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Practical Radiography

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Los Alamos National Laboratory

NEN-2: Advanced Nuclear Technology

12 – 14 February 2018

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Agenda/Outline

- History of X-ray Radiography
- X-Ray Physics
- Scaling Laws & Fundamentals
- X-Ray Production & Source Types
- Image Formation
- Image Resolution
- Detector Types
- Imaging Performance Measures
- Scatter
- Static vs. Dynamic Radiography
- Blast Protection
- Alignment
- Image Analysis & Synthesis
- Design Considerations
- Practical Examples JTOT & Hydrotesting
- Radiography Questions

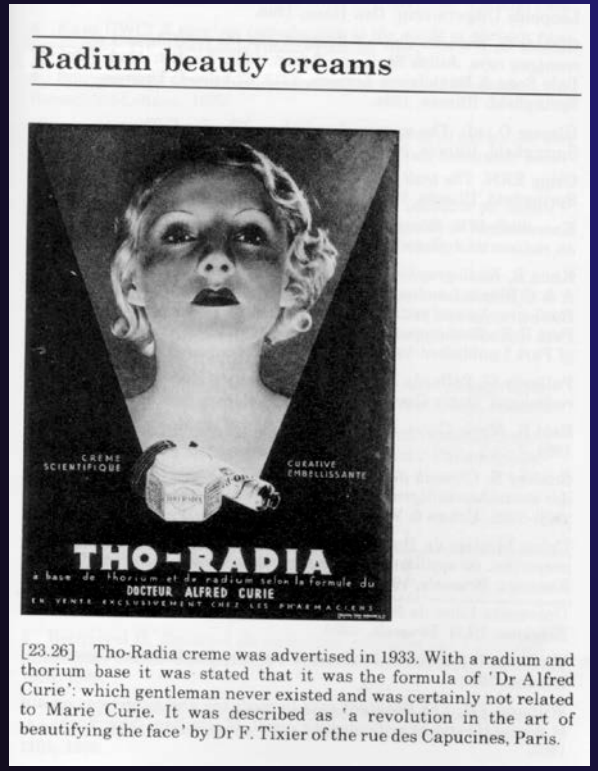
History of X-Ray Radiography

History of X-ray Radiography

- 1895 Roentgen accidentally “discovers” X-rays.
- 1896 Radiographs widely published.
- 1896 Radioactivity discovered by Becquerel.
- 1897 Fluorescence discovered by Poincare.
- 1897 Electron discovered by Thompson.
- 1898 Radium discovered by Curies.
- 1901 Roentgen Nobel Prize.
- 1902 Richardson discovers thermionic emission.
- 1904 Radiation burns attributed to X-rays.
- 1915 Bragg Nobel Prize for X-ray diffraction.
- 1920 Potter-Bucky grid invented.
- 1922 Radiation protection widely adopted.
- 1927 Compton Nobel Prize for scattering.
- 1928 First working LINAC. Wideroe.
- 1930 X-Ray Cineradiography J. S. Watson.

Radiographic Blunders & Frauds

- 1904 “N” rays. “Superior” to x-rays.
- 1933 Radium beauty cream (yikes!).
- 1934 Marie Curie dies from radium exposure.
- 1950 X-Ray vision glasses.
- 1998 Proton radiography. “Superior” to x-rays.



Radium beauty creams

[23.26] Tho-Radia creme was advertised in 1933. With a radium and thorium base it was stated that it was the formula of ‘Dr Alfred Curie’: which gentleman never existed and was certainly not related to Marie Curie. It was described as ‘a revolution in the art of beautifying the face’ by Dr F. Tixier of the rue des Capucines, Paris.

“See” the wondrous X-Ray

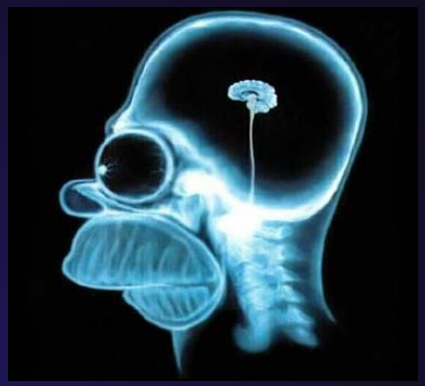
The greatest Scientific Discovery of the Age.

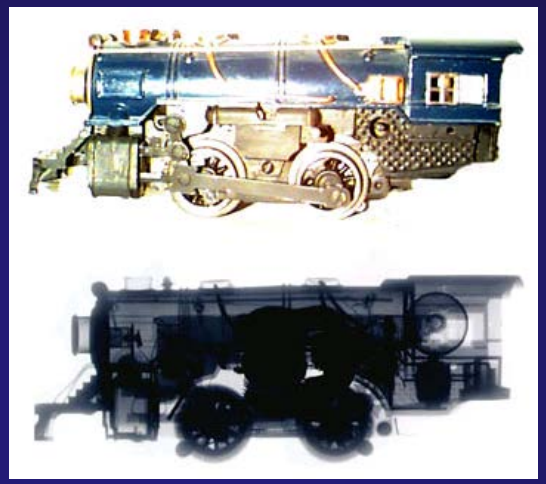
Through a sheet of metal
Count the Coins in Your Purse

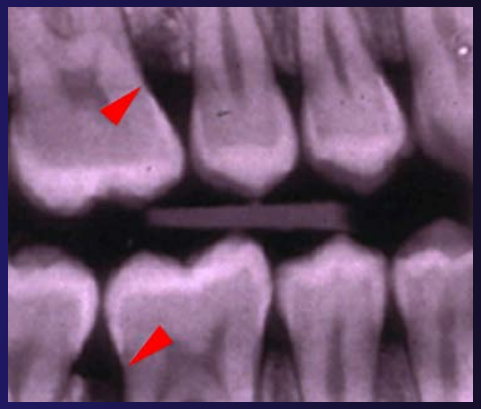
X-Ray Photographs Taken!
Admission - $3

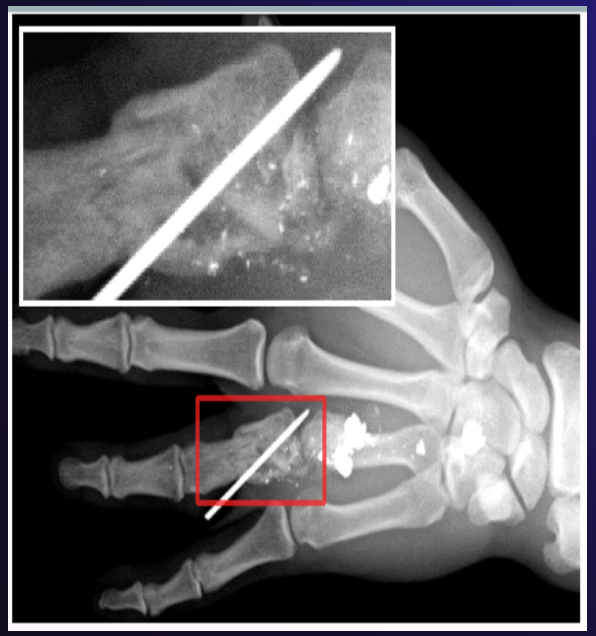
Variety of X-Ray Imaging

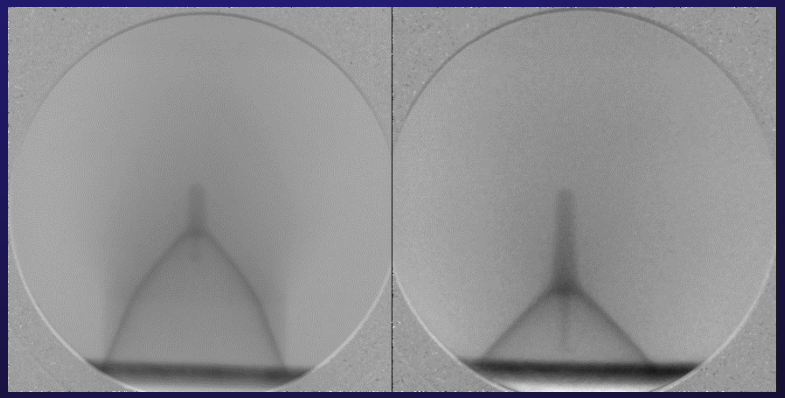
- Explosive testing.
- Medical diagnostics.
- Portal Scanners.
- Weld inspection.
- Airport Scanners.
- Non Destructive Testing.
- Multi-Billion $ annually.





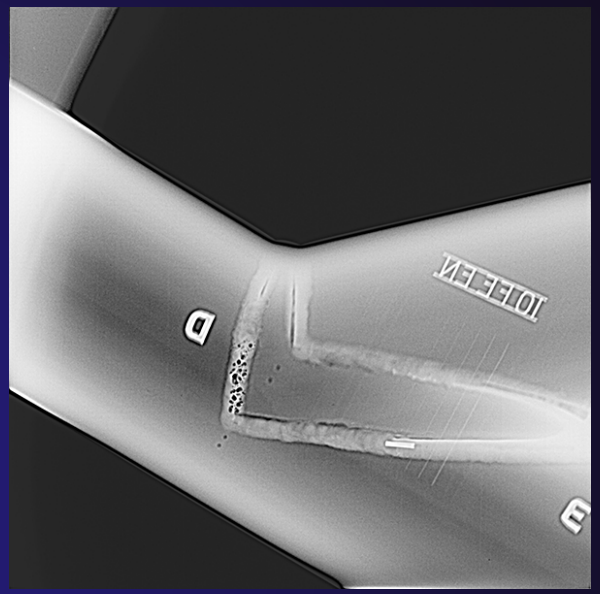






What are radiographs used for?

- Measure size (e.g. castings).
- Measure position (e.g. computed tomography).
- Measure defects (e.g. weld inspection, medicine).
- Measure contraband (e.g. airport scanners).
- Measure density (e.g. hydrotesting).
- Measure existence (e.g. archaeology).
- Measure thickness (e.g. gauging).



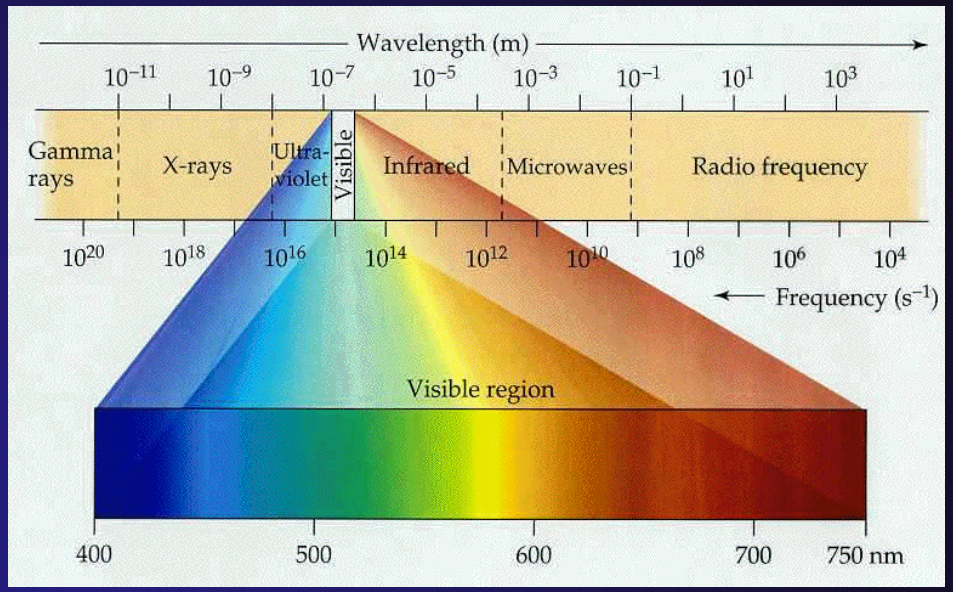
X-ray Physics

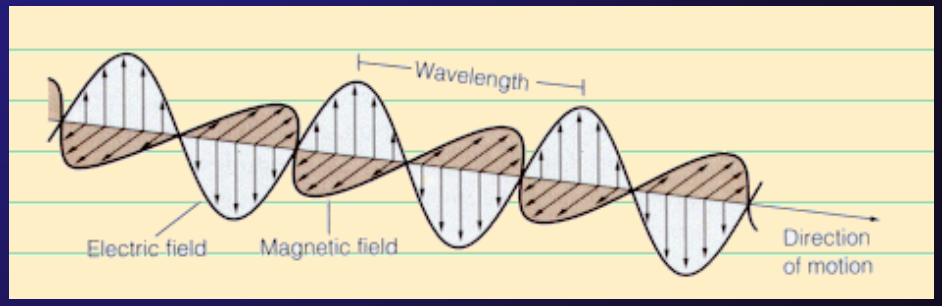
The Nature of Light

- Light is a particle and an EM wave.
- Light comes in discrete packets called photons that are emitted when electrons change their direction of motion.
- Photons have a wavelength, λ, an energy, E, and a frequency, v. They travel at the speed of light, c.
- Useful relations:

$$E = \frac{hc}{\lambda} \qquad c = \lambda v$$

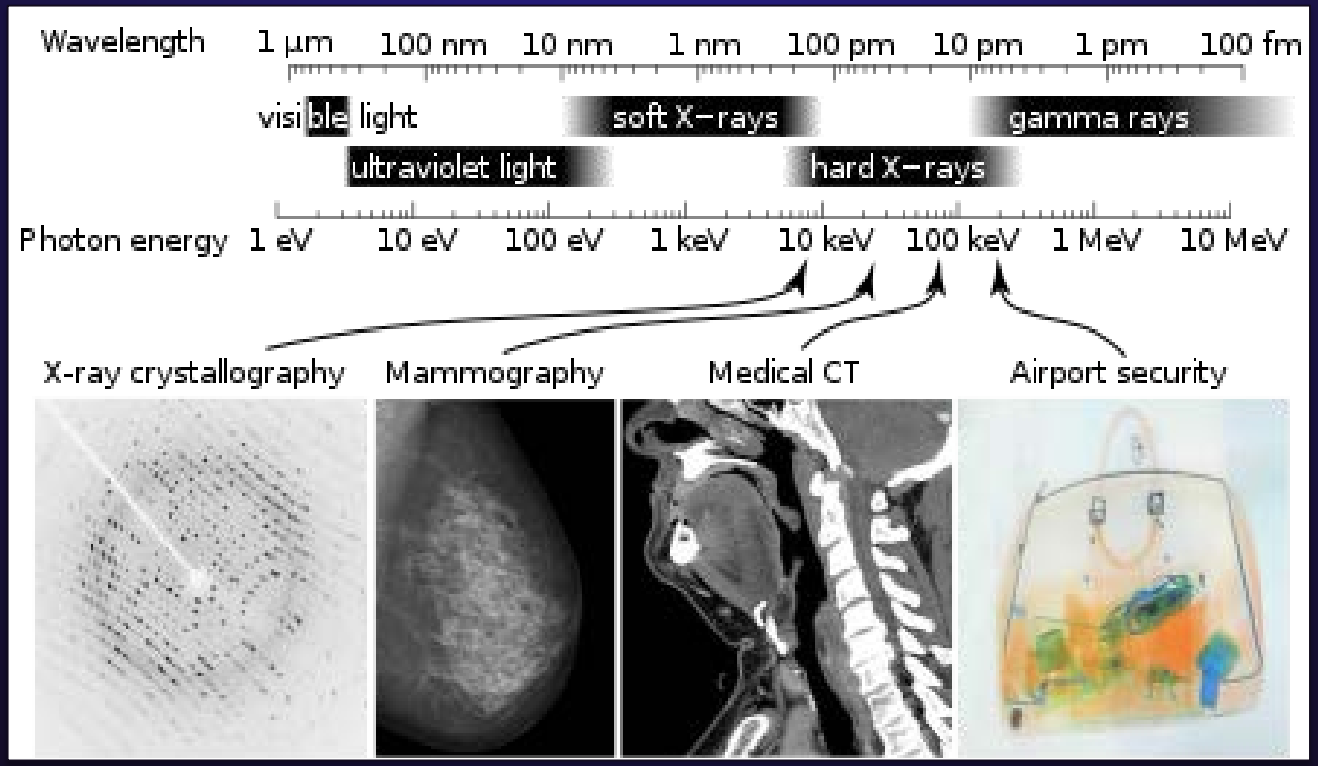
where h is Plank's constant.



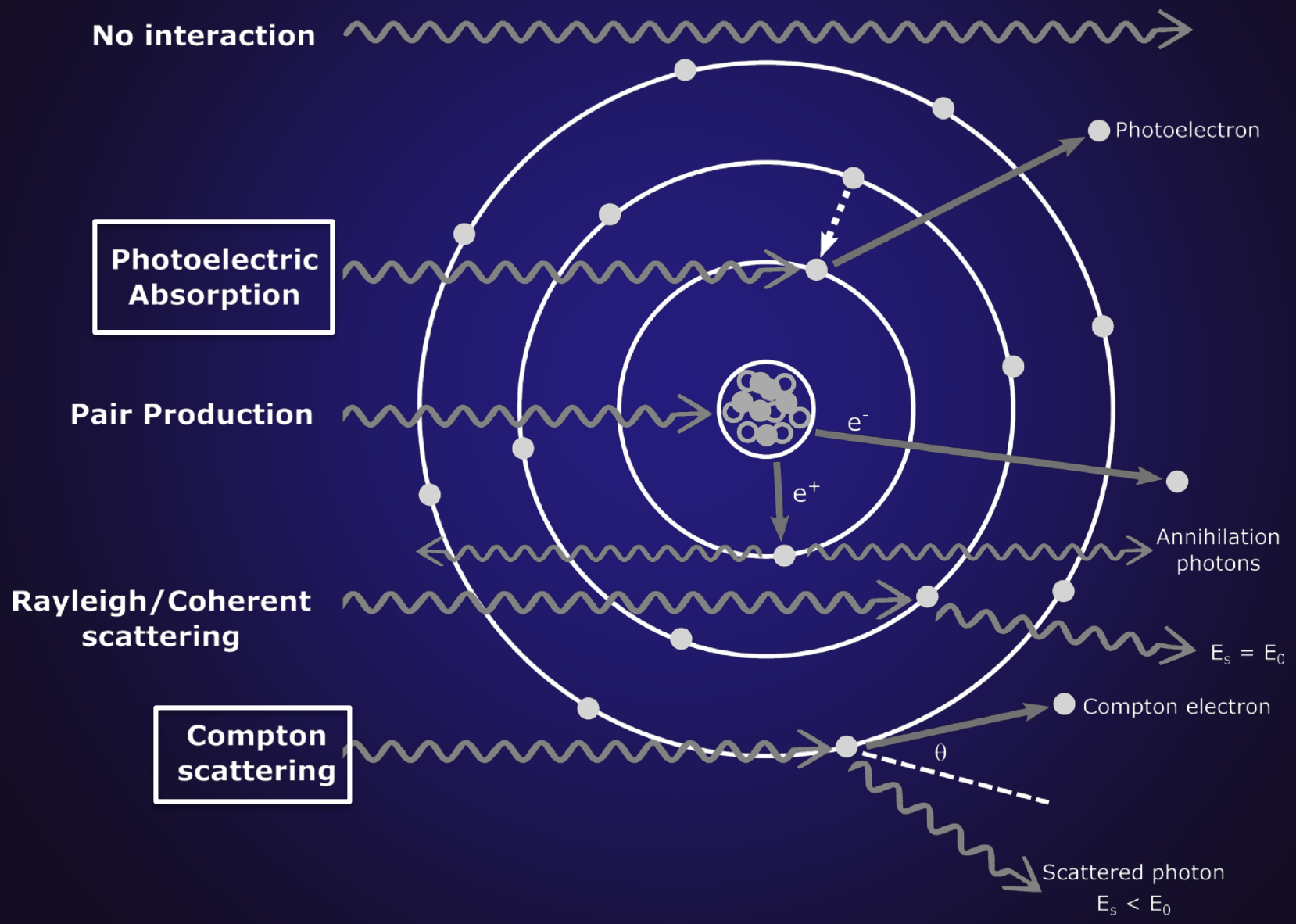


X-rays vs. Gamma Rays

- X-rays are high-energy, short-wavelength, high-frequency photons. Usually from bremsstrahlung or characteristic radiation.
- Gamma-rays are also high(er) energy, short-wavelength, high-frequency photons most often associated with nuclear decay.

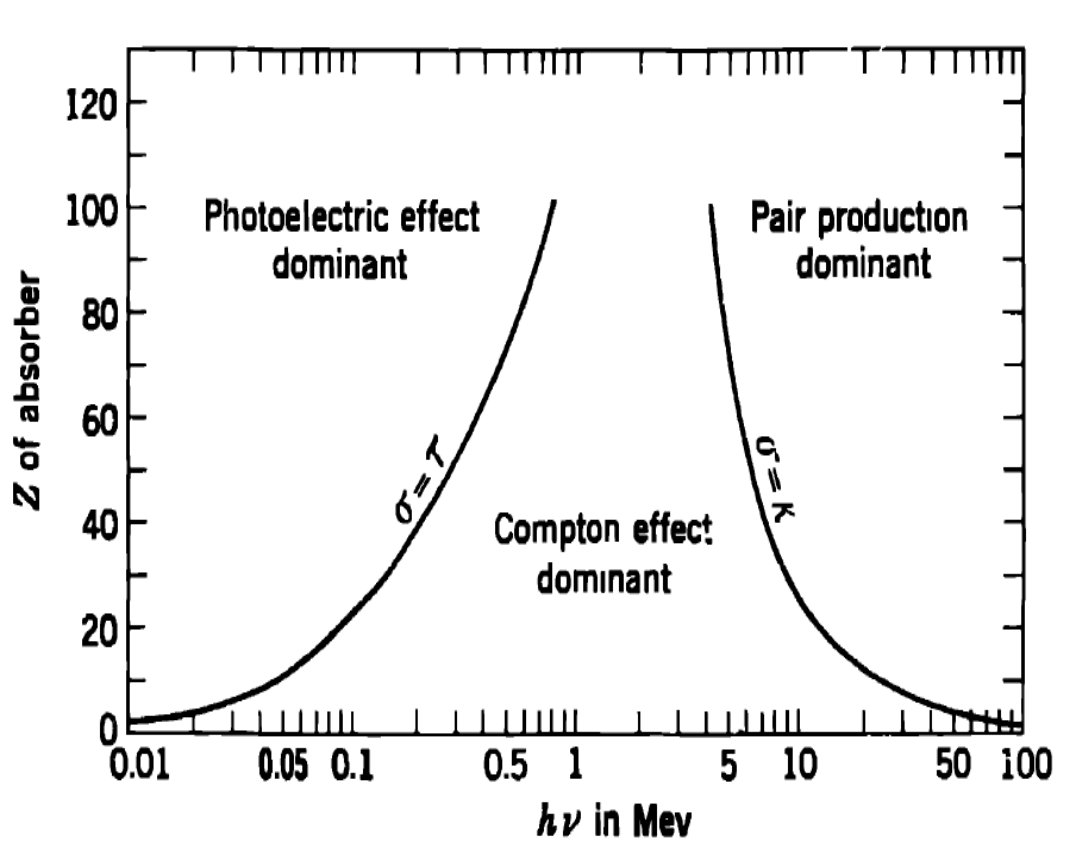


Interaction with Matter



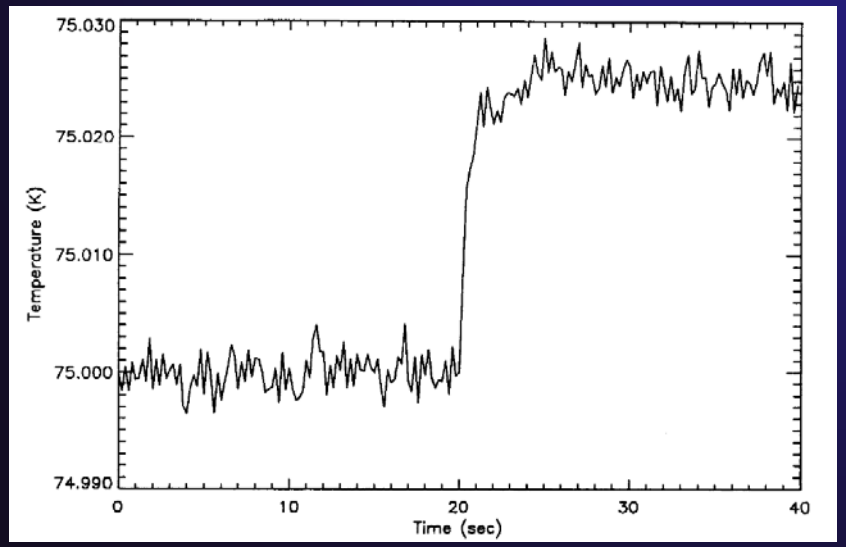
Interactions with matter

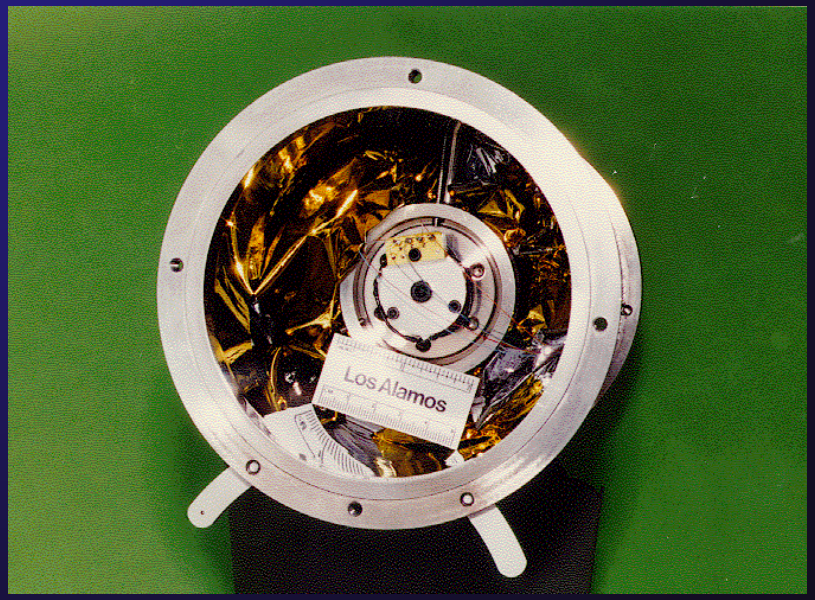
- Photoelectric absorption and Compton scatter are dominant effects for radiography.
- Which interaction dominates depends on energy of photon and Z of material.



Dose - Definition & Measurement

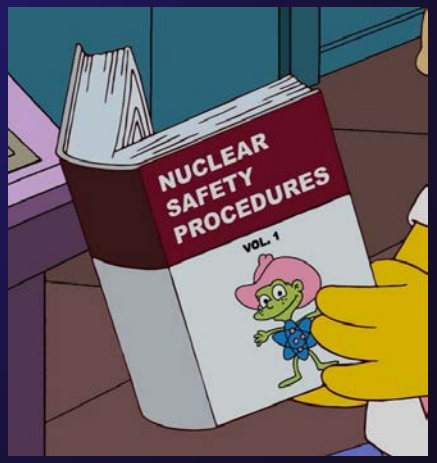
- Absorbed dose is a measure of energy deposited. 1 rad = 100 ergs/g.
- Exposure dose is measured in Roentgens (R) which measures air ionization.
- We measure absorbed dose (rads) by measuring the temperature change.
- 1 Roentgen (R) = 0.877 rad (in air). Consequently, people often mistakenly interchange these two units.
- A REM is a Roentgen Equivalent Man, and measures biological damage.





Radiation Safety

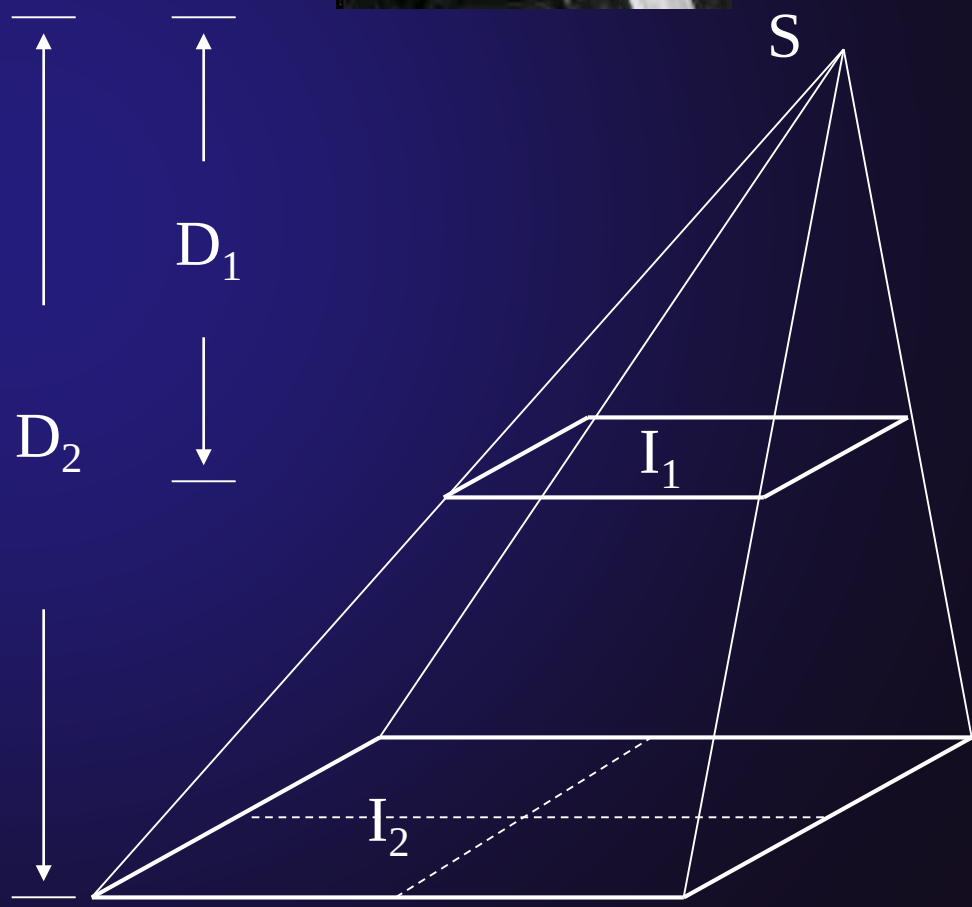
- Any exposure to gamma rays ionizes tissue molecules. Ionizing radiation is known to cause cancer.
- 50 R changes your white blood count.
- 150 R can be lethal.
- 500 R, whole-body, acute, gamma exposure has a ~50% mortality.
- At megavolt energies, an inch of lead offers only a factor of ~3 reduction in dose.
- Radiation exposure has few immediate indicators. e.g. Curies et. al.
- ICRP allows 5 R per year or ~50x background for radiation workers.
- Hand dose limit is 50 R per year or ~500x background for radiation workers.



Scaling Laws & Fundamentals

Inverse Square Law (Newton)

- The light intensity or irradiance (I) is the photon power per unit area (Watts/cm^2). The inverse square law tells us that if we double the distance of a plane to a point source, the intensity goes down by a factor of 4.
- We can use the point source approximation whenever the distance from the source (D) is much greater than the source size (S).



$$\frac{I_2}{I_1} = \left(\frac{D_1}{D_2}\right)^2$$

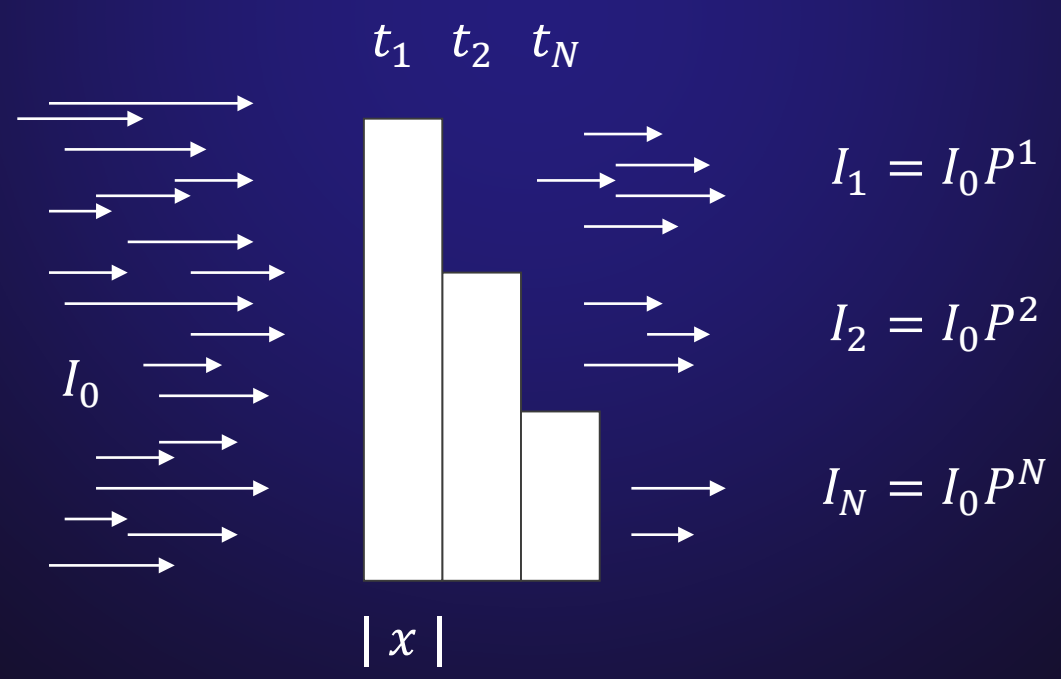
Exponential Attenuation, Beer's Law

- Assume any photon from a radiation field, I_0, has probability, P, of going through a slab of material with thickness, x.
- Further assume that the thickness, t, can be modeled with

$$t_1 = x, t_2 = 2x, \ldots, t_N = Nx.$$

- Then the transmitted intensity through N layers, I_N, is given by

$$I_N = I_0 P^N.$$



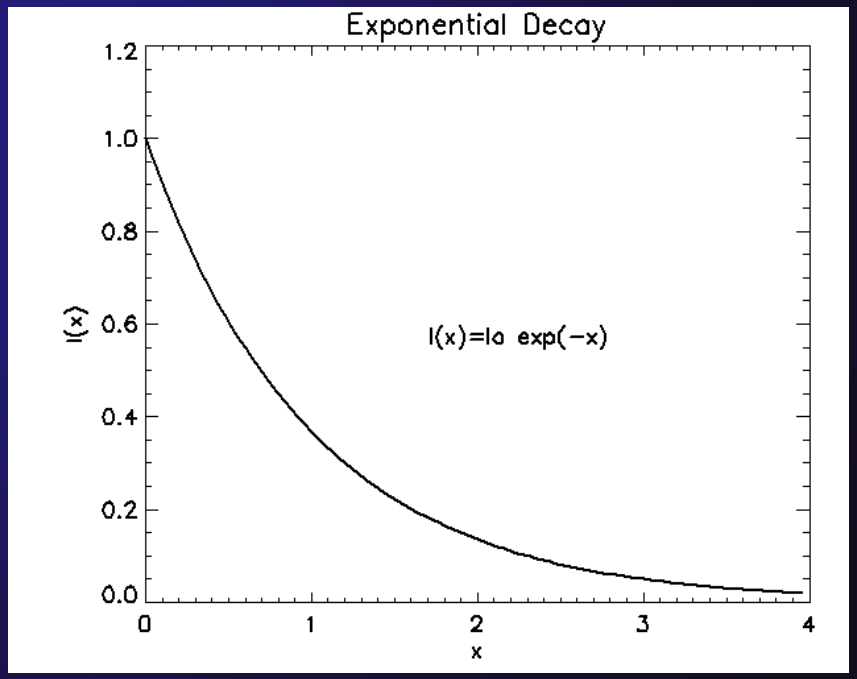
Exponential Attenuation

- If we rewrite P^N as $(\mathrm{e}^{-\mu})^N$. Then, we can rewrite $I_N = I_0 P^N$ as $I^N = I_0 \mathrm{e}^{-\mu N}$. This is the usual form for Beer's Law.
- "μ" is called the linear attenuation coefficient.
- A special thickness where $N = \frac{1}{\mu}$ is called the mean free path. A mean free path of material allows 37% of the x-rays to be transmitted.

- If we have a material of density, ρ, another useful form is:

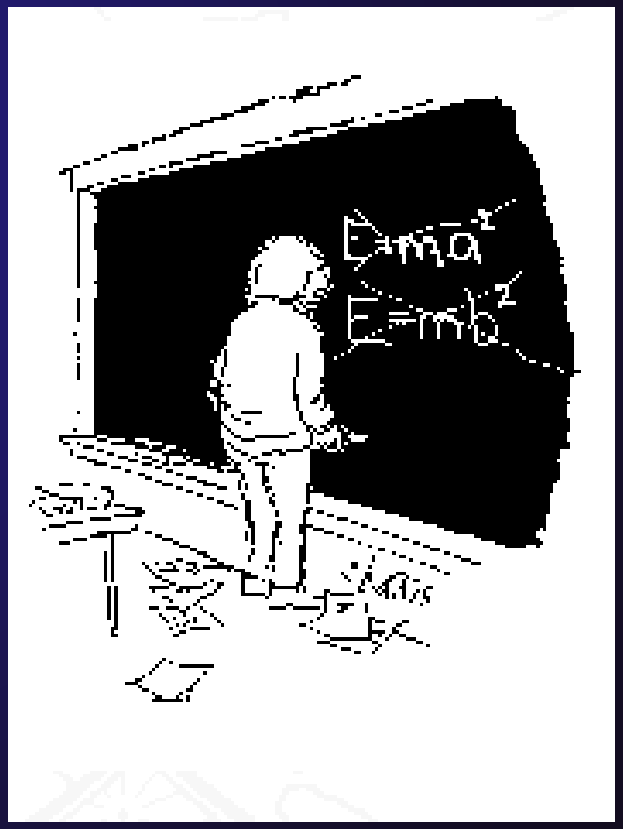
$$I_x = I_0 \mathrm{e}^{-\left(\frac{\mu}{\rho}\right)\rho x}$$

where $\frac{\mu}{\rho}$ is called the total-mass-attenuation-coefficient which is tabulated for all materials and energies.



Computing exposure

- Where $D_{Detector}$ is the dose at the detector (R).
- D_{Source} is the dose of the source (R @ 1 m).
- μ is the linear attenuation coefficient.
- ρ is the density of the material under study (g/cm^3).
- x is the thickness of the material under study (cm).
- r is the distance from the source (m).

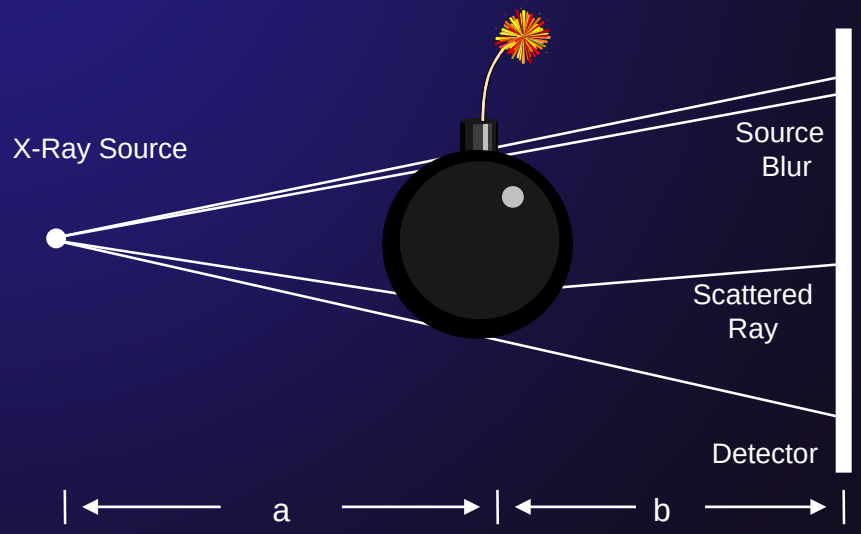


$$D_{\text{Detector}} \approx \frac{D_{\text{Source}} e^{-\mu x}}{r^2}$$

Radiographic Magnification

- Small magnification reduces source blur.
- Large magnification reduces scatter and detector blur.
- A small 1st conjugate increases flux through the test object at the expense of cone beam effects.
- Appropriate conjugates strike a balance between many competing effects.
- It is ALL similar triangles.

$$m = \frac{b}{a} + 1$$



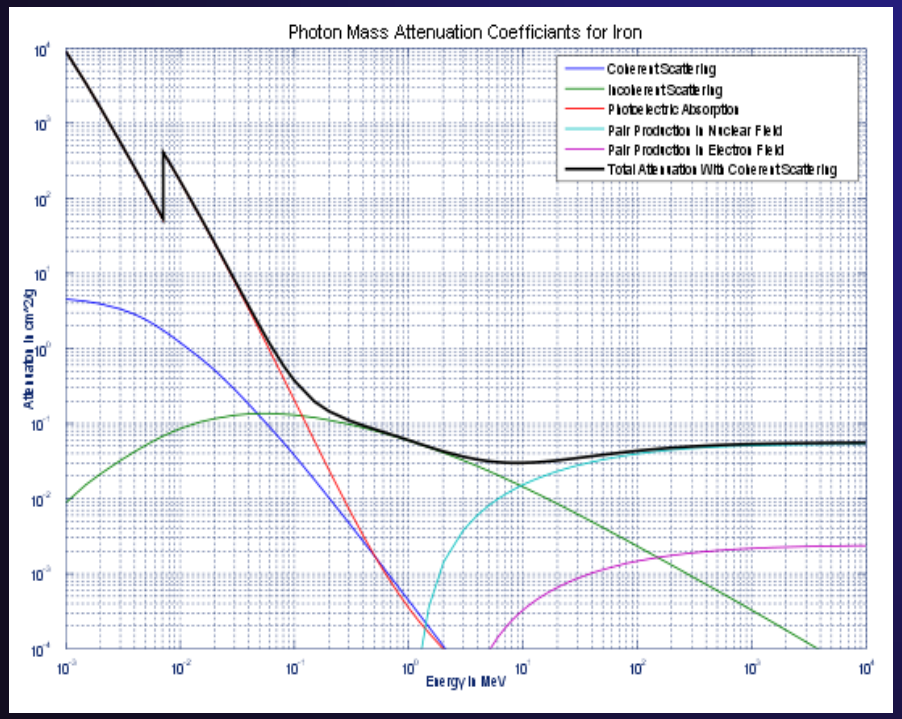
Energy Effects

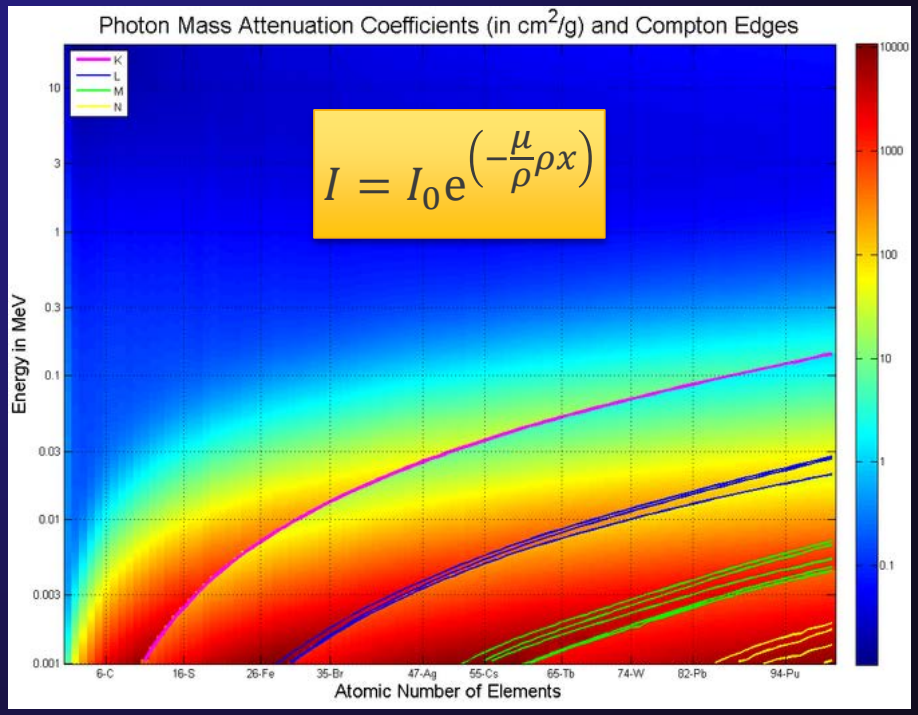
Low Energy

- Not useful for thick objects (<1” steel maximum).
- Increases detector DQE.
- Compact.
- Requires modest shielding (<1/4” lead).
- Increases contrast between high-Z and low-Z materials.

High Energy

- Increases object transmission especially for high-Z (>10” steel).
- Decreases detector DQE.
- Increases detector blur.
- Increases source size and weight.
- Increases shielding thickness (>1” lead).
- Decreases object contrast.





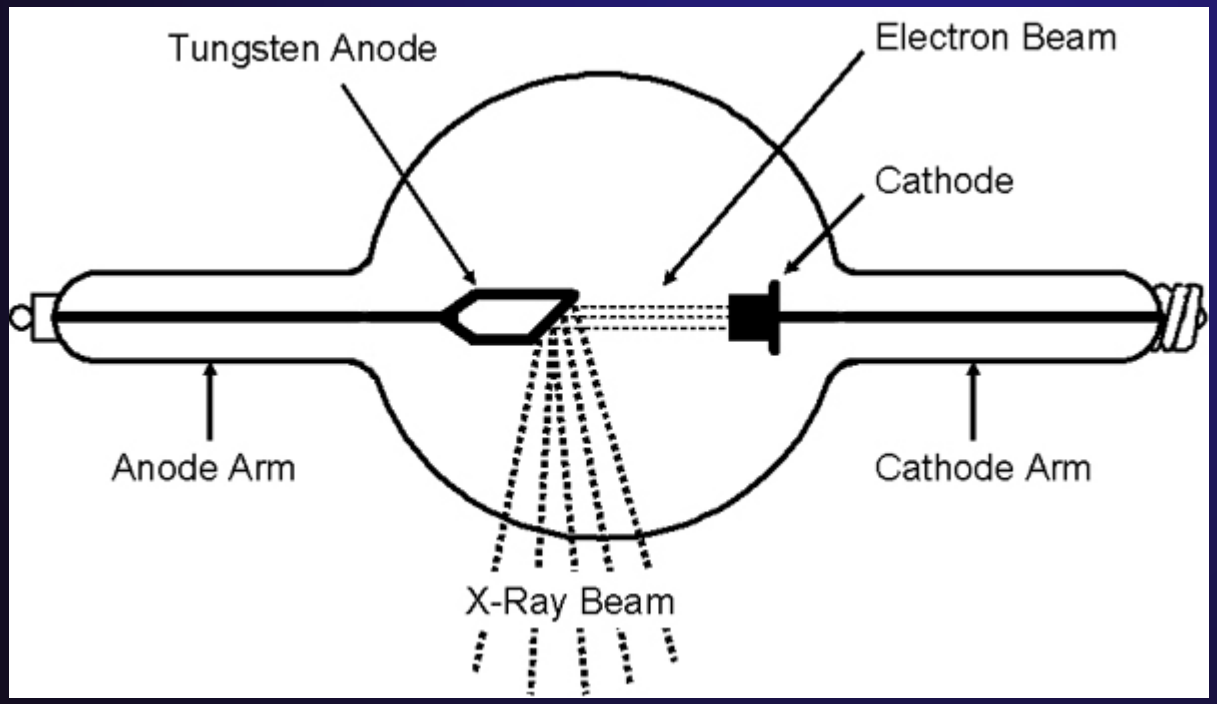
Break

Break

X-ray Production & Source Types

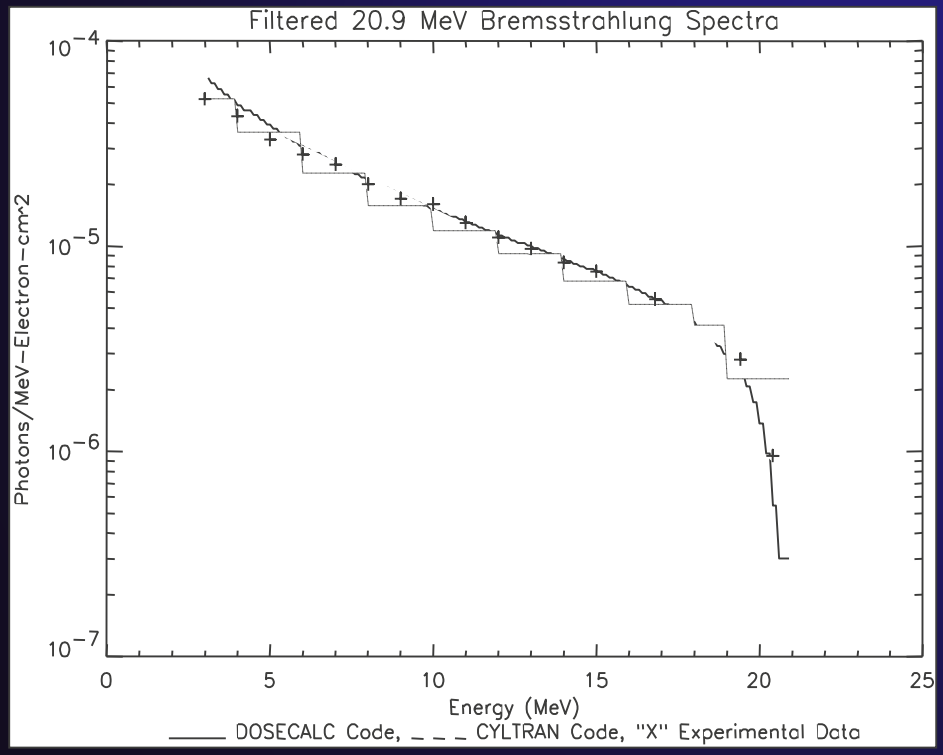
X-ray production by electrons

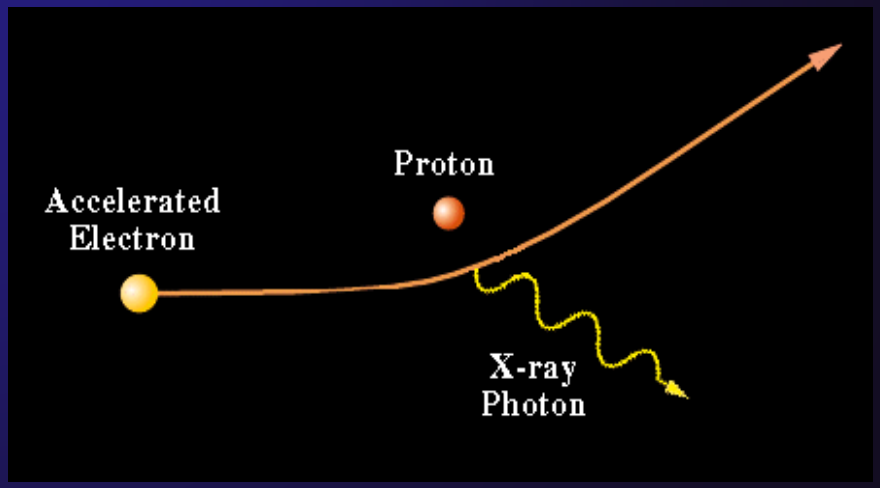
- Free electrons are usually produced with a hot cathode.
- These electrons are accelerated in a vacuum towards a high-Z, anode target (e.g. tungsten, tantalum, lead etc.).
- X-rays are produced when high energy electrons hit the metal target producing bremsstrahlung radiation.



Bremsstrahlung radiation

- Bremsstrahlung is German for “braking radiation” and occurs when energetic electrons interact with the positive nucleus of an atom.
- By nature, bremsstrahlung has a broad spectrum with photon energies up to the peak energy of the incident electrons.



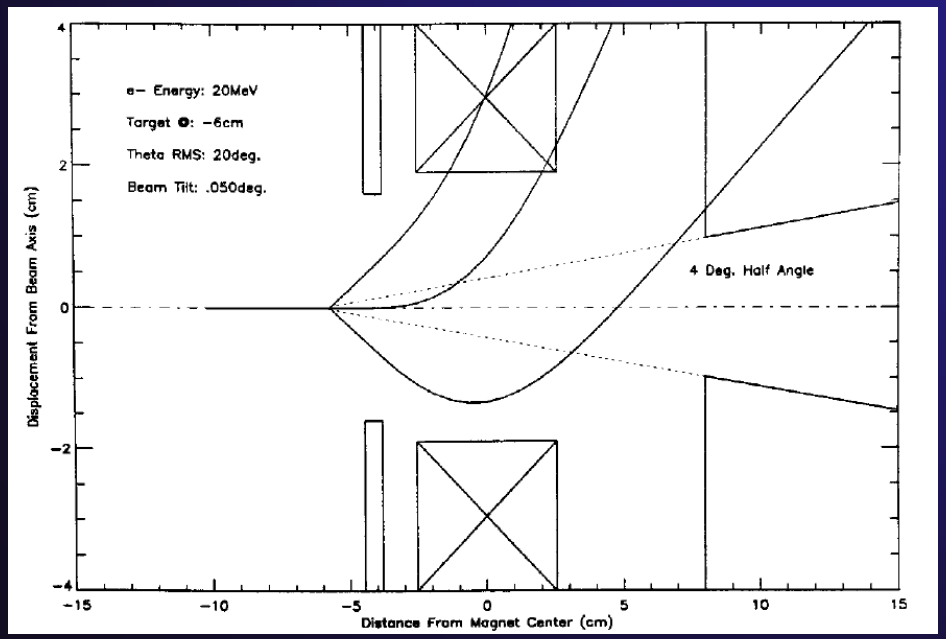


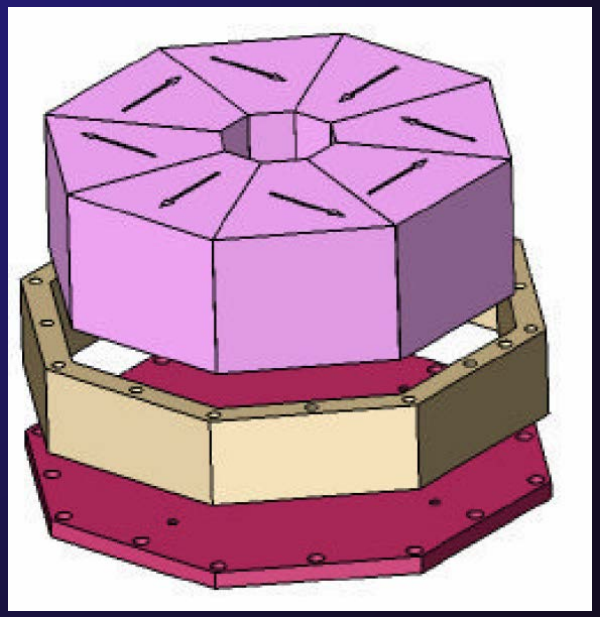
The production of electrons

- Electrons are accelerated in vacuum tubes, sometimes called diodes, linear accelerators, and circular accelerators (e.g. Betatrons).
- Examples include: DARHT, an induction accelerator; PHERMEX, an RF accelerator; CYGNUS a diode machine; and the XRS-3, 300kV heads which are vacuum tube diodes.

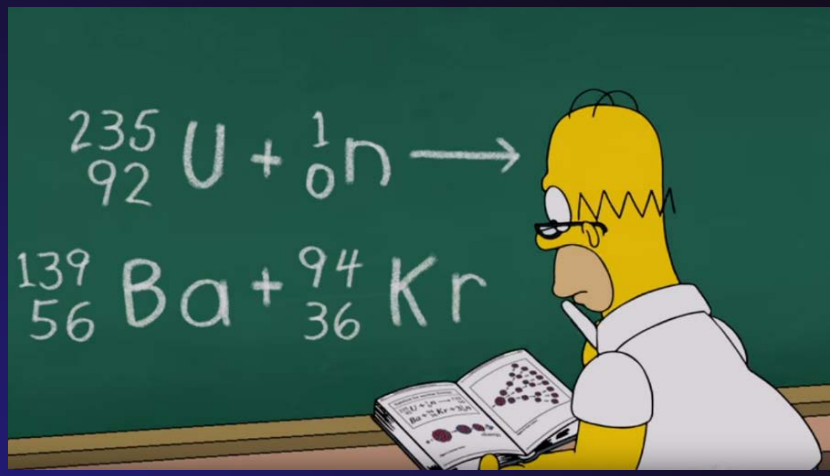
Stopping electrons

- The range of MeV electrons is almost independent of Z and E and is approximately 10 g/cm^2
- Most targets are NOT range thick => high energy electrons pass through the target.
- DARHT utilizes a permanent, “sweep magnet” to eliminate these electrons.
- Sweep magnets can be made from Halbach arrays with peak dipole fields of 1 Tesla.

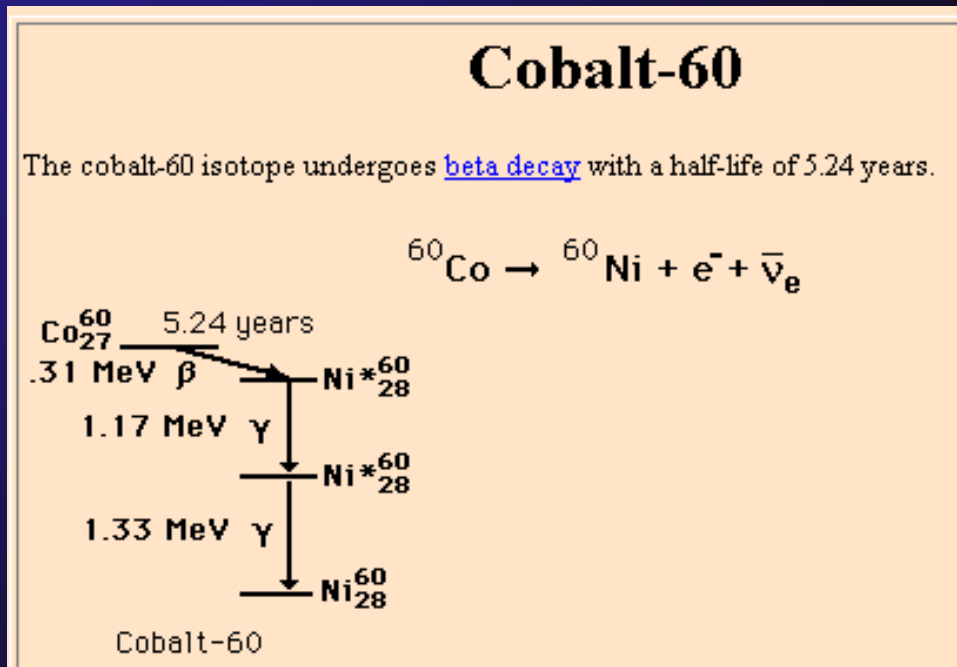




Radio-isotope sources



- Give off radiation due to unstable nuclear decay (e.g. beta decay of Cobalt-60).
- Have low intensity compared to x-ray machines.
- Require no power and can be very compact.
- Have decay “lines” with known gamma-ray energies (e.g. Cobalt-60 @1.17 & 1.33 MeV, Cesium-137 @ 662 keV, Technetium-99 @ 141 keV).
- Have widely varying half-lives.

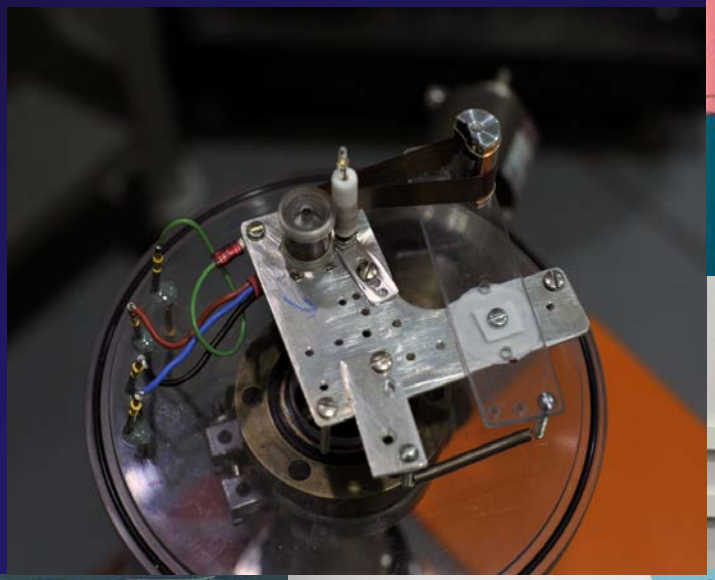


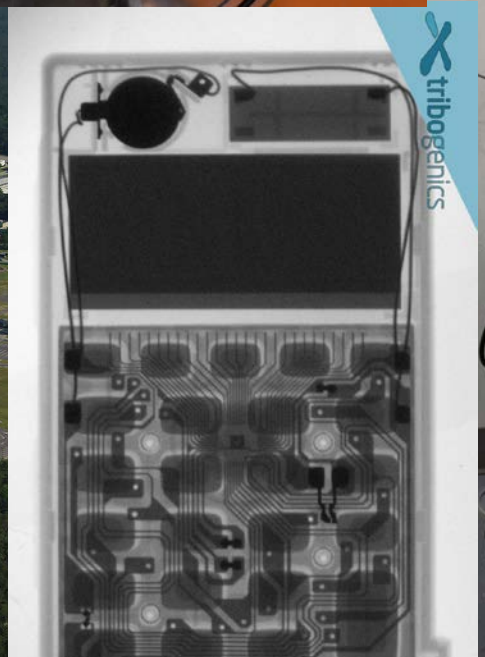
Radio-isotope sources used by JTOT

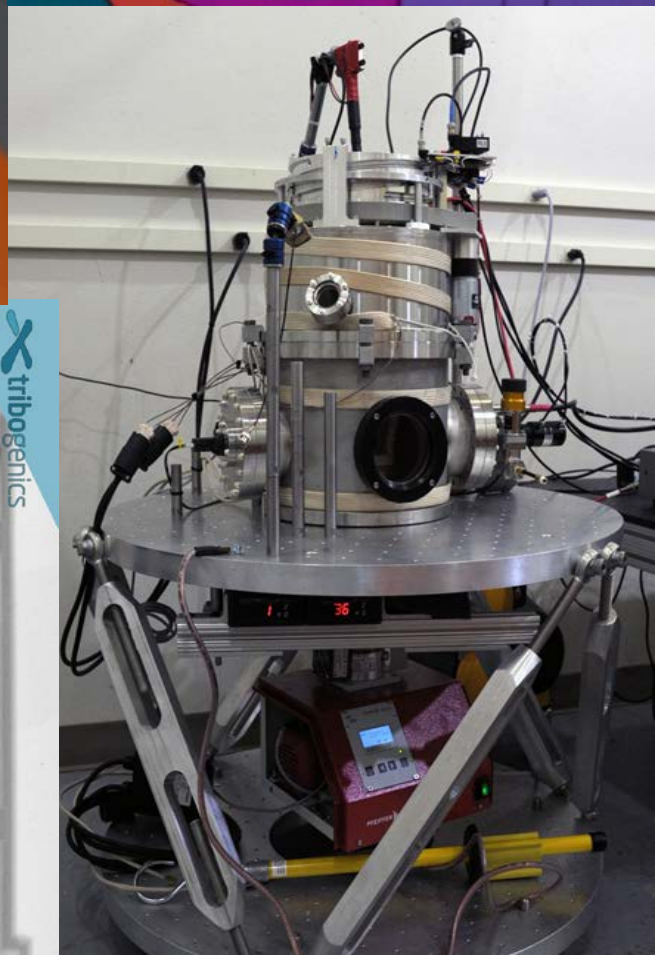
- 5 Ci Cobalt-60 source.
- Americium-242 (thermal) neutron source.
- Lightweight, Cobalt-57 source (122 keV).

Unique sources

- Synchrotron.
- Triboelectric.
- MEXRAY.

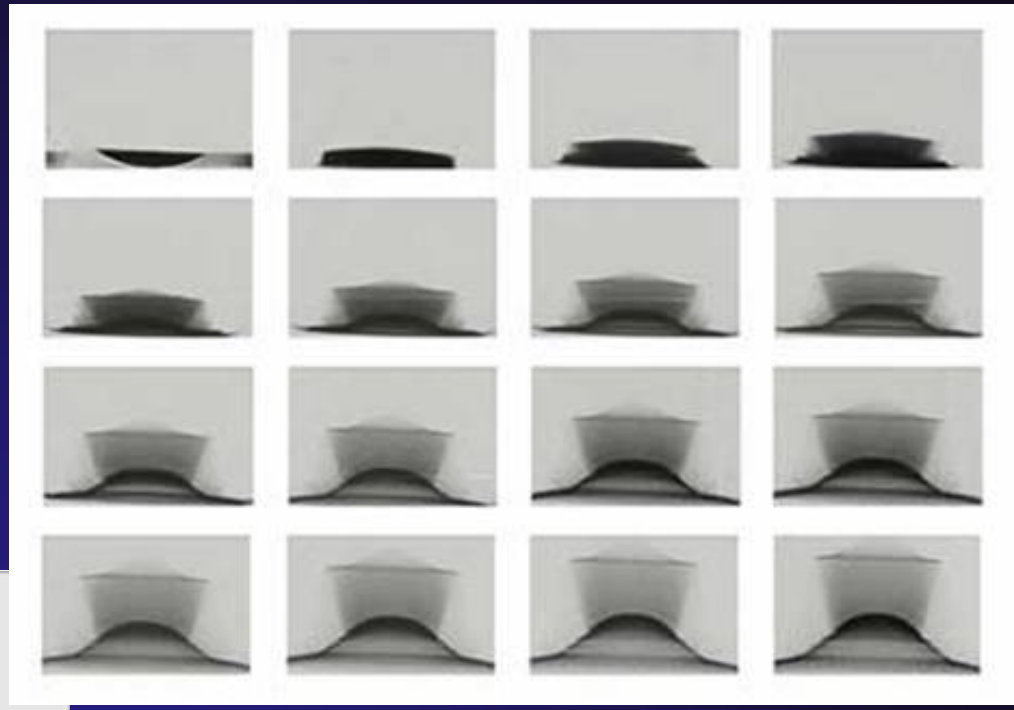


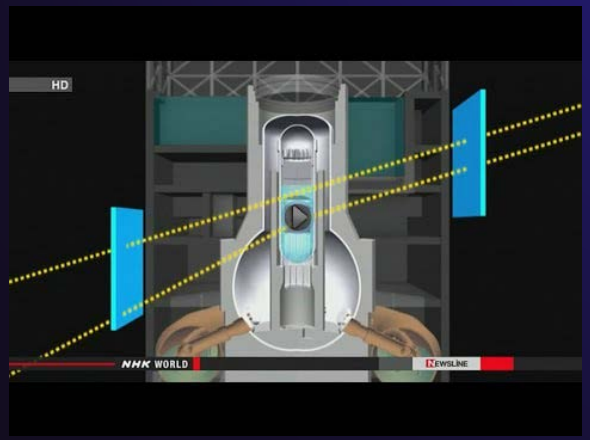


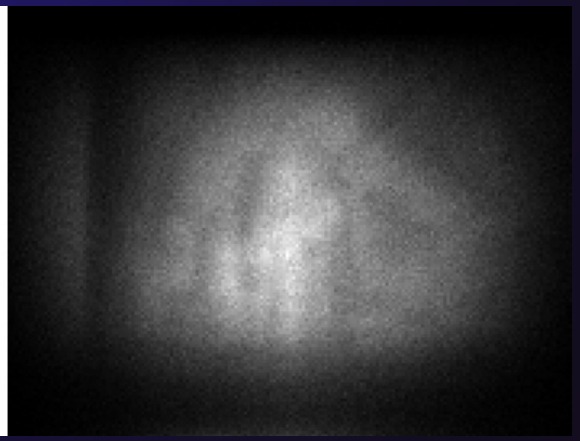


Other particle types

- Thermal neutrons.
- Fast neutrons.
- Proton radiography (aka Prad)
- Muon tomography.







Compact Flash Heads

- Typically provide < 1R @ 1m per flash.
- Available in 2.3 MeV, 1.2 MeV, 1 MeV, 450 keV, 300 keV energies.
- Suitable for shadow radiography, and small scale detonics work including EOS.
- Most are based on 30-year-old Hewlett Packard or Scandiflash systems.

L3 Flash X-Ray System

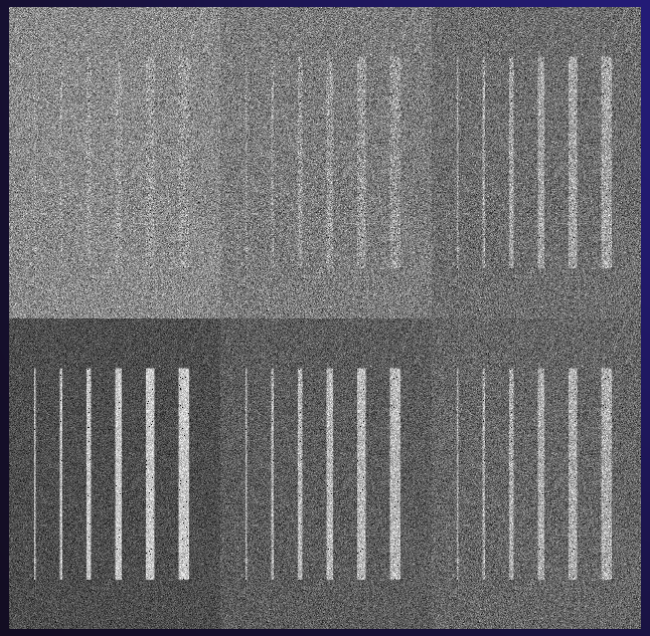
Flash x-ray experiment at “Eenie” (Los Alamos)

Image Formation

Shot (Photon) Noise

- Photons “carry” information. Each detected photon can be thought of as an independent measurement.
- The number of photons detected is proportional to the product of dose and detector efficiency.
- The important parameters are the flux at the object, and the quantum efficiency of the detector.
- Image quality improves slowly with increased dose.

SNR=1 SNR=1.5 SNR=2.5

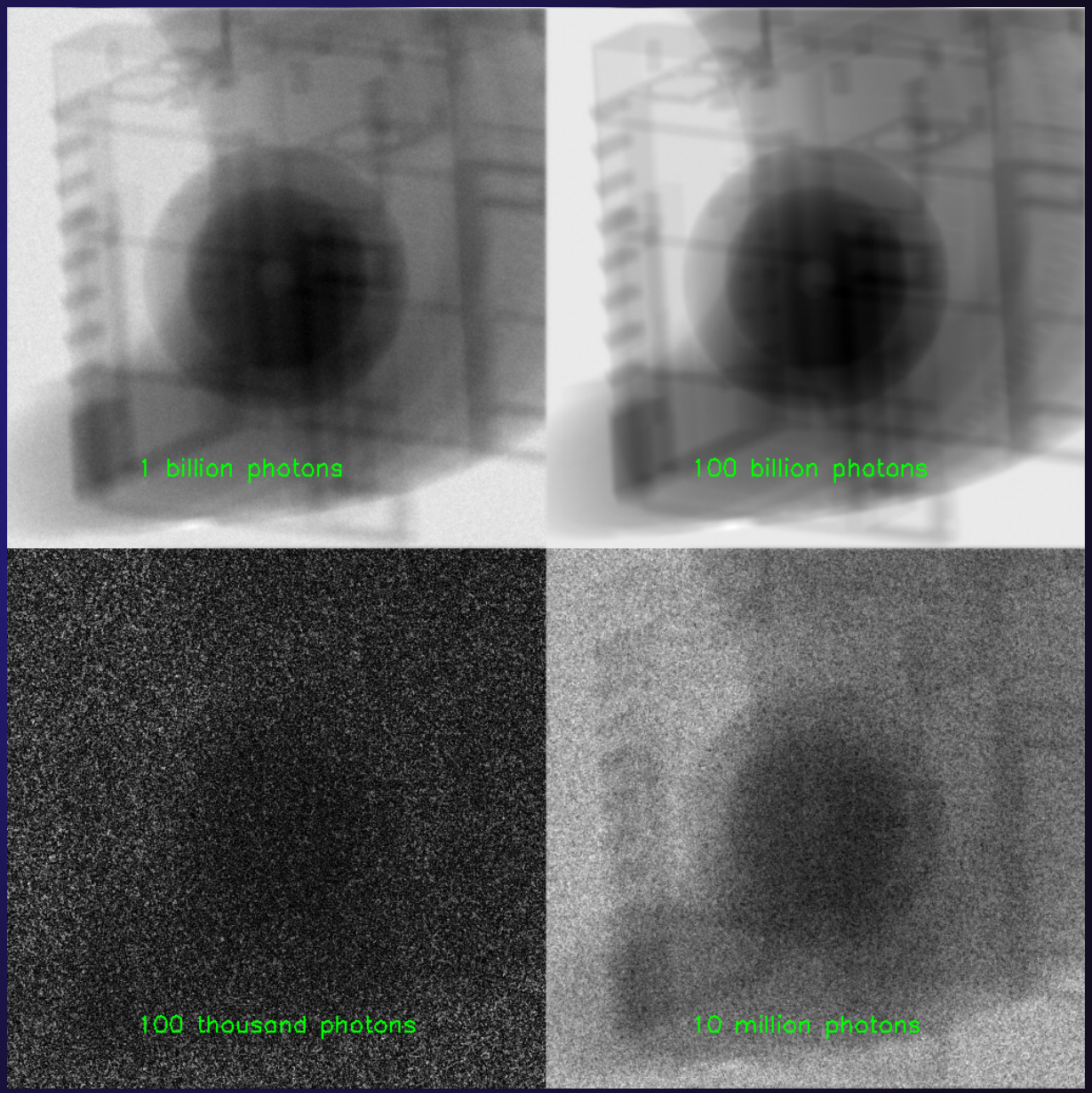


SNR=7.1 SNR=4.5 SNR=3.3

$$SNR = \frac{signal}{noise} = \frac{n_P}{\sqrt{n_P}} = \sqrt{n_p}$$

Image Formation Example (FTO in Tire)

- “Good” images have large numbers of quanta.
- Image utility is task dependent.
- When can you identify the FTO shells?



Linearity

- Modern image processing theory is based upon linear-system theory.
- Many modern imagers are linear (e.g. CCD, photodiode).
- Some are NOT (e.g. light-screened film).
- Most JTOT image data is fundamentally non-linear!
- $y = mx + b$ is NOT linear! (unless $b = 0$).
- Tomographic reconstructions, FFTs, etc. presume linear data.
- Density reconstructions typically limited by scatter background. i.e. b>0.

$$T(\alpha x + \beta y) = \alpha T(x) + \beta T(y)$$

Linear Dynamic Range

- "Linear" => Doubling signal doubles response.
- "Dynamic Range" is the max signal (minus fog) divided by the rms noise.
- Often quoted in "bits" $\log_2$(dynamic range):
  - 2 shades => 1 bit
  - 4 shades => 2 bits
  - 8 shades => 3 bits
- Human visual system is limited to about 6-7 bits grayscale dynamic range

$$Dyn_Range = \log_2\left(\frac{max_signal - fog}{rms}\right)$$

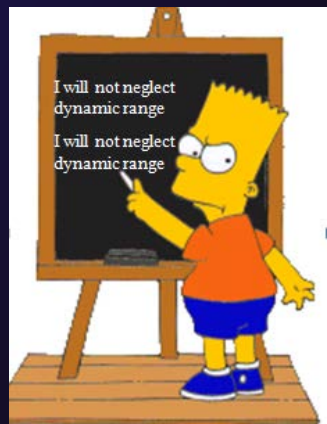
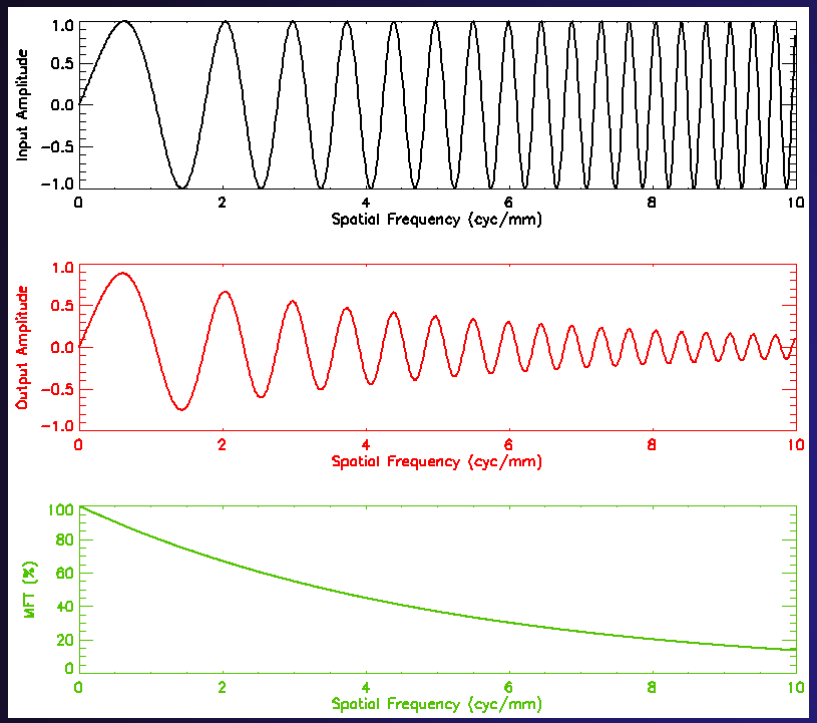
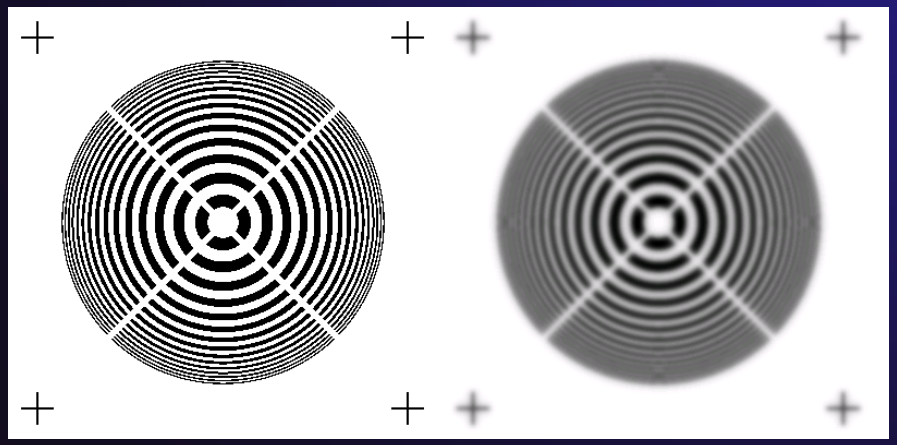


Image Resolution

Modulation Transfer Function (MTF)

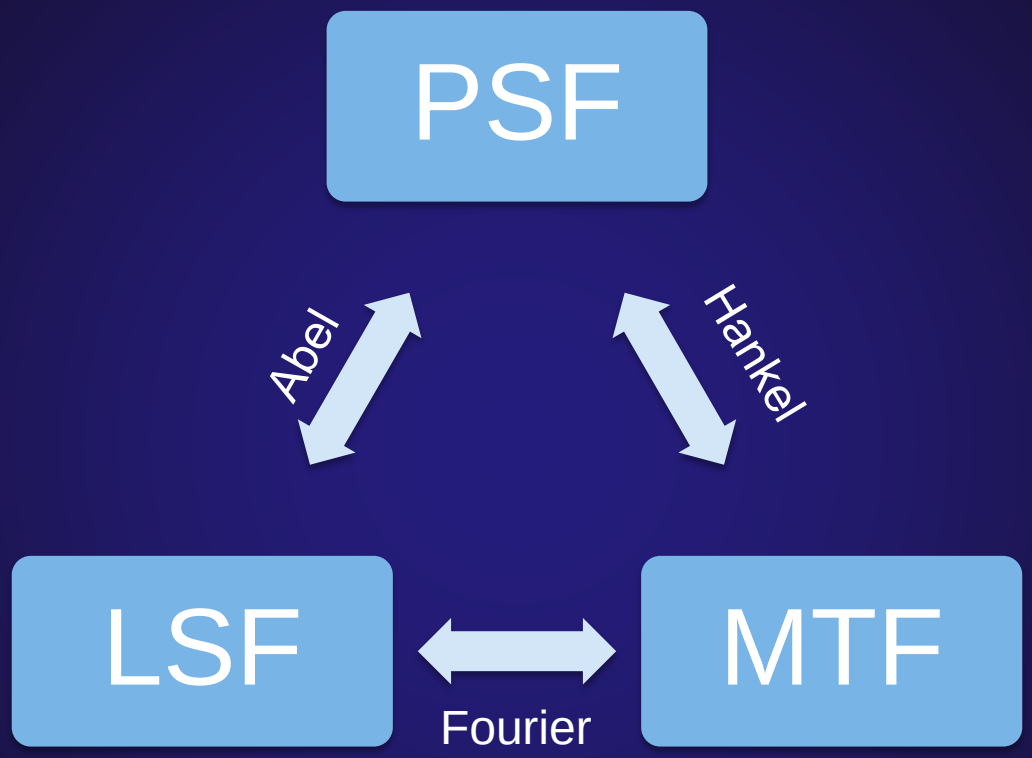




- A common measure of resolution (e.g. 0 - 100% modulation).
- Model is based on linear system theory.
- Component MTF's can be cascaded (in frequency space) to obtain system MTF.
- Almost always a low-pass filter.
- See IDL (MTF.pro) code.

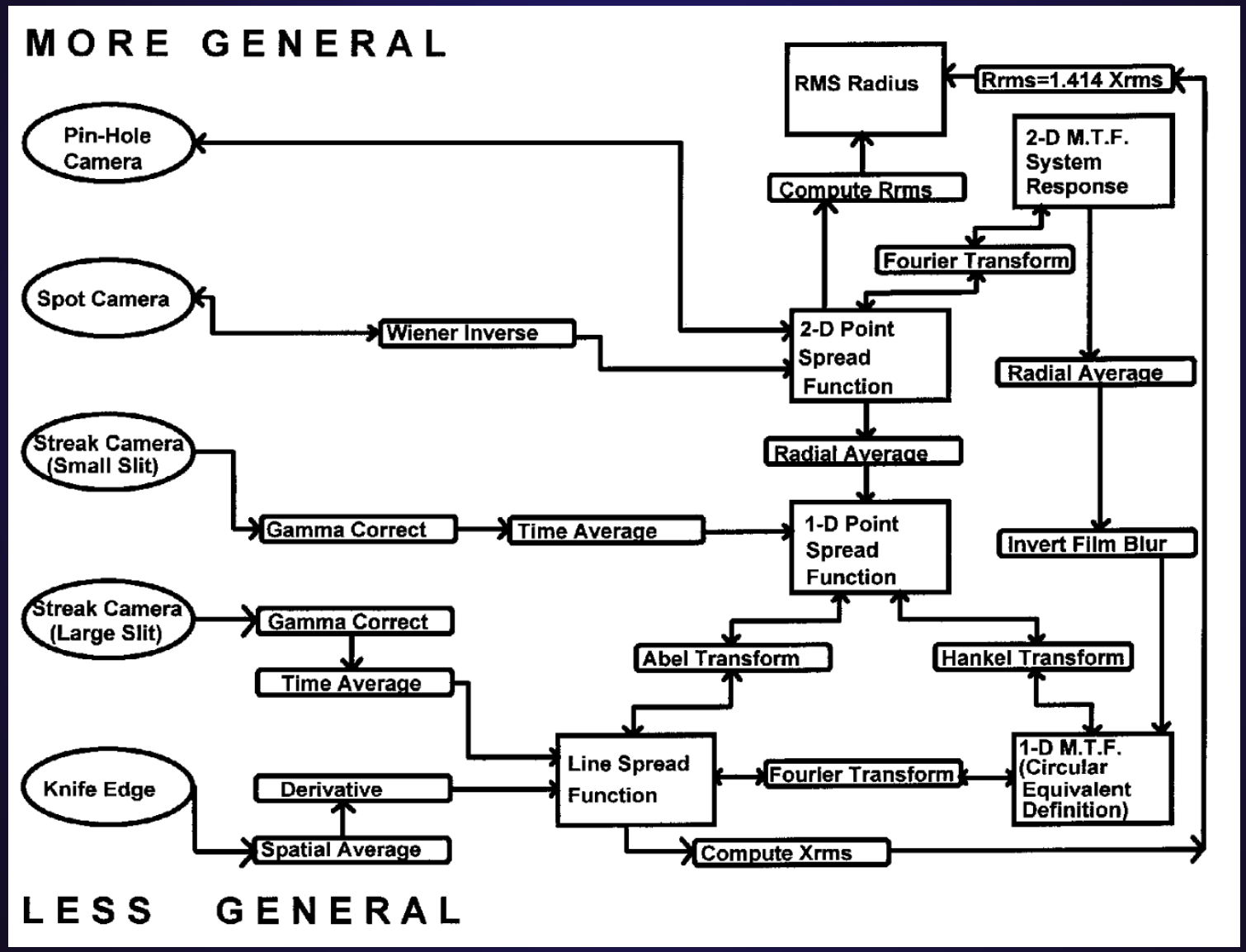
$$MTF(f) = \frac{Output_Modulation}{Input_Modulation}$$

Linear Transforms PSF-LSF-MTF Triangle



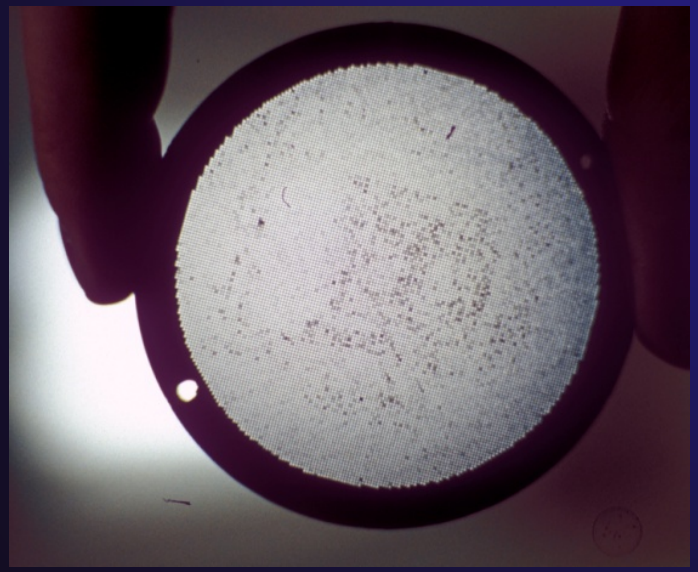
Source Distribution	PSF(r)	LSF(x)	MTF(k)
Uniform disk	$\frac{1}{\pi a^2}$ $r \le a$ 0 $r > a$	$\frac{2}{\pi a^2}\sqrt{a^2 - x^2}$ $x < a$ 0 $x \ge a$	$2\frac{\lvert J_1(ka)\rvert}{ka}$
Gaussian	$\frac{1}{\pi a^2}\exp(-r^2/a^2)$	$\frac{1}{a\sqrt{\pi}}\exp(-x^2/a^2)$	$\exp(-k^2a^2/4)$
Bennett	$\frac{1}{\pi a^2}\frac{1}{[1+(r/a)^2]^2}$	$\frac{a^2}{2(a^2+x^2)^{3/2}}$	$kaK_1(ka)$
Quasi-Bennett	$\frac{1}{2\pi a^2}\frac{1}{[1+(r/a)^2]^{3/2}}$	$\frac{a}{\pi(a^2+x^2)}$	e^{-ka}

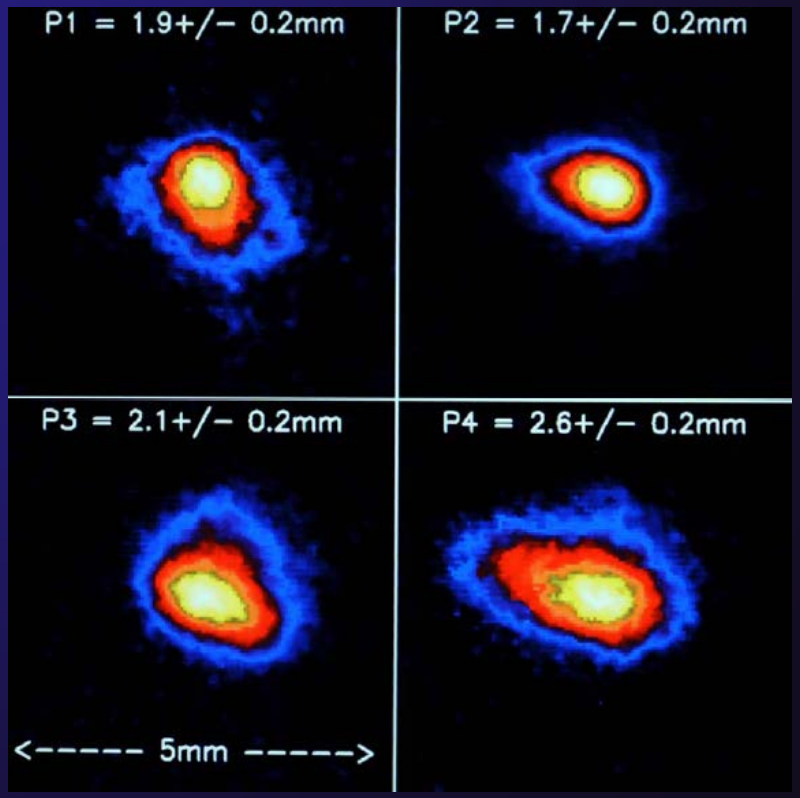
Radiographic Spot Size Measurement Space



Spot Size (aka how big is a fuzz ball?)

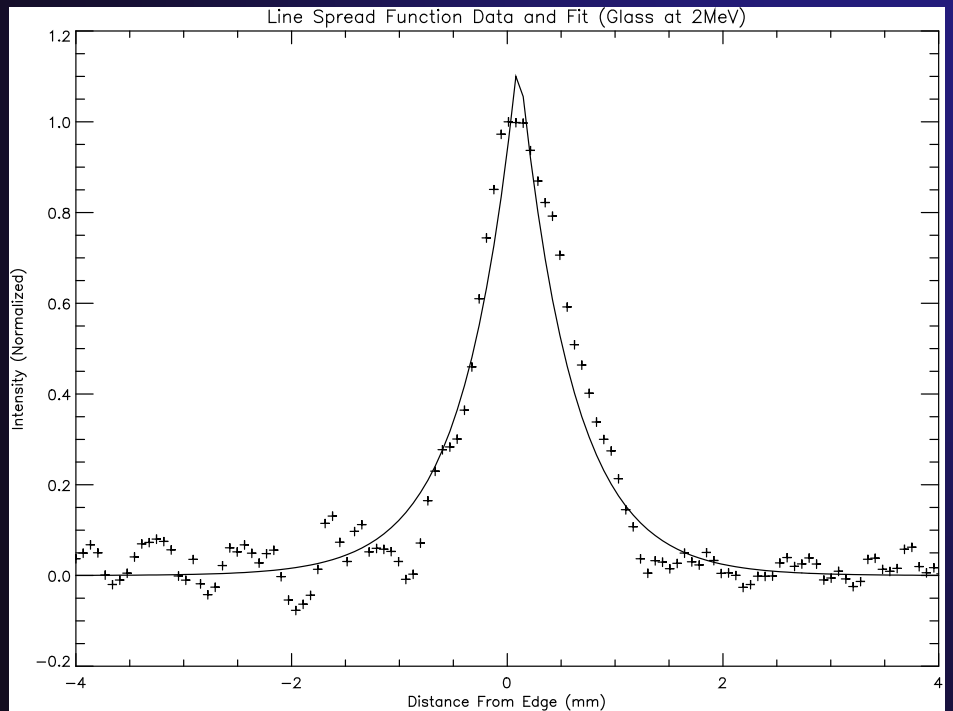
Source Distribution	FWHM	d_{LANL}	d_{AWE}	LR
Uniform disk	$2a$	$2a$	$2a$	na
Gaussian	$1.665a$	$2.661a$	$2.082a$	$0.551/a$
Bennett	$1.287a$	$3.474a$	$2.858a$	$0.636/a$
Quasi-Bennett	$1.533a$	$6.351a$	$4.951a$	$0.477/a$

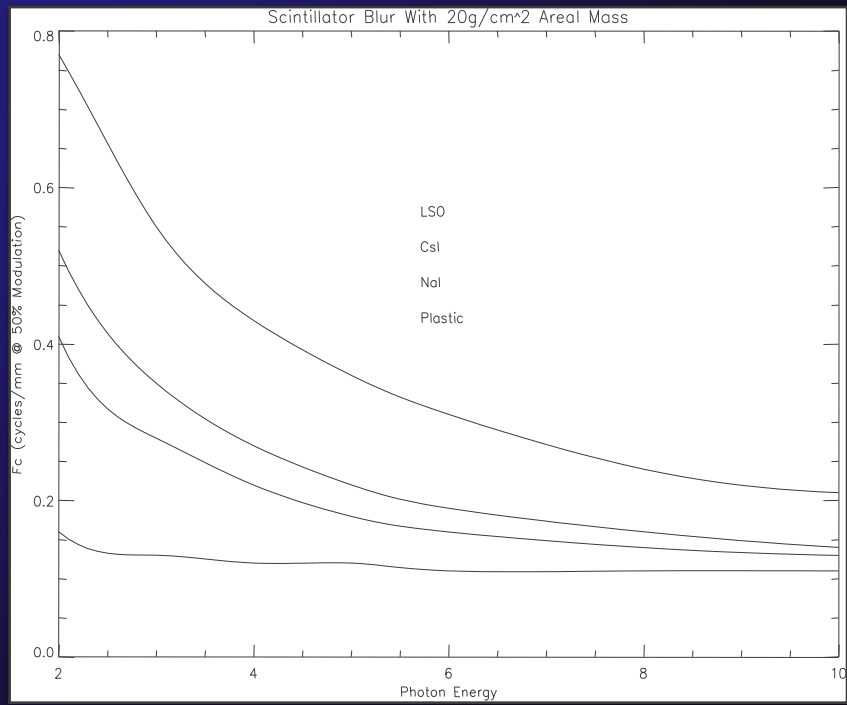




Detector Blur

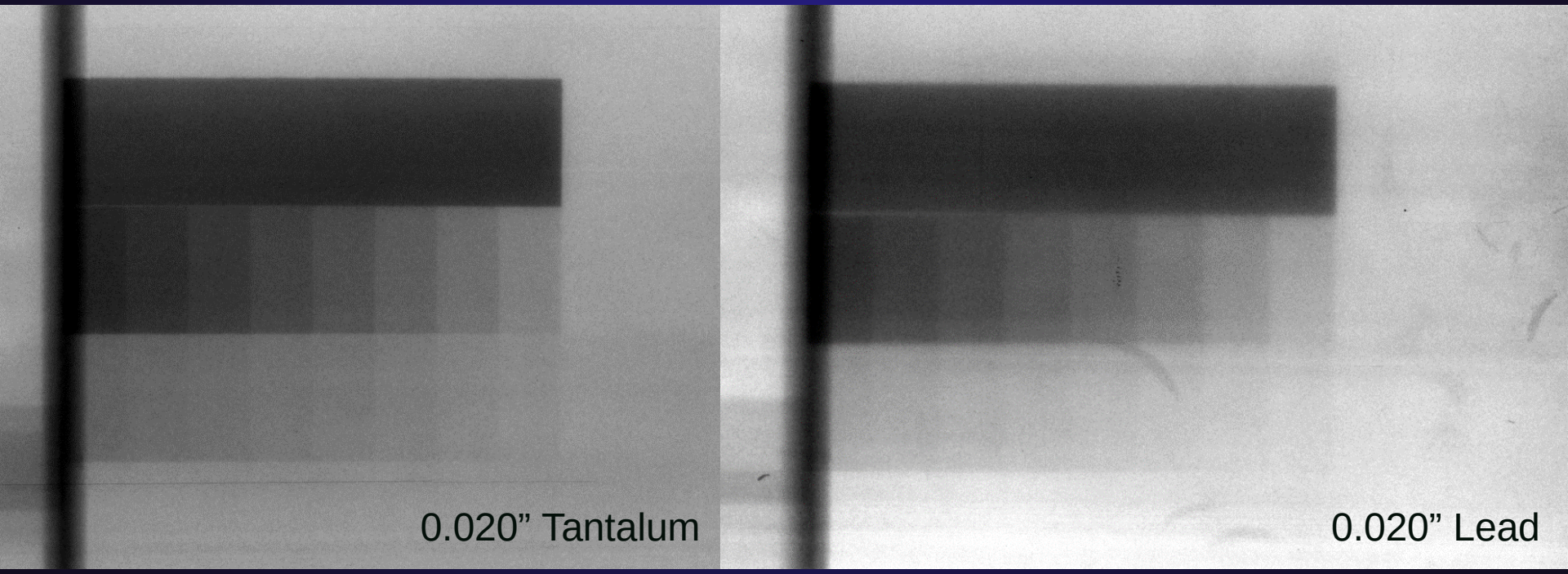
- Caused by Compton scatter.
- Dense material has less blur.
- Typically exponential PSF several mm in extent.
- Goes down with increased radiographic magnification.
- Can be reduced with very thin detectors. e.g. R-film.
- Easily calculated with Monte Carlo codes (e.g. MCNP, ITS).





Reducing Compton Scatter Blur

- Dense intensification screens (e.g. tantalum instead of lead) reduce blur.
- Thin detectors (e.g. phosphors) reduce blur.
- Intimate contact between screen and phosphor (e.g. vacuum packs) reduces blur.



Motion Blur

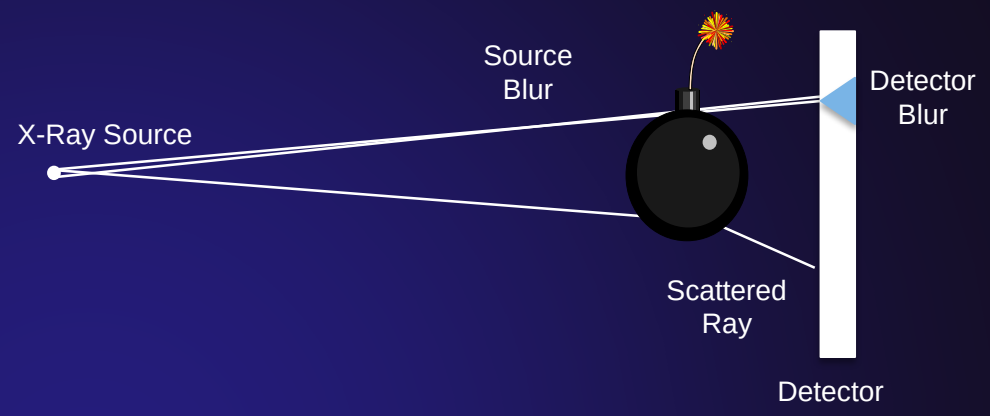
- Typical explosively driven fragment moves ~2 mm/μs.
- Typical explosively driven shock moves 5 – 10 mm/μs.
- Typical detonation velocity is 6 – 8 mm/μs.
- Flash x-rays usually have sub-microsecond exposures.
- For JTOT applications, motion blur can be caused by, wind, object motion, source instability, etc.

Pixel Size and Resolution

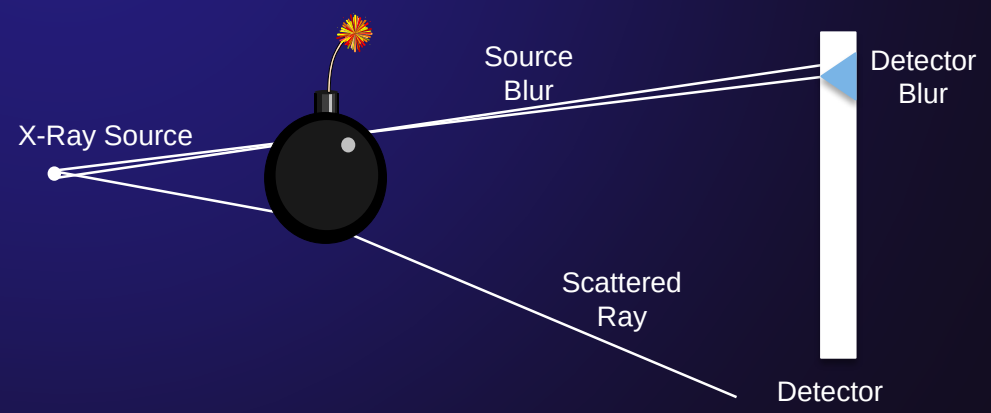
- Pixel size usually does not define system resolution. The MTF does!
- More pixels do not necessarily create a better image.
- Sub-pixel features are often extracted using parametric methods e.g. curve fitting.

Micro-focus geometry

- Small spot, high magnification.
- Better image statistics.
- Reduces blur from scattered radiation.
- MTF Demo using IDL code…

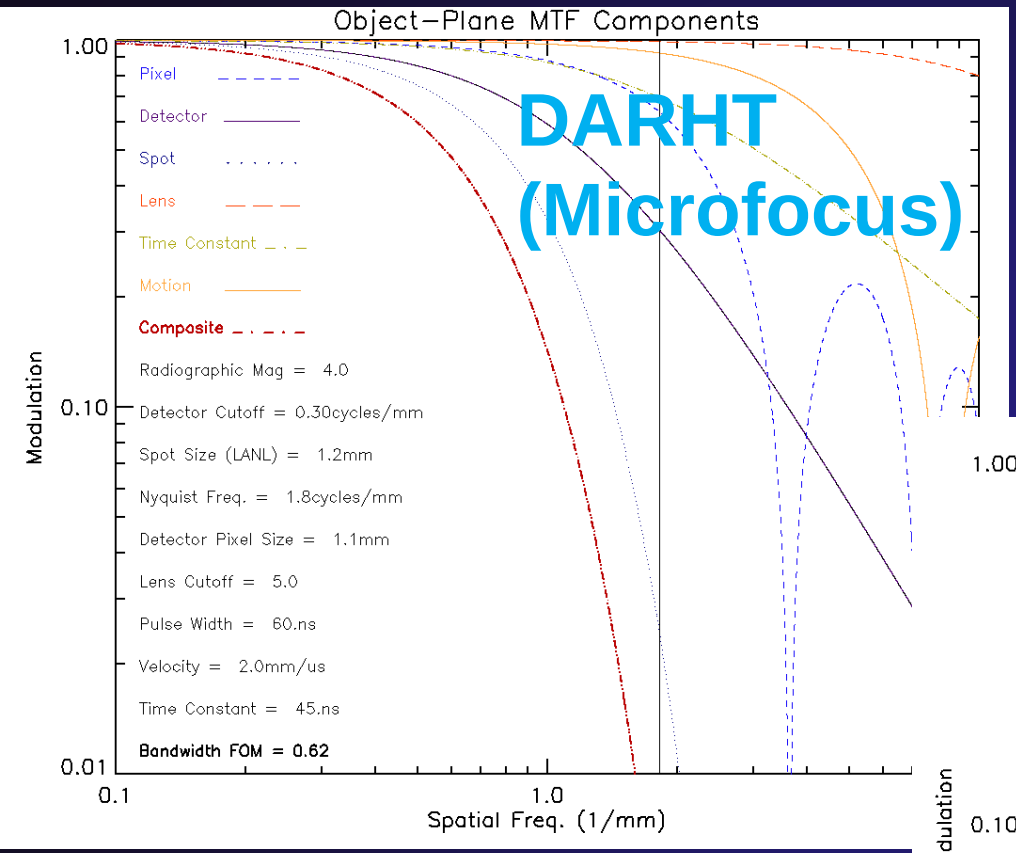


Low Magnification

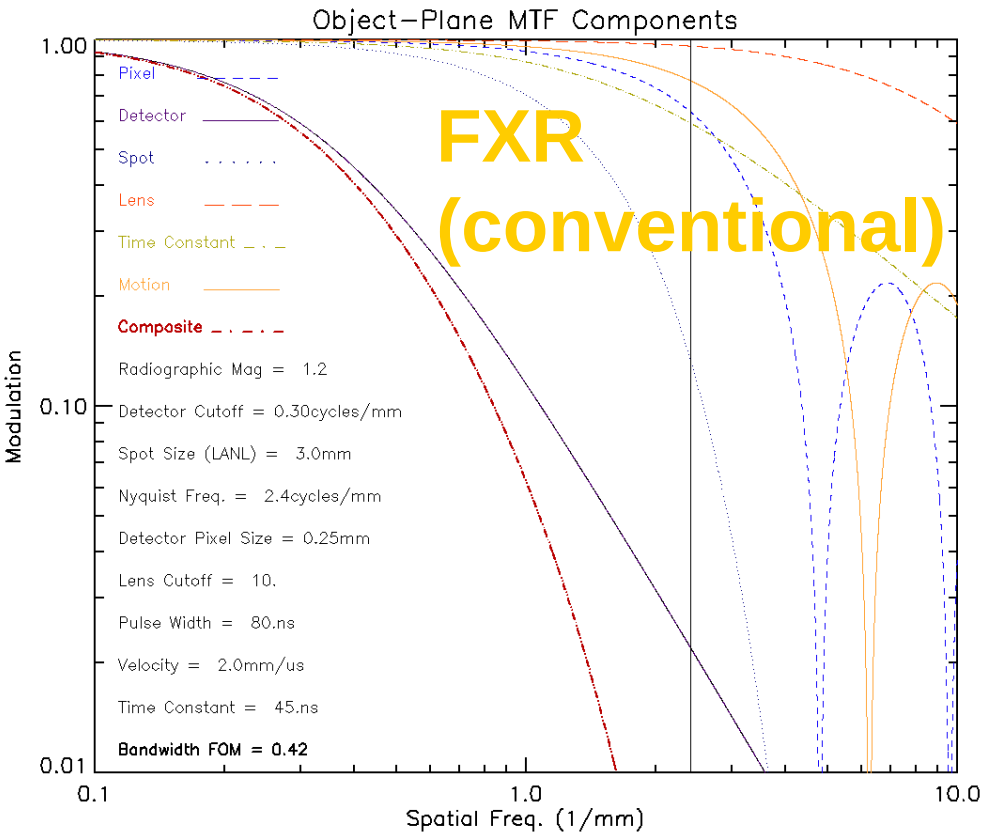


High Magnification

MTF Example (DARHT vs FXR)



- Poor source statistics
- Large object FOV
- Smaller detector
- Poor scatter rejection
- Simplified alignment

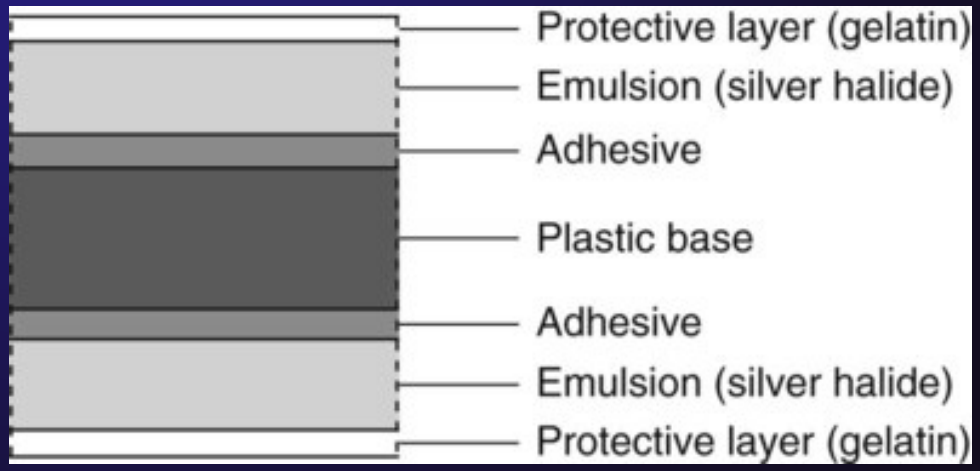


- Better source statistics
- Smaller object FOV
- Larger detector
- Reduced scatter
- Difficult alignment

Detector types

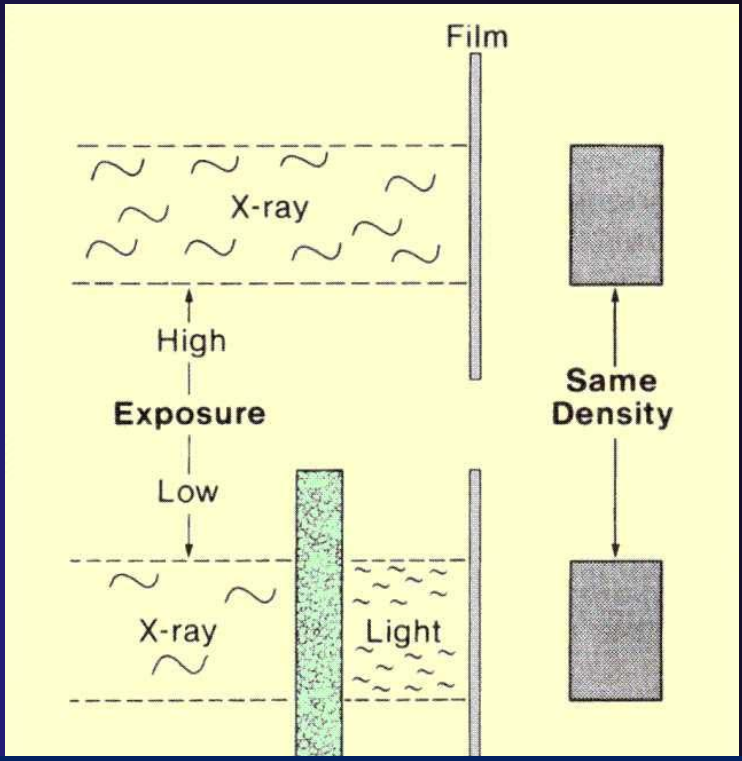
Radiographic film

- Emulsion-gelatin containing radiation sensitive silver halide crystals (AgBr, AgCl).
- Radiation or light incident on the crystals causes some Br^-/Cl^- ions to be liberated and captured by the Ag^+ ions.
- Developing agent gives up electrons to convert silver halide to silver metal.
- Selection of a film depends on many factors: object, radiation type and energy, resolution, ..
- Analog image.
- Film typically has low QE and poor sensitivity.



Light-screened film

- Intensifying screens (phosphor screen) convert x-rays to visible light for which the film is more sensitive.
- Intensifying screen made of calcium tungstate (historical) or rare earth materials (e.g. barium, yttrium, lanthanum or gadolinium compounds).
- Permit lower radiation dose (helpful for medical).
- Light-screened film is more sensitive but non-linear. Direct recording film is less sensitive, but linear. Direct recording film typically has better resolution.

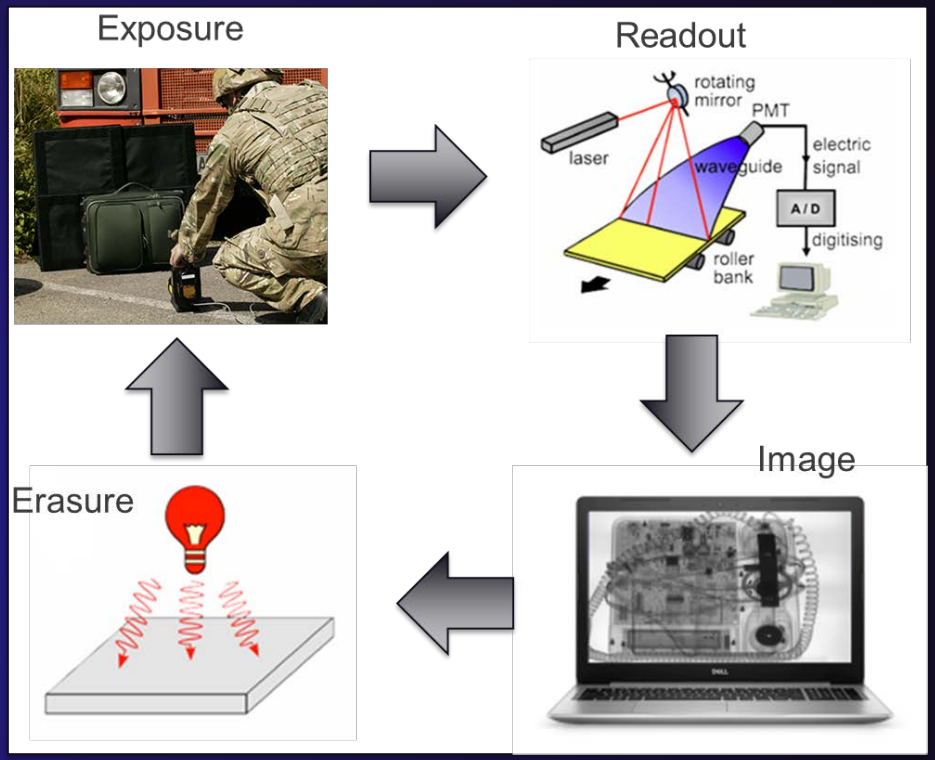


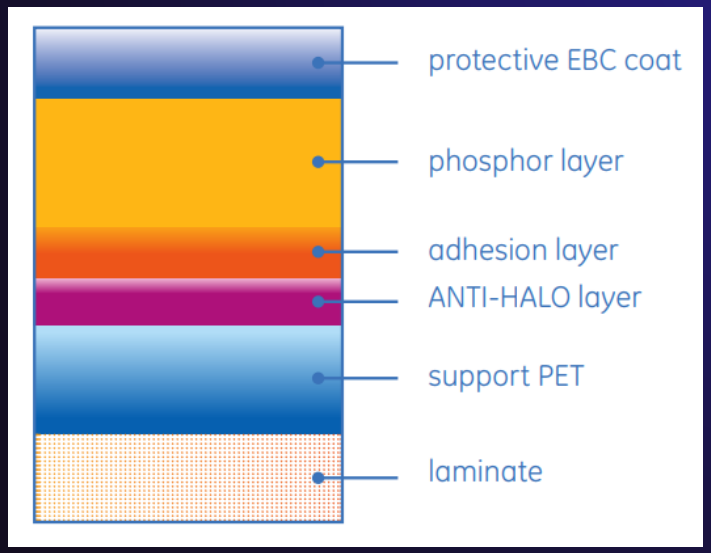
Difference B/W Non Screen & Screen Film

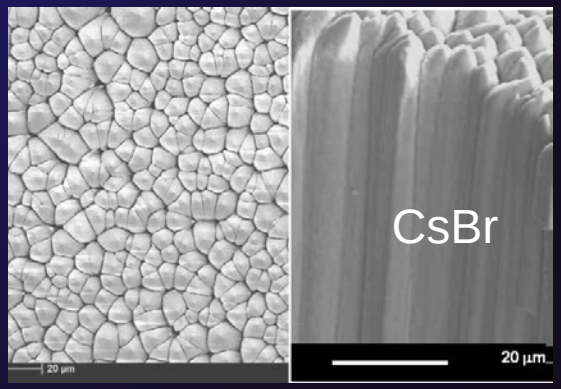
CHARACTERISTICS	DIRECT EXPOSURE FILM	INDIRECT EXPOSURE FILM
Exposed with	Only by x-rays	Mainly by visible light
Used	Without Screen	With screen
Emulsion layer	Thick	Thin
Image formation	In deep	superficialy
Processing time	more	less
Resolution	more	less
Exposure dose	more	less
Used in	Orbit and extremities radiography. Also in Industrial Radiography	General radiography

Storage Phosphors ‘CR’ panels

- Has essentially replaced x-ray film.
- Stored image is proportional to incident dose.
- Plates are reusable after erasing.
- Requires separate read out.
- Resolution is limited by scattering in imaging plate.







Storage Phosphor Scanners

VMI CR 4100 Scanner

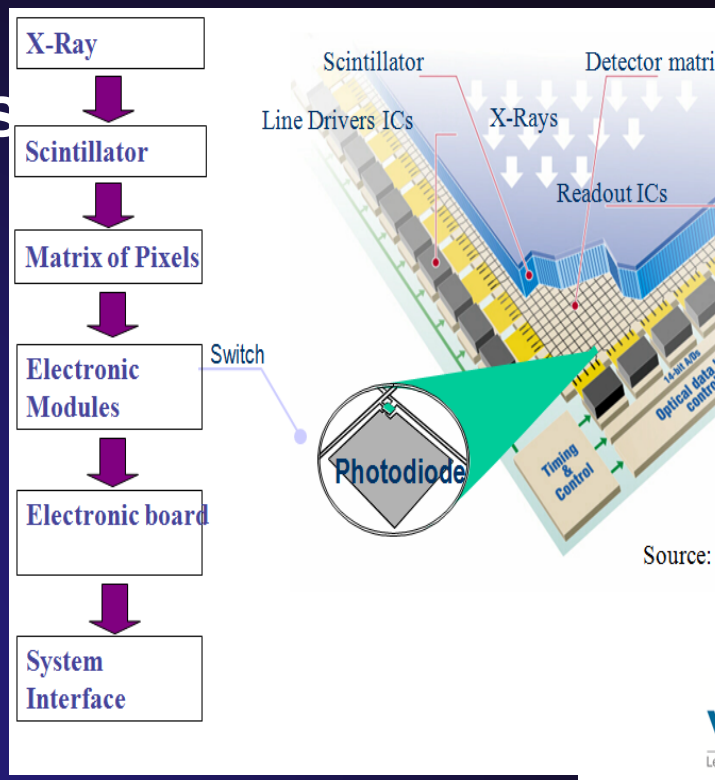
- “Portable” scanners.
- Range in weight from 5 lbs (MiniMAX) to 79 lbs (VMI).
- Priced from $10k (MiniMAX) to $100k (VMI).

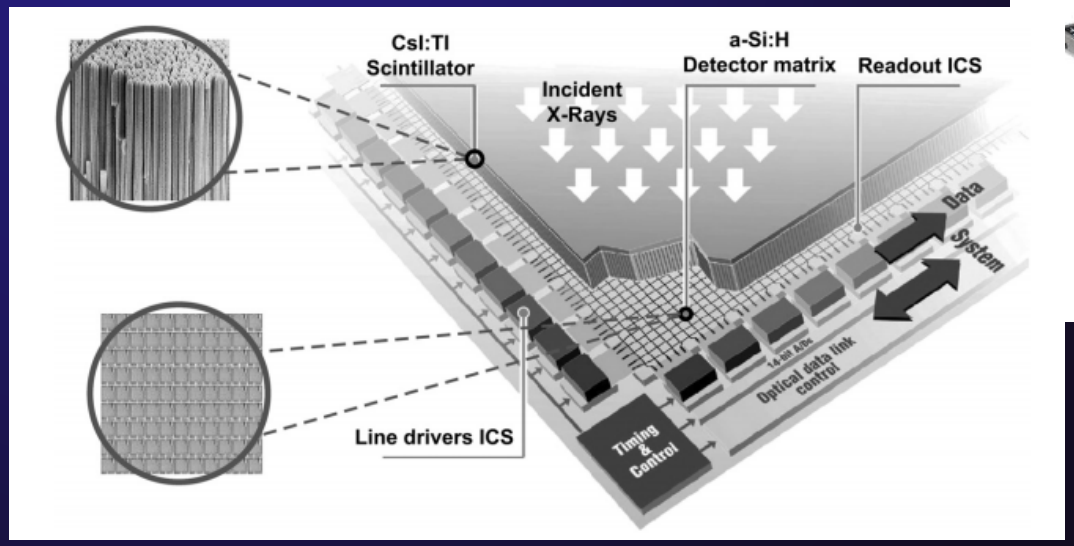
ScanX Scout scanner

MiniMAX

Amorphous Silicon ‘DR’ Panels

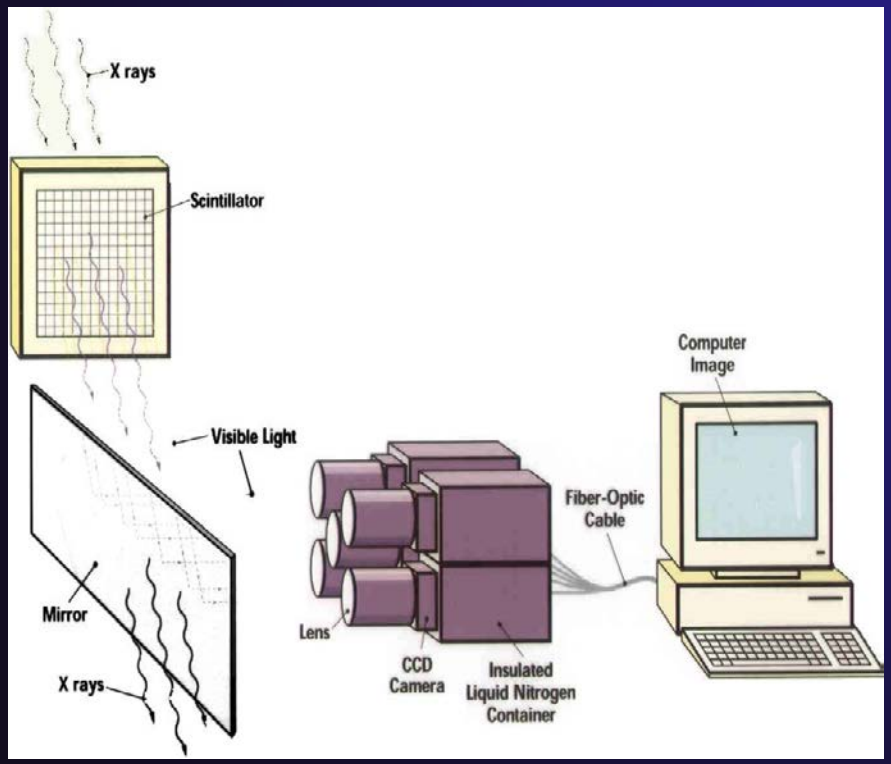
- Commonly CsI or Gd_2O_2S (Gadox) scintillator.
- Highest resolution of any digital x-ray detector.
- Highest cost of common detectors.
- Poor for long exposures (thermal noise).
- Excellent sensitivity (“direct” detection).
- Poor high-energy quantum efficiency.
- Small format, fragile.

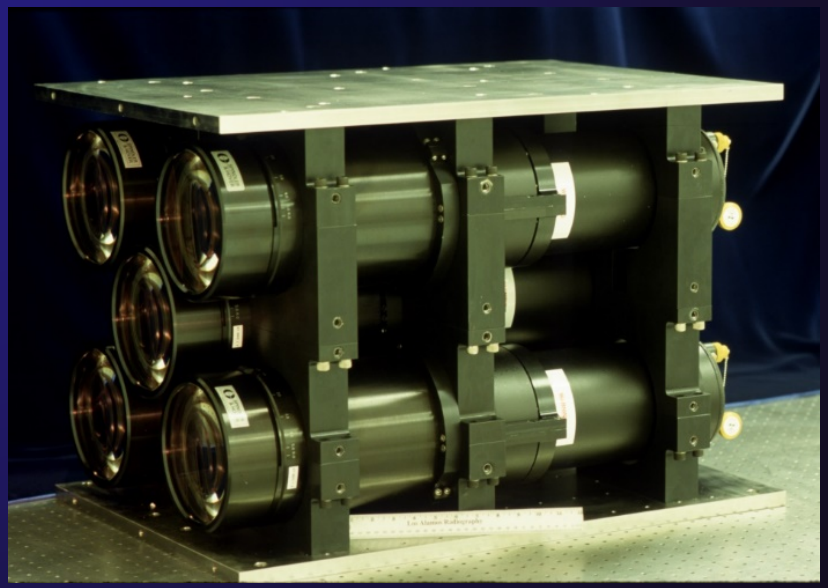




Gamma ray camera

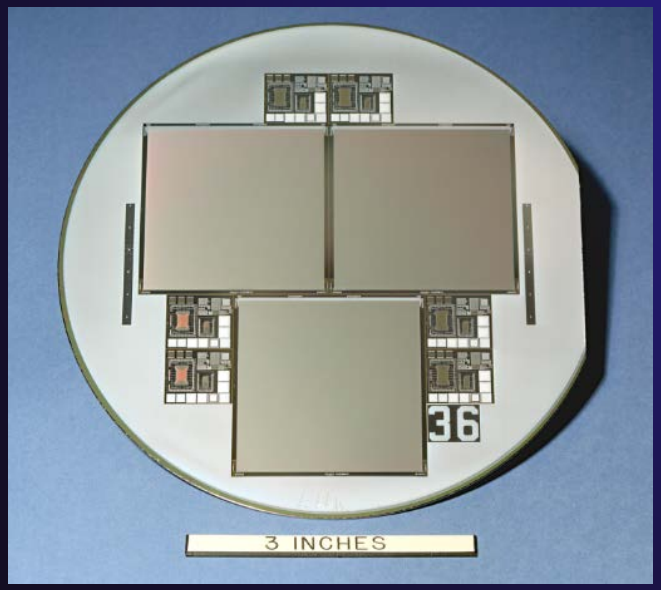
- Scintillator - converts x-rays to visible light.
- Turning Mirror - gets electronics out of x-ray path.
- Lenses - collect visible light from scintillator.
- CCD Camera - record digital image from visible light.
- Very high quantum efficiency (>10%), and excellent MeV sensitivity.
- Capable of very high speed mulitiple-pulsing.

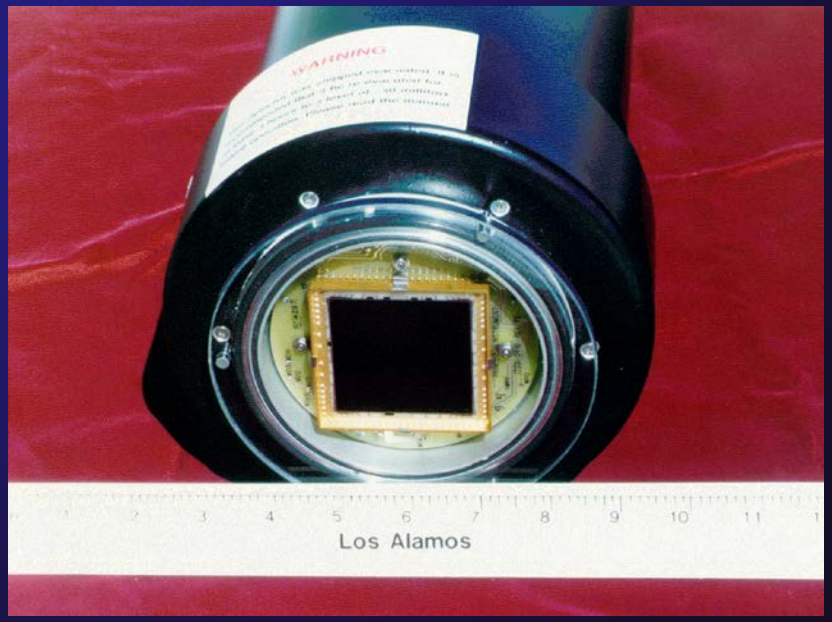




Cooled Scientific Grade CCD's

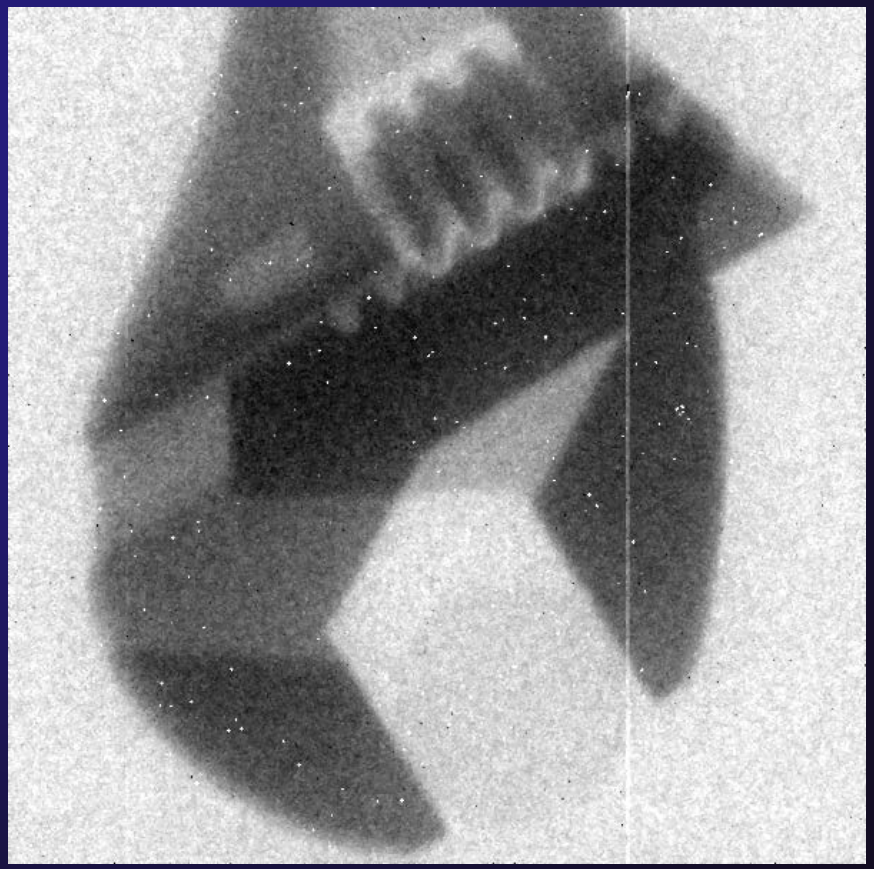
- Have excellent (visible light) efficiency (nearly 90% for green light).
- Are extremely linear.
- Have wide dynamic range.
- Have very low noise.
- Are hard to fabricate in large areas.





Detector Sensitivity

- Direct recording X-ray film: 0.1 R – 20 R.
- Light screened film: 1 mR – 100 mR.
- Fuji storage phosphor: 100 μR – 1 R.
- Gamma ray camera: 5 μR – 1 mR.
- “DR” panel: 10 μR – 1 R.

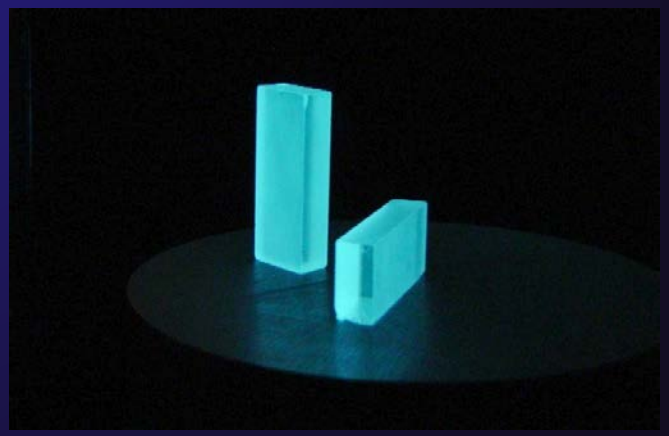


Comparison of detector types

Property	X-ray Film	Computed Radiography	Digital Radiography	Gamma Camera
X-Ray QE	1%	1-10%	1%	>20%
Resolution	Excellent	Good	Excellent	Good
Linearity	Poor	Excellent	Excellent	Good
Dynamic Range	Low	High	High	High
Sensitivity	Poor	Excellent	Excellent	Excellent
Radiation Hard	No	Yes	No	No
Multi-Use	No	Yes	Yes	Yes
Large Area	Yes	Yes	No	No
Compact	Yes	Yes	Yes	No
Lightweight	No	No	Yes	No
Flexible	Yes	Yes	No	No
Robust In Extreme Environments	No	Yes	Yes	No
Flat Fielding	Not Required	Not Required	Not Required	Required

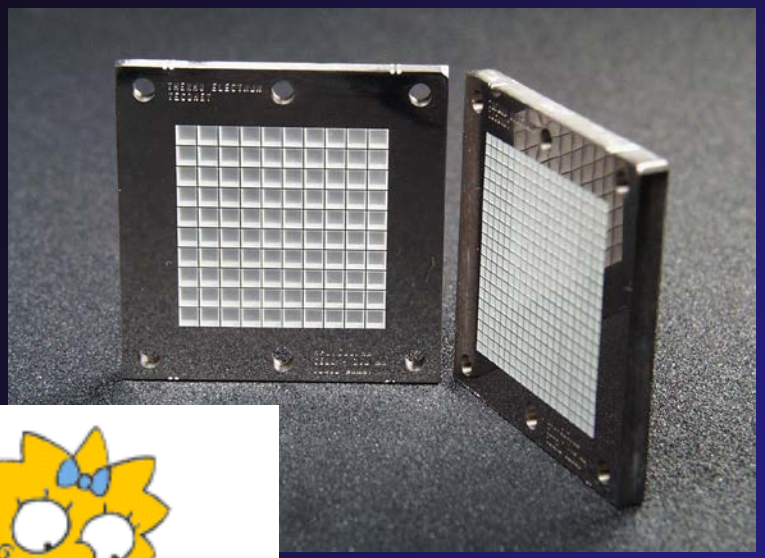
Scintillators

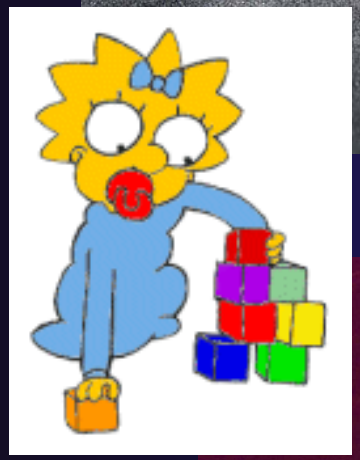
- A scintillator emits a pulse of visible light in response to absorbed radiation.
- The amount of light produced is proportional to the amount of radiation absorbed.
- Scatter by various processes causes blur.
- Desired scintillator properties:
  - Fast scintillation
  - Dense, high Z
  - High light output
  - Low afterglow
  - Transparency to scintillation light
  - Linear



Perfect scintillator doesn't exist – have choose scintillator for specific application

Segmented Scintillators

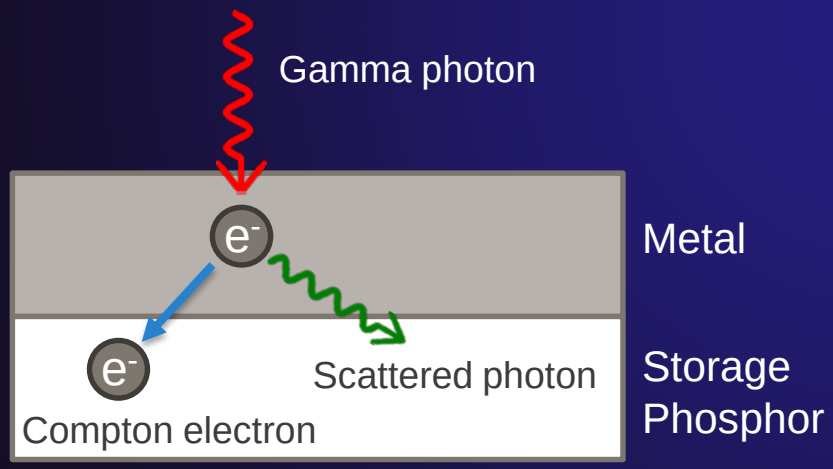


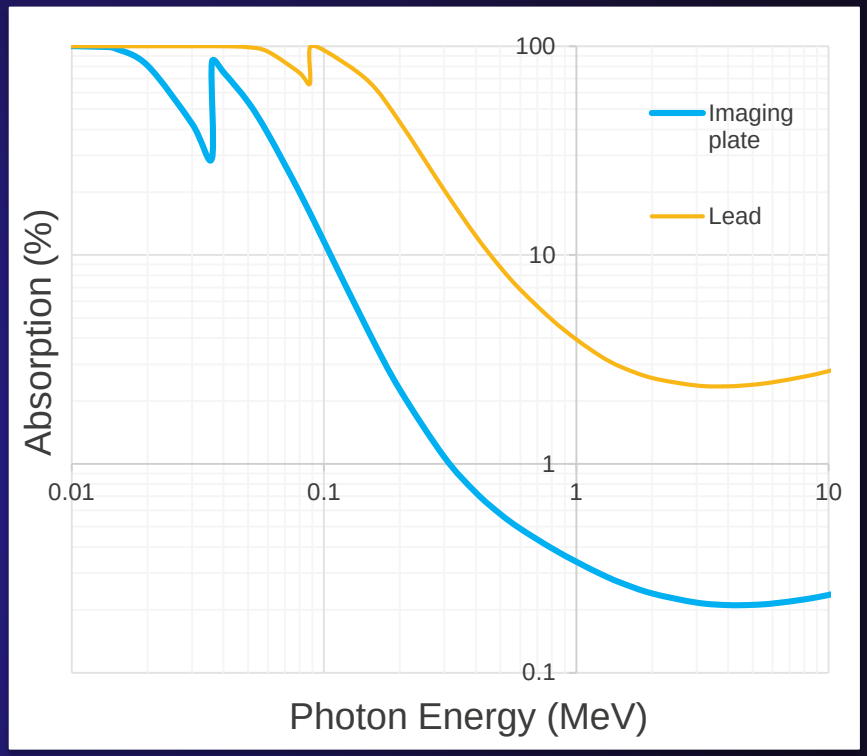


- Essentially built by hand out of little pieces like Zuni jewelry.
- Can be saw-cut (Bicron), polished, extruded (RMD & Tecomet), or acid etched (UCLA).
- Isolates light in individual pixels.
- Reduces depth of focus.

Intensification Screens at High Energy?

- Improves detector quantum efficiency.
- Reduces scatter.
- Reduces Compton scatter blur.
- Electrons produce dominant exposure





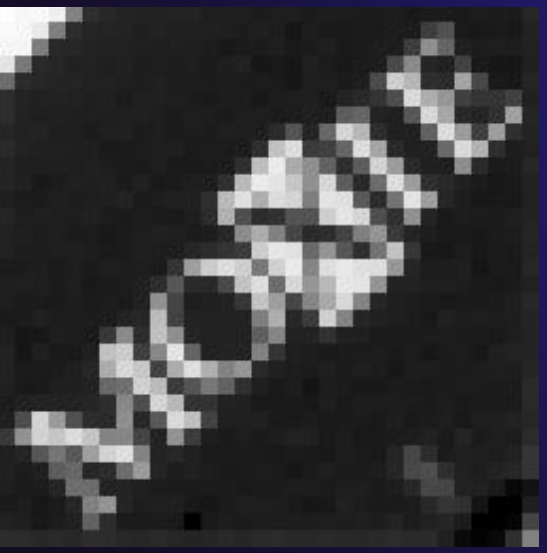
0.02” Lead absorbs 4% of 1 MeV gamma rays

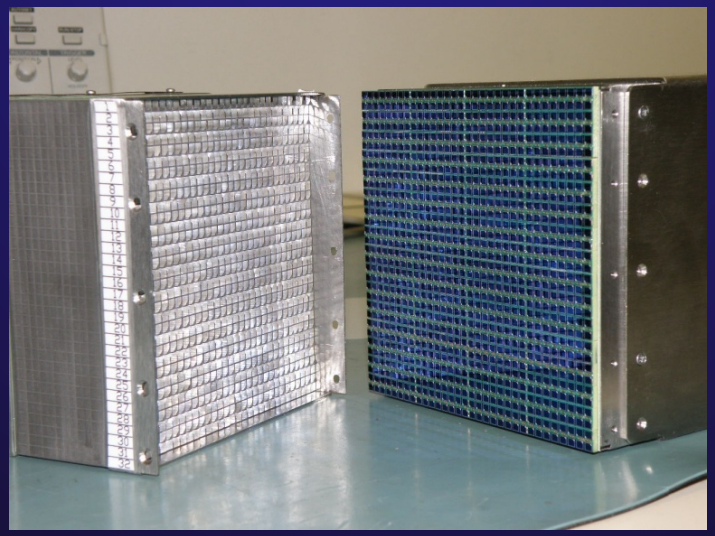
Important part is how much is absorbed in the imaging plate!

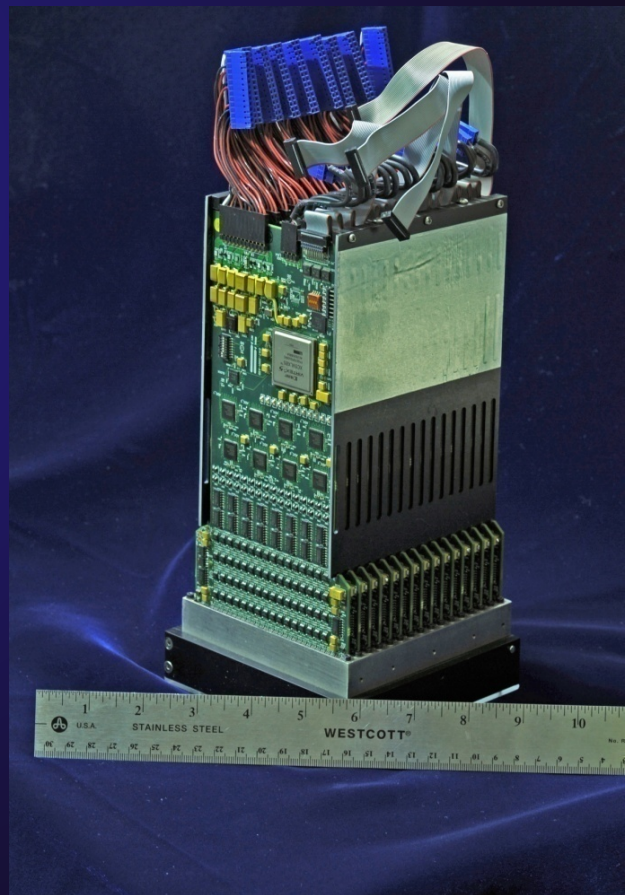
0.02” lead → 190% increase

High Speed Cameras

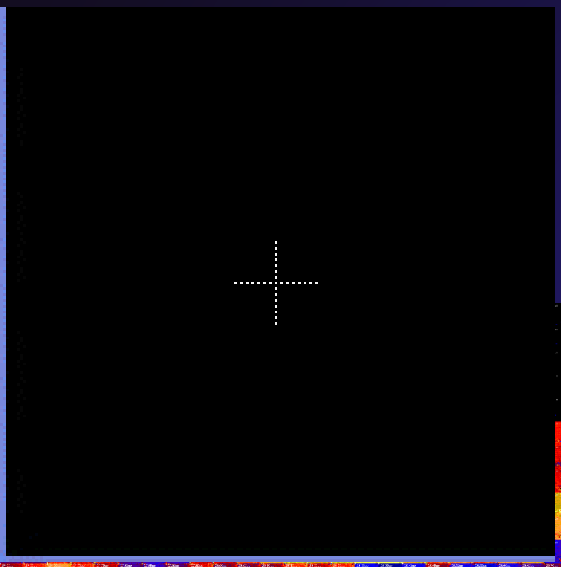
- World's fastest movie camera.
- Uses unique, in-line, modular design.
- Designed for very high QE (50%), high speed 20 Mfps, and large number of frames (4096).
- Can use protons, visible light, or x-rays.
- 32 x 32 pixels x 4096 frames.



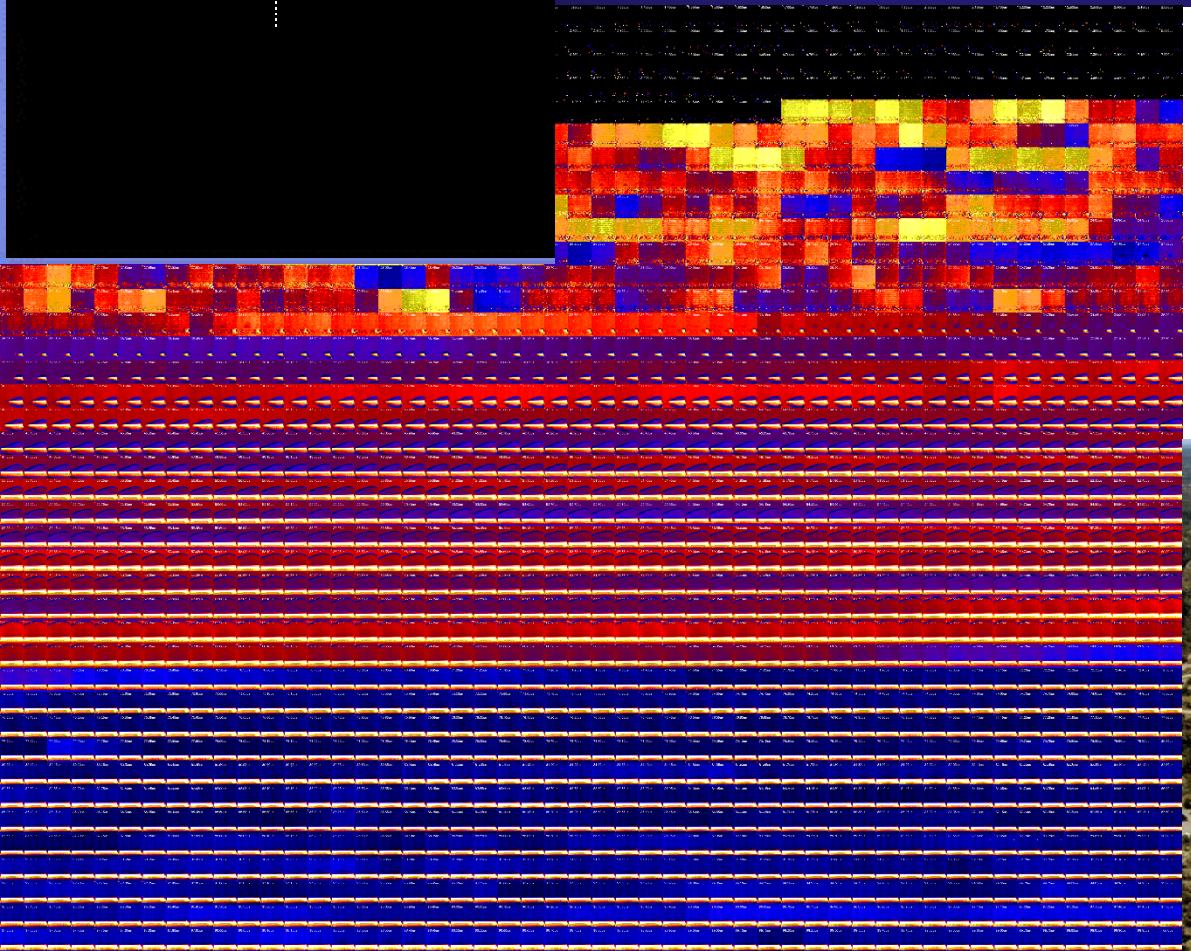


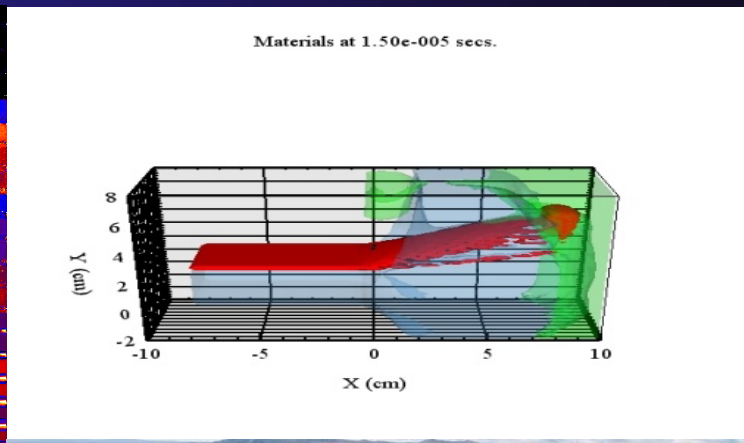


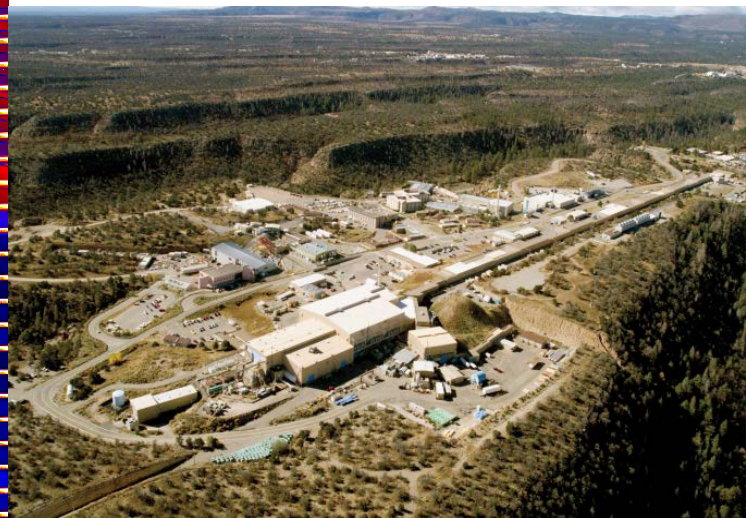
MOXIE Proton Radiography



- This movie shows an end-on detonation of an aluminum flyer plate experiment at LANSCE.
- Each frame is 50 billionths of a second duration.
- Flyer plate is moving ~3x faster than a bullet.





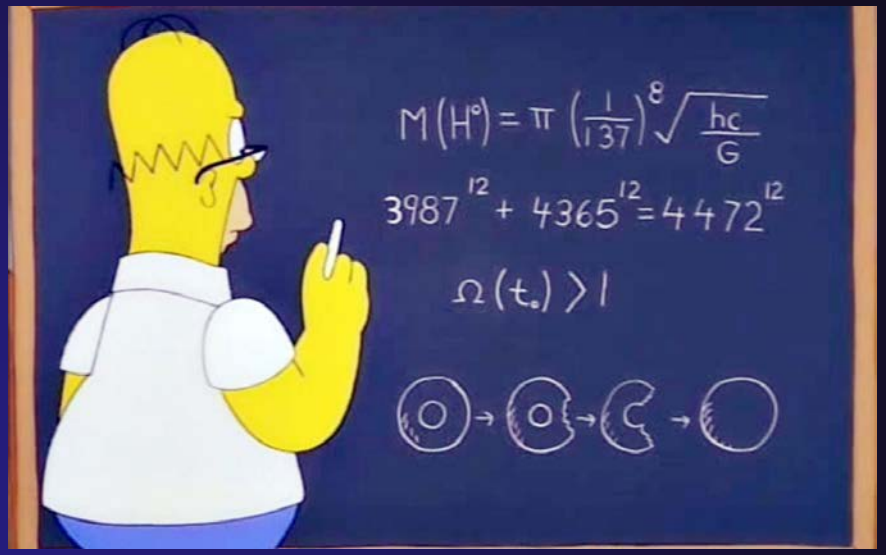


Lunch

Imaging Performance Measures

Figure of Merit (US & UK)

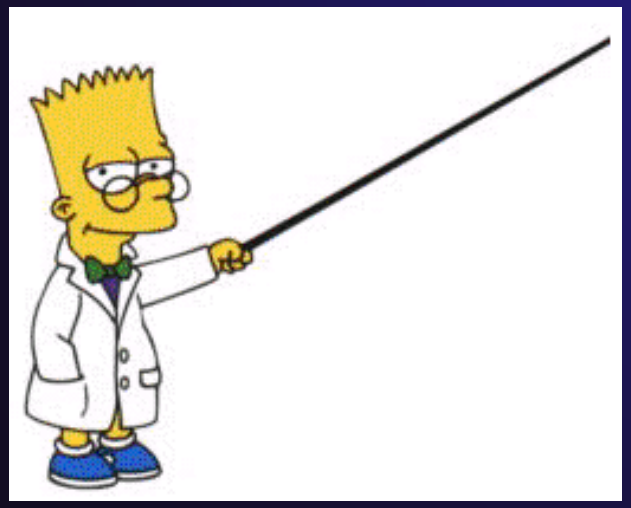
- Spot size, S (mm)
- Dose, D (Rad @ 1 m)
- Detector blur, f_c (lp/mm)
- Detector Quantum Efficiency, Q_{eff}
- Object Plane pixel size, P (mm)
- Magnification, M
- Source-to-Object distance, A
- Average Object Transmission, T
- Object feature velocity, V (km/s)
- Pulse-width, W (μs)
- See IDL (FOM.pro) code.



$$FOM \propto \frac{\log_2\left[1+\frac{P}{A}\sqrt{\left(6x10^6\frac{\gamma-photons}{R-mm^2}\right)DTQ_{eff}}\right]}{\sqrt{2\left[\frac{(M-1)S}{M}\right]^2+\left[\frac{1}{Mf_c}\right]^2+2[VW]2}}$$

Detective Quantum Efficiency

- The DQE is the most general summary measure of imaging performance.
- It measures the ratio of recorded signal power to incident signal power as a function of spatial frequency, f.
- The DQE < 1 and typically DQE < 0.1.
- DQE is NOT the same thing as the "signal-to-noise ratio" (a quantity that is fundamentally ill-defined!)

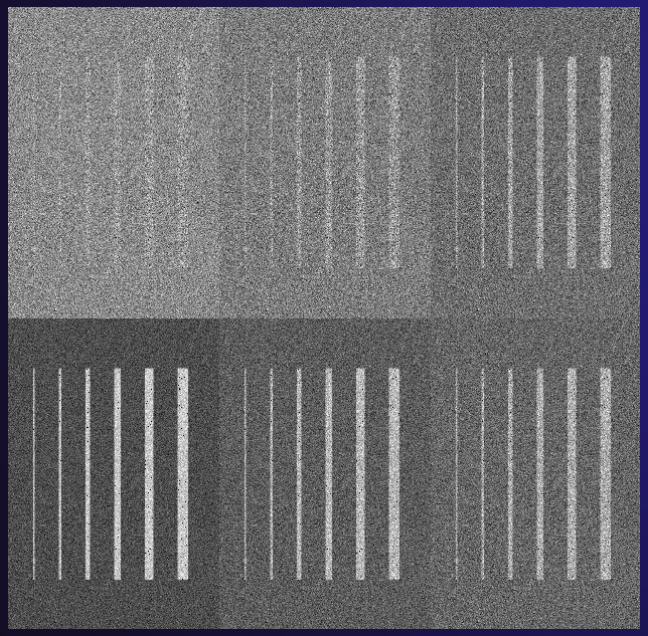


$$DQE(f) = \frac{SNR^2_{Recorded}(f)}{SNR^2_{Incident}(f)}$$

Detective Quantum Efficiency

- DQE is Equivalent to dose.
- Most photons go undetected! This is especially true at high energies.
- DQE is improved by stacking phosphors or using dense scintillators.

DQE=1% DQE=2% DQE=5%



DQE=50% DQE=20% DQE=10%

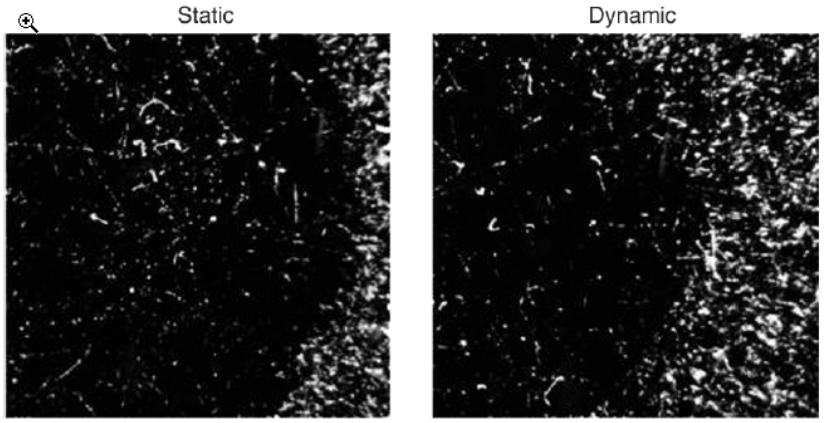
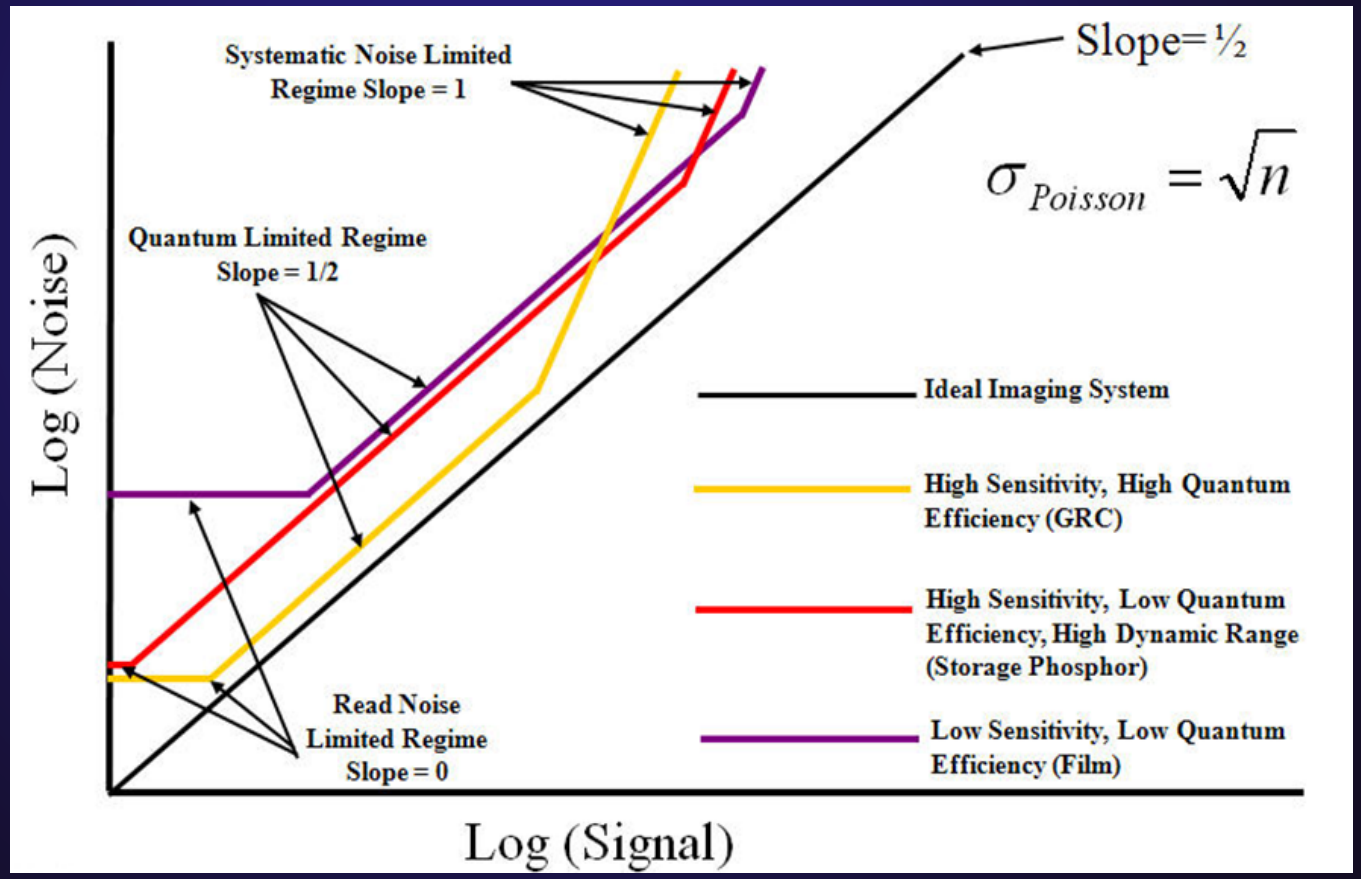


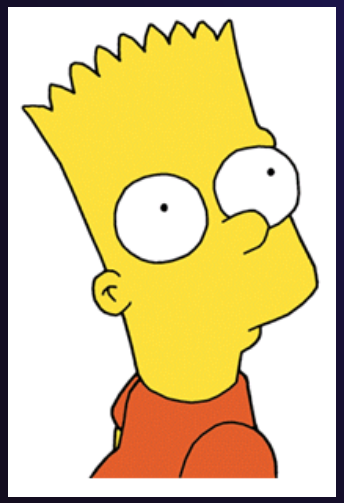
Figure 2. Radiographs of an Explosively Driven Implosion Experiment
These radiographs were taken in 1944 to image the outside edge of the surrogate pit during a hydrotest. The x-rays used to image the implosion were generated with the 15-MeV electron beam from the betatron borrowed from the University of Illinois. The detector consisted of a lead glass converter and a Wilson cloud chamber to detect the recoil electrons. The dark area in each image is the shadow cast by the pit. The radius of the pit is smaller in the right image.

Photon Transfer Curves

- Describes quantum limited performance.
- Shows sensitivity knee.
- No detector is always best.

$$\sigma_{System} = \sqrt{\sigma_{CCD}^2 + \left(\frac{\sigma_p}{K}\right)^2}$$

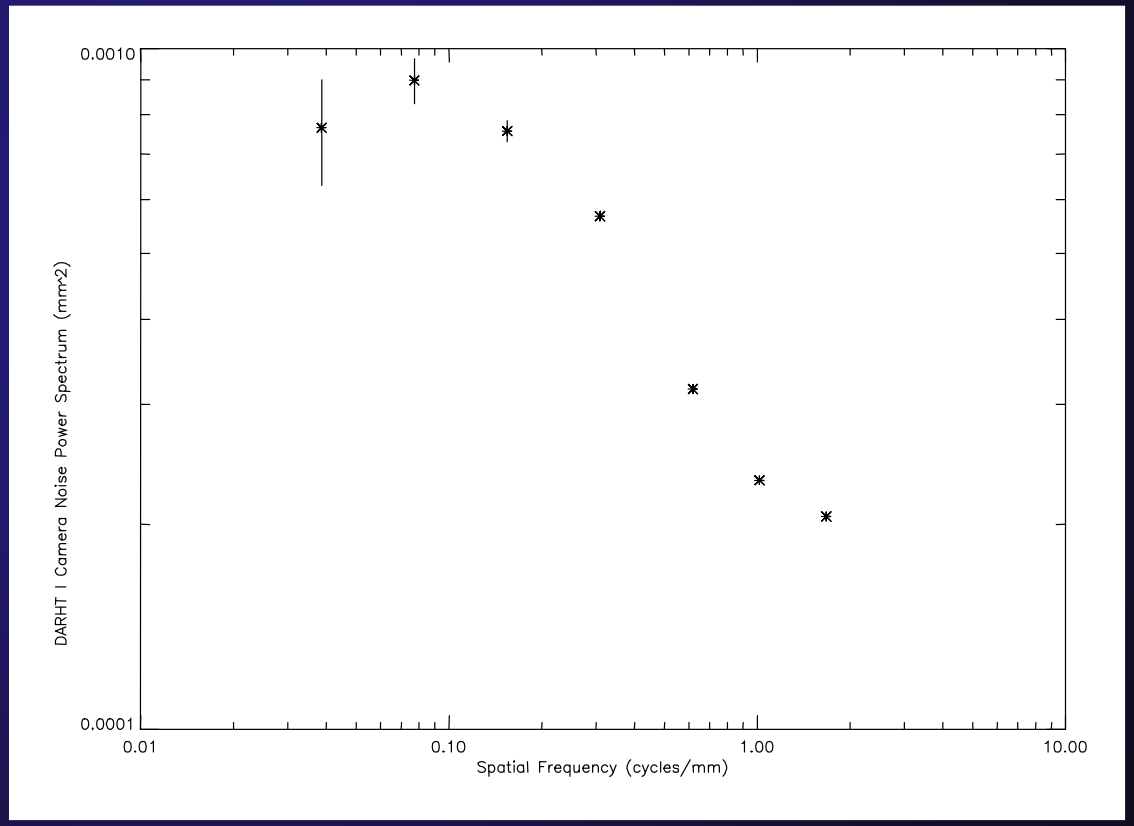




Noise Power Spectrum

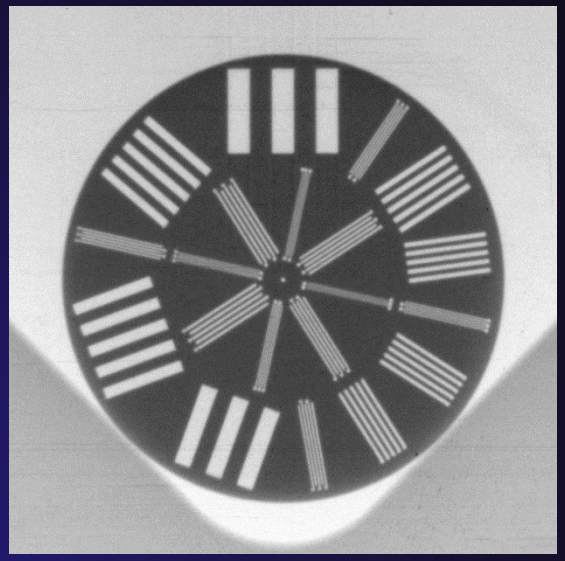
- NPS describes how noise power is distributed in spatial frequency.
- DQE(f) IS the image quality for a feature of “size” f.

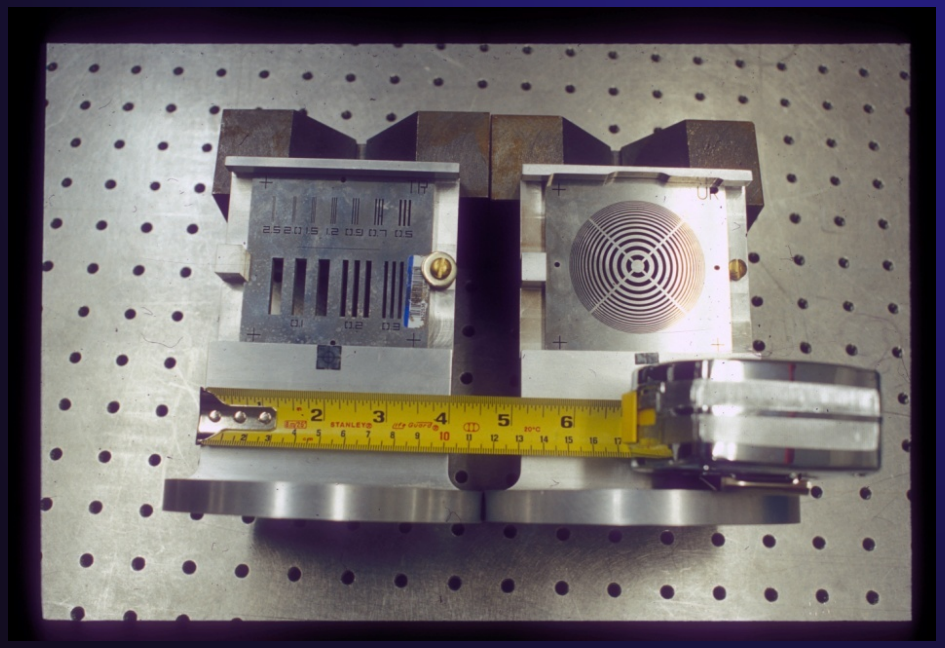
$$DQE(f) = \frac{MTF^2(f)}{NPS(f)N_{eq}}$$



Radiographic Test Objects

- Used to calibrate and assess imaging systems.
- Used to align gas-cavity hydrotests.
- Used to focus electron beam source spot.
- Allows comparison of different facilities and configurations.
- “French Test Object” (FTO) is a widely used, unclassified, international standard.
- Found with both static & dynamic test facilities.

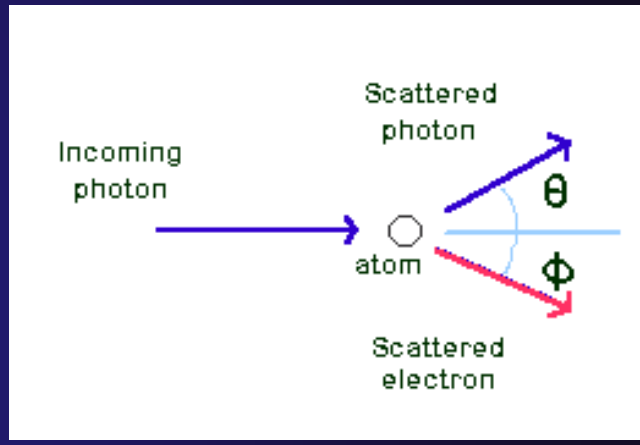




Scatter

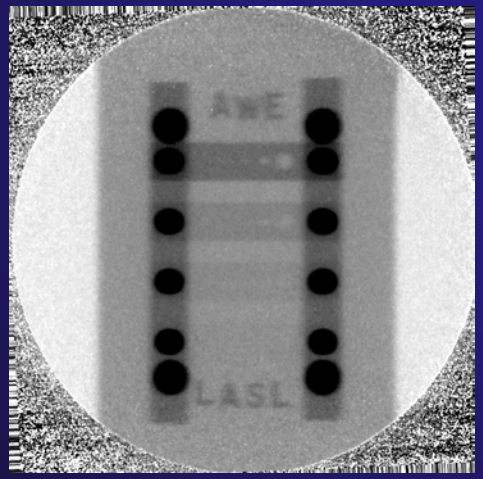
Scattered Light

- Any photon that does not originate as a ray from the source is called “scatter”.
- Is responsible for our ability to see & for blue sky! i.e. blue light scatters more easily.
- Megavolt scatter is mostly Compton scatter with some pair production.
- Increases with: larger field of view, thicker objects, close 2nd conjugate and electron energy.
- Decreases with: collimation, small field of view, large radiographic magnification, Bucky grids and electron energy.



Scott’s first law:
Light scatters, dark does not!

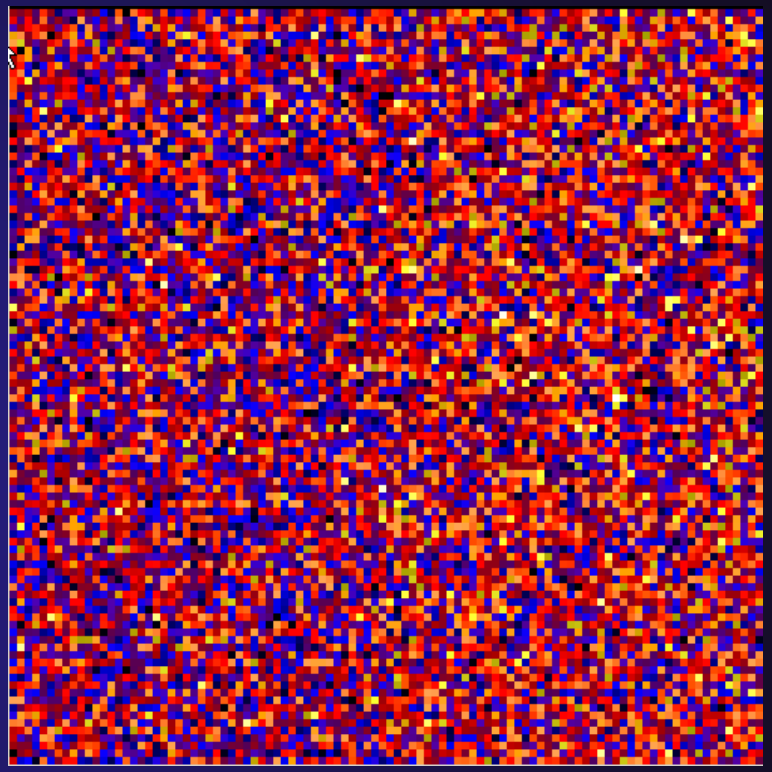
Contrast (Princess and Pea Problem)



- Contrast is just as important as resolution!
- Resolution is a function of contrast. Remember MTF...
- Your eye is only capable of resolving only ~100 distinct shades, but ~40,000,000 colors.
- Digital images can be contrast stretched.
- Scattered light degrades contrast. e.g. lens flare, glare.
- Scattered x-rays degrade contrast too!

Optimal contrast

- Perceived vs statistical contrast.
- Differential absorption
  - Materials absorb and transmit radiation differently depending on their density and material type.
  - Scattered, absorbed, transmitted rays.
- Contrast is result of differential absorption of material.
- Higher energy x-rays/photons required for contrast with thick, dense objects.
- Carefully match both the x-ray flux and the x-ray energy to obtain optimal statistical information

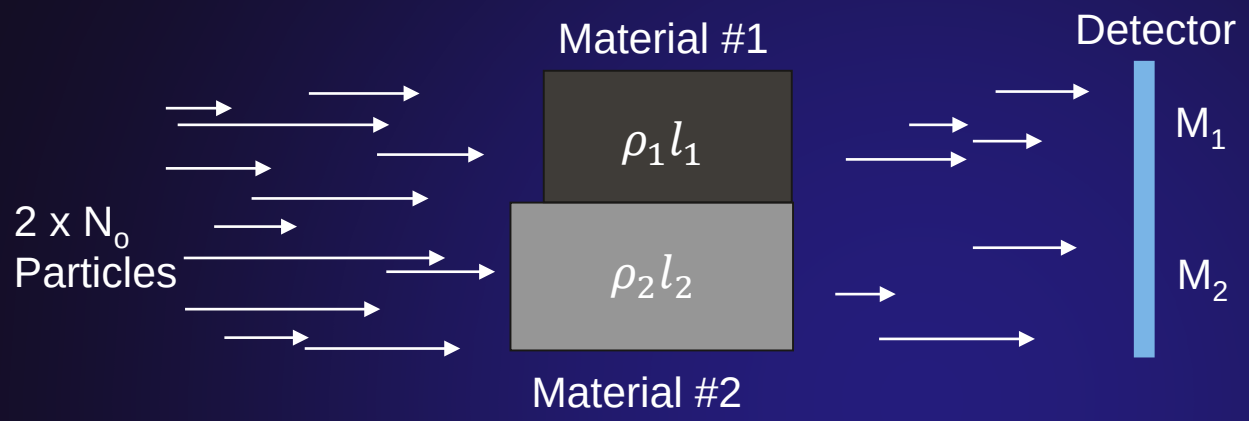


2 Regions (0.5cm x 1cm) with 1% pathlength difference and 0.1mm pixels (α=0.99)

$$\lambda_{opt} = \frac{\rho l}{2}$$

$$\lambda = \left(\frac{\mu}{\rho}\right)^{-1}$$

Statistics of differential absorption



$$M_1 = N_0 \exp\left(-\frac{\mu}{\rho}\rho_1 l_1\right)$$

$$M_2 = N_0 \exp\left(-\frac{\mu}{\rho}\rho_2 l_2\right)$$

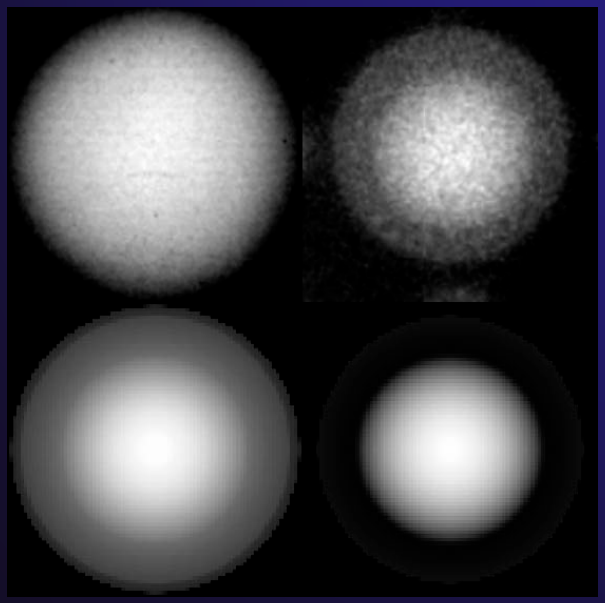
$$\Delta M = M_1 - M_2 = N_0\left[\exp\left(-\frac{\mu}{\rho}\rho_1 l_1\right) - \exp\left(-\frac{\mu}{\rho}\rho_2 l_2\right)\right]$$

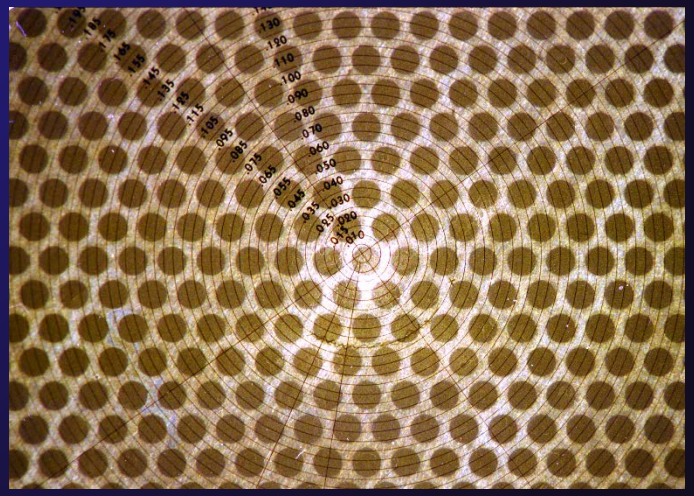
$$\sigma_{\Delta M} = \sqrt{\sigma_{M_1}^2 + \sigma_{M_2}^2} \qquad \sigma_{M_1} = \sqrt{M_1} \qquad \sigma_{M_2} = \sqrt{M_2}$$

$$\sigma_{\Delta M} = \sqrt{M_1 + M_2} = \sqrt{N_0\left[\exp\left(-\frac{\mu}{\rho}\rho_1 l_1\right) + \exp\left(-\frac{\mu}{\rho}\rho_2 l_2\right)\right]}$$

Bucky grid

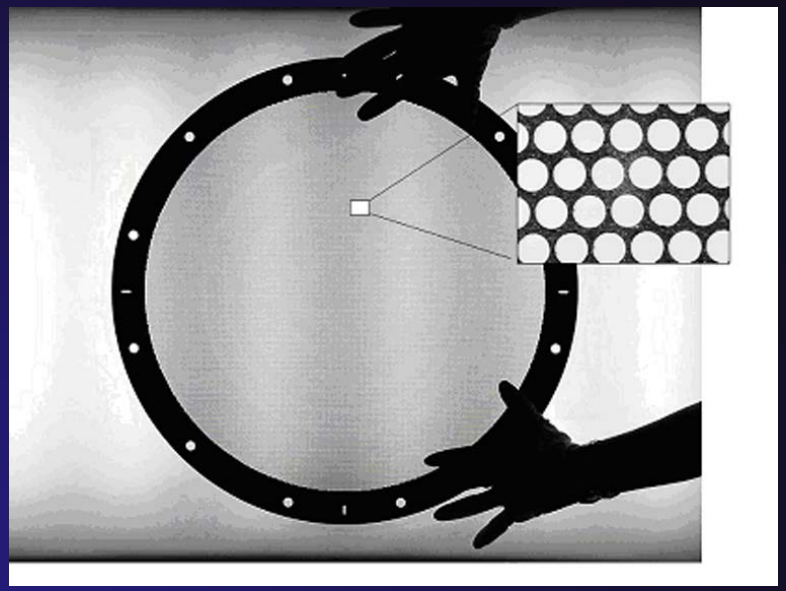
- Bucky Grids were patented in the early 1920's by Hollis Potter and Gustav Bucky and are employed worldwide today at low energies (<100 keV).
- Reduces amount of scatter which reaches the detector.
- Improves contrast resolution, linearity, and signal-to-noise (potentially).

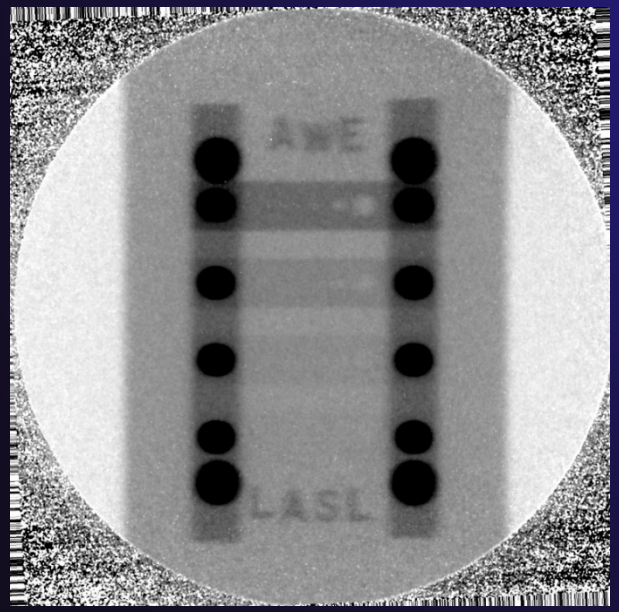




DARHT bucky grid

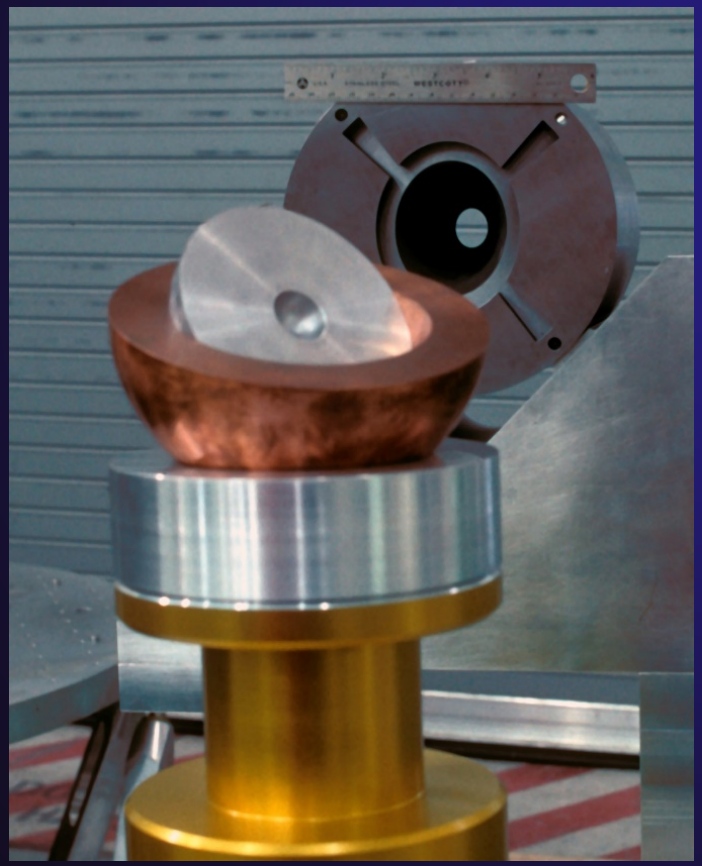
- Precision manufactured cast tungsten.
- 137,000 holes per plate, 120 plates.
- 45 cm diameter, 40 cm thick.
- Rejects scatter >20:1.
- Gauging sensitivity of better than 0.1% through 1 foot of steel.

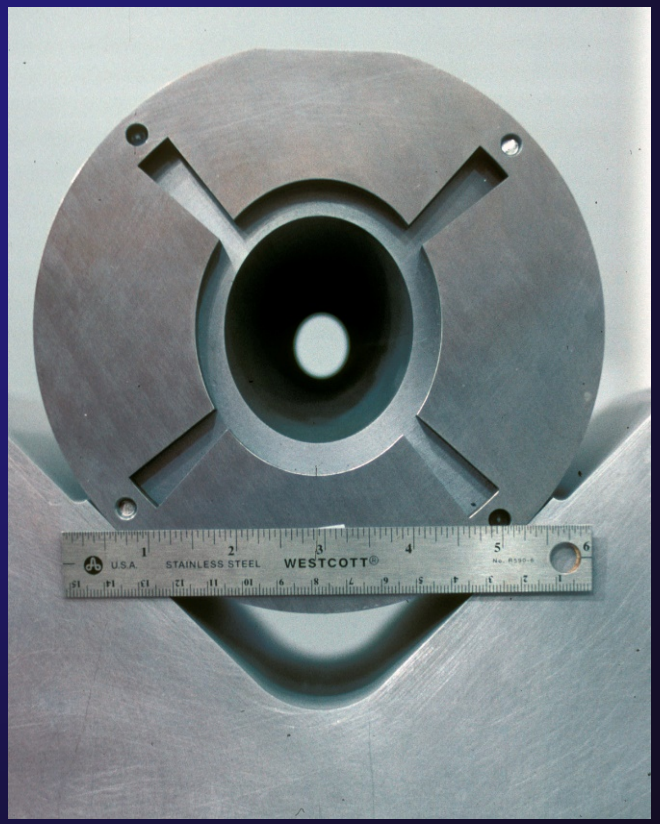




Graded Collimators

- Flatten field and reduce dynamic range.
- Dramatically reduce scatter.
- Are essentially a radiographic apodizing filter.
- Homogenizes the beam spectrum.

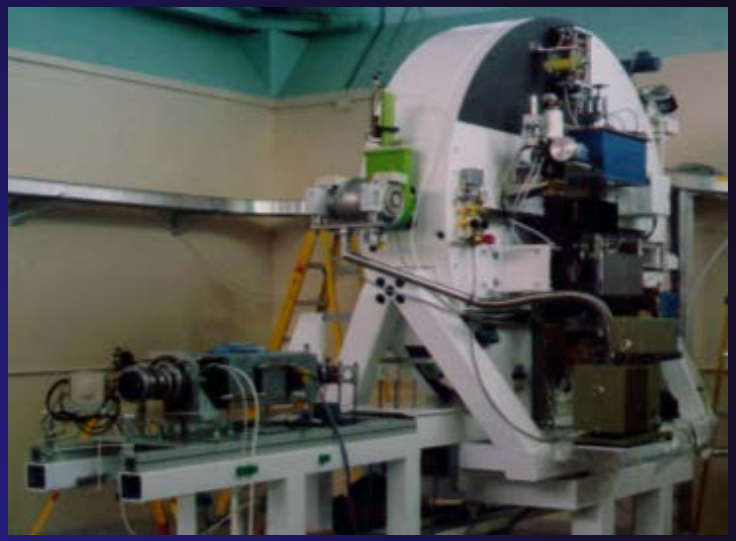




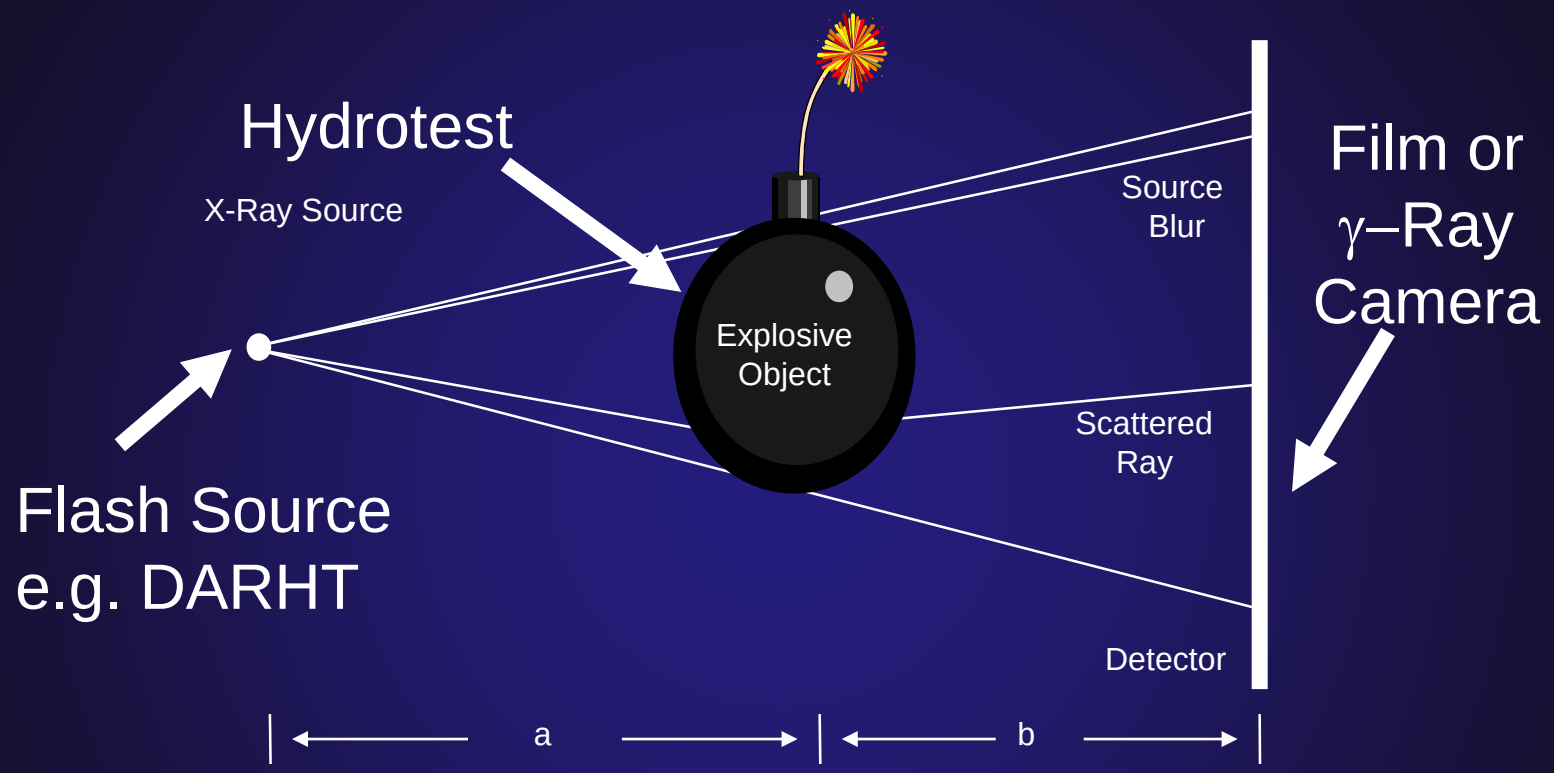
Static vs. Dynamic Radiography

Static Radiography

- Used for calibration studies, pre-shot device inspection, device assembly.
- Typically either a linac or a racetrack microtron.
- Frequently co-located with major hydrotesting facilities.
- Usually heavily shielded indoors.
- Commercially available from JME, Varian, and Scandatronix.



Flash Radiography



"Dynamic radiography has provided important knowledge of primary functional considerations and interactions of a primary with its surroundings, and will continue to be an essential design tool for the foreseeable future."
-Seymour Sack

Hydrotesting history…

- Modern hydrotests can cost ~$10M each.
- Historic shot rate was as high as a few dozen shots PER DAY.
- As a child, I used to set my watch by them.

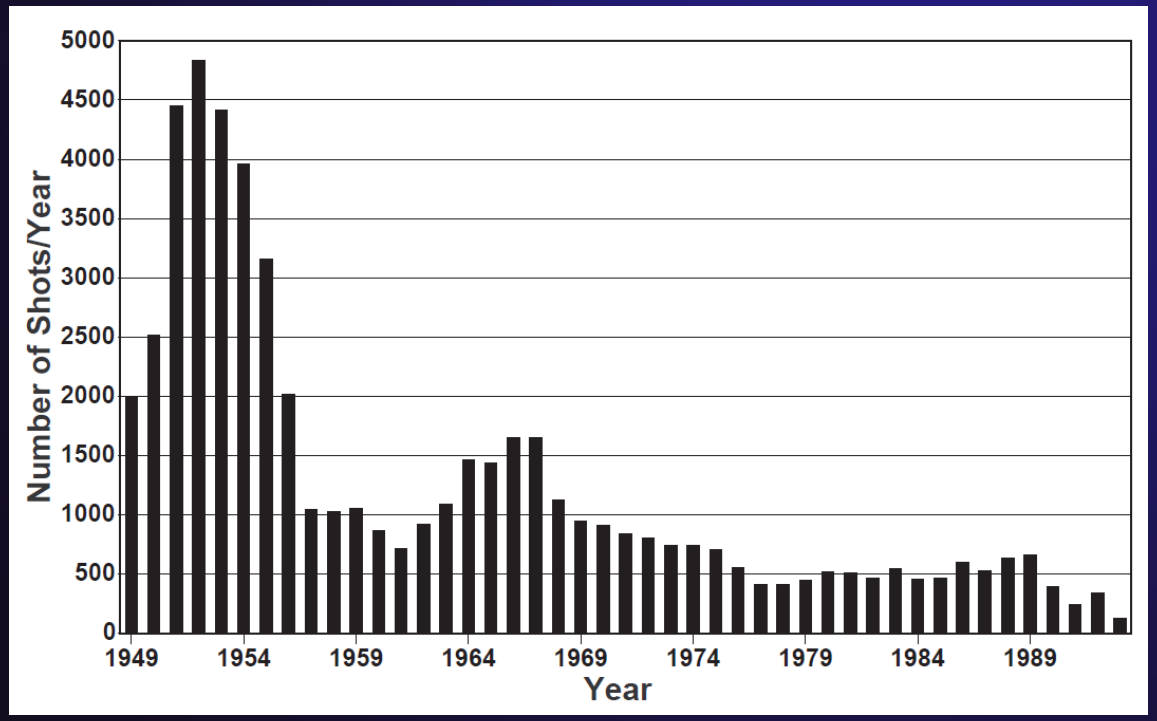


Figure: Shots fired at TA-36 from 1949 through 1993. The shots shown for 1949 are shots fired by the group that occupied the newly created firing sites at TA-36 in early 1950. The intent of this graph is to illustrate the level of work with explosives during various periods. Production and other test firing groups would likely reflect the same level of effort; however, it must be realized that the experimental work became more complex after 1955. The data for 1984 include only shots fired from April through December, and the data for 1993 are only for January through June.

Early Flash Radiography at Los Alamos

"In the early part of the program the chief objective was to adapt X-ray techniques to large scale Early Flash Radiography at Los Alamos implosions. It was proposed to actually follow the course of the implosion by detecting the incidence of the X-rays as a function of time, using a grid of small Geiger counters. The principal aims of the program were: (1) reliable action of the counters, and (2) reduction of the amount of scattered radiation. These objectives were pursued relentlessly, but because of the great technical difficulties, with very little real success, the program was dropped in March, 1945."

– Project Y History.

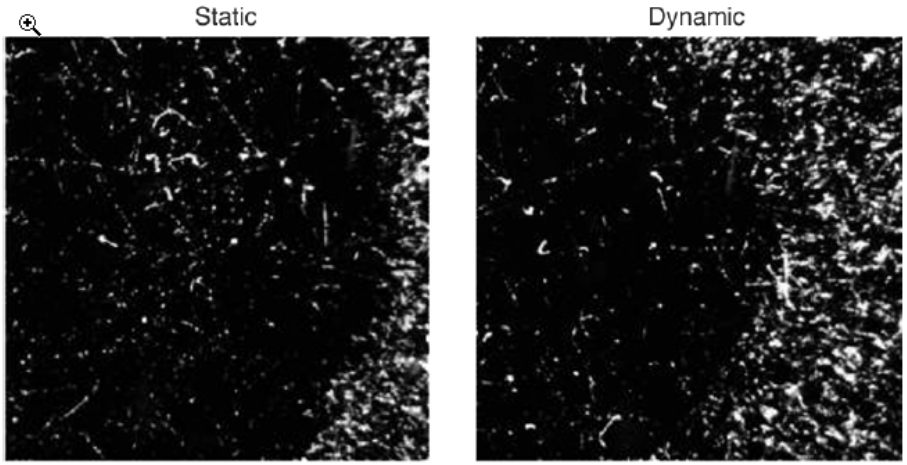
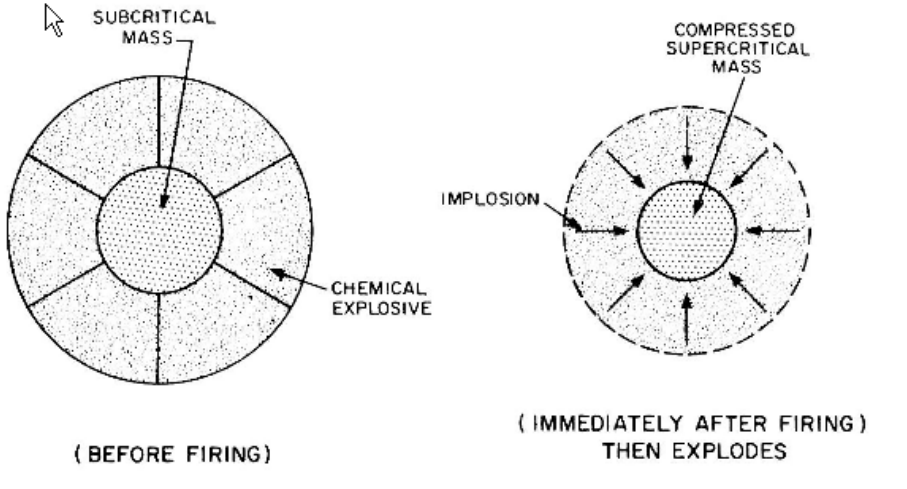
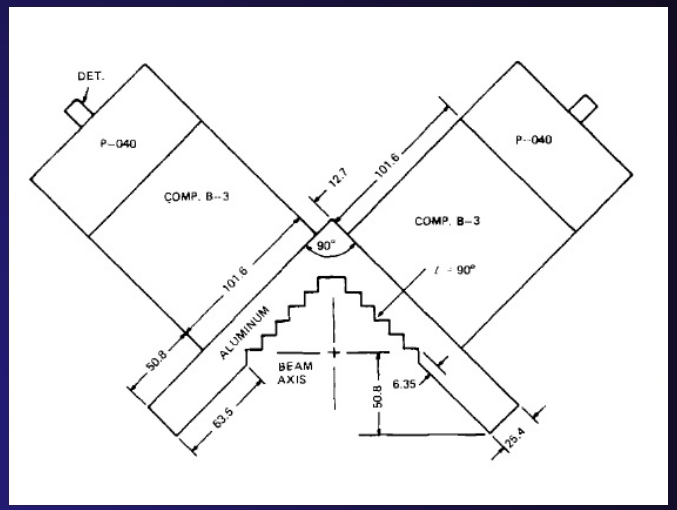


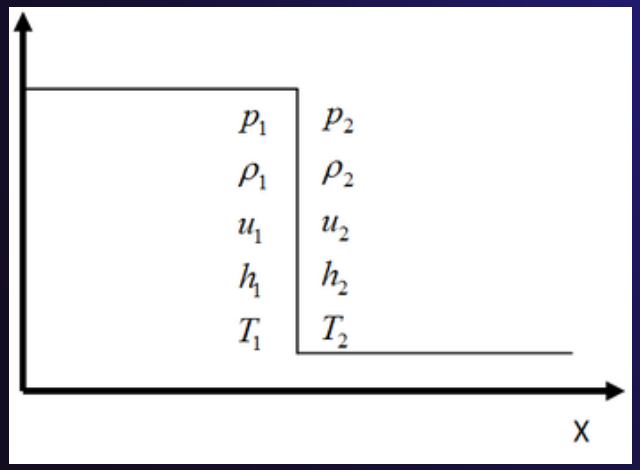
Figure 2. Radiographs of an Explosively Driven Implosion Experiment
These radiographs were taken in 1944 to image the outside edge of the surrogate pit during a hydrotest. The x-rays used to image the implosion were generated with the 15-MeV electron beam from the betatron borrowed from the University of Illinois. The detector consisted of a lead glass converter and a Wilson cloud chamber to detect the recoil electrons. The dark area in each image is the shadow cast by the pit. The radius of the pit is smaller in the right image.

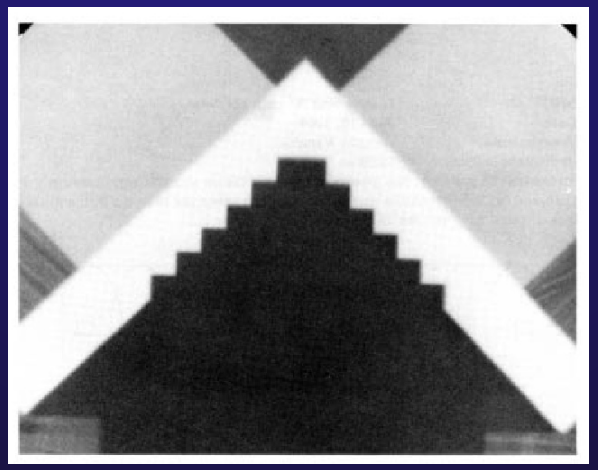


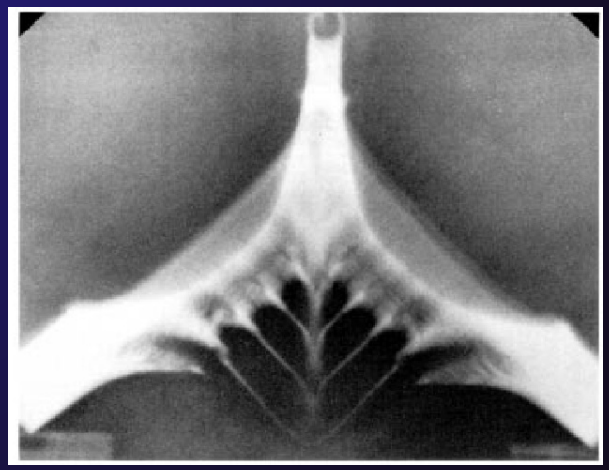
Dynamic (aka Flash) Radiography

- Determines EOS parameters: pressure, temperature, density, shock velocity, particle velocity, internal energy relationships.
- Important in weapons hydrodynamic design & yield calculations.
- High explosives drive shock waves into material.
- Can be measured with gas guns, diamond-anvil cells, pin diagnostics and/or pulsed radiography.



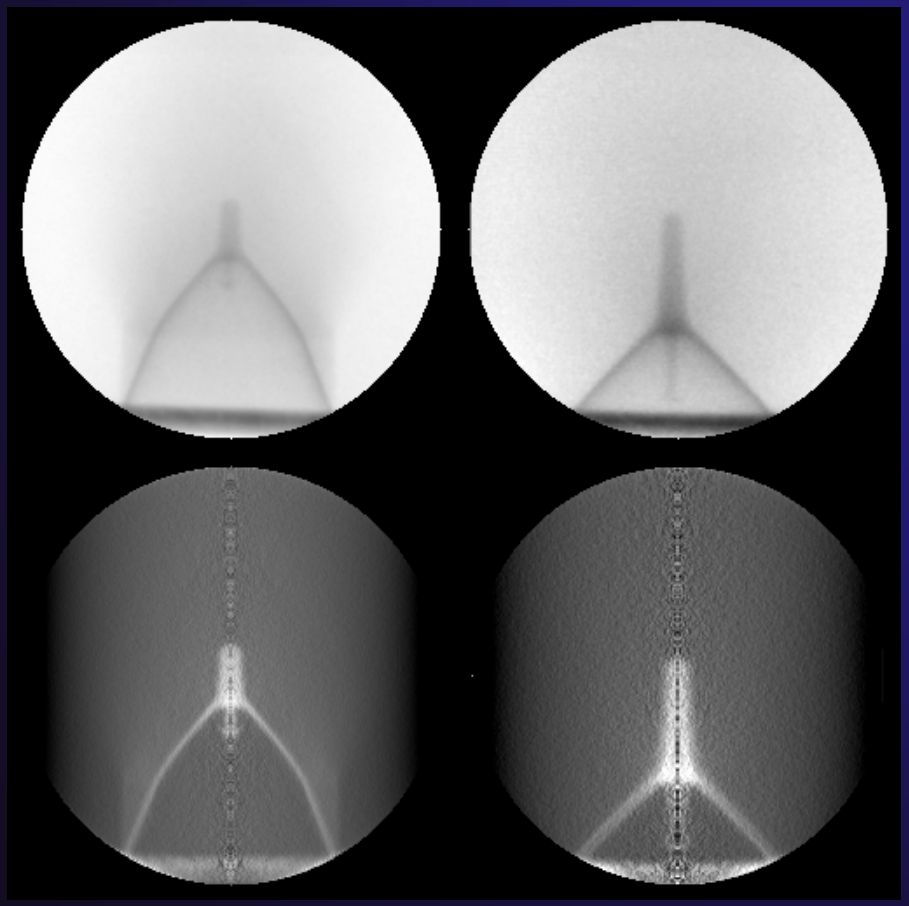


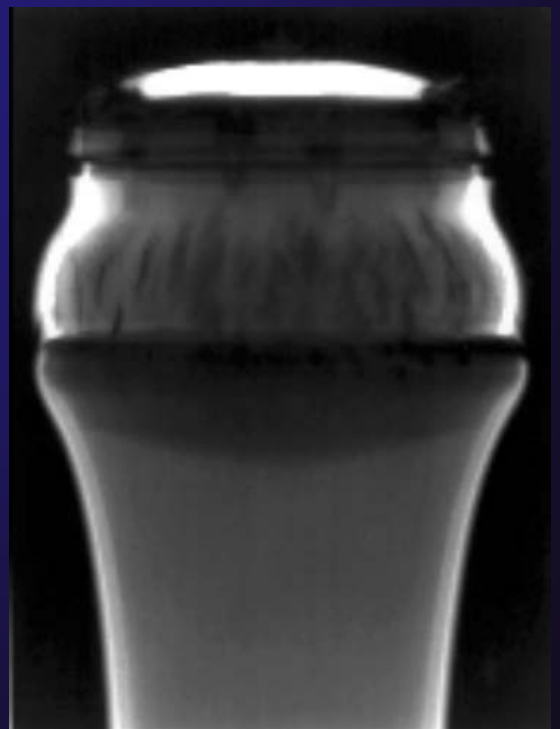




Dynamic Radiography

- Metals and other materials flow like liquids under high temperatures and pressures produced by HE.





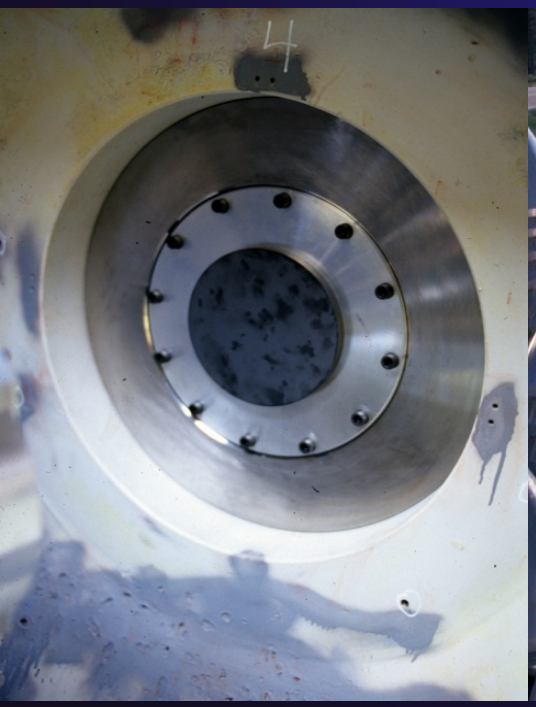
Blast Protection

Flying debris (aka shrapnel)

- Hydrotest shrapnel and debris can fly over a mile (and be collected over a similar distance!).
- Velocities can exceed 2 km/sec.
- Accurate material balance & recovery is nearly impossible for open air shots.
- Some parts remain mostly intact!
- Debris classification remains problematic.

Blast Protection

- Armor for film, gamma cameras, and other diagnostic equipment.
- Typical materials: glass, aluminum, sand bags, armor plate.
- Less common and more expensive: Spectra, boron carbide, Kevlar.



Vessels

- Typically spherical or cylindrical with hemispherical heads.
- Can contain up to several hundred kilograms of high explosives.
- Can be used to contain plutonium and other hazardous materials.
- Can be single- or multi- use.
- Russians call them “Kolbas”.

Firing Chambers

- Large, concrete chambers used to limit off-site exposure to hazardous materials.
- Chamber damage limited by vermiculite, sand bags, foam, and armor.
- Used extensively by AWE (Moguls), and LLNL (CFF).
- Charge limits of 10s of kg.
- On-site cleaning and filtering required.

Foaming

- Used to prevent hazardous material dispersal off-site.
- Also used to increase facility blast loading limits.
- Concentrates worker exposure to hazardous materials.
- Mitigates fire hazards from shrapnel.
- Complicates shot operations.

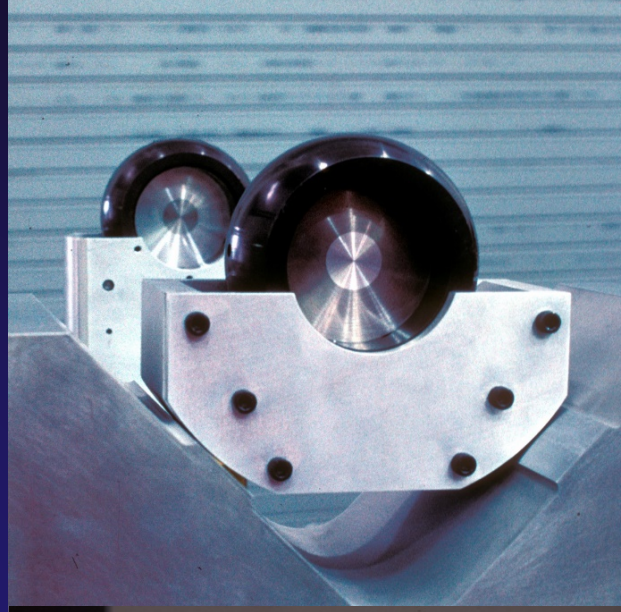
Silos

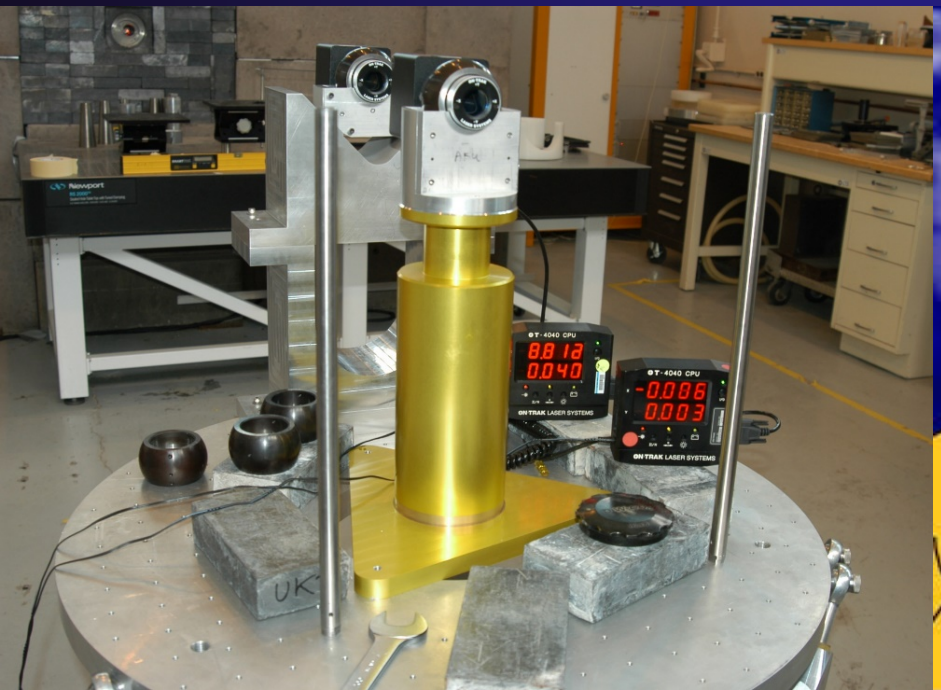
- A hybrid of vessels and foaming.
- Increase blast loading without extremely large metal containers.
- Notable examples include PHERMEX (LANL) and AIRIX (CEA).

Alignment

Radiographic Alignment

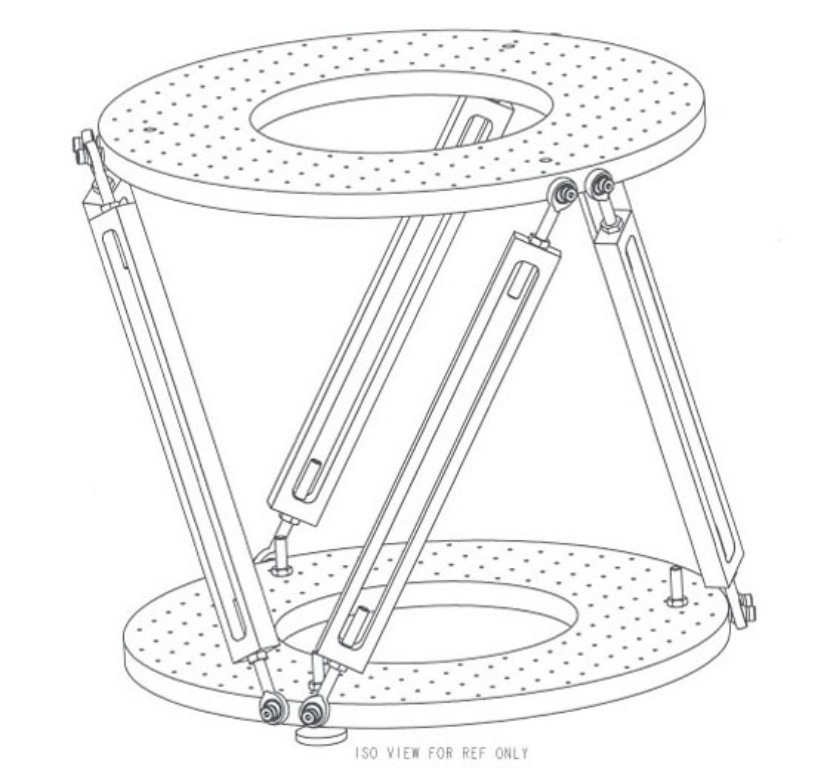
- Uses a combination of optical (typically a transit), radiographic (typically a “ball and washer”), and laser techniques.
- Capable of +/- 0.005” alignment on gas cavity hydrotests.
- “Golden goddess” is a precision machined stand which acts a surrogate for the shot assembly.

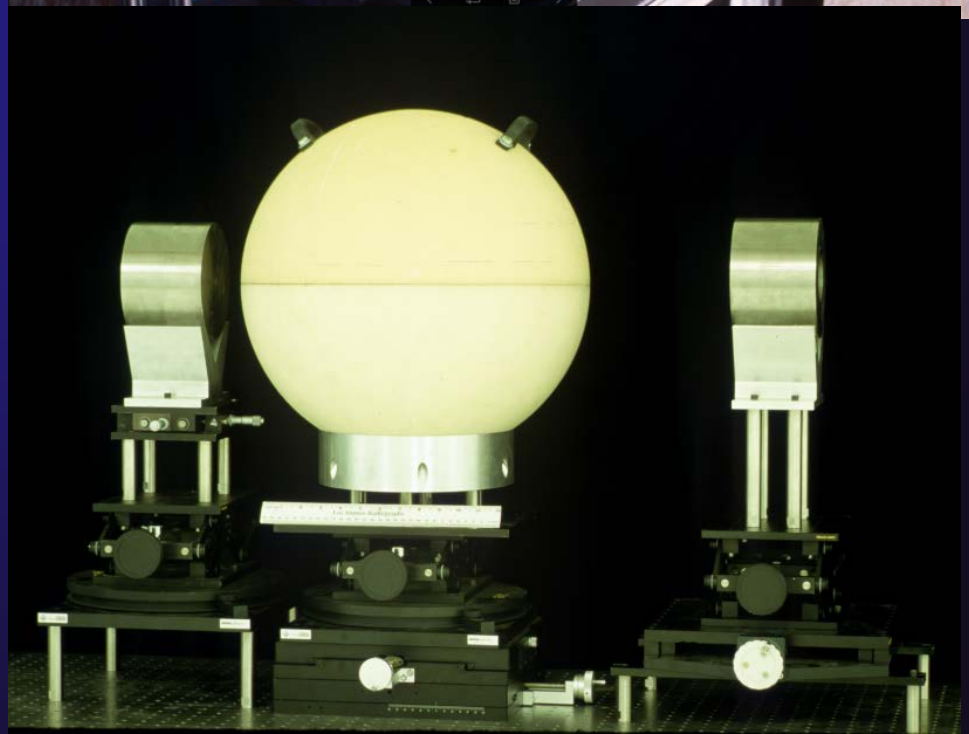




Alignment Stands

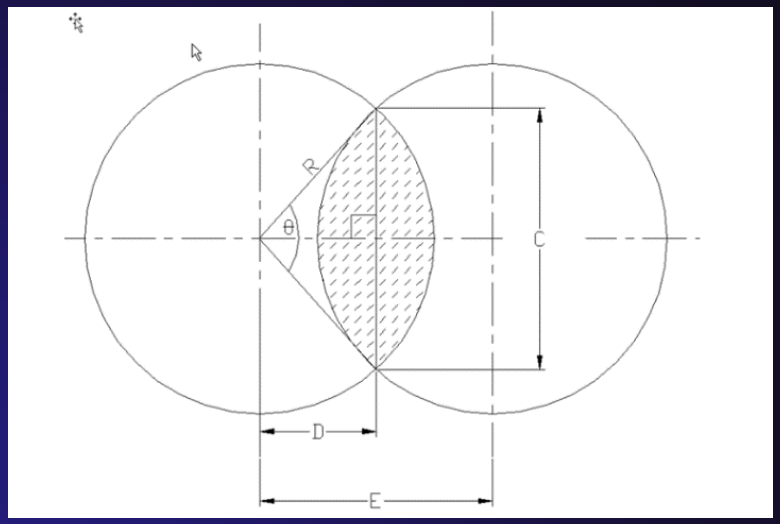
- Frequently use “hexapods”, and optical tables.
- Goal is to align (graded) collimators, shot center, Bucky grid and radiographic spot.

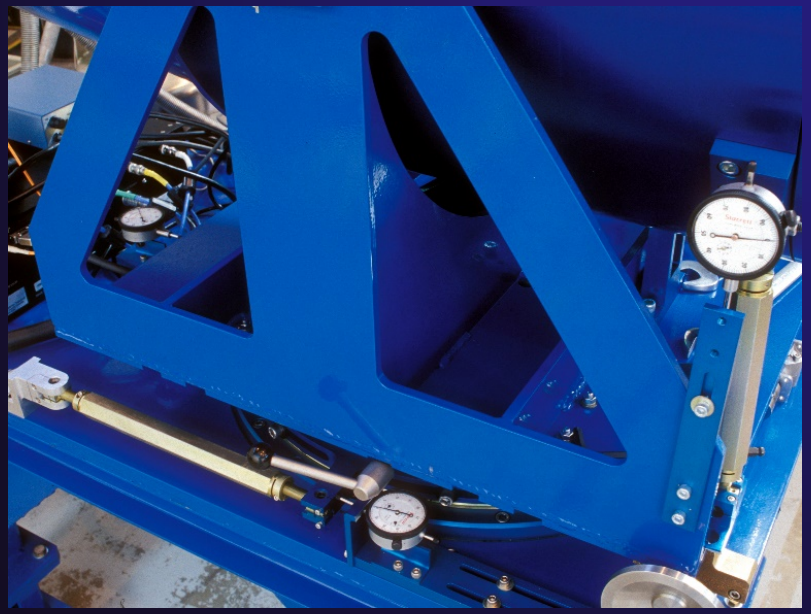


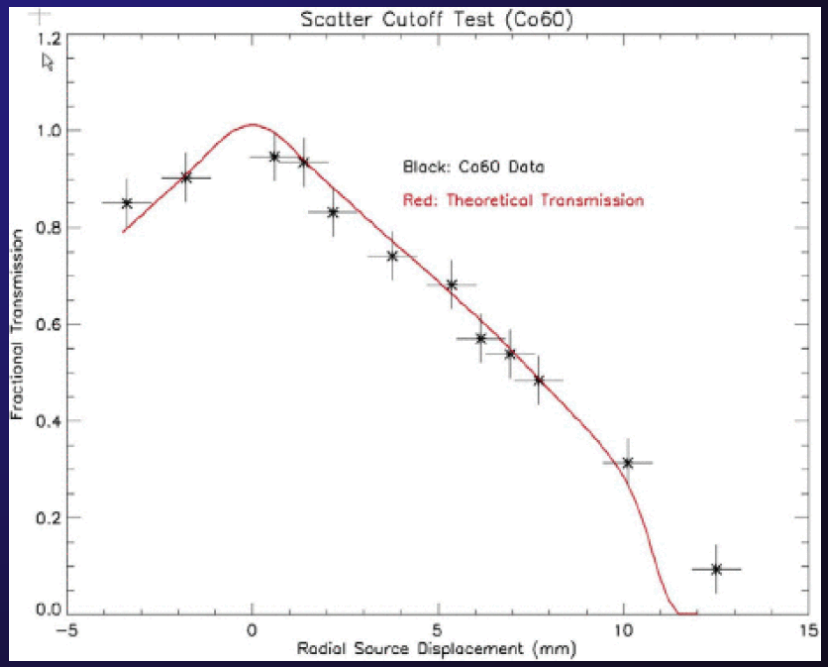


Bucky Grid Alignment

- Issue is how to point 137,000 soda straws within 1/100th of a degree.
- Special, heavy duty tip-tilt table accomplishes this task.
- Accuracy is verified with radiographic fiducials.
- Pointing accuracy is a small fraction of a degree for ~4000 lb grid.







DACS Alignment System at DARHT

- Allows for shot alignment on BOTH radiographic axes at DARHT.
- Requires motion in all six DOF using hexapod.
- “Rough” collimators aligned on an eccentric.
- Graded collimators aligned by construction with “basket”.
- Entire shot assembly is aligned prior to insertion by using radiographic fiducials.
- Originally designed for DYNEX shots with +/-0.010” complete system alignment.
- Temperature compensated to 1st order.
- Pre-weighted for shot stand deformation under graded-collimator and shot load.

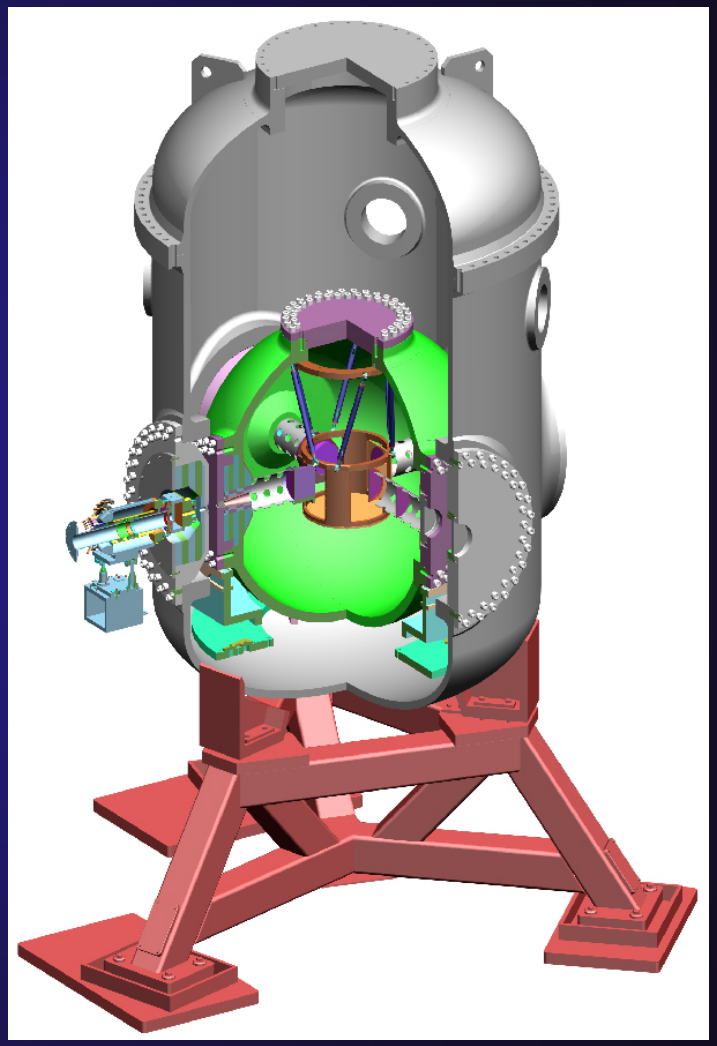


Image Analysis & Synthesis

Image Analysis

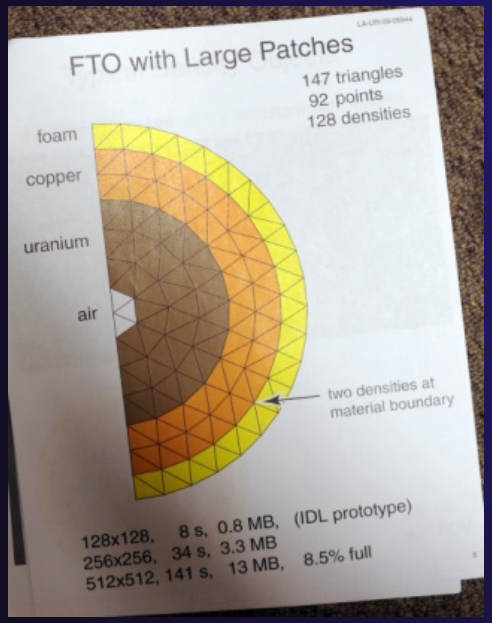
- Analysis does not add information, analysts do.
- Used to correct known or systematic defects, and improve visualization of important features.
- Examples include edge fitting, tomographic unfold, filtering, registration, warping, linearization etc.
- Necessary but not sufficient for quantitative radiography.

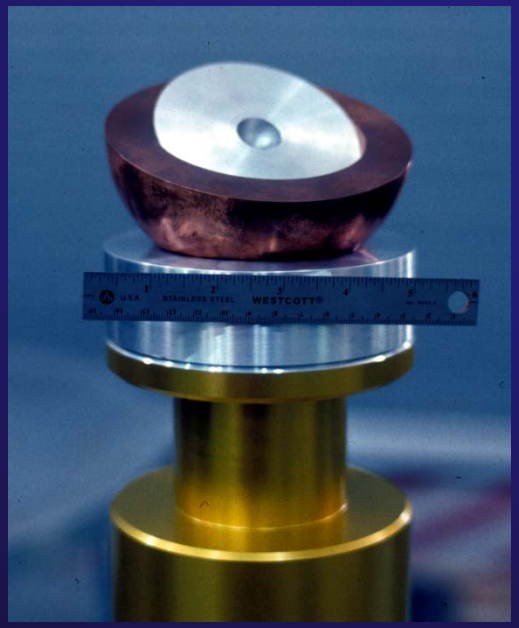
Radiographic Analysis & Synthesis Codes

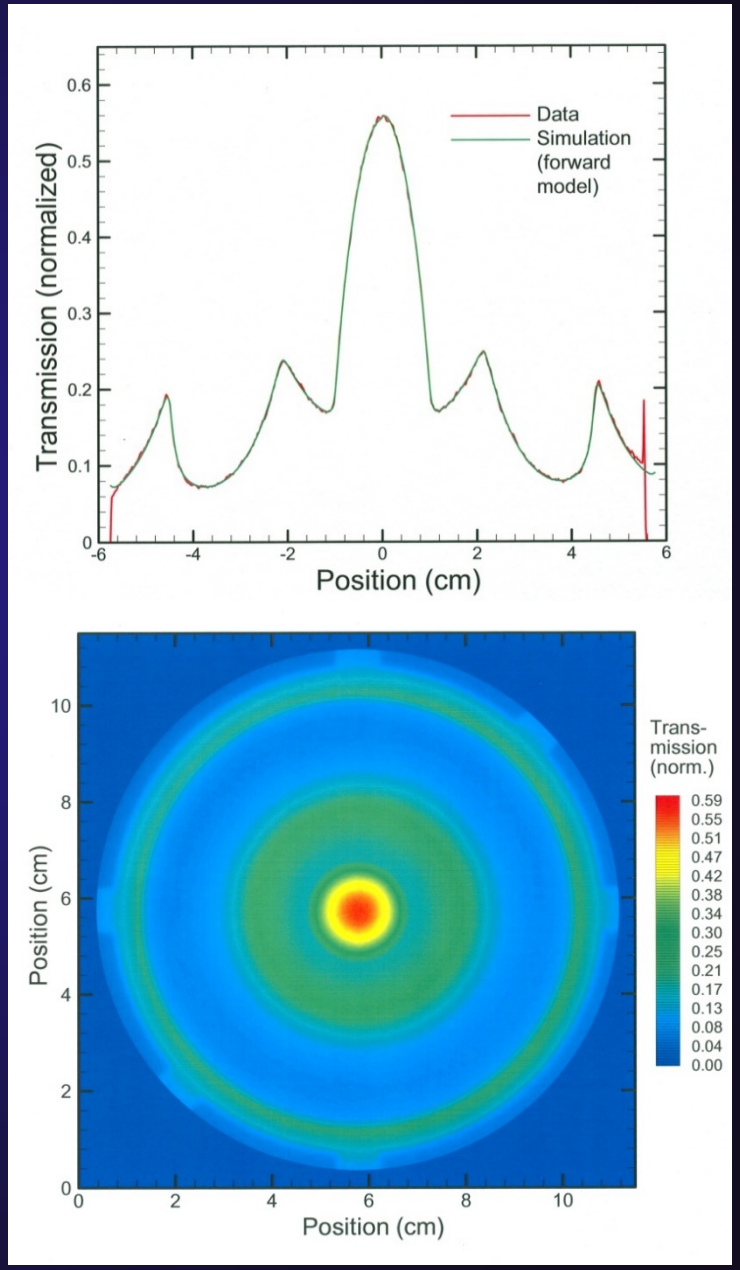
Code	Affiliation	Type	Dim.	Energy	Simulation	Analysis	Scatter	CAD	Hydrocode	Noise Model	Fast?	Interface
MCNP	LANL	Monte-Carlo	3-D	Continuous	Limited	None	Yes	Yes	Yes	No	No	Metacode
ITS	Sandia	Monte-Carlo	3-D	Continuous	Limited	None	Yes	Limited	No	No	No	Metacode
GEANT	CERN	Monte-Carlo	3-D	Continuous	Limited	None	Yes	Yes	No	No	No	Metacode
ALEGRA	Sandia	Monte-Carlo	3-D	Continuous	Limited	None	Yes	Yes	Yes	No	No	Metacode
XTK	Sandia	Photo-Editing	2-D	None	Limited	Limited	No	Limited	No	No	Yes	Graphical
DRIM	LANL	Photo-Editing	2-D	None	None	Limited	No	No	No	No	Yes	Graphical
Photoshop	Adobe	Photo-Editing	2-D	None	None	None	No	No	No	No	Yes	Graphical
BIE	LANL	Forward Model	3-D	Multi-Group	Yes	Yes	Limited	Limited	Yes	Yes	No	Graphical
Syn_Img	LANL	Ray Tracing	2-D	Multi-Group	Yes	None	No	No	No	Yes	Yes	Text
Beer	LANL	Ray Tracing	3-D	Multi-Group	Yes	Limited	No	Yes	Limited	Yes	Yes	Graphical
HADES	LLNL	Ray Tracing	3-D	Multi-Group	Yes	None	No	Yes	Yes	Limited	Yes	Text
XRSIM	Iowa St.	Ray Tracing	3-D	None	Yes	None	Limited	Yes	No	Limited	Yes	Graphical
OSLO	LAMBDA	Ray Tracing	3-D	None	Limited	None	No	No	No	No	Yes	Text
IDL	ITT	Vect. Interpreter	N-D	None	None	Yes	No	No	Yes	No	Yes	Text
MATLAB	UNM	Vect. Interpreter	N-D	None	None	Yes	No	No	No	No	Yes	Text
MAKPIX	LANL	Parametric Model	2-D	None	Limited	Limited	No	No	Yes	Limited	No	Text
Prof. Match	AWE	Parametric Model	1-D	Multi-Group	None	Limited	No	No	Yes	No	Yes	Graphical
PYRAT	LANL	Vect. Interpreter	1-D	Multi-Group	Limited	Limited	Limited	No	Yes	No	Yes	Graphical
JTOT NEEDS		Material ID	3-D	Multi-Group	Yes	Limited	Limited	Yes	Limited	No	Yes	Graphical

DARHT Density Reconstructions

- 1% density reconstructions on FTO => stockpile certification without nuclear testing.
- Uses advanced, forward modeling (BIE) techniques.





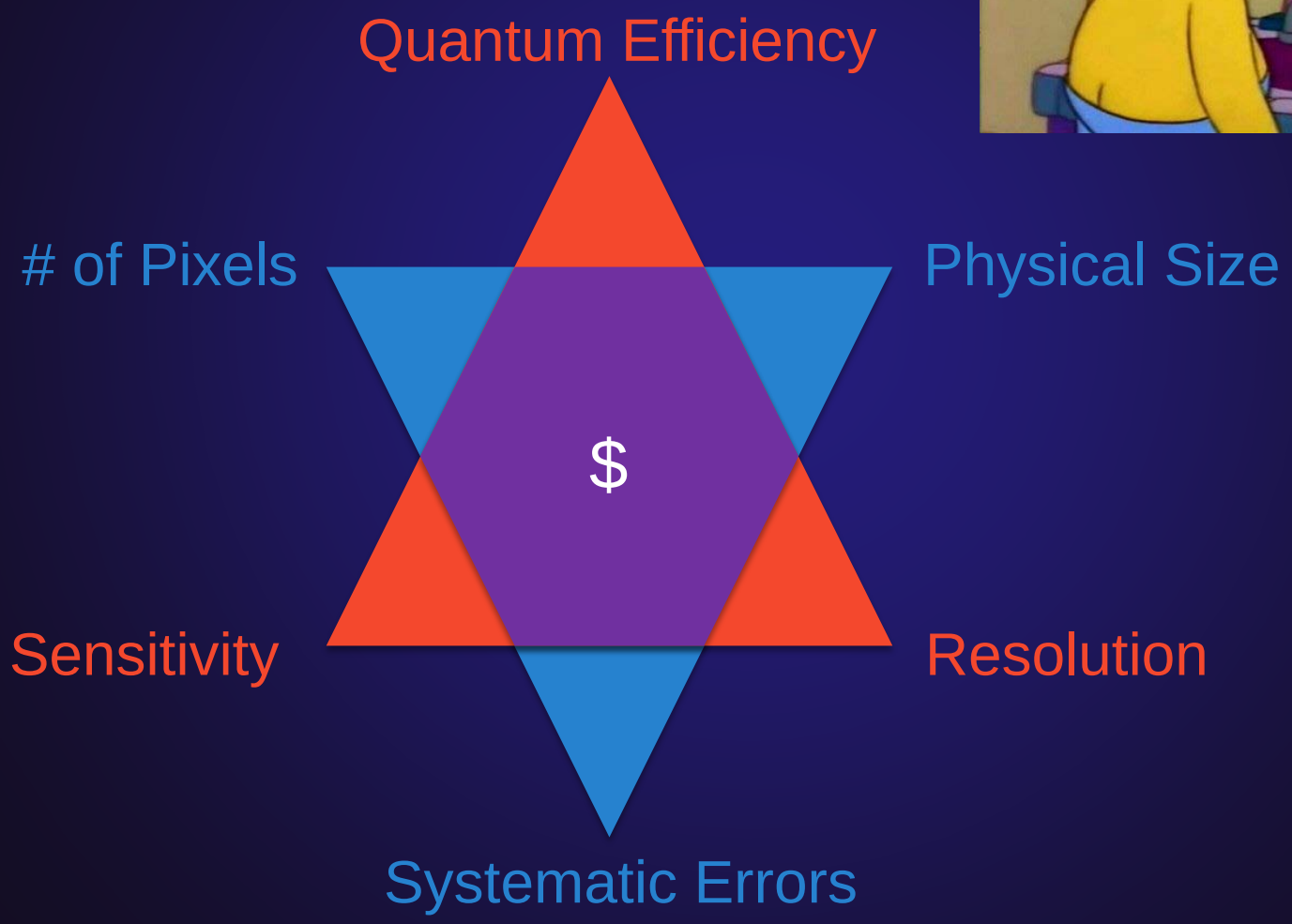


Analysis of FTO Data: Scatter Levels At DARHT And Performance of An Anti-Scatter Grid. Defense Research Review, Vol. 17.1. 2009.

Break

Design Considerations

Real vs Ideal Imagers



Design Issues

- Resolution
- Contrast
- Depth of field
- Optical magnification

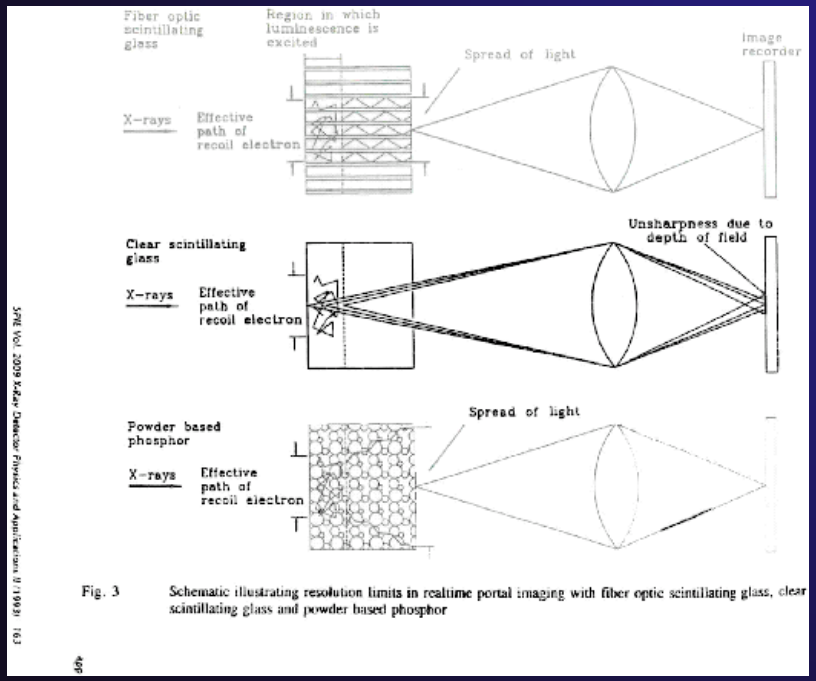


Fig. 3 Schematic illustrating resolution limits in realtime portal imaging with fiber optic scintillating glass, clear scintillating glass and powder based phosphor

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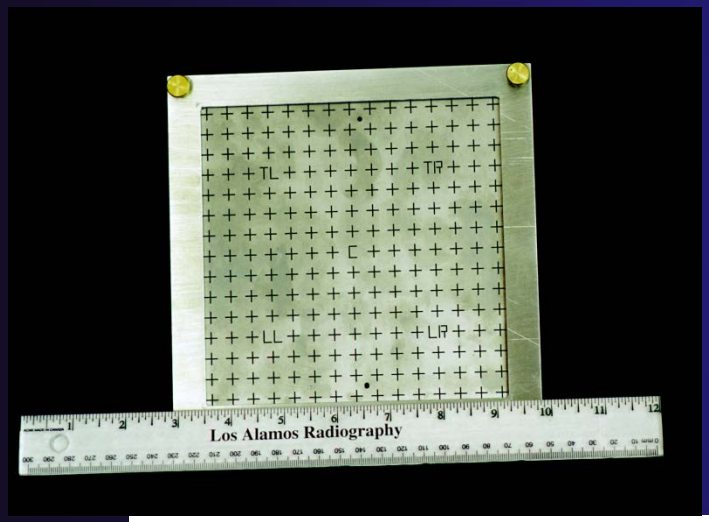
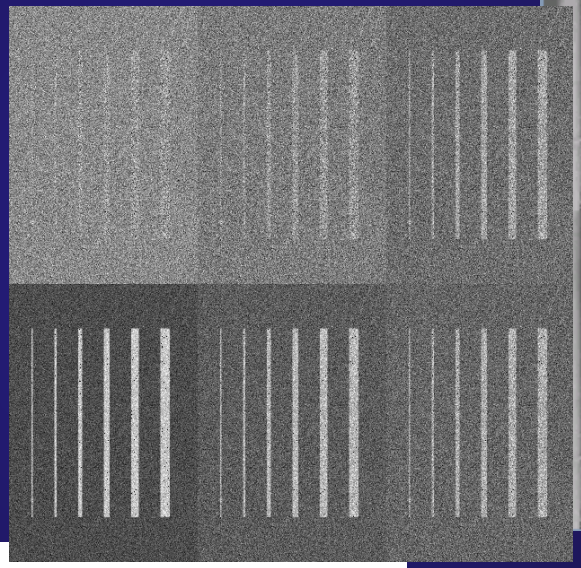
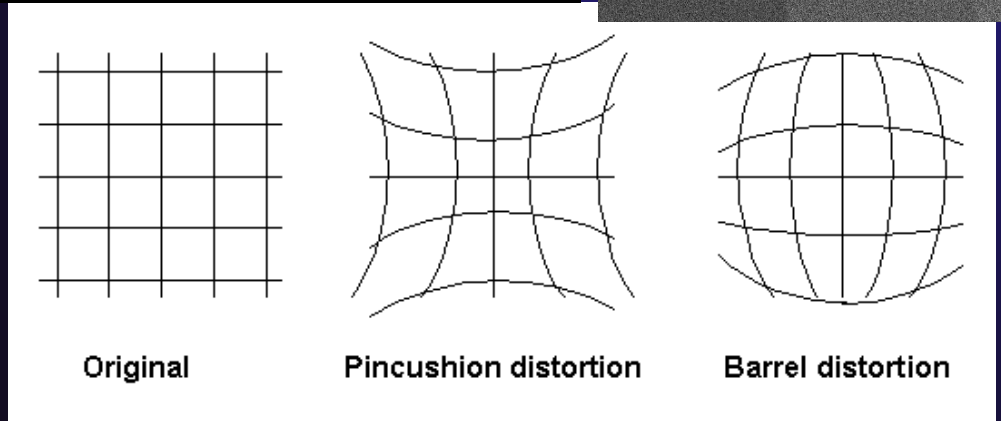
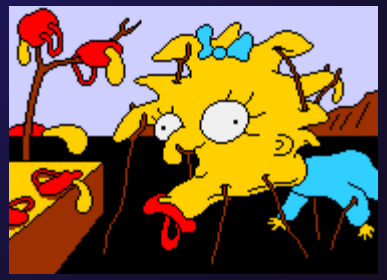
Design Issues cont.

- Quantum Efficiency
- Geometric Distortion
- Dynamic Range









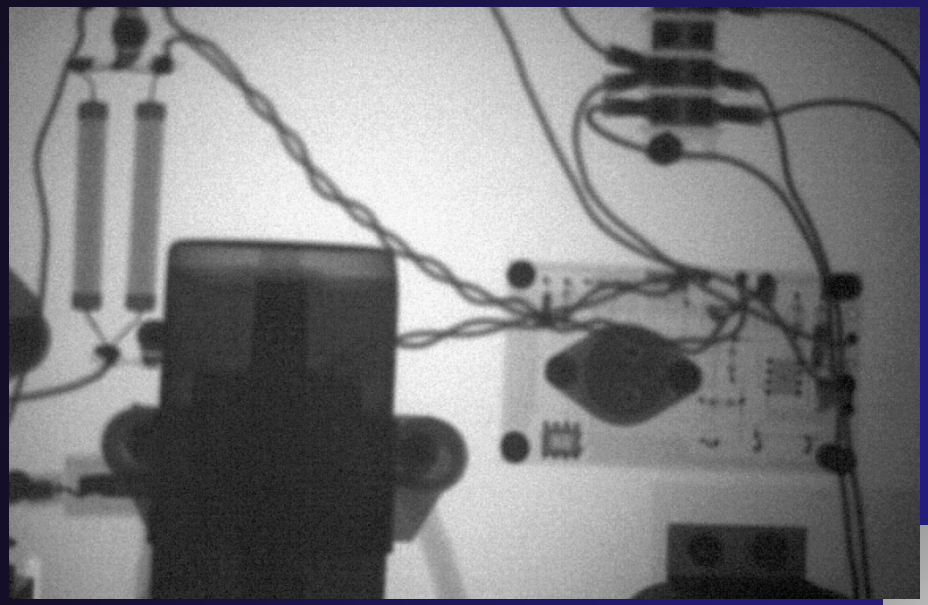
Visible Light Budget For Quantum Limited Performance

- n: visible light photons recorded per x-ray absorbed to maintain quantum limited performance $n >> 1$
- M: optical magnification
- QE_{CCD}: CCD Quantum efficiency at scintillator wavelength
- T_{lens}: Lens transmission
- n_{sc}: Scintillator index of refraction
- $F_{\#}$: Lens F#
- G_{sc}: Average scintillator efficiency in photons/absorbed x-ray

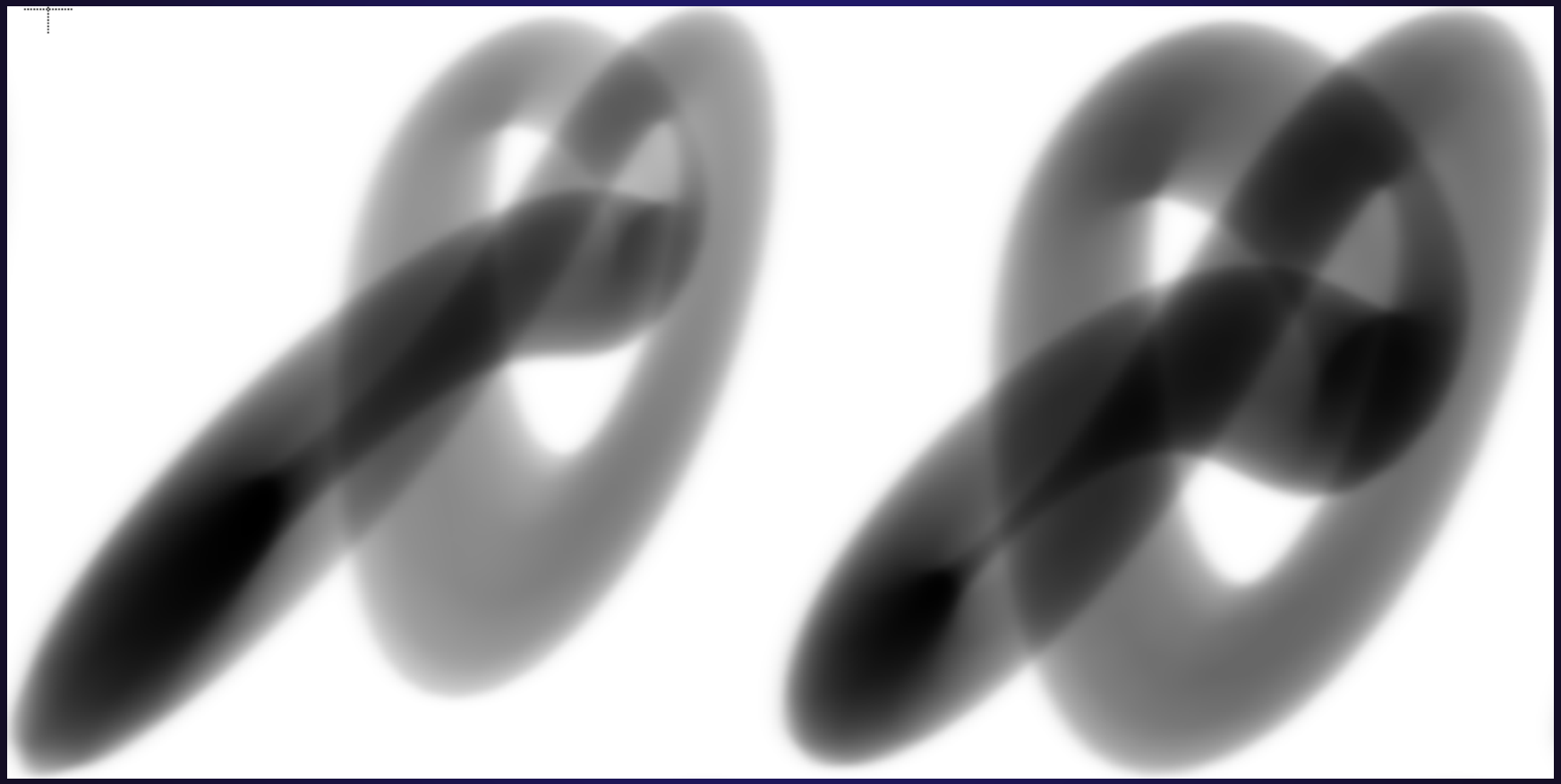
$$n = \frac{G_{sc} M^2 QE_{CCD} T_{lens}}{8\eta_{sc}^2 F_{\#}^2 (1+M)^2}$$

Practical Examples

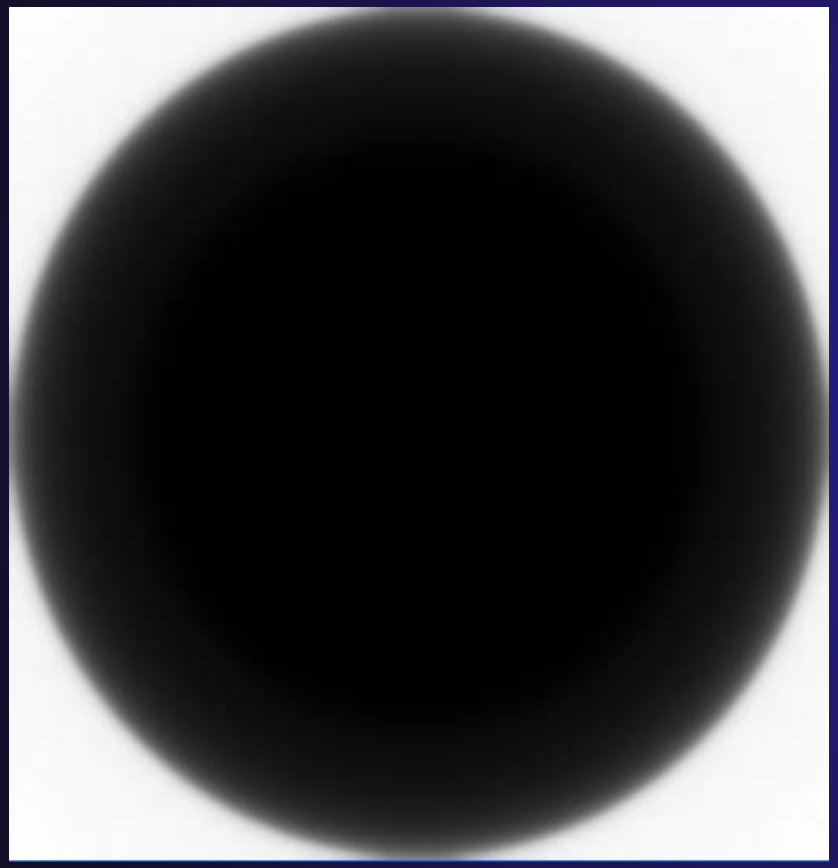
Practical Exercise #1: What are the differences between these two radiographs? Why?

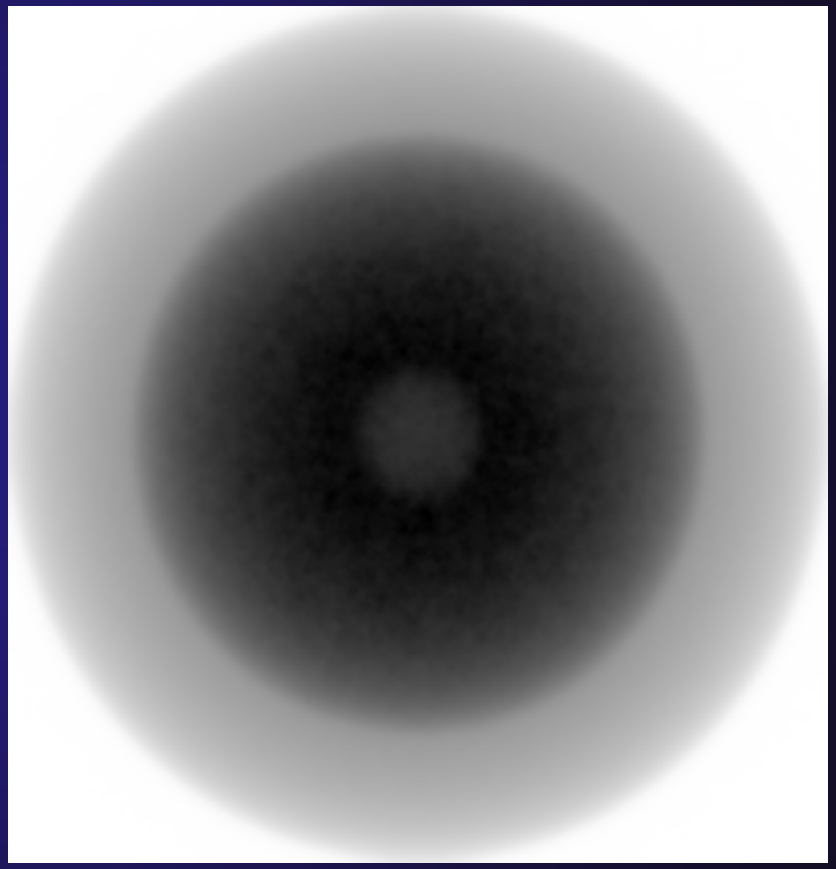


Practical Exercise #2: What are the differences between these two radiographs? Why?

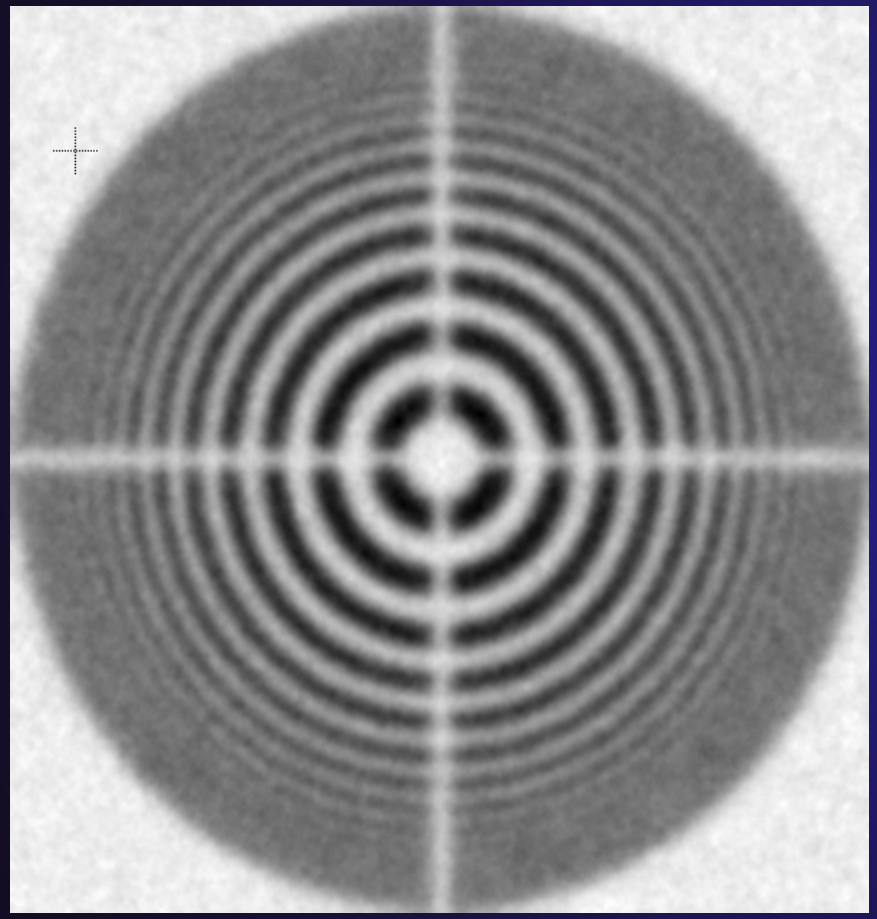


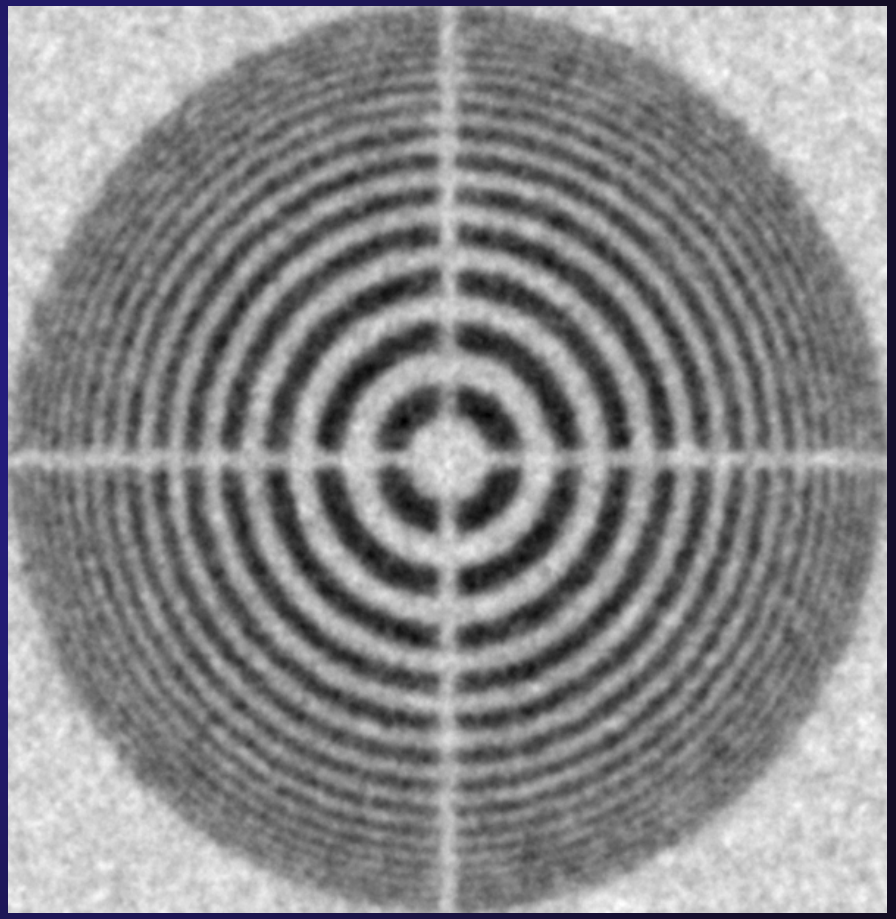
Practical Exercise #3: What are the differences between these two radiographs? Why?



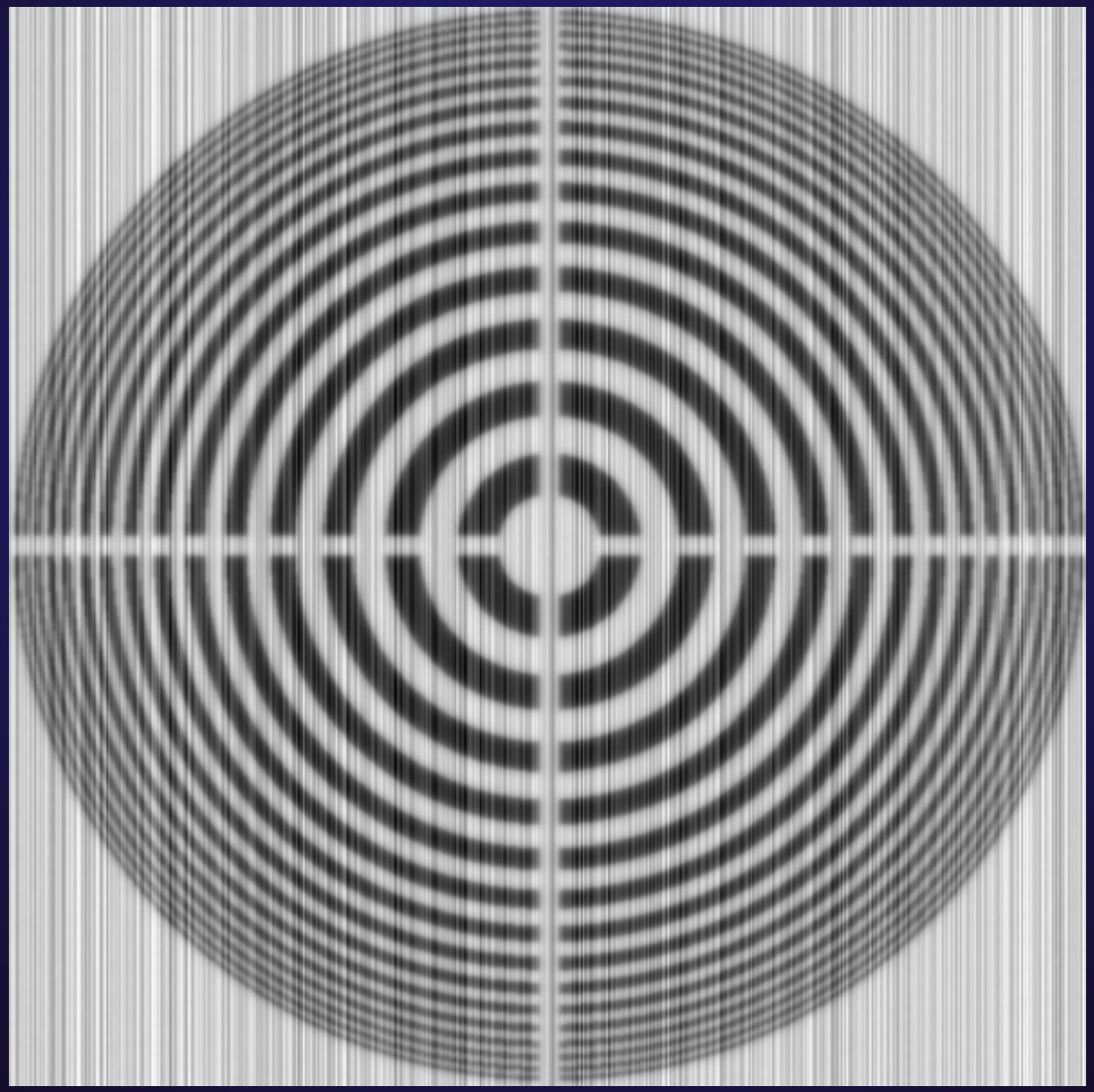


Practical Exercise #4: What are the differences between these two radiographs? Why?

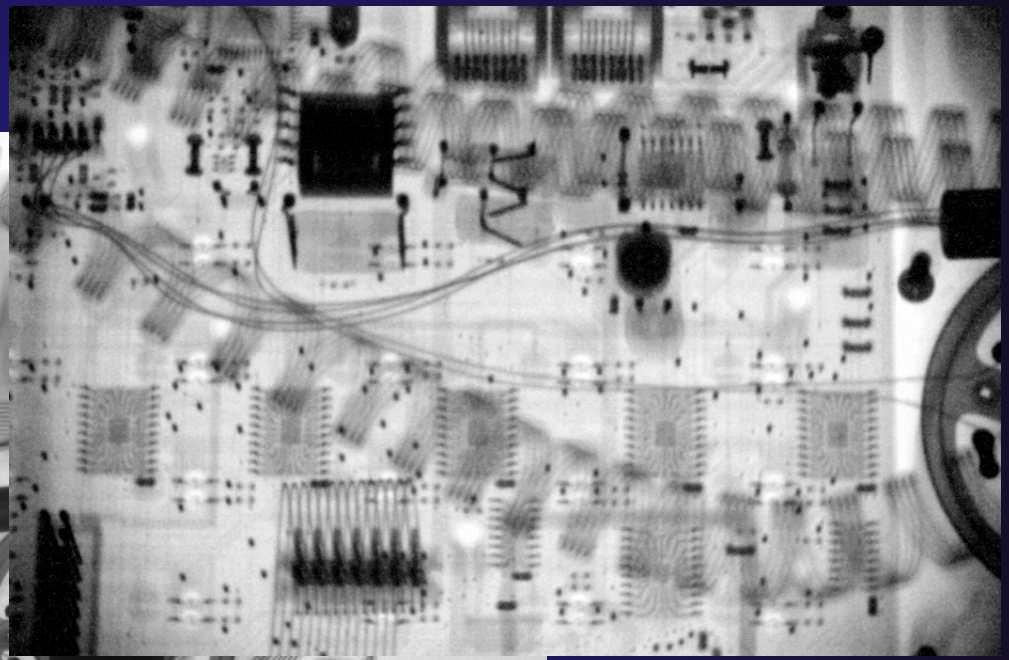


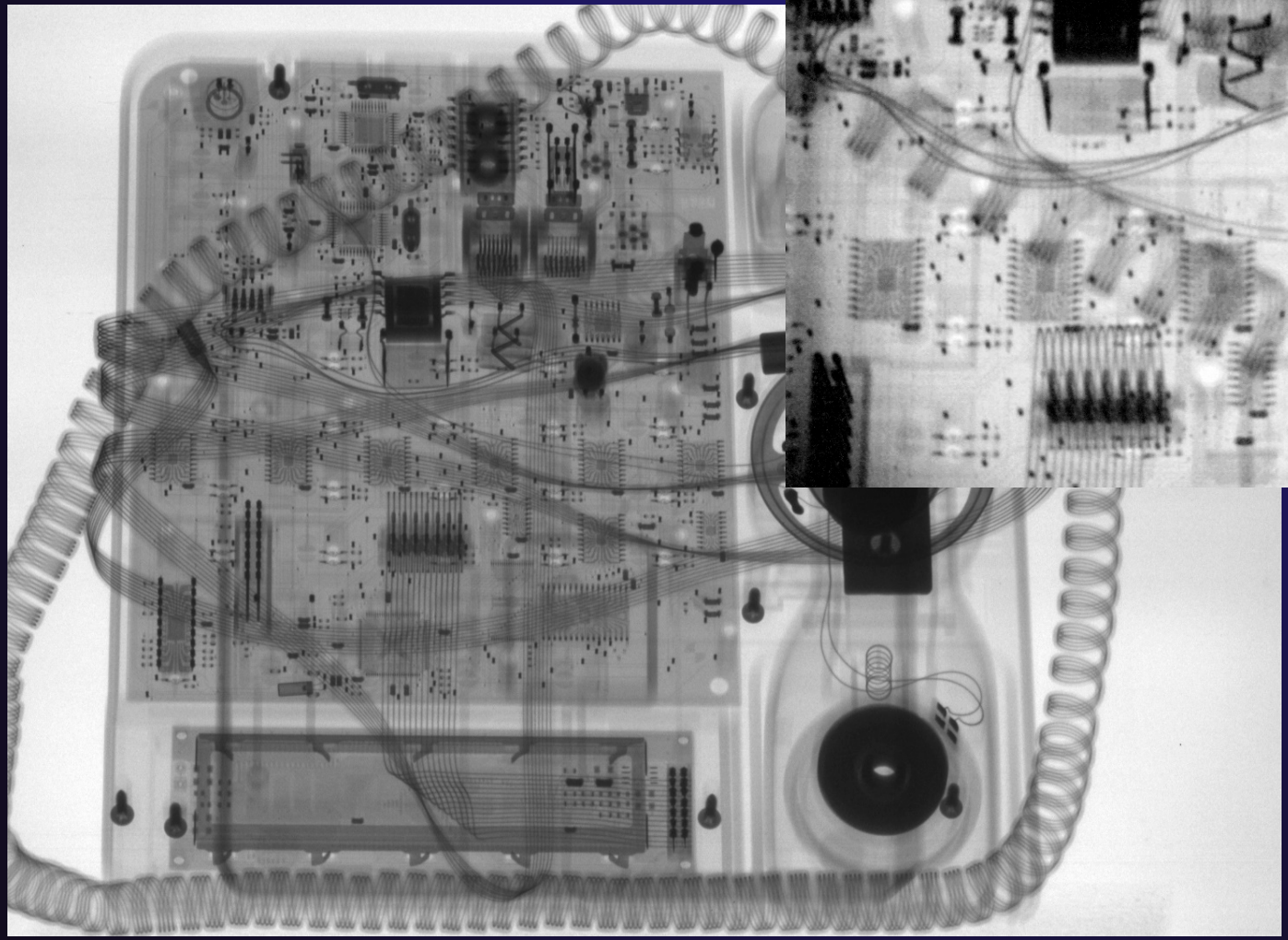


Practical Exercise #5: What should be done to improve this radiograph? Will higher dose help? Why/Why Not?

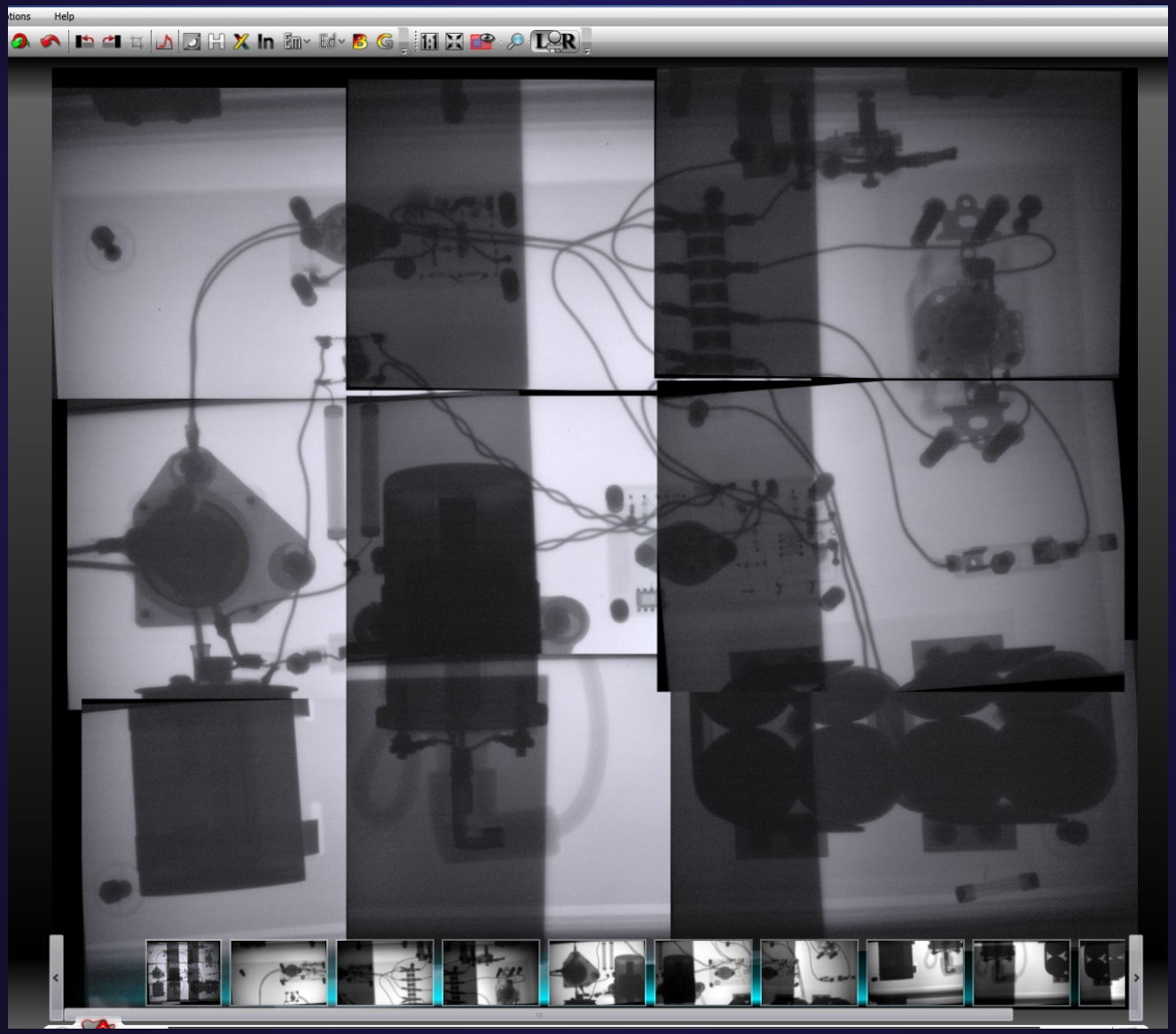


Practical Exercise #6 – How are these images different? Which one is more useful? Why?

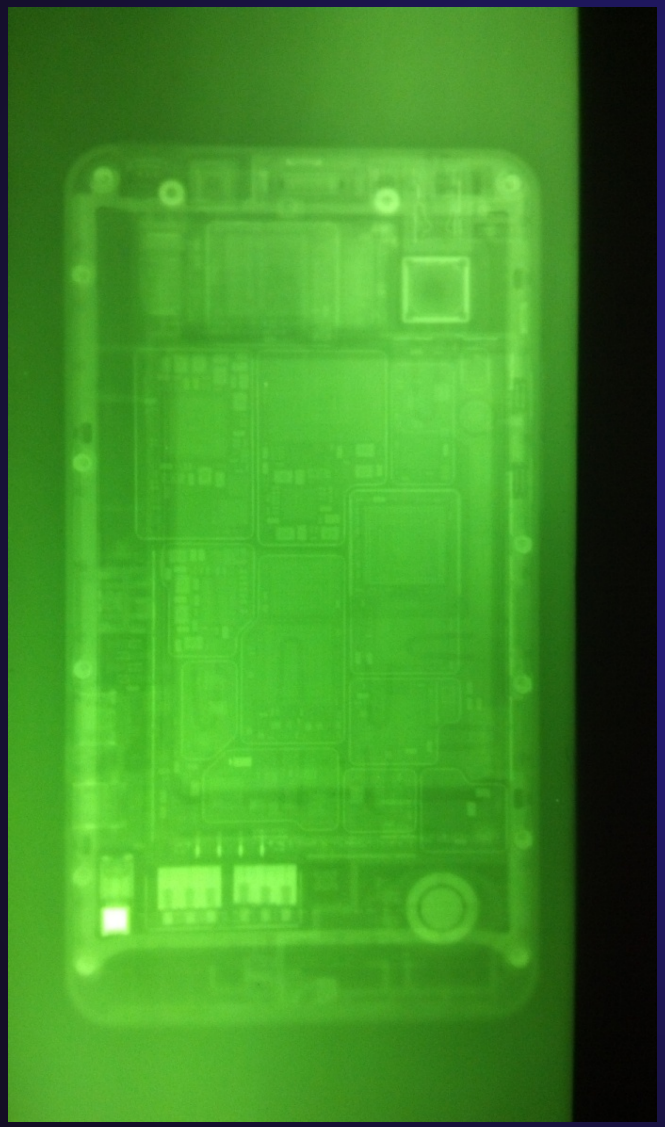


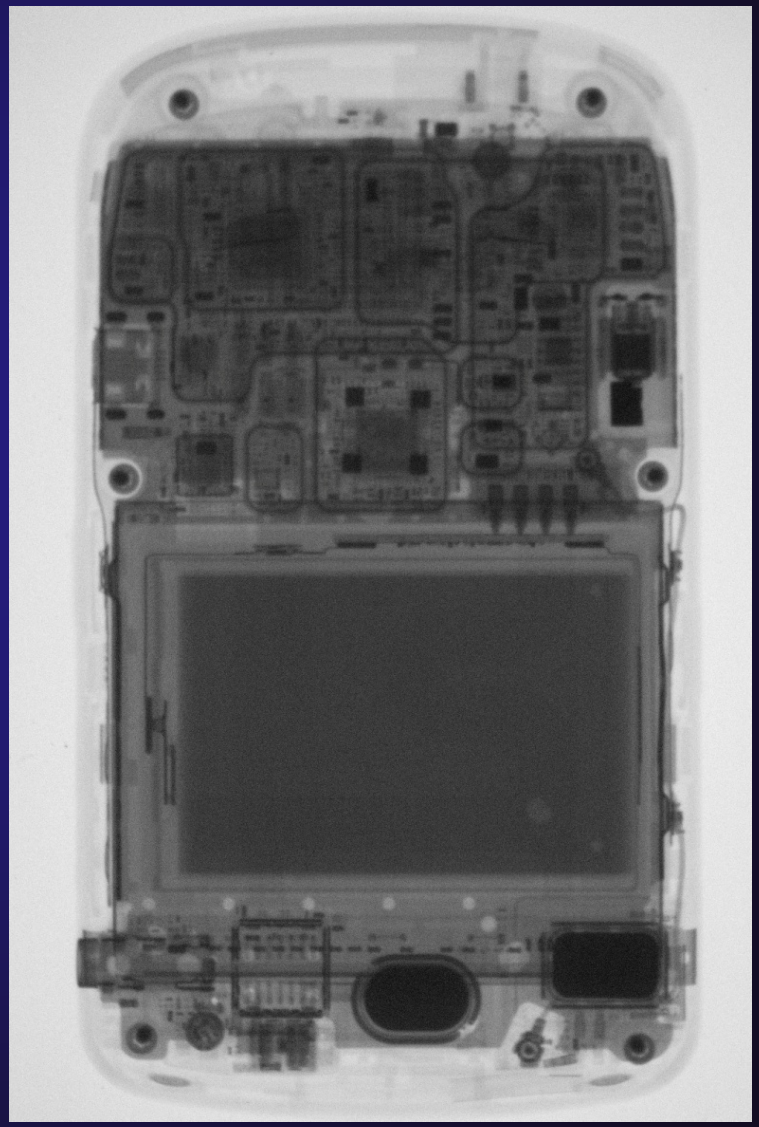


Practical Exercise #7 – What is wrong with this image?



Practical Exercise #8 – Compare & Contrast These?





Radiography Questions

Question 1

Why does DARHT use a 1st conjugate of 1.3 m and a radiographic magnification of 4 for core-punch shots while FXR uses a 1st conjugate of 6 m, and a radiographic magnification of 1.2 for case radiographs? Please be as quantitative as possible with your answer.

Question 2

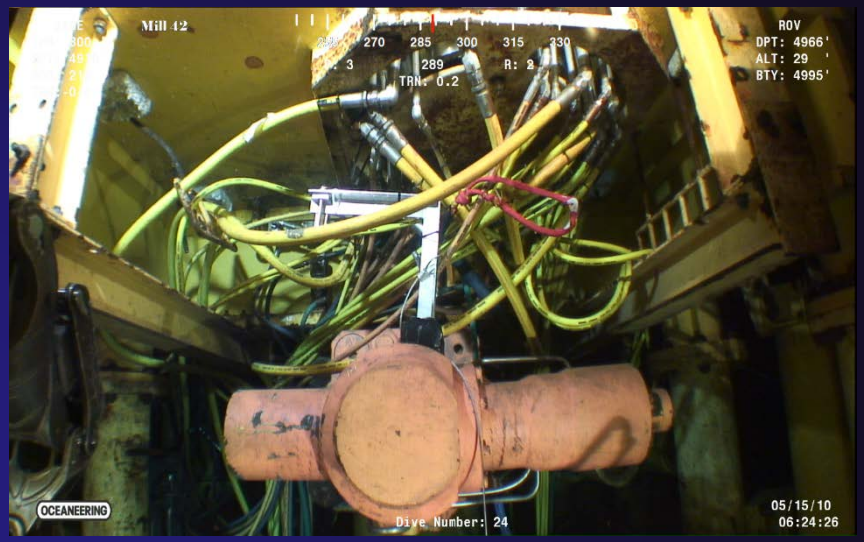
Why does CYGNUS achieve a higher resolution than DARHT? What would happen if we raised the endpoint energy of CYGNUS? Please explain using principles discussed in class.

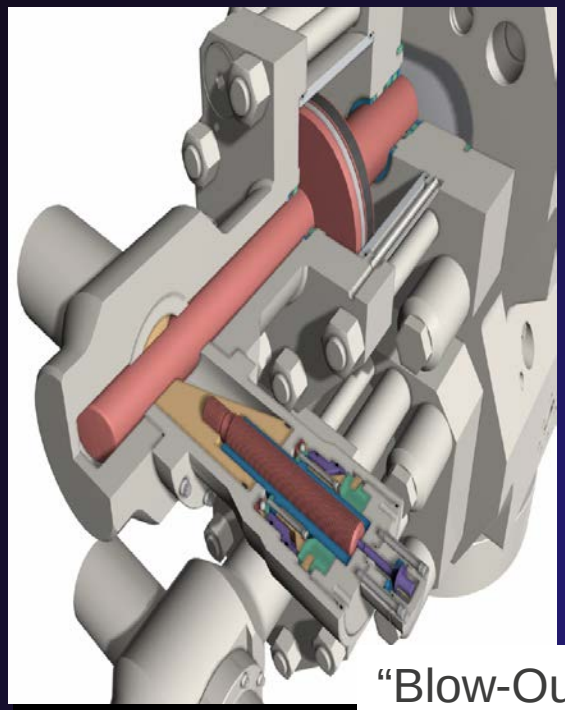
Question 3

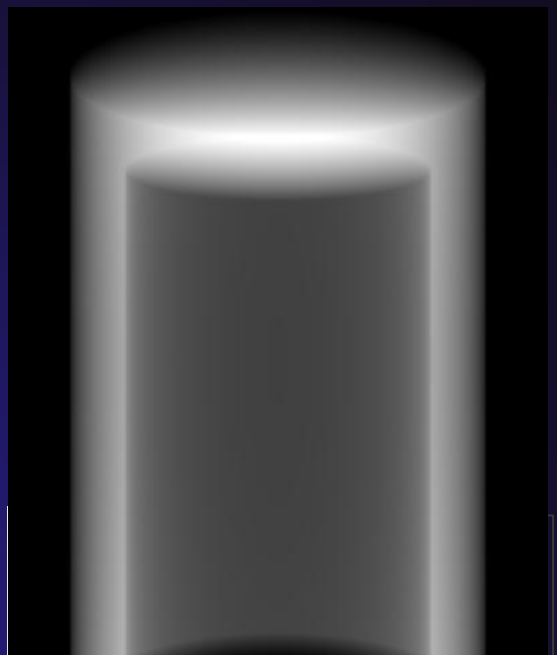
How would YOU go about radiographing a large metal object (like a BP oil shutoff valve) 1 mile underwater? Possible solutions include underwater betatrons, radioisotopes, film, phosphors, electronic detectors etc. Discuss relative merits of each approach including deployment time, cost, complexity, performance etc.

BP Oil Spill

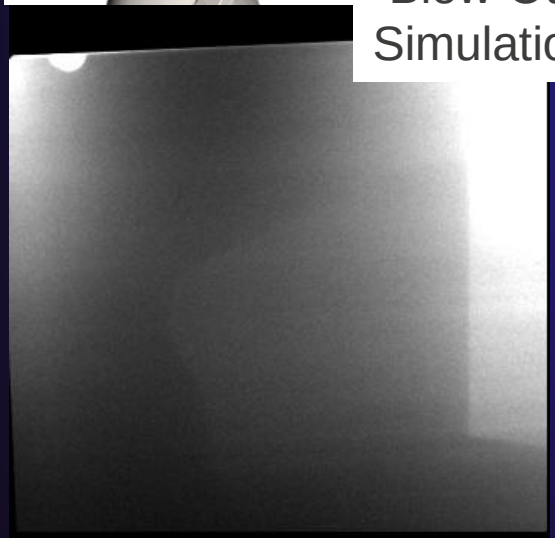
- Used 20 mCi, Co-60 sources with conventional CR screens in armored compression packs to radiograph the “kink” and “blind shear rams”.
- Remotely operated vehicles manipulated the equipment a mile underwater.
- Entire project was successfully executed within days of the emergency callout.
- Data on the President’s desk at week’s end.



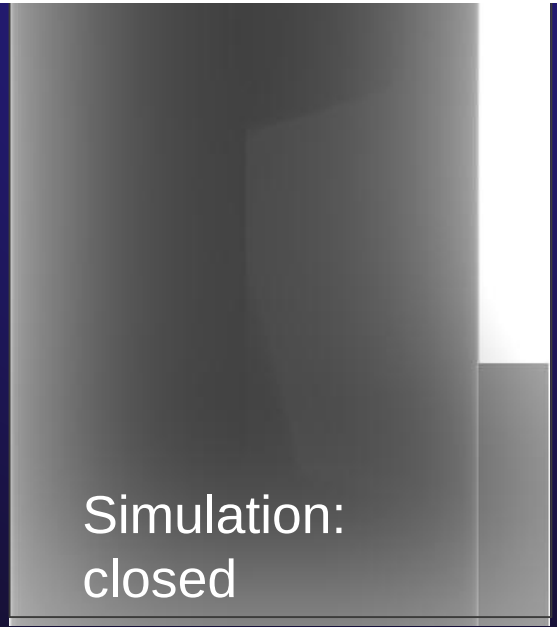




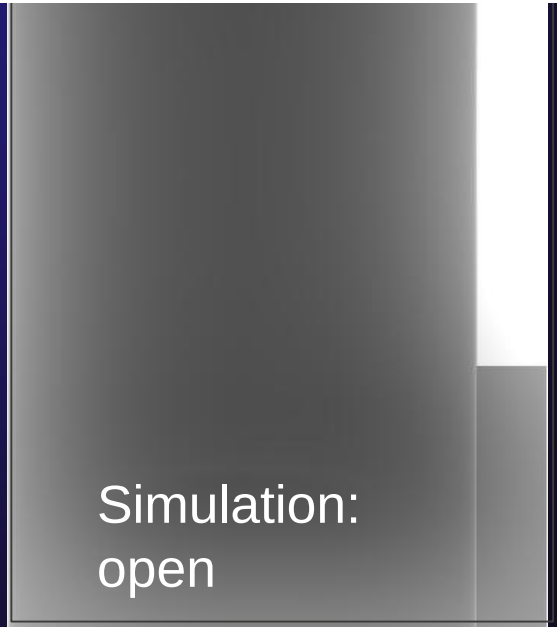
“Blow-Out-Preventer” aka BOP
Simulations performed on Los Alamos’ Bayesian Inference Engine



Data: Image 32



Simulation: closed



Simulation: open

Question 4

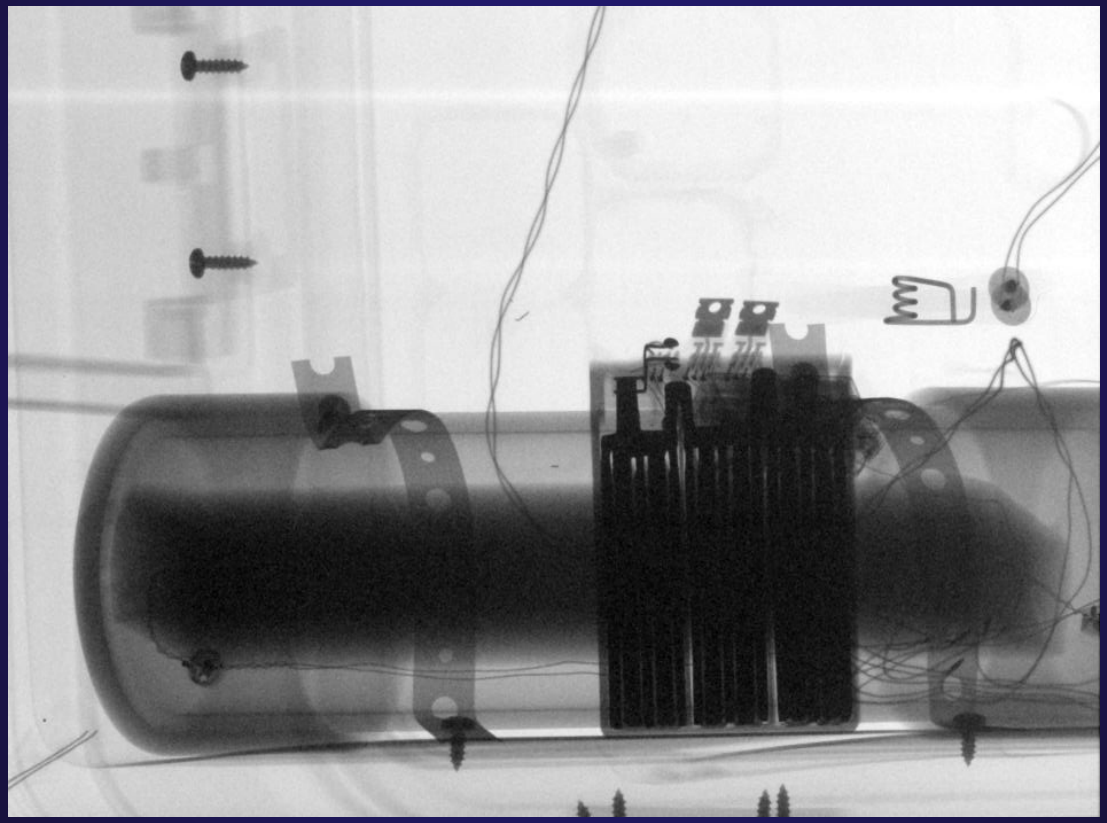
Why does the UK use large, multi-megavolt diodes for core-punch radiography? Why would a diode with a low magnification be expected to perform as well as a much higher energy accelerator with a high magnification? What other factors are important and why?

Question 5

How can case radiographs, which once required large machines like PHERMEX or FXR be performed with 2 MV heads today? Hint, PHERMEX was built in 1963.

Question 6

What is the “optimal” thickness of a uranium slab in terms of radiographic contrast using FXR (18 MV endpoint), CYGNUS (2 MV endpoint), and Cobalt-60 (1.2 MeV line)?

Home time!

Pipe bomb