Development of High Spatial Resolution Detector for Characterization of X-ray Optics

PSD9
9th International Conference on Position Sensitive Detectors.
12th – 16th September, 2011
Aberystwyth, UK.

H.Kudrolli[1], H.Bhandari[1], M.Breen[1], V.Gelfandbein[1], S.R.Miller[1], M.Pivovaroff[2], M.R.Squillante[1] J.Vogel[2], V.V. Nagarkar[1]

[1] Radiation Monitoring Devices, Inc., Watertown, Massachusetts;
[2] Lawrence Livermore National Laboratory, Livermore CA.

ABSTRACT

Technological innovations in grazing incidence X-ray optics have been crucial to the advancement of the field of X-ray astronomy. Improvements in X-ray focusing optics translate to higher sensitivity for X-ray telescopes operating in the energy range above 10 keV. Full characterization of the X-ray optics involves measurement of the point spread function, scattering, and reflectivity properties of substrate coatings. This requires a very high spatial resolution, high sensitivity, photon counting and energy discriminating, large area detector. In this paper we describe the construction of a 2D detector using EMCCD that is well suited to meet these requirements.

A prototype version of this camera was used to calibrate the X-ray focusing optics for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission. Analysis of the data obtained during the ground calibration of the NuSTAR telescopes demonstrated the advantages of such a high resolution 2D detector for hard X-rays (30+ keV), however it showed some limitations for medium energy X-rays (8 – 30 keV). We present here, alternative methods under investigation to improve performance of the detector for medium energy X-rays such as changing the morphology of the CsI:Tl scintillator, improving light transport from scintillator to EMCCD and using a novel bright scintillator, Ba_2CsI_5:Eu.

At-Wavelength Metrology of X-Ray Optics

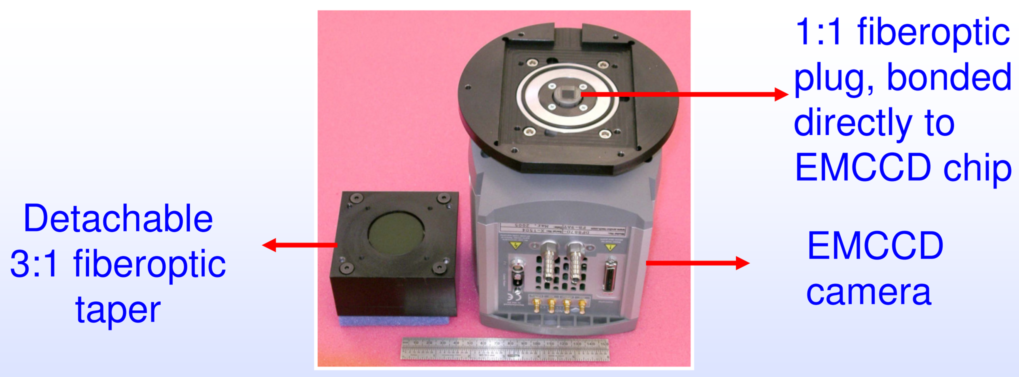
Detector Requirements:

- High spatial resolution (~ 25 µm)
- Operation over a large energy range (5 keV to 100 keV +)
- High sensitivity to X-rays (~100%@ 5 keV, >70%@ 100 keV)
- Large active area (~ 5 x 5 cm²)
- High count rate capability (10^5 events/second)
- Flexible design / adaptable to various mission requirements
- Ease of operation

Solution:

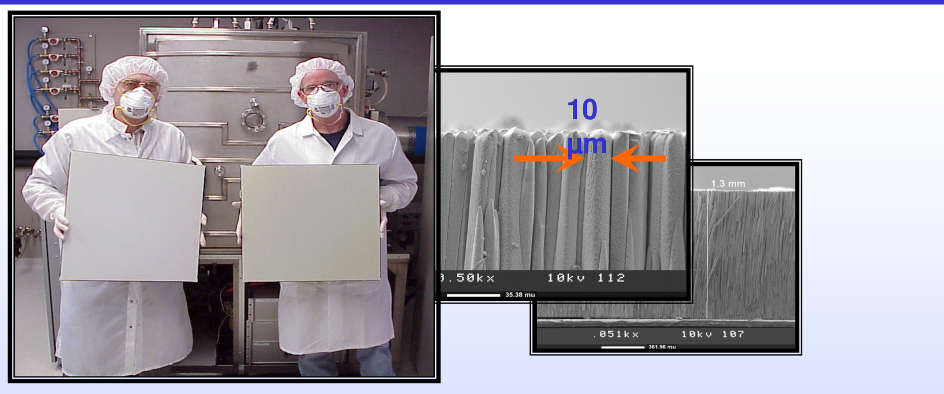
Combine EMCCD with high brightness microcolumnar scintillator with minimum light loss in coupling.

Customized EMCCD



Fiberoptic bonding to EMCCD minimizes scintillator light loss. Detector area: 25.2 mm x 25.2 mm and 49 µm pixel size. [1]

RMD Columnar CsI:Tl



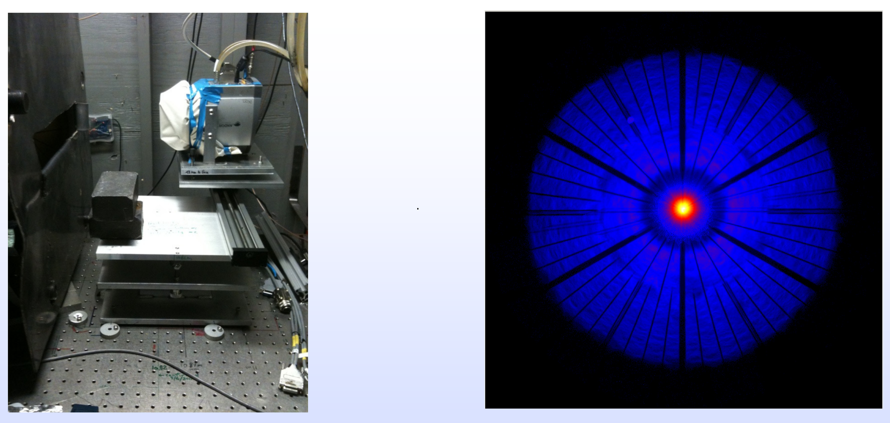
RMD has pioneered development of micro-columnar CsI:Tl for digital radiography. [2]

NuSTAR Project Background

- Nuclear Spectroscopic Telescope Array (NuSTAR) [3]
- Principal Investigator: Dr. Fiona Harrison, CalTech.
- NASA SMEX scheduled launch 2012.
- X-ray telescope sensitive from 6 keV – 80 keV.
- Optics: 2 Wolter-I grazing angle telescope mirrors.
- Detectors: CdZnTe detectors, 250 µm pixel size.

- Optics calibration were conducted Oct 2010 – Apr 2011 at Columbia University's Rainwater Memorial Calibration Facility (RaMCaF) [4]

NuSTAR optics ground calibration



(Left) RMD detector on translational stage in RaMCaF beamline. (Right) Point Spread Function of NuSTAR flight optics.[5]

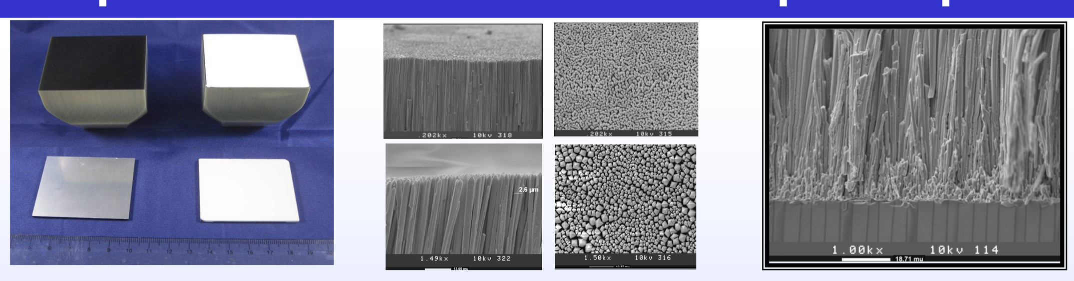
Calibration Results

The RMD Detector played a crucial role in

- Characterization of RaMCaF features such as beam profile, slit sizes, and monitoring through-holes.
- Installation and alignment of telescopes in the beamline.
- Characterization of the point-spread function (PSF).
- Validation of Monte Carlo simulations for finite distance effects, diverging source effects and gravity.[6].

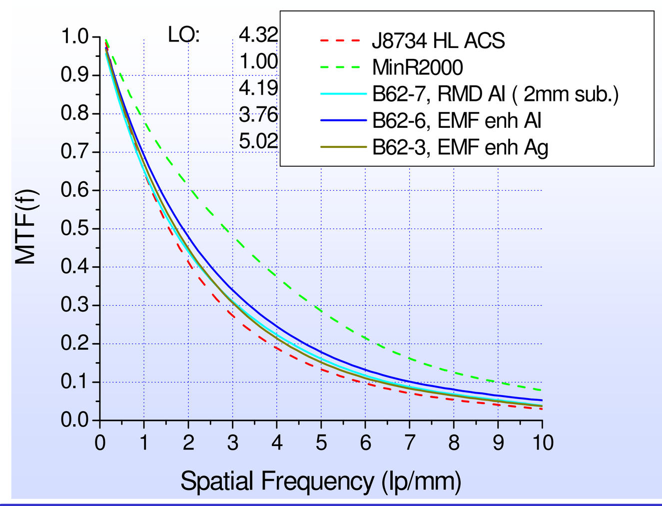
These results show the advantage of using such a detector. However, performance of detector at X-ray energies below 30 keV was sub-optimal. One reason for this is that a CsI:Tl scintillator of thickness 450 µm was used. Optimizing the characteristics of the scintillator would lead to better performance at lower energies.

Deposition of CsI:Tl on Fiber-Optic Tapers



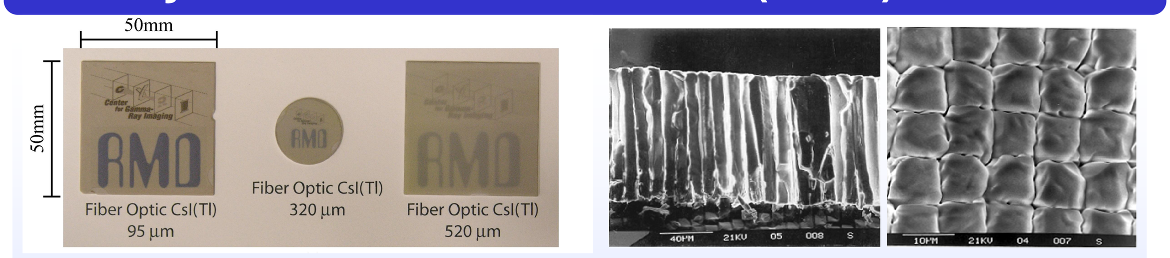
(Left) Photographs of fiber-optic tapers and standard Al backed graphite substrate coated with CsI:Tl show uniform coating. *(Middle)* SEM shows columnar structure on both substrates. *(Right)* SEM at interface of fiberoptic taper and CsI:Tl shows amorphous structure that scatters light. Further optimization of deposition conditions is needed.

Reflector Coating Improvements



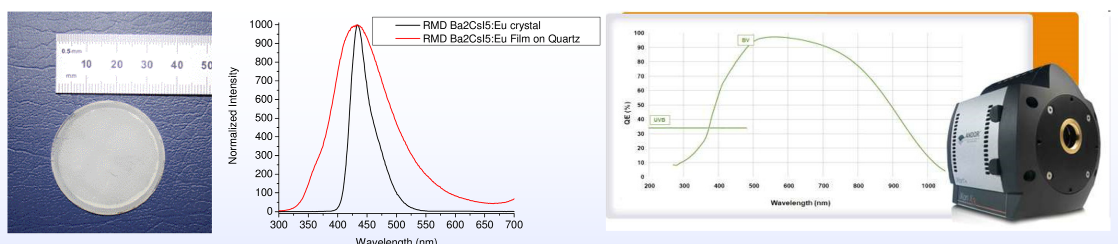
Using silver as reflector material as opposed to aluminum gave 30% increase in light output with no difference in MTF.

Crystalline Microcolumnar (CMS) CsI:Tl



Experiments were conducted to change the morphology of CsI:Tl films to grow them as crystalline microcolumnar films. The SEMs of the CMS films show that the columns are thicker than regular AMS CsI:Tl films and therefore have higher light yield due to less self absorption.

Novel Bright Scintillator: Ba_2CsI_5:Eu



A newly discovered scintillator Ba_2CsI_5:Eu [7] was fabricated in thin film. This scintillator has 97,000 photons/MeV, which is much higher than 60,000 photons/MeV for CsI:Tl. The emission spectra of the thin film form of this scintillator is well matched to the quantum efficiency of EMCCDs.

Detector SNR with CsI:Tl

EMCCD - Fiberoptic Taper Configuration	1:1	2:1	3:1
Active imaging area (mm)	13.3	26.6	39.9
Effective pixel size (µm²)	13x13	26x26	39x39
Screen light output	480	480	480
Light toward the CCD (70%)	336	336	336
Fiberoptic transmission efficiency (%)	100 *	25	11
Light photons Incident on CCD	336	84	37
Signal spread over number of pixels (N)	4x4	2x2	2x2
Signal per pixel (S)	21	21	9
EMCCD QE (%) (QE/excess noise factor F)	79	79	79
Electrons generated at each pixel (S*QE)	17	17	7
Electron Multiplying CCD gain (G)	40	40	40
Excess noise factor (F)	1.2	1.2	1.2
Photon (shot) noise G*F*SQRT(S*QE)	196	196	130
Total dark-related signal (e-/pixel/frame) (D)	0.1	0.1	0.1
Dark noise G*F*SQRT(D)	18	18	18
Read noise e- rms (σR)	40	40	40
Total Noise Per Pixel (σ_{Pixel})	201	201	137
Total System Noise (σ_{Total})	557	395	265
Signal-to-Noise ratio (SNR) S_{Total}/σ_{Total}	19	6.7	4

Worksheet showing the signal to noise performance to detect single 8 keV photons for CsI:Tl scintillator with various taper sizes.

SNR Improvements with other configurations

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

The table shows the expected improvements in SNR by replacing the aluminum reflector with silver and also by replacing the CsI:Tl scintillator with Ba_2CsI_5:Eu.

Detector Specifications

Parameter	Specification
EMCCD Pixel Resolution	1024×1024
EMCCD Pixel Size	13 µm
Scintillator-EMCCD Coupling	Via 2:1 to 4:1 coherent fiberoptic taper
Detector Active Area	27x27 mm² (2:1) to 53×53 mm² (4:1)
Intrinsic System Resolution	26 µm×26 µm
Frame Rate (fps)	10 fps (full frame) to >500 fps (binning)
Scintillator	Field replaceable AMS/CMS scintillators

Conclusions

❖The wide range of energies used in X-ray astronomy require design flexibility in the detector.The ability to replace the scintillators would maximize the utility of the detector. In the new detector design the scintillator is pressure coupled to the fiber-optic taper and is replaceable while the camera is operational.

❖Various methods to improve scintillator performance at lower X-ray energies are under investigation. Optimizing the thickness and morphology of the CsI:Tl improve performance. Using silver reflector gives a 30% improvement in light yield. We have successfully deposited Ba_2CsI_5:Eu, after optimization this will yield further significant improvements in SNR of the detector.

References

[1] V.V.Nagarkar, et. al. NIM A, 563 (2006) oo 45 – 48
[2] V.V.Nagarkar, et. al. IEEE Trans Nucl. Sci. Vol 45#3, pp 492-496, June (1998)
[3] http://www.nustar.caltech.edu
[4] W.W.Craig, et. al. SPIE 2011 Optics and Photonics #8147-15
[5] N.F.Brejnholt, et. al. SPIE 2011 Optics and Photonics #8147-16
[6] J.Vogel, et. al. "Application of an EMCCD Camera for Calibration of Hard X-Ray Telescope" Manuscript in preparation for IEEE TNS
[7] Bourret-Courchesne, E. D. et al., NIM A, 2009, 612 (1), 138-142.

Acknowledgements

We thank NASA for funding this research under grant number NNX11CH32P.

Contact:
Haris Kudrolli, HKudrolli@rmdinc.com
Vivek Nagarkar, VNagarkar@ rmdinc.com

A Dynasil member company.

Radiation Monitoring Devices, Inc.
44 Hunt Street
Watertown, MA 02472-4699, U.S.A.
www. rmdinc. com
Phone: (617) 668-6800
Fax: (617) 926-9980