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Radiographic Detectors for DARHT and ECSE

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J-4, Experiments and Diagnostics Group

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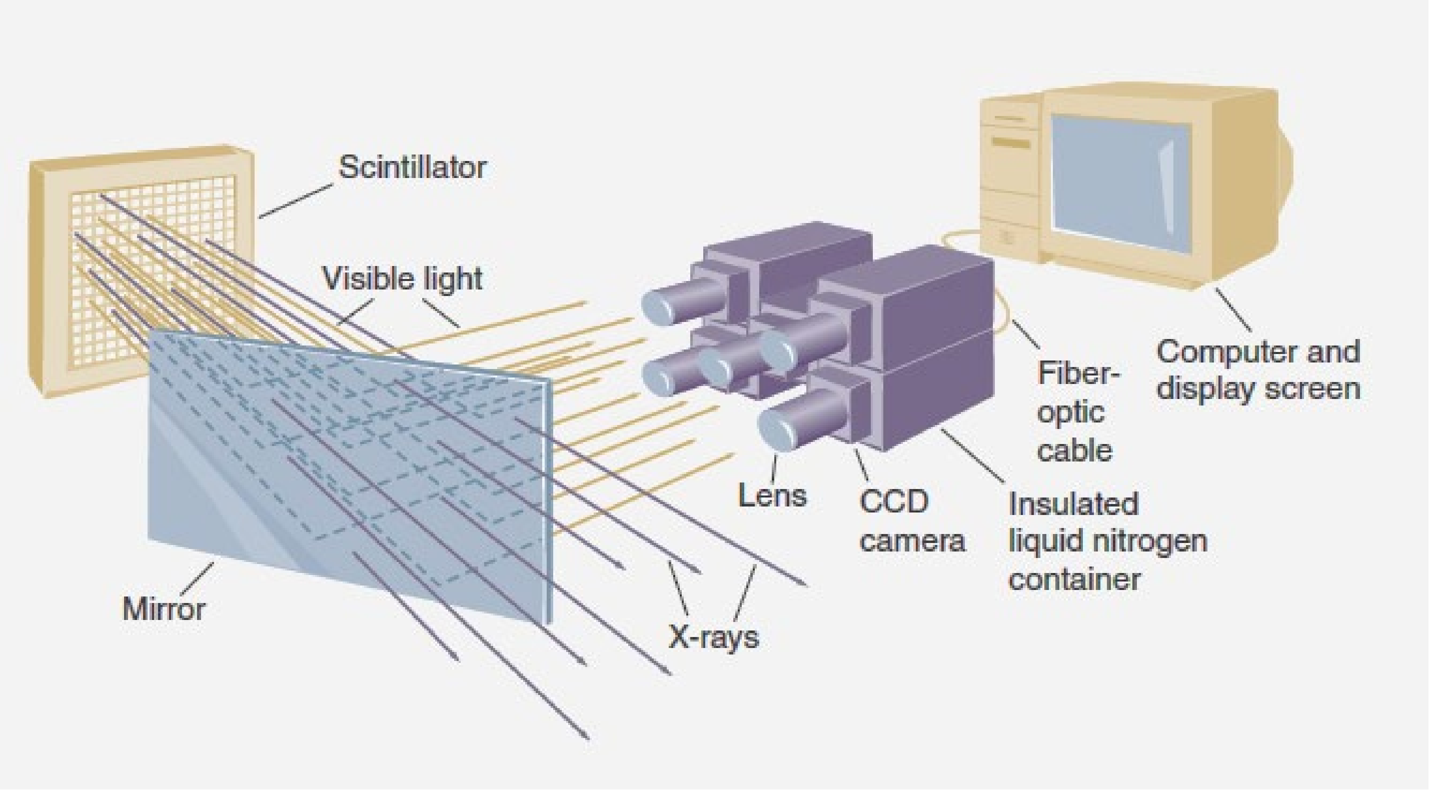
Introduction

- Moderate to thick object radiographic detectors have been in use at LANL's DARHT facility for nearly two decades.
  - They serve as the primary diagnostic for gas cavity hydrodynamic experiments
  - Can reduce the design constraints of the source
  - Performance is dependent on the source and environmental characteristics
    - Bremsstrahlung target interactions
    - Bremsstrahlung energy spectrum
    - Scattered radiation
    - Temperature, humidity etc.
- The Scorpius detector design aims to improve the performance of existing detector designs.

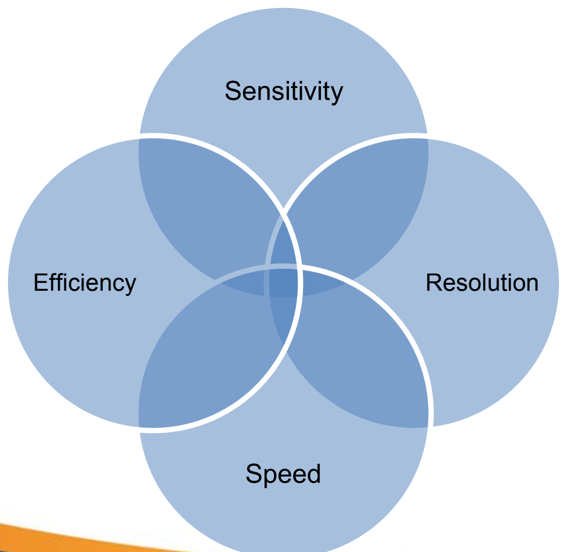
What is a Gamma Ray Camera?

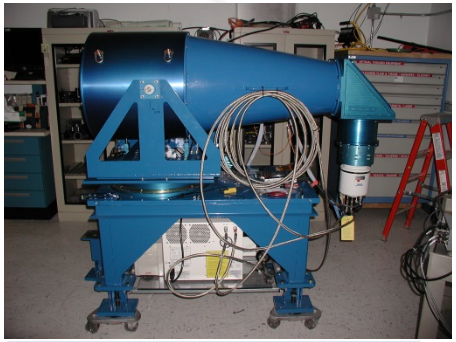


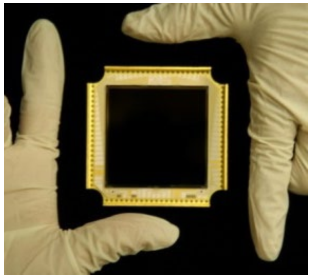
The Los Alamos Gamma Ray Camera (GRC)

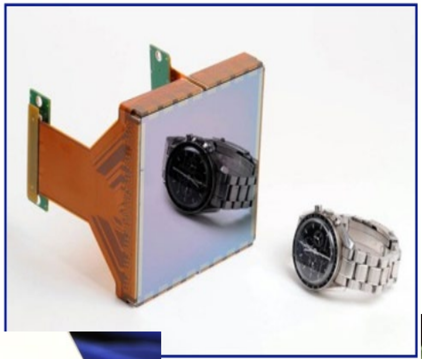
LANL GRC's are the largest, fastest, and most sensitive detectors in the world and are capable of capturing sub-millimeter resolution radiographic images through more than a foot of steel…….

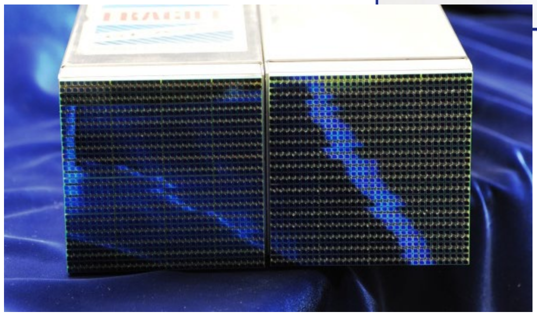
- Are a critical component of radiographic systems *(Past, Present and Future)*
- Offer unique capabilities for eXtreme imaging
- Offer world-class performance
- Combine resolution, speed, efficiency and sensitivity

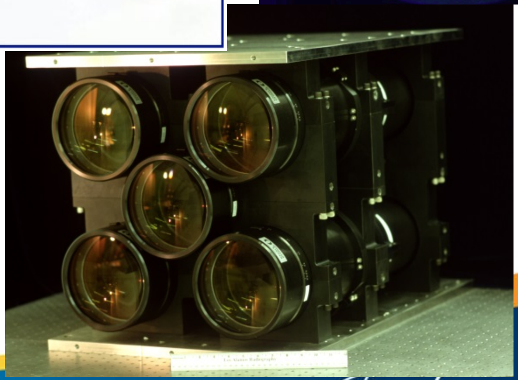












Conceptual design uses, dose equivalent, detective quantum efficiency (DQE) as the primary design metric

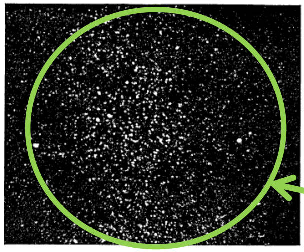


Fig. 1. Number of photons, 3×10^3; high-light luminance (foot-lamberts), 10^{-6}.

Fig. 2. Number of photons, 1.2×10^4; high-light luminance (foot-lamberts), 4×10^{-6}.

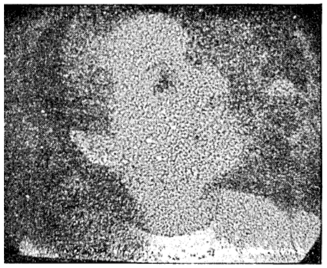


Fig. 3. Number of photons, 9.3×10^4; high-light luminance (foot-lamberts), 3×10^{-5}.

Fig. 4. Number of photons, 7.6×10^5; high-light luminance (foot-lamberts), 2.5×10^{-4}.

Fig. 5. Number of photons, 3.6×10^6; high-light luminance (foot-lamberts), 1.2×10^{-3}.

Fig. 6. Number of photons, 2.8×10^7; high-light luminance (foot-lamberts), 9.5×10^{-3}.

$$DQE(f) = \frac{SNR^2_{recorded}}{SNR^2_{incident}} = \frac{MTF(f)^2}{n\,NPS(f)} \propto \frac{1}{1+\frac{1}{n}}$$

- DQE of primary photons is dominated by the x-ray to visible light converter (Scintillator)
- Film/Phosphors ⇒ DQE~0.1%
- 4cm LSO ⇒ GRC DQE ~40%
- Scintillator Density (7.4g/cc*)
- Scintillator Light Output (30k phot./MeV*)

- DQE of secondary photons is dominated by the visible optics of the system
- Efficient Light Transport ⇒ $n = \dfrac{QE_{CCD}GM^2}{8\eta_i^2F_\#^2(1+M)^2}$

Equivalent to dose, the DQE of the detector is a very important design consideration for any radiographic capability….

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$$F_s = 2B$$

Radiographic System Design

Key Design Variables and Limitations

Magnification $\propto$ Object Resolution & Source Blur

Source Geometry and Size $\propto$ Source Blur

Source Duration $\propto$ Motion Blur

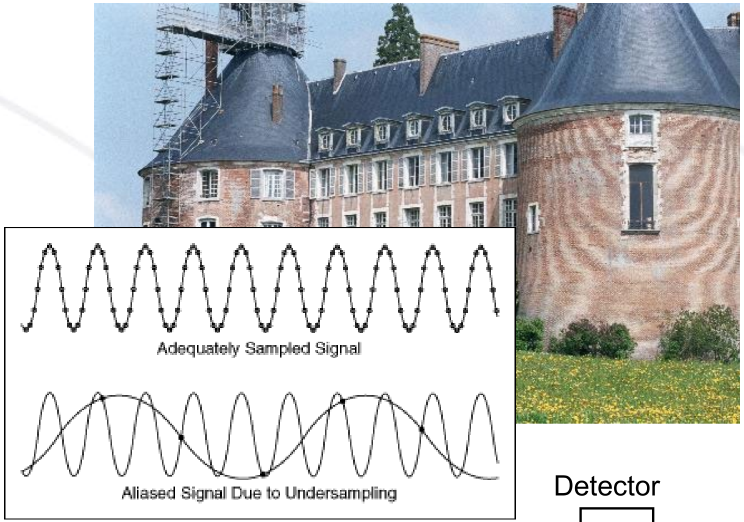
Object Velocity $\propto$ Motion Blur

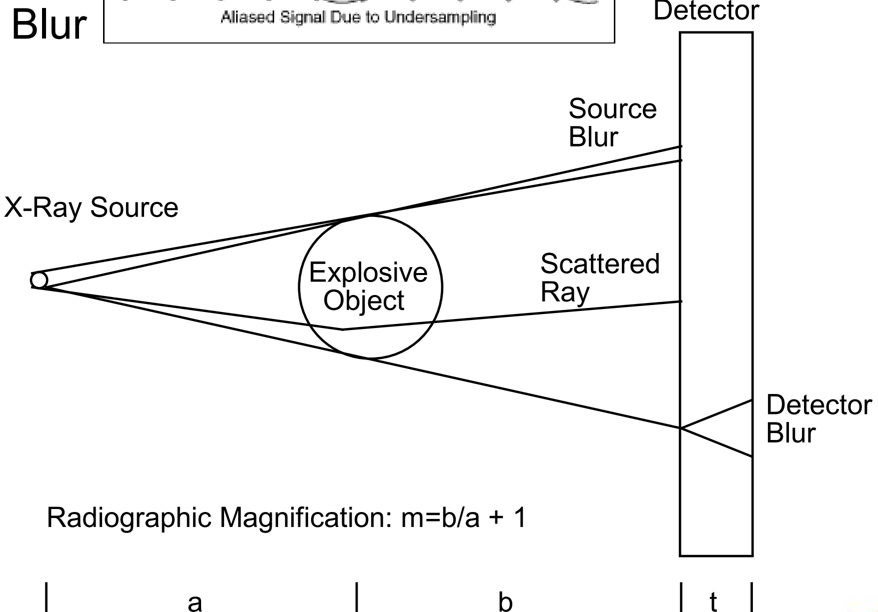
Detector Pixel Geometry (d_x,d_y,d_t) $\propto$ Detector Blur

- Detector Pixel Size $\propto$ Aliasing
- Object feature size
- Magnification

$\propto^{-1}$ Aliasing

Scatter $\propto$ Object Density





Biker Velocity=1.5 ft./sec
Shutter Duration=1 sec
1.5 ft. of blur @ Object

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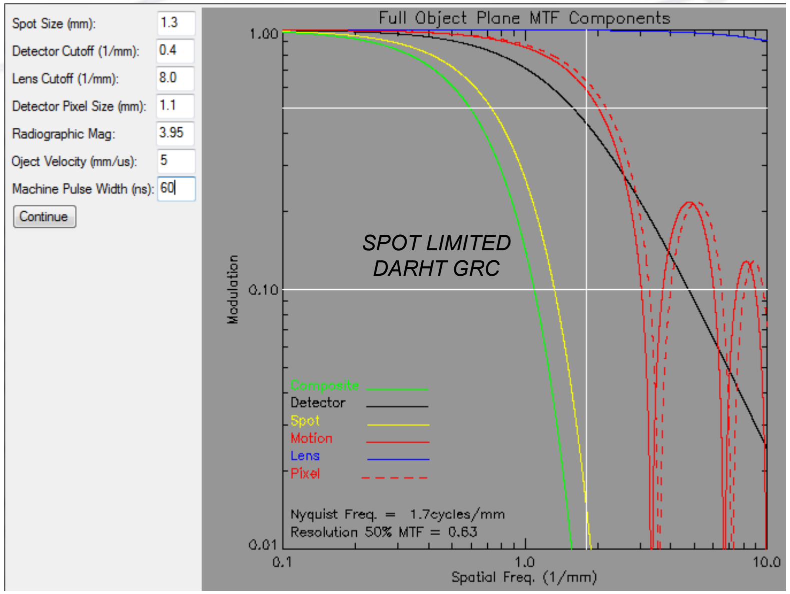
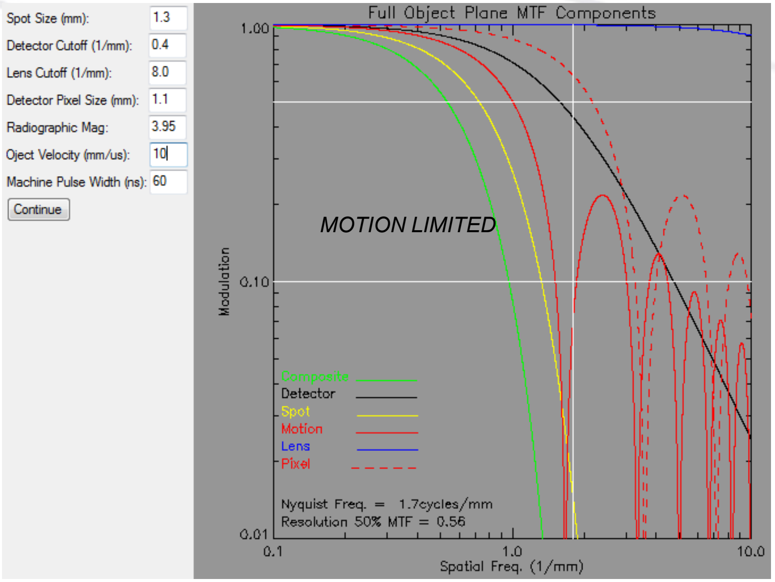
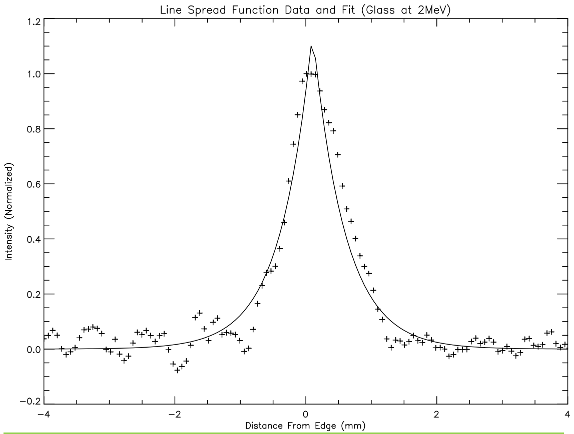
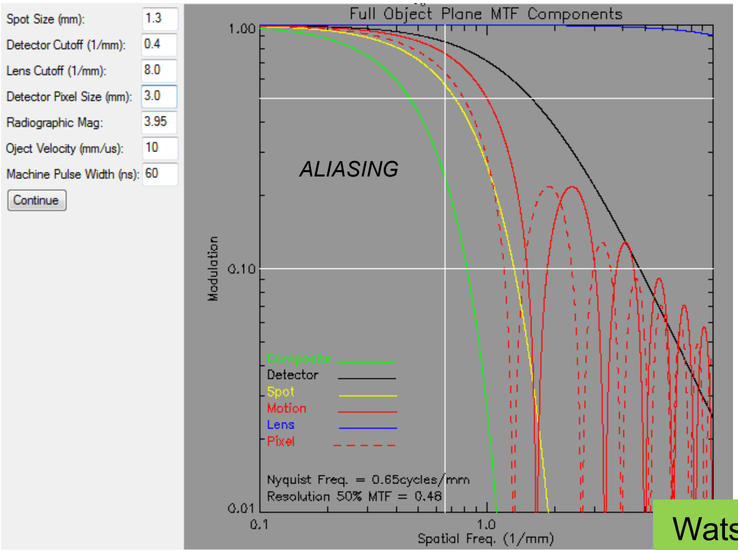
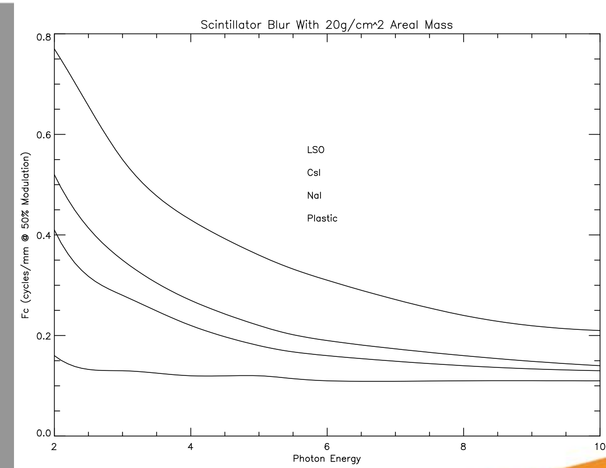
Radiographic Figure of Merit











LANL developed radiation and optical modeling capabilities also inform system design

Watson S.A., “A Closed-Form, Fellget-Linfoot Radiographic Figure of Merit, internal LANL report, 1998

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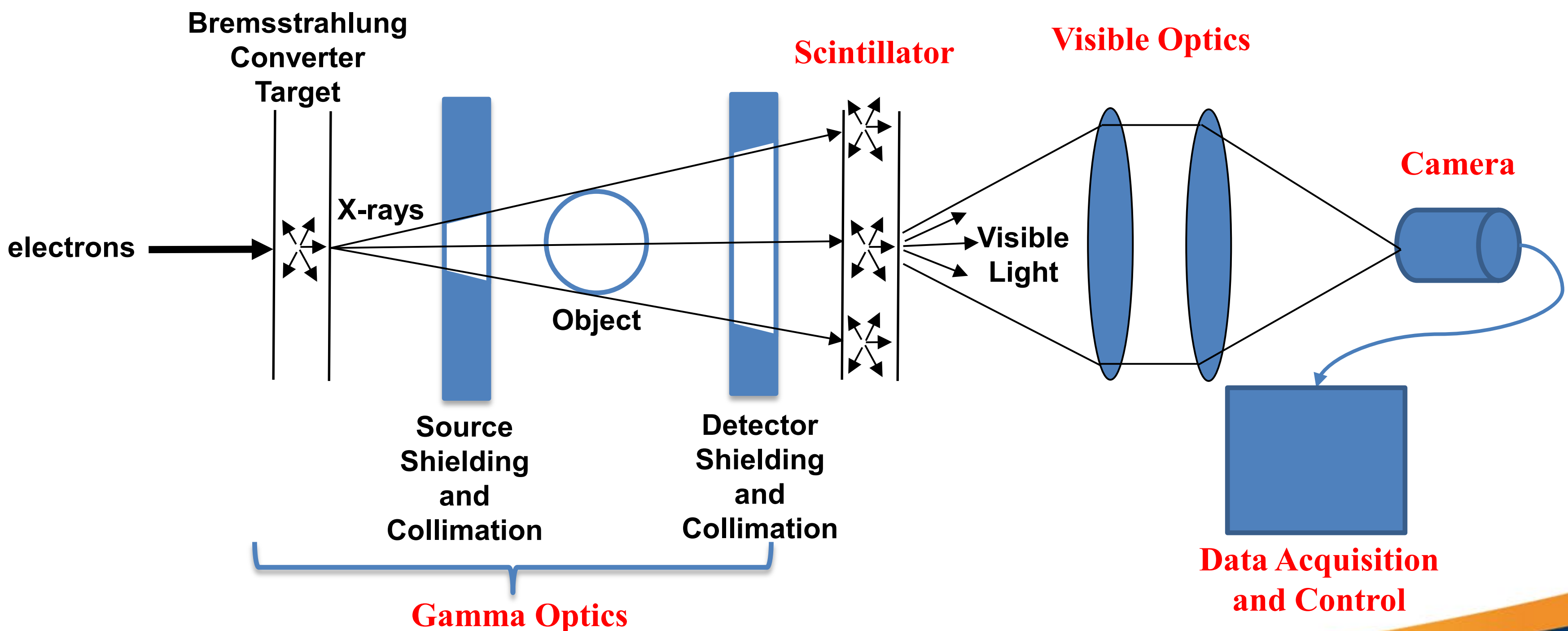
ECSE System Description

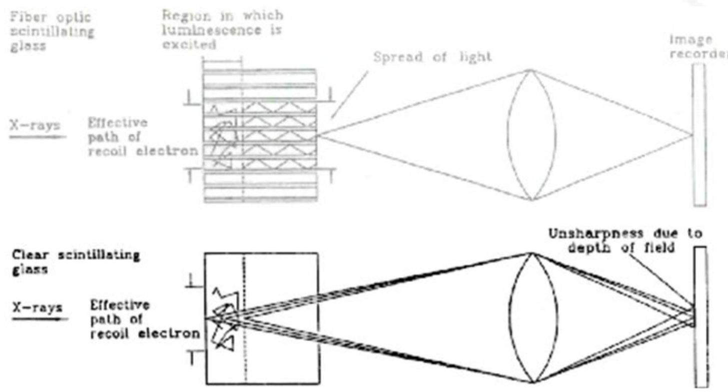
- The scope of the detector begins with the conversion of high energy electrons to a Bremsstrahlung x-ray spectrum and ends with the conversion of these x-rays to visible light that is captured by multi-frame CCD camera. Level 4 WBS elements of the Scorpius detector system are in red text.

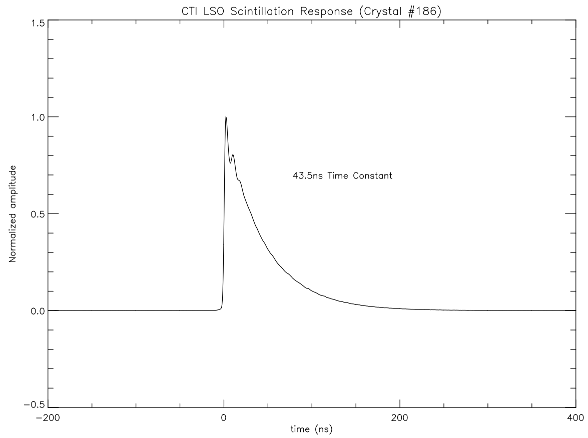


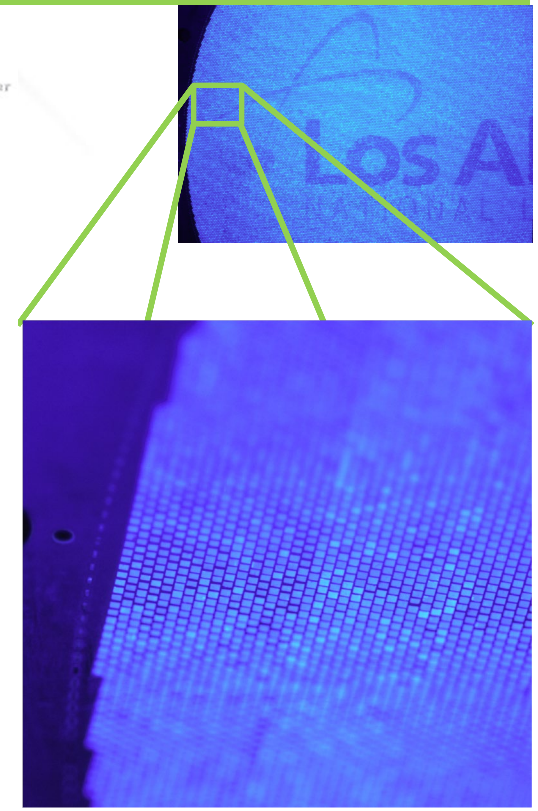
Lu_2SiO_5:Ce (LSO) Segmented Scintillator

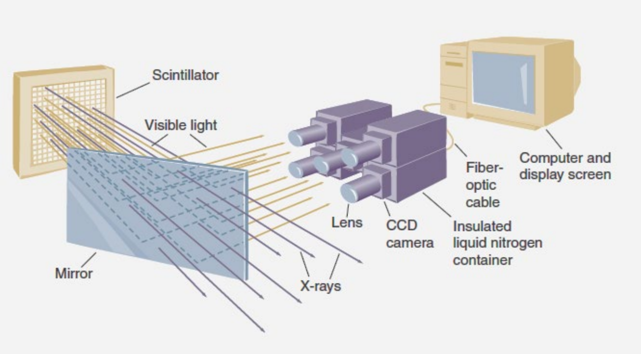
- 45 cm diameter, 1.1mm pitch, 4cm thick
- Focused
  - Reduced Parallax
- High Light Output
  - 30,000 photons/MeV
- High Density
  - 7.4 g/cc
  - High Conversion Efficiency
- Fast Decay
  - Single, 40nsec component
- Low Index of Refraction
  - Efficient Lens Coupling

DARHT uses the 3 largest segmented scintillators in the world





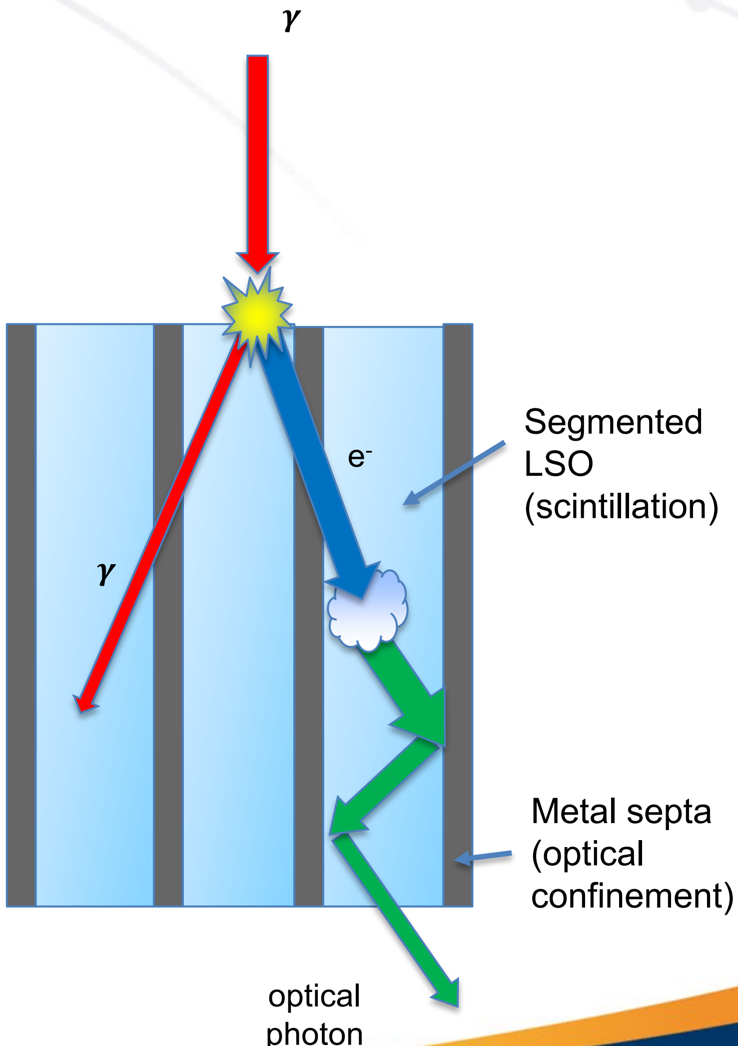




Efficiency of Film is 0.1%, while LSO is >40%

Advancing toward quantitative evaluation of all scintillator components, best configuration for Scorpius

- Polymer back-reflector:
  - Analytical models and data show a back-reflector can improve optical transport efficiency
  - Develop thin-film direct coatings on LSO for evaluation
- Metal septa and optical transport:
  - MCNP models suggest improvements going to high Z septa
  - Collaboration with XCP-3 to develop further MCNP and GEANT models, detailed laboratory characterizations
- Gamma Ray Sensitivity Optimization:
  - Further work required to understand potential impact of other proposed changes



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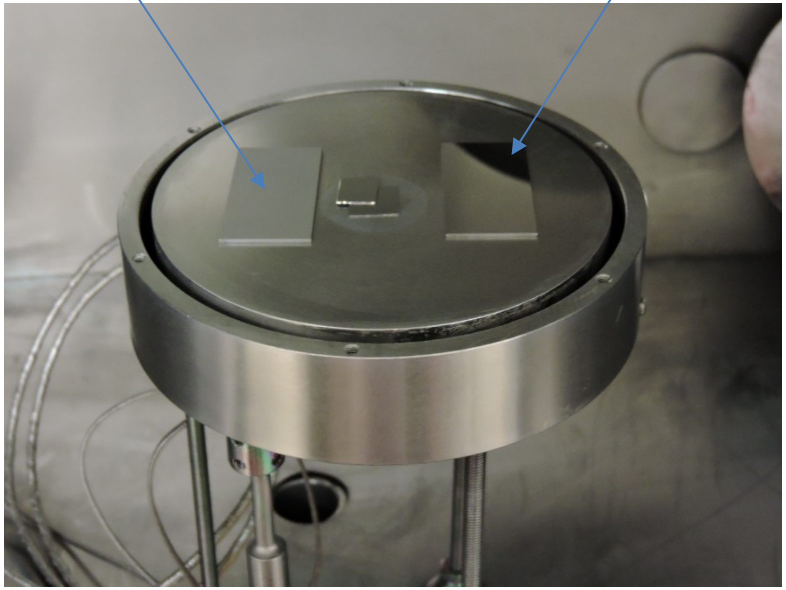
Optimization of efficiency and quality of back-reflection

- An effective back-reflector ensures scintillation light re-directed toward the detector
  - Max. improvement 2x (ideal)
- Developing thin-layer deposition capability on LSO
- Evaluating commercial capabilities in the area.
- Detailed modeling and empirical characterization to be performed
  - GEANT and MCNP modeling
  - Meas. of efficiency vs. deposition location

unpolished LSO

polished LSO



I. Usov and D. Vodnik, MST-7

Optical modeling can show how surface treatments would behave

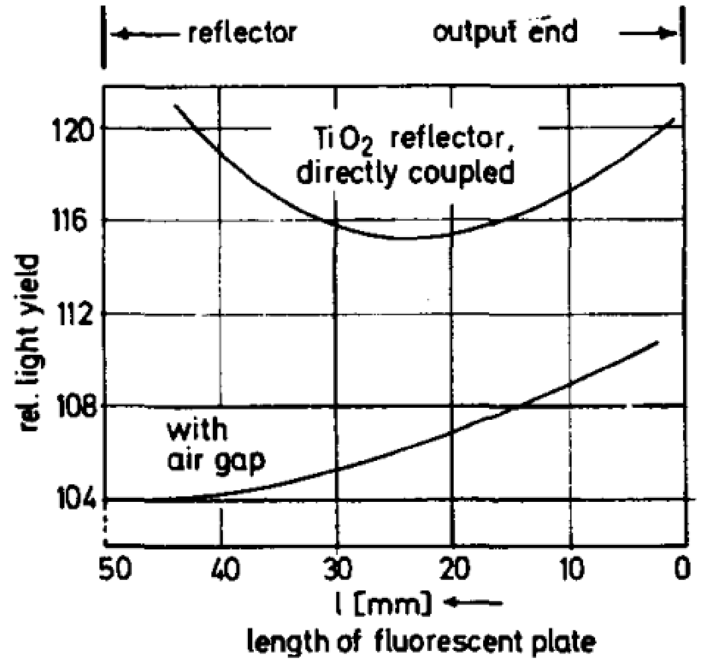
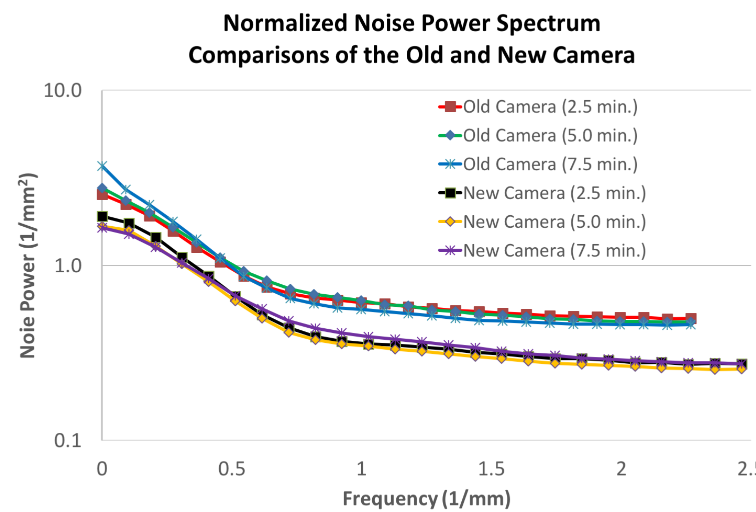


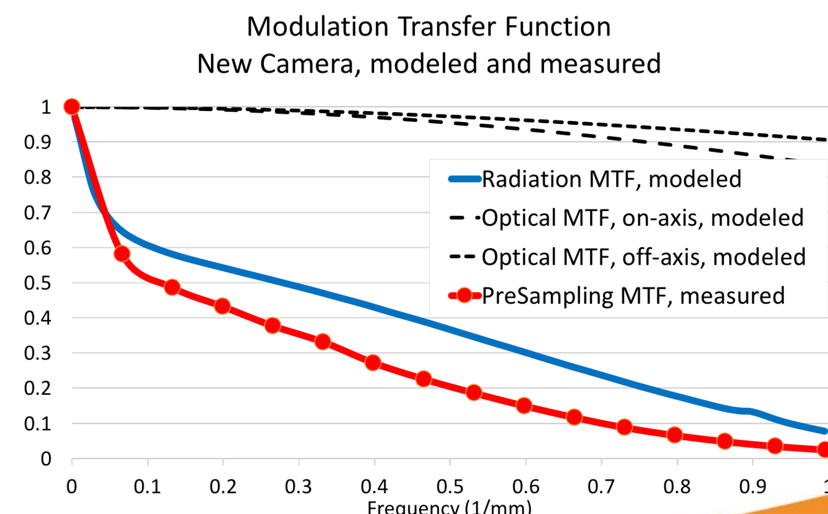
Fig. 9. Relative light collection yield for a directly coupled and an air-gap coupled diffuse TiO_2 reflector. Fluorescent body: rectangular plate of GG 17 glass (Schott); dimensions 50 × 50 × 2 mm.

G. Keil, 1970

Updated NNPS and MTF, data and modeling for upgraded DARHT A1 camera

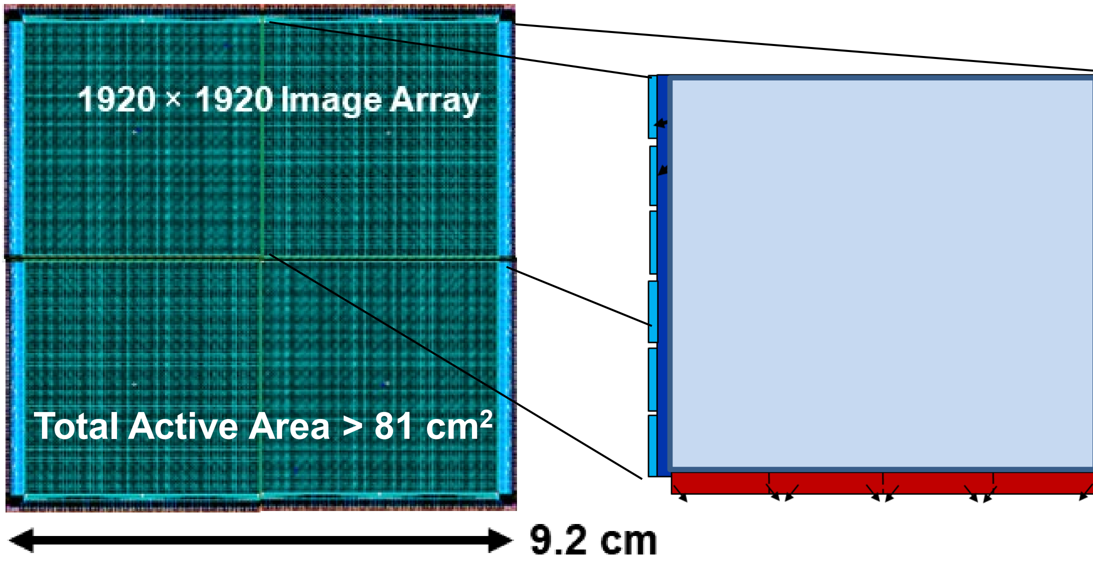
- *Pre-sampling MTF* represents a robust and meaningful metric for evaluating and comparing DARHT-similar GRC designs
- Comparison to EGSnrc modeling at 1.25 MeV provides confidence in relevant estimates
  - blur, secondary radiation, scatter to direct response, pulse height distribution
- Noise improvements at higher spatial frequencies lead to significant improvements in high frequency DQE(f)

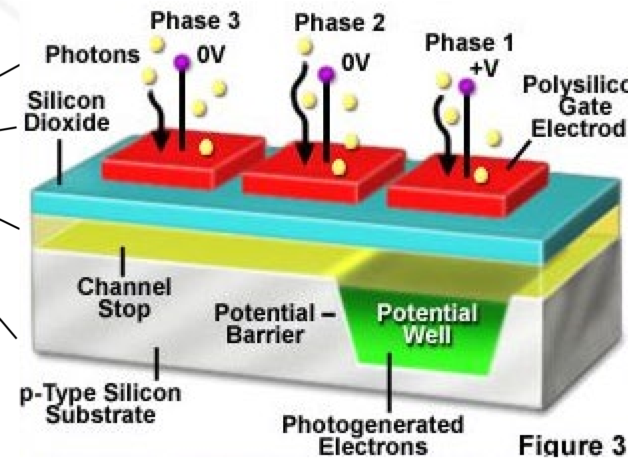


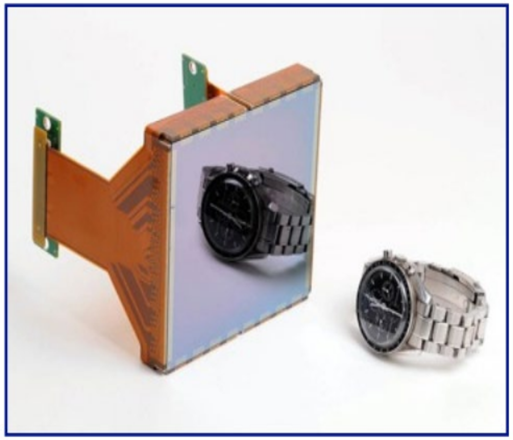


J. Mendez, B. Tobias, et al., LA-UR-18-21779 and LA-UR-18-29908

A simpler, two phase Scorpius imager can benefit yield. Also allows larger active area for improved efficiency to secondary quanta.







- Dedicated Scorpius imager design effort underway at MIT-LL
  - High-Efficiency, High-Speed imager for thick objects (4 frames @5 Million Frames per Second)
  - Simulations are investigating charge collection/transfer speed, and CTE over a wide range of design variables.
- Next Generation DARHT Axis II imager design effort may provide additional capability and risk mitigation for Scorpius
  - High Speed, High-Frame Depth imager for thin objects (8 frames @ 4 Million Frames per Second)

DARHT camera design efforts meet some requirements but not all, prompting need for ASD specific design

Parameter	ASD (IOC)	ASD (FOC)	DARHT 2 (Existing CCID-36)	DARHT 2 (CCID-91 Requirement)	Notes
Frame Rate (MHz)	2	5	2	4	
Number of Frames	2	4	4**	8 **	** Meets Objective
Inter-Frame Time (ns)	500	200	500*	250	*Meets Threshold
Pixel Size (µm)	≤48	≤48	96	48	
Active Area (cm^2)	>36	>36	25	36	
Dark Current (e^-)	<5	<5	100	<5	
Frame Isolation	≥1000:1	≥1000:1	500:1	>1000:1	
Dynamic Range (bits)	≥16,000:1	≥16,000:1	16,000:1	16,000:1	
Read Noise (e) rms	≤3	≤3	5	3	
CCD Quantum Efficiency	≥80%	≥80%	55%	80%	

Optimization present opportunity for dramatic improvements in detector performance vs. DARHT benchmarks

- Potential for significant improvement in signal
  - Demonstrated improvement with new DARHT A1 lens
  - Improvement of back-reflection
  - Addition of index-matching at optical output
- Potential for significant improvement in signal to noise
  - Demonstrated improvement in DQE with new DARHT A1 CCD
  - Potential for additional improvement with optimization of the septal frame material