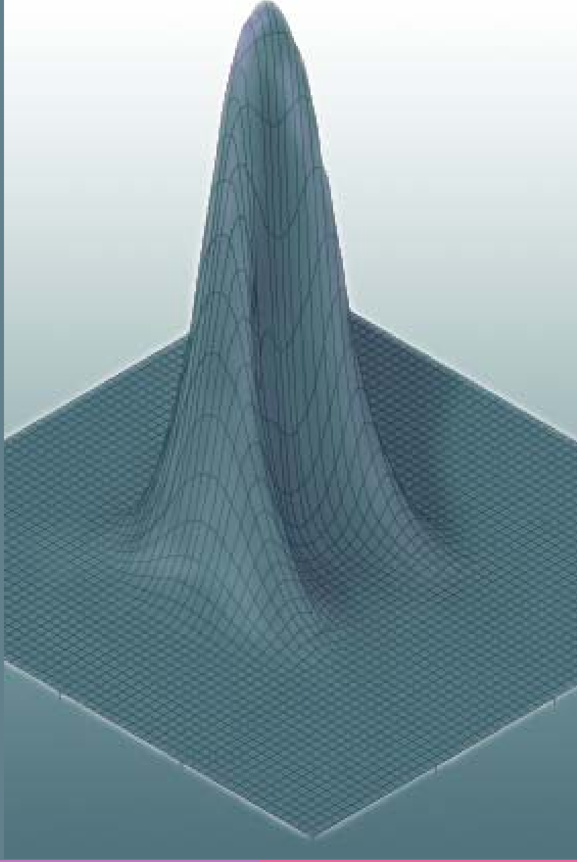
AAPM 2006–Digital Imaging Continuing Education

Design and Performance Characteristics of Computed Radiographic Acquisition Technologies



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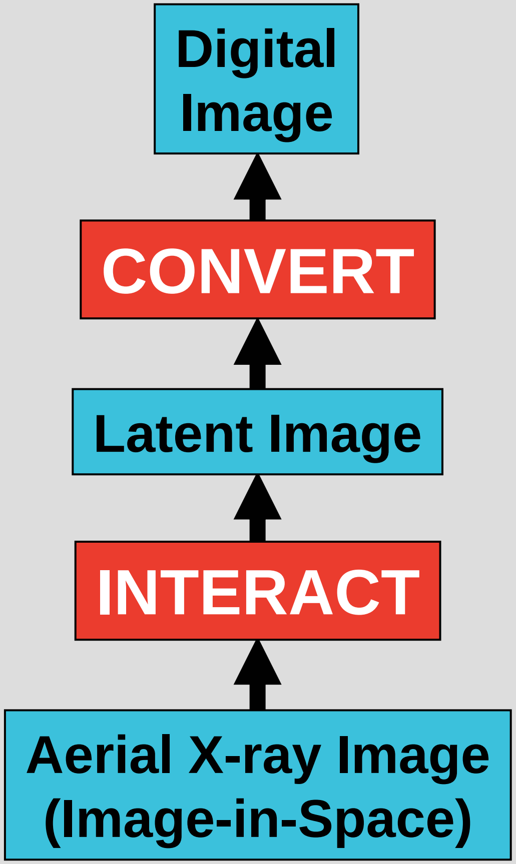
Digital Radiography: Acquisition Technologies in General



Digital Image

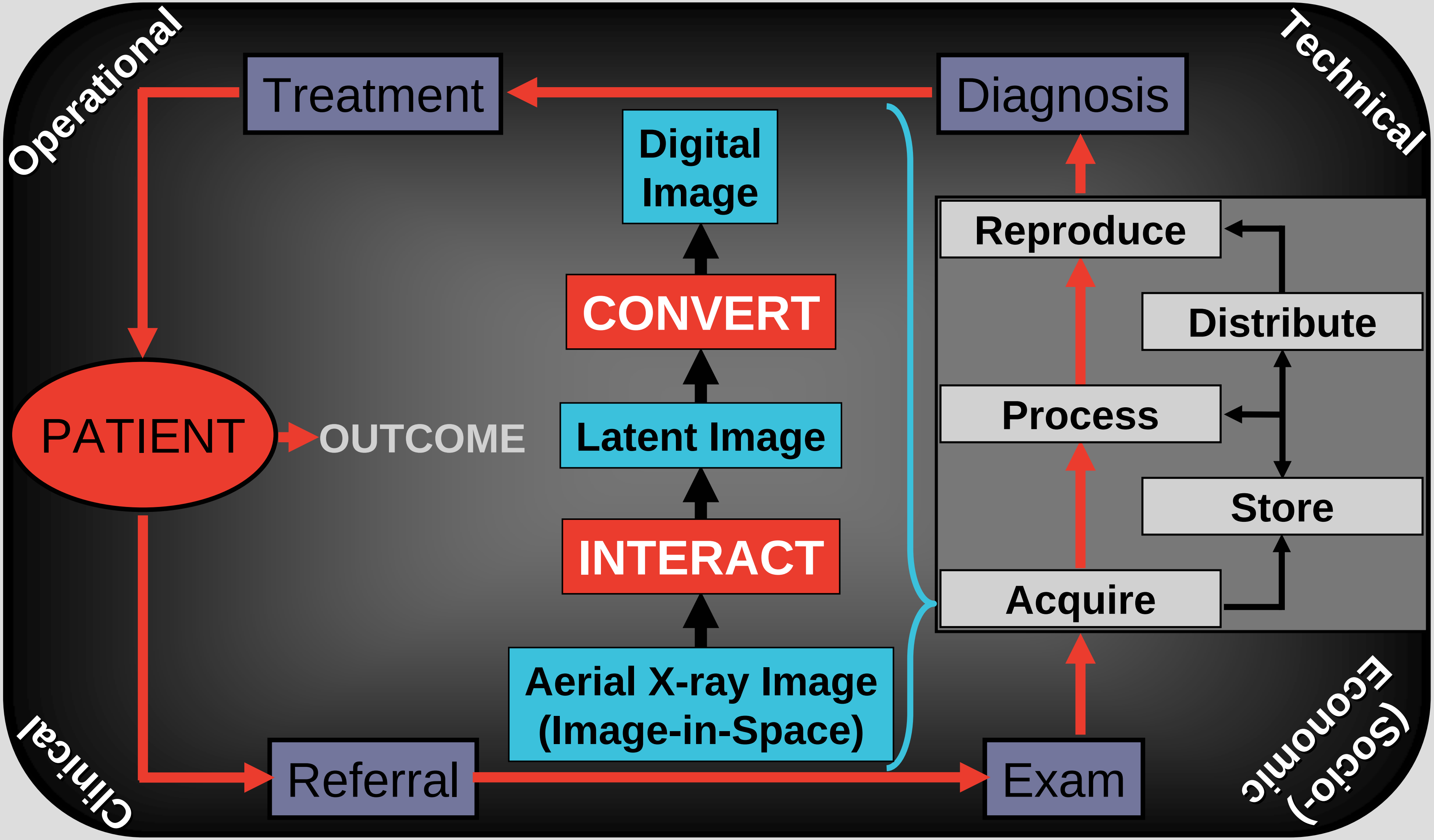
CONVERT

Latent Image

INTERACT

Aerial X-ray Image (Image-in-Space)

Digital Radiography: Acquisition Technologies in Context



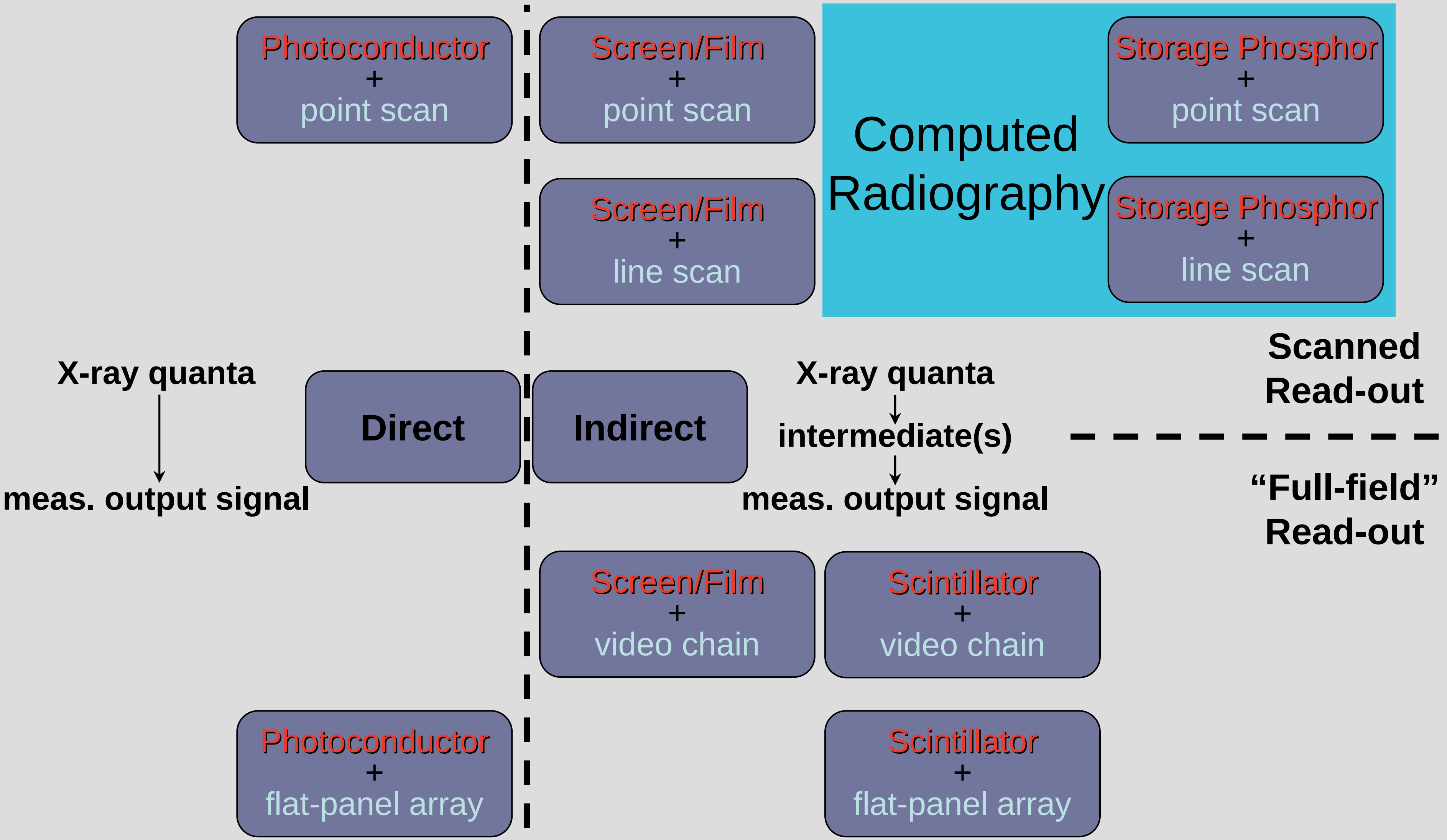
Digital Radiography: A Taxonomy

- Many dimensions along which to classify DR technologies
  - Direct vs. Indirect x-ray-to-signal conversion
  - Scanned (e.g., point, line) vs. Full-field
  - Beam geometry/Detector geometry
  - Detector type/material
  - Dynamic vs. Static
  - …

Related

Digital Radiography: A Taxonomy

(x-ray interaction/detector*, signal extraction)



Photoconductor + point scan

Screen/Film + point scan

Screen/Film + line scan

Computed Radiography

Storage Phosphor + point scan

Storage Phosphor + line scan

Scanned Read-out

X-ray quanta → meas. output signal

Direct

Indirect

X-ray quanta → intermediate(s) → meas. output signal

"Full-field" Read-out

Screen/Film + video chain

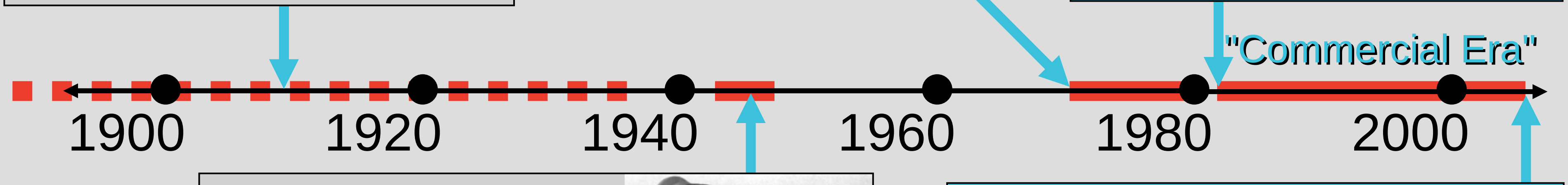
Scintillator + video chain

Photoconductor + flat-panel array

Scintillator + flat-panel array

*** Other detectors (e.g., pressurized gas, Si/metal strips) have also been used**

Historical Context



Full-field (incl. x-ray) imaging with PSL intermediates (1842 - 1936)

R&D on SP scanning systems

Installed Base: 1
Price: $1,200,000
Size: ~ 10 m^2
Speed: 40 plates/hr

Full-field night-vision "cameras" (IR/heat stim. SP)


Kodak

Installed Base: ~20,000+
Price: ~ 10x lower
Size: ~ 10x smaller
Speed: ~ 2-4x faster

CR: the most widespread form of DR!

Learning Objectives

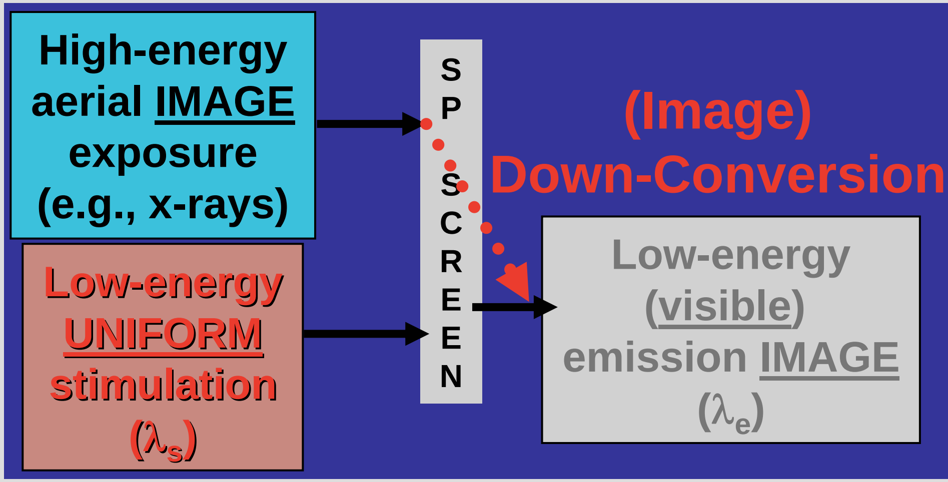
- Describe the form and function of today’s computed radiography (CR) systems
- Identify the main factors that influence the image quality of CR systems
- Compare modern CR systems to other acquisition technologies
- Describe the latest and future developments in CR

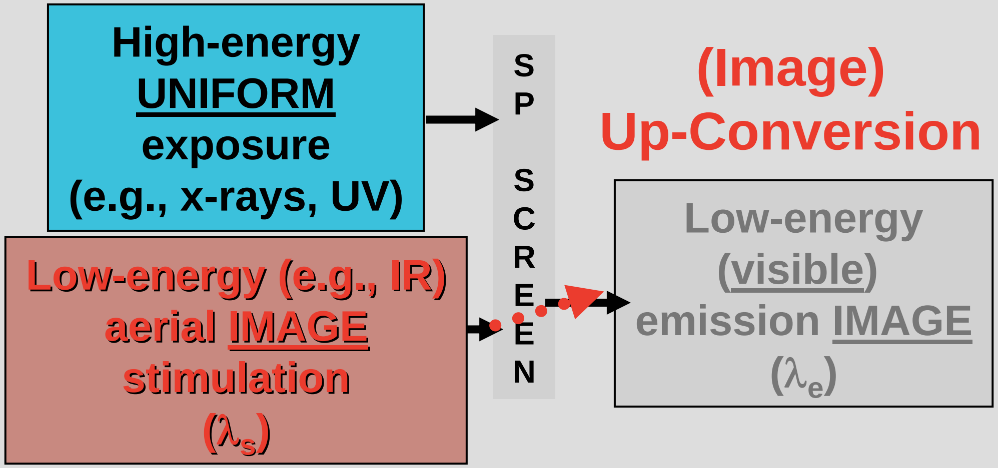
Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments

Basics
CR Characteristics

- Detector is SP screen (PSL screen, Imaging Plate, IP, …)
- Screen can absorb, and store (partially) as a latent image, incoming high-energy electromagnetic radiation
- Exposure to low-energy stimulating radiation (λ_s) causes screen to emit the previously stored energy at a (shorter) wavelength (λ_e) in the visible – λ_s , λ_e must be sufficiently different, or no CR possible





Basics:
CR: Digital Alternative to Screen/Film

- BOTH systems
  - use phosphor screens as x-ray absorbers
  - use screens with similar structures
    (small phosphor particles dispersed in a binder)
  - emit light promptly on x-ray exposure
    (x-ray luminescence)
  - use screens that can be exposed thousands of times
- ONLY storage phosphors
  - can retain a portion of the absorbed x-ray energy
    (as a latent image of trapped electrons, e^-)
  - can be read out at a later time,
    (destructively, i.e., latent image is erased as it is read)

Basics:
CR vs. Screen/Film - Advantages of CR

- Extended Exposure Latitude (10000:1 vs. ~40:1)
  - High exposure flexibility with 1 detector (retakes ↘)
- Reusable Detector
  - Reduction in consumables (film, chemistry) costs (but, full impact only with softcopy interpretation)
- Compatibility/Scalability/Workflow/Productivity
  - No major changes to equipment/rooms/technique
  - Flexible reader placement (centralized and/or distributed architectures)
- Digital Data
  - Gateway for projection radiography into PACS

Computed Radiography Technologies

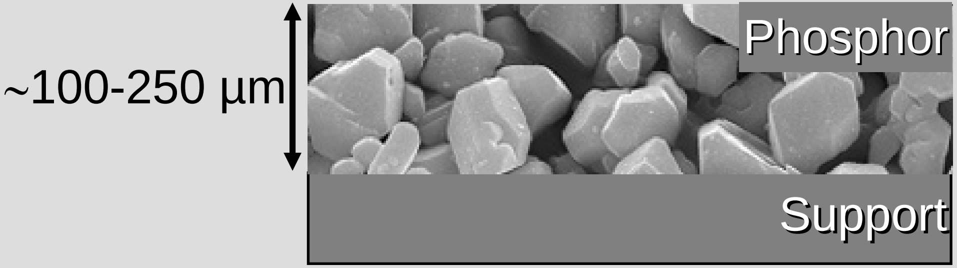
- Basics
- System Design
  - Screens
  - Scanners

A System!

- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments

Design: Storage Phosphor Screens

- Support (flexible, rigid) coated with tiny (3-10 µm) SP particles dispersed in binder
  - Screen is turbid (white)
- Many materials tested, only a few successful
  - SrS:Ce, Sm
  - RbBr:Tl
  - BaFX: Eu^{2+} (where X=Br, I)
  - CsBr: Eu^{2+} (new)

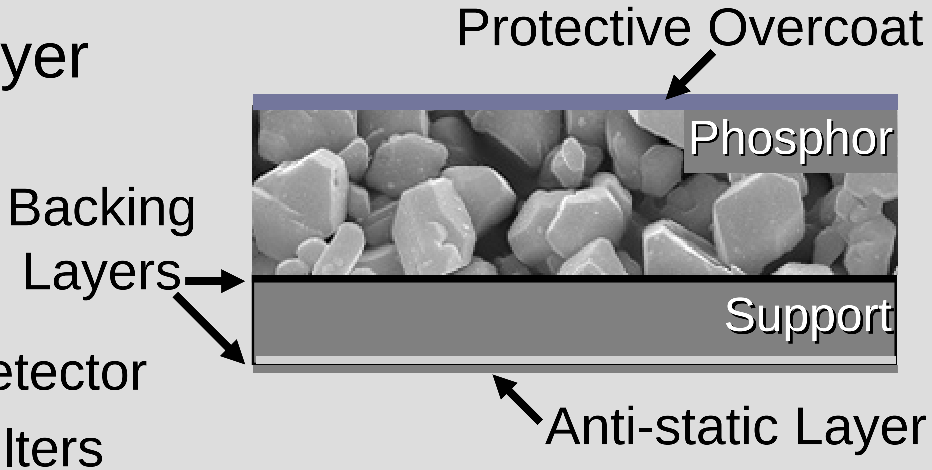


Screen Structure (ideal)

- SP mechanisms/processes at micro (quantum) level still subject of active research!

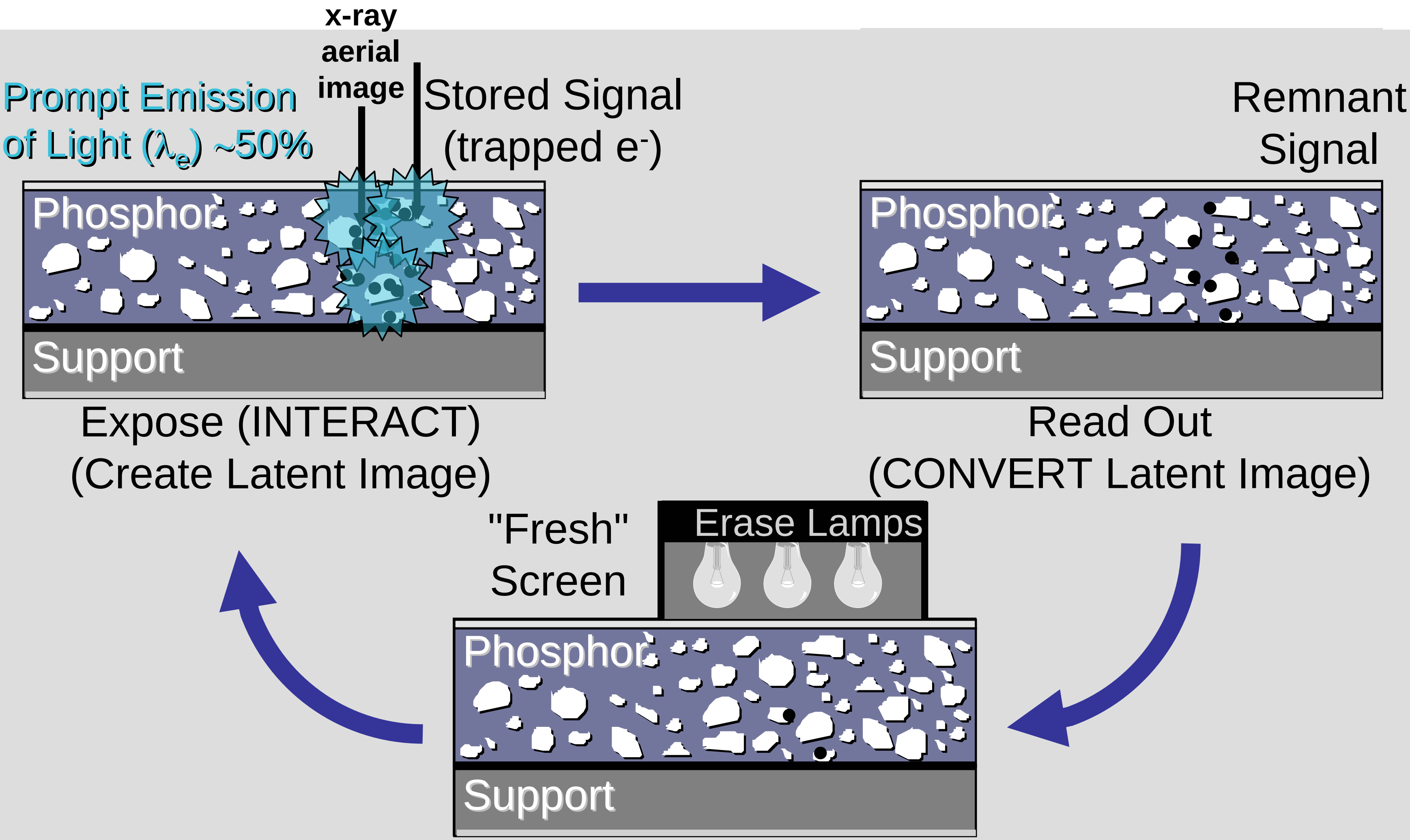
Design: Storage Phosphor Screens

- Manufacturer-specific layers to optimize mechanical, optical, electrical performance, e.g.,
  - Wear, handling layer
  - Electrostatic discharge layer
  - Optical coupling layer
    - reflective backing
      - direct more emitted light to surface/photodetector
    - absorbing backing, dyes, filters
      - reduce spread/transmission of stimulating light (sharpness)
  - X-ray backscatter control layer (lead)



Screen Structure (real)

Design: Three-step Imaging Cycle



x-ray aerial image

Prompt Emission of Light (λ_e) ~50%

Stored Signal ($trapped\ e^-$)

Remnant Signal

Expose (INTERACT)
(Create Latent Image)

Read Out
(CONVERT Latent Image)

"Fresh" Screen

Erase (Reset/Reinitialize)
(Remove Residual Latent Image)

Design: The Flying-Spot CR Scanner

- Components

Mech.

  - IP transport stage
  - Beam deflector

Opt.

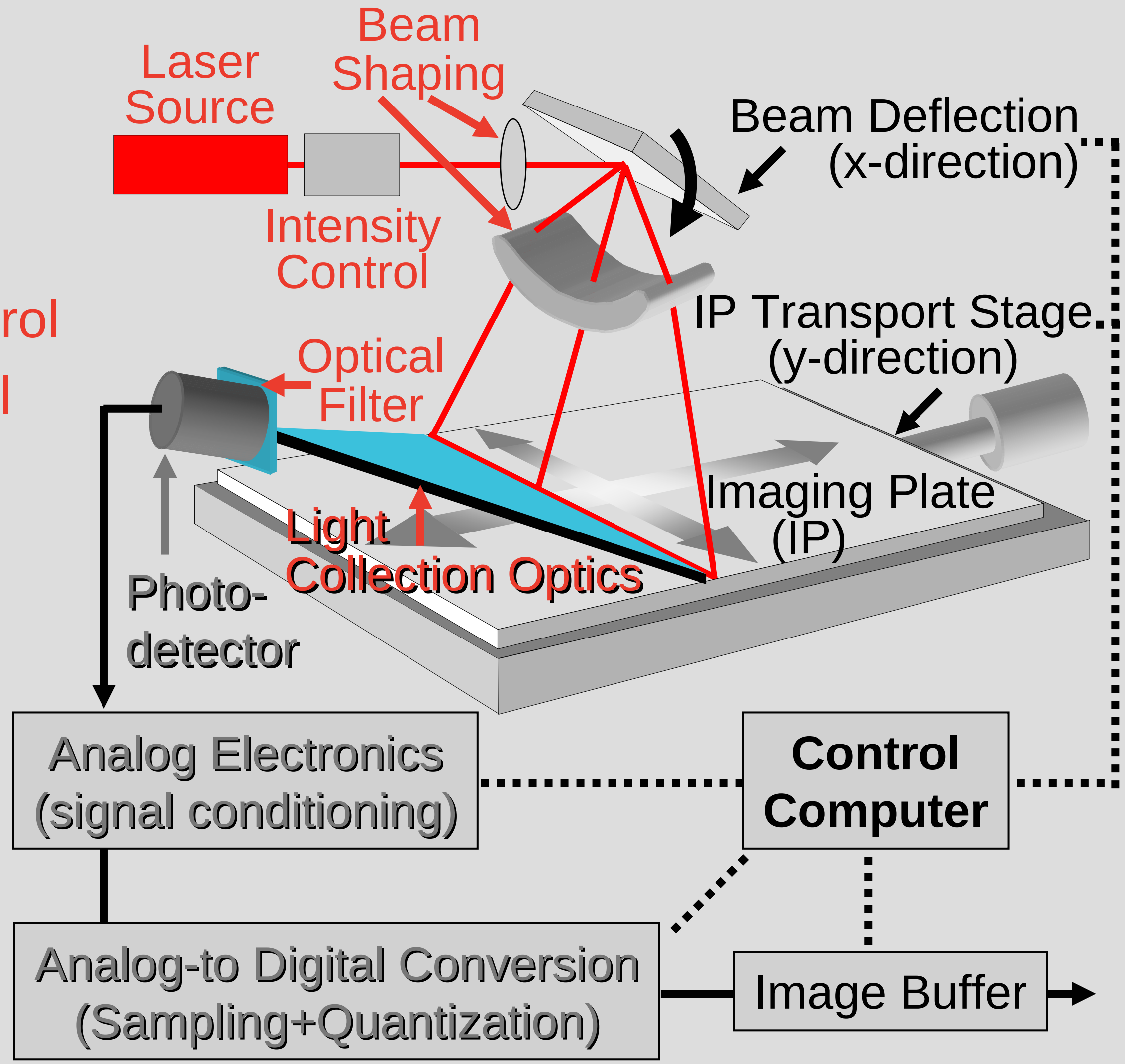
  - Laser + intensity control
  - Beam shaping/control
  - Collection optics
  - Optical filter

Elec.

  - Photodetector
  - Analog electronics
  - A/D Converter

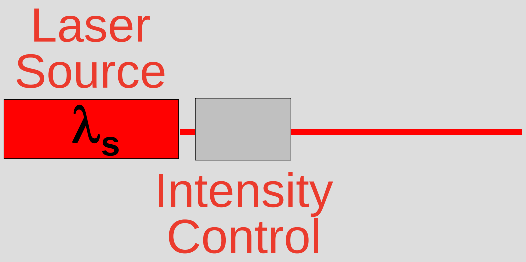
Comp.

  - Image buffer
  - Control computer
  - (Erase station)



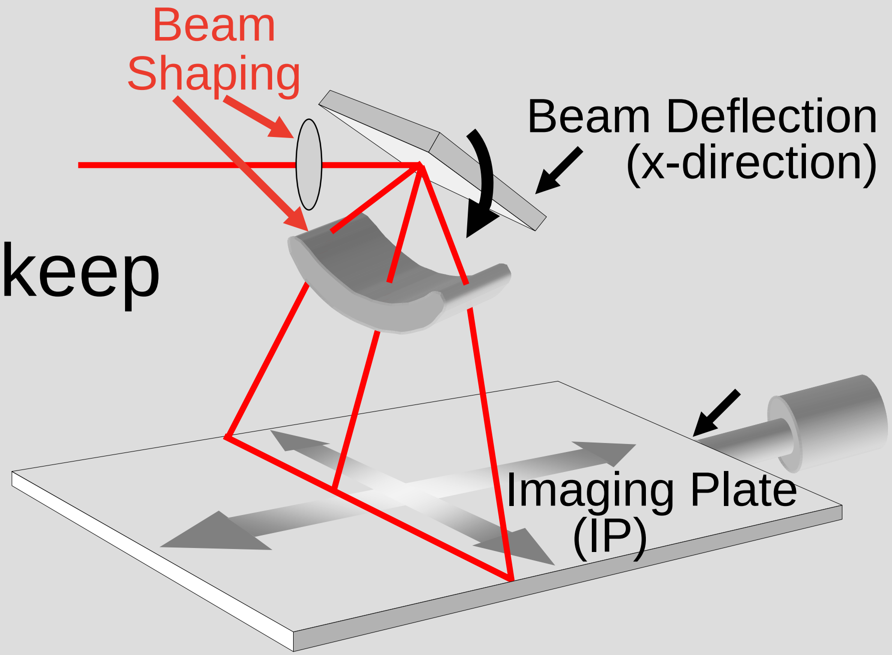
Design: The Flying-Spot CR Scanner
Laser Source + Intensity Control

- ➔Efficient, rapid, accurate read-out of latent image
  - Power: high-power light source = laser (~~gas~~, solid-state) compact, efficient, reliable, tens of mW over ~100 µm Ø
  - Wavelength, λ_s: choice depends on energy needed to stimulate latent image electrons out of traps (typically reddish), and emission spectral range (λ_e, typically bluish)
  - Constancy: laser power must be constant during scan to avoid artifacts/noise (fluctuation tolerance as low as ~ 0.1% - active control with feedback loops)



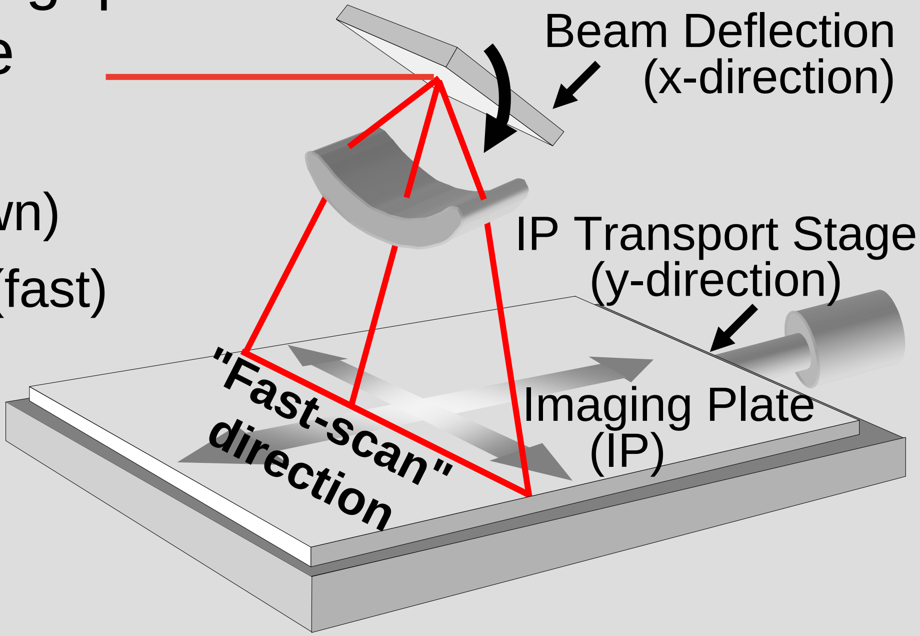
Design: The Flying-Spot CR Scanner Beam Shaping Optics

- Problem: laser point source and beam deflector cause size, shape, and speed of beam at IP surface to change with beam angle (similar to flashlight beam moving along wall)
  - Signal output and resolution depend on beam position - BAD
- Special scanning optics keep beam size/shape/speed largely independent of beam position



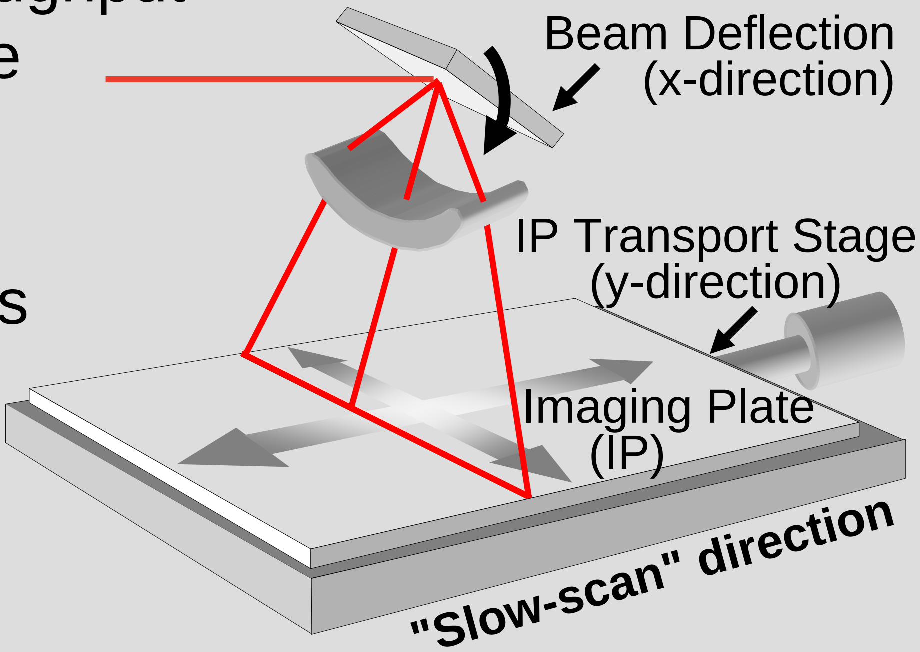
Design: The Flying-Spot CR Scanner Beam Deflector

- Scans beam in one direction across IP surface (transport stage handles orthogonal direction)
  - Desired scan speed/throughput determines deflector type
    - rotating drum (slow)
    - galvanometer/mirror (shown)
    - rotating mirrored polygon (fast)
  - Beam placement accuracy is critical to avoid artifacts (edge jitter, waviness)
    - error tolerance: fractions of the pixel dimension



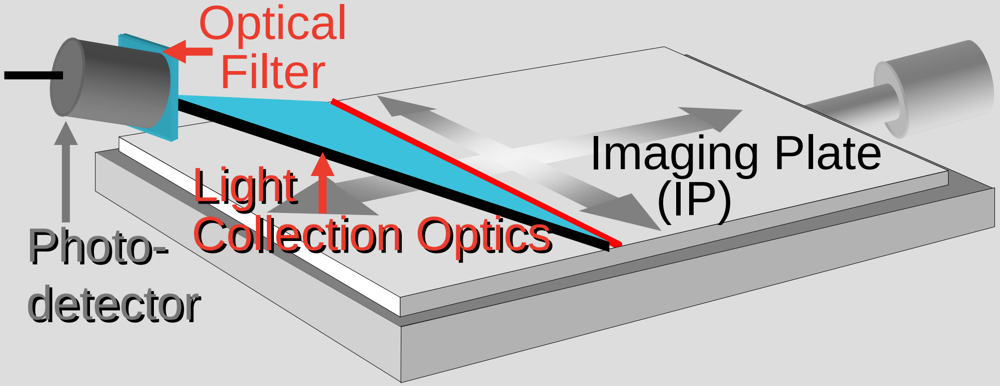
Design: The Flying-Spot CR Scanner Transport Stage

- Moves IP at constant velocity in one direction (Beam deflector handles orthogonal direction)
  - Desired scan speed/throughput determines transport type
    - rotating drum
    - flat bed/table
  - Small velocity fluctuations can lead to artifacts (visible banding)
    - error tolerance: few tenths of 1%



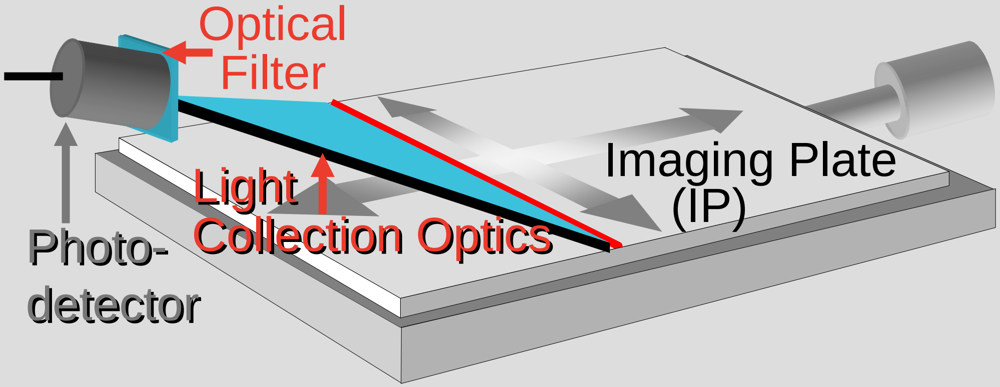
Design: The Flying-Spot CR Scanner Light Collection Optics

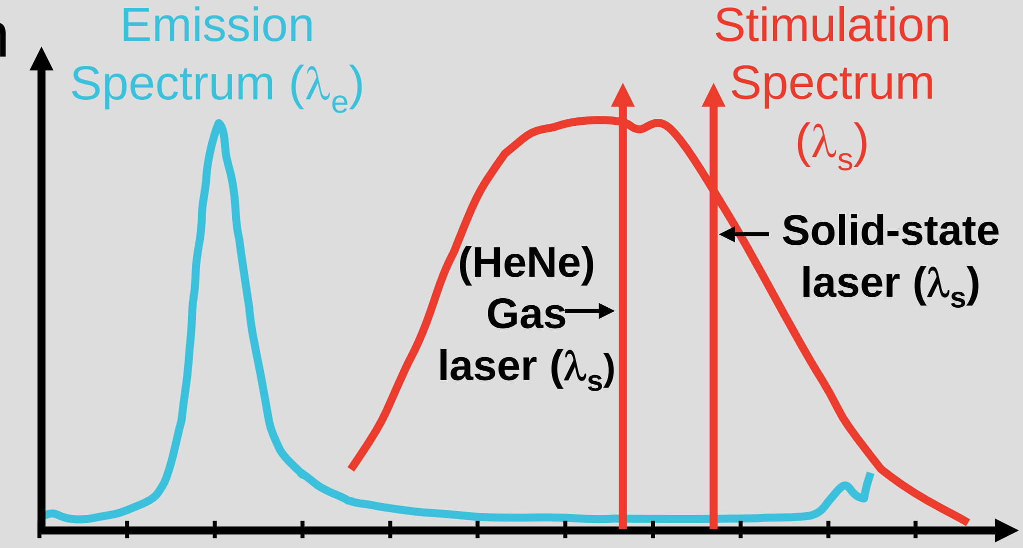
- Problem: stimulated light within phosphor layer is emitted and scattered diffusely in all directions
- Collect/channel as much as emitted light as possible to photodetector (numerical aperture: distance between IP surface and collector)
  - Mirrors
  - Integrating cavities
  - Fiber optic bundles
  - Light pipes



Design: The Flying-Spot CR Scanner Optical Filter

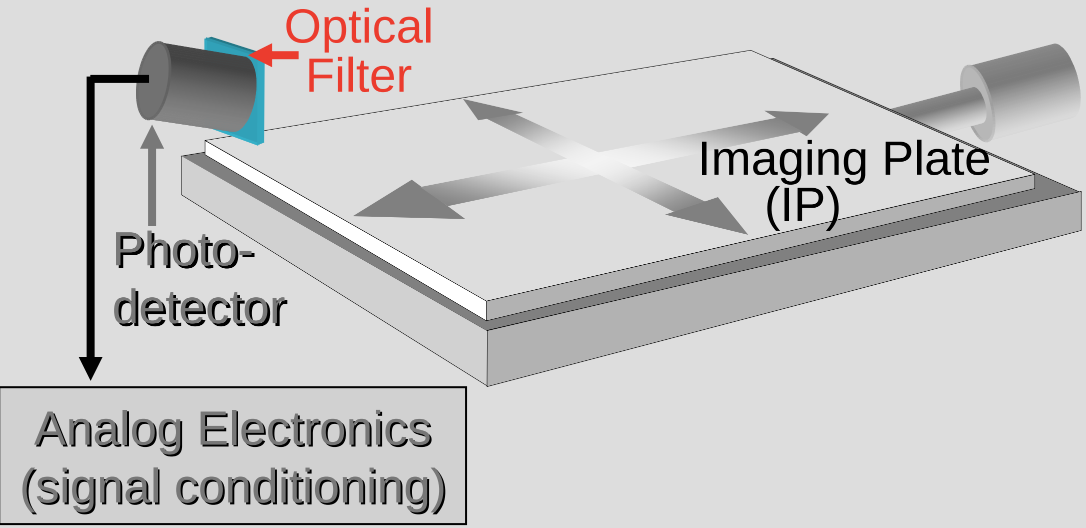
- Intensity of emitted light (λ_e) is $\sim 10^8$ lower than that of stimulating light (λ_s)
- Optical design must find “needle in a haystack”
- Importance of wavelength difference between λ_e, λ_s
  - High-quality optical filter can pass emitted light (λ_e) spectrum to photodetector and block stimulating light (λ_s)

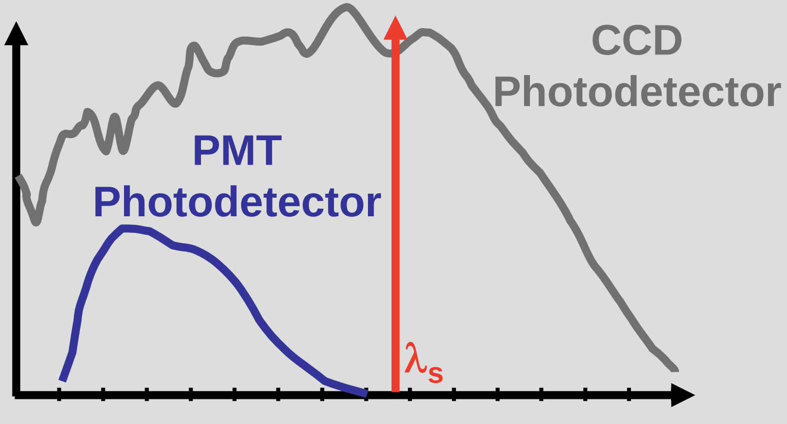




Design: The Flying-Spot CR Scanner Photodetector

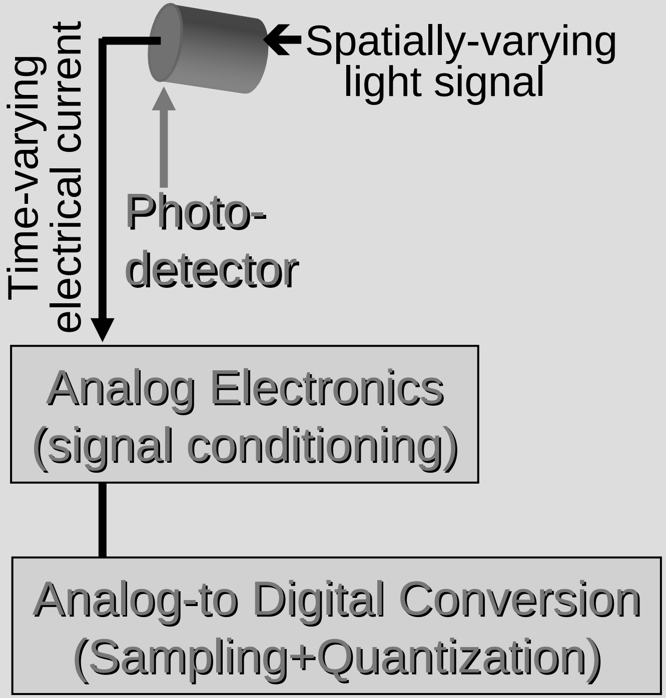
- Weak signal: need high conversion efficiency (light photons → electrons), high gain, low noise
  - Photomultiplier Tube
    - dynamic range ≈ SP ($>10^3$)
    - Quant. Eff. @ λ_e ≈25%
  - Charge-Coupled Device
    - Efficiency ≈ 2x PMT (@ λ_e)
    - But, also sensitive @ λ_s (need low-noise electronics, better optical filter)





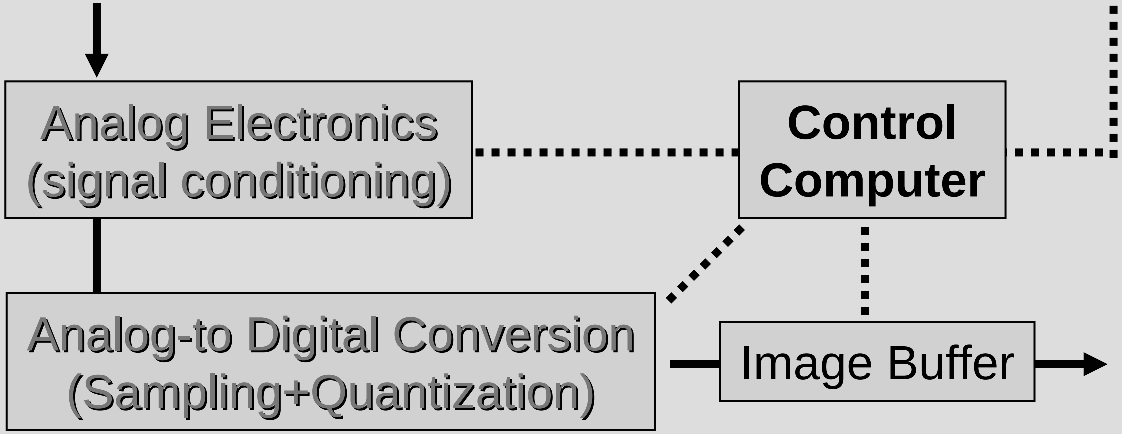
Design: The Flying-Spot CR Scanner Analog Electronics

- Condition/amplify analog, time-varying electrical current from photodetector before A/D conversion
  - Scale/compress large dynamic range of photodetector output to reduce performance requirements, distortion, cost in electronic chain
    - linear (compress after A/D)
    - logarithmic compression
    - square-root compression
  - Remove higher frequencies (> Nyquist) that will cause digitization/aliasing artifacts (fast-scan)



Design: The Flying-Spot CR Scanner Analog-to-Digital Conversion

- Analog signal must be sampled (made discrete in space/time) and quantized (made discrete in value)
  - Sampling rate determines spatial resolution (e.g., making a 2000 x 2500 image in 20 s requires sampling rate of 5,000,000/20 = 250 kpixels/s)
  - Quantizer resolution must be high enough to maintain small, clinically relevant signal differences over full exposure range
    - 12-16 bits/pixel for linear data
    - 8-12 bits/pixel for nonlinear data (e.g., log, sqrt)



Analog Electronics (signal conditioning)

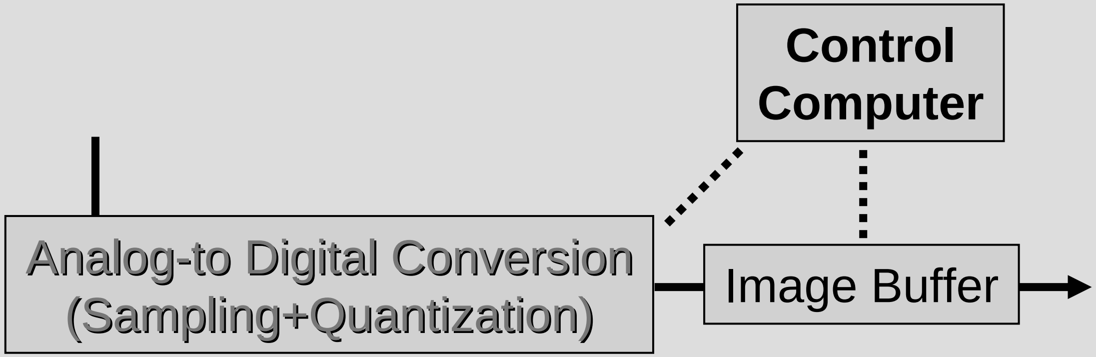
Control Computer

Analog-to Digital Conversion (Sampling+Quantization)

Image Buffer

Design: The Flying-Spot CR Scanner Image Buffer

- Until/unless digital images can be transferred to a more permanent storage location (such as a long-term archive), they need to be buffered (stored) locally (e.g., local hard disk, workstation)
- Buffer capacity depends on local storage needs, image throughput, network load, remote storage availability, system redundancy concept, etc.



Design: The Flying-Spot CR Scanner Erasure

- Remnant signal on screen must be reduced to a level much lower than lowest expected signal from next exposure (otherwise, ghost images)
  - Can become issue in RT applications
- Different designs (screen/scanner-dependent):
  - High-power halogen/incandescent lamps
  - LEDs (recent development)
- Spectrum is important (screen-dependent)

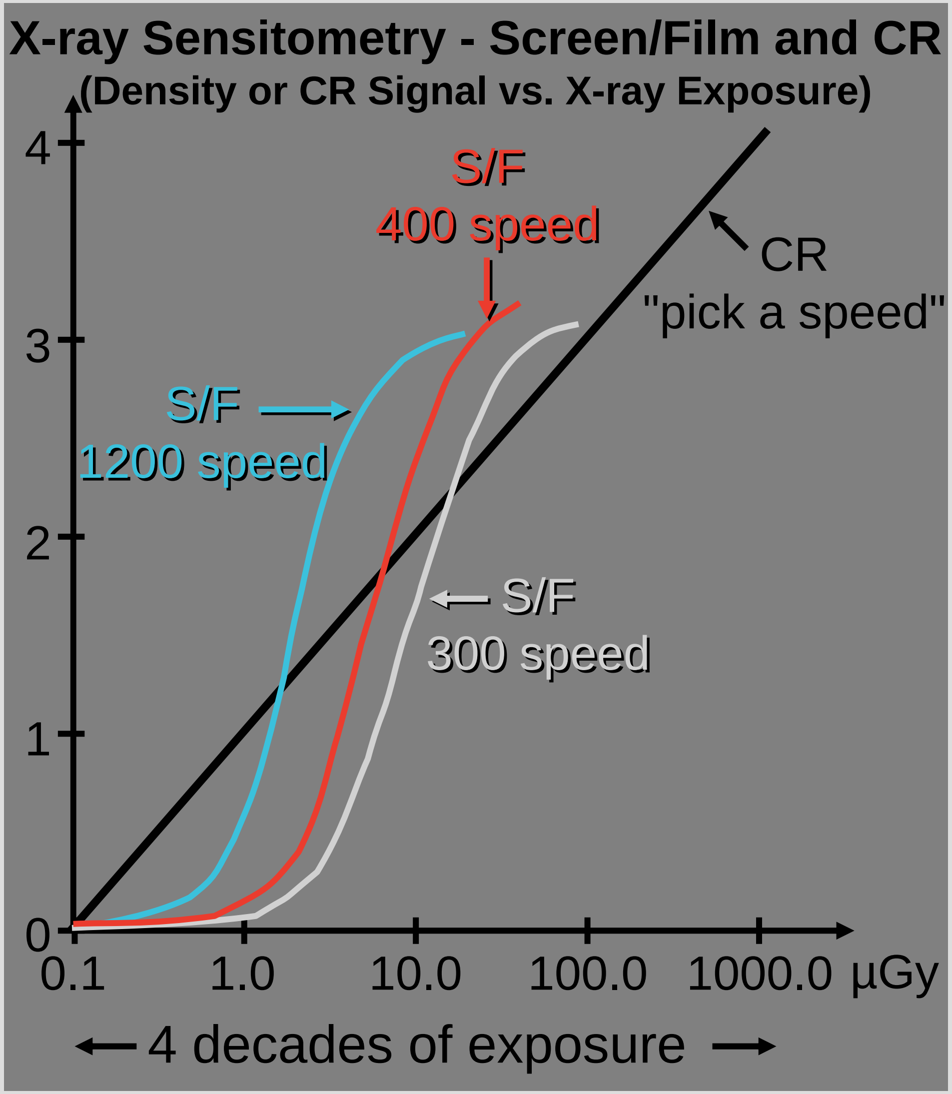
Laboratory Prototype
of Erase Subsystem☺

Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments

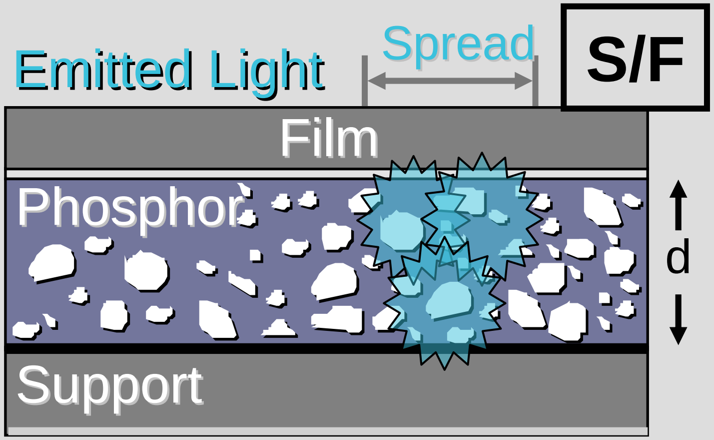
Imaging Performance: Input/Output (I/O) Relationship

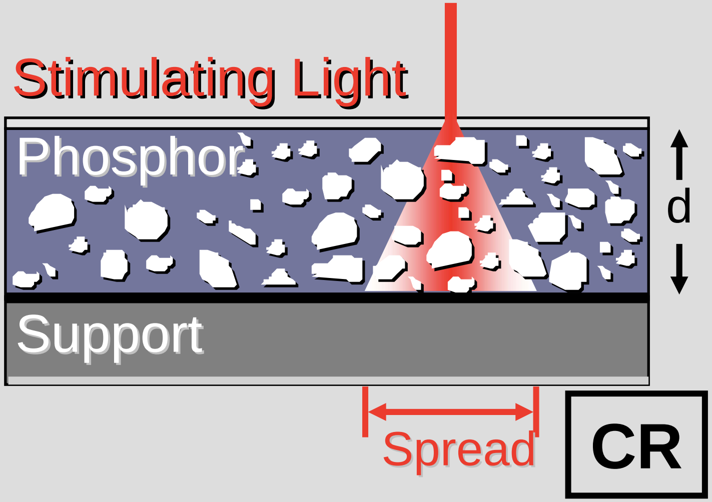
- CR screen is linear detector over >4 decades in exposure (CR scanner may lower this: flare, photodetector response)
- Latitude ≠ Dose Reduction
  - CR is NOT inherently lower dose than S/F: modern CR needs comparable dose to get same image quality
  - However, need many S/F systems to cover the same exposure range covered by one IP and one CR scanner



Imaging Performance: Spatial Resolution

- Spread/scatter of light within phosphor layer is the primary cause of unsharpness
  - S/F: emitted light spread
  - CR: stimulating light spread
- Amount depends largely on layer thickness, d: resolutions of S/F, CR are comparable
- Other factors: dyes, absorbing or reflecting backing, x-ray absorption depth, penetration depth (light), reflect./transm. readout geometry)

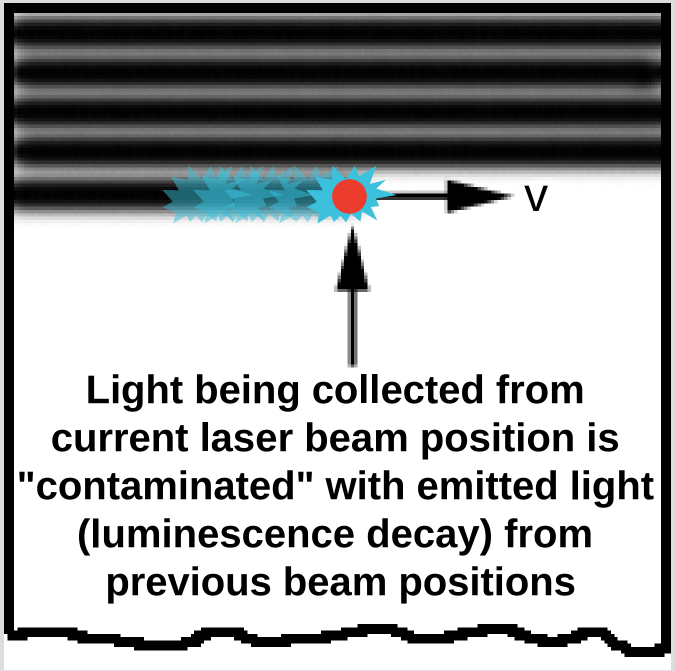




X-ray absorption and resolution are coupled

Imaging Performance: Spatial Resolution - Other Factors

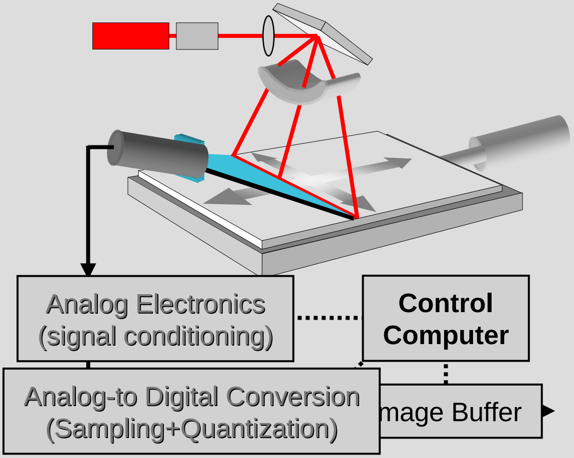
- Afterglow (flying-spot speed limit)
  - Luminescence decay time - screen continues to emit light after beam has passed (material-dependent)
  - If beam "dwell time" on each pixel too short, light from previous pixels collected with that of current pixel (1-dimensional smear/blur)
- Laser power
  - High power: +signal, -sharpness
  - Low power: +sharpness, -signal
- Analog electronics (filter effects)
- Destructive read-out physics (complex!)



Light being collected from current laser beam position is "contaminated" with emitted light (luminescence decay) from previous beam positions

Imaging Performance: Noise

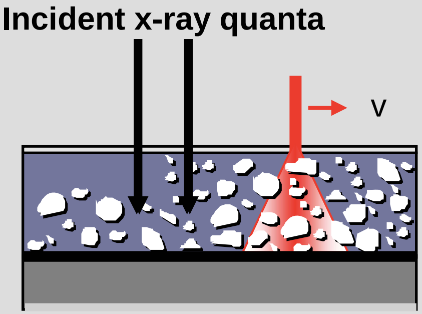
- Random variation of an output signal around the mean value predicted by its I/O Relationship



Exposure-related

Quantum noise

Equipment noise



Screen-related

X-ray quanta absorbed

X-ray quanta scattered

e^- per x-ray quantum

Latent image decay

Screen Structure Noise
- Phosphor layer structure
- Overcoat/backing layer structure
- Phosphor particle size distribution

Scanning-related

Deflector/transport velocity

Laser source/intensity control

Spread/scatter of stimulating beam

Light photons emitted in screen

Light photons escaping screen

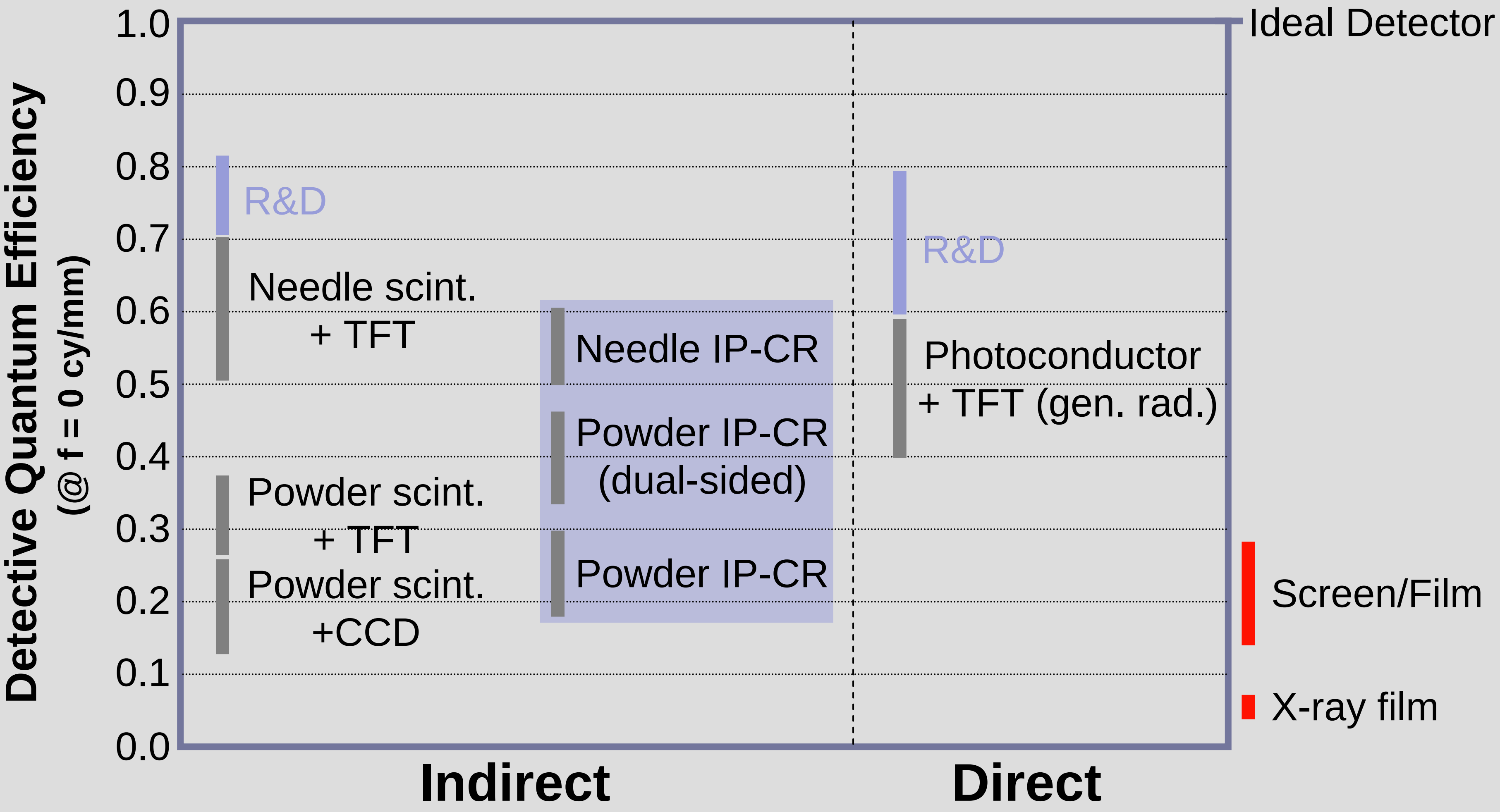
Light photons collected

e^- created in photodetector

Analog electronics

Sampling and quantization

Imaging Performance:
Detective Quantum Efficiency*



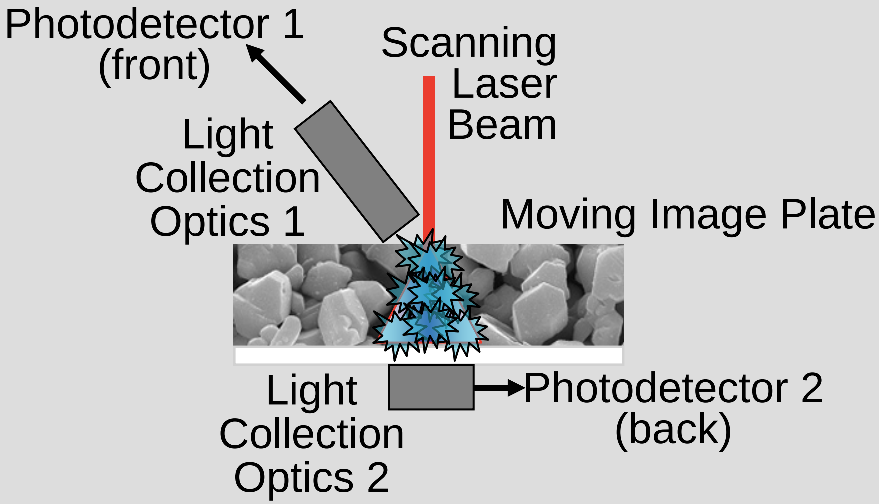
*Caution: mostly literature reports; not all measurements done according to IEC 62220-1

Computed Radiography Technologies

- Basics
- System Design
  - Screens
  - Scanners
- Imaging Performance
  - Input/Output Relationship
  - Spatial Resolution
  - Noise
- New CR Developments

New CR Developments: Dual-sided Read-out*

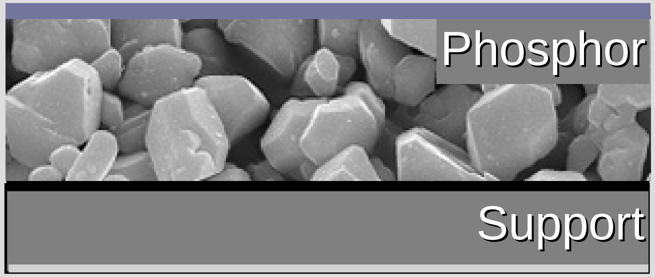
- Use transparent support
- Detect emitted light from both sides of screen
  - More signal in same time
  - Phosphor layer can be thicker (x-ray absorption ➚)
  - Reduce noise by combining front/back signals
  - Sharpness comes from front signal (relatively unchanged), so need frequency-weighted combination of front/back)
  - DQE improvement (at lower frequencies) relative to single-sided readout



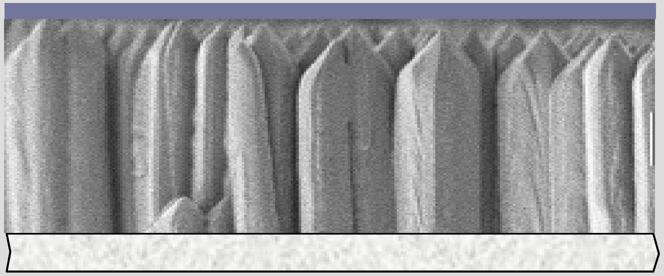
* S. Arakawa, W. Itoh, K. Kohda, T. Suzuki, Proc. SPIE **3659**, pp. 572-581, 1999

New CR Developments: Needle Detectors*

- Some SP materials (e.g., RbBr:Tl, CsBr:Eu^{2+}) grow in needles (like CsI in image intensifiers and indirect flat-panel DR)



Conv. Powder Image Plate



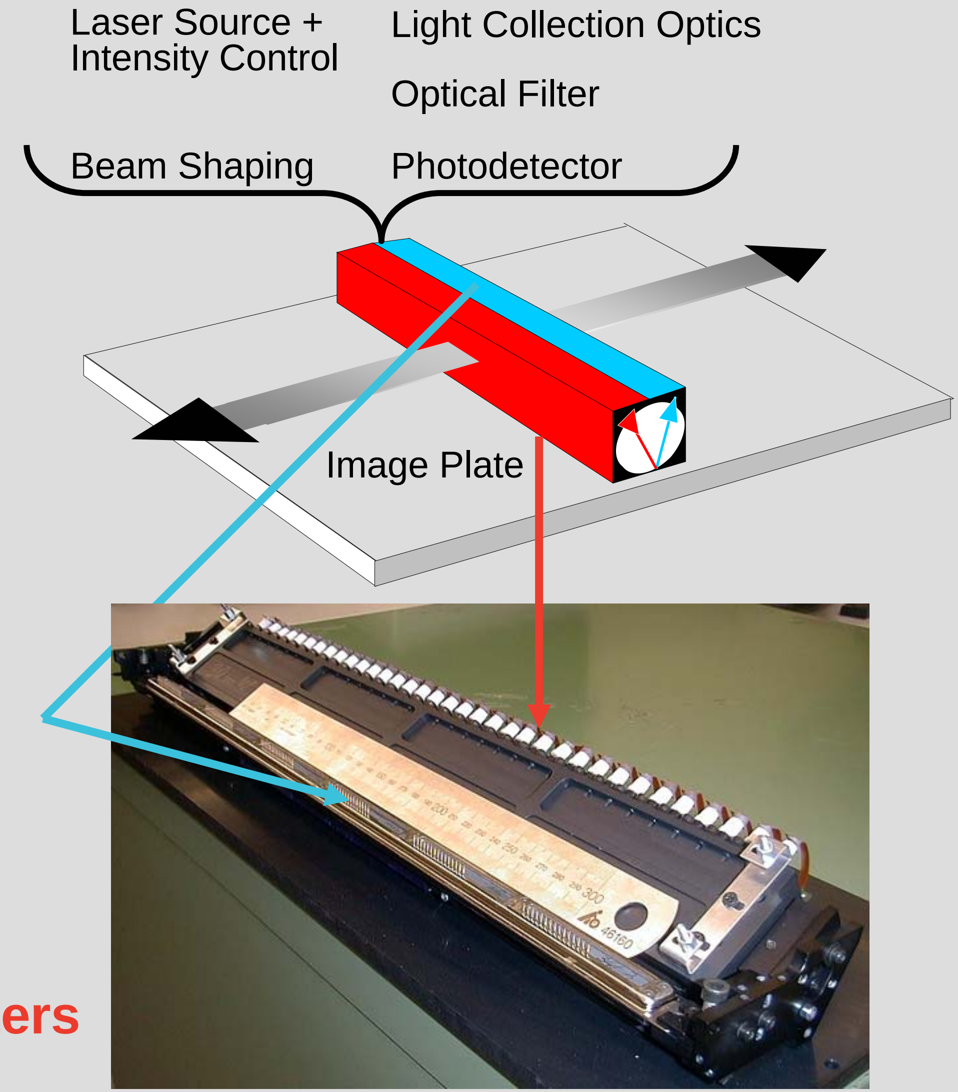
Needle Detector

- Image quality better than powder IP
  - I/O Relationship ↗
    - No binder: higher x-ray absorption
    - Increase layer thickness without degrading resolution (decouple sharpness and absorption)
    - Better conversion efficiency and read-out depth (CsBr)
  - Spatial Resolution ↗
    - Needles act as light pipes to reduce spread/scatter
  - Noise ↘
    - More uniform layer structure

*P. Leblans, L. Struye, Proc. SPIE **4320**, pp. 59-67, 2001

New CR Developments: Line Scanning*

- Discrete components of current, point-at-a-time CR scanners lead to
  - low packing density
  - limits to throughput
- New integrated, line-at-a-time scanners
  - reduce scanner size
  - increase system throughput



Line of laser sources/optics

+

Line of collection optics

+

Line of photodetectors/optical filters

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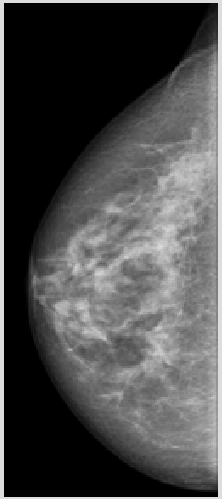
*R. Schaetzing, R. Fasbender, P. Kersten, Proc. SPIE **4682**, pp. 511-520, 2002

New CR Developments: Other

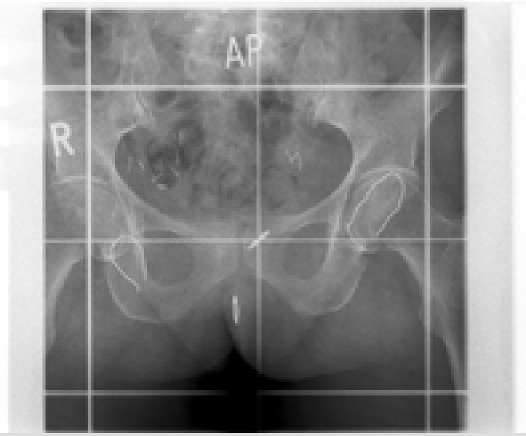
- Energy Subtraction
(multiple IPs in single cassette, x-ray filter)
  - More image processing than acquisition
  - Automated IP/filter handling, image registration
  - Qualitative (Diagnostic) and Quantitative (Bone Mineral Densitometry, Absorptiometry) Imaging

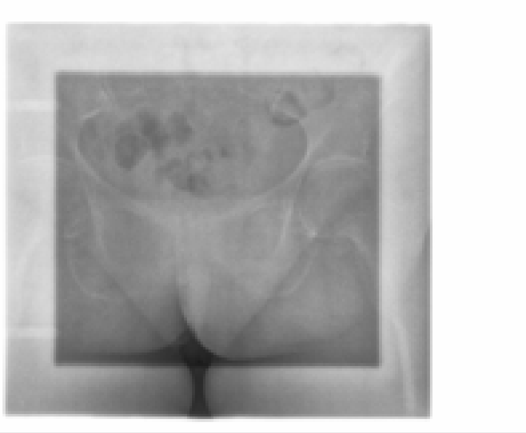
- CR for mammography
  - Special IPs, cassettes
  - High-resolution scanning modes
  - Custom image processing (incl. CAD)

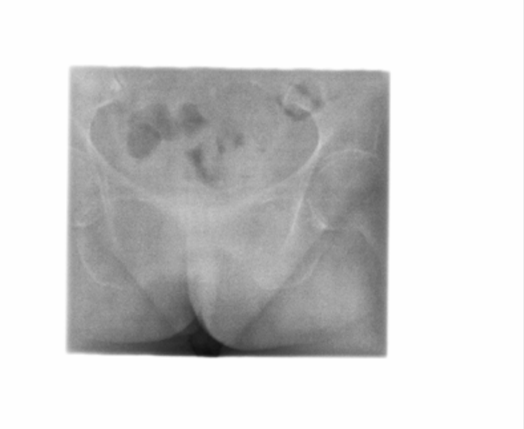


New CR Developments: Other

- "Flat-Panel CR"
  - fixed (needle) detector + movable line scanner in integrated package
- Radiation Therapy
  - Special screens and scanner protocols
  - Simulation, localization, verification
  - Dosimetry







Learning Objectives Revisited

- Describe the form and function of today’s computed radiography (CR) systems
- Identify the main factors that influence the image quality of CR systems
- Compare modern CR systems to other acquisition technologies
- Describe the latest and future developments in CR

CR Acquisition Technologies Summary

- CR technology is <u>mature</u> (but not outdated!):
  - 30+ years of intensive R&D
  - Multiple generations and manufacturers
  - <u>Diagnostically accepted</u> and <u>still expanding</u> (hundreds of man-years of diagnostic experience)
- Performance/image quality now exceeds that of S/F with greater placement flexibility (distributed/centralized)
- New CR developments have
  - Raised image quality and system throughput
  - Decreased size
  - Lowered cost

CR will remain a valuable DR technology in the future

Thank You for Your Attention!

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