Apollo 101

Revision G

GE HealthCare
Xray Detectors

GE Proprietary

Outline

I. Overview

II. Flat Panel

III. Electronics

IV. Packaging and Interconnect

V. Detector Characteristics

VI. Calibration

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Goal of Apollo Digital Detector

Single detector technology to replace all current image receptors in x-ray

Replaces film for radiographic applications

- **plain film**
- **spot film**

Replaces image intensifiers, video cameras, cine cameras, photo spot, etc. for fluoroscopic, vascular and R&F applications

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Apollo Is: Large Area Amorphous Silicon Based Solid-State X-Ray Detector

Panel

- **Array of amorphous silicon thin film photodiodes with associated FET switches.**
- **Scintillator.**

Electronics

- **Chip-on-board, Chip-on-flex scan and readout electronics utilizing special purpose ASICs.**
- **Reference and regulation and detector control boards.**

Compact packaging – minimal overhang beyond imaging area for maximum anatomical utility (patient positioning flexibility); thinner than image-intensifier based systems.

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Why Digital Detector

Film:

Advantages of film based systems are large field, no distortion and high resolution, development, no real time additional step to get them in digital. You Needs

Tube, person,x-ray screen light,film, film digitizer,network

Computed Radiography - the same, except the output is directly digital

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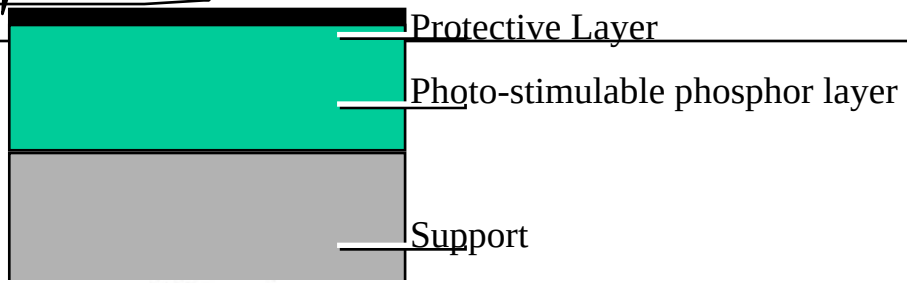

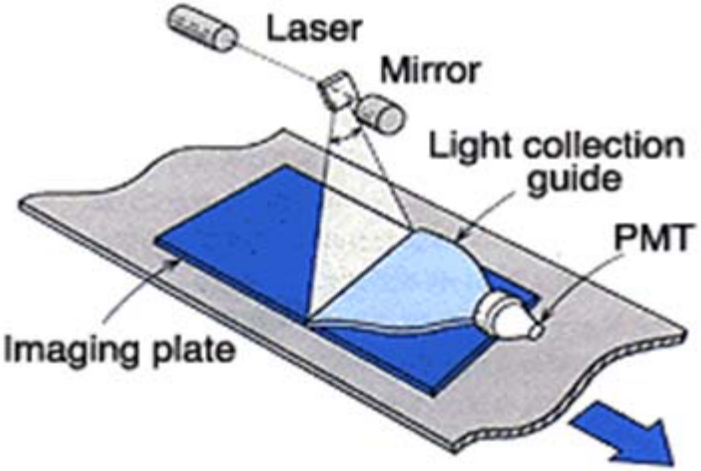

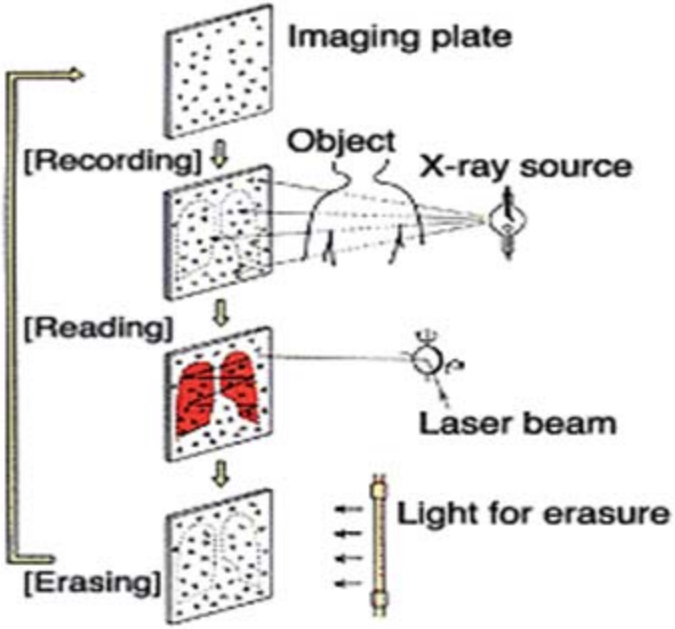

Amorphous Silicon

High image quality at low dose (high DQE)

Capable of fluoro and advanced applications

Considerably higher productivity

Highly integrated

High development cost

CR

Better dynamic range & linearity than film

Easily upgradeable, mobile

Lower DQE & dynamic range than digital detectors

Requires manual processing

Slow image acquisition

Cracks, scratches & jamming

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Advantages of film and video Image Intensifier systems are real time imaging and low dose. But these are also a source of distortion, poor resolution and limited field size.

Tube, person,x-ray image intensifier,light,A/D converter, network

Direct Digital

Direct Digital systems bring all the best at once. Drawbacks are today cost and environmental temperature constraints

Tube, person,x-ray,digital detector, network

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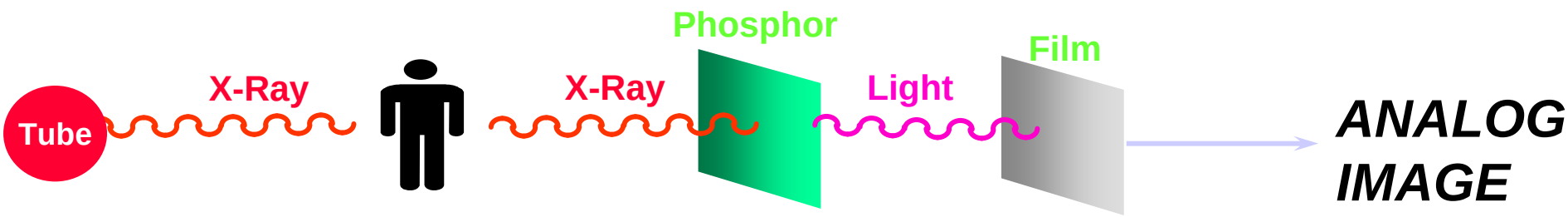
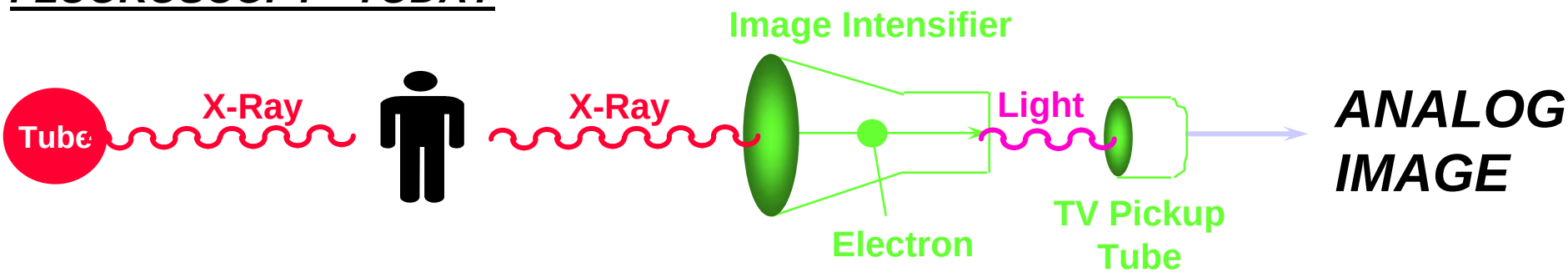
X-Ray Detection

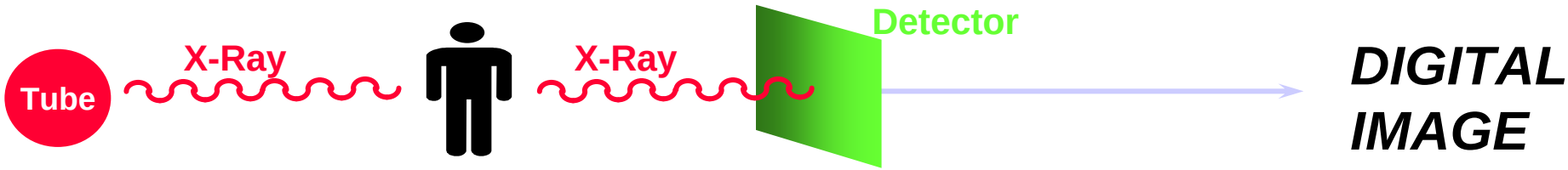
MAMMOGRAPHY & RADIOGRAPHY - TODAY



FLUOROSCOPY - TODAY



ALL APPLICATIONS - DIGITAL DETECTOR



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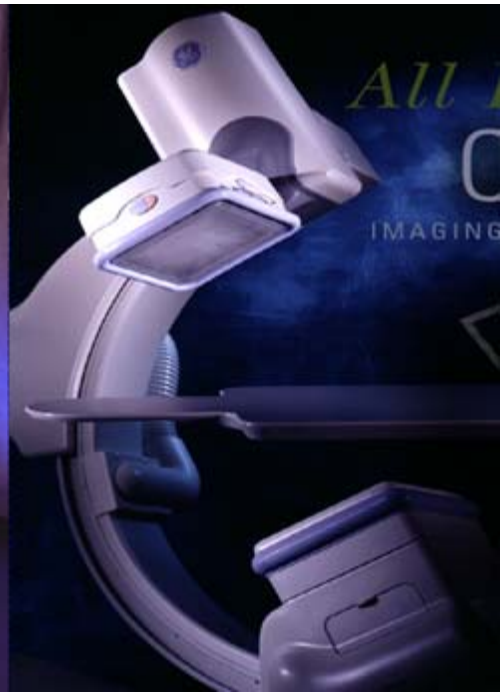
Seno 2000D Mammo

XRQ/i Wallstand

Radiographic Table

Innova 2000 Cardiac



Detector Specs

Active Area	19.2cm x 23cm
Active Matrix	1920 x 2300
Pixel Size	100µm x 100µm
Image Depth	14 Bit
Dynamic Range	10µR - 170mR
Typical DQE	>60% @ 2lp
Maximum Image Size	9MB
Detector readout	< 0.5 sec

Active Area	41cm x41cm
Active Matrix	2k x 2k
Pixel Size	200µm x 200µm
Image Depth	14 Bit
Dynamic Range	60µR - 13mR
Typical DQE	>65% @ 0lp
Maximum Image Size	<10MB
Detector readout	< 0.5 sec

Active Area	20cm x 20cm
Active Matrix	1k x 1k
Pixel Size	200µm x 200µm
Image Depth	14 Bit
Image rate	30 fps

> 1000 Systems Installed Today!

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Innova 4100 Angiographic System

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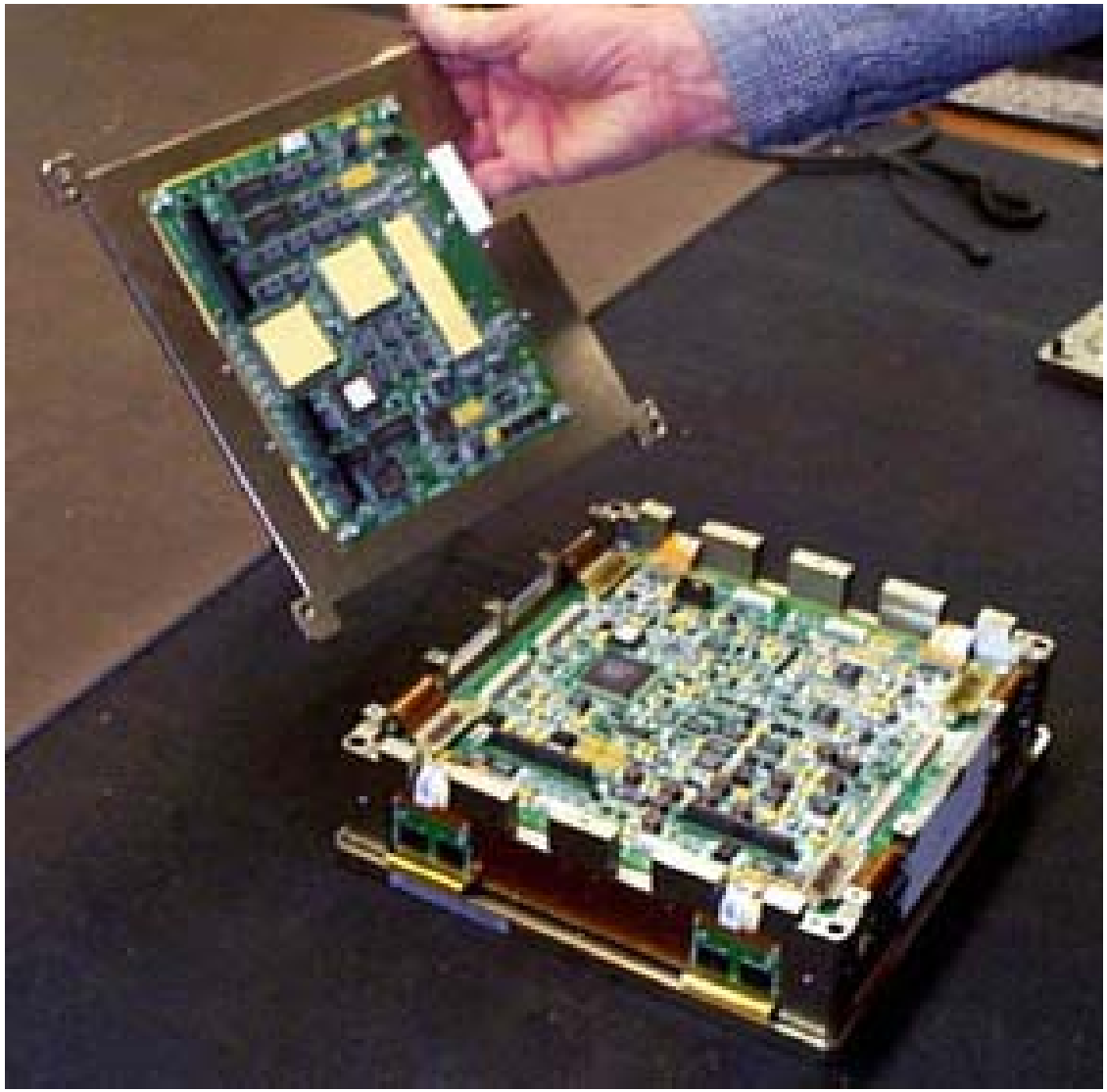

20cm
Detector
Electronics

Packaging and Interconnect

Connect flat panel to electronics, protect all components mechanically, provide compact “pizza box” package

Provide proper environmental conditions (temperature, humidity, etc.) for optimum detector operation.

Connections

- Panel to row and column modules
- Row and column modules to ref and reg board

Interconnect Method--TAB bonding (tape automated bonding)

- Needed because of high density of interconnnects
- Aniostropic conductive adhesive
- Bonding requires heat and pressure

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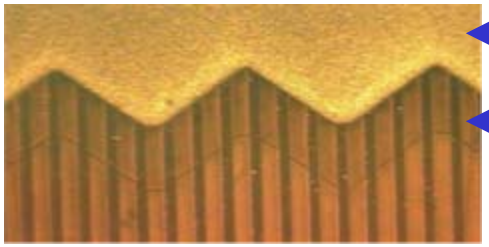
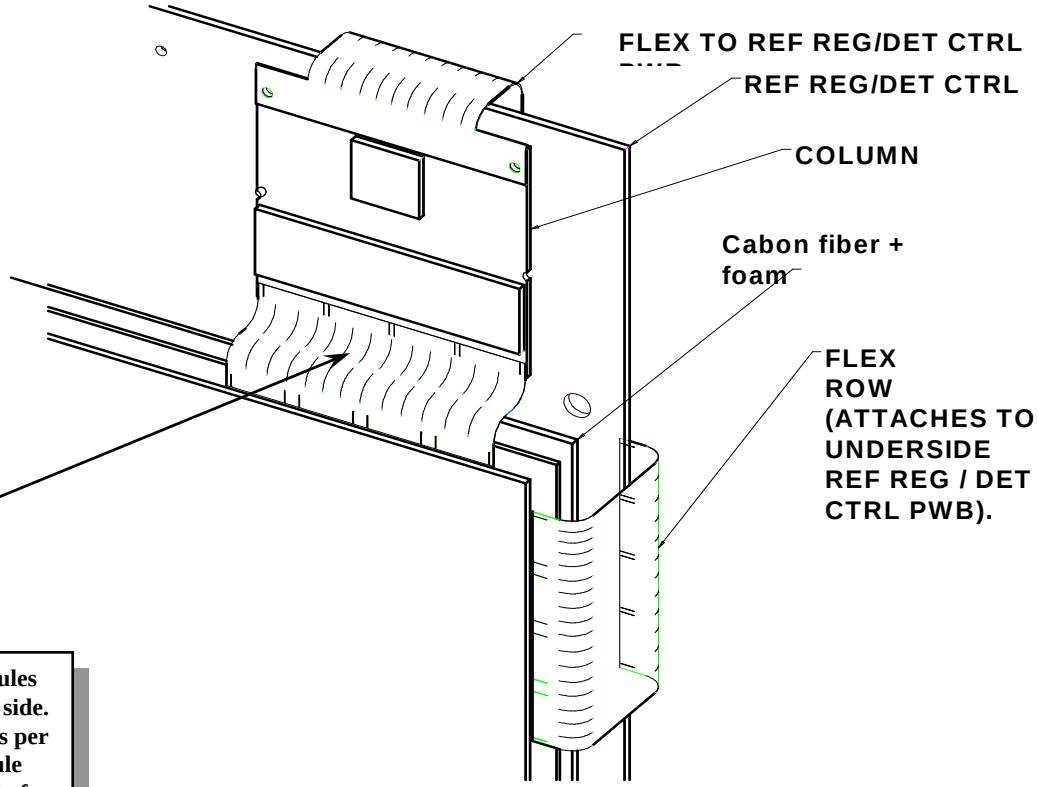
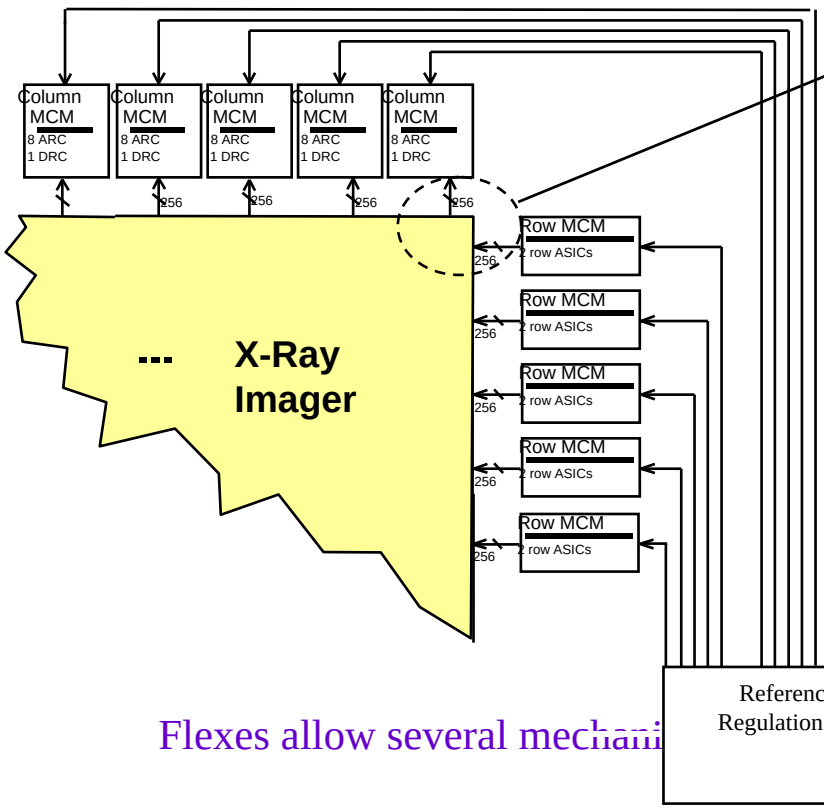
Packaging and Interconnect



Flex: Metal / soldermask transitions patterning



8 Modules on each side. 256 lines per module Total of 4096 lines to connect for data lines.



8 Modules on each side. 256 lines per module Total of 4096 lines to connect for scan lines.

41cm Xray Imager-Need to ensure reliability of all electrical contacts (2048 Data lines, 2048 Scan lines per side, total of 8192 signal connections)

Flexes allow several mechani gurations used in Rad, Mammo, and Cardiac applications

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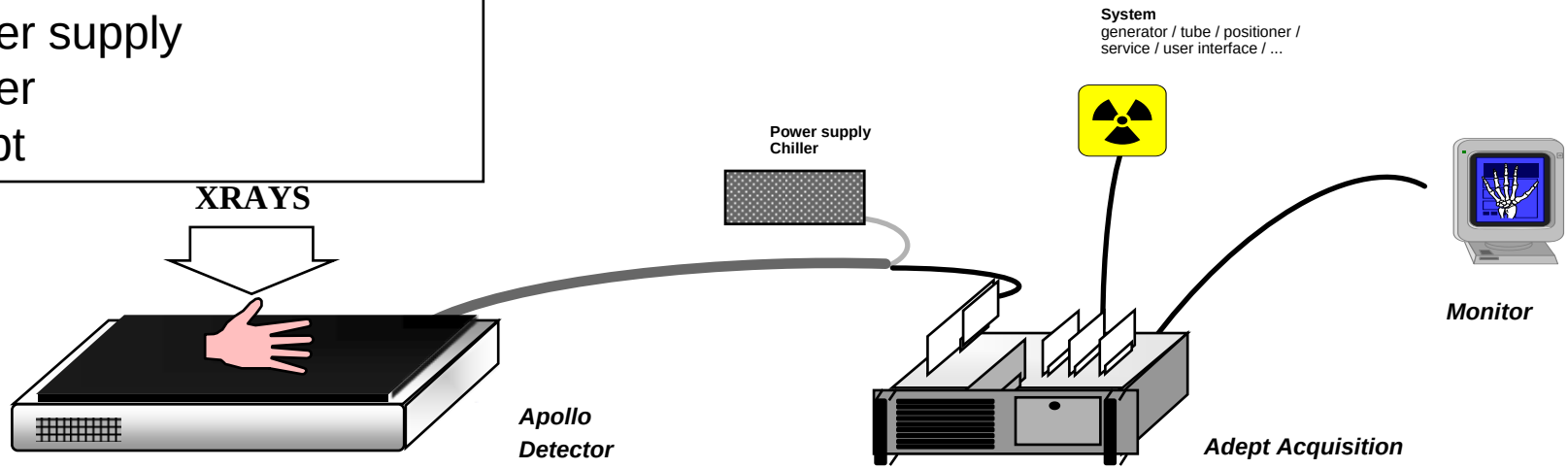
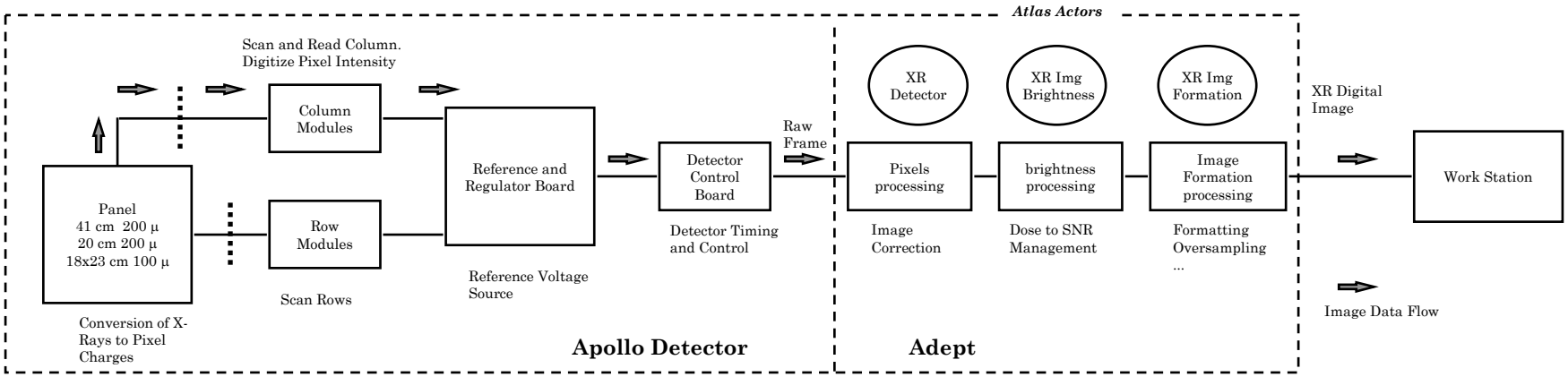
Overview

IDS (Image Detection Subsystem)

- Apollo Detector
- Power supply
- Chiller
- Adept





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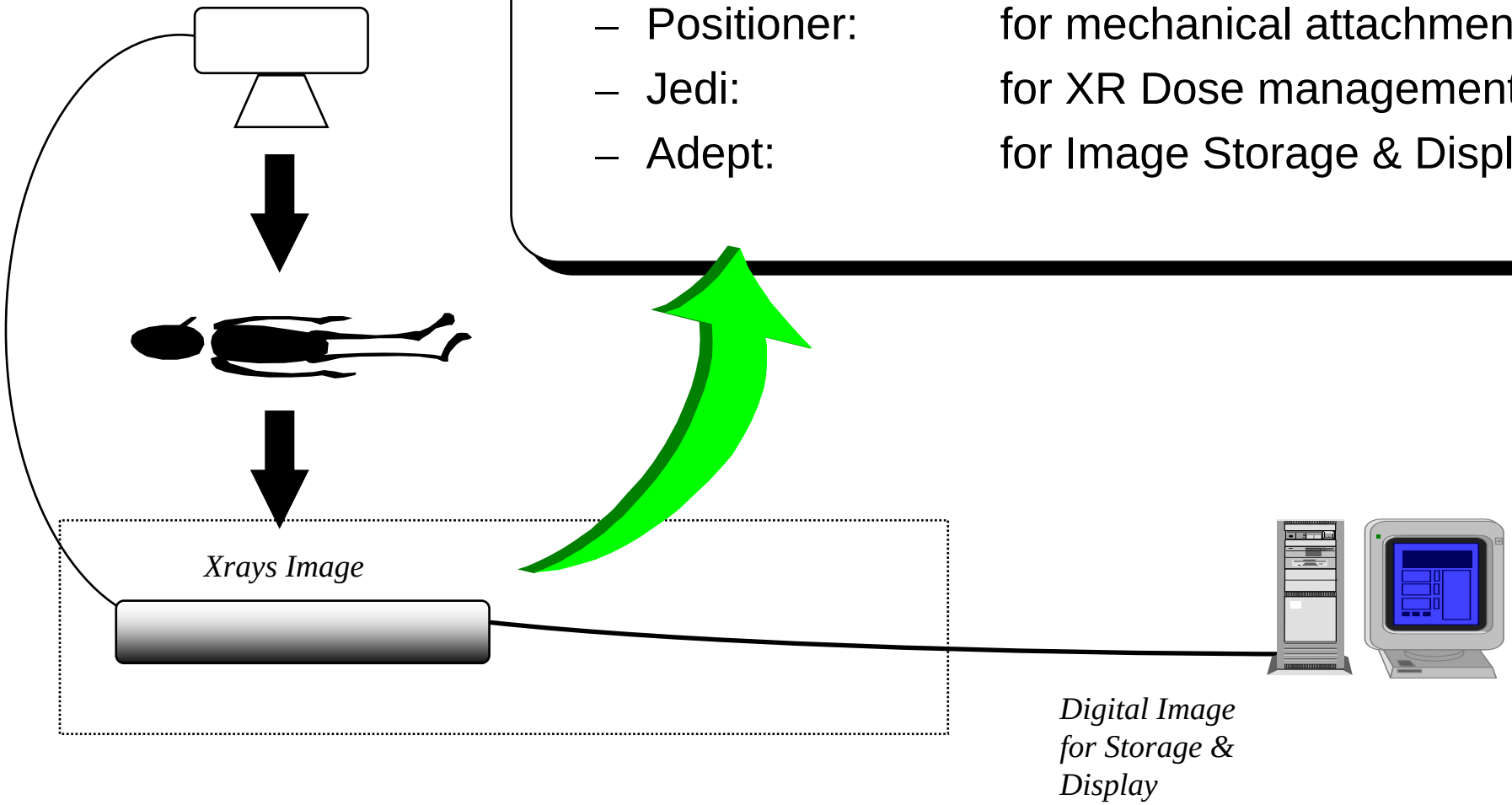
Overview

- **Image Detection Subsystem has interaction with:**
  - Positioner: for mechanical attachment
  - Jedi: for XR Dose management
  - Adept: for Image Storage & Display



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II. Flat Panel

A. Light Sensor

B. Scintillator

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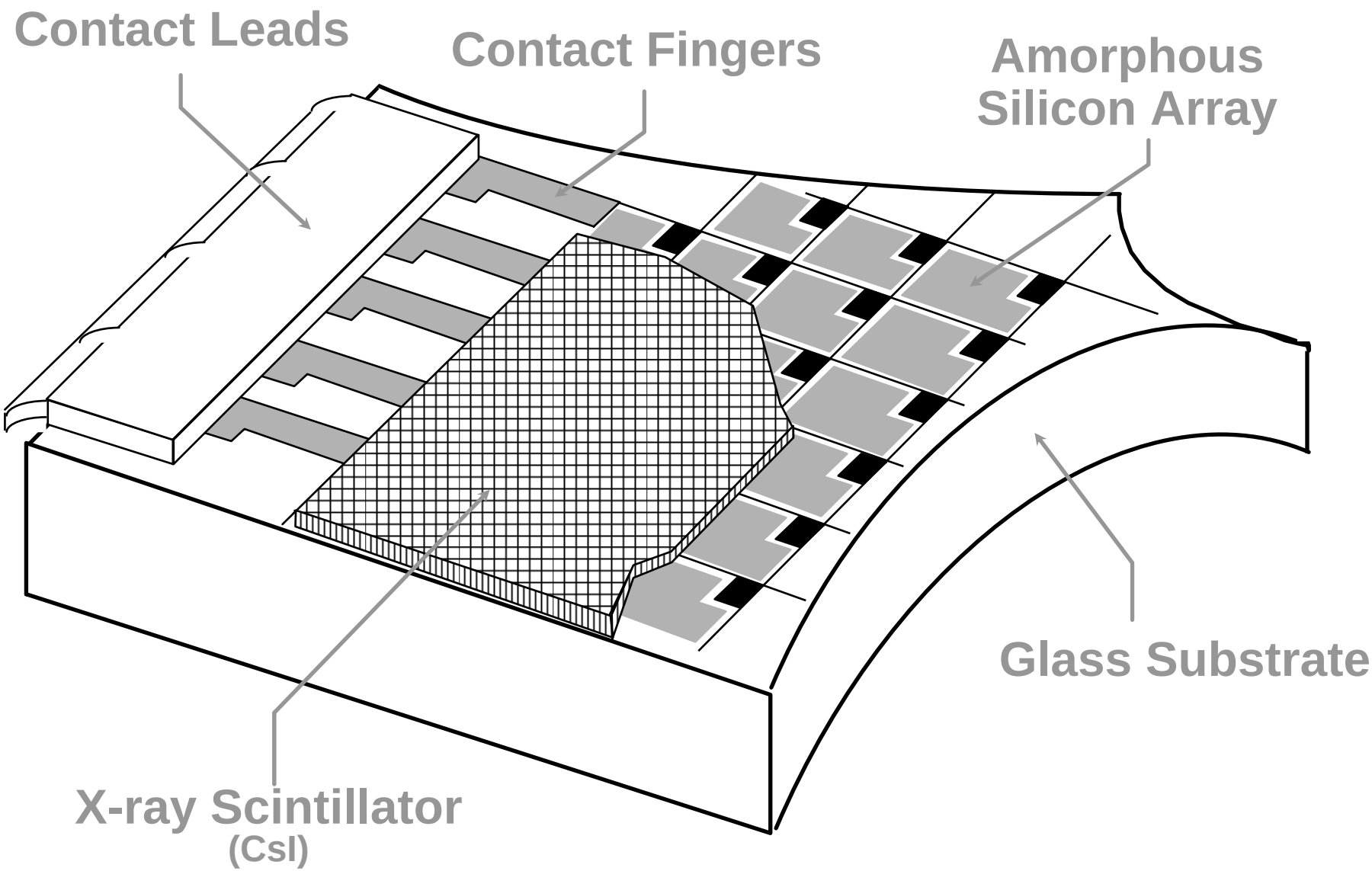
Flat Panel



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Flat Panel - Light Sensor

- Why amorphous silicon?
  - large seamless detectors can be made (PKI--50x50 cm substrate, 41x41 cm active area)
  - manufacturing equipment driven by LCD industry
- Difficulties caused by amorphous silicon
  - compared to single-crystal silicon, 100 to 1000 x increase in defects
  - defects are long-lived ~ 100 sec
  - mobility reduced by ~ 1000 x (affects switching speeds)
  - defects give rise to complicated lag and offset behaviors
- Difficulties are overcome by
  - calibration
  - careful management of detector timing for all applications

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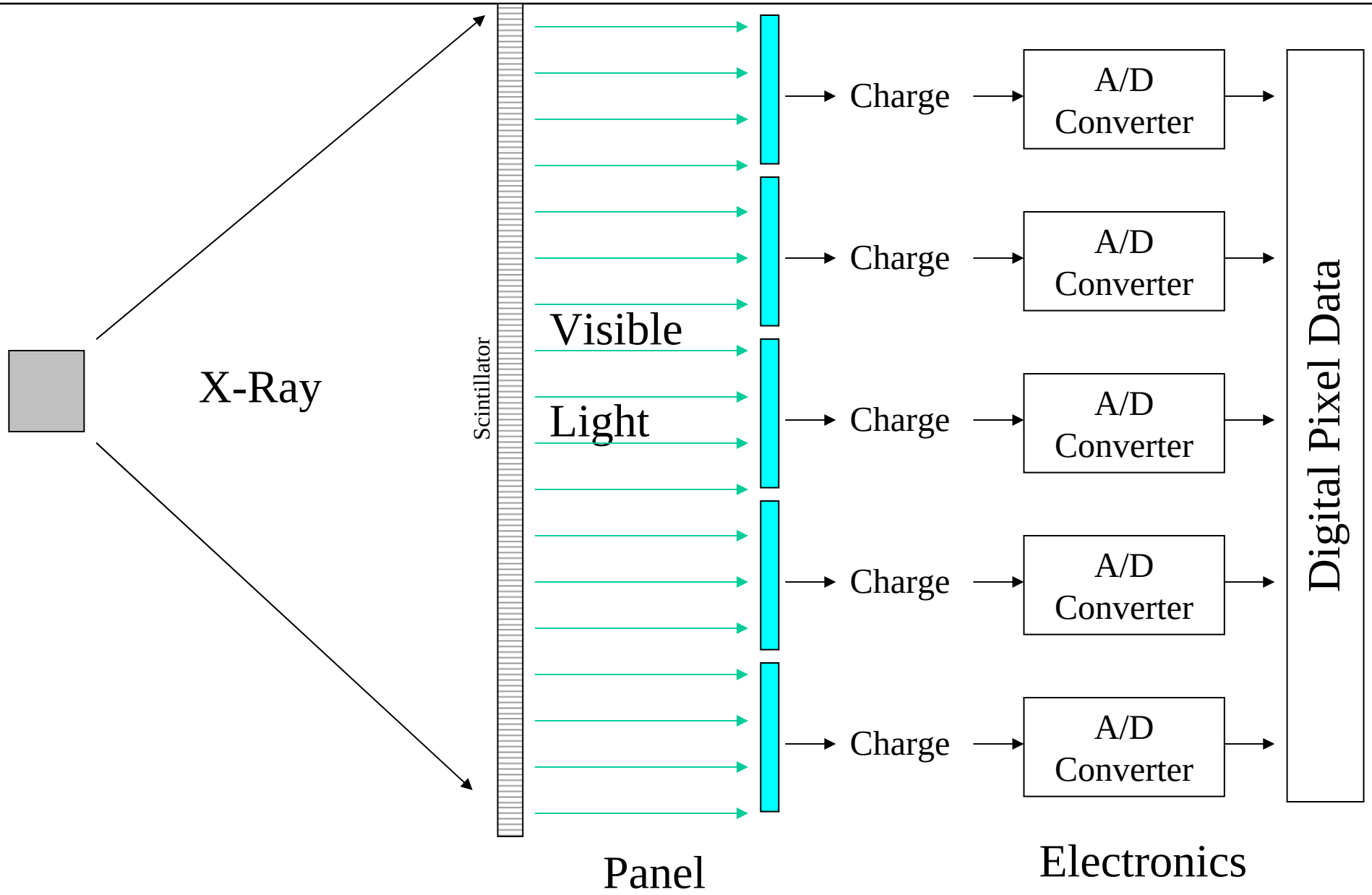
Flat Panel - Indirect Conversion



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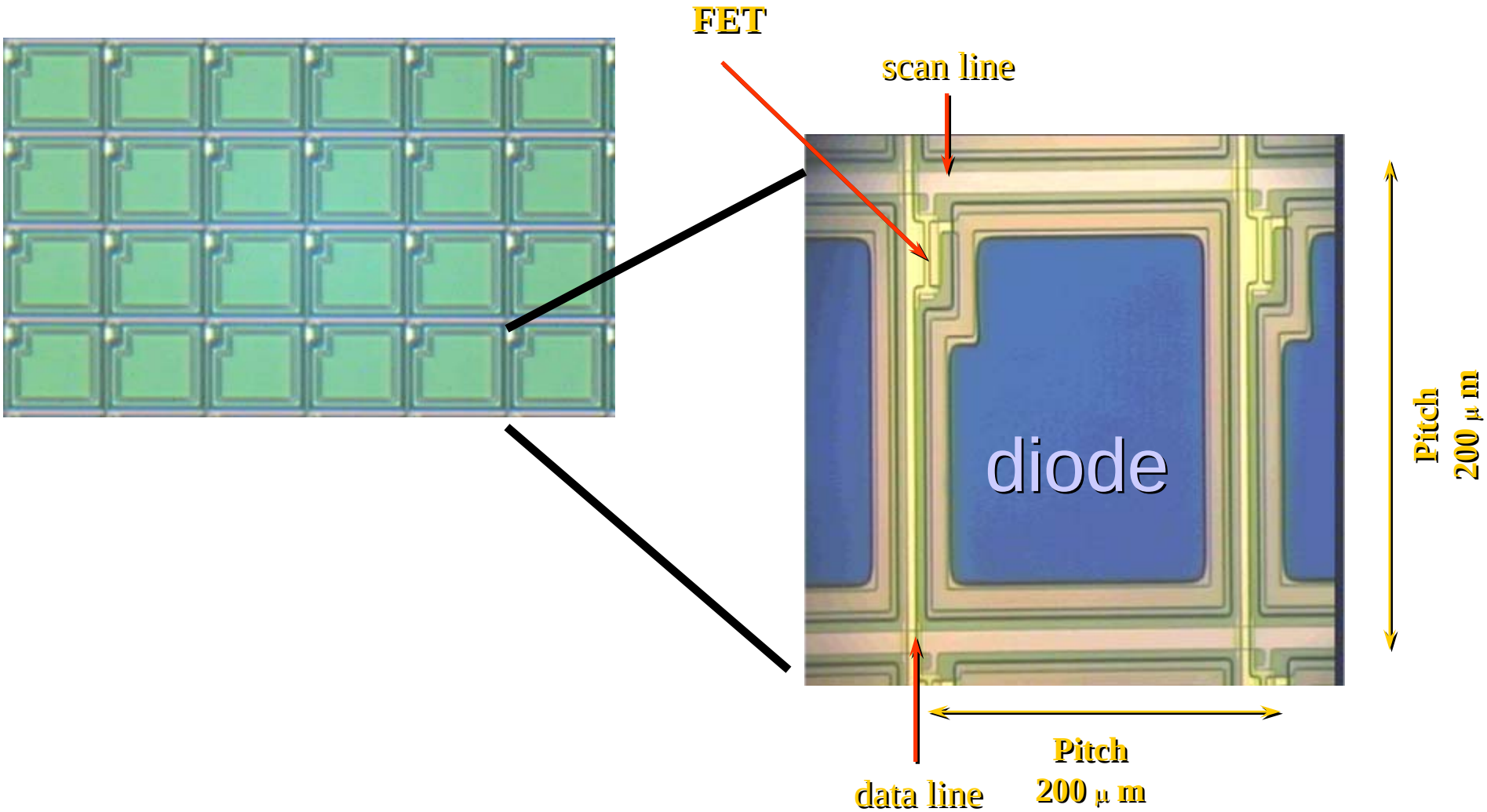
Flat Panel - Light Sensor



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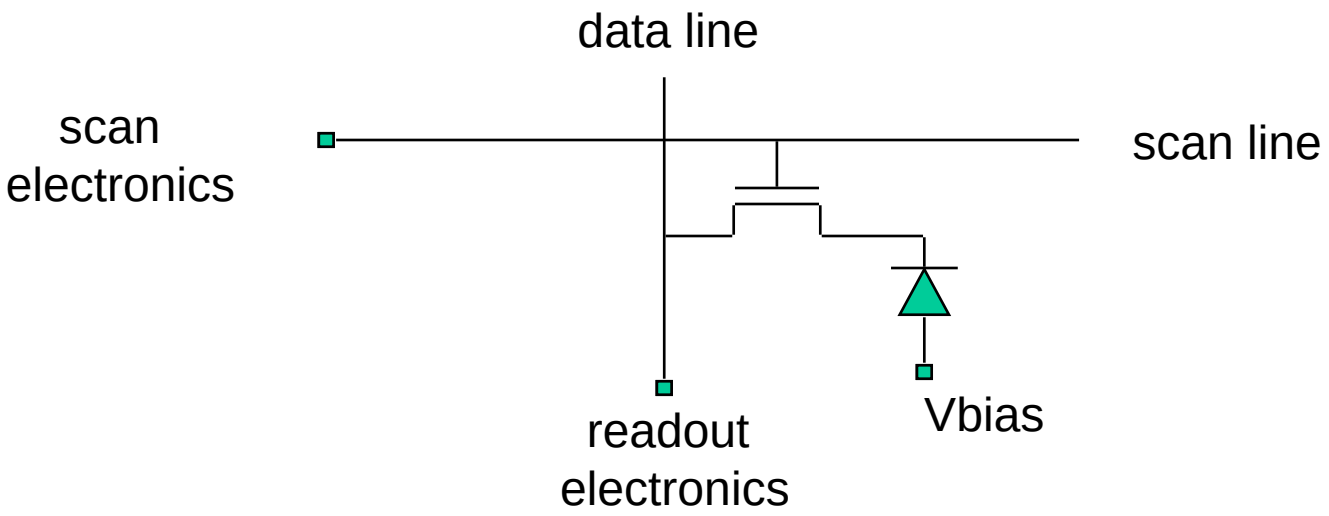
Flat Panel - Light Sensor



- Operation--single element
  - FET is turned on (scan line voltage pulsed high)--diode is charged
  - FET is turned off (scan line low)
  - X-rays exposure creates electron-hole pairs in diode which causes it to partially discharge
  - FET is turned on--diode is re-charged--amount of charge needed is measured by readout electronics

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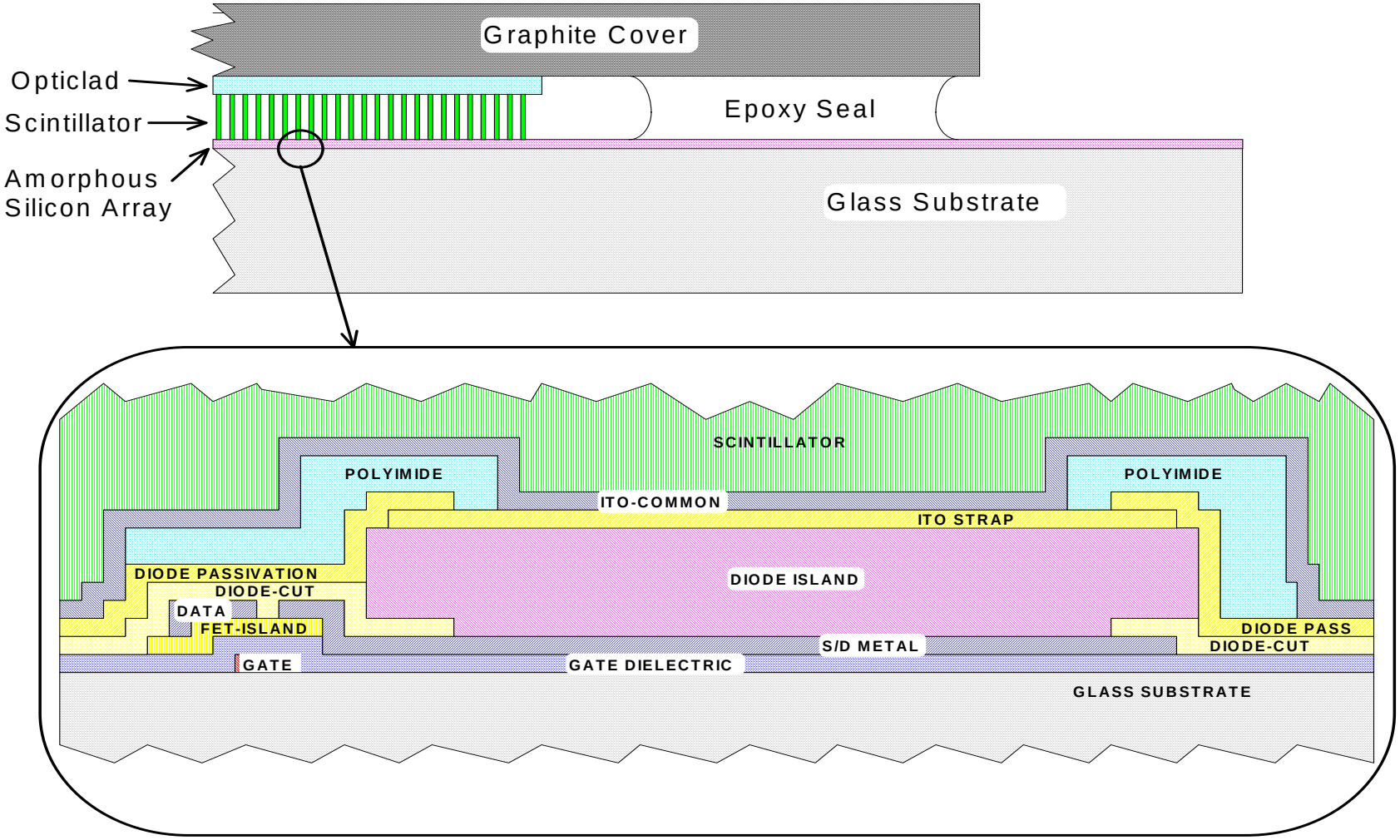
Flat Panel - Light Sensor



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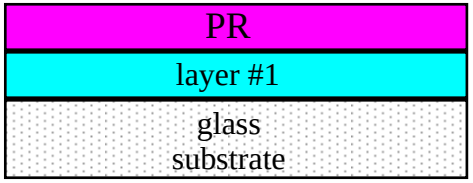
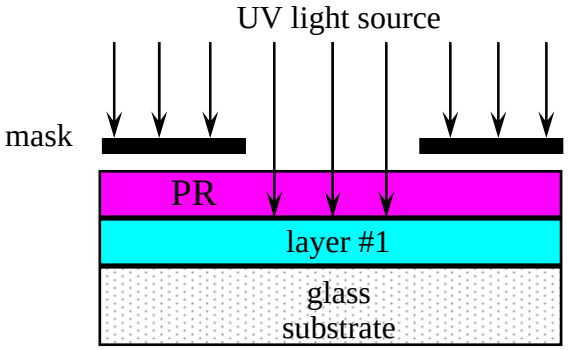
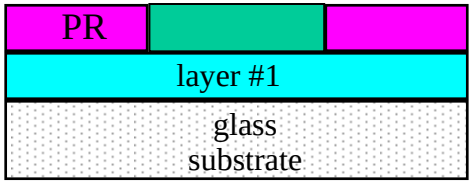
Thin film processing



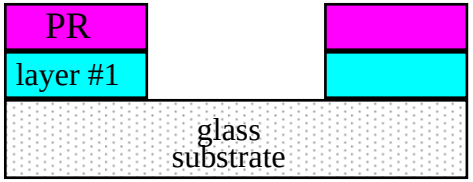
a) Deposit layer #1 & photoresist (PR)



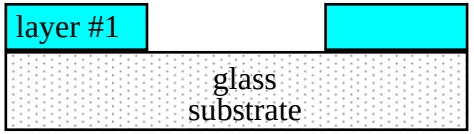
b) Expose PR



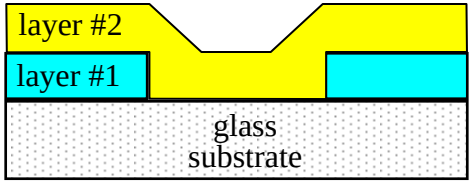
c) Develop PR



d) Etch layer #1



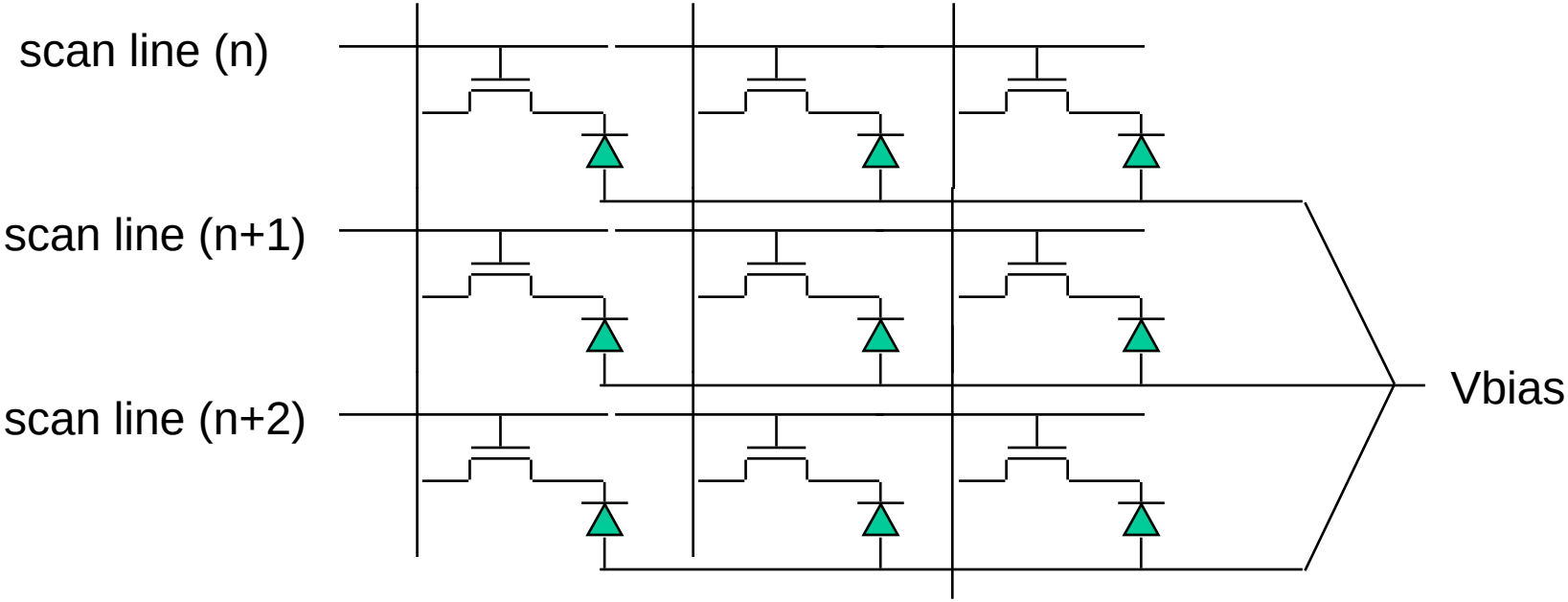
e) Strip PR



f) Deposit layer #2

g - ∞) Repeat

Flat Panel - Light Sensor



- Panel readout
  - All scan lines held off during x-ray exposure
  - Scan lines are turned on one at a time
  - For turned-on row all diodes are re-charged in parallel through separate readout electronics on each column
  - A to D conversion is pipelined so that row n is converted while row n+1 is read out
  - Time for A to D conversion is same as time to read out each line

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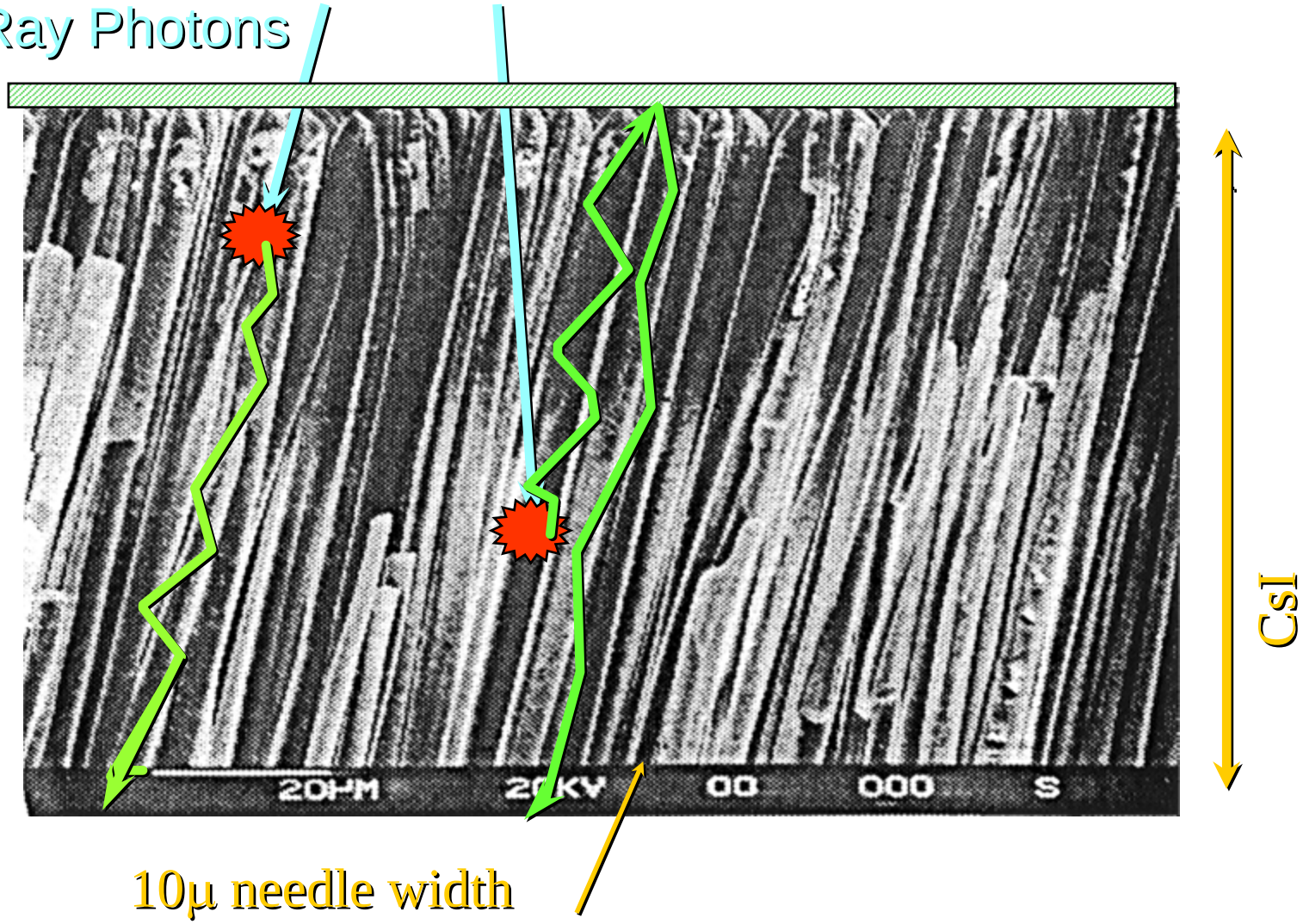
Scintillator



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Flat Panel - Scintillator

- Converts x-rays to light
- We use evaporated CsI(Tl) as the scintillator
  - evaporated on light sensor surface--intimate contact with light sensors
  - grows with needle structure -- needles act like optical fibers -internal reflection greatly reduces lateral spread of light
  - similar to CsI(Na) scintillator used in image intensifiers
  - emission spectrum is well matched to quantum efficiency of diodes (560 nm, 175 nm full width, half maximum)
  - CsI(Tl) is one of the most efficient known scintillators

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III. Electronics

- A. Row Module
- B. Column Module
- C. Reference and Regulation Board
- D. Detector Control Board
- E. IDC

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Electronics

- Row Modules (turn the FETs on and off)
- Column Modules (contain the data readout chips)
- Reference and Regulation Board (supplies critical voltages to the row and column modules)
- Detector Control Board (supplies control signals to detector, receives data from detector)
- IDC-Image Detection Controller (applies detector-dependent corrections)

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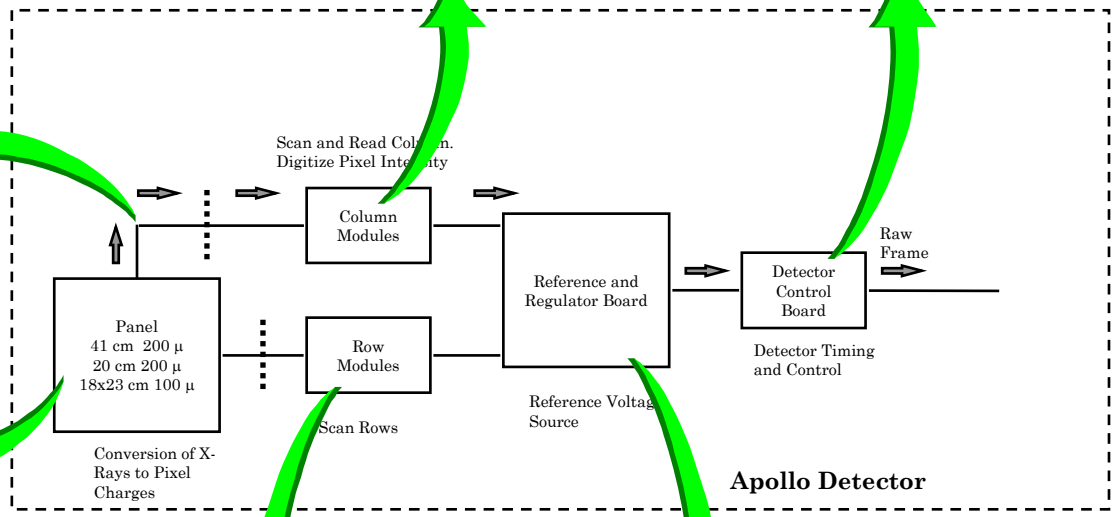
Electronics

Column Modules
- Each Module Read 256 Columns in Parallel
- Digitize the Electrical Charges in the Selected Pixels

Detector Control Board
- Drive the Sequencing of the Detector
- Transfer Image to IDC
- Drive Self Tests

Flex
- Interconnect Row and Column Modules to the Panels and to Ref Reg Bd

Panel
- Convert Incident X-Ray to an Electrical Charge of a Pixel



Row Modules
- Select the Rows to be Read

Ref Reg Bd
- Provide Precise Ref Voltages

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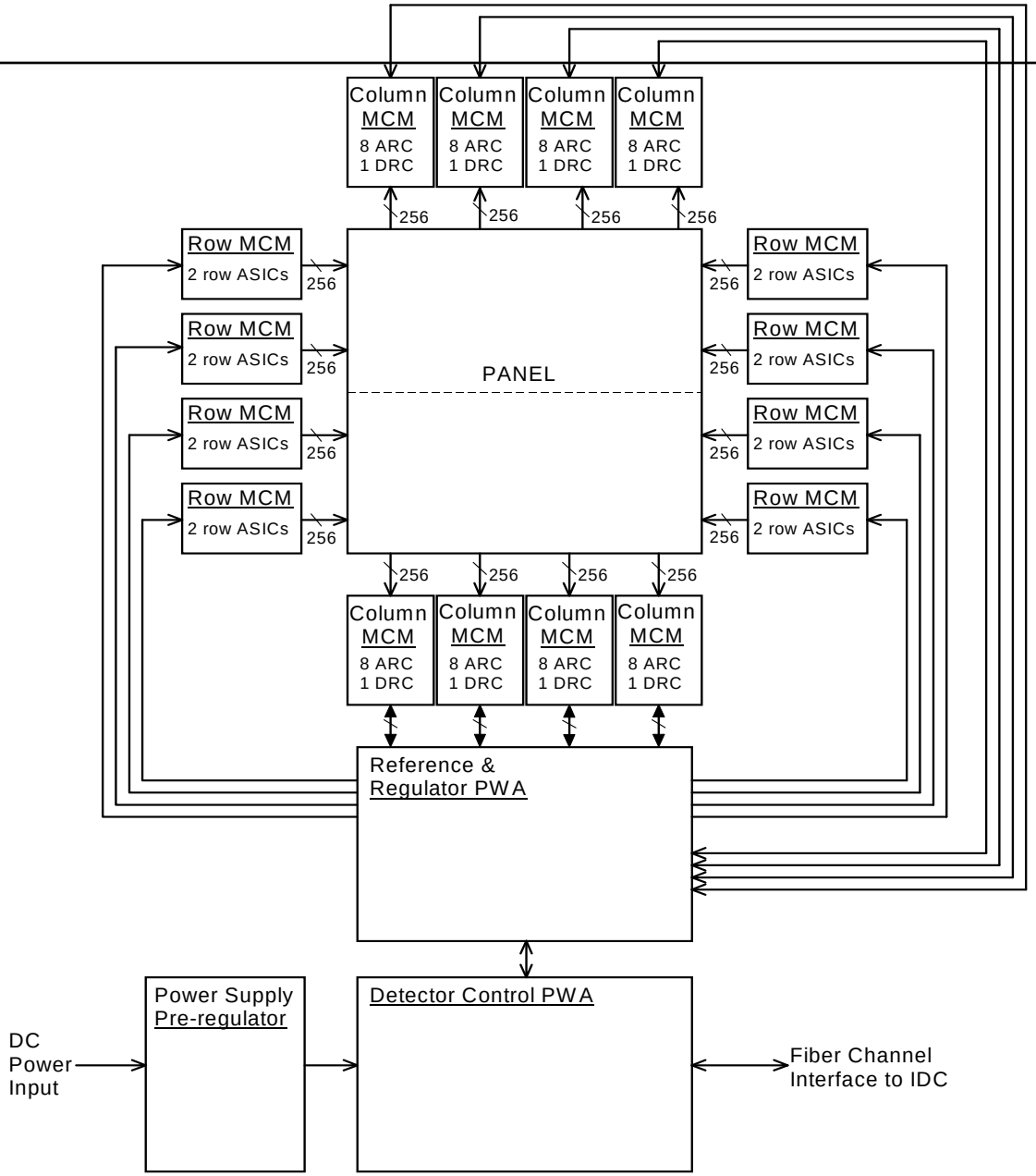
Electronics



20-cm detector block diagram

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Electronics--Row Module

- Chip-on-board technology--bare die are wire bonded to small PC boards, then sealed with epoxy.
- Each module contains two row driver (RDC) ASICs (custom designed to GE specifications by Maxim); each ASIC drives 128 rows
- FETs are held off at typically ~ -11 V
- During readout, rows are sequentially turned on by applying ~ +11 V
- Features of RDC / MCM
  - Compensation-during turn on of any row, 31 other rows are turned off “harder” to compensate for induced transients
  - Enhanced voltage swing and drive compared to off-the-shelf chips for greater dynamic range and low noise operation
  - Multiple scan modes for different FOVs, scan rates
  - Built-in diagnostics

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Electronics--Column Module

- Chip-on-board technology--each module contains eight ARC ASICS (Apollo Readout Chip) and one DRC (digital readout chip)
- ARC
  - senses and converts signal from 32 data lines
  - each data line has its own amplifier and A to D conversion
- DRC converts the output of the ARC into serial form (parallel to serial conversion)

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Electronics--Column Module

- Square root encoding
  - ARC uses a ramp-compare type A to D converter
  - Signal from each data line is held in a comparator
  - Voltage of other side of comparator is fed by a ramp common to all channels of all ARCs
  - Ramp voltage is increased in steps at a regular clock rate
  - When ramp voltage matches held voltage, comparator trips, and ramp counter value is latched
  - Time to convert each line of data is at least as great as the clock period times number of clocks
  - In order to convert the maximum signal range in the minimum time, the voltage step of the ramp is increased as the signal increases
  - The quantum noise increases as the square root of signal
  - The ARC step is increased so that the step size is a fixed proportion of the noise
  - Step size must be small enough that quantization artifacts are prevented

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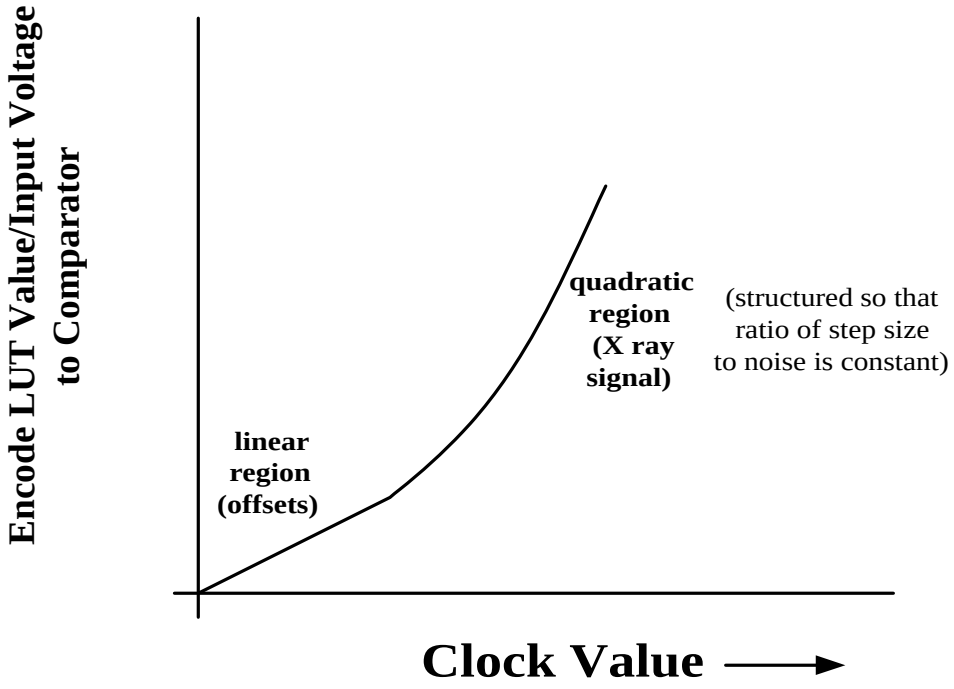
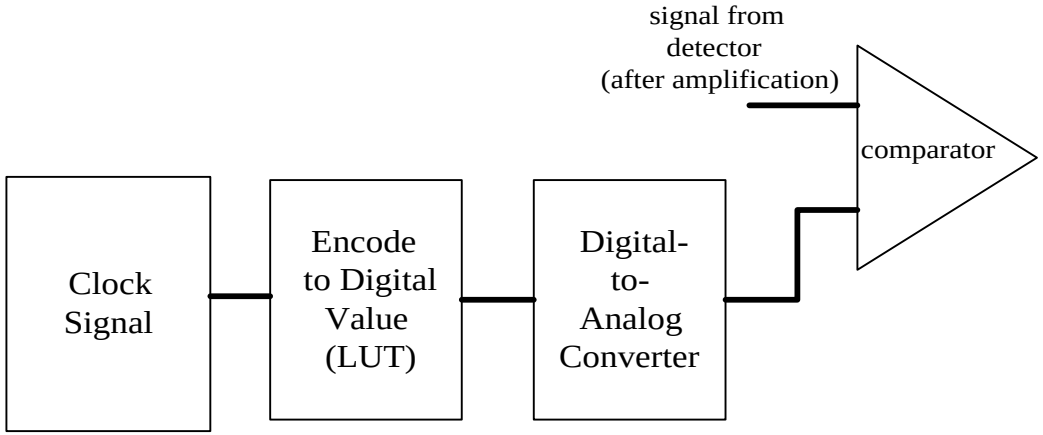
Electronics - Column Module (Square Root Encoding)





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Electronics--Ref and Reg Board

- Provide very low noise bias, reference, and supply voltages to Row Modules and Column Modules.
- Provide a 14-bit reference ramp to the column modules--used by the column module for A/D conversion.
- Provide interface conditioning of control signals bound for Row and Column Modules:
  - High-speed (32.5 MHz) clock signals
  - Low-speed clock signals
  - Static control signals
- Buffer data coming from the Column Modules to the Detector Control Board.
- Provide circuitry for self-test of Apollo detector subsystem.
- Implement Automatic Exposure Control for the detector array.

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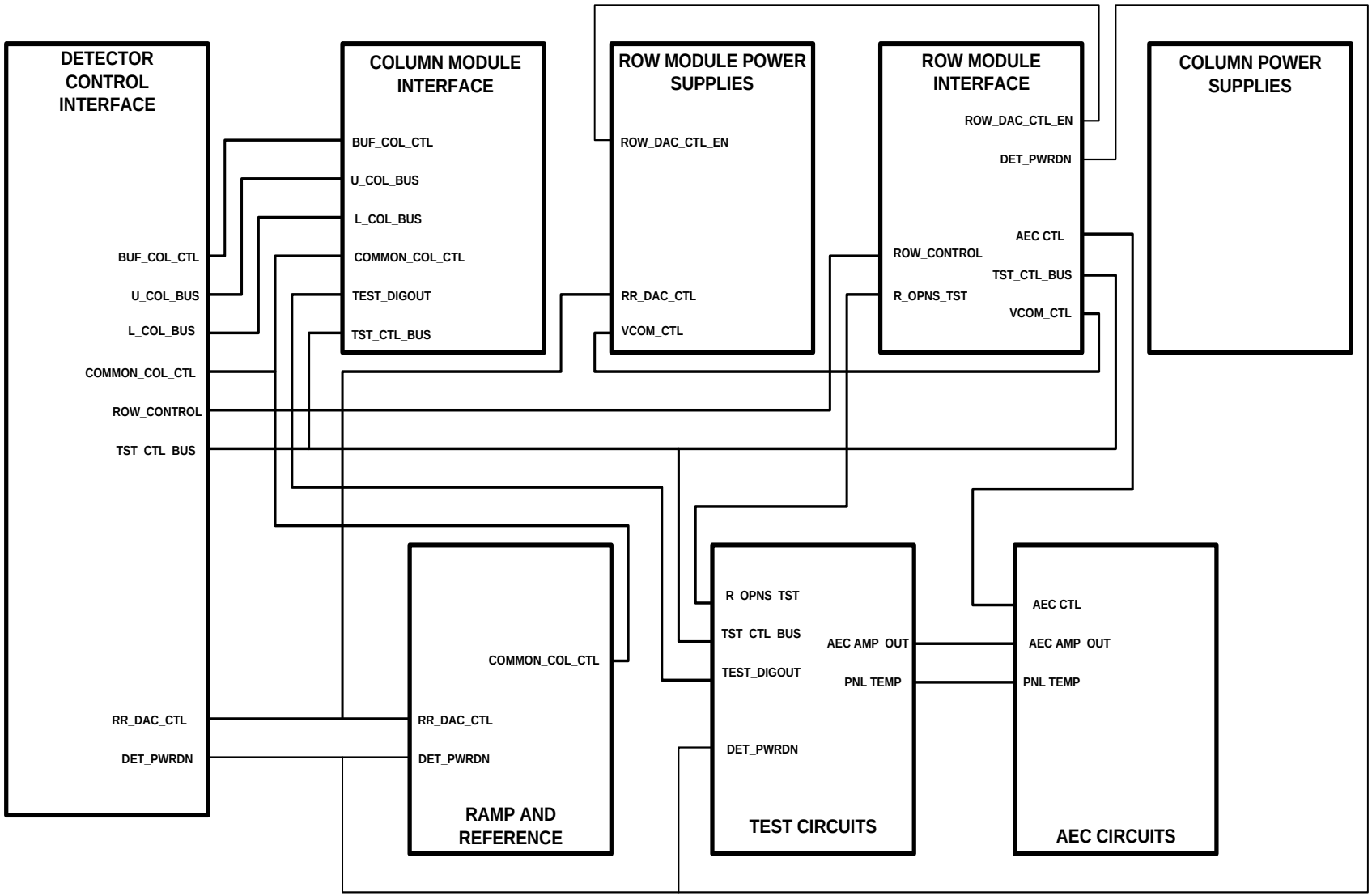
Electronics--Ref and Reg Board



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Electronics--Detector Control Board

- Communicates with the outside world (Adept)
- Reads out the detector
  - Sets the bias voltages
  - Controls the scanning of rows
  - Provides the conversion reference (ramp) data
  - Decodes data from ARC
  - Controls the flow and format of image data out the fiber optics
- Perfoms diagnostic routines and provides diagnostic data to Adept including
  - Test patterns
  - Interconnect integrity
  - Bias and reference levels (AC and DC)
  - Temperature

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Electronics--IDC

- Performs detector dependent corrections
  - offset (one per pixel)
  - gain (one per pixel plus one per column per gain range)
  - bad pixel replacement
- Dose management, brightness control--fluoroscopic applications
- Image formatting--reconstruct oversampled images

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IV. Packaging and Interconnect

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Packaging and Interconnect

- Connect flat panel to electronics, protect all components mechanically, provide compact “pizza box” package
- Provide proper environmental conditions (temperature, humidity, etc.) for optimum detector operation.
- Connections
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  - Row and column modules to ref and reg board
- Interconnect Method--TAB bonding (tape automated bonding)
  - Needed because of high density of interconnnects
  - Aniostropic conductive adhesive
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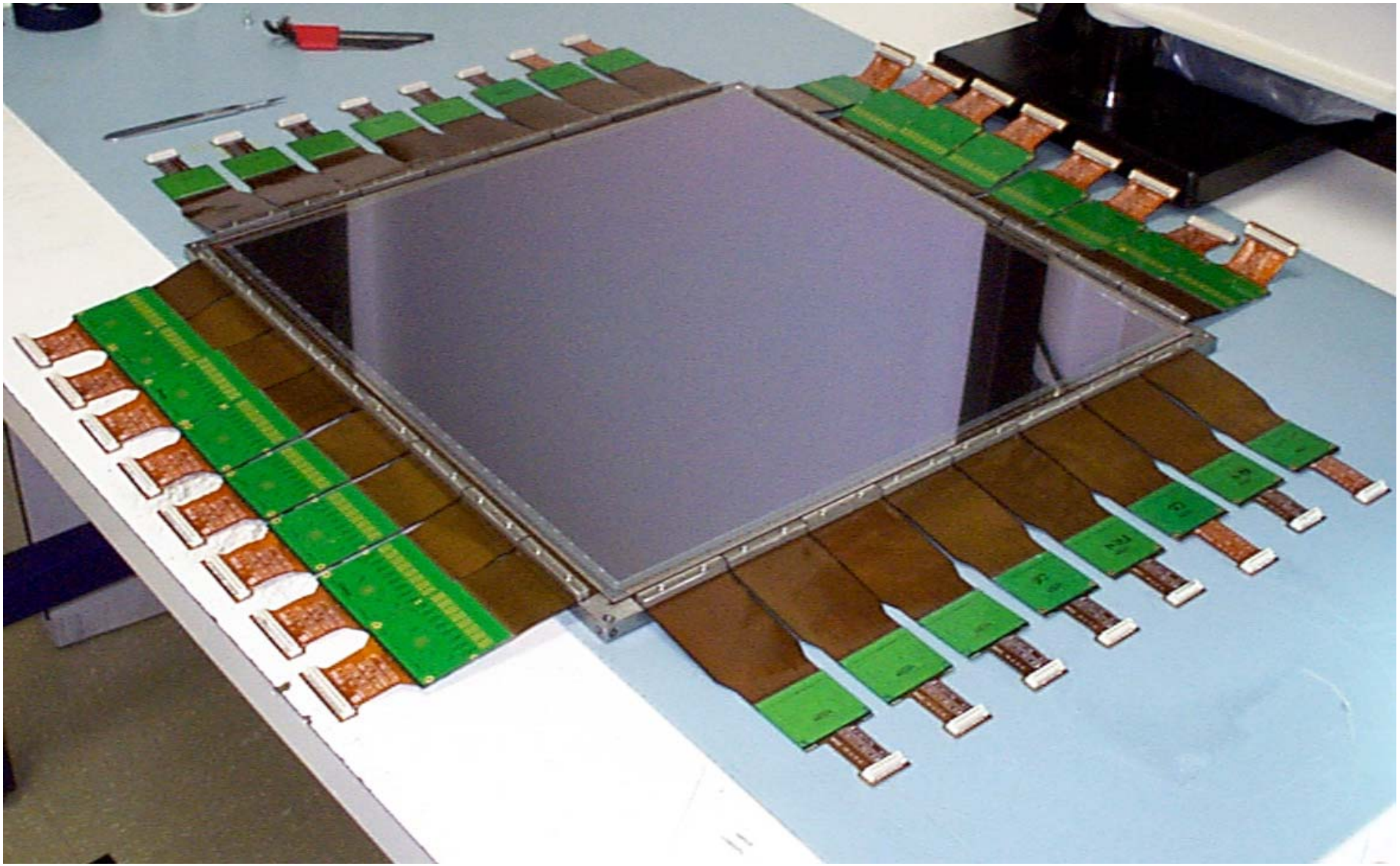
Packaging and Interconnect



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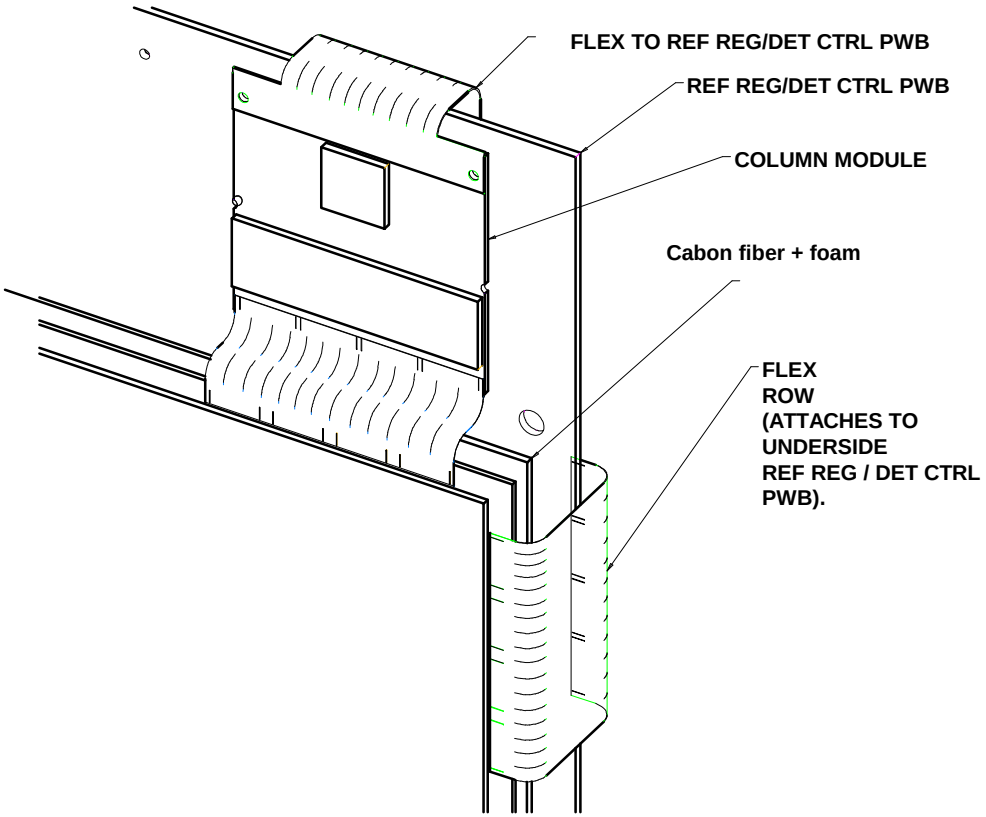
Packaging and Interconnect



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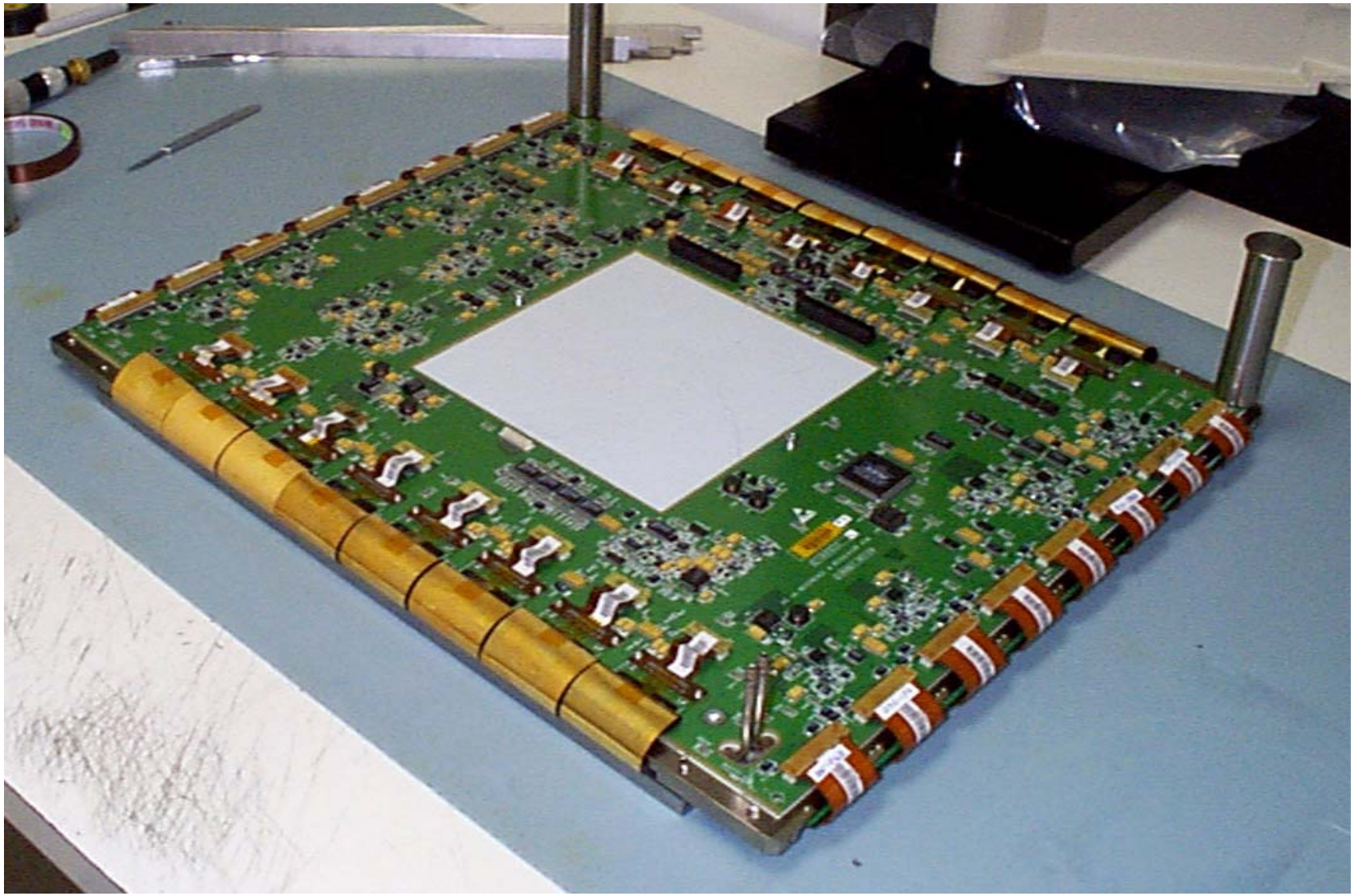
Packaging and Interconnect



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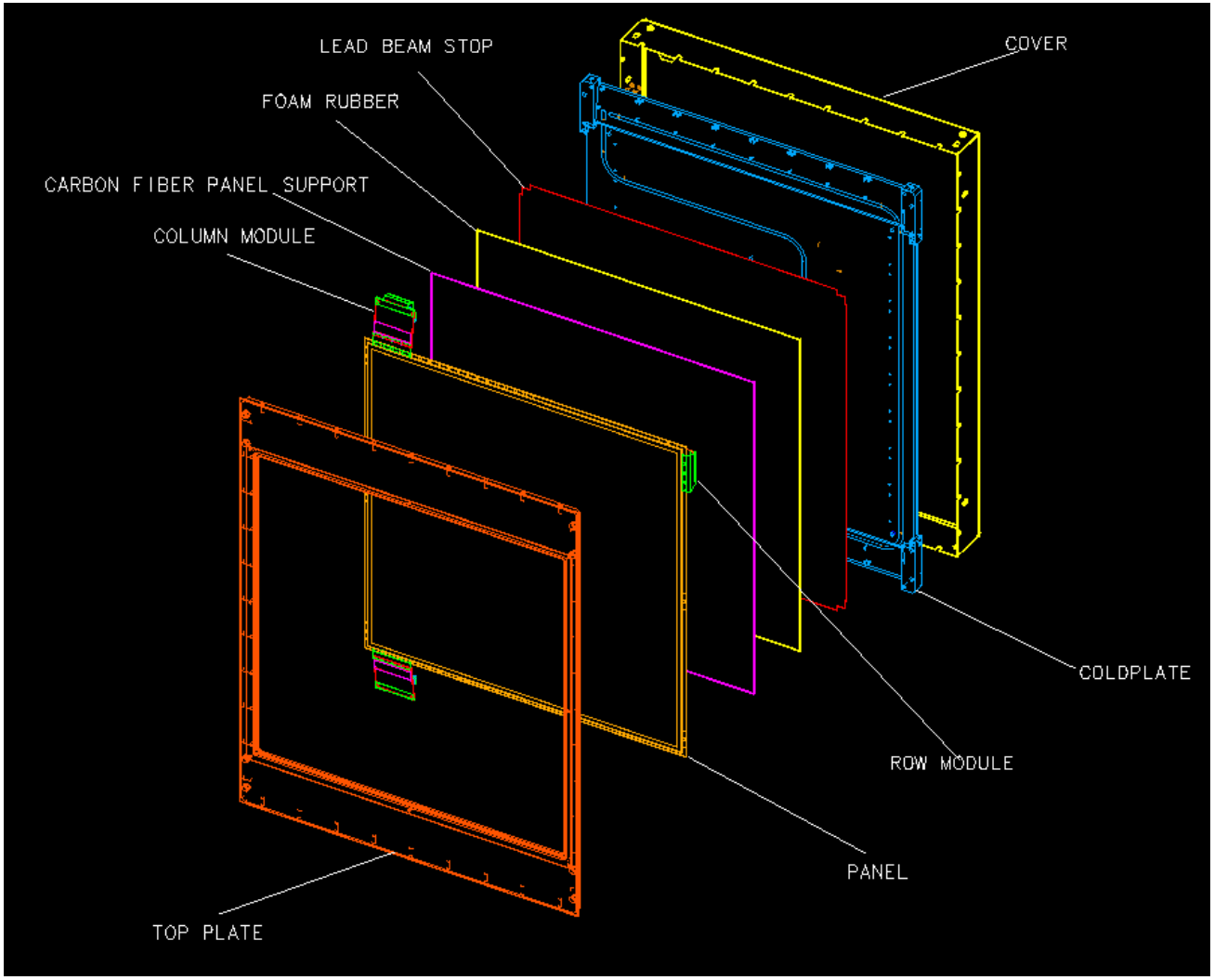
Packaging and Interconnect



GE Proprietary

Overview

GE Proprietary

Packaging and Interconnect

Chiller

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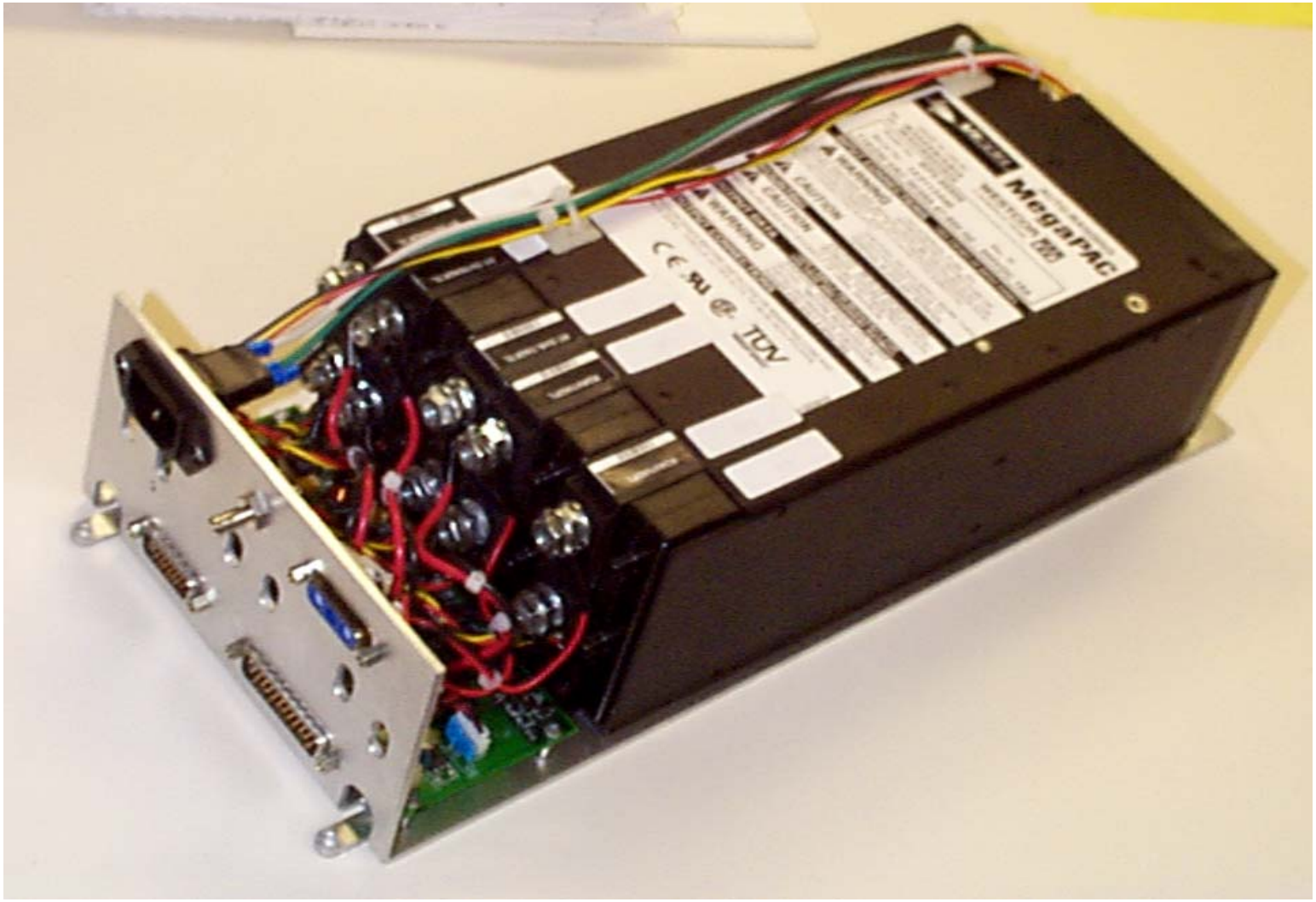
Packaging and Interconnect

Power Supply



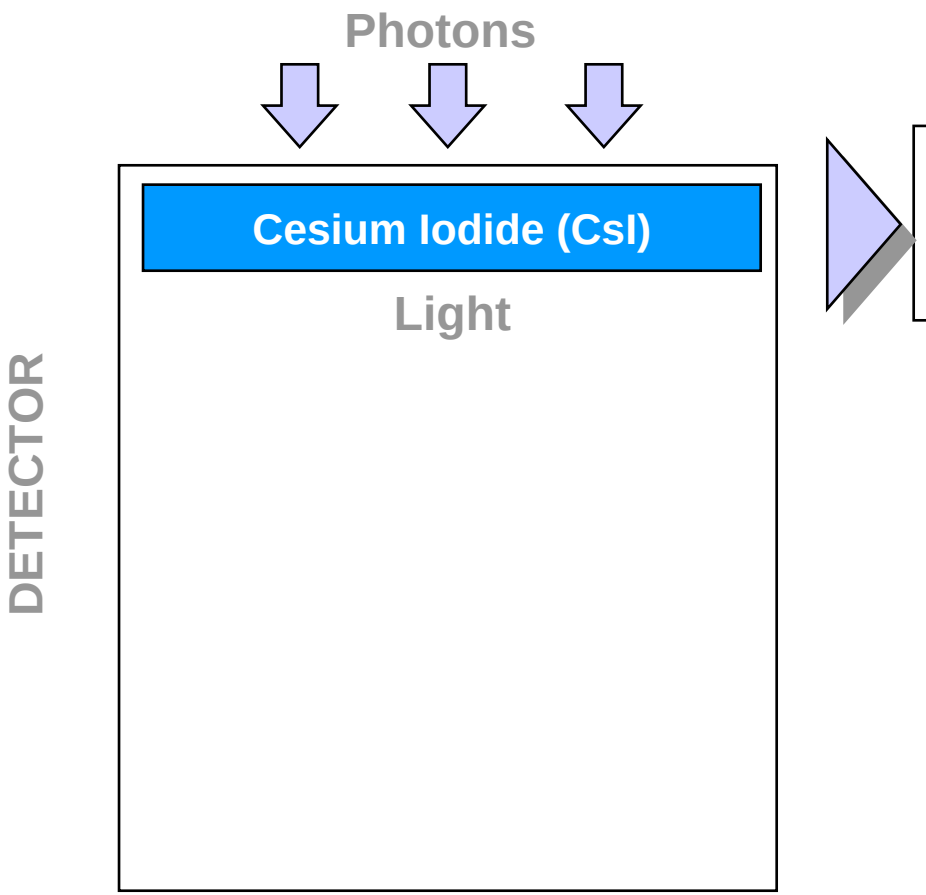
GE Proprietary

V. Detector Characteristics

- A. Signal
- B. Noise
- C. MTF
- D. DQE
- E. Lag

GE Proprietary

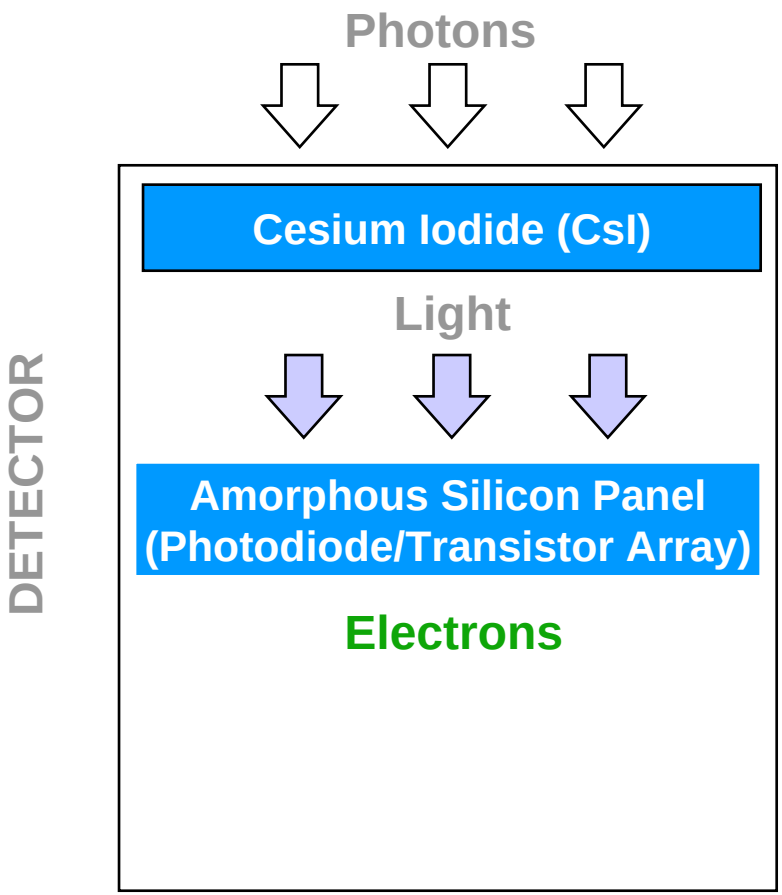
Detector Characteristics--Signal



Cesium iodide scintillator absorbs X-Ray photons and converts them to light

GE Proprietary

Detector Characteristics--Signal

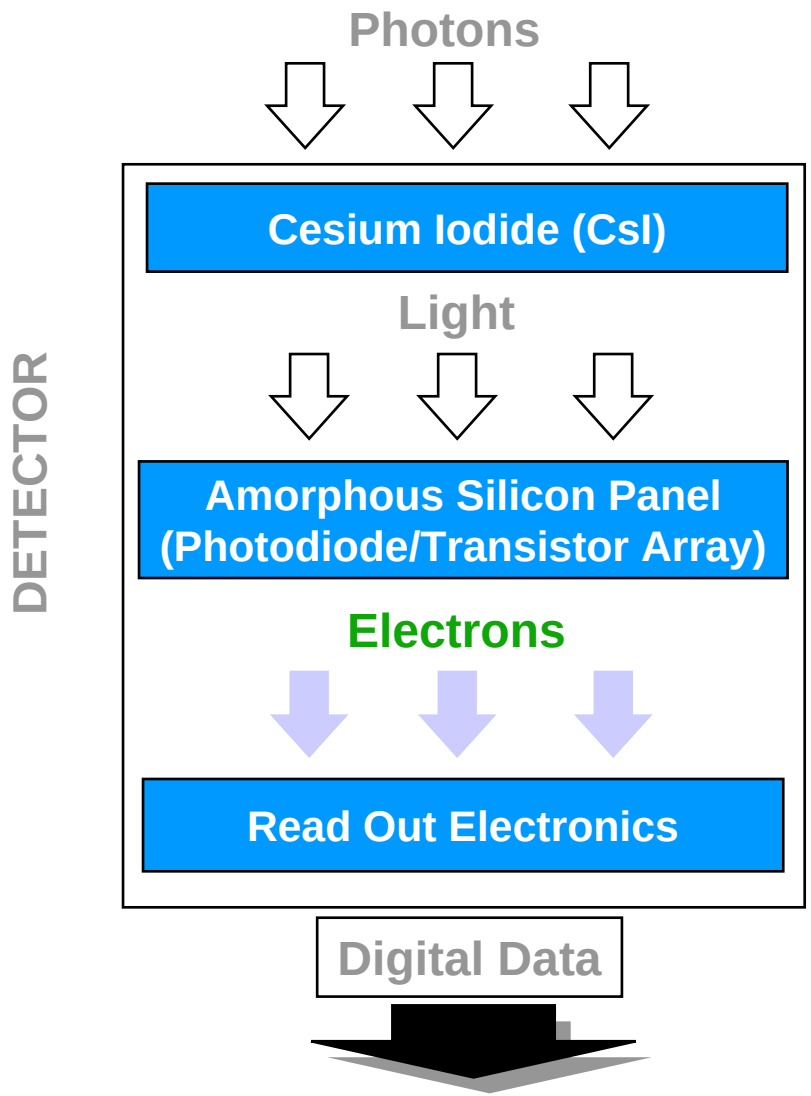


Cesium iodide scintillator absorbs X-Ray photons and converts them to light

Low-noise photodiode array absorbs light and converts it into an electronic charge... Each photodiode represents a pixel or picture element...

GE Proprietary

Detector Characteristics--Signal



Cesium iodide scintillator absorbs X-Ray photons and converts them to light

Low-noise photodiode array absorbs light and converts it into an electronic charge... Each photodiode represents a pixel or picture element...

Charge at each pixel is read out by low- noise electronics and turned into digital data sent to an image processor

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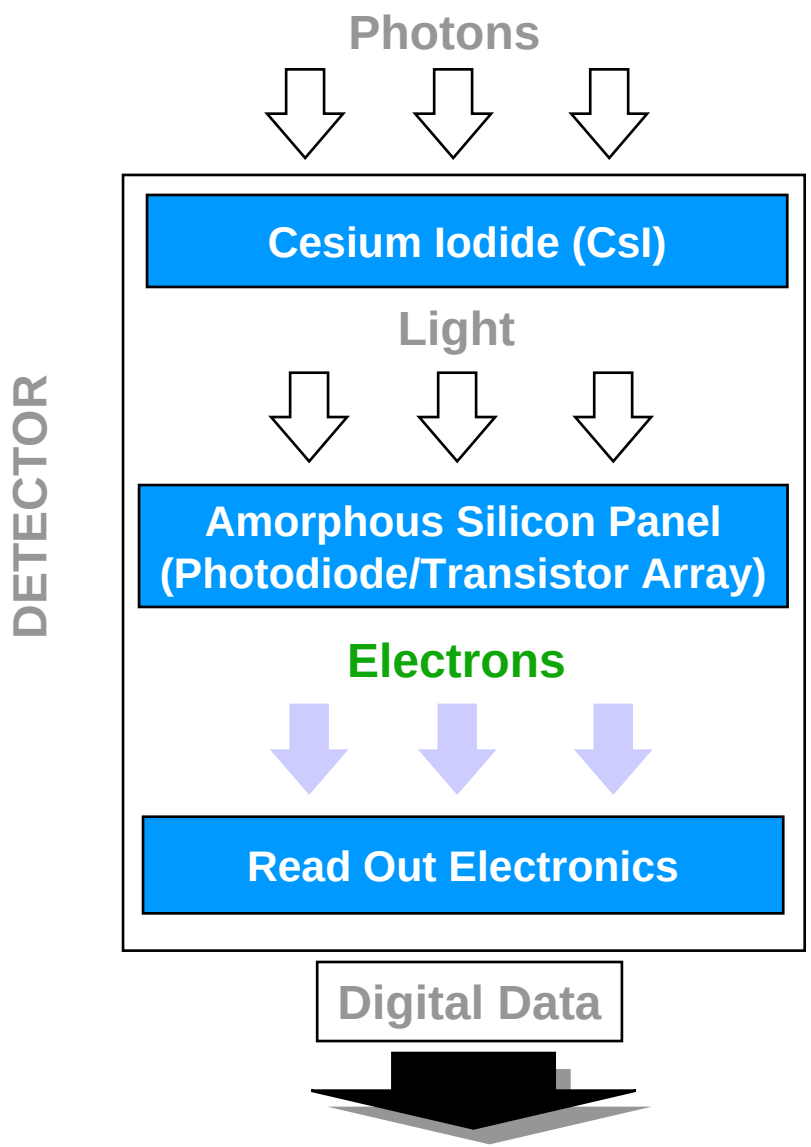
Detector Characteristics--Signal



X-ray absorption

Light emission

Light absorption

Electron-hole generation

Conversion to digital signal

GE Proprietary

Detector Characteristics--Signal

- X-rays to light (x-ray absorption and light emission)
  - Typical x-ray energy ~ 52 keV
  - Probability of absorption in 420 μm CsI ~ 0.81
  - Fraction of absorbed energy transferred to electrons ~ 0.90
  - Scintilation efficiency of CsI(Tl) ~ 0.12
  - Energy of emitted optical photon ~2.18 eV (570 nm)
  - Optical photons / inc x-ray = 52000*.81*.9*.12 / 2.18 = 2080

GE Proprietary

Detector Characteristics--Signal

- Optical photons to electrons(light absorption and electron-hole generation)
  - Opticlad reflection ~ 0.99
  - Absorption of optical photons in CsI ~ negligible
  - Fill factor (photosensitive fraction of panel surface) ~ 0.8
  - Quantum efficiency of diode ~ 0.8
  - .99*.8*.8 = 0.63 electrons/optical photon
- Conversion factor (CF)

  = 2080 optical photons /inc x-ray * 0.63 el /optical photon

  = 1320 electrons / incident x-ray
- Conversion to digital signal (ARC 3)

  ~ 700 to 8000 electrons/count

GE Proprietary

Detector Characteristics--Noise

- X-ray imaging is intrisically limited by the quantum noise of the x-ray photons.
- Quantum noise is proportional to square root of number of x-ray photons absorbed by detector
- Signal is proportional to number of absorbed photons
- Signal to noise is proportional to square root of number of absorbed photons
- Goal of detector design is to make added noise from detector (electronic noise) negligible compared to quantum noise at all clinically relevant signal levels

GE Proprietary

Detector Characteristics--Noise

- Electronic Noise Sources (all sources other than Poisson statistics of x-rays)
  - Johnson noise of data line

$$N_{DL} = C_{DL}\sqrt{\frac{8}{3}kTR_{DL}\frac{BW}{1+\frac{4}{3}C_{DL}R_{DL}BW}}$$

    - 477 el for 20 cm detector, 1309 el for 40 cm detector
  - kTC switching noise

$$N_{kTC} = \sqrt{2kTC_d}$$

    - 845 el (2.2 pF diode)
  - ARC noise (from amplifier loaded with capacitance of data line)

$$N_{ARC} = A_0(C_0 + C_{DL})$$

    - 758 el for 20 cm detector, 988 el for 40 cm detector

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Detector Characteristics--Noise

- Electronic Noise Sources (cont.)
  - Charge Retention noise (shot noise on current from de-trapping electrons in the FET)
    - 433 el (current 20-cm detector)
  - Diode leakage noise (shot noise on leakage current in diode)

$$N_{leak} = \sqrt{Q_D}$$

    - 65 el (0.67 fC of charge)
  - Quantization noise

$$N_Q = \frac{LSB}{\sqrt{12}}$$

- Total Noise (quadrature sum of noise sources)
  - 1330 electrons in 20-cm detector operated in fluoroscopic mode (~ signal from 1 x-ray or 0.1 μR)

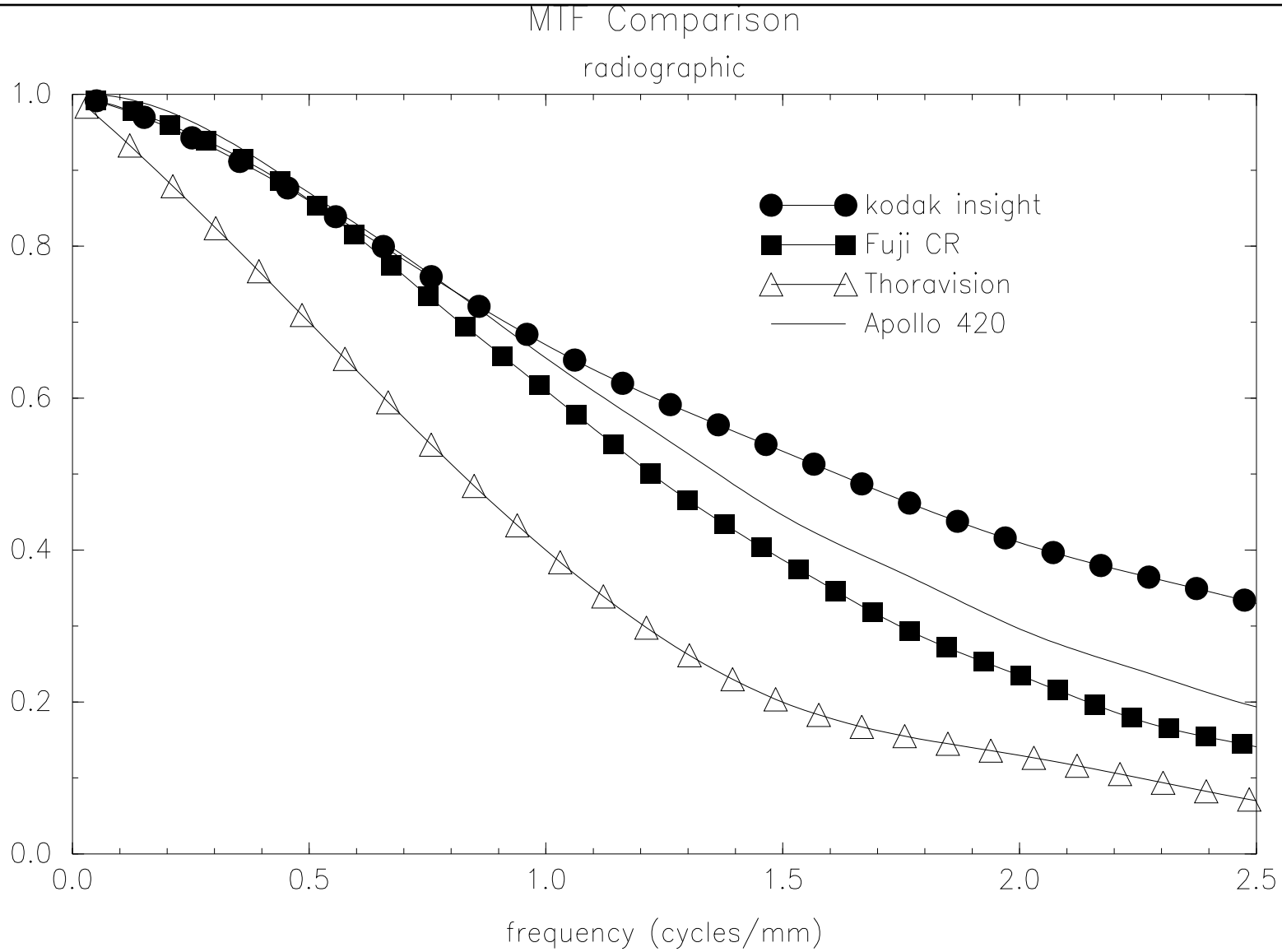
GE Proprietary

Detector Characteristics--MTF

- MTF (Modulation Transfer Function)--measures how the detector passes signal, as a function of spatial frequency
- Sources of MTF degradation
  - Lateral spread of light in scintillator
    - limited by CsI needles
    - increases with scintillator thickness
  - Sampling aperture of pixel: sinc(fx*a)sinc(fy*a)
  - Lateral spread of secondary x-rays
    - not significant away from k-edges of Cs and I

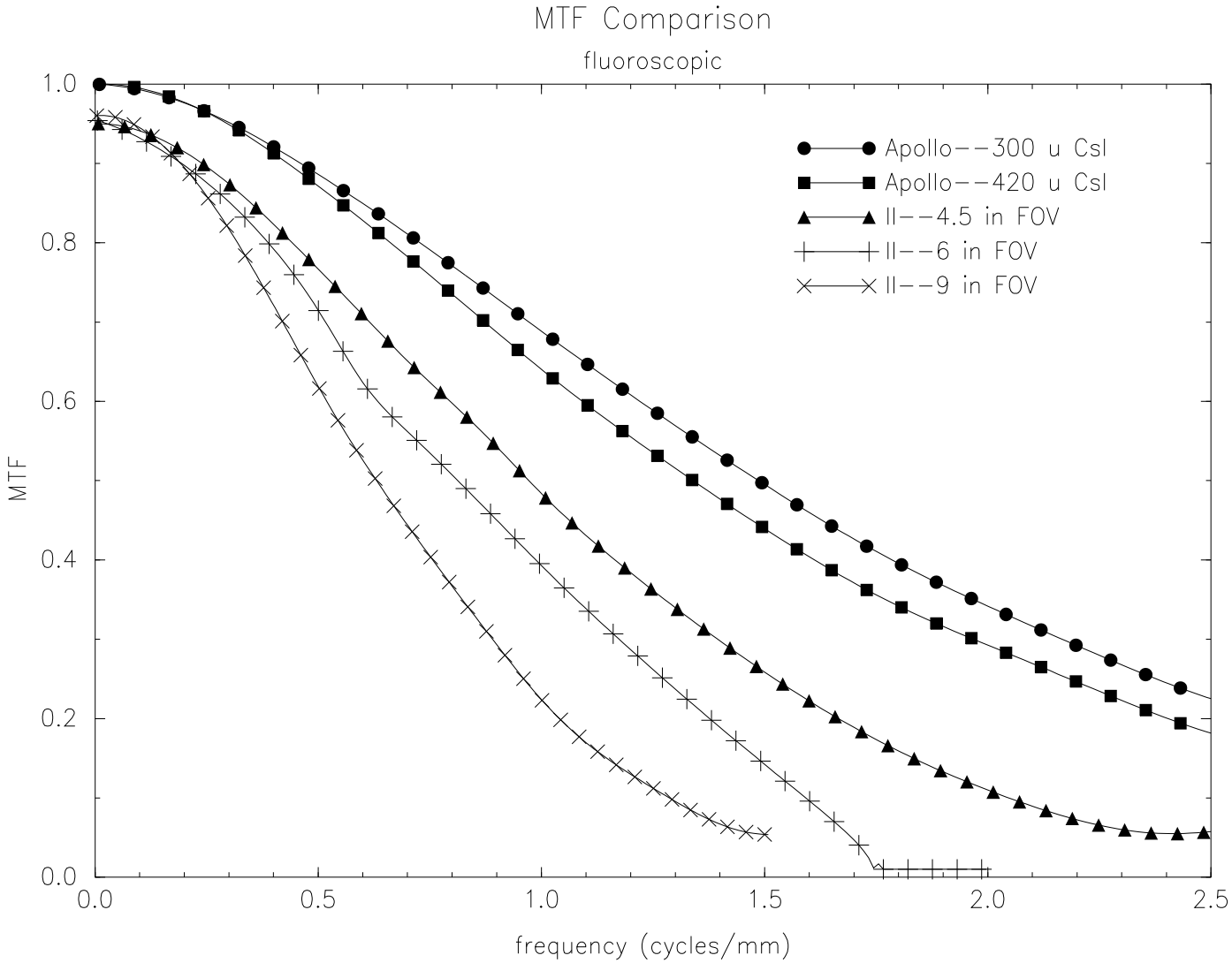
GE Proprietary

Detector Characteristics--MTF



GE Proprietary

Detector Characteristics--MTF



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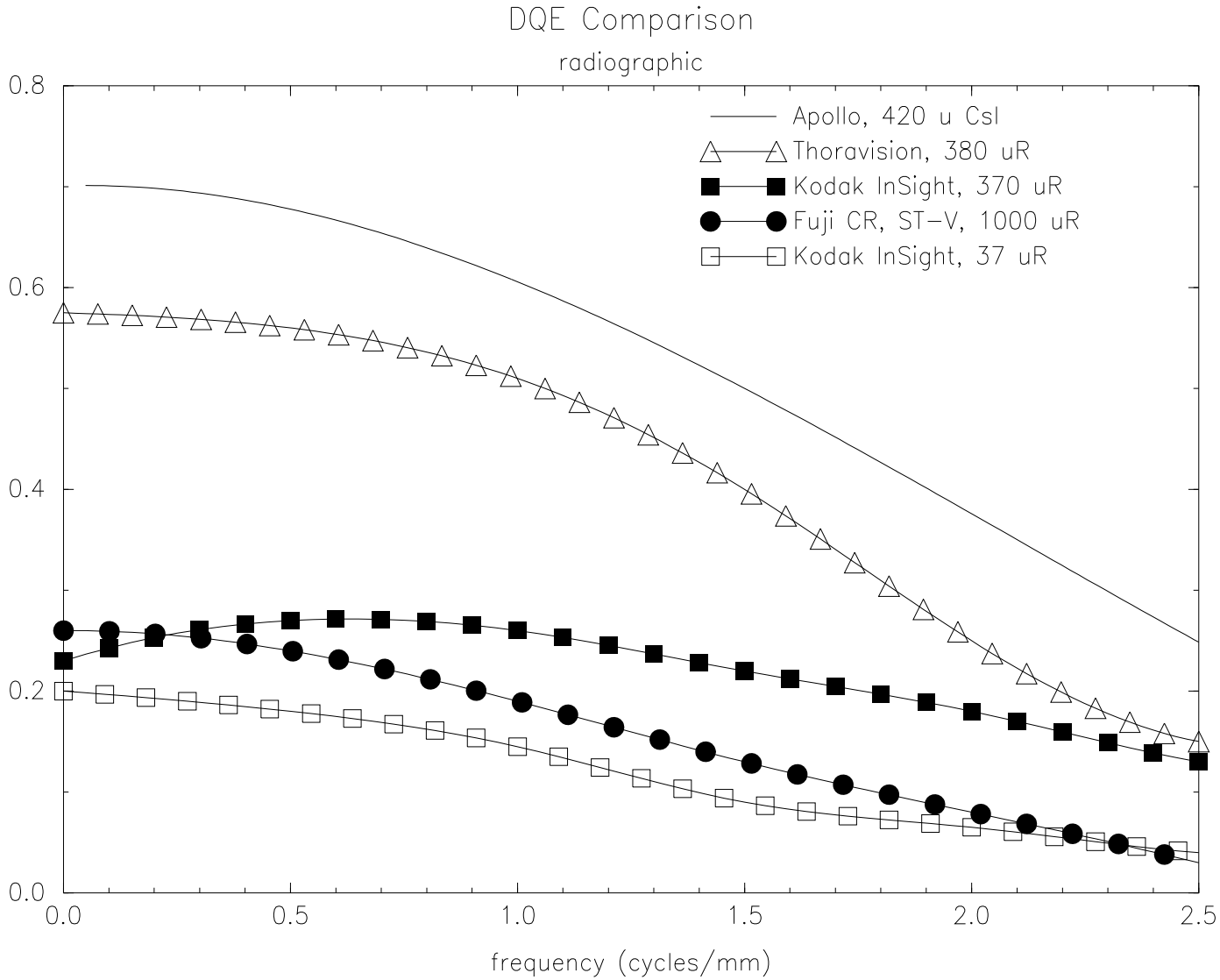
Detector Characteristics--DQE

- DQE (Detective Quantum Efficiency)--Measures how a detector passes signal to noise ratio
- Of more fundamental importance than MTF for a digital detector
- DQE = (SNRout)**2 / (SNRin)**2
- DQE is a function of spatial frequency, exposure, and x-ray spectrum
- Measurement
  - DQE = (Signal*MTF(f))**2 / (NPS(f)*Φ)

    NPS = Noise Power Spectrum, Φ = x-ray fluence

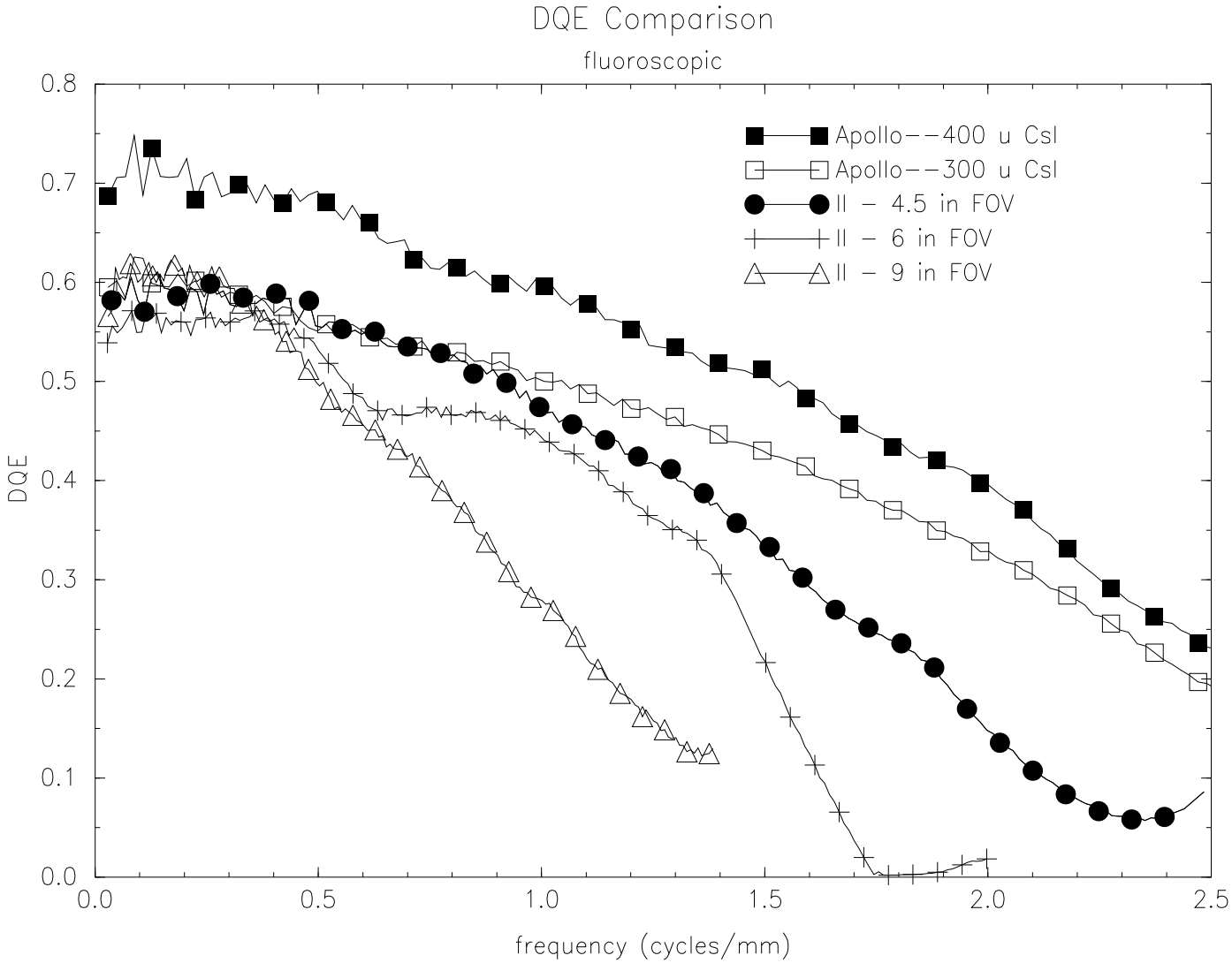
GE Proprietary

Detector Characteristics--DQE



GE Proprietary

Detector Characteristics--DQE



GE Proprietary

Detector Characteristics--Lag

- Lag = image retention from frame to frame
- Sources
  - FET lag--due to RC time constant of FET on resistance and diode capacitance
  - CsI afterglow--due to de-trapping of electrons in scintillator
  - Diode lag--due to de-trapping of electrons in diodes
- Magnitude
  - Short term lag is 1-2%, much less than in a pickup tube used with an image intensifier
  - Long term lag (> 0.5 sec) is larger than in an II system and may cause complications in mixed mode (rad to fluoro) applications

GE Proprietary

V. Calibration / Correction

A. Offset

B. Gain

C. Bad Pixels

GE Proprietary

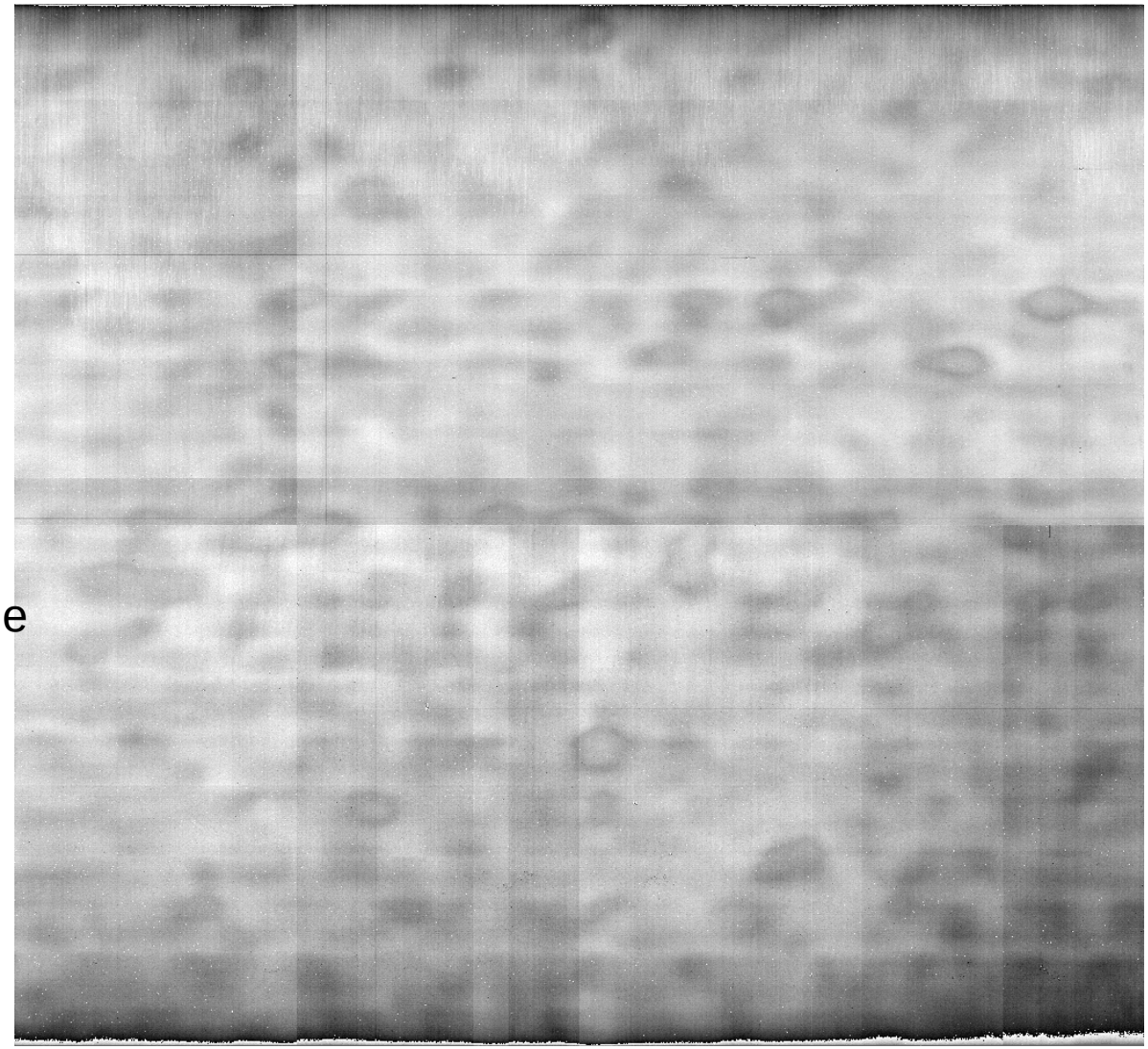
Offset: Image in absence of xray

Sources of Variation

- Diode leakage
- Charge retention
- FET leakage

Offset Correction

- Acquire offset image close in time to the x-ray image using the same timing/config as x-ray image
- For low noise operation average offset images
- Subtract result from x-ray image:
  - Output=Image-Offset



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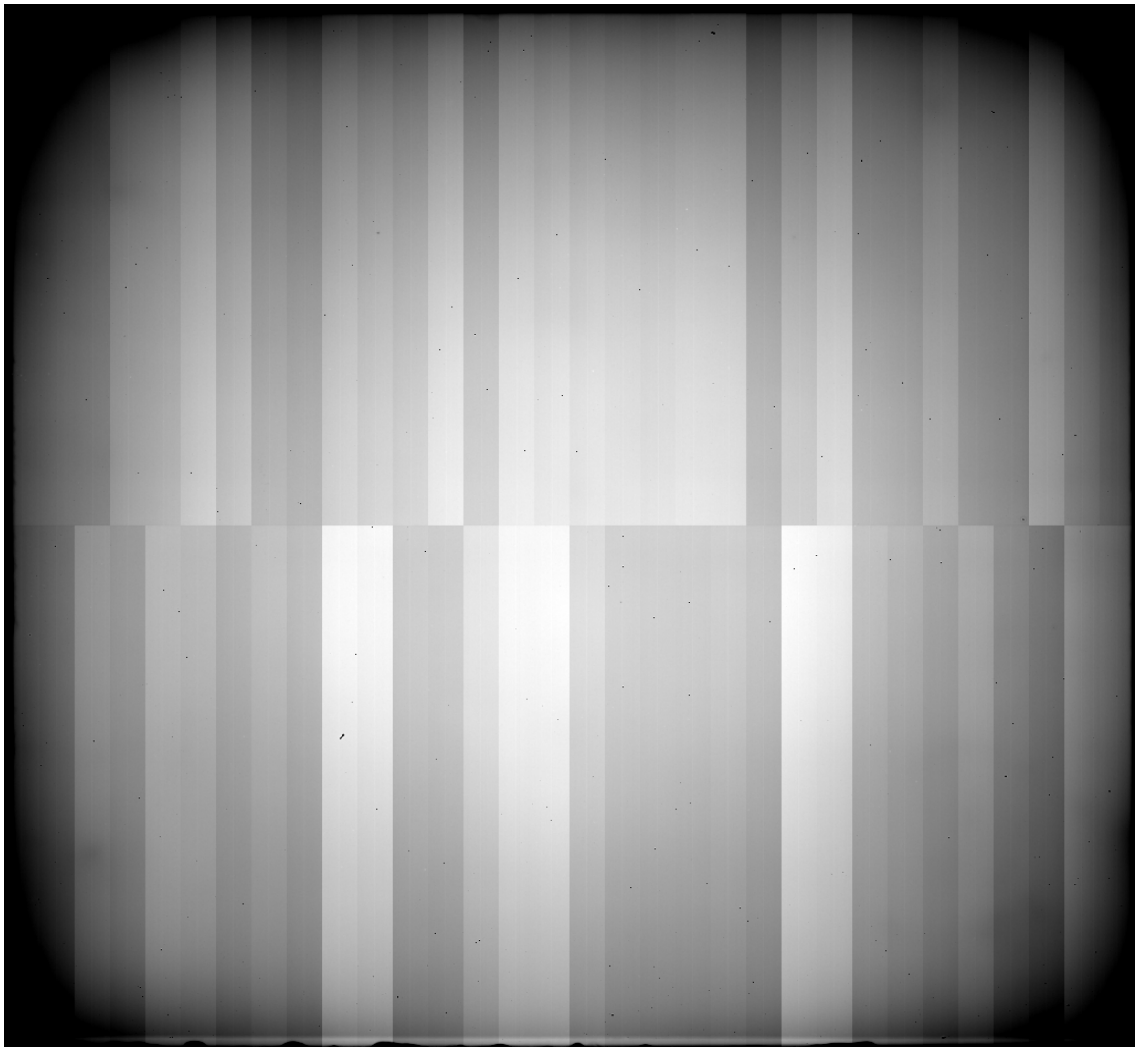
Gain Correction

Sources of gain variation

- Gain of amplifiers
- Quantum efficiencies of diodes
- Thickness/doping of CsI
- Xray tube Non-Uniformity
- Detector CF = f(x-ray spectra)

Gain correction

- Generate gain map (gain correction coefficient for each pixel) during calibration with flat field images.
- G(x,y) = Median/avg(x,y)
- Multiply offset corrected image by gain map.
    - Out = Gain*Image



GE Proprietary

Bad Pixels Correction

- Sources of defects:
  - Non-Responsive; “Dead”
  - High Leakage
  - non-linear response
  - low gain
  - noisy
  - Lag
- Correction: replace defective pixels via interpolation from neighboring pixels
- Detection
  - measure gain, offset, and noise of each pixel
  - flag as bad pixels those which are too low or high in any of these quantities

	N	
W	O	E
	S	

Priority-based Interpolation

- (N+S+E+W)/4
- (N+S)/2
- (E+W)/2
- N
- S
- E
- W

GE Proprietary

Corrected Output Image

Output = BP[Gain*(Input-Offset-Lag)]

Other Calculations/Operations

- Automatic Brightness Control: feedback to exposure management
- Rescale/Encoding: scaling, bit compression
- Rotation
- Decimation (2k-> 1k; 1.5->1k)

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Image Quality
and
X-Ray Digital Detectors

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Why Digital X-Ray imaging?

Digital Image Quality characterization

Digital Detector characterization

Calibration and Correction

GE Proprietary

Why Digital Detectors ?

- Better outcome for radiologist driven by:
  - Better Image Quality at lower dose
  - Faster imaging speed
  - Better consistency

See more, in real time, on all patients ...

- New medical applications:
  - Vascular: 3D reconstruction of stents, ...
  - Rad: Dual energy for chest, ...
  - Mammography: Tomo-synthesis, ...

with new procedures ...

- Economic impact:
  - Higher patient throughput
  - Digital storage and communication

... at lower cost

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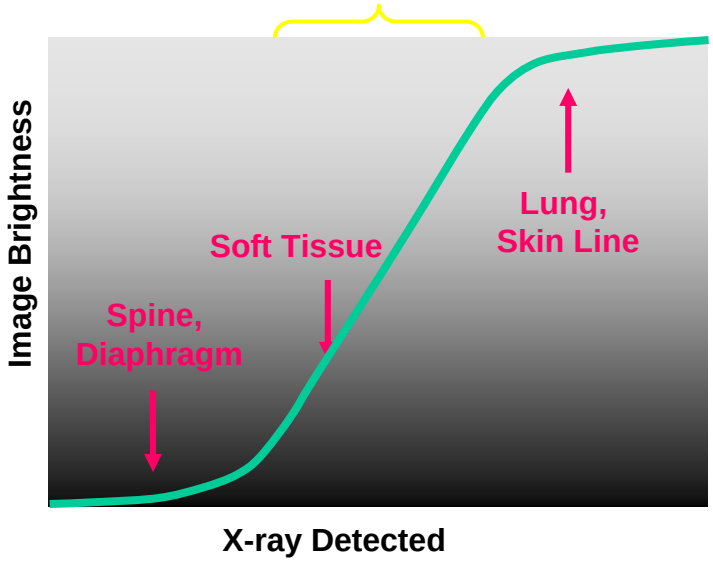
•Film:

•Same medium for image acquisition and image display ⇒ *trade-off* around the sensitometric response

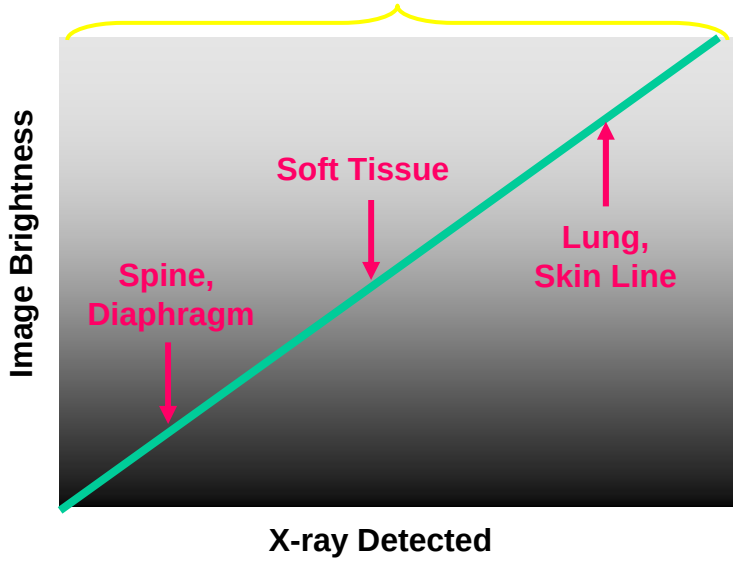
•Digital detector:

•Image acquisition and image display are decoupled ⇒ *independent optimization*

Narrow dynamic range

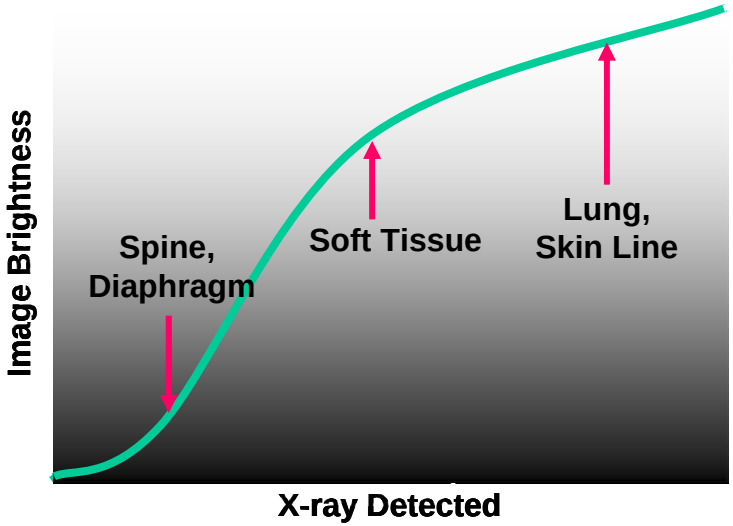


Wide dynamic range



Displaying Relevant Information

Digital detector dynamic range covers the entire range of exposure levels, more than can be display without processing!



…or a Bone Look

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Characterizing Detector Performances

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How to Characterize a Detector ?

•Detector's performances measurement must be sensitive to user's critical requirements

Radiologist visual task:

- detection of abnormalities, tools
- classification of detected signs

Start with Image Quality criteria contributing to maximize Radiologist's visual task results

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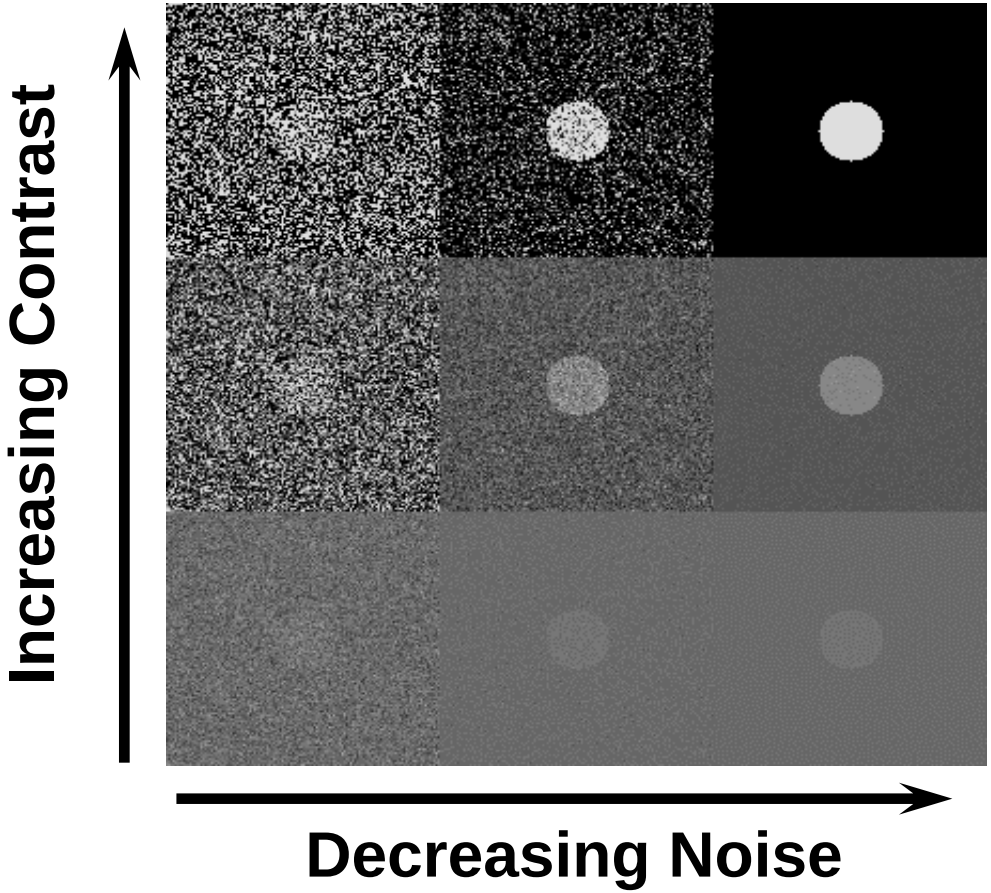
Image Quality Criteria



Both **Low Noise** and **High Contrast** are required for superior image quality and object detectability

Image Contrast to Noise Ratio Best Characterizes "Object" Detectability

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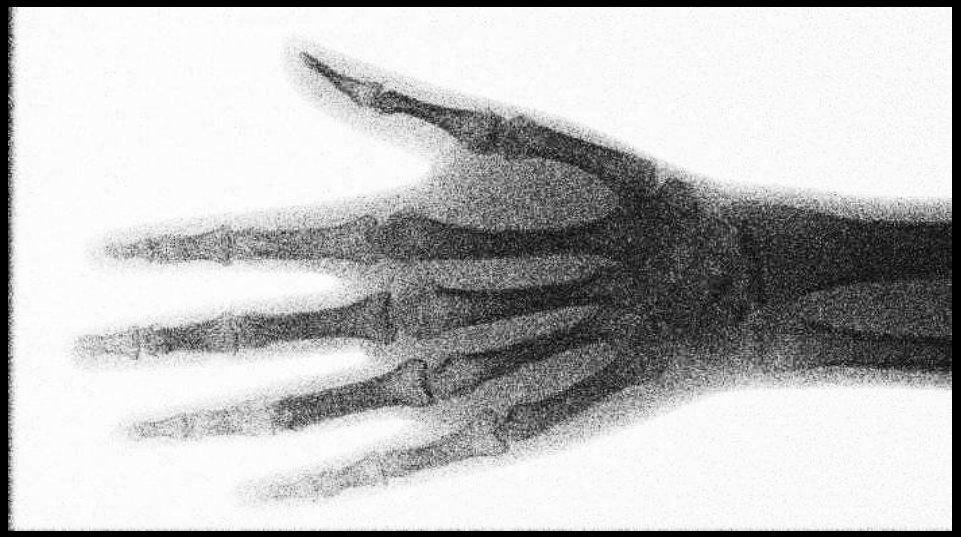
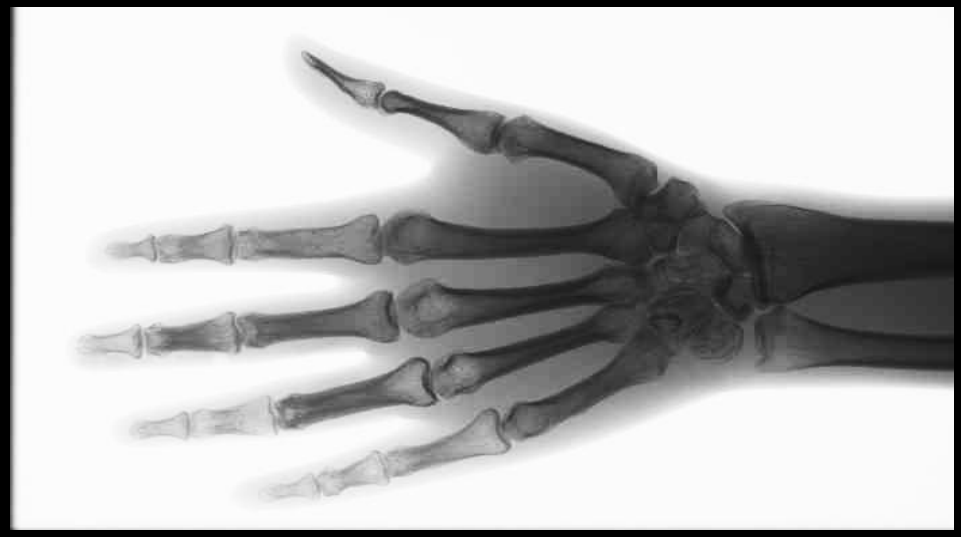
Clinical Example

The Clinical Advantage of SNR



Low dose image



High dose image

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Key Measures of Image Quality

DQE(f): Detective Quantum Efficiency is the efficiency in transducing the inherent information (SNR).

Resolution: Ability to resolve a given frequency. Quantified with MTF(f), modulation transfer function

Dynamic Range: Working dose range. Typically defined as maxSignal/noise floor.

Temporal Response: Quality of dynamic sequences. Typically quantified with lag.

Artifacts: Distracting abnormalities in the image. Quantified by CNR that is based in human visual perception.

Uniformity: Consistent brightness and resolution

There are many performance measures

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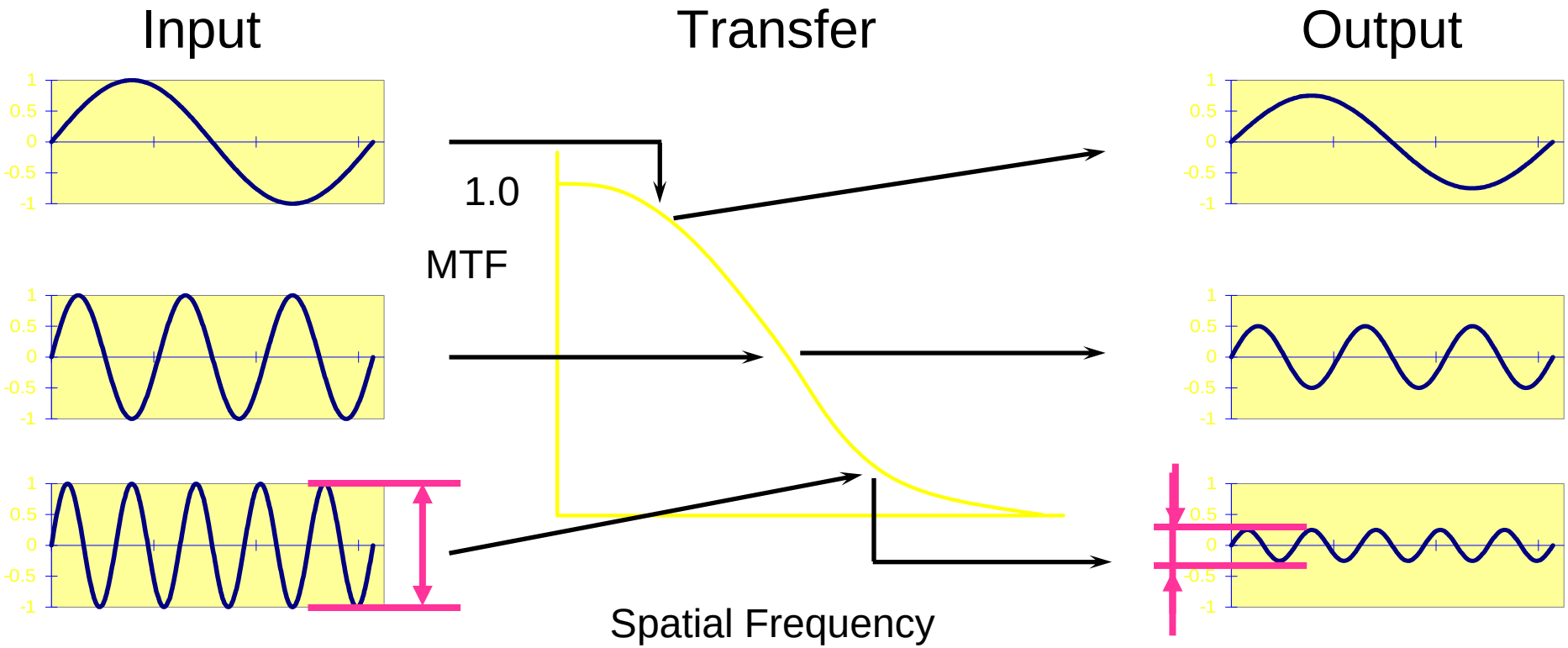
Modulation Transfer Function

$$\text{MTF} = \frac{\text{Modulation at detector output}}{\text{Modulation at detector input}}$$



Imaging systems tend to attenuate the high frequencies leading to blurring.

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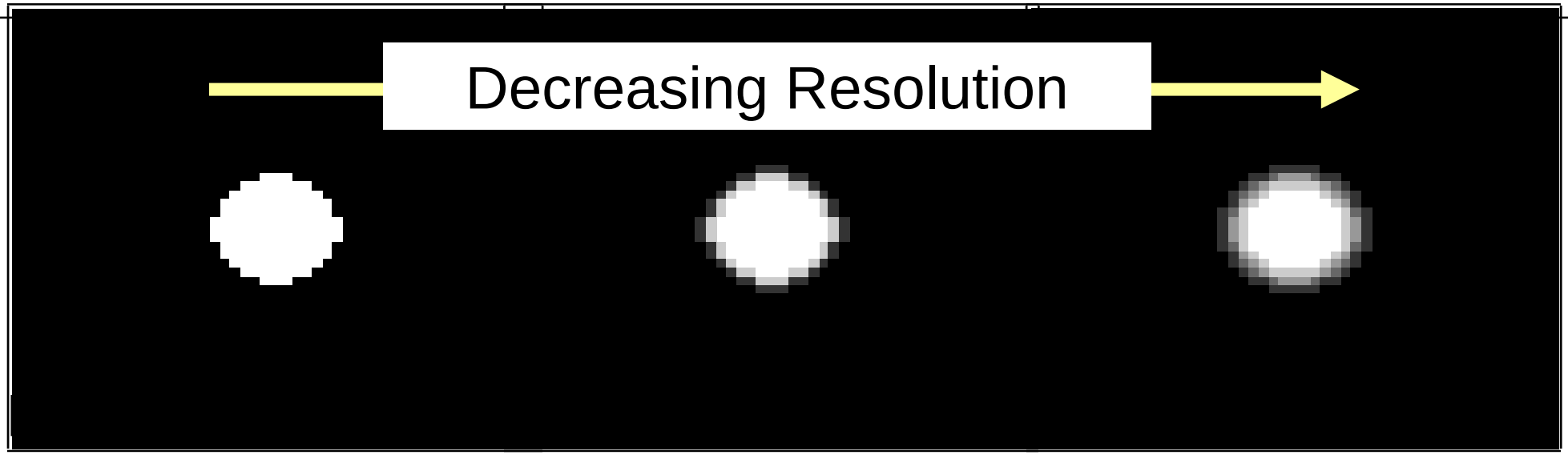
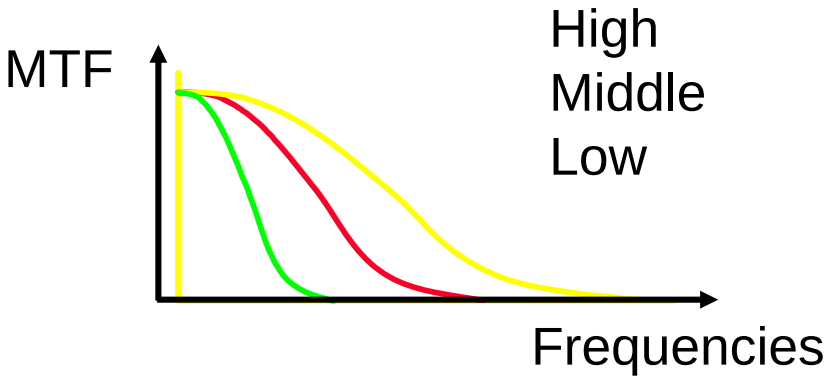


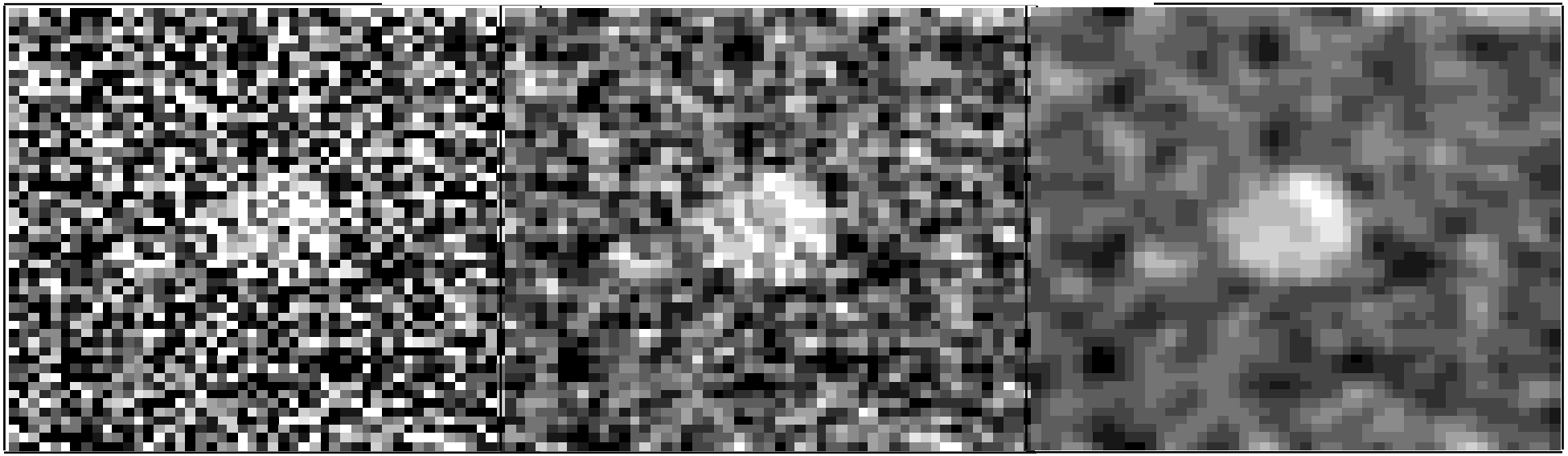


Noiseless image

Window / Level: 5 / 100

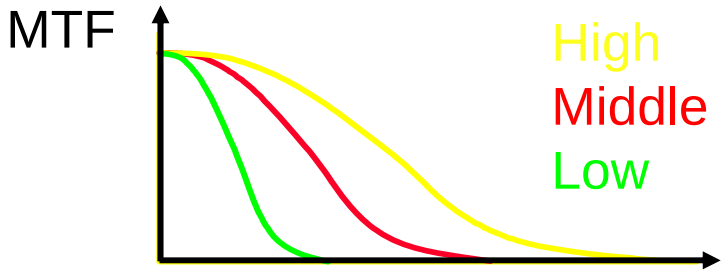
Reducing MTF blurs details.
But object still detectable.

Decreasing Resolution



MTF: High Middle Low

SNR = 1 Window / Level: 11 / 96



Higher resolution may not provide better detectability in noisy images.

GE Proprietary

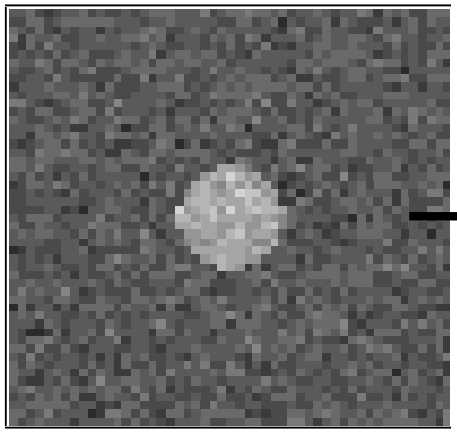
- <u>Detective Quantum Efficiency</u> **(DQE) best describes detector performances for contrast and noise at the different frequencies**

$$\mathrm{DQE}\,(f) = \frac{\mathrm{SNR}_{\mathrm{Out}}^{2}(f)}{\mathrm{SNR}_{\mathrm{In}}^{2}(f)} \propto \frac{\text{Image Quality}}{\text{Patient Dose}}$$

Doubling DQE means:

- Same output SNR ("image quality") at half the dose
- 40% improvement in SNR at same dose

DQE: transfer of information in terms of SNR

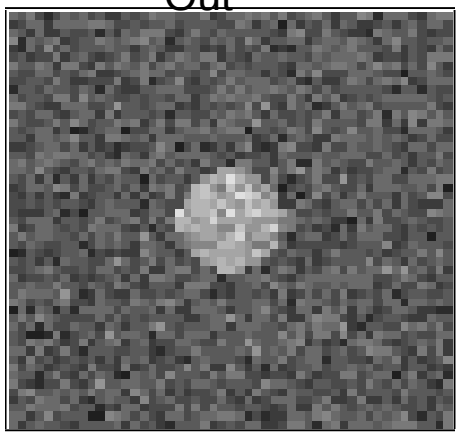


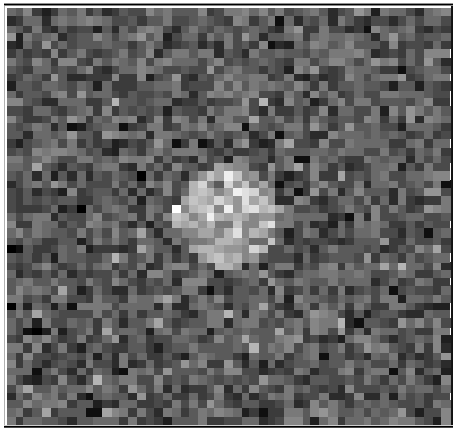
$SNR_{In} = 5$

Detector *A*
DQE = 0.5

Detector *B*
DQE = 0.25

$SNR_{Out} = 3.5$





$SNR_{Out} = 2.5$

Detector *A* superiority

Better Image, Same Dose

Same Image, Half Dose

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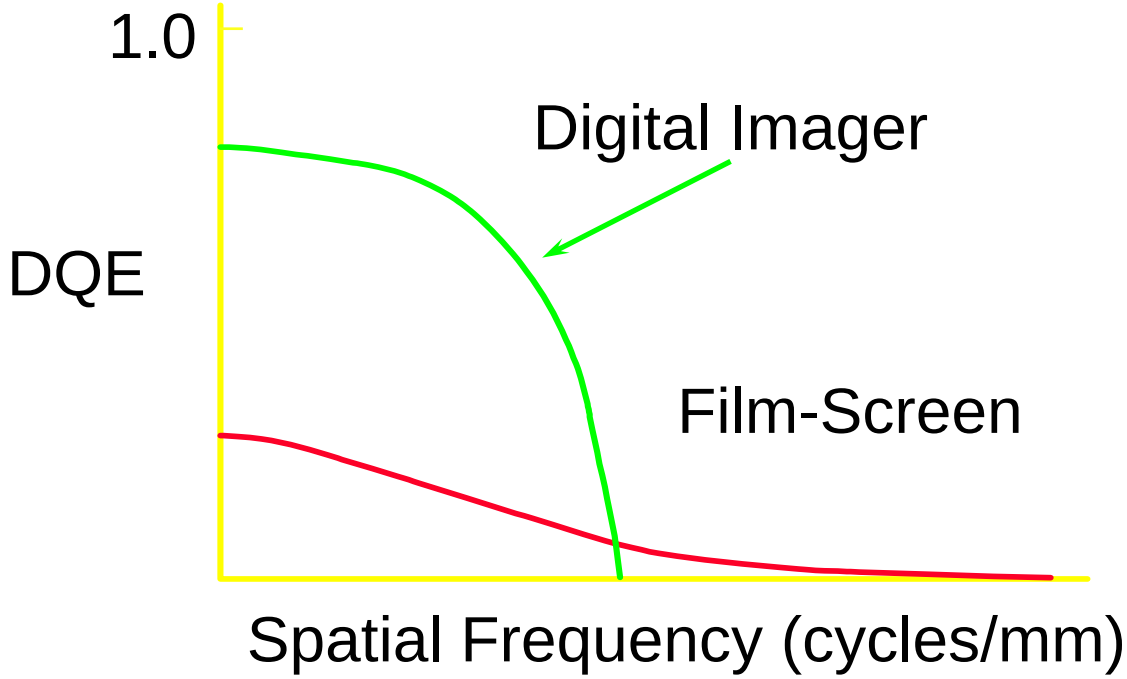
The Resolution Paradox

Paradox: Film / screen has a higher resolution (MTF) than any Digital detector … but observers have better performances with good Digital detectors



The higher the DQE, the higher the SNR, and the greater the probability of detection.

The Spatial Frequency of the Object drives Detectability Differences among Detectors

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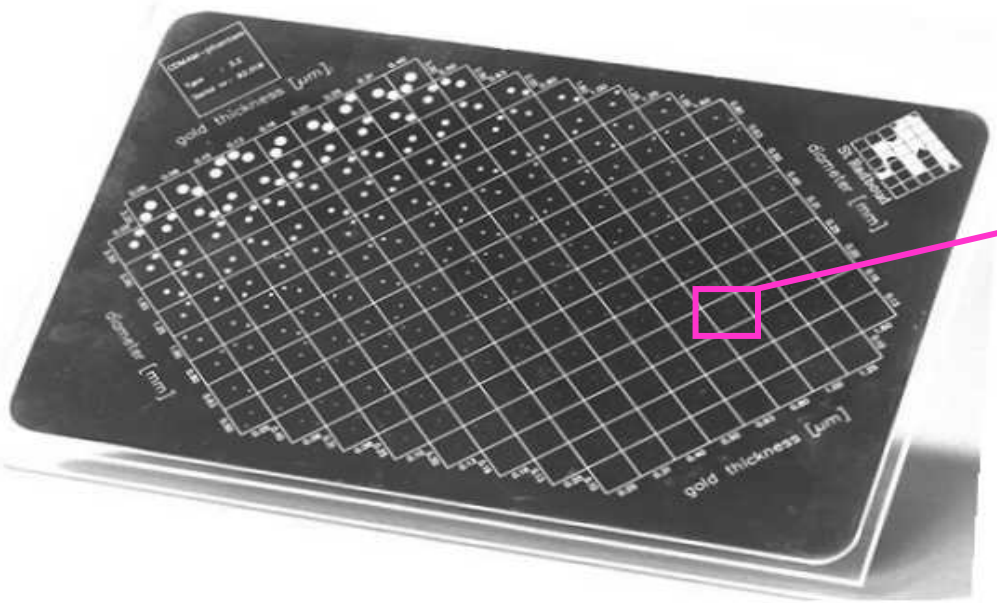
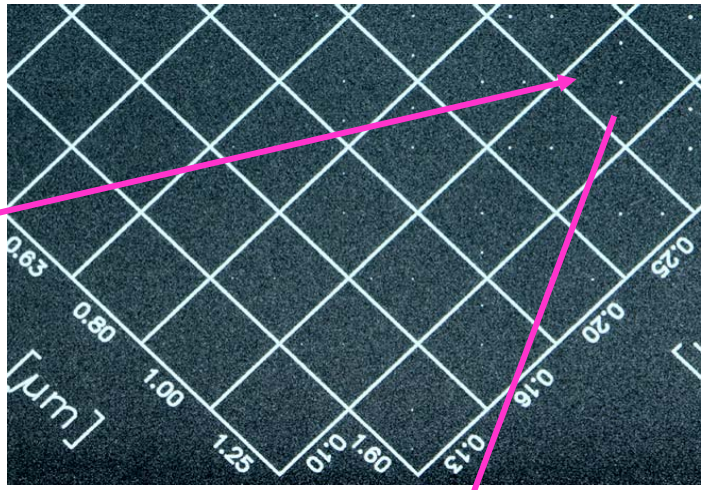
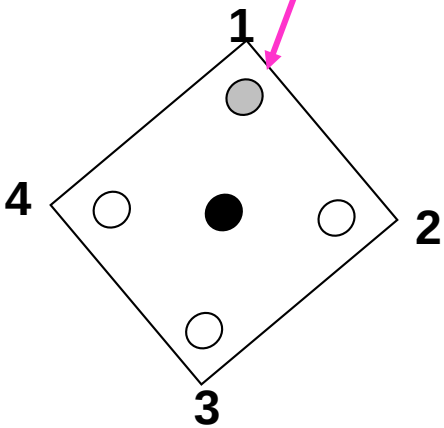
CDMAM Phantom: used for detectability perf. In Mammo



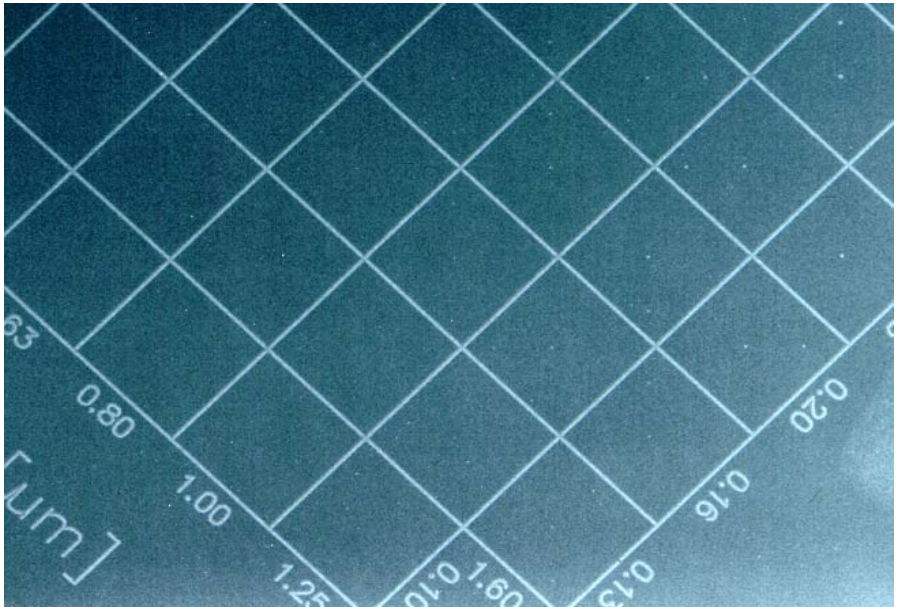


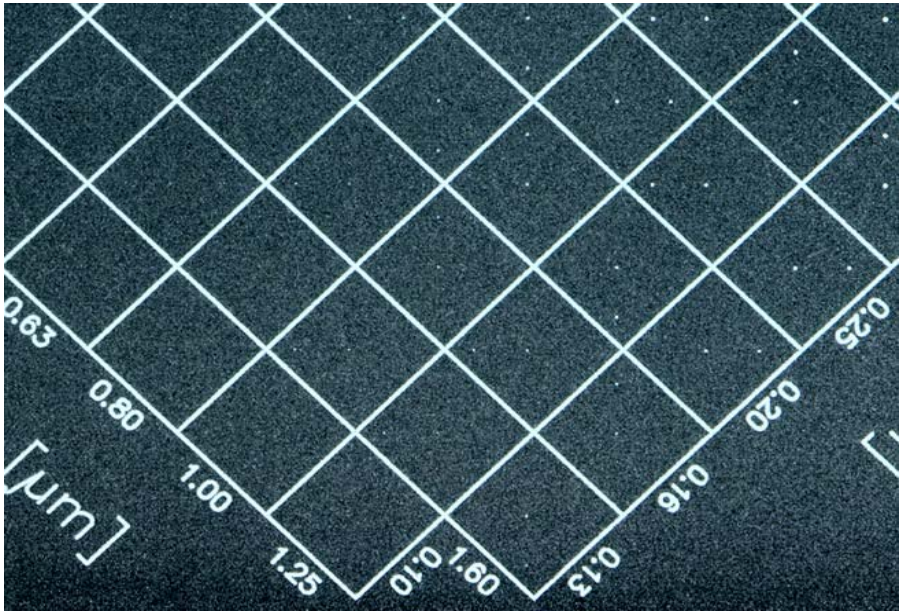


"disk" detected in the position #1

- Plexiglass plaque of 1 cm thickness
- Matrice of 16 rows x 16 columns
- Gold disks with:
  - Diameter (0.1 to 3.2 mm)
  - Thickness (0.05 to 1.6 µm)
- 2 disks/ cell: center + random corner

Contrast Detail Phantom Images



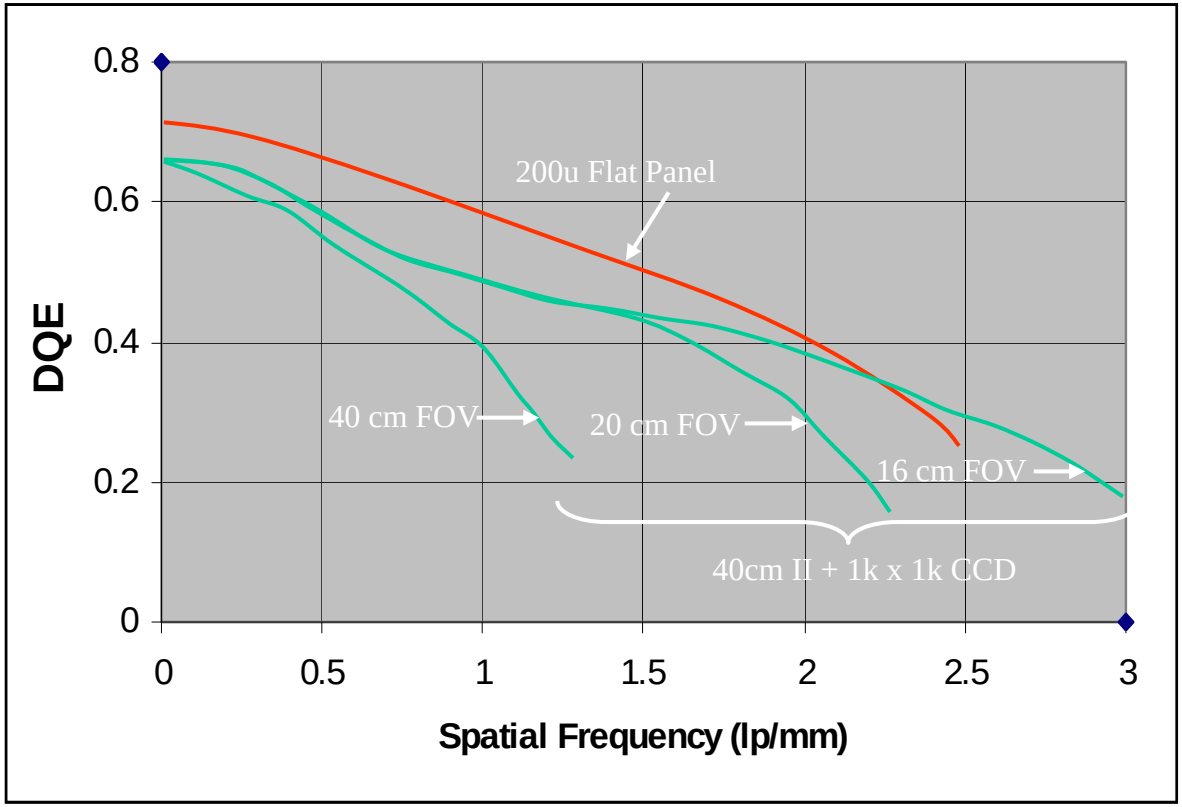


Film ***GE Detector***

Higher DQE Results in Improved Small Object Detectability

DQE: Flat Panel vs II/CCD

- 200µm Pixel Flat Panel
- State of the Art Image Intensifier with CCD



Flat Panel has Significant Advantage in DQE

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