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Integrating Pixel Array Detectors

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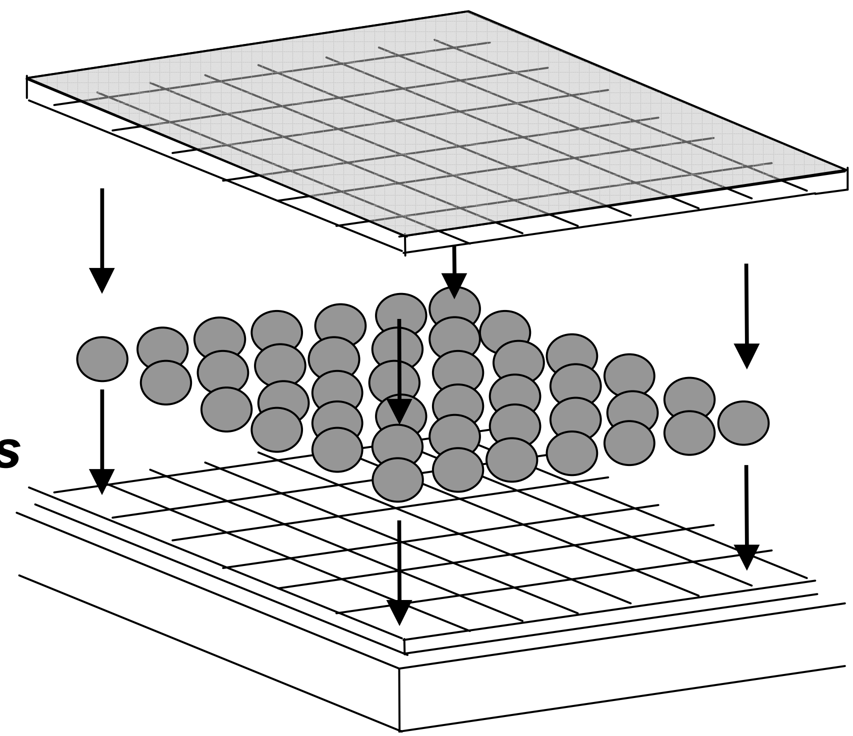

Detector development group

Mark Tate
Alper Ercan
Dan Schuette
Darol Chamberlain
Lucas Koerner
Hugh Phillip

Former members

Sandor Barna
Bob Wixted
Eric Eikenberry
Guiseppe Rossi
Matt Renzi

Basic Pixel Array Detector (PAD)

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Diode Detection Layer

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

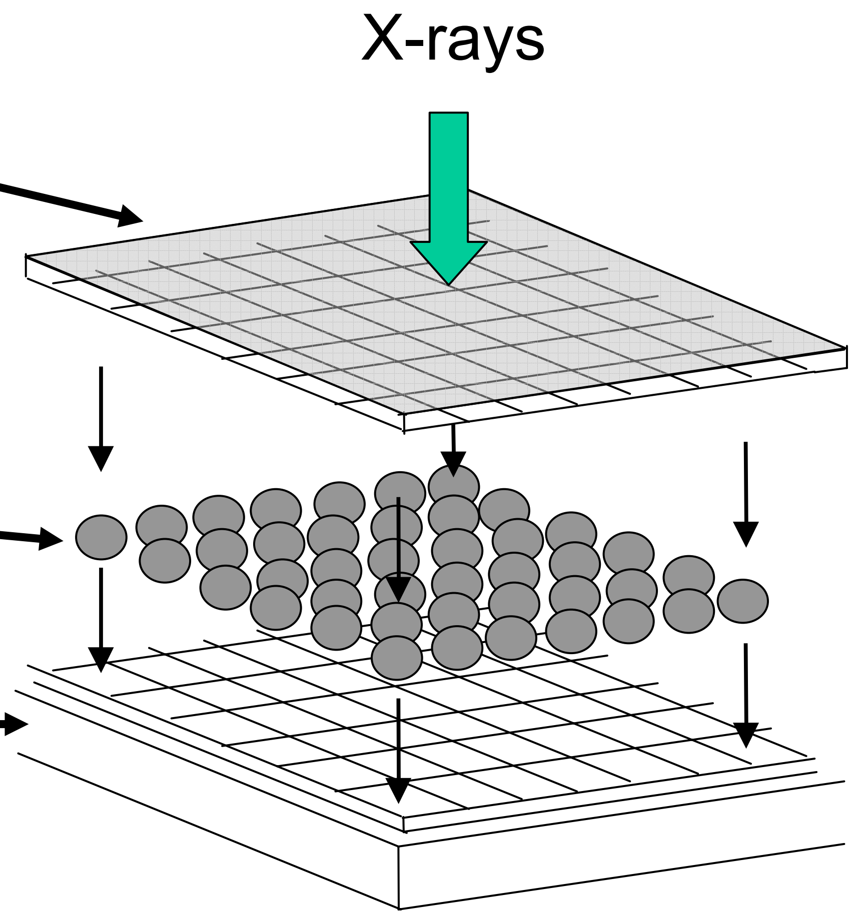
Connecting Bumps

- Solder or indium
- 1 per pixel

CMOS Layer

- Signal processing
- Signal storage & output

Gives enormous flexibility!



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Why Analog-Integrating?

Some Common Sense Rules

Rule #1: <u>There is no universal detector.</u> At best, a given detector is well-suited for a given application.

- **Community needs are met by a spectrum of detectors optimized for different applications.**
- **Analog PADs meet specific needs. Examples will follow.**

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Why Analog-Integrating?

Some Common Sense Rules

Rule #2: The accuracy of a given measurement is not necessarily better or worse just because a photon-counting or an analog-integrating detector is used.

Accuracy depends on many real-world details of both the experiment and the detector, including:

- **Calibrations**
- **Stability**
- **Photon loss due to, e.g., pixel signal-sharing, charge recombination, count-rate limitations, and x-ray absorption by inert structures**
- **Systematic effects, e.g., cross-talk, pickup noise**

Analog-integrators have successfully demonstrated excellent performance to appropriate accuracy in certain experiments.

Why Analog-Integrating?

Some Common Sense Rules

Rule #3: Any detector is only as good as its calibration. In practice area detectors rarely achieve accuracies of 1%, and never better than a few tenths percent.

This is especially true for:

- **Signals whose width is smaller than a pixel**
- **Very high local count-rates**

For certain applications, analog-integrators have been very successfully calibrated.

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Why Analog-Integrating?

Some Common Sense Rules

Rule #4: No matter how good you think a detector is, <u>you are bound to be in for nasty surprises</u> when you actually perform stringent performance tests.

Be skeptical of detector claims that are not backed up by appropriate, independently-repeated test data.

Analog-integrators have been around long enough that many of the nasty surprises are understood.

Analog-Integrating PADs are especially useful for…

- **Very high local count-rates. Examples:**
  - ✓ **Time-resolved radiography (e.g., >10^{10} x-ray/pix/sec)**
  - ✓ **Many XFEL & ERL applications (e.g., x-rays in femtoseconds)**
  - ✓ **Very low contrast imaging against high local backgrounds**

Analog-Integrating PADs are especially useful for…

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- Very high local count-rates. Examples:
  - ✓ Time-resolved radiography (e.g., $>10^{10}$ x-ray/pix/sec)
  - ✓ Many XFEL & ERL applications (e.g., x-rays in femtoseconds)
  - ✓ Very low contrast imaging against high local backgrounds
- **Accurate measurements of small-sized signals. Examples:**
  - ✓ **Microcrystallography from low mosaic spread crystals.**
  - ✓ **Micro-radiography and tomography**
  - ✓ **Accurate difference imaging of spatially fine features.**

Analog-Integrating PADs are especially useful for…

- Very high local count-rates. Examples:
  - ✓ Time-resolved radiography (e.g., >10^{10} x-ray/pix/sec)
  - ✓ Many XFEL & ERL applications (e.g., x-rays in femtoseconds)
  - ✓ Very low contrast imaging against high local backgrounds
- Accurate measurements of small-sized signals. Examples:
  - ✓ Microcrystallography from low mosaic spread crystals.
  - ✓ Micro-radiography and tomography
  - ✓ Accurate difference imaging for images with fine features.
- **Problems involving complex analog signal processing. Example:**
  - ✓ **In-pixel time-correlation of images (e.g., high count-rate speckle experiments).**

Specific Example: High Speed Imaging

Design Requirements

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

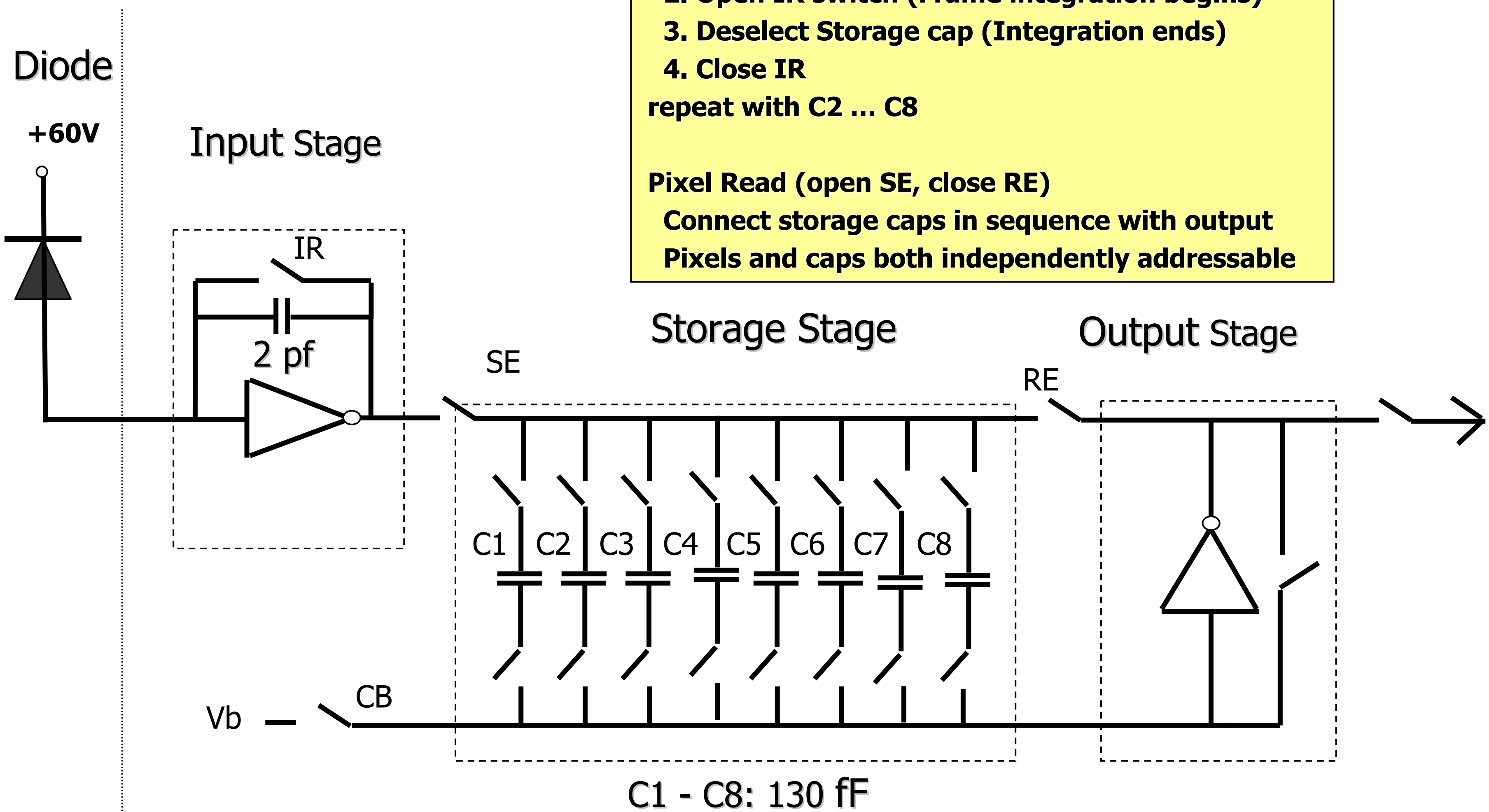
Standard CMOS fabrication service

Cornell Analog PAD

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**



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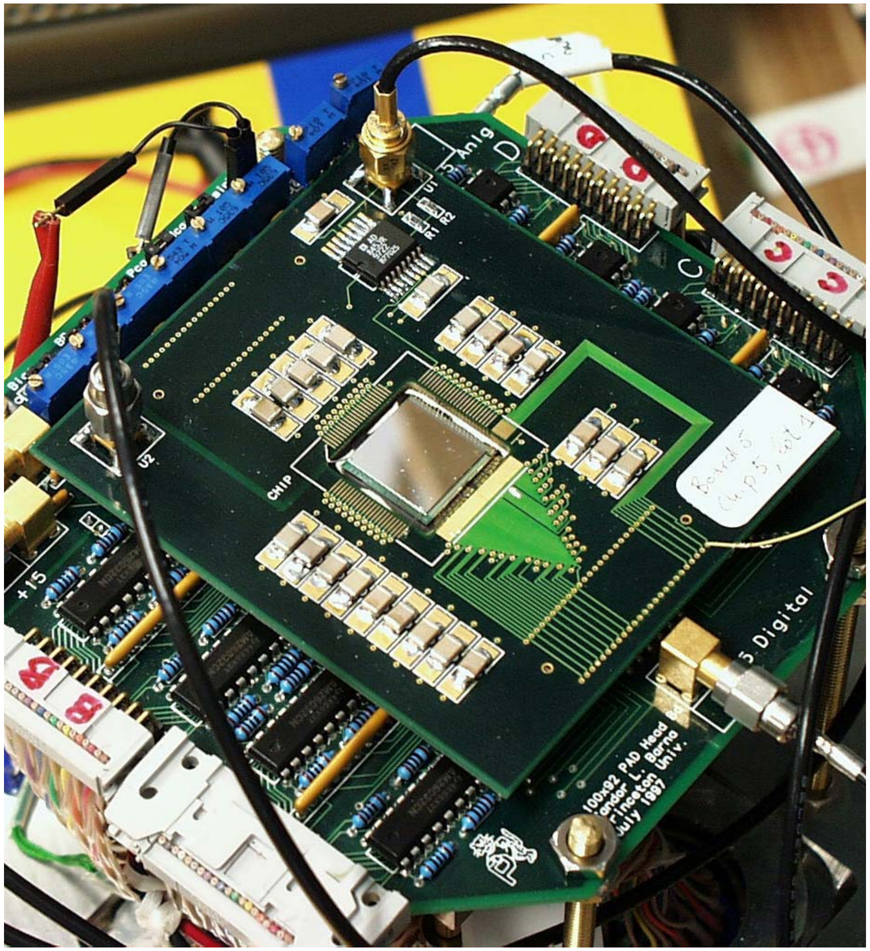
Cornell 100x92 Analog PAD

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

100 x 92 Prototype Tests

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

X-ray beam

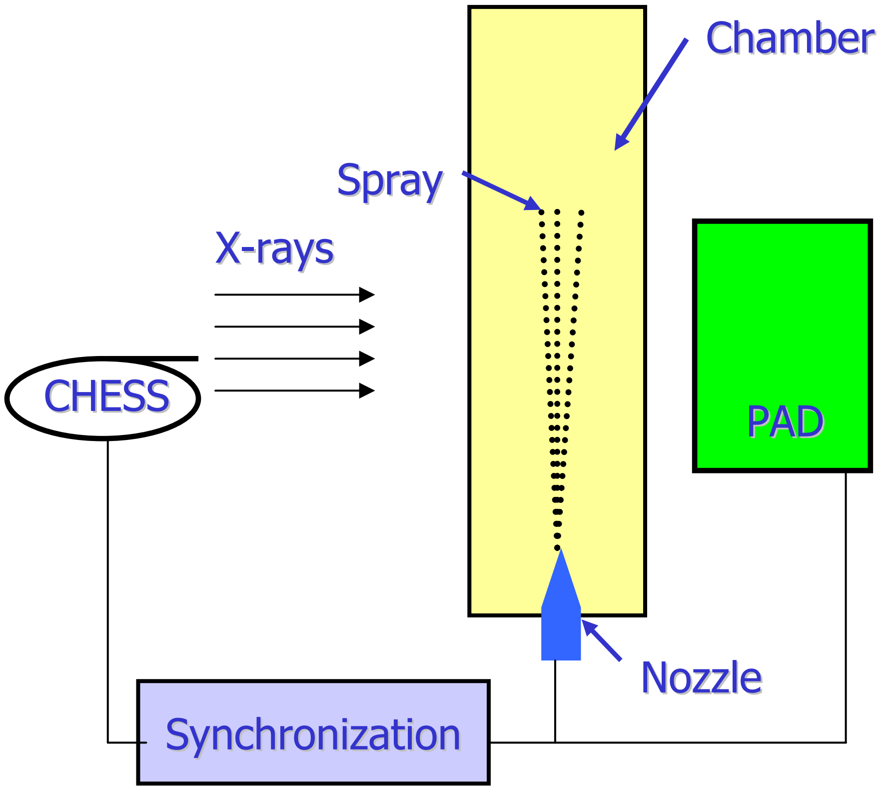
- CHESS Beamline D-1
- 6 keV (1% bandpass)
- 2.5 mm x 13.5 mm (step sample to tile large area)
- 10^8 - 10^9 x-rays/pix/s
- 5.13 μs integration (2x ring period)

Diesel Fuel Injection System

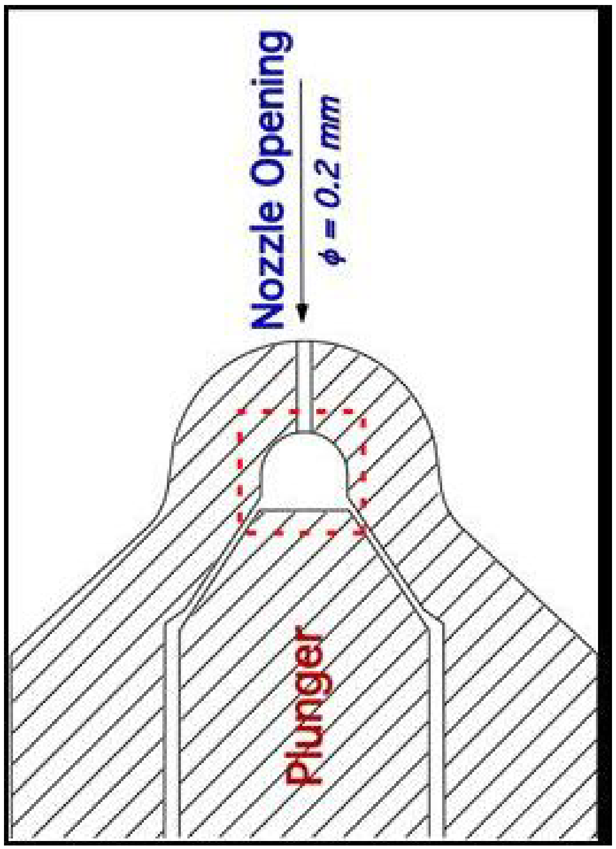
- Cerium added for x-ray contrast
- 1350 PSI gas driven
- 1.1 ms pulse
- 1 ATM SF_6 in chamber

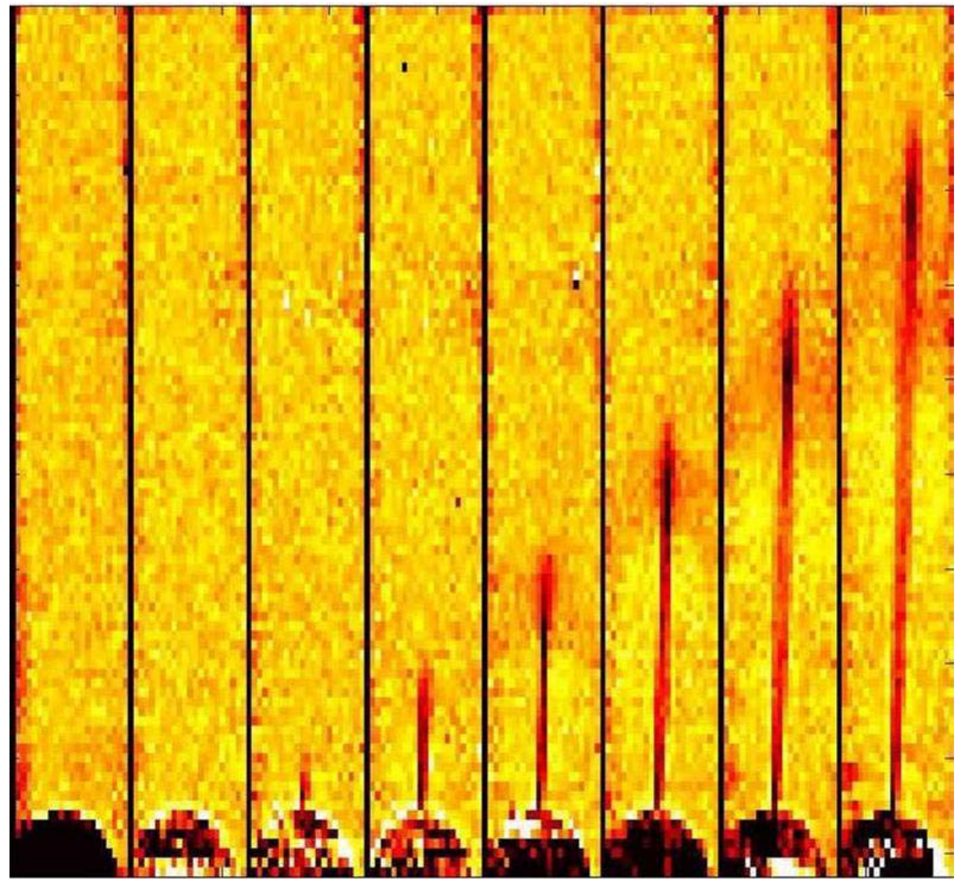
Collaboration: Jin Wang (APS) & S.M. Gruner (Cornell)

See: McPhee, Tate, Powell, Yue, Renzi, Ercan, Narayanan, Fontes, Walther, Schaller, Gruner & Wang *Science* 295 (2002) 1261-1263.



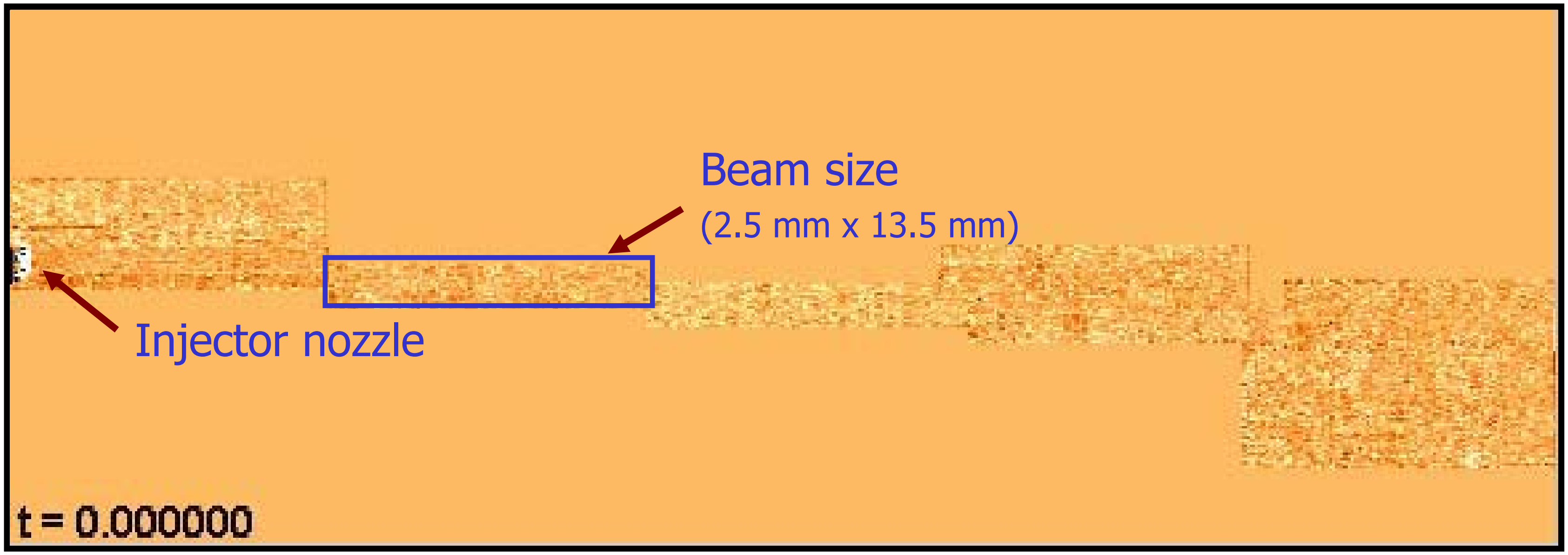
High speed radiography:
Supersonic spray from diesel fuel injector





Diesel fuel injector spray

- 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



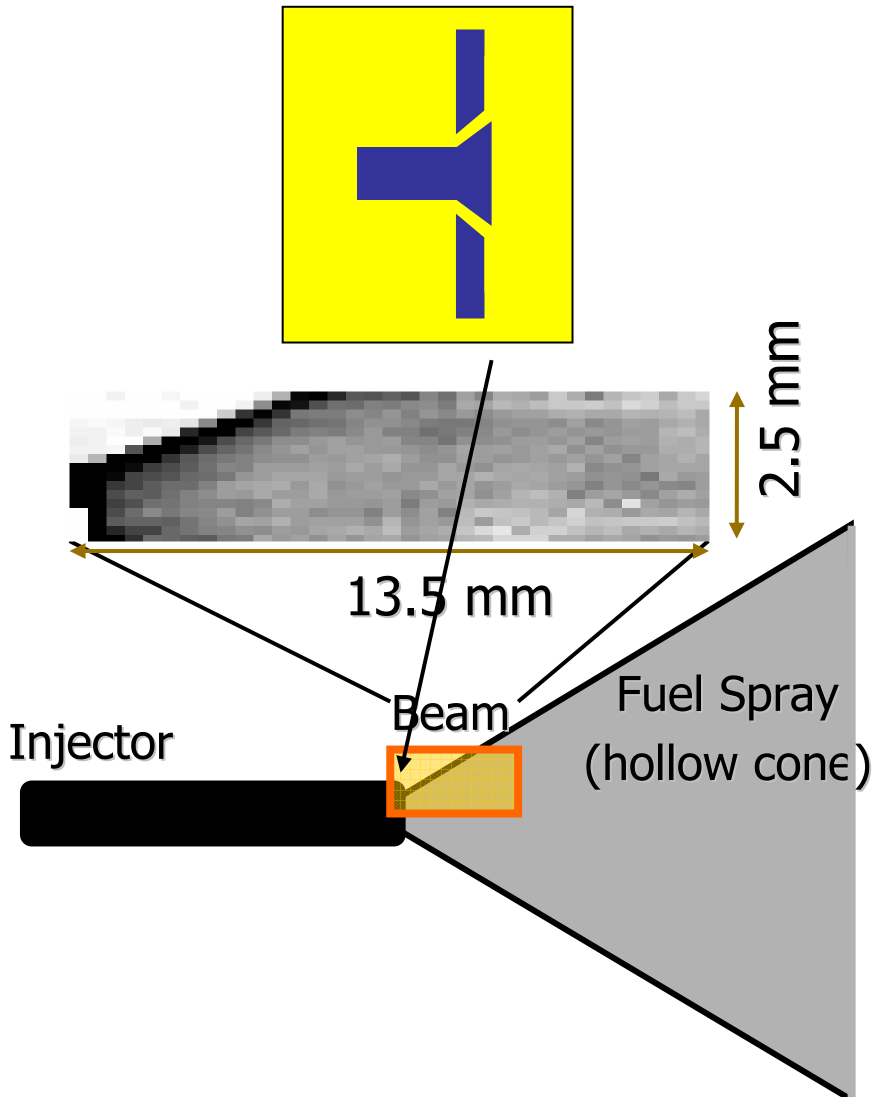
A. MacPhee, *et al*, Science (2002). **295**, 1261-1263.

Gasoline fuel injector spray

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.

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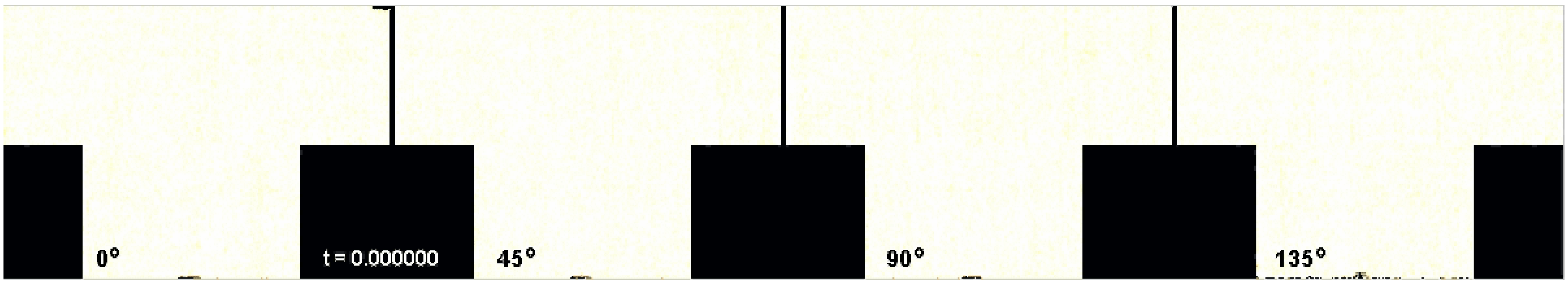
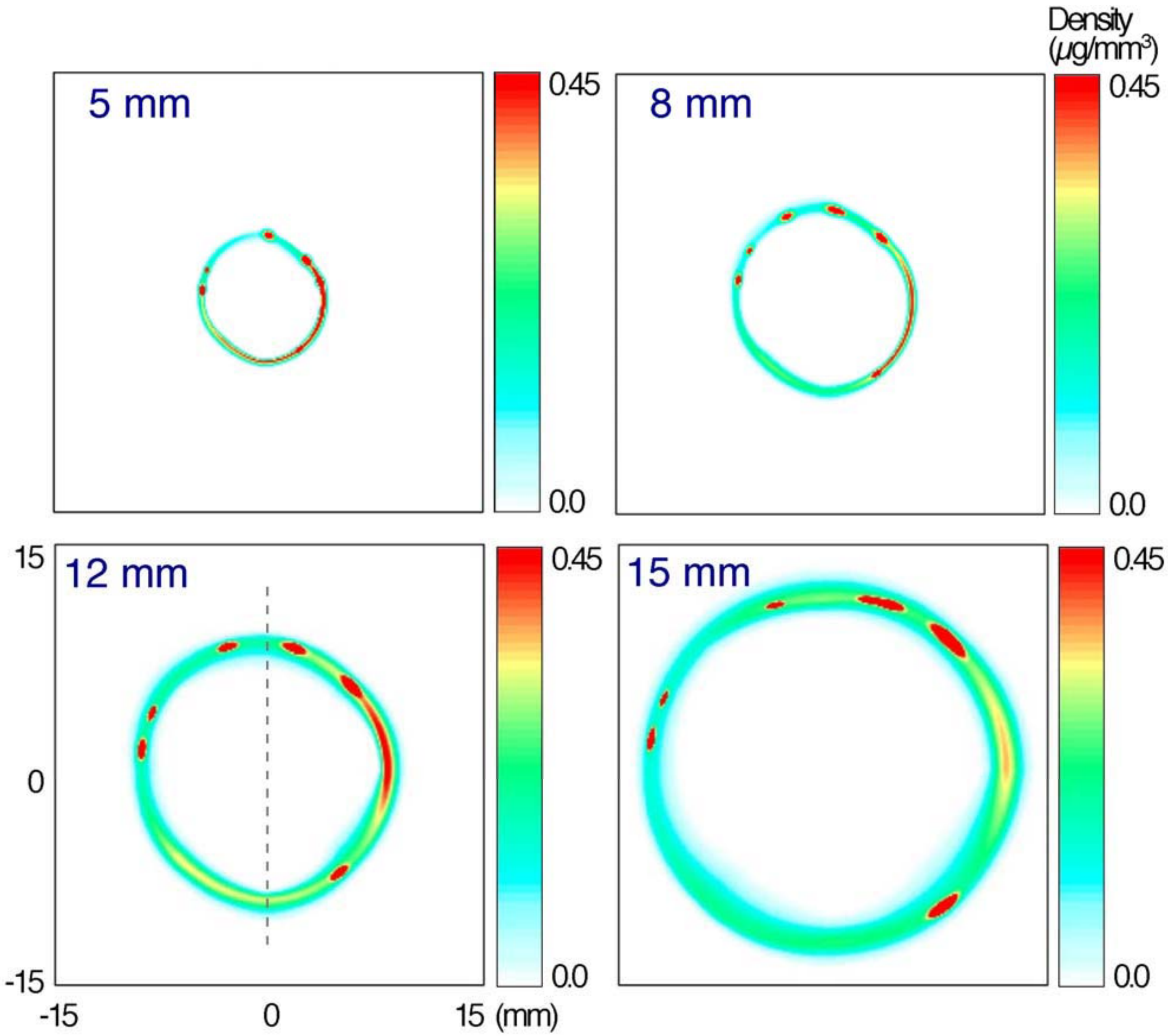
Gasoline fuel injector spray

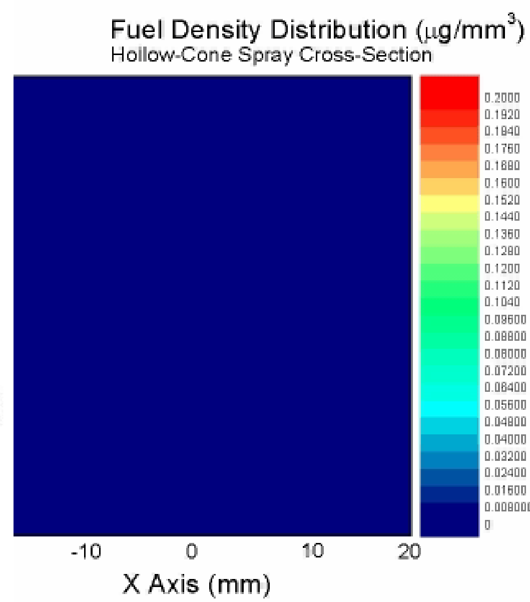


- 1.8 ms time sequence (composite). 10^5 images
- 5.13 μs exposure time. (15.4 μs between frames)
- 88 frames (11 groups of 8 frames), Avg. 20x for noise.
- 1000 x-rays/pixel/μs
- Data taken with 4 projections.

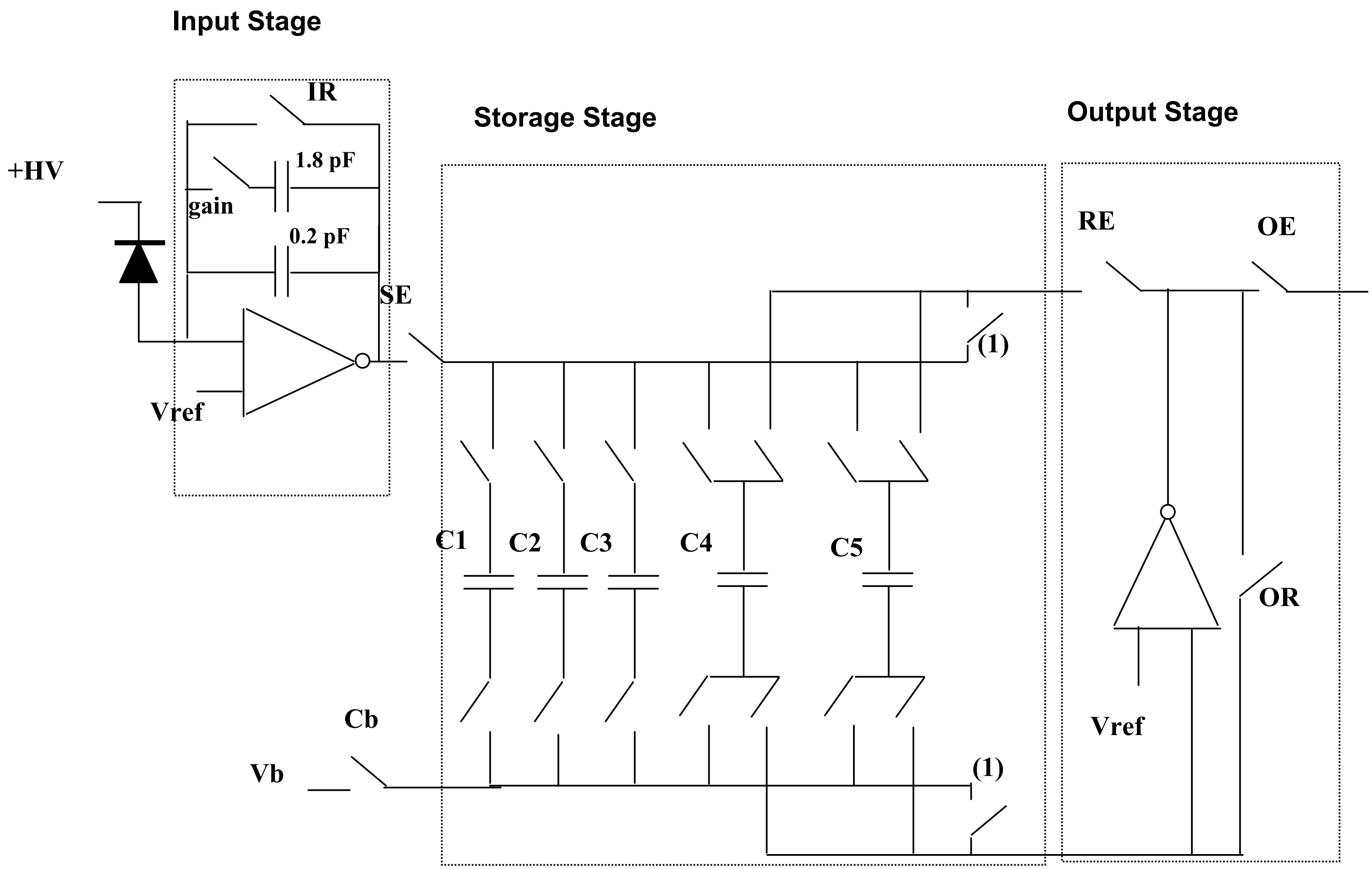
See poster for more experiments

Spray is very nonuniform

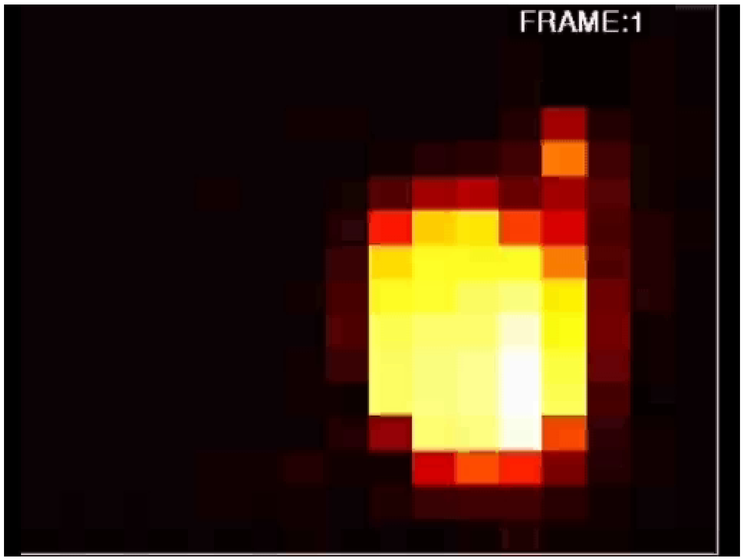


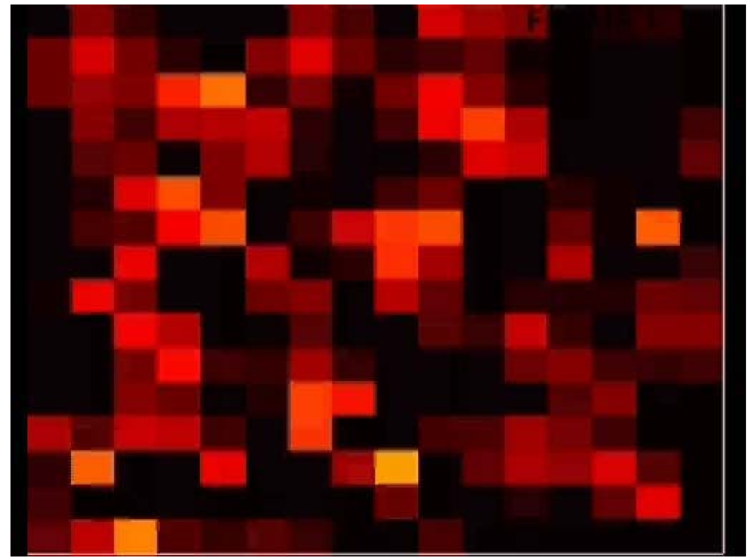


Faster Duty-Cycle: Push-Pull Configuration with Selectable Gain



16x16 Push-Pull laser tests





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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Mixed-Mode Motivation

- Calibration issues limit accuracy to few tenths percent, e.g., 1 part in 1,000 exceeds state-of-art.
- Range of numbers in an image (e.g., SAXS) may span many orders of magnitude.

Suggests that users really want to record images that span many orders of magnitude of intensity across the image, but only need few tenths % accuracy at any location.

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Mixed Mode Pixel

Crystallography detector:

Goals:
- Increase dynamic range (10^7 x-rays)
- Keep high count rates ($>10^8$ Hz)
- Fast framing (< 1ms dead time)
- 2k x 2k pixels, 150 μm pixel size

Methods:
- Integrating pixel w/ digital overflow counter / charge reset
- Analog remainder read at end of frame
- Fabricated in 0.25 μm TSMC 3.3 V, metal on metal capacitors

Collaboration with ADSC. See

S.G. Angello, et al, *IEEE 2004 Nuc. Sci. Symposium*, Rome, (Oct. 16-22, 2004).

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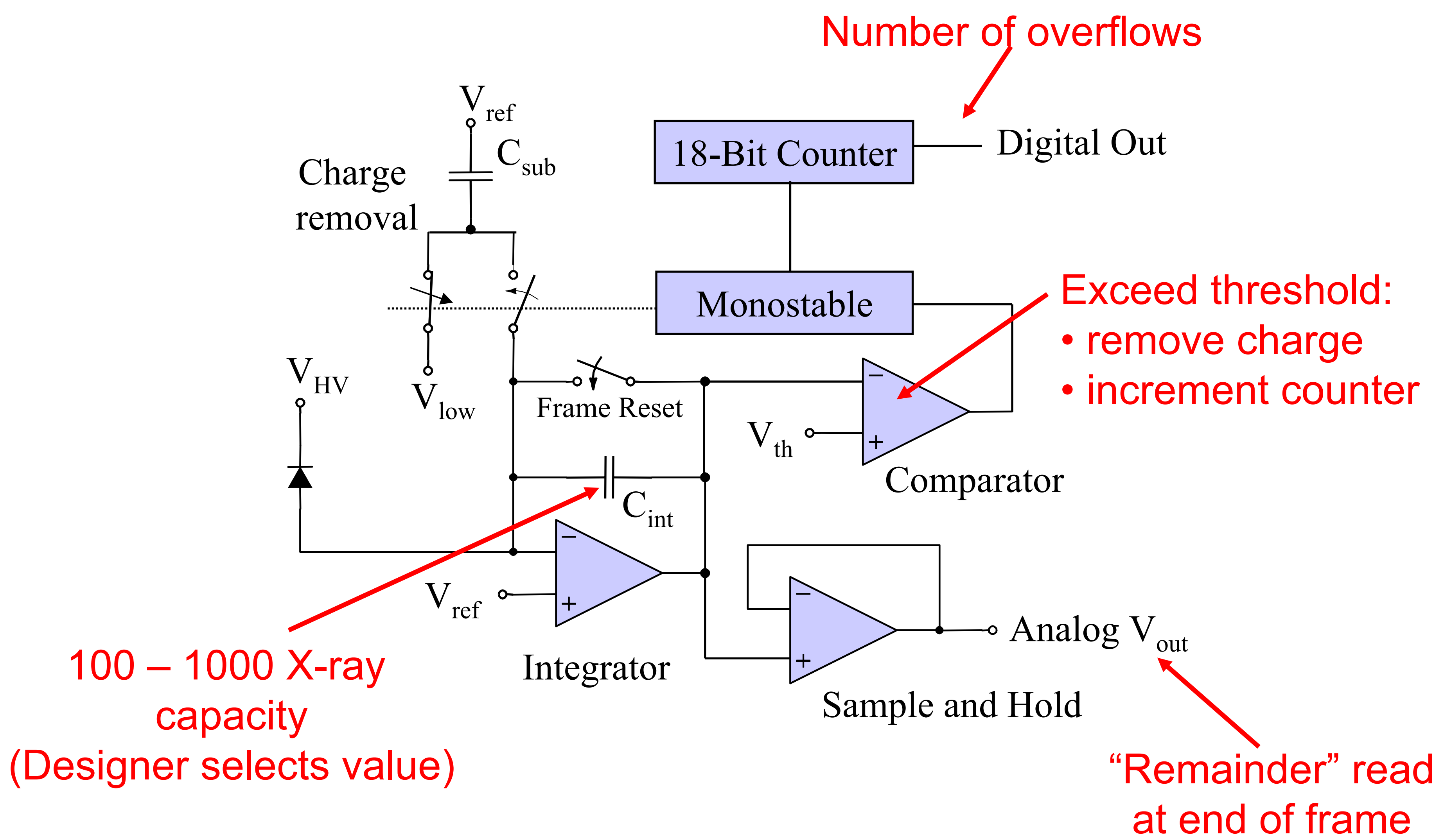
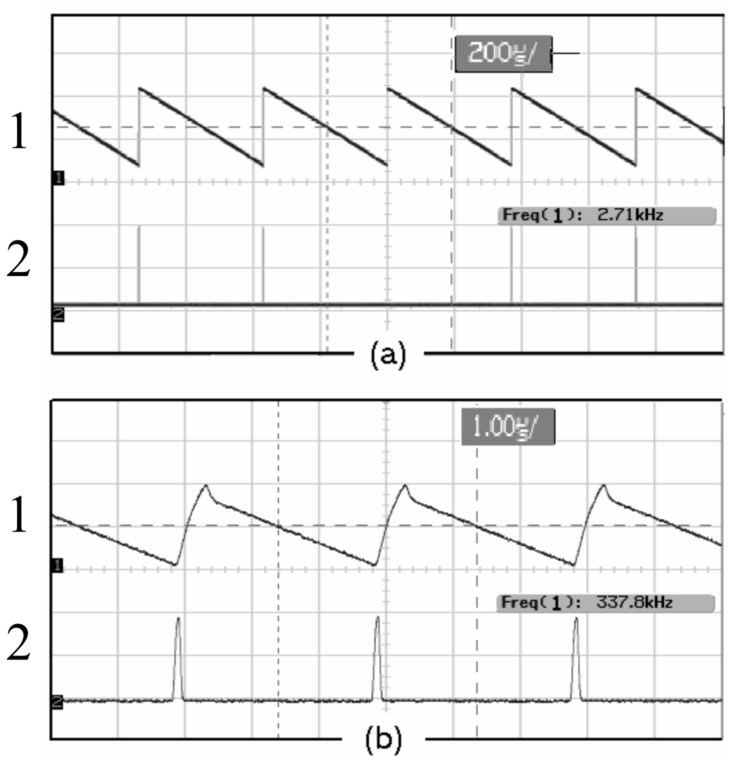
Mixed Mode Pixel

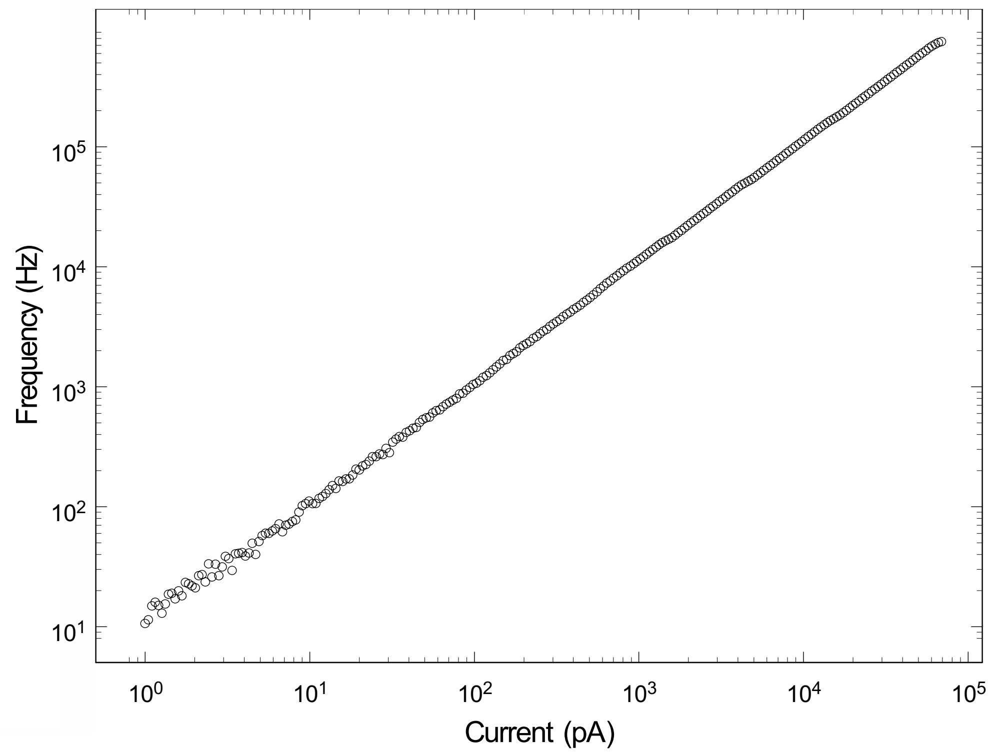
Integrating pixel w/ overflow counter / charge reset



Mixed Mode Pixel

Pixel Tests





Test Points: Input current
1) Integrator a) 250 pA
2) Comparator b) 30 nA

Input Current *vs.* Reset Frequency

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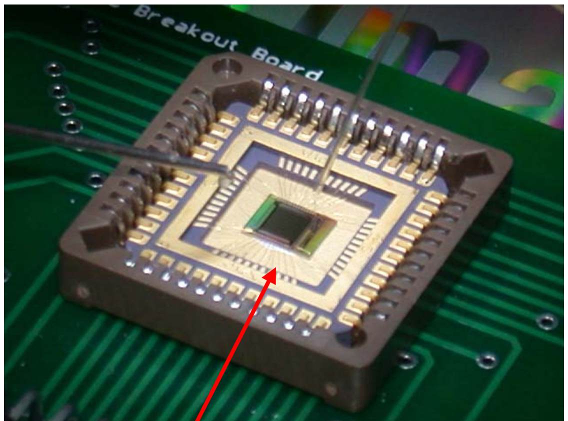
Mixed Mode Pixel

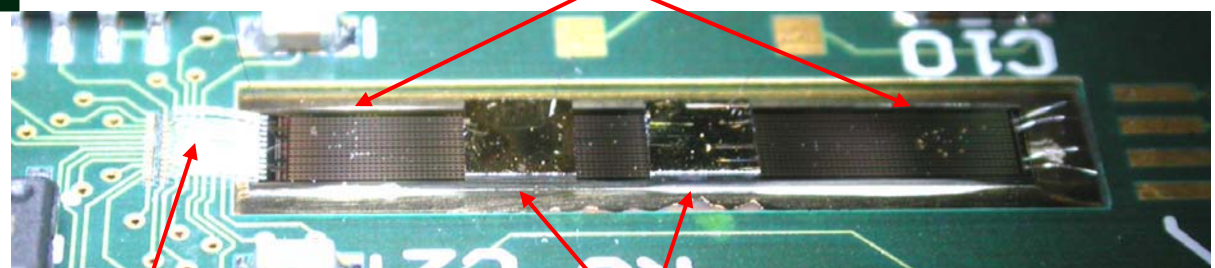


16 x 16 array

Array testing:

- Pixel addressing
- Crosstalk
- Power distribution
- Imaging

16 x 128 array



Wire bonds
16 pixel footprint

16 x 16 diodes

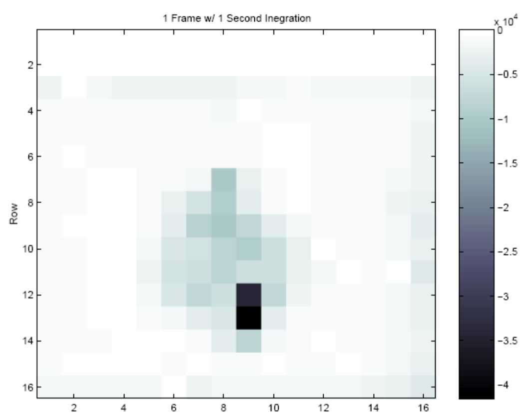


Image of spot projected on 16 x 16 array

Next step: 128x128 arrays
replicating 16x128 units on single die

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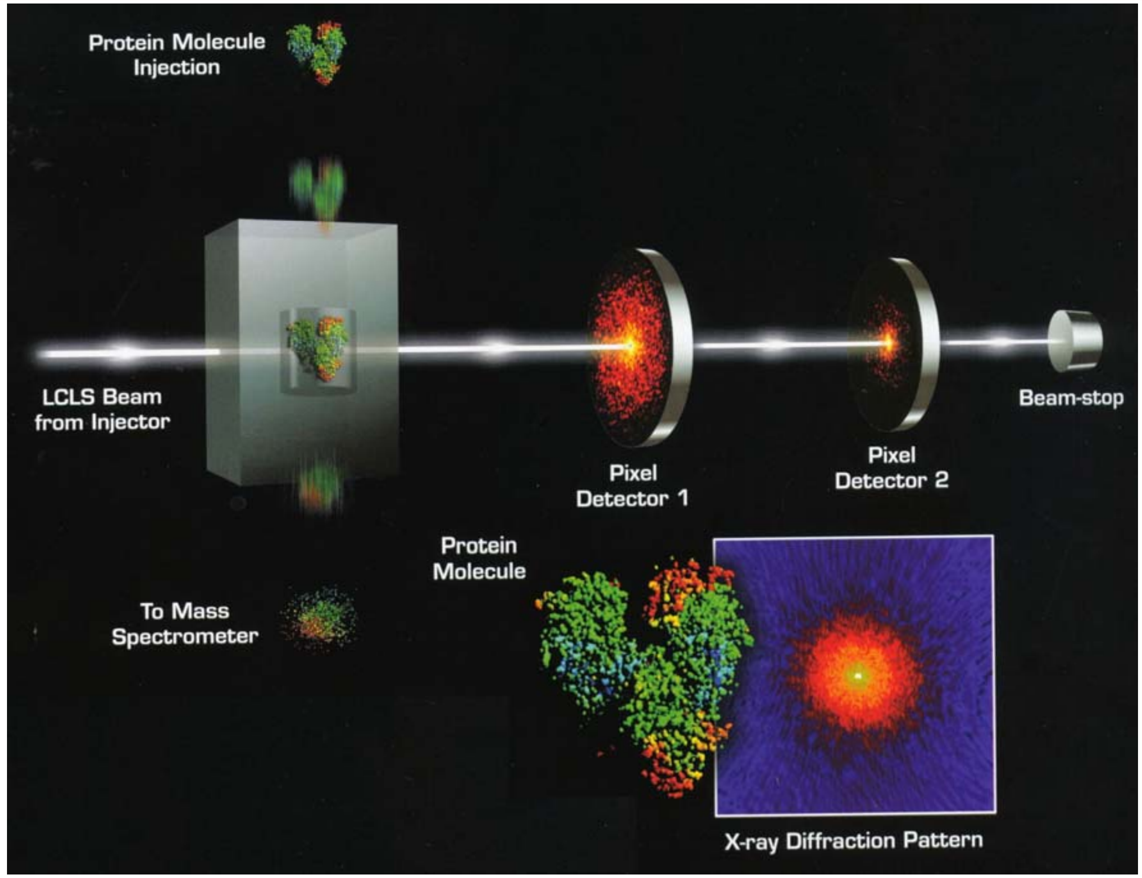
Integrating PAD for LCLS
Single Particle Imaging

Imaging requirements
- Large solid angle coverage
- <230 fs pulses. Perhaps 2fs.
- 120 Hz framing
- 10^{12} x-rays/pulse
- 0 – 1000 x-rays / pixel
  Distinguish between
  0 and 1 x-ray



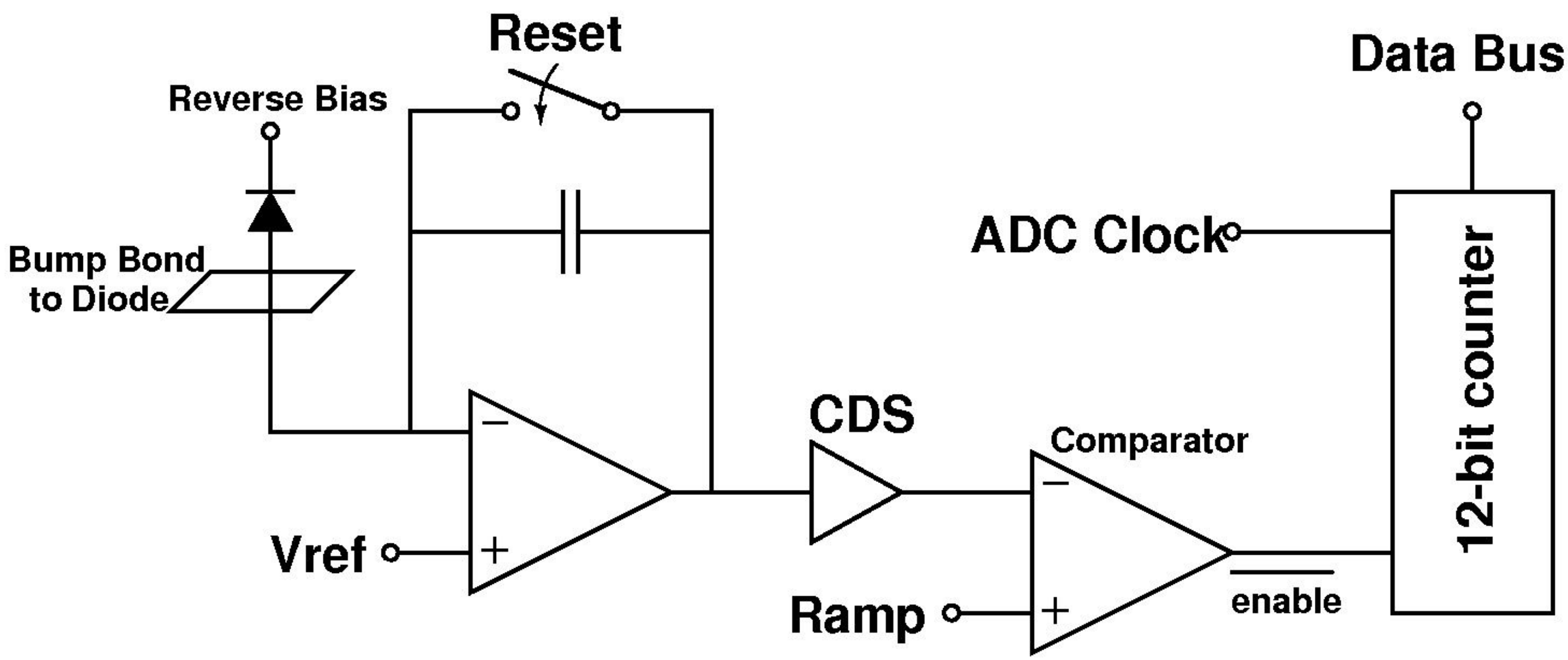
Pixel detector 1: Wide angle

S/N per x-ray >> 1
Dynamic range ~ 10^3
> 512 x 512 pixels

Pixel detector 2: Small angle

S/N per x-ray ~1
Dynamic range ~ 10^3 - 10^4
> 512 x 512 pixels

Integrating PAD for LCLS
Pixel Schematic



Increase S/N for low dose
- Smaller full well
- CDS circuitry

1 ADC per pixel

1st Fabrication: October 2005

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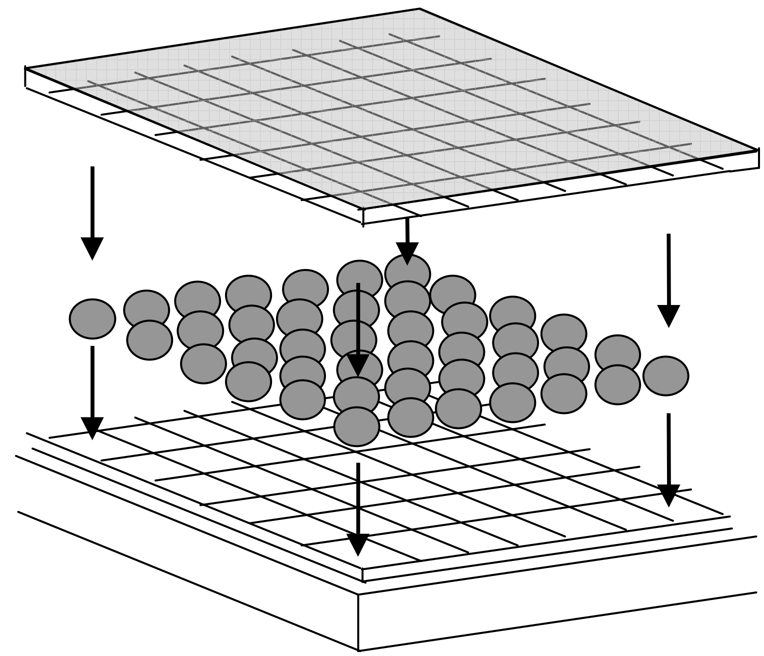

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