Analog X-ray Pixel Detector (APAD) Developments

CHESS & LASSP

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&

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- **Description of APADs**
- **Application examples**

Basic Pixel Array Detector (PAD)

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Diode Detection Layer

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

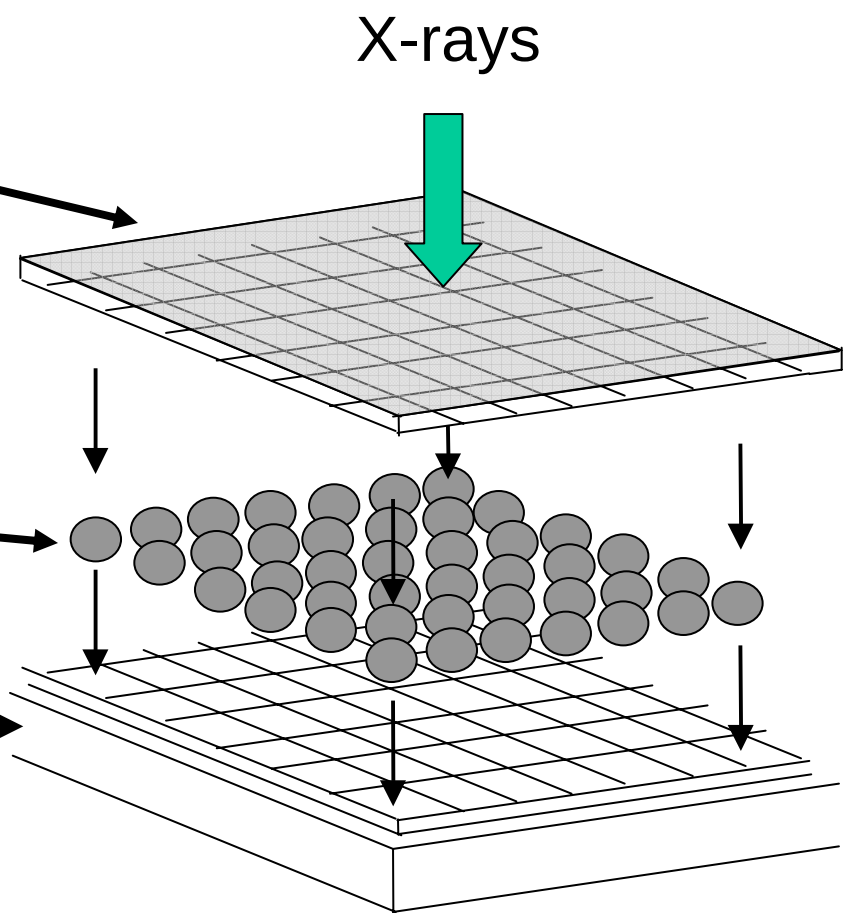
Connecting Bumps

- Solder or indium
- 1 per pixel

CMOS Layer

- Signal processing
- Signal storage & output

Gives enormous flexibility!



Analog & Photon Counting PADs

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 (APADs)

- 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

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Rapid Framing Imager

- In pix storage for several frames
- Selectable integration time (μs to seconds)
- Dead time < few 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

Application Examples

- High-flux radiography
  - Liquid jets
  - Shock waves
  - Crack propagation
- XFEL and ERL applications
  - Single-pulse scattering time sequences
  - Repetitive high frame rate problems
- Phase-sensitive cyclic scattering

Cornell Analog PAD

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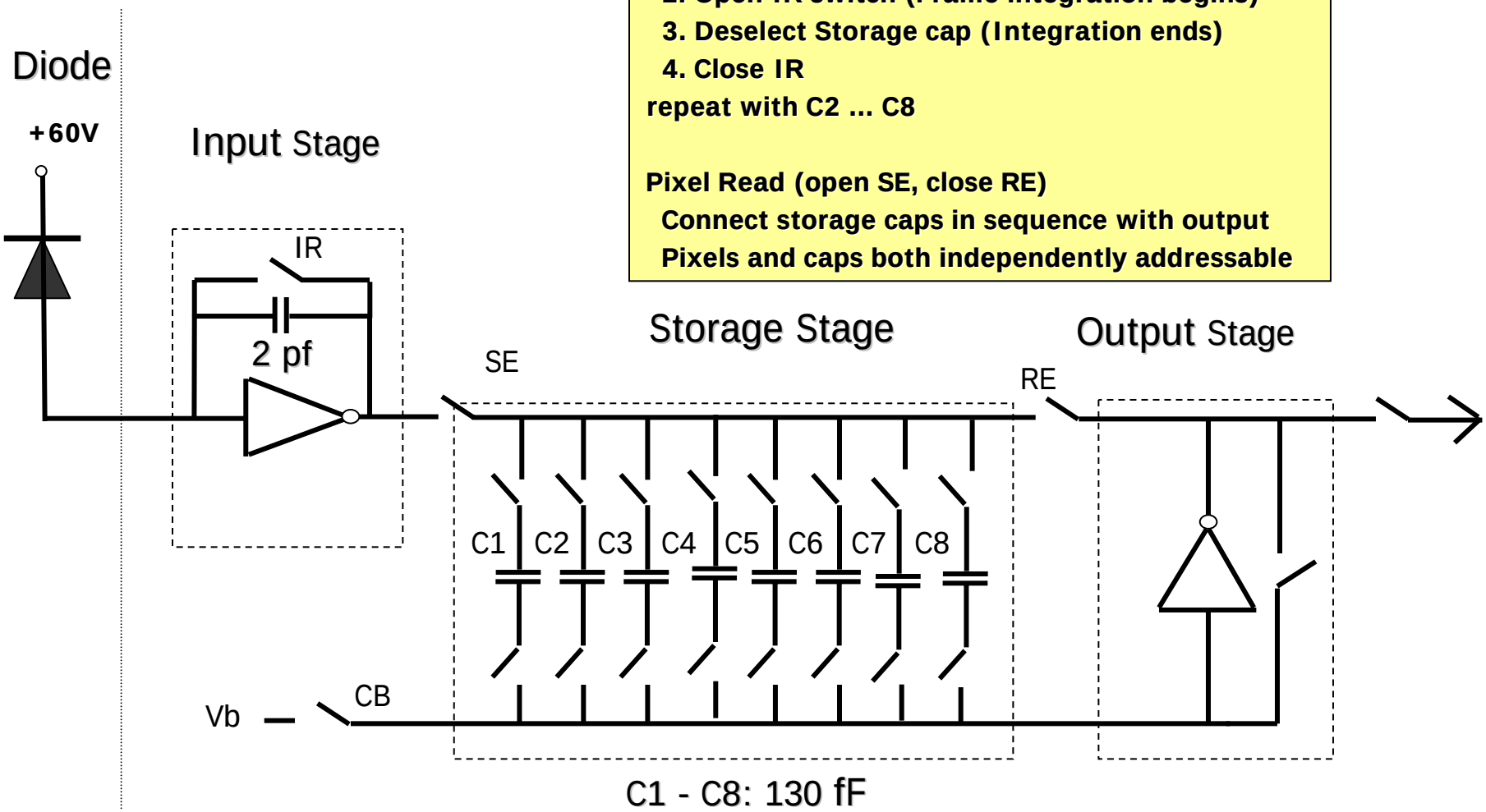
Rapid framing (SE, IR closed)
1. select storage cap C1
2. Open IR switch (Frame integration begins)
3. Deselect Storage cap (Integration ends)
4. Close IR

repeat with C2 ... C8

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



Cornell 100x92 Analog PAD

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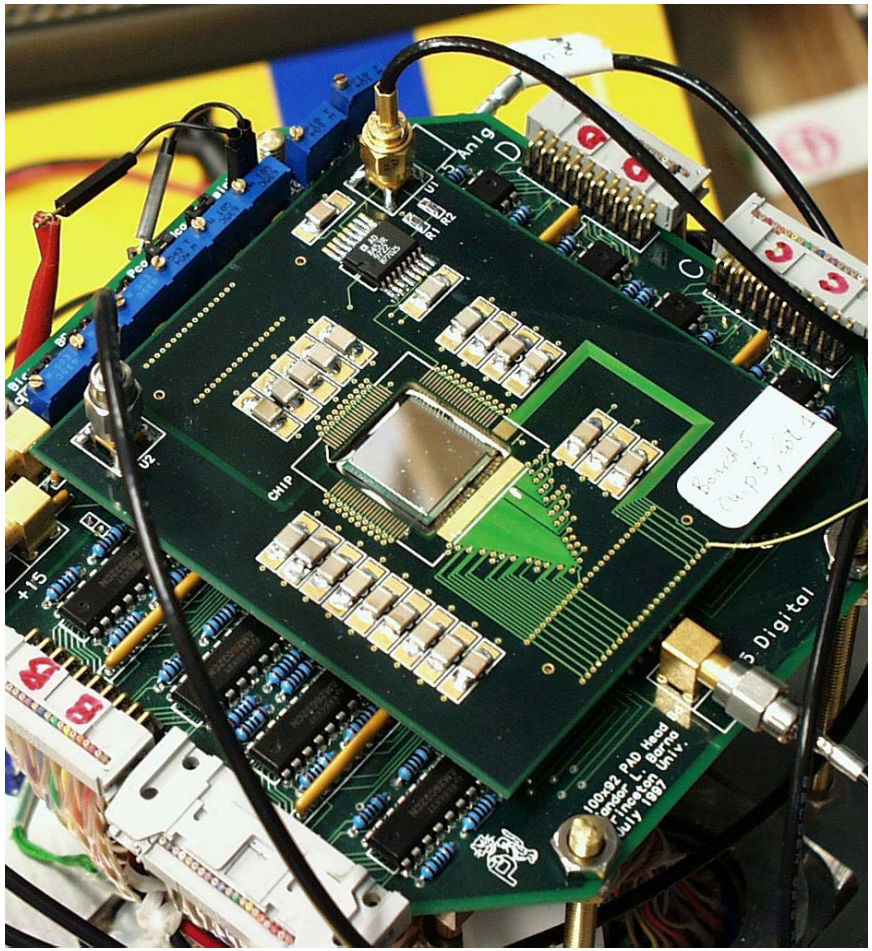
1.2 μm HP CMOS process (MOSIS)
(Linearized Capacitors)
15 x 13.8 mm^2 active area; 100x92 pixels
150 μm square pixel
300 μm thick, high resistivity Si diode wafer (SINTEF)
120 μm solder bump bond (GEC-Marconi)

100x92 PAD developers include:
- Sandor Barna
- Eric Eikenberry
- Alper Ercan
- Sol Gruner
- Matt Renzi
- Giuseppe Rossi
- Mark Tate
- 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, CMOS oxide)	30
• Tolerable radiation dose (kRad)	>300

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)

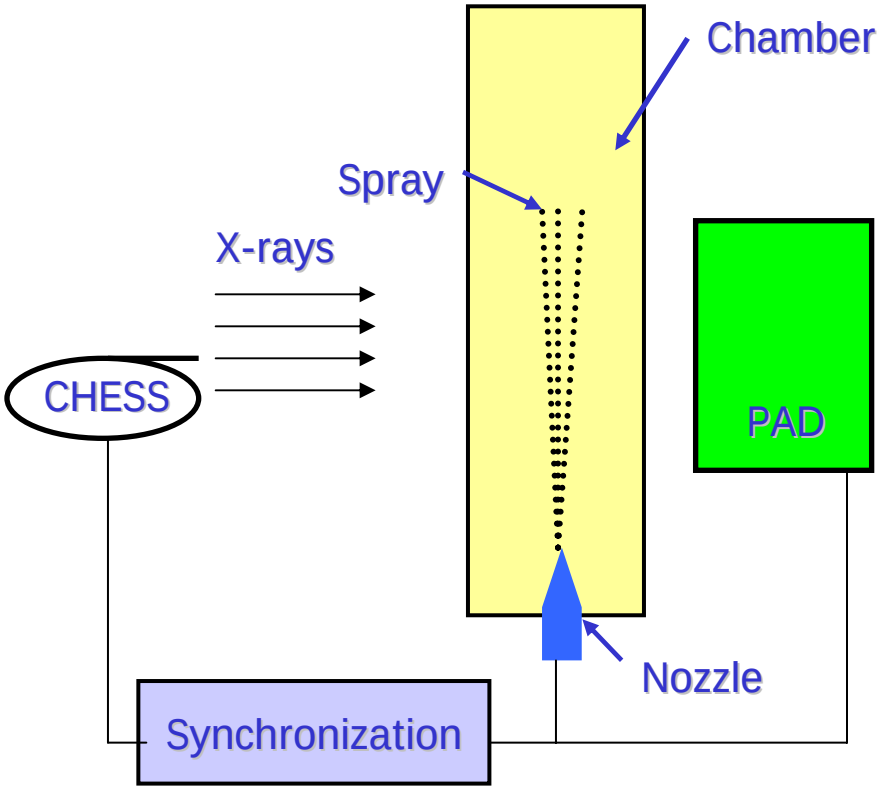
Diesel Fuel Injection System

- 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.**



High speed radiography:

Supersonic spray from diesel fuel injector

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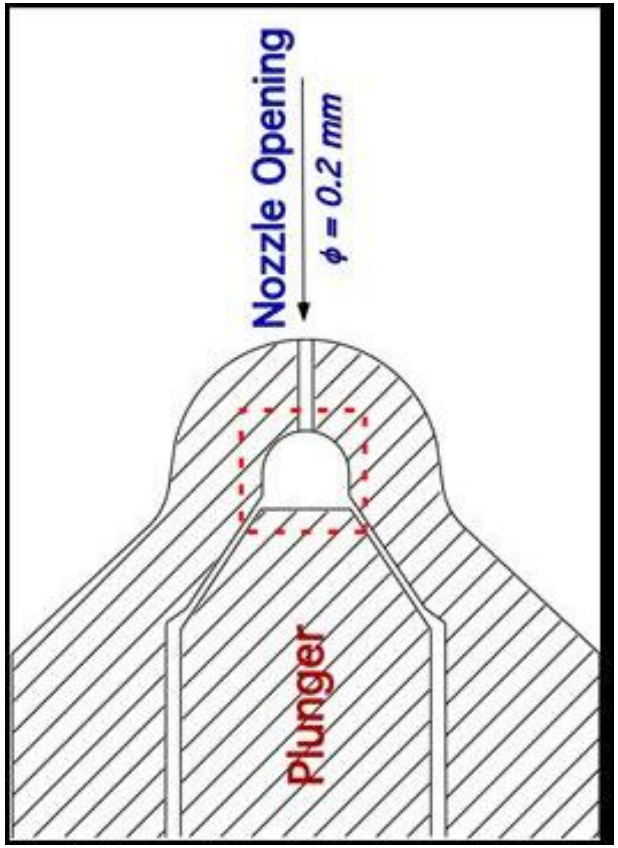

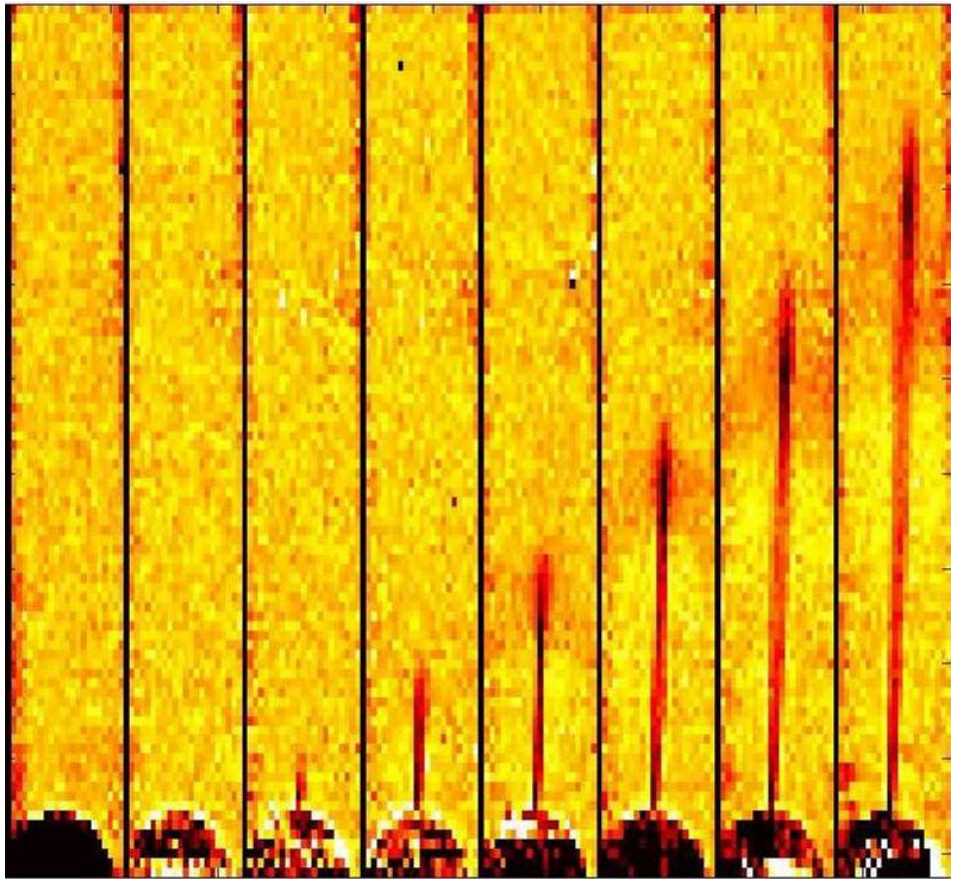

Diesel fuel injector spray

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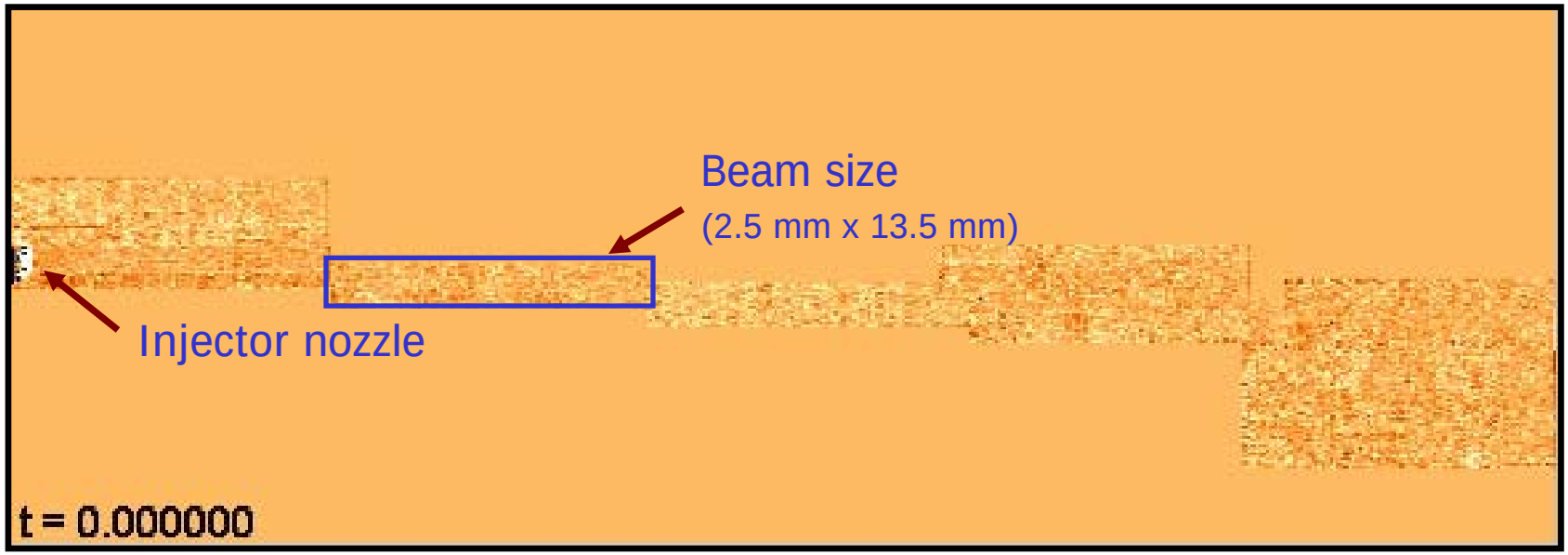
- 1.3 ms time sequence (composite of 34 sample positions)
- 5.13 μs exposure time (2.56 μs between frames)
- 168 frames in time (21 groups of 8 frames) Average 20x for S/N
- Sequence comprised of 5 x 10^4 images



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

Gasoline fuel injector spray

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X-ray beam

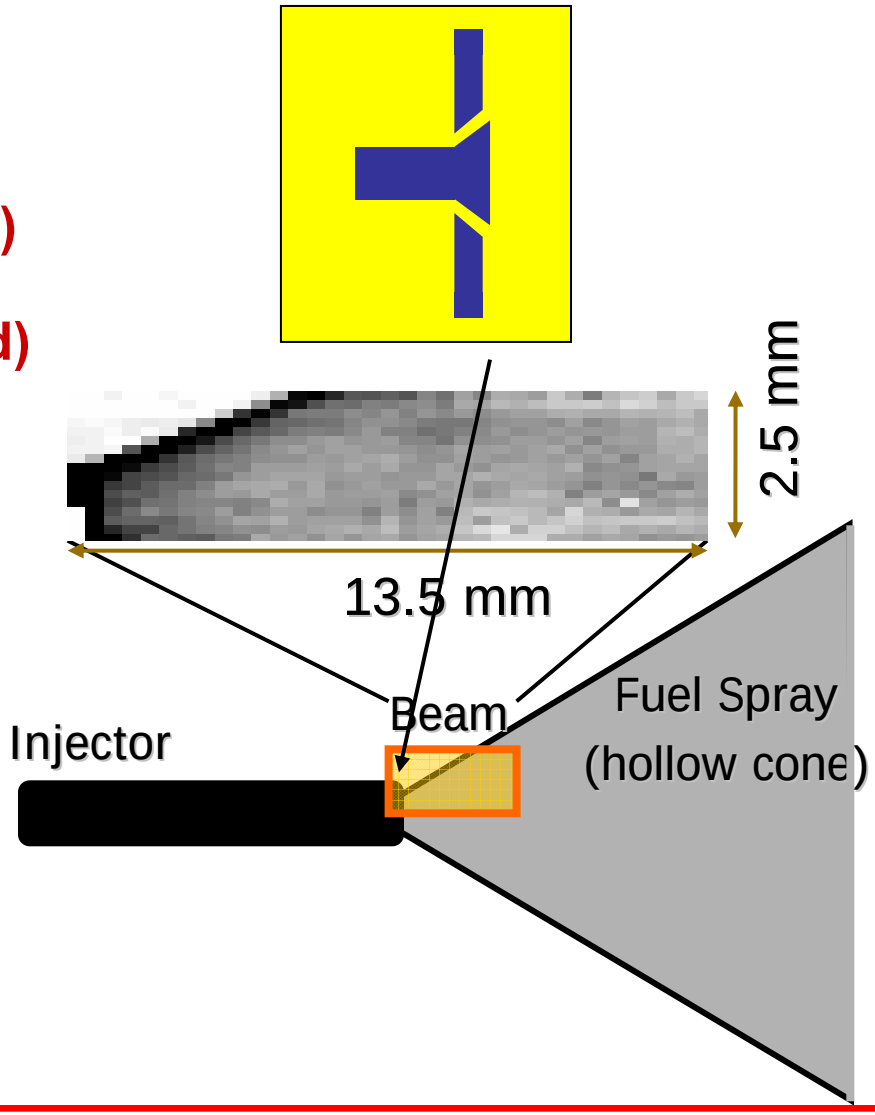
- CHESS Beamline D-1
- 6 keV (1% bandpass)
- 2.5 mm x 13.5 mm
- (step sample to tile large area)
- 10^9 x-rays/pix/s
- 5.13 μs integration (2x ring period)

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. 83 (2003) 1671.



Gasoline fuel injector spray

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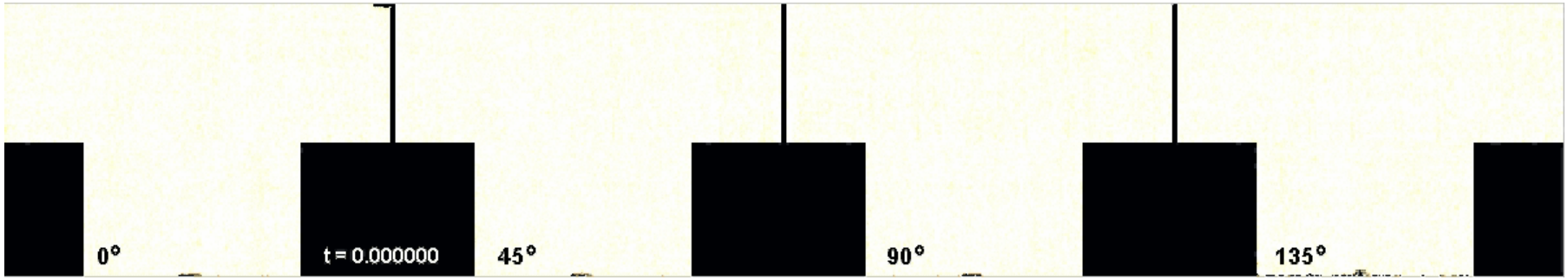

- 1.8 ms time sequence (composite). 10^5 images
- 5.13 μs exposure time. (15.4 μs between frames)
- 88 frames (11 groups of 8 frames), Avg. 20x for noise.
- 1000 x-rays/pixel/μs
- Data taken with 4 projections.

Spray is very nonuniform

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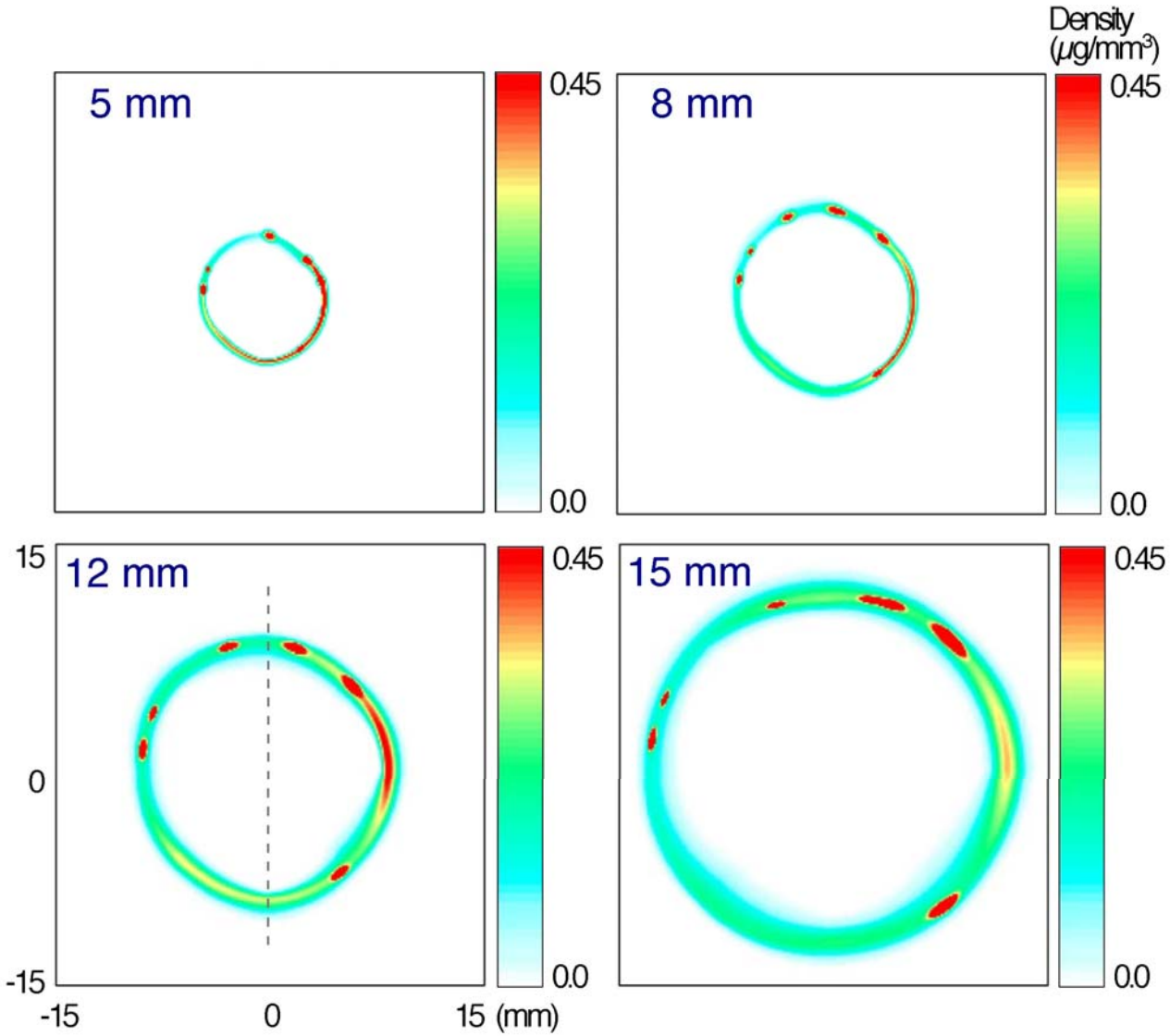

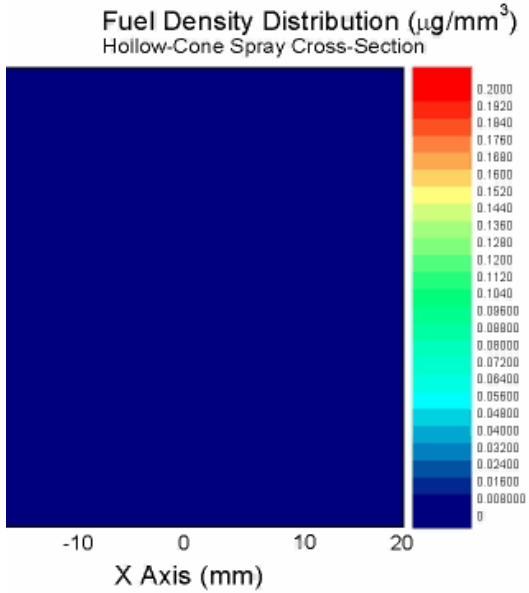

Novel Spray Nozzels

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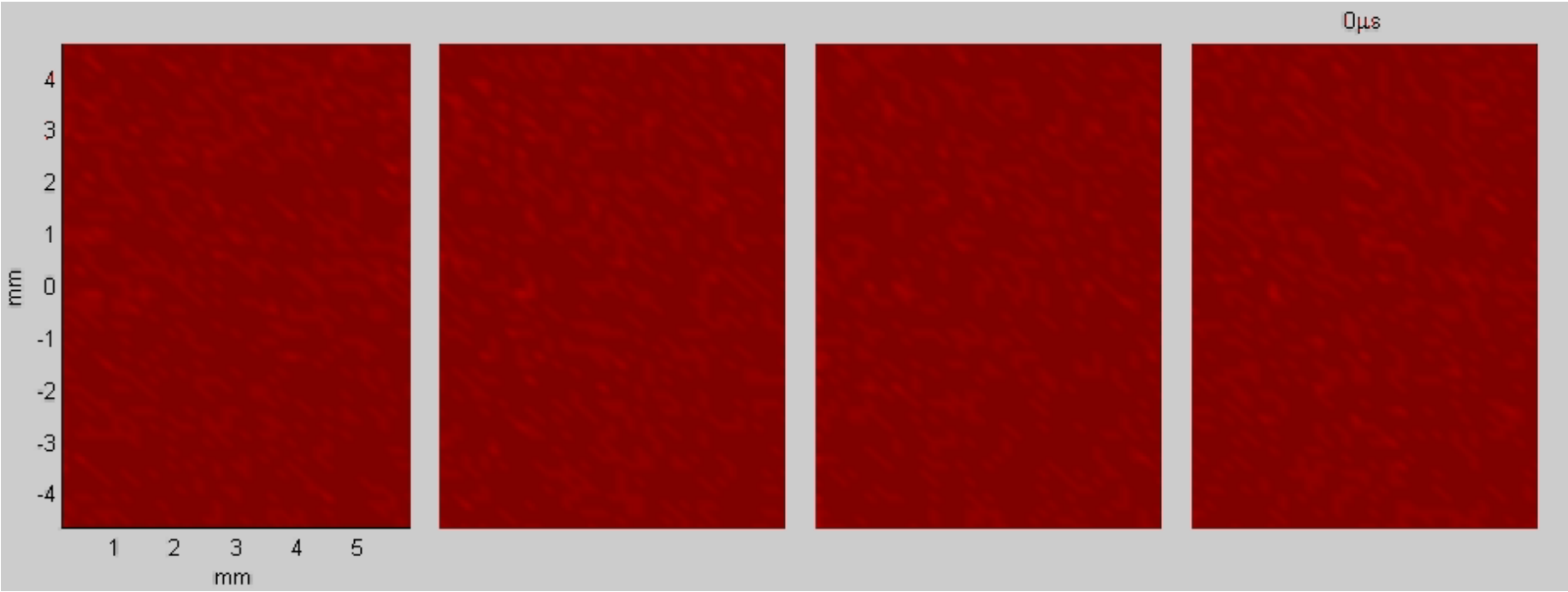

Faster Duty-Cycle:
Push-Pull Configuration with Selectable Gain

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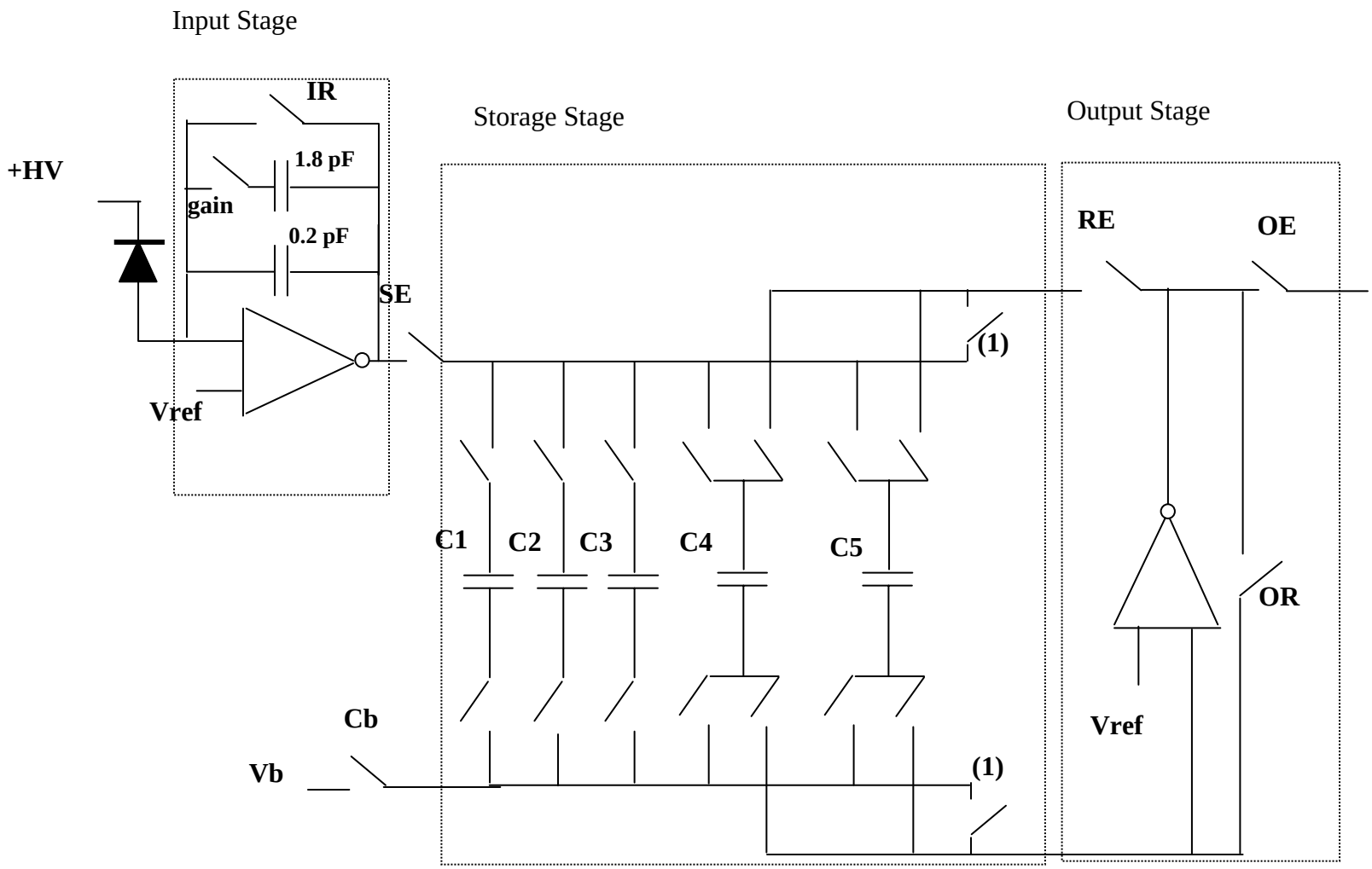

16x16 Push-Pull laser tests

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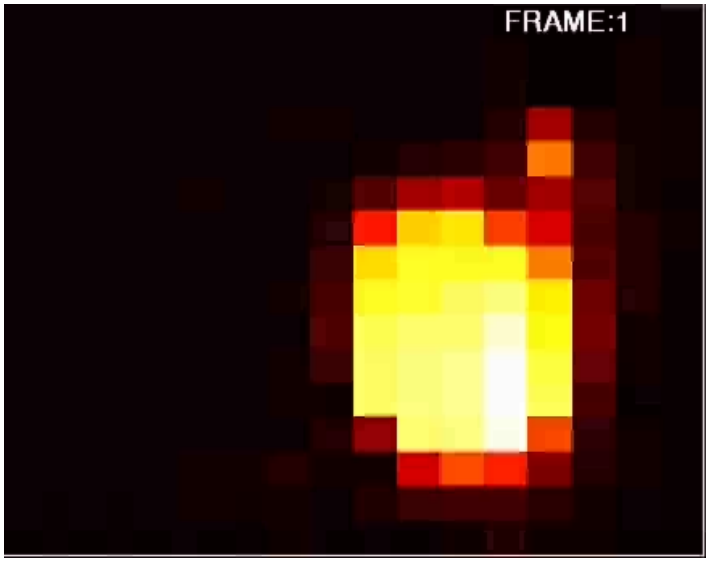
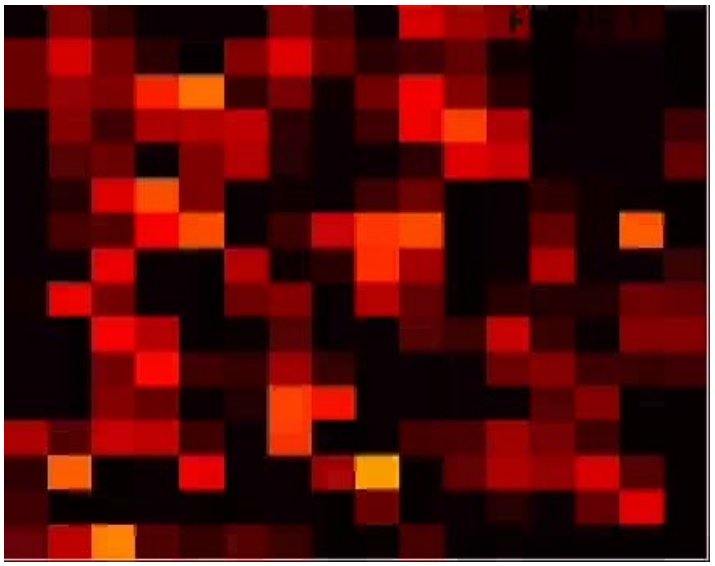


Moving laser spot



Laser shining through chalk dust water.

120 frames/sec

PAD design: Matt Renzi, Alper Ercan

Tests: Alper Ercan

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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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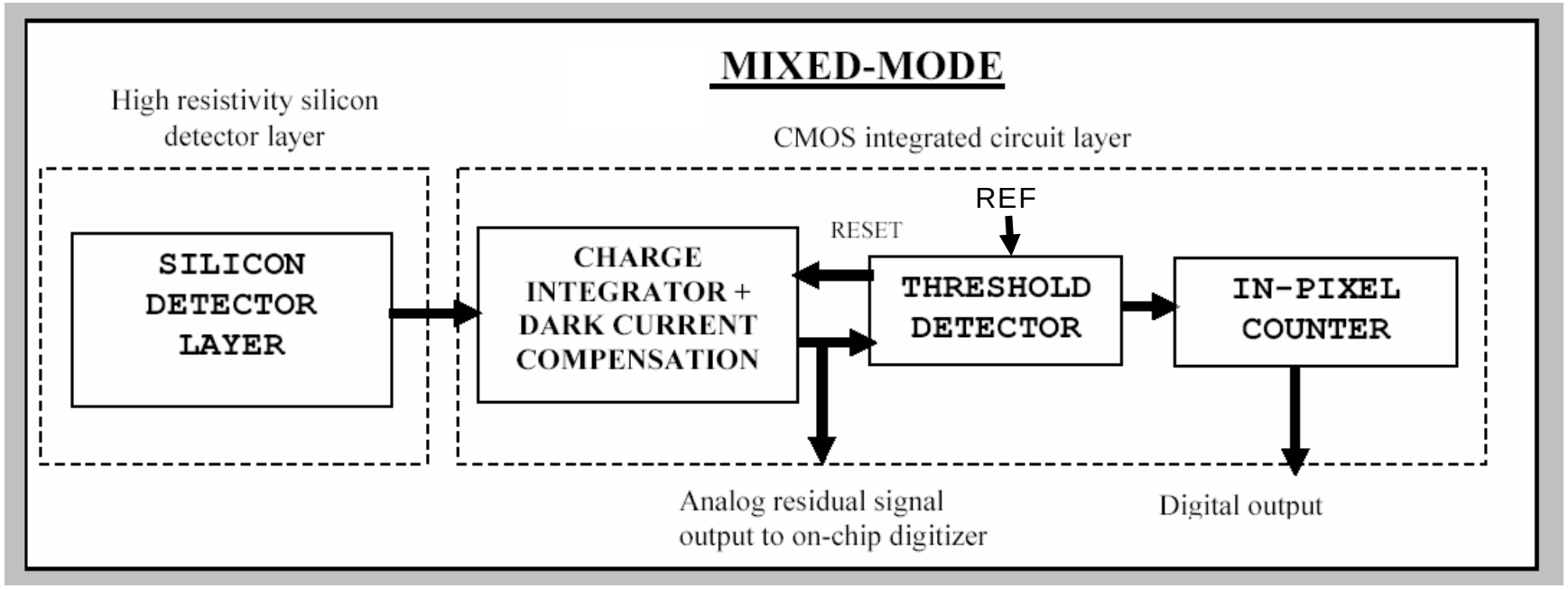

1. Charge integrated up to some max level, set by threshold, Q_T.
2. When Q_T is reached, a bit is added into in-pix digital counter, and the integrator is zeroed.
3. Upon command, the total count is output. The remaining charge in the integrator is digitized, if desired. One ADC/row.

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Design Goals for the MMPAD

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- ✓ 10^8 x-rays/sec, max for each pixel
- ✓ 10 x-rays/sec, min for each pixel
- ✓ 18 bit counter in each pixel: ~150 x-ray/count
- ✓ Readout (dead time) of ½ msec
- ✓ ASIC size: 20x21 mm (128x128 pixel)
- ✓ Measuring precision of 0.25%
- ✓ X-ray energies from 5.9 to 15 keV

ADSC: S. G. Angello, F. Augustine, R. C. Hamlin, T. Hontz, and W. Vernon, Ng. H. Xuong

Cornell: A. Ercan, S. M. Gruner, M. J. Renzi, D. R. Schuette, and M. W. Tate

Support: NIH-NCRR

16x16 MMPAD test chips

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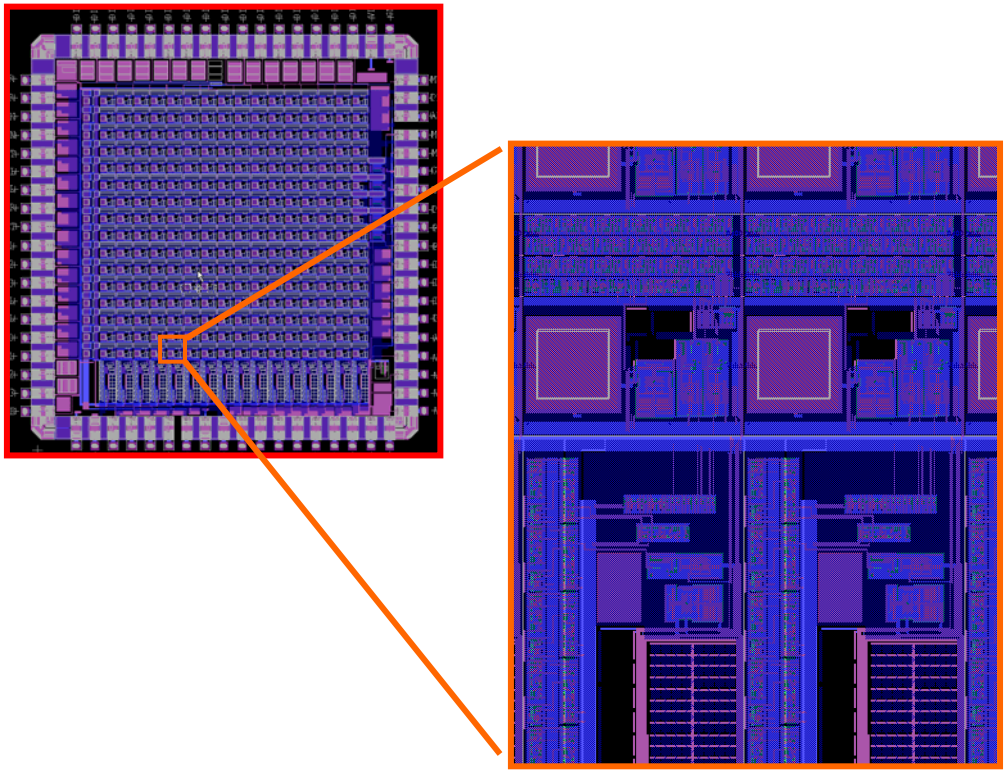

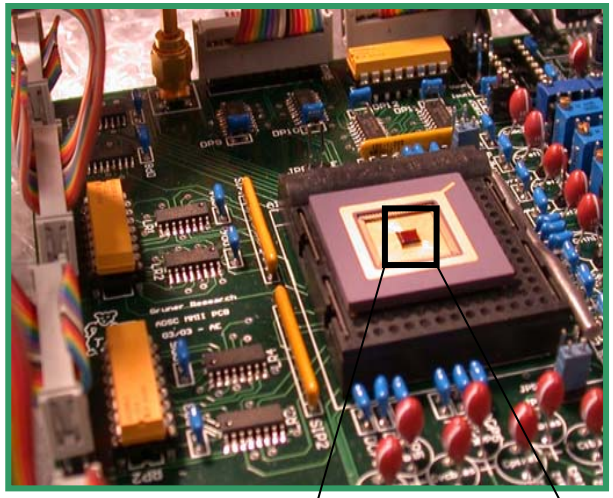

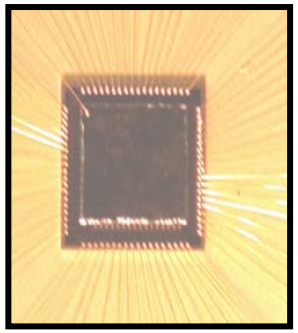

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Summary

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- 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.
- Several rounds of MMPAD test chips have been made.
- Much work remains (packaging, tiling, rad-damage mitigation, etc.), but no show-stoppers.

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Thanks to…

CHESS & LASSP

Former PAD Group Members

- Sandor Barna
- Eric Eikenberry
- Matt Renzi
- Giuseppe Rossi
- Bob Wixted

Cornell PAD Group

- Darol Chamberlain
- Alper Ercan
- Lucas Koerner
- Hugh Philipp
- Dan Schuette
- Mark Tate

ADSC

- Susan Angello
- Skip Augustine
- Ron Hamlin
- Tom Hontz
- Wayne Vernon
- Ng. H Xuong

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