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

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RMD, Imaging, Speed – A historical perspective

Ca. 1908

Ca. 1948
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 cm²)
• High count rate capability (10⁵ 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
**EMCCD advantages**

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

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**RMD Customized EMCCD Camera**

1:1 fiberoptic plug, bonded directly to EMCCD chip

Detachable 3:1 fiberoptic taper

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 has pioneered development of microcolumnar CsI:Tl for digital radiography.
Versatility of vapor deposition

8” Vacuum Flanges

5x5 cm² Fiberoptic Taper

Bare SiPM

CsI:Tl-Coated SiPM

mm² SiPMs
CsI:Tl deposition and comparison

Fiberoptic taper

Graphite substrate with reflector

Fiberoptic taper with CsI:Tl

Graphite substrate with reflector and CsI:Tl
CsI:Tl film morphology

Direct deposition on fiberoptic taper

Deposition on conventional substrate
Silver reflector: 30% brighter than aluminum. Similar MTFs.
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

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>Density (g/cm³)</th>
<th>Effective Z</th>
<th>Light Yield (photons/MeV)</th>
<th>Emission Wavelength (λ_max)</th>
<th>Decay Time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd₂O₂S:Tb *</td>
<td>3.7</td>
<td>59.4</td>
<td>58,000</td>
<td>545</td>
<td>558 μs</td>
</tr>
<tr>
<td>CsI:Tl</td>
<td>4.53</td>
<td>54</td>
<td>62,500</td>
<td>540</td>
<td>680</td>
</tr>
<tr>
<td>Ba₂CsI₅:Eu</td>
<td>5.04</td>
<td>54</td>
<td>97,000</td>
<td>450</td>
<td>1,500</td>
</tr>
<tr>
<td>GdI₃:Ce</td>
<td>5.2</td>
<td>56.59</td>
<td>89,000</td>
<td>563</td>
<td>33</td>
</tr>
<tr>
<td>SrI₂:Eu</td>
<td>4.55</td>
<td>49.85</td>
<td>115,000</td>
<td>435</td>
<td>1,200</td>
</tr>
<tr>
<td>YI₃:Ce</td>
<td>4.6</td>
<td>50.8</td>
<td>98,600</td>
<td>549</td>
<td>34</td>
</tr>
<tr>
<td>CaI₂:Eu</td>
<td>3.96</td>
<td>50.16</td>
<td>86,000</td>
<td>470</td>
<td>790</td>
</tr>
<tr>
<td>Lu₂O₃:Eu</td>
<td>9.5</td>
<td>67.3</td>
<td>30,000</td>
<td>610</td>
<td>1,000 μs</td>
</tr>
<tr>
<td>LuI₃:Ce</td>
<td>5.6</td>
<td>59.7</td>
<td>115,000</td>
<td>540</td>
<td>28</td>
</tr>
</tbody>
</table>

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

- **Ba$_2$CsI$_5$: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$_2$CsI$_5$: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$_2$CsI$_5$ 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

<table>
<thead>
<tr>
<th>EMCCD - Fiberoptic Taper Configuration</th>
<th>1:1</th>
<th>2:1</th>
<th>3:1</th>
<th>4:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active imaging area (square detector side dimension, mm)</td>
<td>13.3</td>
<td>26.6</td>
<td>39.9</td>
<td>53.3</td>
</tr>
<tr>
<td>Effective pixel size (μm²)</td>
<td>13x13</td>
<td>26x26</td>
<td>39x39</td>
<td>52x52</td>
</tr>
<tr>
<td>CsI:Tl light output (Ph/MeV)</td>
<td>60,000</td>
<td>60,000</td>
<td>60,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Incident gamma ray energy (KeV)</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Screen light output</td>
<td>480</td>
<td>480</td>
<td>480</td>
<td>480</td>
</tr>
<tr>
<td>Light toward the CCD (70%)</td>
<td>336</td>
<td>336</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Fiberoptic stub and taper transmission efficiency (%)</td>
<td>100 *</td>
<td>25</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>Light photons Incident on CCD</td>
<td>336</td>
<td>84</td>
<td>37</td>
<td>21</td>
</tr>
<tr>
<td>Signal spread over number of pixels (N)</td>
<td>4x4</td>
<td>2x2</td>
<td>2x2</td>
<td>2x2</td>
</tr>
<tr>
<td>Signal per pixel (S)</td>
<td>21</td>
<td>21</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>EMCCD QE (%) (QE/excess noise factor F)</td>
<td>79</td>
<td>79</td>
<td>79</td>
<td>79</td>
</tr>
<tr>
<td>Electrons generated at each pixel (S*QE)</td>
<td>17</td>
<td>17</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Electron Multiplying CCD gain (G)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>No. of electrons/pixel after on-chip multiplication gain (S<em>QE</em>G)</td>
<td>665</td>
<td>665</td>
<td>293</td>
<td>166</td>
</tr>
<tr>
<td>S_total: Total electron signal per event (S<em>QE</em>G *N)</td>
<td>10,640</td>
<td>2,660</td>
<td>1,170</td>
<td>665</td>
</tr>
<tr>
<td>Excess noise factor (F)</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Photon (shot) noise G<em>F</em>SQRT(S*QE)</td>
<td>196</td>
<td>196</td>
<td>130</td>
<td>98</td>
</tr>
<tr>
<td>Total dark-related signal (e-/pixel/frame) (D)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Dark noise G<em>F</em>SQRT(D)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Read noise e- rms (σR)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Total Noise Per Pixel (σ_pixel)</td>
<td>201</td>
<td>201</td>
<td>137</td>
<td>107</td>
</tr>
<tr>
<td>Total System Noise (σ_total)</td>
<td>557</td>
<td>395</td>
<td>265</td>
<td>203</td>
</tr>
<tr>
<td>Signal-to-noise ratio (SNR) S_total/σ_total</td>
<td>19</td>
<td>6.7</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>
### Comparison of detector SNR with alternate scintillators

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Signal-to-noise Ratio (SNR) ( S_{\text{Total}}/\sigma_{\text{Total}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AMS CsI:Tl with aluminum reflector</strong></td>
<td>( 1:1 ) 7 ( 2:1 ) 4 ( 3:1 ) ( 4:1 ) 3</td>
</tr>
<tr>
<td><strong>AMS CsI:Tl with silver reflector</strong></td>
<td>( 2:1 ) 8 ( 3:1 ) 5 ( 4:1 ) 4</td>
</tr>
<tr>
<td><strong>Ba(_2)CsI(_3):Eu with silver reflector</strong></td>
<td>( 3:1 ) 10 ( 4:1 ) 7 ( 5:1 ) 5</td>
</tr>
</tbody>
</table>
## Andor iXon™ DU 888 EMCCD specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMCCD Pixel Resolution</td>
<td>1024 × 1024 pixels</td>
</tr>
<tr>
<td>EMCCD Pixel Size</td>
<td>13 µm × 13 µm</td>
</tr>
<tr>
<td>EMCCD active area</td>
<td>13.3 mm × 13.3 mm</td>
</tr>
<tr>
<td>Pixel well-depth</td>
<td>80,000 e⁻</td>
</tr>
<tr>
<td>Gain register pixel well-depth</td>
<td>240,000</td>
</tr>
<tr>
<td>Electron multiplication gain</td>
<td>1–1000</td>
</tr>
<tr>
<td>QE at 540 nm (CsI:Tl emission)</td>
<td>95%</td>
</tr>
<tr>
<td>Operating temperature (OT)</td>
<td>TE-cooled to -95°C</td>
</tr>
<tr>
<td>Dark noise at OT</td>
<td>&lt;&lt;1e⁻/pixel/second</td>
</tr>
<tr>
<td>Read noise at 10 MHz readout</td>
<td>&lt;1e⁻ at gain = 40</td>
</tr>
</tbody>
</table>
# Phase II detector specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMCCD Pixel Resolution</td>
<td>1024 × 1024</td>
</tr>
<tr>
<td>EMCCD Pixel Size</td>
<td>13 ( \mu )m</td>
</tr>
<tr>
<td>Scintillator-EMCCD Coupling</td>
<td>Via 3:1 coherent fiberoptic</td>
</tr>
<tr>
<td>Detector Active Area</td>
<td>39 × 39 ( \text{mm}^2 )</td>
</tr>
<tr>
<td>Intrinsic System Resolution</td>
<td>39 × 39 ( \mu )m^2</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>10 fps (full frame) to &gt;500 fps (binning)</td>
</tr>
<tr>
<td>Low X-Ray Energy Scintillator</td>
<td>&lt;100 ( \mu )m thick microcolumnar CsI:Tl</td>
</tr>
<tr>
<td>High X-Ray Energy Scintillator</td>
<td>&gt;400 ( \mu )m thick microcolumnar CsI:Tl</td>
</tr>
</tbody>
</table>
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

$^{241}\text{Am, 59.5 keV}$  $^{109}\text{Cd, 22 keV}$

- 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

<table>
<thead>
<tr>
<th>Phase II Tasks</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigate brighter scintillators and morphology</td>
<td>√</td>
</tr>
<tr>
<td>Purchase customized EMCCD, 3:1 FO taper and 1:1 FO plug</td>
<td>√</td>
</tr>
<tr>
<td>Mechanically bond FO plug to EMCCD chip</td>
<td>√</td>
</tr>
<tr>
<td>Mechanically integrate system</td>
<td>√</td>
</tr>
<tr>
<td>Develop photon-counting software algorithm</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Integrate software algorithm with data acquisition and imaging workflow</td>
<td>Ongoing</td>
</tr>
<tr>
<td>Test detector at RMD</td>
<td>√</td>
</tr>
<tr>
<td>Test detector at NASA X-ray facility</td>
<td>Planned</td>
</tr>
</tbody>
</table>
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$_2$CsI$_5$:Eu scintillator
• Developed single-photon counting algorithms