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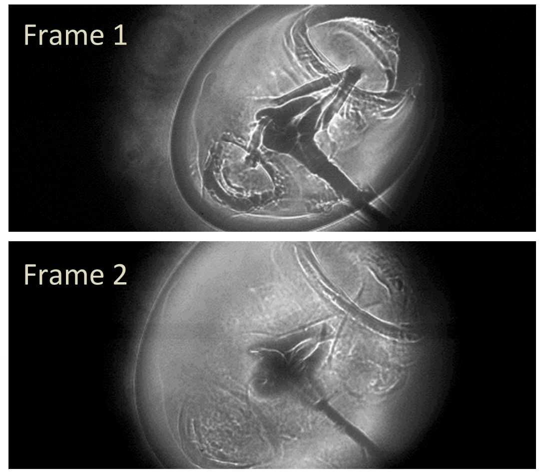

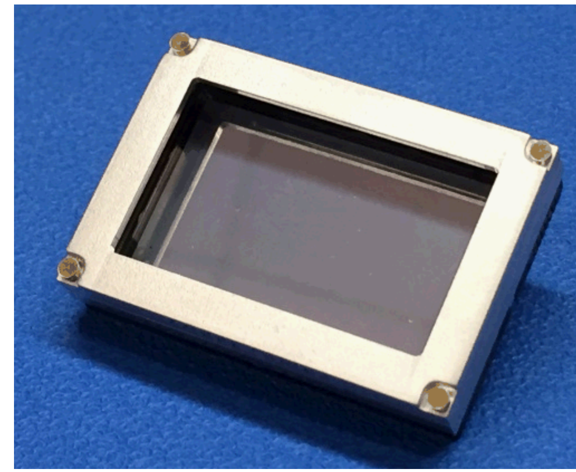

Gated CMOS cameras for ICF and HED Science

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Gregory A. Rochau

Manager, Radiation and Fusion Experiments

Phone: 505-845-7540

Email: garocha@sandia.gov

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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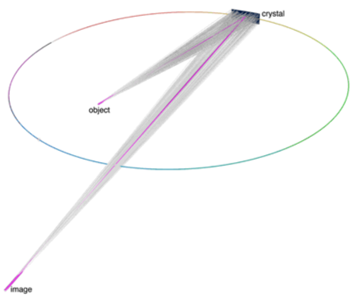
Outline

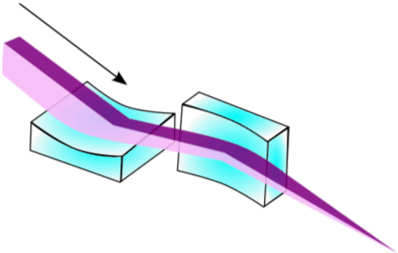
1. What is 'Single Line of Sight (SLOS)' gating and why do we need it?
2. Hybrid CMOS (hCMOS) cameras as SLOS imagers
3. hCMOS + Pulse-Dilation; a marriage made in heaven
4. Extending hCMOS to high x-ray energy (40 keV)

Advanced imaging systems require single line-of-sight (SLOS) gated detection with many frames to achieve high time resolution

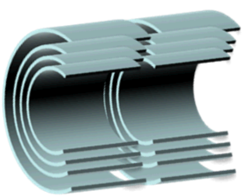
Spherical Crystal



Kirkpatrick-Baez



Wolter

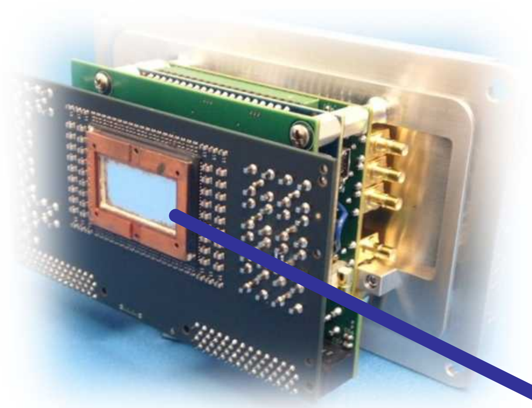


- ICF applications can require >28 frames of data to capture just 8 frames over the stagnation event due to jitter and/or bang-time uncertainty.
  - 20 ps gating desired on NIF
  - 200 ps gating desired on Z
- High sensitivity, high resolution optics are delicate (expensive) and take up space

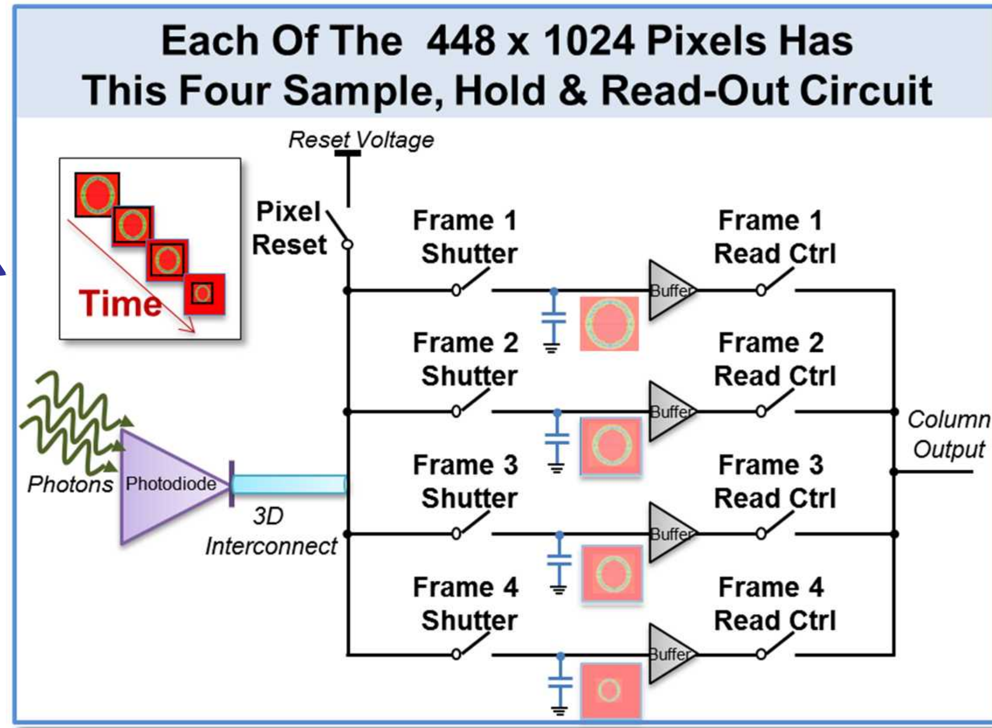
Spherical crystal optics on Z are ‘disposable’

A new high speed CMOS camera coupled to a photo-diode array is enabling multi-frame 2-D x-ray detection along a single line-of-sight

hybrid CMOS camera



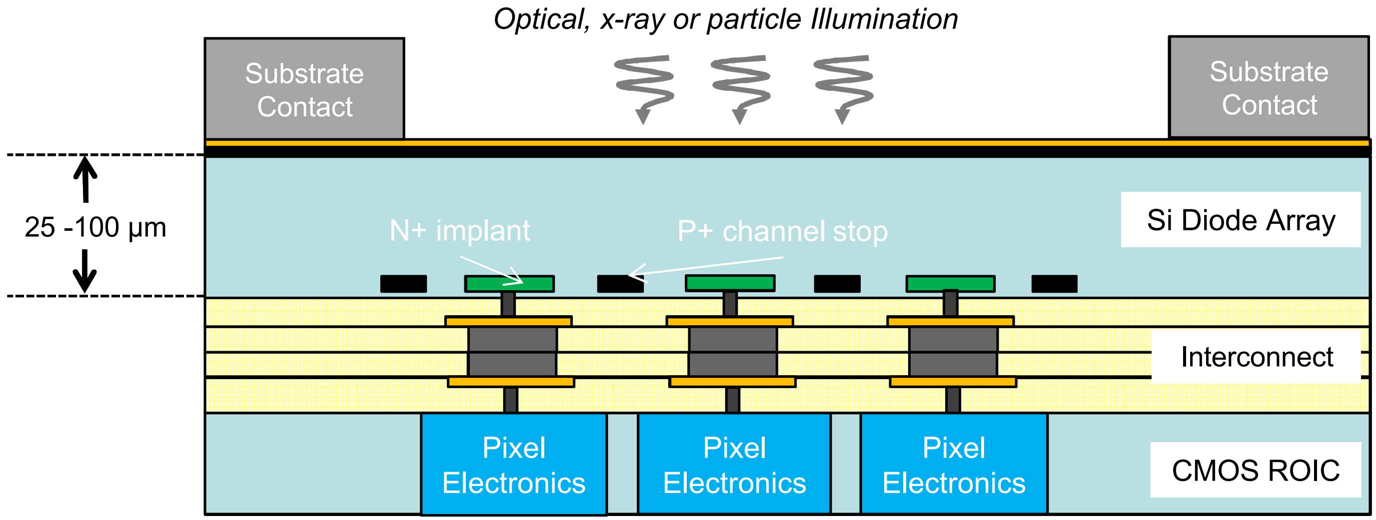
- 25 um x 25 um pixels
- Sensitive to visible light and 0.7-10 keV x-rays



designed and built in collaboration with the MESA facility

Hybridizing enables independent optimization of the diode array and the readout electronics

- Photodiodes can be optimized for sensitivity to relevant spectrum of interest (visible light, x-rays, electrons).
- ROIC stores charge from each photodiode on in-pixel capacitors during selected integration time for each frame.
- Each pixel of photodiode array is directly connected to CMOS ROIC through wafer-to-wafer bonding (Ziptronix 3D oxide-to-oxide bond process).



CMOS Hybrid Image Sensor

UXI ROIC Architecture

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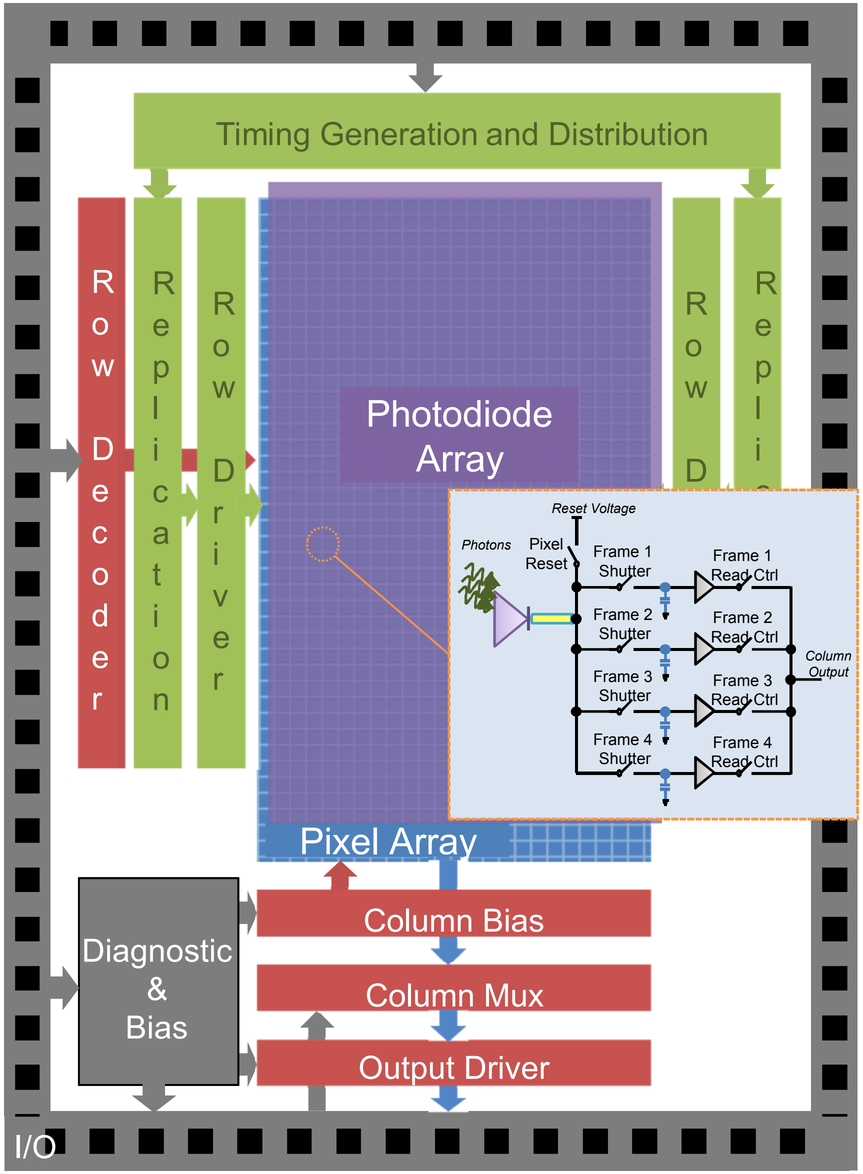
- **Pixel Array**
  - 2-4 Frame In Pixel Storage
  - Global Shutter
- **Timing**
  - High Speed Shutter & Pixel Control
  - Adjustable Shutter Timing 1-19ns
  - Adjustable Delay Between Shutters
- **Readout**
  - Random Access to Pixels (Region Of Interest)
  - Multiple Parallel Channels Of Image Data
- **Photodiode**
  - 0.7-6keV X-rays & 500-900nm Visible Light
- **I/O and Support**
  - Timing Signal Diagnostics



UXI Camera Designs Existing or in Progress

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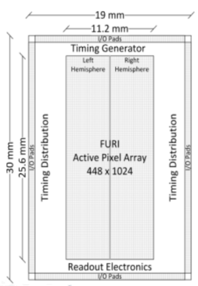
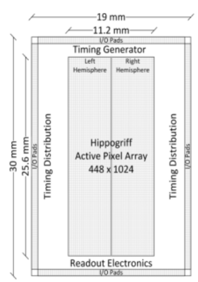
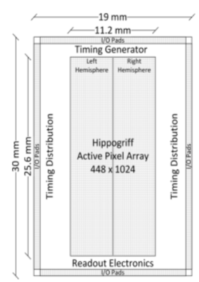
'High' Full Well Sensors

	Presently in Use		New Design
	Furi	**Hippogriff**	**Hippogriff 2**
Year	FY14	FY15	FY17
Min. Gate	~1.5 ns	~2 ns	~1.5 ns
Frames	2	2 (full-chip), 4 or 8 (interlaced)	
Tiling Option	No	No	TBD
CMOS Process	350 nm (SNL)		
Pixels	448 x 1024		
Pixel Size	25 µm x 25 µm		
Capacitor Full Well	1.5 million e^-		

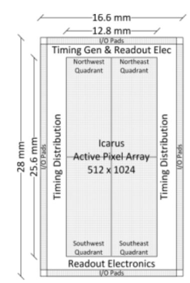


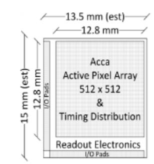




'Low' Full Well Sensors

Pulse Dilation	
Icarus	**Acca**
FY16	FY18
~1.5 ns	~1 ns
4	8
No	Linear Tiling
350 nm (SNL)	130 nm (IBM)
512 x 1024	512 x 512
25 µm x 25 µm	
0.5 million e^-	



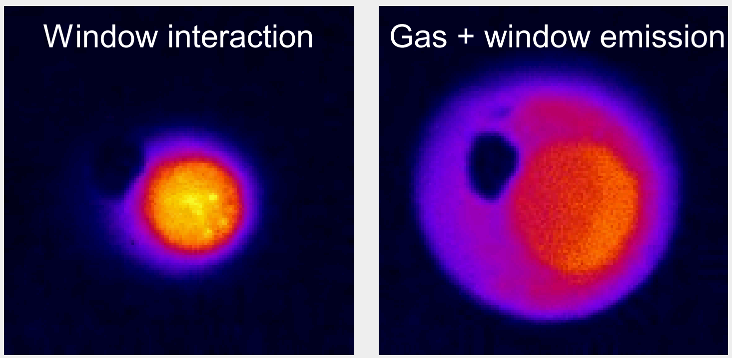


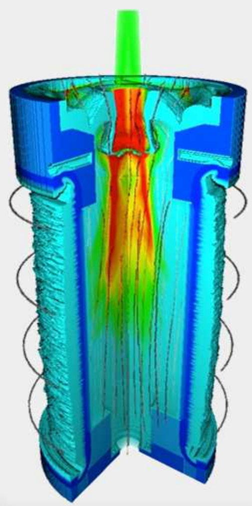
Mixed Signal ASIC/SoC

Multi-frame hCMOS imagers have recently been deployed for gated imaging on both Z and NIF

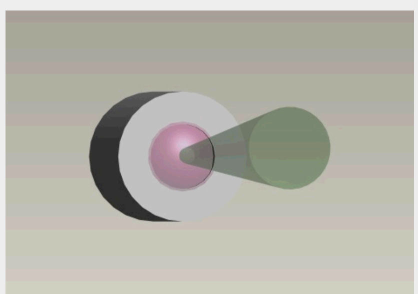
MagLIF laser preheat on Z*

9 ns gate separated by 10 ns



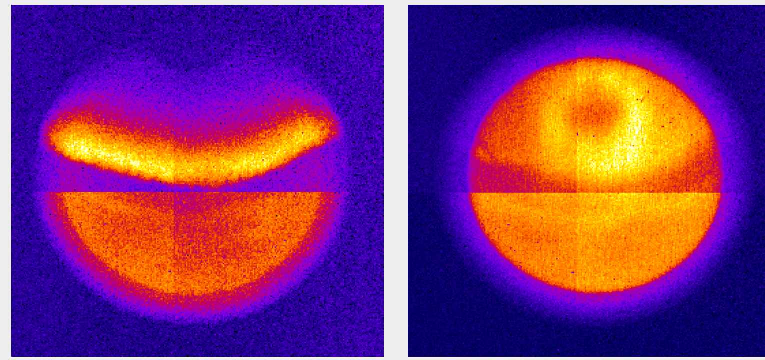


Camera View of LEH

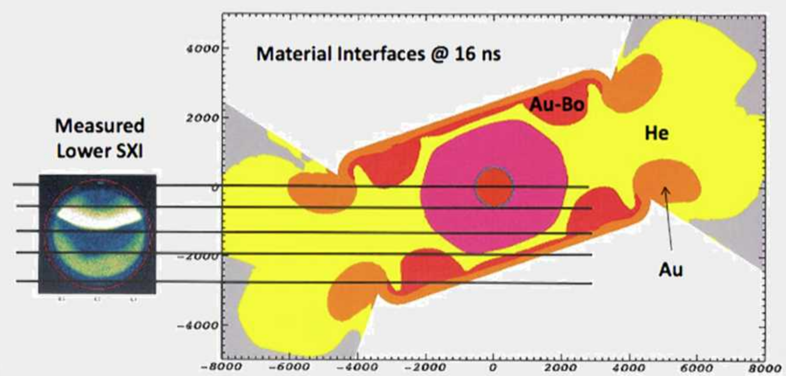


LEH imaging on NIF**

2 ns gate separated by 4 ns



Camera View of LEH



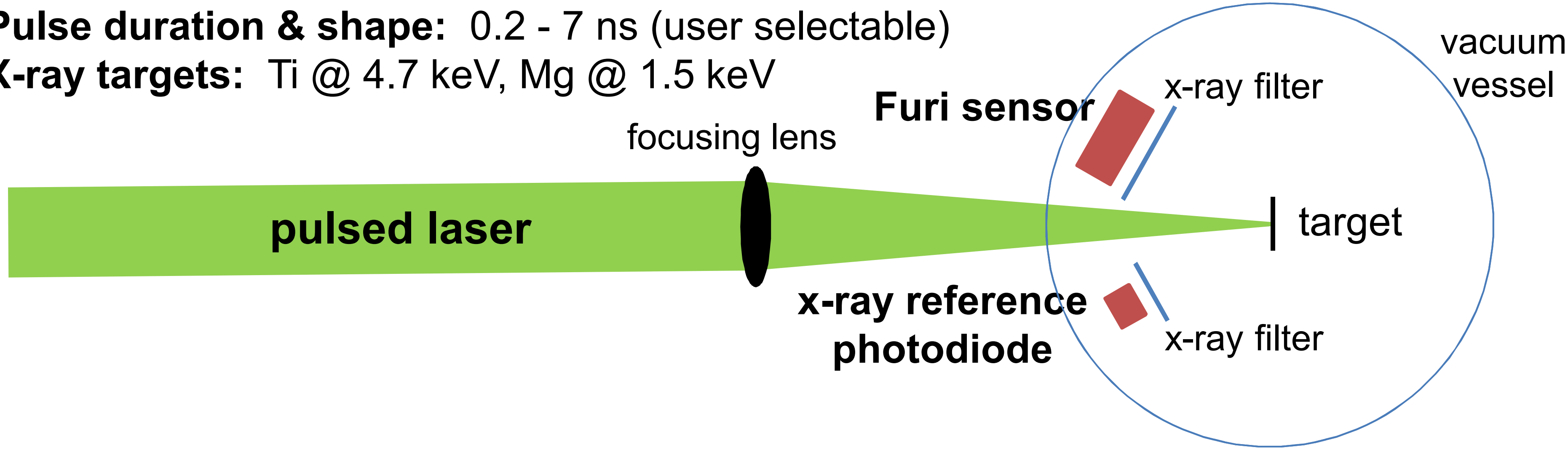
*Porter (SNL) et al.

**Chen (LLNL) et al.

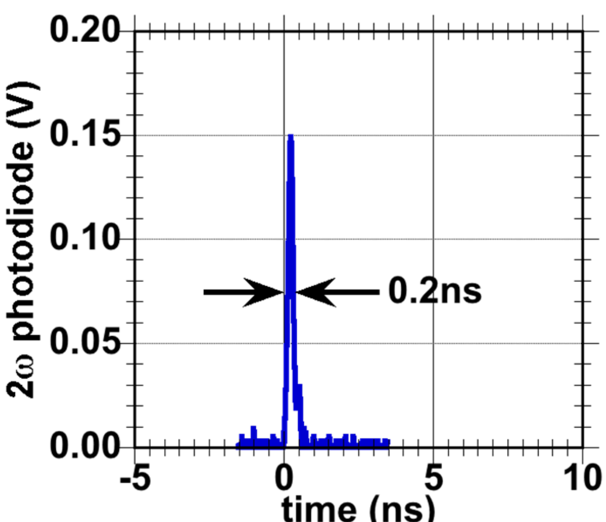
We use a pulsed laser to characterize camera response to either x-rays or visible illumination

Laser wavelength: 532 nm (frequency doubled)
Laser 2ω energy: 0.1 μJ - 15 J (user selectable)
Pulse duration & shape: 0.2 - 7 ns (user selectable)
X-ray targets: Ti @ 4.7 keV, Mg @ 1.5 keV

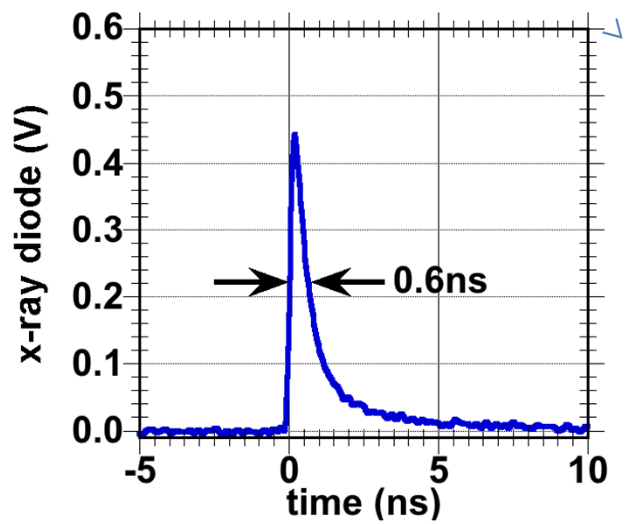
X-ray Characterization Setup



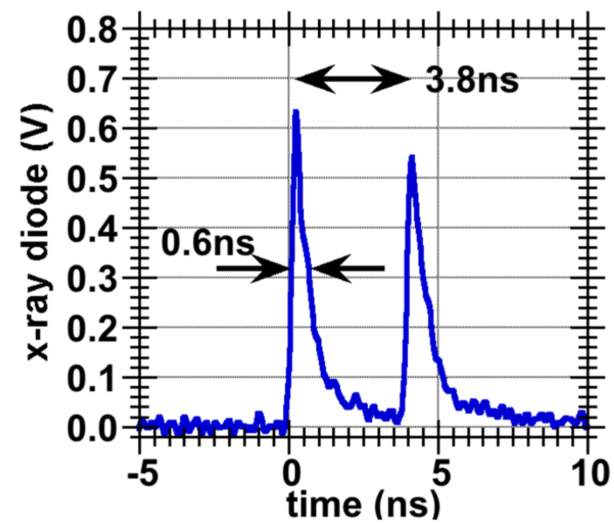
200ps visible illumination



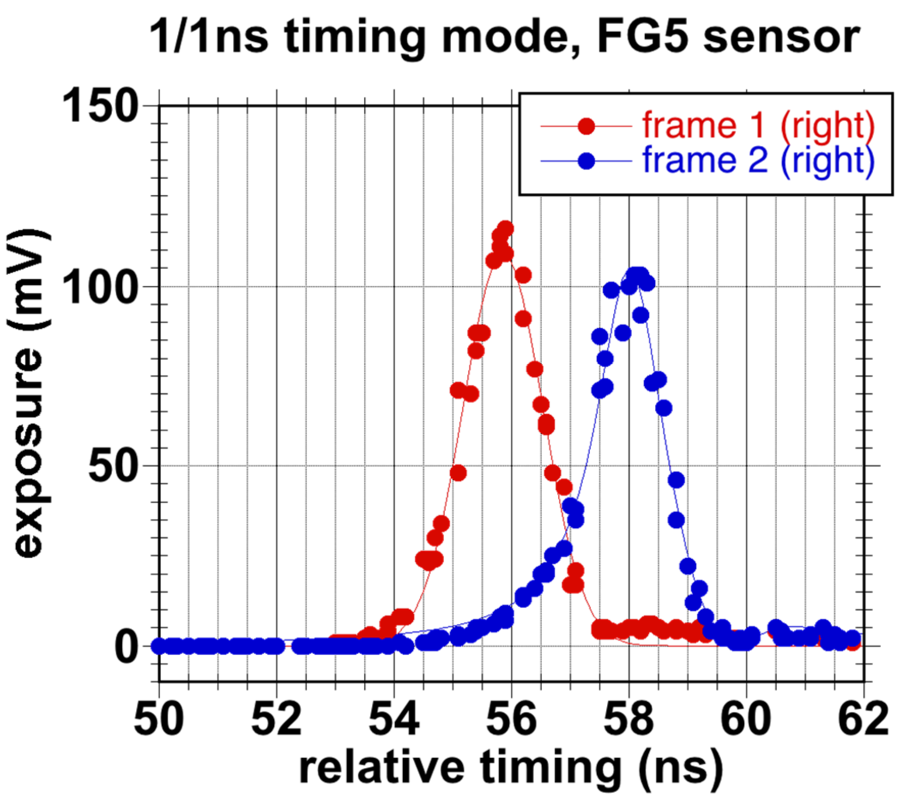
600ps x-ray illumination

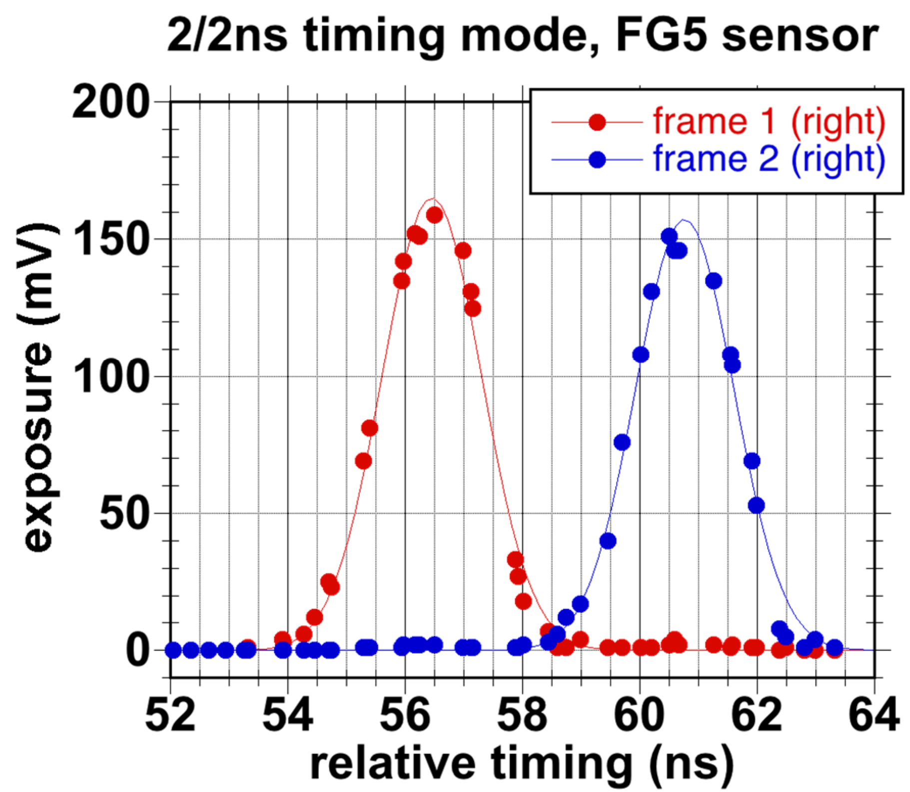


2-pulse x-ray illumination



Example of Furi time-response measurements using 200ps pulsed visible illumination



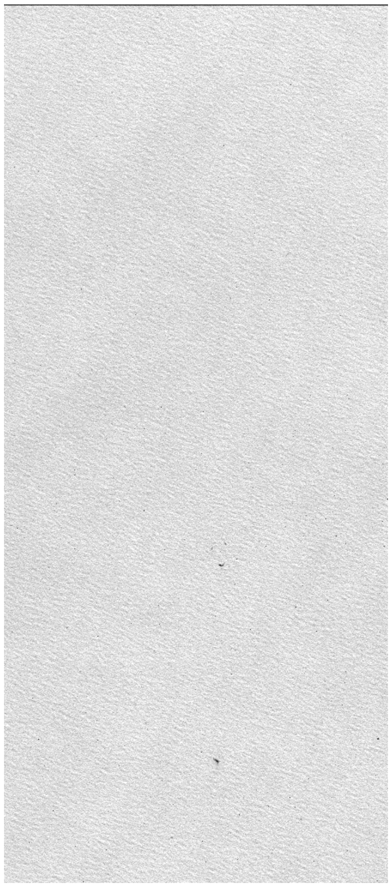


	FWHM (ns)	Frame Δt (ns)	left/right Δt (ns)
frame 1	1.6		0.9
frame 2	1.6	2.1	0.8

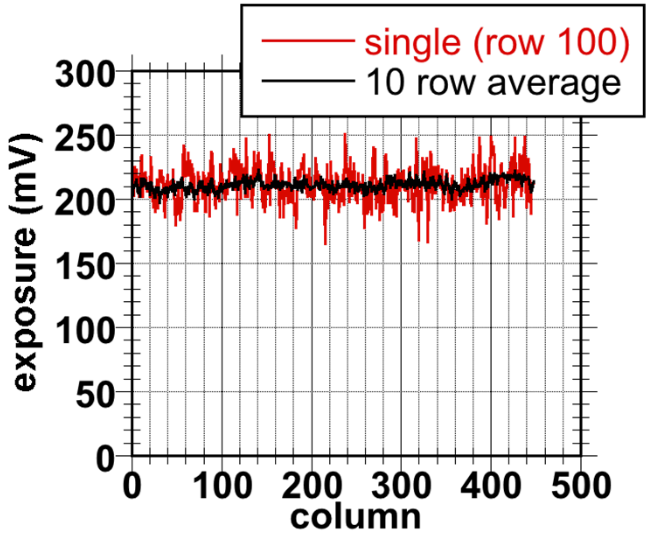
	FWHM (ns)	Frame Δt (ns)	left/right Δt (ns)
frame 1	2.0		0.9
frame 2	2.0	4.3	0.8

Example of Furi flat-field measurement using 600ps pulsed x-ray illumination

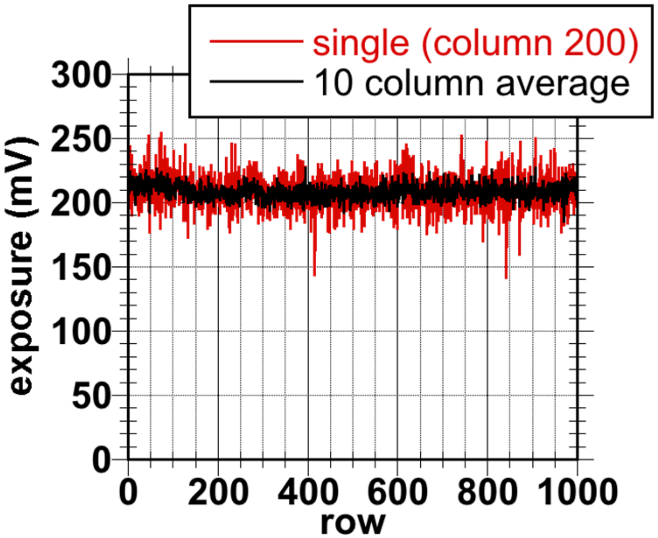
Frame 2, F1X8 sensor
10/10ns timing mode



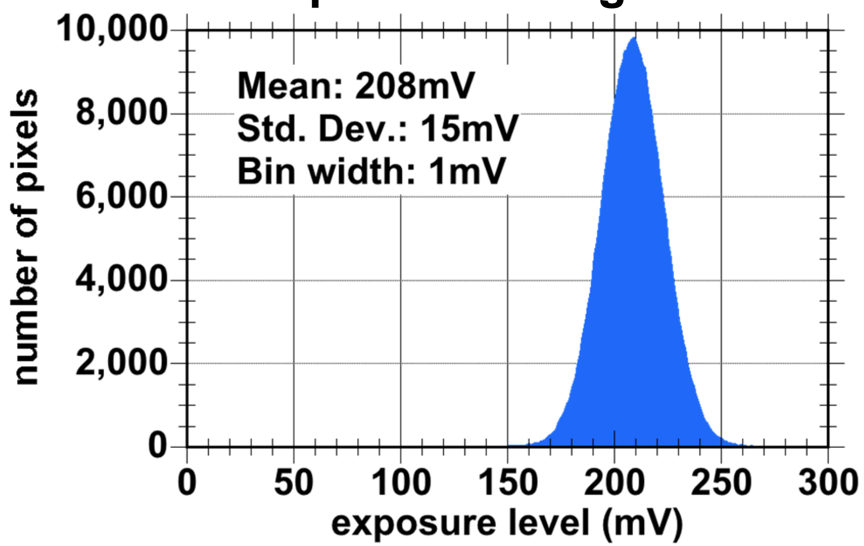
Row lineout



Column lineout

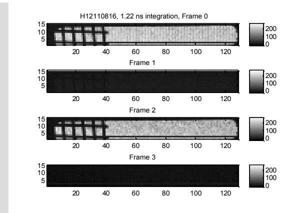


Exposure histogram



In the next 3 years, we will deploy a >1 MP hCMOS imager with 1 ns gate times over 8+ frames

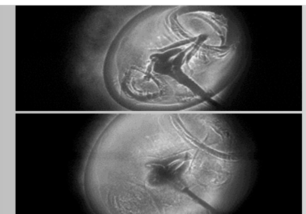
GRIFFIN
1.5ns, 4 Frames
15x128 pixels
350nm Sandia Process



Calibration Mesh X-ray 1.5ns Images

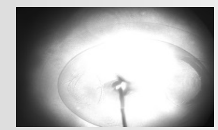
FY13

FURI
1.5ns, 2 Frames
448x1024 pixels
350nm Sandia Process



10ns Blast Wave Visible Images

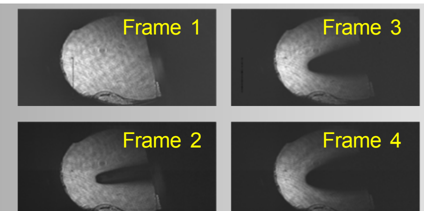
vs.



Commercial Double Exposed CCD

FY14

HIPPOGRIFF
2 ns, 2-8 Frames (Interlacing)
448x1024 pixels
350nm Sandia Process

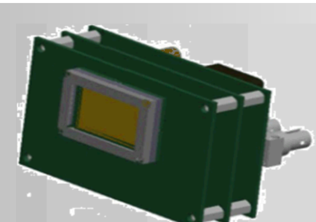


4ns Gas Cell Shadowgraphs

FY15

ICARUS
1.5ns, 4-16 Frames (Interlaced)
512x1024 pixels
350nm Sandia Process

ACCA
1ns, 8 Frames
512 x 512 pixels (1-D tileable)
130nm IBM Process



FY16-18

ACCA-The next generation burst mode hCMOS imager under development at SNL

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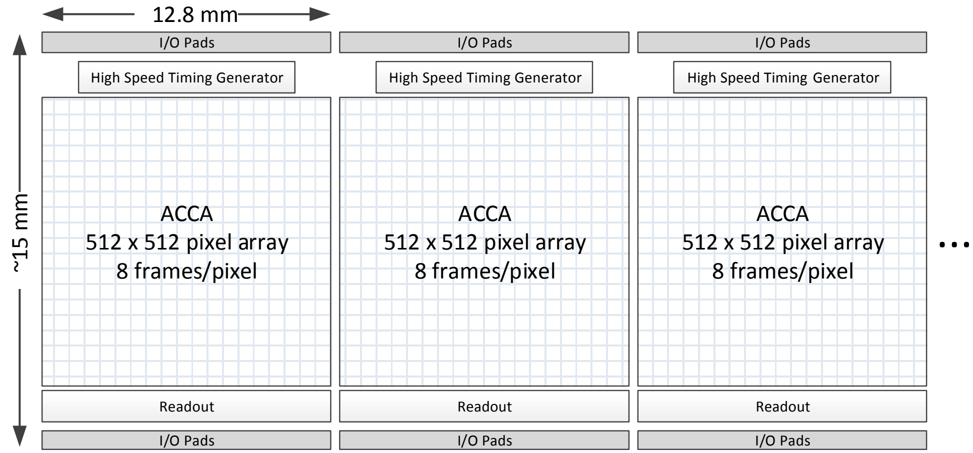
- Specifications
  - 512 x 512 pixel array
  - 8 frames per pixel
  - 1 ns integration time
  - 2 ns frame rate
  - 25 µm spatial resolution
  - Left/Right abutable design
  - 60 dB (1000:1) dynamic range
    - 500e- to 500k e-
  - Reduced readout dead-time
    - 1.45 ms per read-off of 512x512 pixels and 8 frames
      - Improvement from 135 ms on 1st generation imagers
    - 689, 8-frame movies per second in continuous read mode

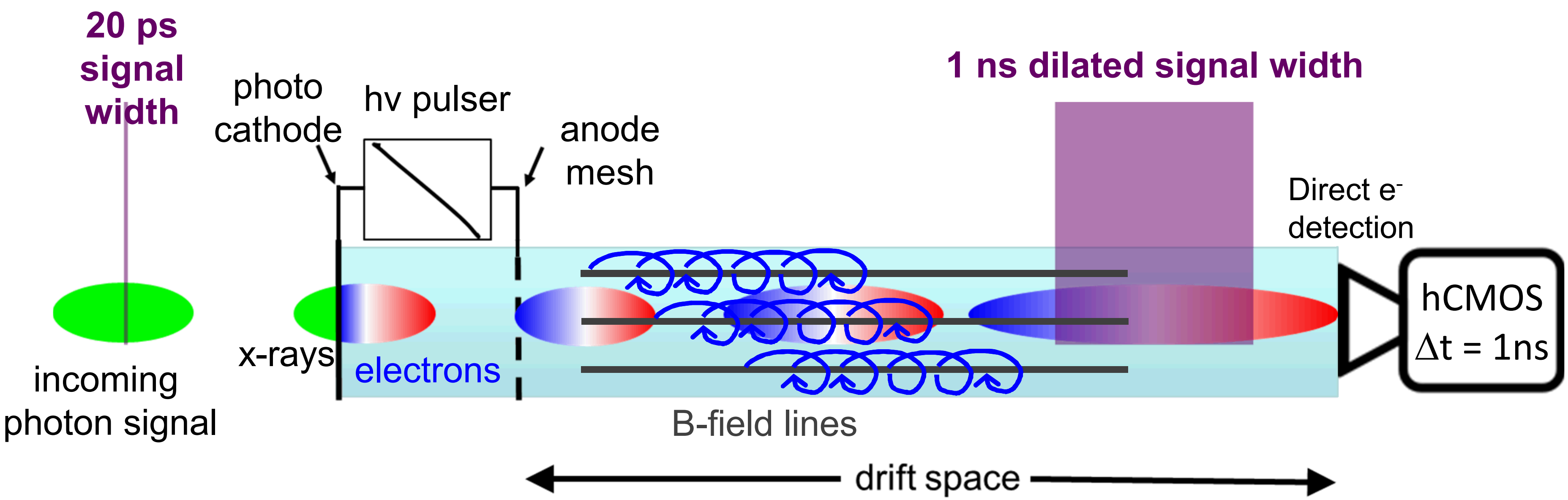


Mixed Signal ASIC/SoC

The ACCA architecture enables a scalable number of frames and form-factor

- Innovations
  - Leveraging higher density 130 nm technology node
    - Increased transistor density and metal interconnect layers enable significant design improvements
  - Left/Right 2-side abutment form factor
    - Infinite tiling in one direction
  - Differential CML H-tree timing distribution
    - Expect improved timing distribution uniformity
    - 2 global clocks distribute Pulse Width Modulation (PWM) encoded shutter information
  - In-pixel digital shutter generator converts the global clock PWM information to individual frame shutters
    - This architecture is scalable in number of frames while never requiring more than the 2 global clock signals to be distributed
- Risks and mitigation strategy
  - New technology (IBM 130nm CMOS8RF process)
    - Process leakage is worse with IBM than SNL's 350 nm CMOS7 process that our current ROICs are fabricated in
      - Increased readout speed to minimize leakage effects (1.45 ms)
      - Cool the device to 0 C
    - Bulk technology susceptibility to radiation
      - Test under radiation

Electron pulse-dilation will act as a tele-temporal lens to significantly increase the time-resolution for SLOS detection



temporal magnification

$$M \approx 1 + \frac{L}{2v_d(\phi)}\frac{|\dot{\phi}|}{\phi} = 50$$

$L = 25\ \mathrm{cm}$ drift length

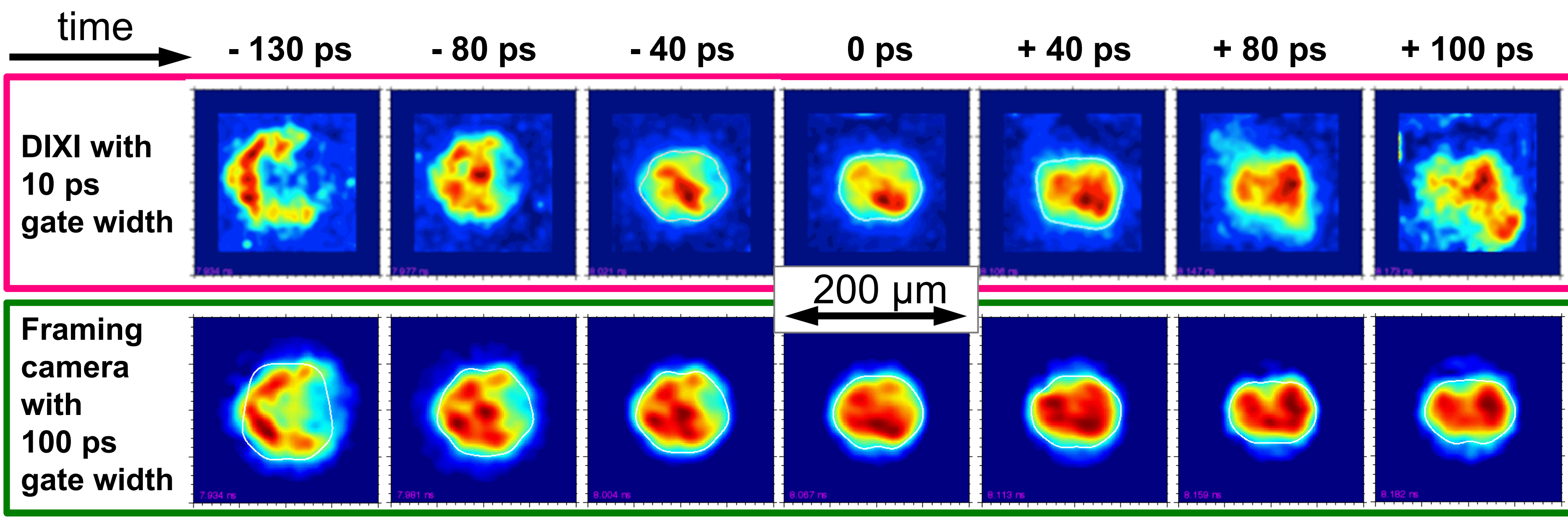
$\phi = 1000\ \mathrm{V}$ drift potential

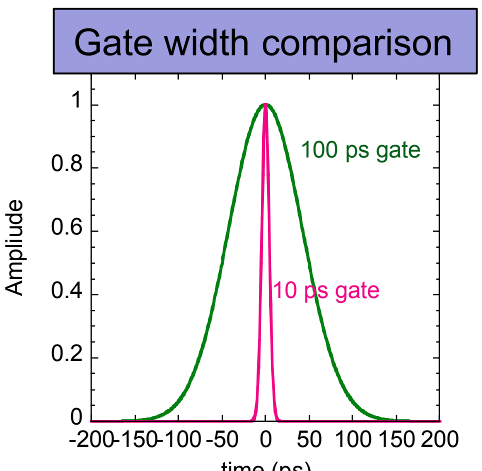
$v_d = 19\,\frac{\mathrm{mm}}{\mathrm{ns}}$ drift velocity

$|\dot{\phi}| = 4\,\frac{\mathrm{kV}}{\mathrm{ns}}$ PC ramp

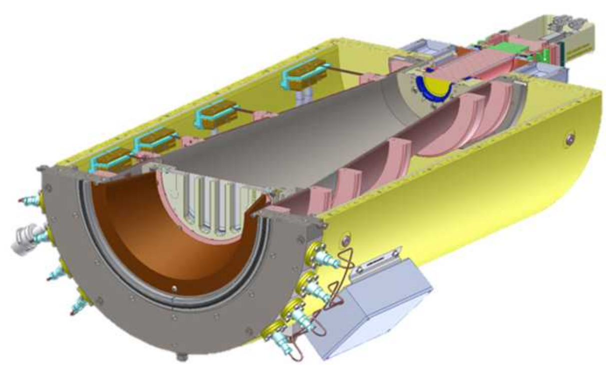
Pulse-dilation separates input information enough to enable multiply gated back-end detector to capture consecutive frames with much slower gate time

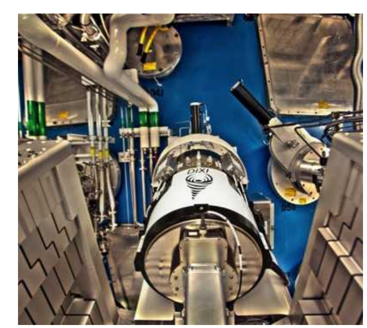
Pulse-dilation on NIF has achieved 10 ps time-resolution, providing a more detailed picture of ICF stagnation



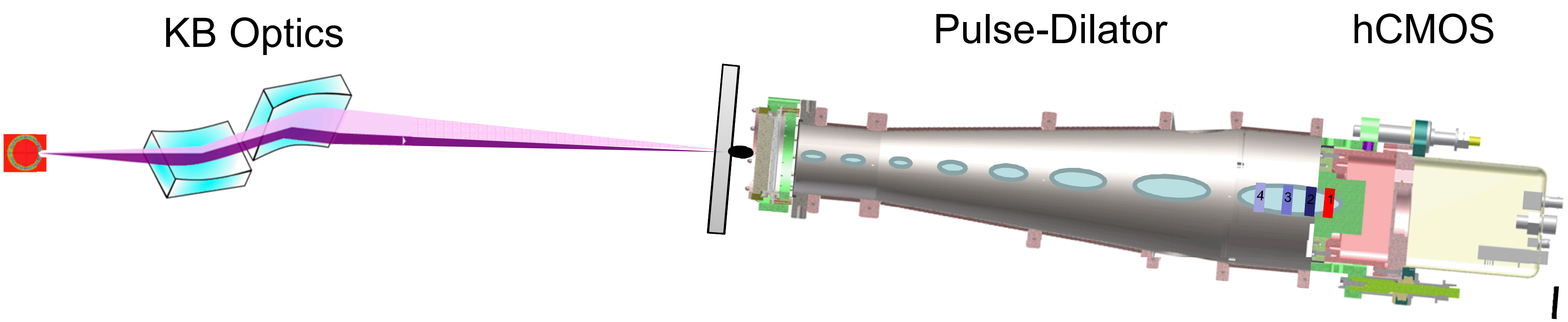


DIXI – Dilation x-ray imager

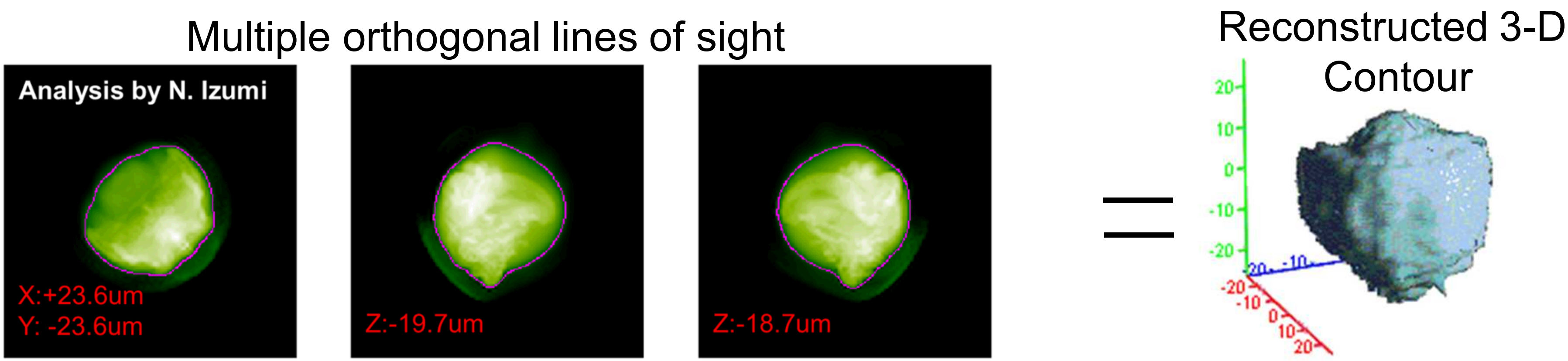




The first implementation of pulse-dilation SLOS will be on NIF with pinhole optics and then K-B microscopes



<u>Three orthogonal LOS can theoretically provide some 3-D information*</u>

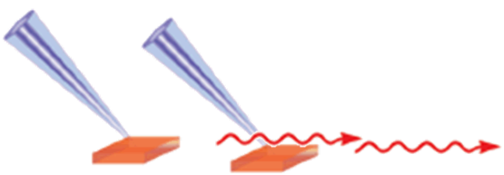


*Izumi (LLNL) et al.

High energy, single line-of-sight gated cameras are needed for face-on point-projection radiography on NIF

Backlighter

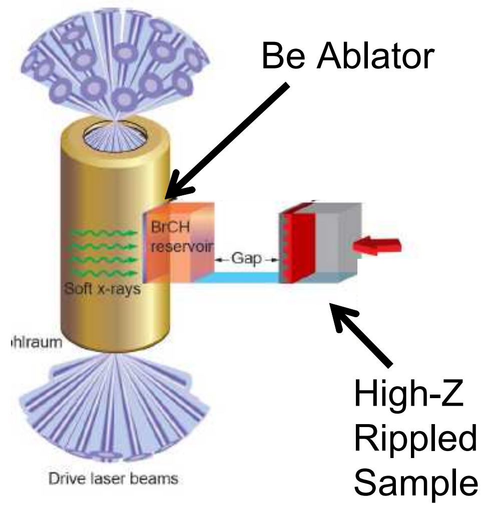
Short-pulse Laser beams

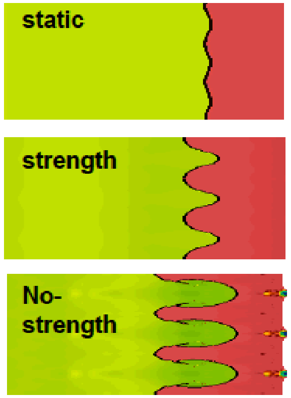


17-40 keV X-rays

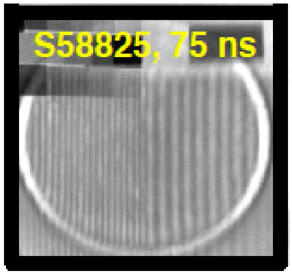
- Optimal energy depends on Z and thickness

RT Strength Platform





Face-on Radiography



Face-on radiography

Detector Requirements

- 2mm x 4mm FOV at target
- <10 um/pixel at tcc
- QE of 50% at 17-22 keV
- 2-4 frames
- 5-20 ns frame separation
- ≥2 ns gate time
- Dynamic Range > 200

Currently On NIF, Z, OMEGA ➡ Image Plate & Film

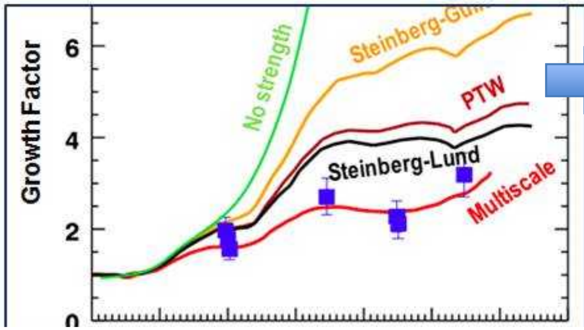
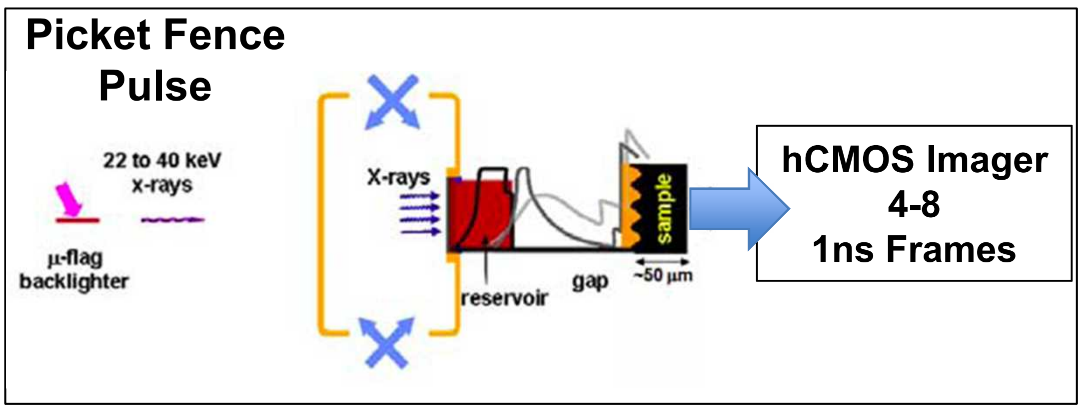


Image Plate Disadvantages

- Multiple Shots Required To Do A Time Scan
- Measurement @Single Time
- Expensive To Process
- Issue of Non-Reproducibility

Image Plate Replacement

Future On All Facilities ➡ Hybrid CMOS (hCMOS) Imager



Hybrid CMOS Capabilities

- >256x256, Buttable
- 4-8, 1ns Frames
- Several Pixel Sizes/DILATION Tube
- 3D X-ray Diode

A hCMOS image sensor can, with X-ray source development, eliminate the need for multiple shots making multiple measurements at user defined times within one shot.

GaAs diodes coupled to a Hippo-like ROIC with 50μm pixels could meet the needs for point-projection backlighting on NIF

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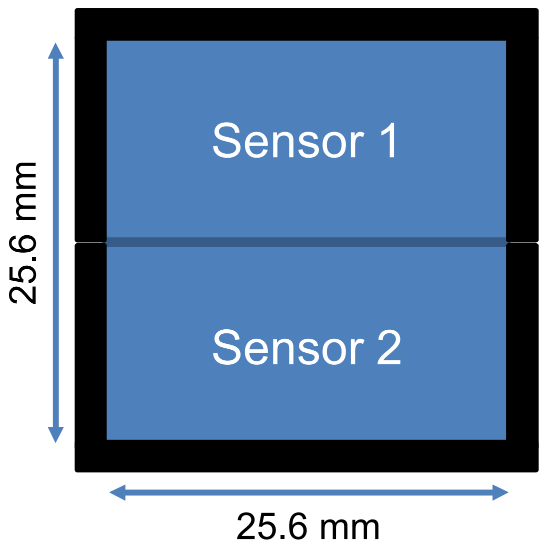
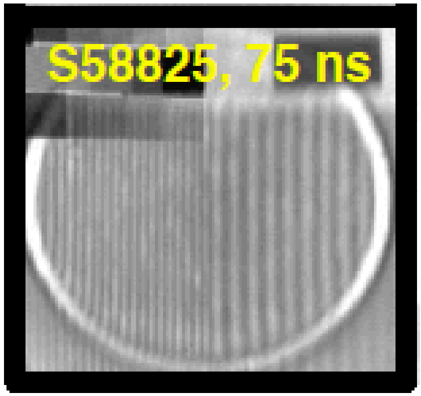




ROIC (Hippogriff like)

- 50um pixels
- 512x512 pixels with 2 tiled sensors
- 2 frames or 4,8 frames interlaced
- ~2ns per frame
- Up to 6E6 e- per pixel per frame (~1200 photons at 22 keV in GaAs)

Detector

- 50um thick GaAs
- Photo-absorption > 50% at < 24 keV
- < 1 ns response time

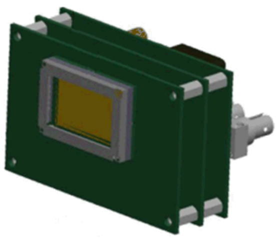
Primary Challenges

- Pixelated GaAs arrays have been built before, but maybe not at this thickness
- Defects in GaAs need to be studied to determine yield (density of good pixels)
- Handling of potentially large currents needs to be studied
- ROIC needs to be re-designed for larger pixels and for 1-side abuttment
- Speed of ROIC needs to be studied with larger pitch and higher capacitance per frame

SLOS imaging is key to the US national diagnostic strategy and will transform capability across ICF and the Science Campaigns

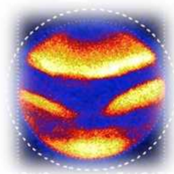
FY14	FY15	FY16	FY17	FY18		FY19
2 Fm, 1.5ns	8 Fm, 2ns (interlaced)	4 Fm, 1.5ns Low-E, e-	8 Fm, 1.5 ns (interlaced)	8 Fm, 1ns	8 Fm, 2 ns (interlaced) 20-40 keV	16 Fm, 1 ns (interlaced)

Key Direct Sensor Applications

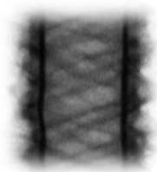


1-2 ns

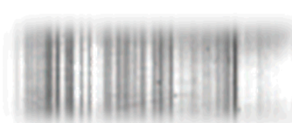
LEH imaging (Z & NIF)



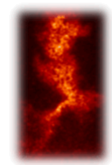
Backlighting (Z)



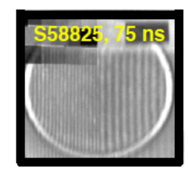
Opacity (Z)



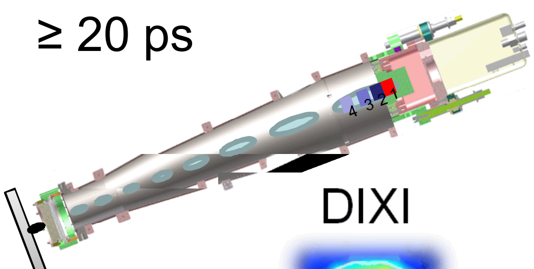
K-α Imaging (Z)



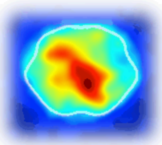
Strength (NIF)



≥ 20 ps

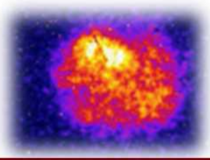


DIXI

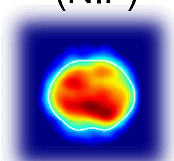


Key Pulse-Dilation Applications

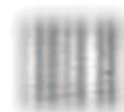
SLOS-1
Pinhole
(NIF)



SLOS-2
KB
(NIF)



SLOS-3
Spectra (Z)



Wolter (NIF)