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Title: Burst-mode 4 MHz CMOS-hybrid imaging system for multi-frame proton radiography

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Teledyne Imaging Sensors

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Burst-mode 4 MHz CMOS-hybrid imaging system for multi-frame proton radiography

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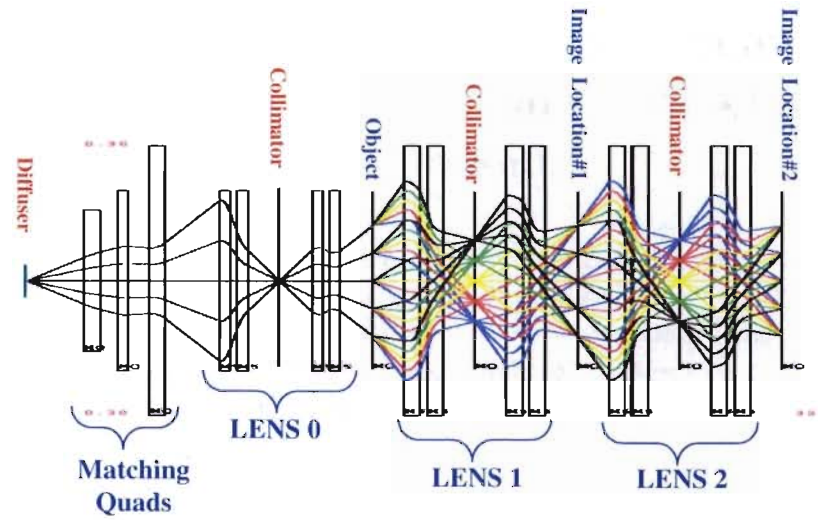
Proton Transmission Radiography

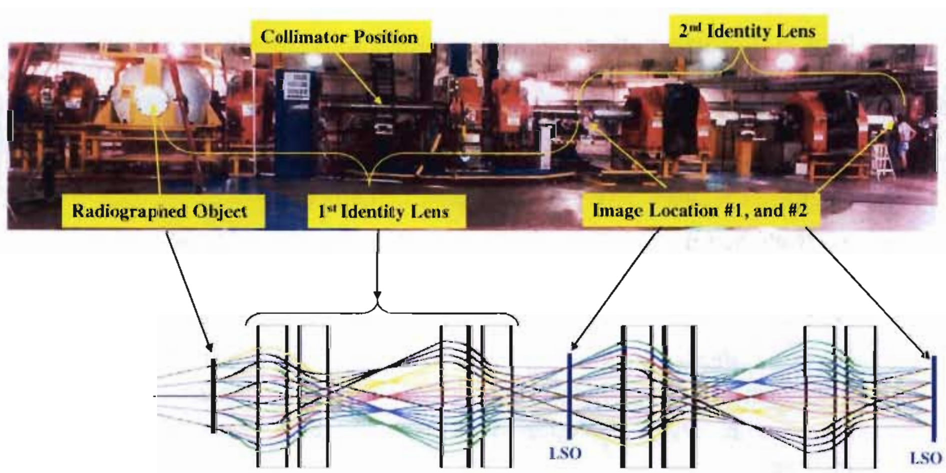
- **Probing particles:** high-energy protons E = 800MeV to 70GeV
  - highly penetrating, long mean free path (λ_I = 194 g/cm^2, 17cm in Pb)
- **Proton flux attenuation:** *nuclear* collisions dominant at high energies, and multiple *Coulomb* scattering dominates at 800MeV.
- Protons being charged particles can be focused in magnetic fields. **Magnetic lenses** form 1: -1 Image of the Object on scintillator plate, or
- **Magnifier** magnets provide - ×**3** and ×7 magnification
- **<u>Multiple</u> beam pulses** serve as strobe pulses: 2-to-1000 bursts; each ~ typ. 50ns wide; (can be adjusted 0.3ns -100ns → motion burl); multiple views of a fast-evolving object (a movie); or tomography of static object
- Needed **camera system** with large multi-frame capability (burst mode), flexible precise triggering (independently vary inter-frame time and shutter width), high-resolution ~1-2Mpx, high QE, large pixels, radiation resistance

C.L. Morris, Los Alamos Science, "Proton Radiography," Los Alamos Science, **30** (2006) 32

Proton radiography (pRAD) beam transport schematic layout

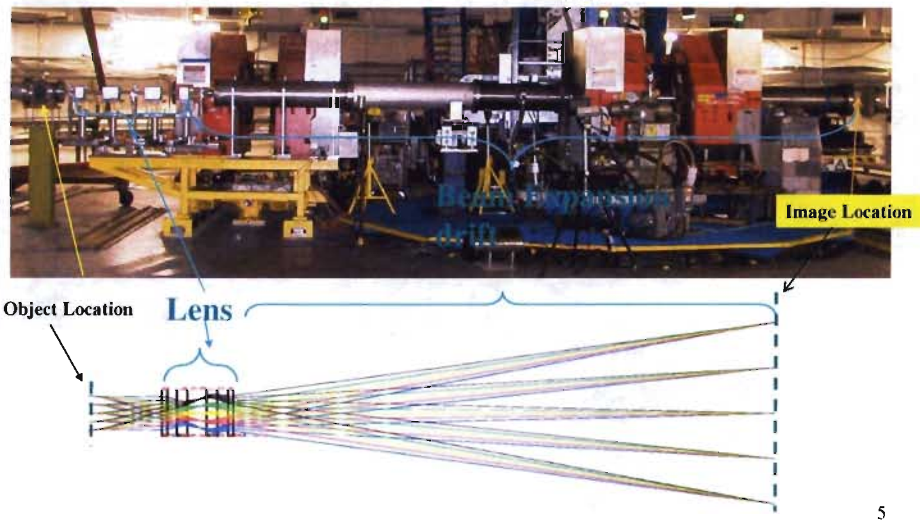


pRAD experimental set-up at LANSCE



×7 Magnifier

Made up of four 1”-DIA bore permanent magnet quads



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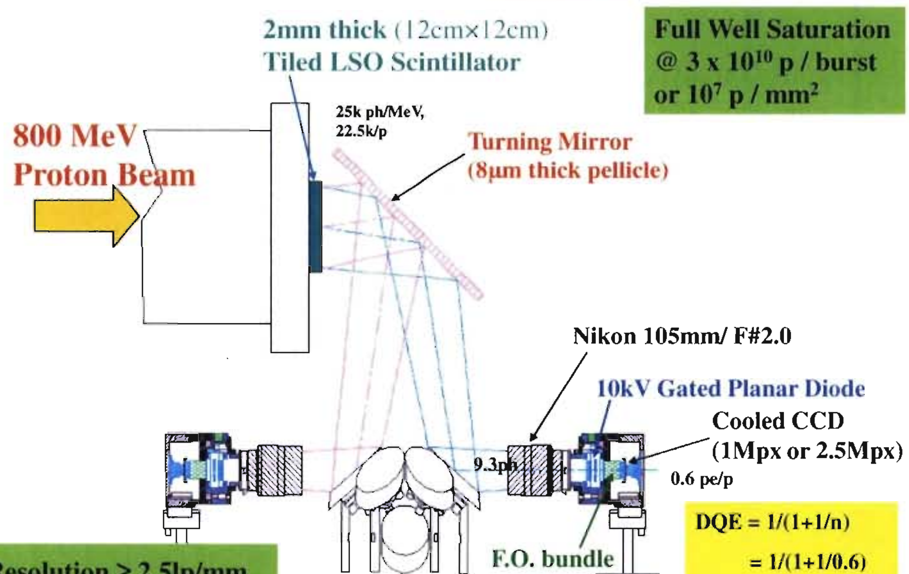
Seven Gated-CCD System

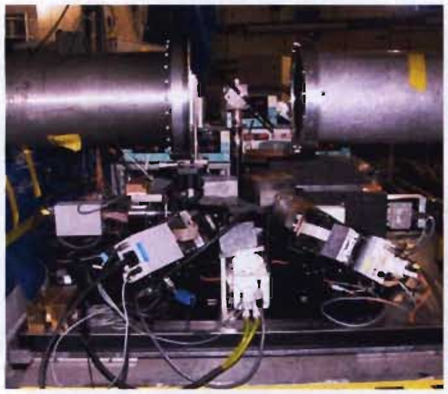


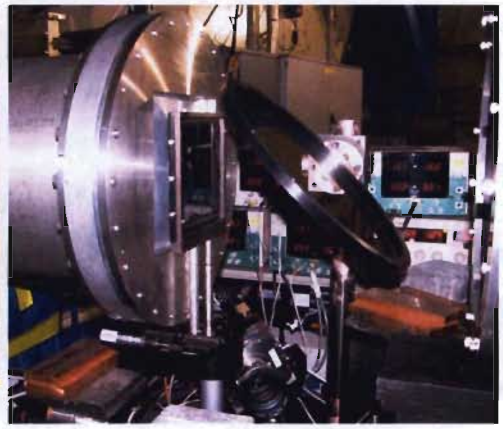
Full Well Saturation
@ 3 x 10^{10} p / burst
or 10^7 p / mm^2

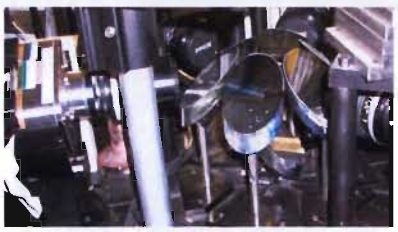
Resolution ≥ 2.5lp/mm
(≤ 200μm)

DQE = 1/(1+1/n)
= 1/(1+1/0.6)
= 0.4

Camera arrangement at Imaging Station #1







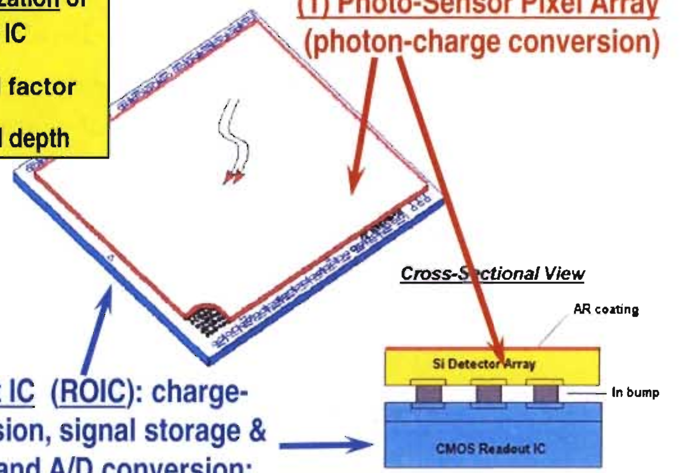
Development of Hybrid-CMOS camera

- Early on pRAD used 11 OE-gated single-frame CCD cameras, and two low-resolution 9-frame Framing cameras (all suffered from low DQE, limited number of frames, min. shutter width ~320ns, FPN noise due to FOB)
- in 2004 designed and fabricated CMOS-hybrid 720×720 px, high-QE, three-frame imager
- Hybrid CMOS ⇒ high QE and optical fill factor, well established fast CMOS and bump bonding technology, radiation resistant

Imager as Two-Component Hybrid Focal Plane Array (FPA)

- Independent optimization of detector and readout IC
- ~100% optical fill factor
- Arbitrarily large well depth

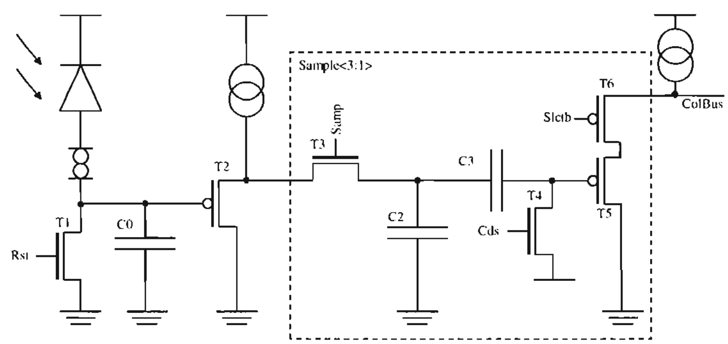
(1) Photo-Sensor Pixel Array (photon-charge conversion)



(2) CMOS Readout IC (ROIC): charge-to-voltage conversion, signal storage & processing, logic and A/D conversion; *SoC: photons-to-bits*

Each pixel in PD Sensor Array bump bonded (dia.<< 10μm) to corresponding pixel in ROIC

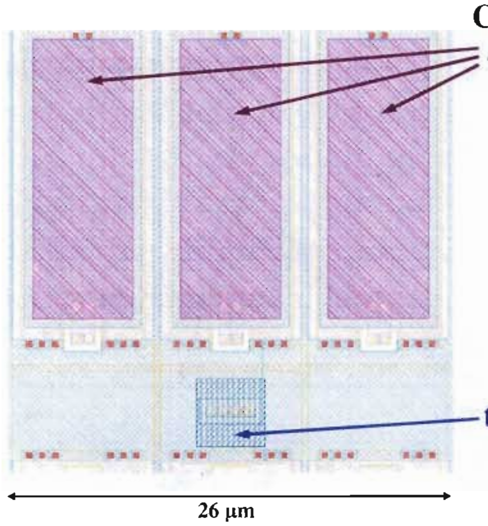
Pixel Design Provides 3-Frame Storage and Correlated Double Sampling (CDS)



Saturation charge determined by node capacitance: C_0

Voltage droop on C2, C3 by FET leakage (sub-threshold) and quality of oxide

ROIC Pixel layout, Metal Layer-4



- size dictated by S/N and rate of charge leakage.
- 26µm pixel footprint allows 3-frame storage, but 22mm CMOS reticle limits the ROIC size and array resolution to 720 × 720 px

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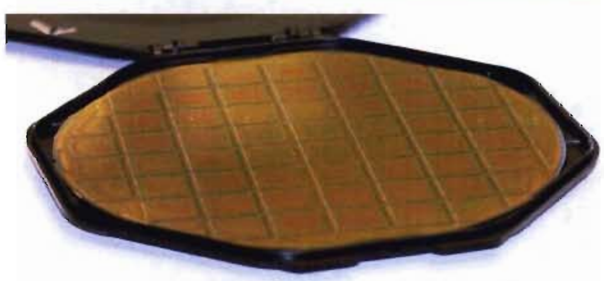
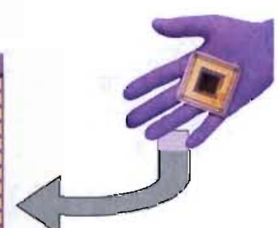
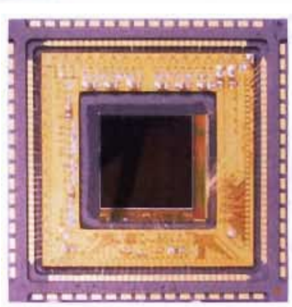
Wafer to Hybrid FPA Chip



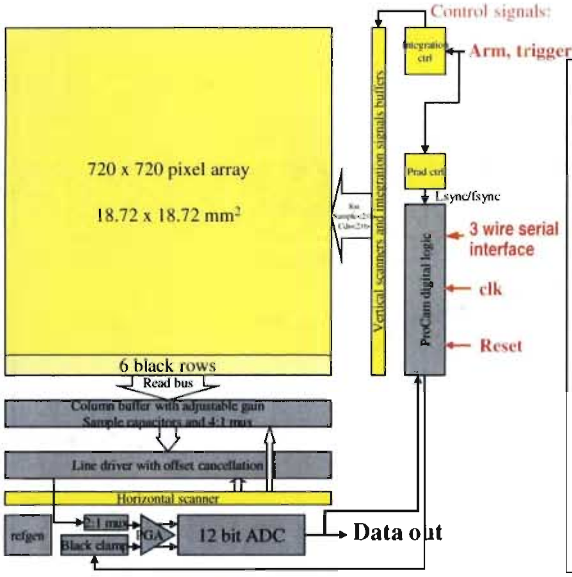
200mm - dia. wafer with 48 CMOS ROIC dies. Foundry delivered 12 wafers





21.4mm×22mm FPA is 2-side buttable - makes possible 1440×1440 px imager in a tiled assembly

System-on-Chip (SoC) Architecture Simplifies Camera Integration



Imager block diagram

- FPA chip needs only external power, master clock and trigger signals.
- The imager requires dual (3.3V and 2.5V) power supplies, "high voltage" detector bias (15V)
- The chip sends out 12 bit digital video data.
- Readout timing and biasing are generated on-chip and can be programmed through a serial interface.

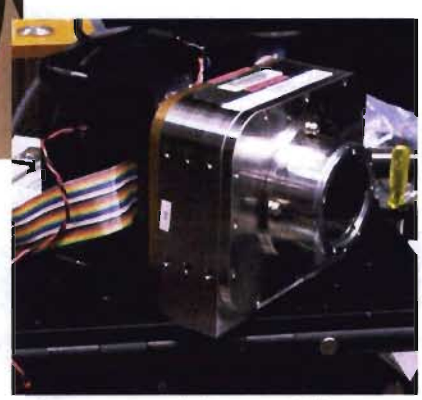
Rockwell/ Teledyne pRAD Cameras

Jan 2005, prototype –in Alu housing

Sizable volume taken up by TEC cooler and fan

CMOS ROIC fabrication worked on 1st iteration

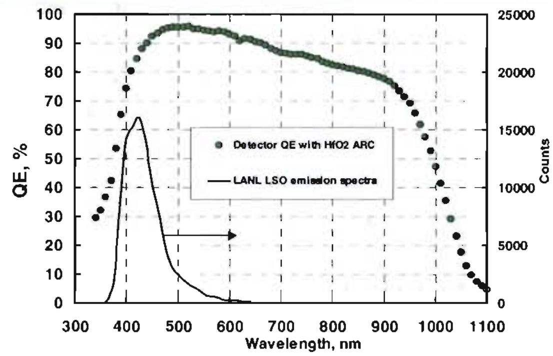
(cost $1.16M)



Camera in stainless-steel Dewar

Silicon PD Array Has Advantages Over Monolithic CMOS or CCD's

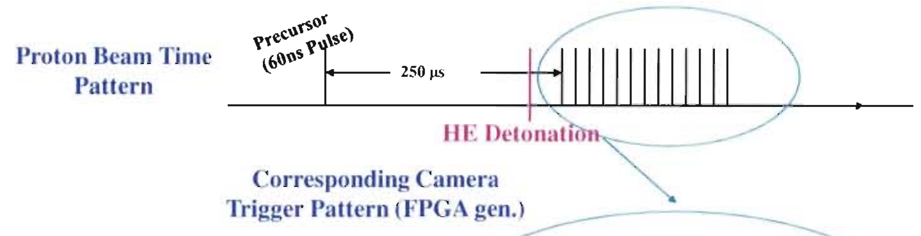
- 100% Fill factor (back-side illuminated)
- >95 % Peak QE (AR coating)
- Good spatial and fast temporal response (fully depleted)
- Low inter-frame cross-talk /good extinction ratio (storage node isolation)
- Broad band spectrum response (depletion depth ~100μm)

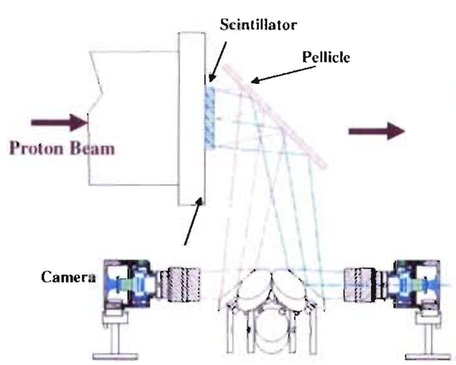


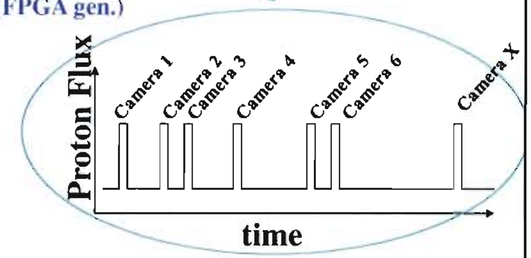
Hybrid Burst Mode Imager

- Number of frames: 3
- Min. shutter time: 150 ns (40ns)
- Inter-frame time: 250 ns
- Array Size: 720×720
- Dynamic Range: 11-bit (12-bit ADC)
- Read Noise: 98 e^-
- Well depth : >200ke^-
- QE 84% (at 415nm)
- Pixel size: 26 μm
- Chip size: 21.4mm×21.9mm
- CMOS technology: 250 nm

Beam and Camera Trigger Timing

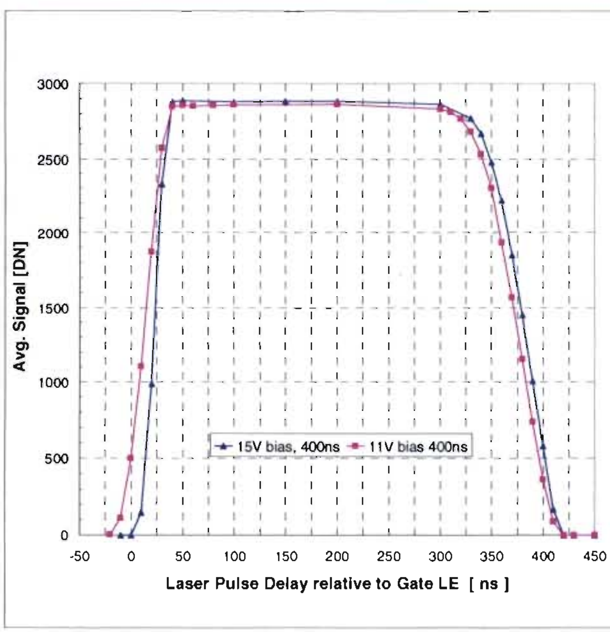


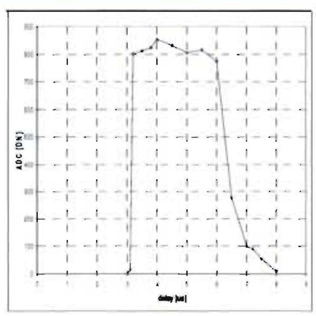




- 19 images at first station
- 22 images at second station
  Typically 180ns to 400 ns exposure times w/LSO; and w/ CsI(Tl) 5μs

Effective Shutter Gate Profile

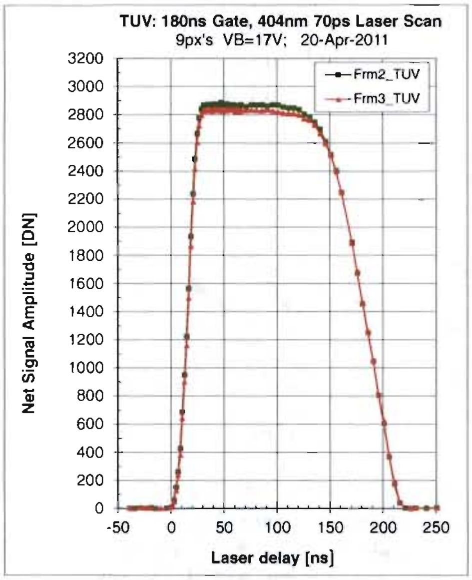


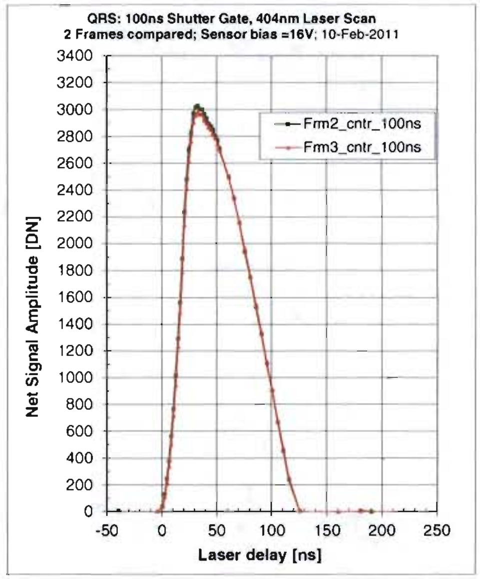


Commercial fast monolithic CMOS imager 2μs TTL shutter

Data taken with 70ps wide, blue laser pulse λ=404nm . Shutter gate 400ns wide, at two detector bias voltage settings.

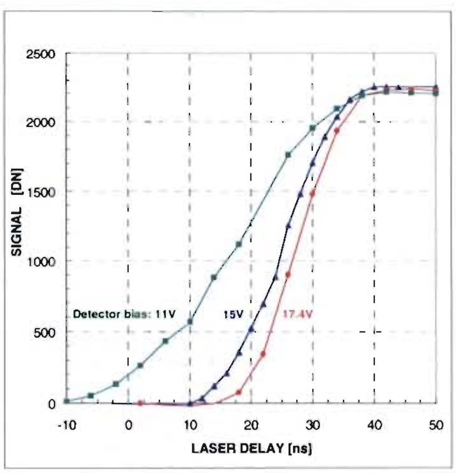
Effective Shutter Gate at Minimum Width

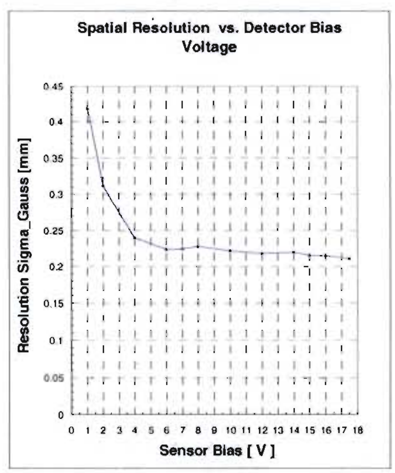




Camera response to laser scan at 180 ns shutter gate (= min width as per design specs), and shorter at 100 ns

Leading Edge Dependence of Shutter Gate

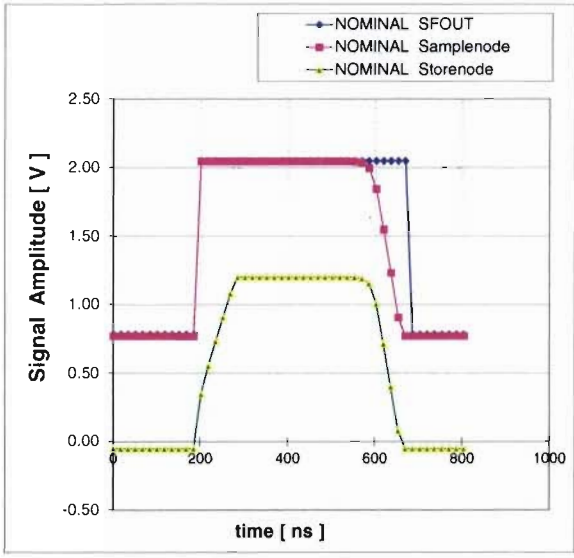




The effective rising edge is longer than the expected carrier collection time (16ns, 11.8 ns and 10.1 ns for 11 V, 15 V, and 17.5 V bias). Carrier plasma and trapping effects in detector.

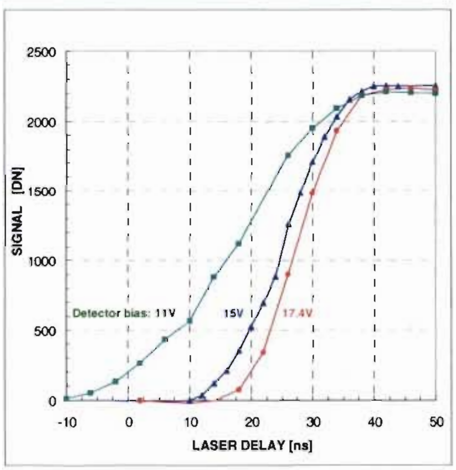
However, the detector bias has remarkably little effect on the spatial resolution, as long as $V_{full\ depletion} \leq V_{bias}$

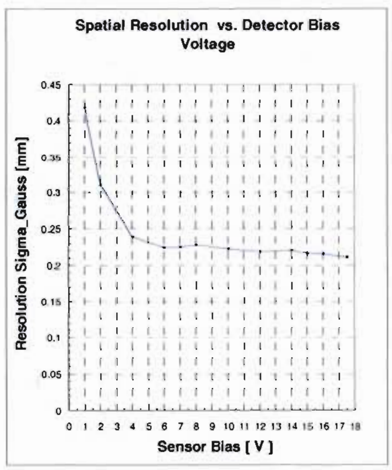
PSpice simulations of pixel response 400ns gate



Response at nominal SF current: CDS ckt. included, but not 100μm detector. Sample-node slew limited (large caps).

Leading Edge Dependence of Shutter Gate





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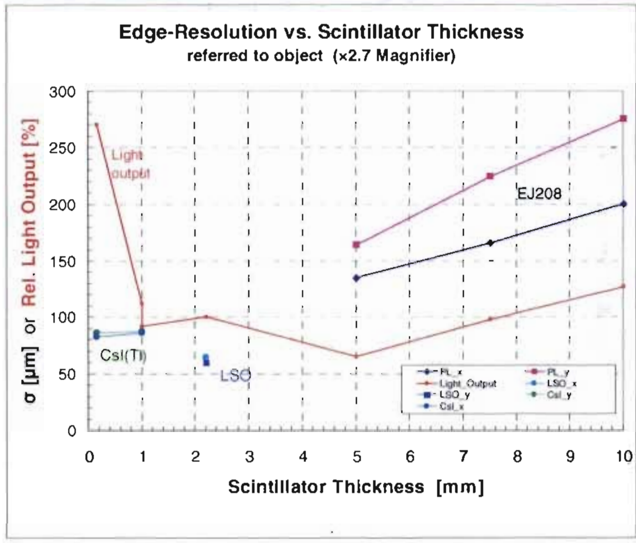
System Resolution as a function Scintillator Type and Thickness



Decay times: CsI(Tl) 1us, LSO = 42ns, and EJ-208 plastic scintillator - 2.3ns

pRAD-1 Hybrid CMOS Cameras - limitations

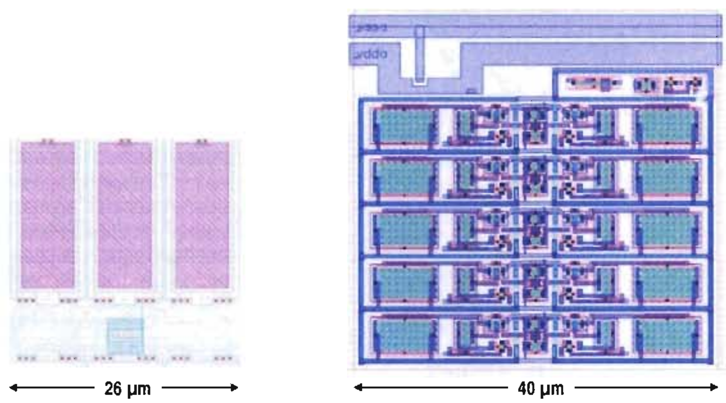
- **spatial resolution** (at IL1) at 720×720 px and 12×12cm FOV camera is limiting the spatial resolution (in the image/scintillator plane: σ = 180μm)
- **exposure time** and inter-frame time are both scintillator- and camera-limited (beam intensity) (2.3ns plastic scintillators help, but poor spatial resolution)
- **number of views** high-resolution frames pRAD is camera limited to 23 (19-frames at IL1, 4-frames at IL2)

⇒ New hybrid CMOS imager is to address those issues (e.g., no. frames at IL1for 6 cam's ×10 = 60)

Hybrid CMOS Imager: 1st vs. 2nd generation

Design Parameter	pRAD-1 Imager	pRAD-2 2nd Gen
Minimum integration time (Global shutter)	150 ns	**50 ns**
Nominal min. inter-frame time	350 ns	150 ns
Effective Dynamic Range	11.4 bits	12 bits
Read noise	100 e-	~ 37 e-
Imaging array size	720×720 px	1100×1100 px
Number of samples/ frames	3	**10**
Pixel pitch	26 μm	**40 μm**
Sensor QE @ 415 nm	84%	>90%
Chip dimensions	21×22 mm^2	**~46.5×49 mm^2**
Optical Fill-Factor	~100 %	~100 %
Saturation charge/ Well depth	>200 ke$^-$	~ 150 ke$^-$

10-frame In-Pixel Storage: Larger Pixels & Advanced CMOS



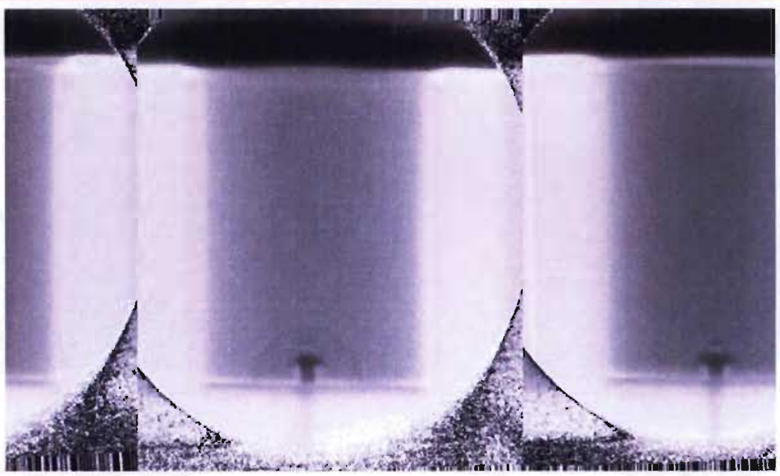
Original 26μm pixel. New 40μm pixel together w/ more advanced 180nm CMOS process (larger capacitance /μm^2) allow to pack 10 MIM storage caps per pixel. ⇒ Large IC chip = 46.5×48.7 mm^2, will need reticle stitching. Impacts cost and yield.

Summary

- Burst mode 4 MHz high-resolution, high QE, 3-frame, 720×720 px, hybrid CMOS imager successfully fabricated on 1st iteration. System-on-chip (SoC) approach produced a compact, reliable and low power imager.
- Six cameras built and operated for several years in radiation environment
- Thick (~100 μm) detector provides high QE from 380 nm to 900 nm, but affects time definition of the shutter. Photo-sensors and circuits generating shutters under 100ns (50ns) need more tuning.
- LSO scintillator optimal resolution and radiation resistance, plastic scintillator faster, but worse spatial resolution (ZnO ?)
- New 50 ns, 10-frame, 1Mpx imager in design close to completion
- Future radiography and FEL facilities need high-resolution **sub-ns** imagers

S. Kleinfelder, et al. IEEE Transactions on Nuclear Science, **56** (2009) 1069

Two Proton Radiography Experiments:
shaped-charge jet penetration of HE and polymer cylinders



~ 9 km/s copper jet generated by a shaped charge; (Left panel) impacting a cylinder of high-explosives and triggering detonation wave; (Right) an inert Teflon cylinder.