Ultra-fast X–ray Imaging

PIXEL 2022 – 12/12/2022
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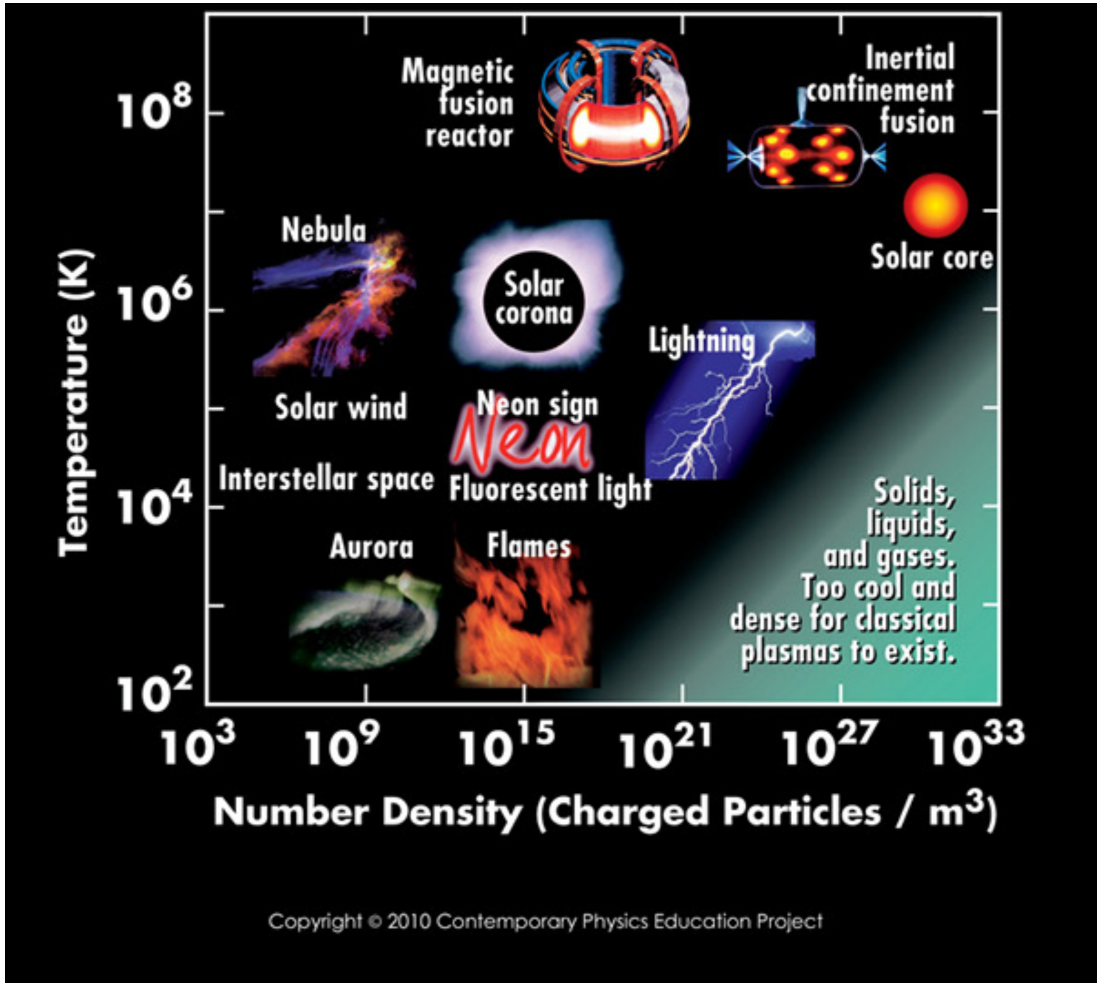
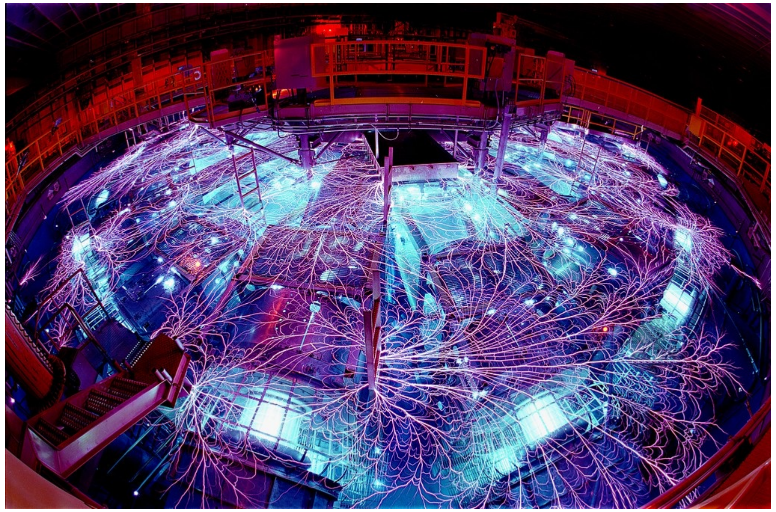
High energy density physics studies matter and radiation under extreme conditions (Energy densities > $10^{11} J/m^3$)

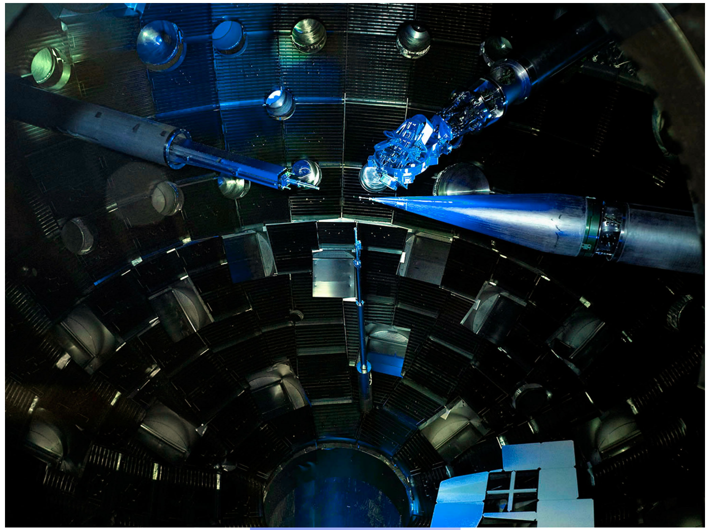
- These scientists study plasmas to investigate:
  - Planetary interiors
  - Inertial Confinement Fusion (ICF)
  - Other astrophysical phenomena



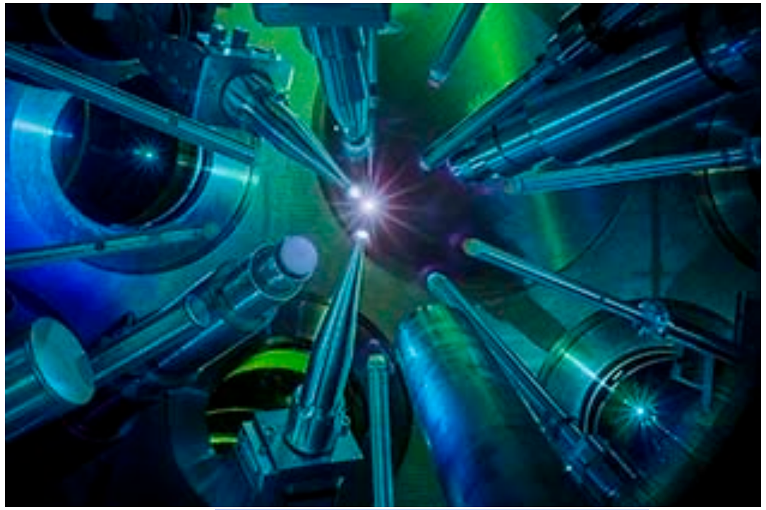
Laboratory facilities exist to study these phenomena



Z-Machine, SNL

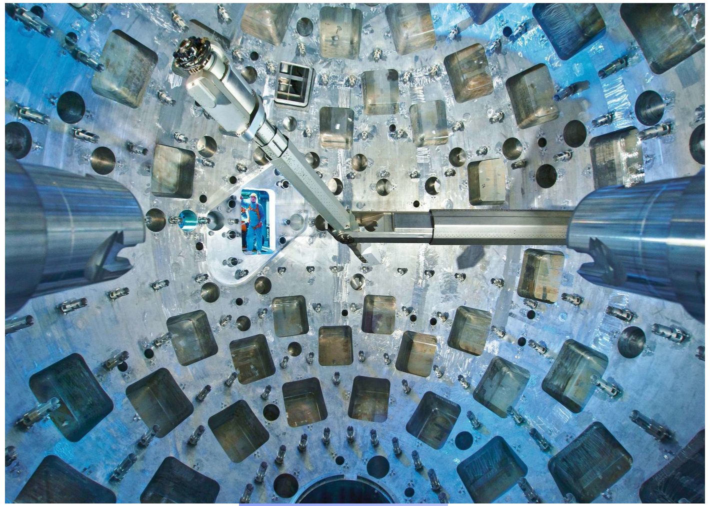


NIF, LLNL

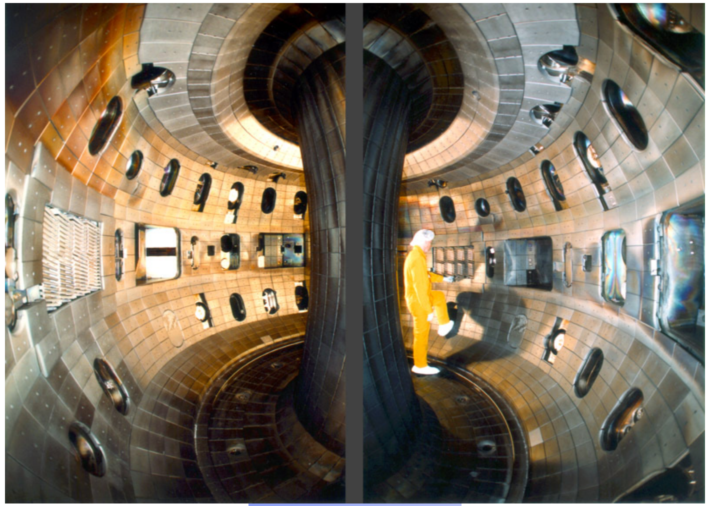


Omega, U of Rochester

LCLS/MEC, SLAC



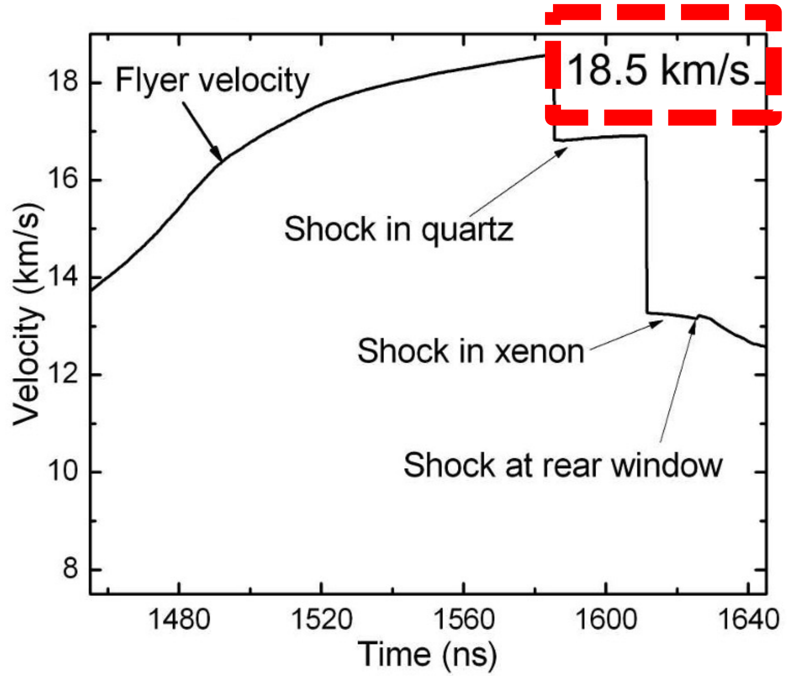
LMJ, CEA



DIII-D, GA

The HEDP diagnostic problem

- These experiments evolve on the picosecond to nanosecond timescale



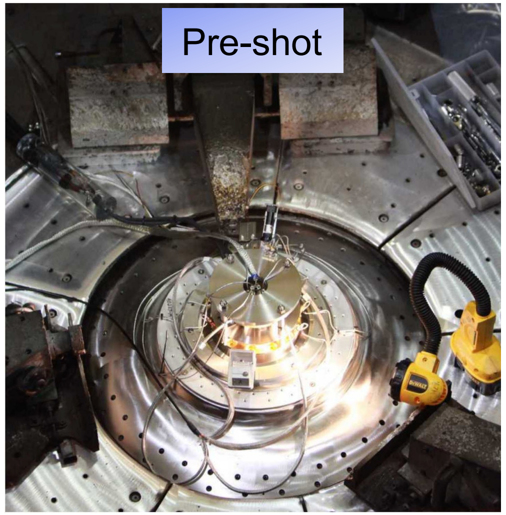
Material is accelerated to extreme velocities

S. Root et al., Phys. Rev. Lett. 105, 085501 (2010).

The HEDP diagnostic problem

- These experiments evolve on the picosecond to nanosecond timescale
  - Single shot, non-repeatable experiments
    - Destructive environments abound
    - Each shot is expensive
      - Need to maximize data obtained on every shot

Z-machine target chamber



The HEDP diagnostic problem

- These experiments evolve on the picosecond to nanosecond timescale
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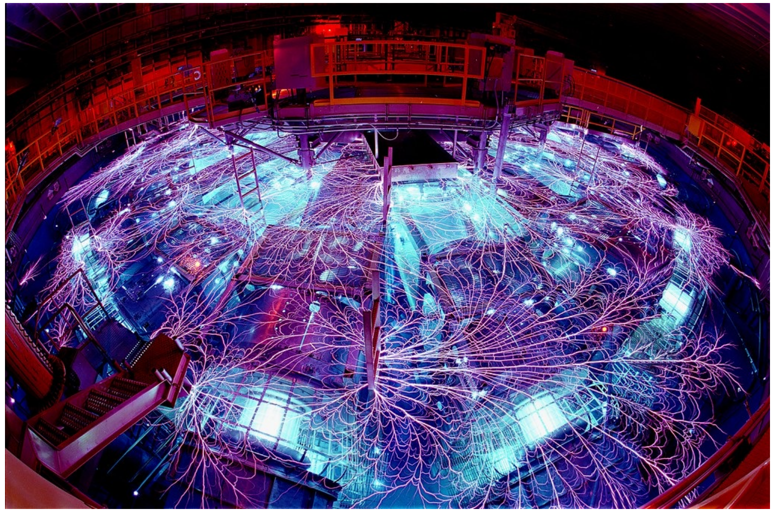
      - Need to maximize data obtained on every shot
  - High EMP and rad dose rate



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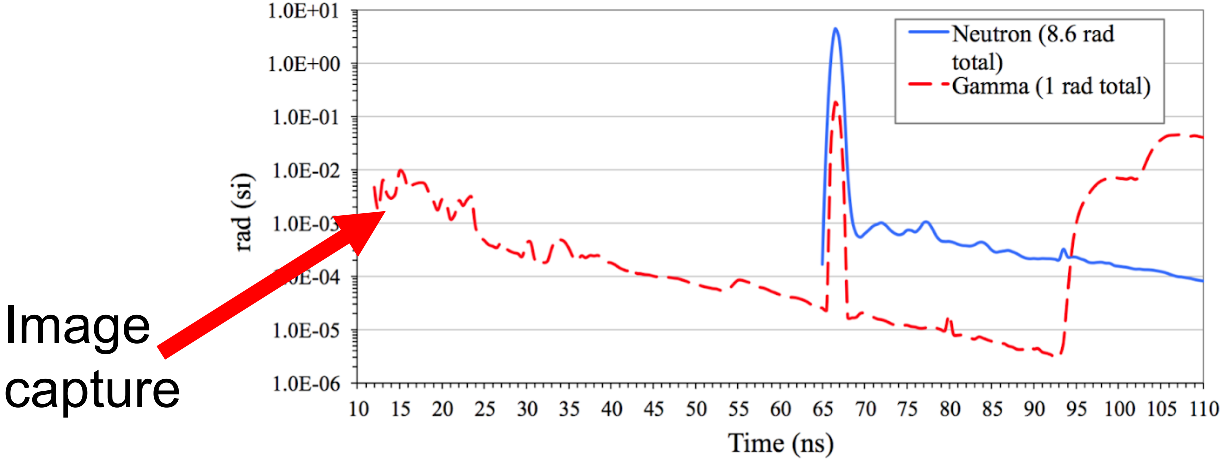

Dose-rate is the primary concern

The HEDP diagnostic problem

- These experiments evolve on the picosecond to nanosecond timescale
  - Single shot, non-repeatable experiments
    - Destructive environments abound
    - Each shot is expensive
      - Need to maximize data obtained on a single shot
  - High EMP
    - Complicated to field low noise microelectronics
  - Time integrating diagnostics have low SNR due to high background radiation

SNR is critical to quality data

The HEDP diagnostic problem

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  - Single shot, non-repeatable experiments
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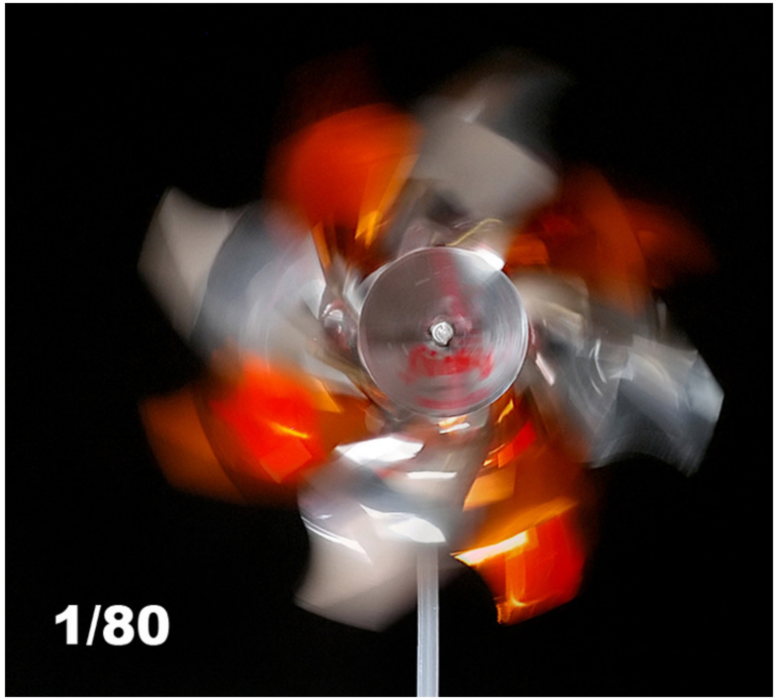
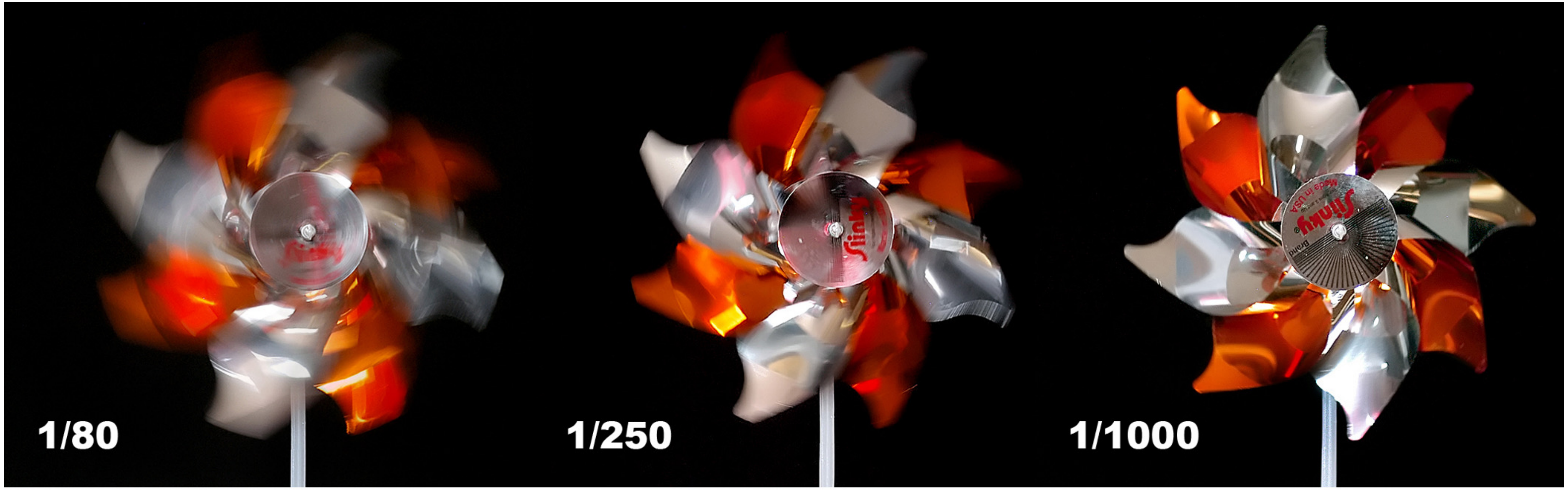
  - Time integrating diagnostics have low SNR due to high background radiation
  - Time integrating diagnostics also suffer from motional blur



Fast shutters mitigate motional blurring

Fast shutters reduce motional blurring

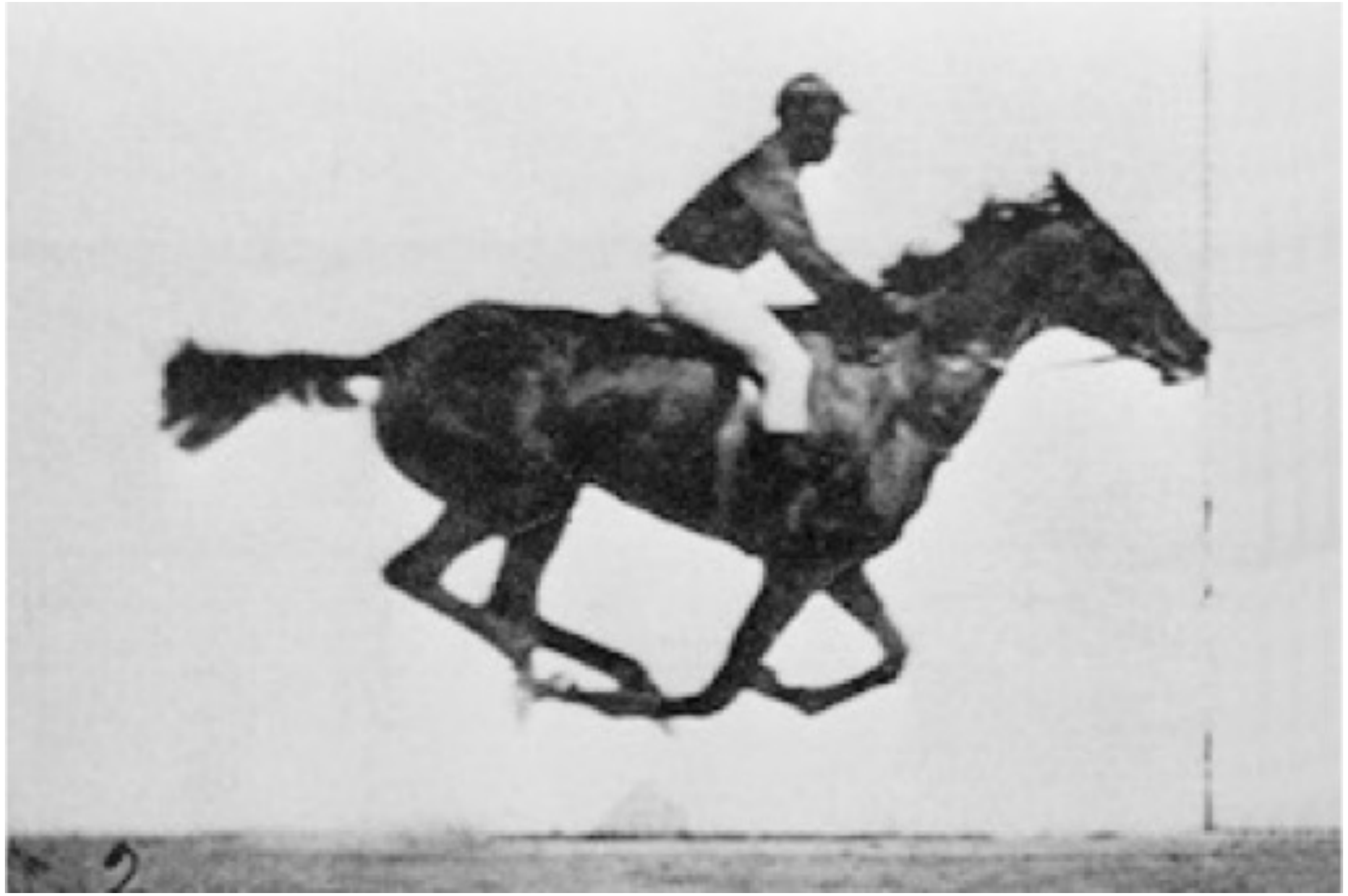


SLOW SHUTTER SPEED FAST

BLUR MOVEMENT STOP

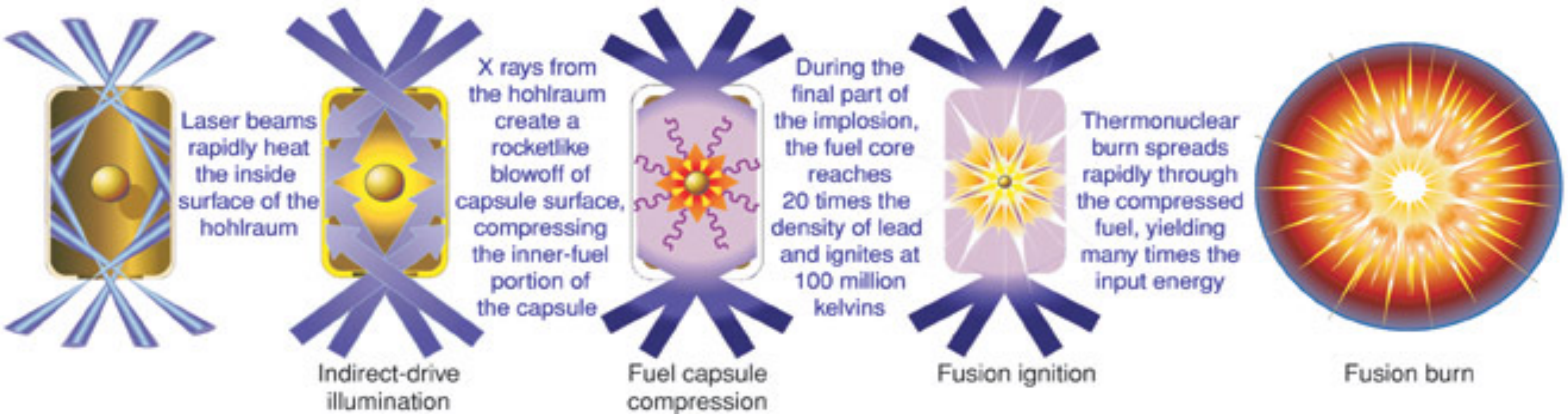
Multiple frames reveal the evolution of the experiment

Multiple frames reveal the evolution of the experiment



"A picture is worth a thousand words. A movie is worth a thousand pictures"
Joe Kilkenny, LLNL

Why does this matter to HEDP/ICF research?



Why does this matter to HEDP/ICF research?

Time Integrating

All events are superimposed. Poor SNR, Motion blurring

Fusion burn

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Single frame, time-gated

Single frame. Captures a single point in time. Not good for non-repeatable experiments.

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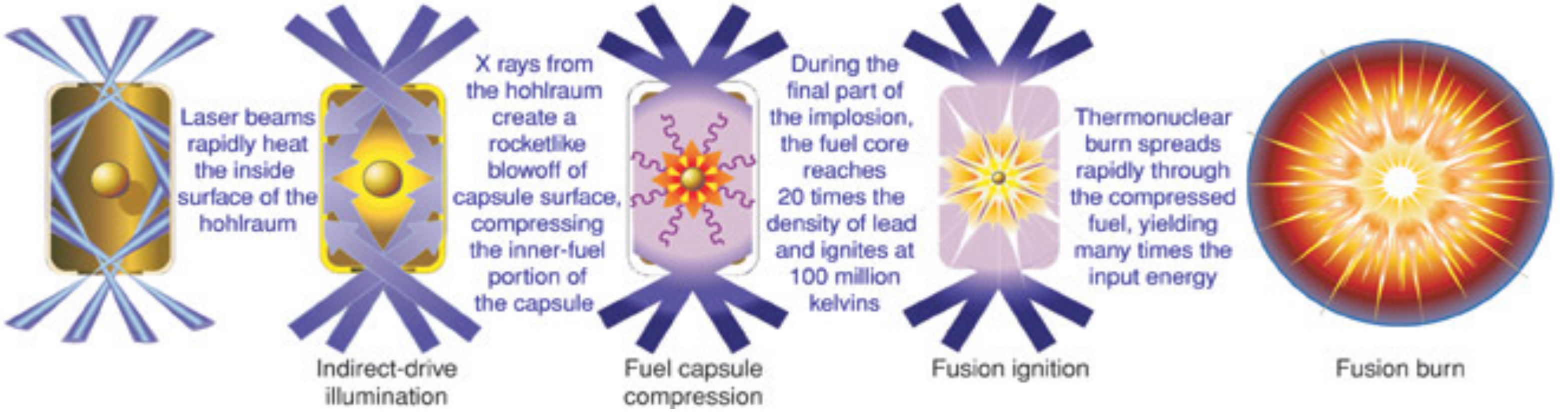
Single frame, time-gated

Single frame. Captures a single point in time. Not good for non-repeatable experiments.

Fusion burn

Multi-frame, time-gate



Most facilities have used well understood analog solutions to date

Image plate

- Excellent DR and spatial resolution
- Time integrating, susceptible to background radiation, poor SNR
- Expensive post processing and film pack exchanges

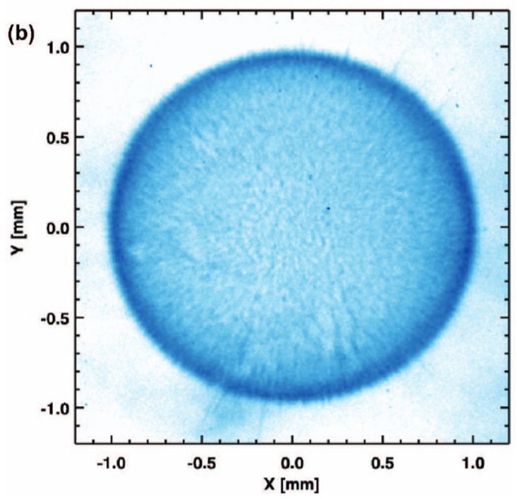


Image plate, ICF capsule implosion

Bennett, et al., Rev. Sci. Instrum. 77, 10E322 (2006)

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Gated MCPs

- Fast time gate
- Suffer from gain errors
- Poor DR
- Require significant, ongoing calibration efforts
- Image stored in phosphor, susceptible to background radiation
- Cannot support advanced optics that require a single line of sight

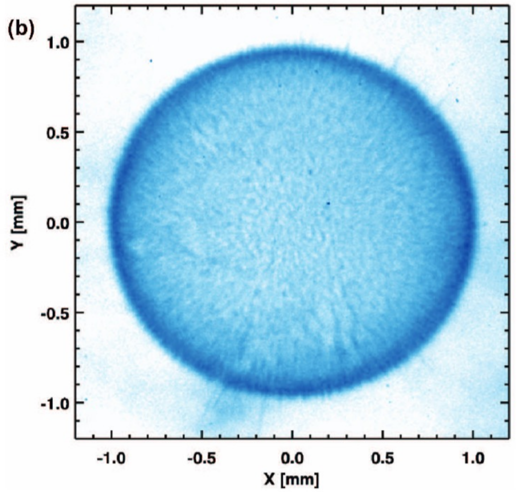
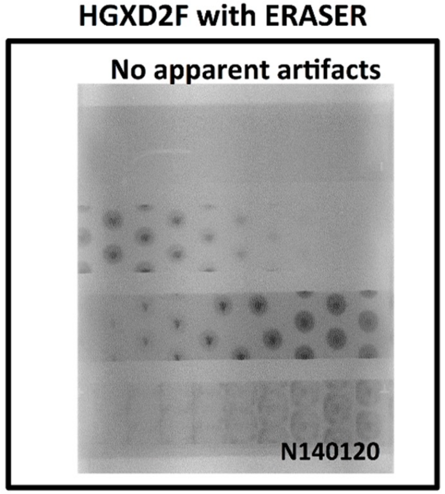


Image plate, ICF capsule implosion



MCP data, X-ray framing camera

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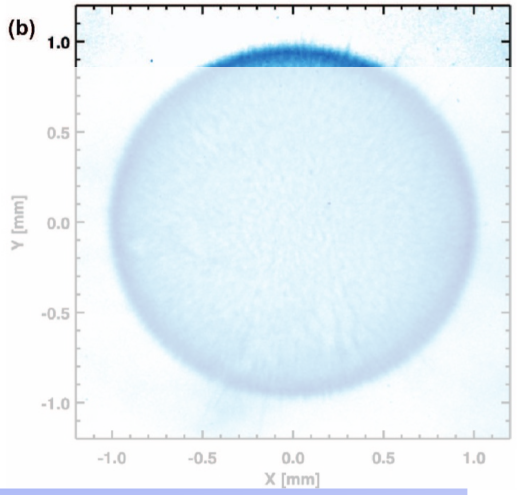

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Can we improve performance through with solid-state imaging?

losion

Gated MCPs

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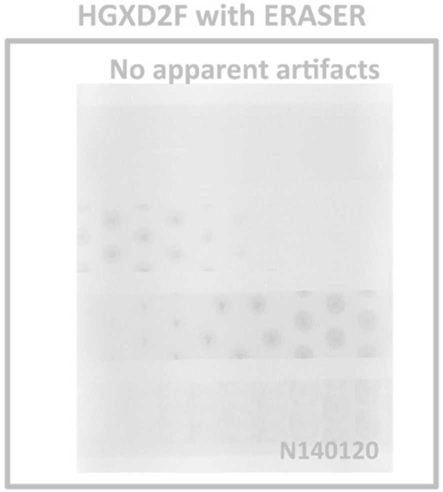
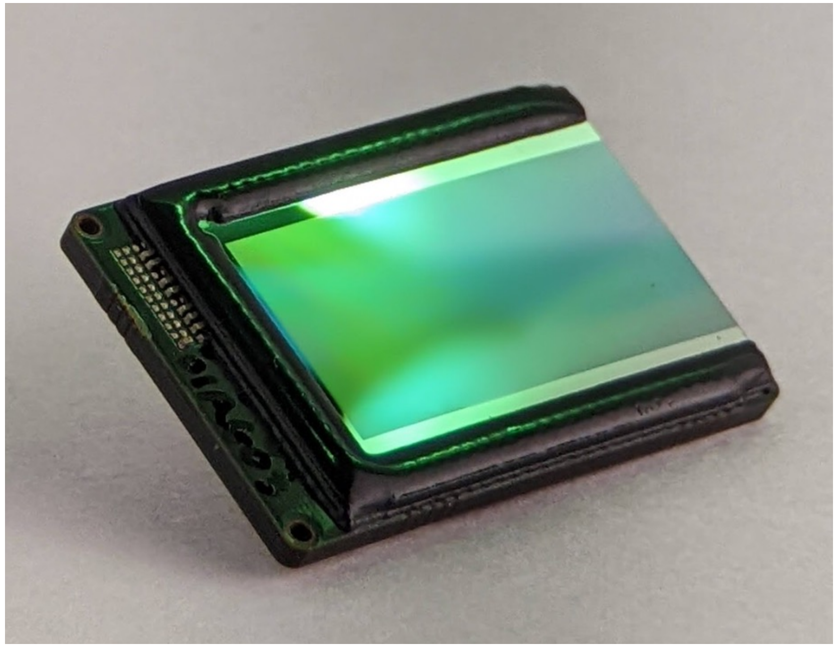


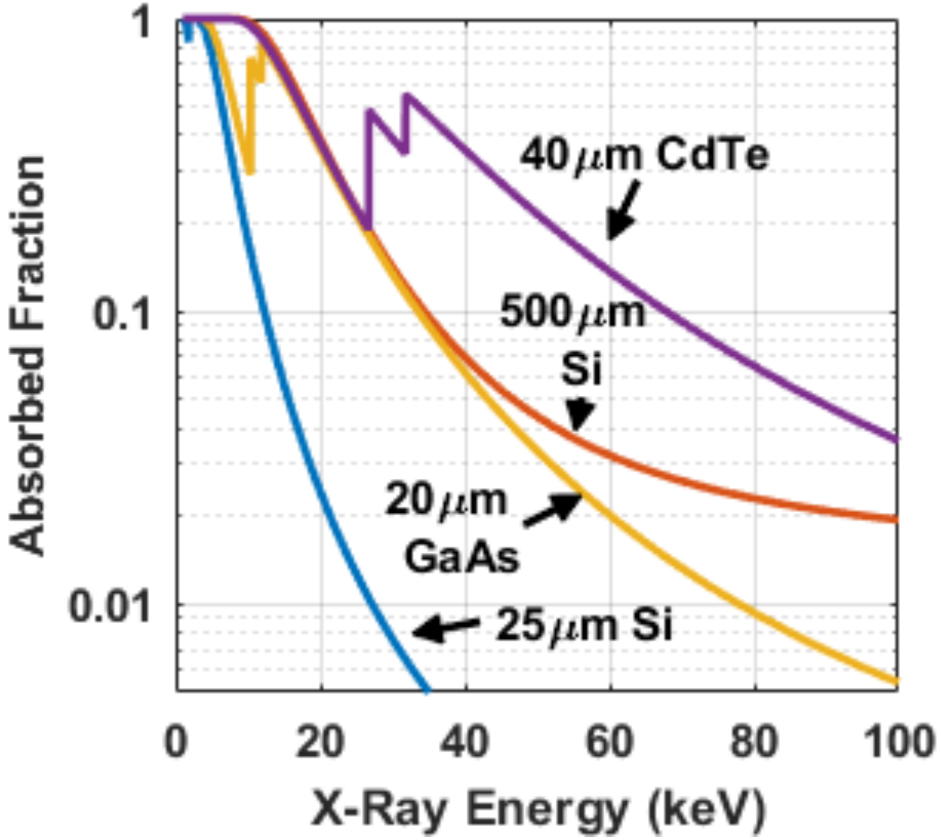
MCP data, X-ray framing camera

Burst-mode, hybrid-CMOS (hCMOS) sensors developed at Sandia National Laboratories offer a solid-state solution to the HEDP community

hCMOS ROICs can be hybridized to different detectors to look across a variety of the electromagnetic spectrum

- Visible light
- Energetic electrons 1-10 keV
- Soft X-rays 2-10 keV
- Hard(er) X-rays 10-50 keV





X-ray absorption vs energy for various materials

Looker, 2019

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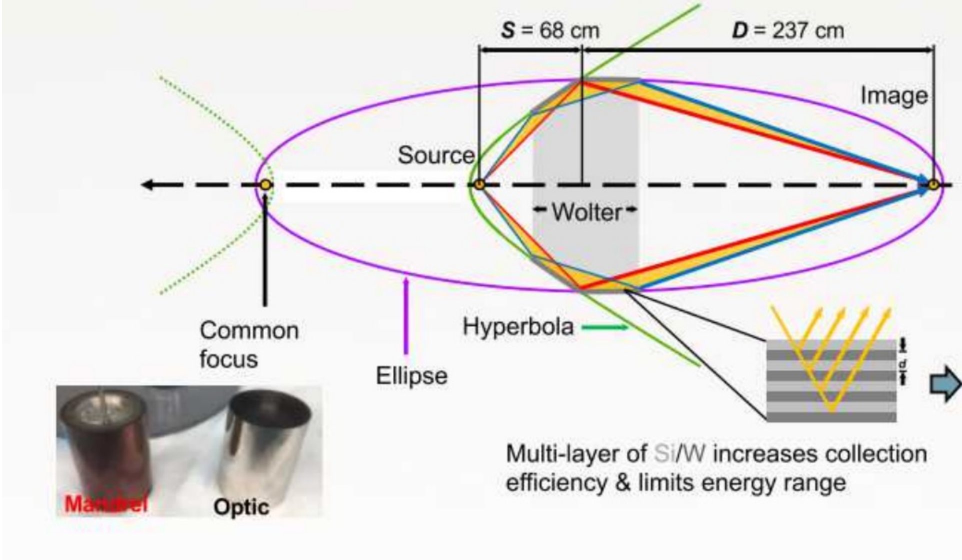
hCMOS sensors can also be mated to different "Lenses" depending on application

- Pinholes
- Curved crystals, Wolter optics
- Tele-temporal lens

hCMOS sensors are compact and can be tiled

Operate un-cooled in vacuum

Digital readout = instant access to data



Wolter optic on Z machine

D.J. Ampleford, 2018

Burst mode imagers store each frame of image data in-pixel to achieve high-speed operation

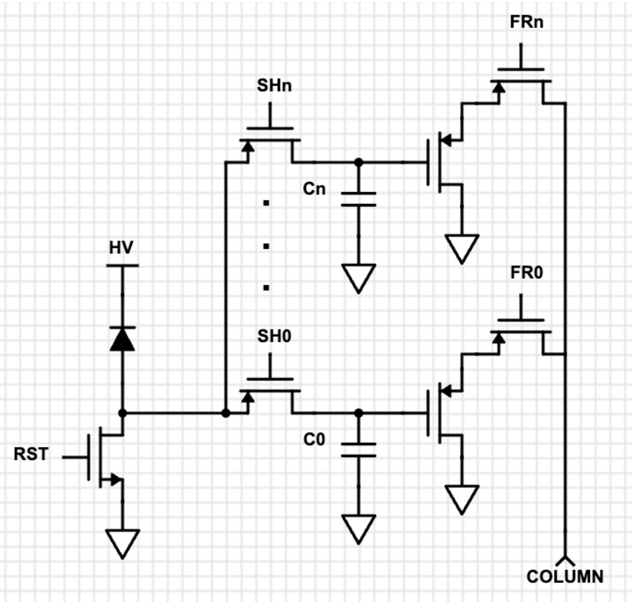
Configure the desired timing mode

- Pre-shot (ms)

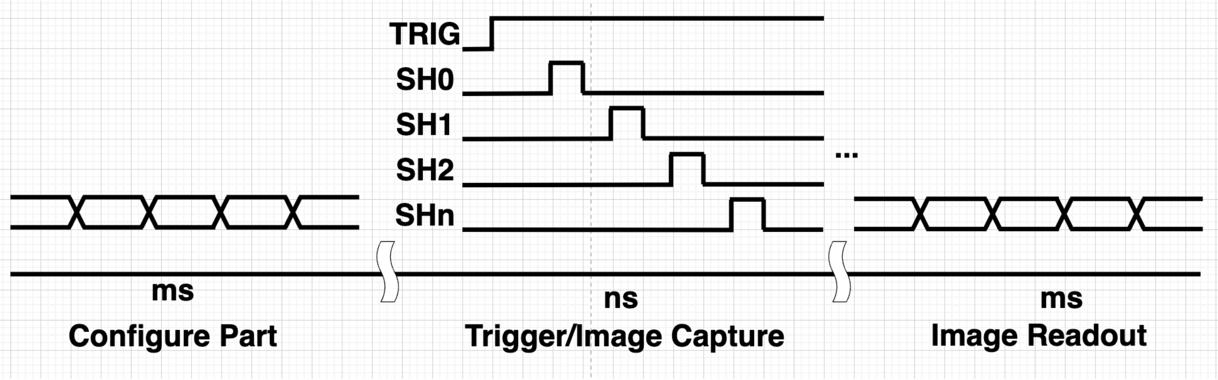
Trigger and capture and store images in-pixel

- Shot (ns)

Read off image data on a slow, millisecond timescale after background EMI/radiation has dissipated



Multi-frame unit pixel



Operational stages

ROIC design goals were developed to satisfy a diverse diagnostic user base

Large detector area
- Expensive to lens X-rays
- Large (10's of mm) timing propagation lengths make it difficult to maintain high-speed signals

Fine spatial resolution
- There is a trade off for number of frames stored in-pixel and full well

User programmable timing to satisfy a broad variety of experiments

Low jitter operation is required for facility synchronization

Radiation hardened

Requirement	Goal
Array size	1024 x 512
Pixel size	25 - 40 um
Number of frames	4-24
Min integration time	< 2 ns
Min inter-frame time	< 2 ns
Timing skew	< 10%
Frame-Frame gain error	< 10%
Full well	500k e-
Noise floor	< 500 e-
Dynamic range	> 60 dB

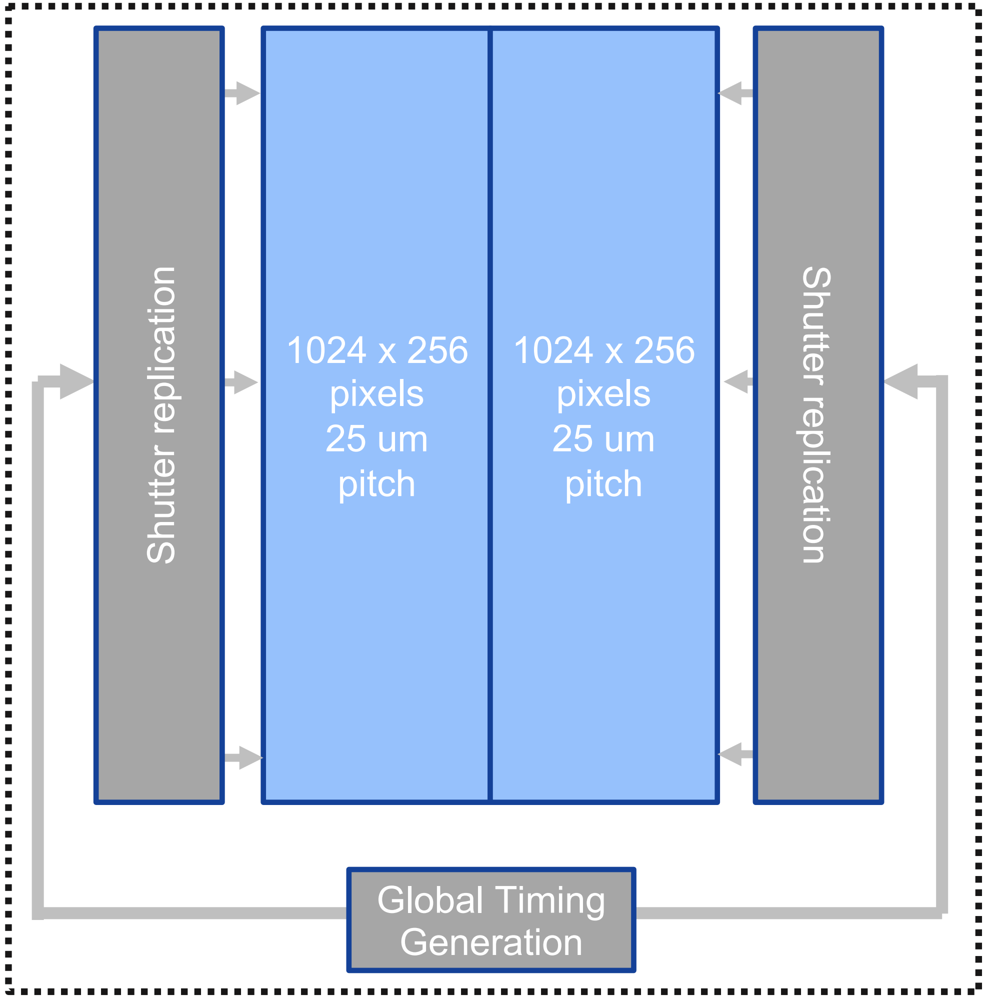
The Icarus sensor has been deployed to 5 facilities in > 12 diagnostics

Specs:

- 1024 x 512 pixels @ 25 um pitch
- 4 frames per-pixel
- 500 k e- full well
- 300 e- noise floor
- > 60 dB dynamic range
- 1.5 ns integration time
- 2 ns inter-frame time

Features:

- Digitally programmable shutter timing
- Independent left/right array shutter timing
- 0.35 um CMOS7 process



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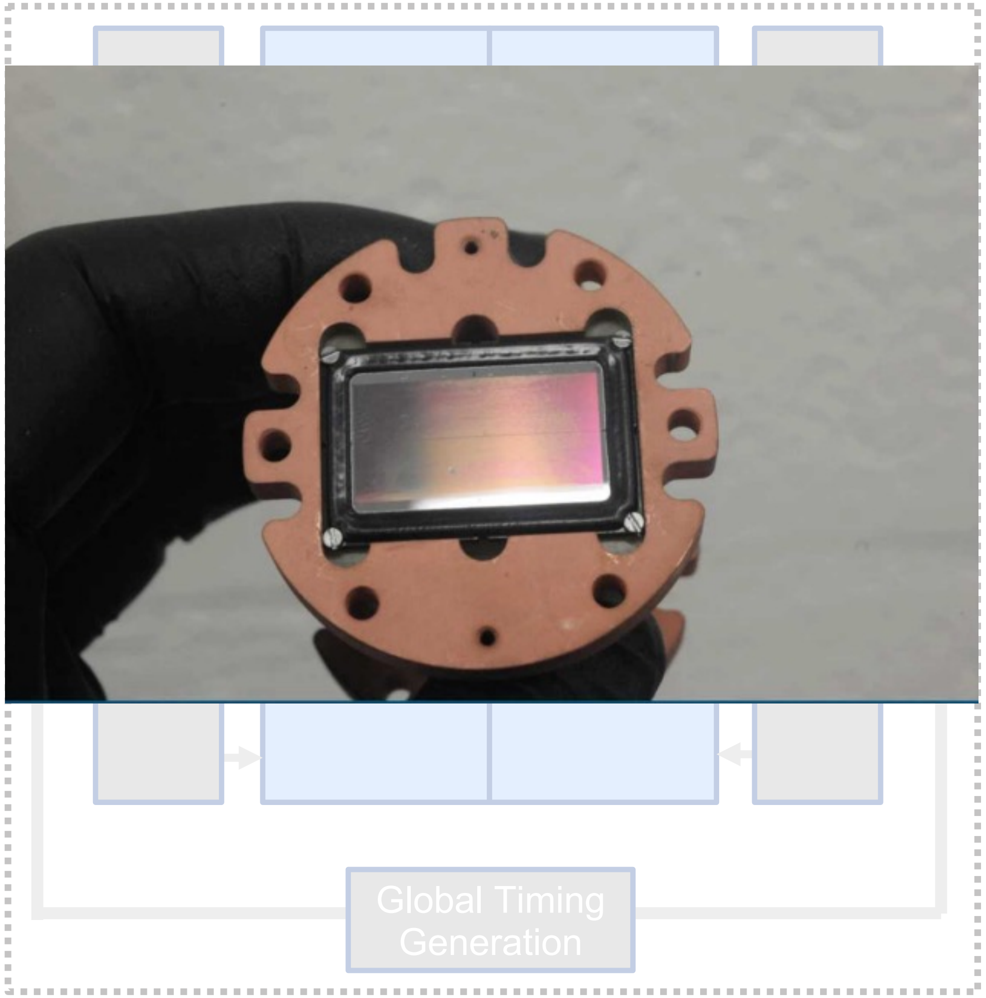
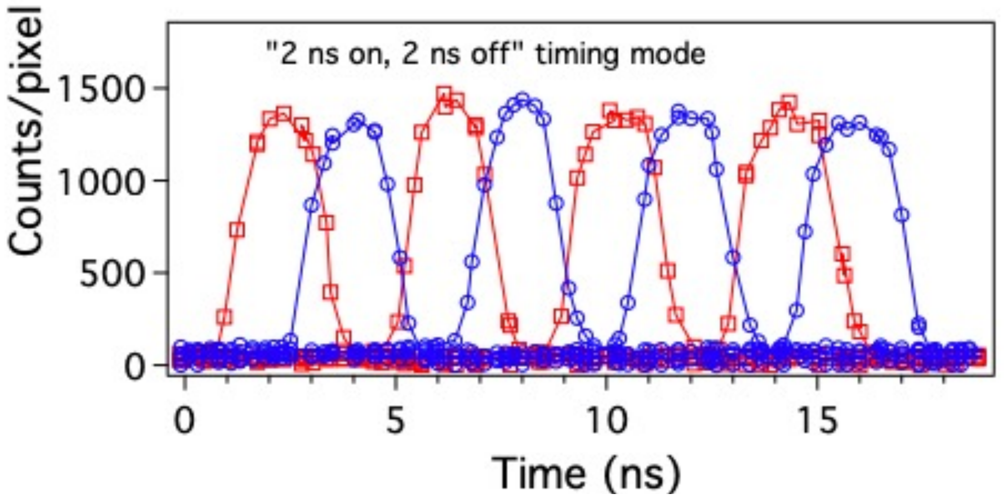
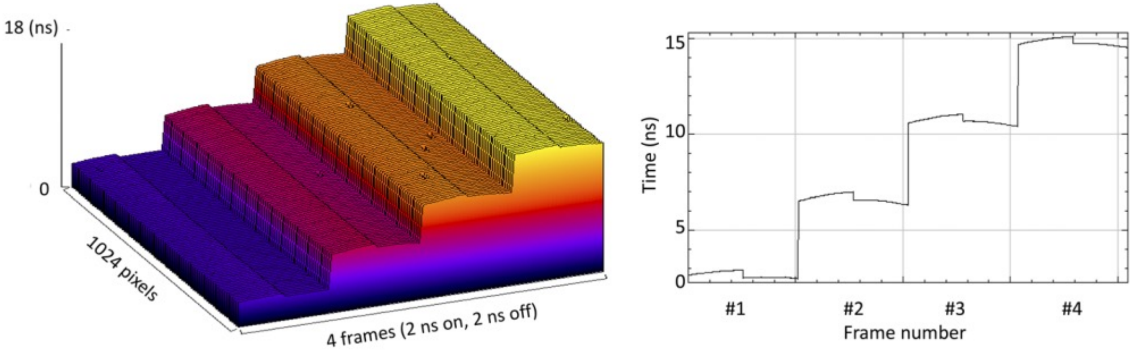


Active image plane: 12.8 mm x 25.6 mm

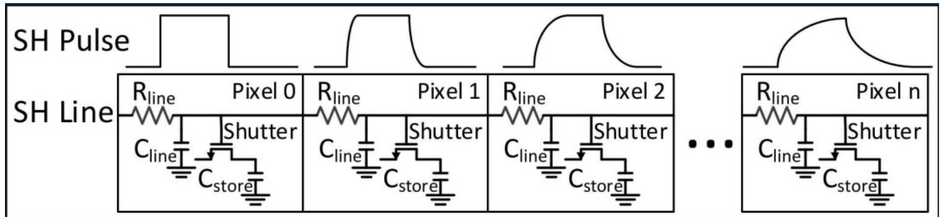
Icarus functional description and operation

Requirement	Goal	Icarus Measured
Array size	1024 x 512	1024 x 512
Pixel size	25 - 40 um	25 um
Number of frames	4-24	4
Min Tint	<2 ns	1.5 ns
Mint inter-frame time	< 2 ns	2 ns
Timing skew	< 10%	20%
Frame-Frame gain error	< 10%	< 1 mV
Full well	500k e-	500k e- @ 1.5 ns
Noise floor	< 500 e-	250 e-
Dynamic range	> 60 dB	66 dB





(a) (b)



H. Chen et al., RSI. 92, 033506 (2021)

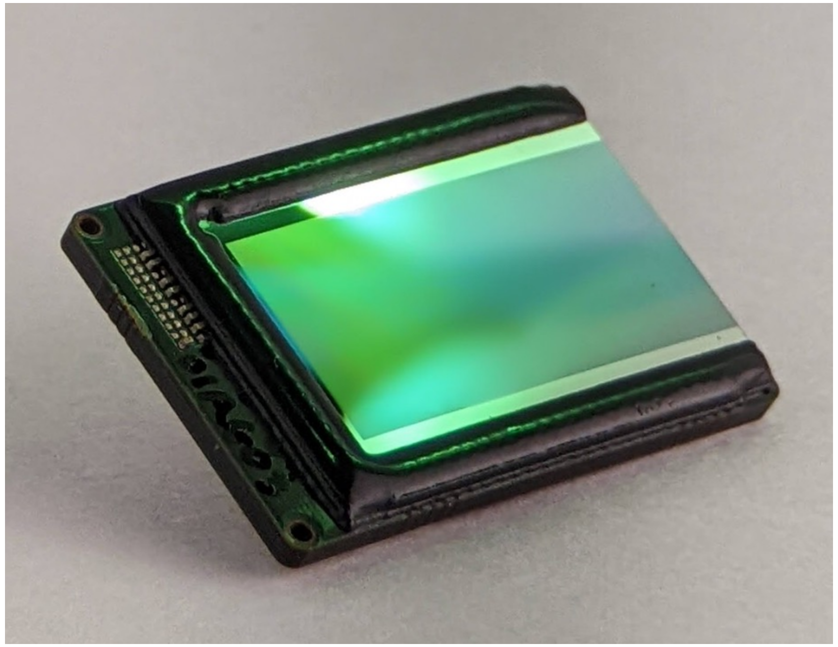
The Daedalus ROIC is a next generation sensor currently being deployed at SNL/NIF

Daedalus has a redesigned timing generation to enable far more functionality than Icarus

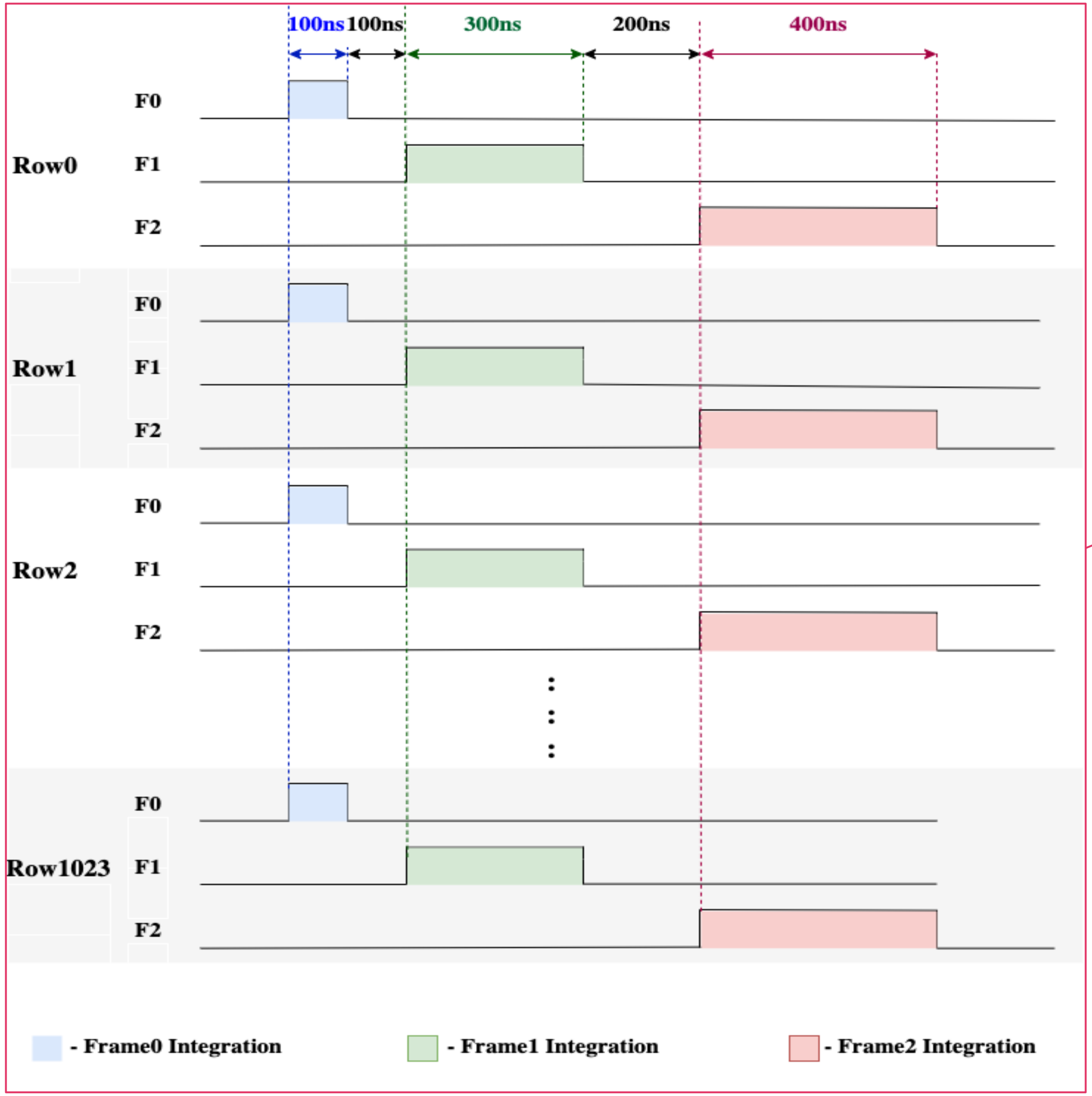
- “Infinite” Interlacing
- Zero dead time
- High full well

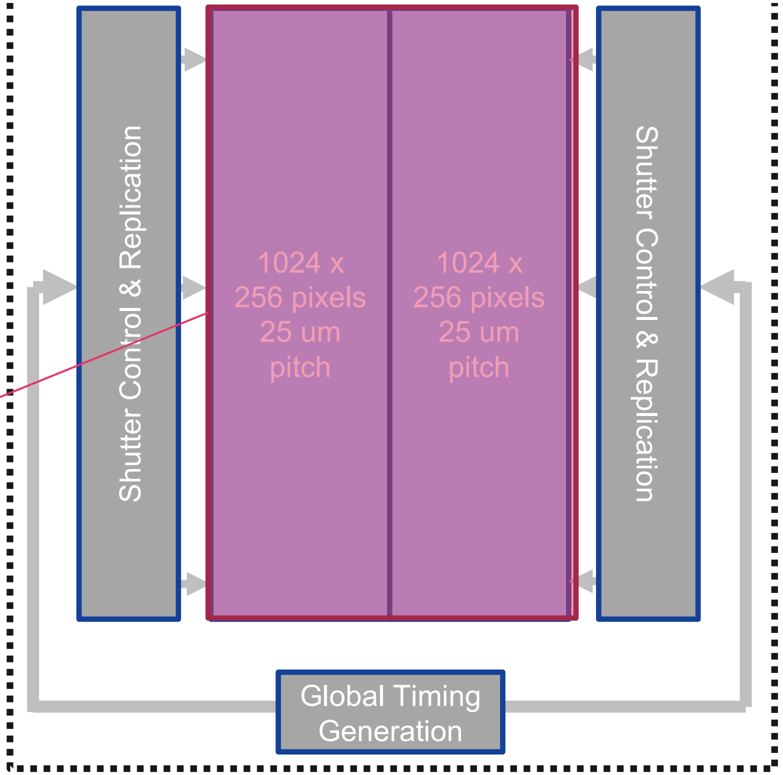
1 side abutable for 2x the image plane

Maintains independent left/right array shutter timing



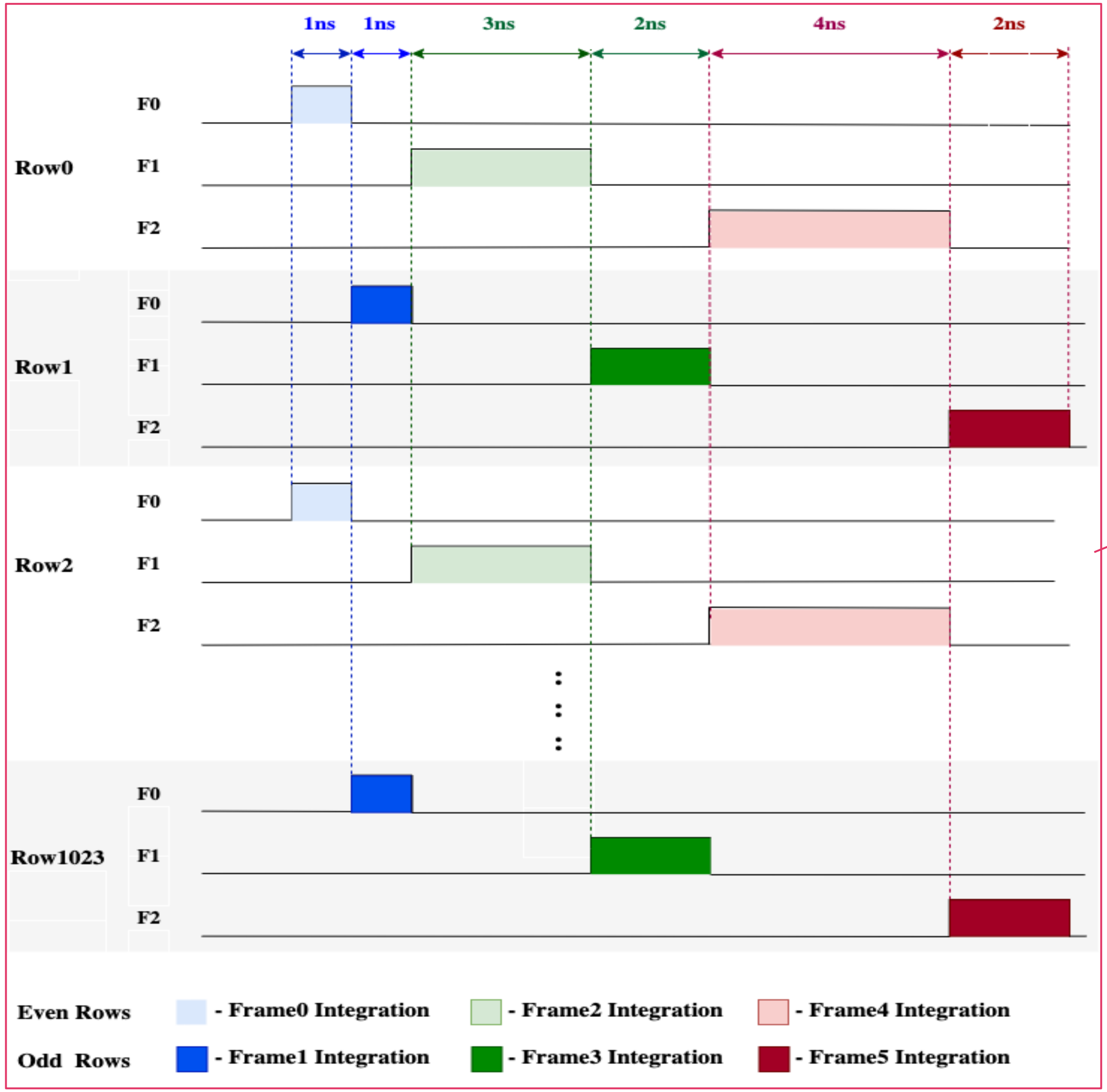
Daedalus uses row-wise shutter logic to enable new timing modes- Standard timing

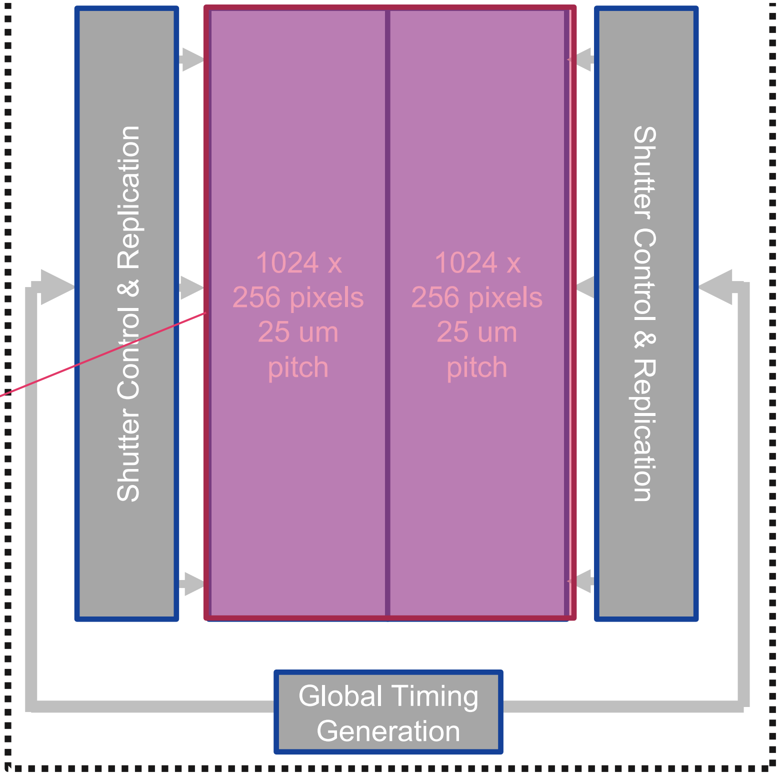




Three frames captured across image plane at full resolution

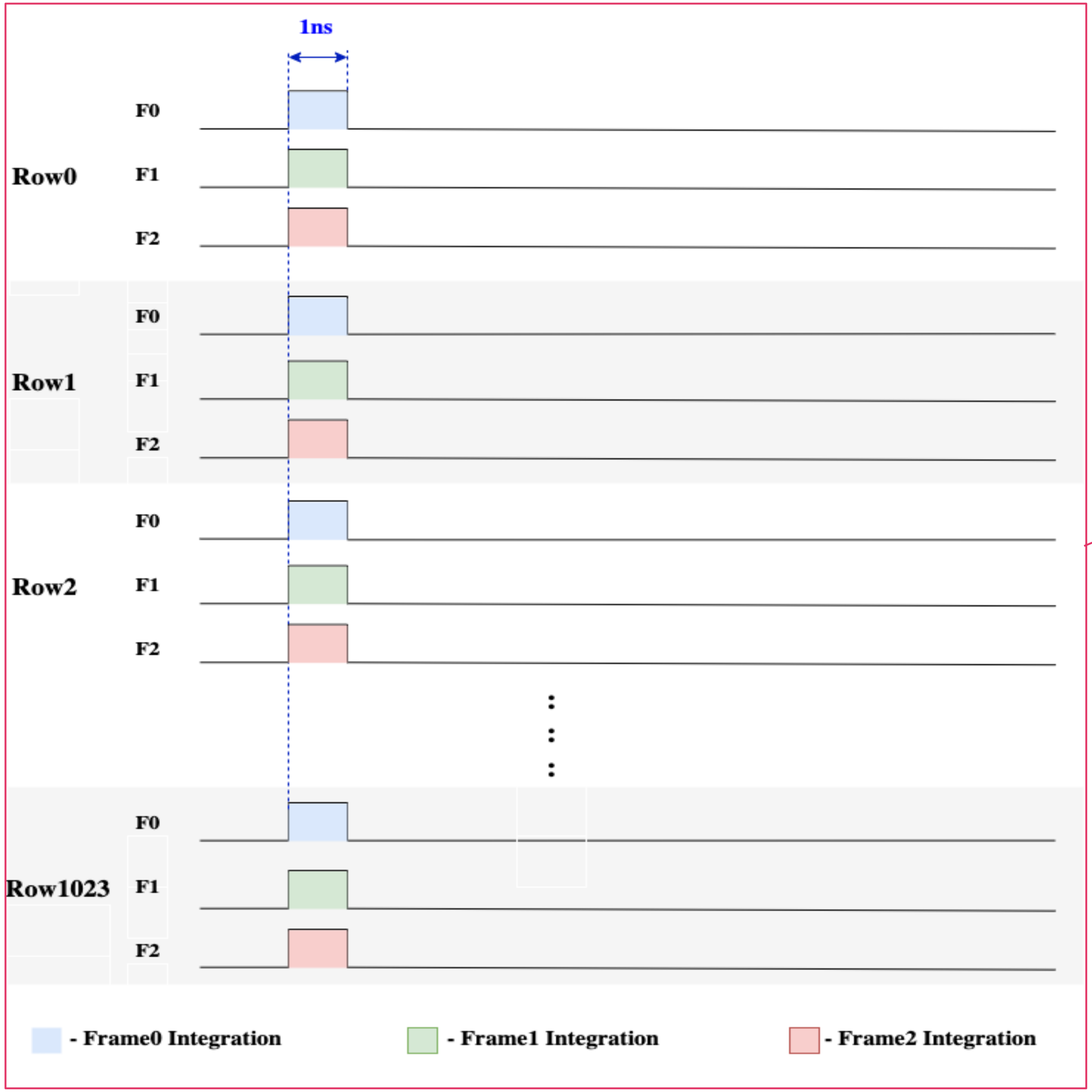
Daedalus uses row-wise shutter logic to enable new timing modes- Zero Dead-Time

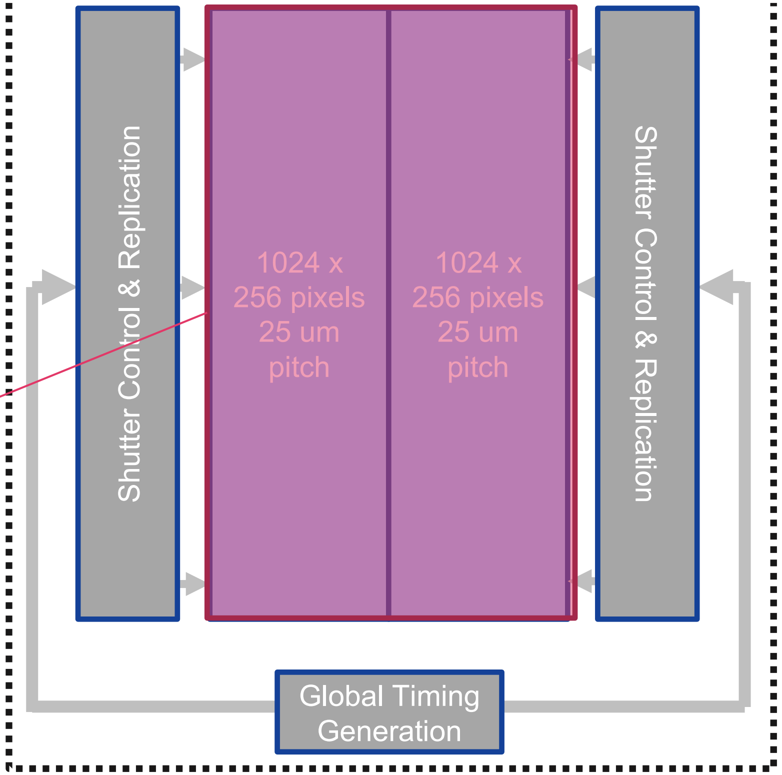




Six frame captured across image plane at 1/2 resolution with no delay between frames (odd row frames shifted in time)

Daedalus uses row-wise shutter logic to enable new timing modes- High Full-Well



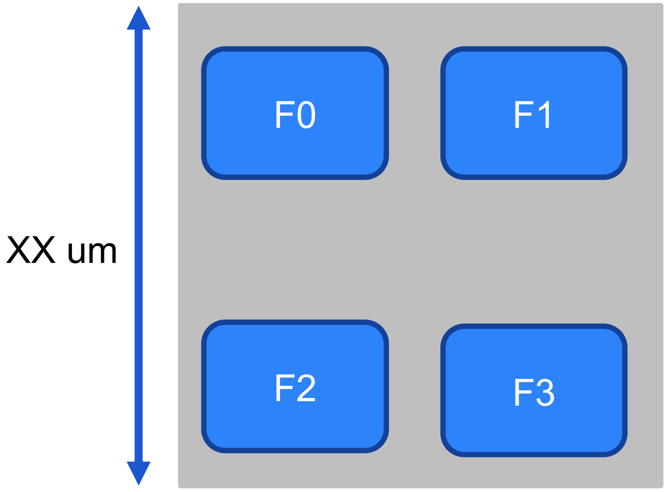


One frame captured across image plane at full resolution and 3X full well

Burst mode pixel design constraints

Frames stored in-pixel

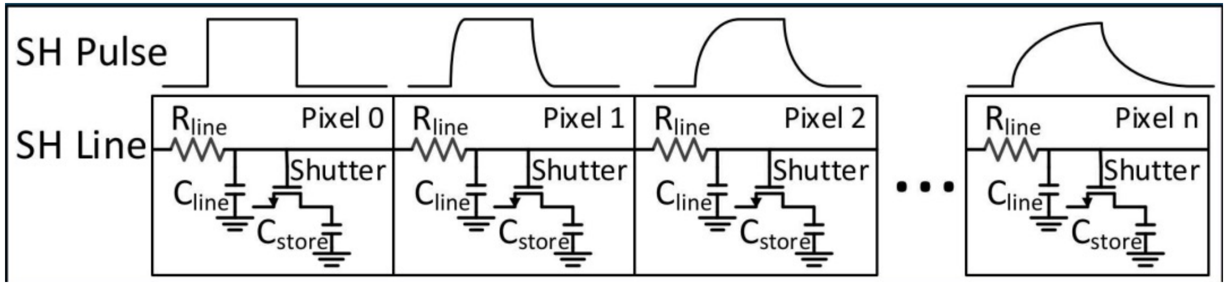
- Each frame requires its own global shutter transistor and storage capacitor
  - This consumes area and is in tension with fine spatial resolution



MIM caps consume both metal and area

Shutter distribution

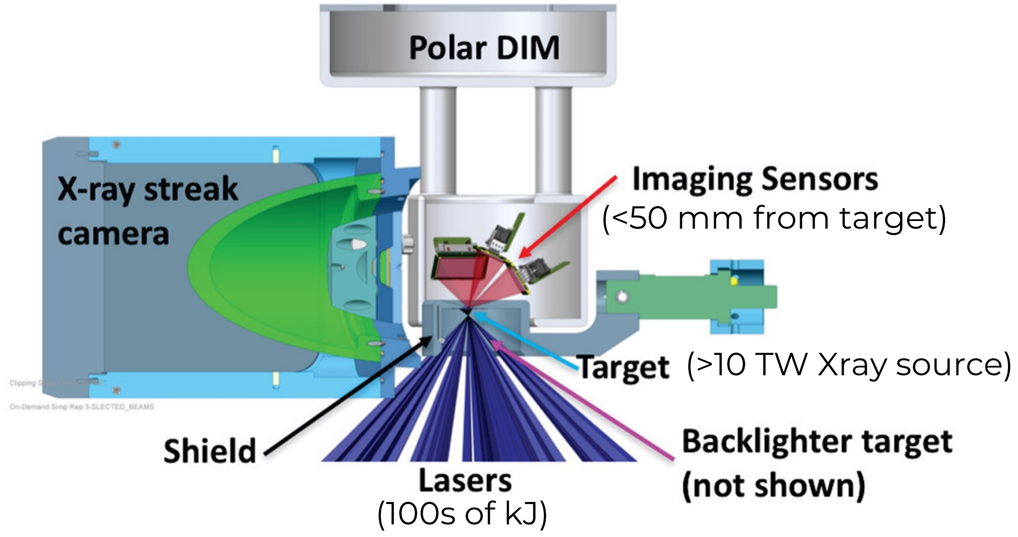
- Row-wise timing skew driving rows
  - Array skew
- Density issues implementing H-tree in fine resolution pixels



Shutter pulse degrades due to driving many shutters and interconnect parasitics

Environmental design constraints

Operates in vacuum at 80C due to form factor constraints

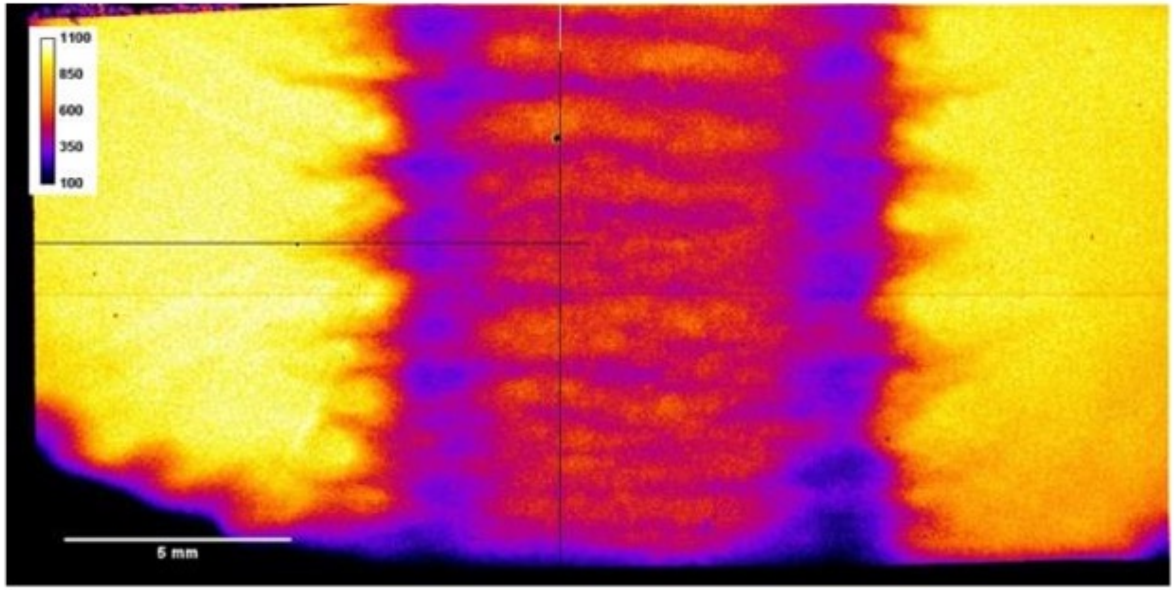


< 50 mm from TCC
> 10 TW of Xrays, massive EMP

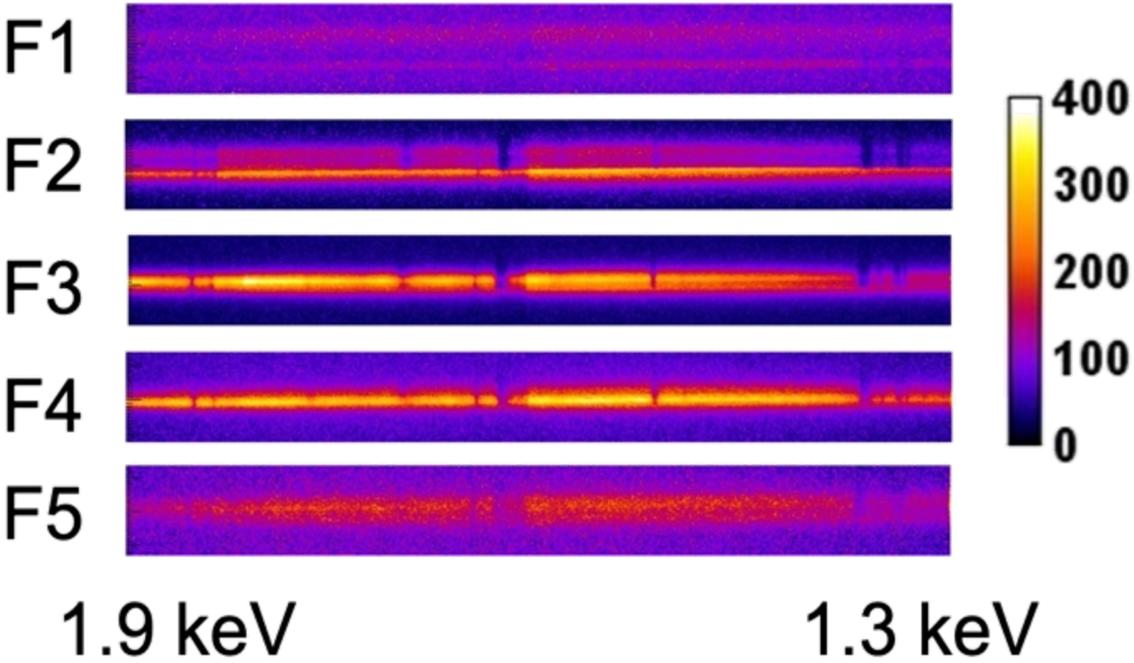
Significant photocurrent on the sensor due to timescale of illumination combined with large full well is a challenge

- Peak dI/dt can be > 40A
- Power supply droop
- Inductive kick of bondwires

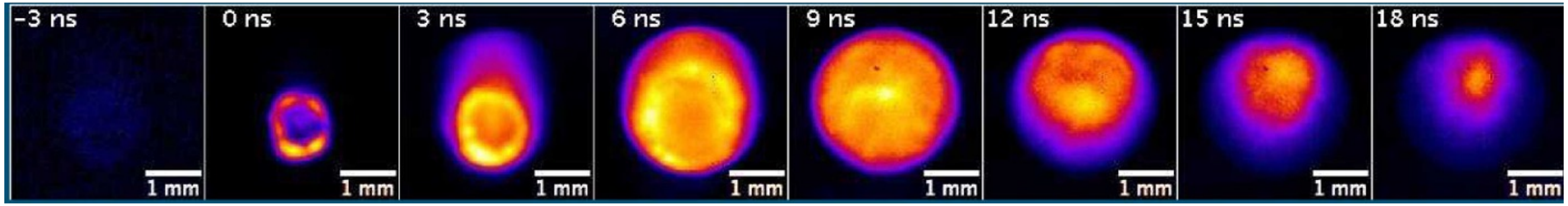
Z machine applications



Time-gated bent crystal backlighter imager, Tint=10 ns



Time-gated opacity spectrometer, Tint=2ns

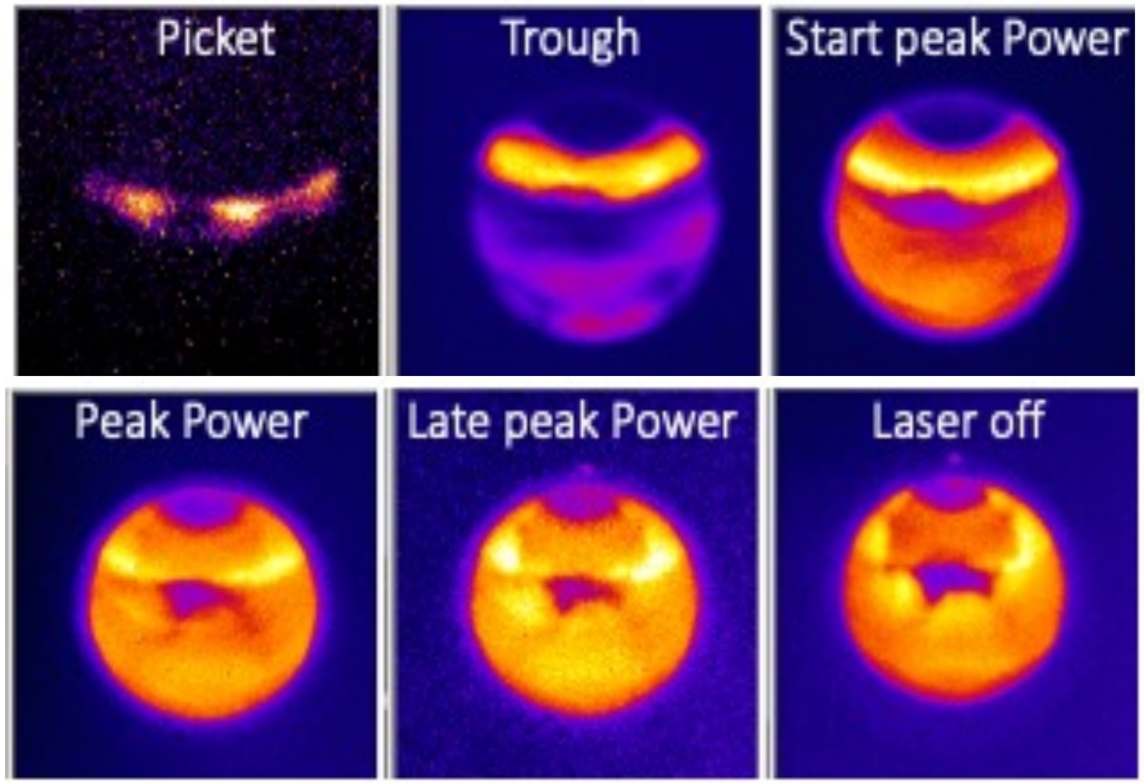


Axial pinhole imager, Tint=2 ns

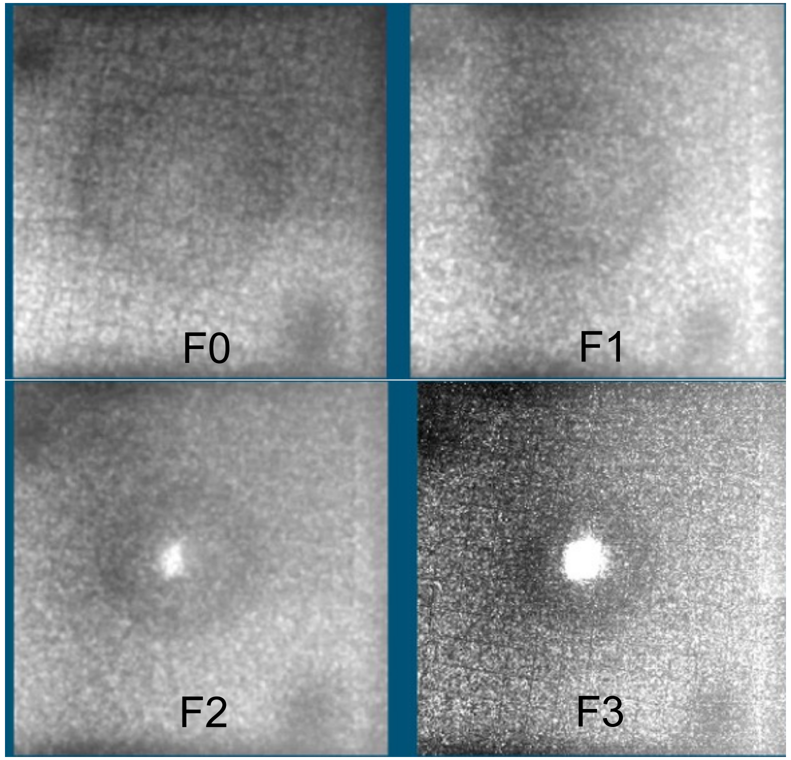
Bennett, et al., Rev. Sci. Instrum. 77, 10E322 (2006)

J.E. Bailey, et al., Rev. Sci. Instrum. 79, 113104 (2008)

NIF applications



Gated Laser Entrance Hole (GLEH) image, 2 ns timing



SLOS implosion hot spot, Tint=55 ps, 8 um spatial resolution

H. Chen et al., RSI. 92, 033506 (2021)

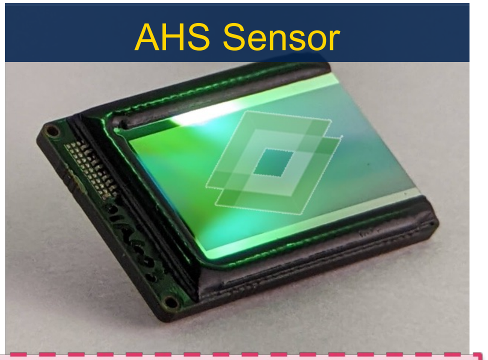
A. Carpenter

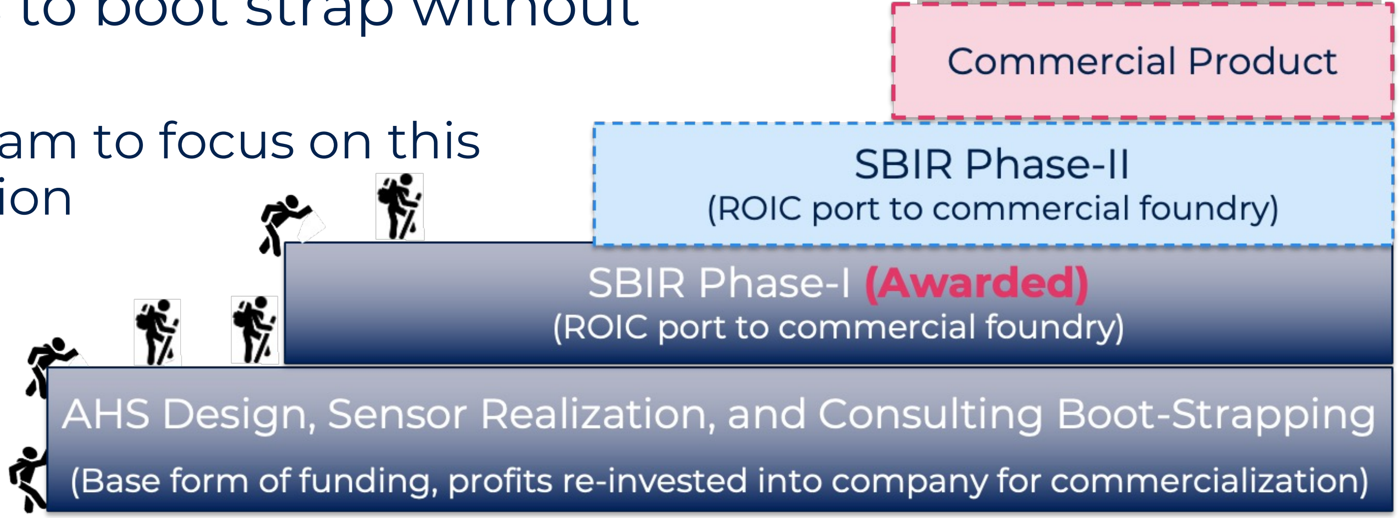
The future: Commercialized hCMOS imagers available to a broad user community

AHS was founded with the intent of providing the existing hCMOS users with expert knowledge while developing a commercial hCMOS imager

How are we going to commercialize?

- Recipient of DOE SBIR phase 1
- Applying for a DOE SBIR phase 2 for FY 23
- Services work is allowing us to boot strap without taking on VC money
  - Independence allows the team to focus on this technology without distraction





Applications and future users

The field of high-speed video is large and diverse

- Many successful products in the 1-10’s of microsecond range
- Fewer products in the 100’s of nanosecond range
- Very few products in the single nanosecond range

AHS is excited to bring a disruptive technology, developed within the DOE laboratory environment for DOE researchers to a much broader user community

Phantom-μs

Shimadzu-100 ns

SIMD/X-1 ns

Questions?

- Thank you for your time!

Liam Claus
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Advanced hCMOS Systems