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Recent Analog X-ray Pixel Detector Developments

CHESS & LASSP

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Support: DOE, NIH

- Description of PADs
- Application examples
- Mixed-Mode PAD

Basic Pixel Array Detector (PAD)

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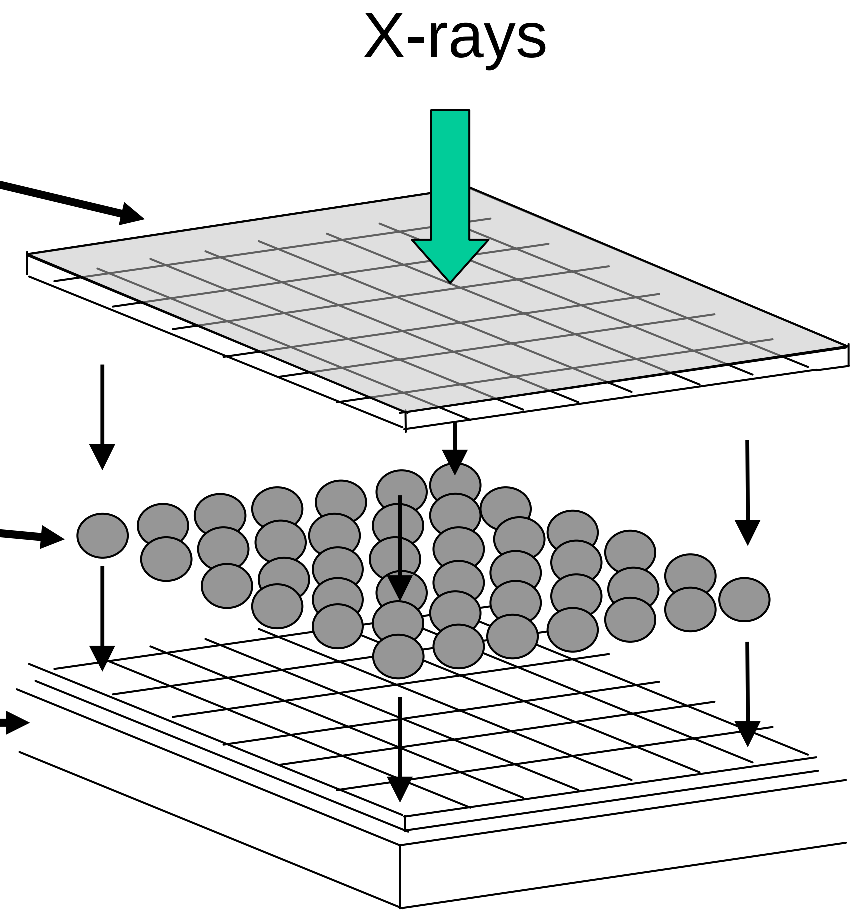
Diode Detection Layer

- Fully depleted, high resistivity
- Direct x-ray conversion
- Silicon, GaAs, CdTe, etc.



Connecting Bumps

- Solder or indium
- 1 per pixel

CMOS Layer

- Signal processing
- Signal storage & output

Gives enormous flexibility!

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Analog & Photon Counting PADs

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Photon counting PADs

- Input amp, followed by shaper and threshold for photon discrimination to output a digital bit, usually to an in-pix counter.
- Pixel count-rate set by speed of electronics processing. 10^6 -10^8 x-rays/sec typical. Susceptible to pile-up.
- Requires very careful noise control.
- "Well-depth" set by number of bits in counter.
- Duty cycle set by need to read in-pix counter if synchronous. If asynchronous, need to isolate input from coupling to digital readout.

Analog PADs

- Input integrator onto in-pix analog storage. Reminiscent of CCD.
- For readout, buffer stored signal to off-pix (usually off-chip) ADC.
- Capable of handling enormous count-rate.
- Well-depth set by analog storage capacity.
- Duty cycle set by time to digitize analog signal if synchronous. If asynchronous, need to isolate input from coupling to analog readout.

High Speed Imaging: Design Requirements

Rapid Framing Imager

- In pix storage for 8 frames
- Selectable integration time (1 μs to seconds)
- Deadtime < 1 μs
- Well-depth > 10^4 x-rays/pixel/frame (for 1% statistics)

Count rate >10^{10} x-rays/pixel/s → Analog integration needed

Pixel size ≤150 μm square

Standard CMOS fabrication service

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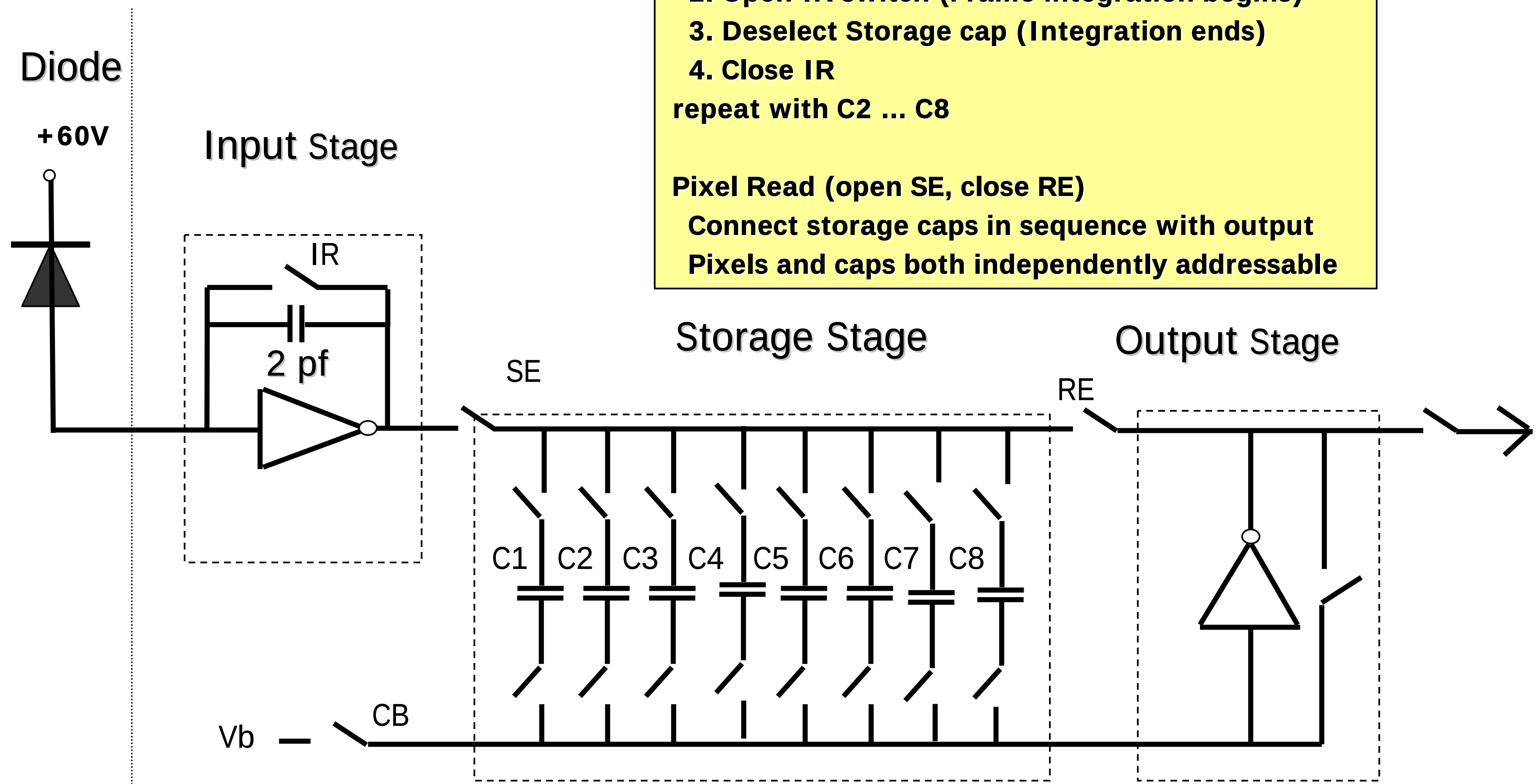
Rapid framing (SE, IR closed)
1. **select storage cap C1**
2. **Open IR switch (Frame integration begins)**
3. **Deselect Storage cap (Integration ends)**
4. **Close IR**

repeat with C2 ... C8

Pixel Read (open SE, close RE)
Connect storage caps in sequence with output
Pixels and caps both independently addressable



C1 - C8: 130 fF

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Cornell 100x92 Analog PAD

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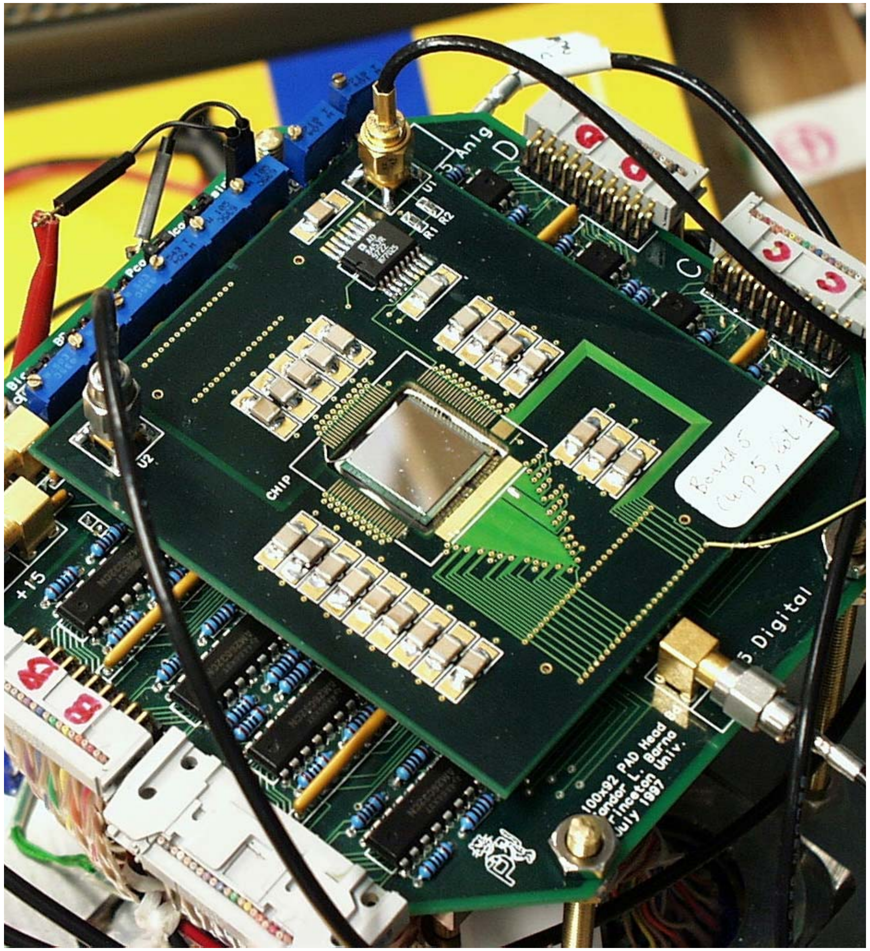
- 1.2 μm HP CMOS process (MOSIS) (Linearized Capacitors)
- 15 x 13.8 mm^2 active area; 100x92 pixels
- 150 μm square pixel
- 300 μm thick, high resistivity Si diode wafer (SINTEF)
- 120 μm solder bump bond (GEC-Marconi)



100x92 PAD developers include:

- Sandor Barna
- Eric Eikenberry
- Alper Ercan
- Sol Gruner
- Matt Renzi
- Giuseppe Rossi
- Bob Wixted

G. Rossi, *et al,* J Synchrotron Rad. (1999). **6**, 1095-1105.

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100 x 92 Prototype Tests

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Test results with 8.9 keV x-rays

• Full well capacity (x-rays)	17000
• Non-linearity (% full well)	< 0.5 %
• RMS read noise : (x-rays/pixel)	2.0 – 2.8
• Dark current (-20 C) (x-ray/pixel/s)	1.6 – 7.7
(fA/pixel)	6 – 40
• Storage capacitor leakage	0.07% / s
• PSF (@75μm)	< 1%
• X-rays stopped in diode	97 %
• Minimum integration period (μs)	0.15
• Minimum deadtime between frames (μs)	0.6
• Rad damage threshold (kRad in CMOS oxide)	30
• Tolerable radiation dose (kRad)	>300

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High speed radiography:

Supersonic spray from diesel fuel injector

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X-ray beam

- CHESS Beamline D-1
- 6 keV (1% bandpass)
- 2.5 mm x 13.5 mm (step sample to tile large area)
- 10^8 - 10^9 x-rays/pix/s
- 5.13 μs integration (2x ring period)

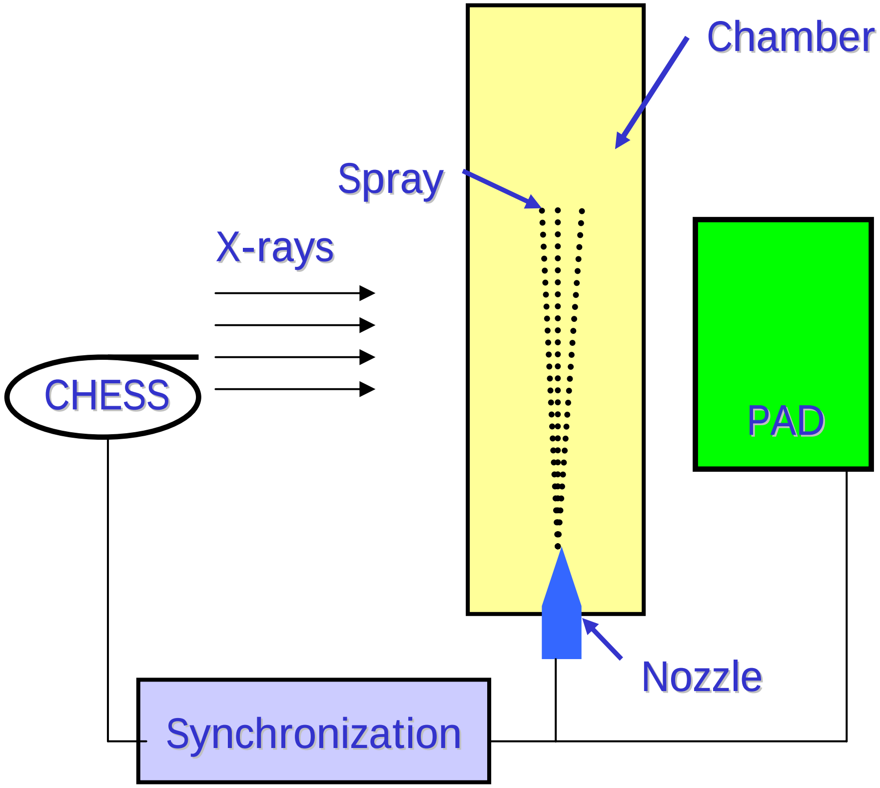
Diesel Fuel Injection System

- Cerium added for x-ray contrast
- 1350 PSI gas driven
- 1.1 ms pulse
- 1 ATM SF_6 in chamber

Collaboration: Jin Wang (APS) & S.M. Gruner (Cornell)

See: McPhee, Tate, Powell, Yue, Renzi, Ercan, Narayanan, Fontes, Walther, Schaller, Gruner & Wang

***Science* 295 (2002) 1261-1263.**



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High speed radiography:

Supersonic spray from diesel fuel injector

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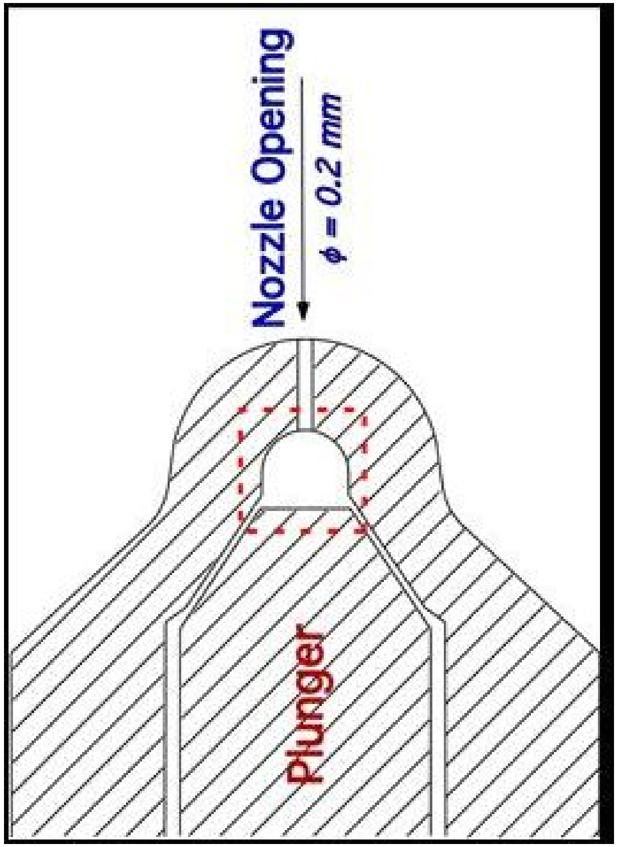

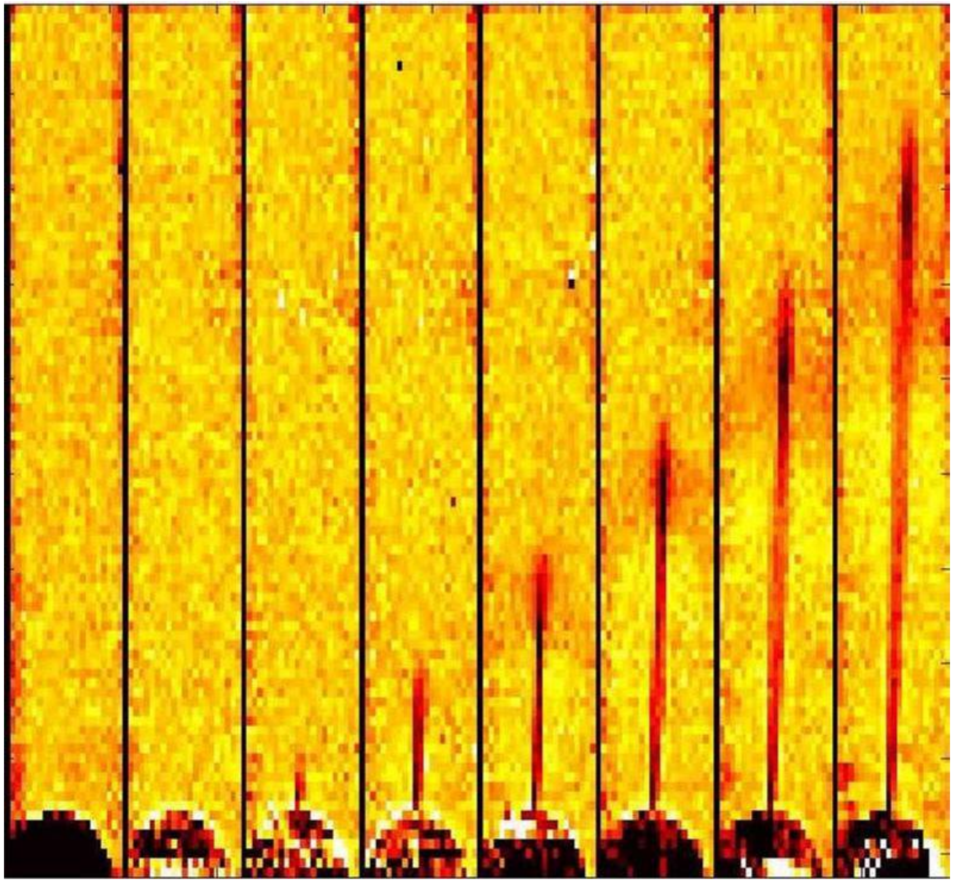

Diesel fuel injector spray

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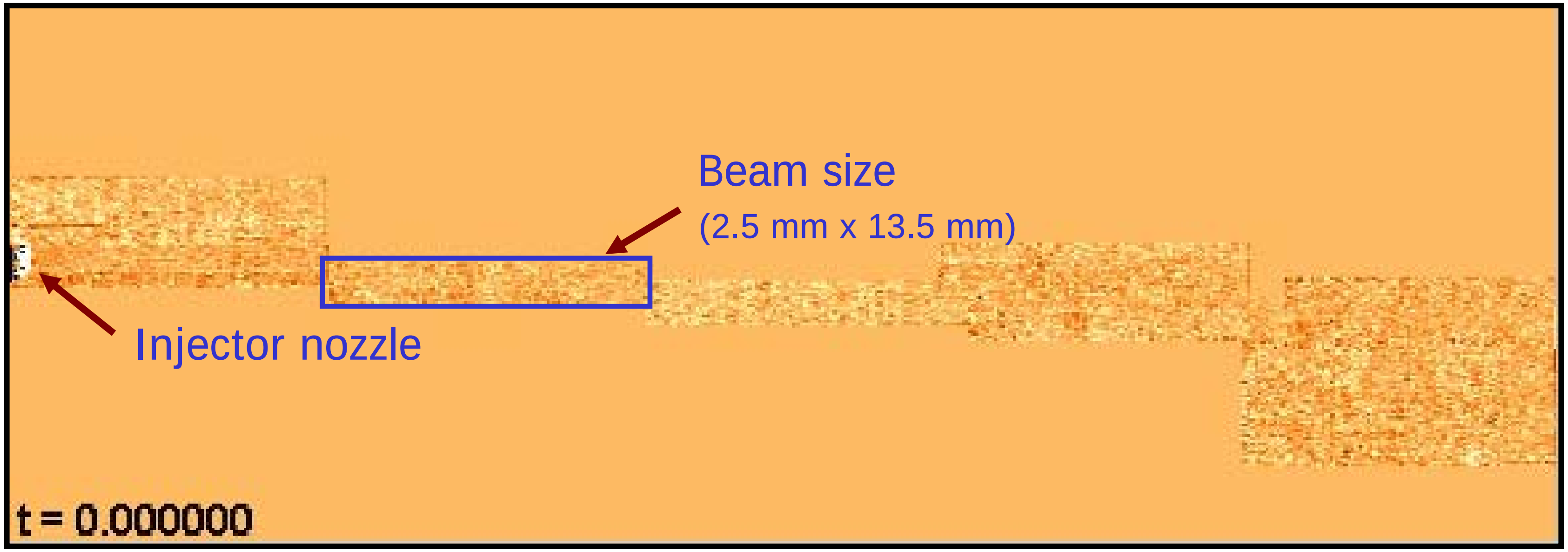
- 1.3 ms time sequence (composite of 34 sample positions)
- 5.13 μs exposure time (2.56 μs between frames)
- 168 frames in time (21 groups of 8 frames) Average 20x for S/N
- Sequence comprised of 5 x 10^4 images



A. MacPhee, *et al,* Science (2002). **295**, 1261-1263.

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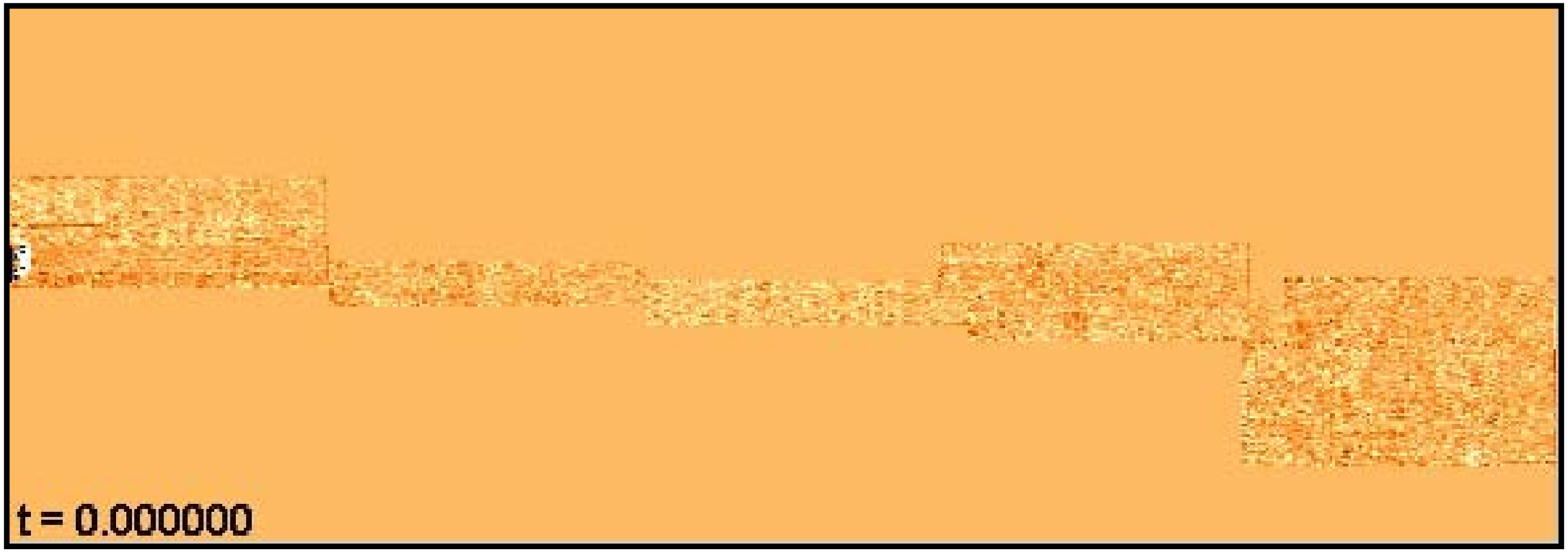

A. MacPhee, *et al,* Science (2002). **295**, 1261-1263.

Gasoline fuel injector spray

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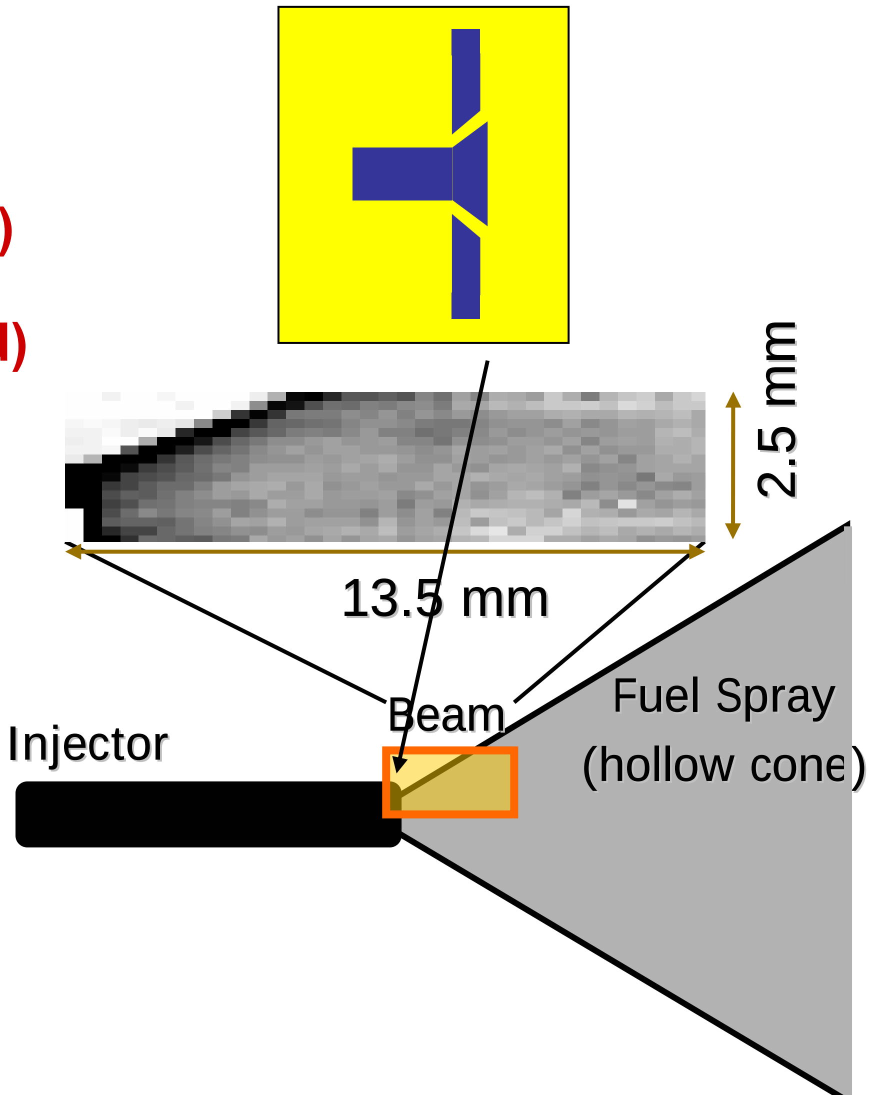
X-ray beam
- CHESS Beamline D-1
- 6 keV (1% bandpass)
- 2.5 mm x 13.5 mm
- (step sample to tile large area)
- 10^9 x-rays/pix/s
- 5.13 μs integration (2x ring period)

Fuel injection system
- Cerium added for x-ray contrast
- 1000 PSI gas driven
- 1 ms pulse
- 1 ATM Nitrogen

Collaboration: Jin Wang (APS) & S.M. Gruner (Cornell)

See: Cai, Powell, Yue, Narayanan, Wang, Tate, Renzi, Ercan, Fontes & Gruner
Appl. Phys. Lett. (in press, 2003)



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Gasoline fuel injector spray

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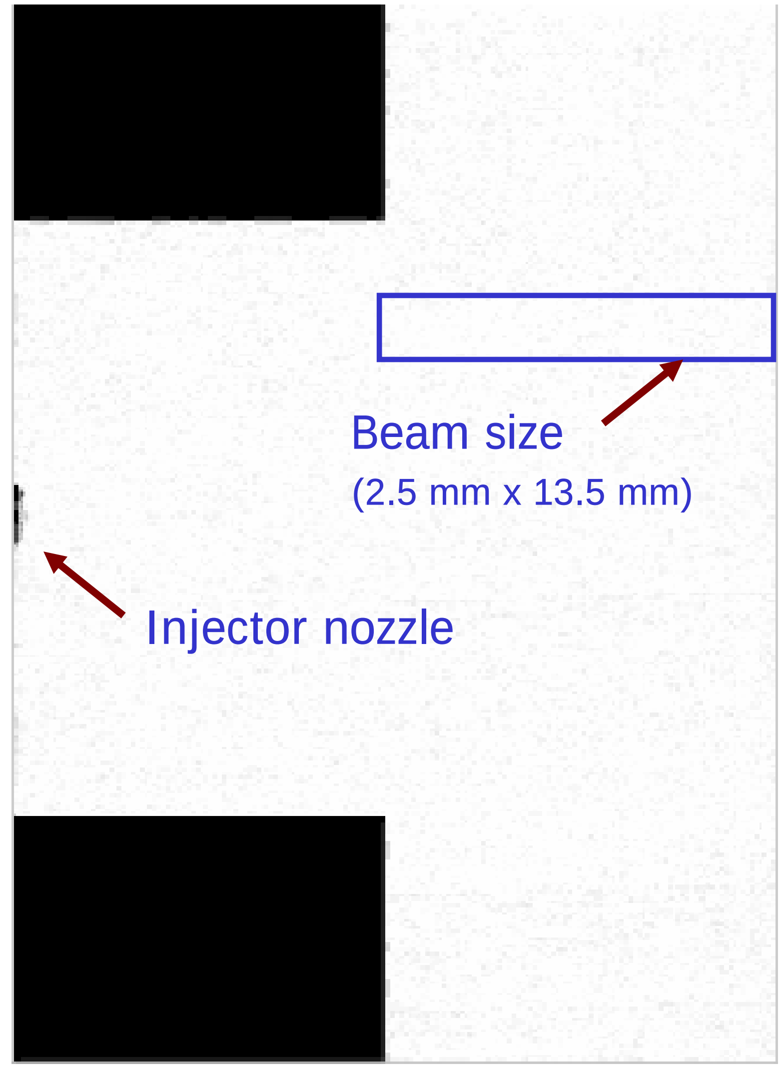
- 1.8 ms time sequence (composite)
- 5.13 μs exposure time
- (15.4 μs between frames)
- 88 frames (11 groups of 8 frames)
- 28 beam positions
- 1000 x-rays/pixel/μs
- Average 20x to improve S/N
- Data taken with 4 projections (2 will be shown)
- Sequence comprised of 10^5 images



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Gasoline fuel injector spray

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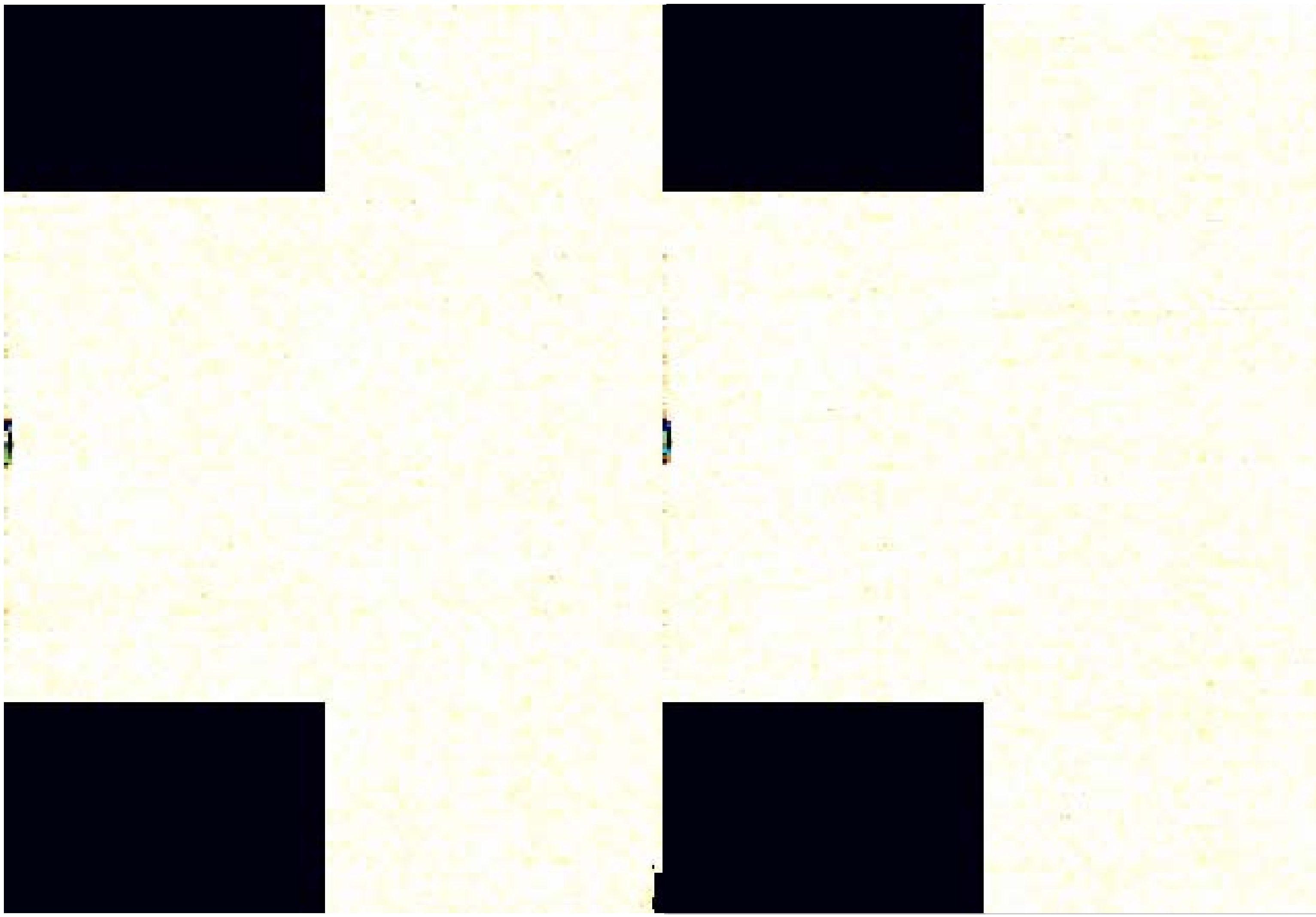
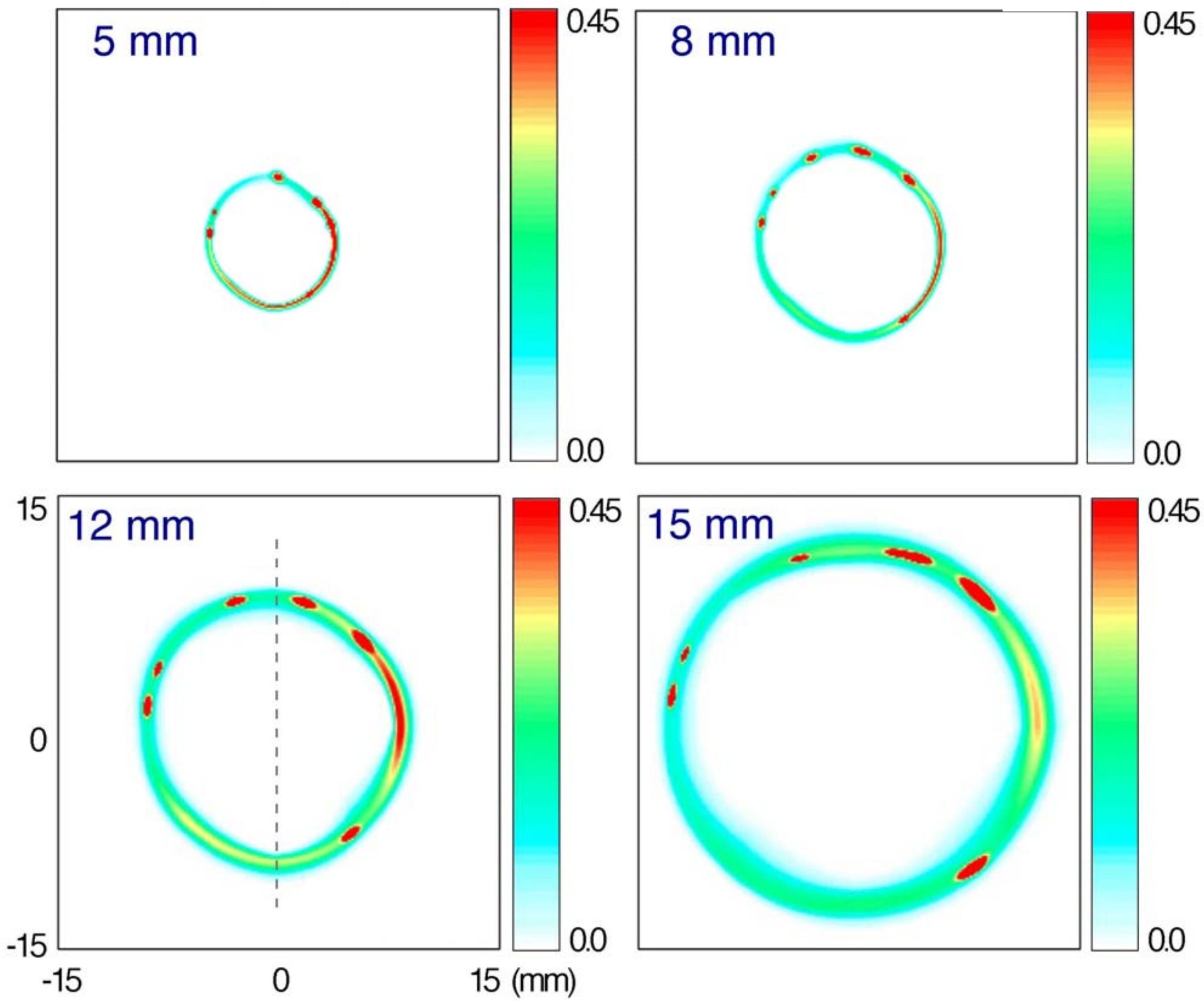


Spray is very nonuniform



Radiation Damage (1.2 μm chip)

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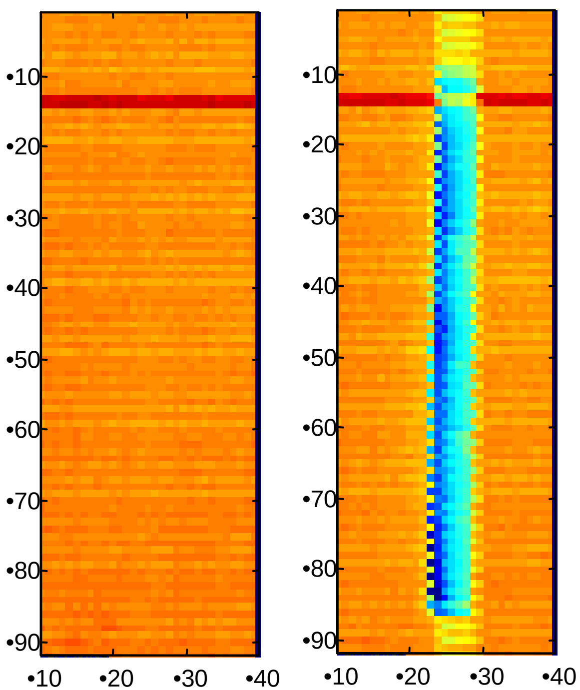
Background images

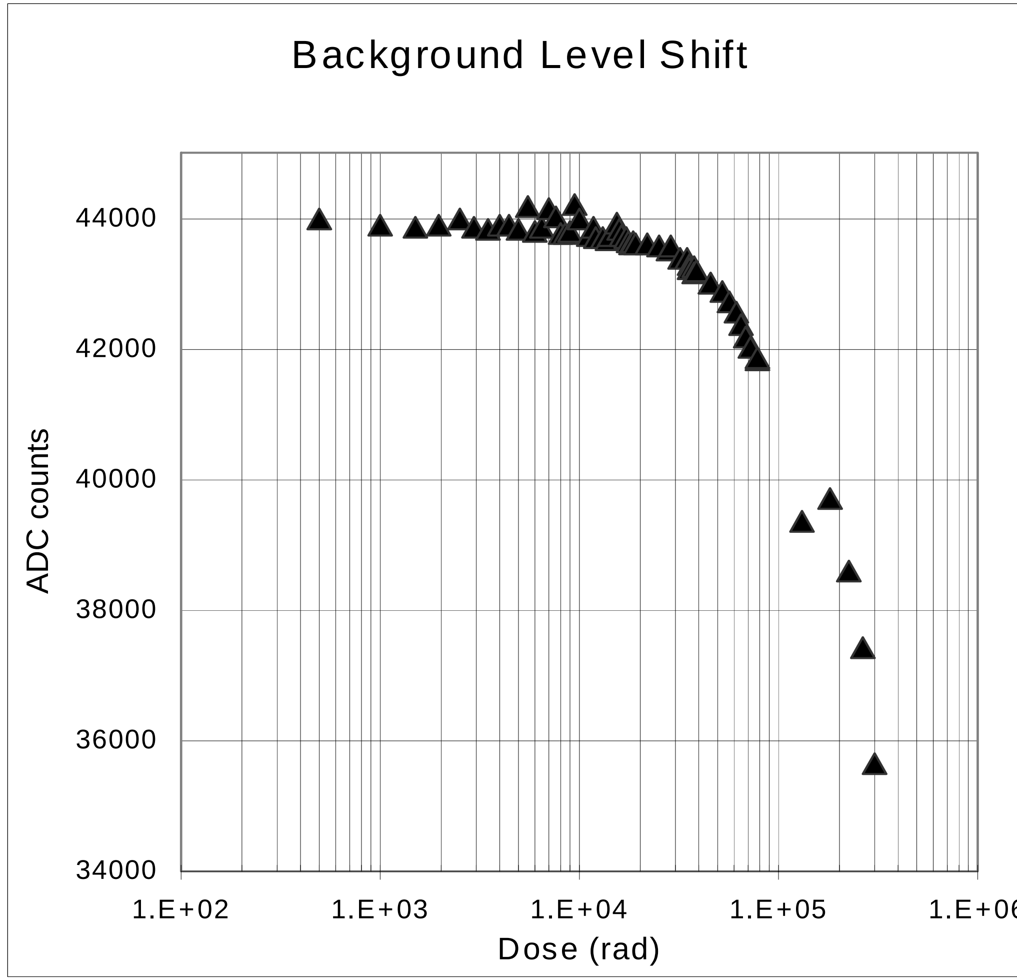
original   300 kRad to oxide



Background level shift

(correctable)

However- losing full well



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Improvements in Radiation Tolerance

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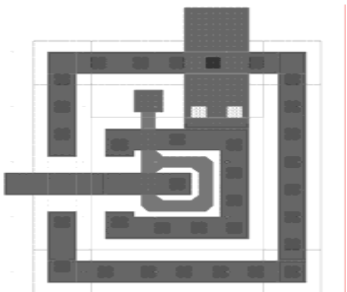
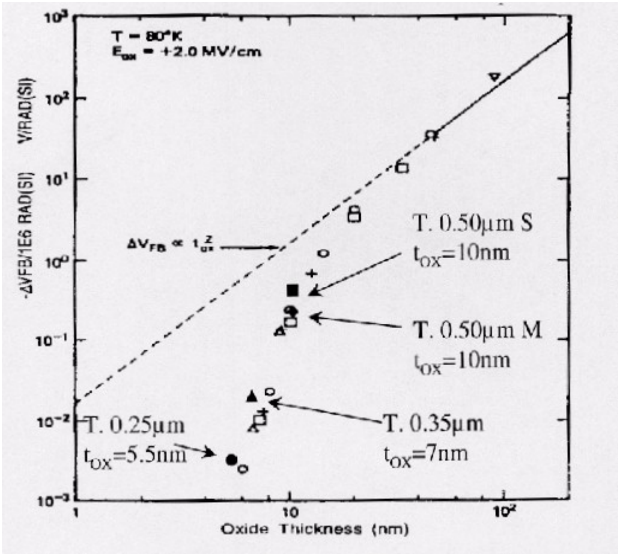
1. **Thinner CMOS oxide**
2. **Enclosed (ring) gates**

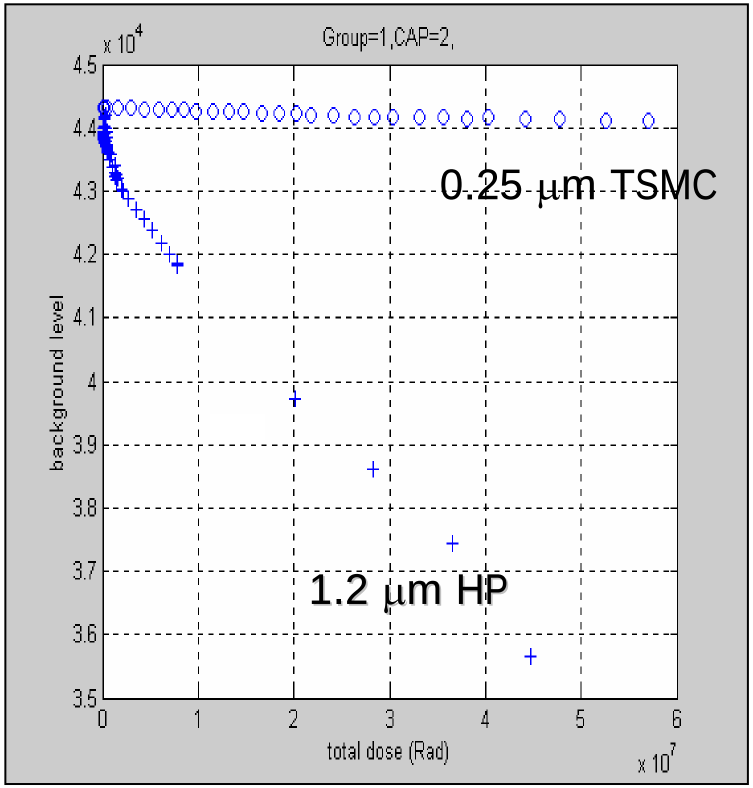




Saks et al., IEEE Trans. Nuc. Sci **33** (1986) 1185.

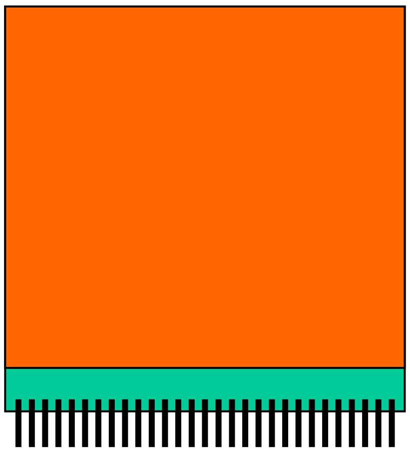
Bkgnd level of amplifier in 16x16 pix detector (enclosed gates, 0.25µm TSMC process).

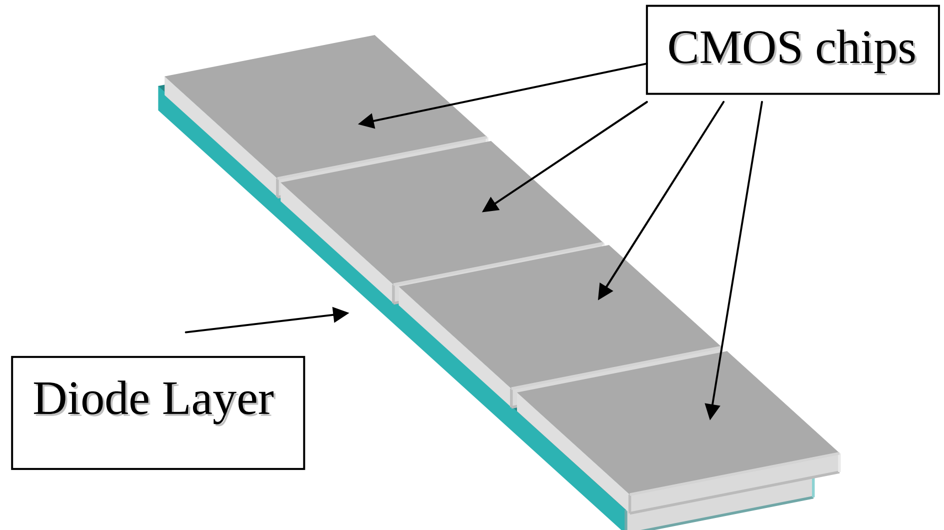
Still good after 60 MRad to detector.



Tiling for larger area

Use 3 side buttable CMOS dies:

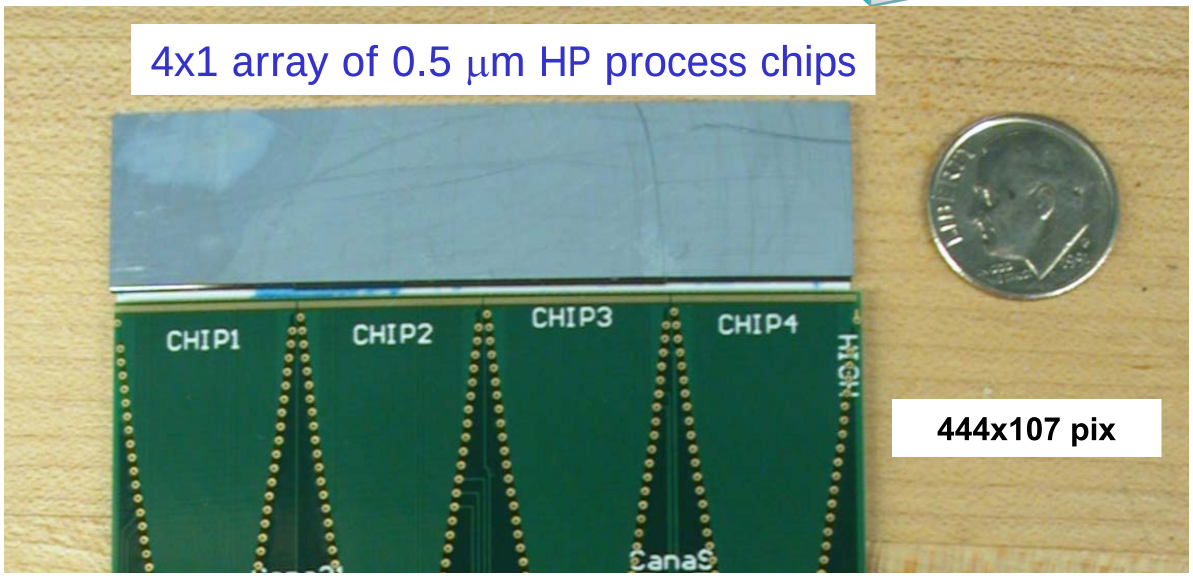




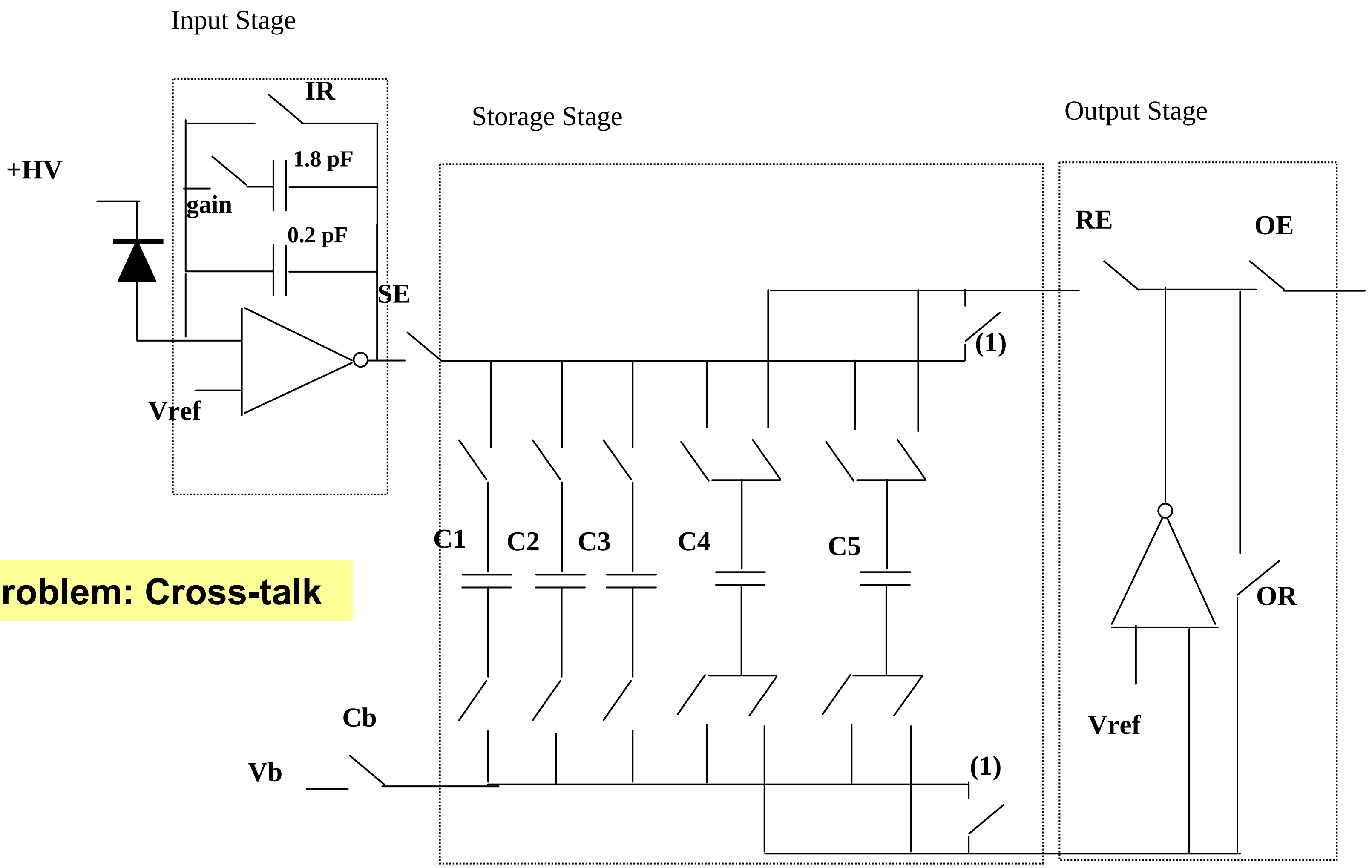
4 chips on larger diode array

(arrays also 3 side buttable)

3 pixel gap between chips



Faster Duty-Cycle: Push-Pull Configuration with Selectable Gain



Problem: Cross-talk

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What do we really want for most experiments?

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Answer: For a given slice of time, a 2-dimensional floating-point array of numbers that maps the x-ray intensity over a given imaging surface.

Question: Given this, how many digits should there be in the mantissa?

Answer: Relative accuracy of existing detectors almost never exceeds 0.2% and, typically barely achieves 1%. Suggests an 8 bit mantissa.

Mixed-Mode PAD (MMPAD)

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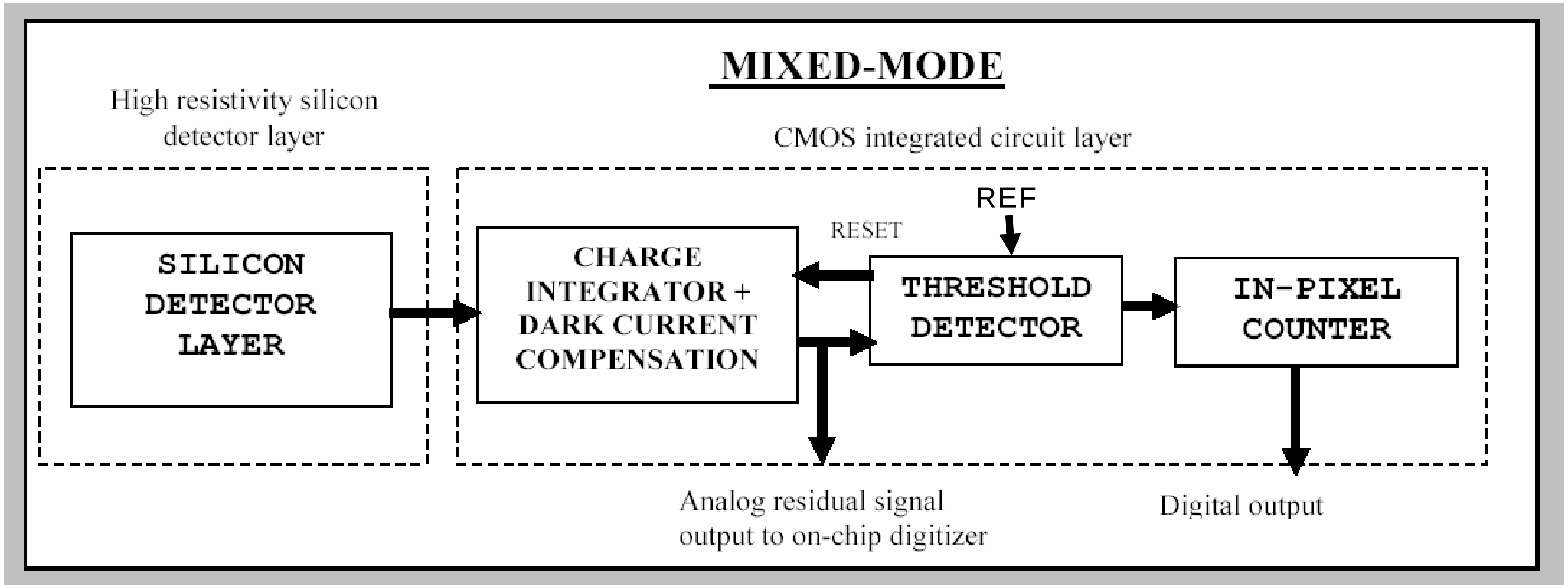

1. Charge integrated up to some max level, set by threshold, Q_T.
2. When Q_T is reached, a bit is added into in-pix digital counter, and the integrator is zeroed.
3. Upon command, the total count is output. The remaining charge in the integrator is digitized, if desired. One ADC/row.

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MMPAD Characterization

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MMPAD principally characterized by few critical parameters:

- $G \equiv$ Charge-to-voltage input amp conversion gain
- $V_{REF} \equiv$ Threshold for zeroing analog integrator
- $V \equiv$ Voltage range allowed by fabrication process
- $C_{INT} \equiv$ Size of integration capacitor
- $M_{ADC} \equiv$ # bits of on-chip ADC
- $N_{DIG} \equiv$ # bits of in-pix digital counter
- $\sigma \equiv$ Total pixel noise

Straightforward to model pixel for given parameters.

Note: $N_{DIG} = 0$ equivalent to traditional analog PAD.

$V_{REF} = 1$ x-ray, $M_{ADC} = 0$ is traditional photon counter.

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Theoretical DQE of MMPAD

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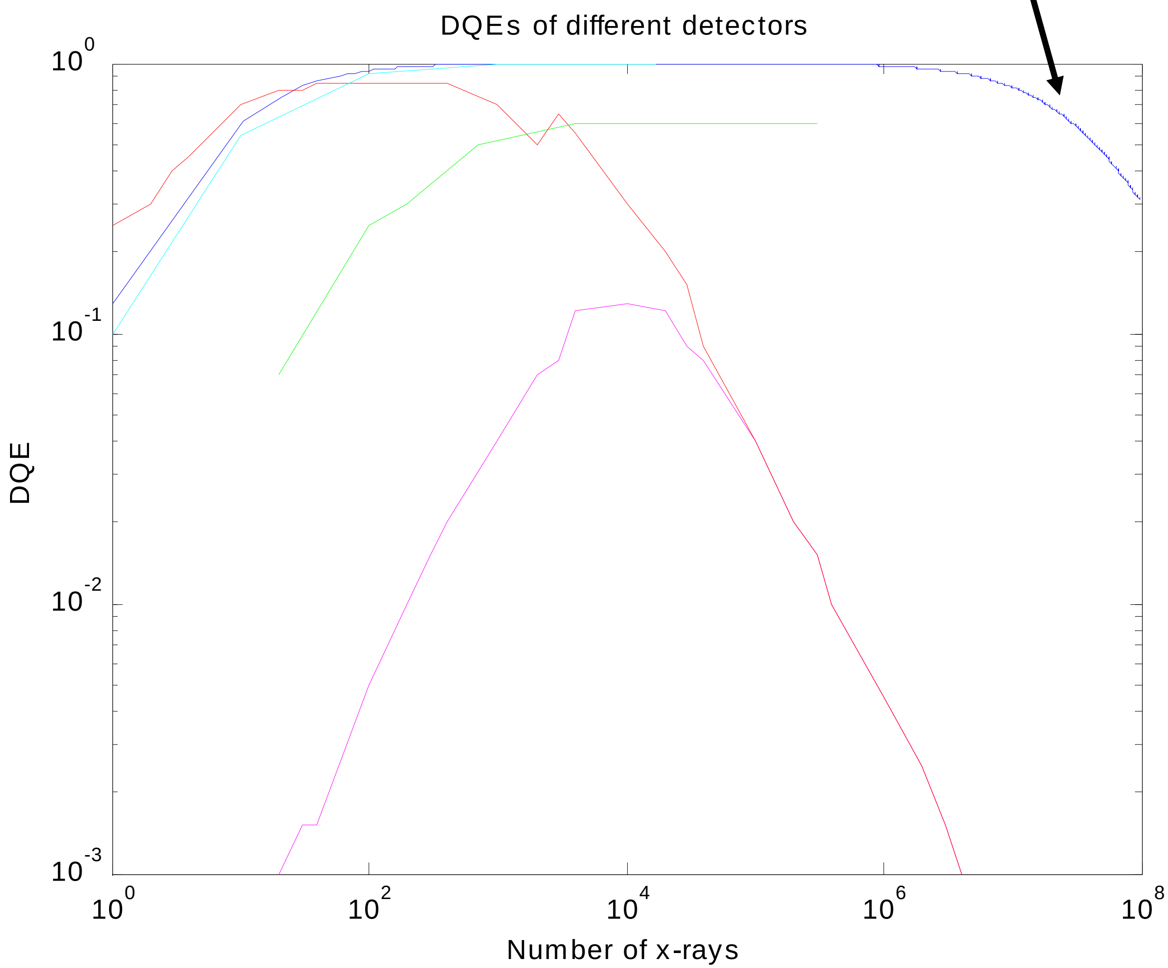
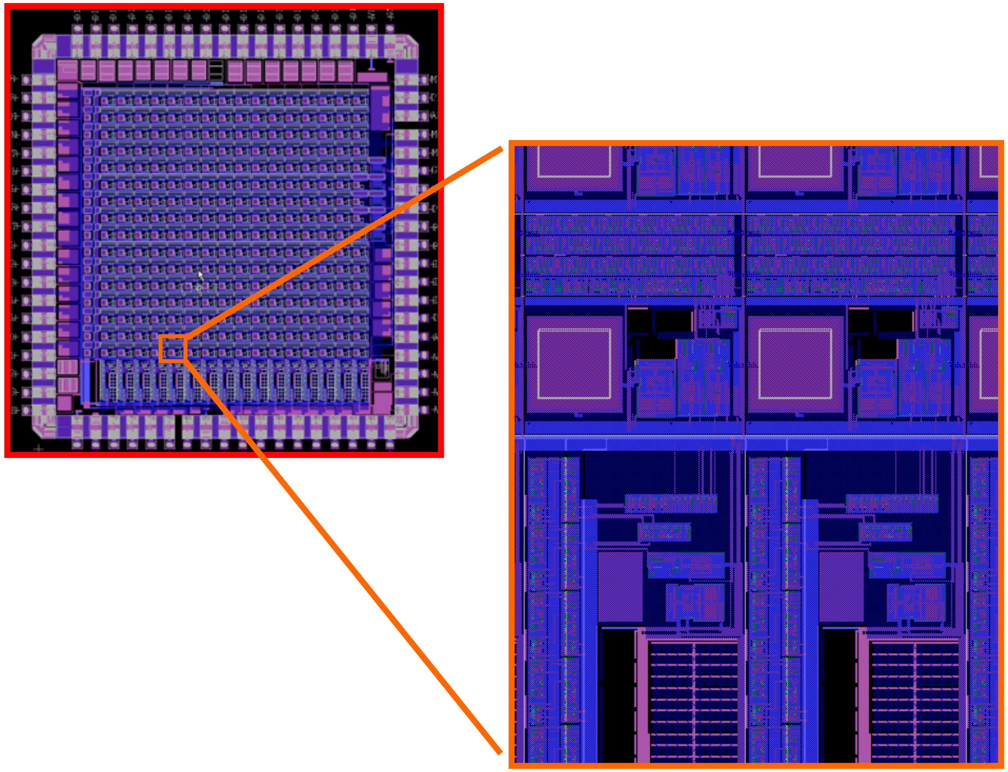
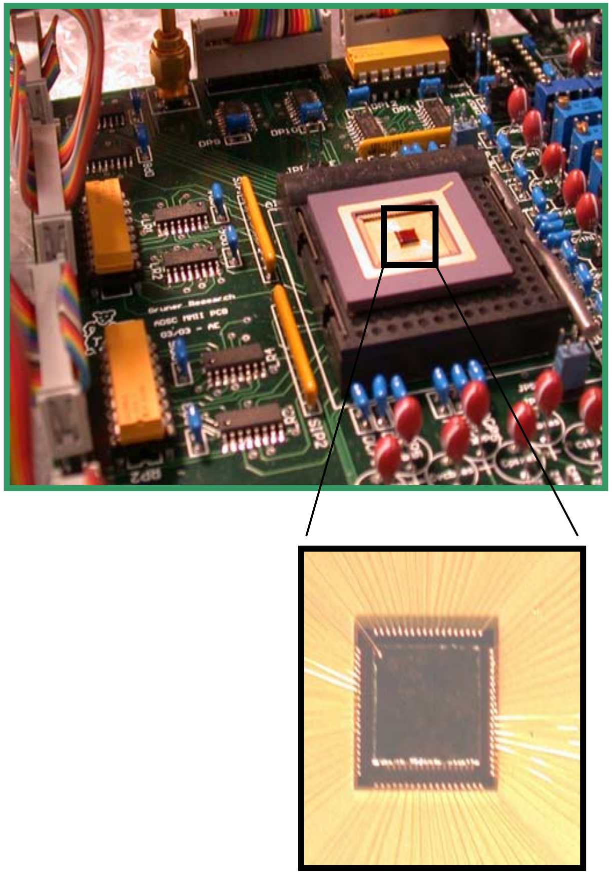


DQE assuming 100% diode layer stopping power

First 16x16 MMPAD test chips





Summary

- Prototype analog PAD already useful for cutting edge science.
- Many variations on CMOS possible.
- Consideration of way image data is actually analyzed suggests MMPAD has advantages of both analog and photon-counting PADs.
- First MMPAD test chips have been made.
- Years of work remain (packaging, tiling, rad-damage mitigation, etc.), but no show-stoppers.