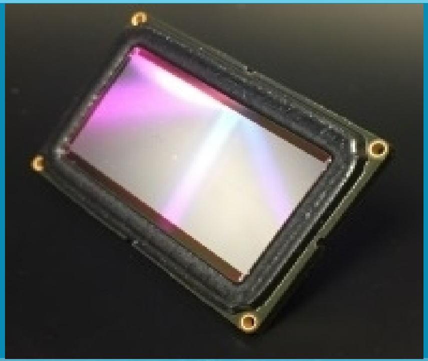
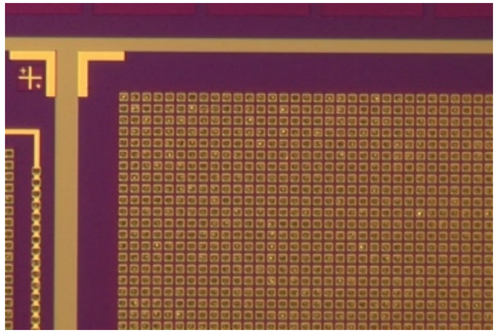
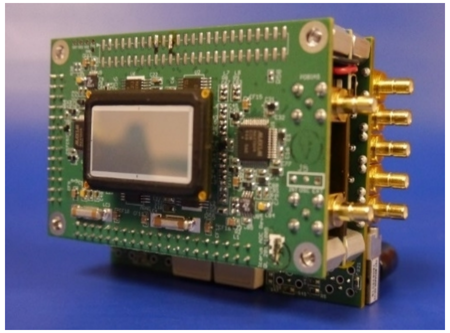
SAND2021-15378C

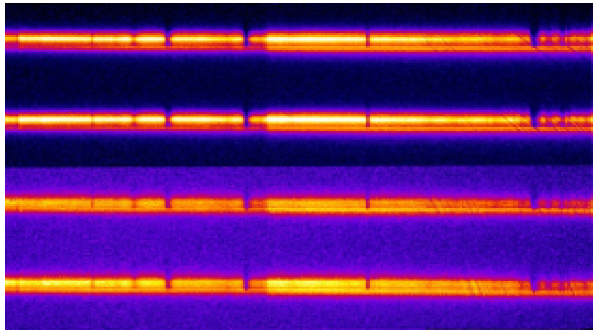
Sandia National Laboratories

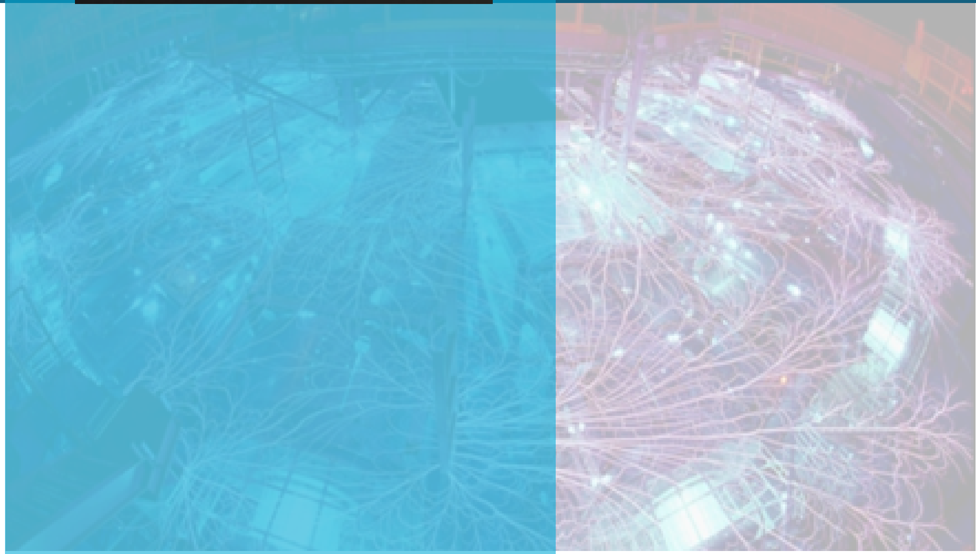
# UXI/hCMOS development and deployment at Sandia National Laboratories











PRESENTED BY

Anthony "Tony" Colombo

On behalf of the Sandia UXI/hCMOS effort

2021 National Diagnostic Workshop, 8 December 2021

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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# Many people have contributed to the UXI/hCMOS effort at Sandia in recent years.

**hCMOS design, fabrication, packaging**

- Liam Claus
- Eric Edwards
- Troy England
- Lu Fang
- Patrick Finnegan
- Tom Hill
- Tim McArdle
- Brandon Mitchell
- Andy Montoya
- Eric Morgan
- Doug Nichols
- Gideon Robertson
- Marcos Sanchez
- Andrew Starbuck
- Michael Wood

**UXI-at-Z development and deployment**

- Tony Colombo
- Aaron Edens
- Mark Kimmel
- Joel Long
- Quinn Looker
- John Porter
- Robert Speas
- John Stahoviak

**Programmatic support**

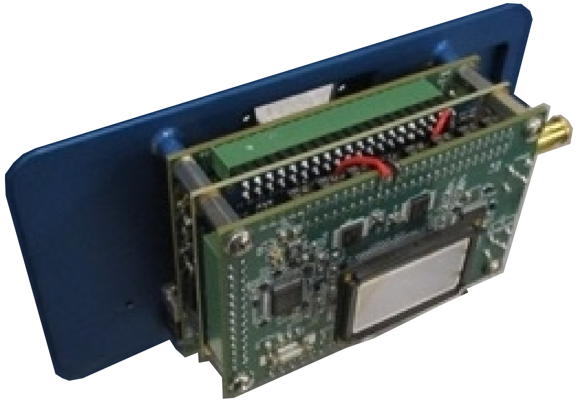
- Michael Jones
- Greg Rochau

**Engineering and fielding support**

- Greg Dunham
- Dan Folker
- Eric Harding
- Robert Hohlfelder
- Paul Gard
- Jeff Kellogg
- Brian Ritter
- Katie Seals
- Shane Speas

# UXI/hCMOS makes nanosecond-gate, burst-mode, framing cameras.

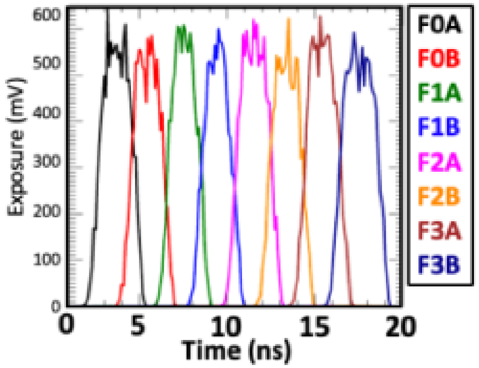
**UXI camera with Icarus hCMOS sensor.**



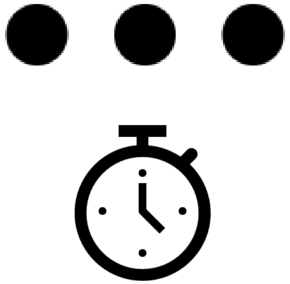
Framing cameras capture a full, 2D image.

- Only one imaging line of sight.
- All pixels image at (approximately) the same time.

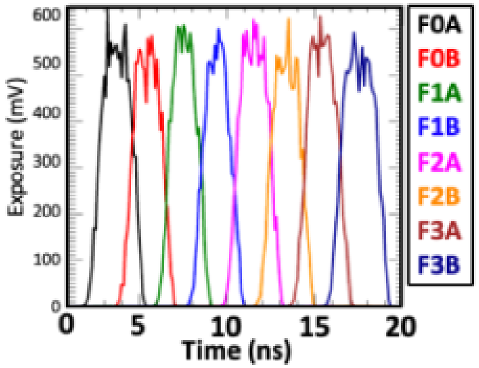
Acquire several frames in a short burst.




Wait many milliseconds.



Acquire another burst of frames.



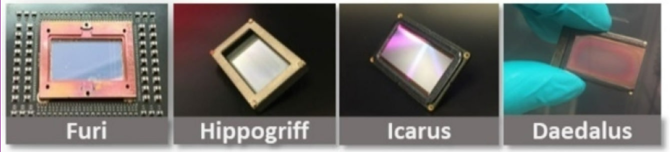

UXI cameras can detect both x-rays and visible photons.

**4 ns frame-to-frame**

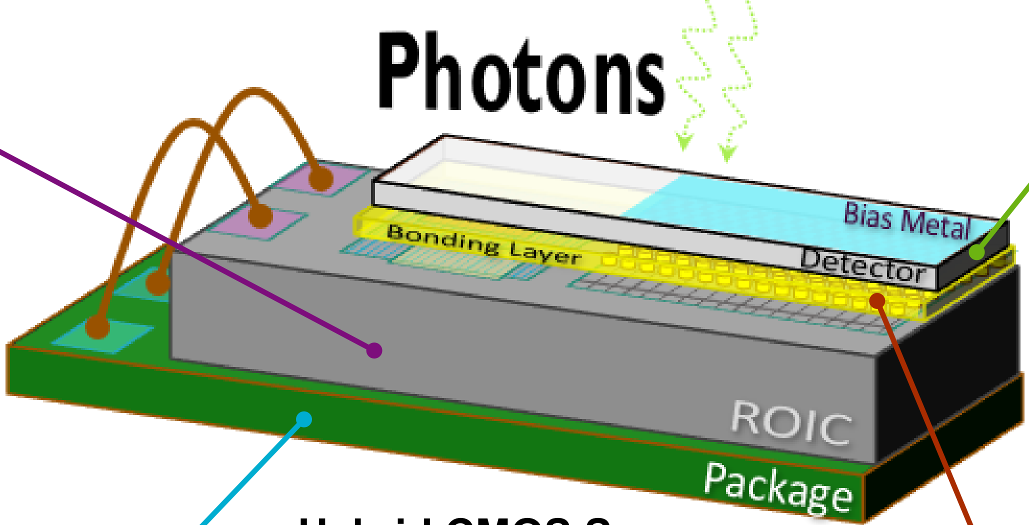
**UXI camera is ultrafast for a (very) short duration.** → **Well matched to single-shot HEDP experiments.**

# Many parts come together to make a hybrid CMOS UXI camera.

## Readout Integrated Circuit

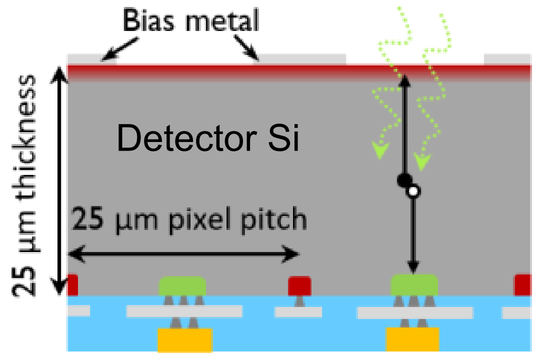



- Fabricated in SNL's 350-nm CMOS
- 1-2 ns minimum shutter time, 2-8 frames
- 1024x512 array of 25 μm x 25 μm pixels
- Adjustable shutter timing

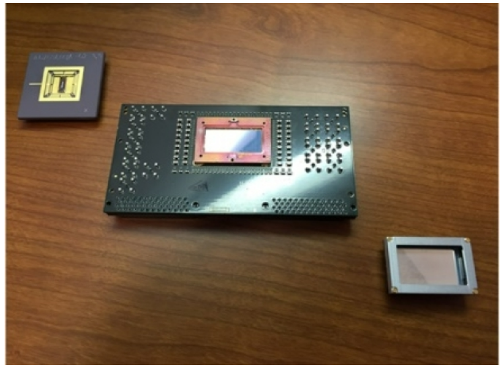


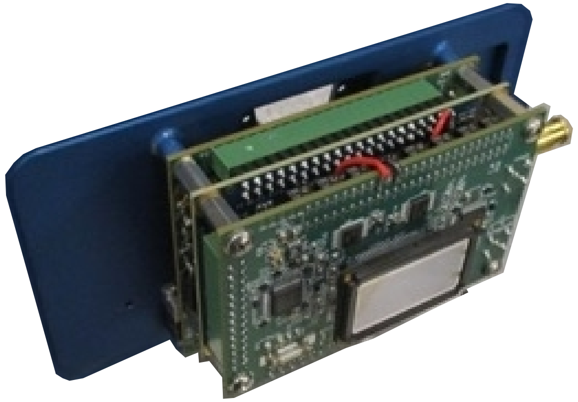

**Hybrid CMOS Sensor**

## Detector Array




## Package

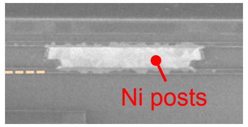




**UXI Camera System Development for Application-Specific Needs**

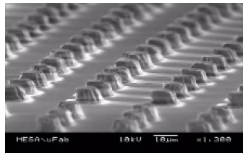
## Integration

**Direct Bond Interconnect (DBI)**




- External supplier
- Wafer-to-wafer bond

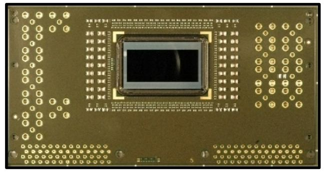
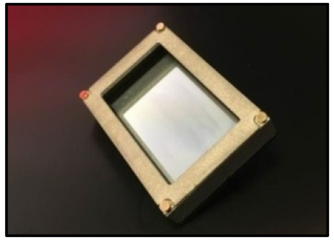
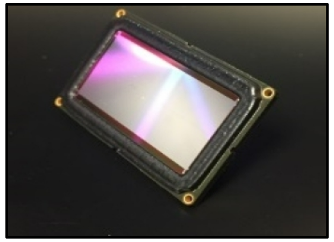
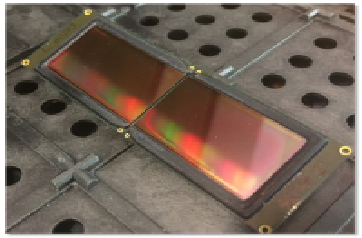
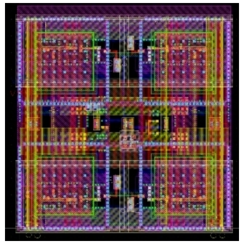
**Indium bump**



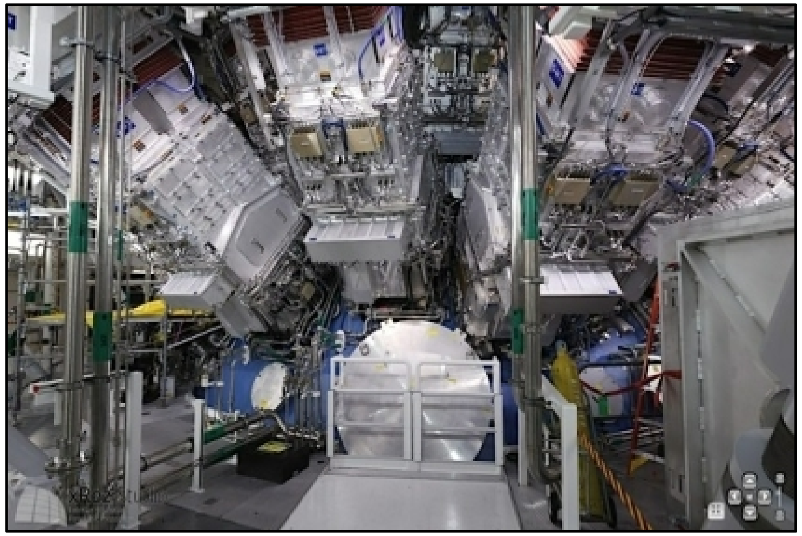
- Processing at Sandia
- Die-level processing

# Icarus is the currently deployed sensor in an advancing hCMOS product line.

| | Retired | | Deployed | In Test | In Production |
|---|---|---|---|---|---|
| | Furi | Hippogriff | Icarus V1/V2 | Daedalus V1/V2 | Tantalus |
| Year | FY14 | FY15 | FY16-18 | FY19-22 | FY23 |
| Minimum Gate Time | ~1.5 ns | ~2 ns | ~1.5 ns | ~1.0 ns | ~0.5 ns |
| Frames | 2 (full resolution) | 2 (full resolution)<br>4 or 8 (Row interlaced) | 4 (full resolution)<br>8 (L/R interlaced) | 3 (full resolution)<br>6+ (Row/L/R interlaced) | 4 (full resolution)<br>16+ (Row/quad. interlaced) |
| Tiling Option | No | No | No | One Side | No |
| CMOS Process | 350 nm (SNL) | 350 nm (SNL) | 350 nm (SNL) | 350 nm (SNL) | 130 nm (Tower Jazz) |
| Pixels | 448 × 1024 | 448 × 1024 | 512 × 1024 | 512 × 1024 | 512 × 1024 |
| Pixel Size | 25 µm × 25 µm | 25 µm × 25 µm | 25 µm × 25 µm | 25 µm × 25 µm | 25 µm × 25 µm |
| Capacitor Full Well | 1.5 million $e^-$ | 1.5 million $e^-$ | 0.5 million $e^-$ | 1.5 million $e^-$ | 0.5 million $e^-$ |

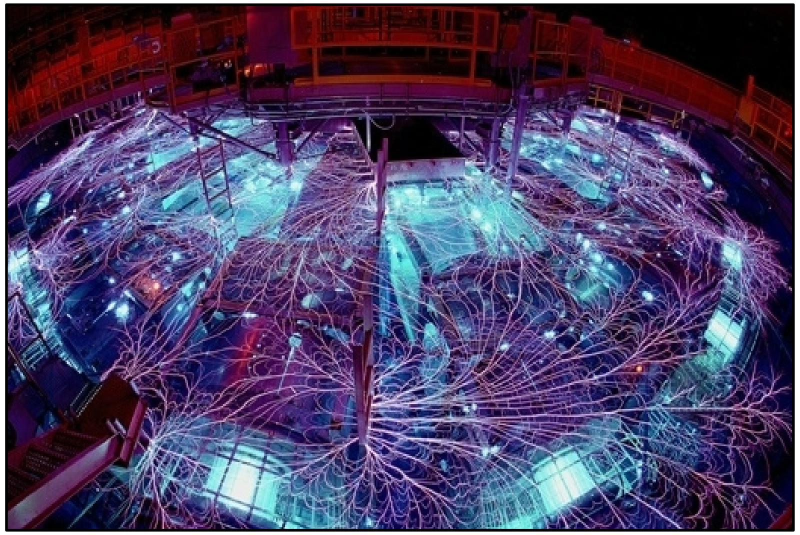






# UXI cameras have been deployed in time-resolved diagnostics across multiple facilities.

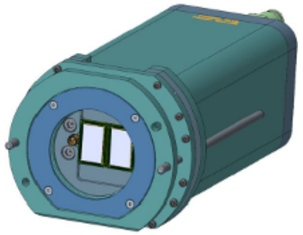


**National Ignition Facility**

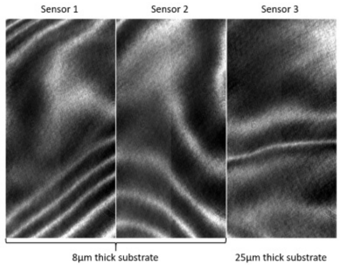
**Omega**



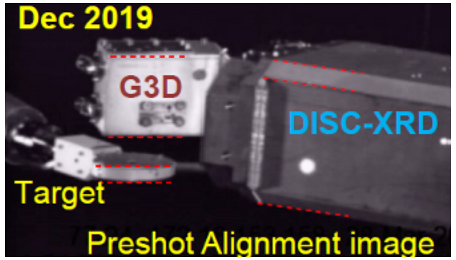
**Z-Machine**

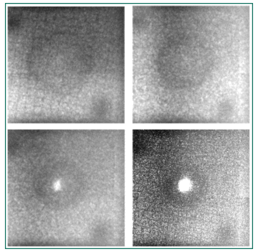


GLEH2

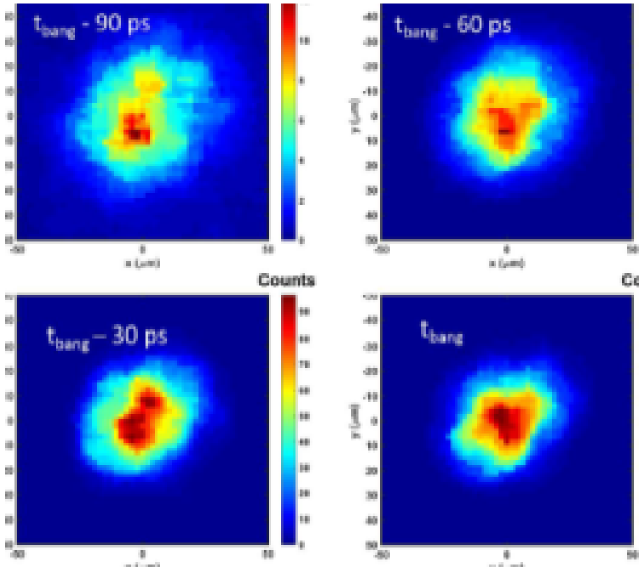



TRNF



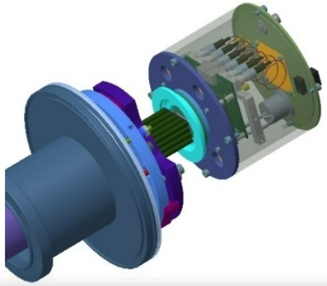



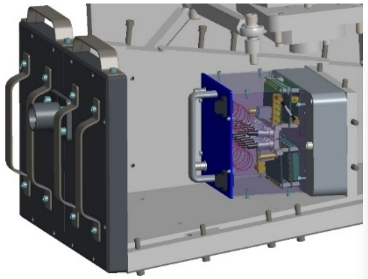
SLOS1-CBI



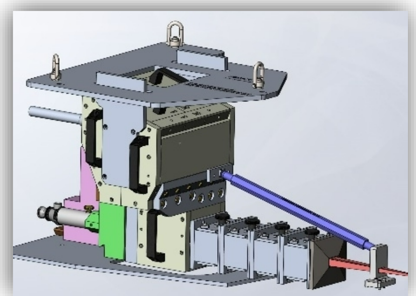

SLOS-TRXI

FOA Pinhole Camera





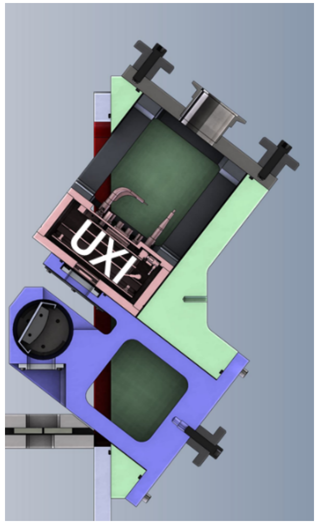
Gated Backlighting

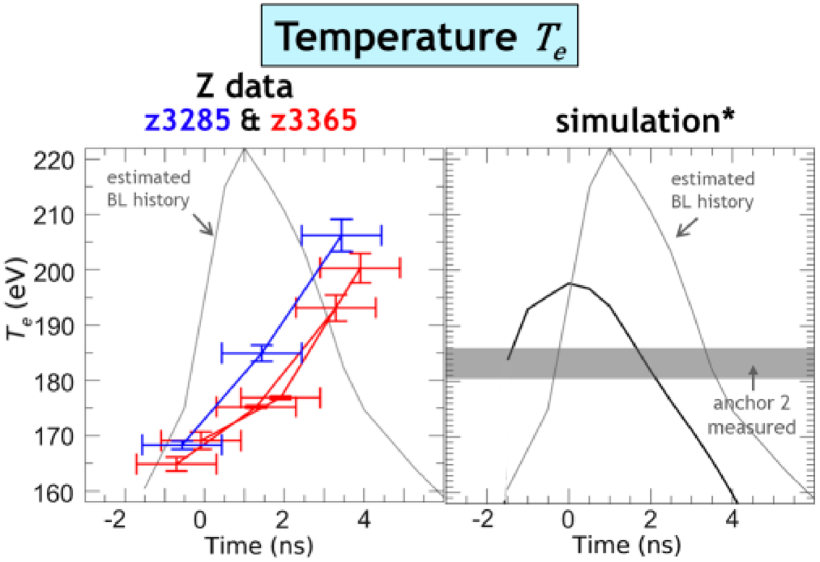


MONSSTR

# UXI cameras provide better data and qualitative insights across multiple diagnostics.

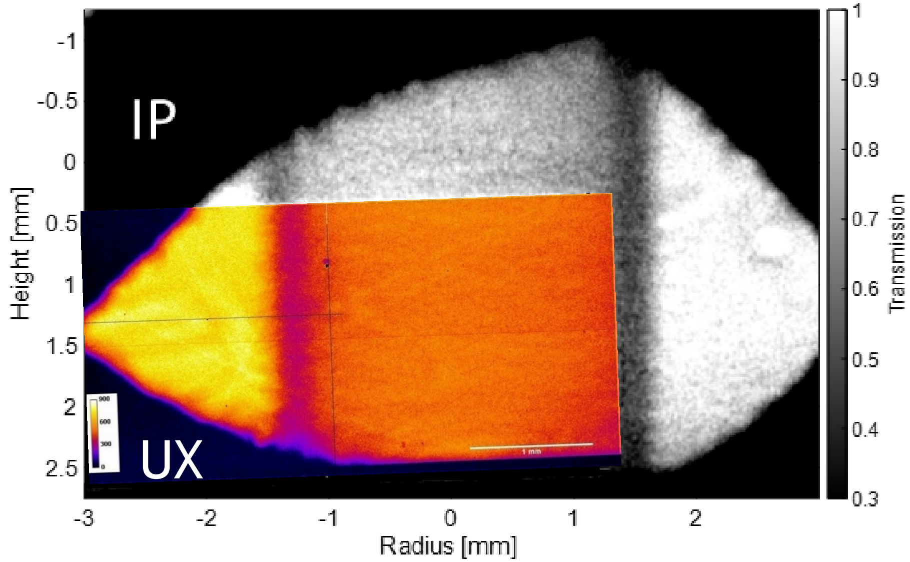
**Opacity Spectrometer: Fe condition evolution trends qualitatively disagree with predictions.**



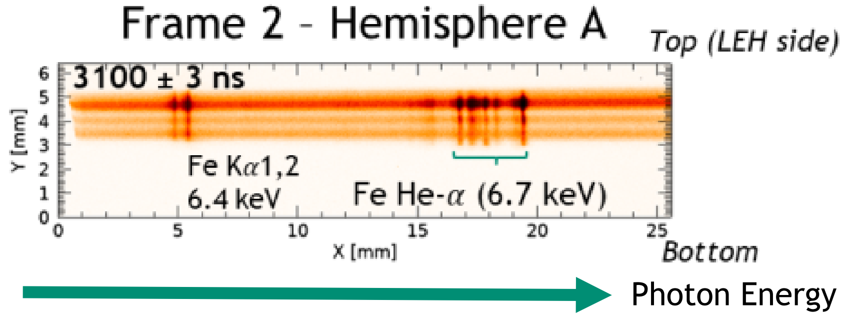




Analyzed data courtesy of Guillaume Loisel. *Simulations: Nagayama et al., *PRE* **93**, 023202 (2016).

**Gated crystal backlighting: Contrast with UXI is superior to image plate.**



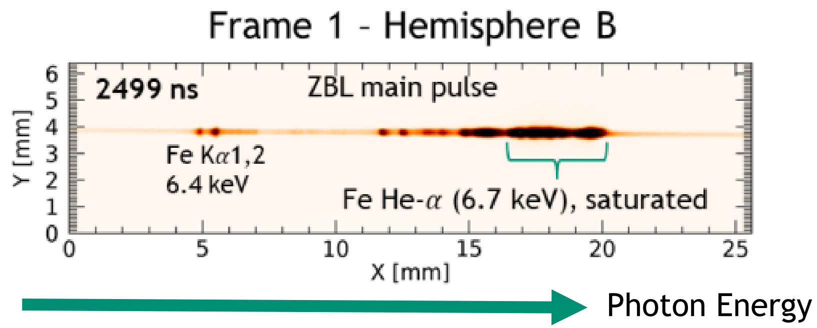

Processed image plate data courtesy of David Yager-Elorriaga.




Time-resolved Fe spectrum of a MagLIF target at stagnation.

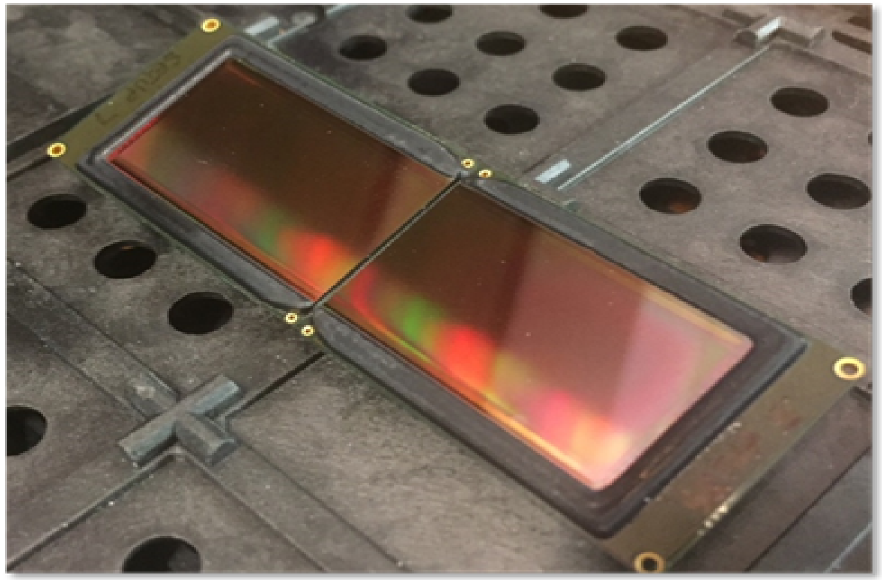
**The MONSSTR records time-resolved x-ray spectra of targets in the Z chamber.**

MONSSTR data analysis courtesy of Eric Harding.




X-ray spectra generated by ZBL striking an Fe backlighter foil.

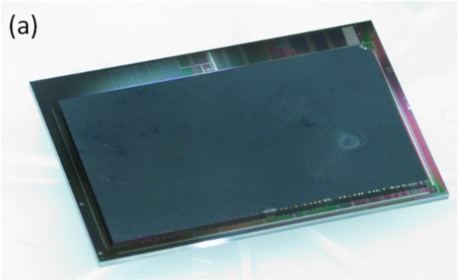
# Upgrades such as tiled Daedalus and GaAs detector arrays are in the works.

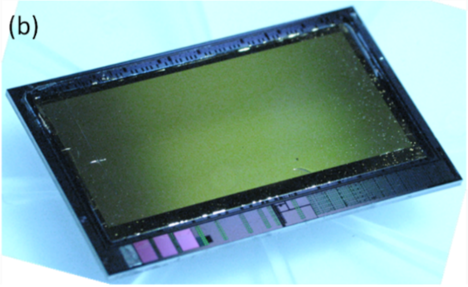


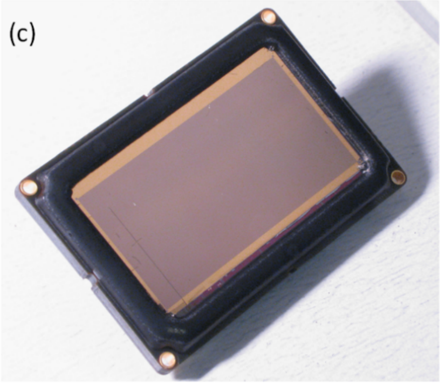
<u>Notable Daedalus Features</u>

- 1-ns gates.
- Row-wise interlacing.
- 3 × deeper full well than Icarus.

Packaged Daedalus V2 sensors are expected in FY 2022.



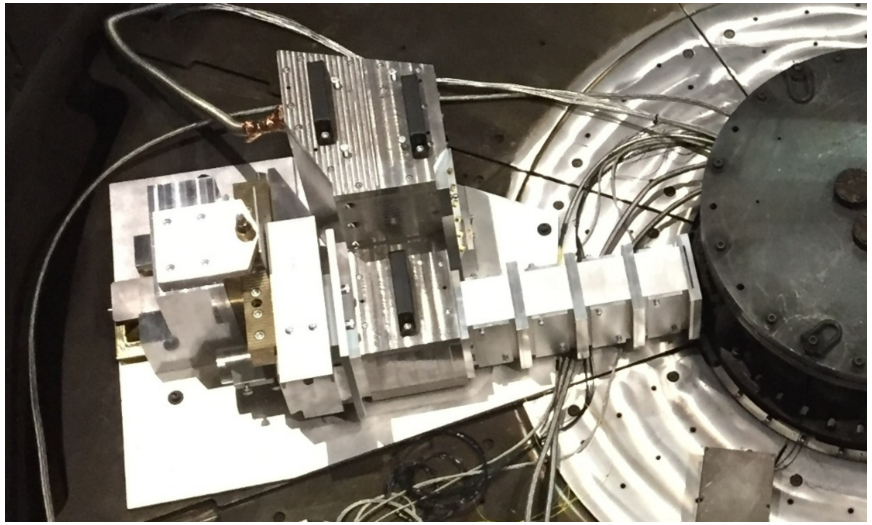




GaAs-hybridized Icarus sensors are expected in FY 2022.

**Daedalus abuts on the short side for more spectral coverage.**

**MONSSTR spectrometer**

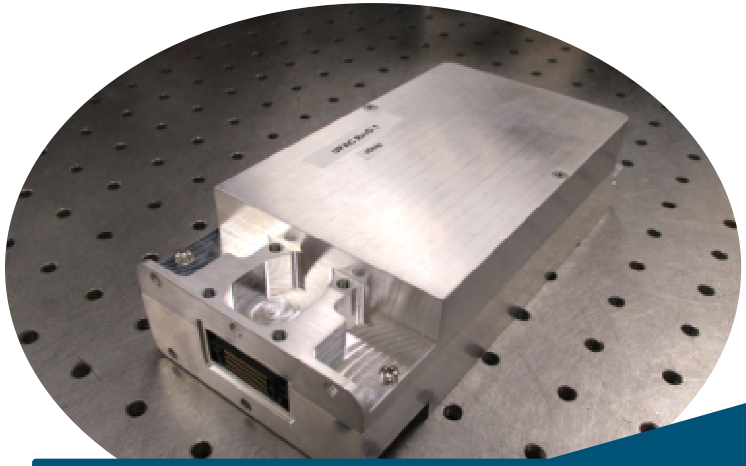


**GaAs detector arrays will be effective to 40 - 50 keV.**

# Other high-speed, solid-state electronic detectors are also in development at Sandia.

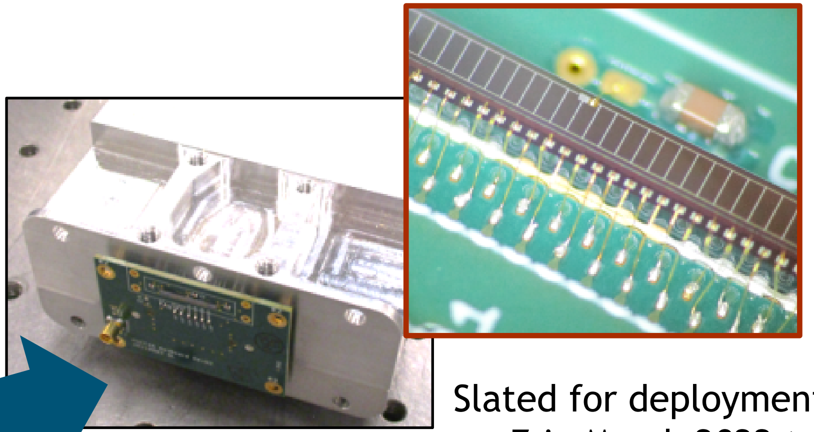
UPAC Key Specifications
Number of Channels : 32
Sample Rate : 9.2 GS/s
Record Length : 114 ns
Analog Bandwidth : 1.9 GHz
Voltage Range : 0.1 – 1.1 V

**Ultrafast Pixel Array Camera (UPAC)**

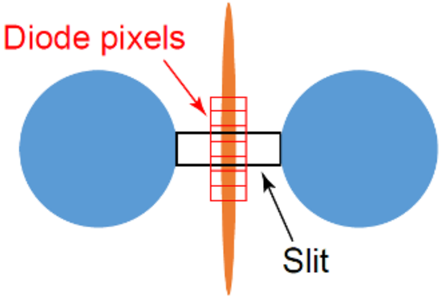


**Application-Specific Interface Cards**

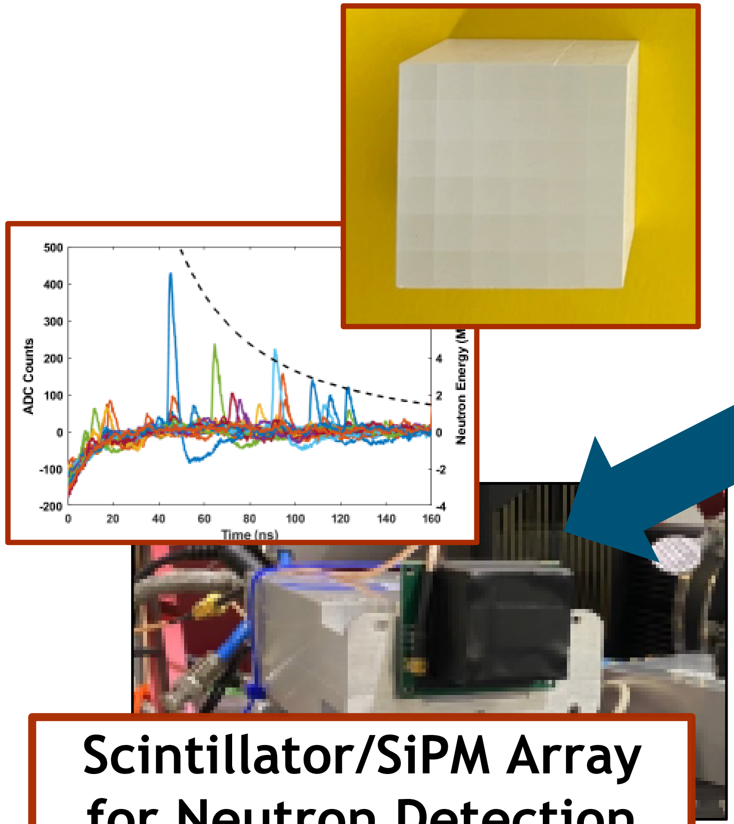
**1D Photodiode Array**



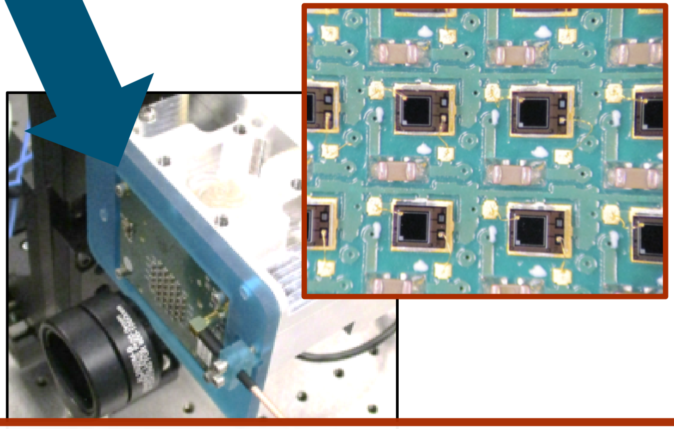
Slated for deployment on Z in March 2022 to measure x-rays.




Magnetically Ablated Reconnection on Z (MARZ) platform.
Image courtesy of Clayton Myers.




**Scintillator/SiPM Array for Neutron Detection**



**2D Photodiode Imaging Array**

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| Tiling Option | No | No | No | One Side | No |
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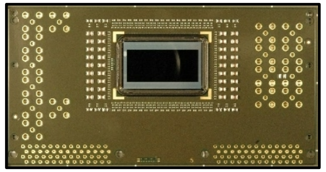
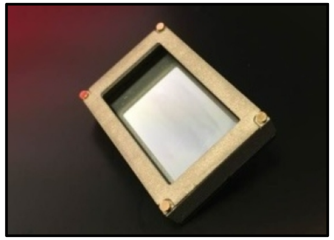
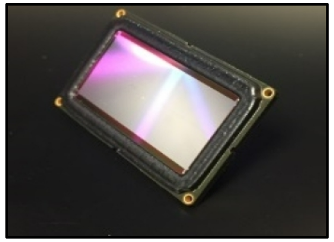
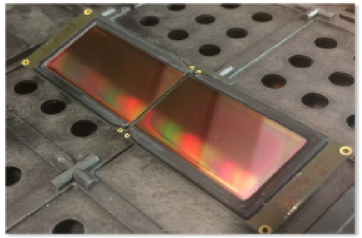
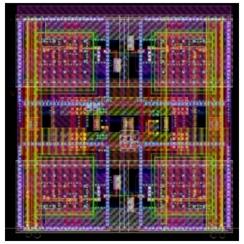
| Pixel Size | 25 µm × 25 µm | 25 µm × 25 µm | 25 µm × 25 µm | 25 µm × 25 µm | 25 µm × 25 µm |
| Capacitor Full Well | 1.5 million $e^-$ | 1.5 million $e^-$ | 0.5 million $e^-$ | 1.5 million $e^-$ | 0.5 million $e^-$ |

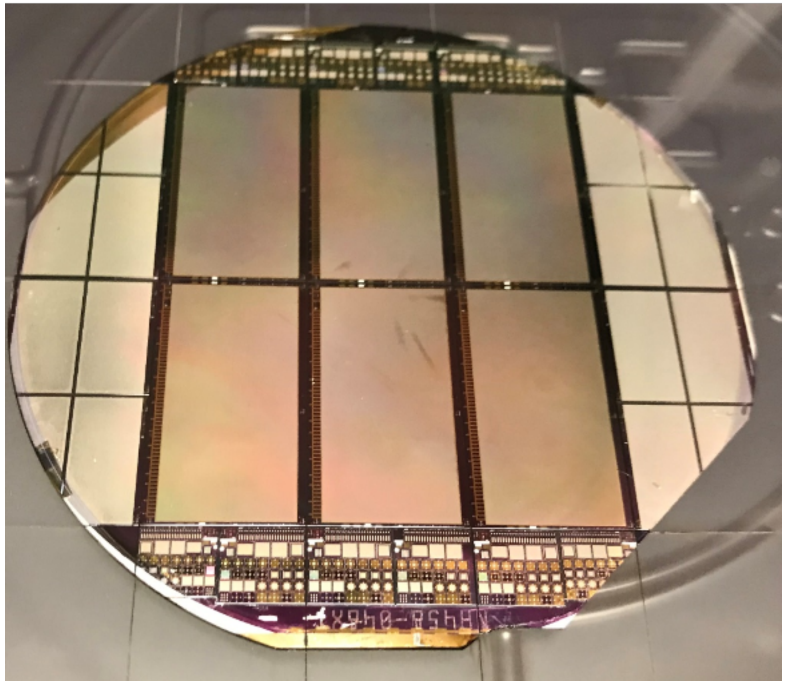
# Backup

# Tentative Daedalus V2 production schedule: First sensors available in June 2022.

| ROIC | Wafer | Hybridization | FY22 | | | | | | | | | | | | FY23 | | | | | | | | | | | | Estimated Available Sensors | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Q1 | | | Q2 | | | Q3 | | | Q4 | | | Q1 | | | Q2 | | | Q3 | | | Q4 | | | | | | | |
| | | | O | N | D | J | F | M | A | M | J | J | A | S | O | N | D | J | F | M | A | M | J | J | A | S | A+ | A/A- | B's | C's | Lower |
| DV2 | 2021:1 | 25umSi | | | H | | T | | P | T | A | | | | | | | | | | | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:2 | 25umSi | | | H | | T | | | P | T | A | | | | | | | | | | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:3 | 25umSi | | | H | | T | | | | P | T | A | | | | | | | | | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:4 | 25umSi | | | H | | T | | | | | P | T | A | | | | | | | | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:5 | 25umSi | | | H | | T | | | | | | P | T | A | | | | | | | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:6 | 25umSi | | | H | | T | | | | | | | P | T | A | | | | | | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:7 | TBD | | | | | | | | | | | | | | | H | | P | T | A | | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:8 | TBD | | | | | | | | | | | | | | | H | | | P | T | A | | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:9 | TBD | | | | | | | | | | | | | | | H | | | | P | T | A | | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:10 | TBD | | | | | | | | | | | | | | | H | | | | | P | T | A | | | 5 | 7 | 1 | 2 | 3 |
| | 2021:E1 | NA | | | | | P | T | | | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 | 0 |
| | 2021:E2 | NA | | | | | | | | | | | | | | | | | | | | | | | | | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | | | | | | | | | | | | | | | | | | 50 | 70 | 10 | 20 | 30 |

F Fabrication H Hybridization P Packaging T Testing A Available

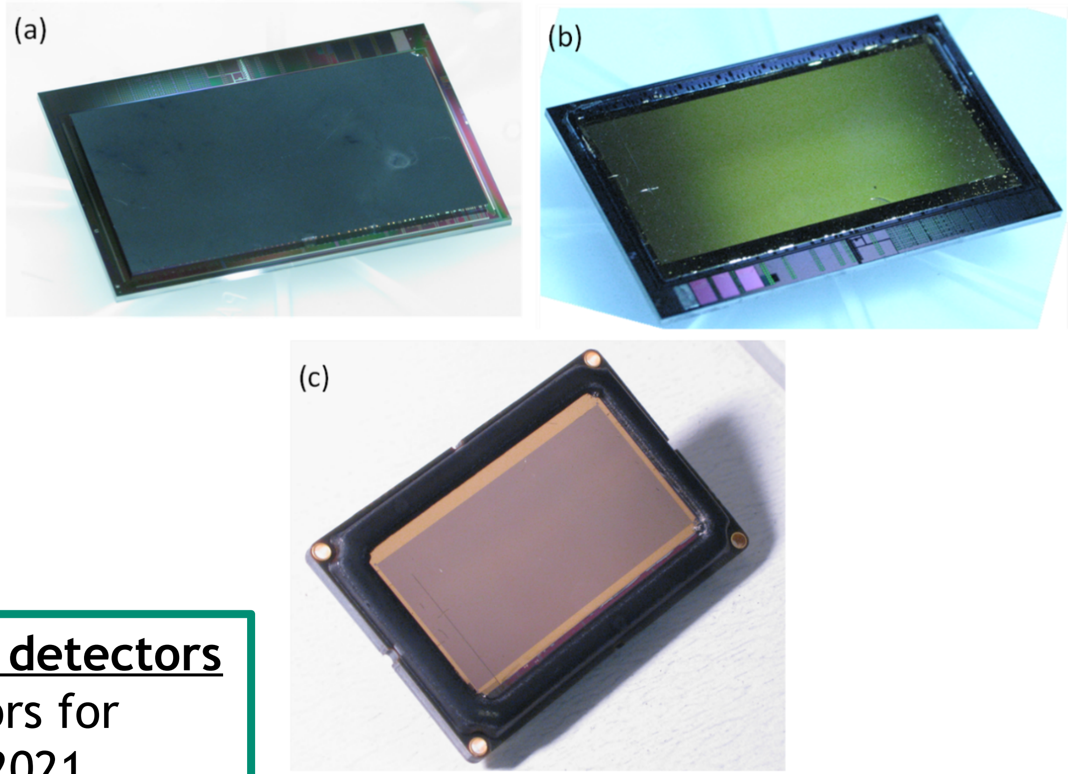
# The first GaAs-hybridized Icarus sensors are expected in early 2022.




3”-diameter wafer containing 6 GaAs detector arrays.

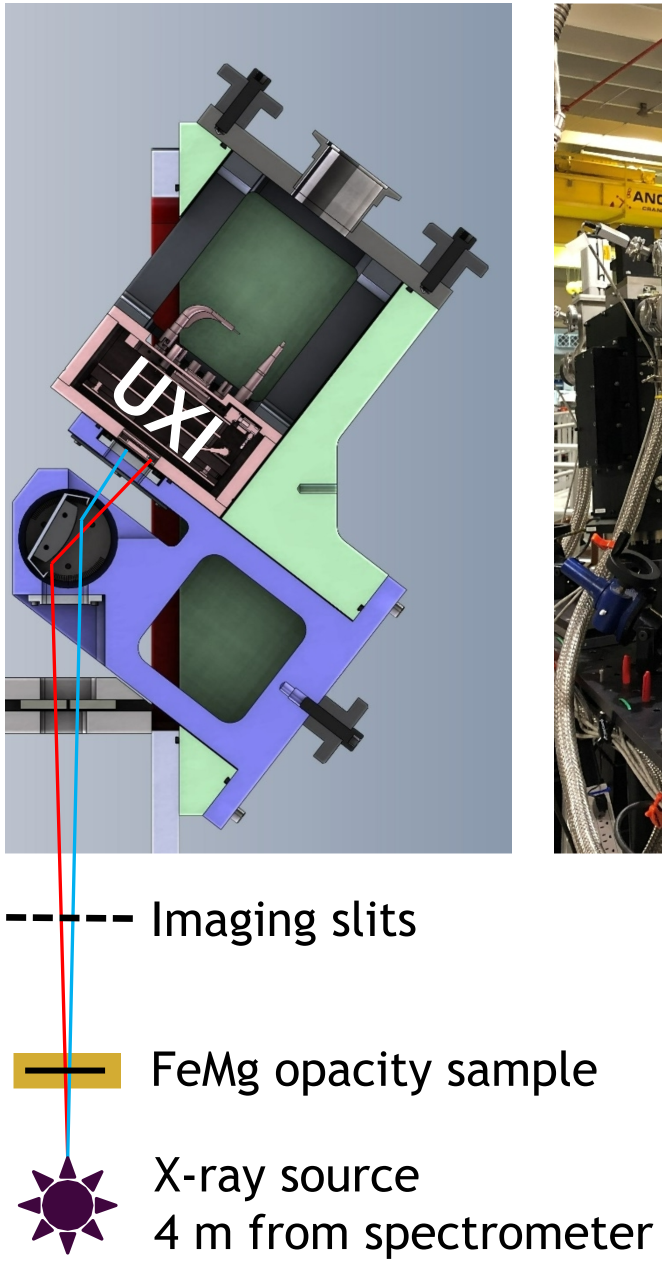
**Deployment Plan for GaAs detectors**

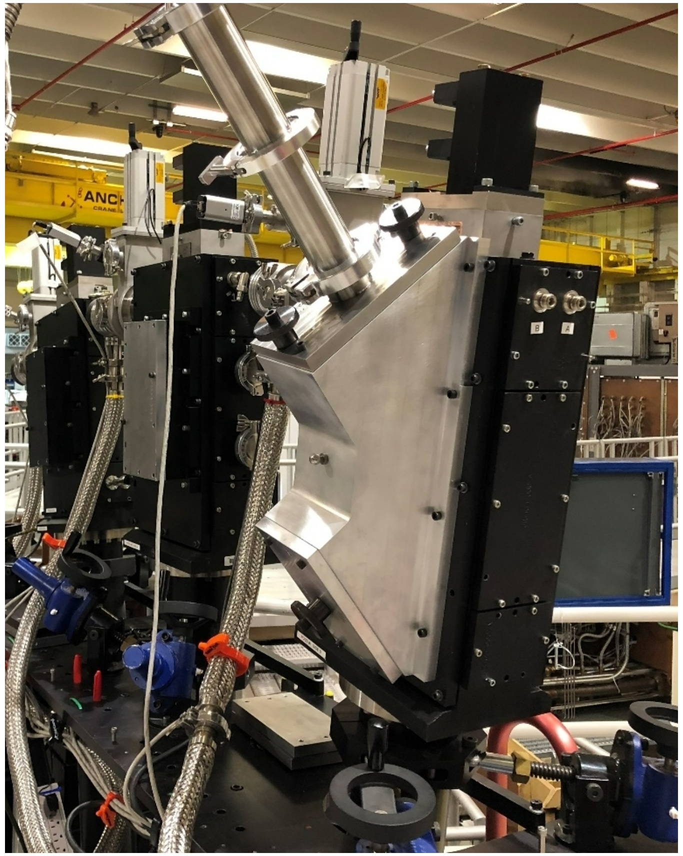
- Send 6 GaAs Icarus sensors for packaging in December 2021.
- Test these Icarus devices and report status to the community before the end of FY 2022.
- If successful, adapt the design to Daedalus. Potential availability in FY 2023.

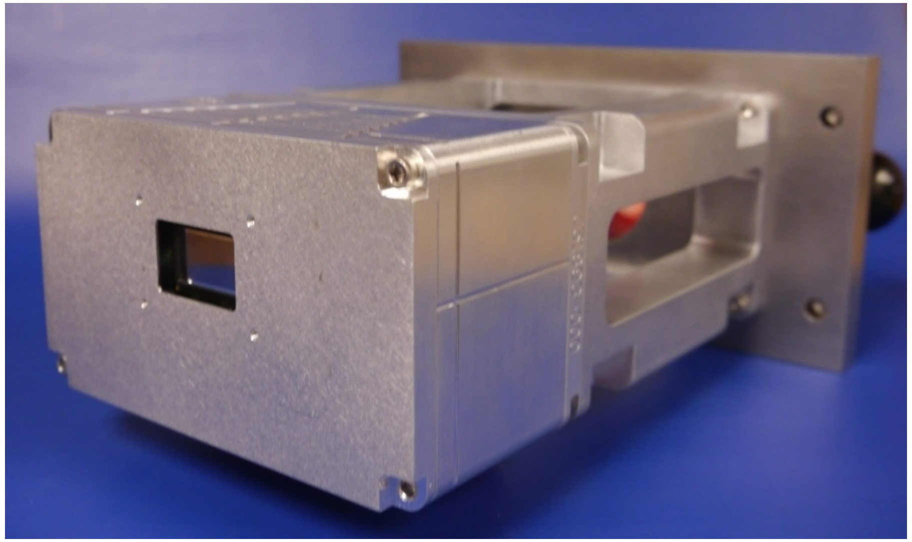



a) After flip-chip bonding.
b) After substrate remove and backside metallization.
c) After final packaging onto an Icarus read-out PCB.

# At Z, the convex crystal spectrometer is used to measure sample conditions and opacities.





**<u>Benefits of time-resolving</u>**

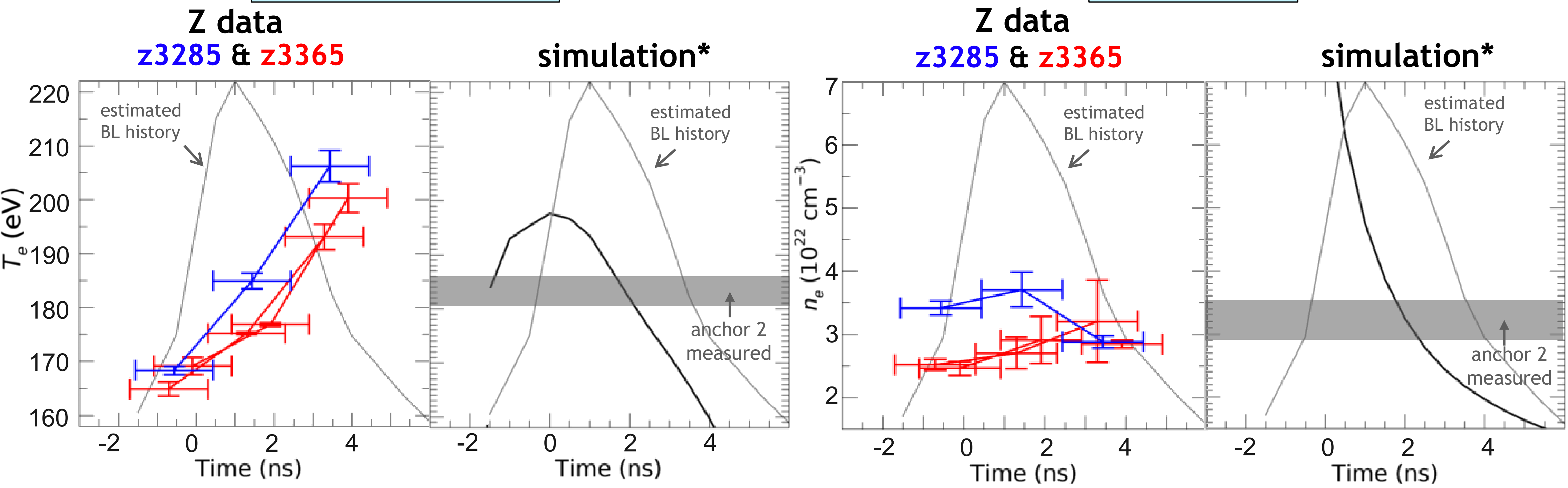
- **Measure multiple different sample conditions per shot…**
- **…instead of integrating over them.**
- **Evaluate sample evolution models.**
- **Assess hypotheses about discrepancies between models and data.**
- **Gate out time-integrated background.**

Spectrometer: Bailey et al, *RSI* **79**, 113104 (2008).
Opacities, e.g.: Bailey et al, *Nature* **517**, 56–59 (2015).

# Time-resolved results are challenging the understanding of this experimental platform.

Fe condition evolution trends disagree with simulation predictions.

**Temperature $T_e$** **Density $n_e$**




"Anchor 2" ~ Solar

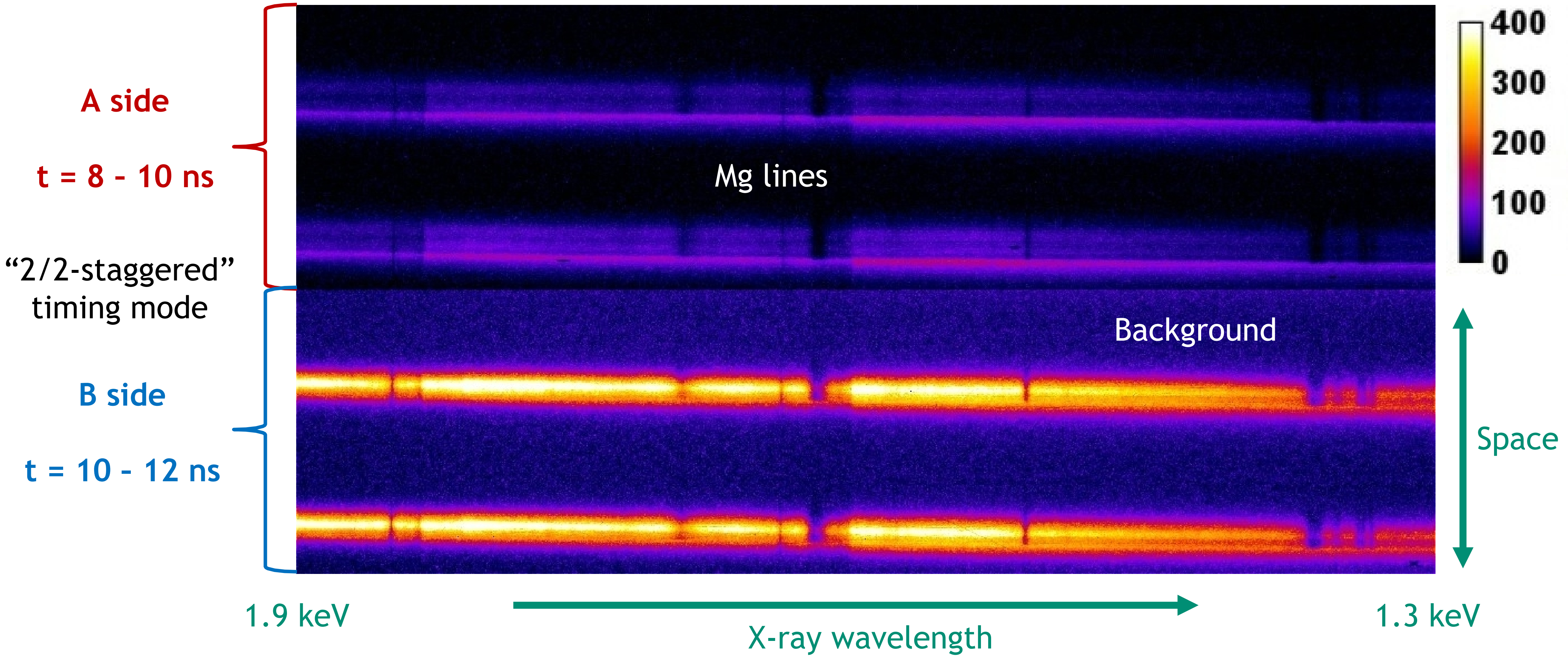
$T_e$ = 182 eV, $n_e$ = 3.1×10$^{22}$ cm$^{-3}$

**Analyzed data courtesy of Guillaume Loisel.**

*Simulations: Nagayama et al., *PRE* **93**, 023202 (2016).

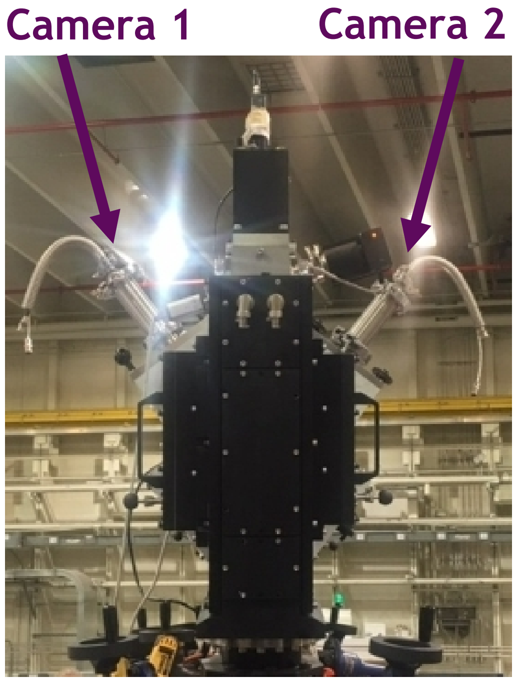
# In some applications, each camera frame can capture two different exposures without dead time.

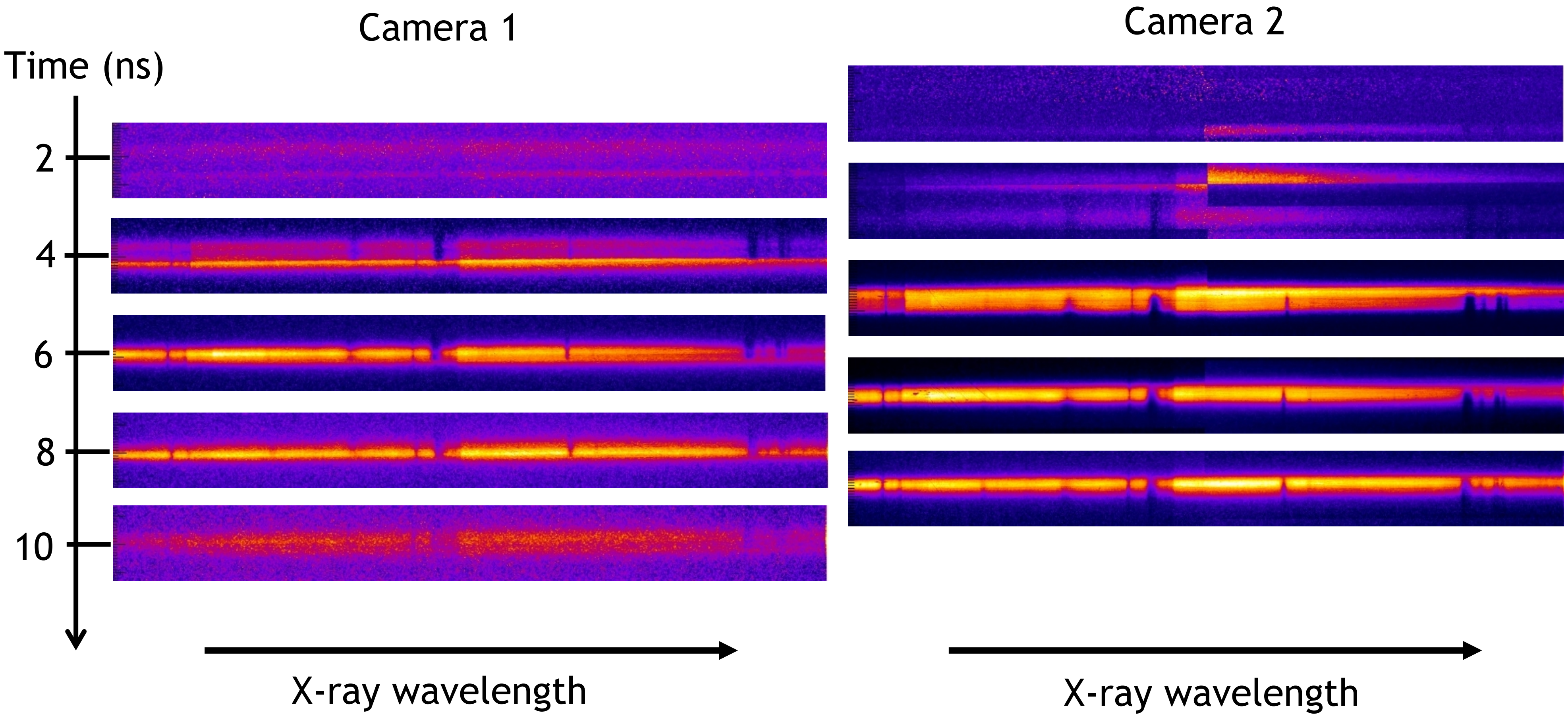
**Opacity Spectrometer in the Axial Package**
**Z3365 Camera 1, 3rd Frame (of 4)**



# Using 2 cameras in the Axial Package, we routinely collect 10+ exposures per Z shot.

**Z3365**

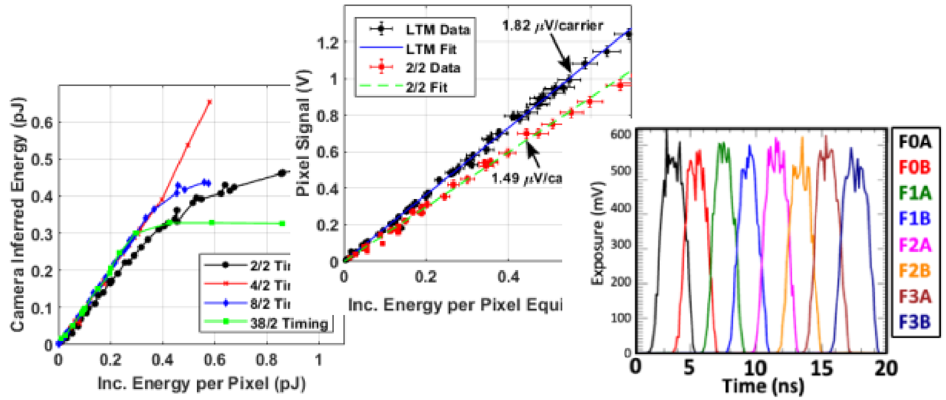


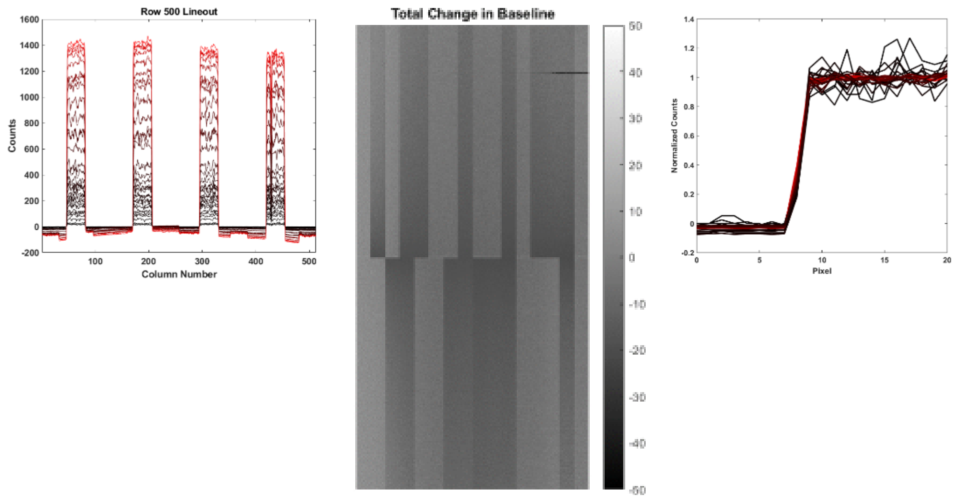
# Use-inspired characterization of diagnostics is crucial because illumination can have nonlocal effects on the sensor.

<u>Example requirements from end-user</u>

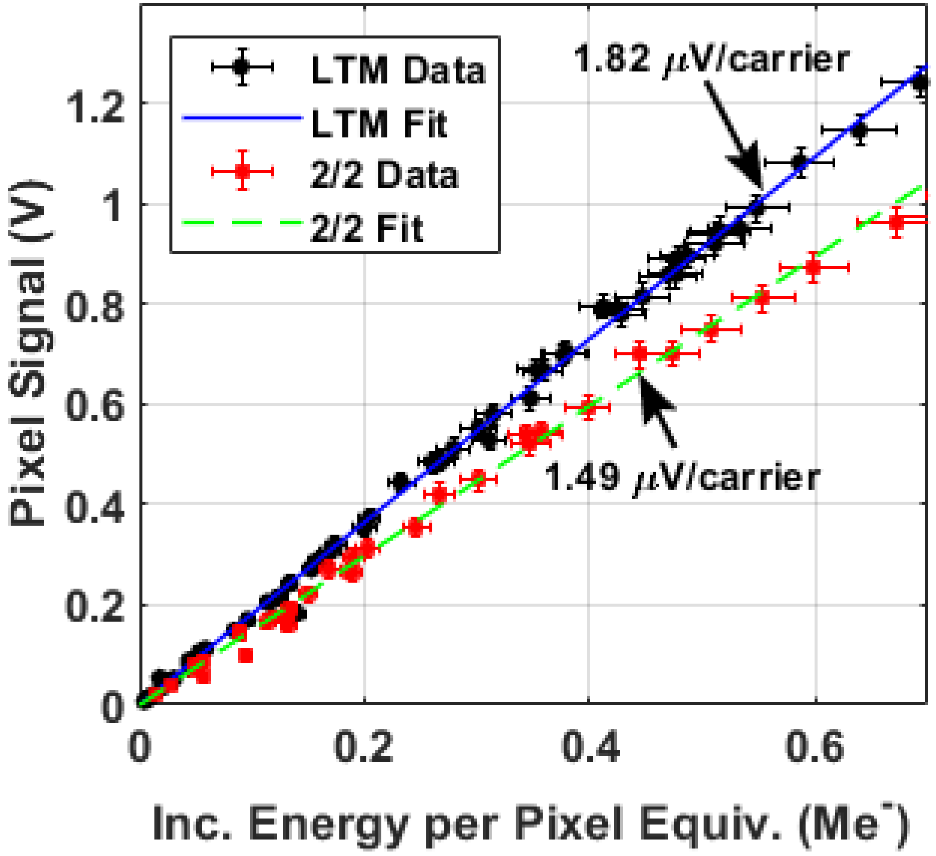
- Accurate Mg line transmission measurement:
  - High S/N spectra.
  - Linear photon response.
  - Sufficient spectral resolution.
  - Avoid feature saturation.
  - Reproducibility.
- Multiple timesteps to truly observe evolution.




Calibrated x-ray, optical, fabrication, and temporal characterizations.



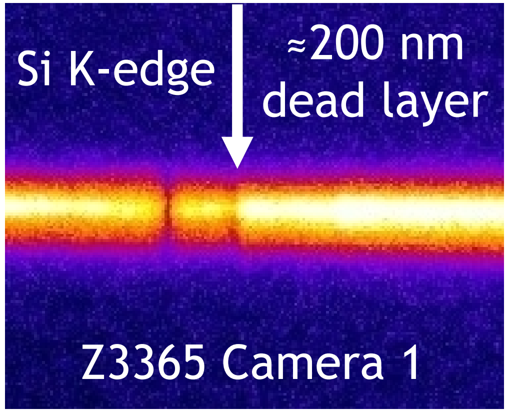
# The parameters for absolute UXI camera sensitivity have been measured.




Linearity is good through maximum spectrometer signal.

**2/2 timing sensitivity is different from other modes!**

**Shot data is consistent with fab spec of dead layer thicknesses.**



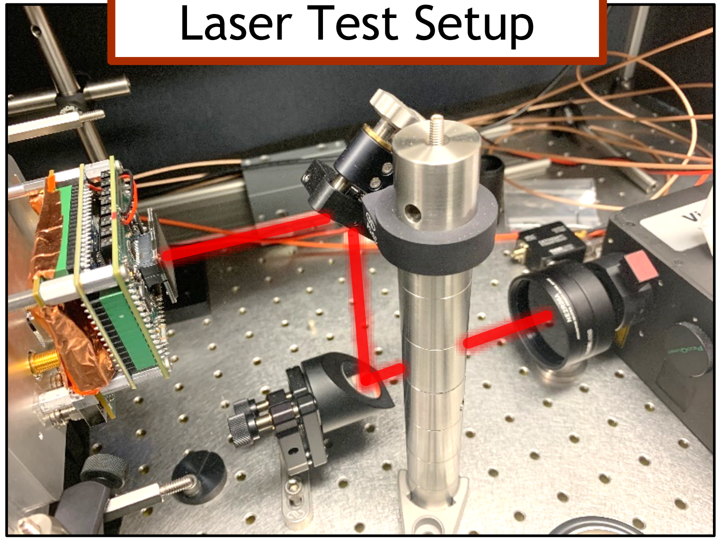

Detector is 25 μm thick Si.

Total camera response

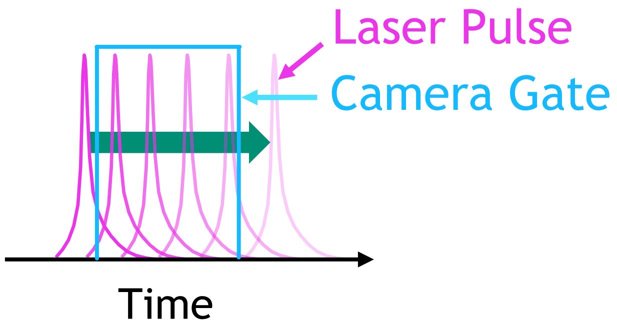
Gain: Looker, Colombo, Kimmel, & Porter, *RSI* **91**, 043502 (2020).

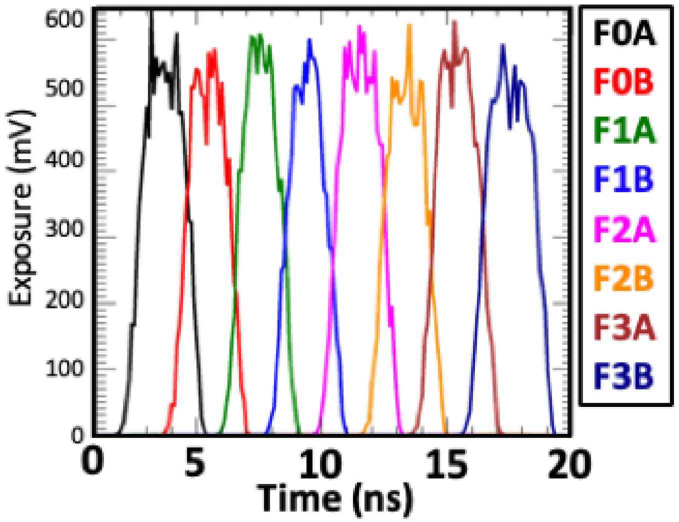
# We do a bevy of other camera tests and characterizations to qualify diagnostics for deployment in Z.

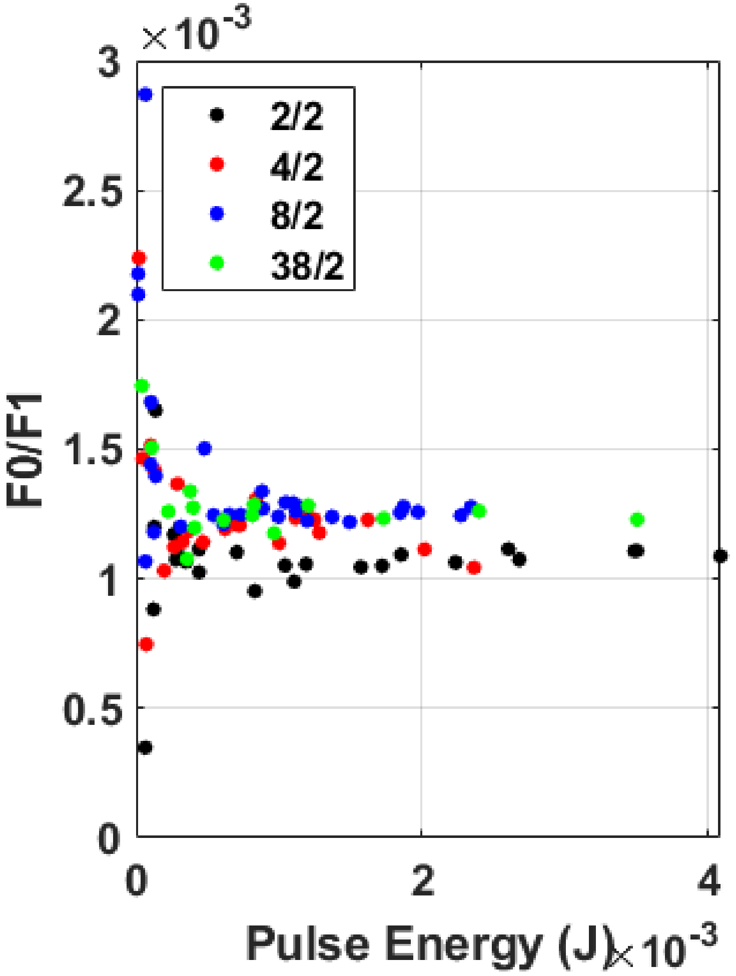
Laser Test Setup



Gate profiles validate cameras' temporal performance.



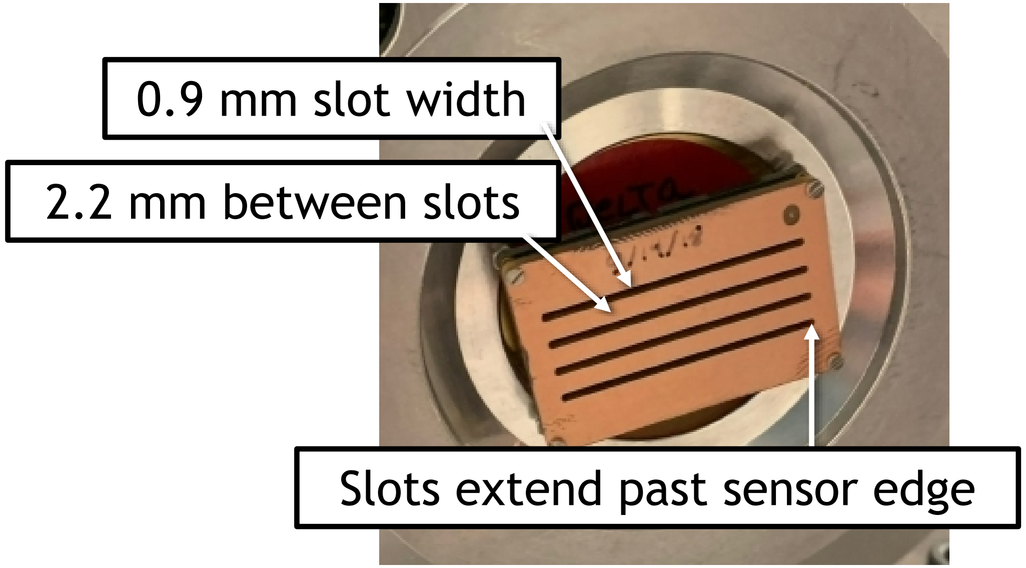



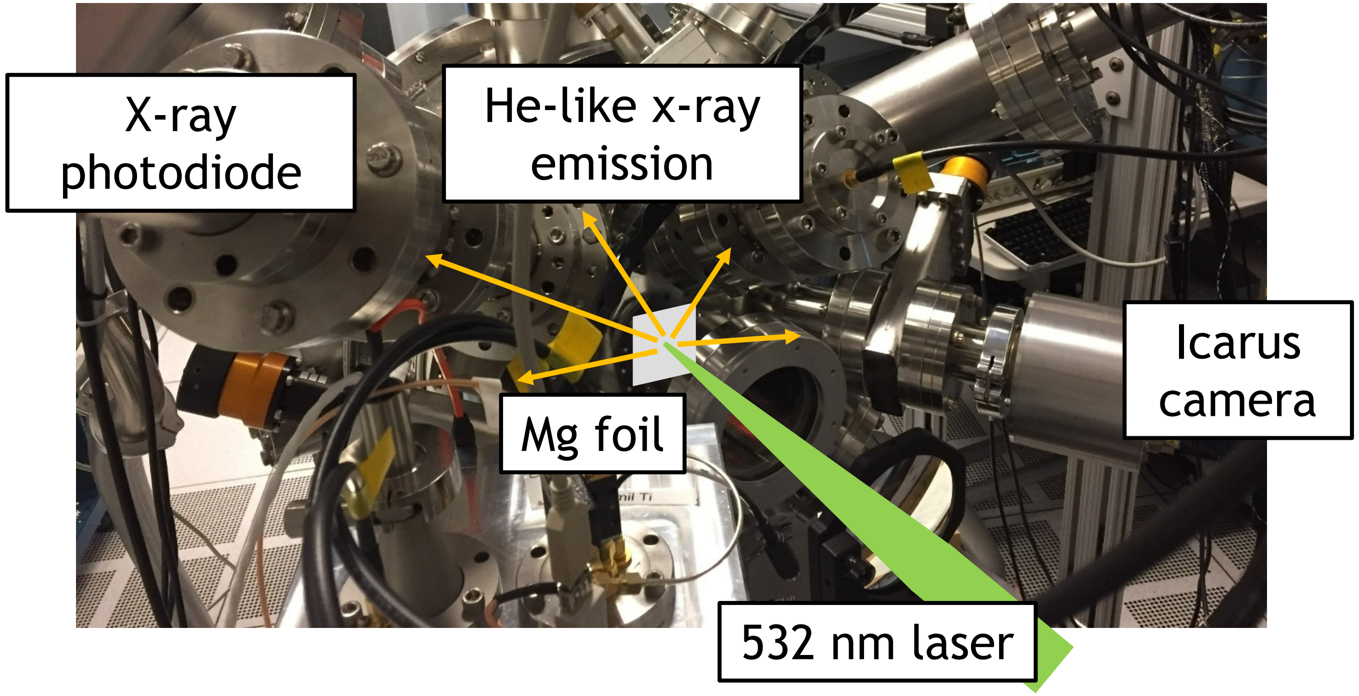




Slatfield testing shows that interframe crosstalk is relatively weak.

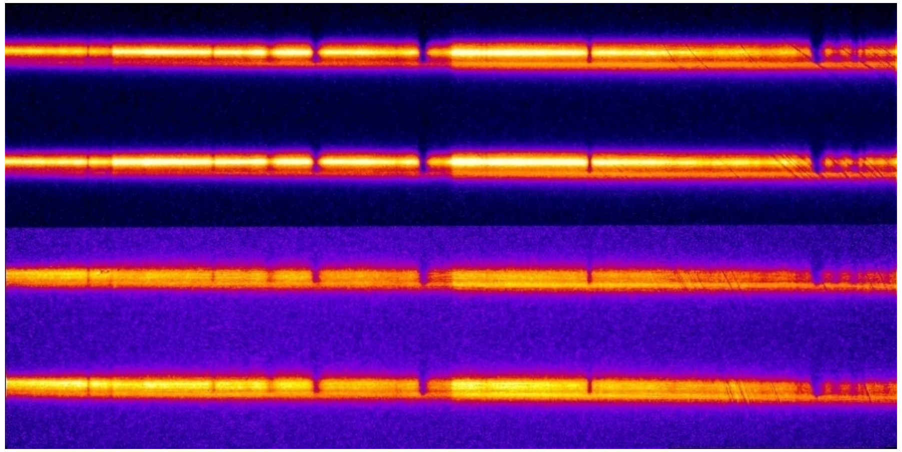
Crosstalk: Looker, Colombo, Kimmel, & Porter, *RSI* **91**, 043502 (2020).
More on gate profiles: Hurd et al., *Proc. SPIE* **10763**, 107630L (2018); Hart et al., *Proc. SPIE* **11038**, 110380Q (2019).

# We fabricated a custom mask to replicate the opacity spectrometer’s illumination pattern for high-fidelity testing.




2nd frame of Z3286

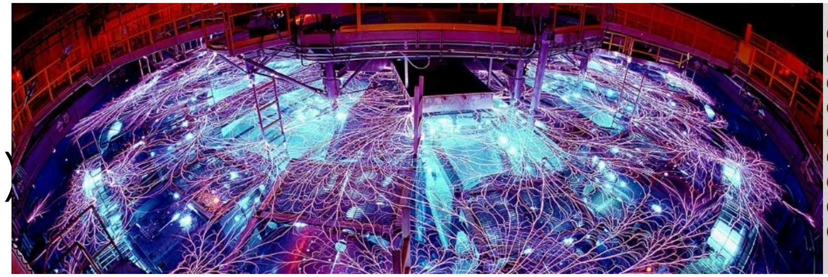


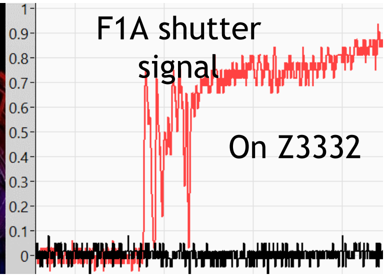
Chaco 1.35 keV pulsed source with “slatfield” mask

# Z poses major environmental challenges: EMI, x-rays, shock, impact, debris, and soot.

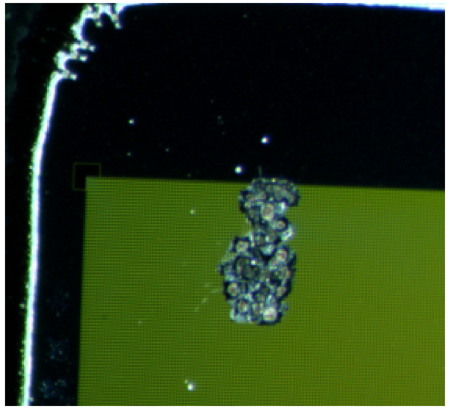
## Types of challenges, ranked (approximately)

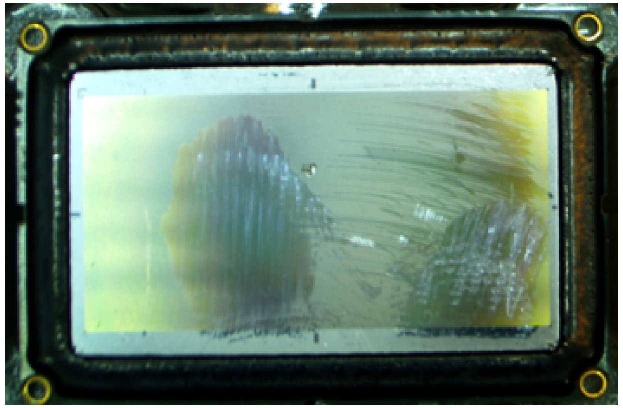
(1) EMI
(& X-rays)



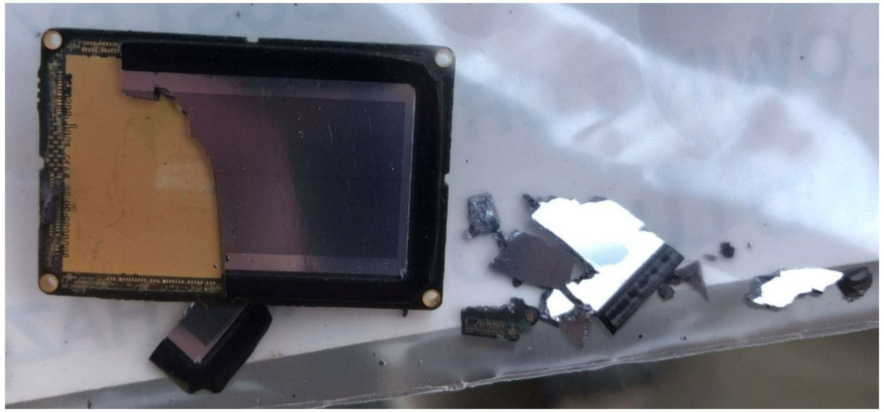



(2) Debris & Soot





(3) Shock & Impact



## Best practices

Isolate, regulate, buffer, multiply shield power line.
Sandwich PCB traces between ground planes.
Use fiber-optic data lines.
Alternate sets of insulating and conductive shielding layers.
Minimize number and size of camera body penetrations.

No line of sight from Z load to UXI if possible.
Mechanical protection in front of devices.
(At the cost of signal…)

Robust mounting for camera systems—appropriately stiff or loose, depending on the application.

# Frame signals are recorded on capacitors under the detector layer.

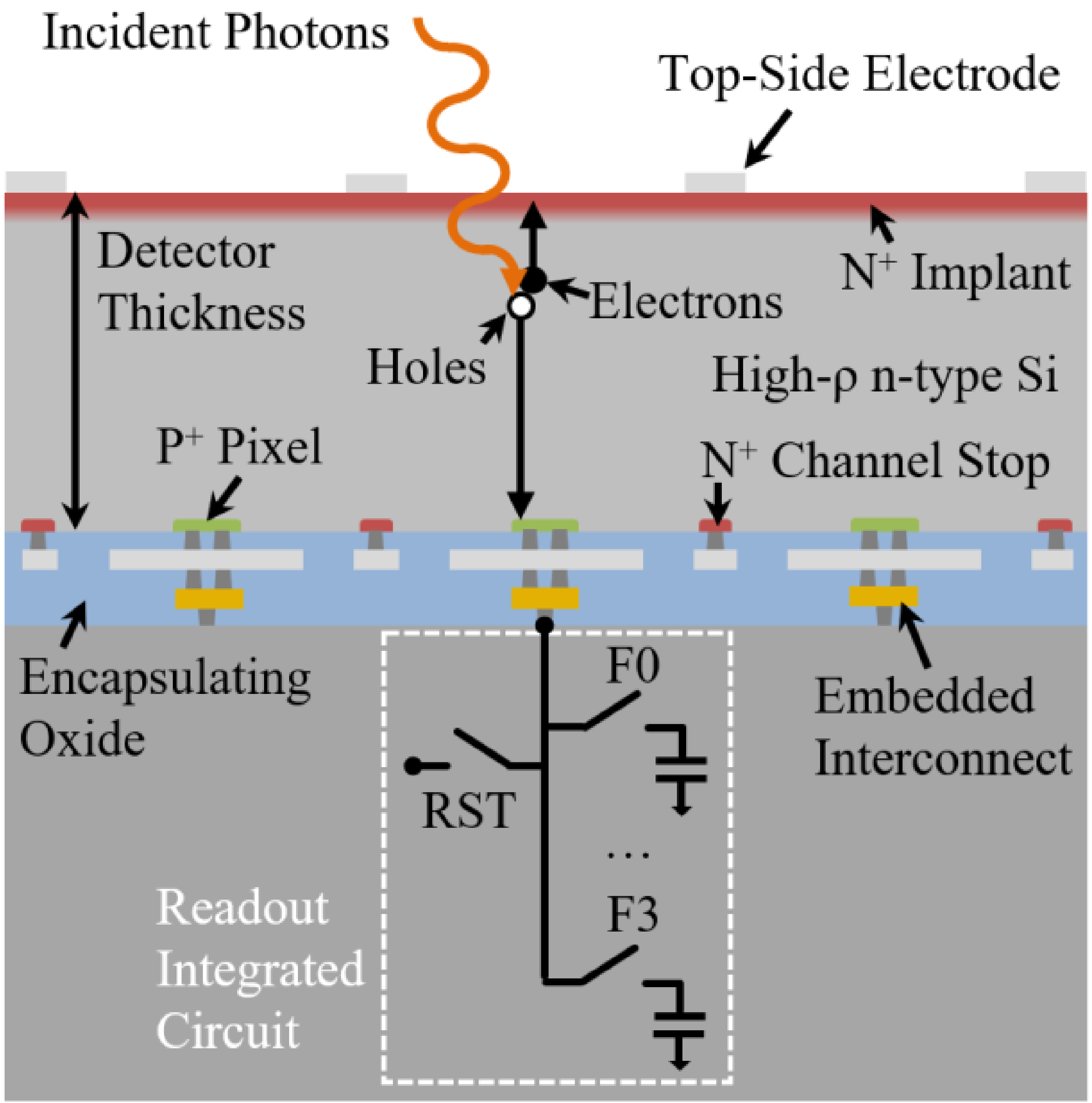



Fig. 1. Illustration of the Icarus sensor structure. A cross-section of the hybrid structure shows the Si detector layer (top) attached to the ROIC, with a schematic representation of the ROIC front end (bottom). The Si detector layer, with a physically defined thickness, generates a current pulse in response to illumination. The ROIC then samples the current with multiple integration frames according to a programmed timing pattern.

Figure from Looker, Colombo, and Porter, *RSI* **92**, 053504 (2020);