RMD
A Dynasil Company

High-resolution detector for at-wavelength metrology of X-ray optics

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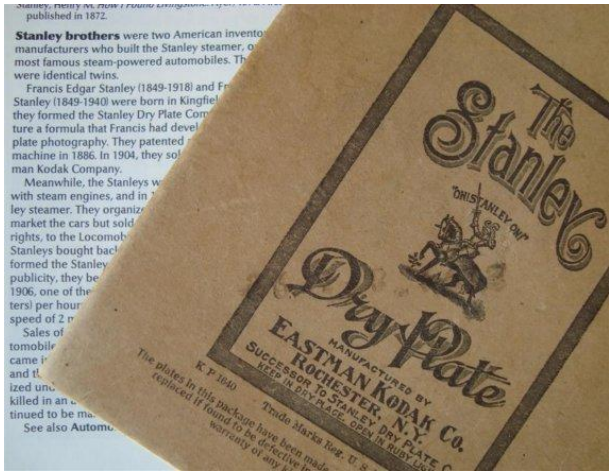
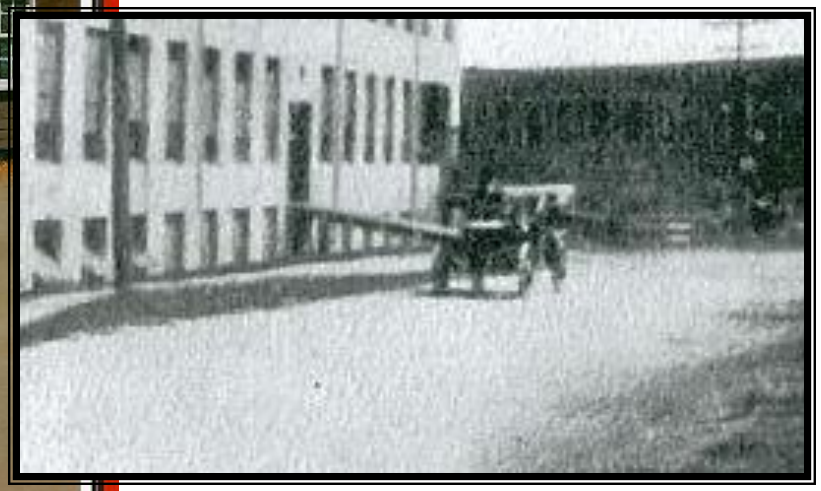
RMD, Imaging, Speed – A historical perspective



RMD, Imaging, Speed – A historical perspective

1897 - 1902 - 1924

World automobile speed record, 1906-1911, 127.7 mph



Outline

- Program overview
- Structured scintillators
  - Advantages
  - Fabrication methods (vapor deposition, e-beam deposition, laser pixelation)
- Detector
  - Design
  - Specifications
  - Evaluations
- Software
  - Single photon detection algorithm
  - Simulation and analysis
- Conclusions

Program objectives

- Phase I Goal:
  - *Demonstrate the feasibility of developing a high resolution detector for at-wavelength metrology of X-ray optics.*
- Phase II Goal:
  - *Develop a prototype high-resolution detector for at-wavelength metrology of X-ray optics, fully characterize its performance, and deliver it to NASA.*

The Team

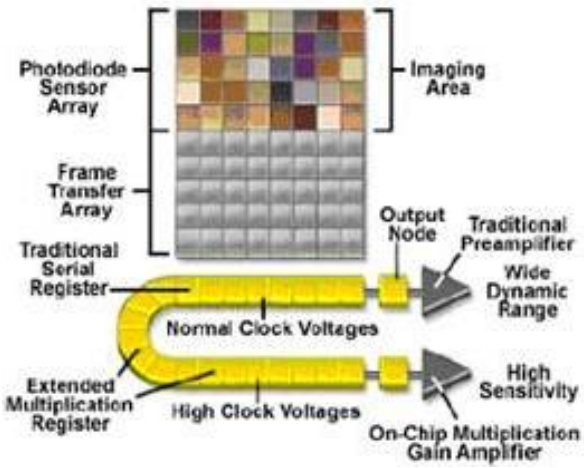
- RMD
  - Detector design and development
    - Scintillator fabrication
    - Detector design and fabrication
    - System integration
    - Evaluations and feasibility studies
- LLNL
  - NuSTAR X-ray optics calibration
  - Application-specific needs
    - Single-photon counting algorithms
    - Detector evaluation

Detector requirements for NuSTAR mission

- High spatial resolution (~25 μm)
- Operation over a large energy range (5 keV to 100 keV +)
- High sensitivity to X-rays (~100% to >70%)
- Large active area (~5×5 cm^2)
- High count rate capability (10^5 events/second)
- Flexible design / adaptable to various mission requirements
- Ease of operation

Our Solution

- Combine a low-noise EMCCD camera with a high performance structured scintillator



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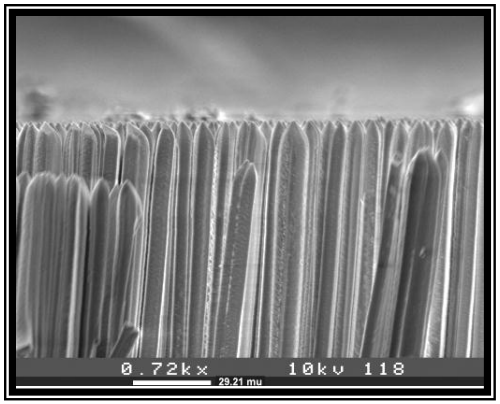

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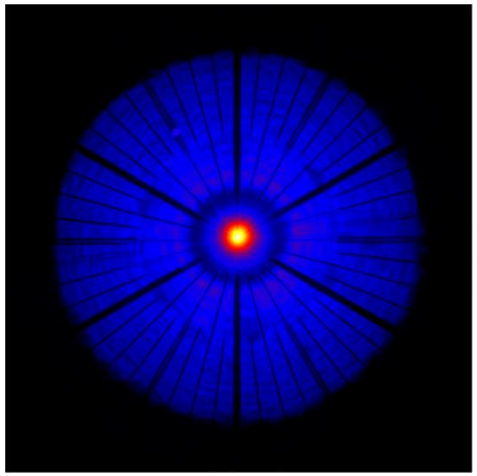


EMCCD block diagram

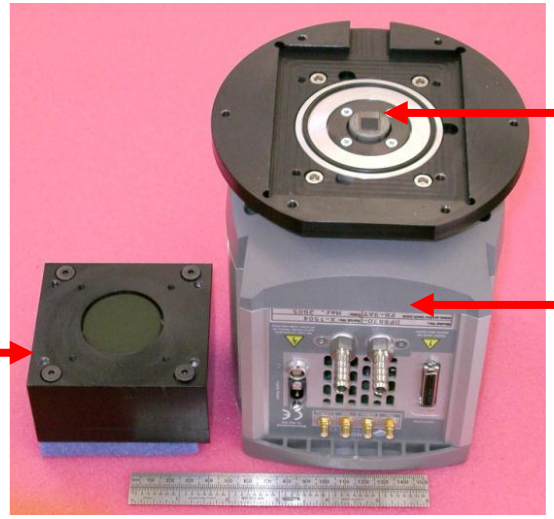
Microcolumnar CsI:Tl film

Resulting test image

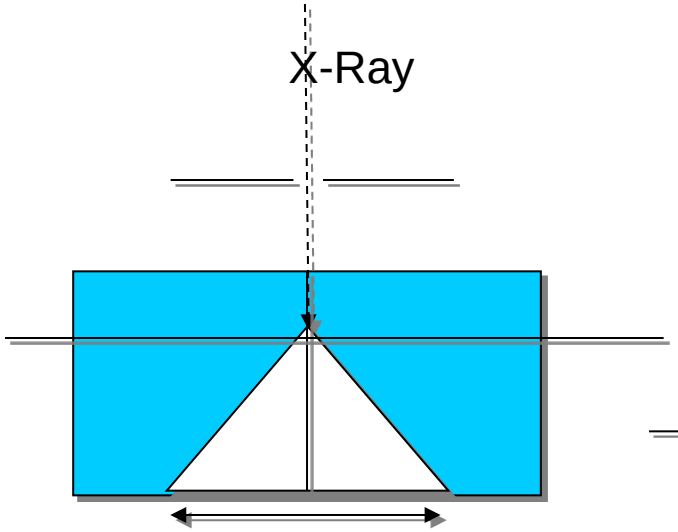
EMCCD advantages

- Commercially available
- Proven technology
- Low-light imaging
- No readout noise
- High spatial resolution
- High quantum efficiency
- Solid-state technology

RMD Customized EMCCD Camera

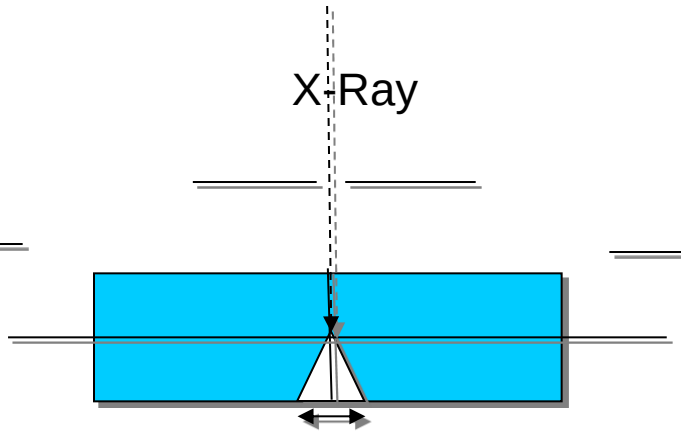


Why structured scintillators?



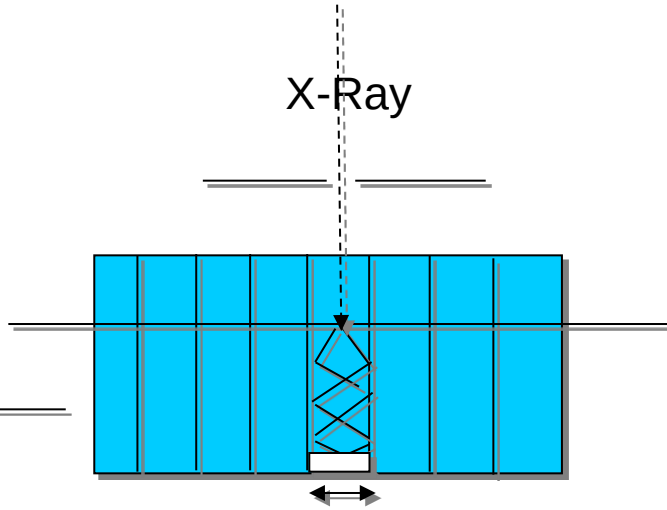
- High absorption (mm/cm thick material).

Poor spatial resolution (wide light spread).



- Poor absorption (μm thin material).

High spatial resolution (limited light spread).



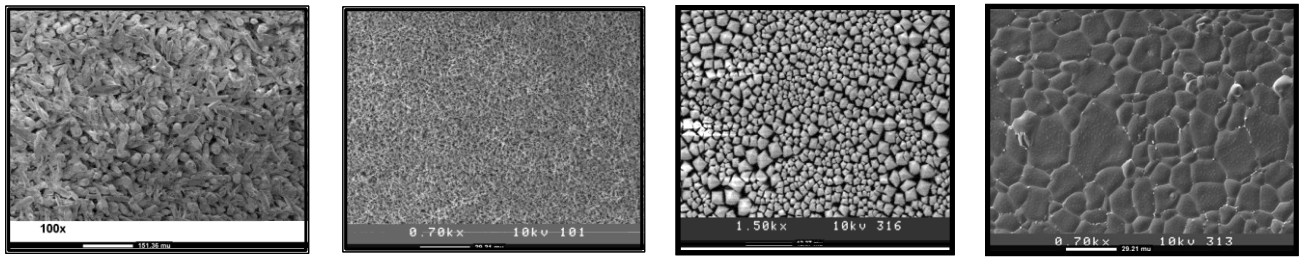
- High absorption (mm/cm thick material).

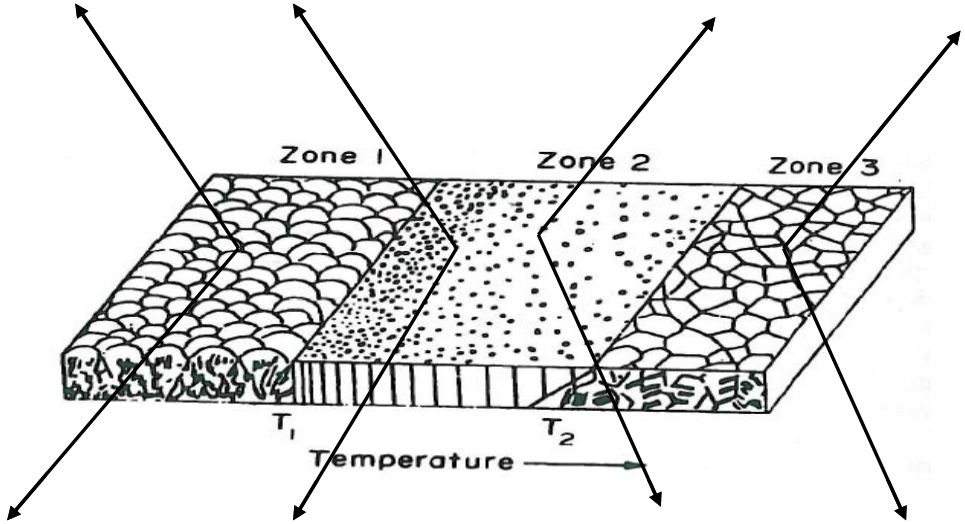
High spatial resolution (channeling of the light).

Scintillator fabrication techniques

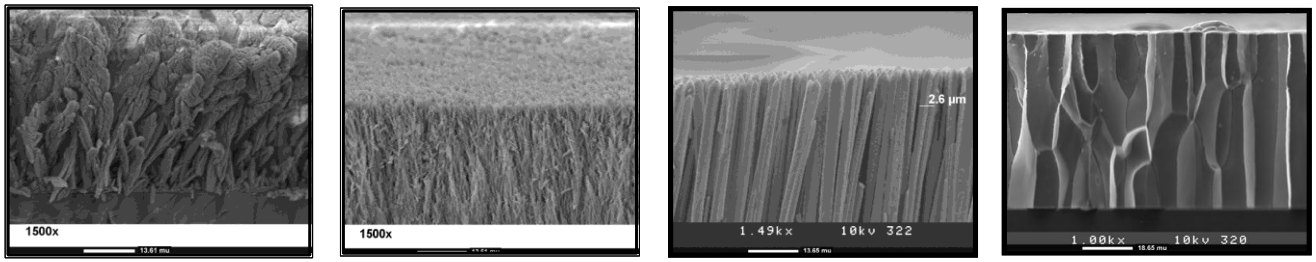
- Vapor deposition
  - Scintillators for X-ray imaging
  - Scintillators for neutron detection and imaging
- E-Beam deposition
  - Thin film scintillators for microtomography
  - High temperature materials that cannot be evaporated
- Hot wall evaporation
  - Scintillators for gamma ray detection and spectroscopy.
  - Scintillator fabrication with dopant gradient, novel formats and shapes
- Isostatic pressing and sintering

Structure control in films

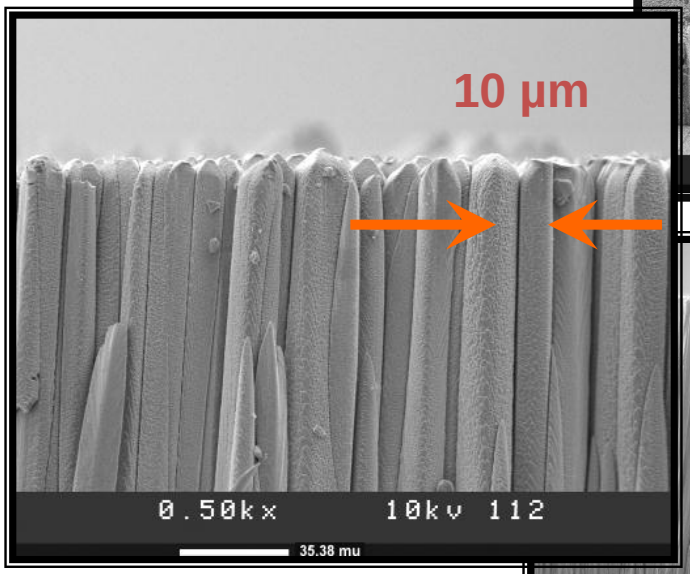


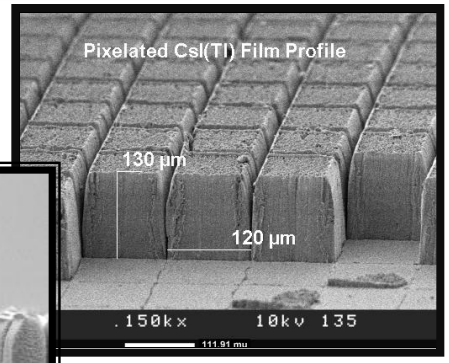


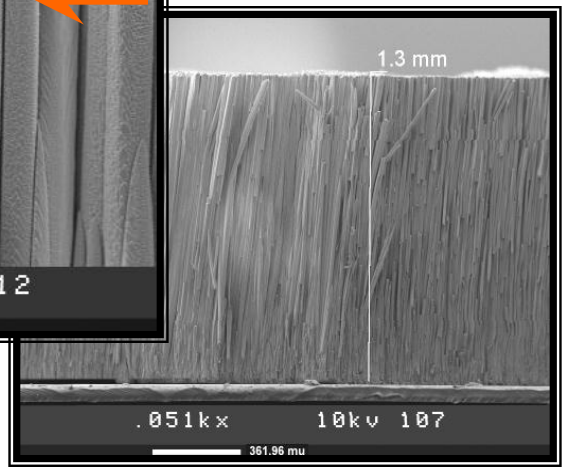
- Zone 1 occurs at $T_s/T_m < 0.3$
  Amorphous Phase
- Zone 2 occurs at $0.3 < T_s/T_m < 0.5$
  Mixed Phase
- Zone 3 occurs at $T_s/T_m > 0.5$
  Crystalline Phase

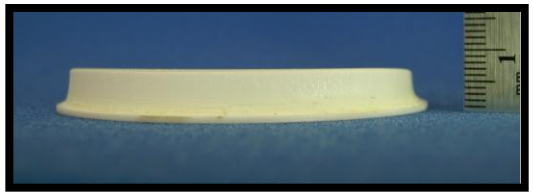


RMD columnar CsI:Tl films



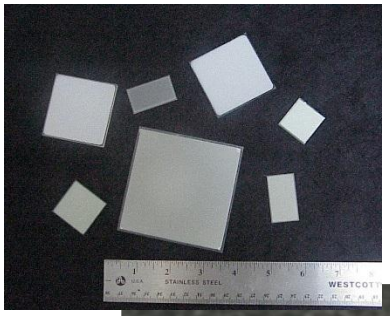


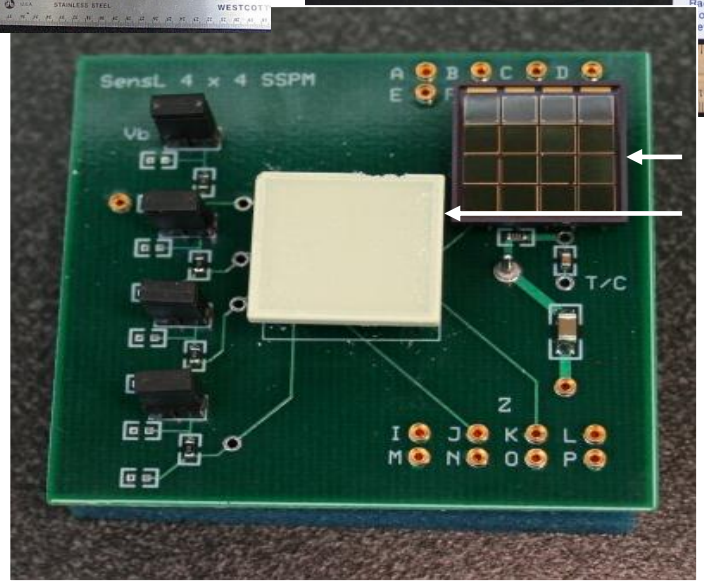




RMD has pioneered development of microcolumnar CsI:Tl for digital radiography.

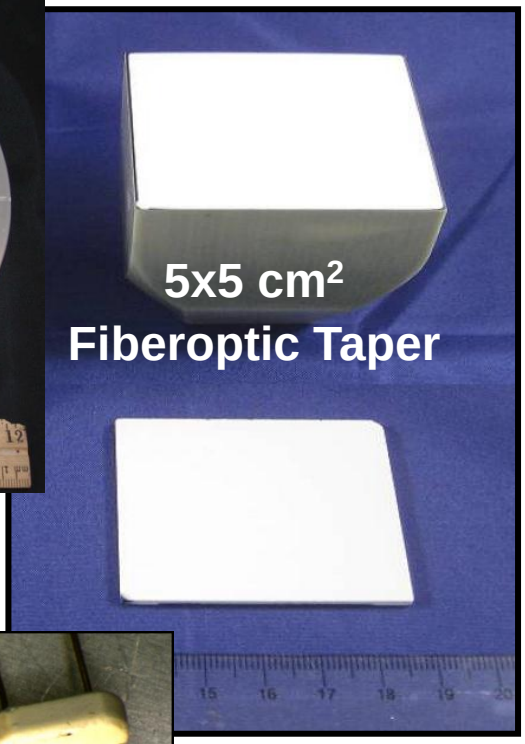
Versatility of vapor deposition

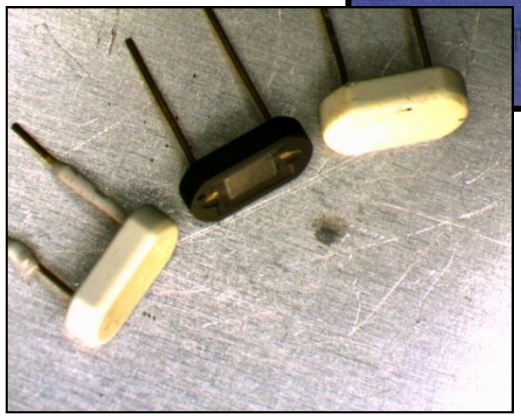




Bare SiPM

CsI:Tl-Coated SiPM





mm² SiPMs

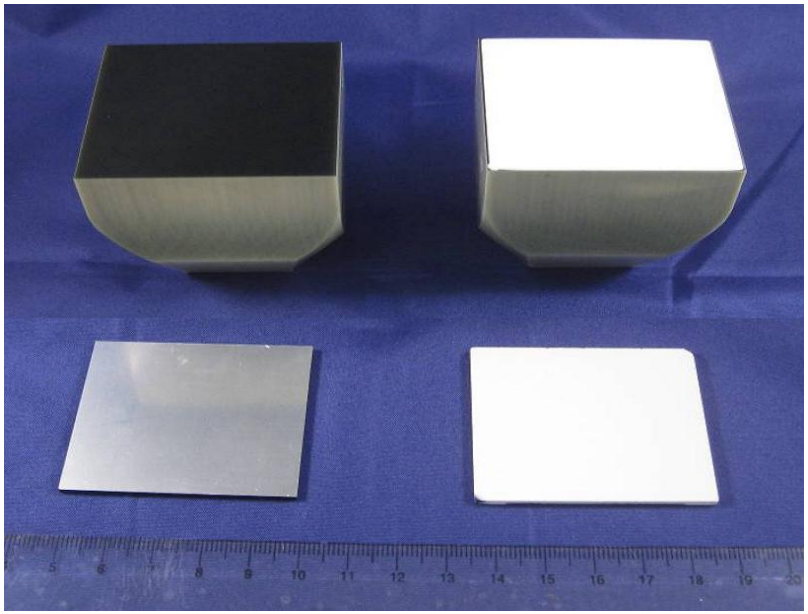
CsI:Tl deposition and comparison

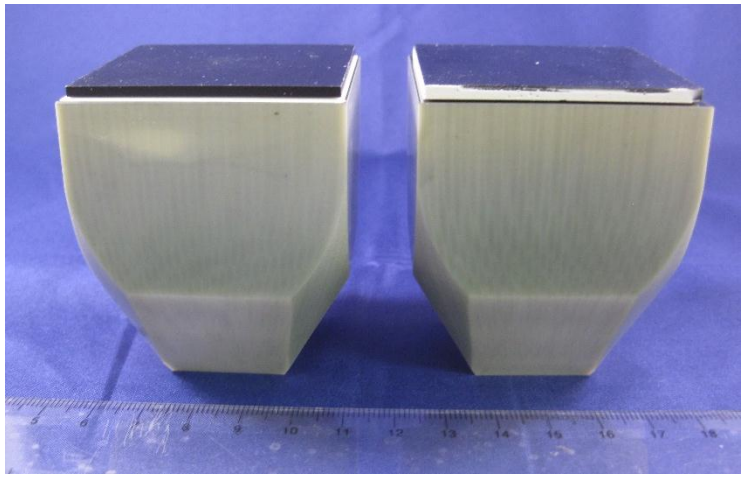
Fiberoptic taper

Fiberoptic taper with CsI:Tl

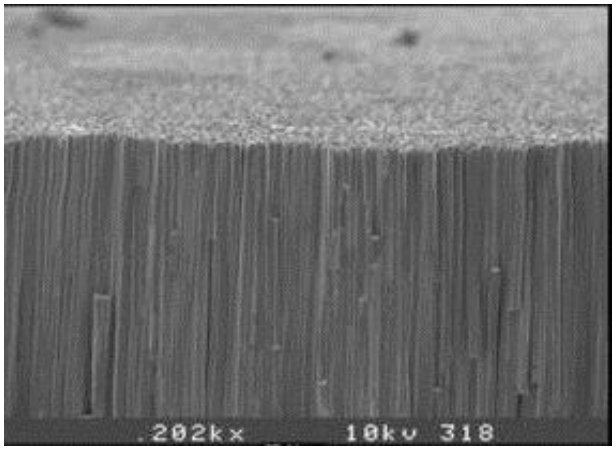
Graphite substrate with reflector

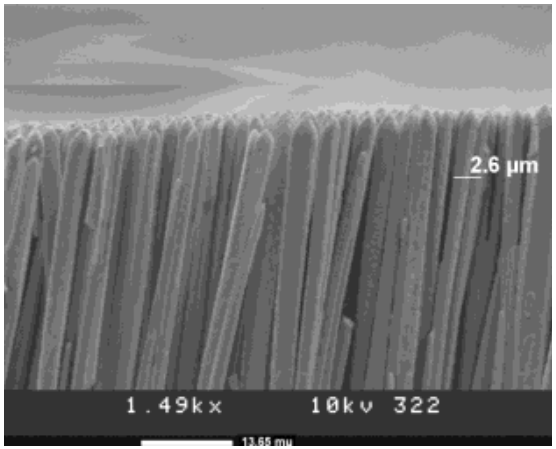
Graphite substrate with reflector and CsI:Tl

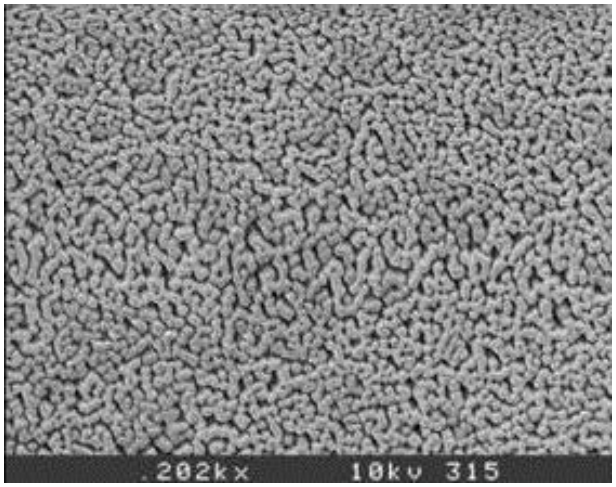




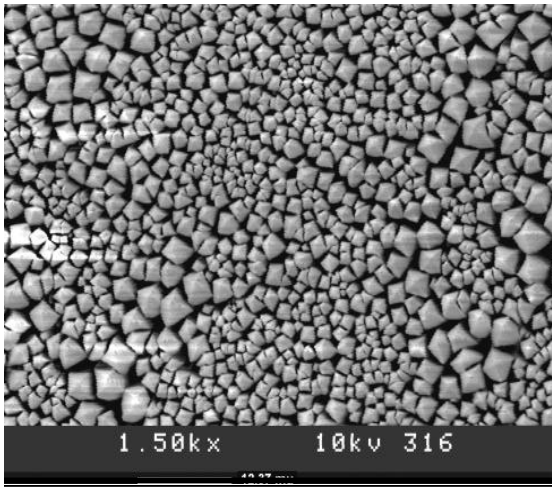
CsI:Tl film morphology







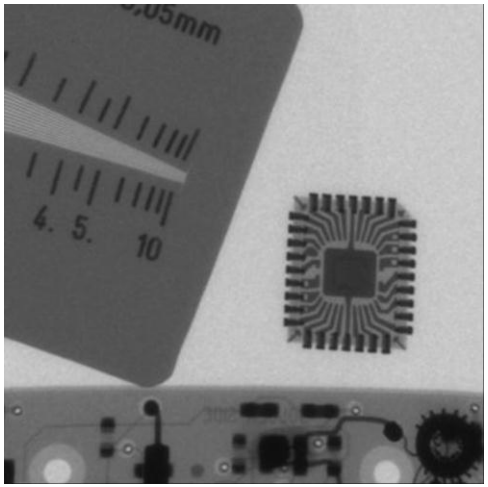
Direct deposition on fiberoptic taper

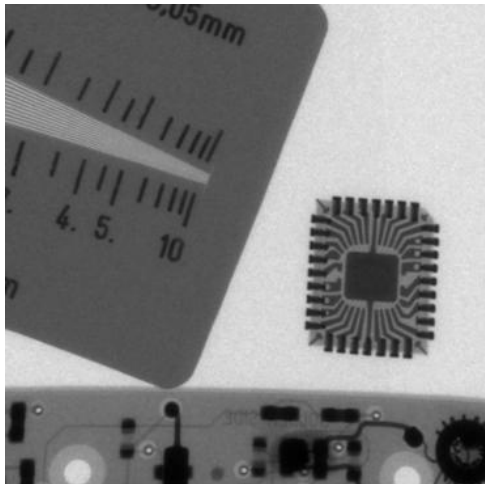


Deposition on conventional substrate

Reflector comparison

Parylene
CsI:Tl
Parylene
EMF-Al*
Parylene
Graphite





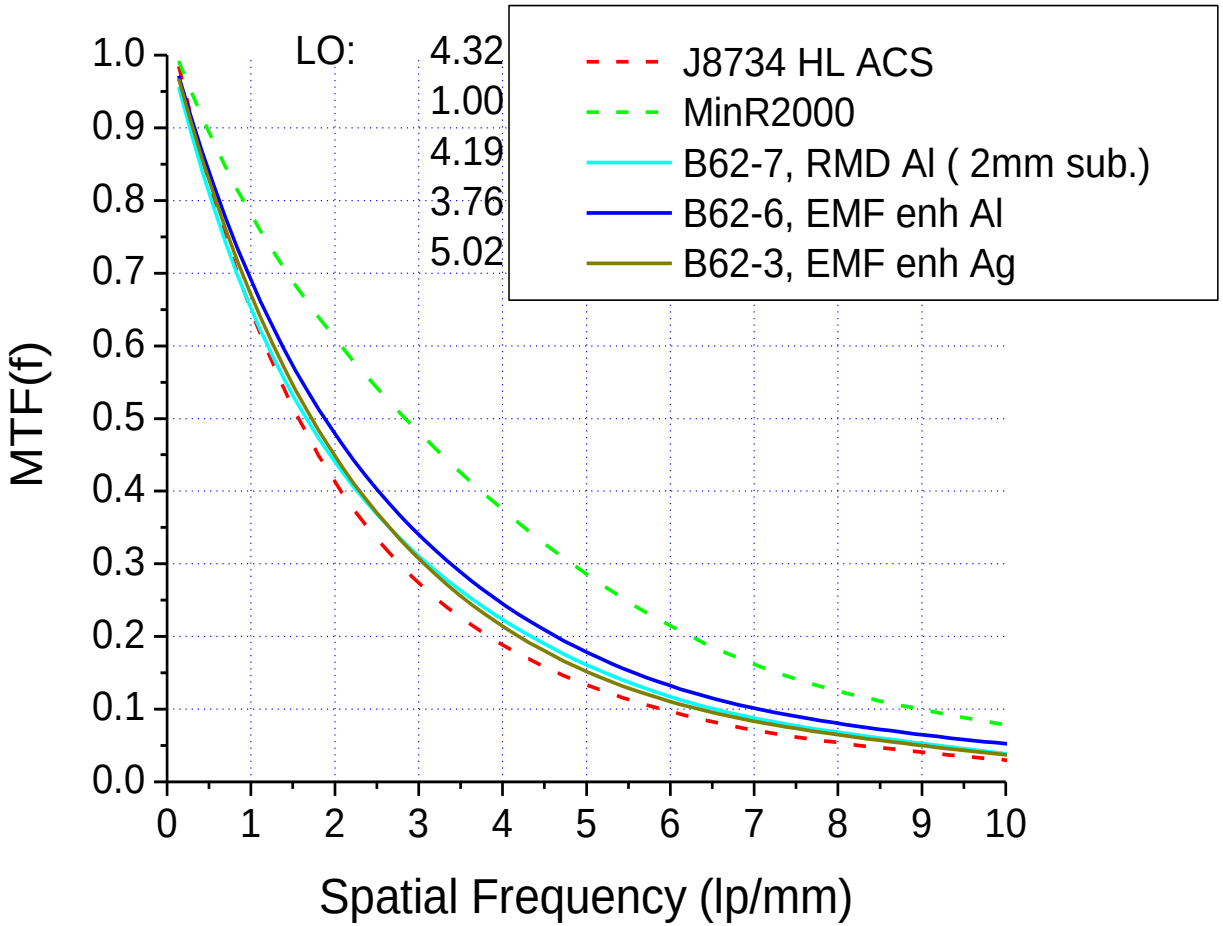
Parylene
CsI:Tl
Parylene
EMF-Ag*
Parylene
Graphite

Aluminum reflector

Silver reflector

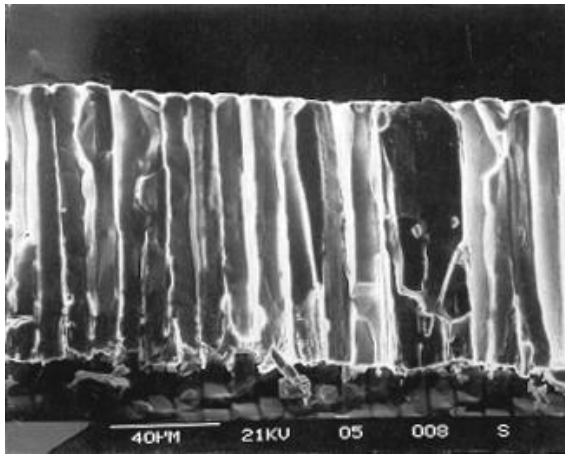
Silver reflector: 30% brighter than aluminum.
Similar MTFs.

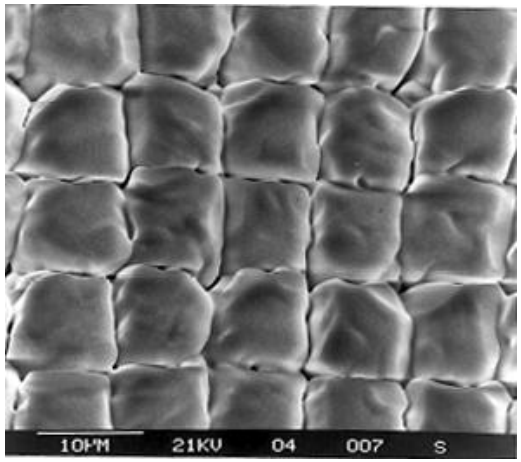
MTF



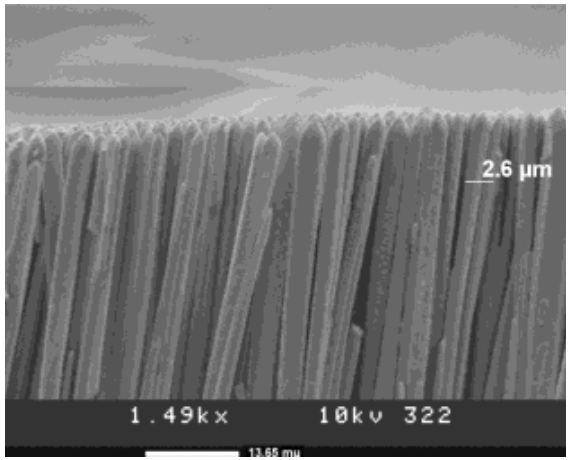
J8734 HL: 150 µm thick; 70 kVp, 10 mA, 10 Pulses

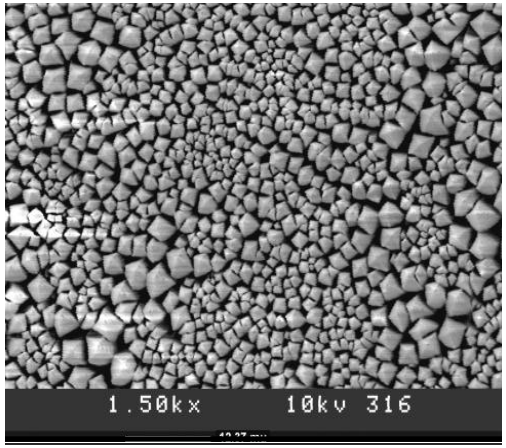
Alternate deposition approach





Crystalline microcolumnar CsI:Tl films





Conventional amorphous microcolumnar CsI:Tl films

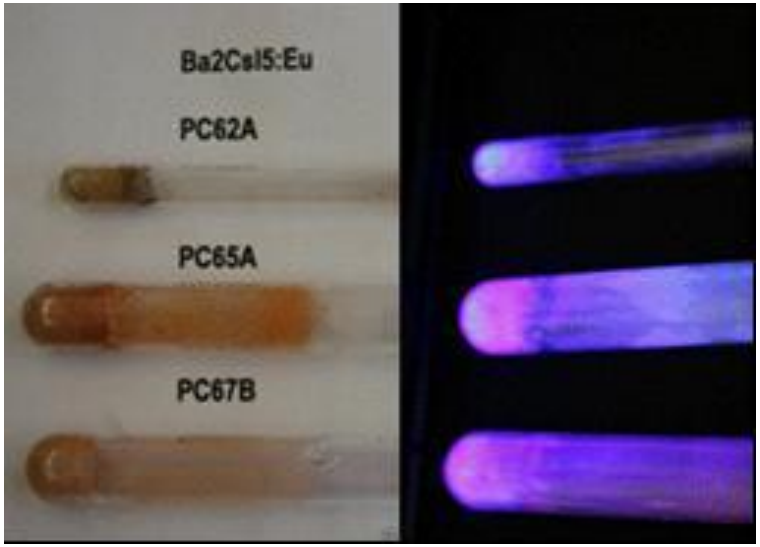
Properties of scintillation materials

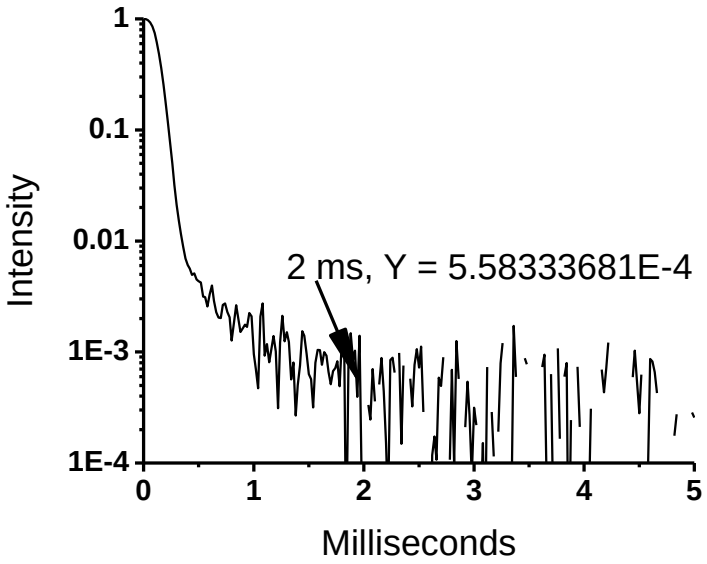
Scintillator	Density (g/cm^3)	Effective Z	Light Yield (photons/MeV)	Emission Wavelength (λ_{max})	Decay Time (ns)
Gd_2O_2S:Tb *	3.7	59.4	58,000	545	558 µs
CsI:Tl	4.53	54	62,500	540	680
Ba_2CsI_5:Eu	5.04	54	97,000	450	1,500
GdI_3:Ce	5.2	56.59	89,000	563	33
SrI_2:Eu	4.55	49.85	115,000	435	1,200
YI_3:Ce	4.6	50.8	98,600	549	34
CaI_2:Eu	3.96	50.16	86,000	470	790
Lu_2O_3:Eu	9.5	67.3	30,000	610	1,000 µs
LuI_3:Ce	5.6	59.7	115,000	540	28

Properties of various bright scintillators for hard X-ray imaging
Highlighted materials are grown in microcolumnar form at RMD

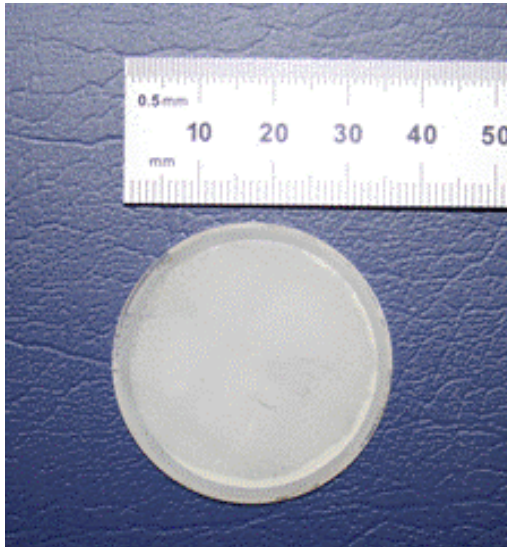
Alternate scintillator

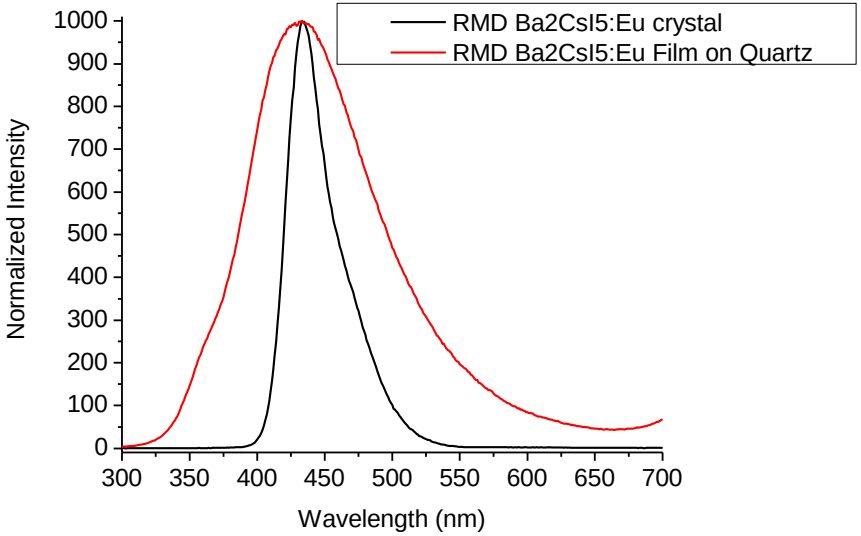
- Ba_2CsI_5:Eu
  - Light yield: 97,000 ph/MeV
  - Emission: 400 to 600 nm
  - Density: 5.06 gm/cc
  - Decay time: 1.5 microsecond
  - Afterglow: Negligible



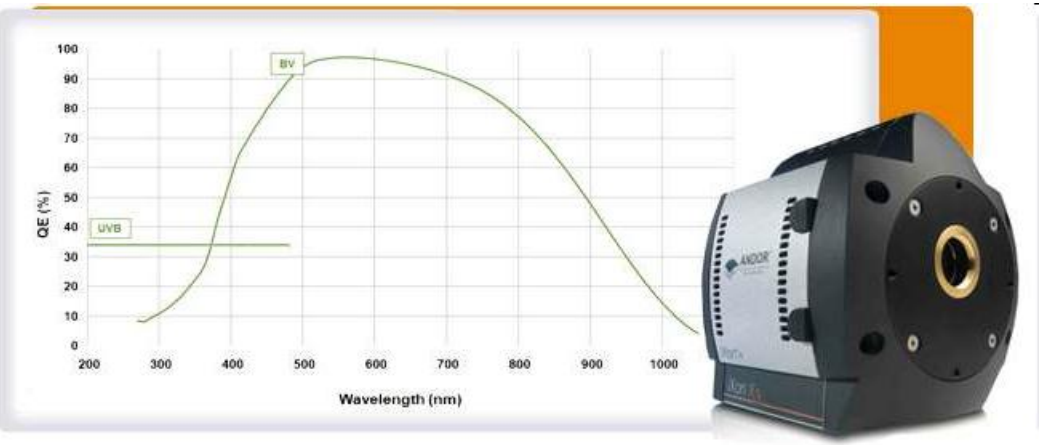


Alternate scintillator

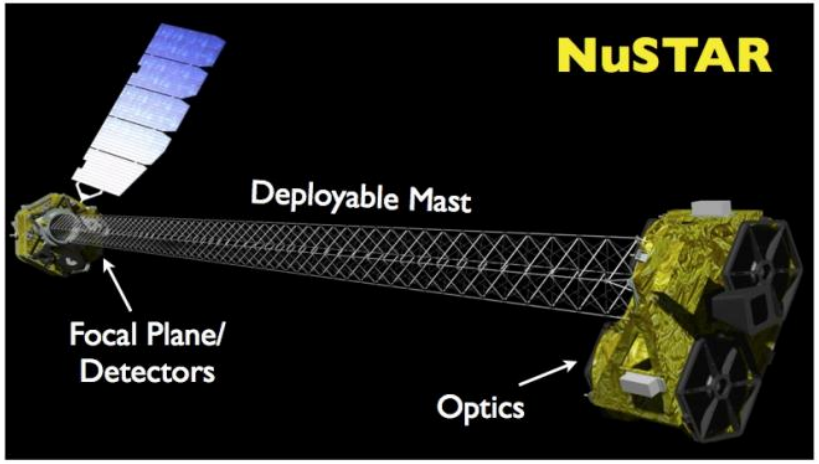


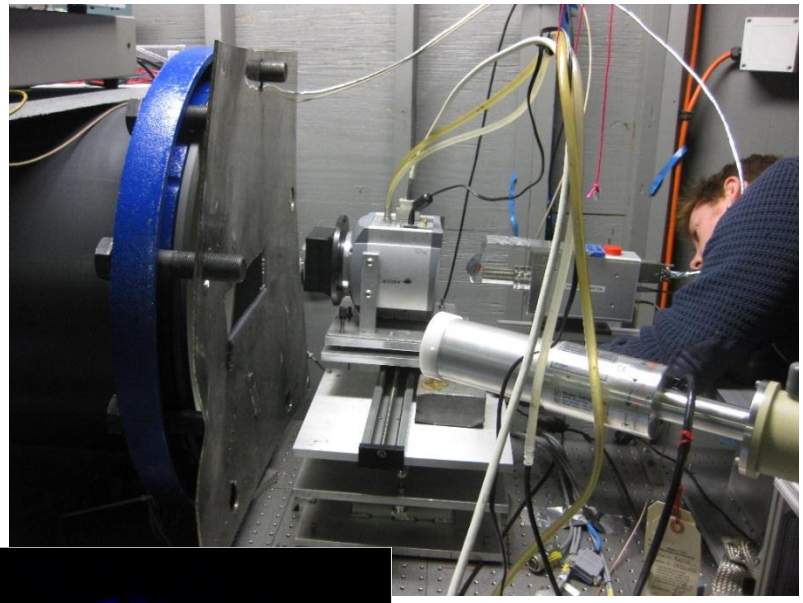


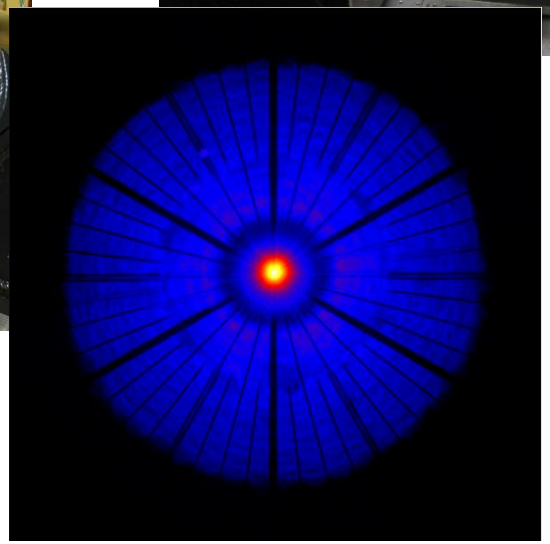
Ba_2CsI_5:Eu
High Brightness



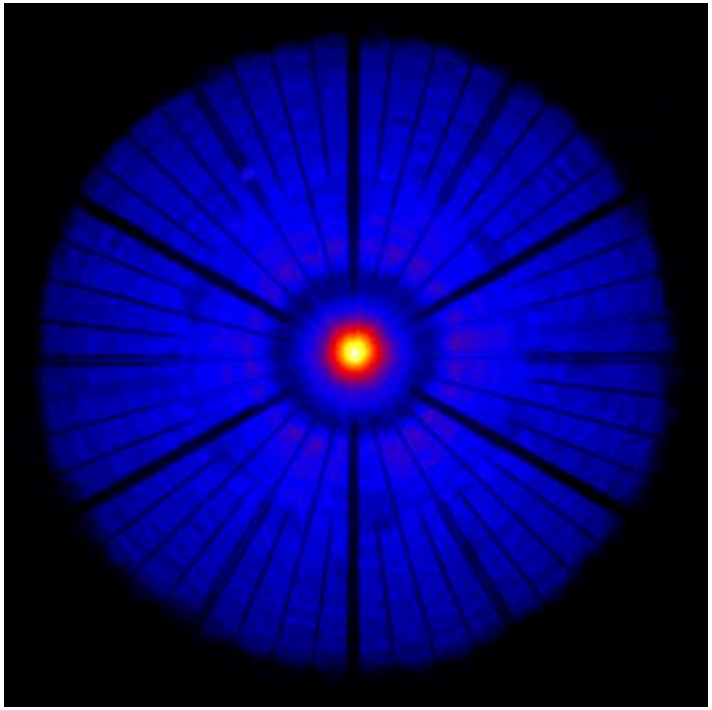
NuSTAR calibrations at Nevis Laboratories



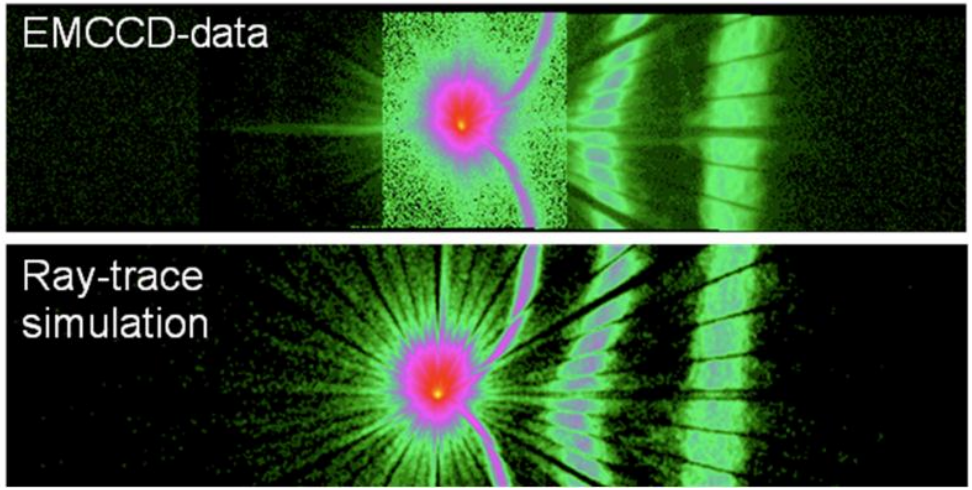




NuSTAR calibrations



PSF of NuSTAR Flight Module 2, obtained using RMD's detector.



Comparison of data acquired with the RMD detector and that simulated using the NuSTAR ray-trace simulation; X-ray source located 8 arc minutes off axis

The excellent agreement was used to tune and validate the ray-trace simulation

Phase II detector design

- Design input from Phase I results
- Wide range of applications require design flexibility to replace scintillators in convenient manner
  - Pressure coupling of scintillators is preferred
    - Field replaceable
    - Permits scintillator selection for low- and high-energy X-rays
  - Graphite substrates with silver reflectors
    - AMS/CMS CsI:Tl films
    - AMS/CMS Ba_2CsI_5 films
- EMCCD Detector
  - Larger pixel array (1024×1024)
  - 1:1 fiberoptic plug bonded to the EMCCD chip
  - Replaceable 3:1 fiberoptic taper

Detector SNR with CsI:Tl

EMCCD - Fiberoptic Taper Configuration	1:1	2:1	3:1	4:1
Active imaging area (square detector side dimension, mm)	13.3	26.6	39.9	53.3
Effective pixel size (μm^2)	13x13	26x26	39x39	52x52
CsI:Tl light output (Ph/MeV)	60,000	60,000	60,000	60,000
Incident gamma ray energy (KeV)	8	8	8	8
Screen light output	480	480	480	480
Light toward the CCD (70%)	336	336	336	336
Fiberoptic stub and taper transmission efficiency (%)	100 *	25	11	6
Light photons Incident on CCD	336	84	37	21
Signal spread over number of pixels (N)	4x4	2x2	2x2	2x2
Signal per pixel (S)	21	21	9	5
EMCCD QE (%) (QE/excess noise factor F)	79	79	79	79
Electrons generated at each pixel (S*QE)	17	17	7	4
Electron Multiplying CCD gain (G)	40	40	40	40
No. of electrons/pixel after on-chip multiplication gain (S*QE*G)	665	665	293	166
S_{total}: Total electron signal per event (S*QE*G *N)	10,640	2,660	1,170	665
Excess noise factor (F)	1.2	1.2	1.2	1.2
Photon (shot) noise G*F*SQRT(S*QE)	196	196	130	98
Total dark-related signal (e-/pixel/frame) (D)	0.1	0.1	0.1	0.1
Dark noise G*F*SQRT(D)	18	18	18	18
Read noise e- rms (σR)	40	40	40	40
Total Noise Per Pixel (σ_{Pixel})	201	201	137	107
Total System Noise (σ_{Total})	557	395	265	203
Signal-to-noise ratio (SNR) S_{Total}/σ_{Total}	19	6.7	4	3

Comparison of detector SNR with alternate scintillators

Signal-to-noise Ratio (SNR) S_{Total}/σ_{Total}	1:1	2:1	3:1	4:1
AMS CsI:Tl with aluminum reflector	19	7	4	3
AMS CsI:Tl with silver reflector	22	8	5	4
Ba_2CsI_5:Eu with silver reflector	28	10	7	5

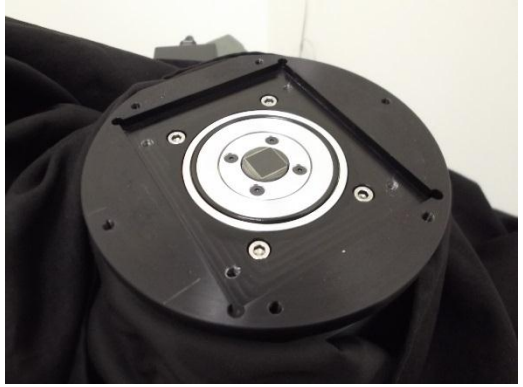
Andor iXon™ DU 888 EMCCD specifications

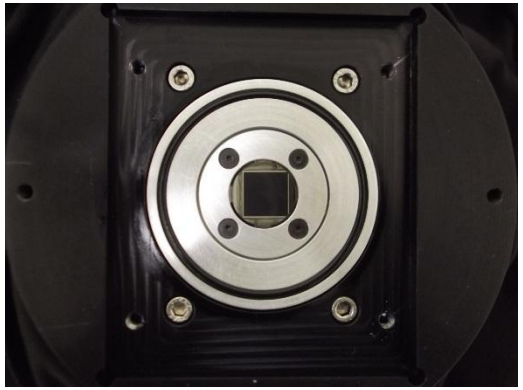
Parameter	Specification
EMCCD Pixel Resolution	1024 × 1024 pixels
EMCCD Pixel Size	13 μm × 13 μm
EMCCD active area	13.3 mm × 13.3 mm
Pixel well-depth	80,000 e^-
Gain register pixel well-depth	240,000
Electron multiplication gain	1-1000
QE at 540 nm (CsI:Tl emission)	95%
Operating temperature (OT)	TE-cooled to -95°C
Dark noise at OT	<<1e^-/pixel/second
Read noise at 10 MHz readout	<1e^- at gain = 40

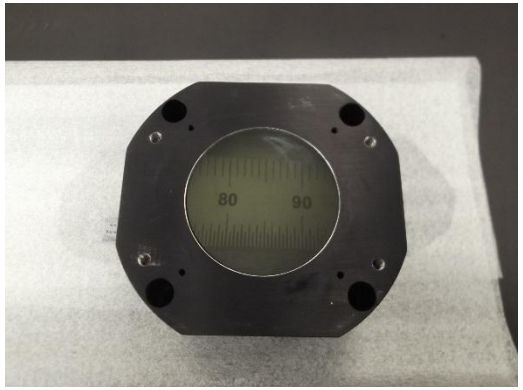
Phase II detector specifications

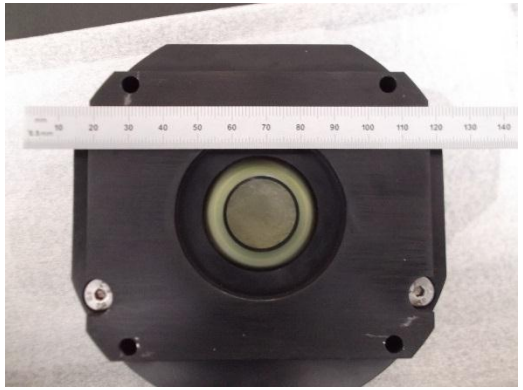
Parameter	Specification
EMCCD Pixel Resolution	1024 × 1024
EMCCD Pixel Size	13 μm
Scintillator-EMCCD Coupling	Via 3:1 coherent fiberoptic
Detector Active Area	39 x 39 mm^2
Intrinsic System Resolution	39 × 39 μm^2
Frame Rate	10 fps (full frame) to >500 fps (binning)
Low X-Ray Energy Scintillator	<100 μm thick microcolumnar CsI:Tl
High X-Ray Energy Scintillator	>400 μm thick microcolumnar CsI:Tl

The Customized Phase II Detector





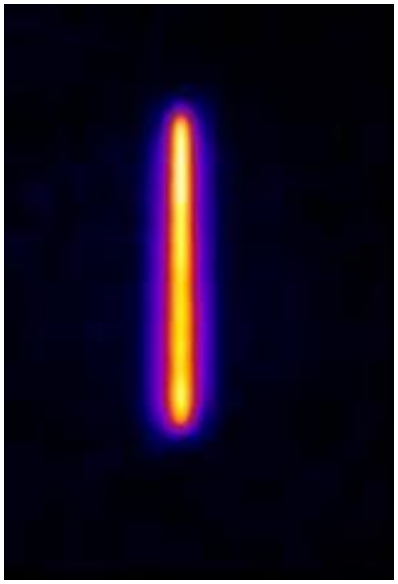




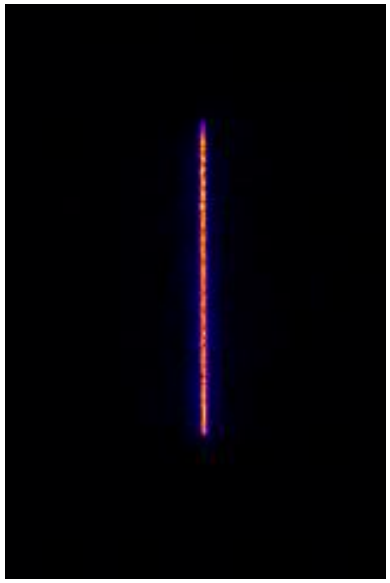
Algorithm development

Benefits of X-ray photon counting approach:

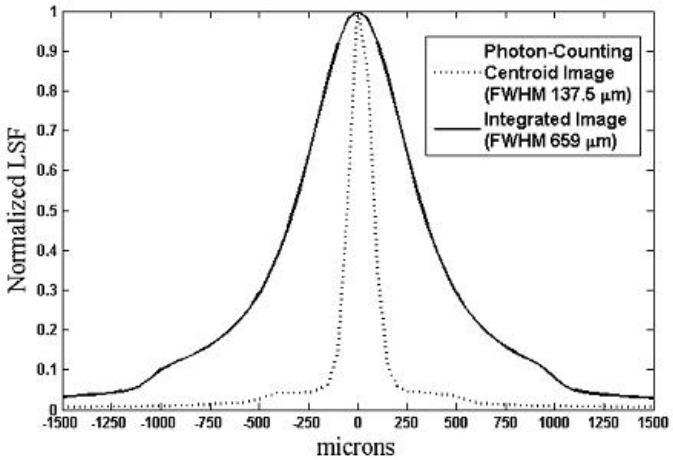
- Higher resolution
- Energy Information



Integration mode



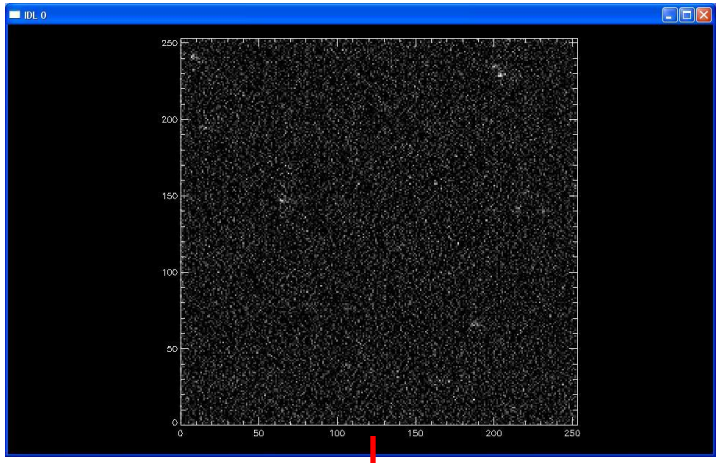
Photon counting mode



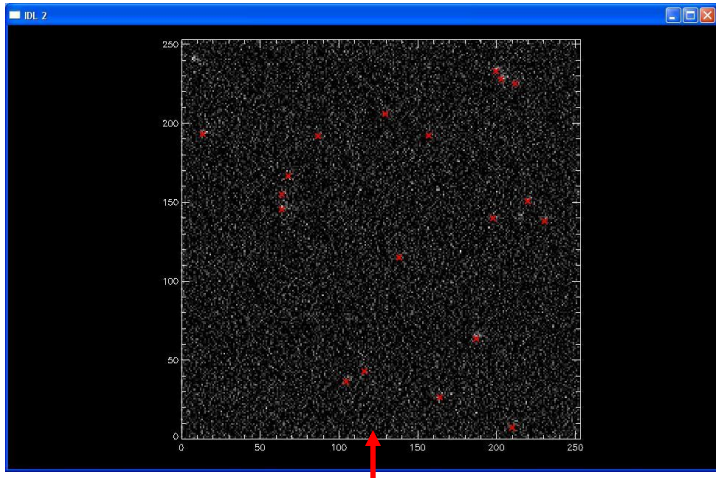
Results with ^{99m}Tc (140 keV)

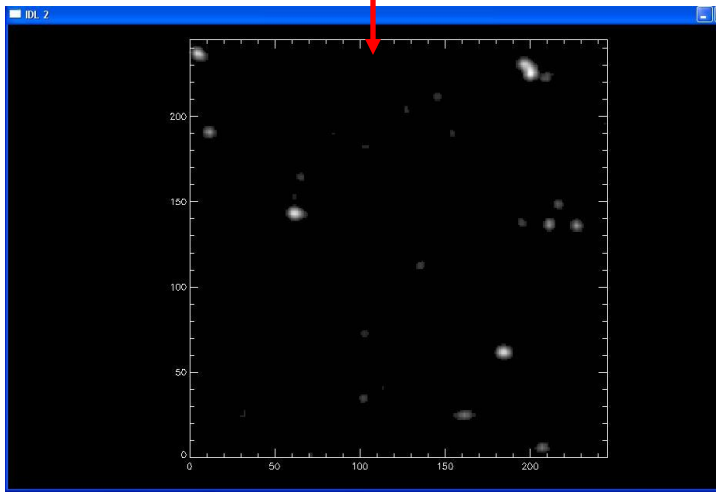
Single-photon imaging

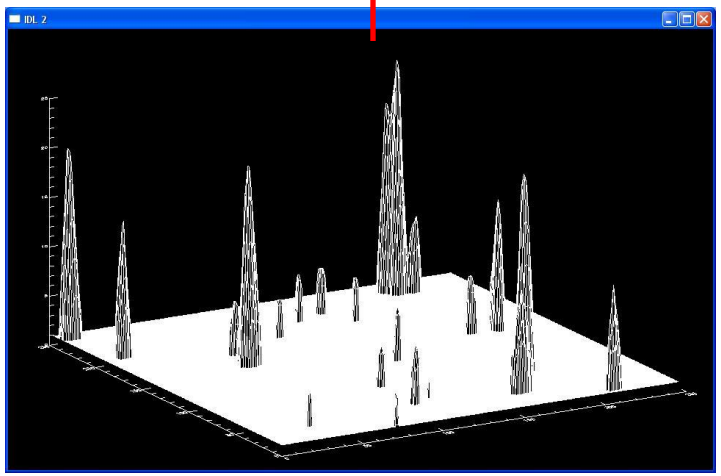
Raw data



Events identified





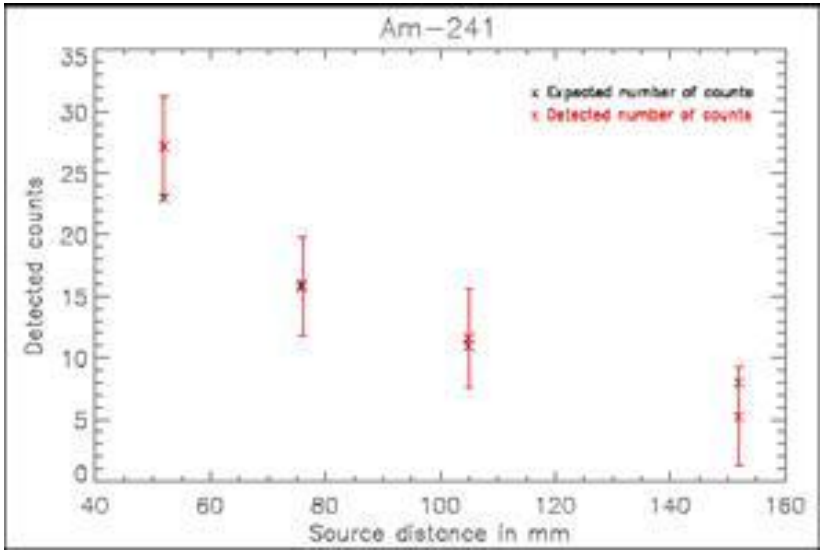


Algorithm applied

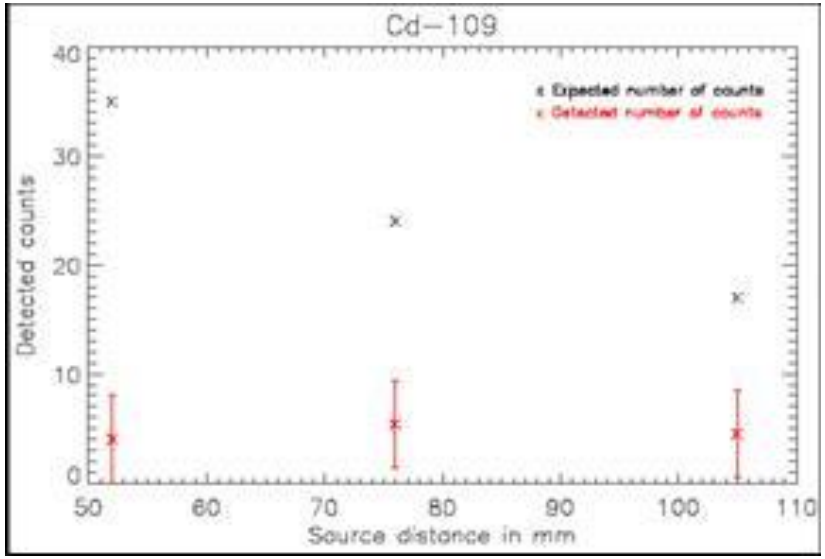
Alternate view

Algorithm development

^{241}Am, 59.5 keV



^{109}Cd, 22 keV



- 450 mm thick AMS CsI:Tl aluminum-backed graphite plate used for algorithm and test.
- Lower energy range challenging.
- Tune scintillator thickness to incident energy.
- Brighter scintillators.

Single-photon counting algorithms

- First data acquired using new scintillator
- Shown here: ^{57}Co source events observed with EMCCD and scintillator B80-22 using a 3:1 taper
- Single-photon counting algorithms written in IDL
- Optimization of various cuts to discriminate between signal counts and noise is ongoing
- First results look promising for various energies

Status update

Phase II Tasks	Status
Investigate brighter scintillators and morphology	√
Purchase customized EMCCD, 3:1 FO taper and 1:1 FO plug	√
Mechanically bond FO plug to EMCCD chip	√
Mechanically integrate system	√
Develop photon-counting software algorithm	Ongoing
Integrate software algorithm with data acquisition and imaging workflow	Ongoing
Test detector at RMD	√
Test detector at NASA X-ray facility	Planned

Summary

- Developed highly structured CsI:Tl layers on fiberoptic tapers
  - Characterized scintillator performance
  - Assembled the EMCCD detector, including software
  - Demonstrated high-resolution X-ray imaging with photon counting
- Demonstrated feasibility through NuSTAR optics calibration at Nevis Laboratories
  - Evaluated alternate scintillator approaches for enhanced sensitivity, including:
    - Crystalline microcolumnar CsI:Tl
    - Novel Ba_2CsI_5:Eu scintillator
- Developed single-photon counting algorithms