SAND2014-4803C

A Time-Gated Hybrid CMOS Sensor with Multi-frame Storage for High-Speed X-ray Imaging

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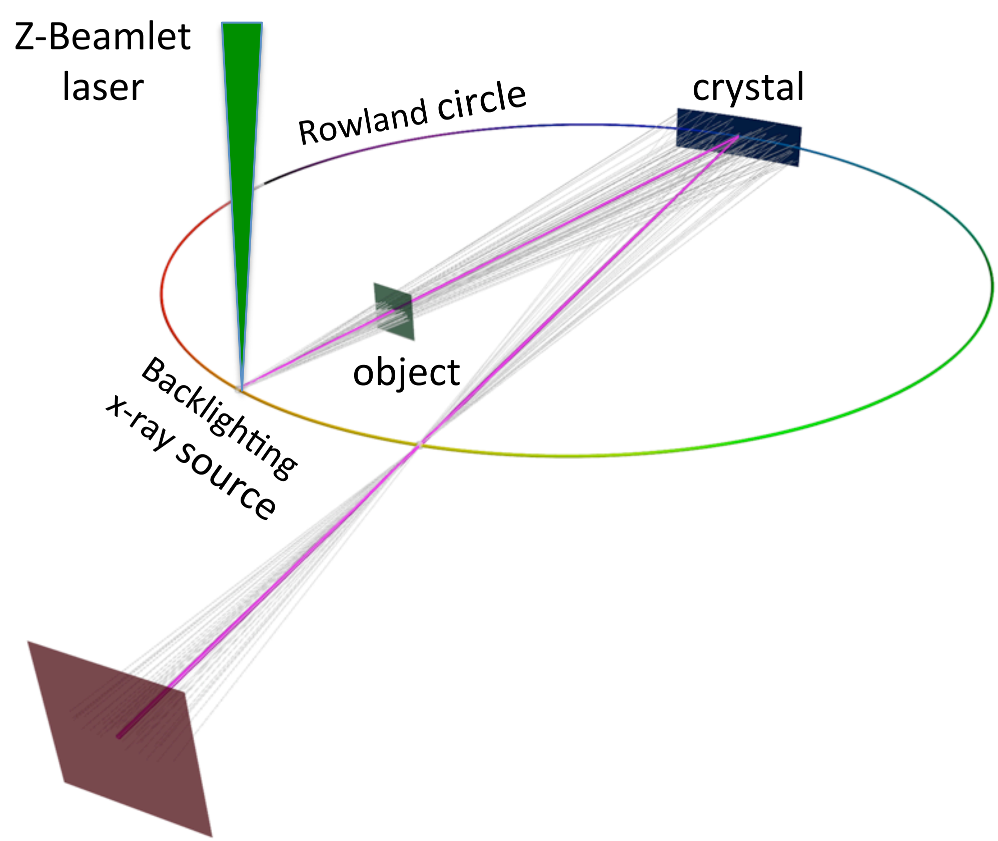
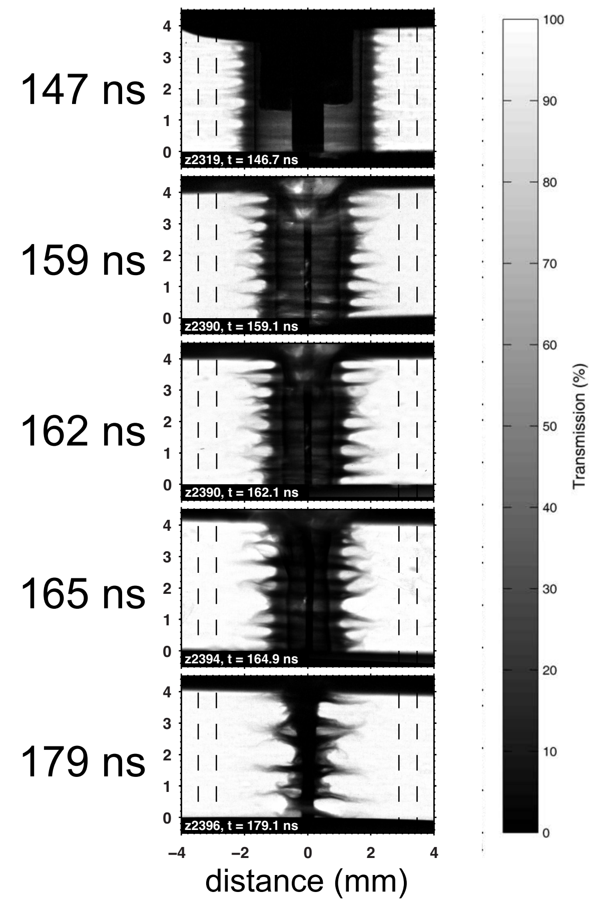
Outline

- Motivation
- Sensor design and performance goals
- Characterization and initial use
- Future plans and conclusion

Motivation

- **Develop a single-line-of-sight imager to take x-ray "movies" of HED experiments**
  - **Backlighting with spherically-bent crystal imager**
  - **Plasma x-ray emission**





R. D. McBride, et. al., Physics of Plasmas, 20, 056309 **(2013)**

Desired imager characteristics

- High spatial resolution (25µm or better)
- High speed (1ns or better)
- Many frames (10 or more frames)
- High sensitivity to visible light, x-rays, or particles (sensitive to single keV x-ray photons)
- Large dynamic range with accurate calibration (1000 or better)
- Radiation tolerant (can operate on large ICF facilities)
- Large sensor (multi-cm scale size)
- High timing precision (50 psec or better)
- Low trigger insertion delay (few 10's ns)
- Compact, rugged, and easy to use (10cm scale or smaller, operable in vacuum or air, controlled over Ethernet network)

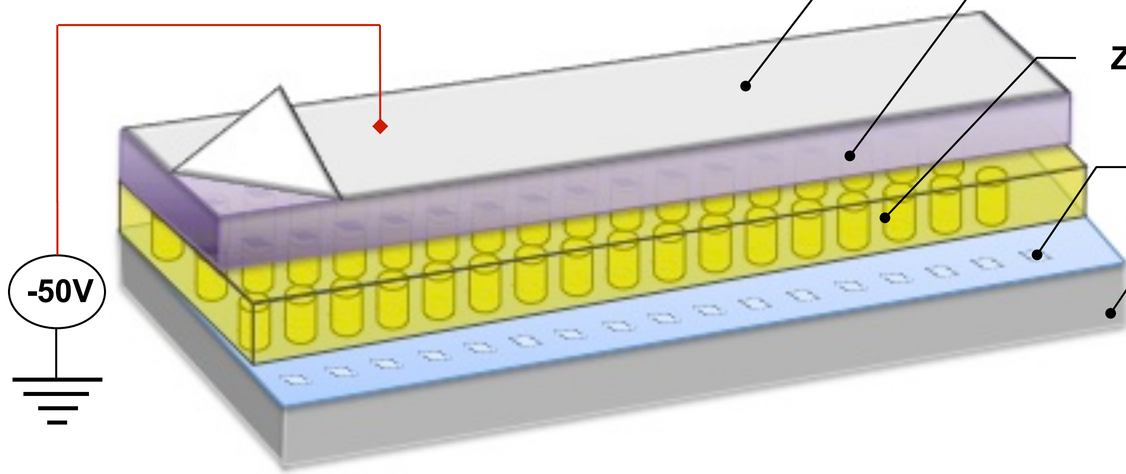
Comparison of high-speed CMOS imagers

	LLNL/ Lincoln Lab	LANL/ Teledyne	Sandia
Pixel pitch	30 μm	26	25 μm
Pixel array dimensions	512 x 512	720 x 720	1024 x 448
Min. integration time	0.25ns	50ns	1ns
Frames/pixel	1	3	2 - "Furi" 4 – "Hippogriff" & "Icarus" 8 – in design
Wavelength sensitivity	visible	visible	visible & x-ray
CMOS process	180nm	250nm	350nm

LLNL/Lincoln Lab: A. T. Teruya, et. al., SPIE conference (2012)

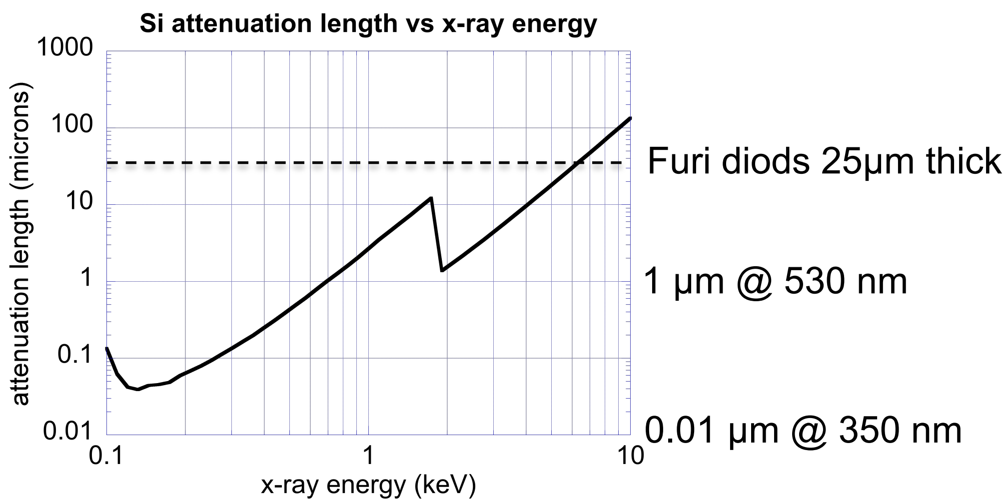
LANL/Teledyne: V. M. Douence, et. al., SPIE proceedings (2005)

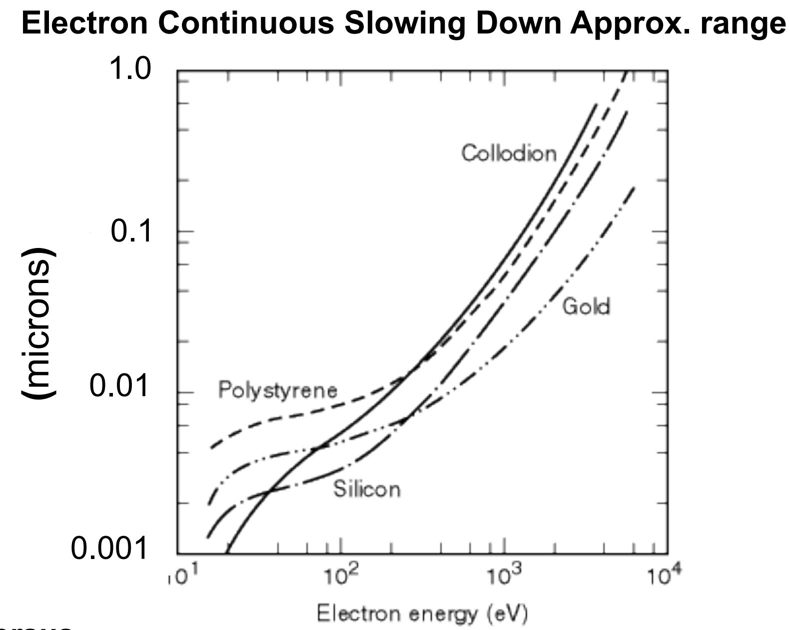
A hybrid CMOS sensor is made possible by advances in 3D integration in the semiconductor industry

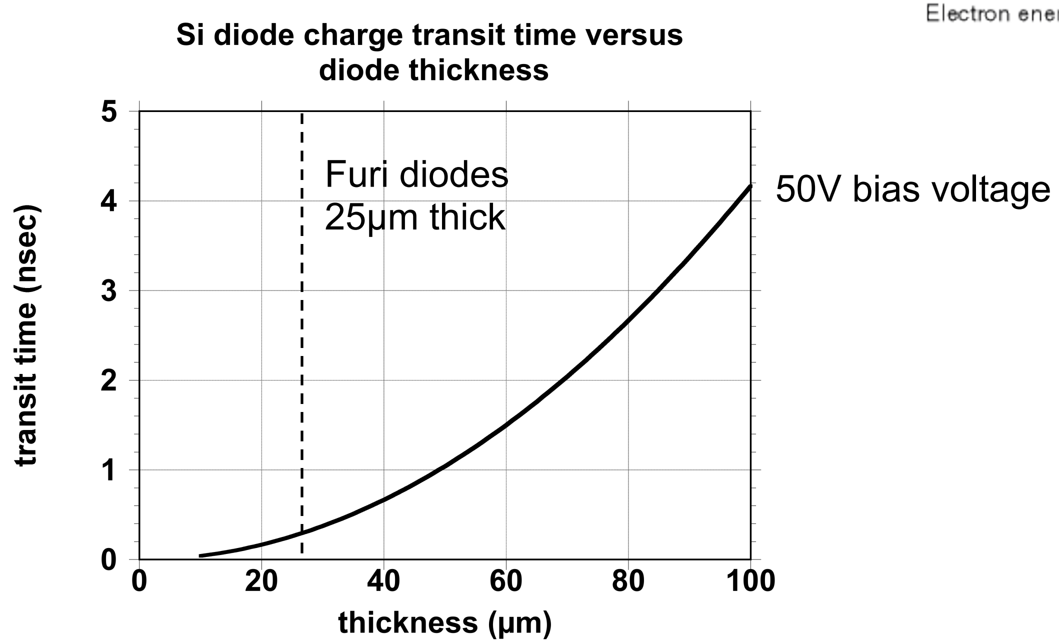


- Silicon diode array converts incident radiation into electron-hole pairs
- CMOS integrated circuit stores charge from each diode on in-pixel capacitors during selected integration time for each frame
- Diode array is directly connected to CMOS integrated circuit through wafer-to-wafer bonding (3D integration)
- Commercial electronics used for sensor control and readout

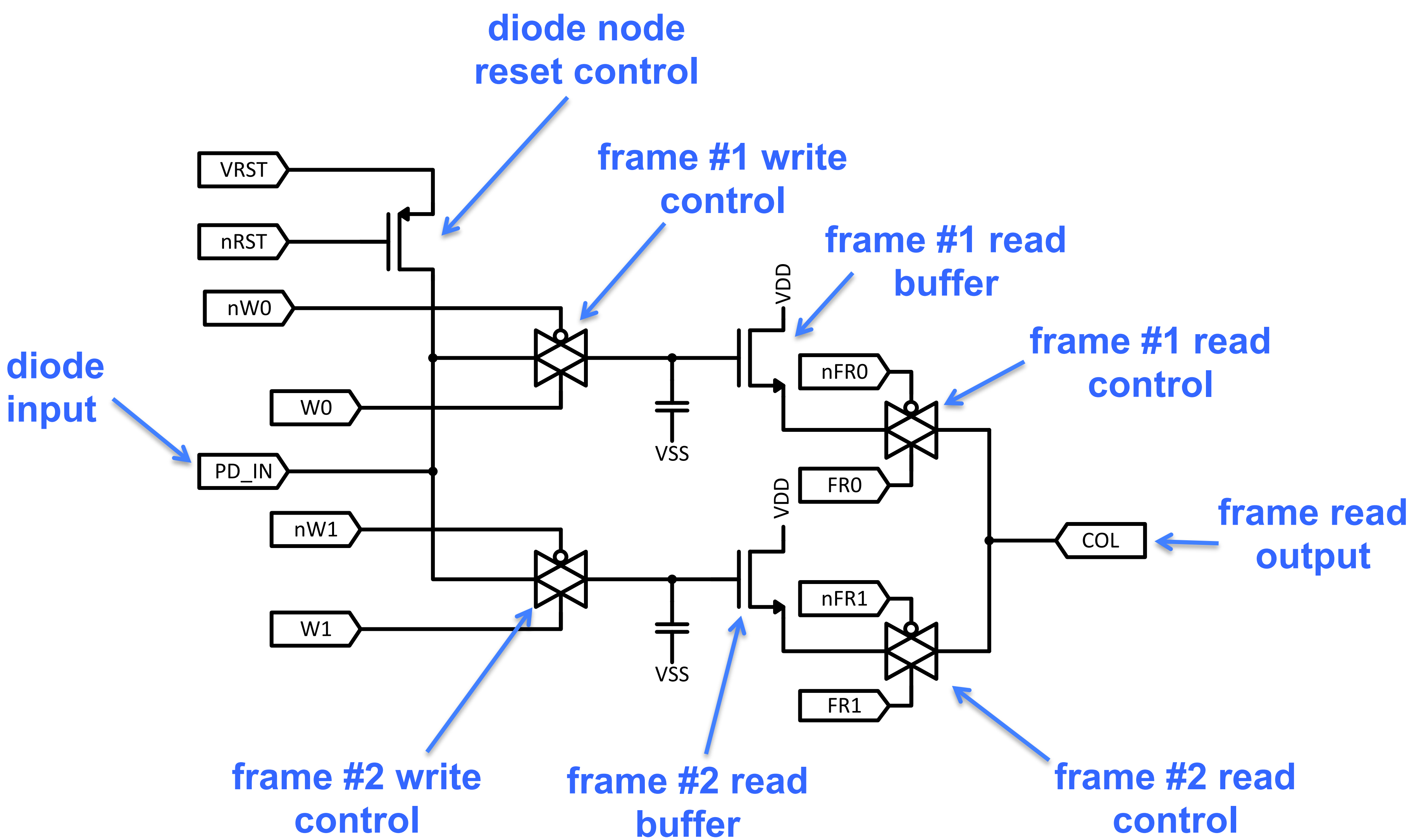
Tradeoff between Si diode detection sensitivity and time response



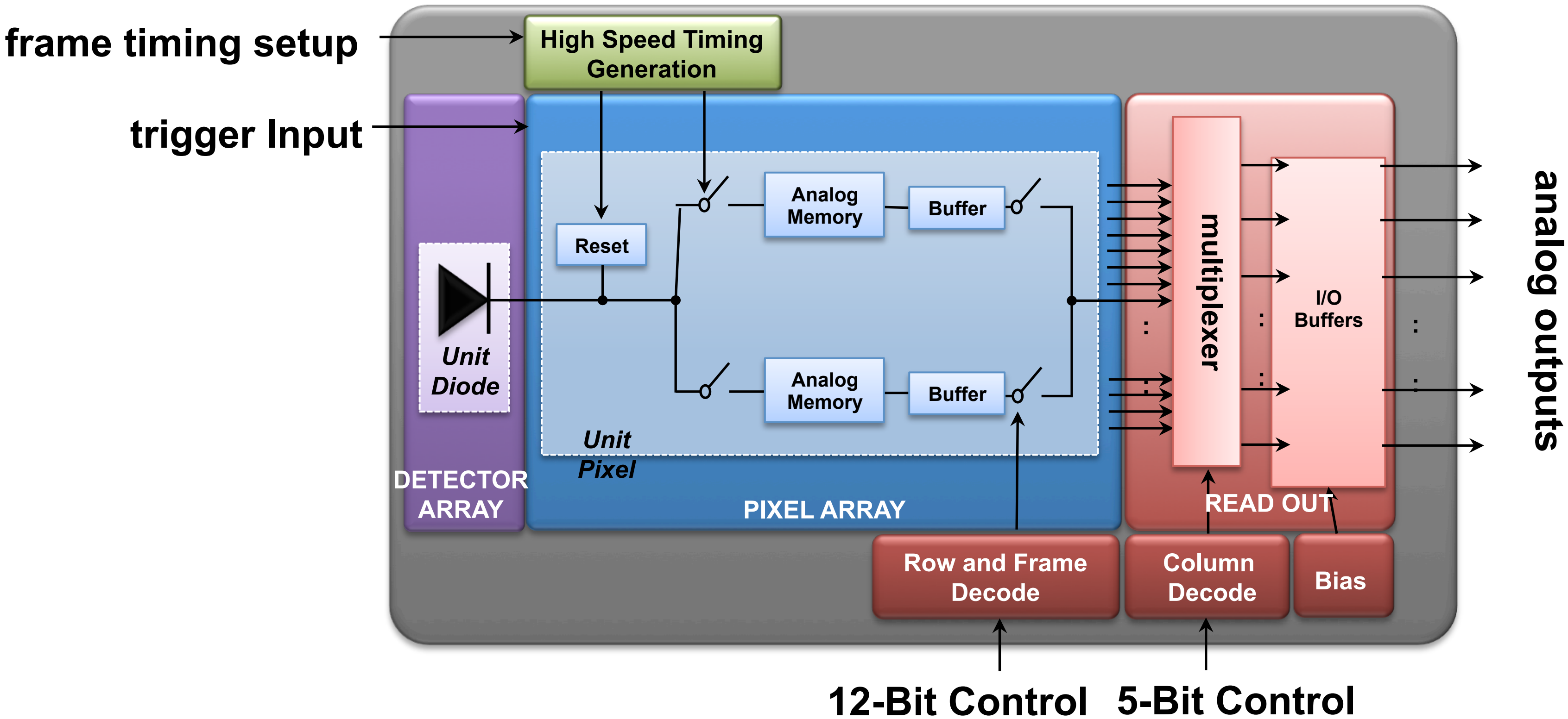




The unit pixel is composed of 11 transistors and 2 analog storage capacitors



The ASIC incorporates high speed timing generation, frame gate distribution, and data readoff



Hybridization enables near 100% diode fill factor and use of a variety of diode arrays with the same ASIC

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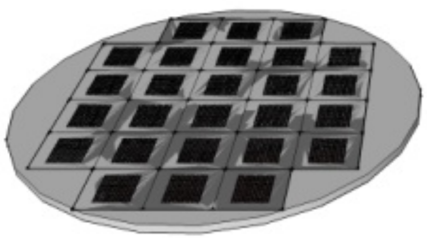
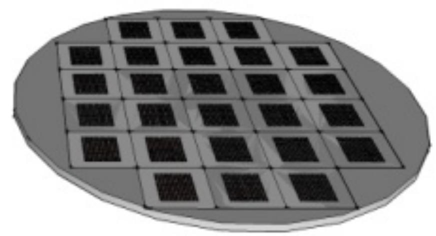
6” ASIC wafer fabricated with Sandia 0.35 µm CMOS7 process





6” diode wafer fabricated at Sandia

diode wafer flipped and bonded to ASIC wafer by Ziptronix

silicon from diode handle wafer removed and thin-film bias electrode applied by Ziptronix

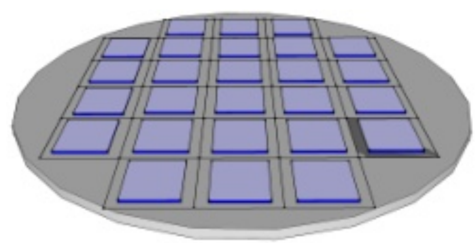
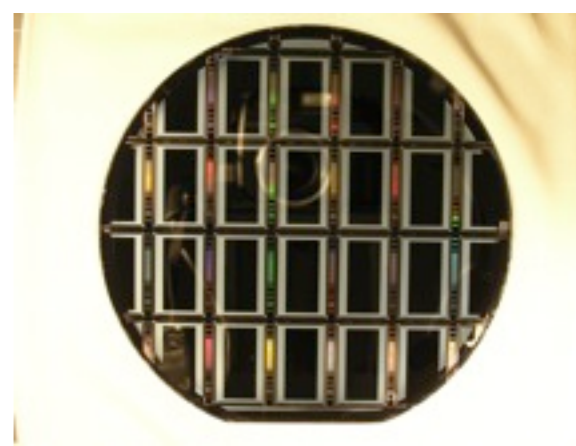
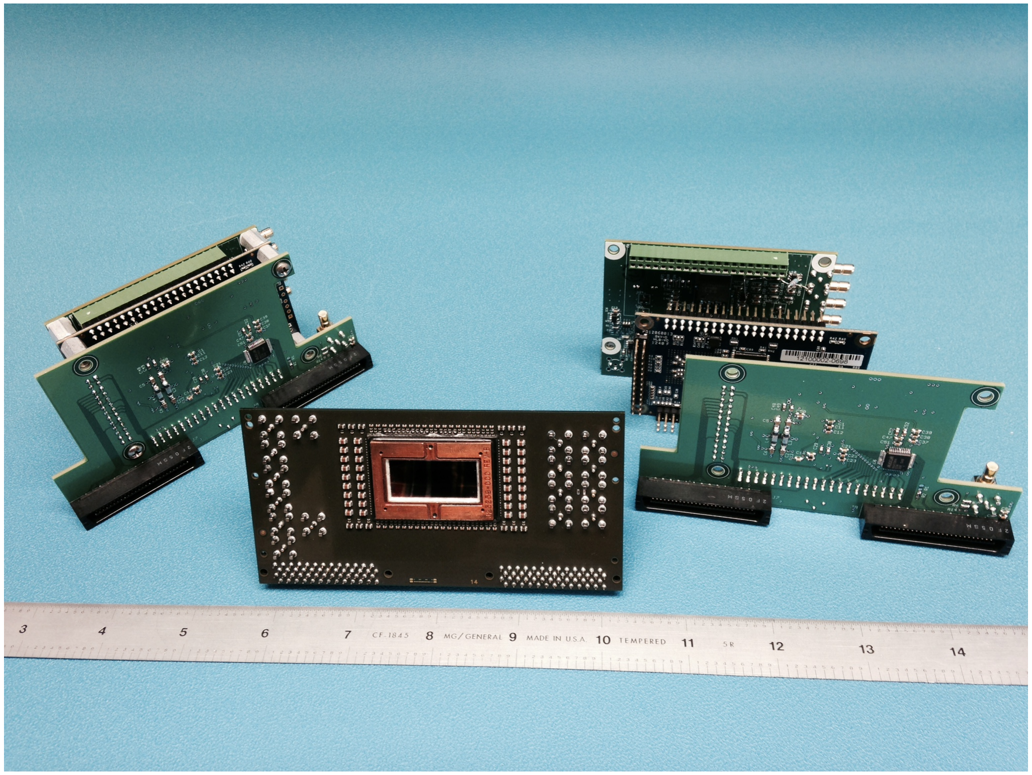


Photo of hybridized wafer after die sawing



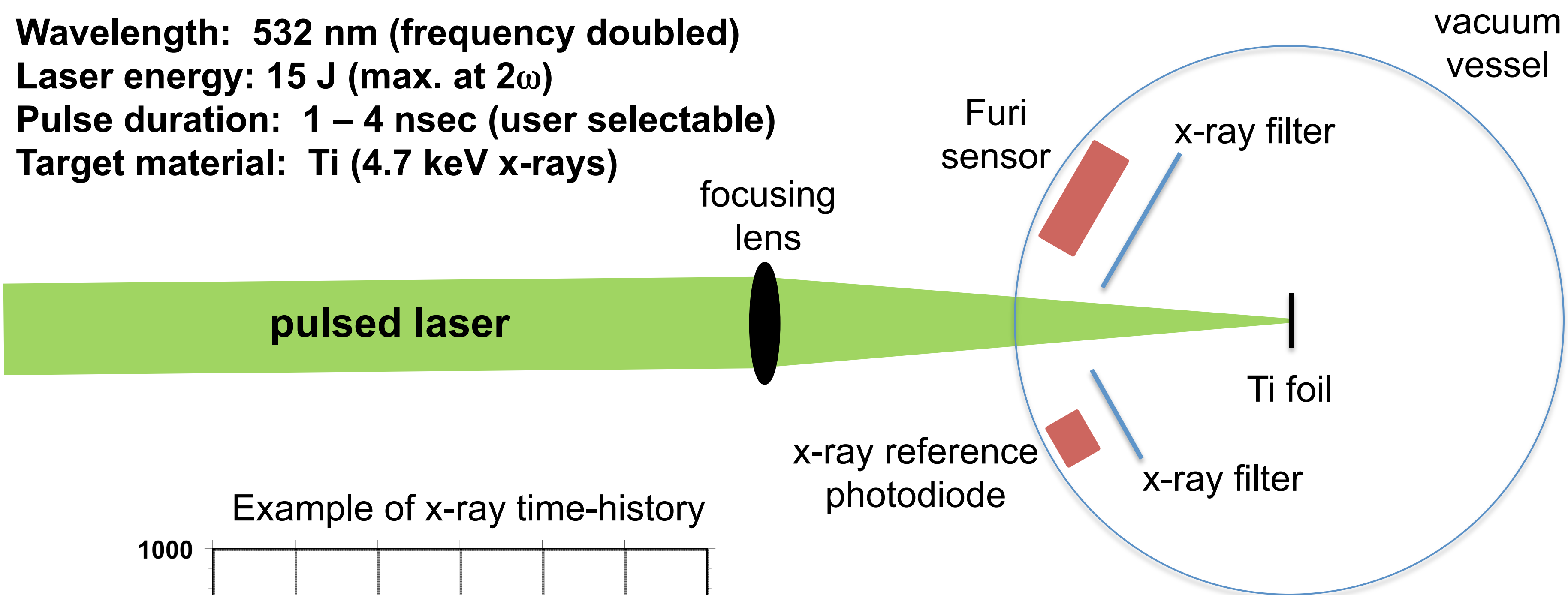
Compact electronics package can be readily integrated into a range of diagnostic systems

- Inputs/Outputs
  - 7V power
  - slow and fast triggers
  - Frame timing monitors
  - serial communication computer interface

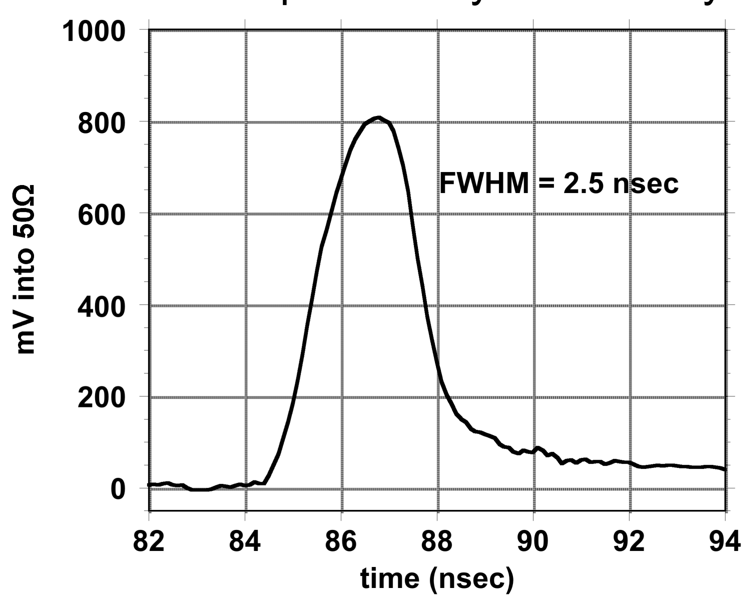


A pulsed laser-produced-plasma x-ray source is used to uniformly illuminate the sensor

Wavelength: 532 nm (frequency doubled)
Laser energy: 15 J (max. at 2ω)
Pulse duration: 1 – 4 nsec (user selectable)
Target material: Ti (4.7 keV x-rays)

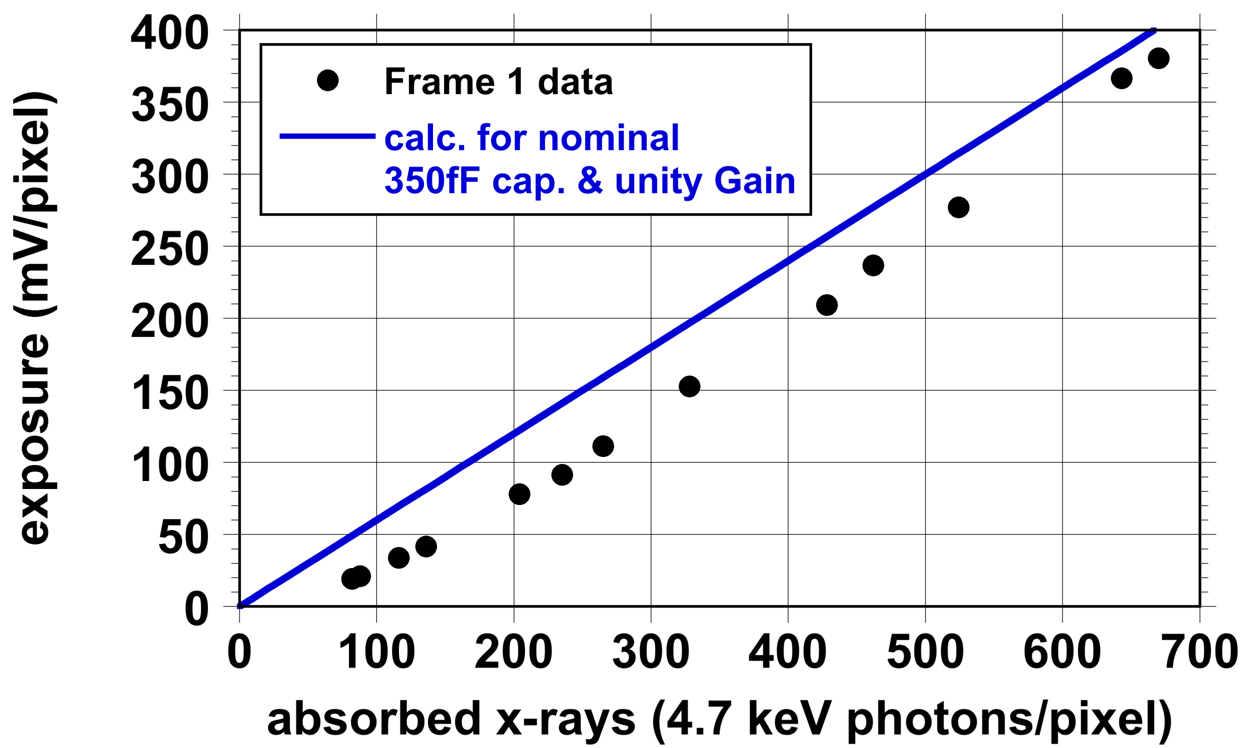


Example of x-ray time-history



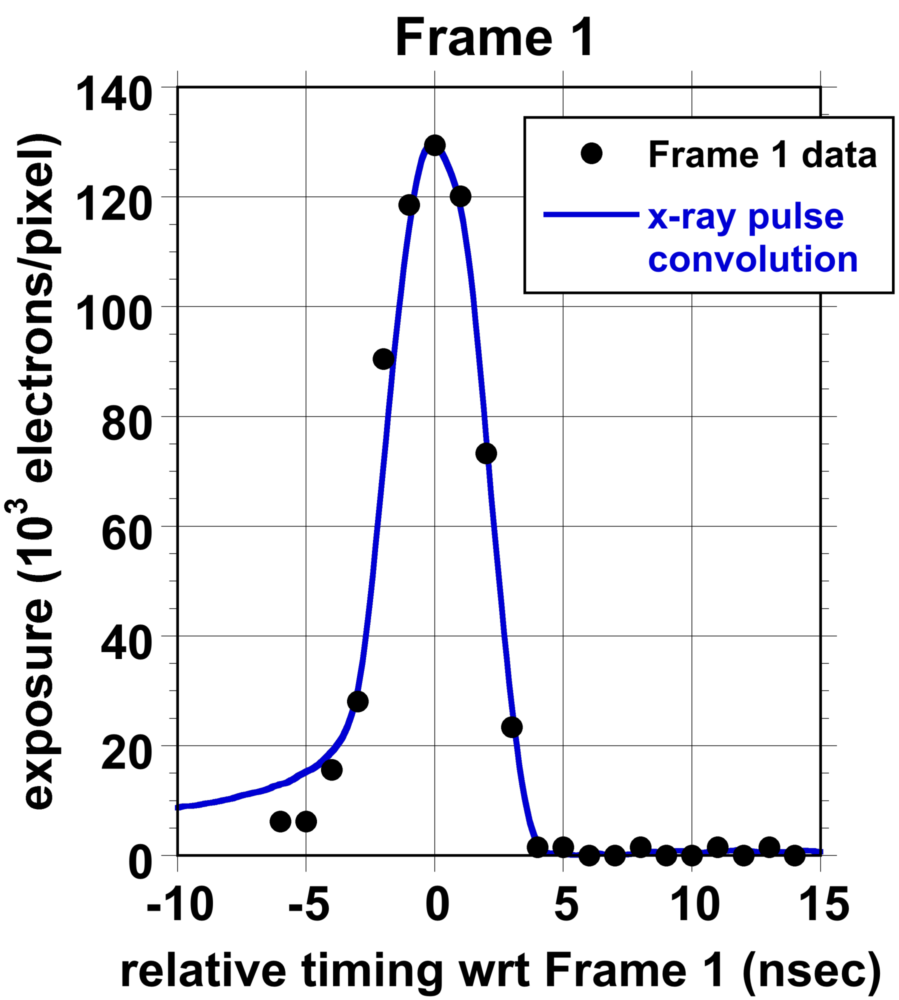
A large-area calibrated reference Si diode is used to measure the absolute x-ray sensitivity for each pixel

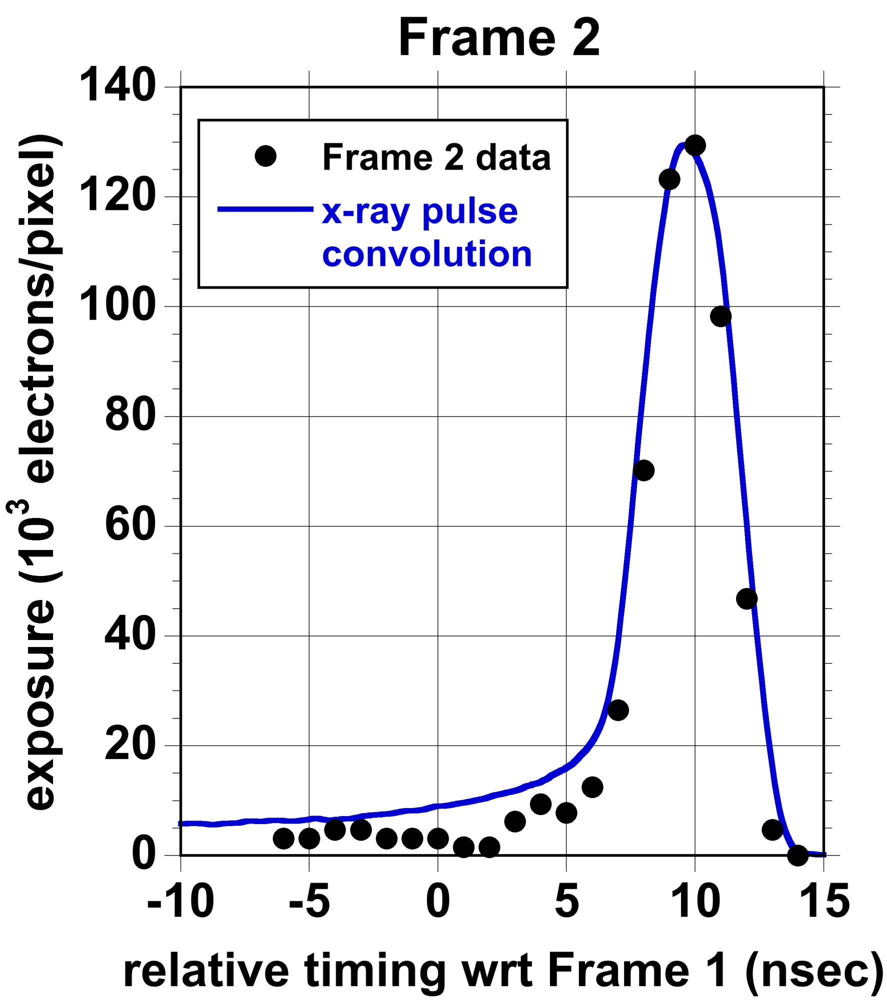
- Expected response: V_{pixel} = Gain(V) x Q_{pixel}/C_{pixel}
  where Q_{pixel} = absorbed x-ray flux/3.6eV and C_{pixel} = 350fF
- For a nominal unity Gain we expect 1,300 electrons per absorbed 4.7keV photon to produce a voltage change on the pixel capacitor of 0.6mV
- Initial measurements indicate dynamic range ≥ 200. We're presently working to optimize the noise floor of the sensor and readout electronics and determine maximum safe exposure level.



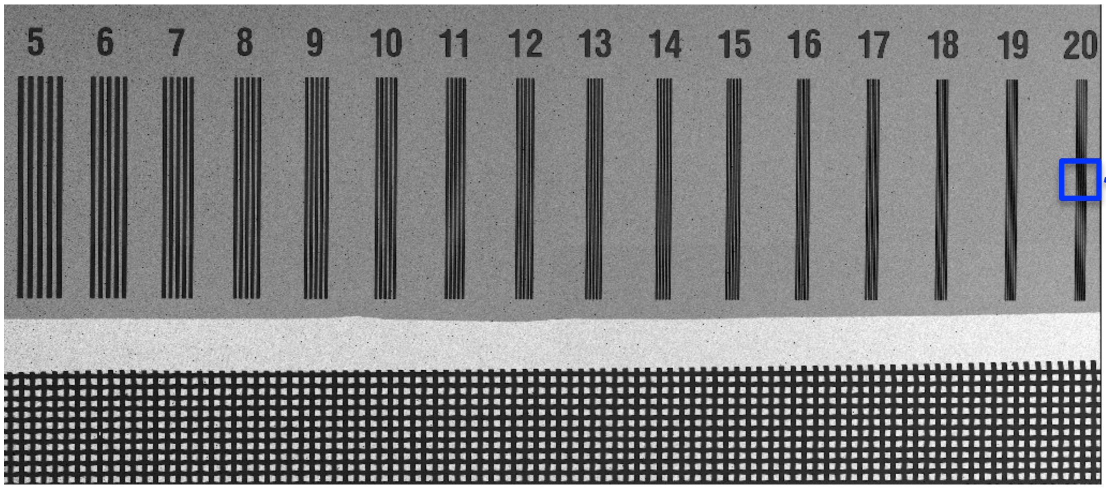
The time response is determined by varying the timing between the x-ray pulse and the frame gate times

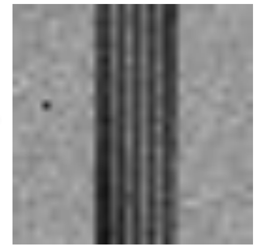
- x-ray pulse FWHM = 2.5ns, frame gate time = 4ns, 10ns frame separation
- x-ray pulse convolved with 4ns gate time for comparison with measurements



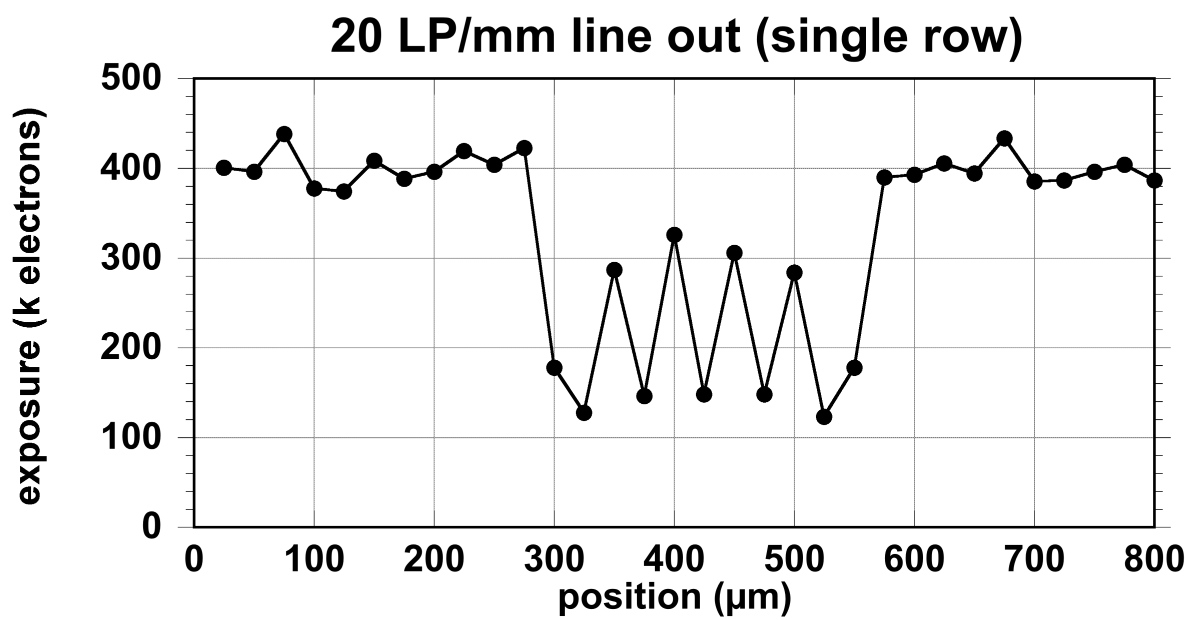


An x-ray line-pair test pattern is used to measure the spatial resolution

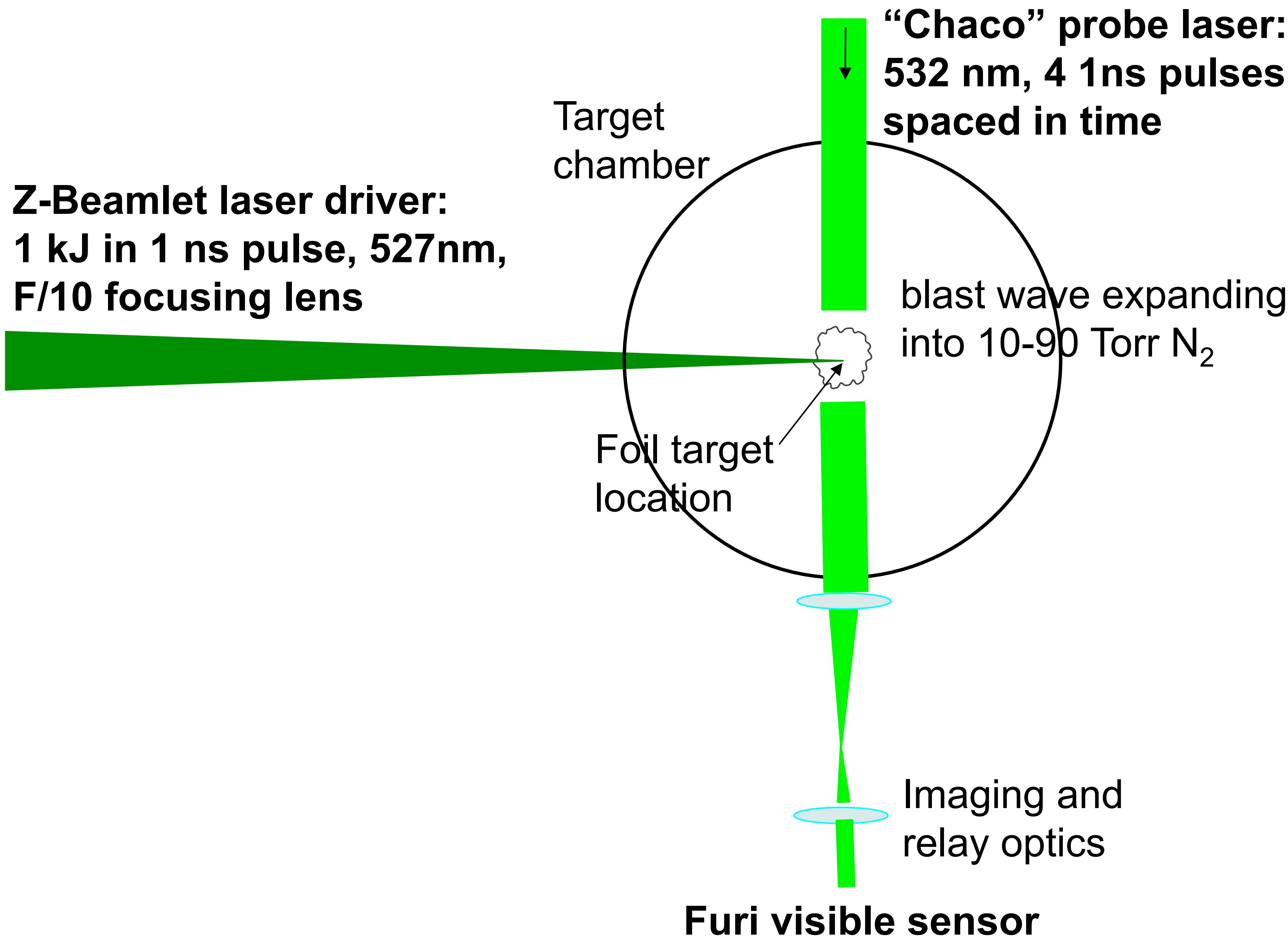




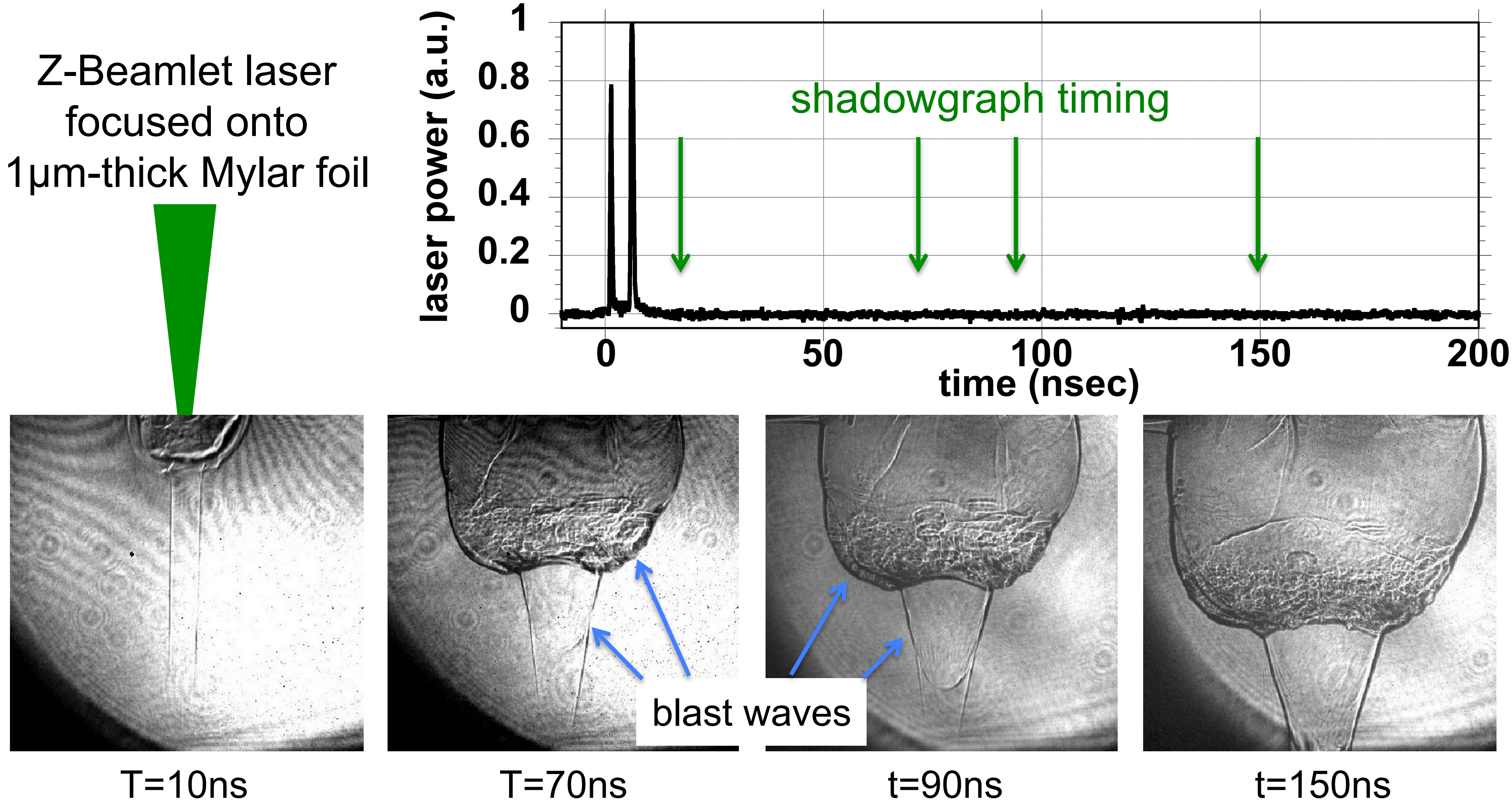
20 line-pair/mm
32 x 32 pixels



Demonstration of image capture on a dynamic object: Shadowgraphs of a laser generated blast wave



Example of blast wave shadowgraphs recorded with visible Furi sensors on a single experiment



- **Time-gating enables each individual shadowgraph to be seen and eliminates the bright plasma emission that occurs when Z-Beamlet strikes the thin foil**

The path to more frames and faster shutters

- **Interlacing (gate adjacent pixels on/off at different times)**
  - Trade off reduced spatial resolution in one dimension for more frames
  - An interlaced version of the Furi sensor with 4 and 8 frame options has been fabricated and will be available for testing in the July/August time frame

- **More frames per pixel**
  - Max of 4 frames possible with 350nm CMOS process with full well of 10^6 electrons ("Icarus" sensor in fabrication and available for testing by the end of 2014)
  - 8-16 frames possible using130nm CMOS process (8-frame sensor presently being designed)
  - 32 frames per pixel should be possible using even smaller CMOS fabrication process

- **Use electron pulse-dilation tube to "stretch" fast events to match 1ns integration time ("temporal zoom lens")**
  - Requires diode array optimized to few keV electron detection

Conclusion and Future Plans

- **Fabricated a a large-aperture hybrid CMOS sensor and demonstrated fast multi-frame x-ray and visible image capture**
  - Developing cameras with more frames with a goal of 32 frames/pixel in 3-4 years

- **Begin use in HED experiments in 2015**
  - 4-frame x-ray backlighting on Z using bent-crystal-imager
  - 4-frame x-ray imaging through LEH on NIF (in collaboration with LLNL and GA plan to use SXI pinhole camera)
  - Demonstrate <100ps frame capture by coupling to electron pulse-dilation tube in collaboration with LLNL, GA, and Kentech