Imaging Educational Course: TU-E-134-01

Developments in Imaging Receptors and Applications in Projection X-ray Imaging:

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Disclosure:

- John Yorkston works for Carestream Health that manufactures and sells CR and DR systems for medical applications

Digital Acquisition: Introduction

- "CR" technology introduced in 1980's
  - Originally referred to "storage" phosphor based systems
  - Cassette based imaging with separate readout scanner
  - Similar workflow as screen-film cassettes

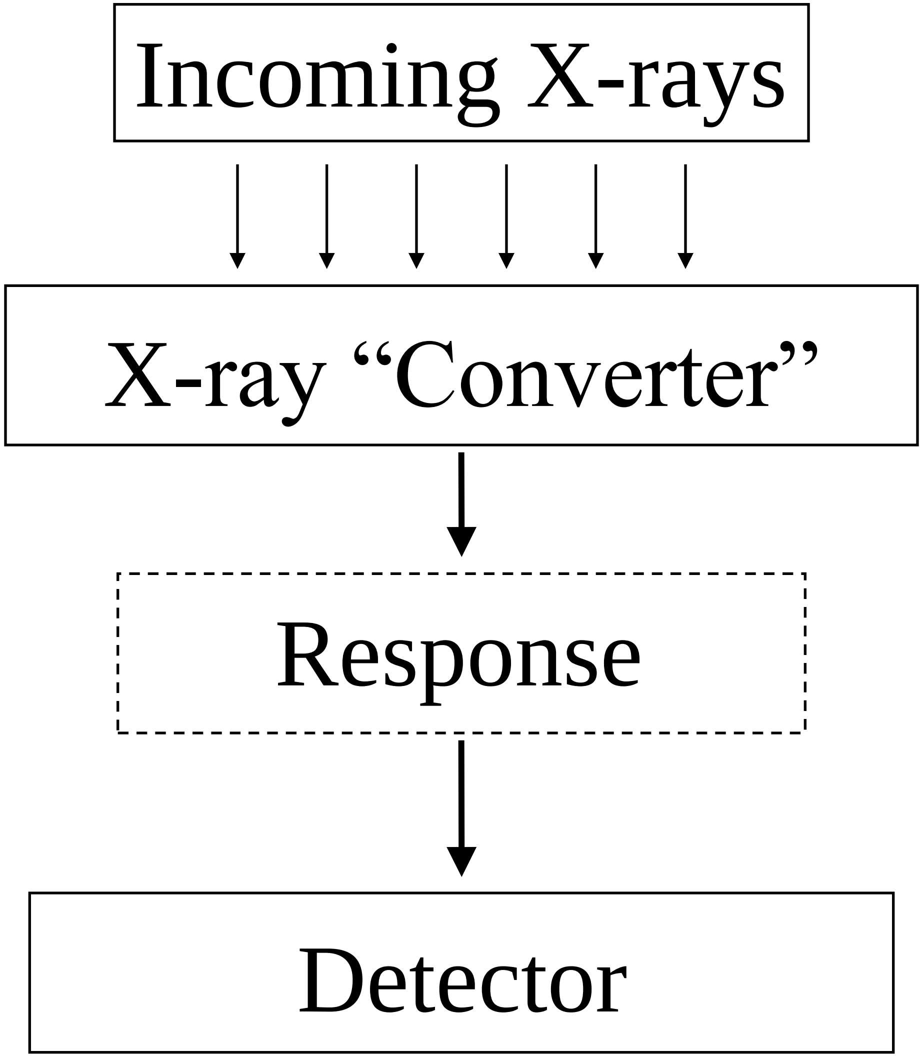
- "DR" technology introduced in mid 1990's
  - Originally referred to a-Si:H (and CCD) based systems
  - Integrated with x-ray system
  - Fully "electronic" readout with no moving parts
- Since then a number of novel hybrid systems:
  - "Avalanche" of new terms and nomenclature that confuse and confound
  - Much of this originates in the "marketing" departments of companies

Educational Goals:

- Identify features that define the underlying technology
- Decipher confusing terminology present in marketplace
  - Know what questions to ask
- Appreciate differences between competing approaches
  - All systems have their pros and cons…
  - Important to know which suits your application and budget
- Understand recent/future developments
  - New detector design and system configurations
  - New types of "future" detectors and their capabilities

Digital Image Formation:

- X-rays modulated by object
- X-Ray Converter/Absorber
- Secondary quanta response
- Secondary quanta detector



Outline:

- Discuss x-ray absorption material selection
- Review secondary quantum detection options
- Review current status of projection x-ray technology
  - Highlight new developments in designs and their rationale
- Review future detector developments
  - New configurations (e.g. flexible substrates, “smart pixels”)
  - New capabilities (e.g. photon counting and energy resolution)

X-Ray Absorption Materials:

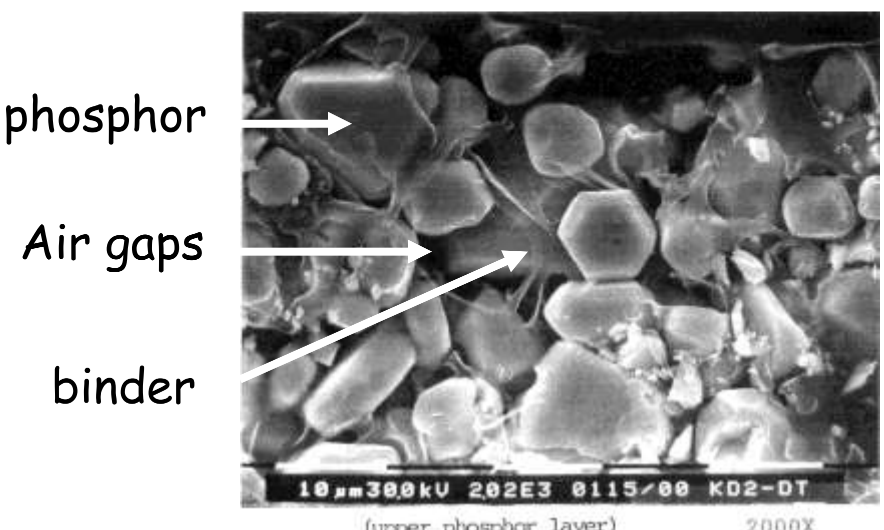
- Advantageous properties for an x-ray absorber include:
  - Absorb as many x-rays as possible
  - Provide accurate measure of how many x-rays interacted
  - Maintain information on spatial location of point of interaction
  - Manufacturable over suitably large physical areas
- Two different types of materials used:
  - Phosphor materials that generate light
  - Photoconductor materials that generate electrical charge

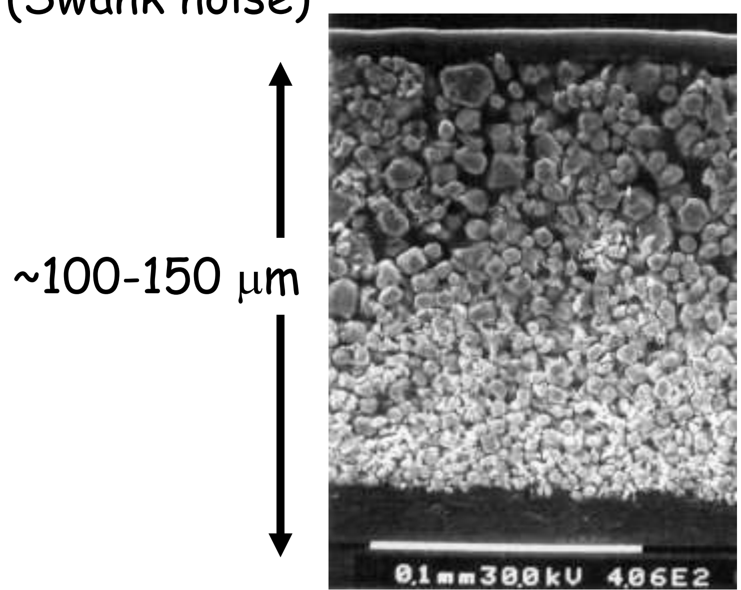
X-Ray Phosphors:

- Two categories of x-ray phosphor materials
  - Prompt emission materials (e.g. $Gd_2O_2S(Tb)$ also known as GOS)
    - » Emit light "instantaneously" on absorption of x-ray
    - » Formed basis for "modern" screen-film systems
  - Photo-stimulated emission materials (e.g. BaFBr(I))
    - » Fraction of x-ray energy stored in long lived "latent" sites
    - » Require readout with stimulating radiation (typically laser)
    - » Also known as "storage" phosphors
    - » Formed basis for Computed Radiography (CR) systems
    - » Actually emit ~50% of energy as "prompt" light
    - » Require erasure step to remove remaining signal
- Traditionally created as particle-in-binder (PIB) layers
    - » Also known as phosphor-in-binder or POWDERED Phosphor

X-Ray Phosphors:

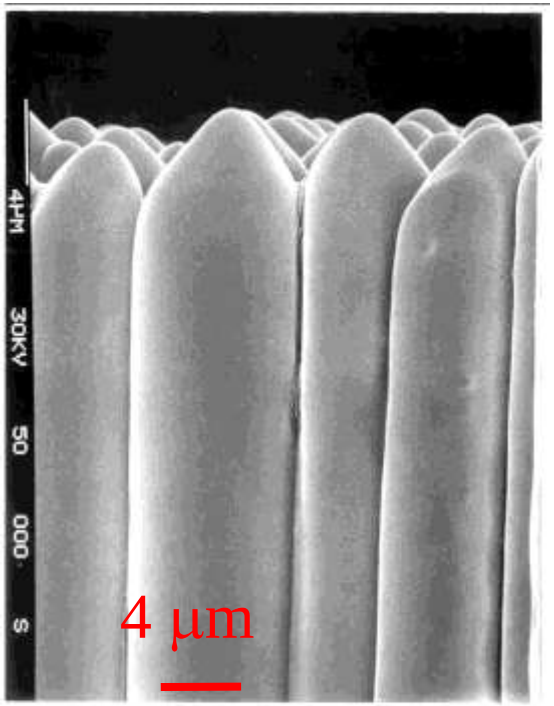
- PIB configured from small phosphor grains in plastic
  - Relatively "easy" to manufacture (after decades of development)
  - Very physically robust
- Issue with creating thick layers to increase absorption
  - Light scatters within material
  - As thickness increases so does light spreading
    - » Reduces resolution and increases noise (Lubberts effect)
  - Escape efficiency of light from screen varies through screen depth
    - » Also results in increased noise (Swank noise)

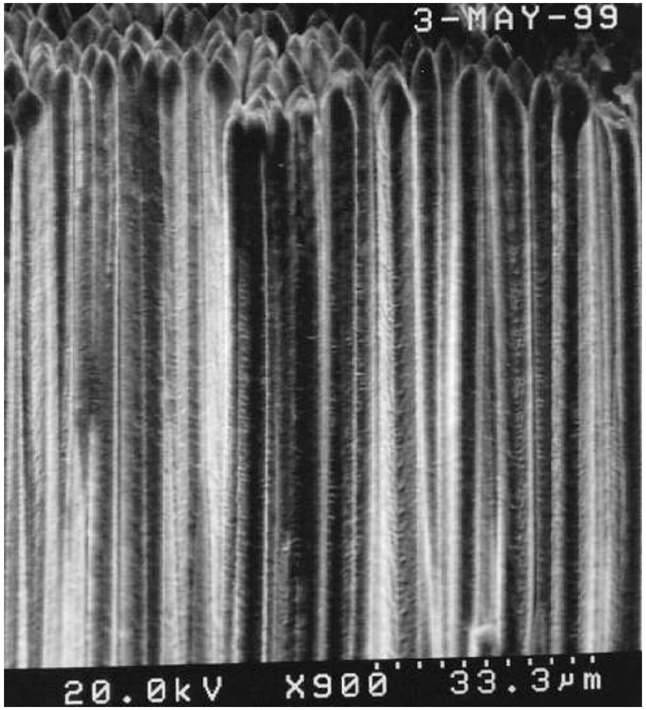




X-Ray Phosphors:

- More recently "structured" phosphors have been used
  - Prompt emission type: CsI(Tl)
  - Stimulated emission type: CsBr(Eu)
  - Reduces effect of thickness on spatial resolution: allows thicker layers
  - Improves light escape efficiency so reduces Swank noise
  - Allows higher "packing fraction" than PIB so higher effective absorption



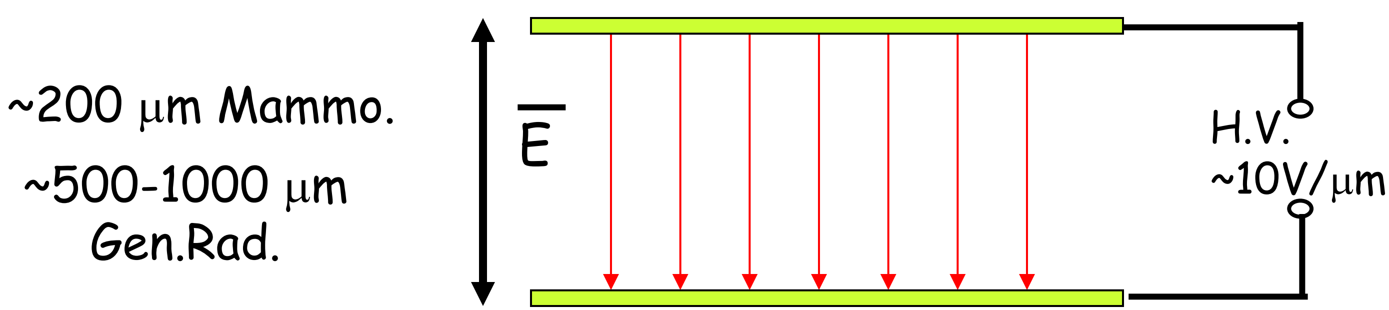


~200 µm Mammo.

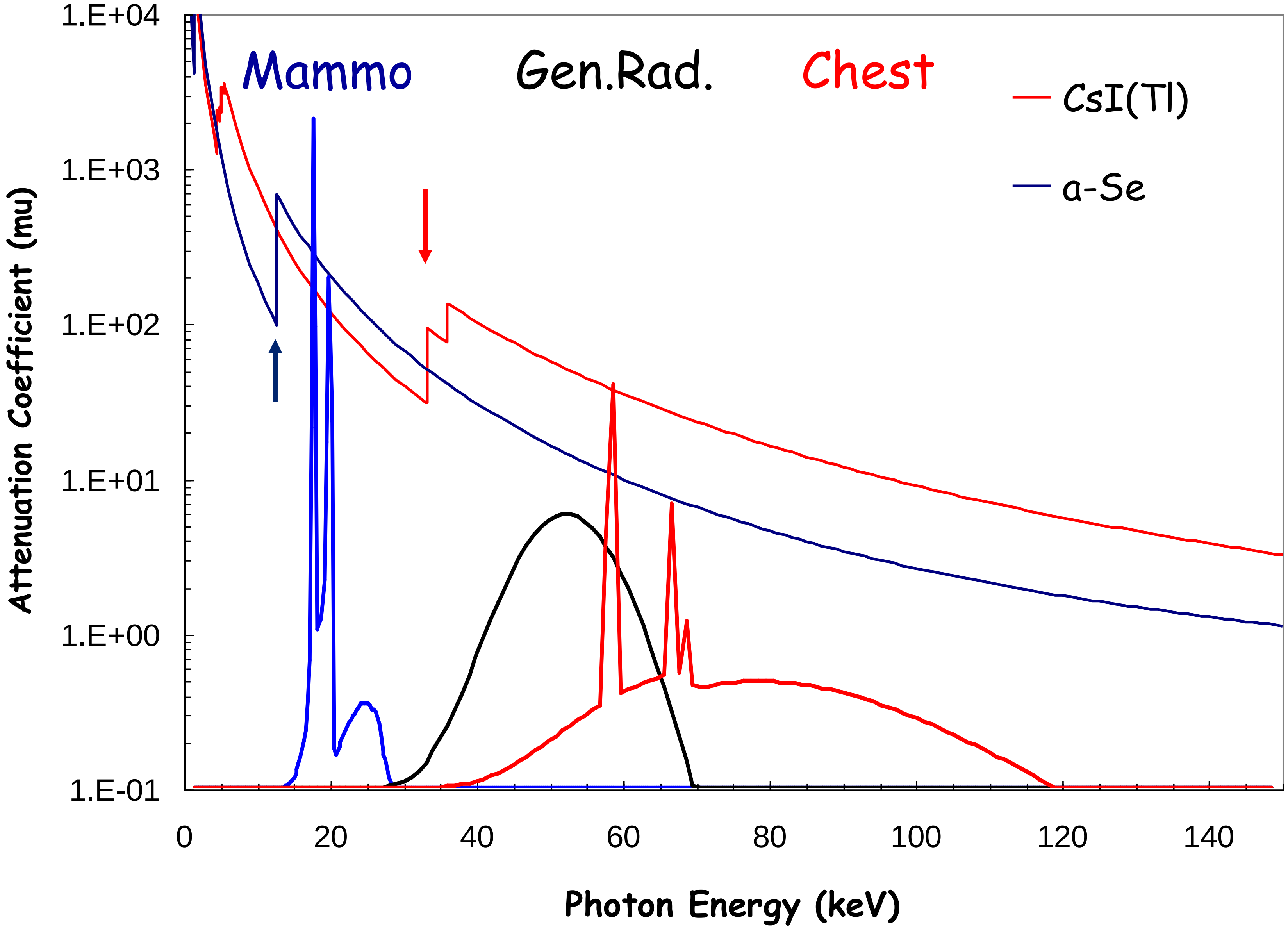
~500-600 µm
Gen. Rad.

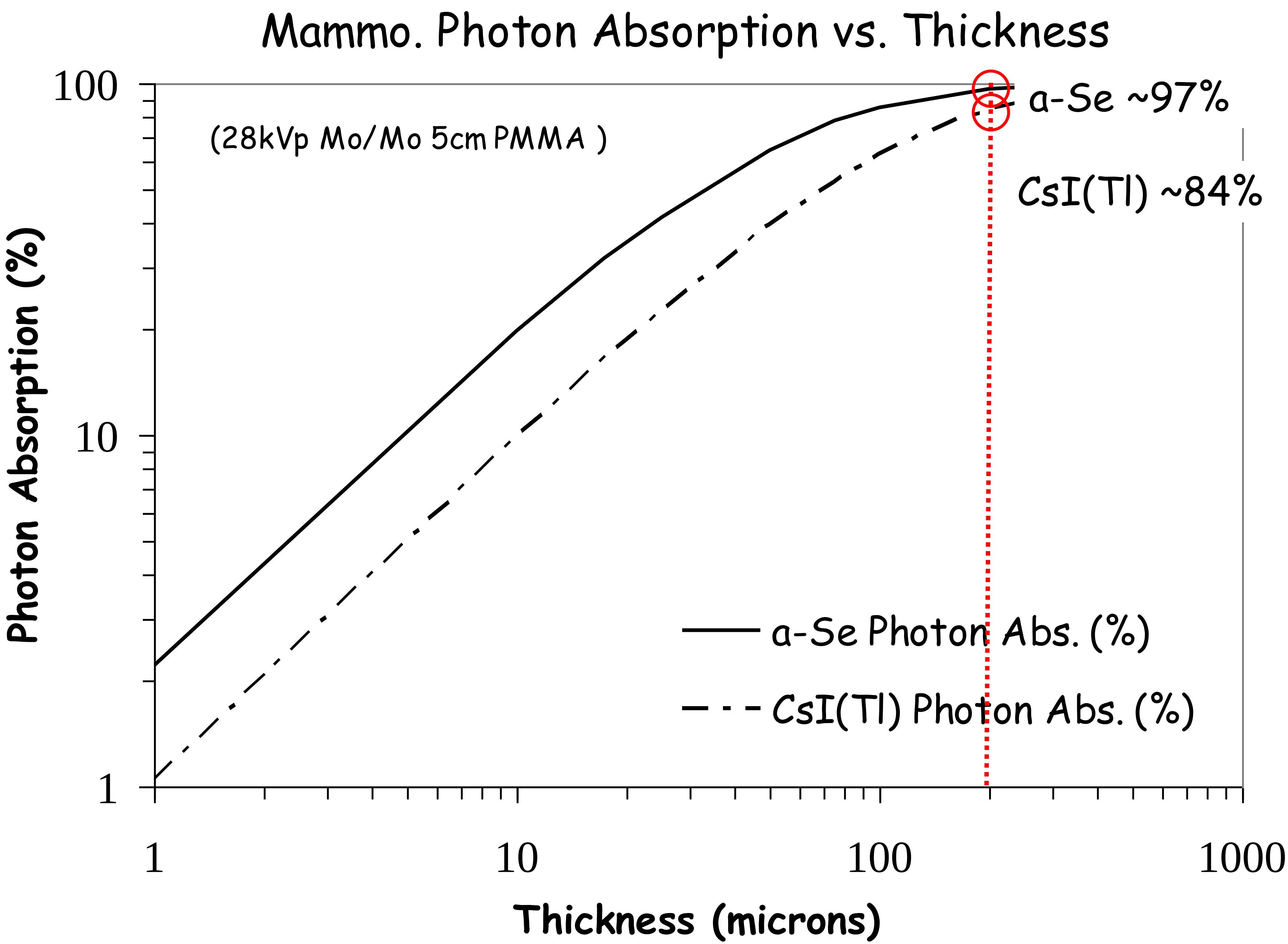
X-Ray Photoconductors:

- Somewhat different issues than phosphors:
  - Require applied voltage to "energize" layer and allow charge collection
  - Internal field constrains lateral drift of released charges
  - Near perfect spatial resolution almost independent of thickness
  - High collection efficiency so low Swank noise
  - Most mature material is amorphous selenium (Z=34)
    - » Low Z value limits x-ray absorption at diagnostic energies (>60kVp)
    - » Difficult to manufacture thick layers (~1000μm) over large area
    - » More suited to mammographic applications (<30kVp)
  - Other materials include c-Si, CdTe, CdZnTe, HgI, PbI, PbO, Xenon.



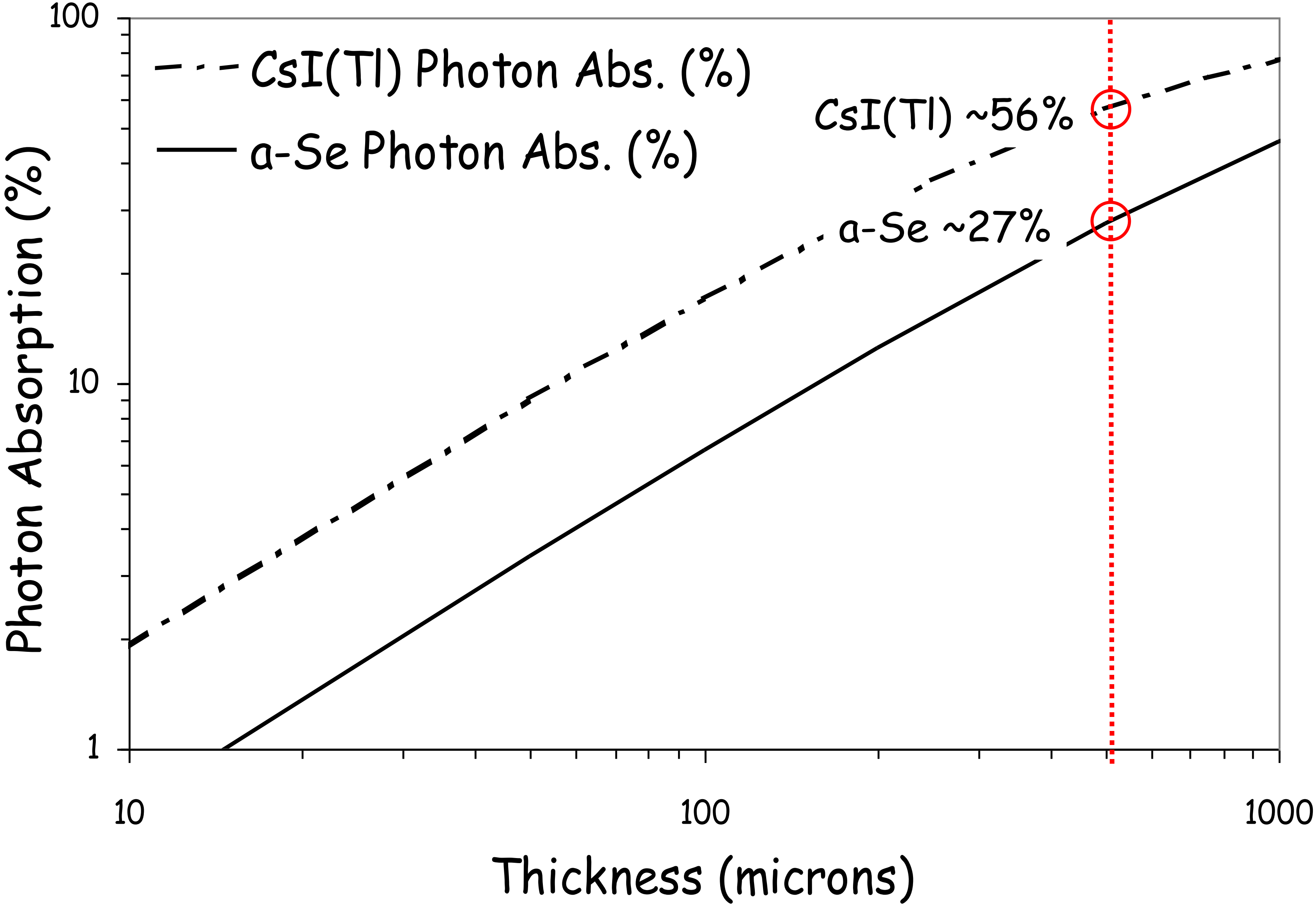
Primary Photon Absorption





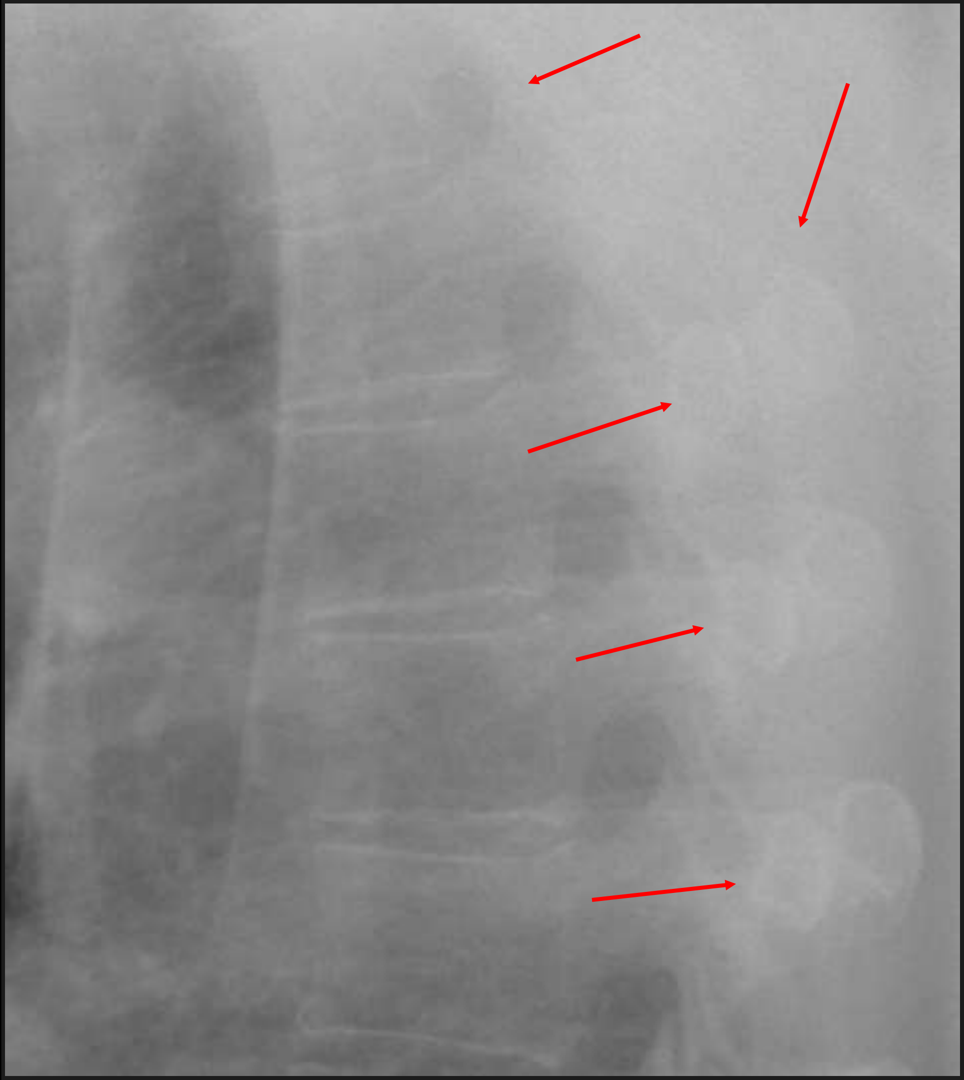
Mammo. Photon Absorption vs. Thickness
(28kVp Mo/Mo 5cm PMMA)
a-Se ~97%
CsI(Tl) ~84%
a-Se Photon Abs. (%)
CsI(Tl) Photon Abs. (%)
Photon Absorption (%)
Thickness (microns)
100
10
1
1
10
100
1000

RQA-9 Photon Absorption vs. Thickness

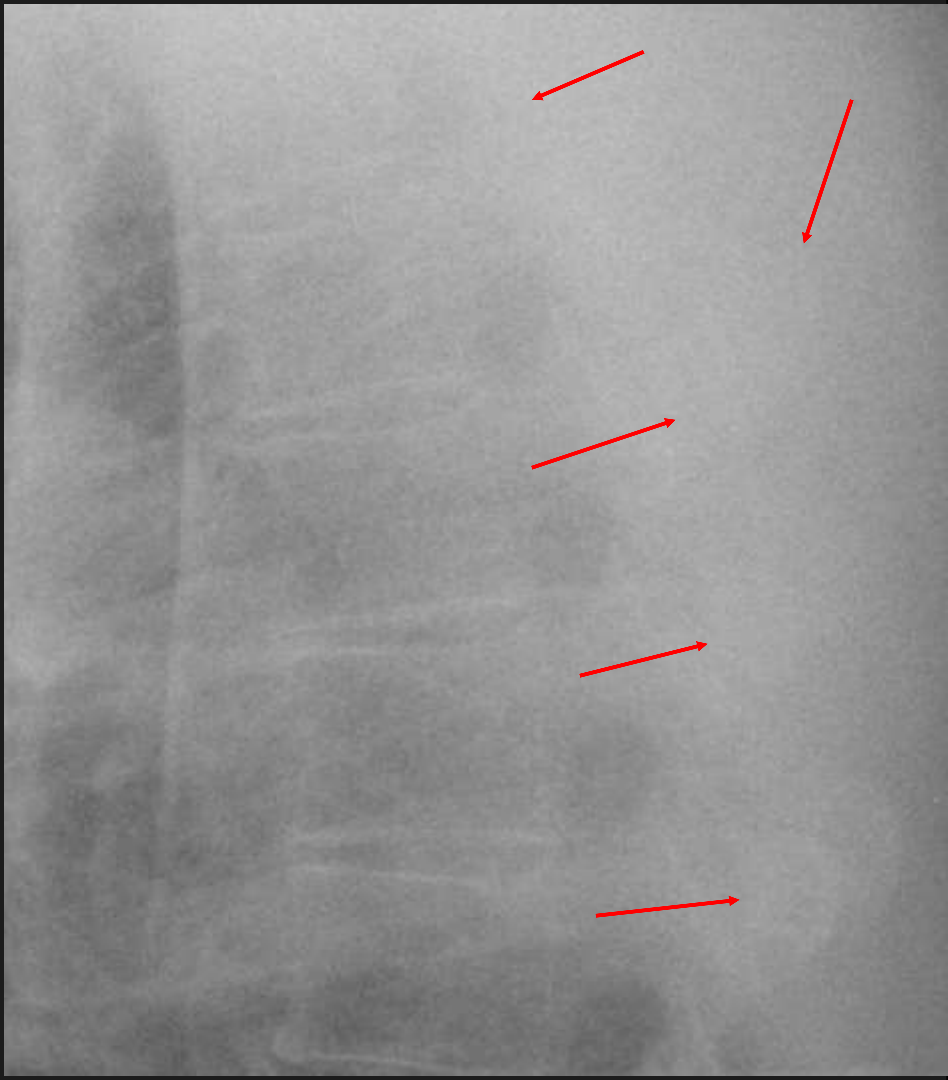


Clinical Image Comparisons: Lateral Chest (120kVp)

500μm CsI(Tl)



500μm a-Se



X-Ray Absorption Materials Summary:

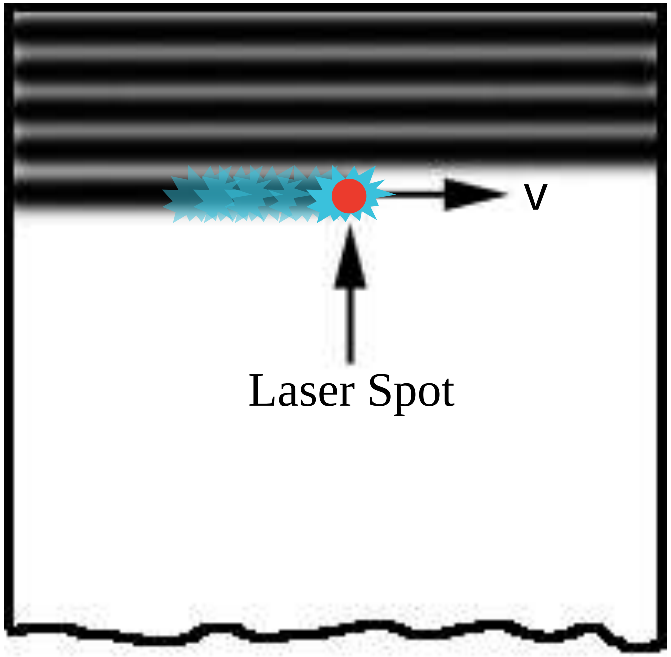
- Can be divided into 3 main types:
  - Prompt emitting phospors (Gd_2O_2S(Tb), CsI(Tl))
  - Stimulated emission phosphors (BaFBr(I), CsBr(Eu))
  - Photoconductors (a-Se)
- Phosphors can be sub-divided into:
  - Powdered or Particle-in-binder layers
  - Structured/Needle/Focused Phosphors
- All have sufficiently good properties to be “useful”
- Which is “best” depends on specifics of application

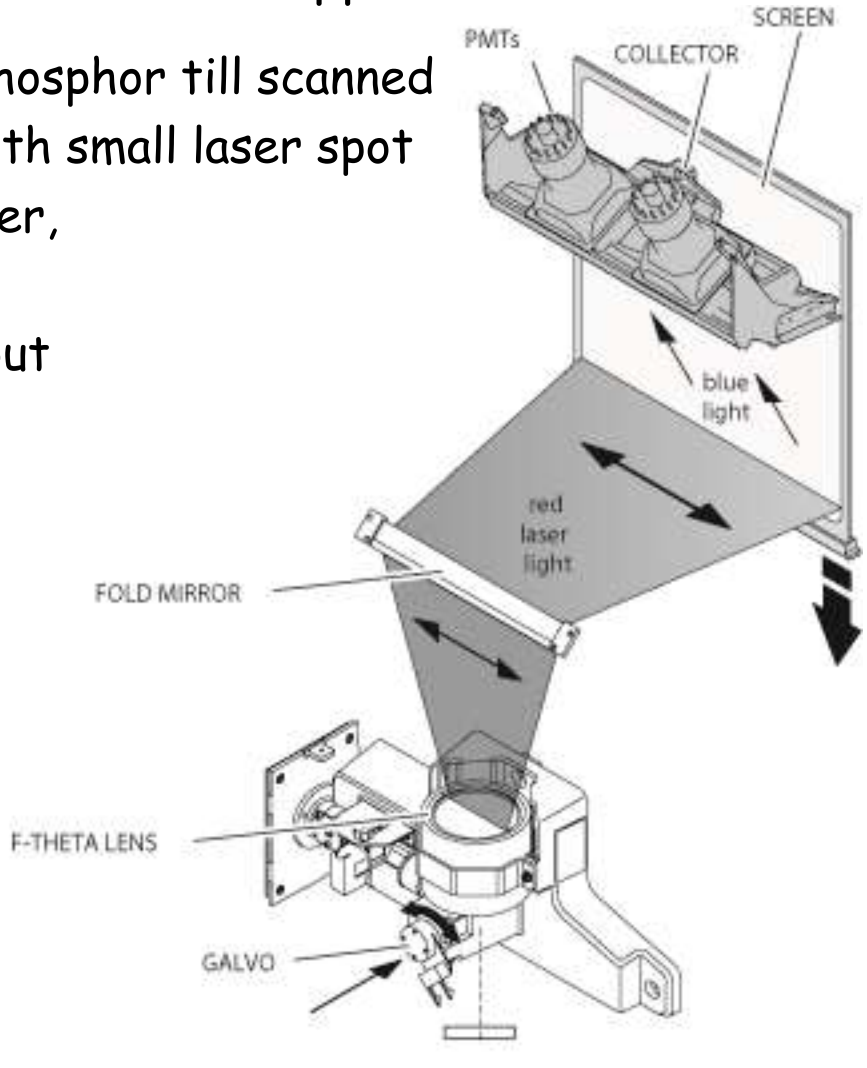
Secondary Quanta Detection:

- Issues are similar for phosphors and photoconductors
  - Need accurate measure of generated signal over large areas
  - Maintain image "quality" produced by x-ray absorption layer
- Possible approaches include
  - Point by point scanning
  - Line scanning
  - Full area readout

Point by Point Scanning:

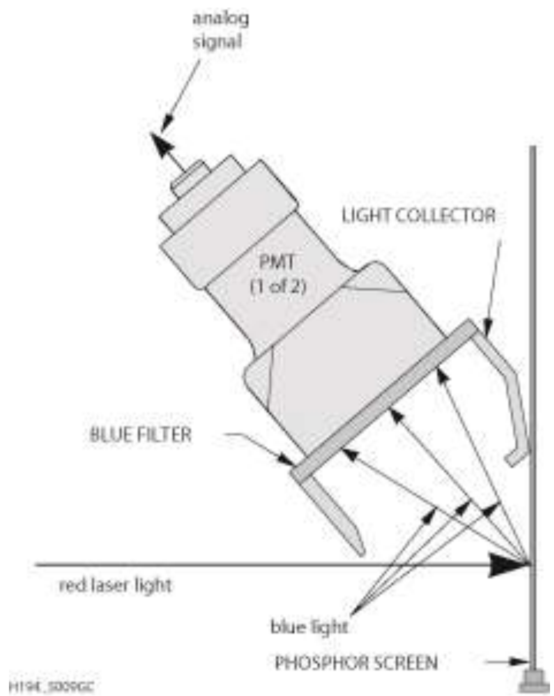
- Storage Phosphors/CR lend themselves to this approach
  - Image information "stored" in phosphor till scanned
  - Allow time to scan whole area with small laser spot
  - Spot ~100μm in size, 10mW power,
  - Dwell time ~few μsecs/pixel
  - ~30 or so seconds for full readout





Point by Point Scanning:

- Optics and mechanical motion require “large” system
- Issue with collection efficiency of stimulated light
  - Secondary quantum sink at collection stage
- One solution: read out signal from both sides of phosphor



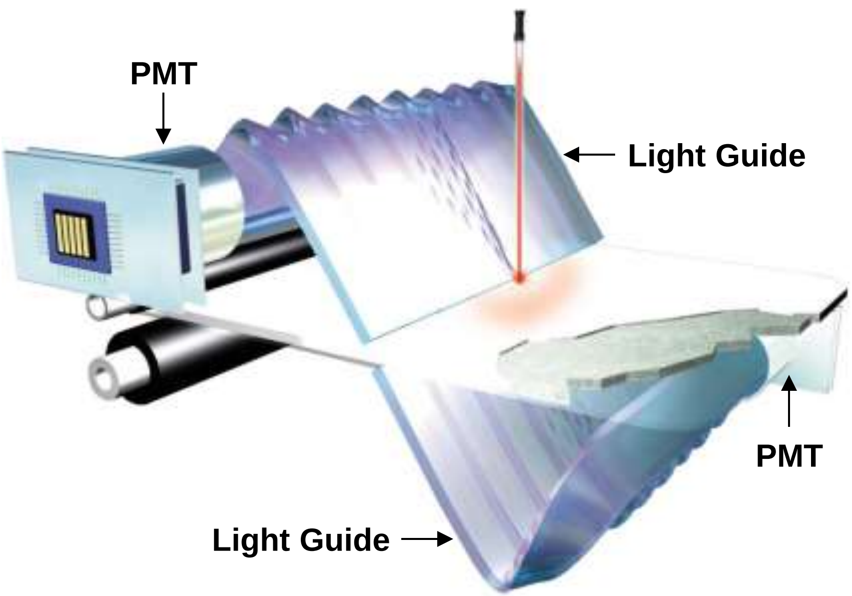
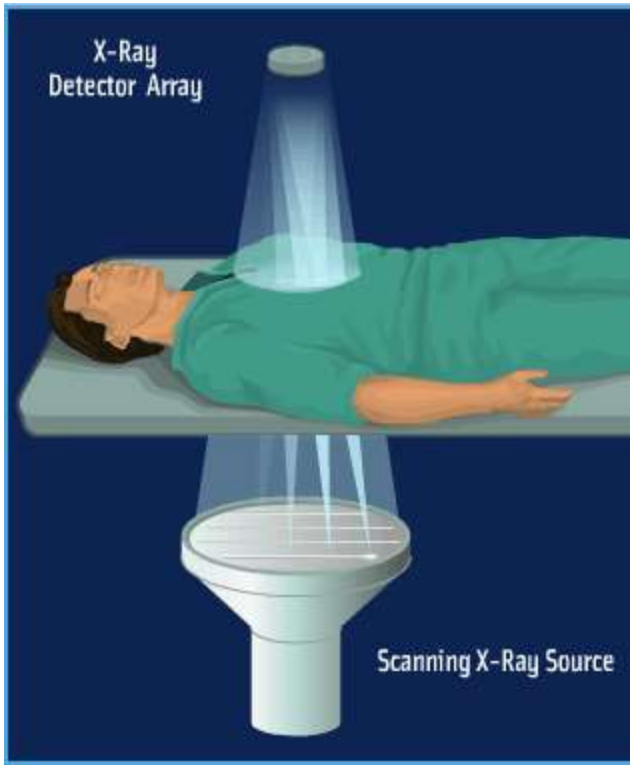


Image courtesy R. Uzenoff Fuji Medical

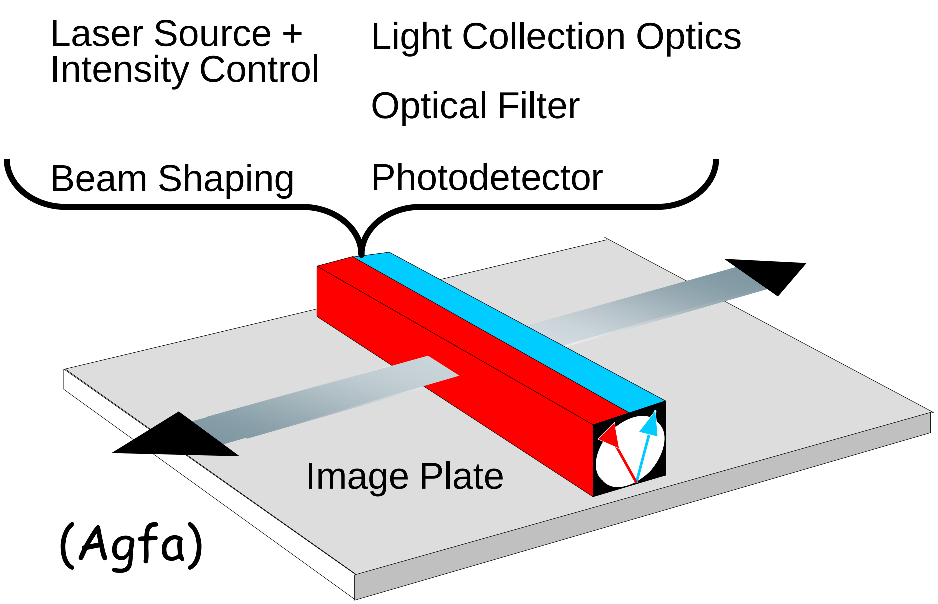
Point by Point Scanning:

- NovaRay's ScanCath™ inverse geometry system (SBDX)
- Uses large area source and small area detector
  - Pixellated CdZnTe photon counting detector
  - Transmission anode target with collimator
  - Excellent scatter rejection
  - Targetted to cardiac imaging at 30 fps.
  - Automatically collects tomosynthesis data



Line/Slot Scanning:

- To improve scan speed read out a line at a time.
- With storage phosphor can readout lines after area exposure
  - Incorporate line laser and solid state collector in compact single unit
  - Significantly reduces space requirements for beam path optics
  - Still requires mechanical motion
  - Also possible with photoconductor (e.g Thoravision)



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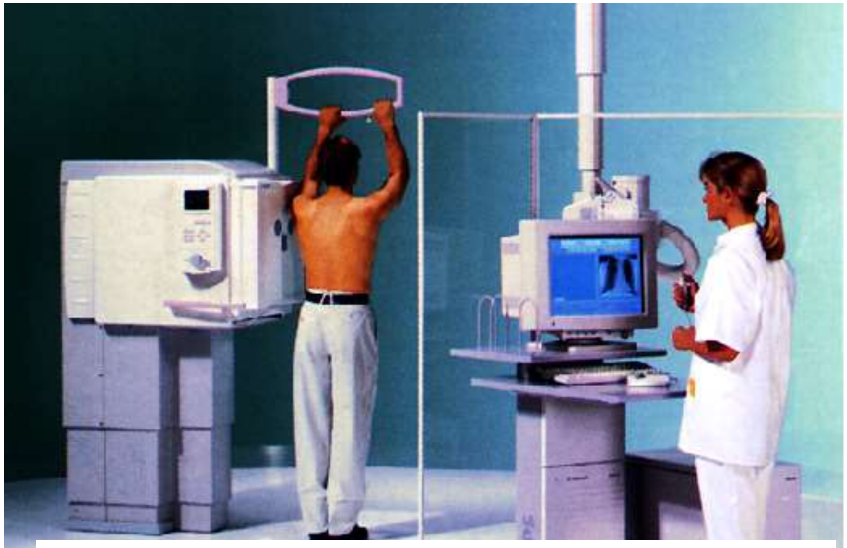


Philips Thoravision a-Se Chest System

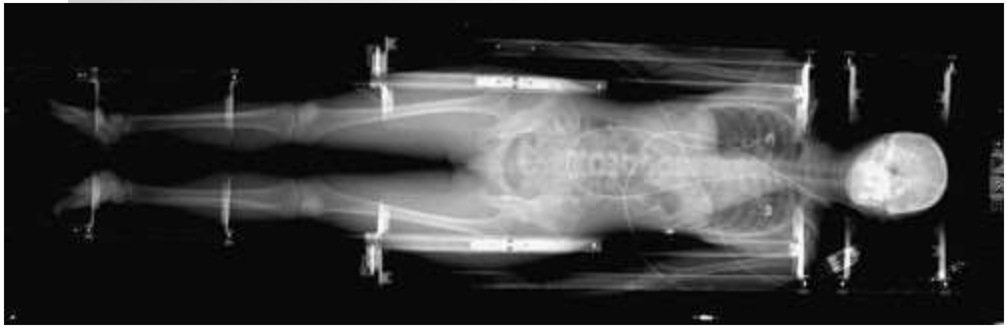
Line/Slot Scanning:

- With <u>prompt emitting</u> phosphors need to collimate x-rays
- Numerous versions of line/slot scanned systems
- Most use some form of linear CCD as detector
  - c-Si photon counting mammo system recently approved by FDA
  - Gas wire chamber based systems have also been reported
- Good coupling between phosphor and CCD, good DQE
- Excellent scatter rejection
- Still require mechanical motion and collimation alignment
- Scan times of multiple seconds

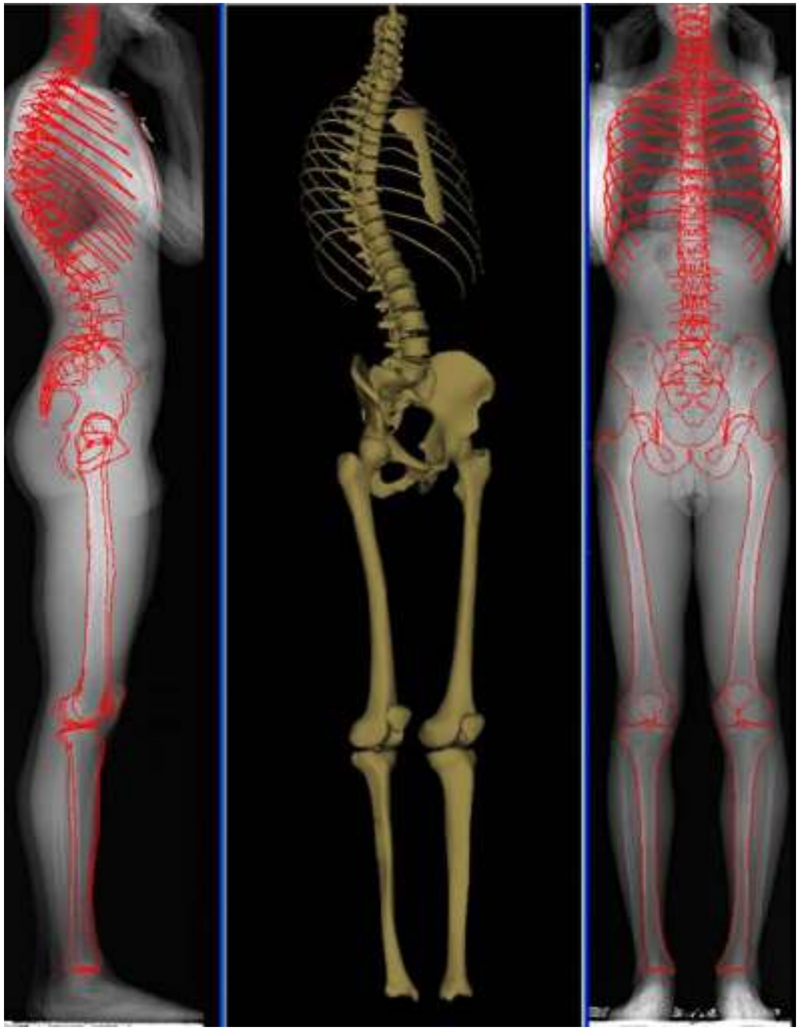
- Commercial examples that used CsI(Tl) coupled & linear CCD's include:
  - Thorascan (Oldelft) chest system
  - Senoscan (Fischer) mammo system

Line/Slot Scanning:

- Lodox Statscan
    - Full body scan 13 secs
    - Linear CCD with CsI(Tl)



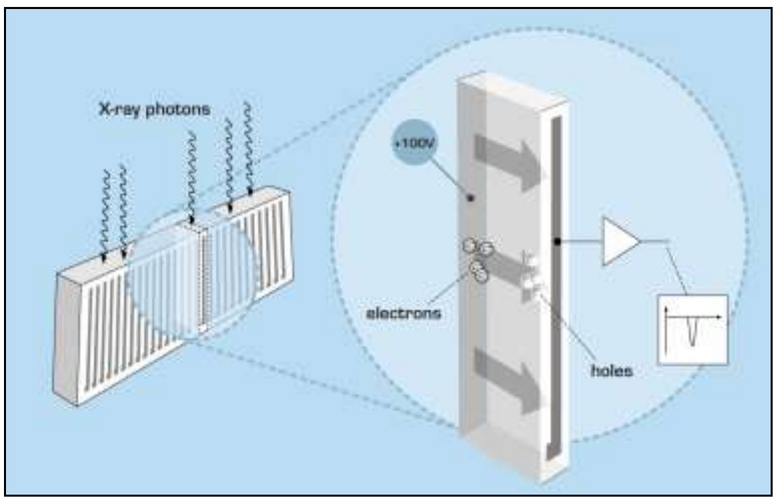
Line/Slot Scanning:

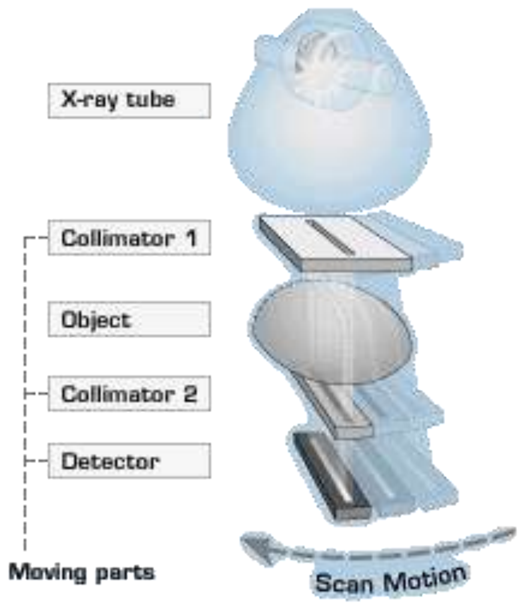


- Biospace EOS
    - Full body scan 20 secs
    - Perpendicular wire/gas chambers

Line/Slot Scanning:

- Crystalline Si low x-ray absorption efficiency (Z=12)
  - Si chip fabrication uses thin layer of processed materials (~100's μm)
  - Not thick enough for direct x-ray absorption
  - Increase effective thickness by rotating thin layer of c-Si
  - Used in commercial scanning "photon counting" mammo system
  - Takes multiple seconds for scan





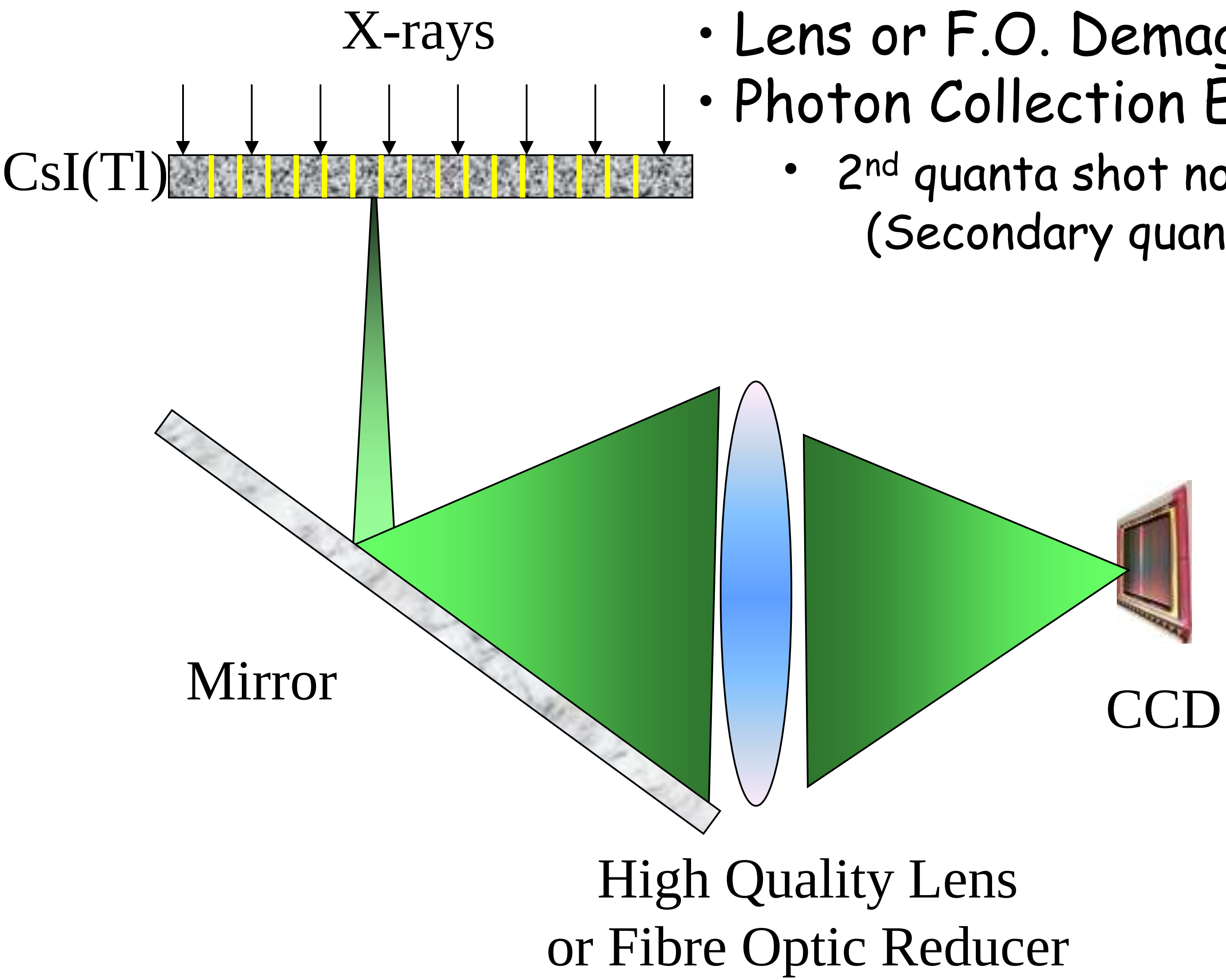
Philips MicroDose

Full Area "Electronic" Readout:

- Earliest approaches used CCD detectors

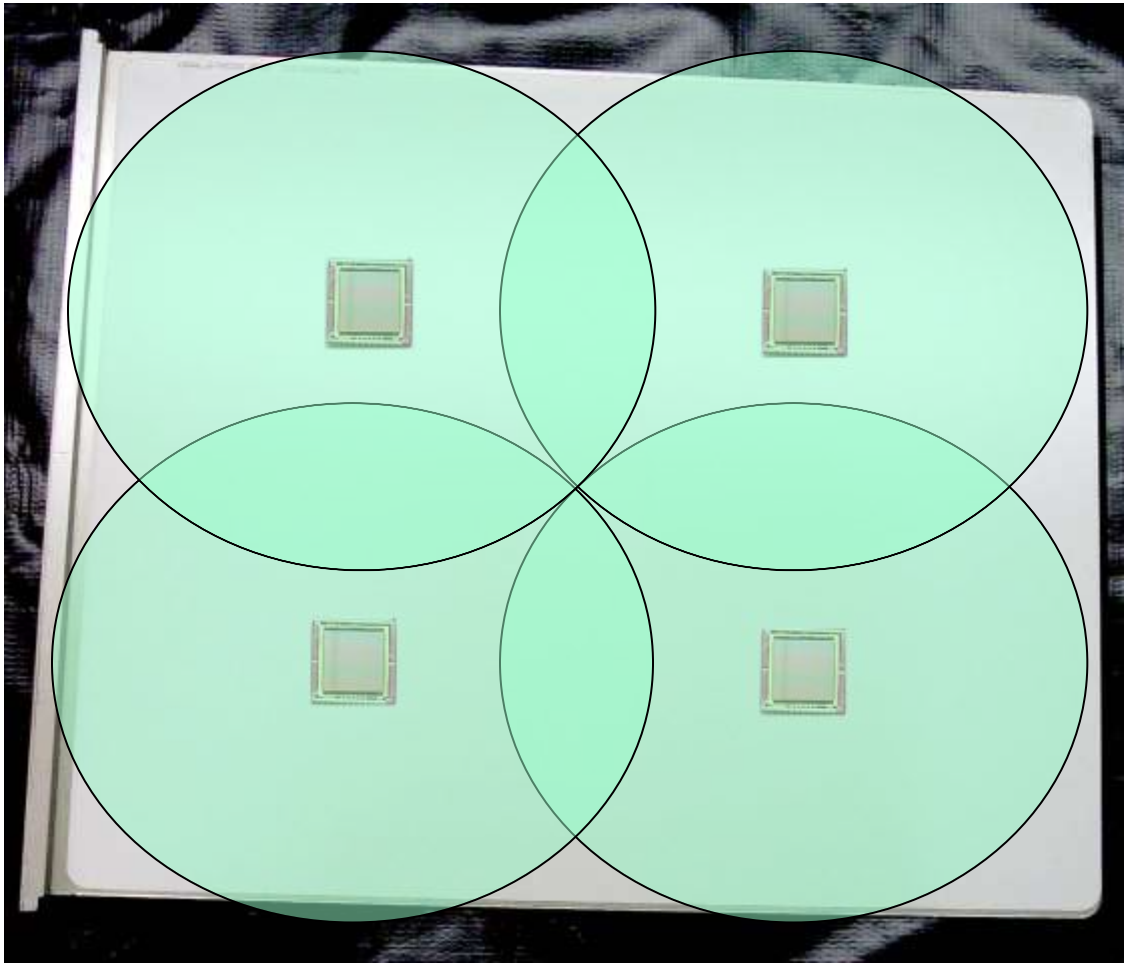
Area Readout: Single CCD Configuration

- Lens or F.O. Demag. ~x10-12
- Photon Collection Efficiency ~0.1%
  - 2nd quanta shot noise dominant (Secondary quantum sink)



(Courtesy Imaging Dynamics Corp.)

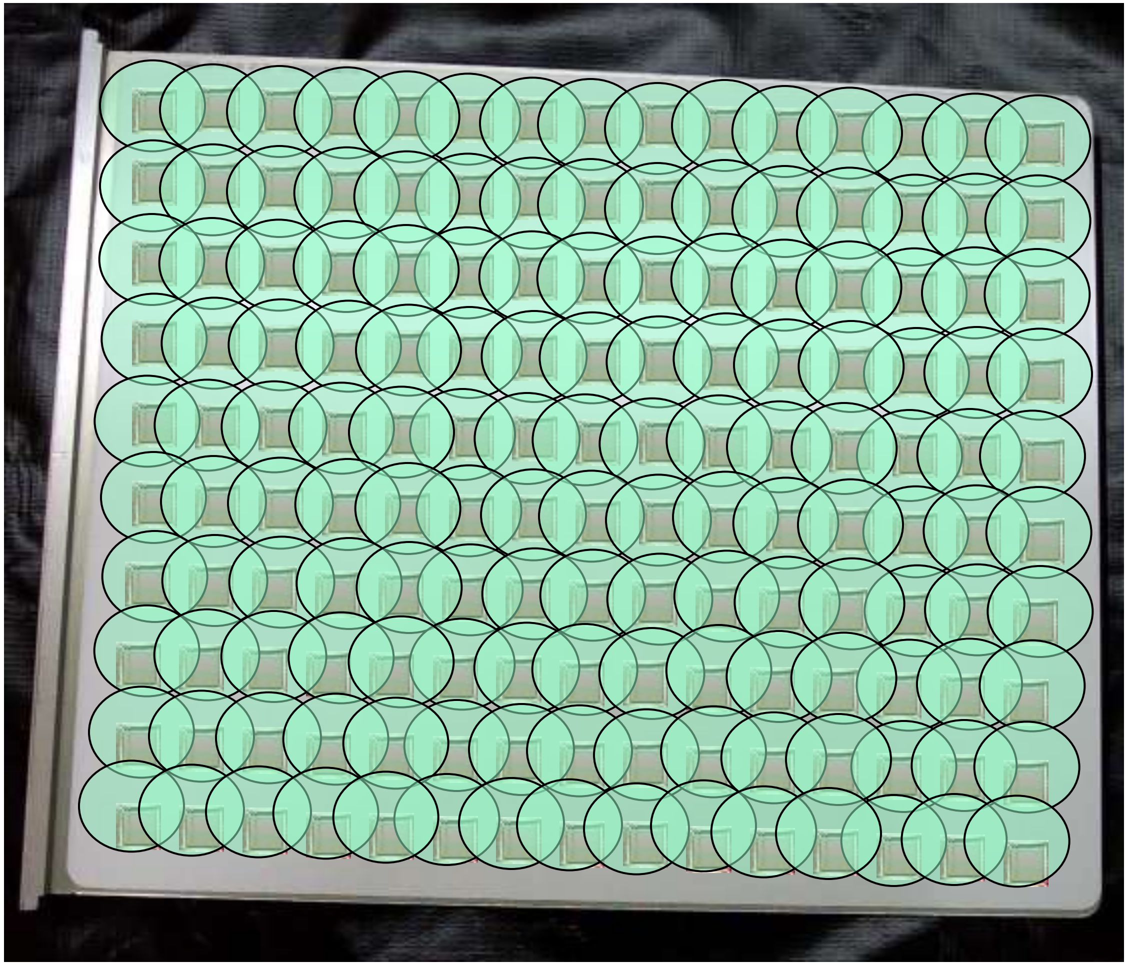
Area Readout: Multiple CCD Configuration



- SwissRay and Apelem
  - reduces de-mag.

(Source: SwissRay Corp.)

Area Readout: Multiple CCD/CMOS Config.

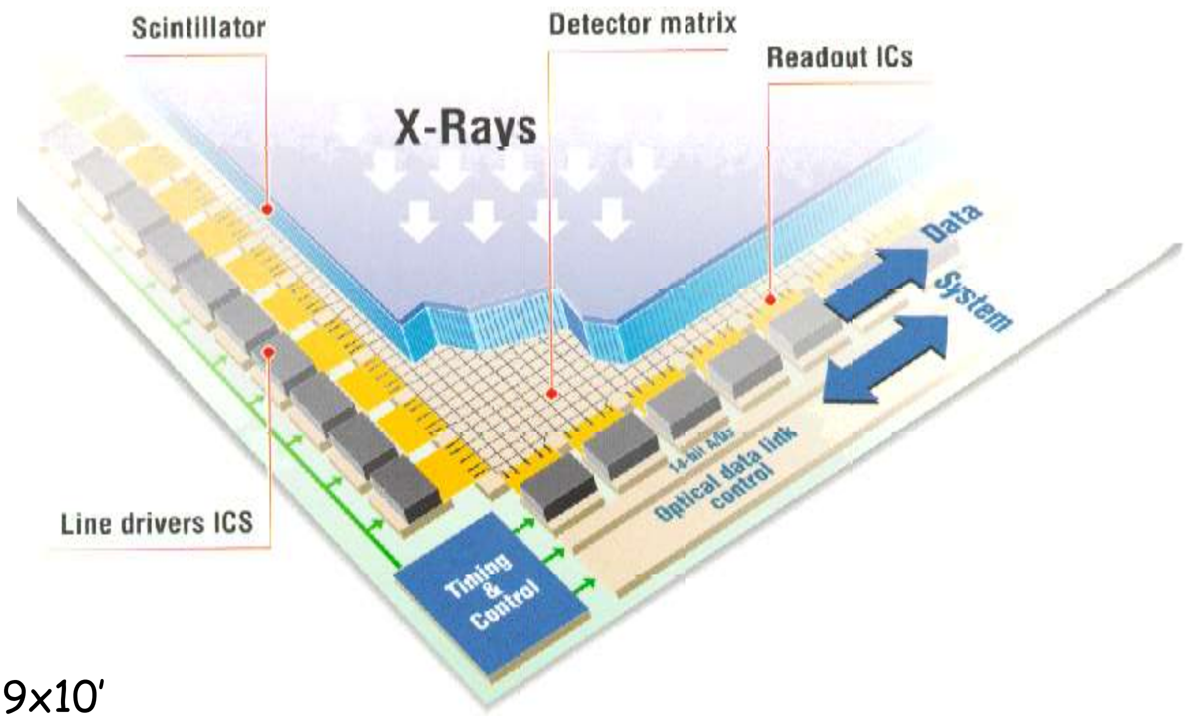


- CaresBuilt and Naomi
  - Tiling of image an issue

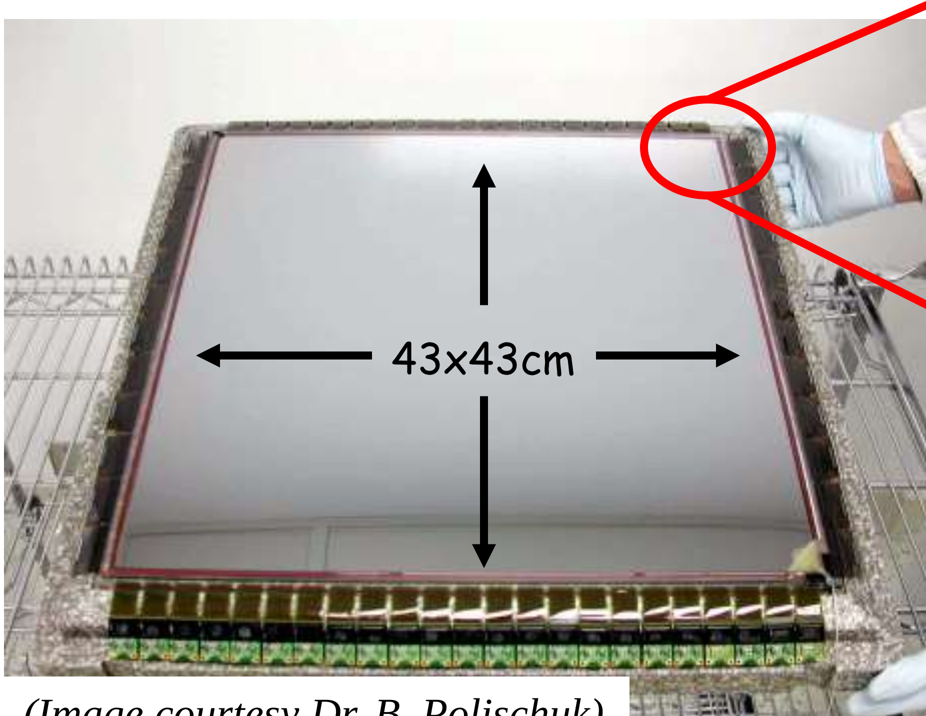
Area Readout: a-Si:H Flat Panel Readout

- Fabricated using large area a-Si:H deposition facilities
    - 14x17" or larger readily available with pixels down to <100μm
    - Can use prompt emitting phosphor or photoconductor
    - Directly coupled to x-ray absorption layer (high transfer effic.)
    - "Electronic" readout can operated in static or fluoroscopic modes

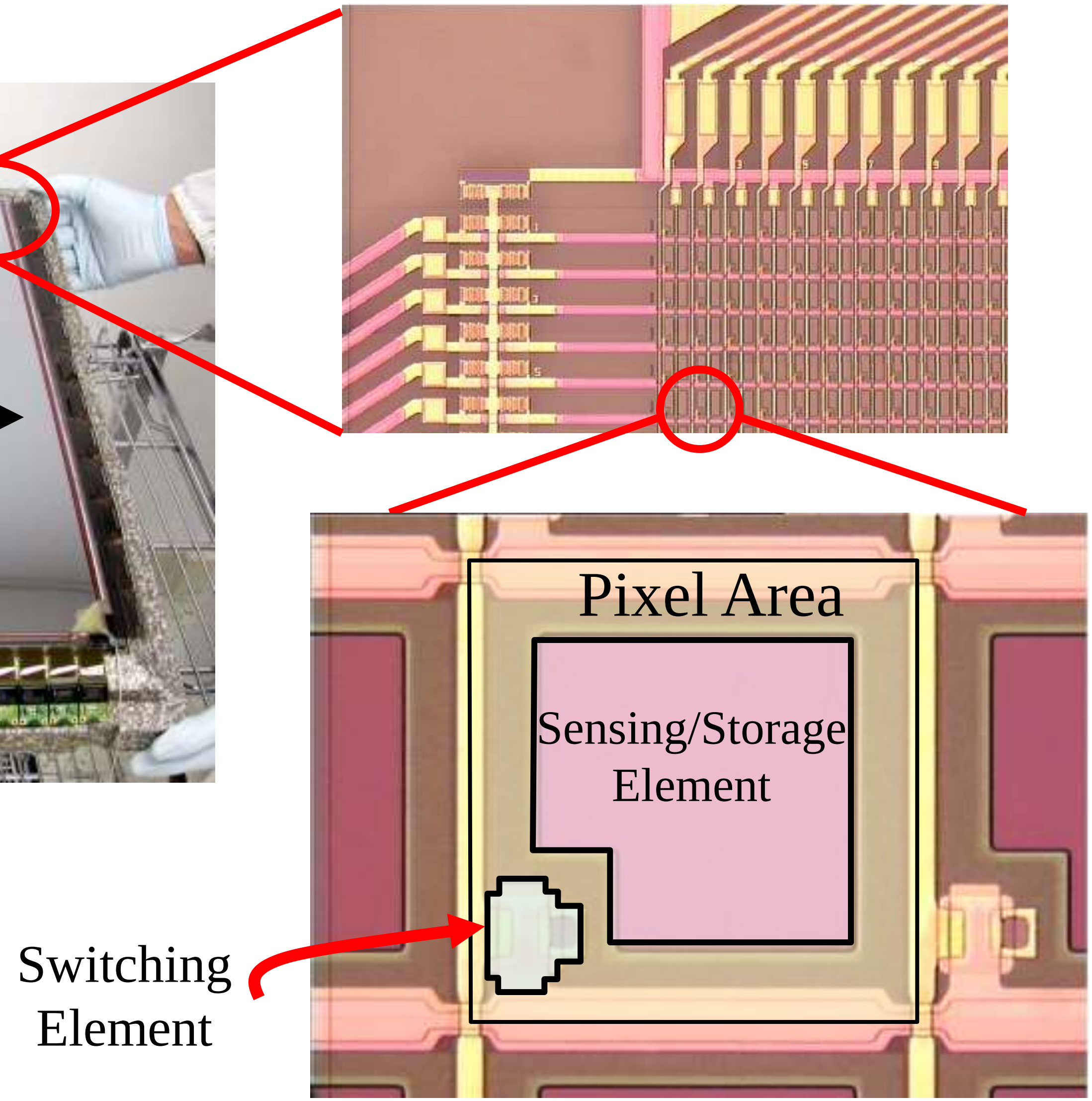
Sharp Gen. 10 Glass Substrate 9x10'



Area Readout: a-Si:H Flat Panel Readout



(Image courtesy Dr. B. Polischuk)



Area Readout: a-Si:H Flat Panel Readout

- Advantages of a-Si:H readout arrays
  - Large area fabrication (>40cm dimensions) allowing non-tiled detector
  - "Mature" fabrication infrastructure (based on display industry)
    - Many peripheral components now available "off-the-shelf"
  - Excellent image quality due to high 2^{nd} quanta collection efficiency
  - True "electronic" readout (no mechanical moving parts)
  - Advanced application capable (i.e. supports "real-time" readout speeds)
  - Very tolerant of radiation damage (due to amorphous structure)

- Challenges for a-Si:H readout arrays
  - Relatively high "additive" electroinc noise
    - Compromises low exposure perfomance
  - Fabricated on "fragile" glass substrates (0.5mm thick or less)
  - Inherent materials properties affect "image quality"
    - Low carrier mobility limits "smart" pixel capabilities
    - Large feature sizes may limit "fill factor" of small pixels

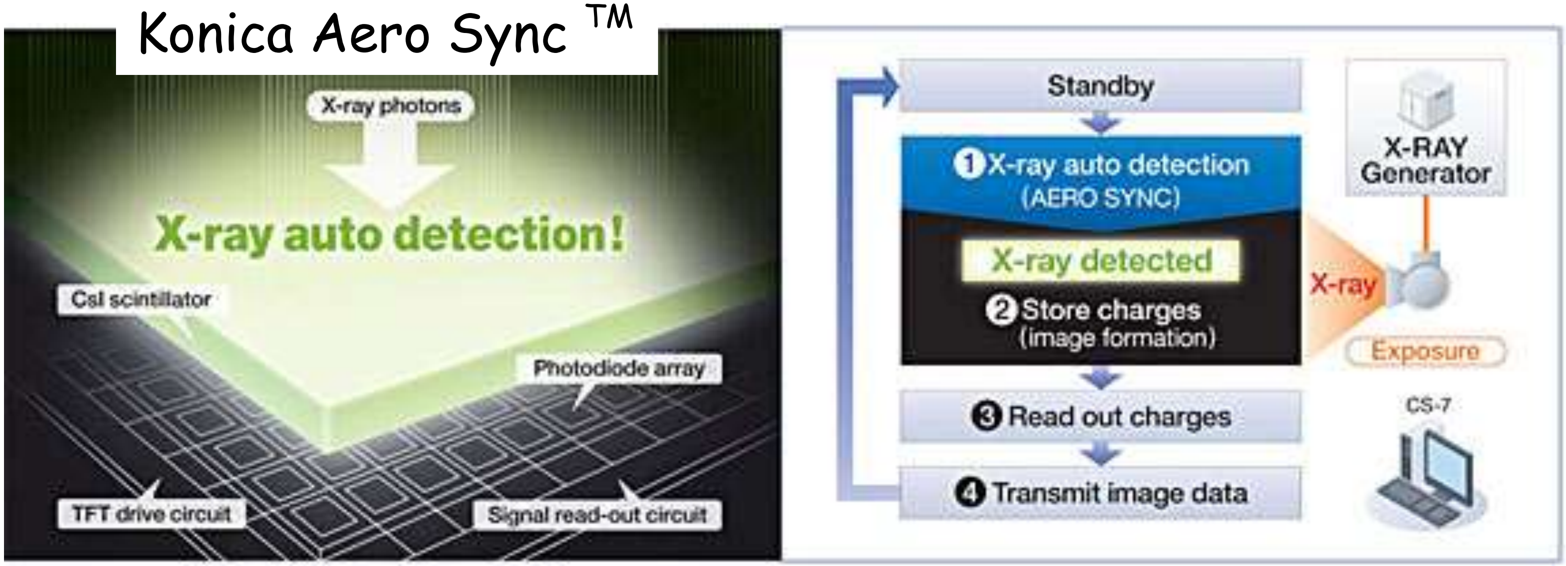
Recent Developments: a-Si:H Portable Systems

- Recently, portable 14x17" & 17x17" detectors introduced
  - Initially rather heavy/bulky/thick with tether
  - More recently wireless, battery powered with cassette form factor
  - Smaller sized detectors (10x12") now being introduced

Recent Developments: Beam Triggered Readout

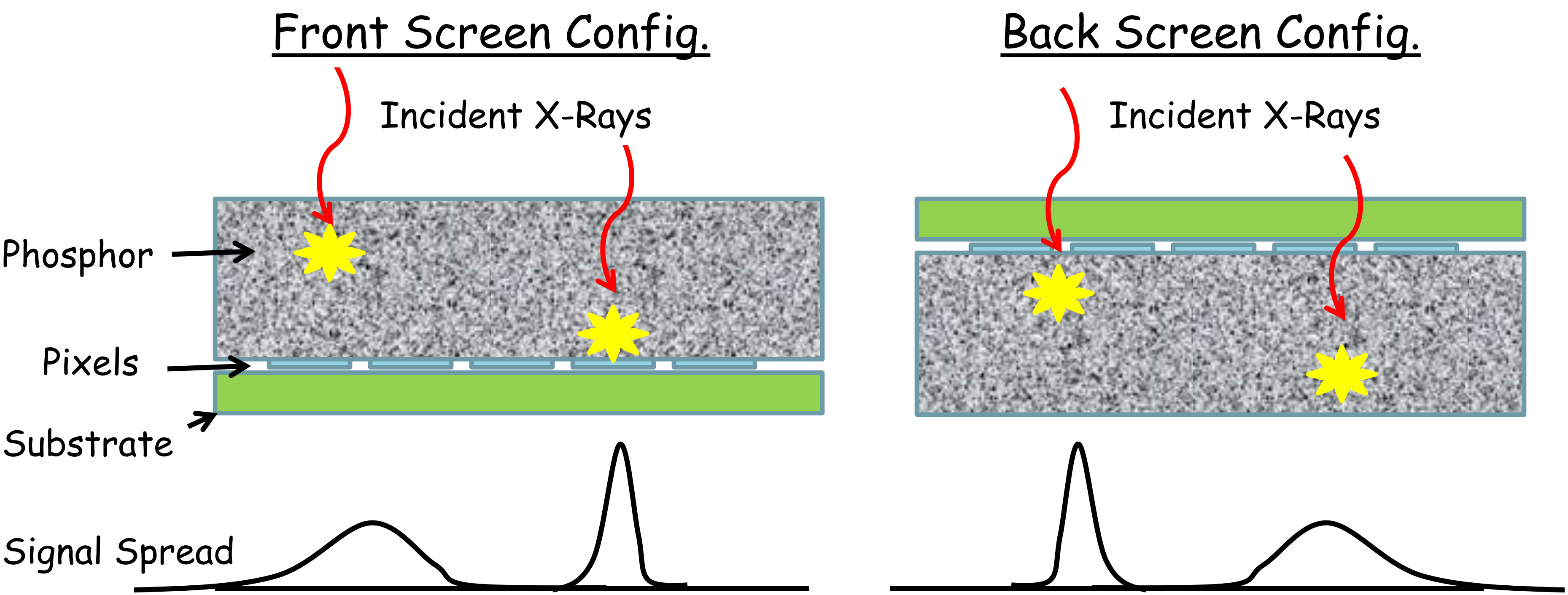
- Synchronization between detector & x-ray delivery essential
  - Unlike screen/film and CR which are always "active"
- Traditional flat panel detectors integrated with generator
- New approaches have no hardwired "electrical" interface
  - Makes retrofitting of older systems easier

Konica Aero Sync ™



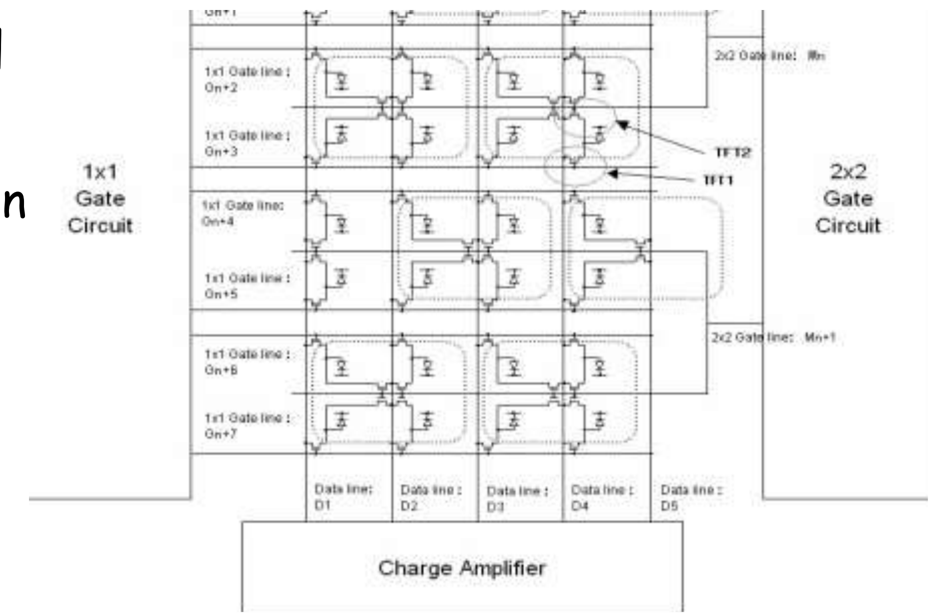
Recent Developments: Back Screen Config.

- Concept previously used in film/screen mammography
- Most advantageous when:
  - Energy deposition weighted towards entry side of screen (e.g. mammo)
  - Have low x-ray absorption substrate
  - Can reduce Swank noise and Lubberts Effect hence improving IQ



Recent Developments: Smart Pixels

- Numerous research groups reported on pixel level circuitry
  - Main goal to amplify signal level to reduce effect of addt. noise
  - Issue with size of a-Si:H TFT's which can reduce fill factor
- First large area demonstration of multiple TFT a-Si:H pixels
  - 17x17" CsI detector, 150um pixels
  - 1x1 or 2x2 binning at pixel level
  - Improves noise performance
    - Adds signals before digitization



From: Ito et.al. SPIE Phys. Med. Imaging 8668 (2013) 866807-1

Recent Developments: New Materials

- New substrate materials
  - Flexible substrates e.g. plastic, metal & glass (~0.1mm thick !)
    - These would allow conformable, large area, very robust detectors
    - Available 30cmx300m for roll-to-roll proc.

Corning Willow Glass™

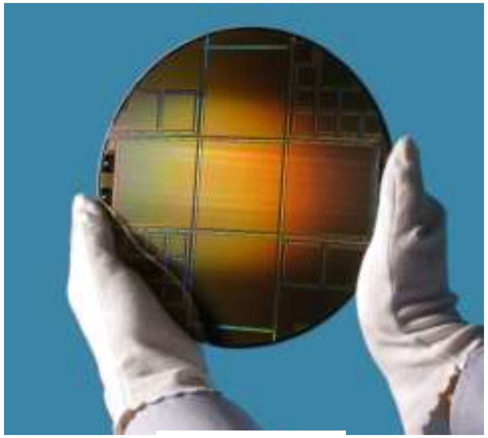
- New fabrication materials
  - Low temperature poly-Si
    - Has improved carrier mobilities
  - IGZO
    - Compatible with large area deposition
    - Has better carrier mobility hence smaller feature sizes
    - Allows more complex circuitry at pixel level
- New X-ray converters for lower dose applications
  - Mostly photoconductors that generate more signal per x-ray (e.g. PbI, HgI, CdTe, CdZTe, PbO)
  - Still mainly academic and commercial research activities

Recent Developments: Flexible Substrates

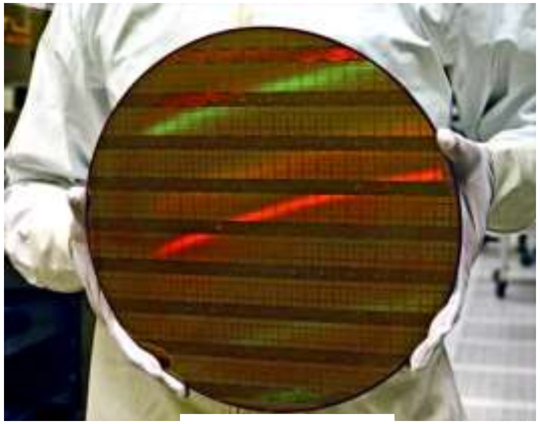
- Worlds first com. available curved screen TV from LG (~$10,000 !)
  - Uses a flexible substrate and IGZO instead of a-Si:H
  - 4.3mm thick !!

Area Readout: CMOS Technology

- Fabricated with "standard" silicon IC chip technology
  - Typically use standard 8" Si wafer fab. capability
  - Limits physical dimensions of sensor
  - Small feature size (<10nm) allows complex pixels
    - e.g. Pixel level amplification, and dose sensing
  - Larger sensor tiles can reduce yield and increase cost



8 inch

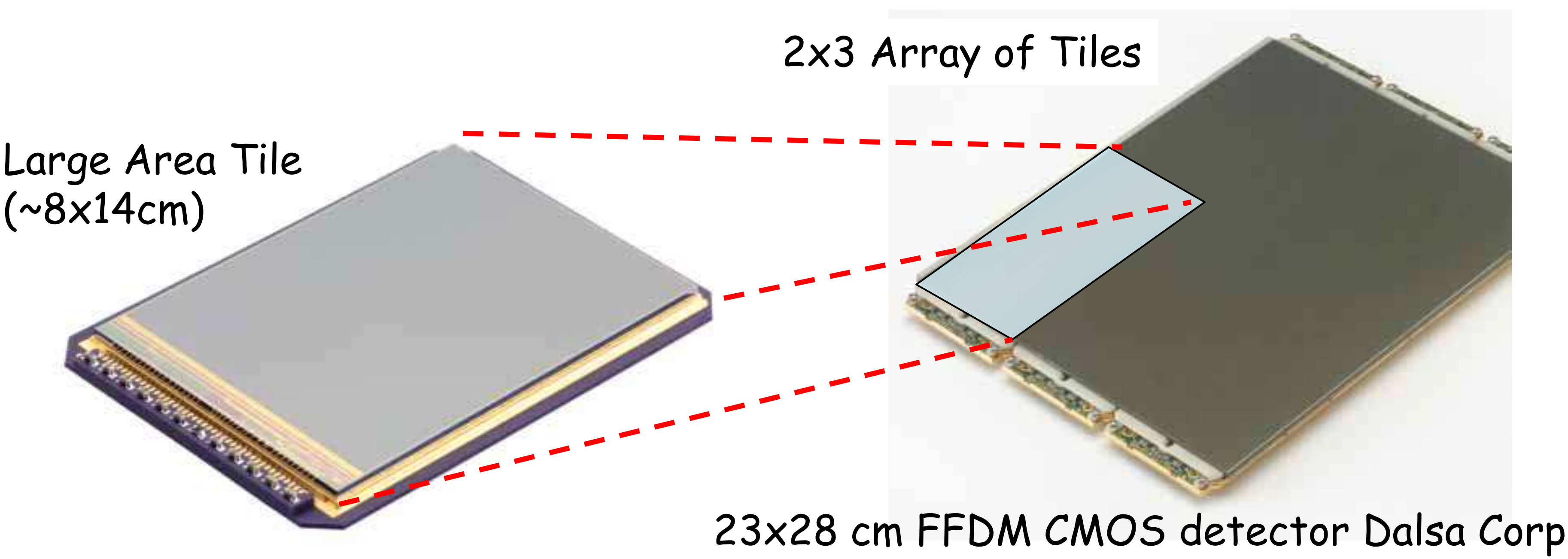


12 inch

18 inch (Intel)

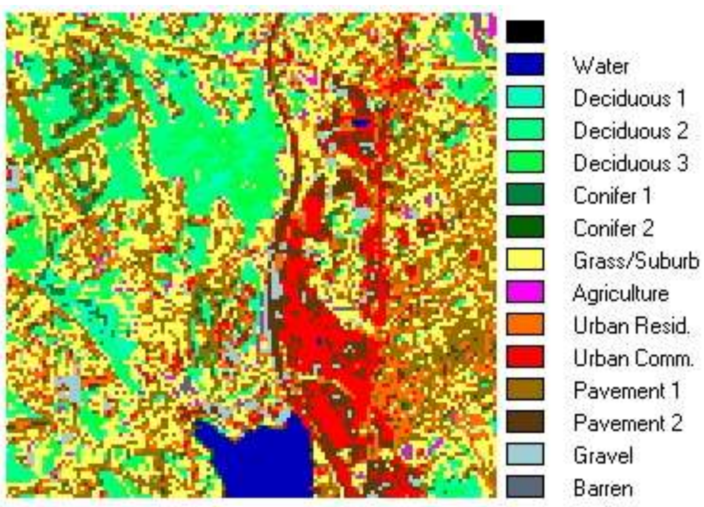
Area Readout: CMOS Technology

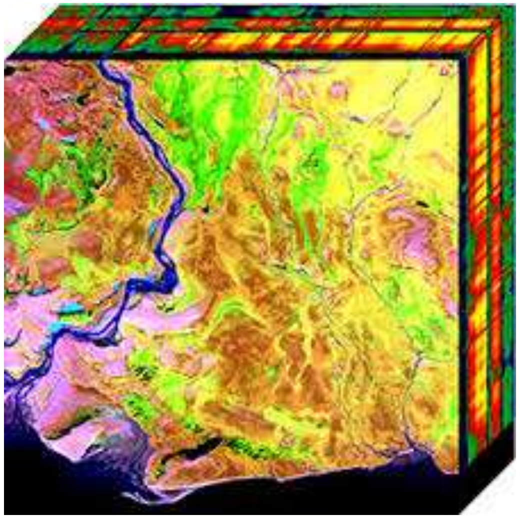
- Recent development is "large" 3 side buttable CMOS tiles
  - Very low "additive" readout noise (100's el. c.f. 1000's for a-Si:H)
  - High speed readout (~30+ f.p.s)
  - Integrated electronics (e.g. ADC's and pixel level circuitry)
  - Directly coupled to x-ray absorption layer (high transfer effic.)
  - High fill factor even with small pixels (<75um)



Area Readout: CMOS Technology

- CMOS allows energy integrating or photon counting
  - Energy integrating typically utilizes CsI or GOS bonded to chip
  - Photon counting typically uses photoconductor (CdTe or CdZnTe)
    - Use of CdTe and CdZnTe currently limits size of sensor to < ~2-5 cm
    - Energy selective imaging is possible
    - Photons can be weighted according to image information "content"
- Energy resolved photon counting allows multi-spectral imaging





Summary:

- Knowing the basic components allows for informed choices.
- Storage phosphor systems: Faster, smaller and cheaper
  - Slow readout speeds prevent "real time" use
- a-Si:H Flat Panels: Form factor and functionality (and price!)
  - New materials continue to be investigated
  - Watch for developments in display manufacturing (e.g use of IGZO)
- CMOS: Increasing commercial visibility and viability
  - Confined to smaller area applications at present (tiled arrays)
    - Dental intra-oral, mammography, small field fluoro, CBCT
  - Excellent image quality and energy selective imaging capabilities

Performance Summary:

	Point/Line Scanning		Full Area Readout					
	Stimulated Emission Phosphor		Prompt Emission Phosphor				Photoconductor	
	BaFBr(I)	CsBr(Eu)	a-Si:H +GOS	a-Si:H +CsI(Tl)	CCD/CMOS lens/fib.opt.	Tiled CMOS	200μm a-Se (mammo)	500μm a-Se (gen.rad.)
Speed of Readout	- - (+ if integ.)	- (+ if integ.)	+ +	+ +	+ + +	+ + +	+ +	+ +
Image Quality	+	+ +	+ +	+ + +	+	+ + +	+ + +	+ +
Robustness	+ ++	-	+ + +	-	+ + +	+ +	-	- -
Size	- -	-	+	+	- -	+	+	+
Cost	+ + +	+	-	-	+ + +	-	-	-
Adv. Apps. (tomo& DE)	-	-	+	+ +	+	+ + +	+ +	+