SAND2016-8551C

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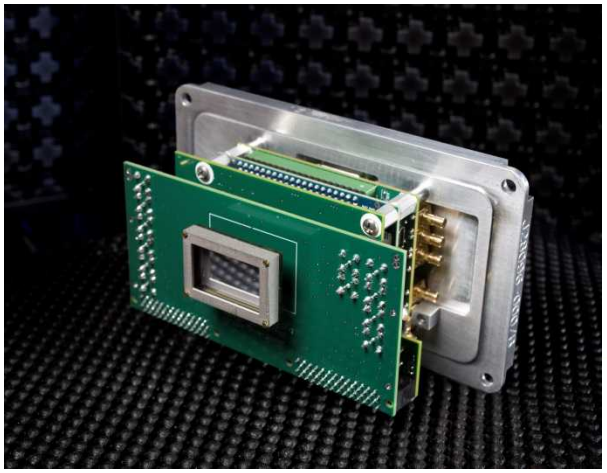

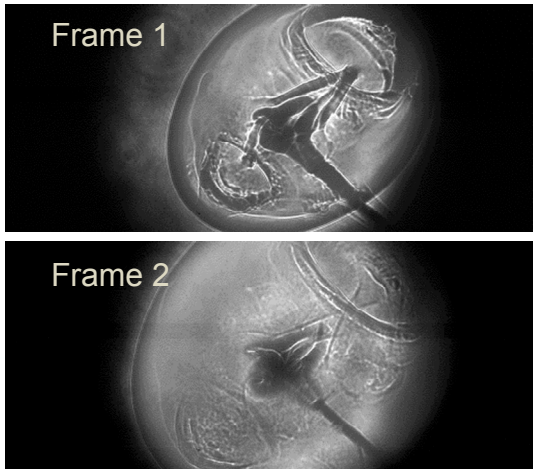

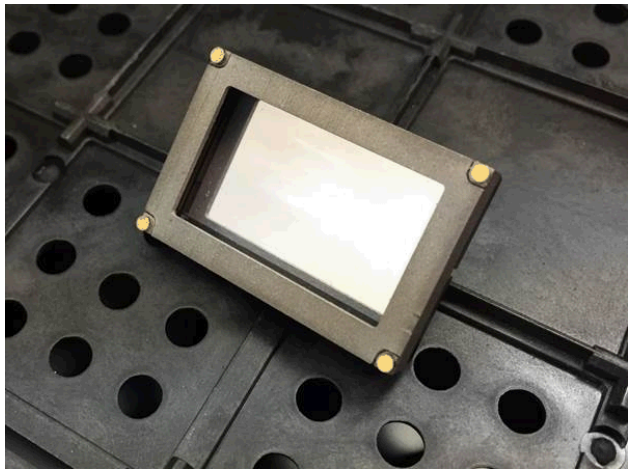

Initial characterization results of a 1024 x 448, 25 µm, multi-frame camera with 2 ns integration time for the Ultra-Fast X-ray Imager (UXI) program at Sandia National Laboratories

June 29, 2016

L. Claus, G. Robertson, L. Fang, R. Kay, M. Kimmel, M. Sanchez, J. Stahoviak, D. Trotter, J.L. Porter

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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A fast, time-gated, multi-frame, hCMOS camera can offer significant benefits to HEDP diagnostics

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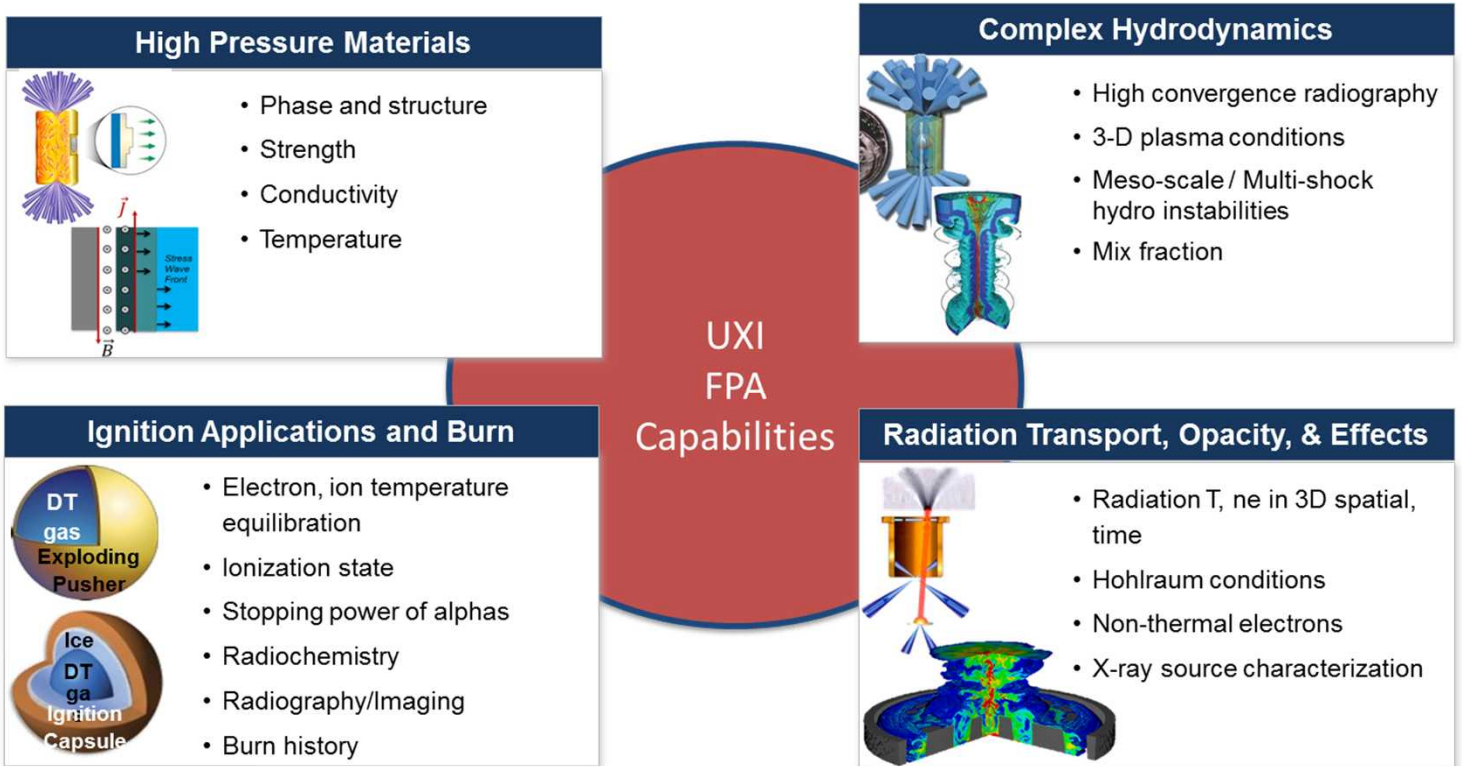
- hCMOS imagers can achieve ns level time-gating via electronic shutters
  - Multiple image frames deliver temporal history of experiments
  - Can yield improved SNR by gating out background radiation
  - CMOS scalability provides large detector area and high spatial resolution



A fast, multi-frame imager offers significant potential in HEDP research

The UXI program has pursued the 3 key technologies required for an hCMOS imager

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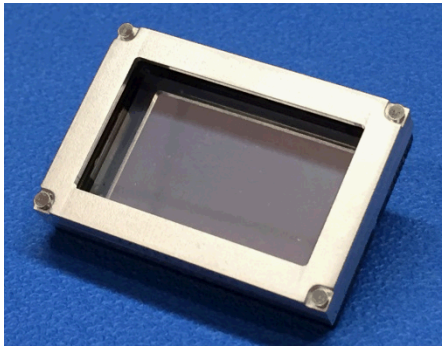
Read-Out Integrated Circuit (ROIC)

Under the UXI program, SNL has developed a portfolio of ROICs demonstrating incremental improvements and features

- 25 µm spatial resolution
- 448-512 x 1024 format
- ~ 2 ns integration time
- 2-4 frames native, 8 frames interlaced
- 500 k - 1.5 M e^- full well



Hippogriff in SOP package w/ 25 µm Si photodiodes

Detectors

Under the UXI program, SNL has developed a number of silicon detector variants:

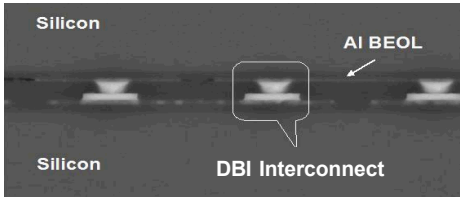
- **25 µm thick** –Vehicle for 4.7-6.1 keV X-ray, energetic electron, and visible light detectors
- **100 µm** thick – Possibly useful for up to 13 keV X-ray detection (Absorption 30% @ 13 keV)

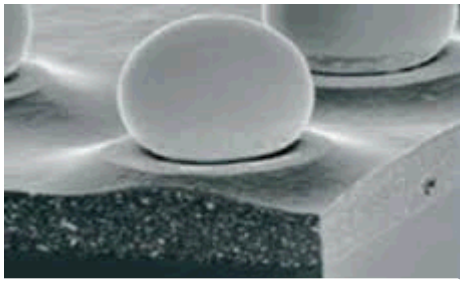
Hybridization

Indium and Direct Bond Interface (DBI) are both options:

- DBI is licensed by SNL and in development in-house
- DBI off-site at Novati
- Indium available in house

Oxide-to-oxide "Direct Bond Interface"





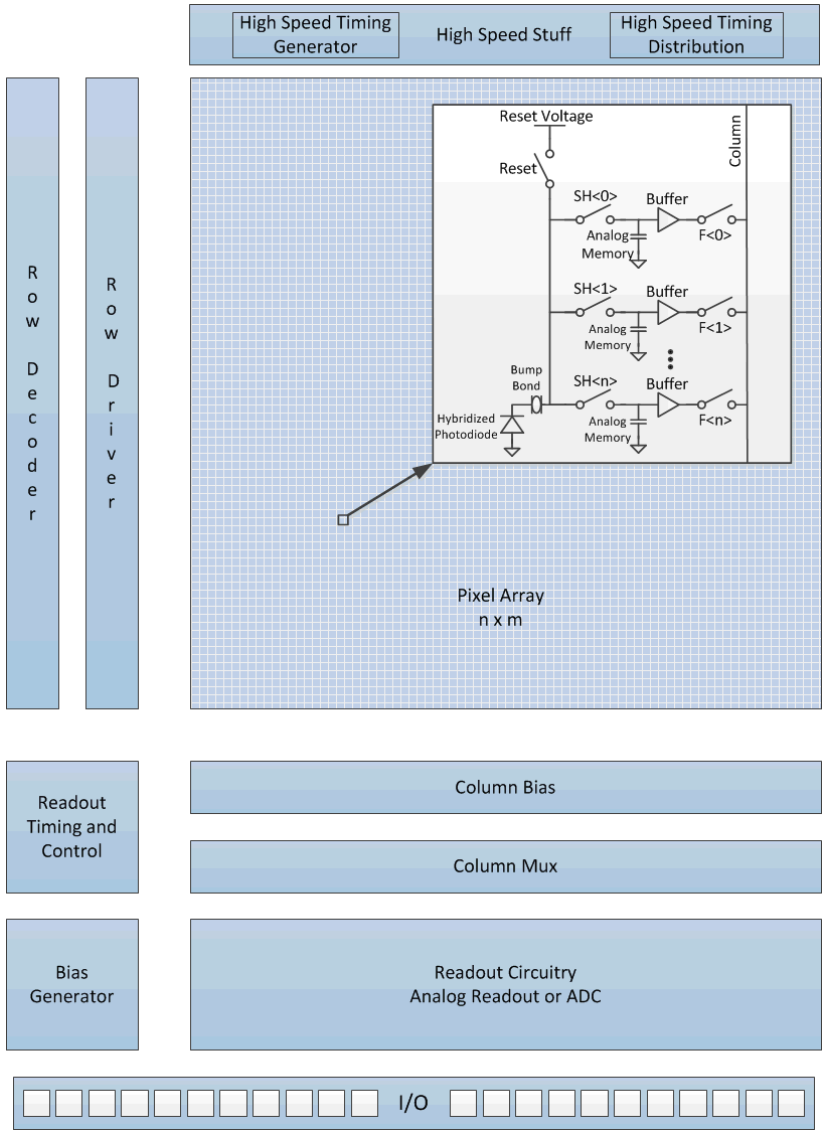
Indium Bump

Mixed Signal ASIC/SoC

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

An hCMOS framing camera adds in-pixel storage to deliver multiple “frames” of data

- Multiplexes multiple pixels into one
- Transistor switch acts as an electronic “shutter”
- In pixel storage holds image data during fast sampling operation
- High speed shutters require on-chip timing generation
- Custom circuitry distributes these electronic shutters to the pixels



Mixed Signal ASIC/SoC

UXI Programmatic Goals

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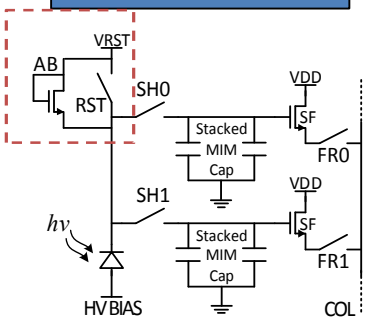
Specification	Goal	Furi	Hippogriff
Spatial resolution	25 um	✓	✓
Sensitive to visible and X-rays	<10 keV	✓	✓
Sensor format	Multiple-cm's	✓	✓
Trigger insertion delay	Few 10's of ns	✓	✓
Radiation Tolerant	Function in ICF facilities	✓	✓
Form factor	Small	✓	✓
Dynamic range	1000:1	✓	TBD
Integration time	1 ns	1.5-2ns	1.5-2ns
Timing uniformity	100 ps or better	900ps	400ps
Number of frames	8 or more	2	✓

Hippogriff is an iteration of Furi* leveraging as much IP as possible while adding interlacing functionality

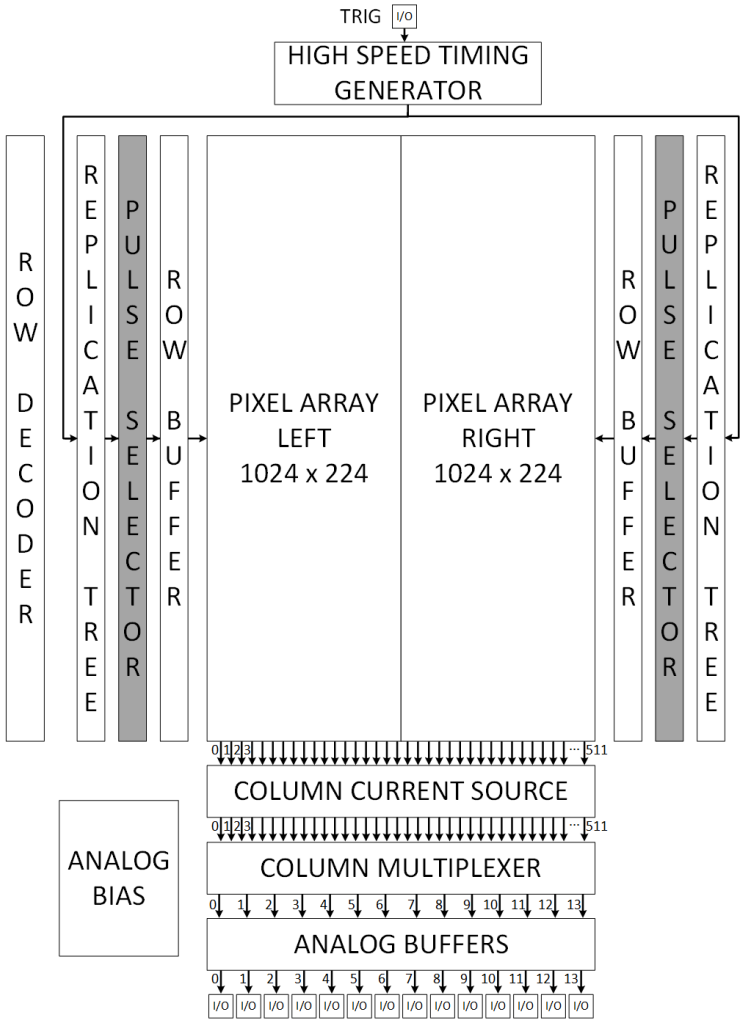
- ROIC features
  - 1024 x 448 pixels on 25 µm pitch
  - 2 frames native
  - < 2 ns integration time
  - < 2ns inter-frame time
  - 60 dB dynamic range
  - 1.5 M e- full well
  - 1500 e- noise floor
  - Common anode detector

Hippogriff Pixel



- Improvements/modifications from Furi
  - Added interlacing capability to trade spatial resolution for number of frames
    - Up to 4 rows/8 frames
  - Improve predicted hemisphere timing offsets
  - Integrated anti-bloom transistor in pixel

Hippogriff Block Diagram



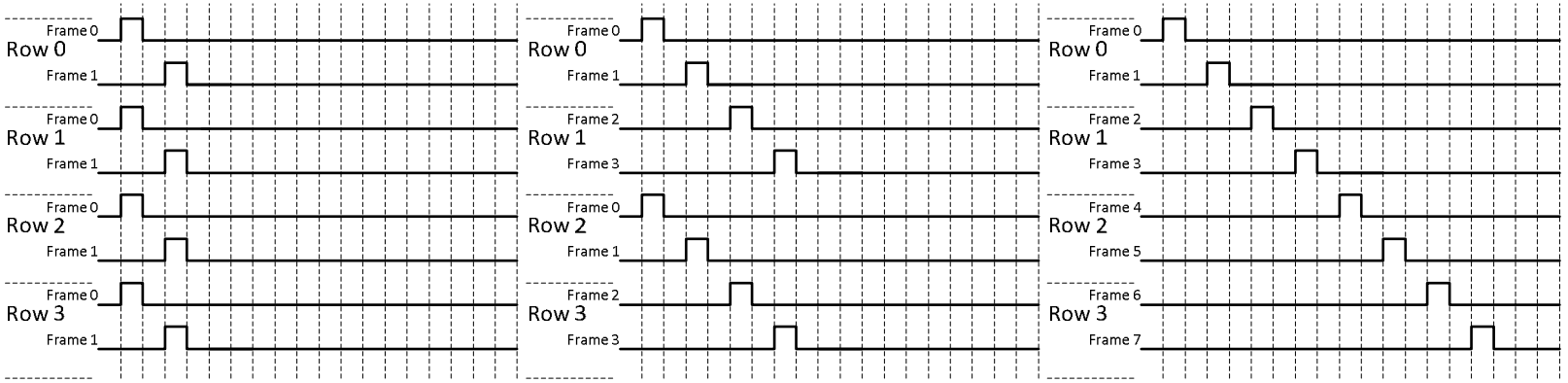
Active array size: 11.2 mm x 25.6 mm

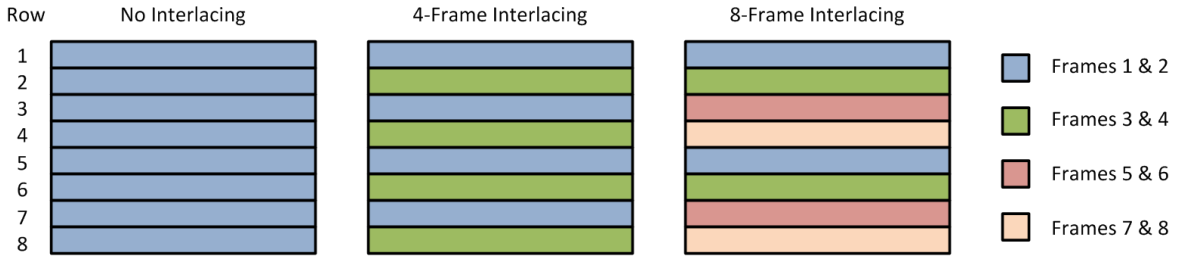
Mixed Signal ASIC/SoC

*Claus, L., et. al., "An overview of the Ultra-Fast X-ray Imager (UXI) program at Sandia Labs," Proc. SPIE **9591**, 95910 (2015).

Hippogriff was designed to explore adding more frames at relatively low design cost and time

- Hippogriff implements 3 timing configuration modes



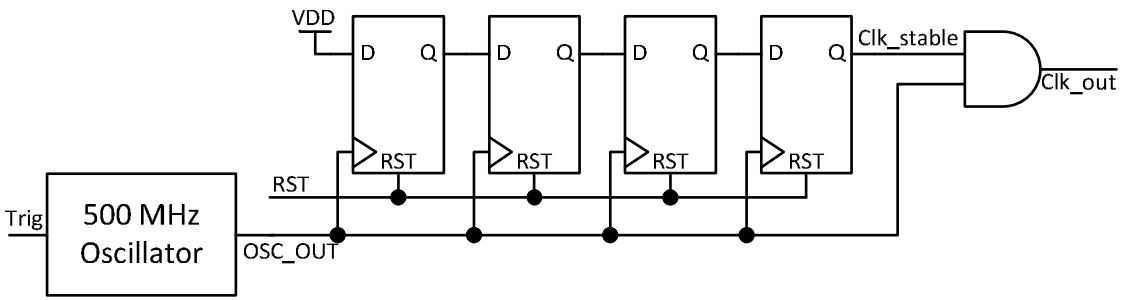


# Frames	Frame Resolution
2	1024 x 448
4	512 x 448
8	256 x 448

Mixed Signal ASIC/SoC

Clock hold-off circuitry improves shutter fidelity

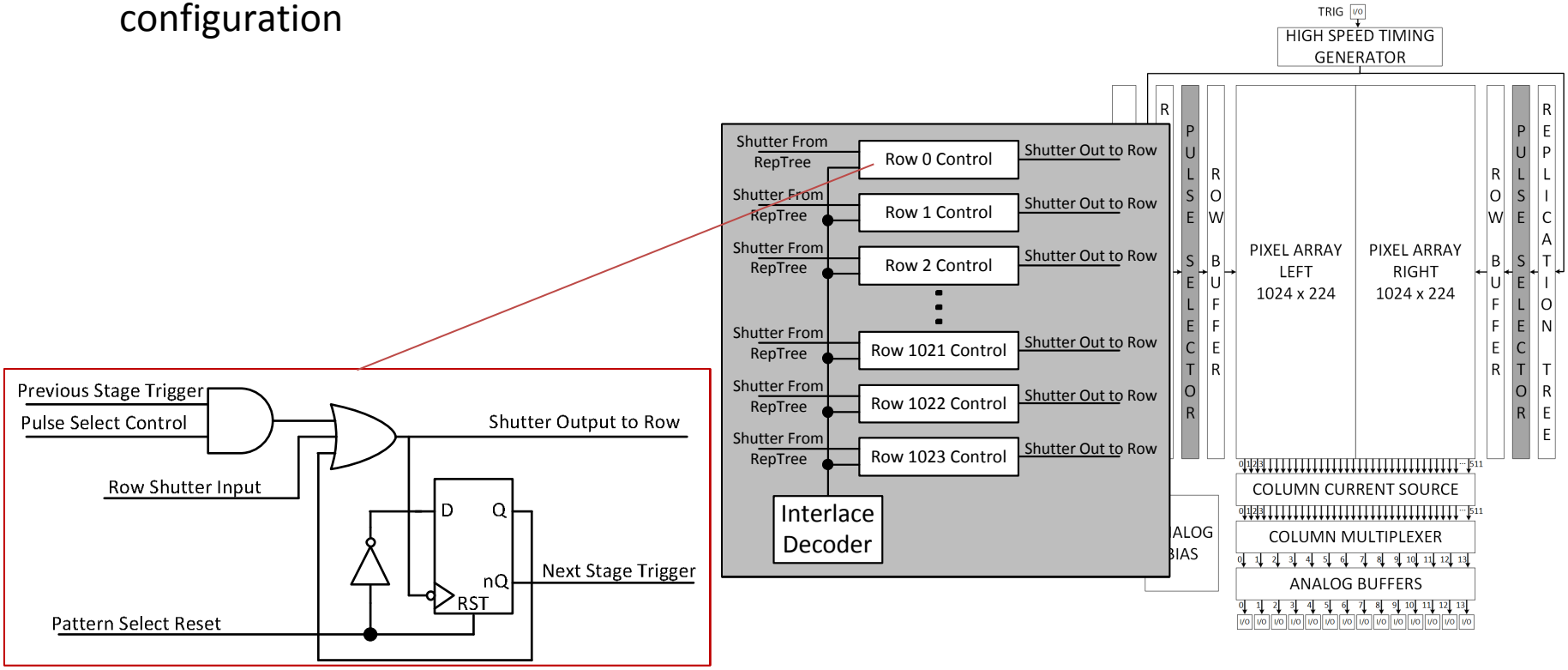
- Concern that the first 2 oscillator pulses would be non-50% duty cycle on Furi due to startup bias conditions
- Timing generator requires stable 50 % duty cycle operation to generate uniform shutters
- Hippogriff incorporated a “clock hold-off block”
  - Gates the first 4 clock pulses out of the oscillator from the high speed timing generator
  - Ensures oscillator has started up and is running at 50% duty cycle
  - Comes at the expense of 4 additional clock pulses in latency from trigger to shutters arriving at the array



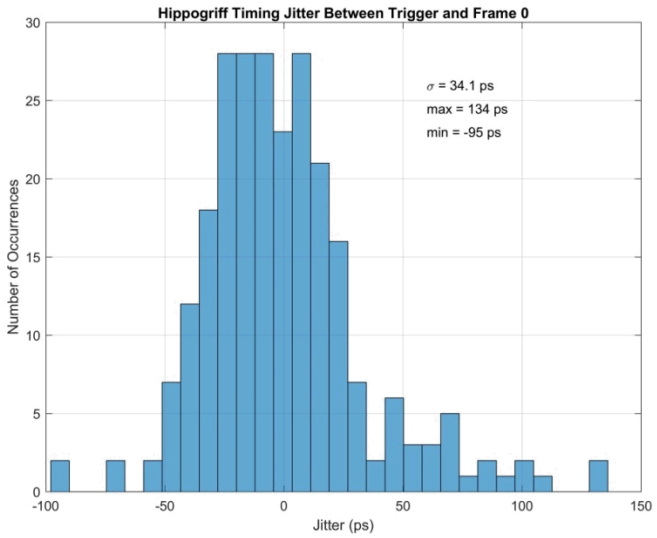
Mixed Signal
ASIC/SoC

Pulse selector block enables interlacing functionality

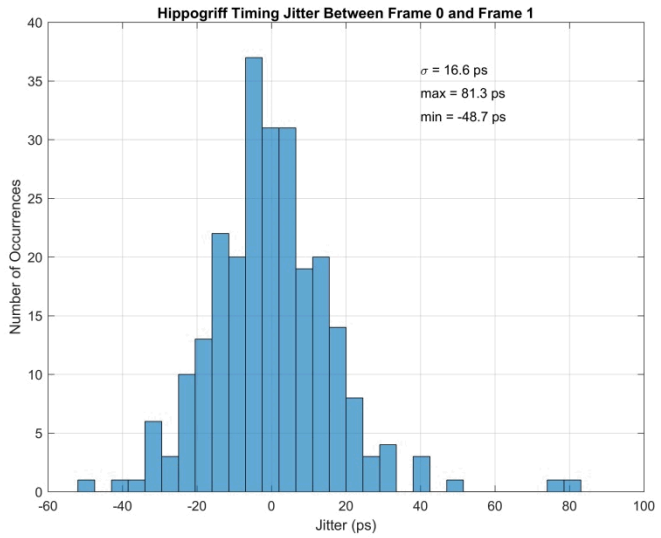
- Hippogriff architecture introduced a “Pulse Selector” block inserted between RepTree and RowBuff
  - Manages the propagation of shutter pulses based on interlacing configuration



Electrical test results demonstrate good timing fidelity

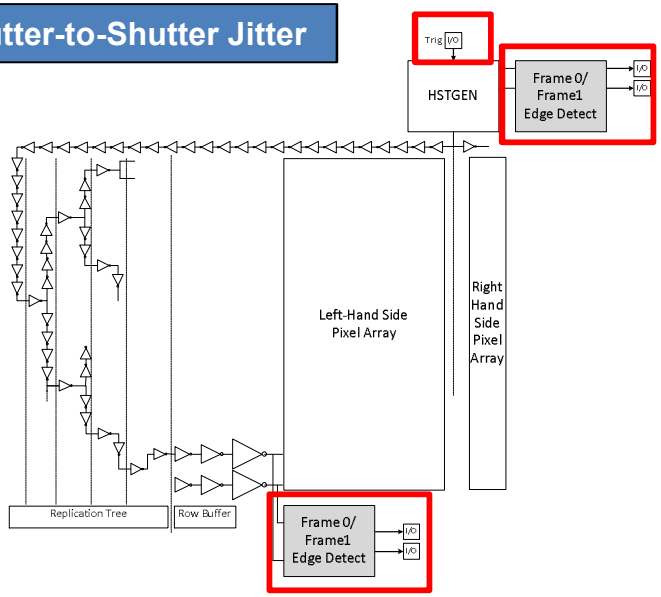


Trigger-to-Shutter Jitter



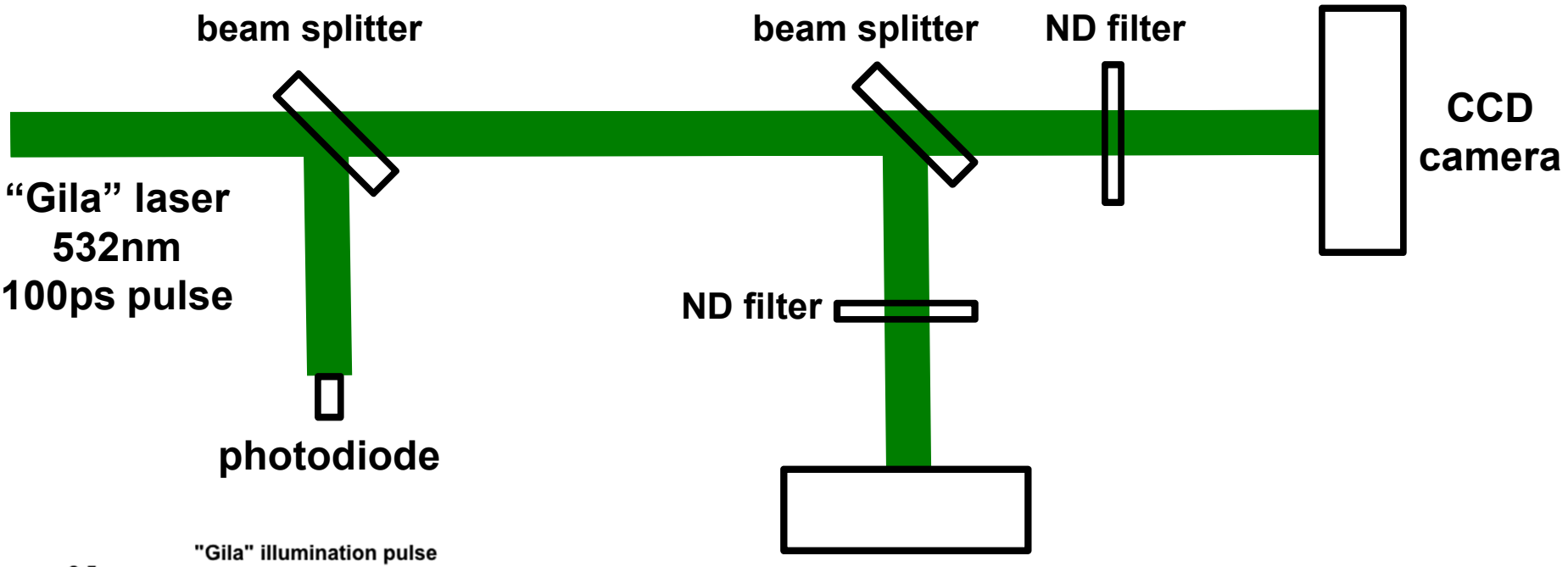
Shutter-to-Shutter Jitter

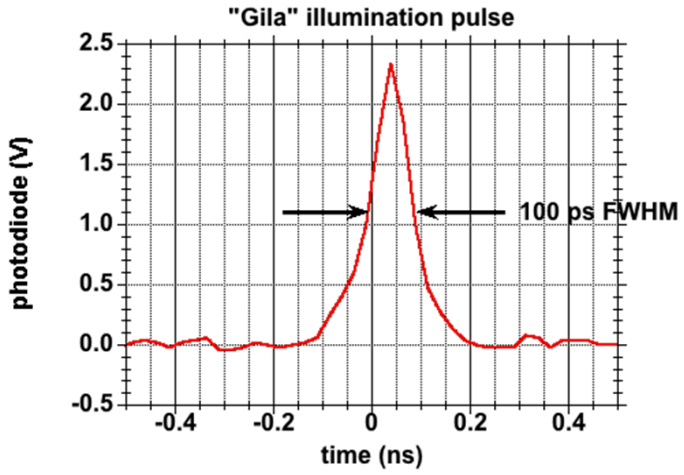
	Hippogriff	Furi
Trigger-to-shutter generation delay	53.9 ns	34.0 ns
Shutter-to-pixel array delay	26.6 ns	48.13 ns
Total insertion delay	80.5 ns	82.13 ns



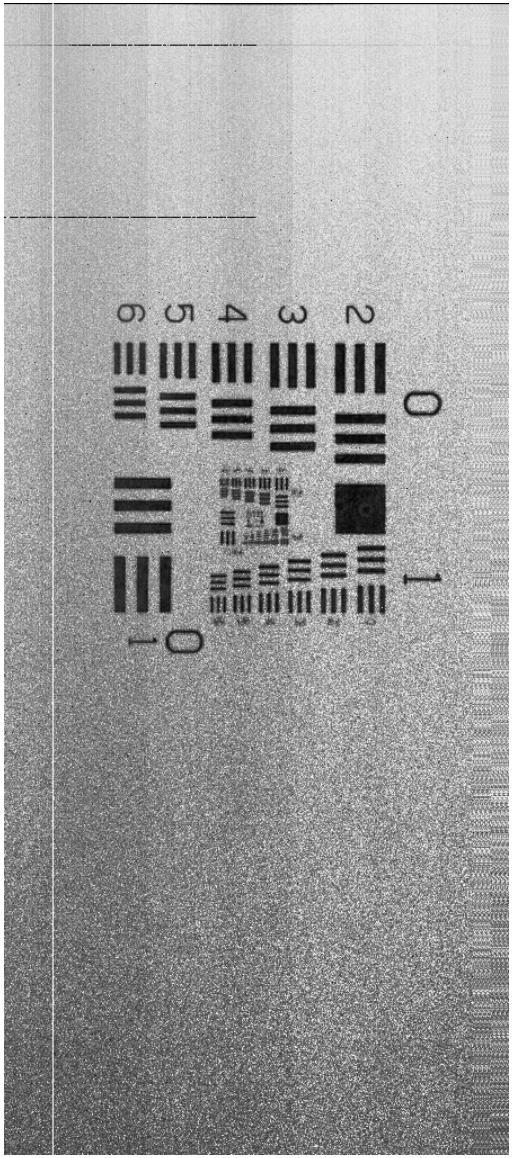
Mixed Signal ASIC/SoC

Visible illumination setup used for data collection at ZBL

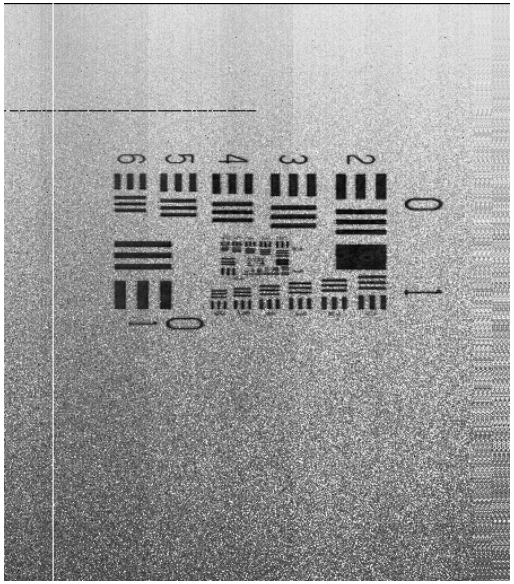




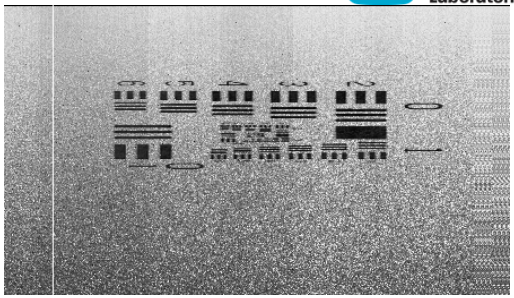
AFTP 2, 4, 8 frame comparison, 10-10 timing



2 Frame Mode, F0



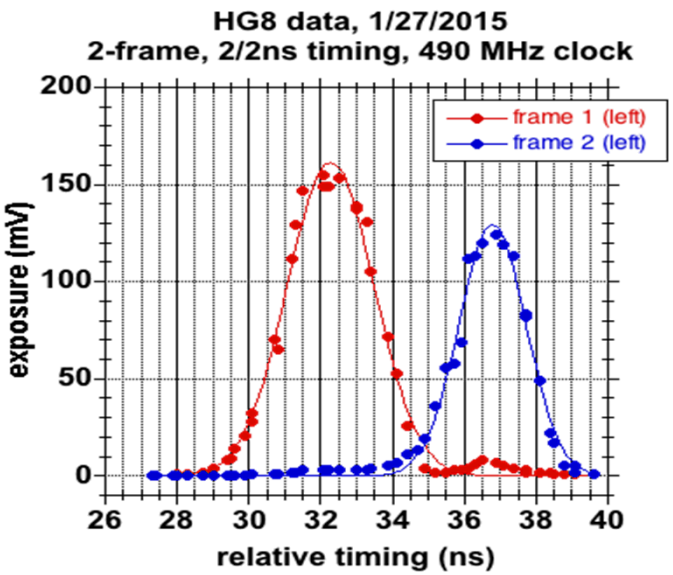
4 Frame Mode, F0

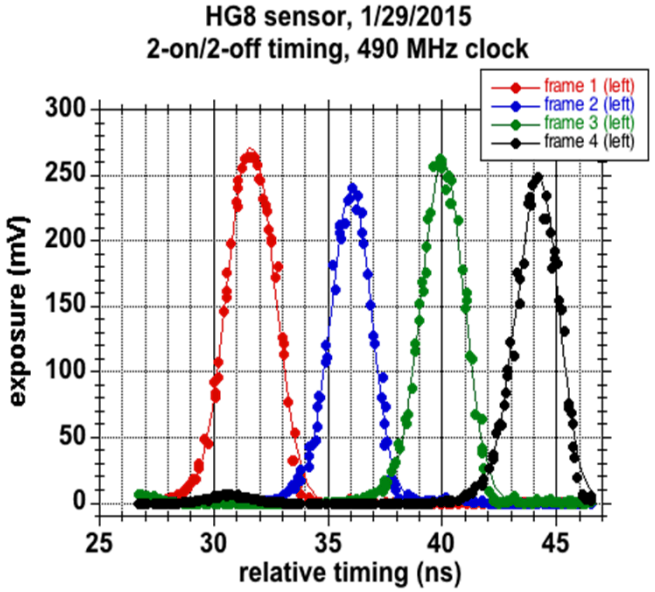


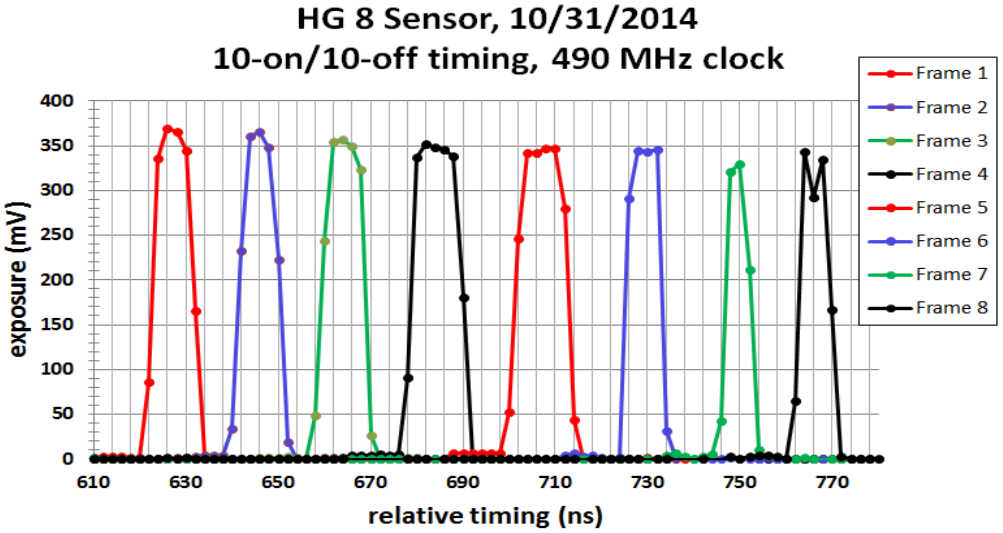
8 Frame Mode, F0

Mode	Spatial Resolution X	Spatial Resolution Y
2 Frame	25 um	25 um
4 Frame	25 um	50 um
8 Frame	25 um	100 um

2, 4 and 8 frame shutter profiles have been obtained

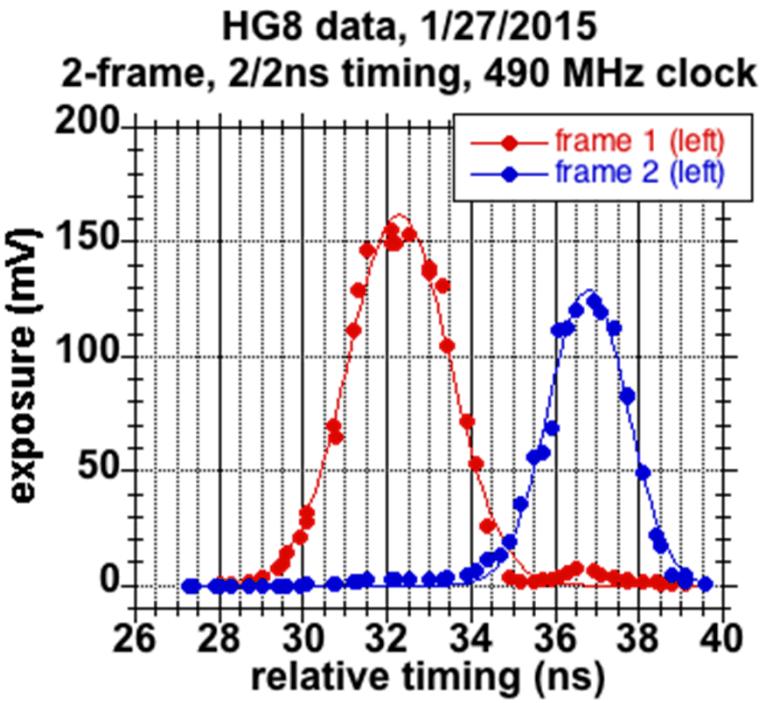


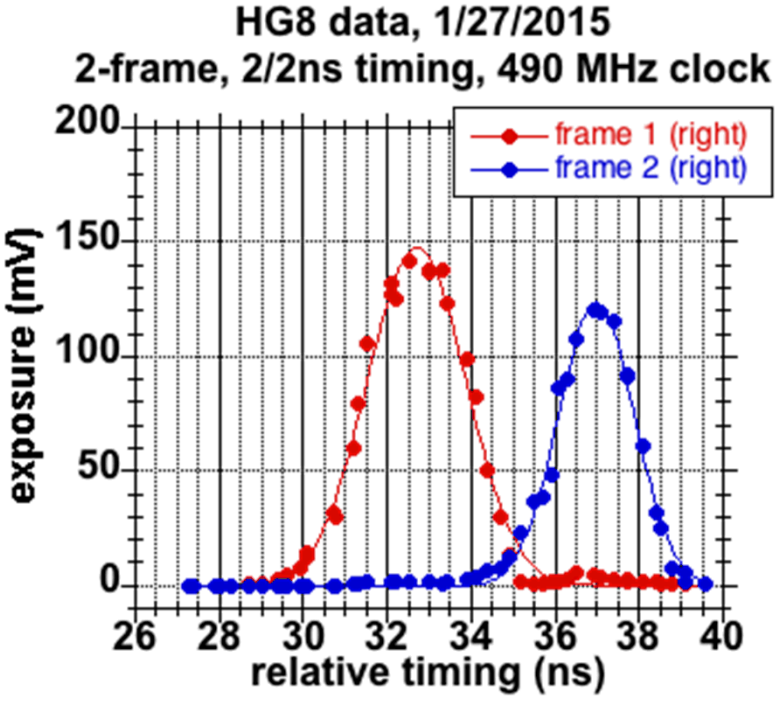




Mixed Signal ASIC/SoC

Left/Right hemisphere timing error was improved over Furi





	Hippogriff		Furi
Mode	2 Frame	4 Frame	2 Frame
Frame	Left/Right error (ps)	Left/Right error (ps)	Left/Right error (ps)
1	400	500	800
2	200	400	900
3		300	
4		400	

L/R hemisphere timing error

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Hippogriff has been used in the ZBL test chamber to investigate MagLIF laser pre-heating and other HEDP experiments

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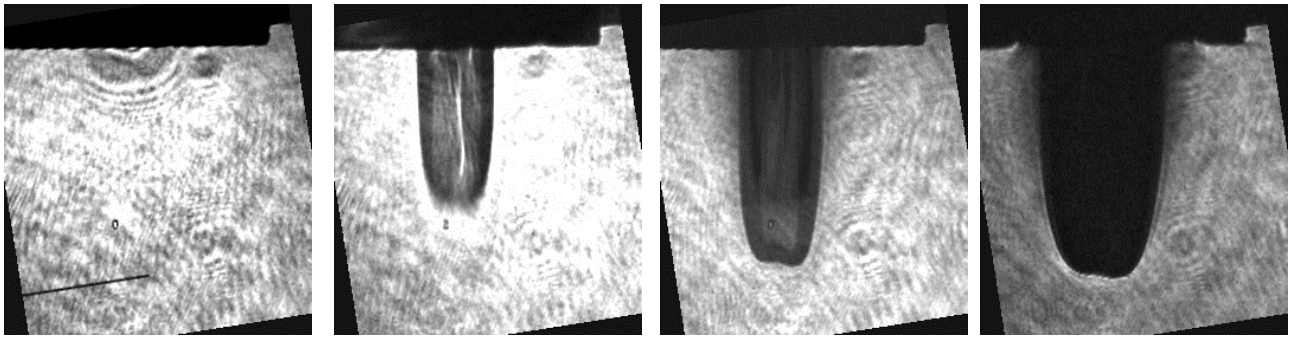
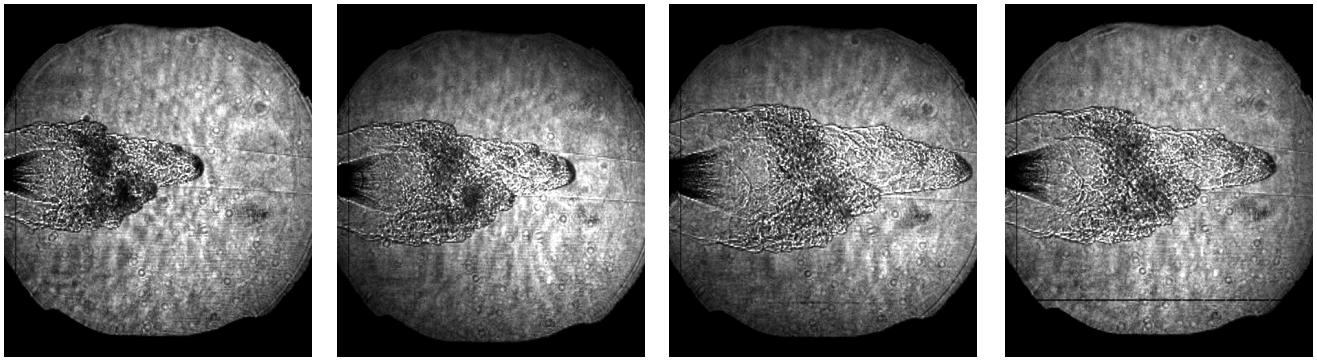
t=0 ns | t+2 ns | t+4 ns | t+6 ns



Hippogriff images showing the evolution of a blast wave in laser heated gas to understand the laser preheating phase of Magnetized Liner Inertial Fusion (MagLIF)

t=0 ns | t+2 ns | t+4 ns | t+6 ns

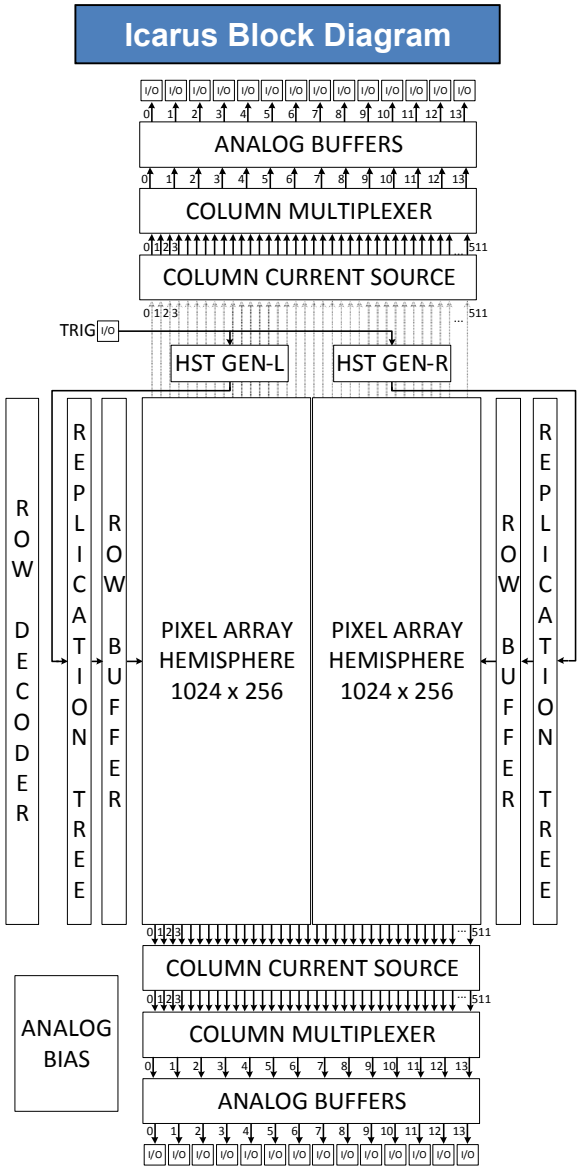


Imaging magnetized radiative blast waves in collaboration with researchers from the University of Texas at Austin

Mixed Signal ASIC/SoC

Icarus represents a significant architectural change from the previous ROICs and is a true second generation UXI camera

- ROIC features
  - 1024 x **512** pixels on 25 um pitch
  - **4 frames per pixel**
  - < 2 ns integration time
  - < 2ns inter-frame time
  - 60 dB dynamic range
  - **500 ke$^-$ full well**
  - **500 e$^-$ noise floor**
  - **Common Cathode detector**
- Improvements/modifications on previous ROICs
  - Tunable anti-bloom transistor
  - Fully independent hemisphere timing
  - L/R hemisphere shutter timing tuning capability
  - Shorted intermediate reptree output stages to improve R-R timing error
  - Top/Bottom readout channels
  - CC pixel allows a more robust power distribution architecture
  - Incorporated on chip bypass capacitors



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Summary and future work

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- Summary:
  - Hippogriff demonstrated interlacing works
  - Improved L/R hemisphere offset by ~50% (200-500 ps)
  - Good performance down to 2 ns T_{int}

- Future Work:
  - Measure linearity and dynamic range
  - Obtain 8 frame shutter profile at 2 ns timing
  - Flat field the sensor

Hippogiff demonstrated interlacing works and there was an improvement to the L/R hemisphere offsets

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Spec	Goal	Furi	Hippogriff
Spatial resolution	25 um	25 um	25 um
Sensitive to visible and X-rays	<10 keV	Yes	Yes
Large format sensor	Multiple-cm's	2.56 cm x 1.12 cm	2.56 cm x 1.12 cm
Low trigger insertion delay	Few 10's of ns	83 ns	80.5
Many frames	8 or more	2	**2 (8 with interlacing)**
High timing precision	100 ps or better	900 ps	**400 ps**
Large dynamic range	1000:1	Yes	TBD
High speed integration time	1 ns	1.5-2 ns	2 ns
Radiation Tolerant	Function in ICF facilities	100's of shots at NIF	Expect similar performance
Camera form factor	Small	Reasonable	Yes