# Spatial Resolution of Crystal Based Hard X-ray Imager


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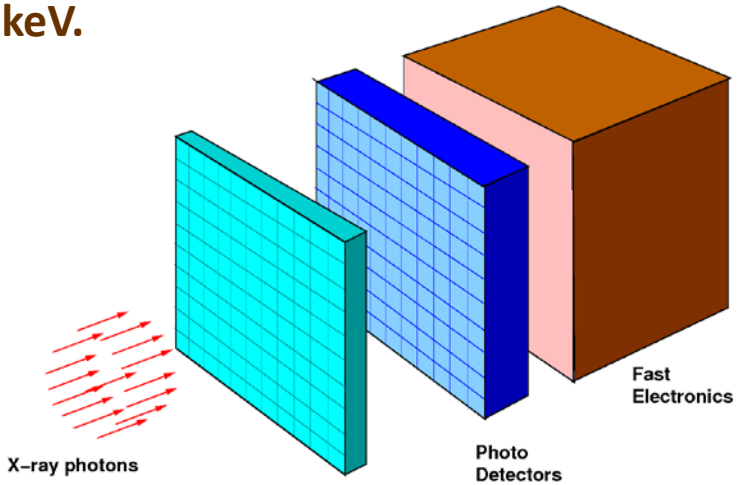
# Inorganic Scintillator-Based Imager for GHz Hard X-ray Imaging

Requirements:

Fast inter-frame & hard x-ray require ultrafast sensor in bulk

| Performance | Type I imager | Type II imager |
|---|---|---|
| X-ray energy | **up to 30 keV** | **42-126 keV** |
| Frame-rate/inter-frame time | **0.5 GHz / 2 ns** | **3 GHz / 300 ps** |
| Number of frames per burst | ≥ 10 | 10 - 30 |
| X-ray detection efficiency | above 50% | above 80% |
| Pixel size/pitch | **≤ 300 µm** | **< 300 µm** |
| Dynamic range | $10^3$ X-ray Photons/pixel/frame | ≥ $10^4$ X-ray Photons/pixel/frame |
| Pixel format | 64 × 64[a] (scalable to 1 Mpix) | 1 Mpix |

- **With 0.5 ns decay time $BaF_2$ provides high light output in the 1st ns and a good efficiency for hard X-rays from 30 to 126 keV.**
- **Yttrium doping in $BaF_2$ suppresses its slow scintillation significantly and maintains its ultrafast scintillation light.**
- **A total absorption front imager:**
  - **Pixelated ultrafast crystal screen;**
  - **Pixelated ultrafast photodetector;**
  - **Ultrafast electronics readout.**
- **This paper discusses spatial resolution for such imager.**



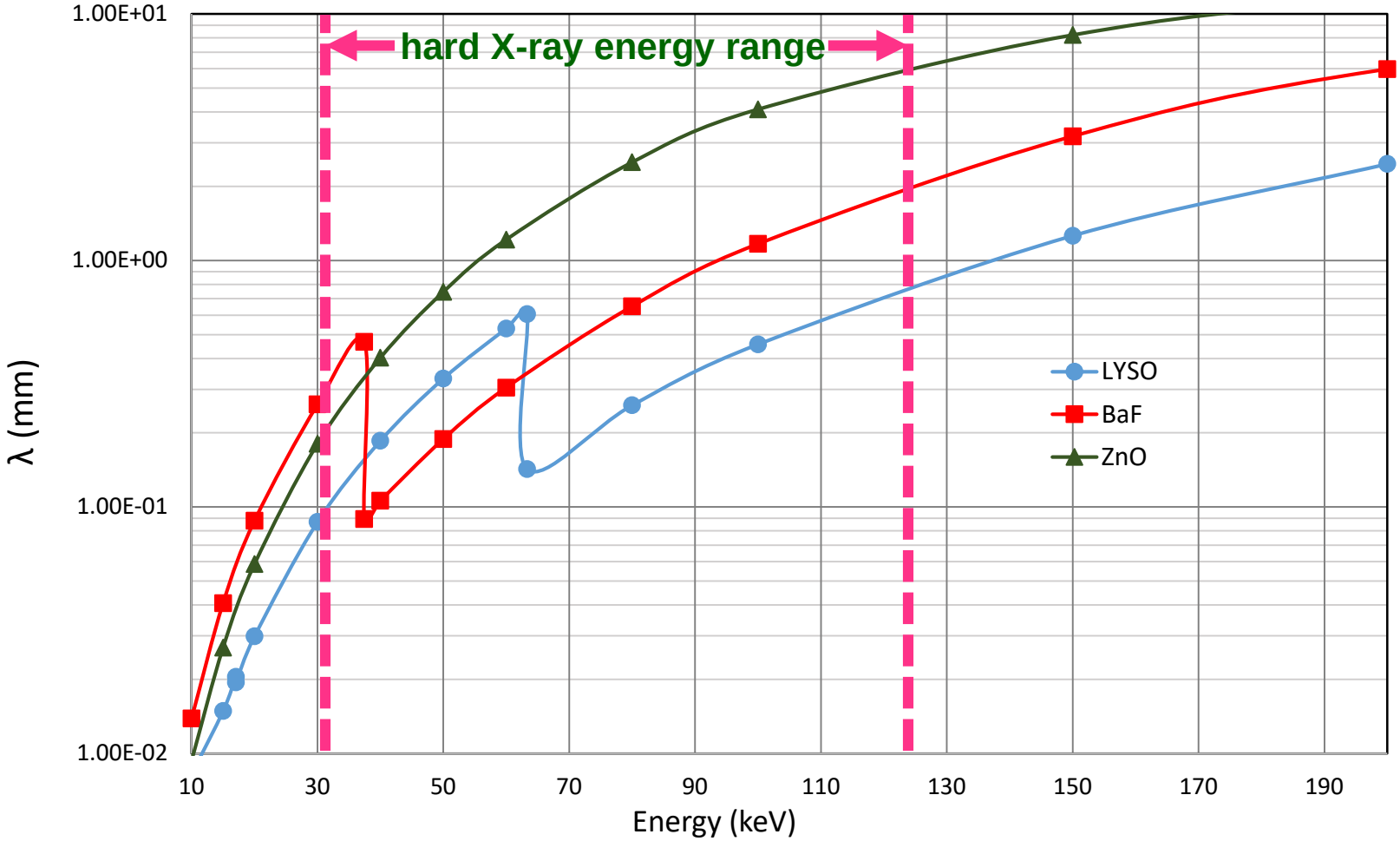

Presented in the "Ultrafast Hard X-Ray Imaging Workshop", August, 2016

# 12 Fast Scintillators Tested at APS

| | $BaF_2$ | $BaF_2$ (:Y) | ZnO (:Ga) | YAP (:Yb) | YAG (:Yb) | β-$Ga_2O_3$ | LYSO (:Ce) | LuAG (:Ce) | YAP (:Ce) | GAGG (:Ce) | LuYAP (:Ce) | YSO (:Ce) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($g/cm^3$) | 4.89 | 4.89 | 5.67 | 5.35 | 4.56 | 5.94[1] | 7.4 | 6.76 | 5.35 | 6.5 | 7.2[f] | 4.44 |
| Melting points (°C) | 1280 | 1280 | 1975 | 1870 | 1940 | 1725 | 2050 | 2060 | 1870 | 1850 | 1930 | 2070 |
| $X_0$ (cm) | 2.03 | 2.03 | 2.51 | 2.77 | 3.53 | 2.51 | 1.14 | 1.45 | 2.77 | 1.63 | 1.37 | 3.10 |
| $R_M$ (cm) | 3.1 | 3.1 | 2.28 | 2.4 | 2.76 | 2.20 | 2.07 | 2.15 | 2.4 | 2.20 | 2.01 | 2.93 |
| $\lambda_I$ (cm) | 30.7 | 30.7 | 22.2 | 22.4 | 25.2 | 20.9 | 20.9 | 20.6 | 22.4 | 21.5 | 19.5 | 27.8 |
| $Z_{eff}$ | 51.6 | 51.6 | 27.7 | 31.9 | 30 | 28.1 | 64.8 | 60.3 | 31.9 | 51.8 | 58.6 | 33.3 |
| dE/dX (MeV/cm) | 6.52 | 6.52 | 8.42 | 8.05 | 7.01 | 8.82 | 9.55 | 9.22 | 8.05 | 8.96 | 9.82 | 6.57 |
| $\lambda_{peak}$ [a] (nm) | 300<br>220 | 300<br>220 | 380 | 350 | 350 | 380 | 420 | 520 | 370 | 540 | 385 | 420 |
| Refractive Index[b] | 1.50 | 1.50 | 2.1 | 1.96 | 1.87 | 1.97 | 1.82 | 1.84 | 1.96 | 1.92 | 1.94 | 1.78 |
| Normalized Light Yield[a,c] | 42<br>4.8 | 1.7<br>4.8 | 6.6[d] | 0.19[d] | 0.36[d] | 6.5<br>0.5 | 100 | 35[e]<br>48[e] | 9<br>32 | 115 | 16<br>15 | 80 |
| Total Light yield (ph/MeV) | 13,000 | 2,000 | 2,000[d] | 57[d] | 110[d] | 2,100 | 30,000 | 25,000[e] | 12,000 | 34,400 | 10,000 | 24,000 |
| Decay time[a] (ns) | 600<br>0.5 | 600<br>0.5 | <1 | 1.5 | 4 | 148<br>6 | 40 | 820<br>50 | 191<br>25 | 53 | 1485<br>36 | 75 |
| LY in 1st ns (photons/MeV) | 1200 | 1200 | 610[d] | 28[d] | 24[d] | 43 | 740 | 240 | 391 | 640 | 125 | 318 |
| 40 keV Att. Leng. (1/e, mm) | 0.106 | 0.106 | 0.407 | 0.314 | 0.439 | 0.394 | 0.185 | 0.251 | 0.314 | 0.319 | 0.214 | 0.334 |

# X-ray Attenuation Length in Crystals

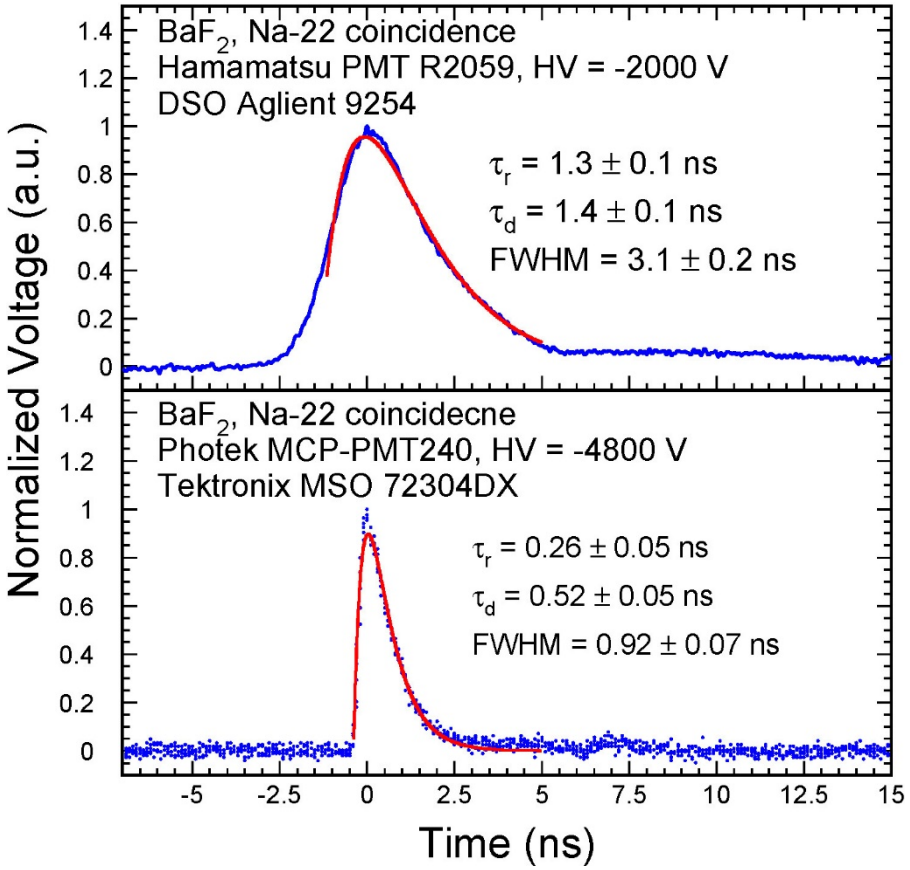
Five λ @ 100 keV: 5 and 2 mm for $BaF_2$ and LYSO, respectively



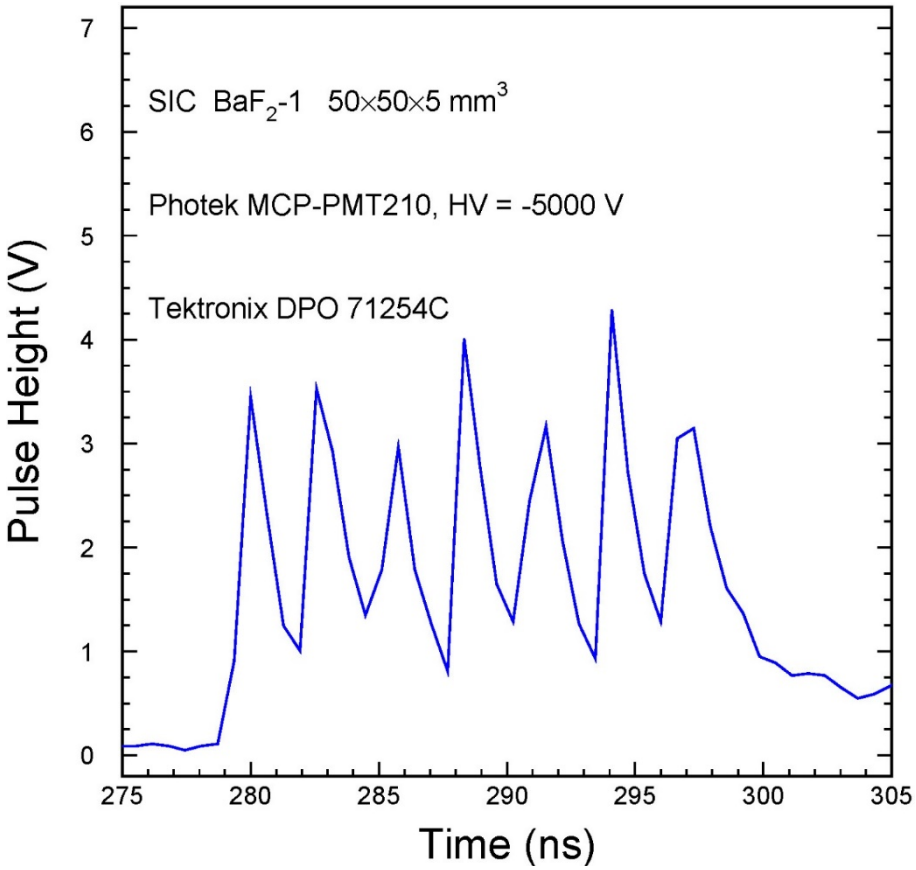

NIST data: https://www.nist.gov/pml/x-ray-mass-attenuation-coefficients

# $BaF_2$ Pulses in Lab and APS

3.1& 0.92 ns pulse width measured by PMT (top) & MCP-PMT (bottom) with a decay time of 0.52 ns. 5 mm $BaF_2$ plates resolve well 30 keV X-ray septuplets of 27 ps width with 2.83 ns spacing at APS (right), demonstrating GHz capability.



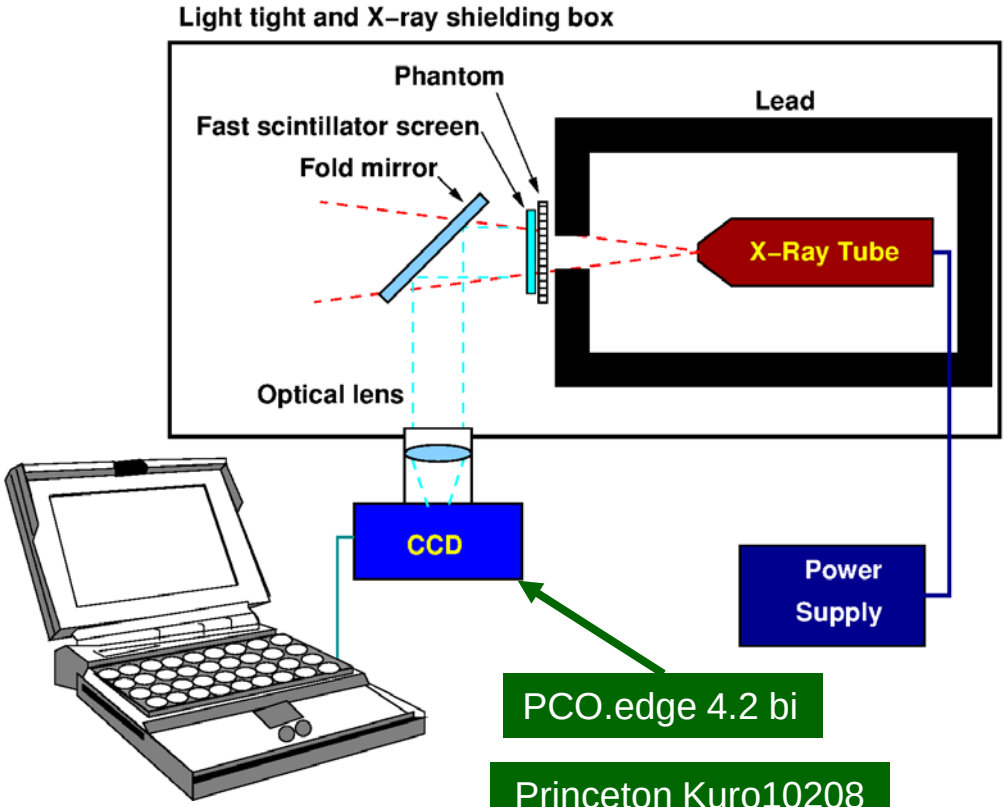

IEEE TNS **65** (2018) 2097




NIMA **940** (2019) 223-229

# X-ray Imaging with CCD Cameras

Spatial resolution of pixelated and monolithic crystal screens measured by PCO & Princeton CCD cameras for ~8 keV X-rays from an AmpTek ECLIPSE-III tube




PCO.edge 4.2 bi

Princeton Kuro10208

| Crystal | LYSO | $BaF_2/BaF_2$:Y | ZnO:Ga |
|---|---|---|---|
| X-ray weighted λ | 19 µm | 48 µm | 39 µm |
| 99% X-ray absorbed | 90 µm | 220 µm | 180 µm |

Soft X-ray Source

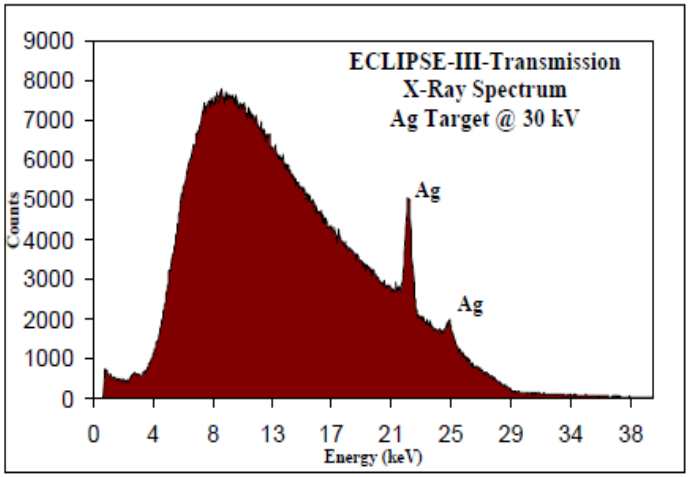
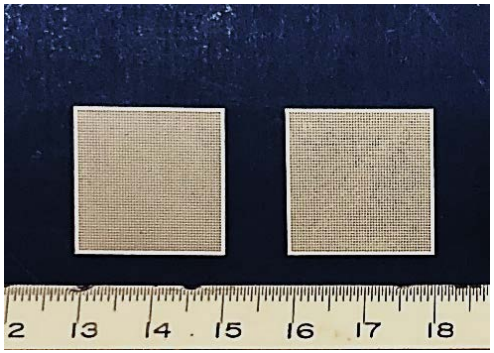
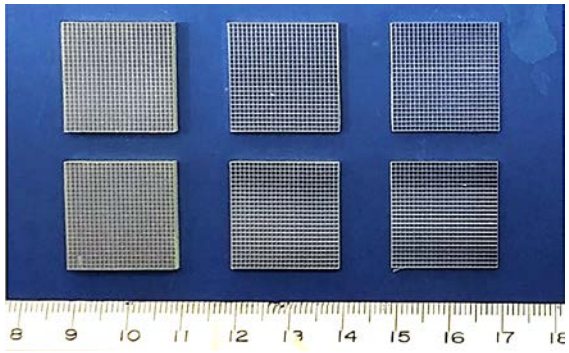



Figure 3: ECLIPSE-III X-Ray Spectrum

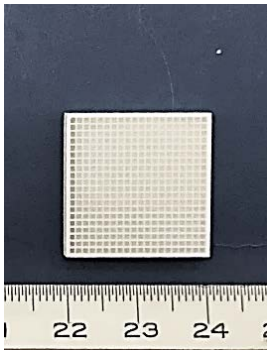
# Pixelated Crystal Screens



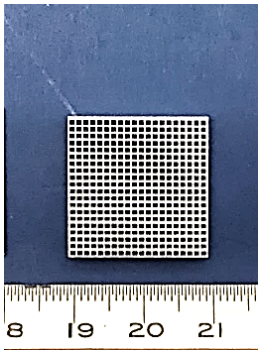
SIC LYSO:Ce



Tianle LYSO:Ce



BGRI $BaF_2$



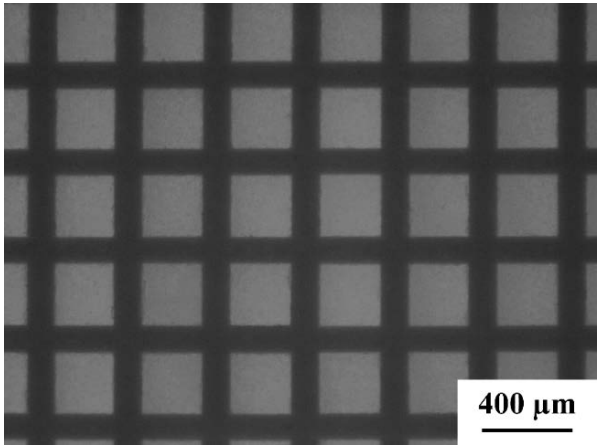
SIC $BaF_2$:Y

| Crystal | Dimension ($mm^3$) | Pitch (mm) | Gap (mm) | Depth (mm) | Reflector | # of Wrapped faces | Vendor | # of λ (40 keV X-ray) | # of samples |
|---|---|---|---|---|---|---|---|---|---|
| LYSO:Ce | 20×20×1 | 0.40 | 0.12 | 0.7 | $TiO_2$ | 4 | SIC | 5.4 | 2 |
| LYSO:Ce | 20×20×1 | 0.828 | 0.08 | 1 | ESR | 4 | Tianle | 5.4 | 6 |
| $BaF_2$ | 20×20×5 | 0.98 | 0.18 | 4 | $TiO_2$ | 5 | BGRI | 47.2 | 1 |
| $BaF_2$:Y | 20×20×5 | 0.98 | 0.18 | 4.5 | $BaSO_4$ | 4 | SIC | 47.2 | 1 |

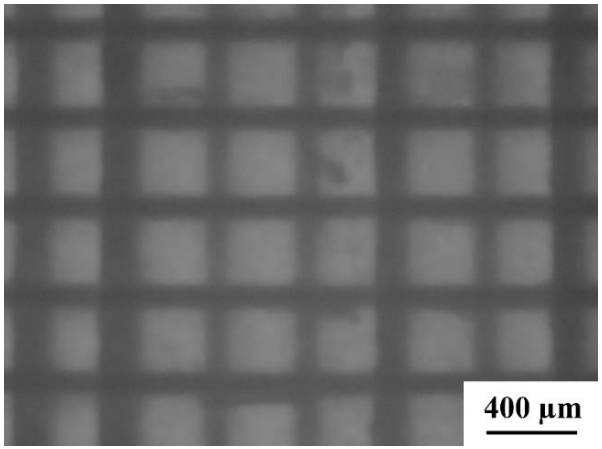
Screens with a pitch down to 300 μm produced by mechanical slicing
Laser dicing may reach down to 25 μm: See US patent US6087618A

# Pixelated LYSO and $BaF_2$ Screens

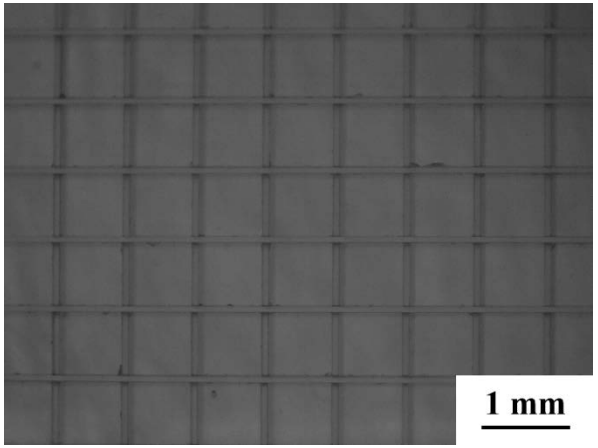
SIC and BGRI crystal screens are not cut-through



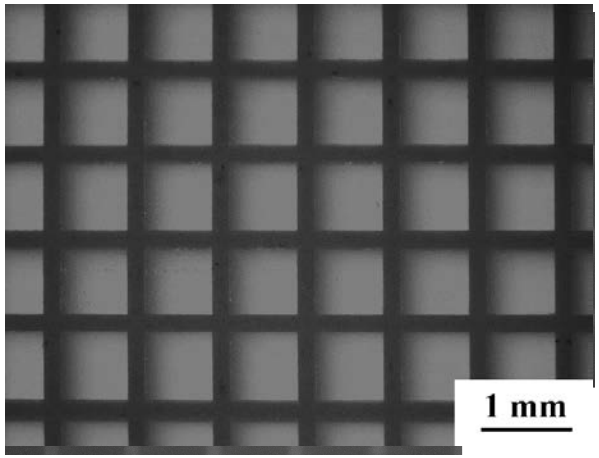

SIC LYSO front



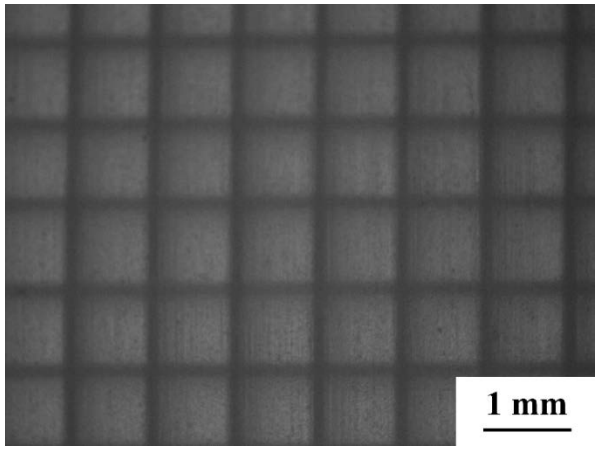

SIC LYSO back



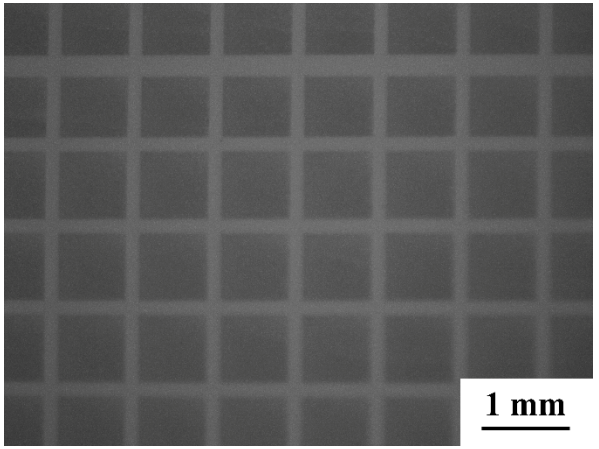

Tianle LYSO




SIC $BaF_2$:Y front



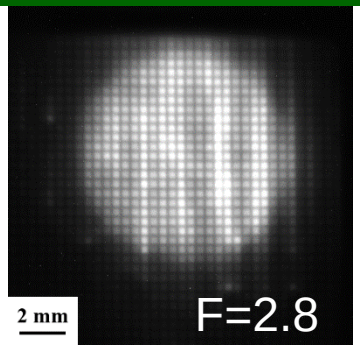
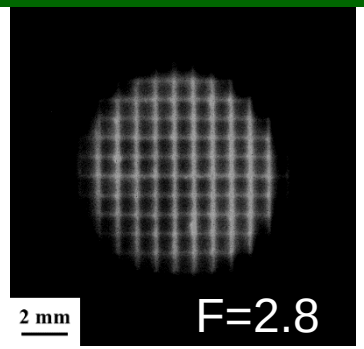
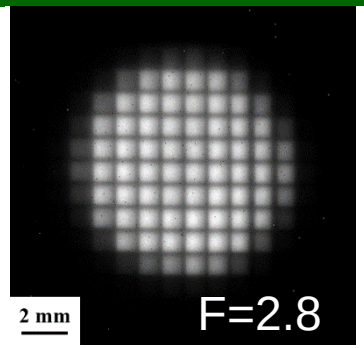
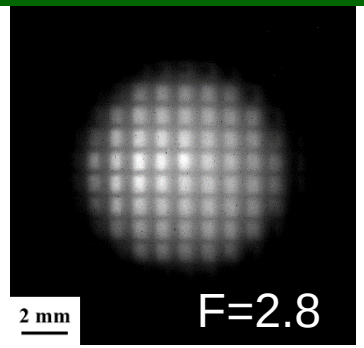

SIC $BaF_2$:Y back




BGRI $BaF_2$

# X-ray Imaging by PCO Camera (I)

Spatial resolution and dynamic range defined by crystal pitch and thickness, respectively

| SIC LYSO: 400 μ pitch | Tianle LYSO: 828 μ pitch | BGRI $BaF_2$: 980 μ pitch | SIC $BaF_2$:Y: 980 μ pitch |
|---|---|---|---|
|  |  |  |  |
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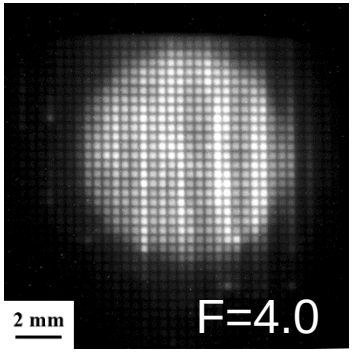
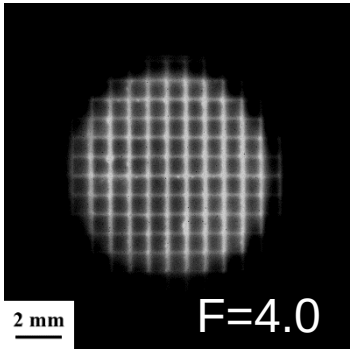
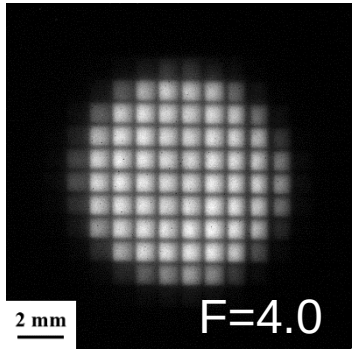
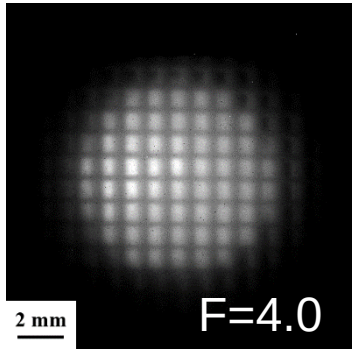
|  |  |  |  |
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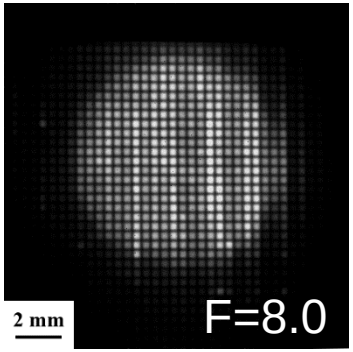
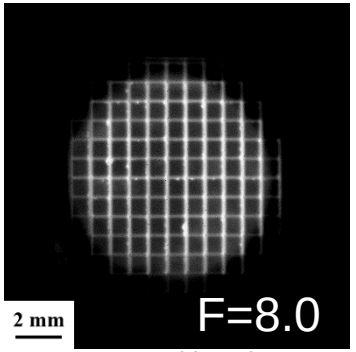
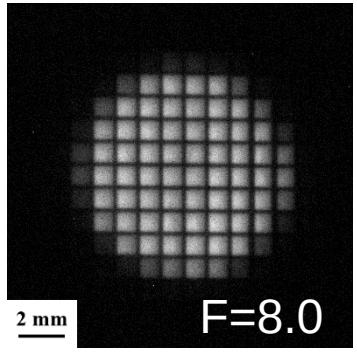
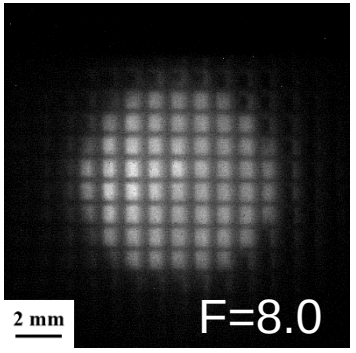
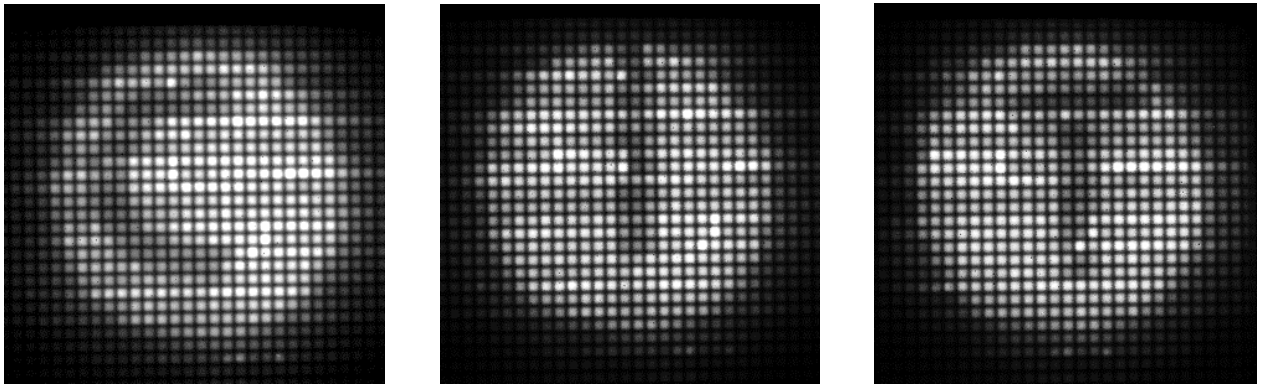
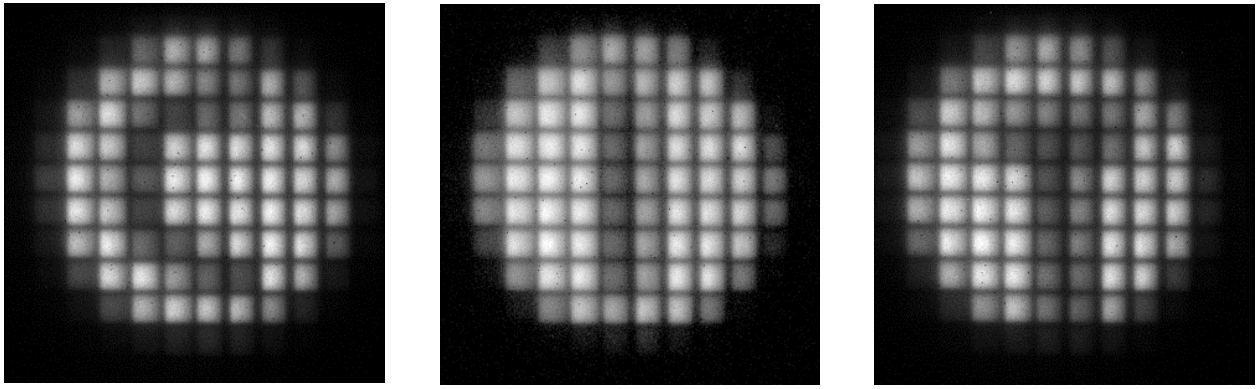
|  |  |  |  |
|  |  |  |  |

# X-ray Imaging by PCO Camera (II)

SIC LYSO with 400 μ pitch



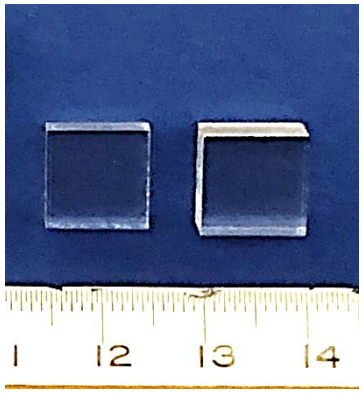
BGRI $BaF_2$ with 980 μ pitch



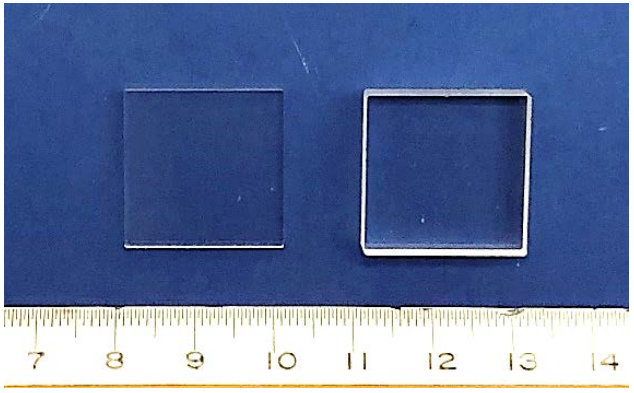
CIT Phantom


Resolution of 25 μ may be reached by crystal screens with laser dicing

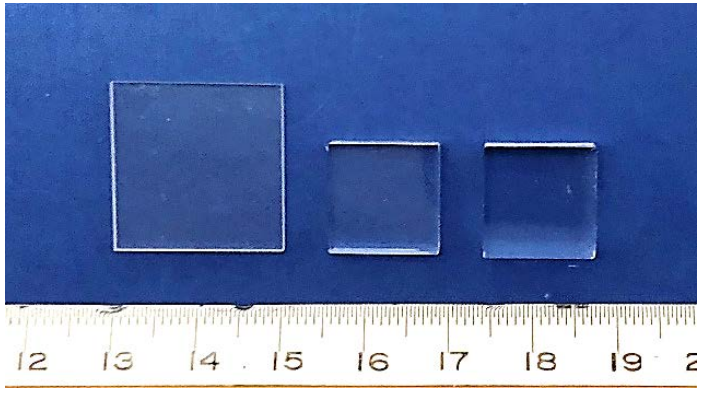
# Monolithic Crystal Screens



SIC LYSO:Ce



BGRI $BaF_2$



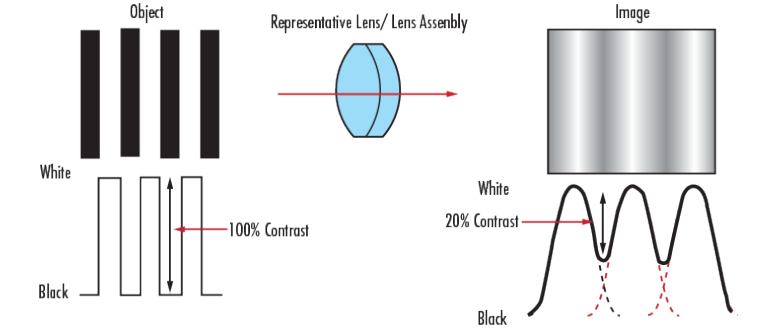
SIC $BaF_2$:Y

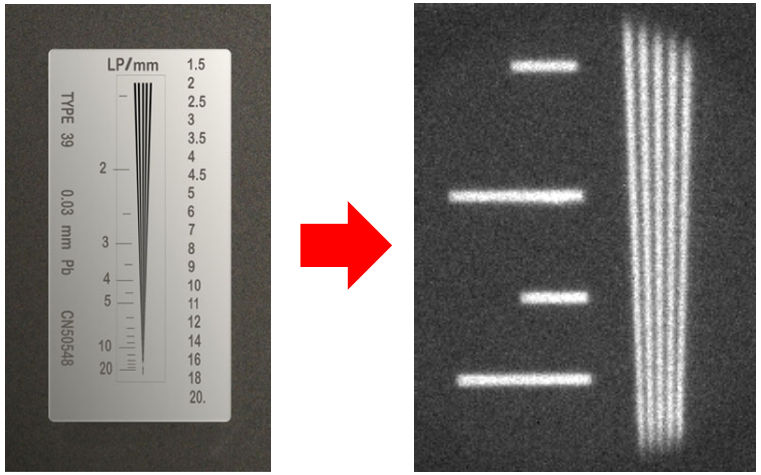
| Crystal | Dimension ($mm^3$) | Producer | # of λ (40 keV X-ray) | Amount |
|---|---|---|---|---|
| LYSO:Ce | 10×10×3 | SIC | 16.2 | 1 |
| LYSO:Ce | 10×10×5 | SIC | 27.0 | 1 |
| $BaF_2$ | 20×20×1 | BGRI | 9.4 | 1 |
| $BaF_2$ | 20×20×5 | BGRI | 47.2 | 1 |
| $BaF_2$:Y | 20×20×1.5 | SIC | 14.1 | 1 |
| $BaF_2$:Y | 13×13×3 | SIC | 28.3 | 1 |
| $BaF_2$:Y | 13×13×5 | SIC | 47.2 | 1 |

# Line-Pair Pattern Phantom and Modulation Transfer Function (MTF)

$$MTF = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

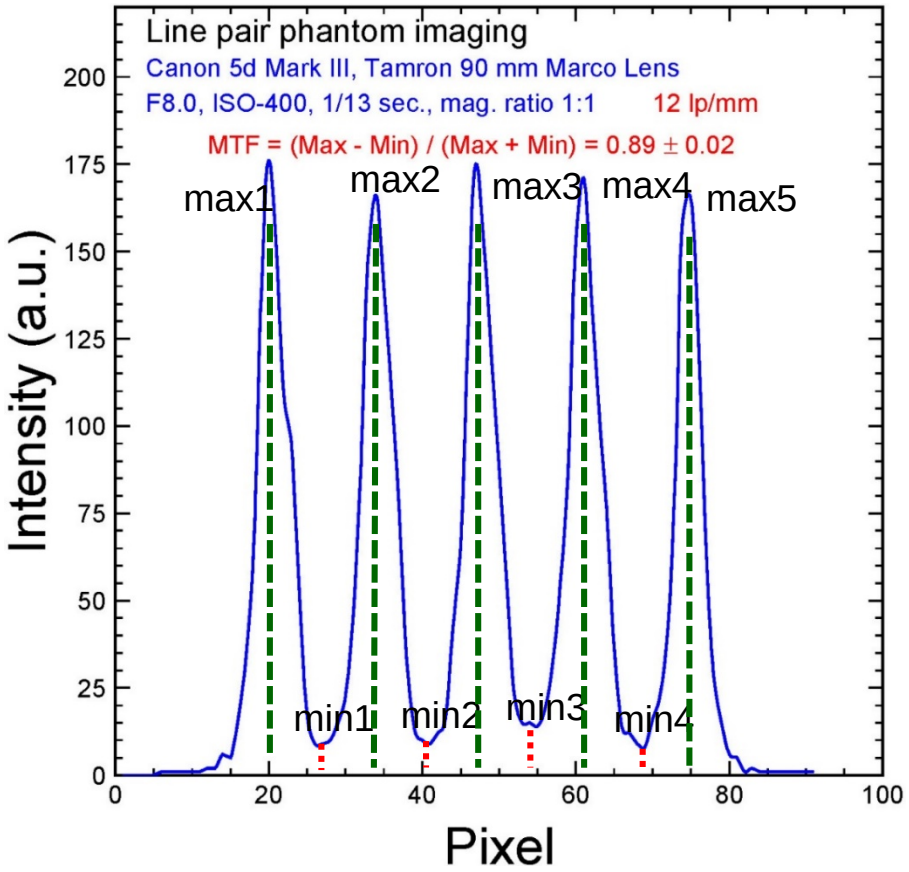
The MTF value is defined as an average of 8 values for 5 peaks and 4 valleys



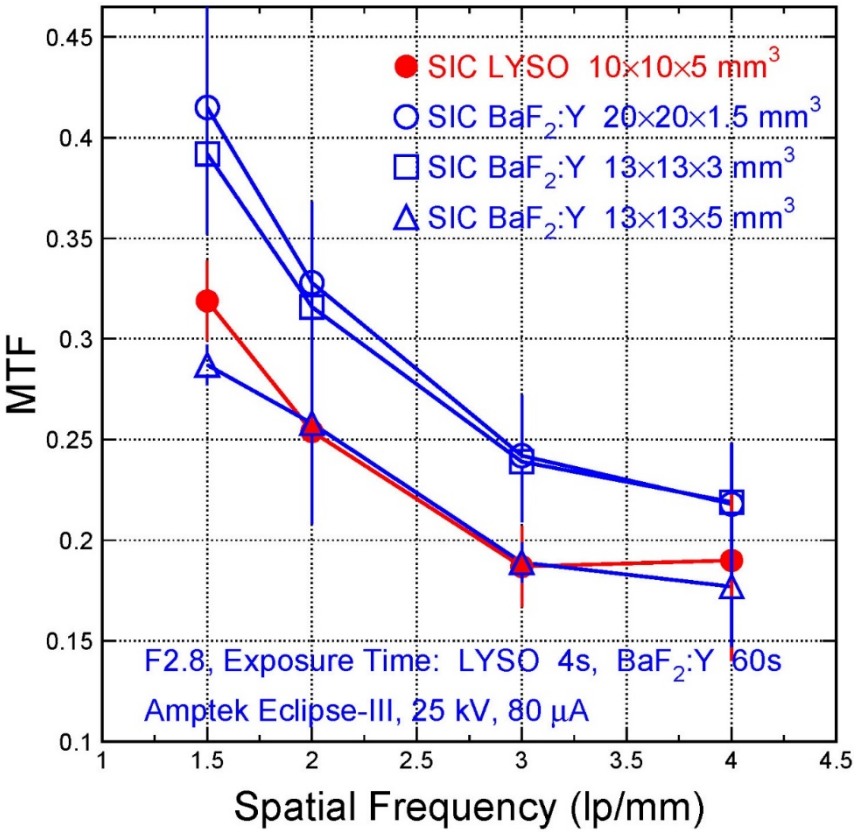

line-pair pattern

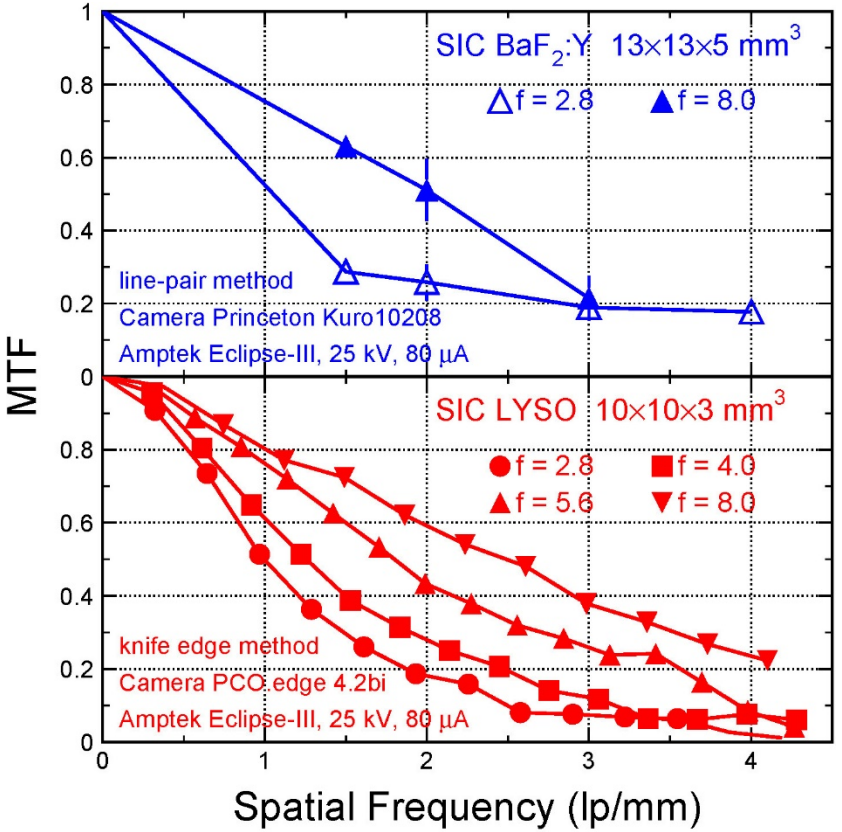
X-ray imaging



# Spatial Resolution vs. Screen Thickness and Optical Aperture

Spatial resolution degrades for thicker $BaF_2$:Y crystal screens
Better spatial resolution obtained by using smaller aperture



# Summary

GHz hard X-ray imaging presents an unprecedented challenge to timing and spatial resolutions for inorganic scintillator-based front imager.

Beam test with 30 keV X-rays from APS show that 5 mm $BaF_2$ plates resolve well 30 keV X-ray septuplets of 27 ps width and 2.83 ns spacing.

Pixelated $BaF_2$, $BaF_2$:Y and LYSO crystal screens with a pitch down to 300 μm may be fabricated by mechanic slicing. Their spatial resolution and detection efficiency for hard X-rays are defined by the pitch and thickness, respectively.

Thicker monolithic crystal screens show poorer spatial resolution, which may be improved by using smaller optical aperture with a loss in both efficiency and dynamic range for hard X-rays.

Plan to pursue pixelated crystal screens with a pitch down to 25 μm by laser slicing. Additional ultrafast inorganic scintillators considered are ZnO:Ga films and all inorganic Cs Pb halide perovskite QD etc.

# Acknowledgements

The authors would like to thank PCO and Princeton companies for providing the CCD cameras used in this investigation.

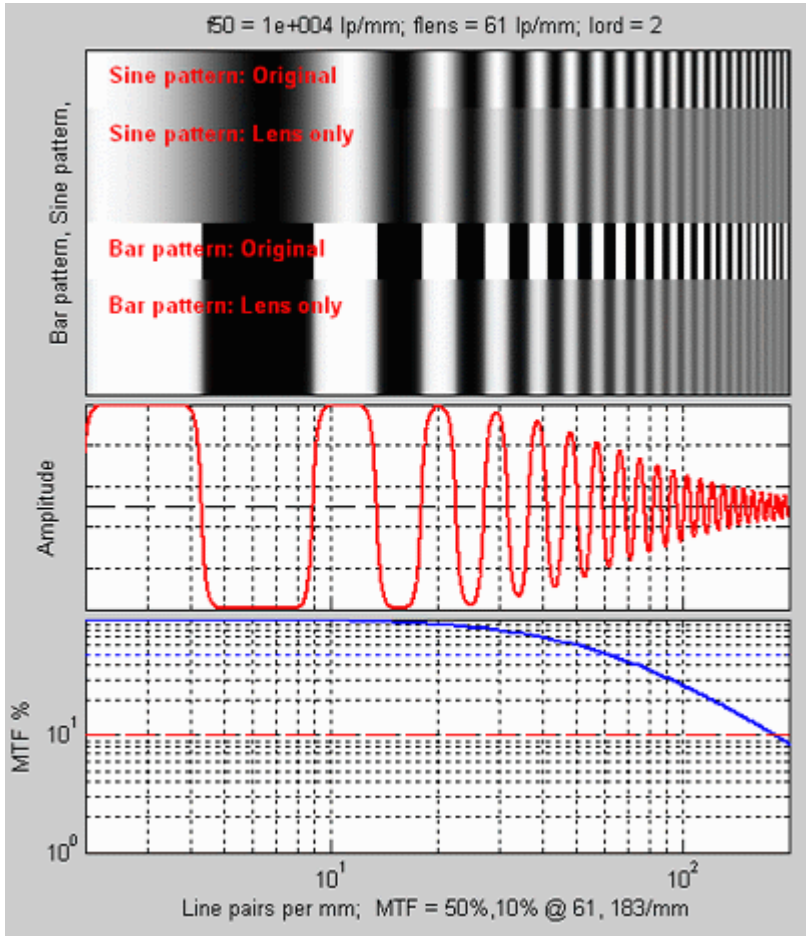
This work was supported in part by the US Department of Energy Grants DE-SC0011925.

# Specifications: UV CCD Cameras

## UV CCD camera are used to determine spatial resolution

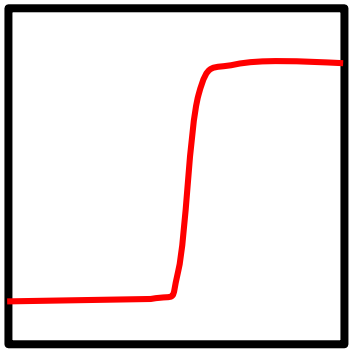
| Company | Model | Pixel size (μm) | Pixel Number | QE @ 220 nm | QE @ 420 nm | Frame rate (fps) | Exposure Time | External Trigger | Full Scale (e) | Noise (rms, e) |
|---|---|---|---|---|---|---|---|---|---|---|
| Hamamatsu | C8000-30 | 14 | 640×480 | 0.70 | 0.65 | 31.4 | 30.8ms-1s | CMOS | 30000 | 150 |
| Hamamatsu | C9100-23B | 16 | 640×480 | ~0.4 | 0.65 | 70.4 | 1μs-1s | CMOS | 140000 | 8 |
| Princeton Instruments | KURO1020B | 11 | 1200×1200 | ~0.50 | 0.75 | 41 | 5ms-10s | TTL | 80000 | typ. 1.3 |
| Intevac Photonics | MicroVista UV | 10.8 | 1280×1024 | ~0.35 | ~0.75 | 30 | 30μs-260ms | N/A | 35000 | <50 |
| PCO | pco.edge 4.2 bi UV | 6.5 | 2048×2048 | ~0.50 | ~0.70 | 40 | 10μs-20s | TTL | 48000 | typ. 1.9 |
| EHD Imaging | SCM2020-UV | 6.5 | 2048×2048 | ~0.31 | ~0.70 | 45 | 0.1ms-1000s | TTL | 54000 | <2 |
| Amsterdam Scientific Instruments | TPX3Cam | 55 | 256×256 | 0 | >0.3 | >1M | ? | Yes | 1000ph | ? |

# MTF Measured by Knife Edge Method

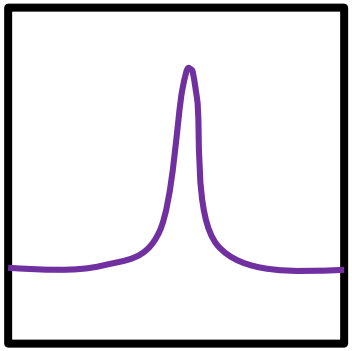



Intensity function across the edge

**Edge Spread Function (ESF)**

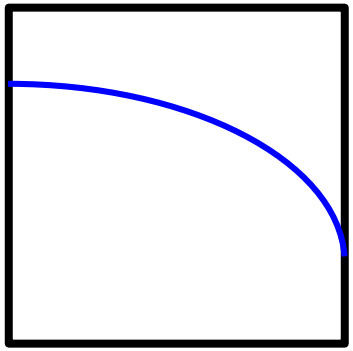


**Line Spread Function (LSF)**



first derivative of ESF

**Modulation Transfer Function (MTF)**



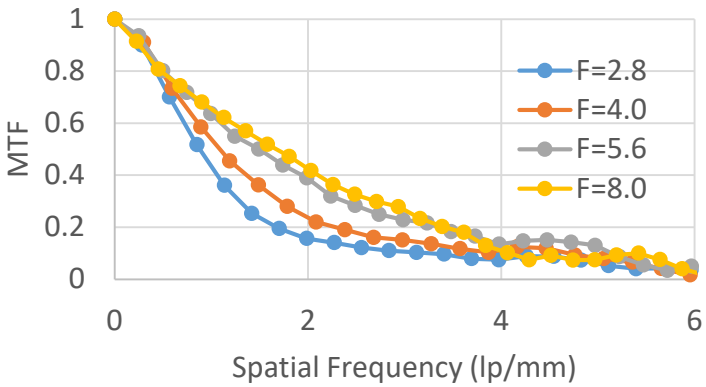
Fourier transform of LSF

# X-ray Imaging: effect of thickness and aperture

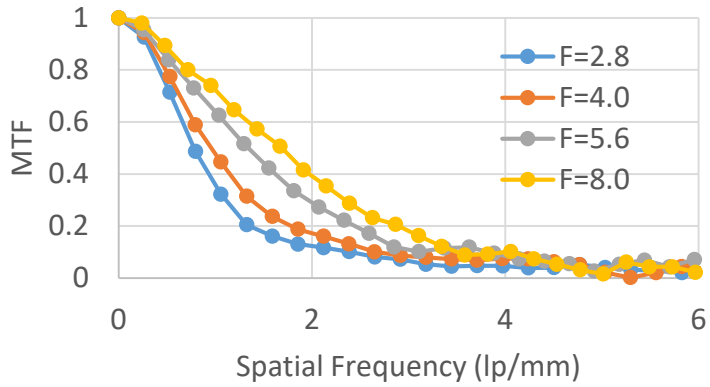
A better spatial resolution may be obtained by a smaller aperture

PCO.edge 4.2 bi camera + knife edge method

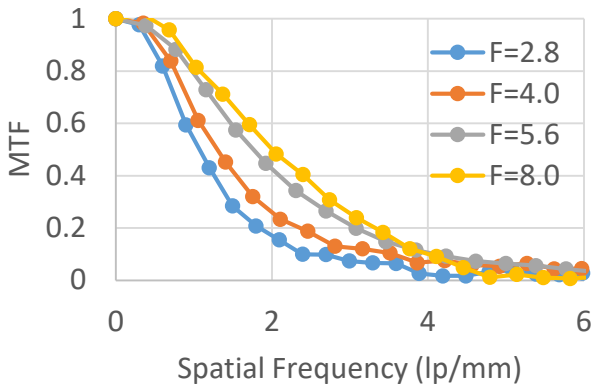
SIC LYSO of 20×20×0.1 mm$^3$



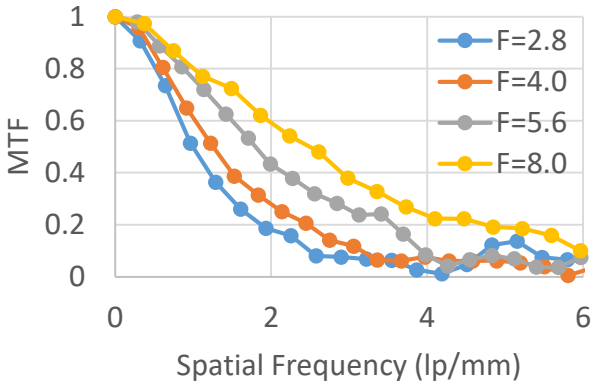

SIC LYSO of 20×20×1 mm$^3$




SIC LYSO of 20×20×2 mm$^3$




SIC LYSO of 10×10×3 mm$^3$




SIC LYSO of 10×10×5 mm$^3$