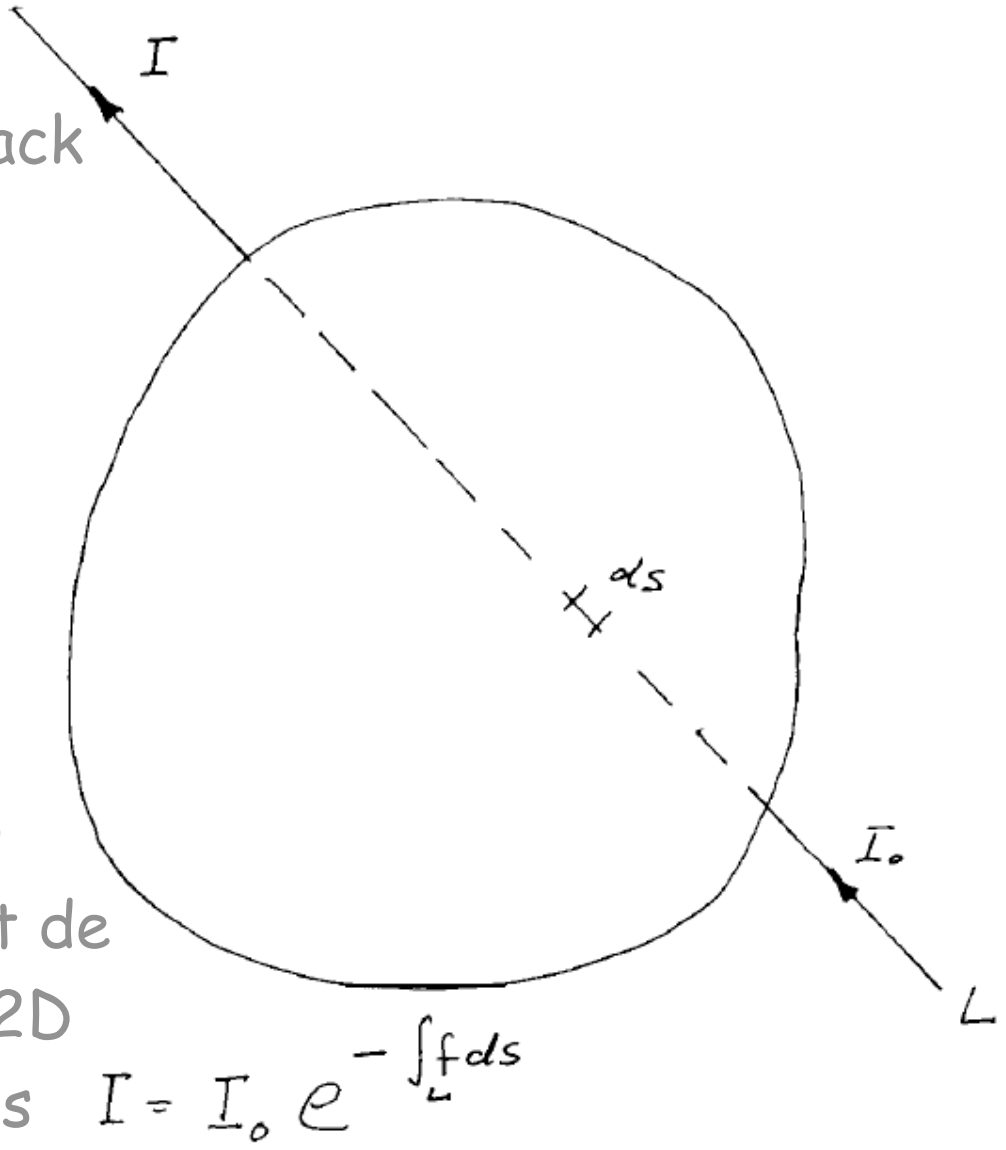




Reconstruction tomographique en 2D

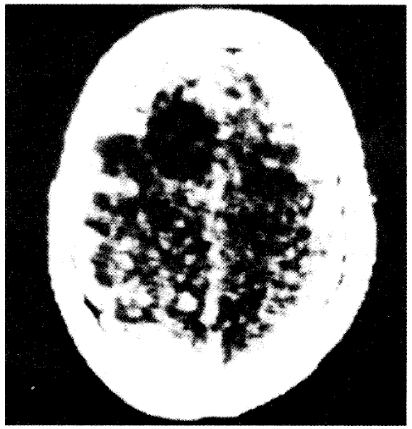
1963: Alan McLeod Cormack

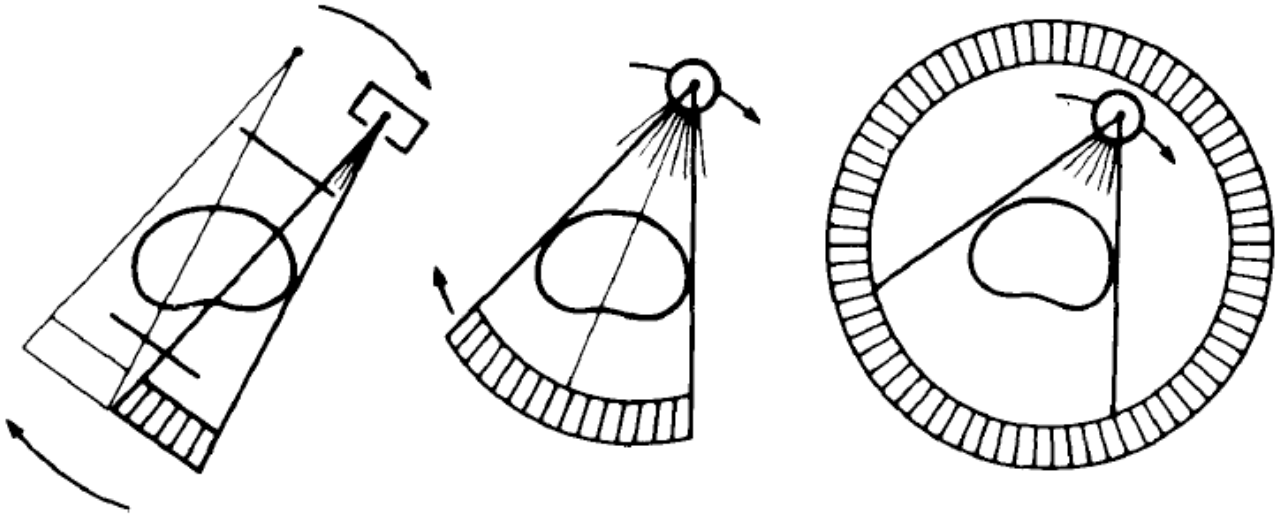
Redécouvre une solution mathématique publiée par Radon en 1917 permettant de reconstruire un objet en 2D à partir de ses projections



Tomodensitométrie (TDM)

1972: Godfrey N Hounsfiled



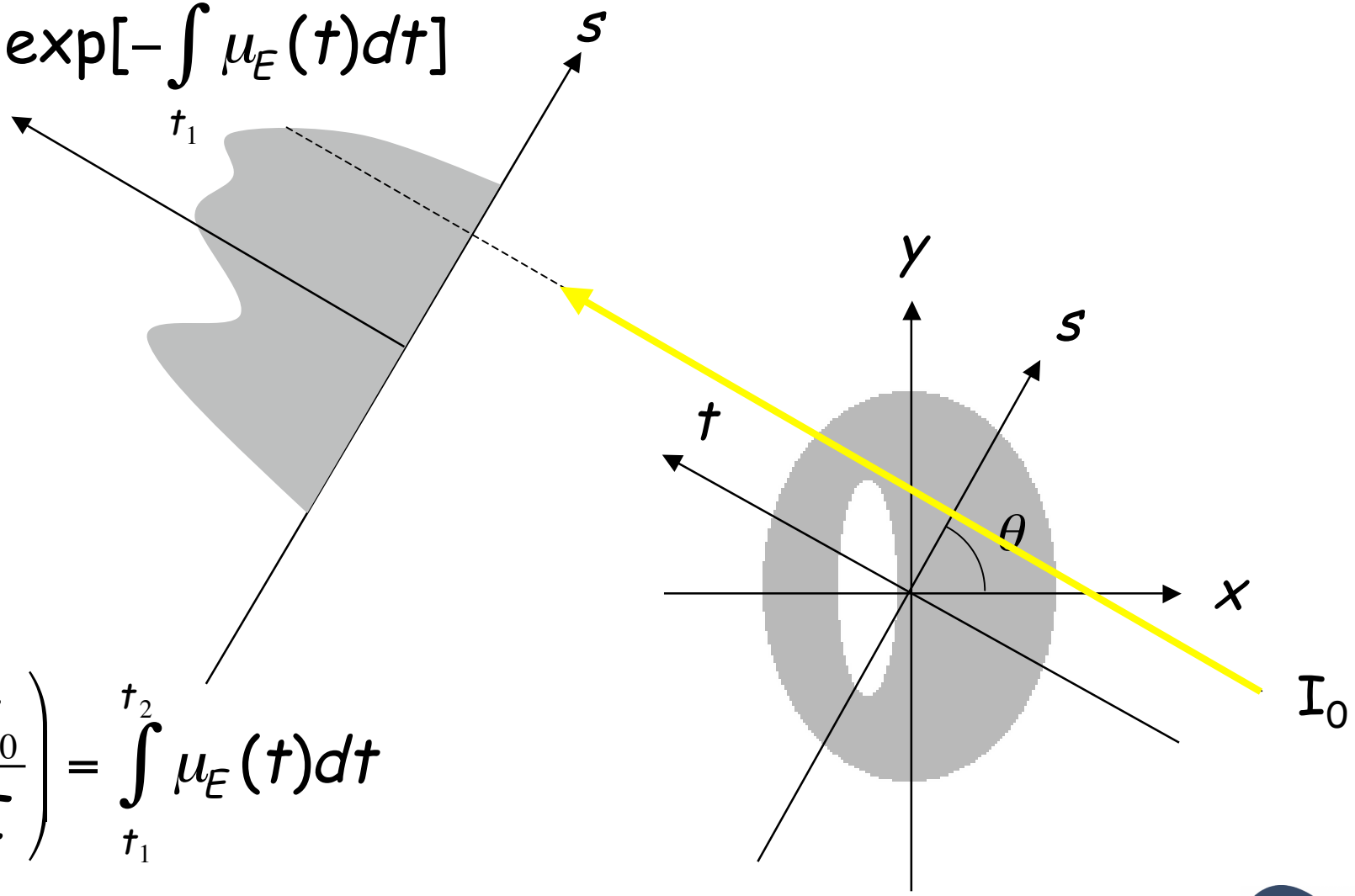


Développe chez EMI le premier scanner à rayons X ou CT (Computed Tomography)

1979: Hounsfield et Cormack reçoivent le prix Nobel de médecine pour le dévelop-pement de la tomographie assistée par ordinateur

Tomographie par transmission

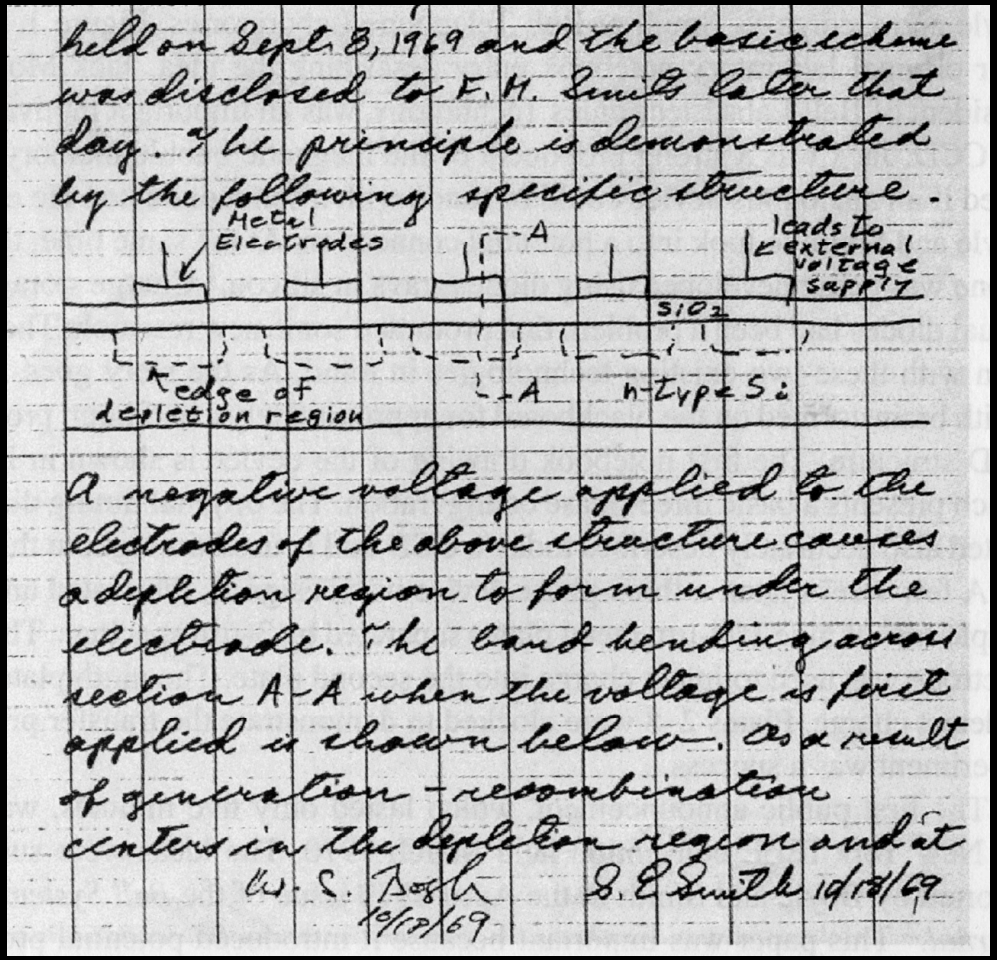
$$I = I_0 \exp\left[-\int_{t_1}^{t_2} \mu_E(t)dt\right]$$



$$\ln\left(\frac{I_0}{I}\right) = \int_{t_1}^{t_2} \mu_E(t)dt$$

Détecteurs à intégration de charges

held on Sept. 8, 1969 and the basic scheme was disclosed to F. H. Smith later that day. The principle is demonstrated by the following specific structure.



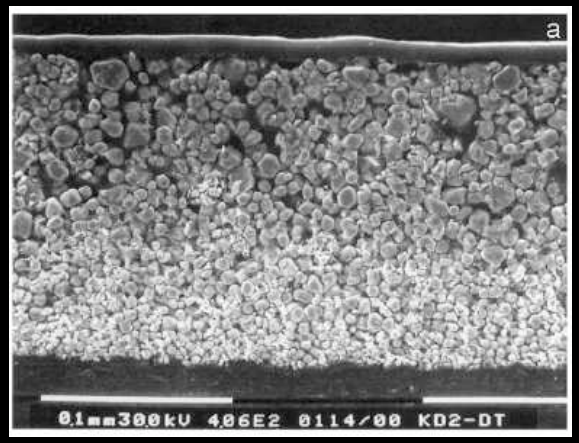
A negative voltage applied to the electrodes of the above structure causes a depletion region to form under the electrode. The band bending across section A-A when the voltage is first applied is shown below. As a result of generation-recombination centers in the depletion region and at

W. S. Boyle 10/12/69 G. E. Smith 10/12/69

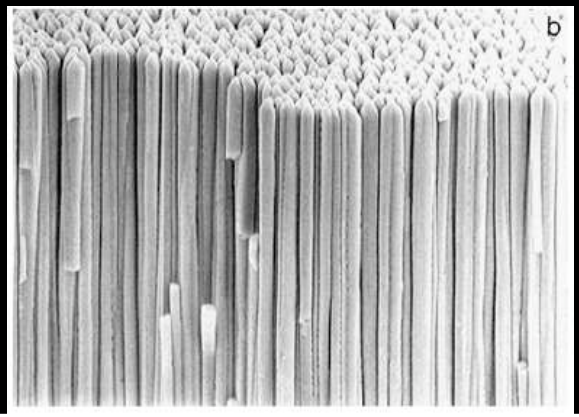
W.S. Boyle and G.E. Smith, 8 sept. 1969

Prix Nobel de Physique en 2009

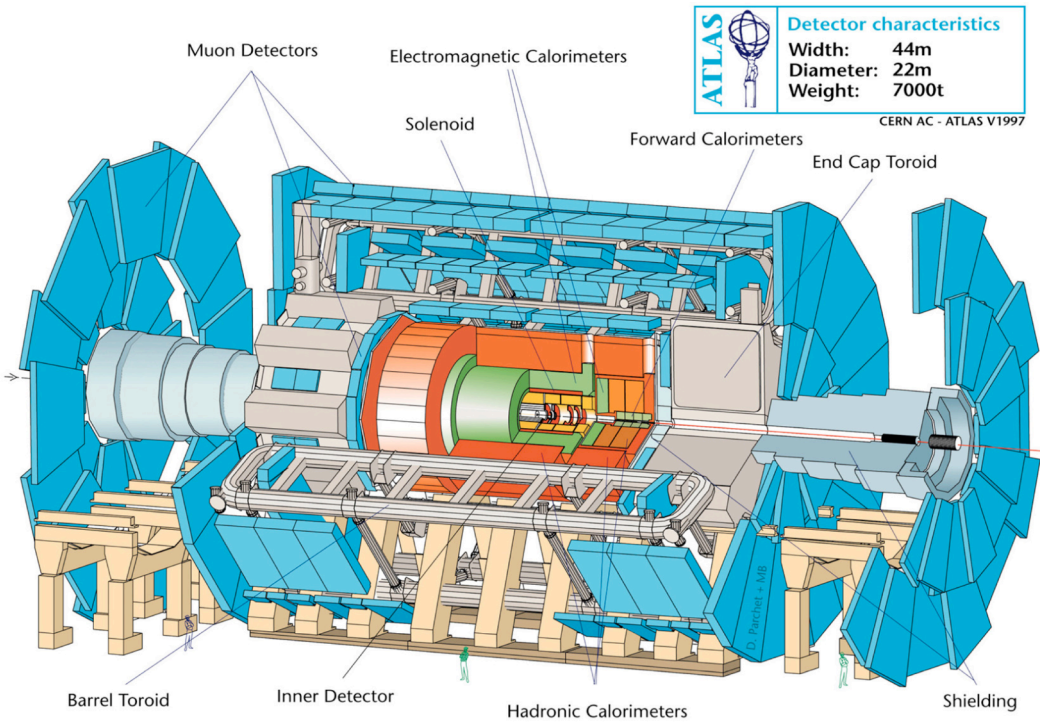
Caméra CCD (Charged Couple Device)



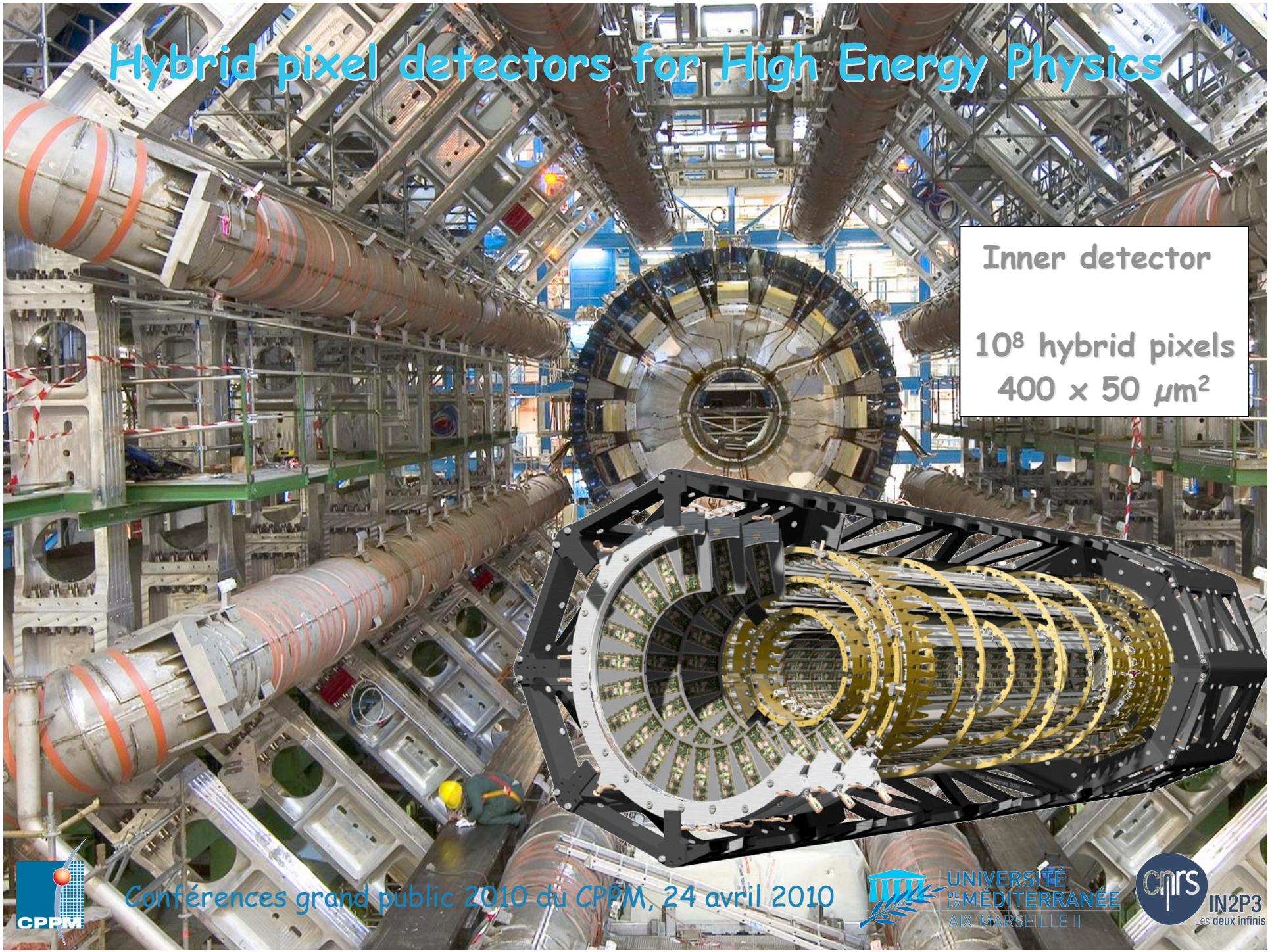
Pixels CMOS (Complementary Metal-Oxyde Semiconductor)



Le scanner X : le passage du noir et blanc à la couleur pour bientôt, grâce aux pixels hybrides



Hybrid pixel detectors for High Energy Physics



Inner detector

10^8 hybrid pixels
400 x 50 μm^2

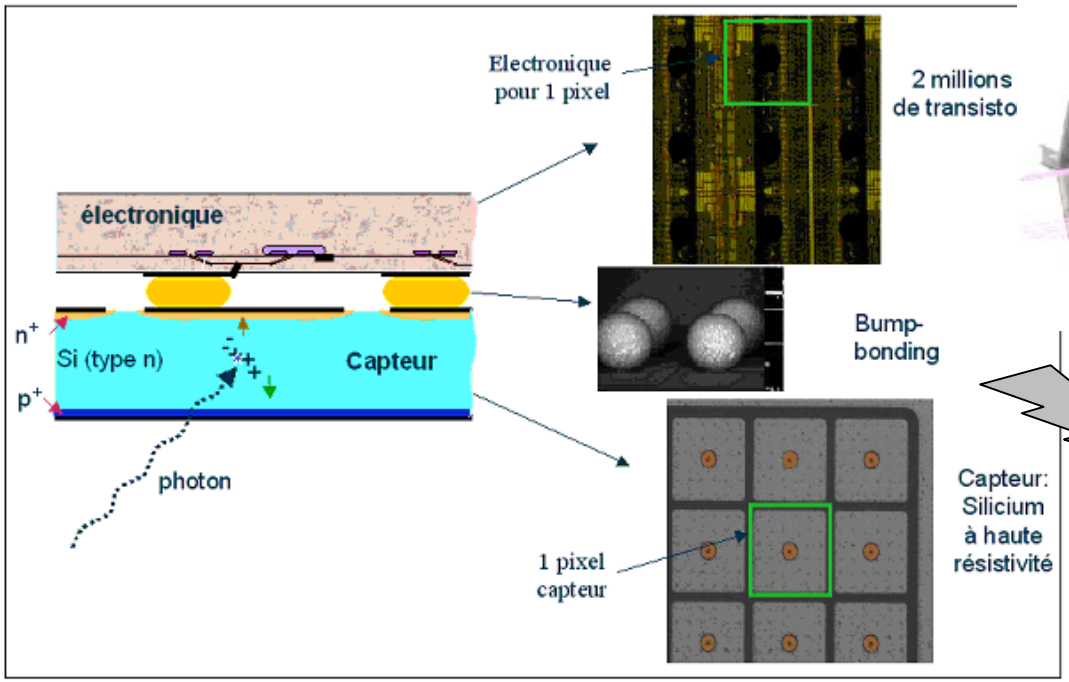
Conférences grand public 2010 du CPPM, 24 avril 2010

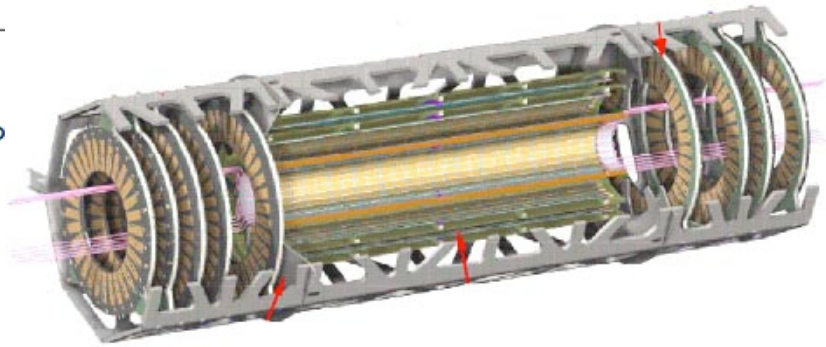
CPPM

UNIVERSITÉ DE LA MÉDITERRANÉE AIX-MARSEILLE II

cnrs IN2P3 Les deux infinis

Détecteurs à pixels hybrides en TDM





- suppression du bruit
- sélection en énergie
- très grande dynamique

- acquisition de données très rapide
- choix du substrat de détection (Si, CdTE, AsGa)
- efficacité optimale

¿ amélioration du contraste ?
¿ réduction de la dose ?

Comptages de photons versus intégration de charge

Comptage de photons

- ✓ Taux de comptage très bas (0,01 ph/pixel/s) → **Faibles doses**
- ✓ Grande dynamique de taux de comptage (10^{-2} - 10^{6} ph/pixel/s) → Grande dynamique de comptage (80 dB) → **Meilleure détectabilité à bas contraste**

Seuil de détection en énergie

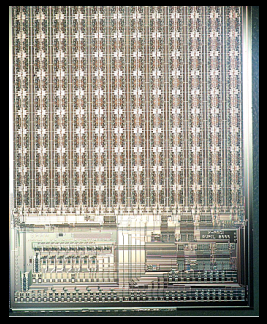
- ✓ Sélection de l'énergie des rayons X → Discrimination des photons diffusés → **Meilleur contraste**

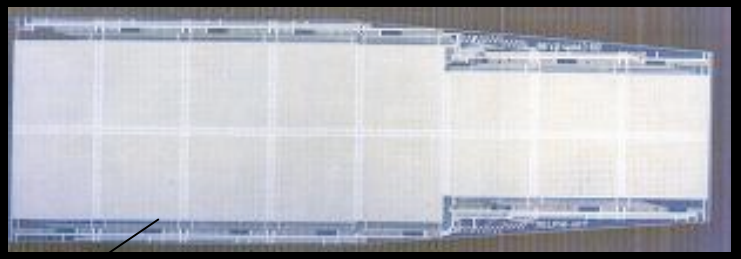
Choix du capteur

- ✓ Utilisation de capteurs de haute densité → Meilleure efficacité de détection → **Meilleure détectabilité à bas contraste + Faibles doses**

Premier prototype XPAD1 (2003)

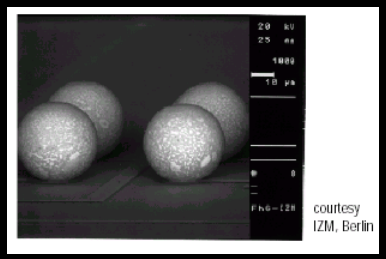
XPAD1:
- amplificateur
- 1 discriminateur
- compteur 15-bits

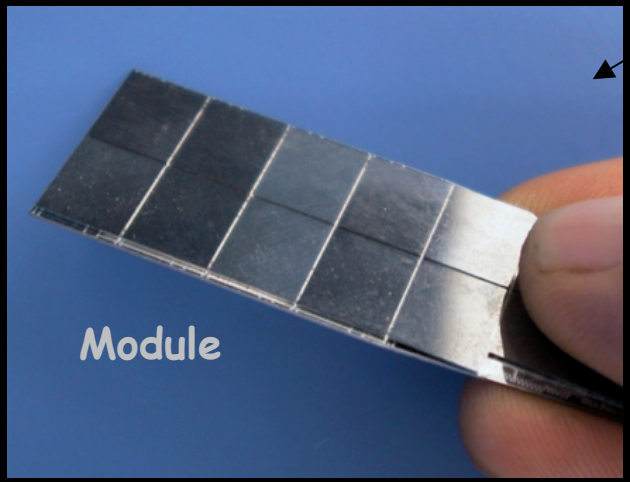




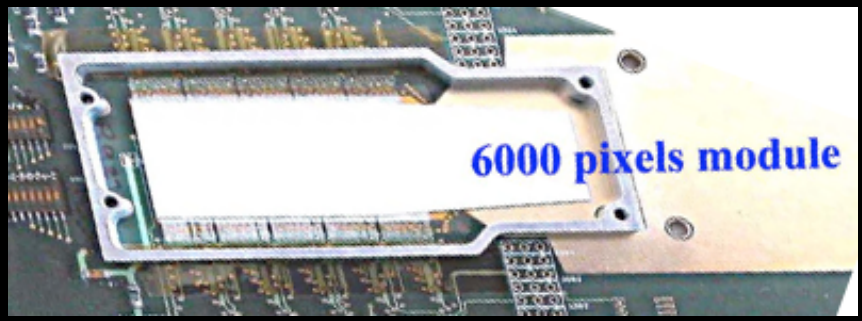
Capteur de silicium pixellisé
330 x 330 μm^2
(DELPHI)

Bump-bonding



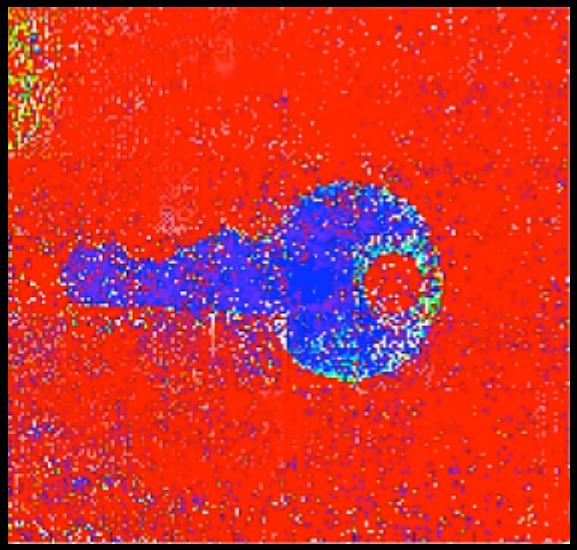


10 chips bump-bonded on
a 4 x 1.6 cm^2 Si sensor



Pixels hybrides prototype

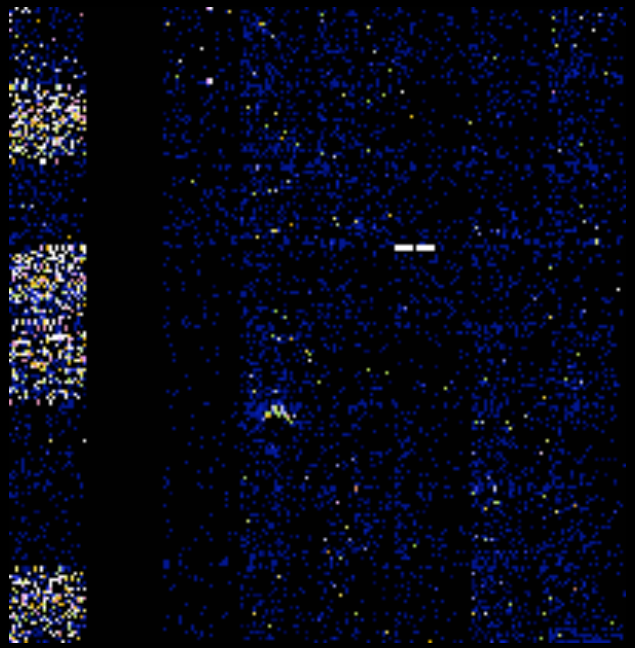
… et premières images (2004)



Clé de bureau
(données brutes)

Diffusion à petit angle :
200 images de 10 ms espacées de 2 ms

European Synchrotron Radiation Facility (ESRF)



Premières images PIXSCAN/XPAD2 (2005)

360 projections (1 projection par degré)
Reconstruction FDK (recFDK Creatis)

Calibration géométrique

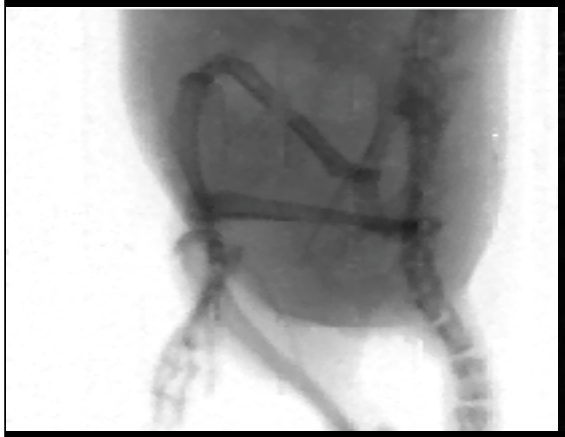
Aile de caille

Coupe sagittale

Premières images avec PIXSCAN/XPAD2

Acquisition de projections coniques d'une souris anesthésiée

Projection d'intensité moyenne



Projection d'intensité minimale

courtesy: F. Debarbieux, IBDML

Projection d'intensité maximale (MIP) après reconstruction tomographique des projections coniques par l'algorithme de Feldkamp, Davis, et Kress (FDK)

Angiographies avec PIXSCAN/XPAD2

Souris sacrifiée directement après l'injection d'un agent de contraste

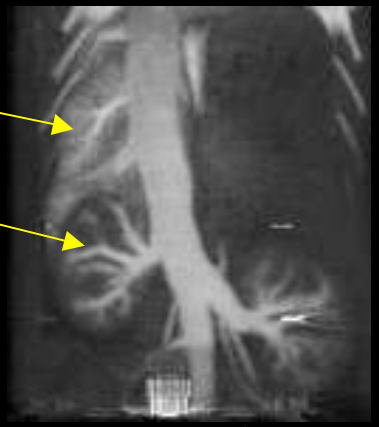
200 µL dans la veine de queue et 400 µL intracardiac

Sans agent de contraste

Trachée artère

Rate

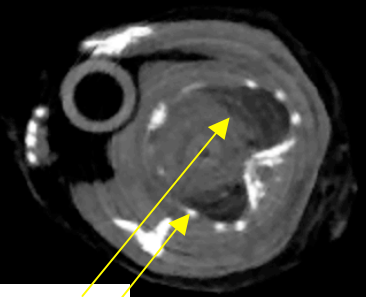
Rein



Coronale

Sagittale

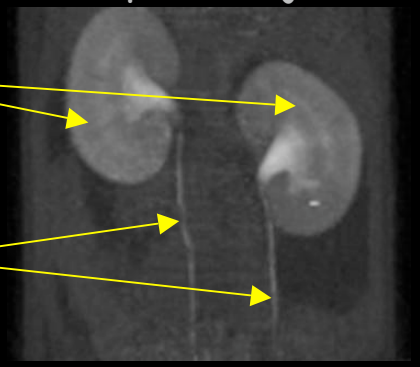
Souris sacrifiée 5 min après l'injection



Poumons

Reins

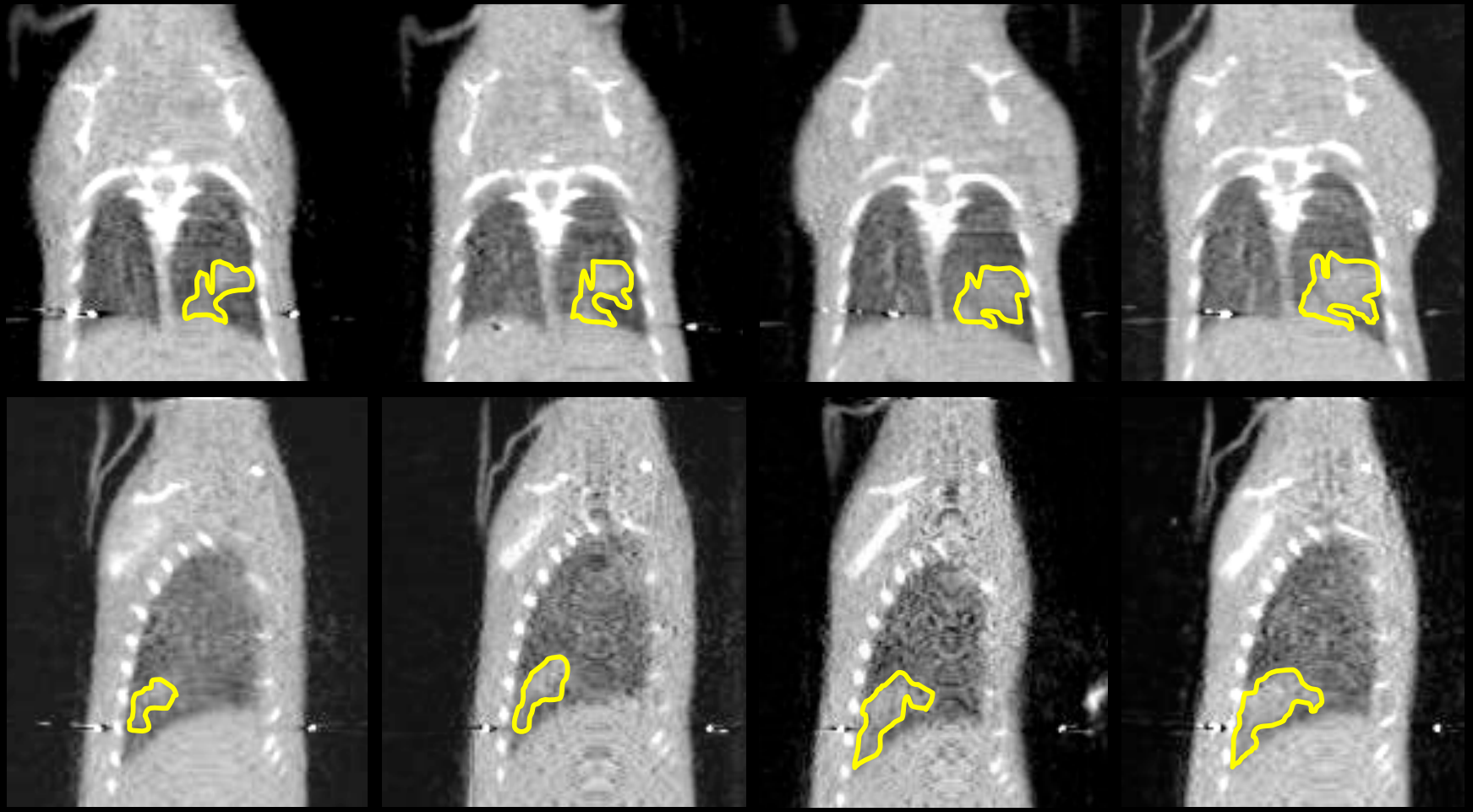
Uretères



courtesy: F. Debarbieux, IBDML

Exposition 1.5 s, seuil 14 keV, source (50 kV, 500 µA), filtre 6 mm Al, 8000 coups/pixel

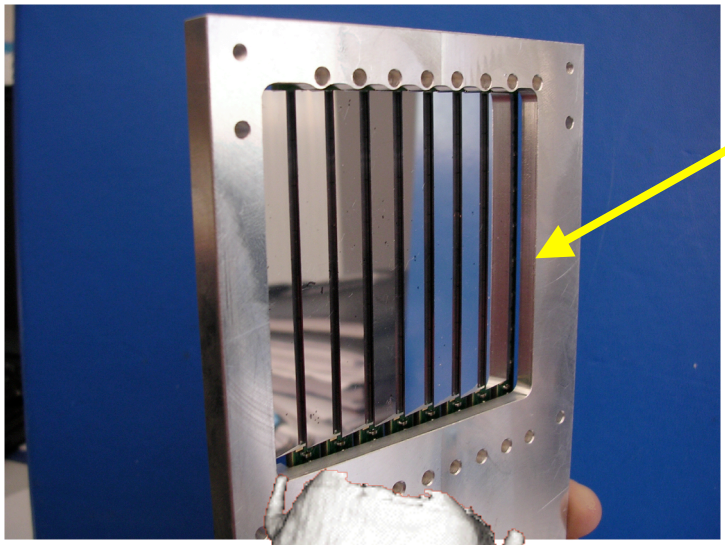
Suivi longitudinal de la croissance tumorale



D14 D18 D21 D24

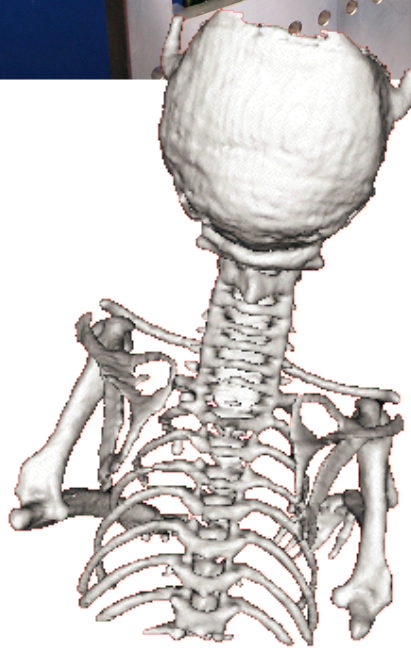
courtesy: F. Debarbieux, IBDML

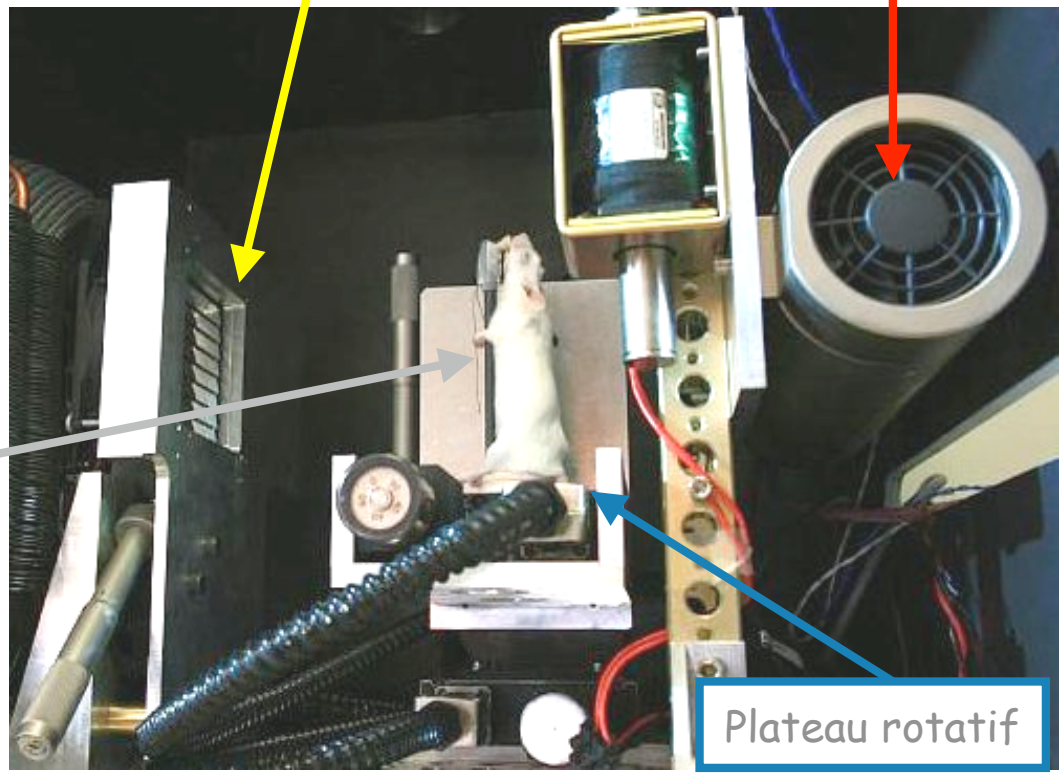
Démonstrteur micro-CT PIXSCAN



XPAD2 Hybrid Pixel Detector
330 x 300 μm^2 pixels

Source de rayons X





Plateau rotatif

Nouveau circuit XPAD3

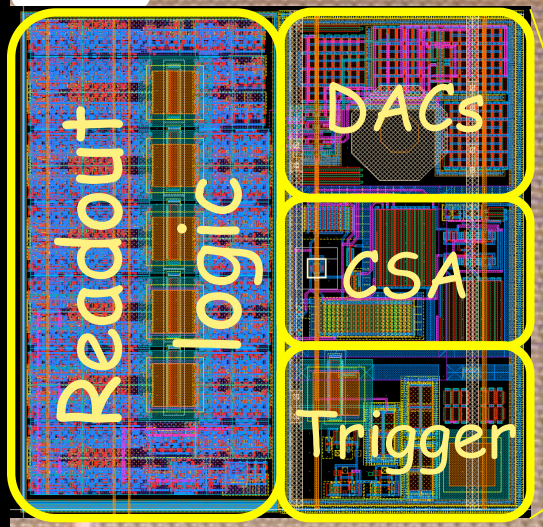
Production des circuits (IBM 0,25 µm)

XPAD3-S
Si n type

XPAD3-C
CdTe

9600 pixels
130 x 130 µm²
1 x 1,5 cm²
circuit

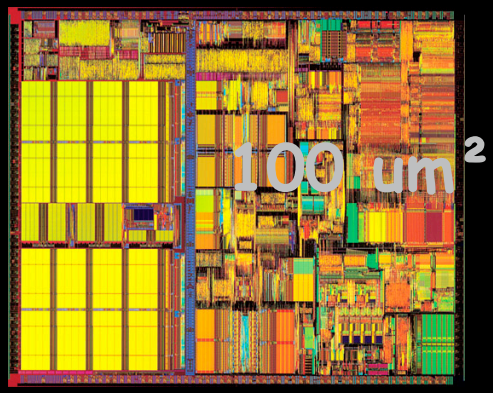
Pixel



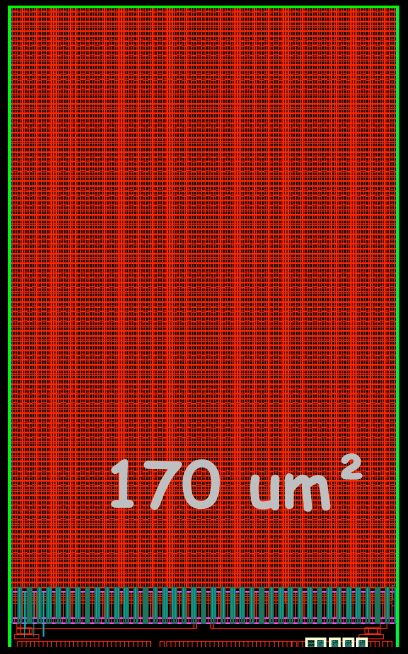
- Double seuil (sélection de l'énergie)
- Lecture continue pendant l'exposition
- Captures 2 ms
- Résistant aux radiations

Détecteur de 7 x 12 cm² monté sur le démonstrateur PIXSCAN en 2007
Souris coprs-entier avec une résolution de 60 µm

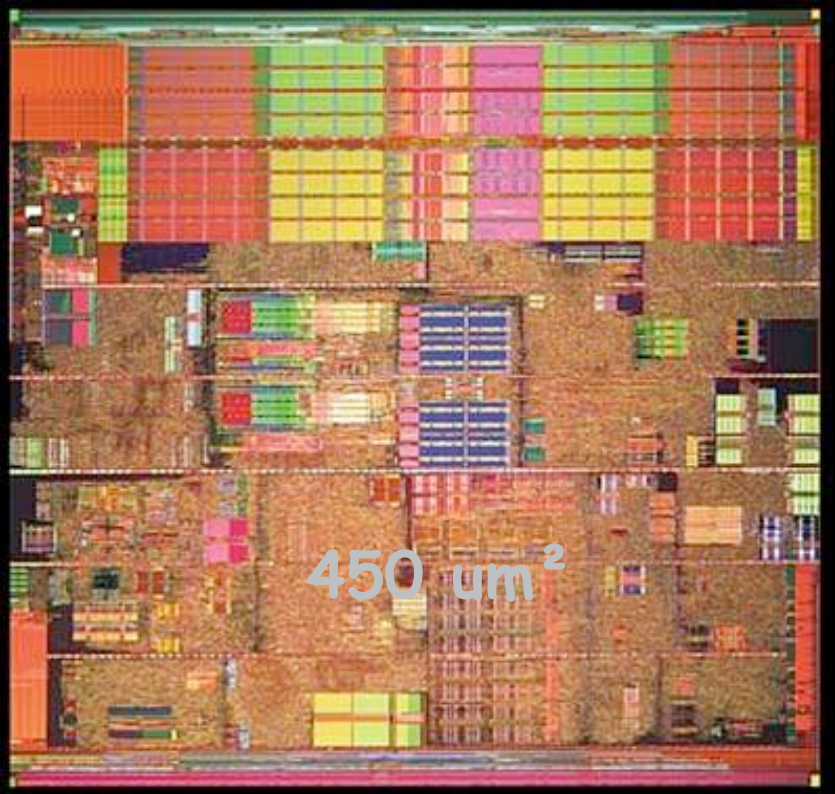
Développement du circuit XPAD3



Pentium 3
Technologie 0,25 um
9 MTr

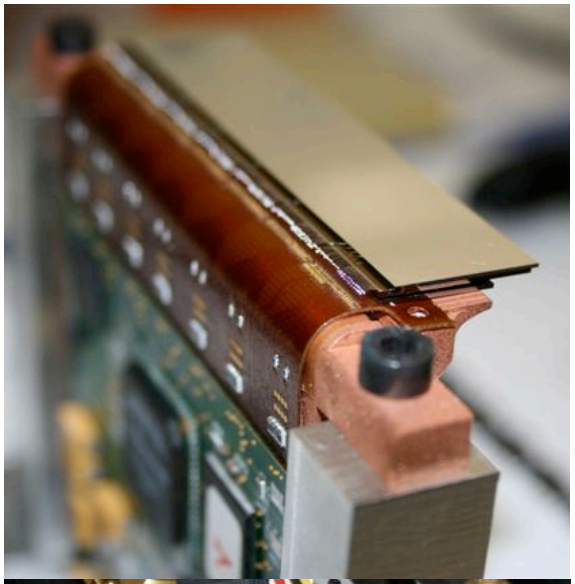


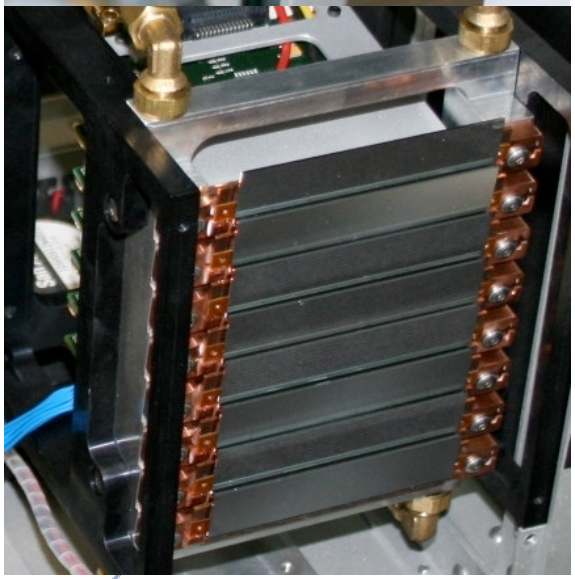
XPAD3
Technologie 0,25 um
15 MTr

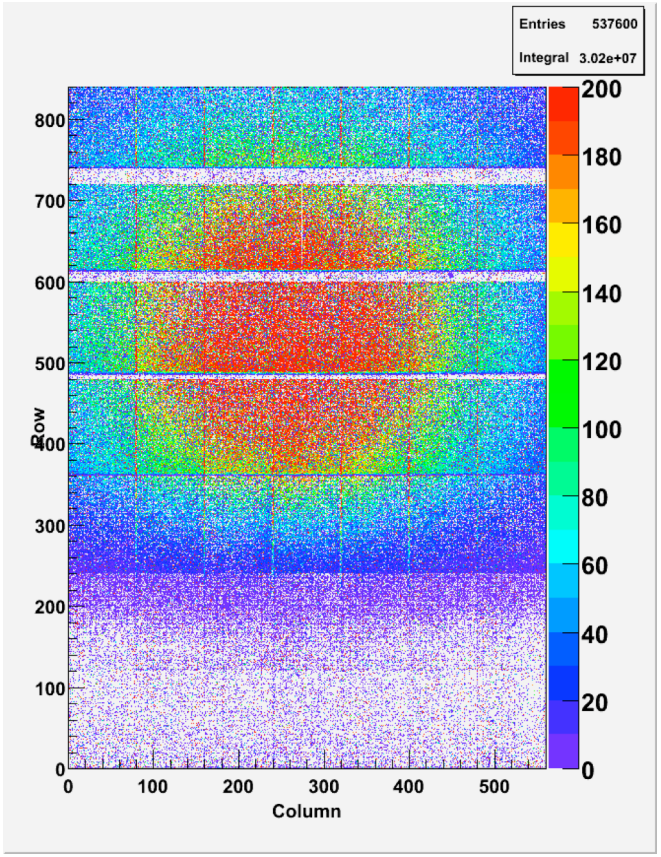


Pentium 4
Technologie 0,18 um
42 MTr

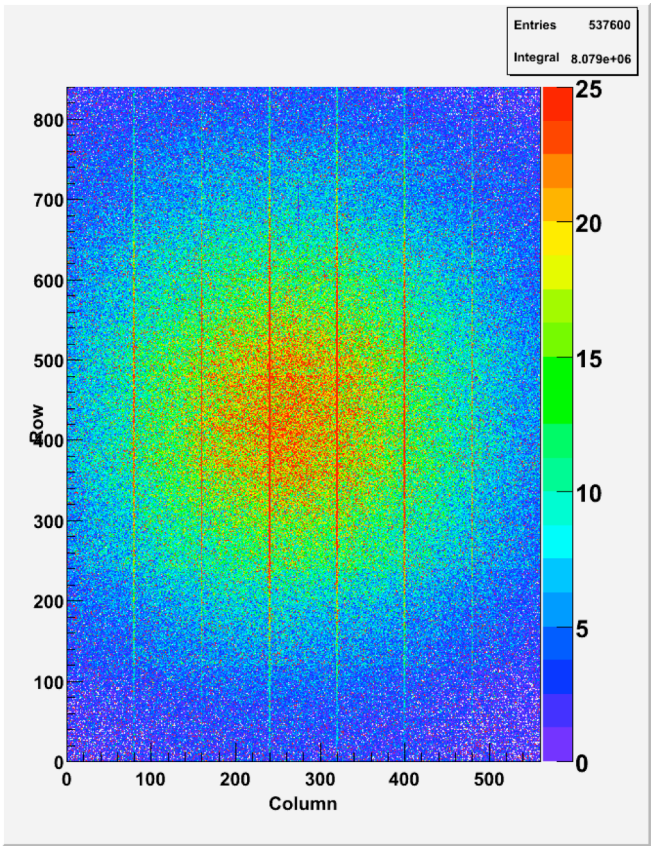
Détecteur XPAD3 : 500,000 pixels de 130 µm





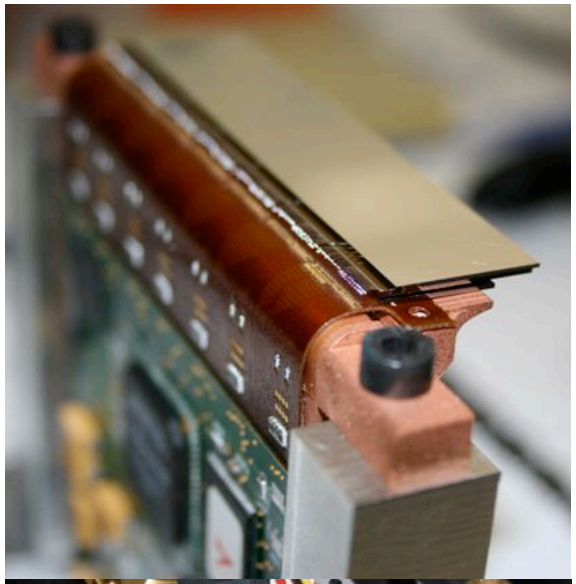


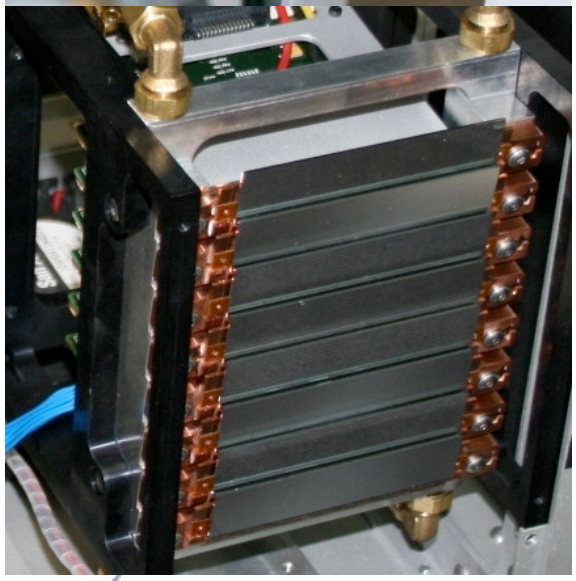
Fe-55, 5.9 keV

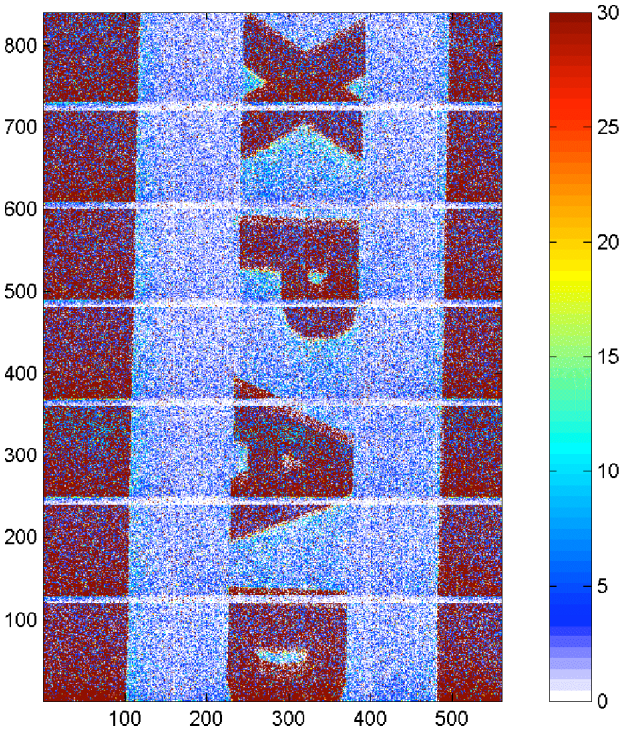


Am-241, 60 keV

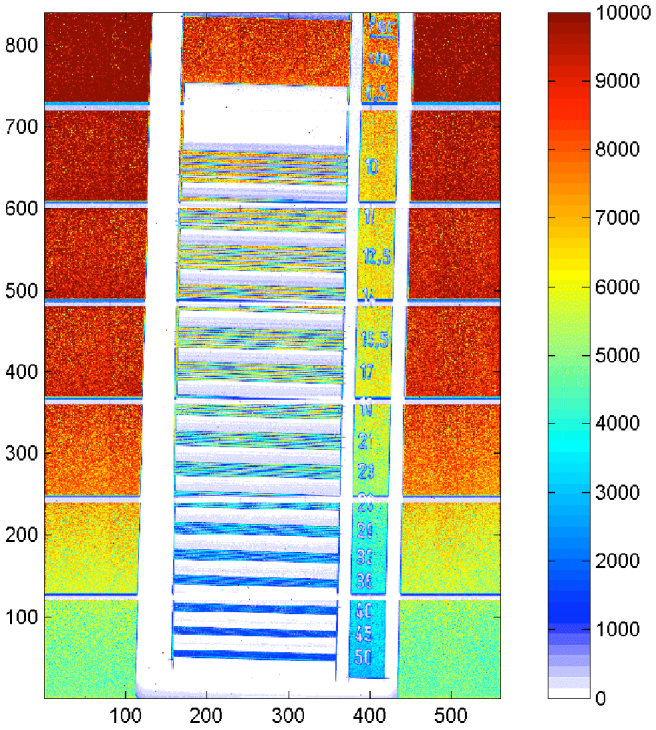
Détecteur XPAD3 : 500,000 pixels de 130 µm





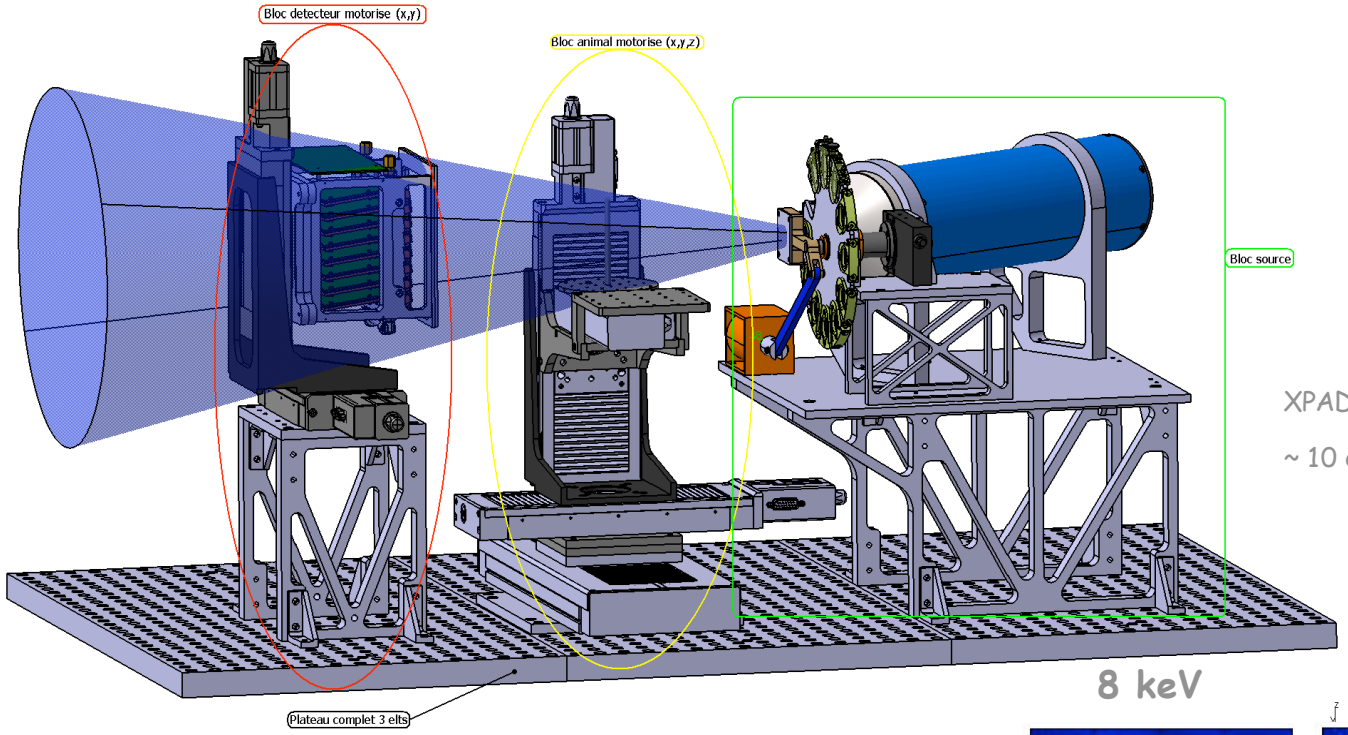


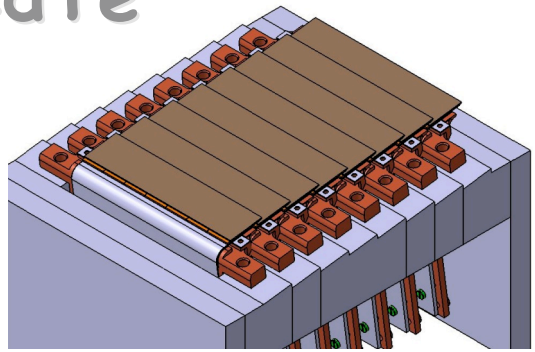
SOLEIL 5 keV



SOLEIL 14 keV

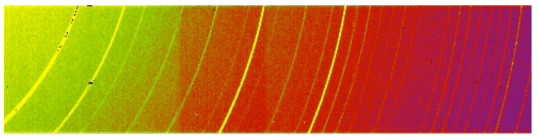
Caméras XPAD3-S Si et CdTe



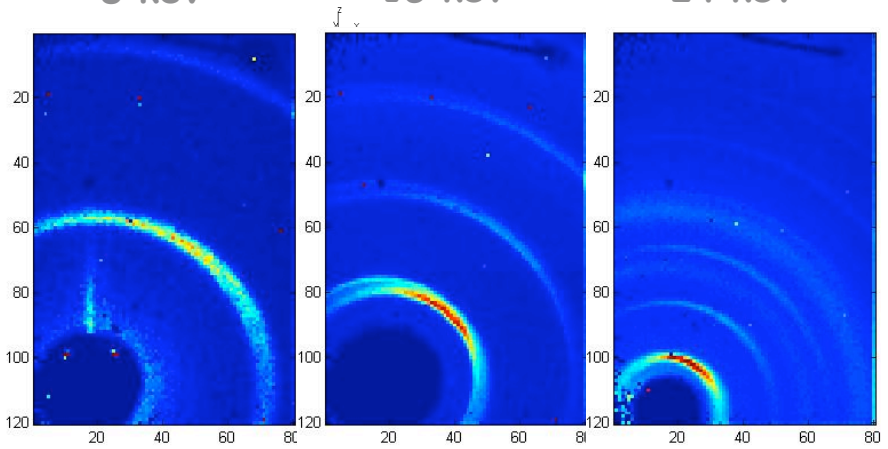


XPAD3: 67200 pixels (130 x 130) μm^2/barrette

~ 10 dead pixels (< 0.015% dead pixels)



8 keV 15 keV 24 keV



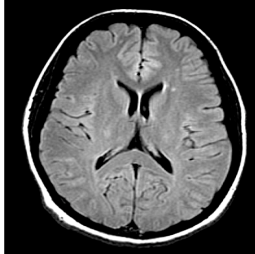
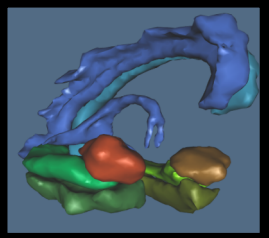
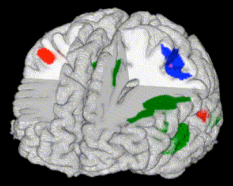
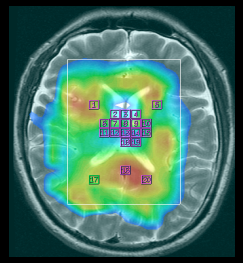
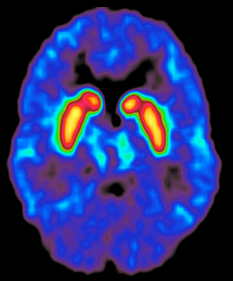
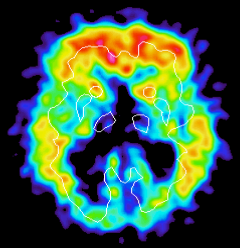
Démonstrateur PIXSCAN II

20 kpixels CdTe XPAD imager (2 chips)

S. Basolo *et al.*, *Nucl Instrum Meth A* **589** (2008) 268

En direction de l'imagerie moléculaire

Imagerie anatomique → **Imagerie fonctionnelle** → **Imagerie moléculaire**

- Morphologie
- Morphométrie

- Hémodynamique
- Perméability vasculaire
- Oxygénation/hypoxie des tissus
- Activité CNS
- Métabolites
- pH

- Agents de contrastes spécifiques
- Imagerie des récepteurs fonctionnelles
- Pharmacocinétique

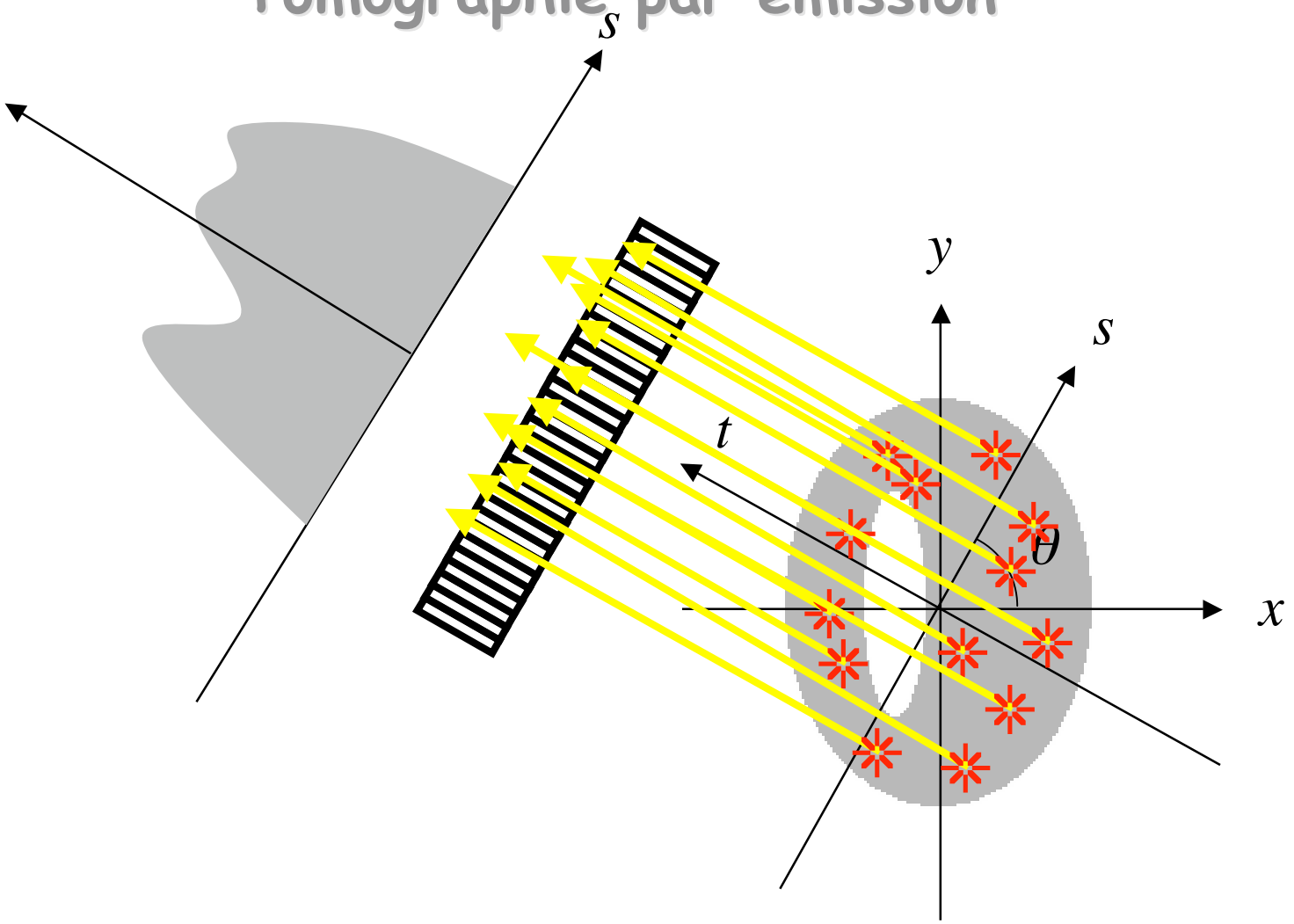
STRUCTURE → **MECHANISME** → **CIBLE**

MACROSCOPIQUE

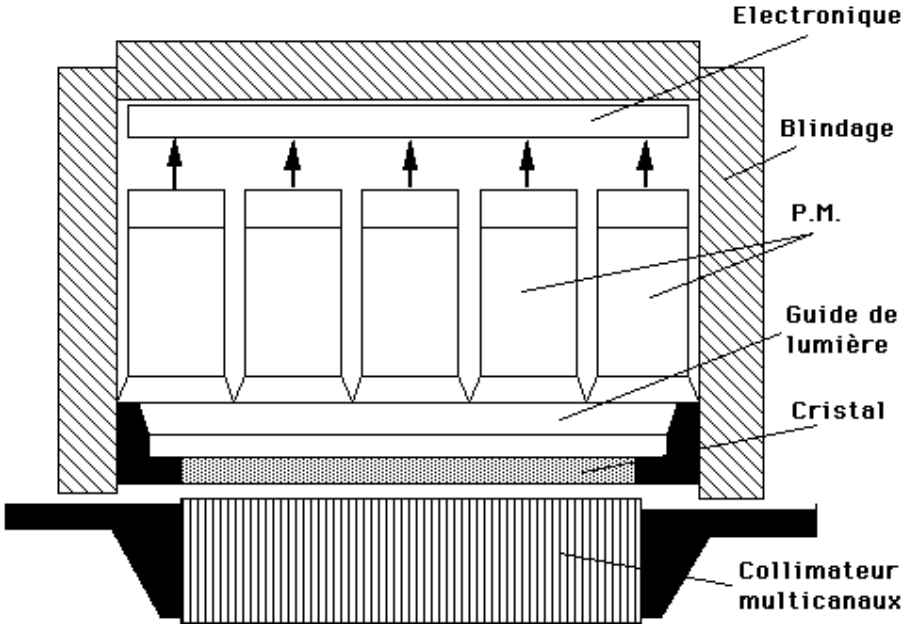
MICROSCOPIQUE

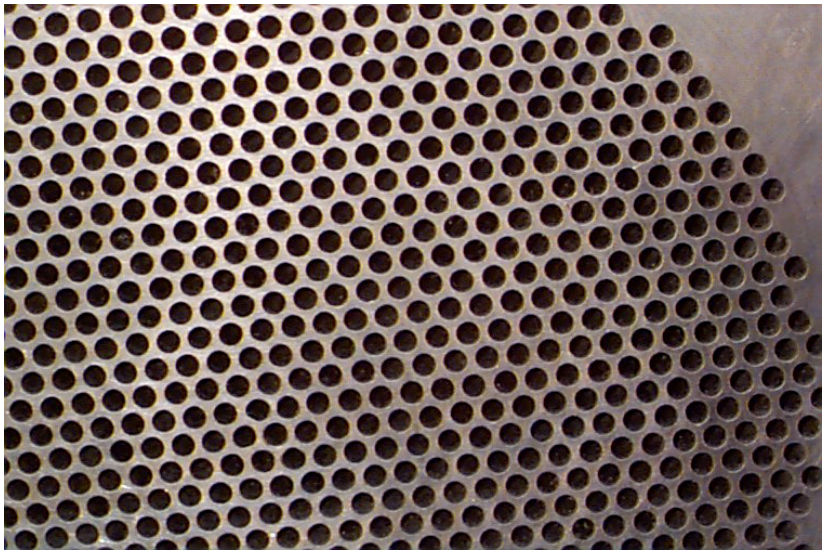
courtesy: J. Prior, CHUV

Tomographie par émission



Gamma camera (H Anger, Berkeley, 1952)





HO Anger, *Scintillation camera with multichannel collimators*. J Nucl Med 65 (1964) 515-31

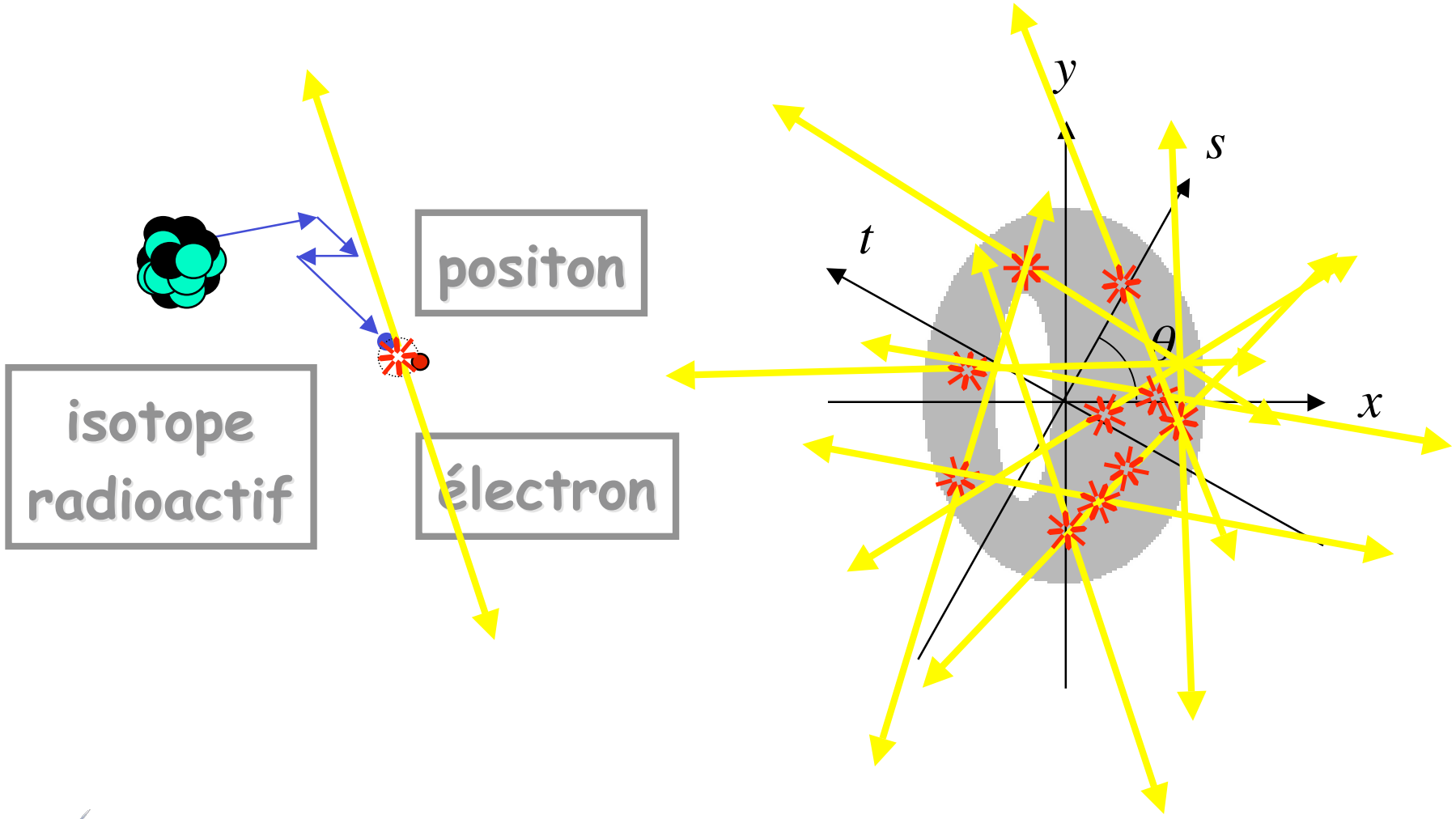
Tomographie par émission monophotonique (TEMP)

Single Photon Emission Computered tomography (SPECT)

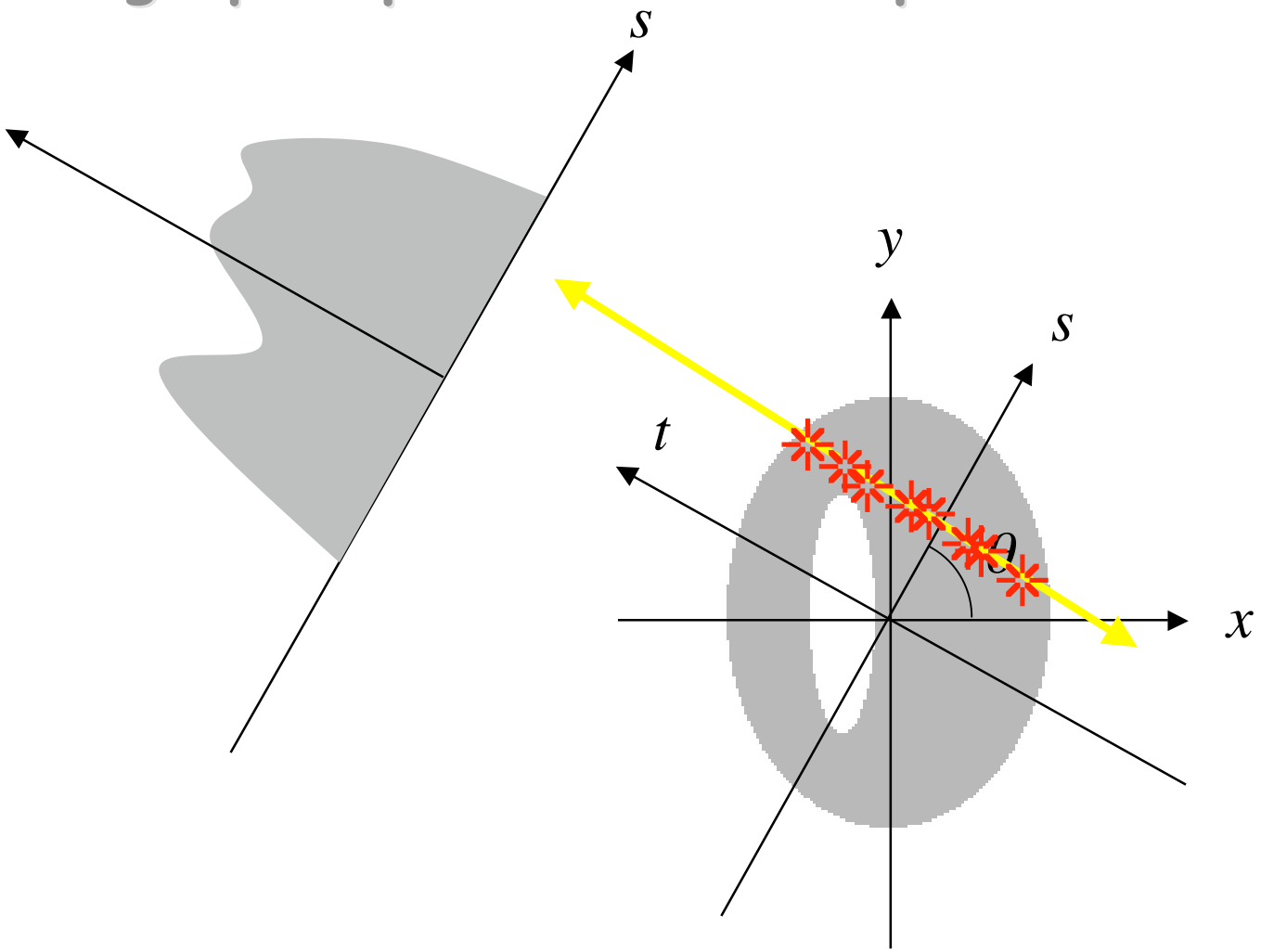
^{99m}Tc (6 h)	140 keV
^{201}Tl (73 h)	70 keV
^{123}I (13 h)	159 keV
^{133}Xe (5 min)	81 keV

Sensibilité absolue	~ 10^{-4}
Résolution spatiale	6-8 mm
Dose absorbée	5-30 mSv

Tomographie par émission de positons

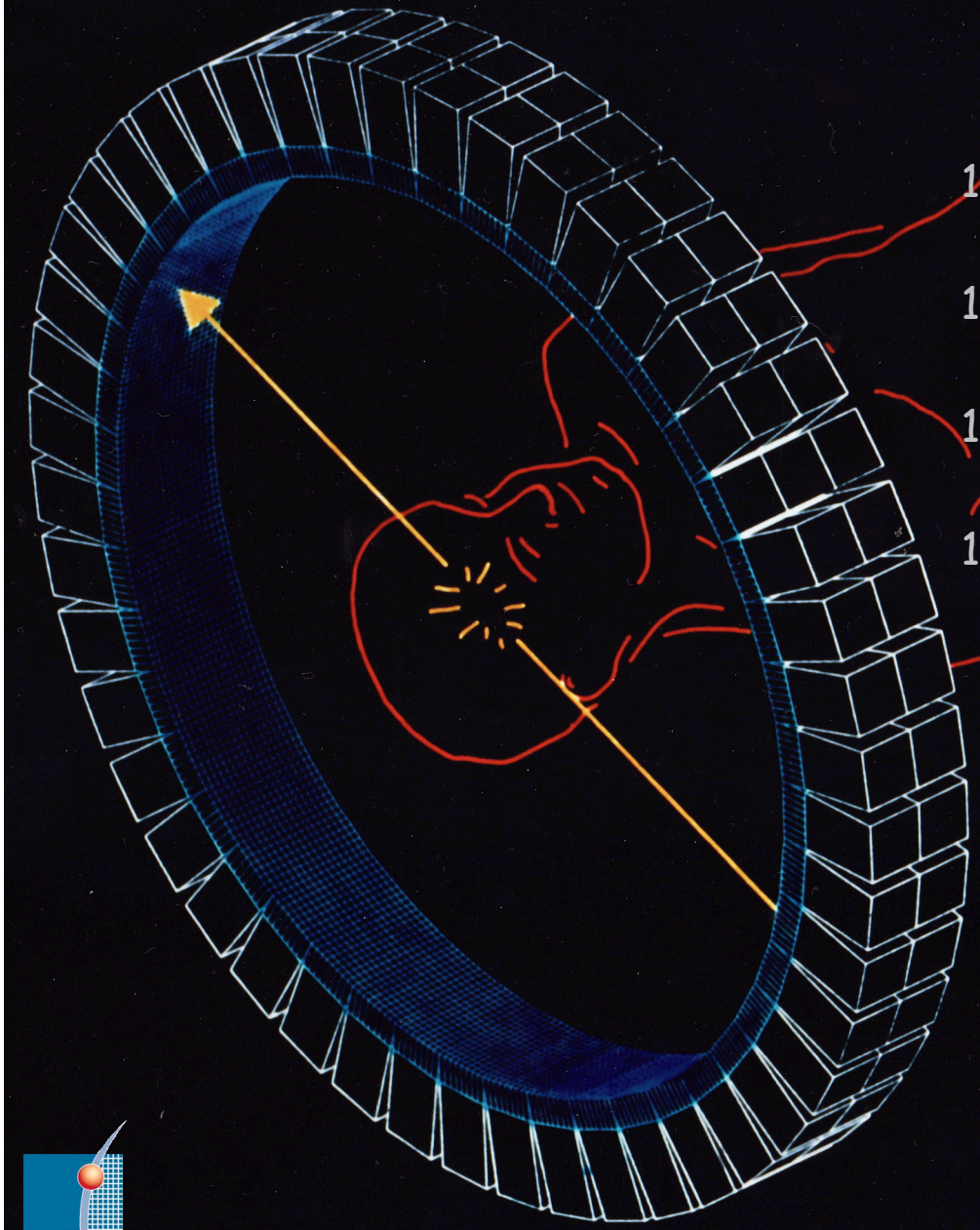


Tomographie par émission de positons



Tomographie par émission de positons (TEP)

Positron Emission tomography (PET)



^{15}O (2 min) 511 keV

^{13}N (10 min) 511 keV

^{11}C (20 min) 511 keV

^{18}F (110 min) 511 keV

Sensibilité absolue ~ 10^{-2}

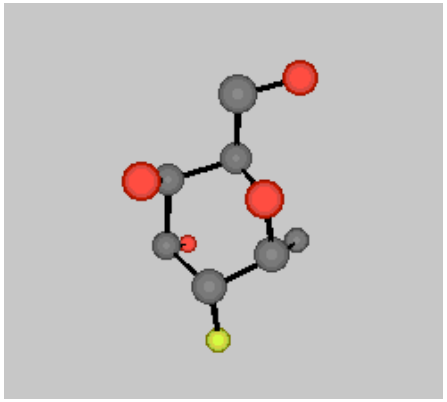
Résolution spatiale 3-5 mm

Dose absorbée 5-10 mSv

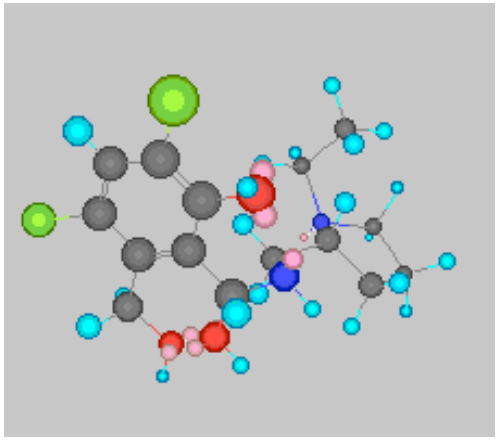
M.R.C. Cyclotron Unit.
Hammersmith Hospital.
London.

CPPM

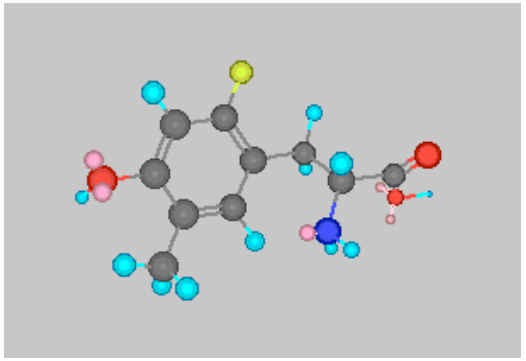
Marquages radio-pharmaceutiques



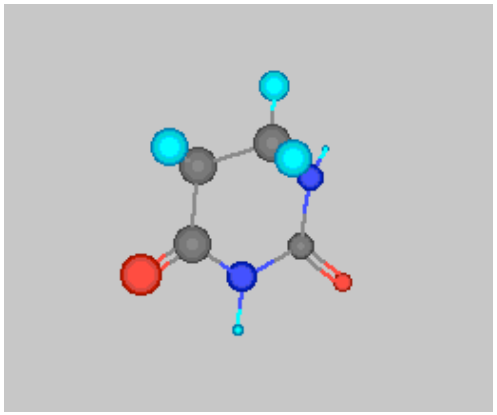
[^{18}F]FDG



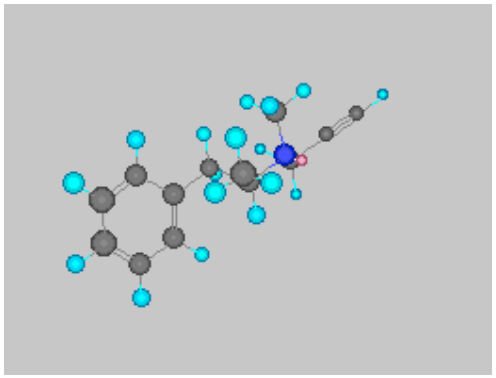
[^{11}C]Raclopride



[^{18}F]FluoroLDopa



[^{18}F]Fluorouracil



[^{11}C]L-deprenyl

Distribution normale de FDG

Fixations physiologiques du FDG

Cerveau

Thymus (enfants)

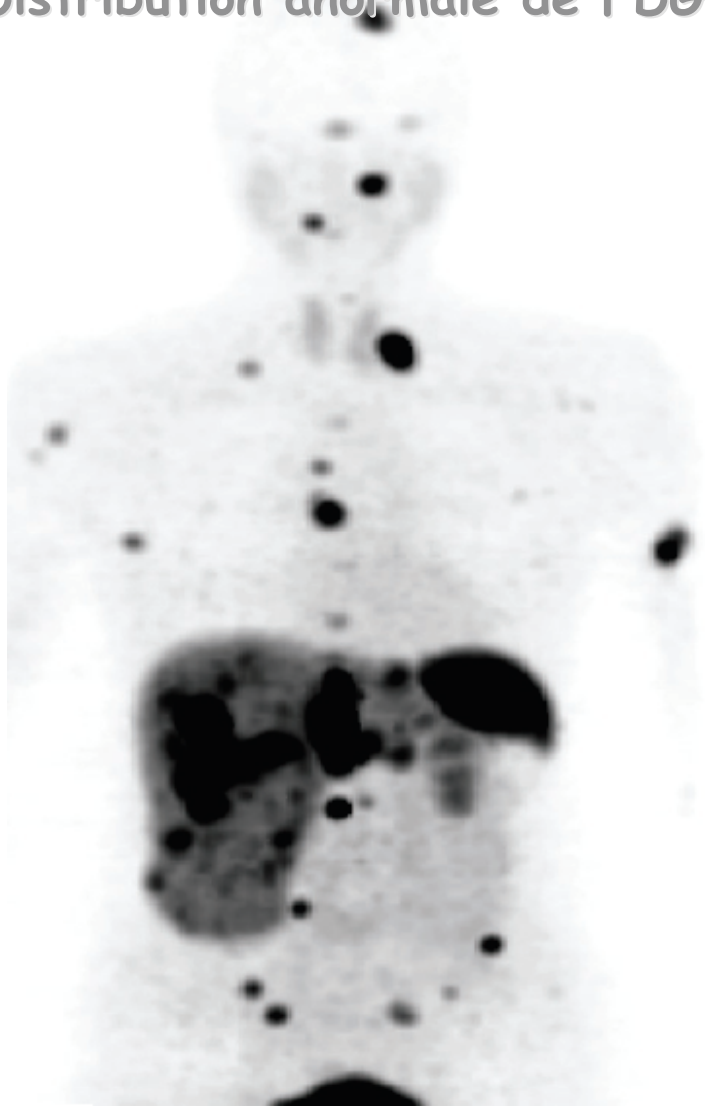
Cœur

Elimination urinaire:
Reins
Uretères

Vessie

Distribution normale de FDG

Distribution anormale de FDG

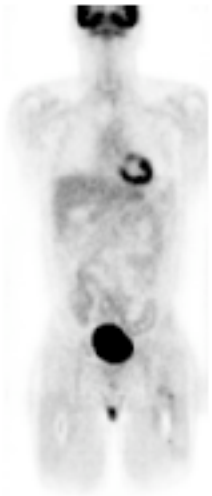


Préclinique + Clinique

microPET Focus 220

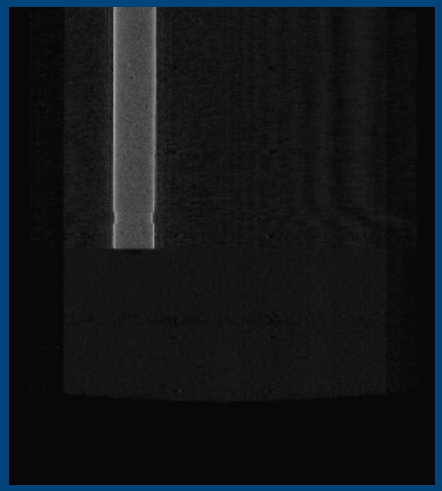
Souris
6 MBq

ECAT EXACT HR+

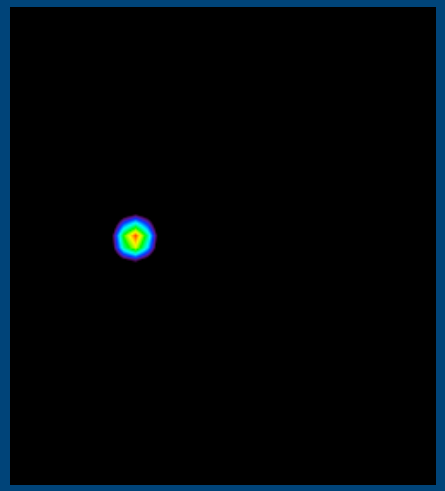


Humain
390 MBq

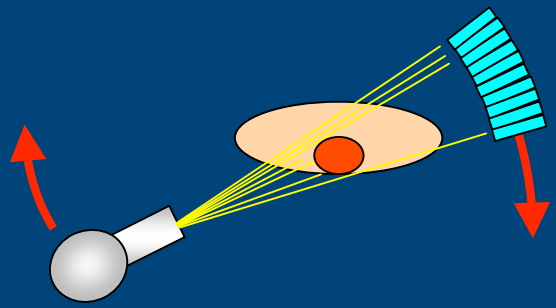
Anatomie + Fonction



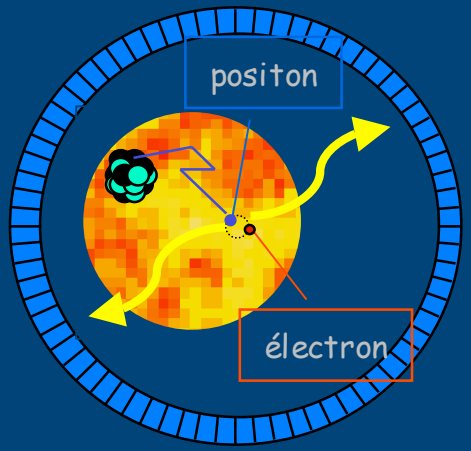
Programme de fusion



Rayons X : TDM -> anatomie

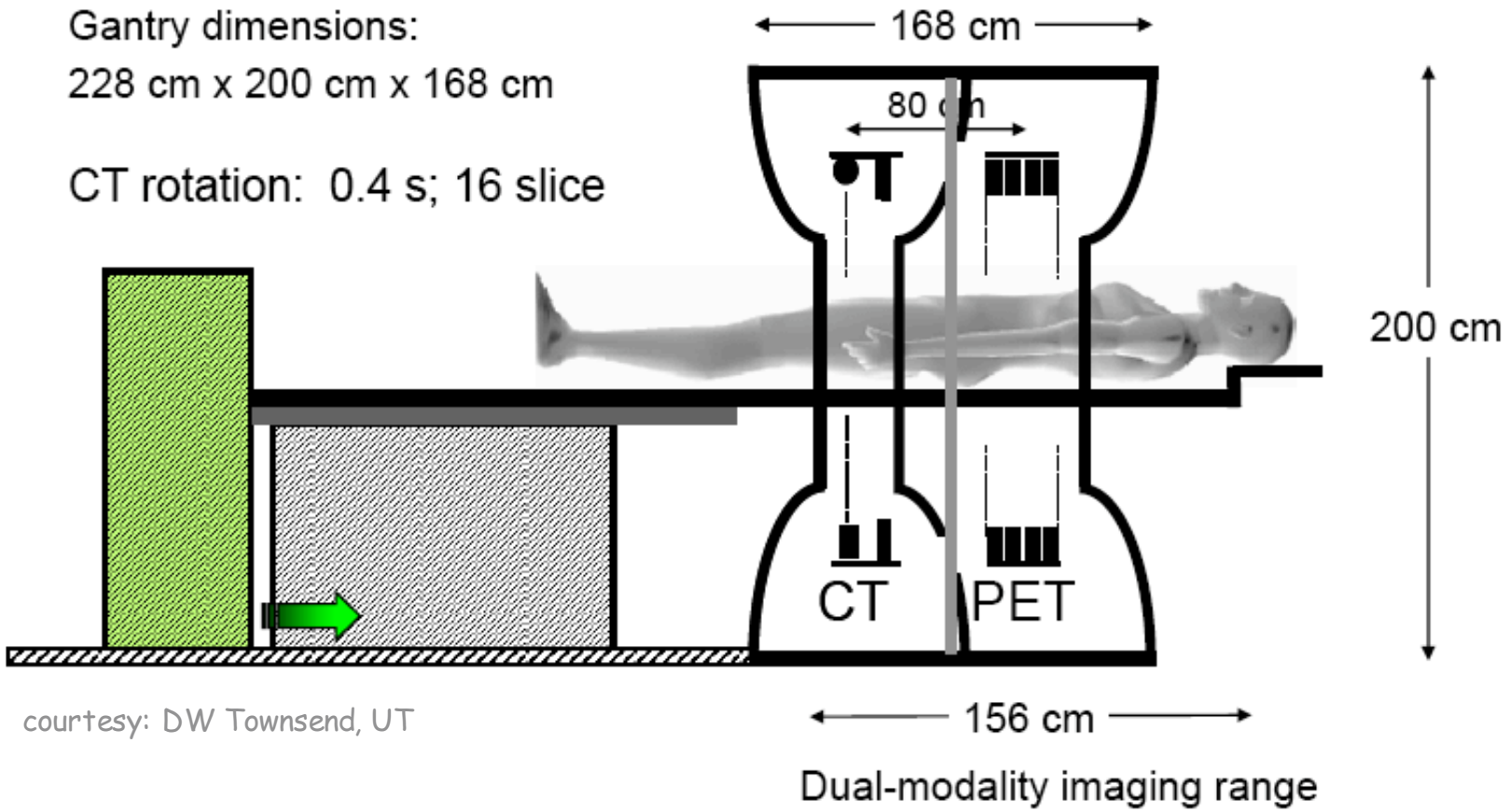


Positons : TEP -> fonction



Fusion d'image

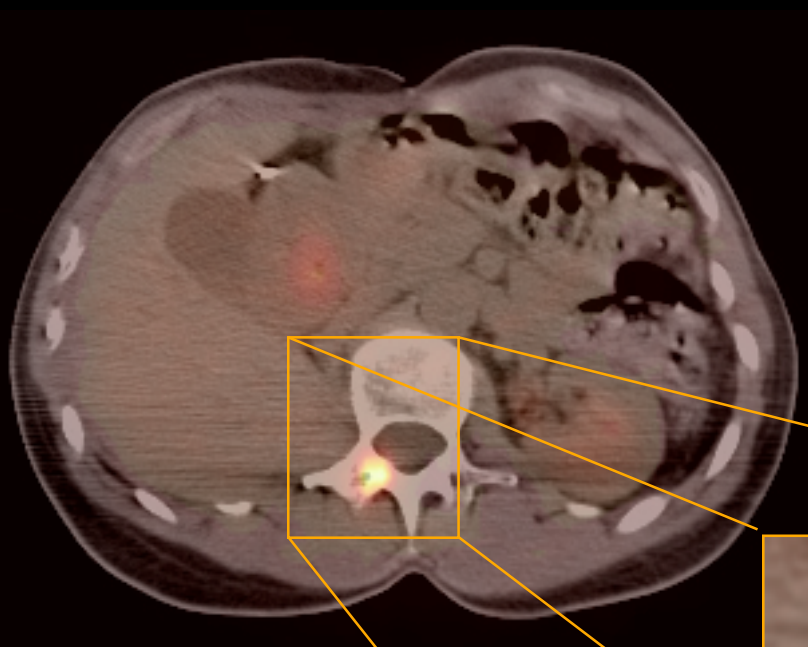
Design typique d'un scanner TEP/CT clinique



courtesy: DW Townsend, UT

2001: 1er scanner TEP/CT commercial installé à Zurich par GE
2005: plus de 650 scanners TEP/CT installés, 95% des ventes de scanners TEP

CT: 160 mAs; 130 KV_p; pitch 1.6; 5 mm slices PET: 6.3 mCi FDG; 3 x 10 min; 3.4 mm slices



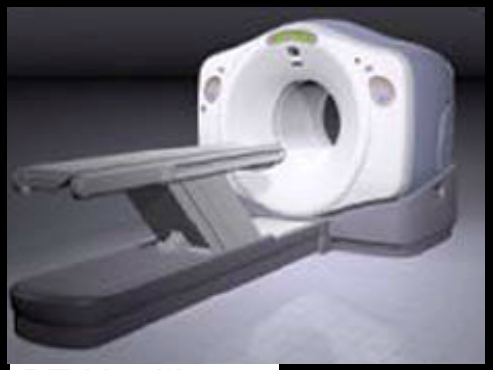
40 year-old woman with multiple endocrine syndrome (MEN-1) and history of malignant pheochromocytoma

MIBG scan one year ago showed right adrenal lesion; adrenal resected but no tumor found. PET suggested a lesion in the adrenal resection bed but PET/CT showed lesion located in spine.

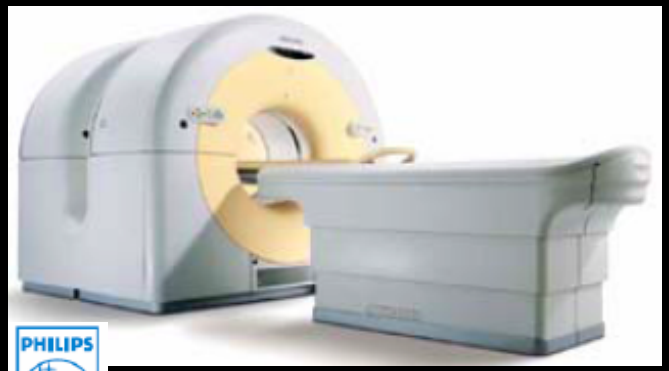
UPMC, 1998

courtesy: DW Townsend, UPMC

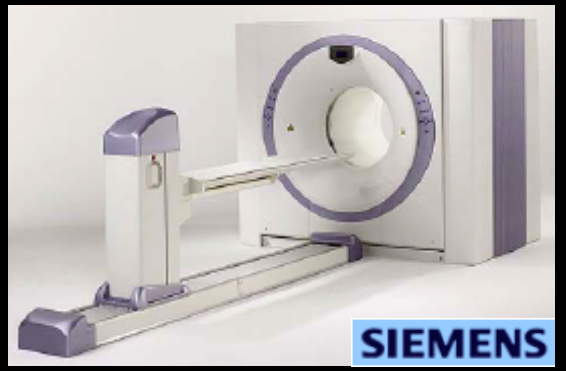
Scanners TEP/CT cliniques commerciaux



Discovery ST, VCT



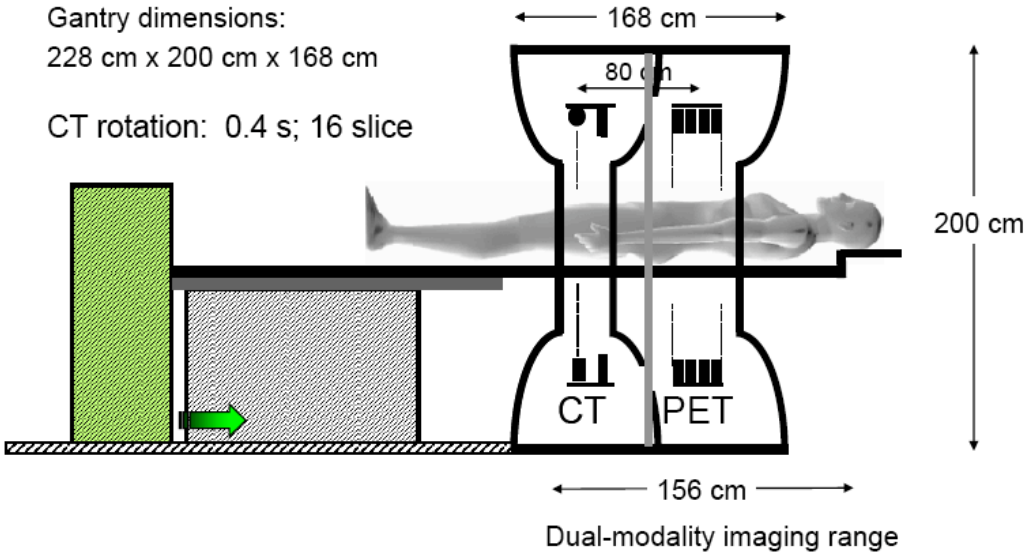
Gemini GXL



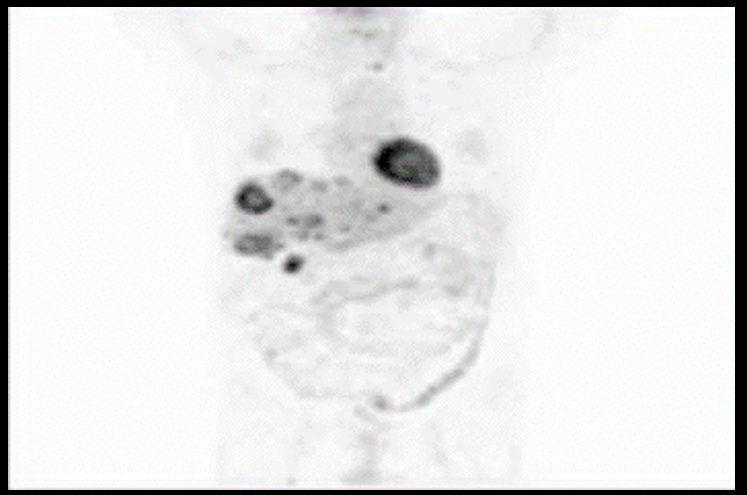
Biograph 6, 16, 64

BGO	GSO	LSO
6 mm x 6 mm x 30 mm	4 mm x 6 mm x 30 mm	4 mm x 4 mm x 20 mm
2D/3D (septa)	3D only (no septa)	3D only (no septa)
8, 16, 64 slice CT	6, 10, 16 slice CT	8, 16, 64 slice CT
70 cm port	70 cm port	70 cm port
11,7 ns coincidence	6 ns coincidence	4,5 ns coincidence

Design typique d'une caméra TEP/TDM



courtesy: D.W. Townsend, UTennessee



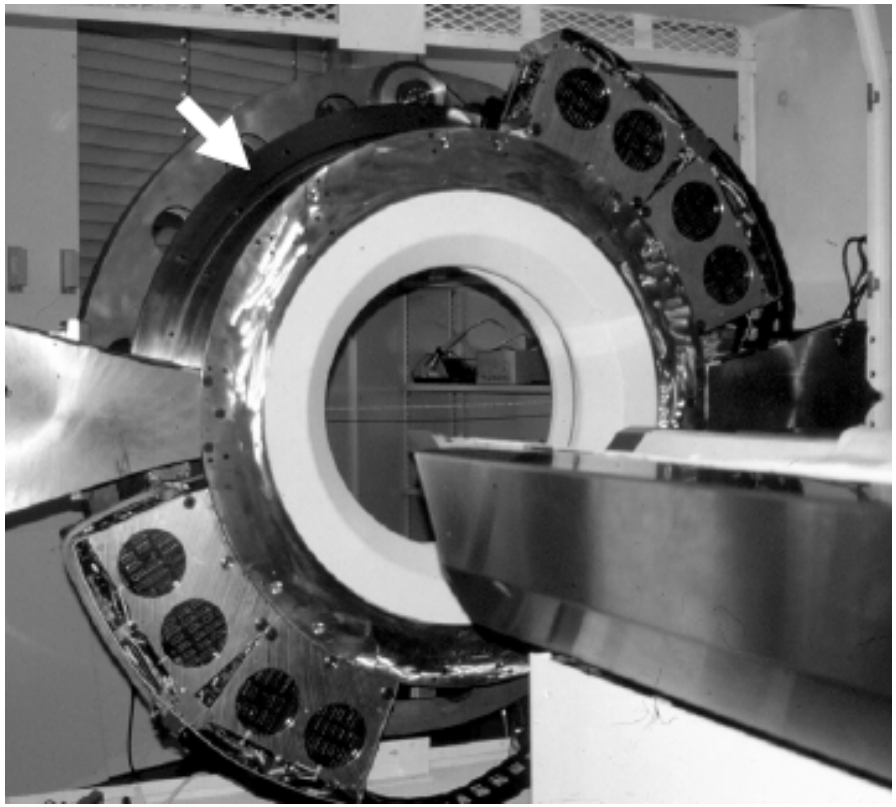
courtesy: D. Visvikis, LaTIM

2001: 1ère caméra commerciale TEP/TDM installée à Zurich par GE

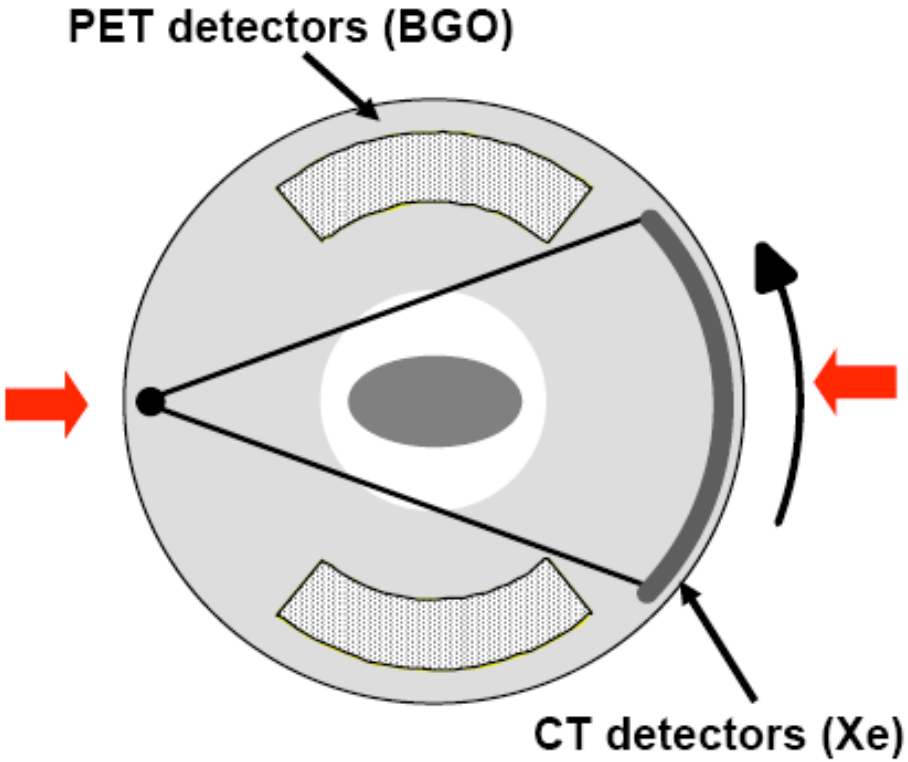
2005: > 650 caméras TEP/TDM, 95% ventes TEP

1991: Concept du TEP/TDM, D.W. Townsend (HUG)

1991: Concept du TEP/TDM, D.W. Townsend (HUG)

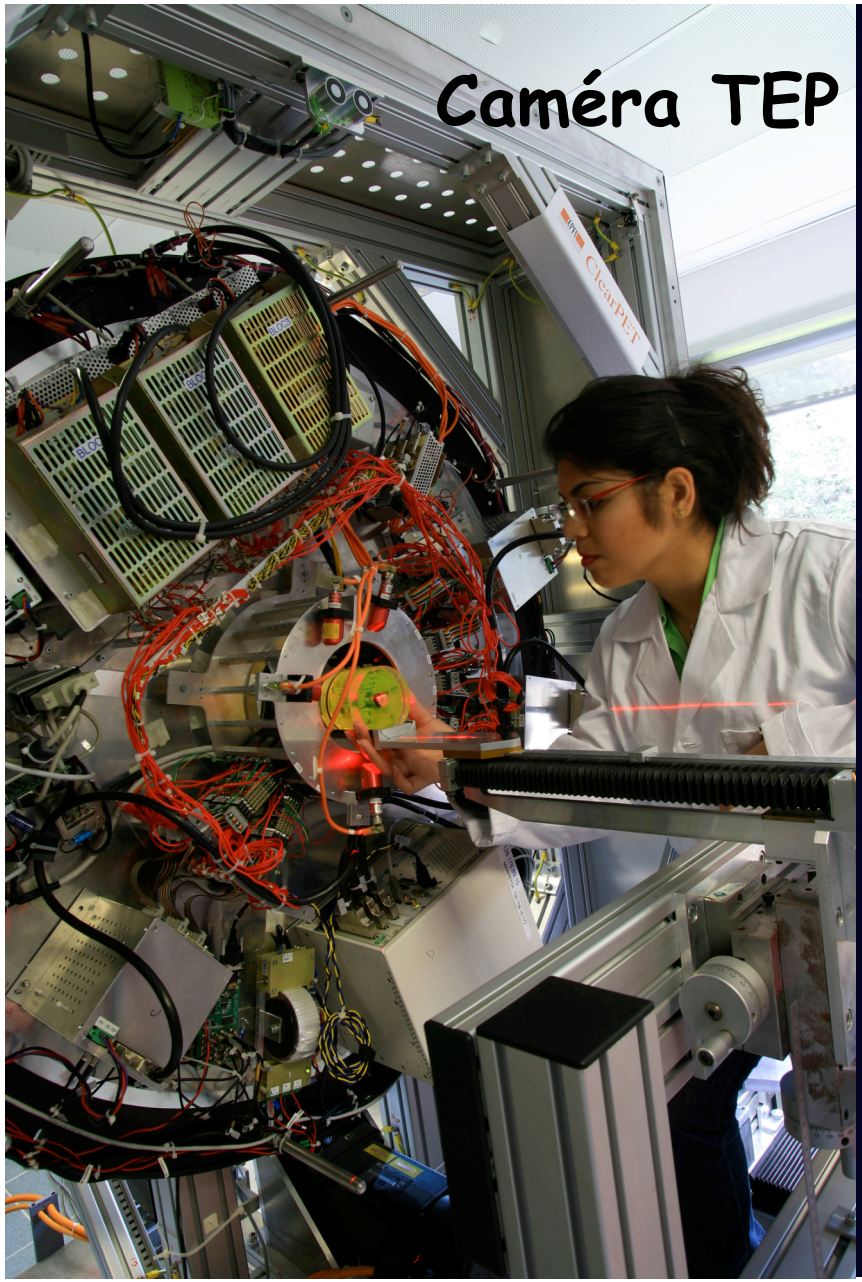


PRT-1

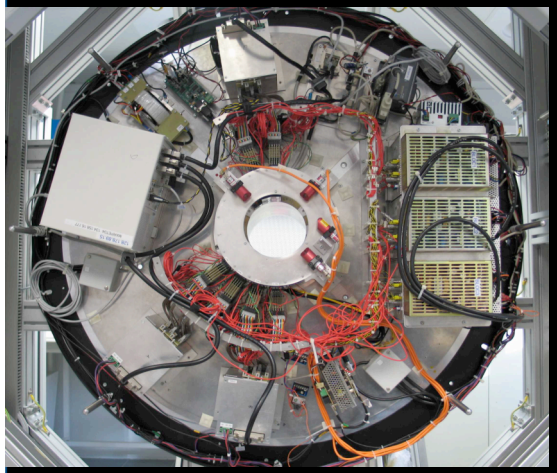


courtesy: D.W. Townsend, UPMC

Caméra TEP pour petits animaux ClearPET



ClearPET + XPAD = ClearPET/XPAD



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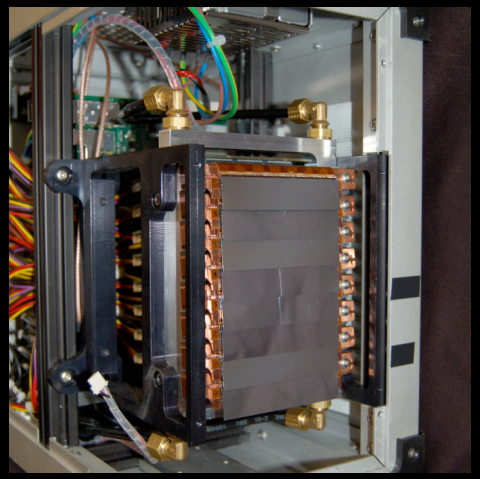

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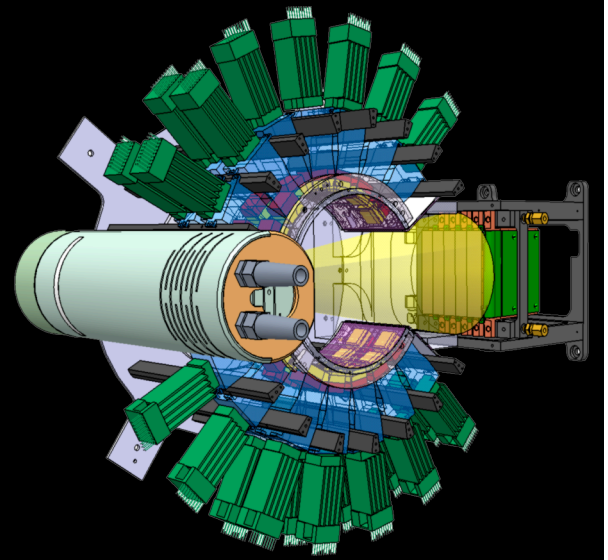


ClearPET (EPFL)

- Géometrie ouverte
- Détecteurs phoswich LSO/LuYAP
- 2 x 64 cristaux de 2 x 2 x 8 mm^3
- PMT multi-anodes à 64 canaux

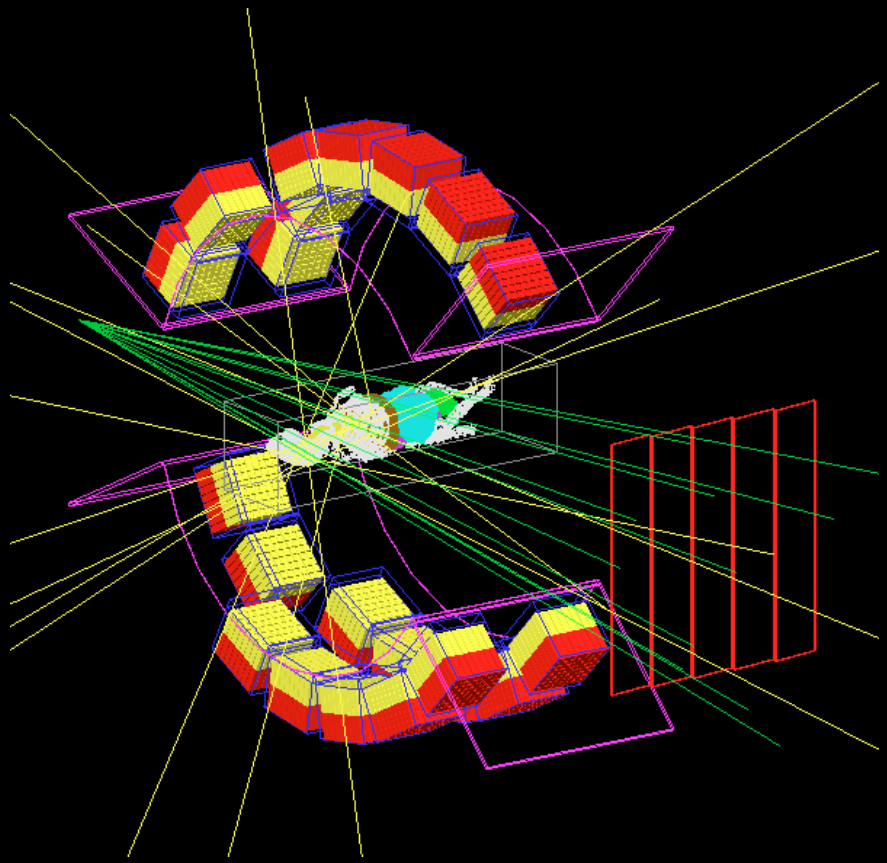
XPAD (CPPM)

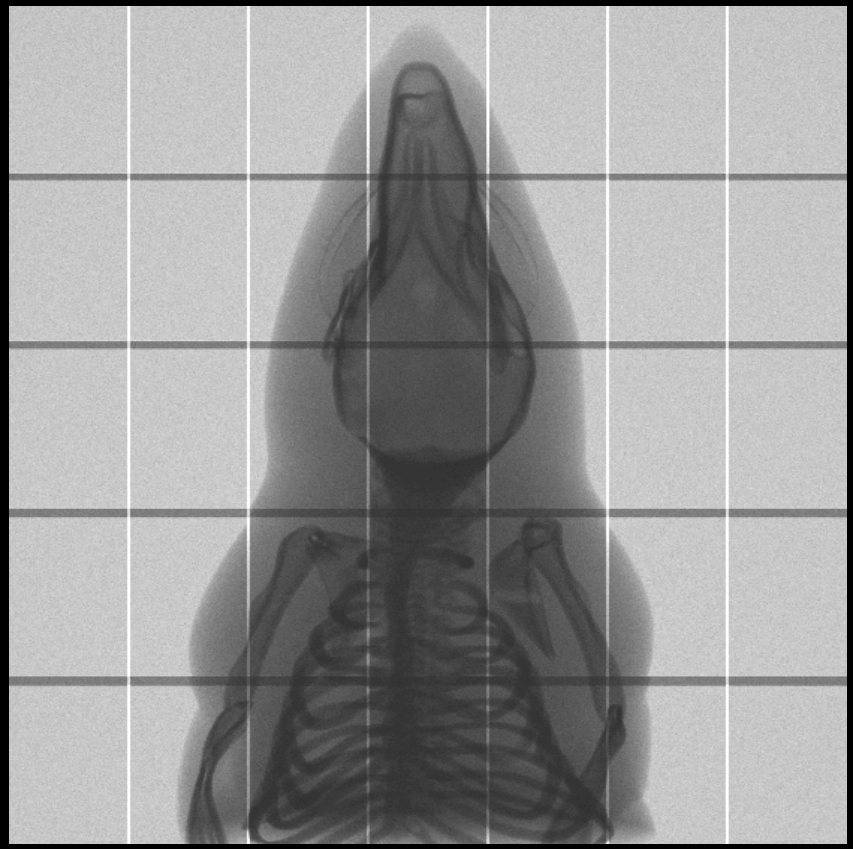
- Détecteur XPAD3
- 500 μm Si pixellisé
- Pixels 130 x 130 μm^2
- 0,5 Mpixels
- Seuils réglables 5-35 keV
- Tube RTW anode de Mo

CleartPET/XPAD

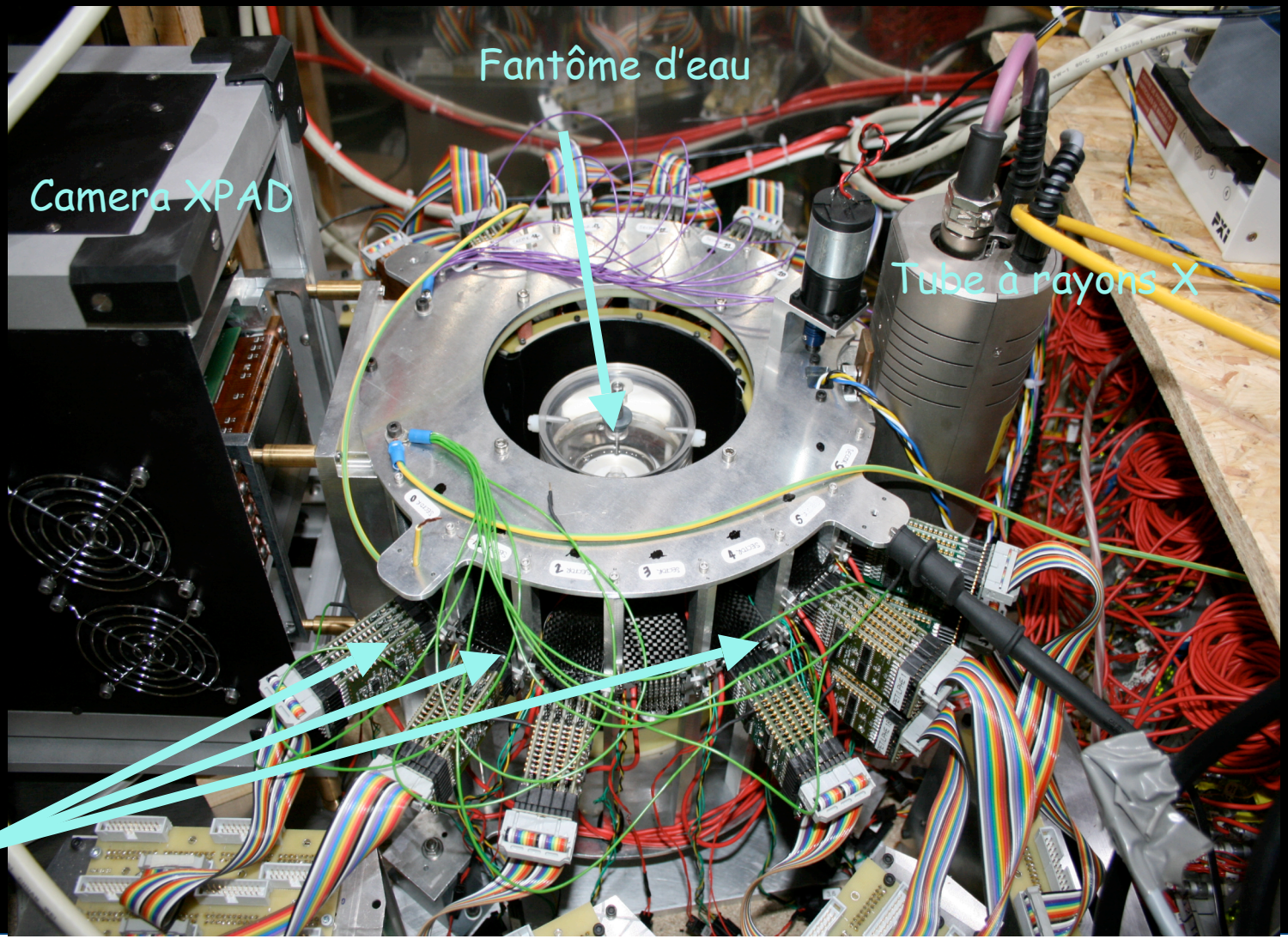
- Tomographie hybride TEP/TDM simultannée
- TEP : 55 mm axial
  111 mm transverse
- TDM : 59 mm axial
  38 mm transverse

Simulation Monte Carlo avec la plate-forme GATE





Preuve de concept pour la tomographie TEP/CT simultanée

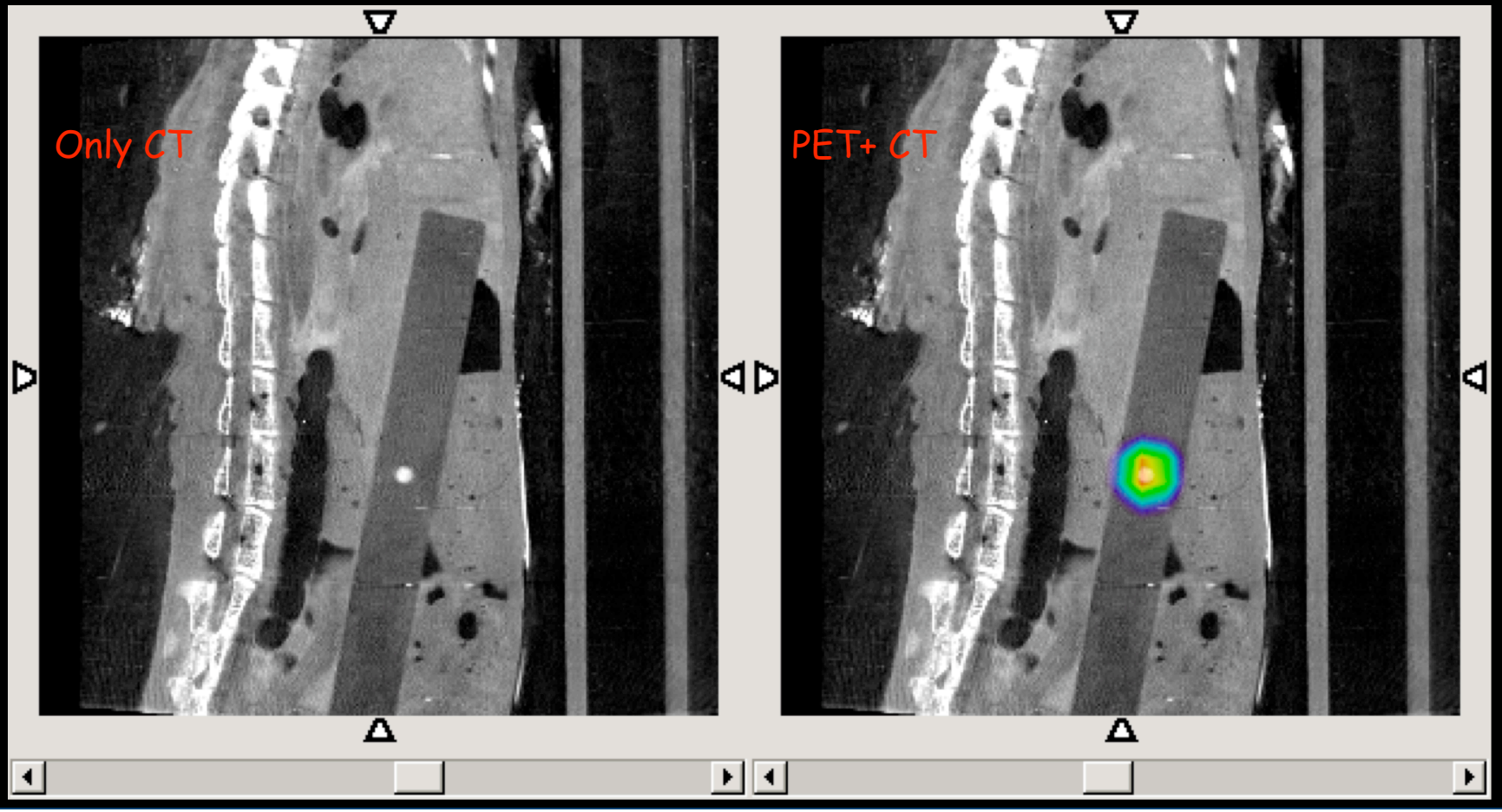


Scan TDM d'une tarente

- Rendus volumiques superposés
- Segmentation des poumons
- 40 kV, 800 µA,
  filtre Nb/Mo
- 720 projections
- 1 s/projection
- 10000 photons/pixel
- Dose (air) : 1 mGy/s à 160 mm

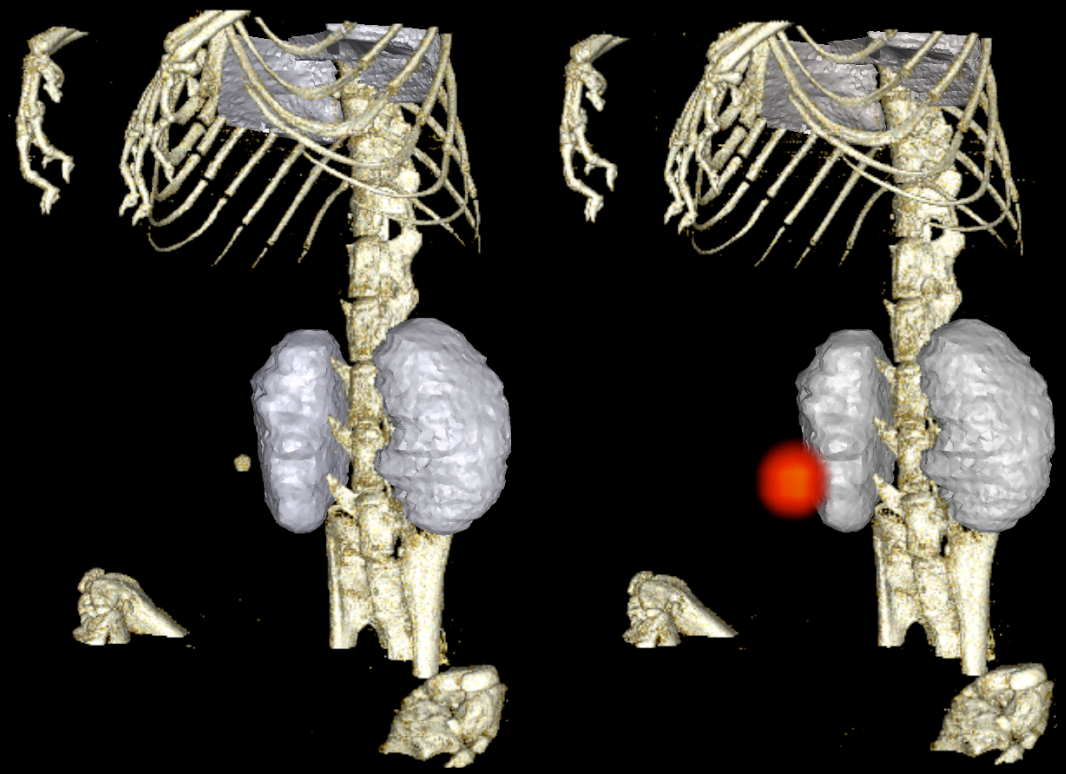
Scan TEP/TDM d'une souris acquis simultanément

Source de ^{22}Na scellée dans un disque de plastic
inséré chirurgicalement dans l'abdomen d'une souris morte

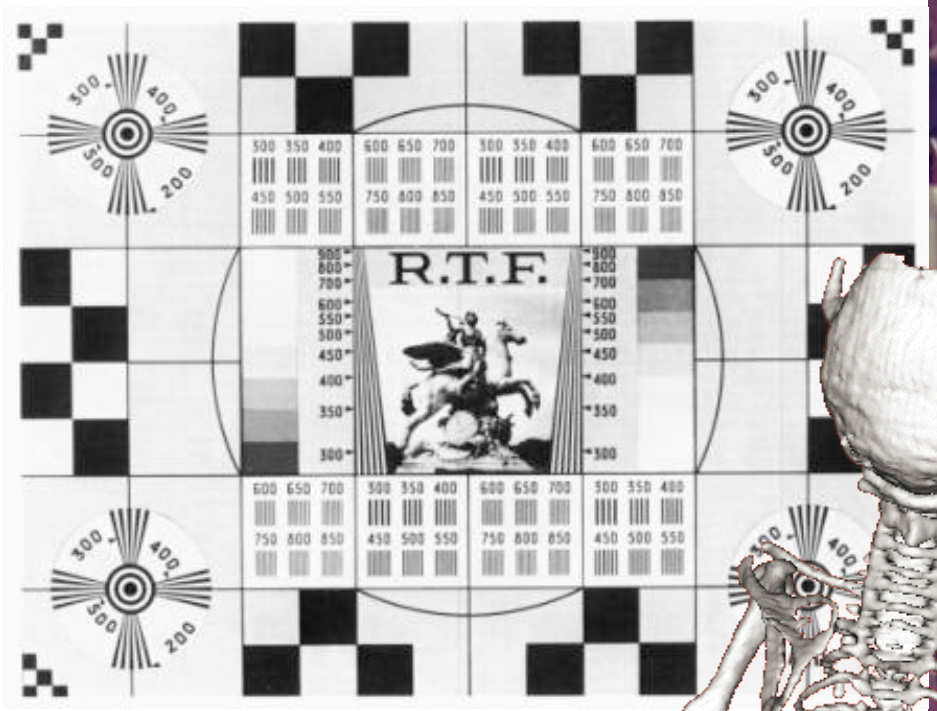


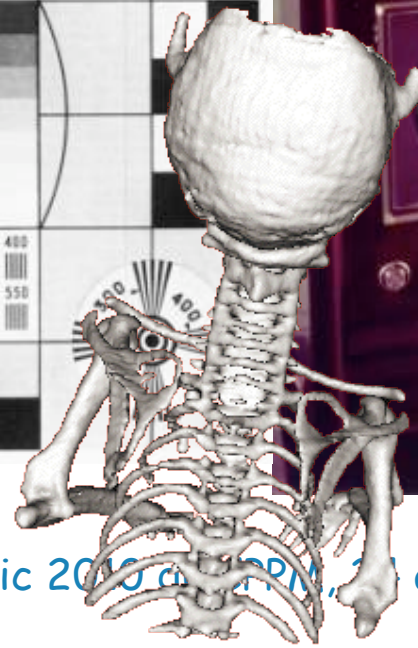
Scan TEP/TDM d'une souris acquis simultanément

- Rendus volumique
- Segmentation des poumons et des reins
- 40 kV, 800 µA, filtre Nb/Mo
- 360 projections
- 1 s/projection
- 10 000 photons/pixel



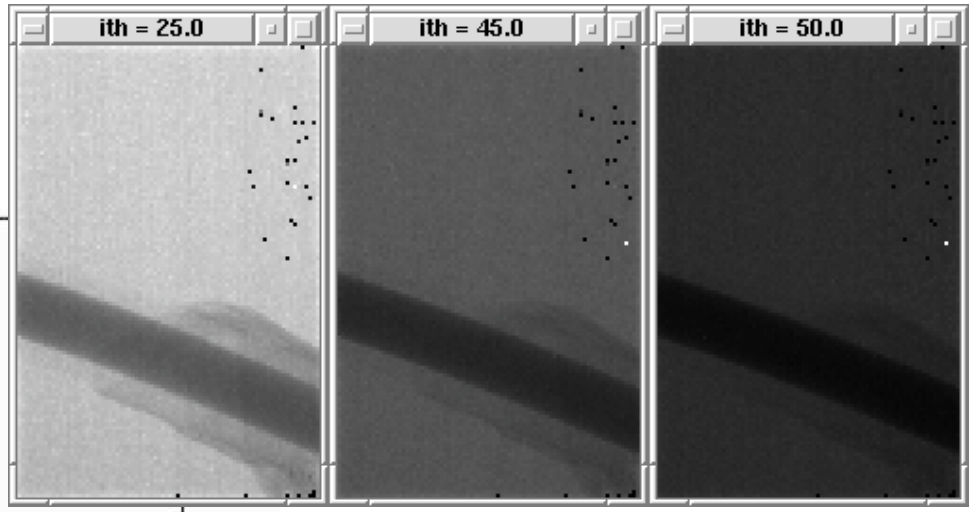
Le scanner X : le passage du noir et blanc à la couleur pour bientôt, grâce aux pixels hybrides

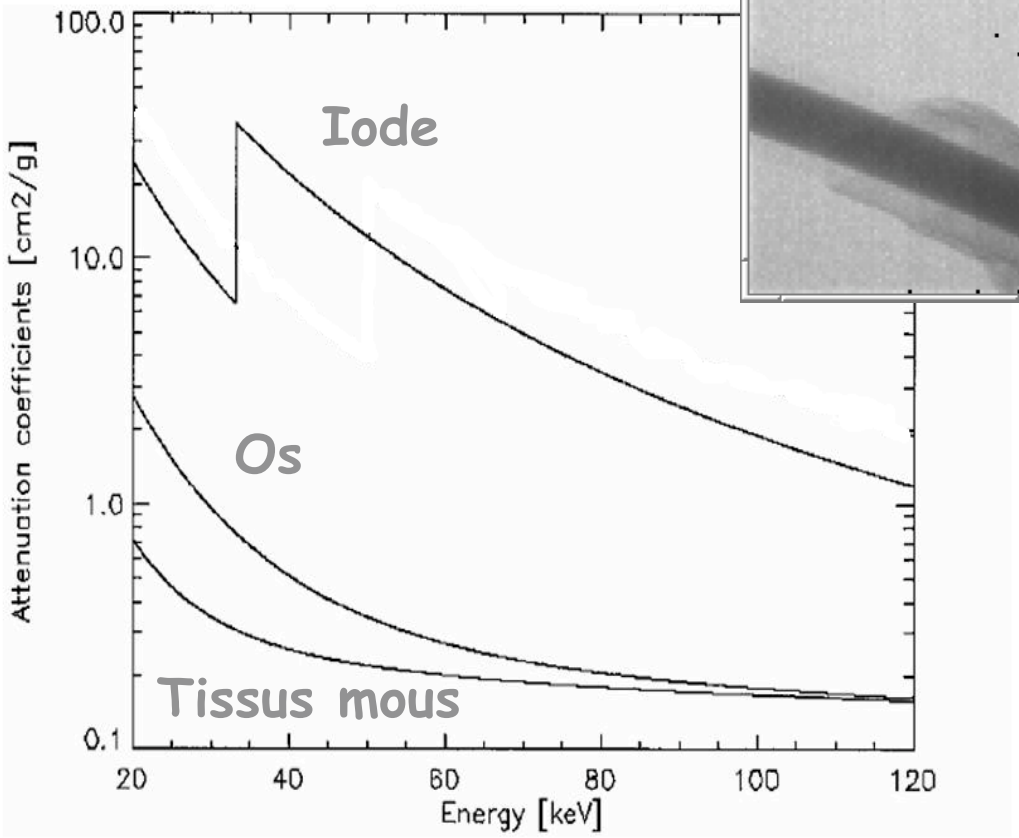


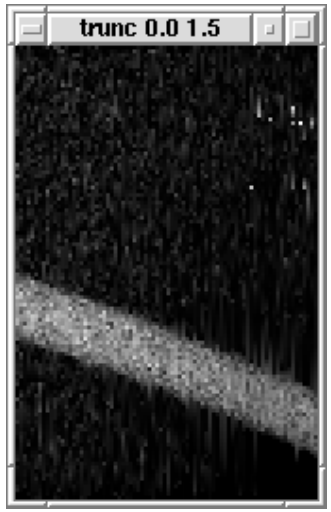


Scanner X : du noir et blanc à la couleur

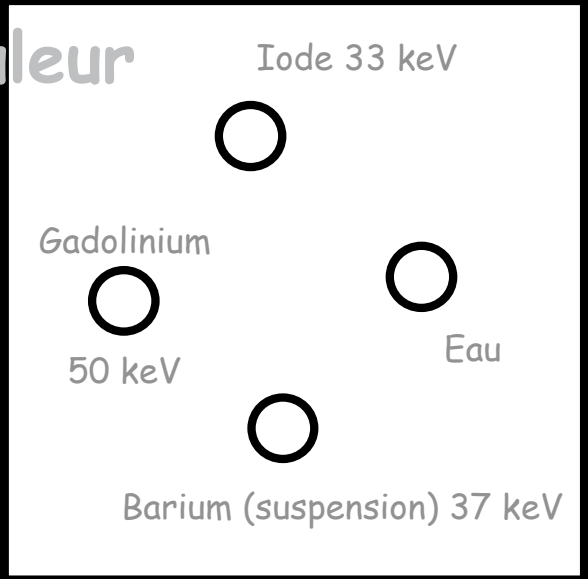
Magnification de contraste



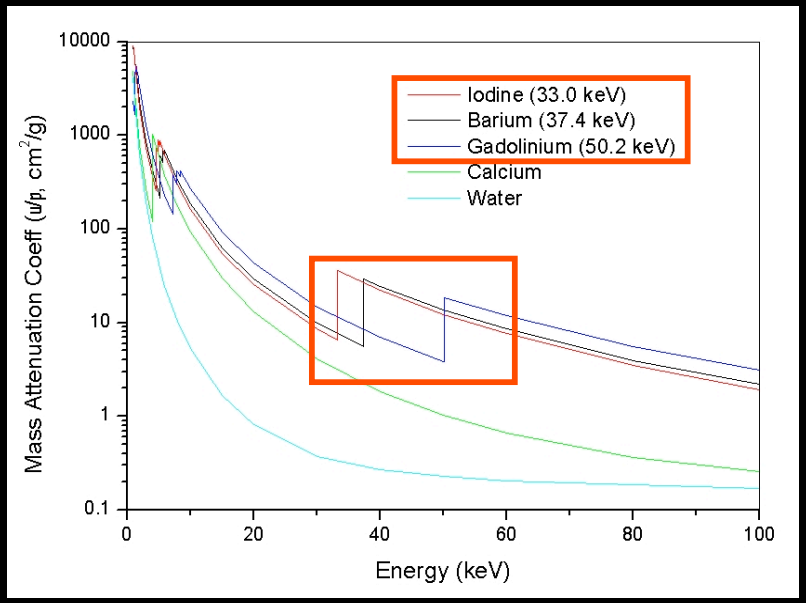


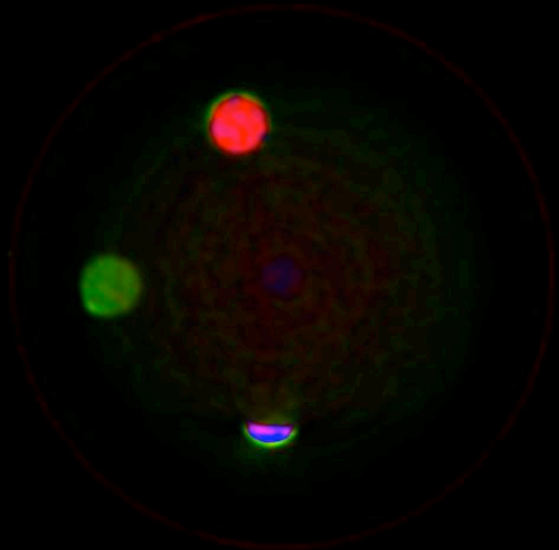


Scanner X: du noir et blanc à la couleur



Capteur CdTe efficace jusqu'à 100 keV



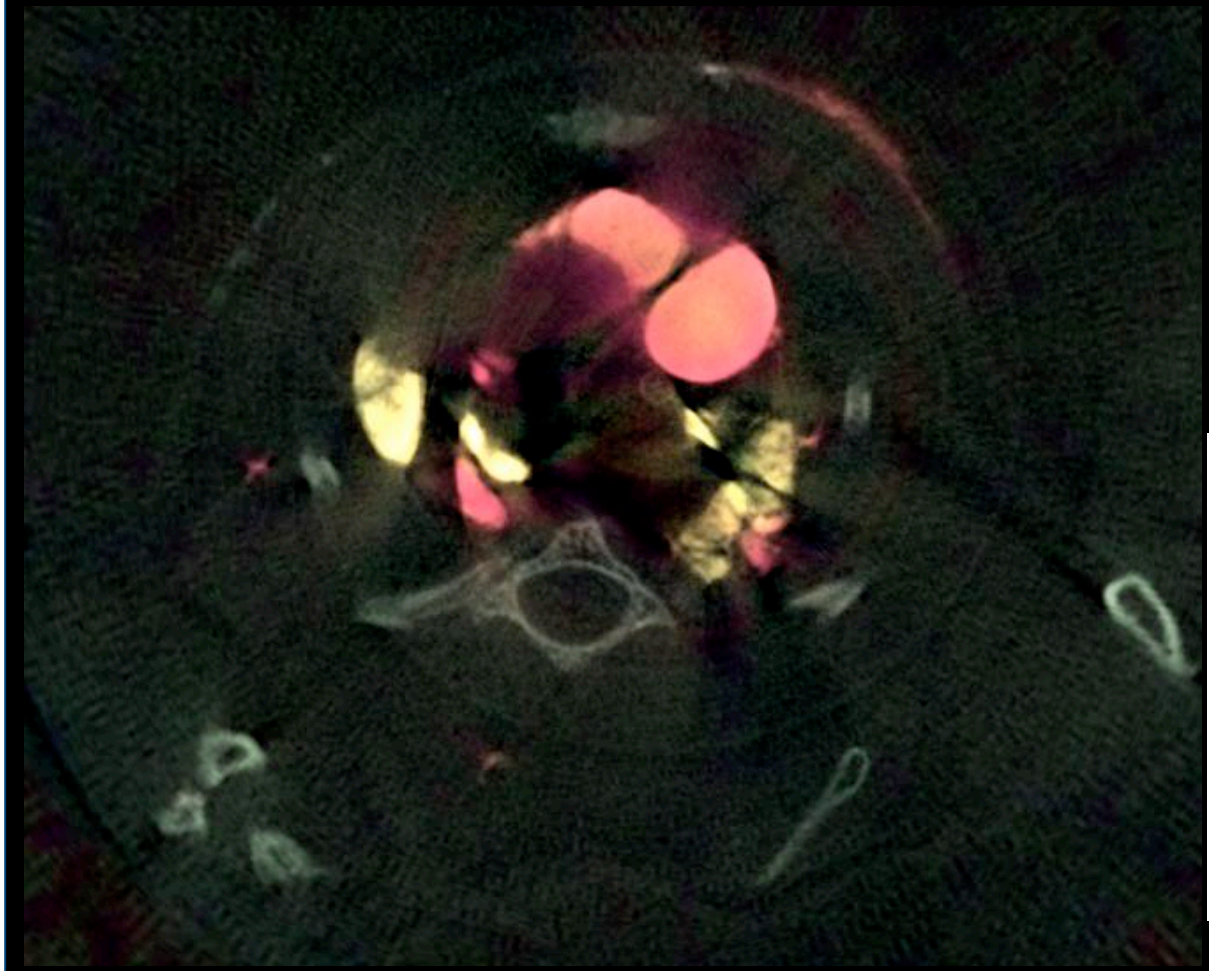


3 pharmaceutiques, fantôme perspex

Université Albert-Ludwigs à Freiburg
et université de Canterbury

courtesy: A. Butler, MARS Biomedical Imaging Ltd.

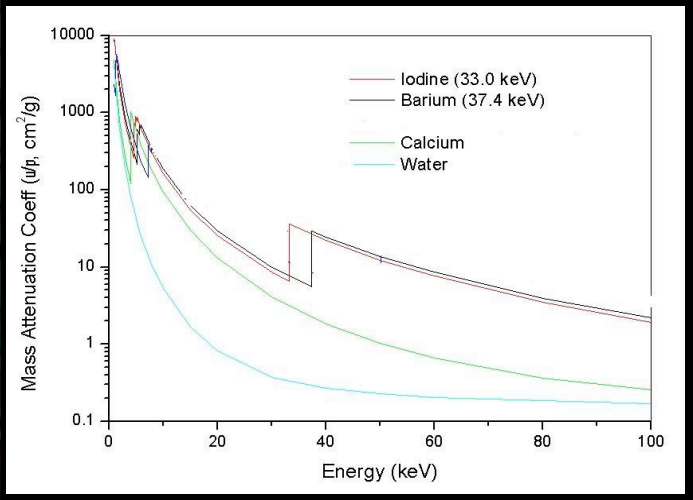
Scanner X : du noir et blanc à la couleur



Iode : circulation pulmonaire

Barium : poumons

Calcium : os normaux



Système quantitatif developpé à l'université d'Erlangen-Nürnberg

courtesy: A. Butler, MARS Biomedical Imaging Ltd.

Equipe imagerie X et gamma

Physique, instrumentation, informatique :

- Alain Bonissent
- Didier Benoit (fGATE -> IMNC)
- Oussama Buhadida (doctorant LPC)
- Yannick Boursier (MCF, UAM 09)
- Jean-Claude Clémens
- Franca Cassol
- Pierre Delpierre
- Pierre-Yves Duval
- Jérémy Godart (doc IMNC, Dr 08)
- Sonia Karkar (IR, UAM 06)
- Maryam Khodaverdi (postdoc 06-07 -> Philips)
- Rana Khoury (Dr 08)
- Christophe Meessen
- Christian Morel (PR, UAM, 05)
- Stan Nicol (doctorant 06)
- Hamid Ouamara (doctorant 10)
- Peter Weiss (postdoc)

Biologie :

- Franck Debarbieux (MCF, UAM 05)
- Thiéric Rodriguez (IBDML)

Electronique/microélectronique :

- Stéphanie Godiot
- Patrick Breugnon
- Benoît Chantepie (Dr 08)
- Arkadiusz Dawiec (doctorant 08)
- Bernard Dinkespiler
- Michel Jevaud
- Mohsine Menouni
- Patrick Pangaud
- Jérôme Royon

Mécanique :

- Jean-Philippe Logier
- Mathieu Niclas
- Françoise Rivière
- Eric Vigeolas