

# X-Ray Medical Imaging and Pixel detectors

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# OUTLINE

- X-ray medical imaging.  
The requirements, some particular features
- Present detectors.
- The new X-ray Flat detectors  
scintillator and photoconductor approach
- How can pixel detectors help medical imaging?  
The detecting material, the readout circuit

## CONCLUSIONS

# X-ray Imaging in Medicine : Radiography, Fluoroscopy, Computed Tomography (1)

The oldest medical imaging technique : projection **radiography** discovered by Röntgen in 1895 :

- About 200 000 systems in the world: best for bones, but also widely used for soft tissues, often with contrast agents, such as barium sulfate for gastro-intestinal imaging.
- **Mammography** is a particular case, as it concerns soft tissues and aims at the detection of very fine calcifications.

# X-ray Imaging in Medicine : Radiography, Fluoroscopy, Computed Tomography (2)

- **Fluoroscopy :**

Originally visual observation of the fluorescent screen.

Now with electronic image converters : XRII

Angiography is a particularly important application of fluoroscopy :

imaging blood vessels after injection of an iodine compound in an artery to detect stenosis or other pathologies.

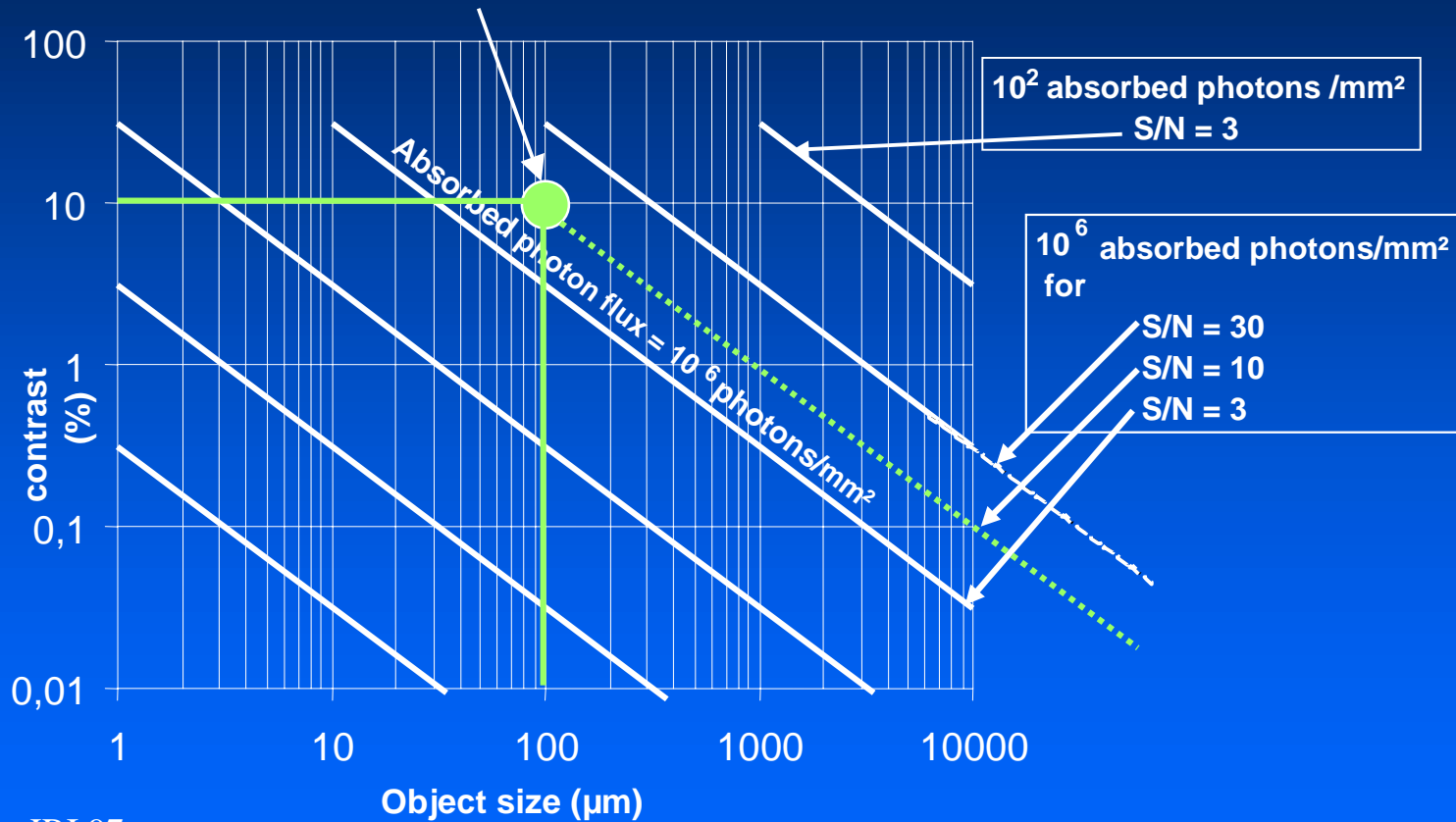
- **Computed tomography** is a 3D imaging technique based on the reconstruction of the object from many linear projections. At present, it does not rely on imaging detectors

# **X-ray Imaging in Medicine : competition with Ultra-Sound, Magnetic Resonance Imaging ?**

- Imaging techniques without ionizing radiation will certainly develop at the expense of X-rays :
  - US is easy to use and cheaper than other modalities.
  - MRI provides invaluable information on soft tissues, and is becoming fast enough to adress cardiac imaging, but will remain expensive.
- X-rays will definitely remain for many years the most practical and cost effective imaging technique for bones, joints, and mammography.

# Physical limitations

Poisson statistics imply a trade off between size-dose-contrast.  
For instance, a **100  $\mu\text{m}$  detail with 10 % contrast** will be detected with a 10:1 Signal to Noise ratio only if the photon flux exceeds  $10^6$  photons / $\text{mm}^2$  (with an ideal detector)



After M.Arques, JRI 97

# X-ray image sampling

The image from a digital detector is spatially sampled, and therefore must comply with the laws of sampling :

Neither signal nor noise spectra should exceed  $\frac{1}{2 \cdot \text{sampling pitch}}$  (Nyquist)

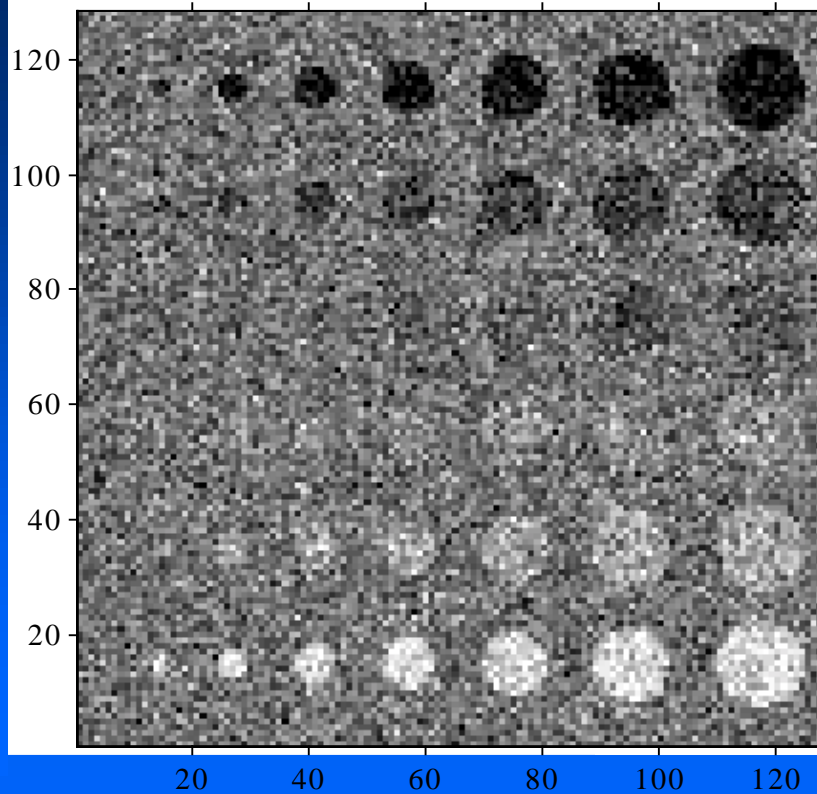
Failure to comply with this law results in aliasing.

A spatial response of the converter layer smaller than the pixel is deceptive : the noise spectrum extends well beyond the Nyquist limit, so that it piles up in the  $[0 - \frac{1}{2 \cdot \text{sampling pitch}}]$  range.

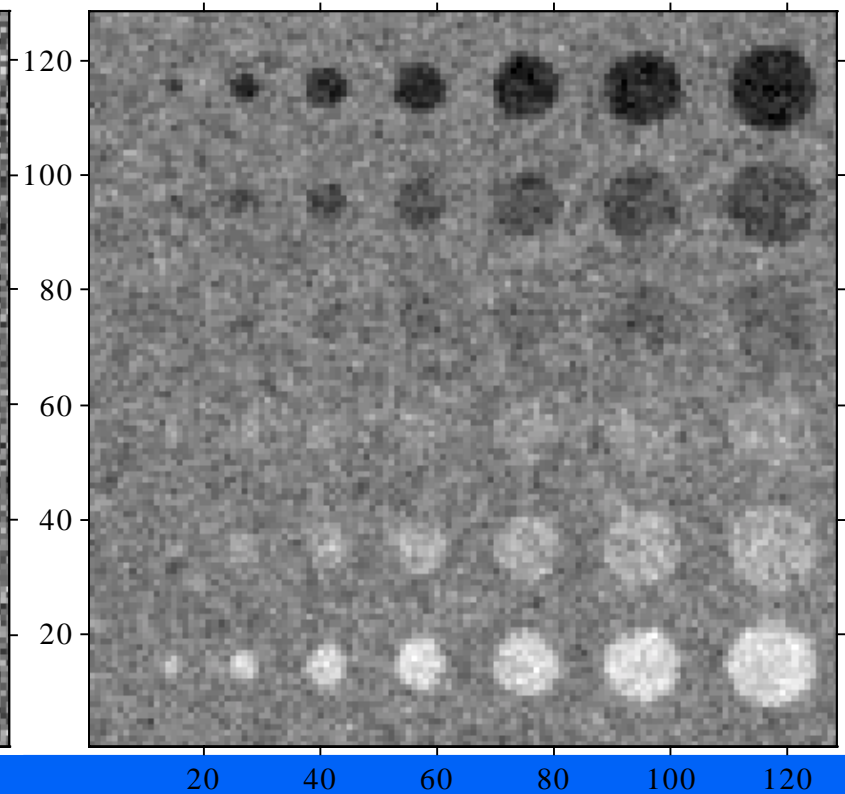
When the spatial response stops at the Nyquist limit, signal and quantum noise are filtered by the same MTF, and the input S/N is preserved as long as the other noises remain small.

# Simulated images : photoconductor and scintillator based detectors

Photoconductor, PSF = Pixel



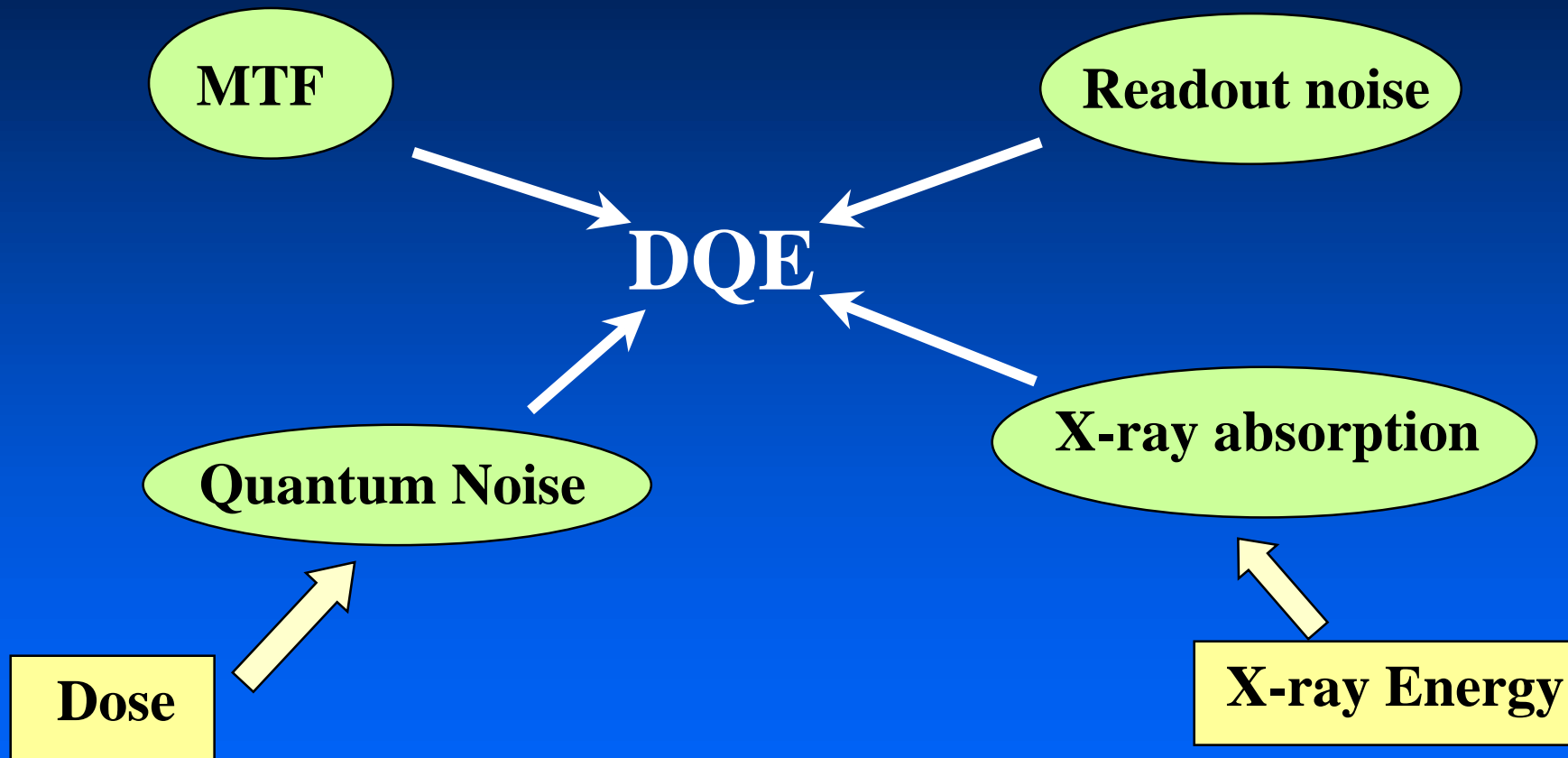
500  $\mu\text{m}$  CsI, measured PSF





# DETECTIVE QUANTUM EFFICIENCY :

## A measure of how well X-rays are used



# Compared requirements for RADIOGRAPHY and FLUOROSCOPY

	General radiography	Mammography	Fluoroscopy
Size	>40 x 40 cm	>18 x 24 cm	>30 x 30 cm
Pixel size	~ 150 $\mu\text{m}$	60-100 $\mu\text{m}$	200-400 $\mu\text{m}$
Typical nb of incid.X/pel	~1000	~5000	~10
Corresponding dose	2.5 $\mu\text{Gy}$	100 $\mu\text{Gy}$	25 nGy
Energy range	30-120 keV	~20 keV	30-120 keV
Input equiv. noise	< 5 X quanta	< 5 X quanta	< 1 X quantum
Dynamic range	12 bit	12 bit	12 bit
Readout time	1-5 s	1-5 s	~30 ms (30fps)

# The present detectors in Radiography (1)

## Film

- At present, the most widely used detection scheme is the **screen-film**.
- A light sensitive silver halide film is sandwiched between two radioluminescent screens, usually made of  $\text{Gd}_2\text{O}_2\text{S:Tb}$  powder in a binding agent.
- The sensitivity vs resolution trade-off results from :
  - the thickness of the absorbing screen,
  - the light absorption or reflection of the backing layer,
  - the size of the grains in the screen.

# The present detectors in Radiography (2)

## Screen - Optics - CCD

- Based on existing elements.
- Possible extension to dynamic imaging.
- The basic obstacle is to get more than 1 el. /X-ray in the CCD ("Quantum sink" situation )
  - According to the laws of optics the collection of light decreases as  $1/\text{demagnification}^2$ . Coupling a 20 cm screen to a 2 cm CCD results in a very poor light collection
  - Fiber optics are the best way to couple a screen to a CCD (but the most expensive...)
- Some optical gain is necessary : X-ray Image Intensifiers

# The present detectors in Radiography (3)

## Storage Phosphors

Electrons created by the absorption of X-rays are stored as a latent image in a screen. It is then read by laser scanning

- Provides a digital image with a very broad dynamic range.
- Handled like film : Thin, identical formats and read time, disposable if damaged. Image quality and resolution comparable to that of screen-films.
- Single reading station for several units.
- Not suitable for fluoroscopy

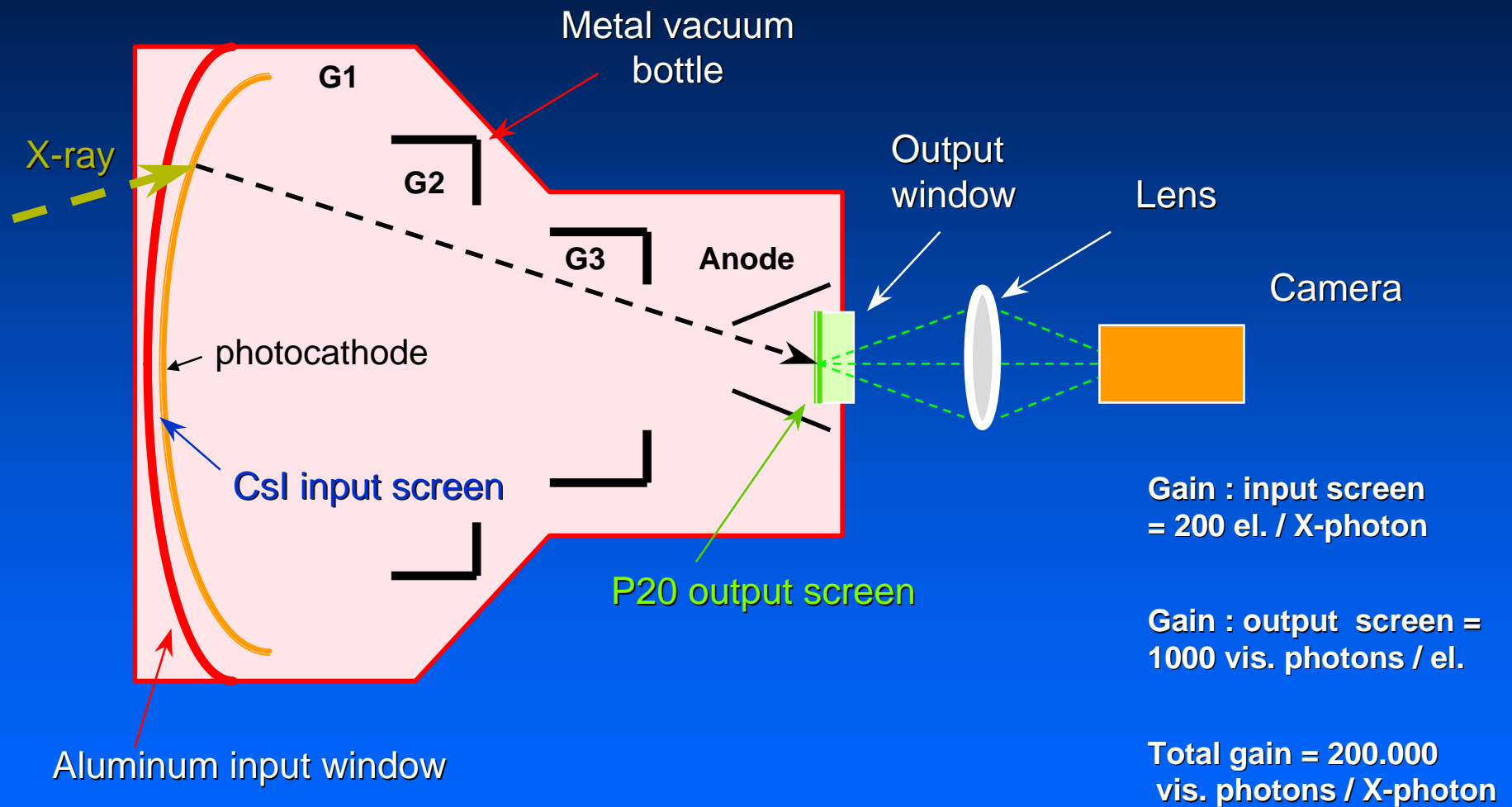
# The present detectors in fluoroscopy

X-ray Image Intensifiers are widely used. They offer an unequaled range of performance :

- X-ray detection efficiency close to the theoretical limits,
- Excellent S/N, even for very low X-ray flux
- Large size, up to  $\varnothing$  400 mm
- Dynamic imaging capability,
- Zooming
- Mature technology, affordable

However, they are bulky, especially for large diameters, and suffer from strong geometrical and magnetic distortion.

# Operation of an X-ray image intensifier



# X ray Image Intensifiers from TTE





# X-ray Flat Detectors, the emerging technology

Two approaches :

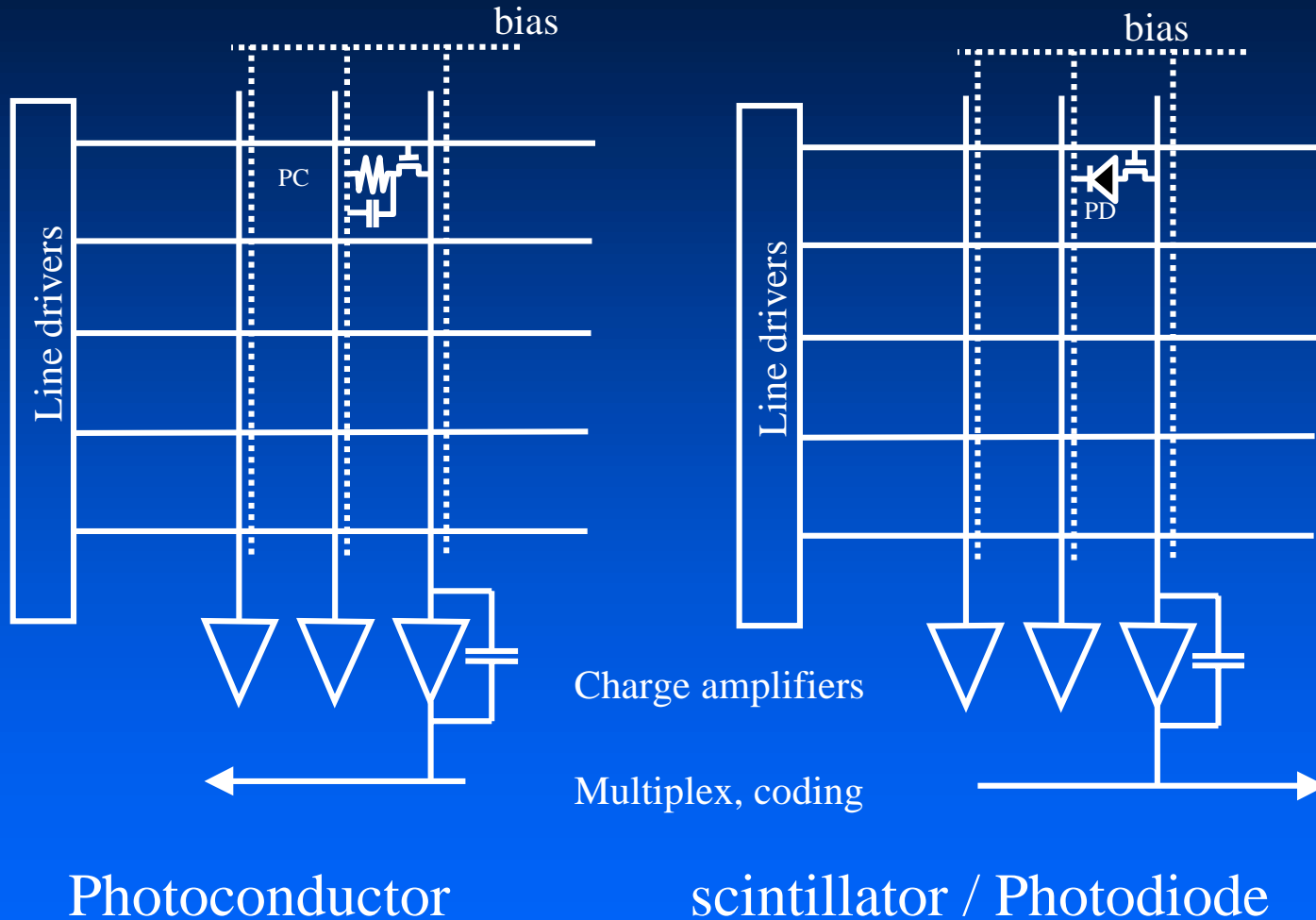
- The scintillator/visible image sensor
- The photoconductor/charge sensor

Both have led to commercial systems.

So far, only amorphous silicon can be obtained in the required sizes. Image sensors as well as charge detection arrays can be built with a technology derived from that of LCD active matrices

An assembly of standard single crystal Si circuits is also possible, but such tiling results in challenging technical obstacles.

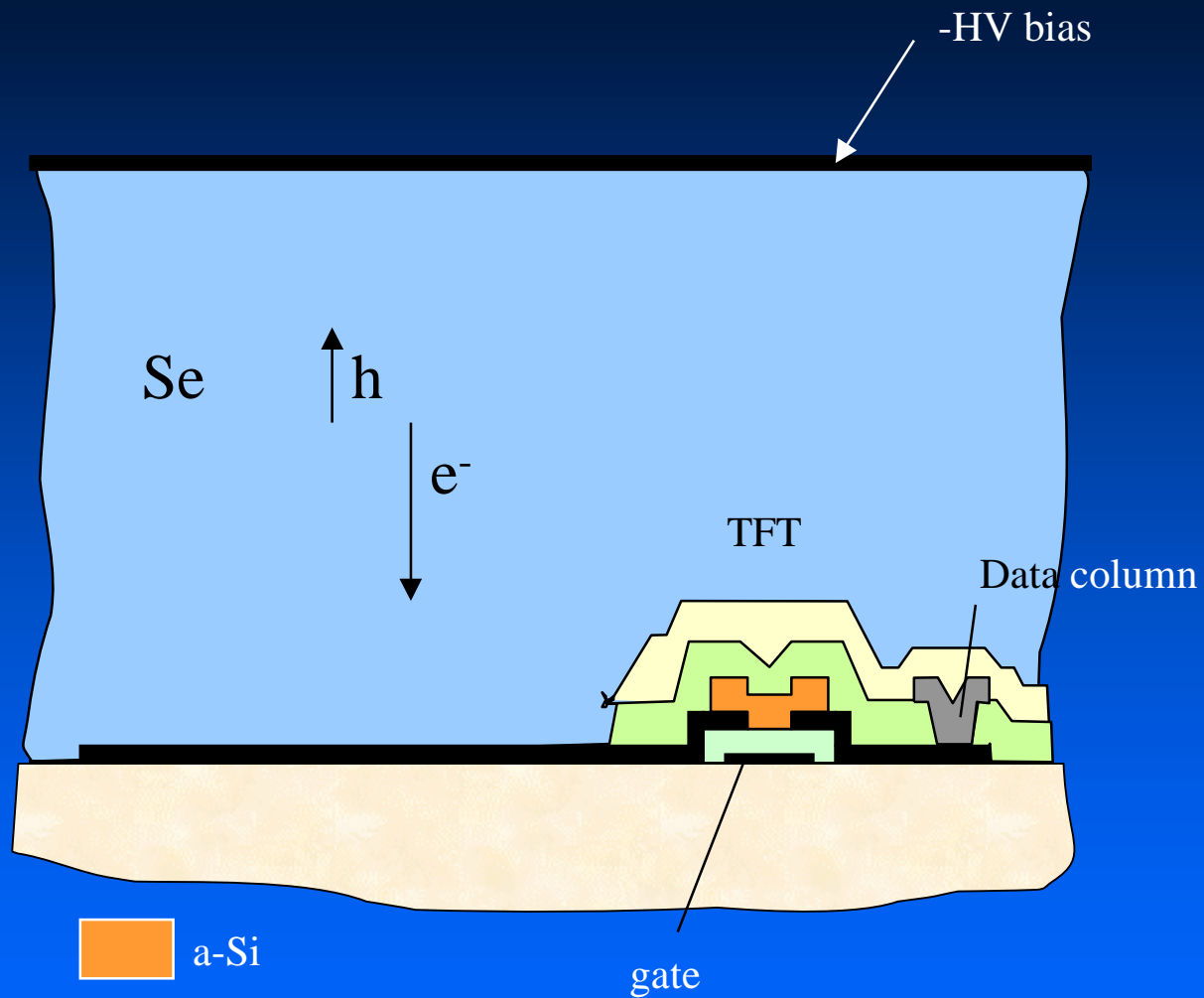
# Readout Architecture



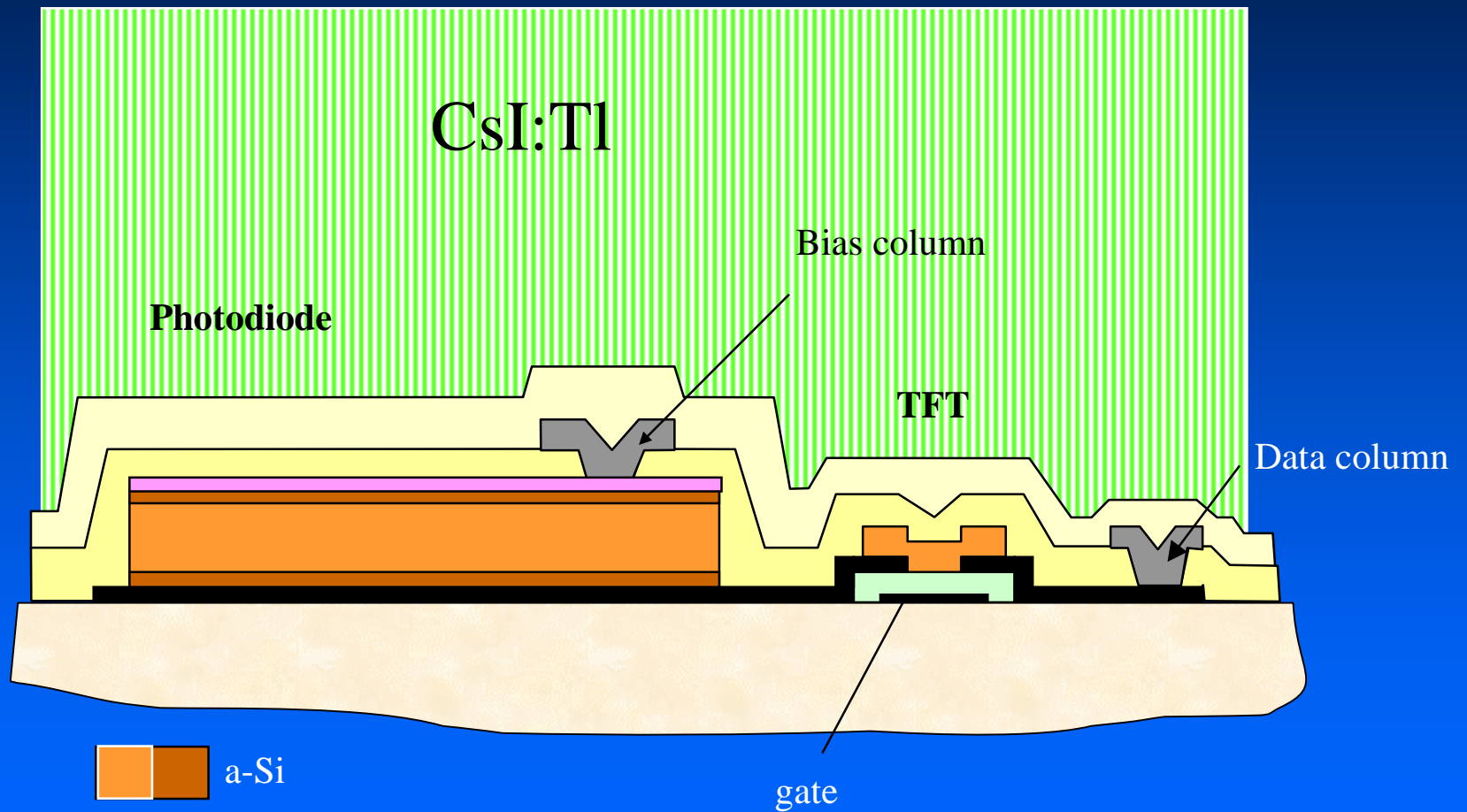
Photoconductor

scintillator / Photodiode

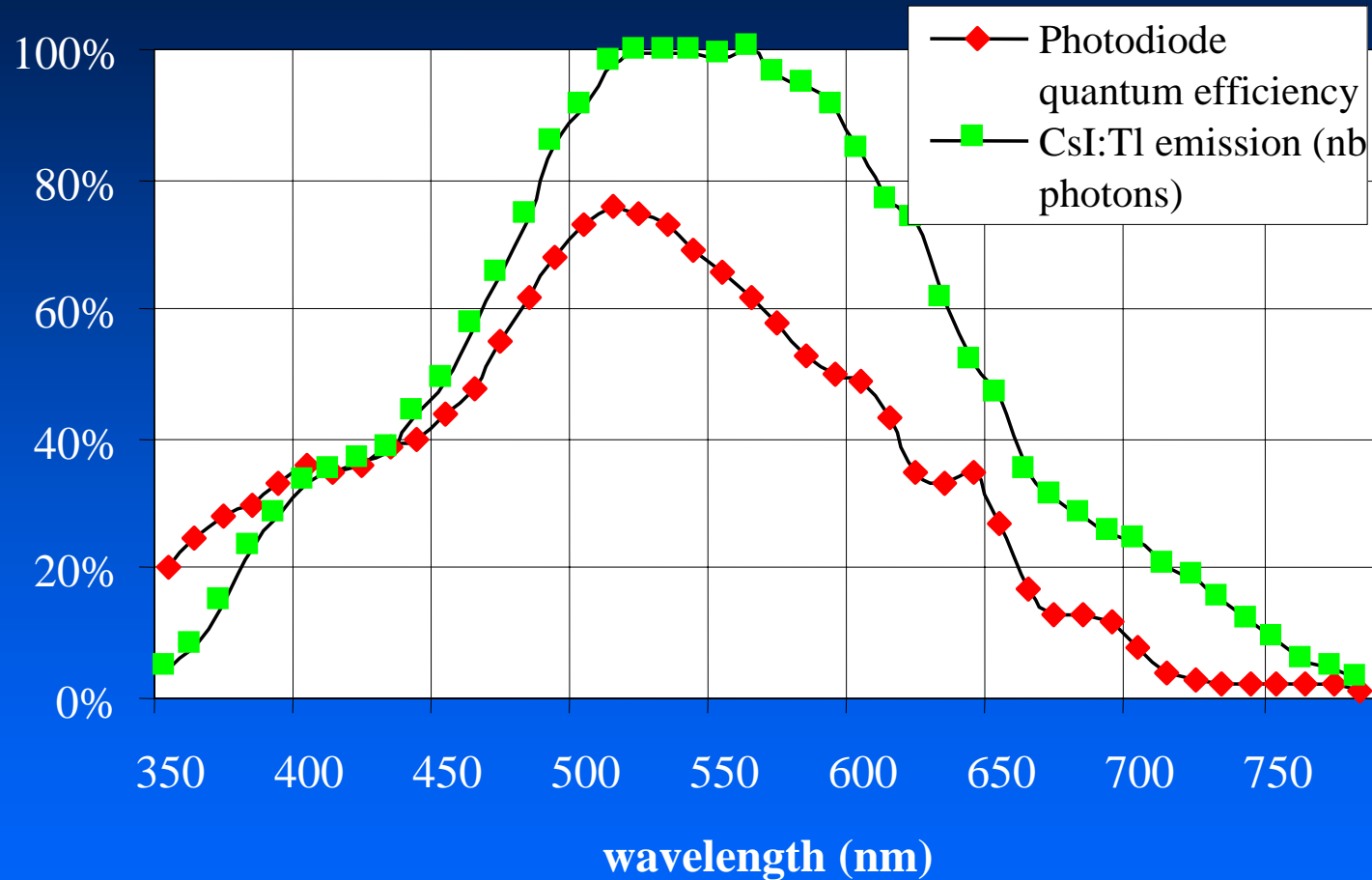
# The Photoconductor based pixel



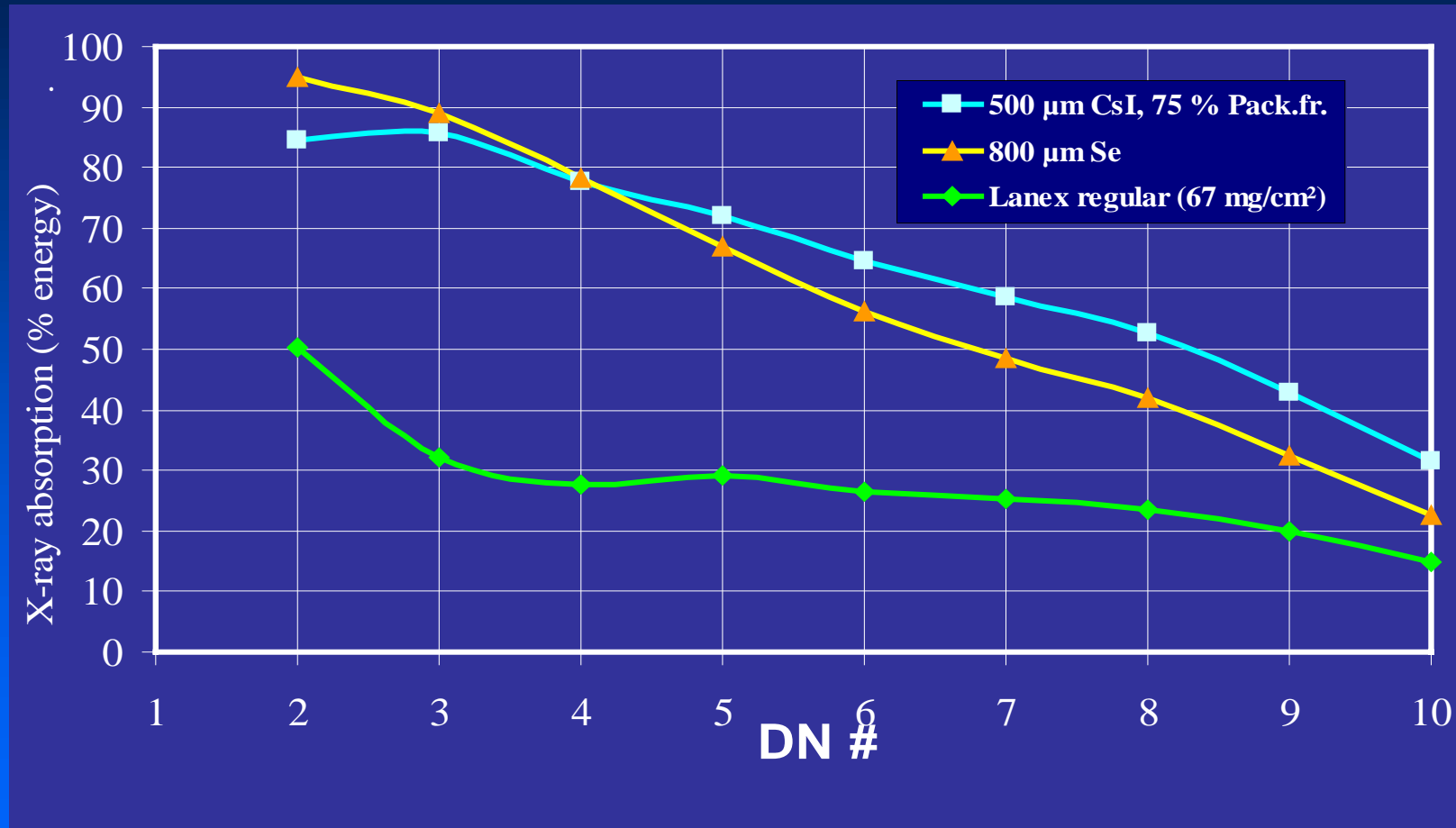
# Cross-section of a scintillator-photodiode-TFT pixel



# Photodiode quantum efficiency and CsI:Tl fluorescence spectrum



# Energy absorption of different materials (standard DN spectra, escape taken into account)



# Compared Performance of scintillator based detectors

	Colbeth et al. <sup>1</sup>	Jung et al. <sup>2</sup>	Weisfield et al. <sup>3</sup>	Kameshima et al. <sup>4</sup>	Chaussat et al. <sup>5</sup>	Granfors <sup>6</sup>
Structure	Gd <sub>2</sub> O <sub>2</sub> S:Tb or CsI:TI/TFT	CsI:TI/TFT	Gd <sub>2</sub> O <sub>2</sub> S:Tb/TFT	Powd.phos./MIS	CsI:TI/DD	CsI:TI/TFT
Overall active size (cm)	19.5 x 24.4	20 x 20	40.6 x 29.3	43 x 43	43 x 43	41 x 41
Number of pixels	1536 x 1920	1024 x 1024	2304 x 3200	2752 x 2752	3120 x 3120	2048 x 2048
Pixel size	127 μm	200 μm	127 μm	160 μm	143 μm	200 μm
X-ray abs. @RQA5	~40%(Gd screen)	~80 %	~40% (Gd screen)	N.A.	~80%	~75%
Presamp.MTF @ 2 lp/mm	20%	20%	40%	40%	35%	N.A.
Read noise (equ. X phot.) / acq.time	4-5X / 35ms	~1X / 35ms	3-4 X / 5s	N.A. / 1s	4-5 X / 1.5s	N.A. / <5s ( ~1X / 35ms for 20 x 20cm.)
Dynamic range	N.A.	N.A.	4000:1	6000:1	4000:1	N.A.

N.A.= not available.

<sup>1</sup> Varian 99, <sup>2</sup> Philips 98, <sup>3</sup> dpiX 98, <sup>4</sup> Canon 98, <sup>5</sup> Trixell 98, <sup>6</sup> General Electric 2000  
RQA5 is a standard for X-ray quality : 70 kV DC on the X-ray tube, 23 mm of Al filtration to simulate the patient.

# Compared performance of photoconductor based detectors

	A.Tsukamoto et al. <sup>1</sup>	G.Shaber et al. <sup>2</sup>	J.Rowlands et al. <sup>3</sup>
Structure	500 $\mu\text{m}$ a-Se/TFT	500 $\mu\text{m}$ a-Se/TFT	300 $\mu\text{m}$ a-Se/TFT
Overall active size (cm)	23 x 23	35.6 x 43	5 x 7.5
Number of pixels	1536 x 1536	2560 x 3072	360 x 480
Pixel size	150 $\mu\text{m}$	139 $\mu\text{m}$	160 $\mu\text{m}$
X-ray abs. @RQA5	70%	52%	37%
Presampl.MTF @ 2 lp/mm	80%	85%	80%
Read noise (equ. X phot.)/ acquisition time	N.A./ 35 ms	12-15X/a few sec	N.A.
Dynamic range	N.A.	4000:1	N.A.

N.A.= not available. <sup>1</sup>Toshiba 99, <sup>2</sup> Sterling 98, <sup>3</sup> University of Toronto 98.  
RQA5 is a standard for X-ray quality : 70 kV DC on the X-ray tube, 23 mm of Al filtration to simulate the patient.



## Commercial devices

Clinical tests have been performed for many years, and several manufacturers are now starting the production :

**Scintillator screen / a-Si array :**

TRIXELL, GEMS, CANON

**Selenium :**

KodaK-HOLOGIC (formerly STERLING)

According to the manufacturers, various applications are (or will soon be) covered : General and chest radiography, mammography, cardiac angiography

# Pixium 4600 and radiographic table



## Thorax image with a pixium



TRIXELL

# The benefits of the new X-ray Flat detectors

- **Improved conditions :**

Immediate readout. The patient no longer waits in painful positions for the development of the film, and a new shot. The clinician has easier access to the patient during intervention.

- **Reduced running cost** (increased throughput of radiology rooms, no film, no chemicals, no waste processing, cheaper storage of data).

- **Less dose:** depending on the device, the required dose is 100 to 40% of the film dose (for a given S/N in the image).

- All the advantages of a digital image : processing, transfer, archiving, access to Computer Aided Diagnosis,....

# The weak points of the new X-ray Flat detectors

- High investment costs (detector + image display & process.), because the detector relies on specific techniques (a-Si photodiodes, converter material,...) and requires the assembly of many expensive components.
- Difficult image corrections : offset and gain correction accuracy limited by small non-linearities and drifts.
- At very low dose (fluoroscopy), obtaining a S/N comparable to that of XRII requires extreme care (costly!)

## What next?

Development time extremely long :

The work on the present generation started in the mid eighties

=> **It is time to prepare the next generation !**

**Which improvements are worth a new development?**

*A spectacular improvement in resolution or dose is unlikely.*

Reduce manufacturing costs without compromising on performance : make it simpler!

Increase the S/N in fluoroscopy

Open new modalities dual energy, tomosynthesis,...

# The detecting material

Obviously the cornerstone of future devices.

Should combine :

- Strong X-ray absorption from 20 to 150 keV,
- large area deposition technique,
- Chemical, thermal compatibility with Si,
- high resistivity,
- high  $\mu\tau E$ , preferably with a low  $E$ ,
- low e-h creation energy (50 eV in Se, 5 eV desirable),
- environmentally acceptable ( $\text{HgI}_2$ ...?)

At present, there is no consensus on a potential workhorse.

# Can pixel detectors meet the requirements of medical imaging (1)?

Single crystal silicon technology will soon reach the point where elaborate functions can be implemented in a 100-200  $\mu\text{m}$  pixel, with a realistic yield over a large area.

A suitable converter material is still to be found : CdTe, PbI<sub>2</sub>, HgI<sub>2</sub>, PbO,....

Discrimination and counting in a pixel would open new possibilities : suppression of offset correction, dual energy, better linearity, no longer escape noise...

However, it should be borne in mind that the counting rate will be huge : in the worst (but common) case where the patient does not cover the whole detector,  $\sim 10^7$  photons/s hit each pixel.



# Can pixel detectors meet the requirements of medical imaging (2)?

- Tiling will still be required for general radiography.
- Integration of driving and readout circuits will help to reduce manufacturing costs, but redundancy will be mandatory in order to reach reasonable yields.
- The better linearity should alleviate the task of matching the different tiles to avoid the checkerboard effects.
- Realistic assembly techniques are still to be found
- **COST** will most likely be the driving force, more than performance, as the pressure on health budgets will undoubtedly increase.

## Conclusions

- X-ray imaging may benefit from the development of pixel detectors :
  - Simpler devices thanks to higher integration.
  - Rely on the standard Si technology.
  - Better S/N at very low doses.
- Besides the work on Si circuits, the need for a good X-ray converter is a prerequisite.