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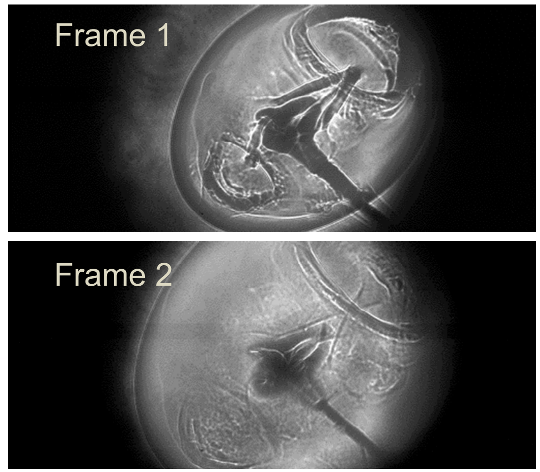

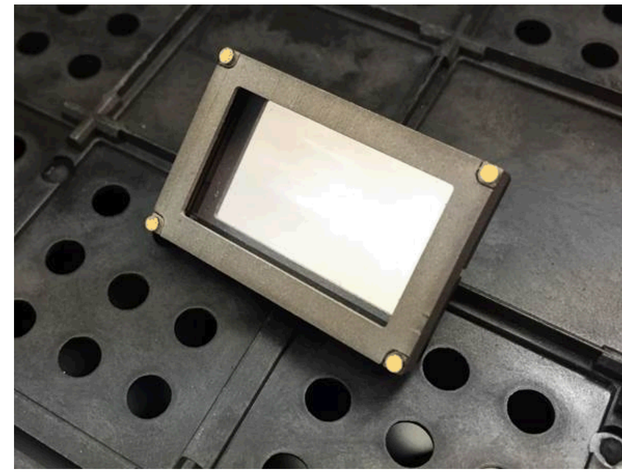

Design and characterization of an improved, 2 ns, multi-frame imager for the Ultra-Fast X-ray Imager (UXI) program at Sandia National Laboratories

August 8, 2017

L. Claus, T. England, L. Fang, G. Robertson, M. Sanchez, D. Trotter, A. Carpenter, M. Dayton, P. Patel, J.L. Porter

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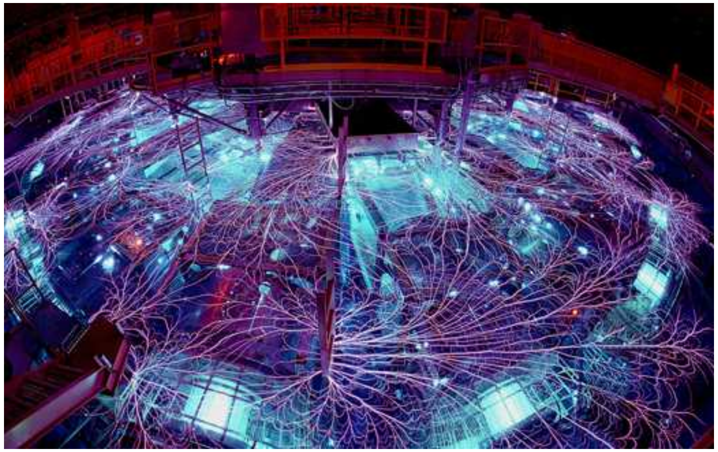
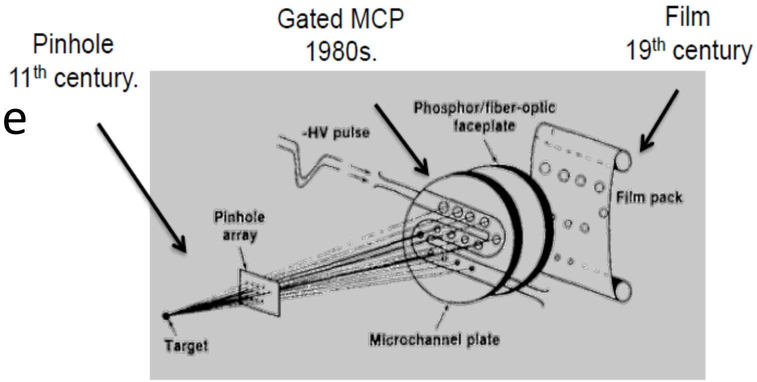
The Ultrafast X-ray Imager (UXI) program set out to develop nanosecond time-gated, multi-frame imagers for the ICF programs at Sandia and the other national ICF facilities

- X-ray imaging is a valuable diagnostic for High HEDP research
- Multi-frame, time-gated X-ray imagers produce “movies” of an experiment
- Faster frame-rate movies (temporal resolution) reduce motion blur and smaller pixels (spatial resolution) improve the image quality
  - Delivers deeper understanding of experimental results
- Existing time-gated X-ray imagers are based on microchannel plate technology developed in the 1990’s and suffer from a number of limitations
  - Moderate dynamic range
  - Gain errors
  - Difficult to calibrate



Z-machine



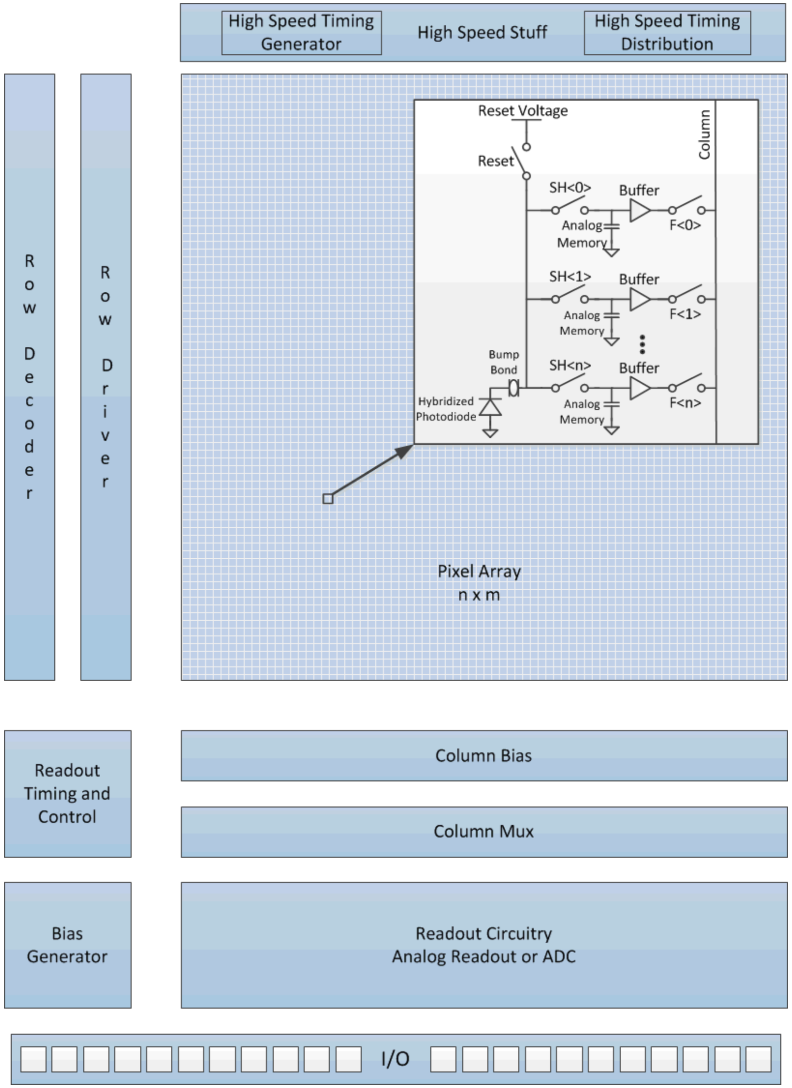
Bradley, Bell, Kilkenny et al., NOVA & OMEGA, c. 1990

Existing gated X-ray imager

Mixed Signal ASIC/SoC

UXI cameras incorporate in-pixel storage to deliver multiple frames of data in a burst mode type operation

- Multiplexes multiple pixels into one
- A transistor switch acts as an electronic “shutter” for each frame
- In pixel storage holds image data during the fast sampling operation
- High speed shutters require on-chip timing generation
- Custom circuitry is required to distribute these electronic shutters to the pixels
- Readout occurs on a slow time scale after the experiment is complete



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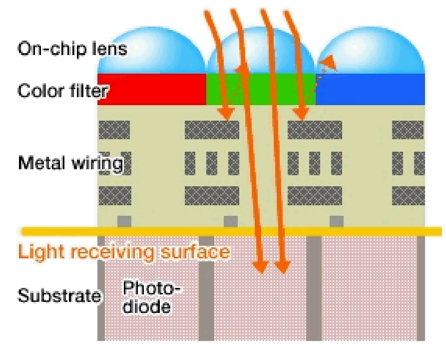
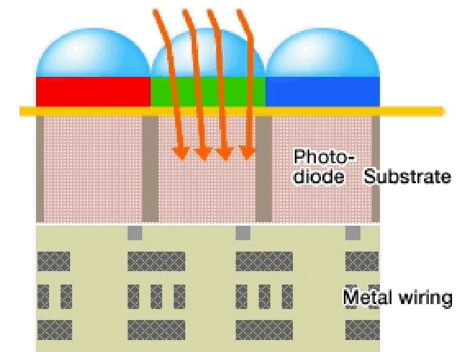
There are multiple ways to incorporate the photodetector element into a CMOS imager

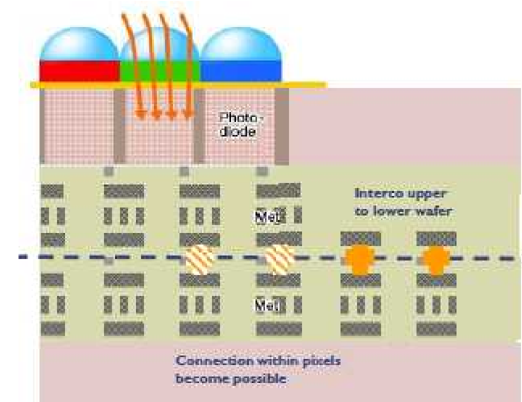
- Frontside (FSI)
  - PD integrated into the pixel silicon itself
  - Simple to build
  - Suffers from low fill factor and light absorption issues



- Backside (BSI)
  - Diode integrated into the backside substrate of the camera
  - Slightly more complicated to build
  - Significantly improved light sensitivity



- **Hybrid (hCMOS)**
  - Detector is a separate element from the camera itself
  - Most expensive to build
    - Requires a separate hybridization step
  - Allows for heterogeneous detector/ROIC pairing
  - Essentially a backside detector with respect to fill factor



A hybrid sensor enables independent optimization of the diode array & the readout electronics (ROIC)

Icarus is somewhat of a departure from the previous UXI ROICs

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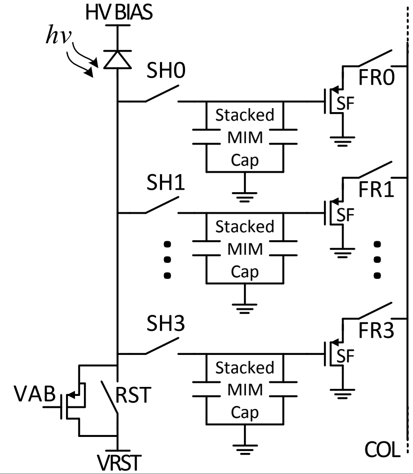
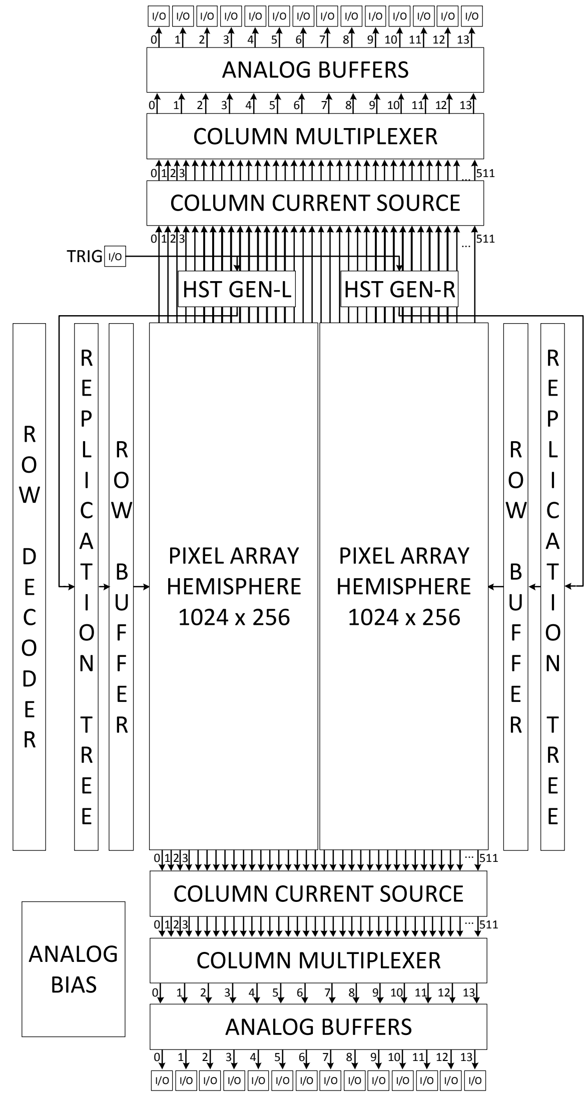
- ROIC features
  - 1024 x **512** pixels on 25 µm pitch
  - **4 frames**
  - **500 ke$^-$ full well**
  - **500 e$^-$ noise floor**
  - 60 dB (1000:1) dynamic range
  - < 2 ns integration time
  - < 2ns inter-frame time
  - **Common Cathode detector**



Icarus pixel

- Improvements/modifications on previous ROICs
  - Tunable anti-bloom transistor
  - Fully independent hemisphere timing
    - No row-wise interlacing
  - L/R hemisphere shutter timing tuning capability
  - Shorted intermediate reptree output stages to improve R-R timing error
  - Increased HST generator user adjustability
  - Top/Bottom readout channels
  - Incorporated on chip bypass capacitors
  - CC pixel allows a more robust power distribution architecture



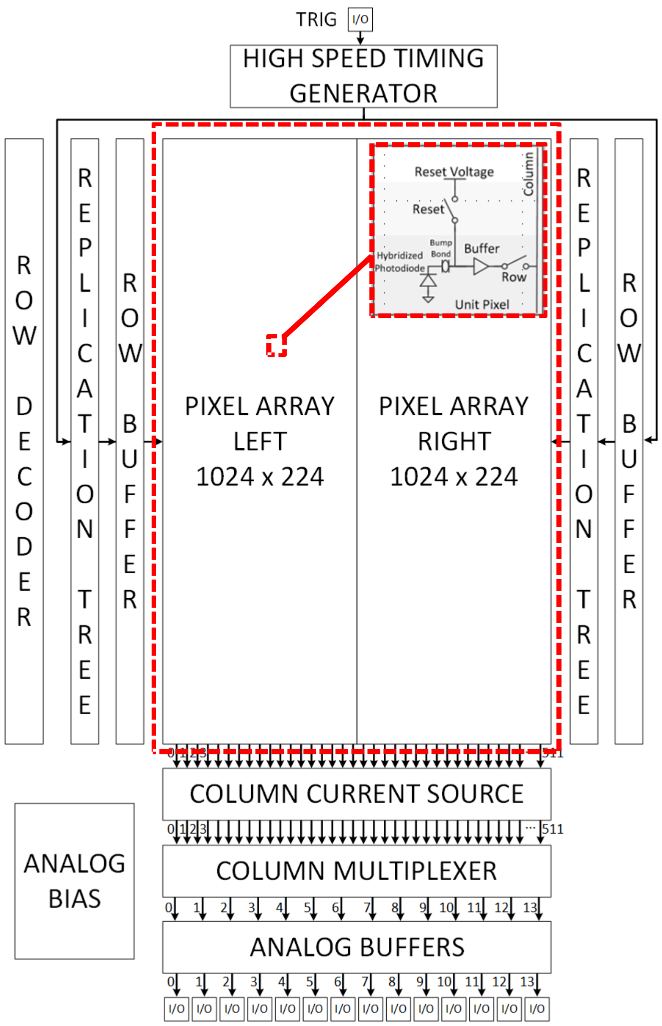
Icarus block diagram

Active array size: **12.8 mm** x 25.6 mm

Mixed Signal ASIC/SoC

UXI has maintained a consistent ROIC architectural concept with changes and improvements made from generation to generation

- 3 primary components
  1. Unit pixel/Pixel array
     - Multiple frames/shutters
     - In-situ storage
     - Fast operation



Mixed Signal ASIC/SoC

UXI has maintained a consistent ROIC architectural concept with changes and improvements made from generation to generation

- 3 primary components
  1. Unit pixel/Pixel array
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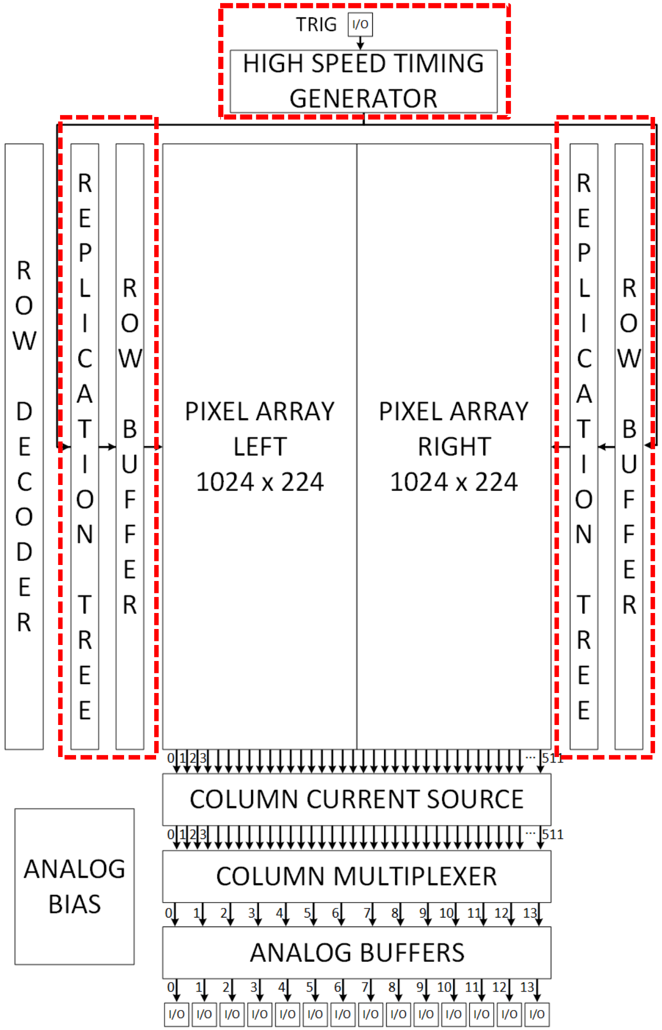
  2. Timing generator and propagation circuitry
     - Precision, low jitter oscillator
     - Programmable digital timing generator
       - **Allows different integration time and inter-frame time to be chosen for each shutter**
     - Shutter timing distribution



Mixed Signal ASIC/SoC

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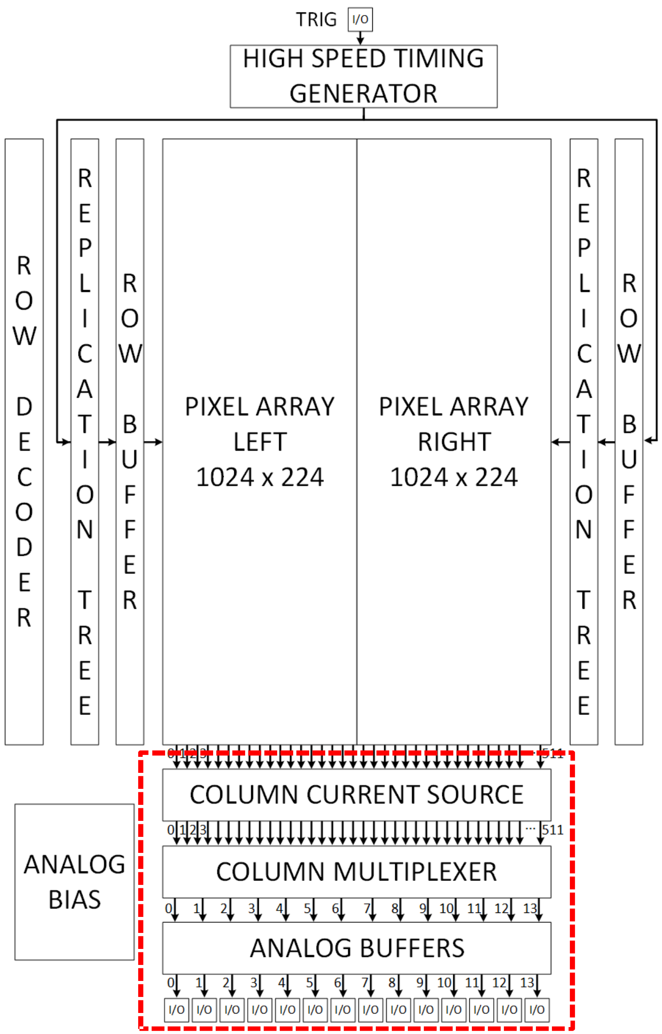
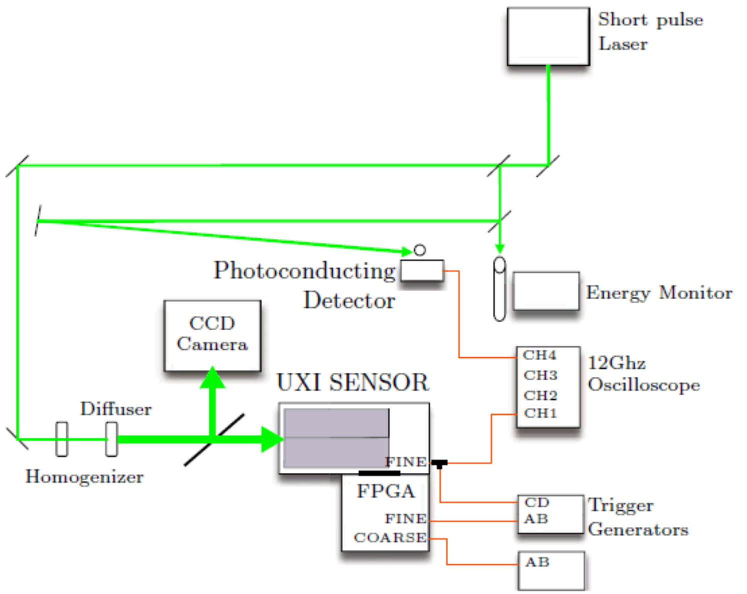
  2. Timing generator and propagation circuitry
     - Precision, low jitter oscillator
     - Programmable digital timing generator
       - **Allows different integration time and inter-frame time to be chosen for each shutter**
     - Shutter timing distribution
  3. Readout electronics
     - Readout occurs at slow speed, after the experiment
     - Simple electronics to minimize risk
     - Parallel analog readout

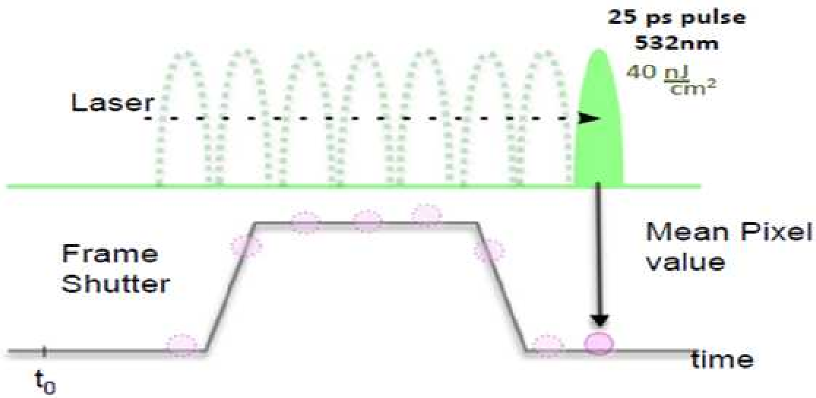


Testing occurs at LLNL and SNL

- LLNL's optical testing via 532 nm laser stimulus



- Shutter profiles are constructed by walking the laser pulse through the camera shutters



Mixed Signal ASIC/SoC

Icarus displays significantly reduction in trigger-to-pixel shutter latency over past UXI cameras

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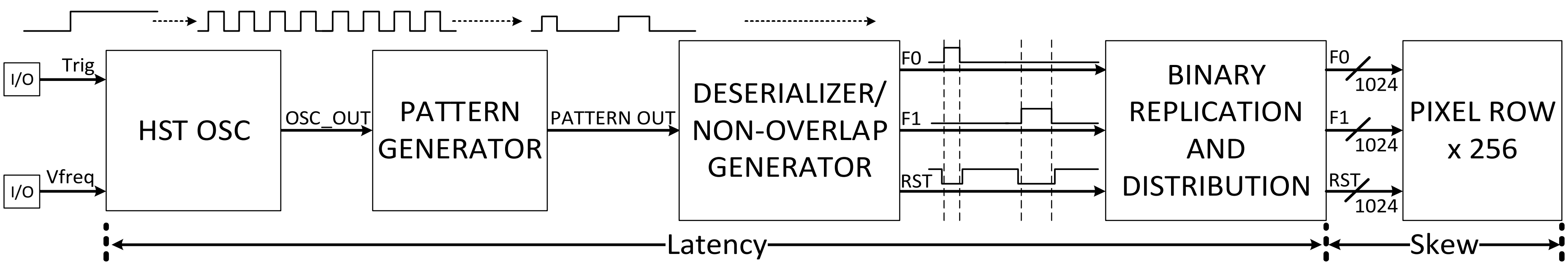
- Trigger to pixel shutter latency requires the camera to be pre-triggered prior to photons incident on the detector array
  - External asynchronous trigger initiates the device
  - There is a fixed delay from this trigger until the shutters arrive at the pixels



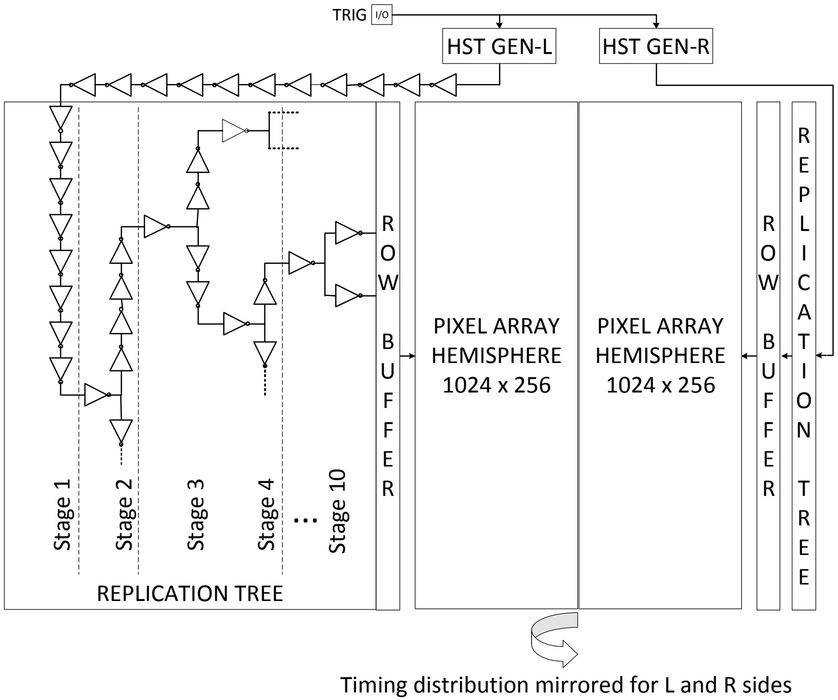
Timing path latency

Camera	Trigger-to-shutter latency	Timing propagation latency	Trigger-to-pixel latency
Furi	34 ns	48.13 ns	82.13 ns
Hippogriff	54 ns	26.6 ns	80.5 ns
Icarus	**32 ns**	**4.7 ns**	**36.7 ns**

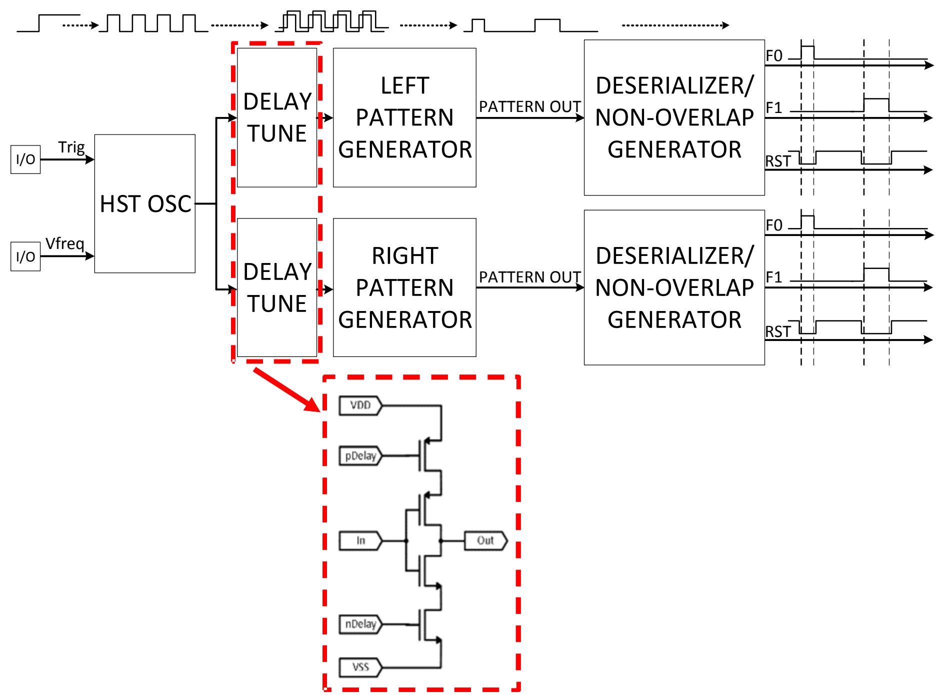
Mixed Signal ASIC/SoC

Independently timed hemispheres offers many timing possibilities including tuning out process induced timing offsets observed in past cameras

- Driving pixel rows from L/R hemispheres is needed to allow nanosecond shutters to propagate across a row
- Past imagers have shown 400-900 ps timing error between hemispheres
- Independent hemisphere control also enables hemisphere fine tuning to minimize these offsets



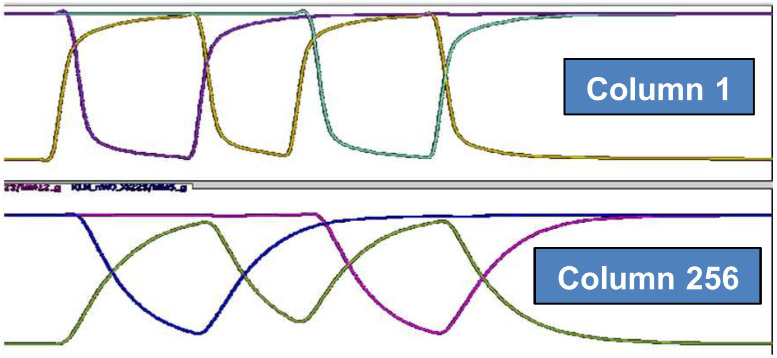
Independent hemisphere timing distribution

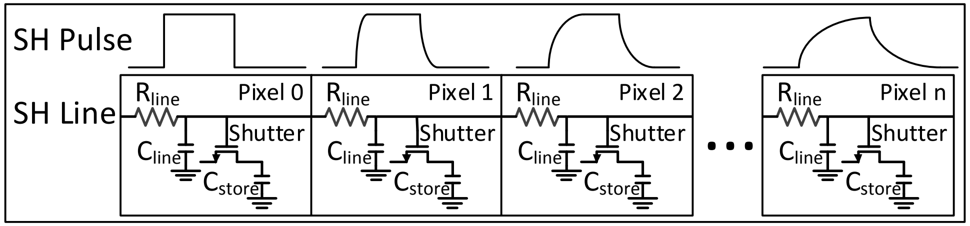


Hemisphere fine tuning elements

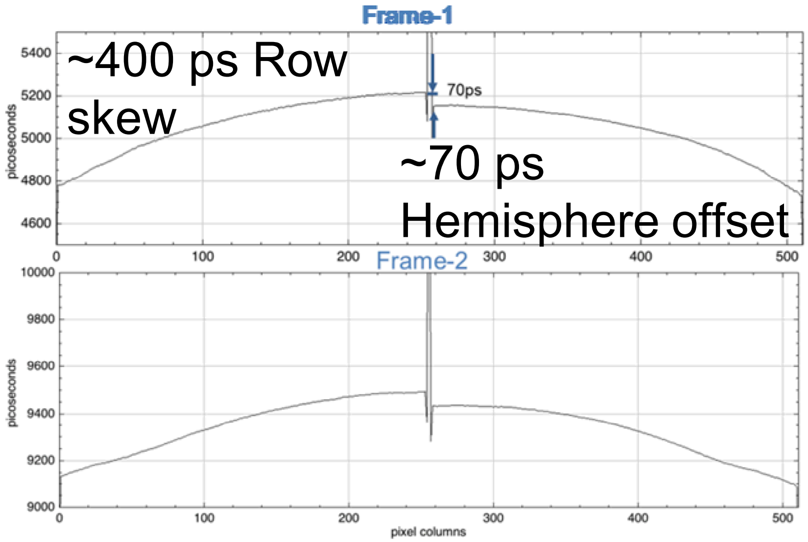
Row skew is also an issue with current UXI camera implementations

- Driving the distributed RC load of many pixels introduces a timing skew from the outermost pixel columns to the innermost pixel columns



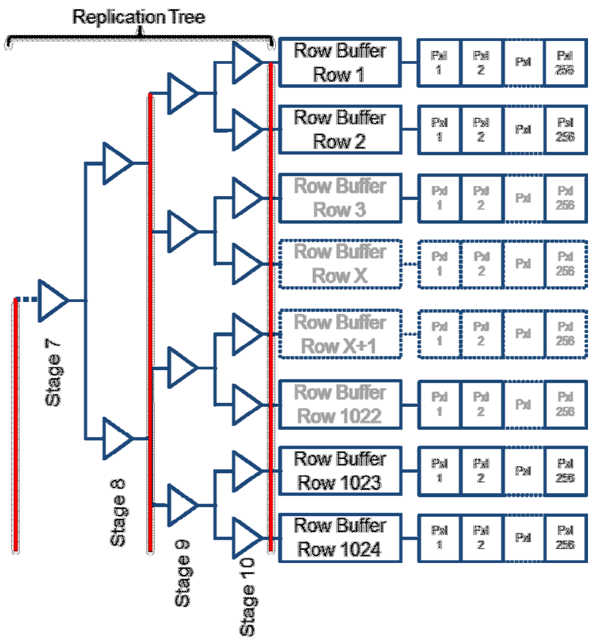


- Icarus exhibited slightly worse timing skew (400 ps) than past camera due to increasing the pixel row length from 224 to 256
  - Hemisphere offset tuned to 70 ps

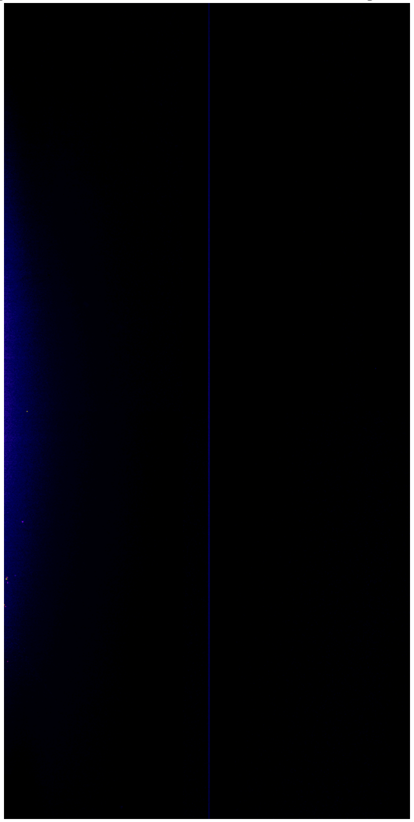


Past imagers also displayed vertical timing offsets based on the binary replication of the shutter signals

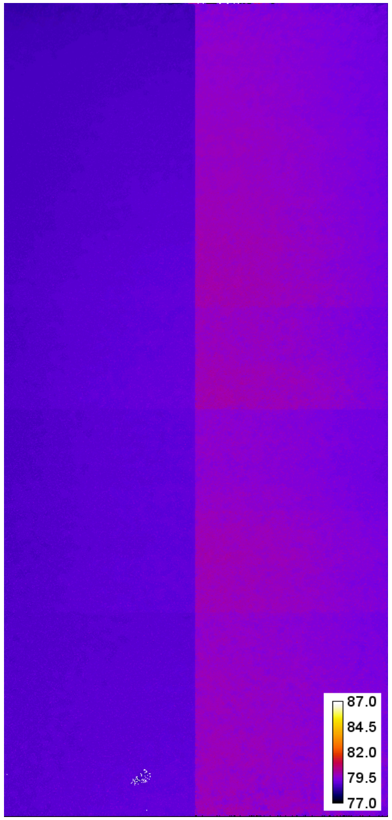
- Shorting replication tree output stages rebalances these timing signals with a slight impact to total dynamic current consumption



Replication tree shorting concept



Vertical lineout of L/R hemispheres for an Icarus sensor

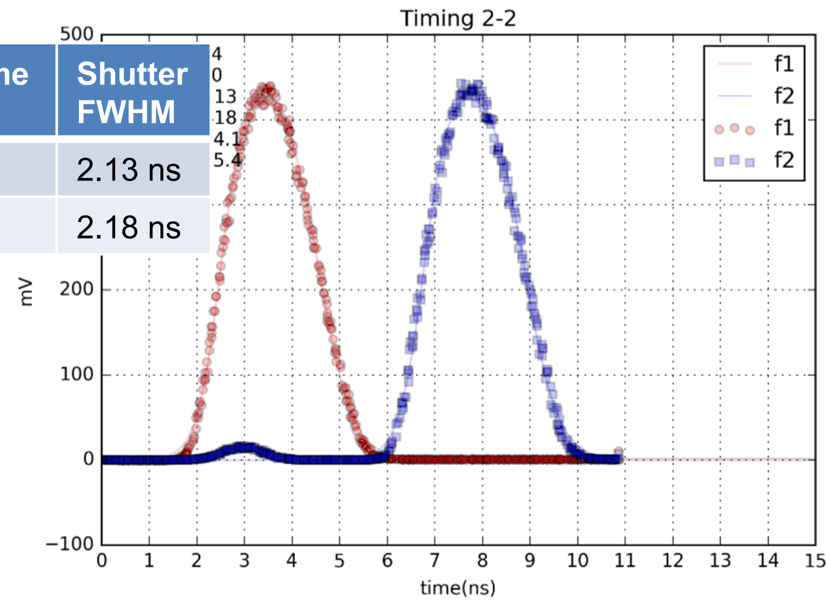


Past imager with binary striations evident

Shutter profiles are obtained by walking a laser pulse through the shutters in 20 ps increments

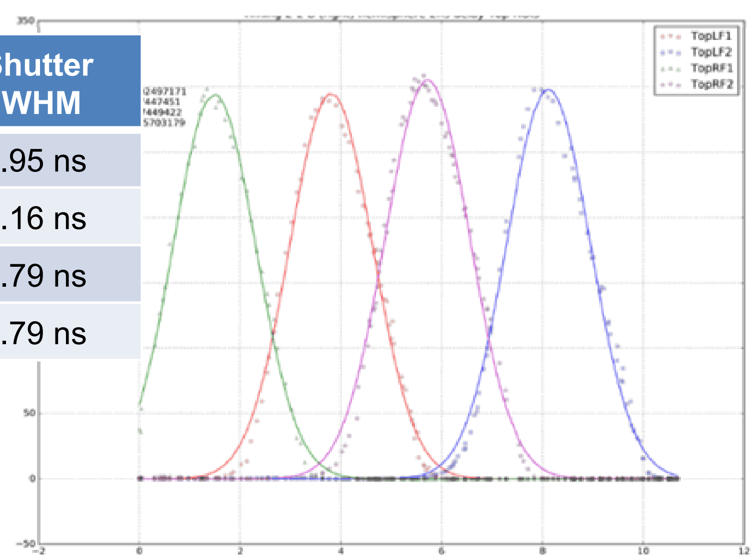
- Good timing uniformity was exhibited with the camera tuned to 2 ns integration time
  - Only 2 frames per pixel were useable due to a physical design issue discovered in the pixel

Frame	Shutter FWHM
F1	2.13 ns
F2	2.18 ns



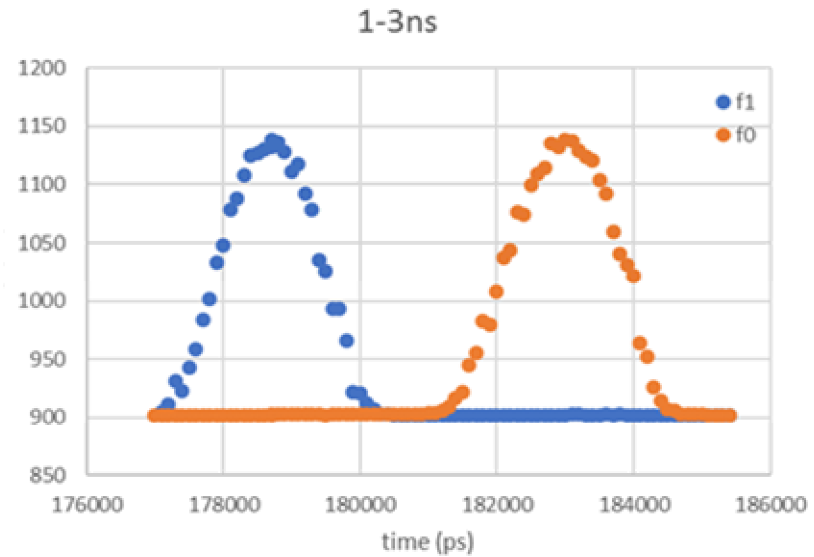
- Independent timing was utilized to configure L/R hemisphere shutters to deliver four frames of data with zero dead time

Frame	Shutter FWHM
F1_L	1.95 ns
F2_L	2.16 ns
F1_R	1.79 ns
F2_R	1.79 ns

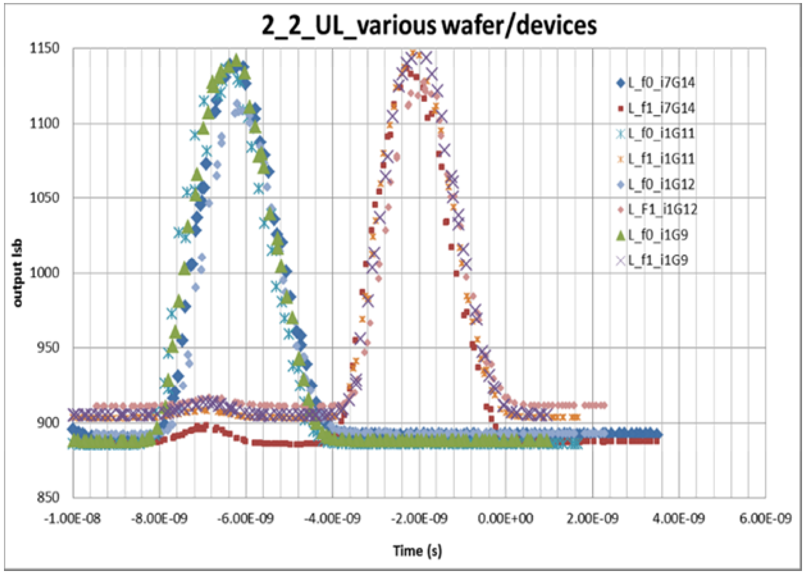


Maximum shutter speed was investigated in addition to repeatability across multiple sensors

- 1-3 timing yielded fastest achievable integration time of 1.7 ns
  - 1-1 timing did not perform at speed
    - Reset signal failed to propagate

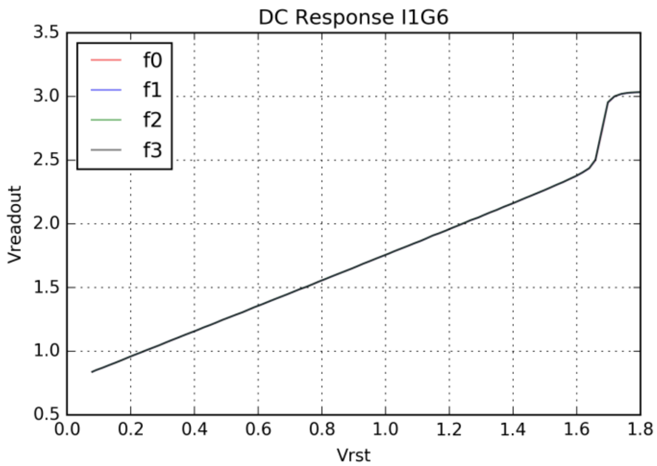


- 4 sensors across 2 wafers were tested and demonstrated repeatable performance
  - Slight offsets exist from die to die for this data set
  - Offsets are removed by subtracting camera specific dark background images

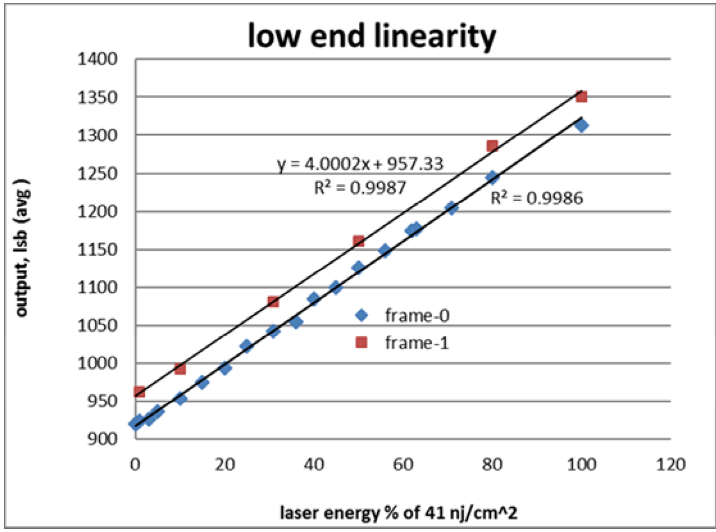


Readout linearity was examined by stimulating the camera both electrically and optically

- A DC readout transfer function was obtained by driving an external electrical stimulus into the pixel array
  - Full readout dynamic was observed with this method

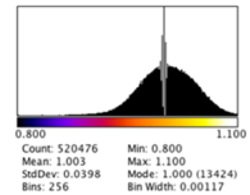


- Optical stimulus was also used to examine low signal linearity
  - Slight frame-to-frame offsets exist but are removed with background subtraction
  - Test source limitations prevented full well scale illumination
  - Slight non-linearity observed at low end of DR

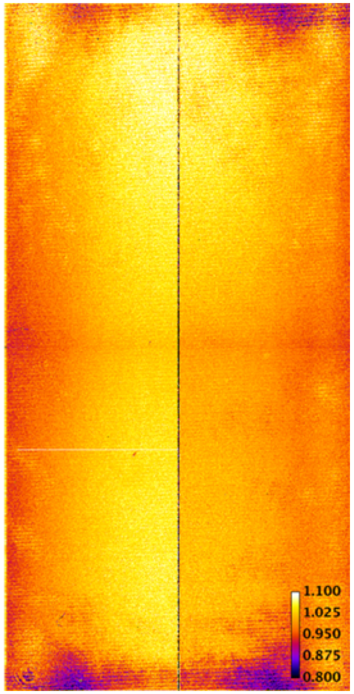


Frame to frame isolation and read noise were investigated

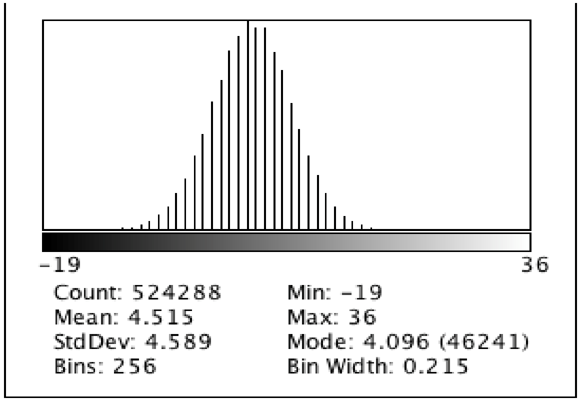
- Sensor was illuminated in one frame and the dark frame response was measured
  - Amplitude of Bright frame was ~½ full well
  - Dark frame observed 1 LSB coupling



< 1LSB
F-F error

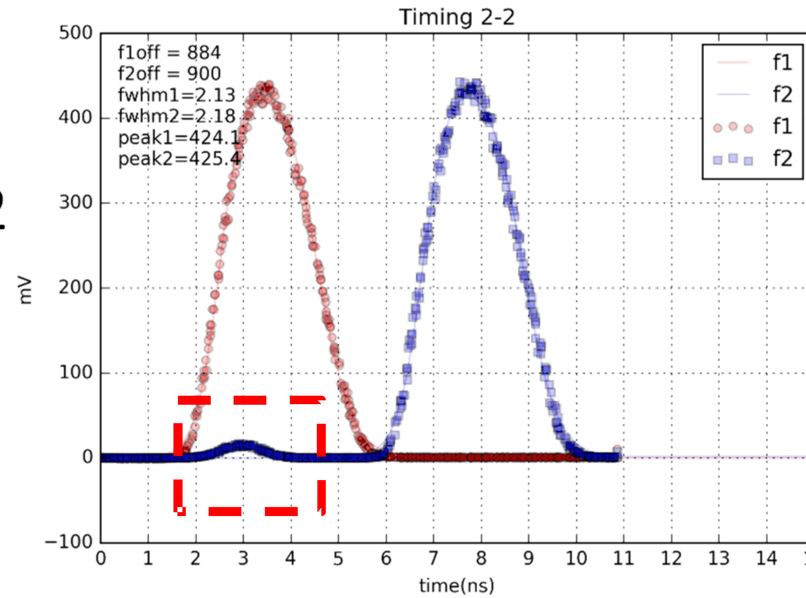


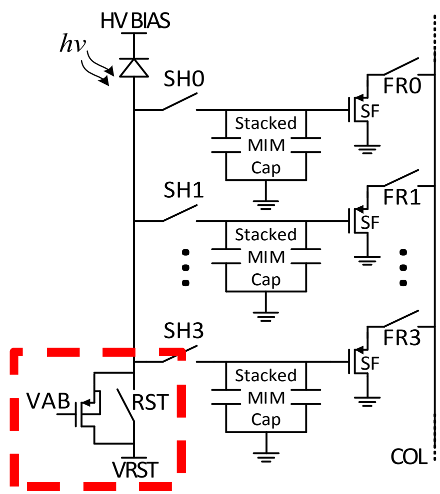
- Read noise was investigated with a high resolution ADC on an LLNL designed system board and measured to be 1/3 LSB or 178 e^-

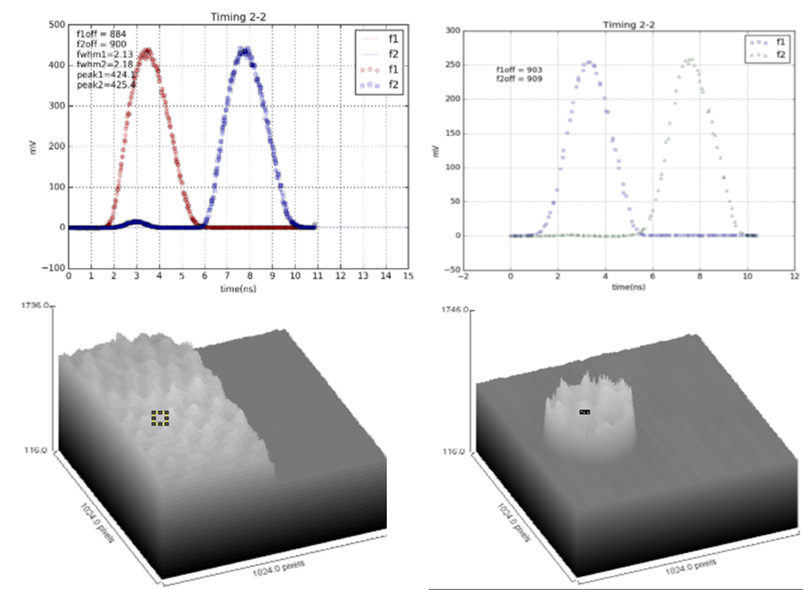


Total array Illumination introduced some non-ideal response

- It was observed that a secondary, minor peak would occur in frame 2 when frame 1 is illuminated
  - This effect was correlated with total detector array area exposed to photocurrent
  - Reducing total array exposure minimizes this issue
  - This implies a global return supply (VRST) voltage droop



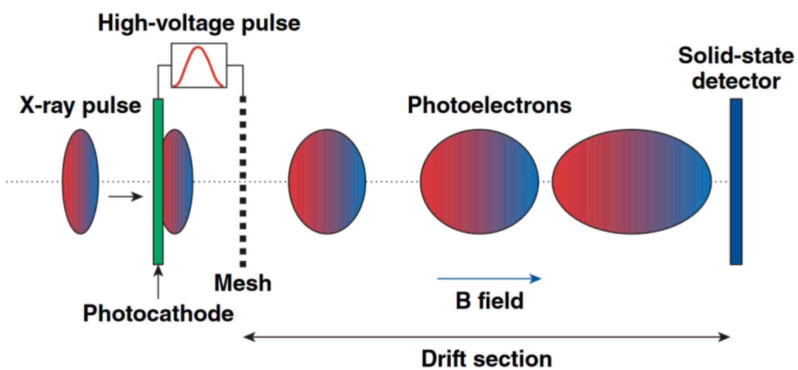




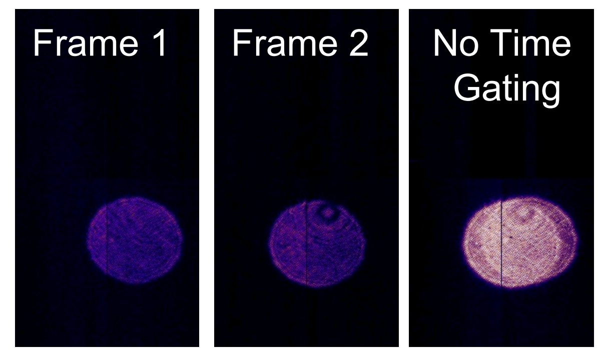
Mixed Signal ASIC/SoC

An Icarus camera, fielded in SLOS-TRXI will serve as the back end detector for a 20 ps, 2D diagnostic

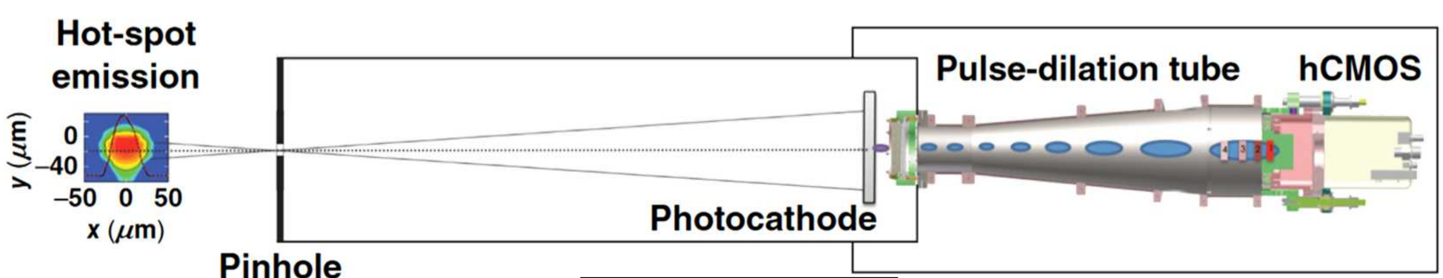
- General Atomics pulse-dilation technology fielded at Omega
  - Tele-temporal lens temporally magnifies an input signal
  - Yields multiple image frames with **20 ps** time gates
- Will capture time-resolved images of hot-spot self-emission



Pulse-dilation concept



20 ps, time-gated images taken in SLOS



SLOS-TRXI schematic

Mixed Signal ASIC/SoC

The Sandia hybrid CMOS (hCMOS) effort has delivered burst mode imagers enabling multiple new diagnostics for HED/ICF science

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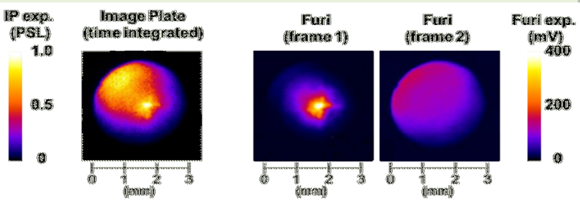
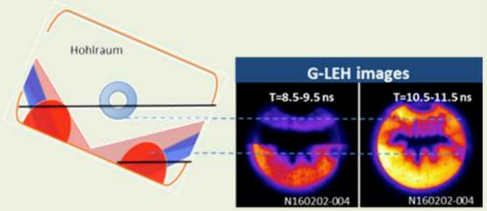
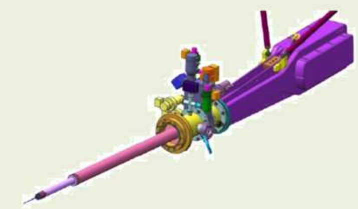
IN USE

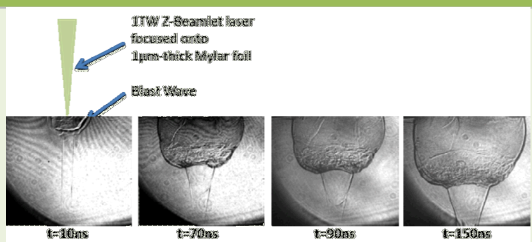


Z-Machine Gas Cell Shadowgraphs

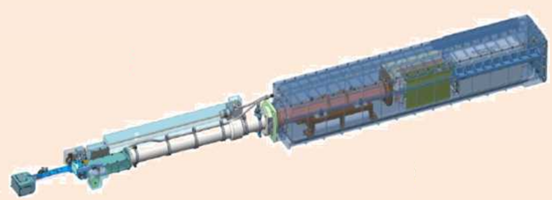


NIF Gated Laser Entry Hole (G-LEH) Diagnostic

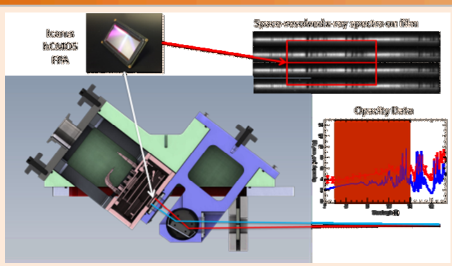

LLE OMEGA SLOS1-TRXI Diagnostic



Z-Machine Target Chamber Blast Wave Propagation


NIF SLOS1-CBI Diagnostic

IN DEV.



Z-Machine Spectrometer

Z-Machine	NIF	OMEGA

Mixed Signal ASIC/SoC

New diagnostics are being enabled by the realization of hCMOS imagers

Icarus delivered significant improvements over past UXI imagers

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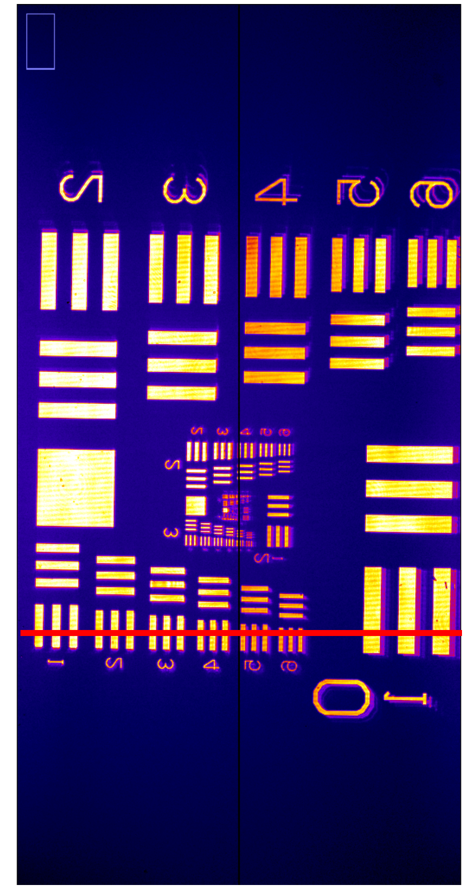
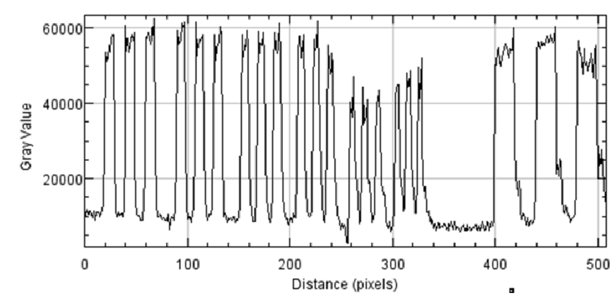
- Fine, 25 µm spatial resolution
- < 1 LSB frame to frame coupling
- < 1 LSB read noise
- Tunable hemisphere offsets
- Repeatable 2 ns shutter profiles
- 1.7 ns minimum integration time



- Extensive testing has also identified some items for future design to improve
  - Illumination induced rail span issues
  - Faster integration time
  - 4 frames per pixel design issue



Mixed Signal ASIC/SoC

Thanks to the many individuals who have helped make Icarus a successful camera deployed across the ICF complex

- SNL
  - Marcos Sanchez, Troy England, Andrew Montoya, Brandon Mitchell, Lu Fang, John Stahoviak, John Porter, Greg Rochau, Doug Trotter, Quinn Looker, Gideon Robertson, Tom Gurrieri, Sean Pearson, Jason Michnovicz
- LLNL
  - Arthur Carpenter, Matthew Dayton, Pratik Patel
- GA
  - Terry Hilsabeck, Kyle Engelhorn
- LLE
  - Wolfgang Theobald

Questions?

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