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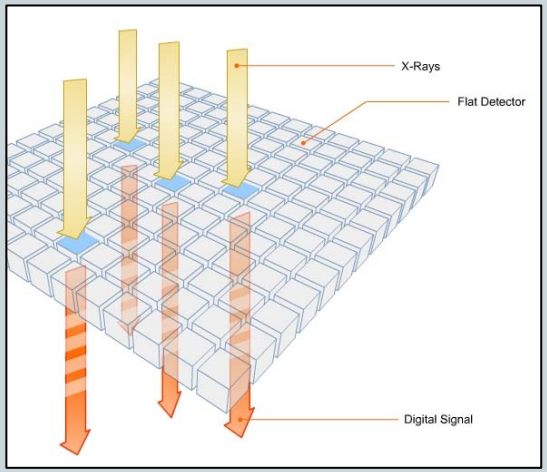
X-ray detectors in healthcare and their applications

Pixel 2012, Inawashiro

September 4th, 2012

Martin Spahn, PhD



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- Clinical applications of X-ray imaging
- Current X-ray detector technology
  (case study radiography and angiography)
- Drivers shaping X-ray imaging
- An outlook to the possible future of X-ray detectors:
  Opportunities and challenges
- Summary

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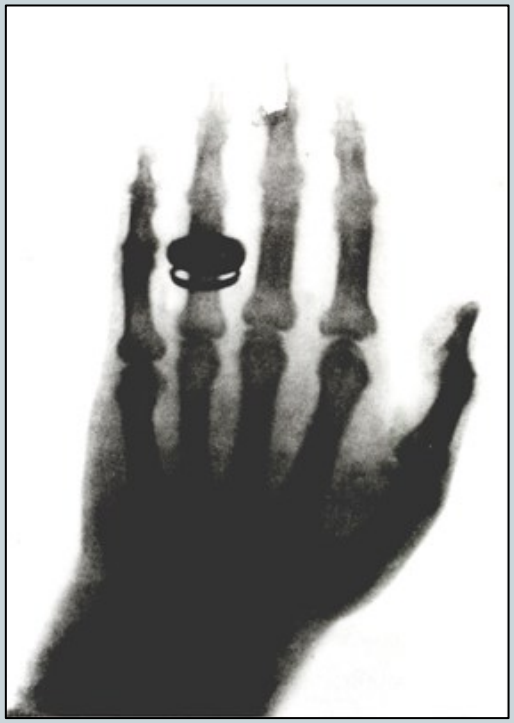
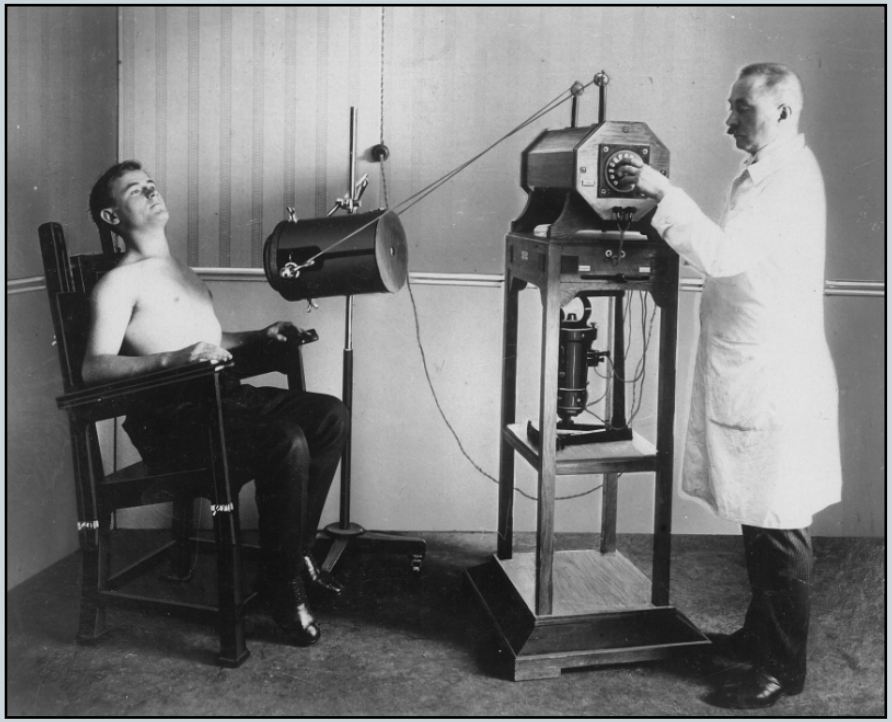
X-ray imaging is more than 100 years old …





… and has become an indispensible tool for a broad spectrum of clinical imaging applications

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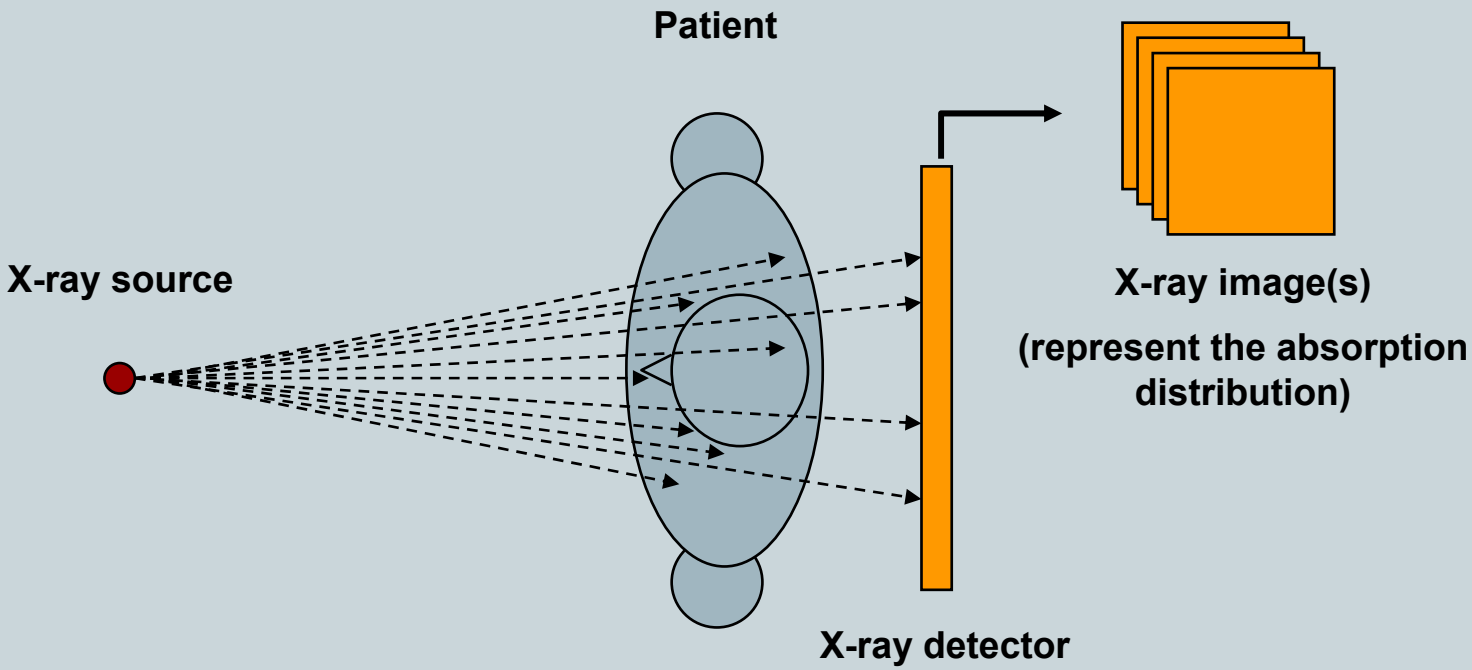
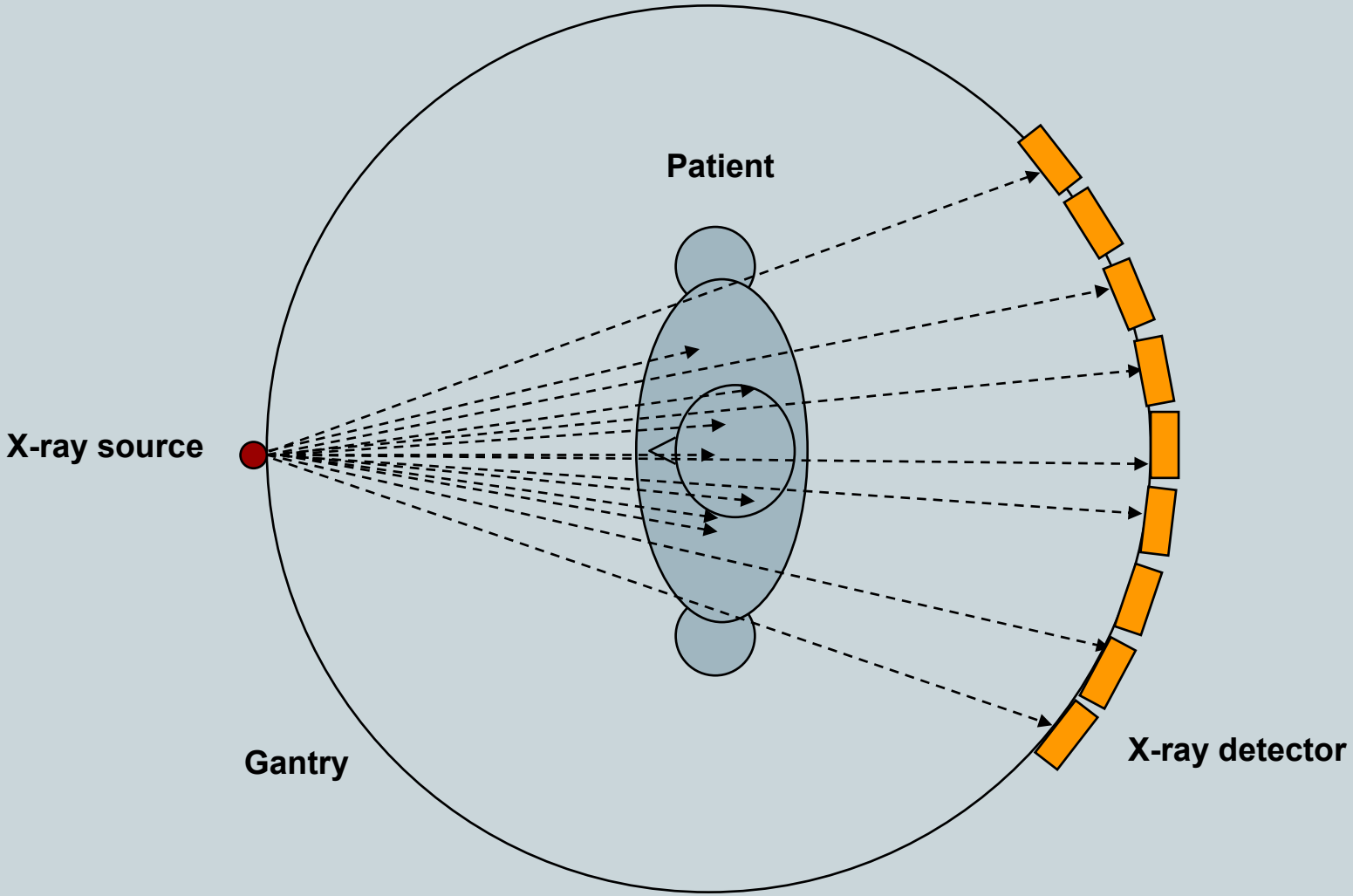
The geometry of X-ray acquisition systems is common to different medical imaging modalities



Multi-slice CT (computed tomography) uses a fan-beam geometry with multiple image acquisitions during the rotation



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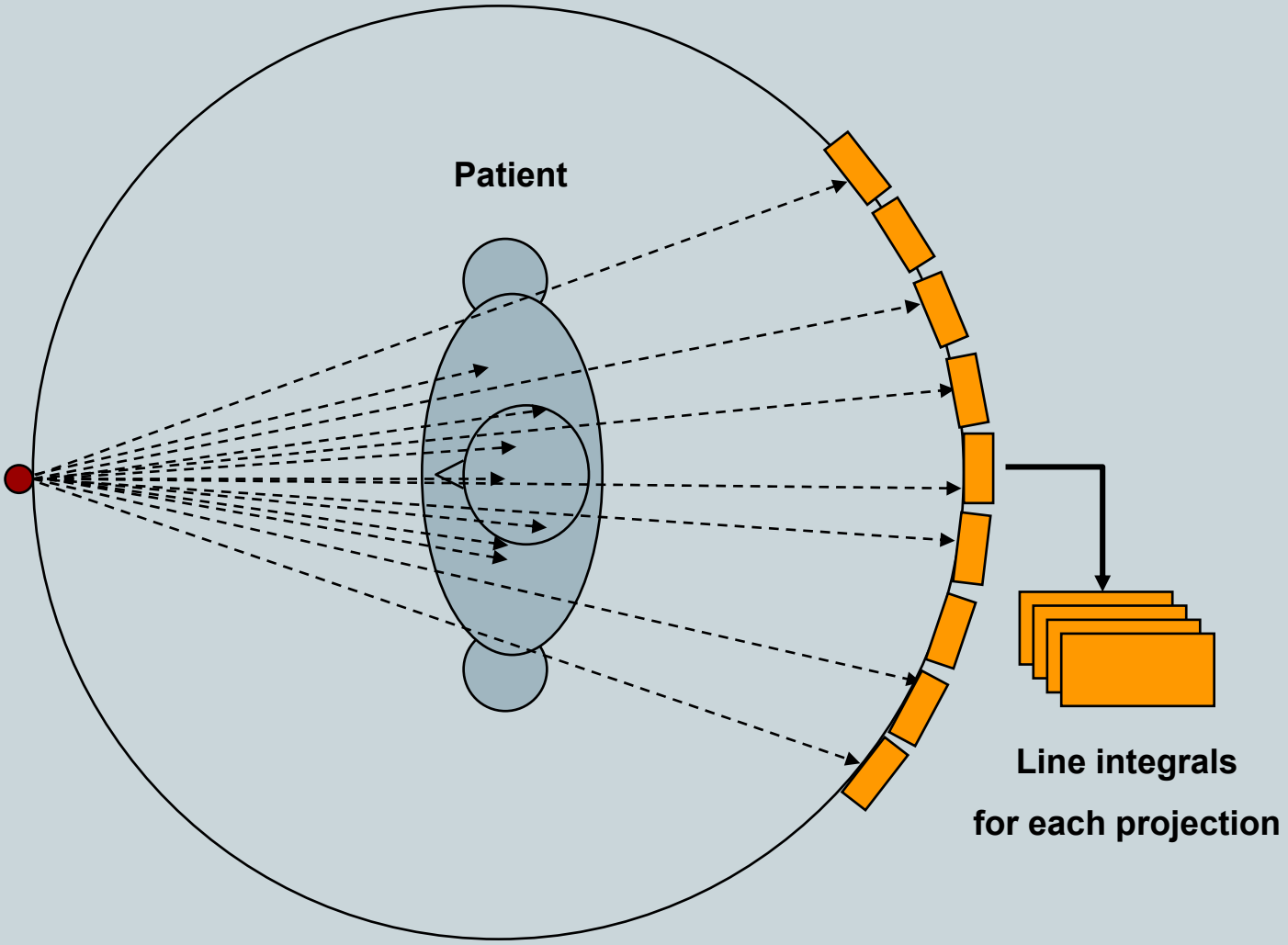
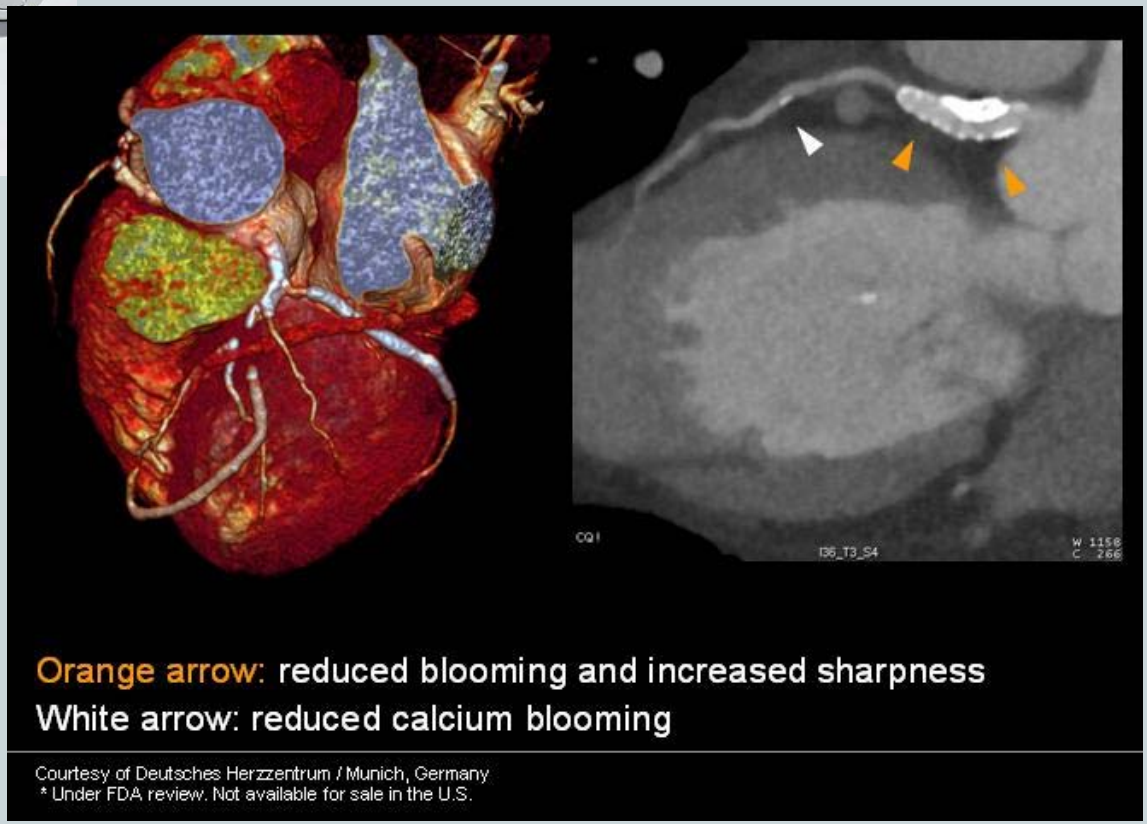


Coronary CTA: In-stent restenosis evaluation



Results may depend on specific product configuration

Screening & diagnostic mammography: High conspicuity of a tumor-suspicious lesion

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- Depiction of small structures, such as microcalcifications
- Clear visualization even in dense glandular tissue

With courtesy of Prof. Dr. Uhlenbrock & Partner, Dortmund, Germany

Results may depend on specific product configuration

Dr. Martin Spahn, Siemens AG Healthcare

Card-angiography: Visualization of stenosis in left coronary artery

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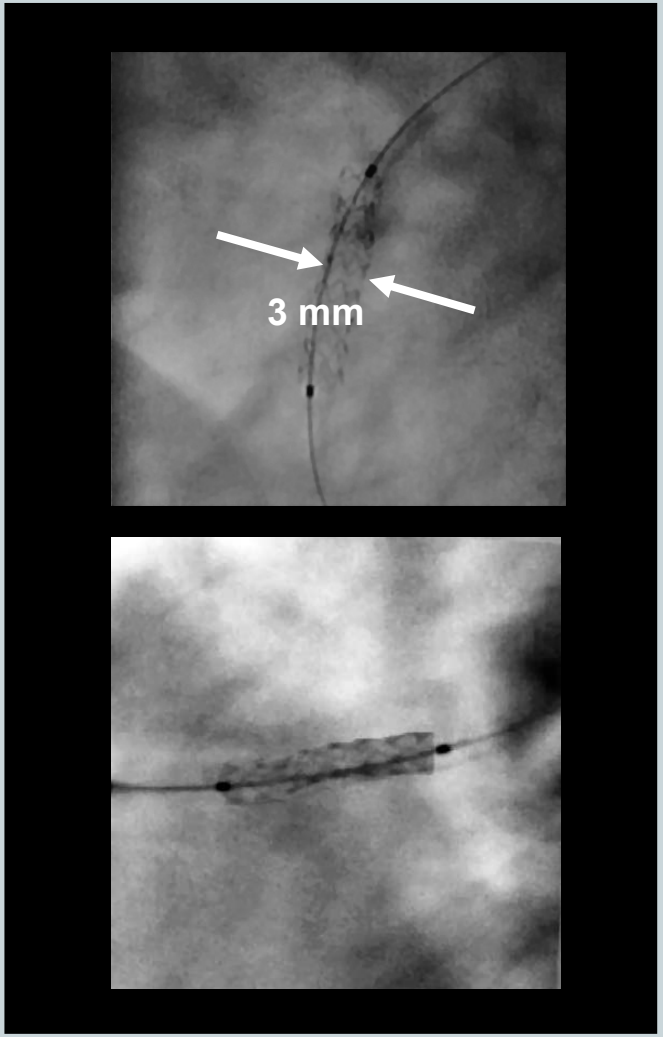
Card-angiography: Visualization of stents

- Visualization of fully depleted stent
- Visualization of stent struts



Results may depend on specific product configuration

Rotational angiography allows generation of volumetric data and CT-like images

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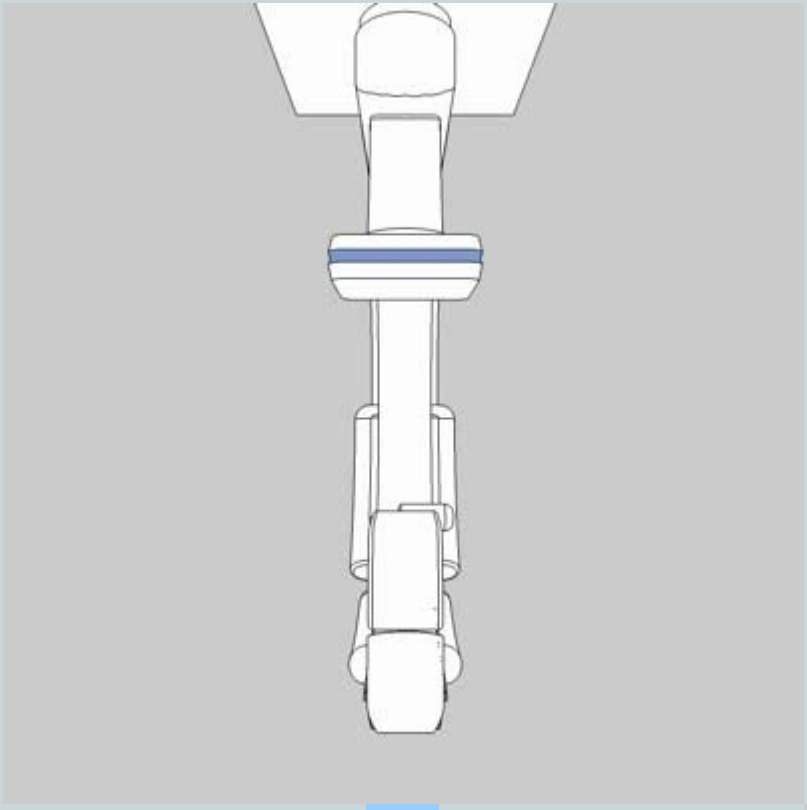
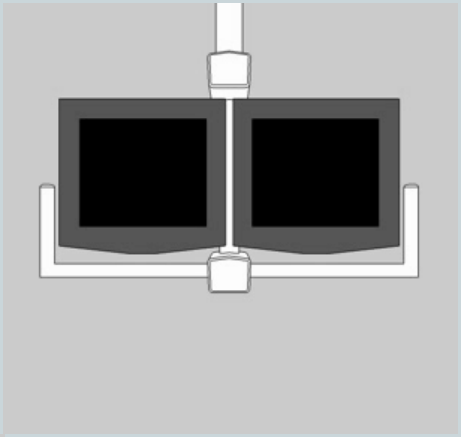


Rotational Angiography



Rotational angiography allows generation of volumetric data and CT-like images

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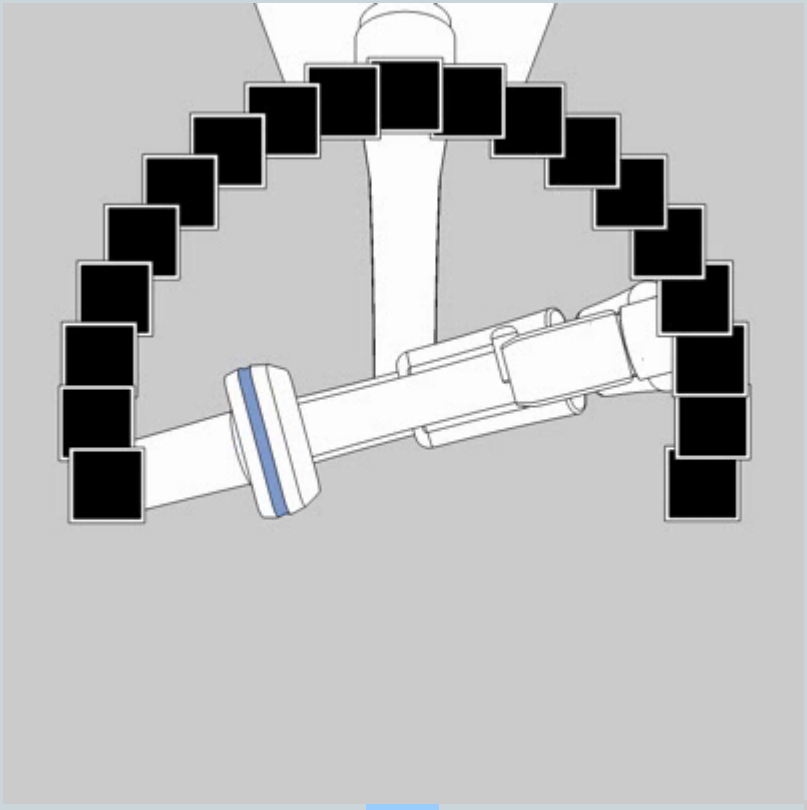
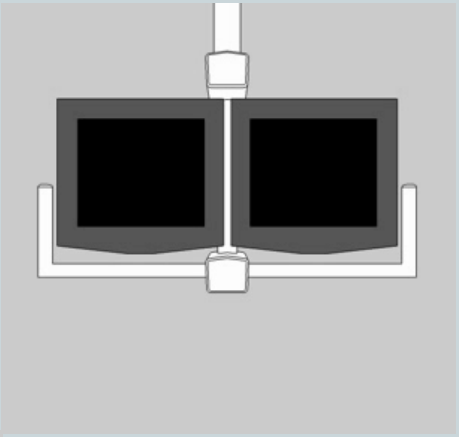


Rotational Angiography

Display in the room



Reconstruction and visualization on the workstation

Image transfer

Neuroradiology: Rotational angiography requires low contrast resolution and high dynamic range

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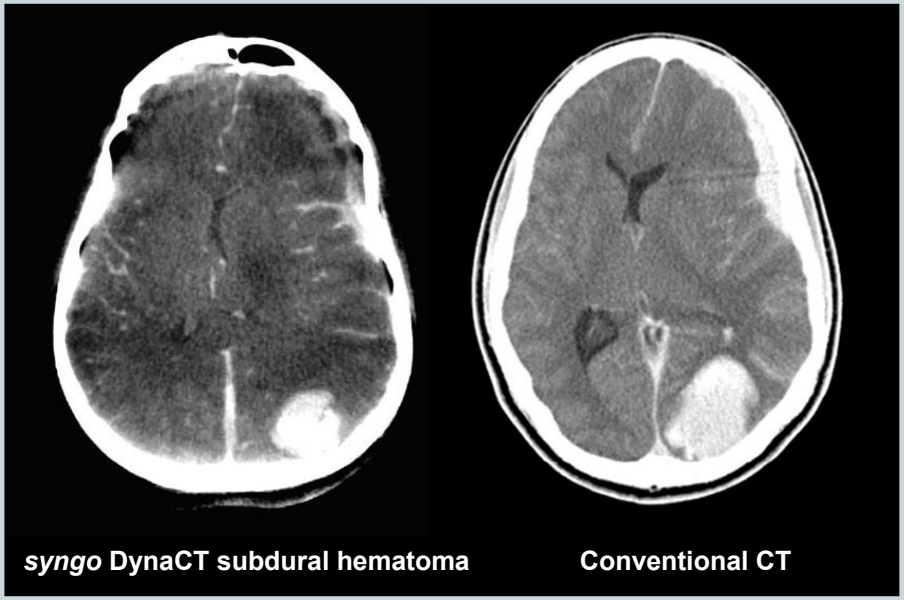

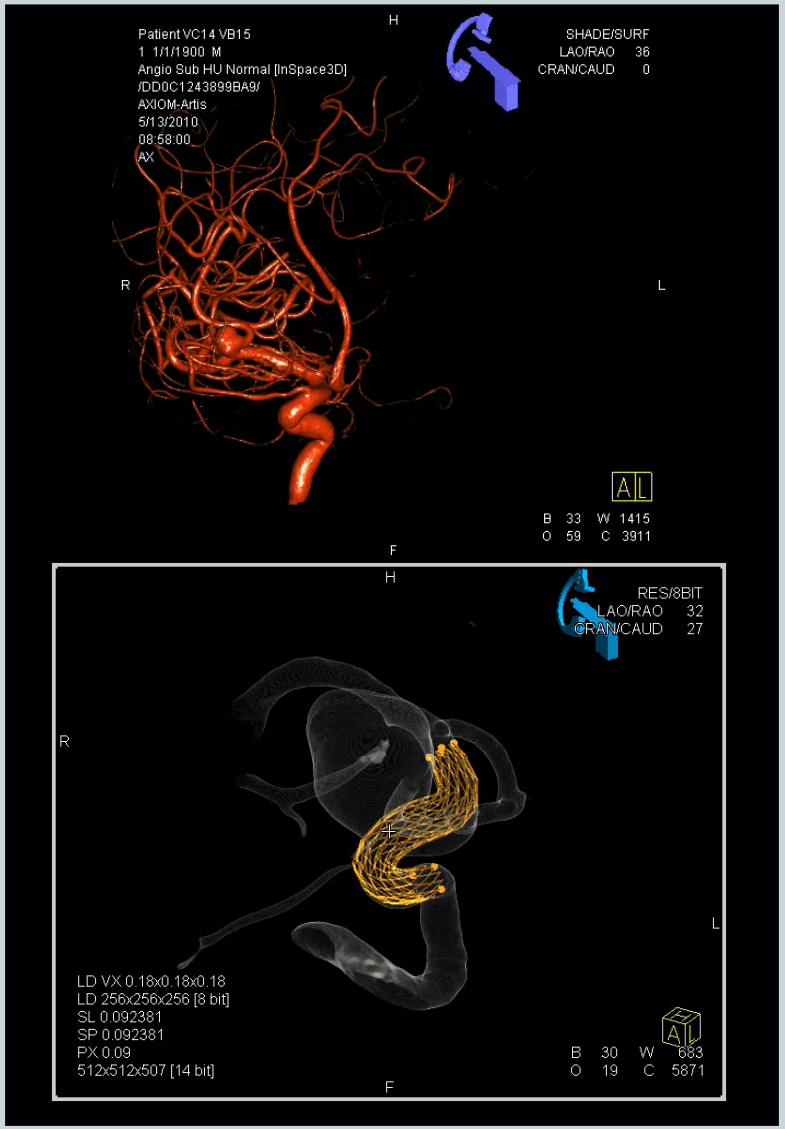

Results may depend on specific product configuration

Dr. Martin Spahn, Siemens AG Healthcare

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Neuroradiology: Good spatial and temporal resolution for dynamic flow evaluation (iFlow)

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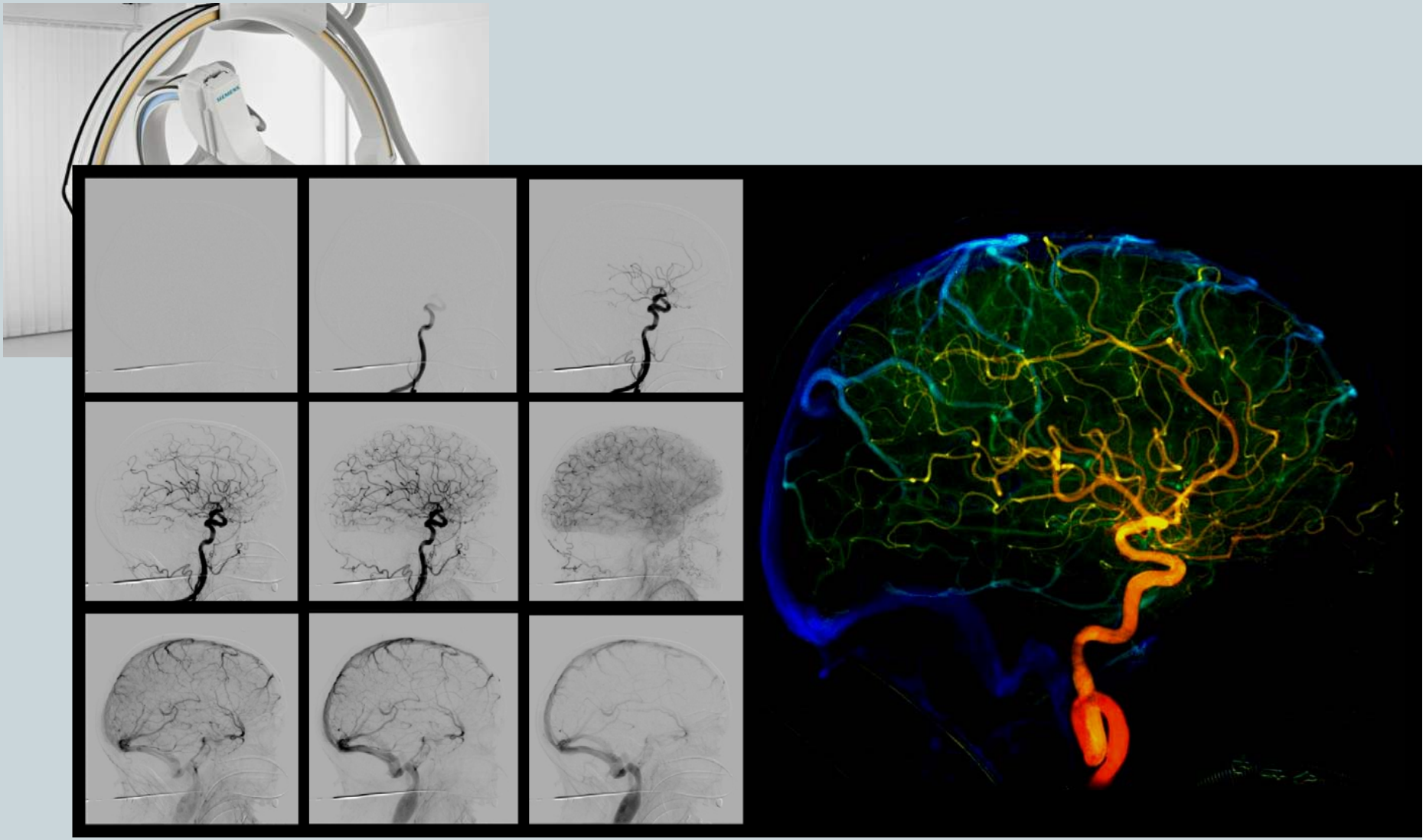

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Most flat detectors are based on indirect conversion via a scintillator and an active pixel matrix of a-Si photodiodes

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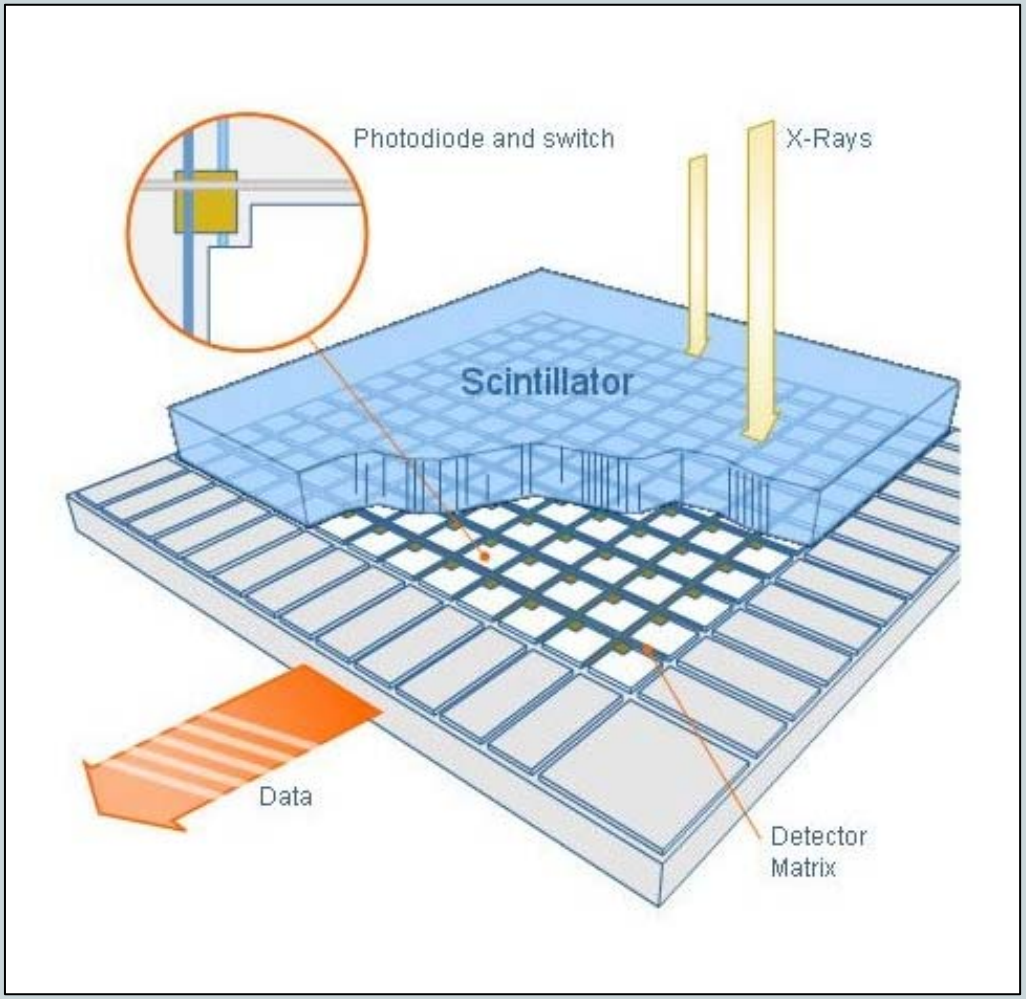

What are the advantages of the CsI scintillators and amorphous silicon active matrix photodiode arrays?

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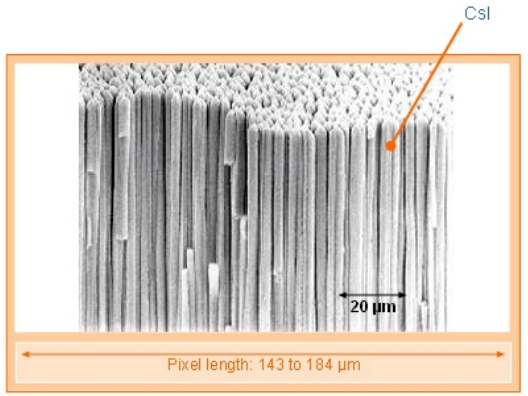
Scintillators based on CsI:Tl

- Good absorption properties due to high atomic numbers (55 and 53 for Cs and I, respectively)
- Needle-structure allows good light collection (high MTF)



Photodiode arrays based on amorphous Silicon (a-Si)

- LCD technology for consumer market (TVs, monitors) has made the technology available
- Semi-conductor properties (photodiodes, TFTs)
- Plasma-deposition process allows large area detectors (40x40 cm^2) with several million pixels
- Radiation hardness

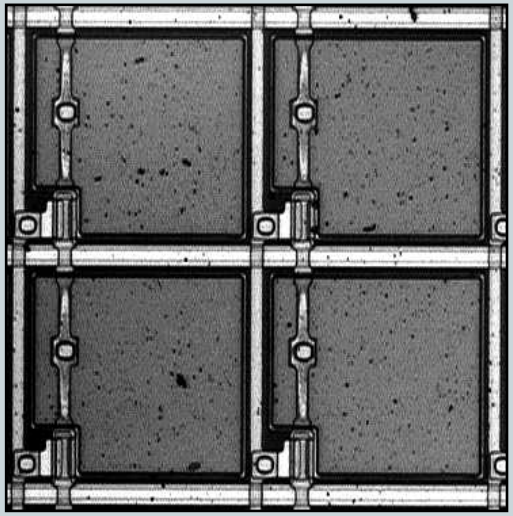


Image acquisition process:
The a-Si PIN photodiode readout is destructive

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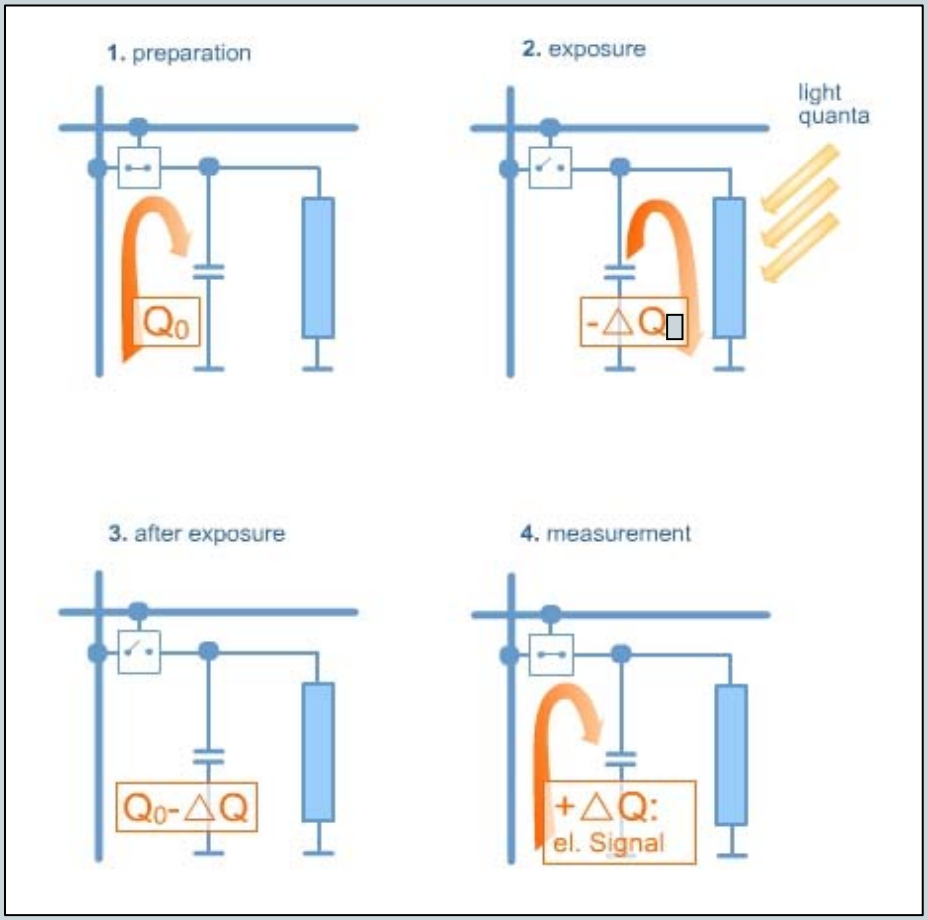

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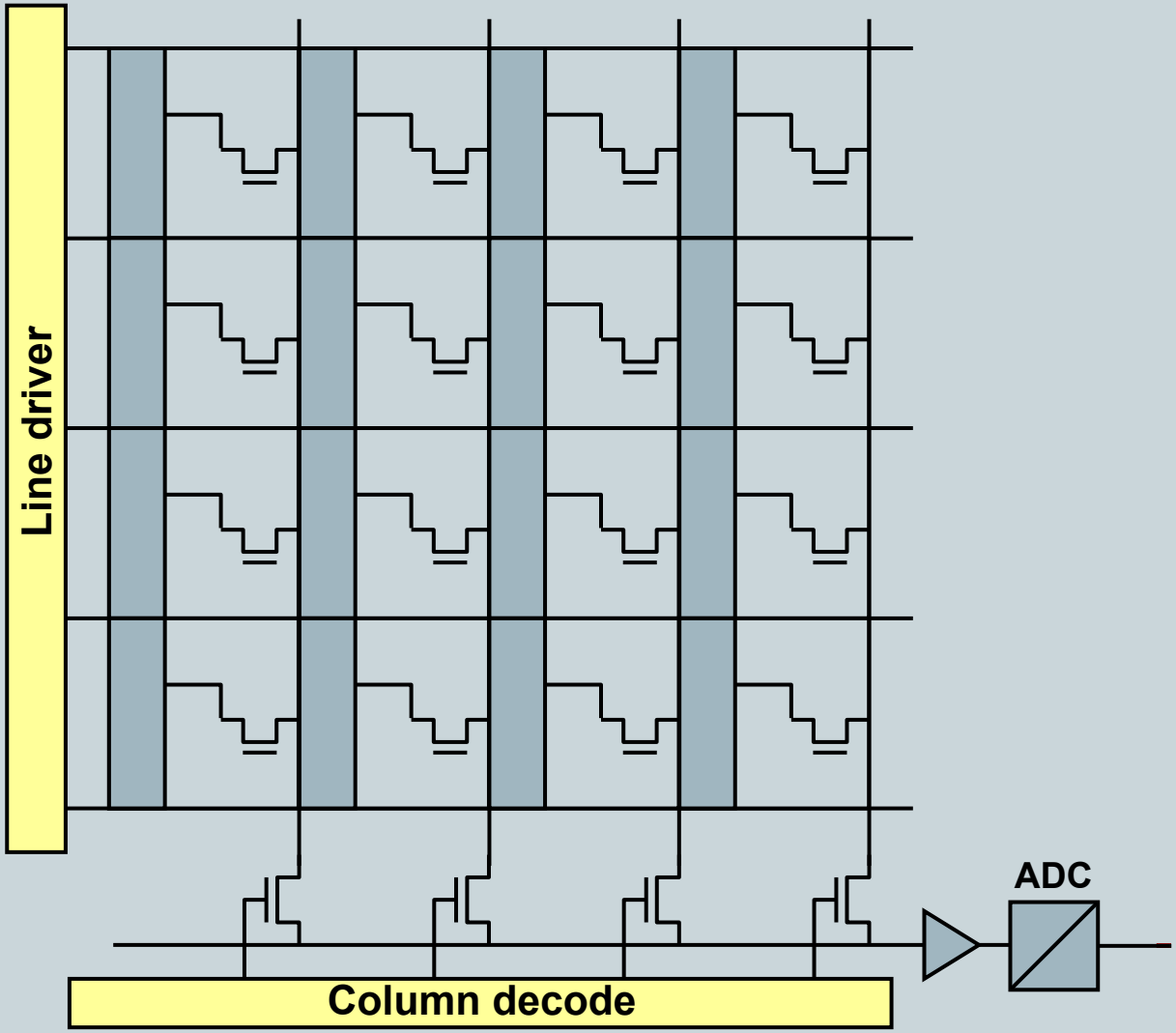
Readout process for active pixel matrix



Flat detectors based on CsI/a-Si have replaced image intensifiers and analog film

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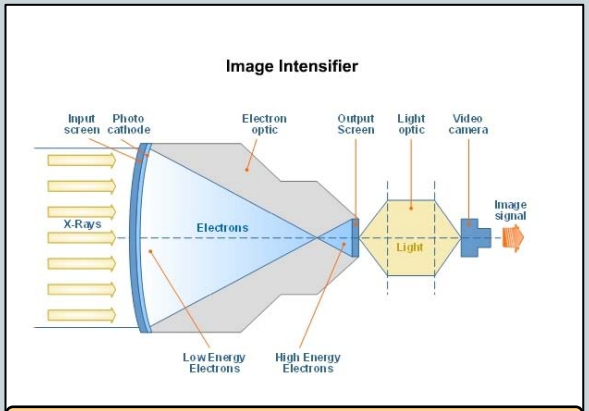
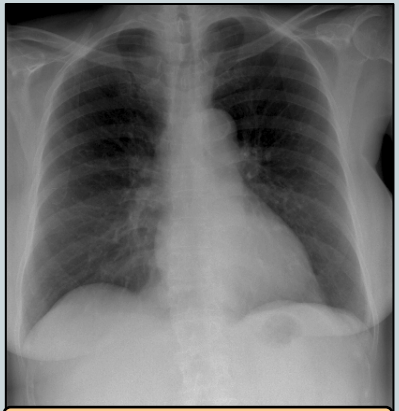


Image intensifier camera system



Analog film

Flat detectors

How did the introduction of flat panel detector technology impact radiology and cardiology?

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Radiography/mammography in the radiology department:

- Higher DQE improved X-ray dose efficiency
- Loss of film is no longer an issue
- Acquisition medium (detector) and display medium (monitor) are separated allowing independent optimization and image processing
- Real-time access of physician to image data via PACS
- Patient data and procedure preparation via HIS/RIS
- Productivity increase due to workflow improvements
- Computer-aided detection (CAD) in mammography

Angiography in the radiology/cardiology department:

- Improved angulations due to compact build
- Improved 3D-imaging (14/16 bit, no image distortions)
- Litte or no susceptibility to magnetic and electromagnetic fields

Different clinical applications generate different requirements for the respective X-ray detectors*

	Multi-Slice CT	General X-ray	Angiography	Mammography
Detector area [cm^2]	10 x 100 (segmented)	43 x 43	20 x 20 30 x 40	24 x 30
Pixel size [μm]	1000	150 – 200	150 -200 (and binning)	85
Pixel matrix (typ.)	100 x 1000	3000 x 3000	2000 x 2000	3000 x 4000
Frame rate [1/s]	5000	1 (single)	1 – 60 (depends on appl. DSA, fluoro, 3D)	1 (single or tomosynthesis)
Max. photon energy [keV]	80 – 140	40 – 150	40 – 125	23 – 35
Max. photon flux [$1/mm^2 \cdot s$]	~ 10^9	~ 10^8	~ 10^8	~ 10^7
Current technology	Gd_2O_2S PD array (Si)	CsI PD/TFT (a-Si)	CsI PD/TFT (a-Si)	▪ a-Se/electr. & TFT (a-Si) ▪ CsI & PD/TFT (a-Si)

* Values are typical. They may differ in particular implementations

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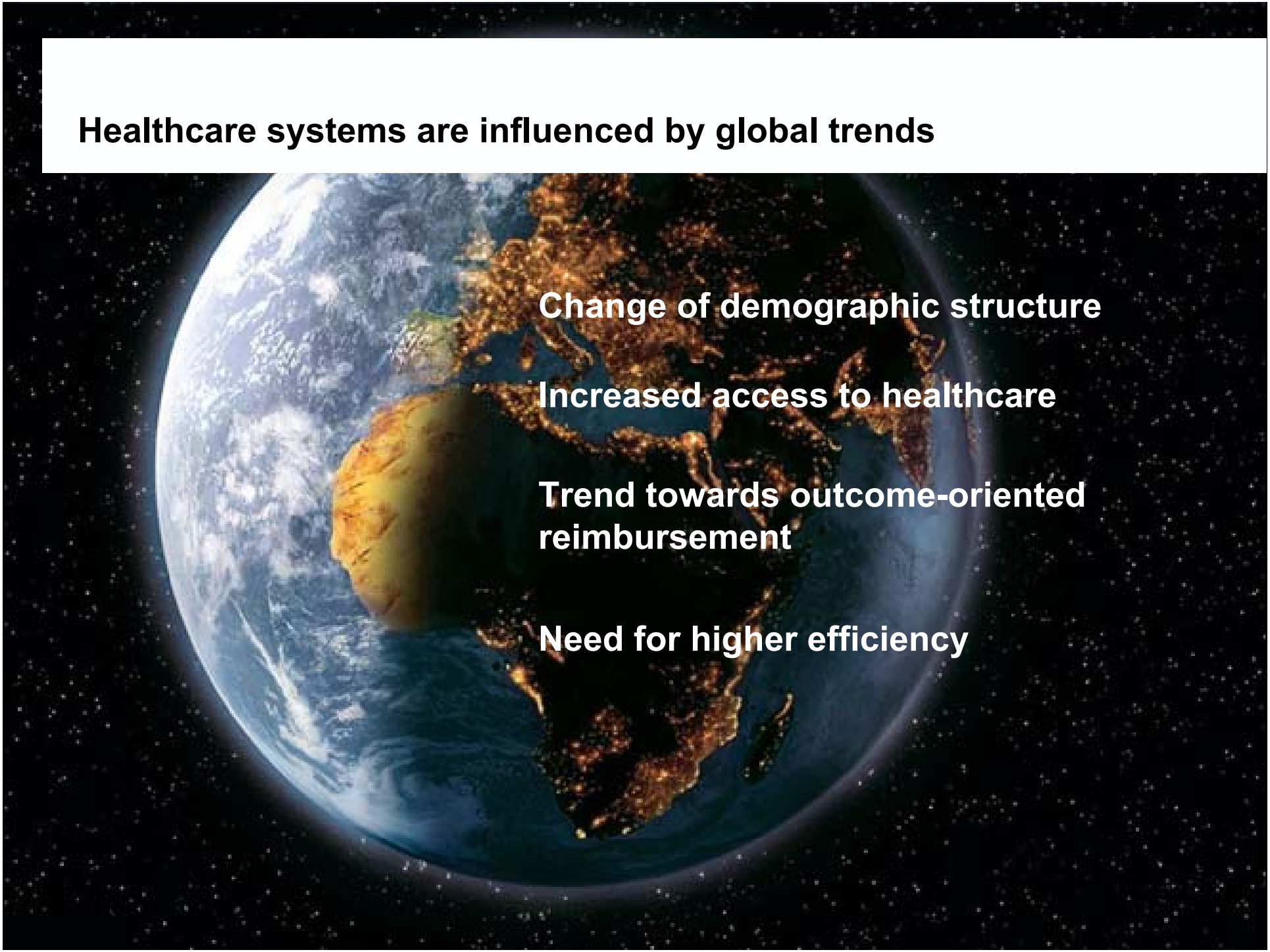
Healthcare systems are influenced by global trends



- Change of demographic structure
- Increased access to healthcare
- Trend towards outcome-oriented reimbursement
- Need for higher efficiency

Medical imaging will have to adapt to changes in the healthcare environment

Increased dose awareness

Trend towards comodity (cost)

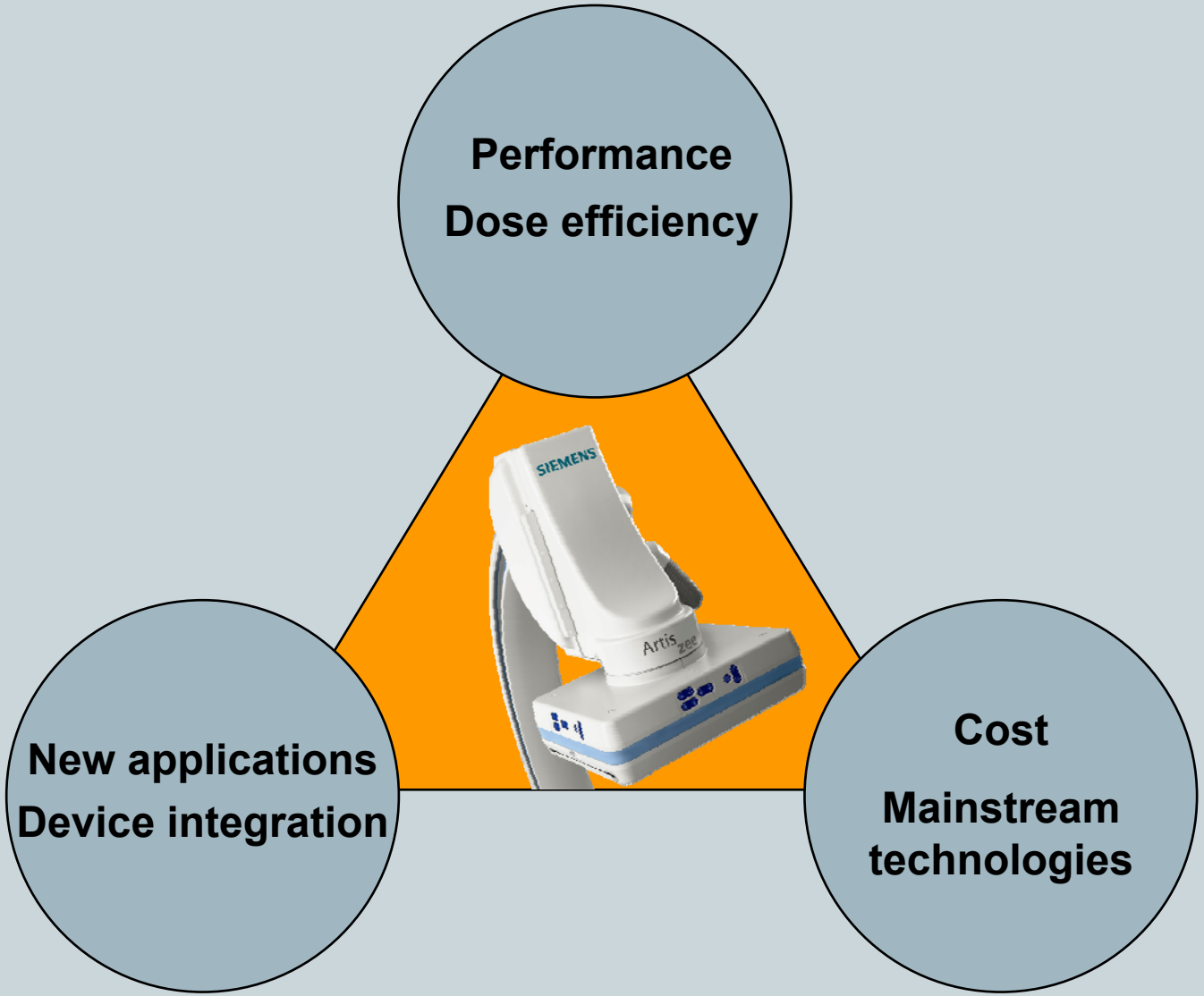
Medical Imaging

Additional value for the clinician

Image fusion

Trend towards minimally invasive procedures

Diagnostic/therapeutic X-ray systems and in turn X-ray sensors will have to support the healthcare trends



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What detector technologies are on the horizon for future X-ray imaging?

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Integrating detectors based on amorphous silicon

- **Image quality improvements**
- **Cost reduction**

Flat detectors based on CsI / a-Si: Evolution in performance improvements and cost reduction

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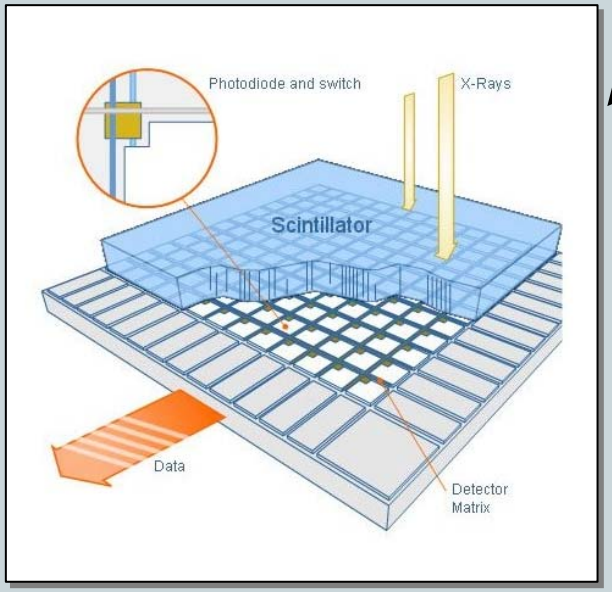

Flat Detector	Main components	Performance Parameter
	Scintillator	DQE(f) – detective quantum efficiency MTF(f) – modulation transfer function
	Optimization	
	Sensor plate (aSi)	DQE(f) MTF(f) Electronic noise Image lag Readout speed
	Optimization	
	Readout Chip	Electronic noise Readout speed
	Optimization	
	Electronics, Mechanics, FW, Data interface	Bit depth Readout speed

What detector technologies are on the horizon for future X-ray imaging?

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Integrating detectors based on amorphous silicon	▪ Image quality improvements ▪ Cost reduction
Integrating detectors based on CMOS	▪ Image quality and performance improvements ▪ Higher integration

Flat detector technology:
Integrating detectors with CMOS readout

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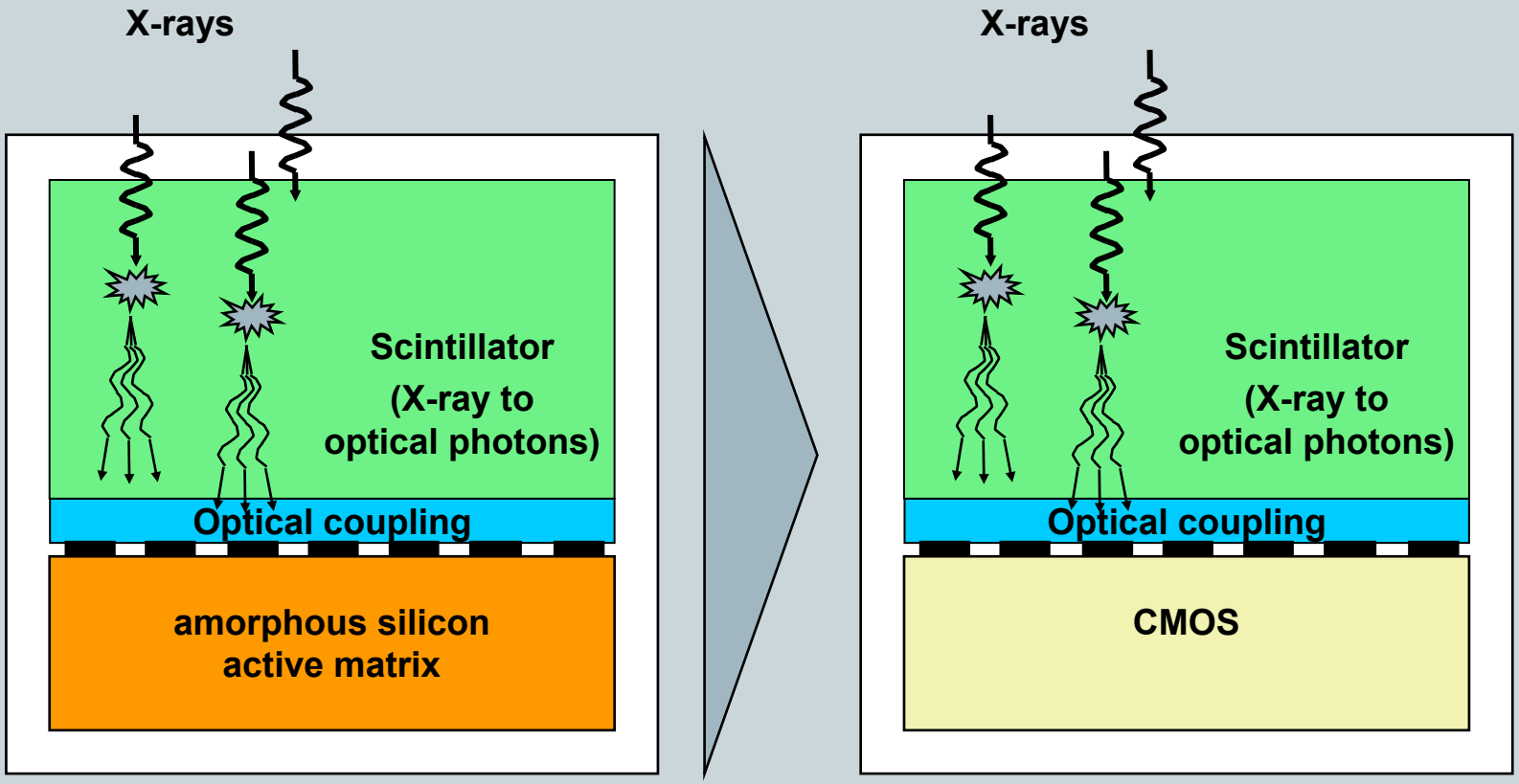

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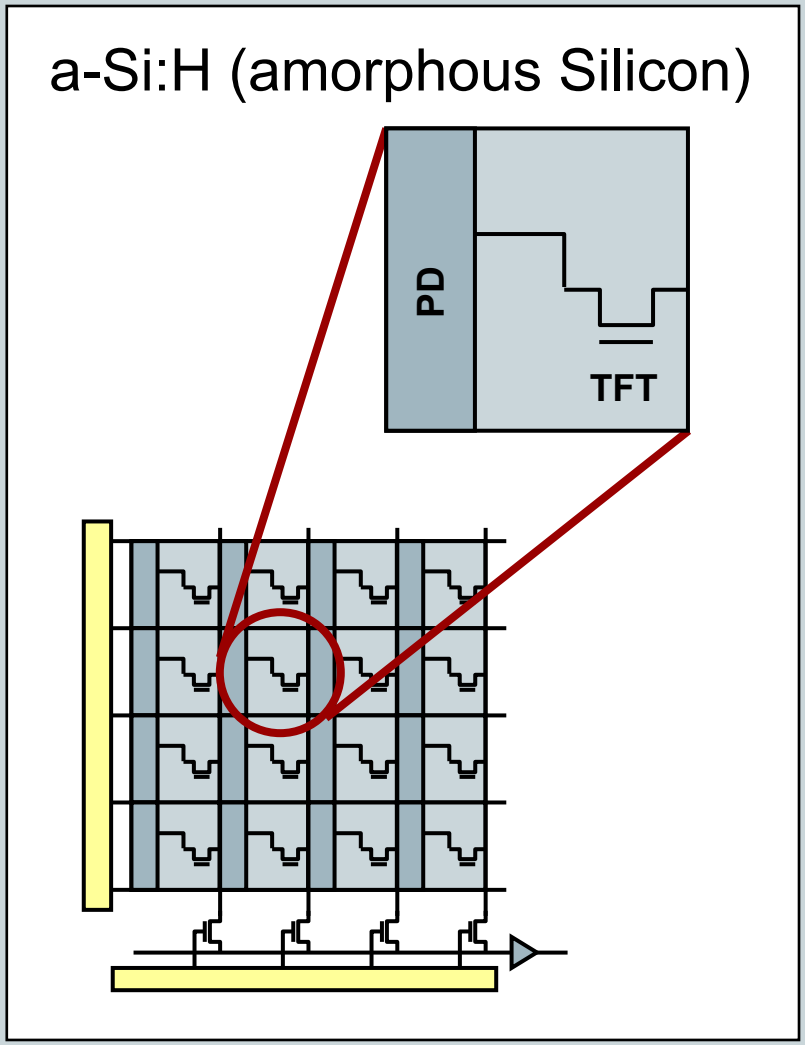
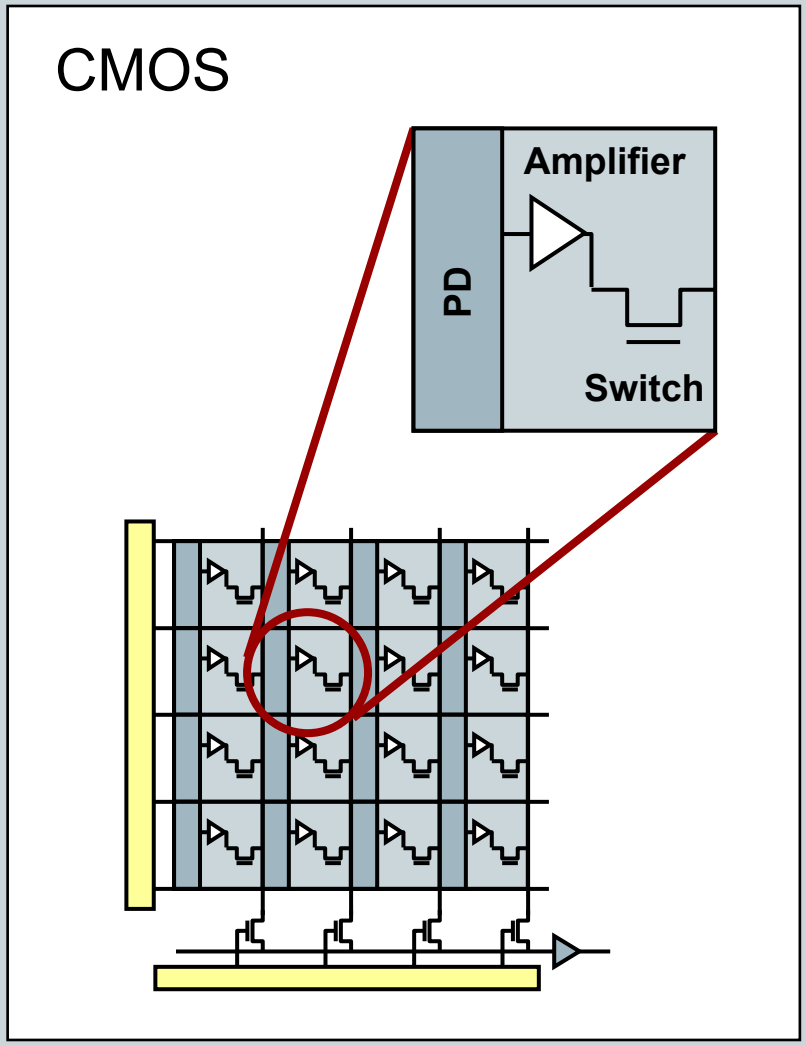
CMOS enables on-pixel amplification





Multi-transistor designs on pixel allow enhancement of features and enable new functions

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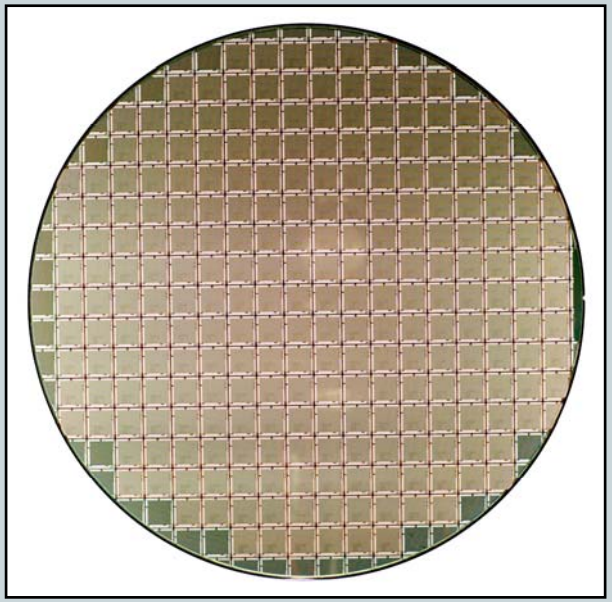
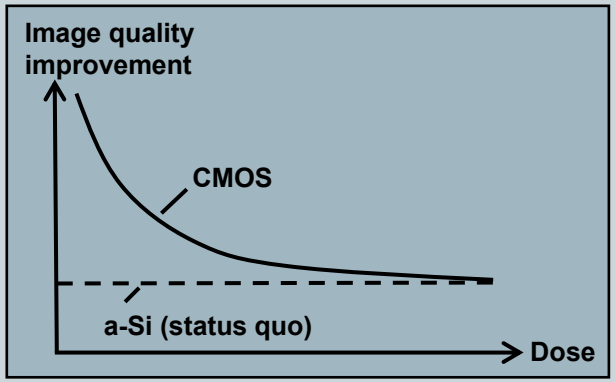
- On-pixel amplification
- Fast readout
- Non-destructive readout
- Global shutter
- Small structures

- Improved low dose imaging
- Lag-free imaging
- High frame rates
- High fill factors
- Improved bi-plane imaging (X-ray scatter)





What detector technologies are on the horizon for future X-ray imaging?

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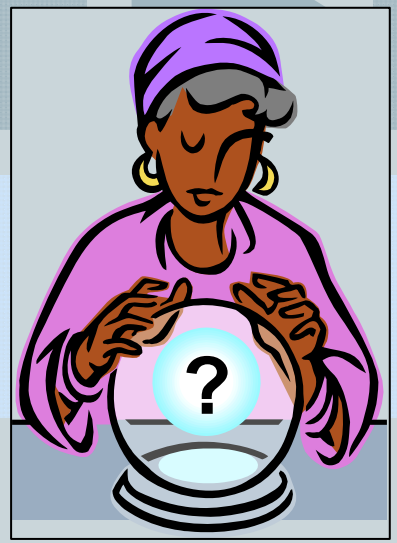
Integrating detectors based on amorphous silicon	▪ Image quality improvements ▪ Cost reduction
Integrating detectors based on CMOS	▪ Image quality and performance improvements
Counting detectors based on complex ASICs	▪ Dose reduction ▪ New applications



Counting detectors based on CdTe / ASIC
Detector schematics

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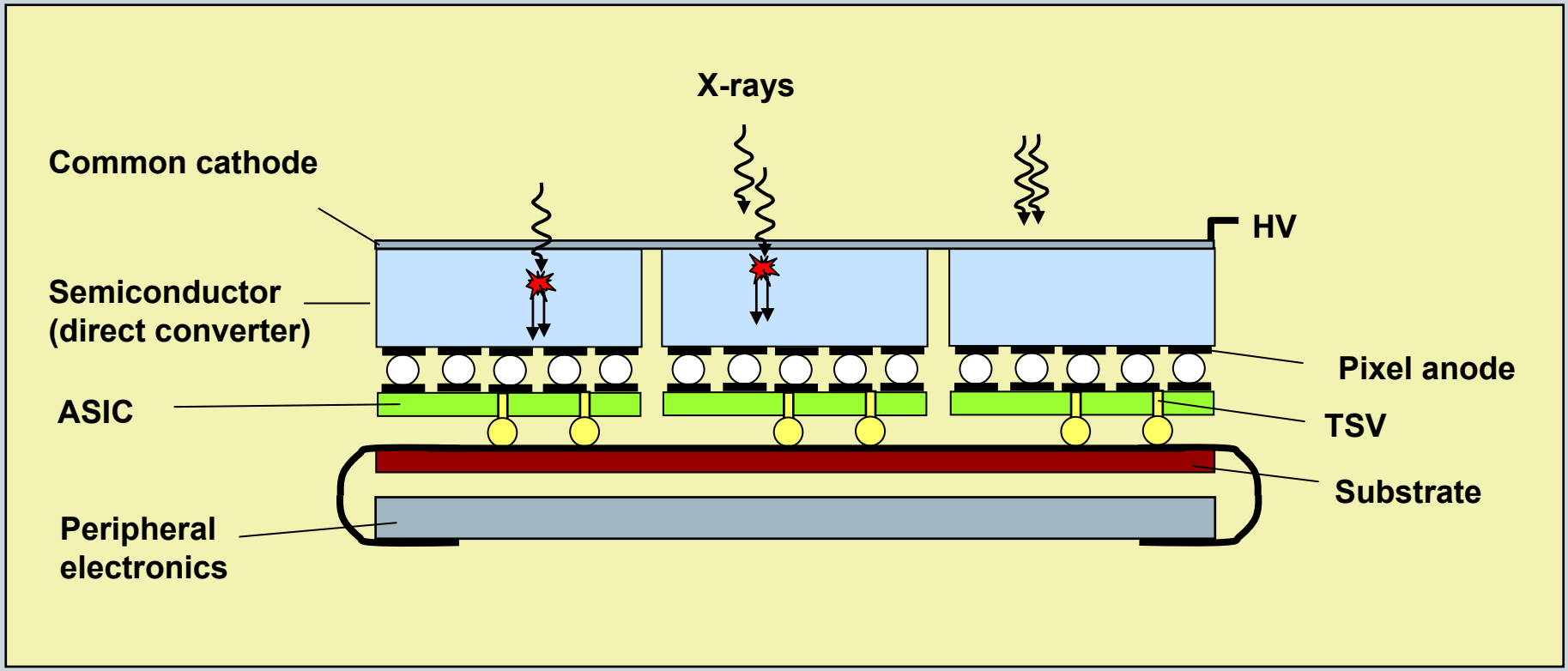

Counting detectors based on CdTe / ASICs
Opportunities: Changing X-ray imaging

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Lower dose:

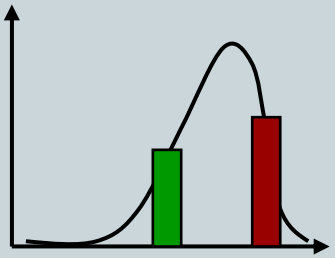
- Improved DQE (detective quantum efficiency)

$$SNR^2_{out}(f) = DQE(f) \cdot \underbrace{SNR^2_{in}(f)}_{\text{proportional to dose}}$$

- Quantum-noise-limited imaging (no electronic noise)

Improved contrast (CNR):

- Low energies contribute more (equal weighting of spectrum)
- Weighting of energy bins in case of energy discriminating counting detectors



New imaging applications:

- Material discrimination techniques („color imaging“)
- Material-selective imaging (K-edge imaging)

Schematic structure of counting pixel

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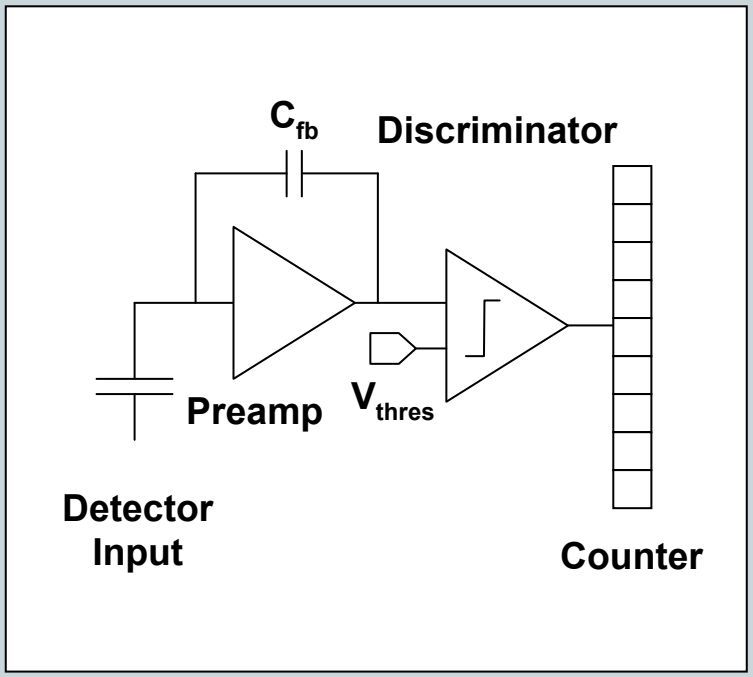

Schematic structure of counting pixel with energy discriminating capability (color imaging)

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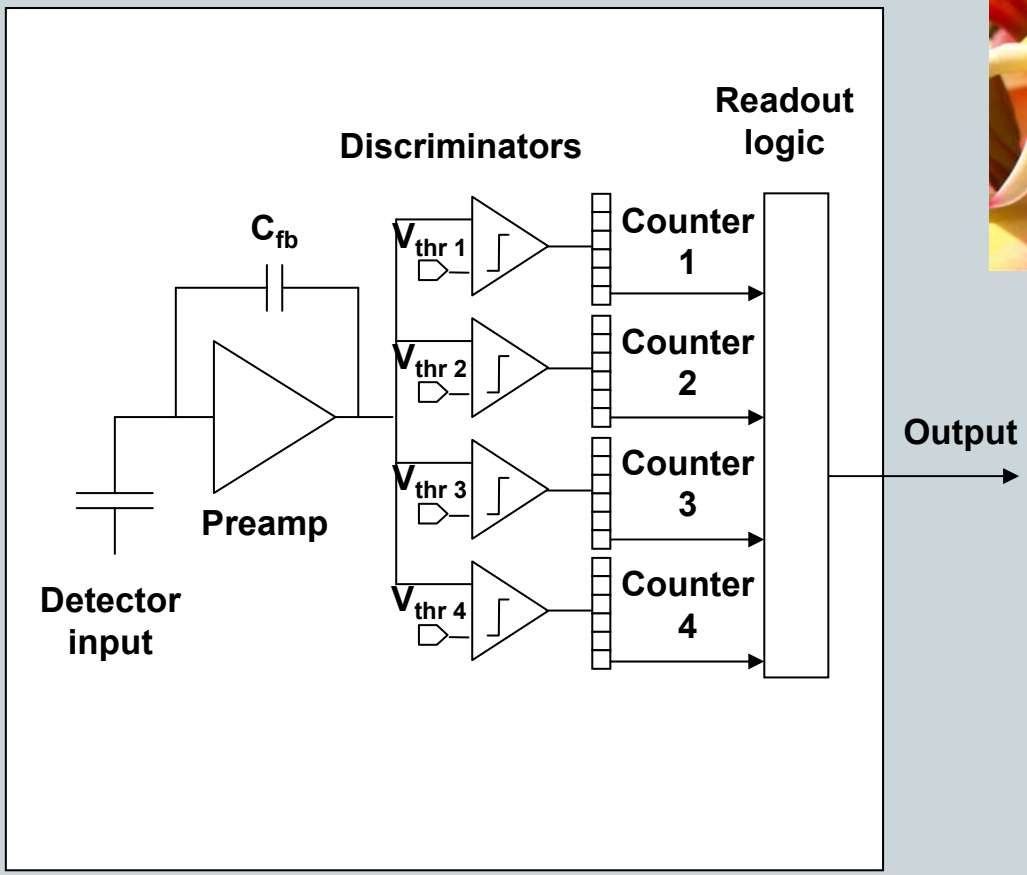

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Technological challenges of counting X-ray detectors

- Detector material:
  - K-escape and charge sharing
  - Material inhomogeneity (inclusions, charge collection inefficiency, …)
  - Temporal drifts (trap filling, polarization, …)
- Hybridization:
  - Reliable bump-bonding
  - Mechanical stress (thermal issues)
- ASIC:
  - Pile-up at high X-ray fluxes
  - Complex pixel structure (pulse shaper, amplifier, comparator, counter, readout logic)
  - Power consumption
  - TSV technology if 4-side buttable detector modules are required

Example of a counting ASIC pixel layout
The Medipix3 Chip

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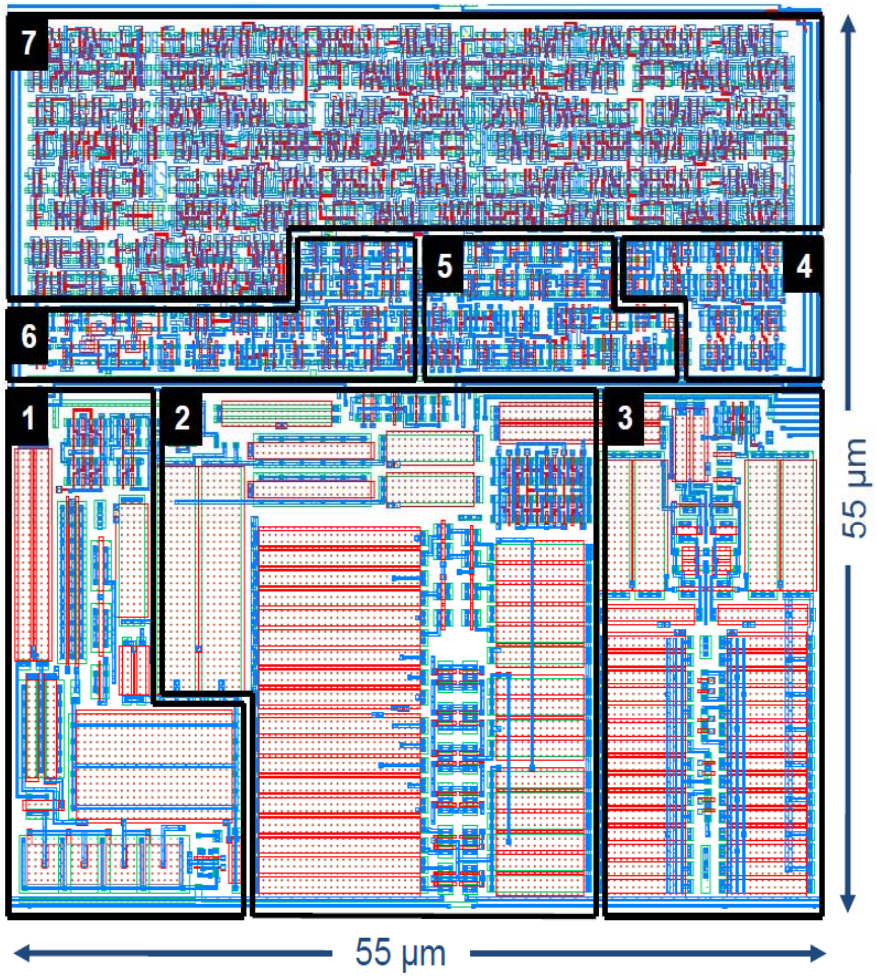
1. Preamplifier
2. Shaper
3. Two discriminators with 5-bit threshold adjustment
4. Pixel memory (13-bits)
5. Arbitration logic for charge allocation
6. Control logic
7. Configurable counter

~1600 transistors



Source: Rafael Ballabriga „New Charge Summing for Medipix3“ Workshop on Spectral Xray Imaging, CERN, Geneva 2011
The Medipix Collaboration, Dr. Michael Campbell, spokesperson

Hybrid prototype CT scanner with integrating and counting detectors has been built by Siemens

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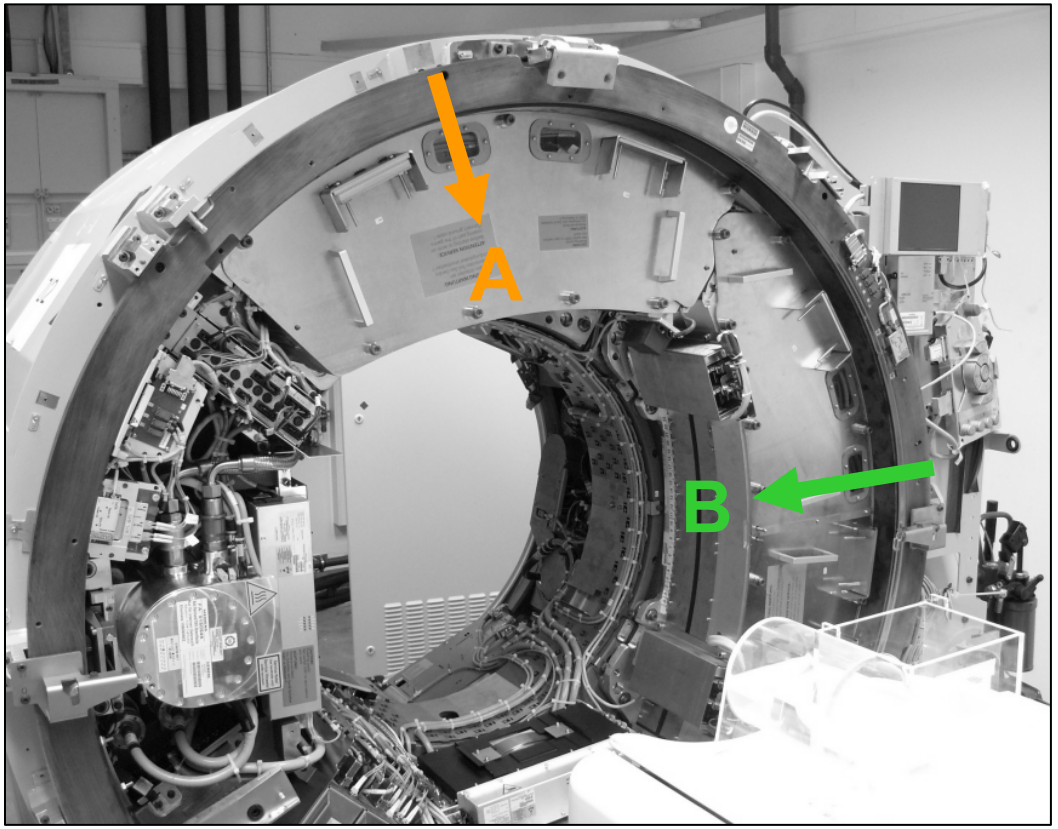
The Hybrid Prototype CT Scanner

- Gantry from a clinical scanner with two X-ray systems:

  A: conventional detector
  B: counting prototype

- Focus-detector distance 1.1m
- Bore diameter 78cm
- Gantry rotation time 1.0s / rot.
- Peak X-ray flux $2.5 \times 10^8/(s \cdot mm^2)$

  80kVp up to 555mA
  100kVp up to 250mA
  120kVp up to 150mA
  140kVp up to 100mA



Please note: This device is an inhouse prototype scanner for research purposes, not intended for patient examinations!

Source: S. Kappler et al., Siemens Healthcare, SPIE Medical Imaging 2012

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Summary

- Healthcare systems are adapting to global trends such as demographic changes, outcome orientation of clinical processes and the need for highly efficient procedures
- Changes in the healthcare systems influence the development of detector technology such as performance, dose efficiency and cost
- Current mainstream technologies are based on integrating detectors deploying a-Si active matrices (radiography, angiography, mammography) or photo-diode arrays (CT)
- New technologies (CMOS, photon counting) are on the horizon or subject of R&D

X-ray technology has come a long way ...
... and there is still much ahead

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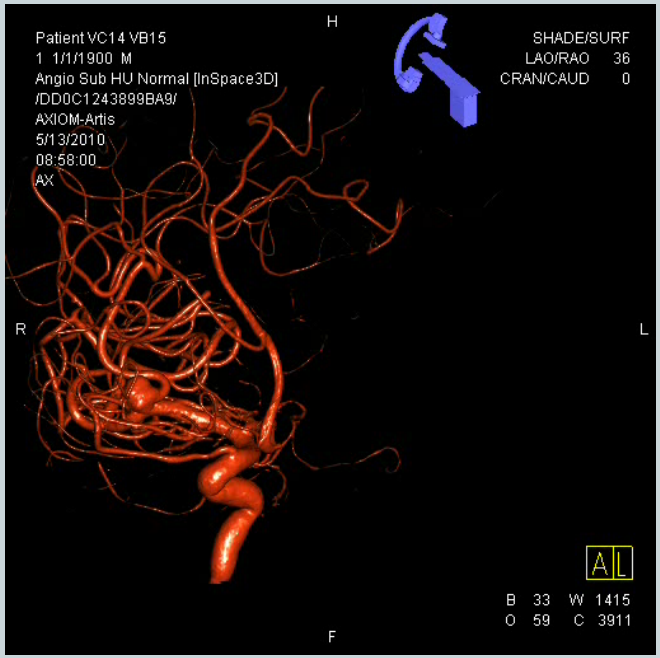

Thank you

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