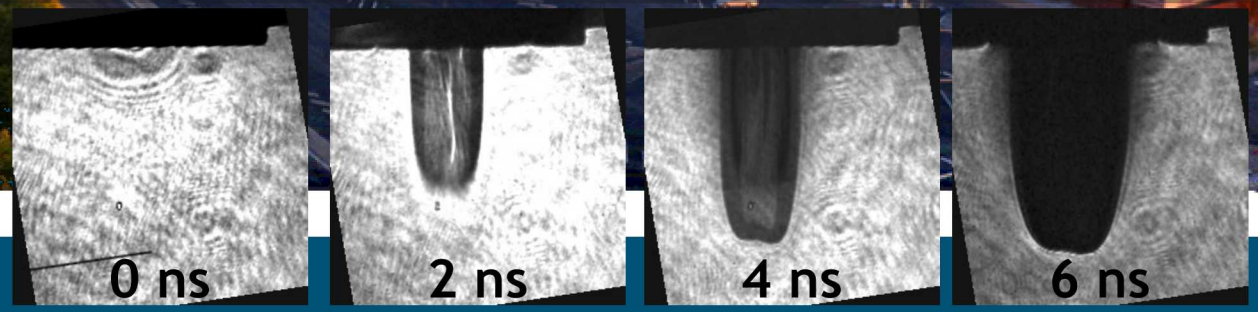
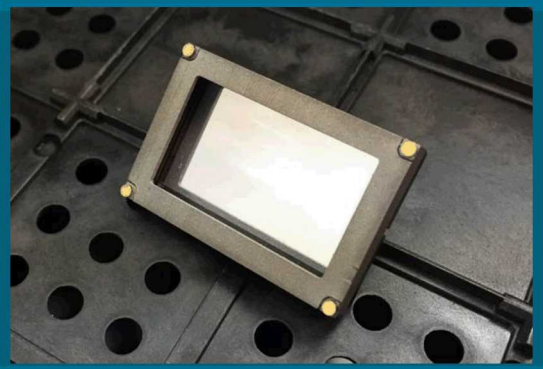
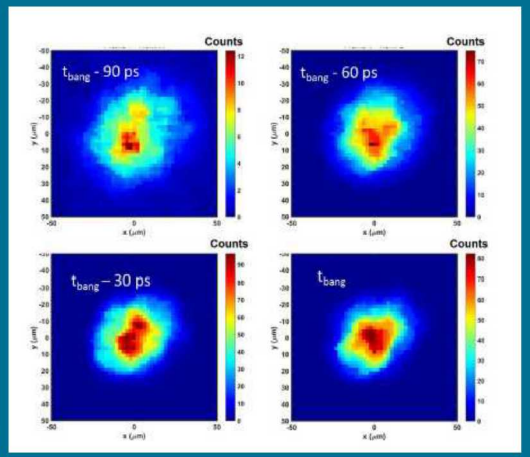
hCMOS update







PRESENTED BY

Liam D. Claus, 08/16/2019

SAND2019-10313PE

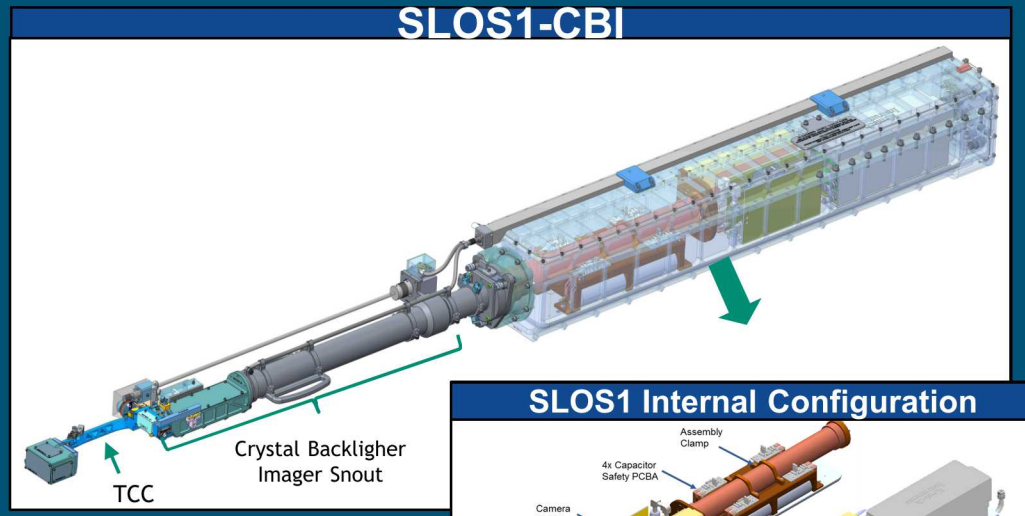
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

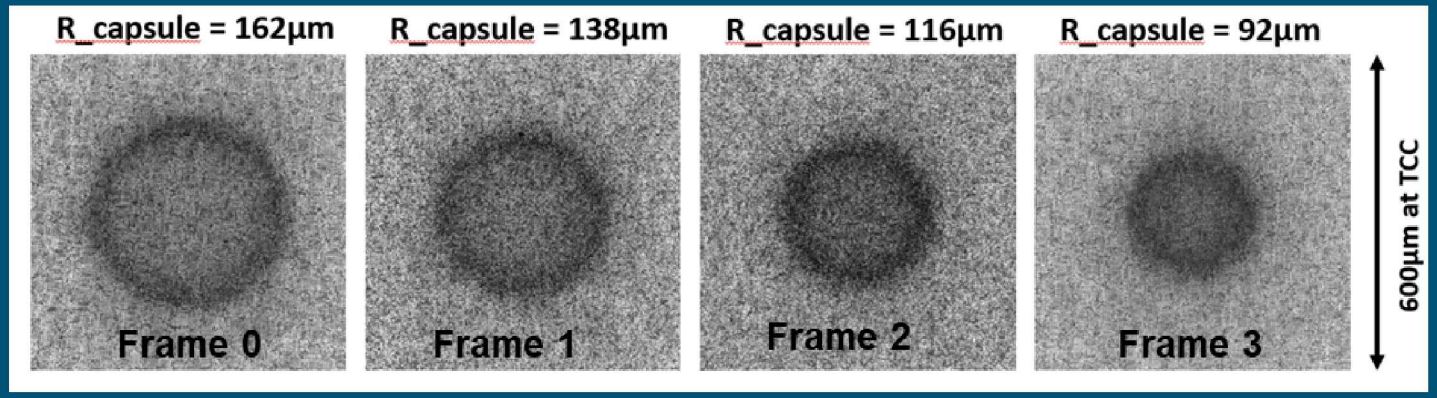
An Icarus sensor was deployed on the transformative diagnostic SLOS+CBI platform

The Single Line of Sight (SLOS) Diagnostic is a multi full frame X-ray imaging diagnostic with gating temporal resolution in the range of 35ps to 100ps. SLOS combines pulse dilation with hCMOS sensor technology

Icarus V2 used for 4 image frames

The SLOS + CBI platform is an integral part of the campaign to study different approaches to mitigating mix at the ice-ablator interface in HDC capsules

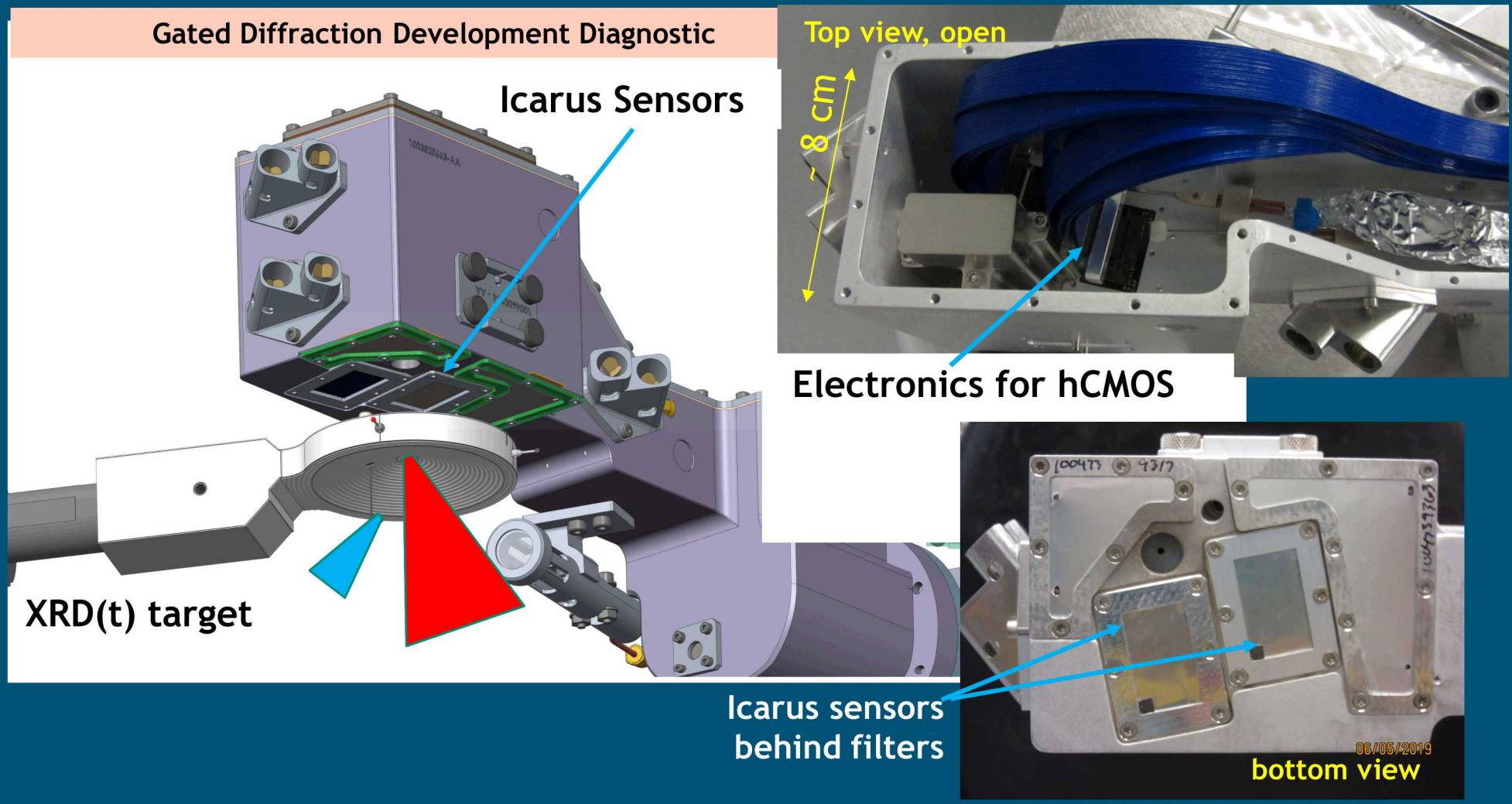




7keV CBI+SLOS radiographs

Slide courtesy of E. Hurd

The time-resolved x-ray diffraction platform at NIF will rely on hCMOS sensors to observe phase transitions in situ

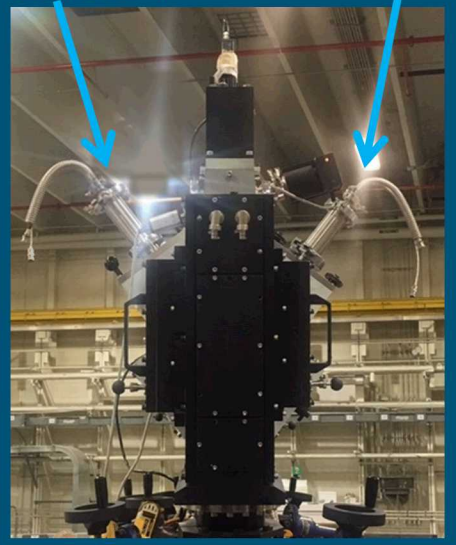


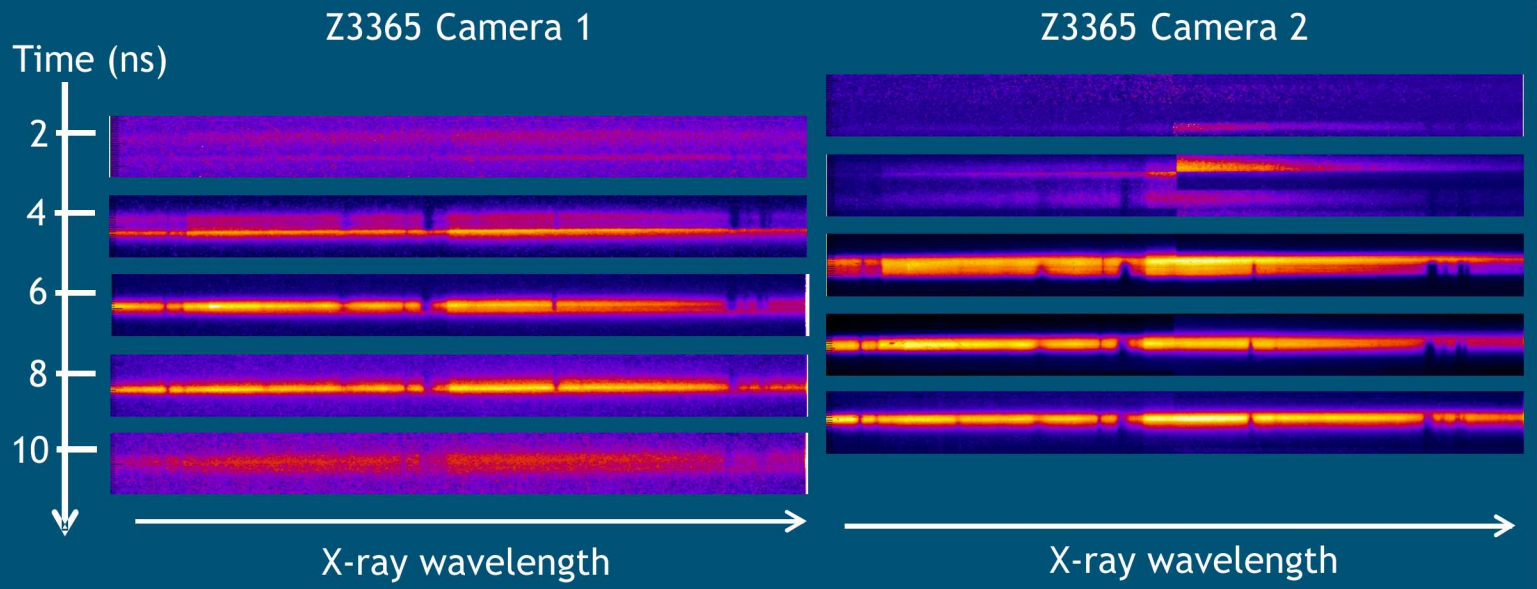
We've used this platform for two NIF shots – current status: Timing in Sensors

Slide courtesy of R. Benedetti

Z has made recent progress with UXI in the Center Section, the Final Optical Assembly, and the Axial Package

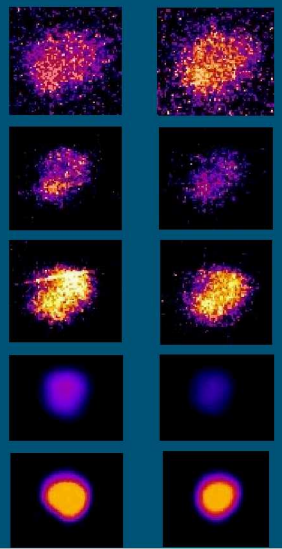
Opacity Spectrometer with 2 UXI Cameras in the Axial Package





Axial Pinhole Camera In the Final Optical Assembly

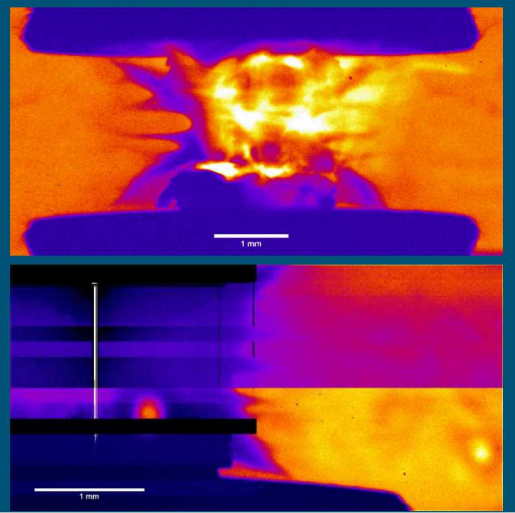
Slide courtesy of T. Colombo



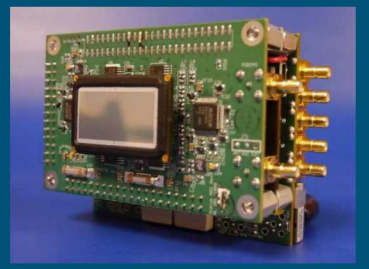
Time series of images from Z3371 MagLIF Preheat Te.

2 UXI cameras will be deployed on MagLIF Bz Scaling (August 2019).

Gated Backlighting in Z Center Section



Recent electronics testing on Z3387 & Z3388



DE0_NANO a.k.a. “UXI 2.0”

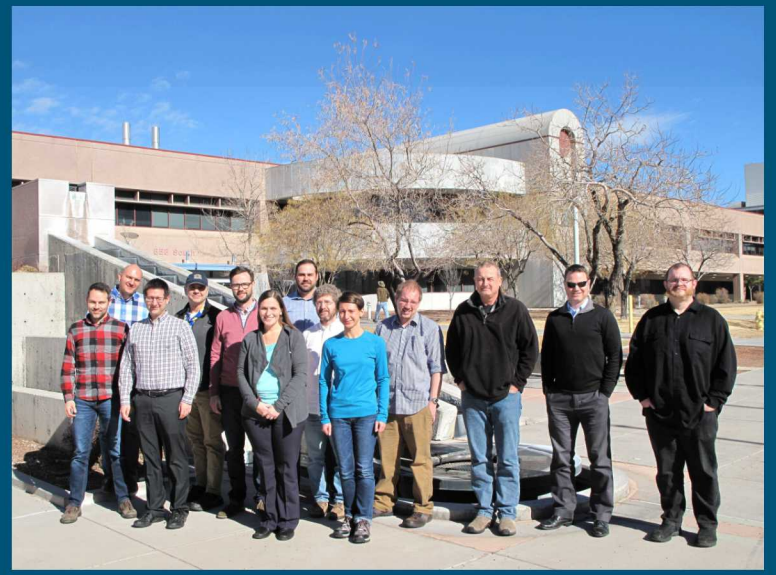
Successfully operated electronics (non-imaging) near/during stagnation.

Z-System Board a.k.a. “UXI 3.0”

Passed first low-level tests of functionality.

The first national hCMOS working group met at SNL in January of 2019

- Representatives from LLNL, SNL, Omega and SLAC participated
  - Test capabilities and methodologies were discussed for all facilities to optimize test and characterization efforts
  - Issues and observations were discussed
    - Document of 23 issues or concerns was constructed
    - 19 issues or concerns have been resolved or understood since January
    - 4 issues are still outstanding
    - This will have significant impact on improving future designs
  - hCMOS delivery/production was compared with diagnostic needs through FY21
    - 15 Diagnostics
    - 7 Icarus V1
    - 21 Icarus V2
    - 19 Daedalus



The supply chain has sensors staged at different levels of readiness to support FY20 deliveries

FY19 Sensor Delivery

USER	SENSOR			TOTALS
	IcarusV1	IcarusV2	DaedalusV1	
SNL	6	4	--	10
LLNL	2	7	2	11
LLE	--	2	--	2

Supply chain pipeline

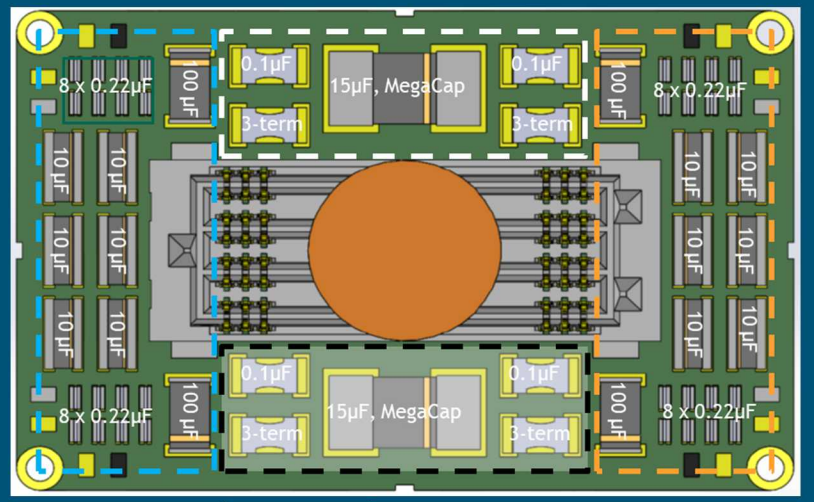
SENSOR	SUPPLY CHAIN STAGE				
	Unbonded Wafers		Hybridization	Die Ready For Packaging	Available Sensors
	ROIC	Detector			
IcarusV1	8	5	3 wafers Cu DBI	17	1
IcarusV2	4		2 wafers (IO opening at SNL)	117	11
DaedalusV1	6	12	3 wafers (IO opening at SNL)	49	3

The sensor package was identified as a limiting component to overall system performance

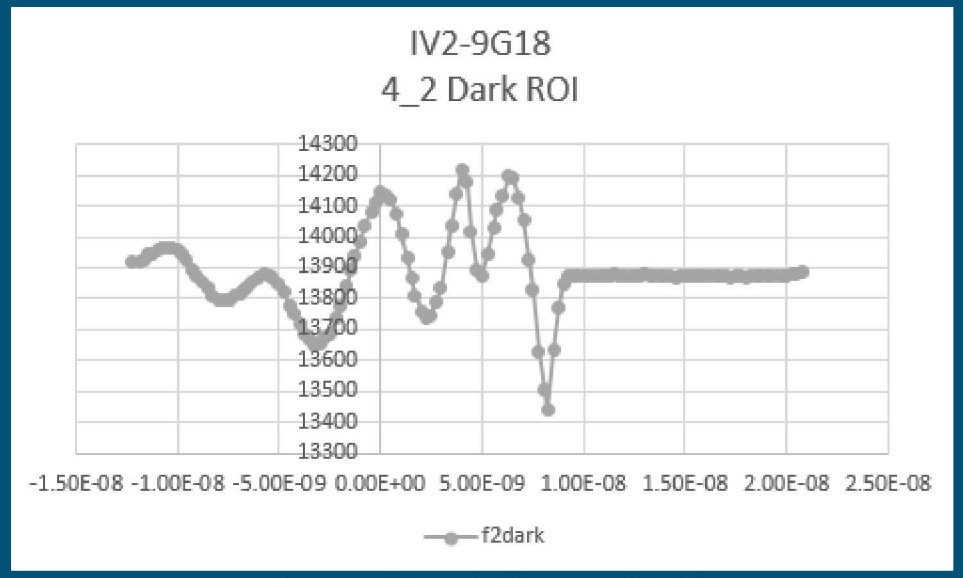
Bondwire/package inductance introduces ringing on the diode bias line that manifests in the data

Effort was applied to modeling existing package design

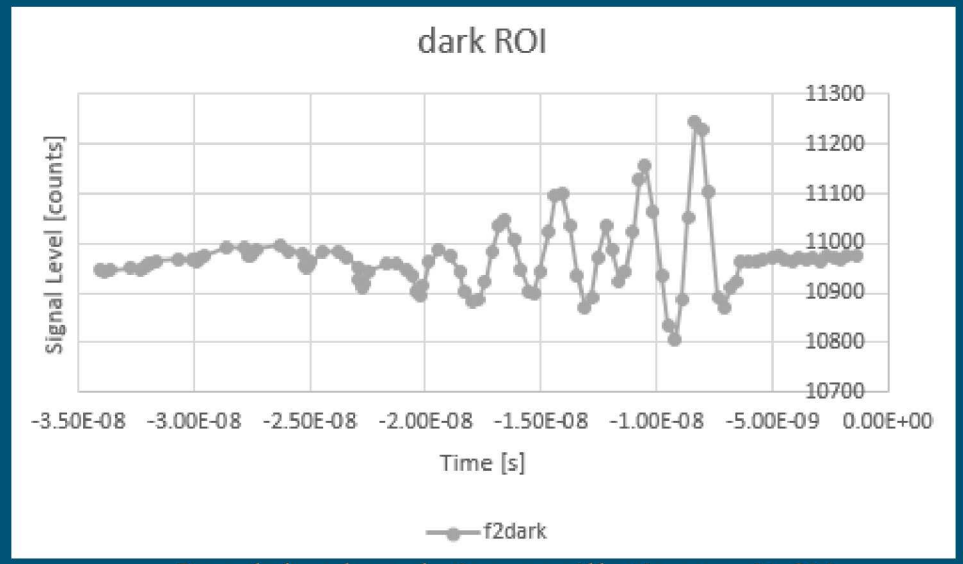
- Areas of improvement were identified
- New package has been designed
- Packaged IV2's expected in Q1, FY20



New package with 5 X improvement in BW inductance



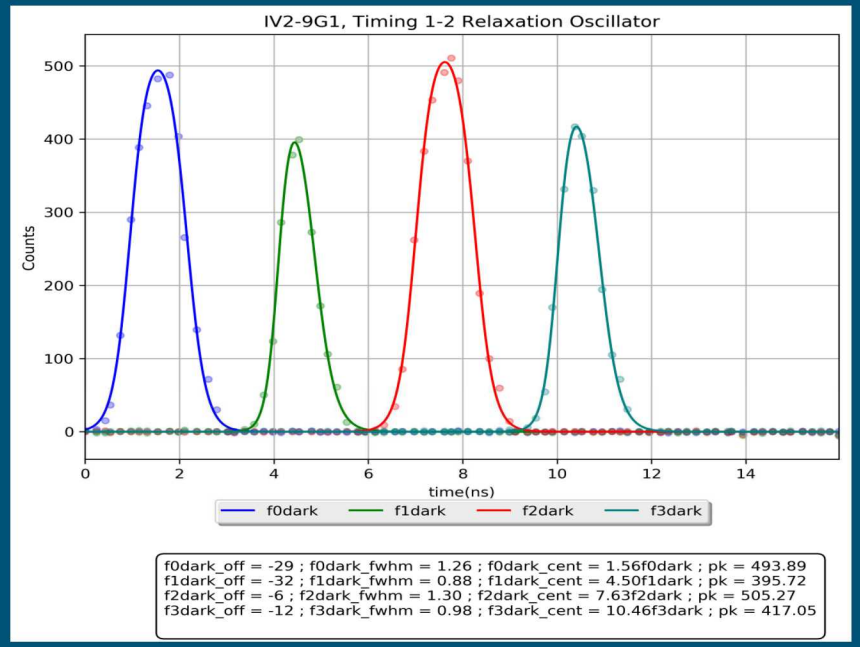
Icarus bondwire oscillations



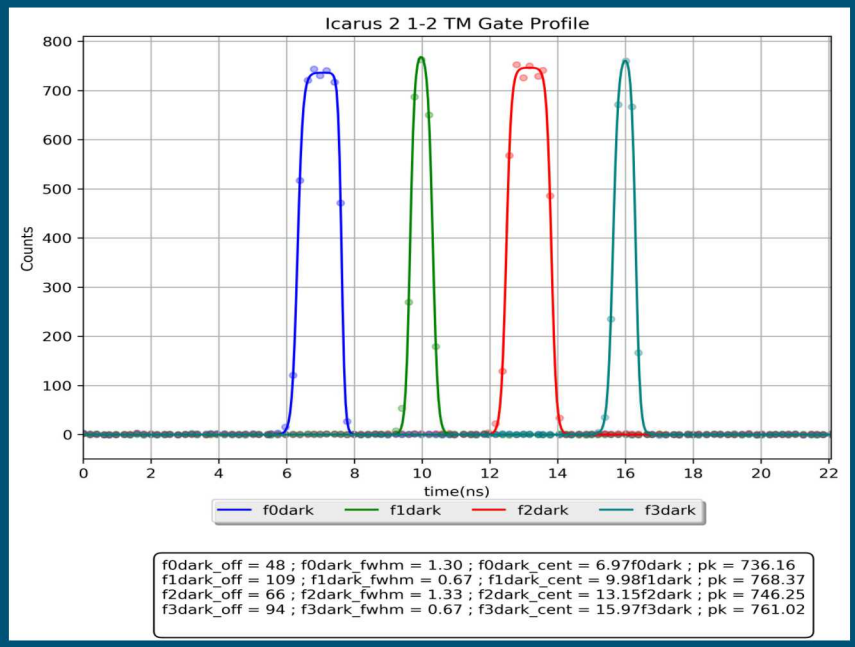
Daedalus bondwire oscillations wit 2X improvement in peak-peak oscillations

The current silicon photodiode design has been identified as a limiting factor for system performance

Data collected at NIF and further investigated at Z have indicated diode speed is noticeable



25 µm 1-2 shutter profile

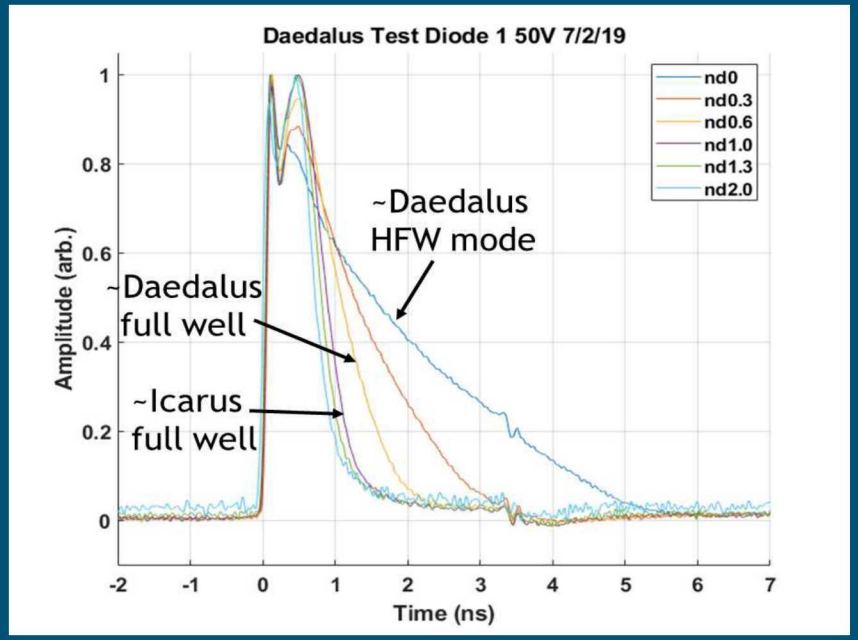


8 µm 1-2 shutter profile

The current silicon photodiode design has been identified as a limiting factor for system performance

Data collected at NIF and further investigated at Z have indicated diode speed is noticeable

- Highly dependent on photocurrent magnitude

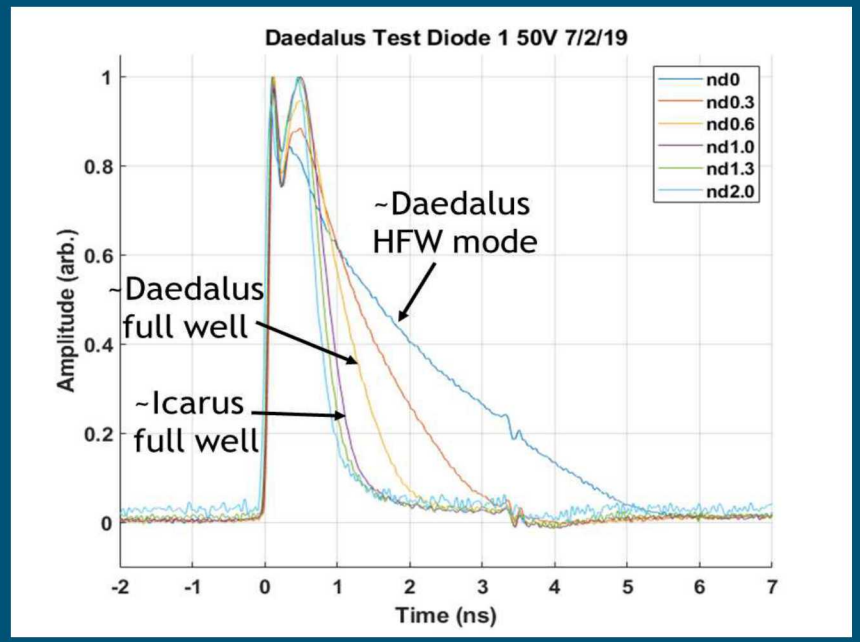


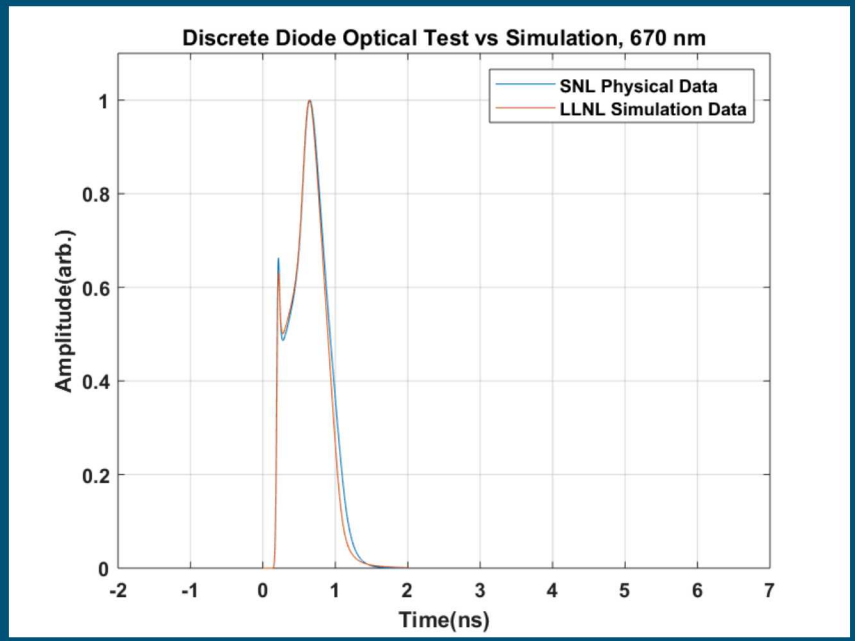
Z testing compared to modeling

The current silicon photodiode design has been identified as a limiting factor for system performance

Data collected at NIF and further investigated at Z have indicated diode speed is noticeable

- Highly dependent on photocurrent magnitude
- A modeling collaboration between SNL and NIF have verified this behavior



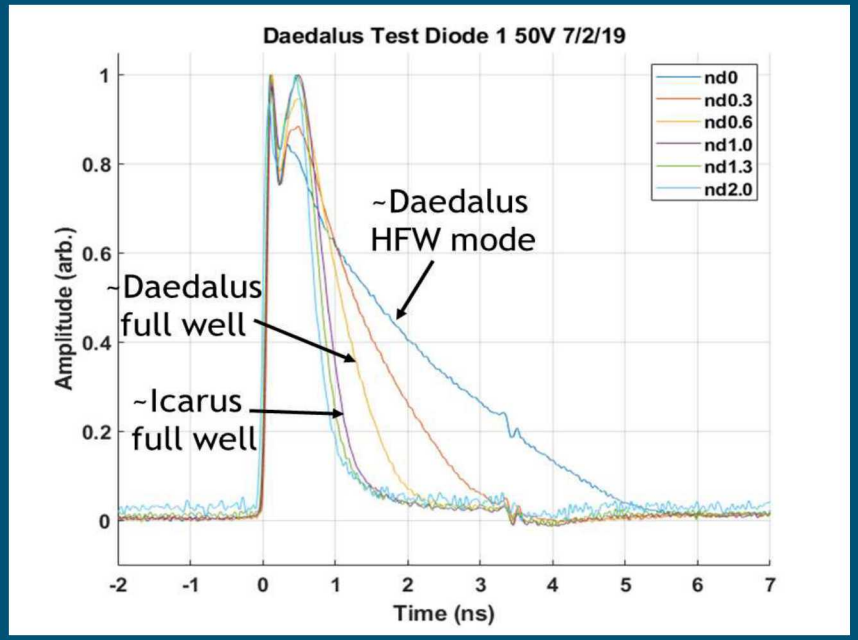


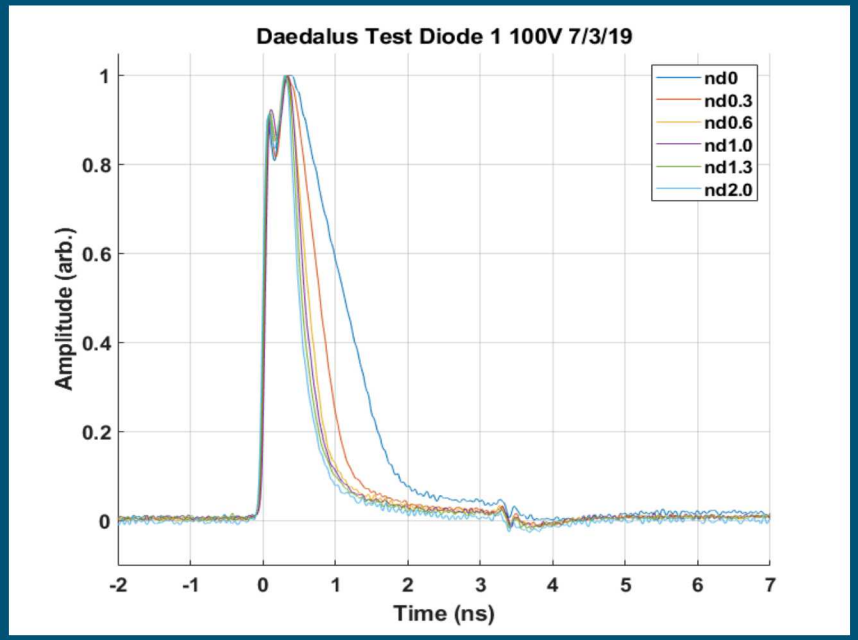
Z testing compared to modeling

The current silicon photodiode design has been identified as a limiting factor for system performance

Data collected at NIF and further investigated at Z have indicated diode speed is noticeable

- Highly dependent on photocurrent magnitude
- A modeling collaboration between SNL and NIF have verified this behavior
  - Bias dependent



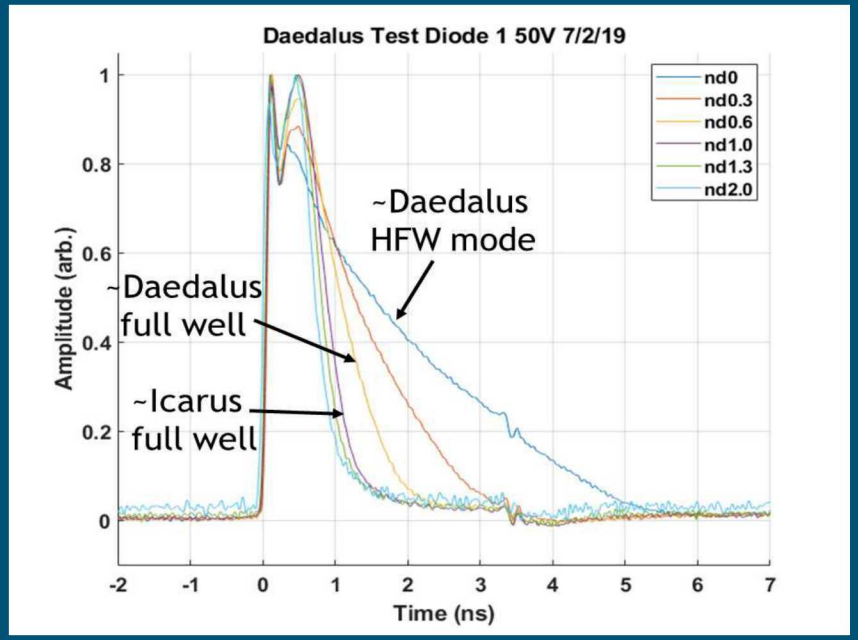


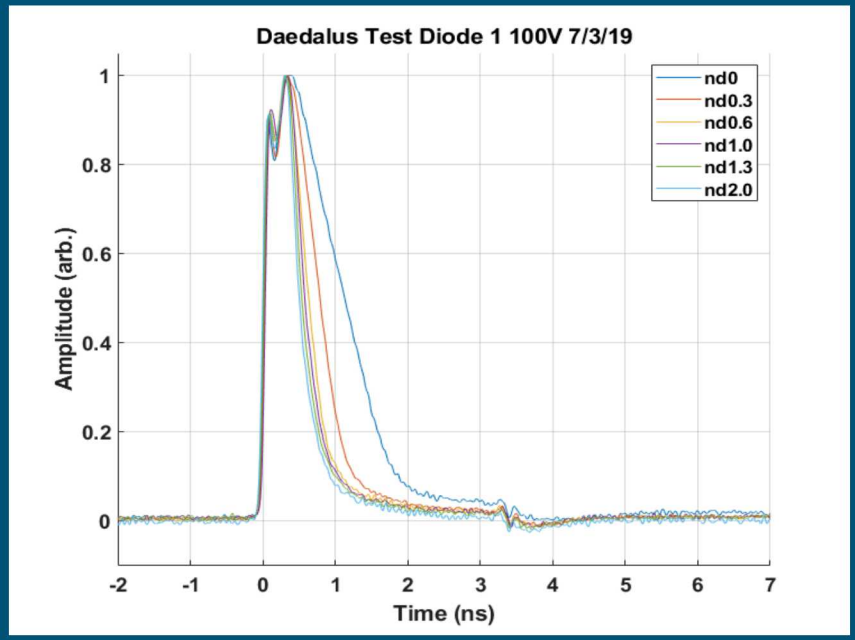
Z testing bias dependence data

The current silicon photodiode design has been identified as a limiting factor for system performance

Data collected at NIF and further investigated at Z have indicated diode speed is noticeable

- Highly dependent on photocurrent magnitude
- A modeling collaboration between SNL and NIF have verified this behavior
  - Bias dependent
  - Dictates a diode design capable of improve breakdown performance





Z testing bias dependence data

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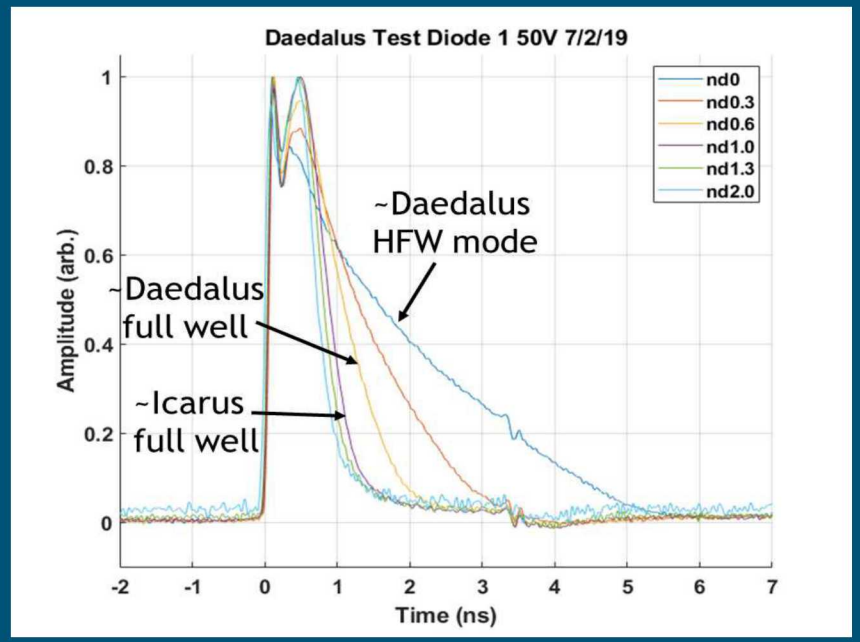
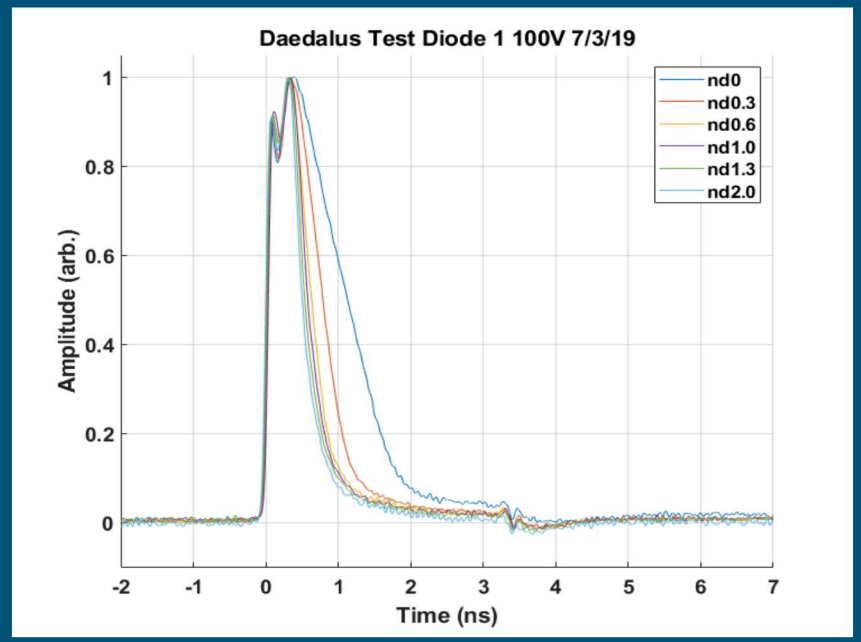
Data collected at NIF and further investigated at Z have indicated diode speed is noticeable

- Highly dependent on photocurrent magnitude
- A modeling collaboration between SNL and NIF have verified this behavior
  - Bias dependent
  - Dictates a diode design capable of improve breakdown performance

A new diode test reticle has been designed to investigate improved Si diode designs

- Expected tape out Q4, FY19
- Devices for testing expected Q3, FY20



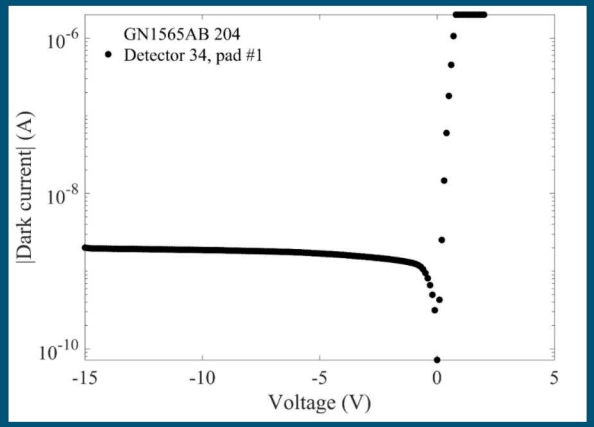


Z testing bias dependence data

Compound semiconductor diode work continues at SNL and LLNL in order to realize high energy diodes

SNL GaAs Diodes

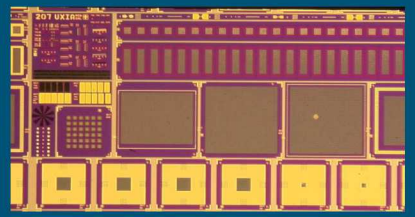
- FY19 Completed Milestones
  - Grow high purity starting material
  - Develop low processing temperature n-ohmic contacts
  - Design and fabricate a test design suitable for hybridization
  - Develop a process to electrically isolate GaAs arrays (pixelate)
  - Test a pixelated GaAs array hybridized to a fanout wafer
- FY20 Goals
  - Build and test a 0.5 Mpixel GaAs array bonded to Daedalus V1



Test Results of Pixelated GaAs Array

Device Description	Number of wafers
Process development structure	2
Standard structure, X = 4,000 nm	2
Standard structure, X = 20,000 nm	7
Standard structure, X = 40,000 nm	2

GaAs 3” Wafers Grown



GaAs Test Structure

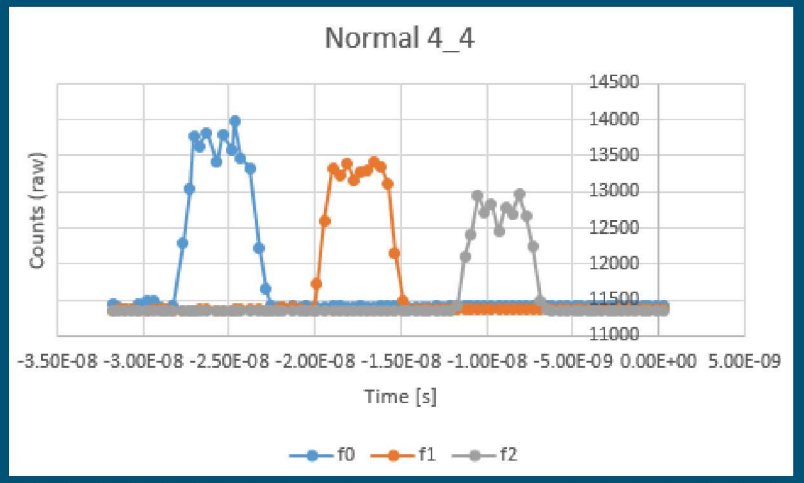
LLNL Ge Diode

- FY19 Completed Milestones
  - Simulated PIN Ge Diode design and performance
  - Setup partnership with LSRL for Epi Growth
  - Grew epitaxial Ge PIN photodiodes 6um, 17um, 30um, and 60um thick (and multi pass diodes 8um+8um)
  - Fabricated PIN diodes and performed electrical testing
  - Fabricated optically sensitive PIN photodiodes (packaging underway)
  - Plan to complete optical transient response tests and X-ray QE tests in the next 6 weeks
- FY20 Goals
  - Fabricate diode arrays (2x2, 4x4, 10x10)
  - Initiate X-ray imaging testing with arrays

Daedalus has had 8 days of laser lab testing at NIF

With only a few days of actual test time, the NIF team has collected a significant amount of test data

- Shutter profiles have been obtained

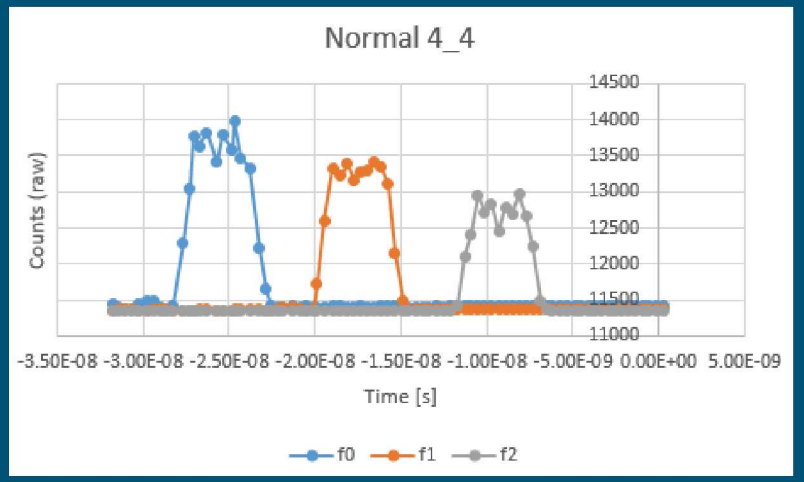


4-4 timing shutter profile

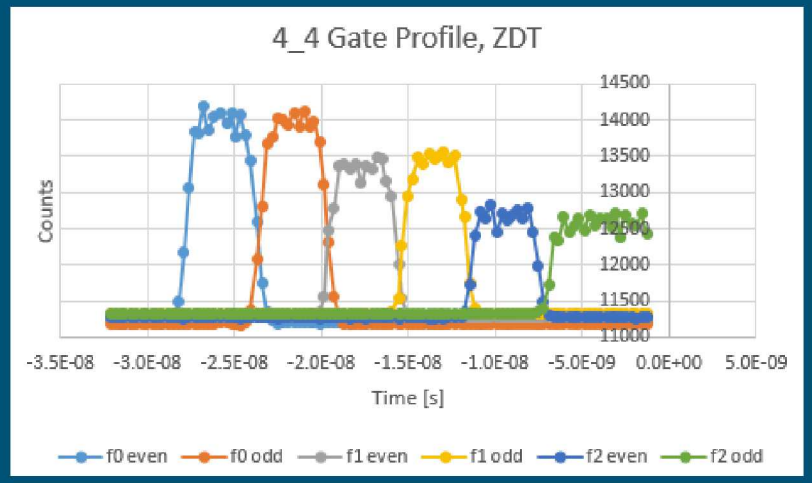
Daedalus has had 8 days of laser lab testing at NIF

With only a few days of actual test time, the NIF team has collected a significant amount of test data

- Shutter profiles have been obtained
- Zero-Dead-Time (ZDT mode is functional)
  - Firmware modification required to resolve last frame issue



4-4 timing shutter profile

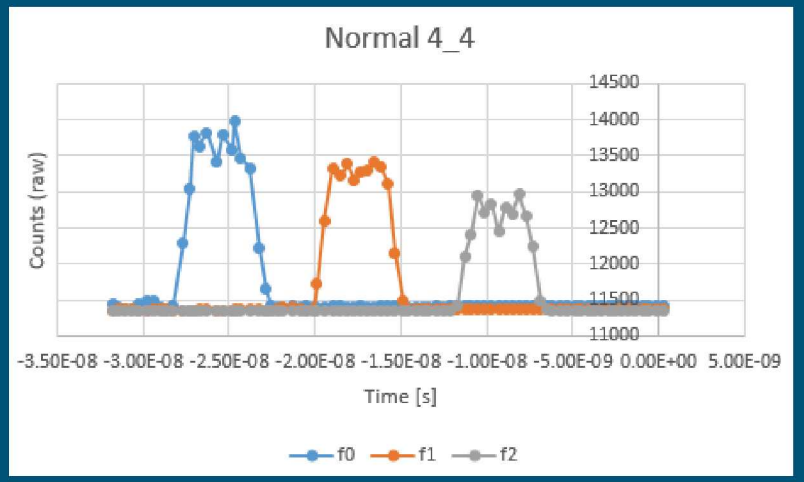


4-4 Zero Dead-Time (ZDT) shutter profile

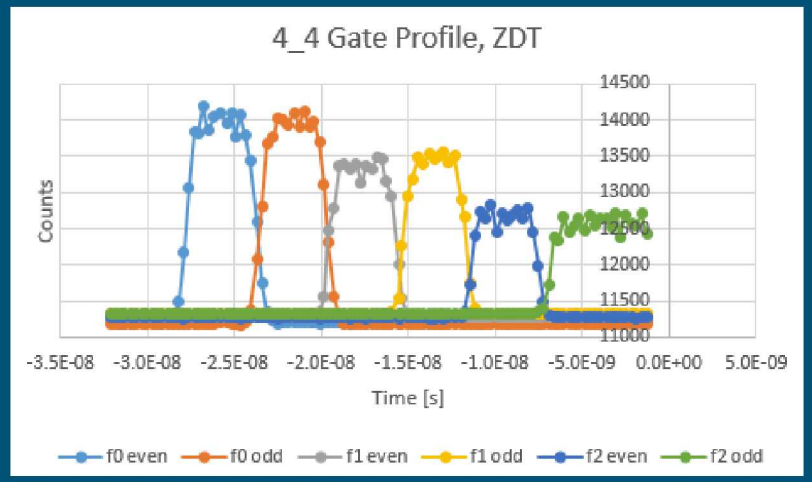
Daedalus has had 8 days of laser lab testing at NIF

With only a few days of actual test time, the NIF team has collected a significant amount of test data

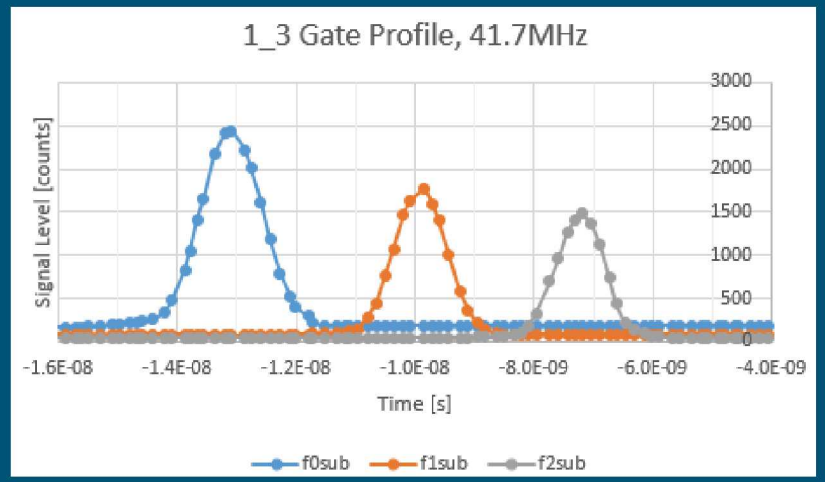
- Shutter profiles have been obtained
- Zero-Dead-Time (ZDT mode is functional)
  - Firmware modification required to resolve last frame issue
- 750 ps timing has been propagated through the entire timing chain in 1:3 timing mode
  - ~1 ns FWHM profile due to diode speed



4-4 timing shutter profile



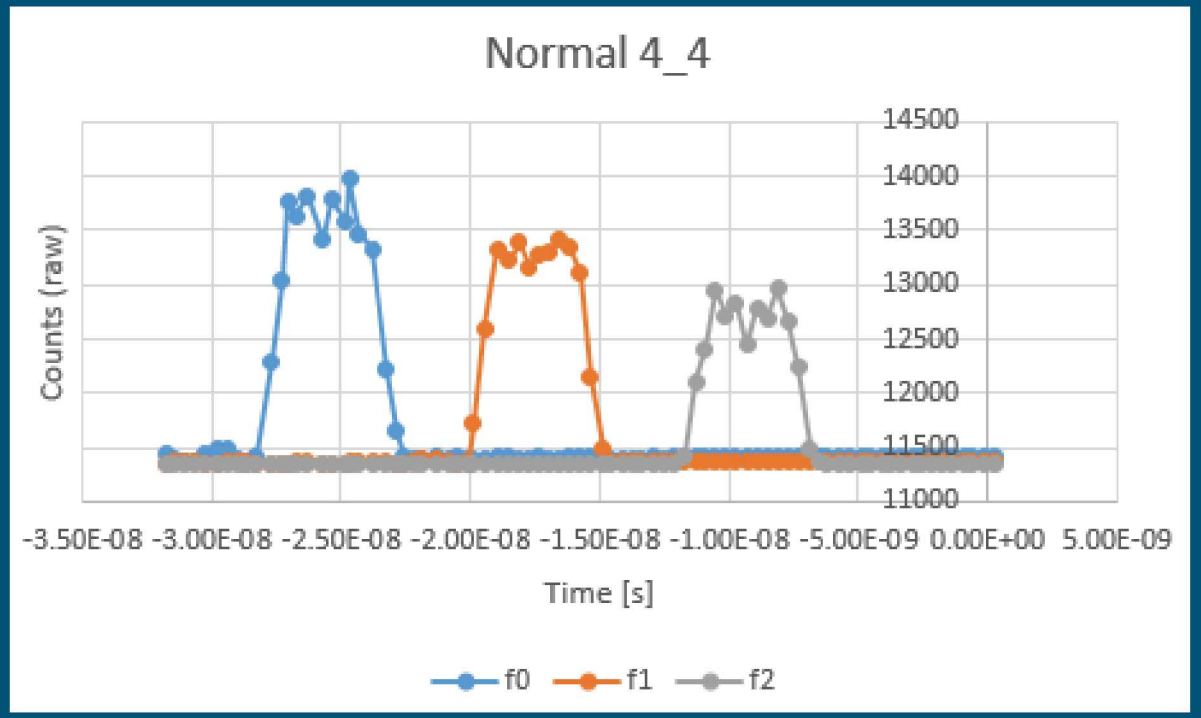
4-4 Zero Dead-Time (ZDT) shutter profile



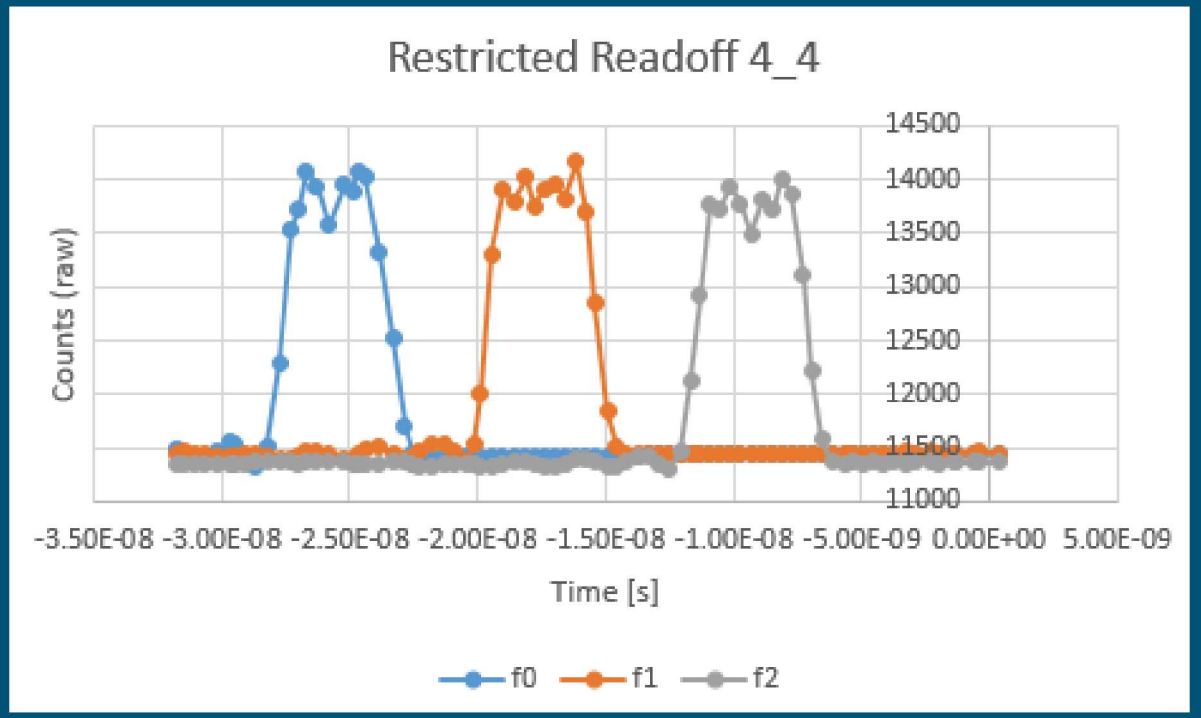
750 ps 1-3 shutter profile

Daedalus suffers from significant capacitor leakage

~6-8% charge bleeds off during a full array readout



Full array readoff

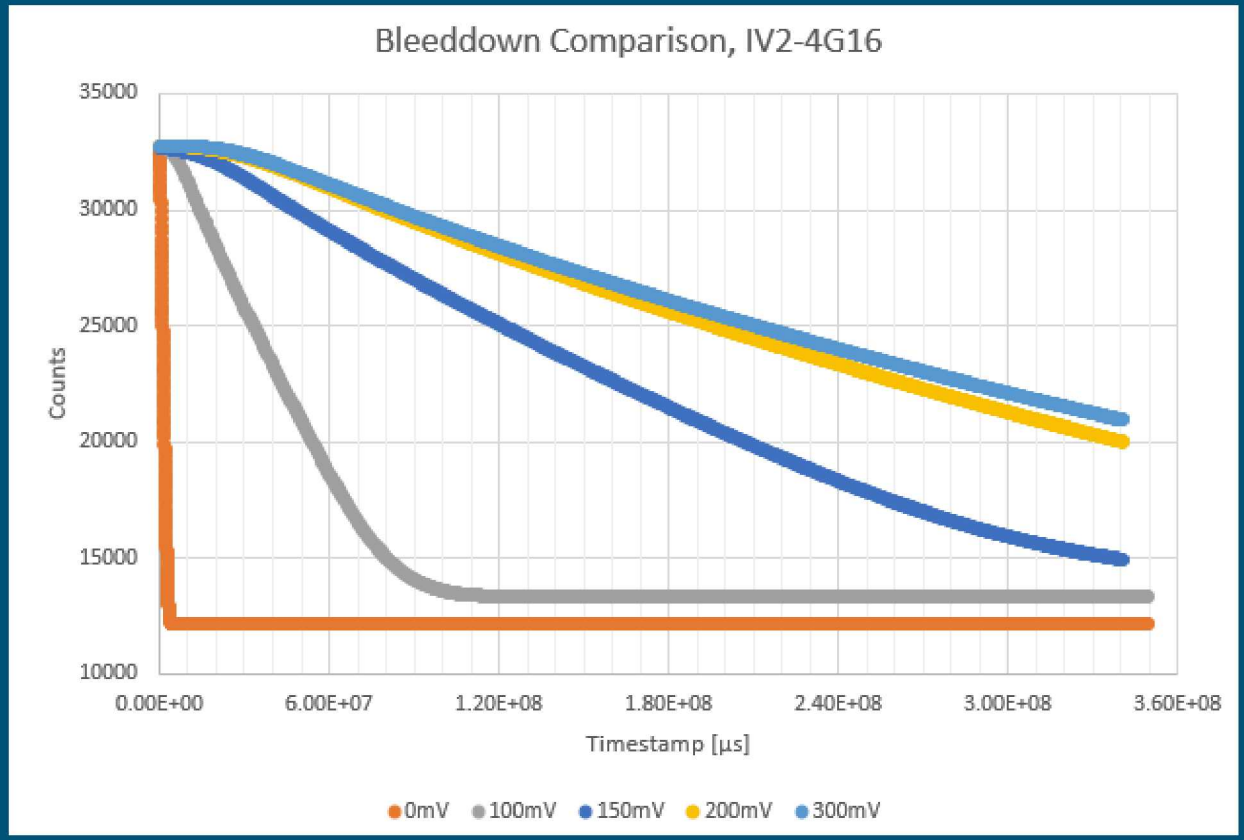


ROI readoff of ~200 rows

Daedalus suffers from significant capacitor leakage

Verified with Icarus

- CMOS7 subthreshold leakage models are insufficient and this mechanism was not identified in simulation
- Icarus has a tuning capability to mitigate leakage
- Daedalus removed this capability to improve on known limitations of Icarus at the time of Daedalus tapeout
- Redesign is simple to reintroduce, but impact to layout is significant



Daedalus V2 is in design and projecting a Q1 FY 20 tapeout

More testing should occur prior to tapeout to verify last untested blocks

- Interlacing functionality
- Digital hemisphere tuning cells
- Linearity/full well should be understood

The next generation ROIC design is in progress in the Jazz 130 nm process

Pixel array of Icarus/Daedalus like pixels to provide a useable image plane

No abut ability for first iteration

Independent quadrant control

Maximum pixel array size with a 25 µm pixel pitch is projected to be 1024 x 512

Test pixel banks leverage support circuitry needed for any design

Pixel design priority will be

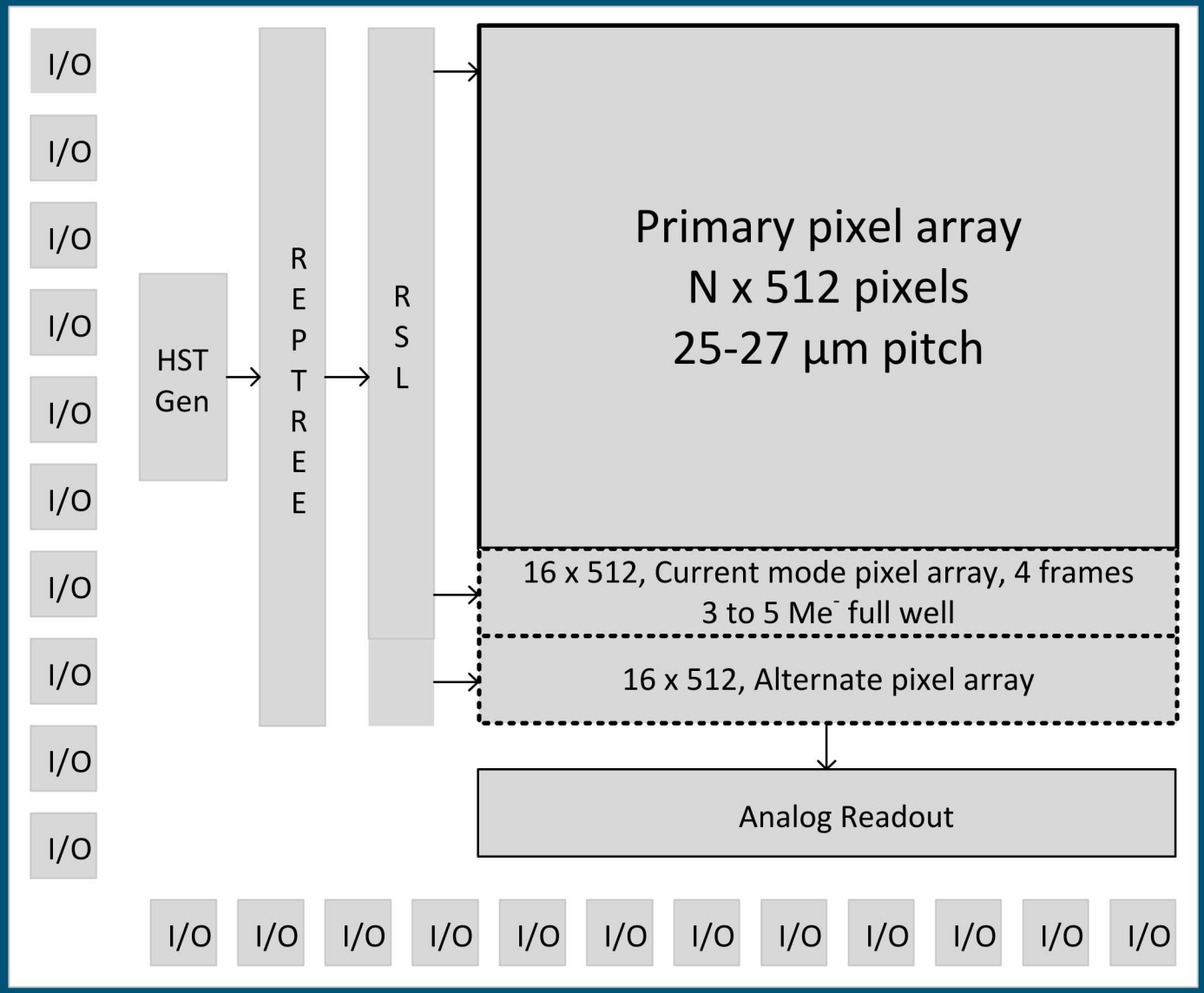
1. Icarus/Daedalus like, 4 frames
2. In-pixel timing, 6 frames
3. Current mode, HFW, 4 frames

Requirement	Next Gen
Array size	1024 x 512
Pixel size	25 µm
Number of frames	4-6
Min integration time	500 ps
Min inter-frame time	500 ps
Timing skew	< 10%
Gain errors	< 10%
Full well	500k-5 M e^-
Noise floor	250 e^-
Dynamic range	> 60 dB (11 bit)
Abutable	None

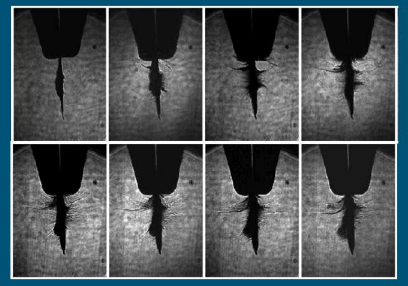
Next generation ROIC design is in progress in the Jazz 130 nm process

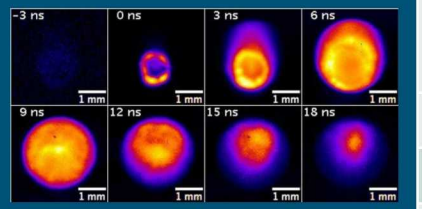
Building blocks of ROIC hierarchy are in progress

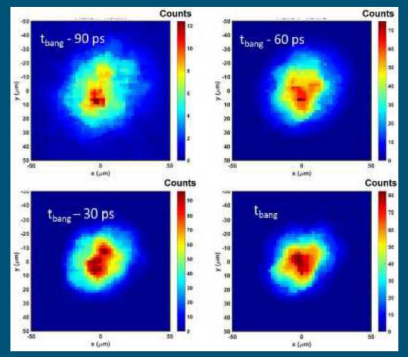
- Global timing circuitry is operating at 500 ps with good margin
- Icarus like pixel is LVS clean undergoing parasitic simulations
  - Significant effort has been put into pixel capacitor leakage mitigation
- 6 frame pixel layout is in progress
  - Leakage mitigation is more difficult with this architecture
- Design work is still ongoing but priority has been reduced for Daedalus V2 redesign

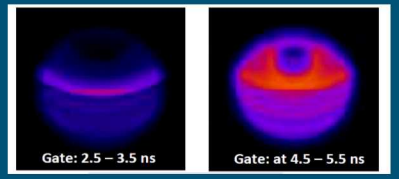


Myriad diagnostics leveraging hCMOS sensors span the entire field of HED science and facilities



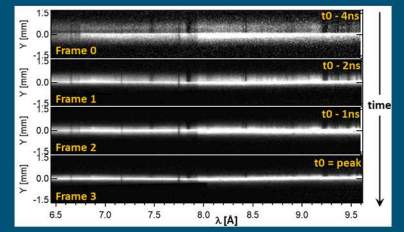


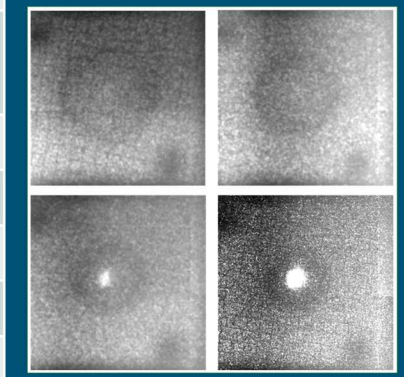


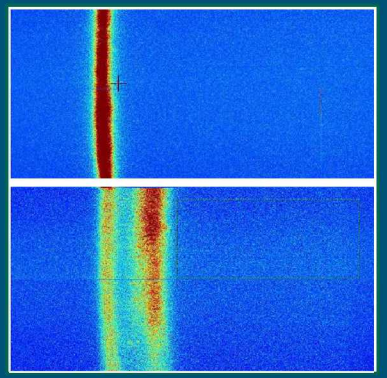


Application	Program	NIF	Z	Other
Laser Source Imaging	ICF, C1,C4	G-LEH	FOA Imager	CEA-DMX
Hot spot imaging	ICF, C1	SLOS-KBO	SCI	Omega-SLOS-TRXI
		Toroidal Imager	SLOS-Z	
Backlighting	ICF, C1	SLOS-CBI	Crystal Backlighter	
Diffraction	C2	TARDISt	XRD	SLAC
Opacity	C4		CCPt	
Shadography	ICF		Blastwave	
Hot Spot Spectroscopy	ICF, C1		XRS3t	
High Energy Imaging	ICF, C2, C4	Strength	Wolter	SLAC
			CRITRt	

Green = Fielded
Orange = In progress
Black = Proposed





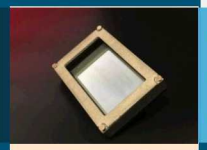
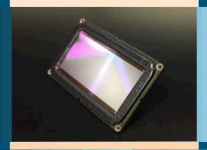
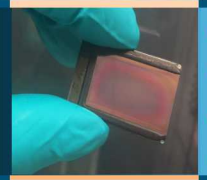
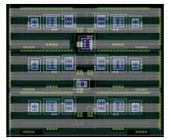


hCMOS sensor technology continues to move forward with an emphasis on understanding existing sensor, more frames, faster integration time, and higher full well

FY20 Focus

- IcarusV1/V2 sensor realization (hybridization, packaging, and delivery)
- Daedalus V2 design/fabrication
- Tantalus design
- Faster Si diode fabrication and test
- GaAs diode array fabrication

FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23
Hippogriff	Icarus V1		Icarus V2	DaedalusV1		Daedalus V2/HE		Tantalus
Delivered	*Delivered*		*Delivered*	*In Progress*				

Furi / Hippogriff		▪ 1st full-scale multi-frame sensors ▪ 1.5-2ns minimum shutter ▪ Optimized for 1-10 keV x-ray detection
IcarusV1/ IcarusV2		▪ 1st cameras compatible with pulse-dilation ▪ 1 ns min. shutter with 2 or 4 (Icarus-2) frames per hemisphere ▪ Optimized for soft x-ray, visible, and e- detection
Daedalus/ DaedalusV2&HE		▪ 3 frames per hemisphere (≥6 frames with interlacing) ▪ 1-side abuttment for spectroscopy and z-pinch imaging applications ▪ Large well for high energy x-rays while maintaining low end sensitivity ▪ **Daedalus HE will use GaAs/Ge detector**
Tantalus		▪ 1st sensor in new foundry process **Design goals include** ▪ 6 frames per pixel w/ independent quadrants (≥12 frames with interlacing) ▪ 0.5 ns minimum shutter
	UXI Sensors	

Backup

FY19 and FY20 UXI Sensor Needs at NIF Updated: 1/8/2019 Arthur Carpenter

DIAGNOSTIC	DIAGNOSTIC DELIVERY (FY/QTR)	USER	SENSOR USED	Icarus1	Icarus2	Icarus2 (spare)	Daedalus	Daedalus (spare)	SENSOR NEED DATE	Backup Sensor
hSLOS-KBO	FY19/Q4	NIF	Icarus2-ARC-8um		2	1			FY19/Q1	Icarus2
G3D (XRDt p1)	FY19/Q2	NIF	Icarus1	2					FY19/Q1	Icarus2
G3D (XRDt p2)	FY19/Q4	NIF	Daedalus-100um Si				2	1	FY19/Q3	Daedalus-25um
HEXI Phase 1	FY19/Q4	NIF	Daedalus-200um Si				2	1	FY19/Q2	Daedalus-100um / 25um
GLEH2	FY19/Q4	NIF	Icarus2-ARC-25um Si		2	1			FY19/Q2	Icarus1 or Daedalus-25um
hDISC	FY19/Q4	NIF	Daedalus-25um Si				1	1	FY19/Q2	Icarus1
FIDDLE (XRDt Full)	FY20/Q1	NIF	Daedalus-100um Si				4	2	FY19/Q4	Daedalus-25um
GLEHI (CEA-LMJ)	FY18/Q4	NIF/CEA	Icarus1	1					FY18/Q2	Icarus1
PDS Imager*	FY19/Q3	NIF	Icarus2-ARC-25um Si		1	1			FY19/Q1	NA
SLOS1-CBI upgrade	FY20/Q1	NIF	Icarus2-ARC-8um Si		1	1			FY19/Q4	NA
HEXI Phase 2	FY20/Q4	NIF	Daedalus-50um_GaAs/Ge				2	1	FY20/Q3	NA
SLOS1-TRIXI upgrade	FY20/Q1	LLE	Icarus2-ARC-8um Si		1	1			FY19/Q4	Icarus2
Gated NIS*	FY20/Q1	NIF	Icarus2-ARC-25um Si		1	1			FY19/Q4	Icarus2
SLAC-t2	FY18/Q4	LCLS	Icarus2-25um Si		1	1			FY18/Q1	NA
SLAC-t3	FY20/Q1	LCLS	Daedalus-200um Si				1	1	FY19/Q4	Daedalus-25um
2D Visar*	TBD	NIF	TBD		1				FY19/Q2	PoP with Icarus1
LDRD SwIF*	TBD	NIF	TBD	1	1				TBD	TBD
2D OTS*	TBD	NIF	TBD	1	1				TBD	TBD
2D Visar (LLE)*	TBD	Omega	TBD	1	1				TBD	TBD
2D OTS (LLE)*	TBD	Omega	TBD	1	1				TBD	TBD

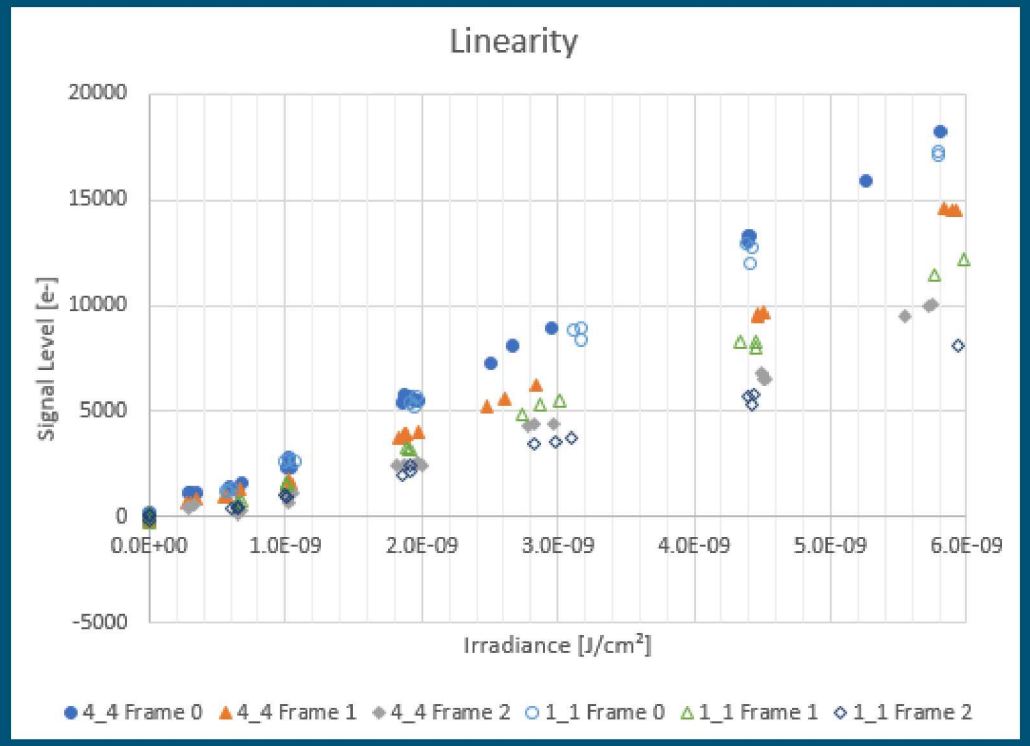
*Preliminary Concept

	Icarus1	Icarus2	spares	Daedalus	spares
total:	7	14	7	12	7

Daedalus has had 8 days of laser lab testing at NIF

An initial linearity sweep has been conducted

- Low end linearity is good

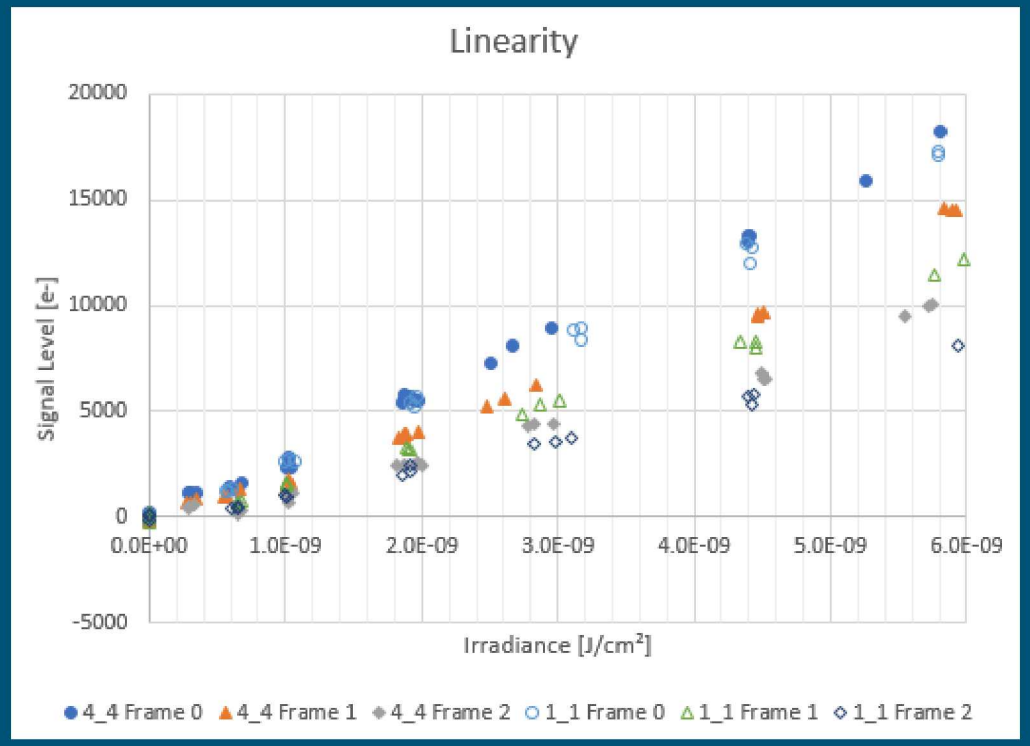


Full linearity sweep

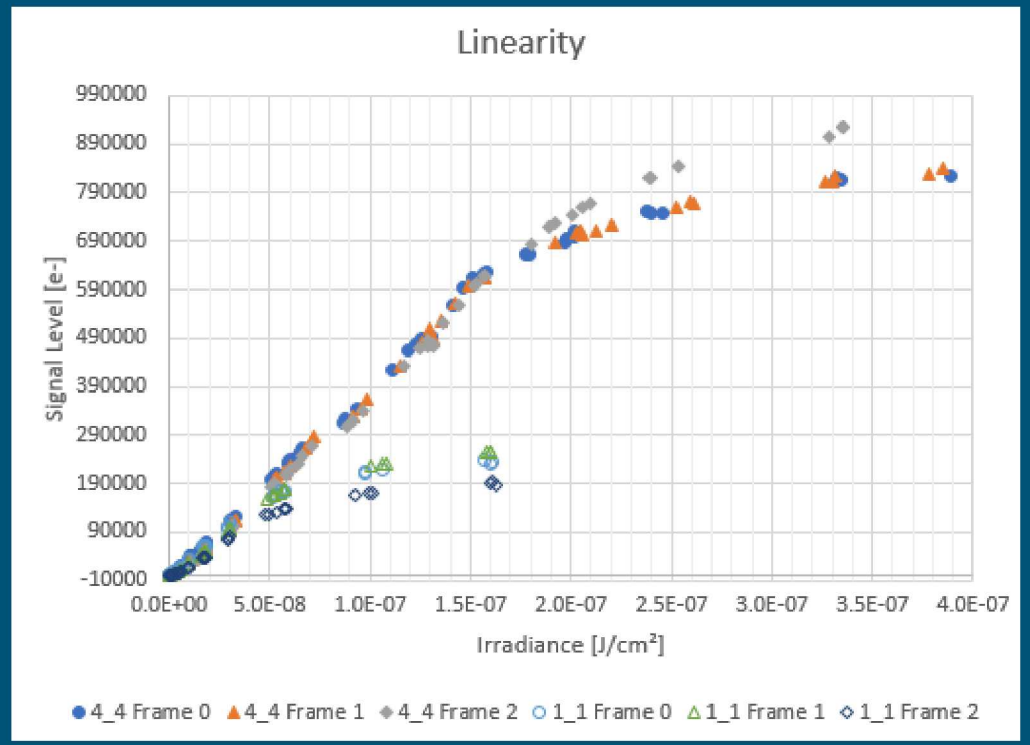
Daedalus has had 8 days of laser lab testing at NIF

An initial linearity sweep has been conducted

- Low end linearity is good
- Full well rolls off sooner than expected
  - Further investigation is needed on this



Full linearity sweep



Low signal linearity sweep