New 1D and 2D Detectors for Synchrotron Radiation Research

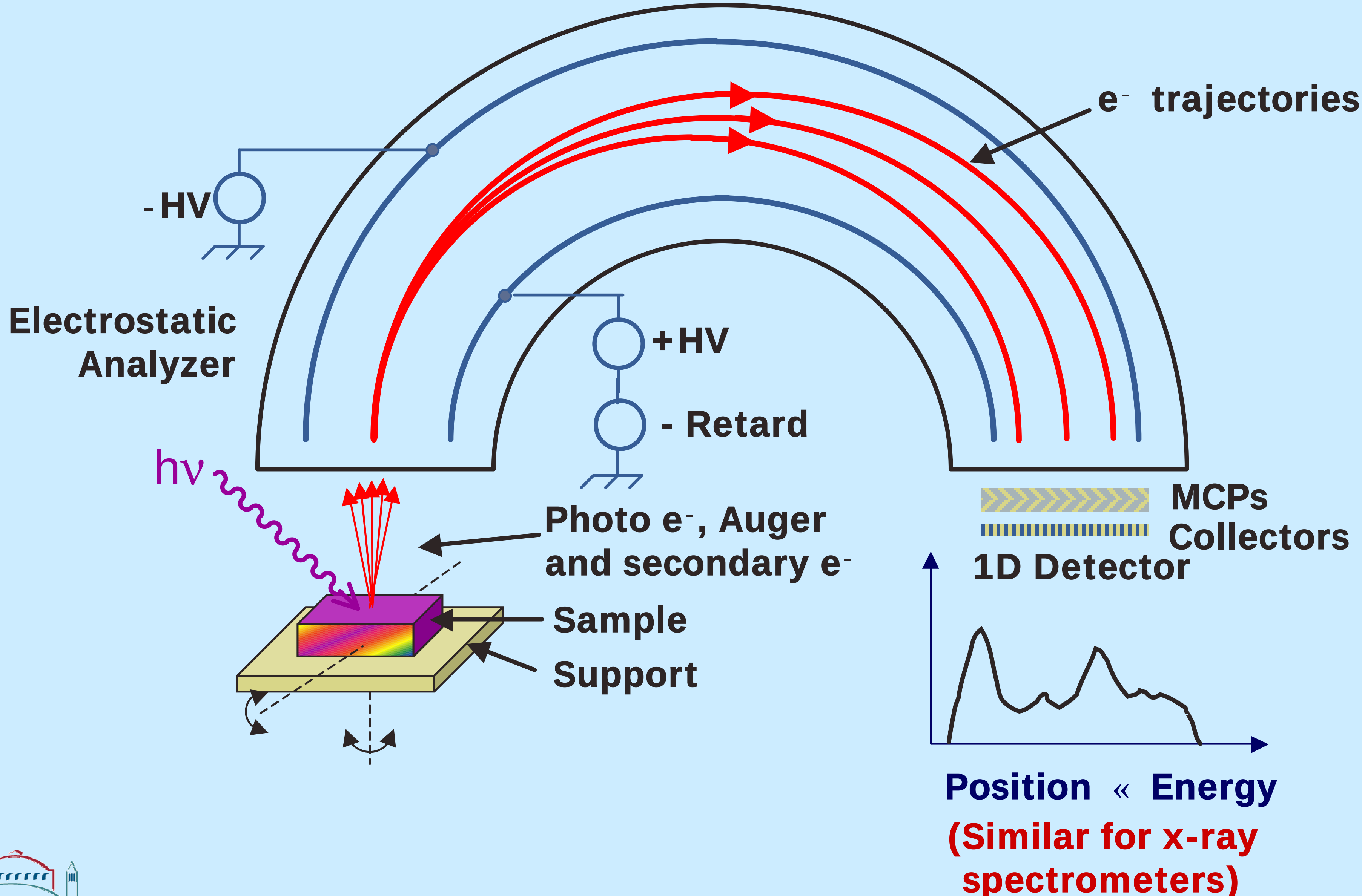
Higher Countrates, Time- and Spatial-Resolution

J-M Bussat[1], P. Denes[1], C. S. Fadley[1,2], B. Ludewigt[1], H. A. Padmore[1]
[1]Lawrence Berkeley National Laboratory, [2]Dept. of Physics UC Davis

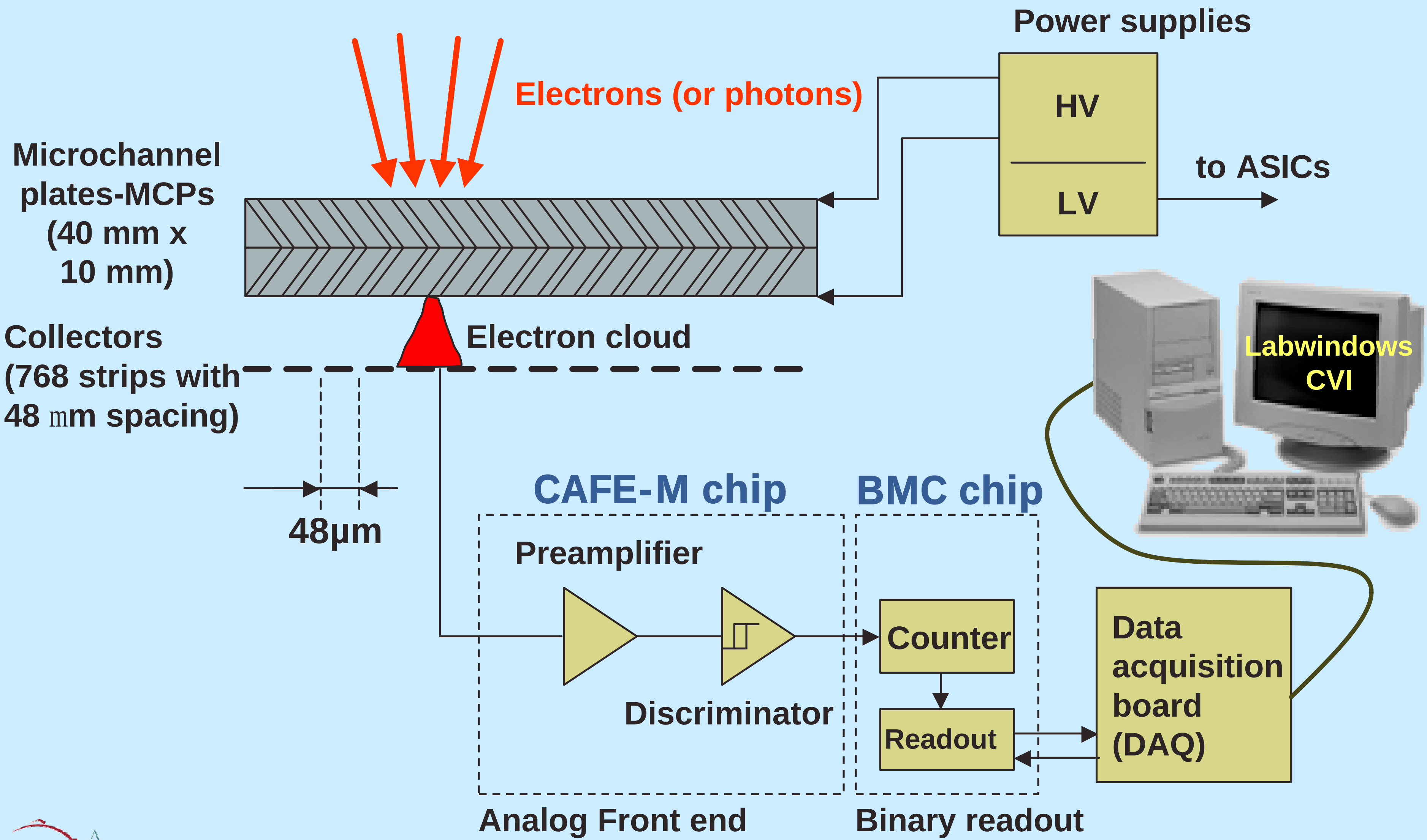
- **Current detector activity at LBNL**
  - **1D Spectroscopy Detector - 2 GHz count rate with $\Delta E/E \sim 1.3 \times 10^{-4}$, 150 μs readout**
  - 2 Protein Crystallography Readout ICs (0.35μ and 0.25μ CMOS) (not discussed)
- **Proposed new 2D detectors for spectroscopy, diffraction, holography**

Strategy: Capitalize on large investment in IC/detector development for high-energy physics

1D Detector and Electron Spectrometer



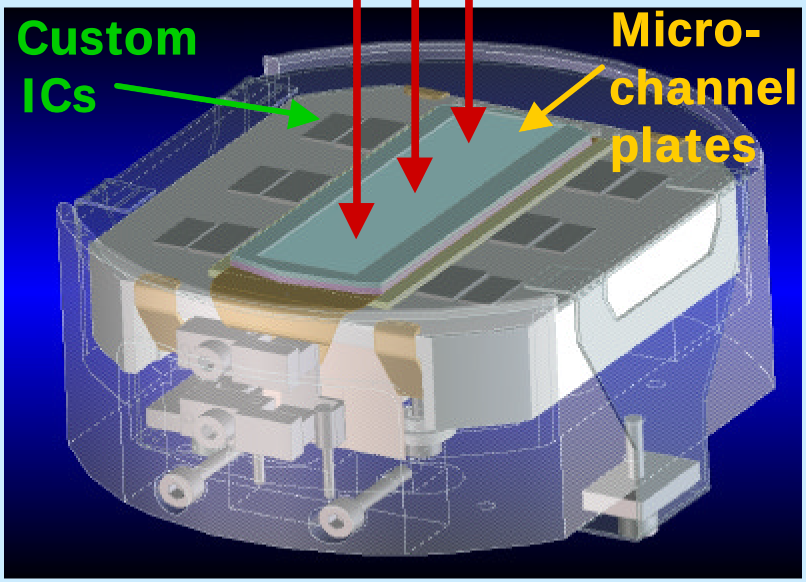
GigaHertz 1D Detector for Electron and X-ray Emission Spectroscopy



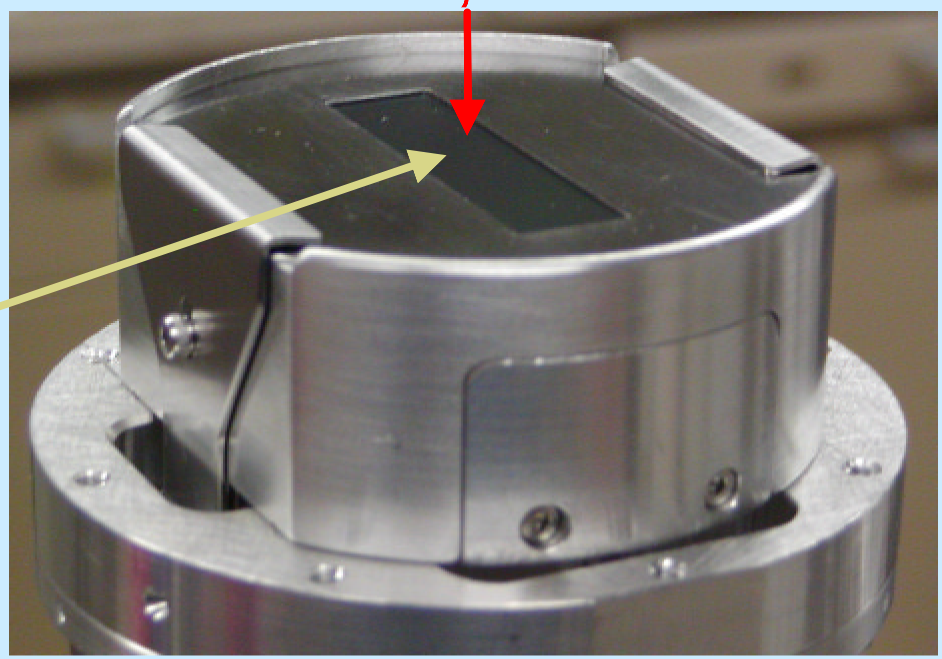
ALS High-Speed 1D Detector--Project Overview

- ~2 GHz overall linear count-rate ®
  100-1000x faster than present detectors
- Position resolution of 75 m®
  DE/E » 1:10^4
- Spectral readout in as little as 150 ms®
  time-resolved measurements
- Programmable, robust
- Sized to fit existing spectrometers (Scienta, PHI, ...)

e^- or hn



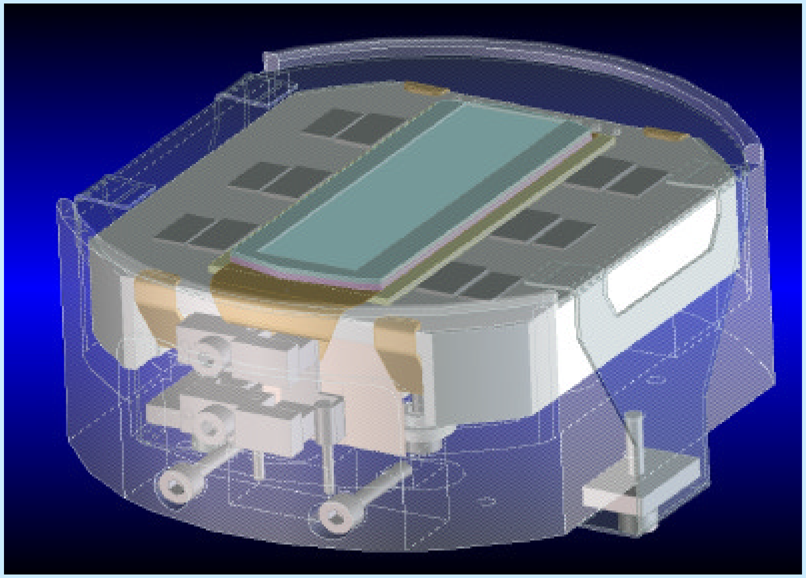
e^-, hn

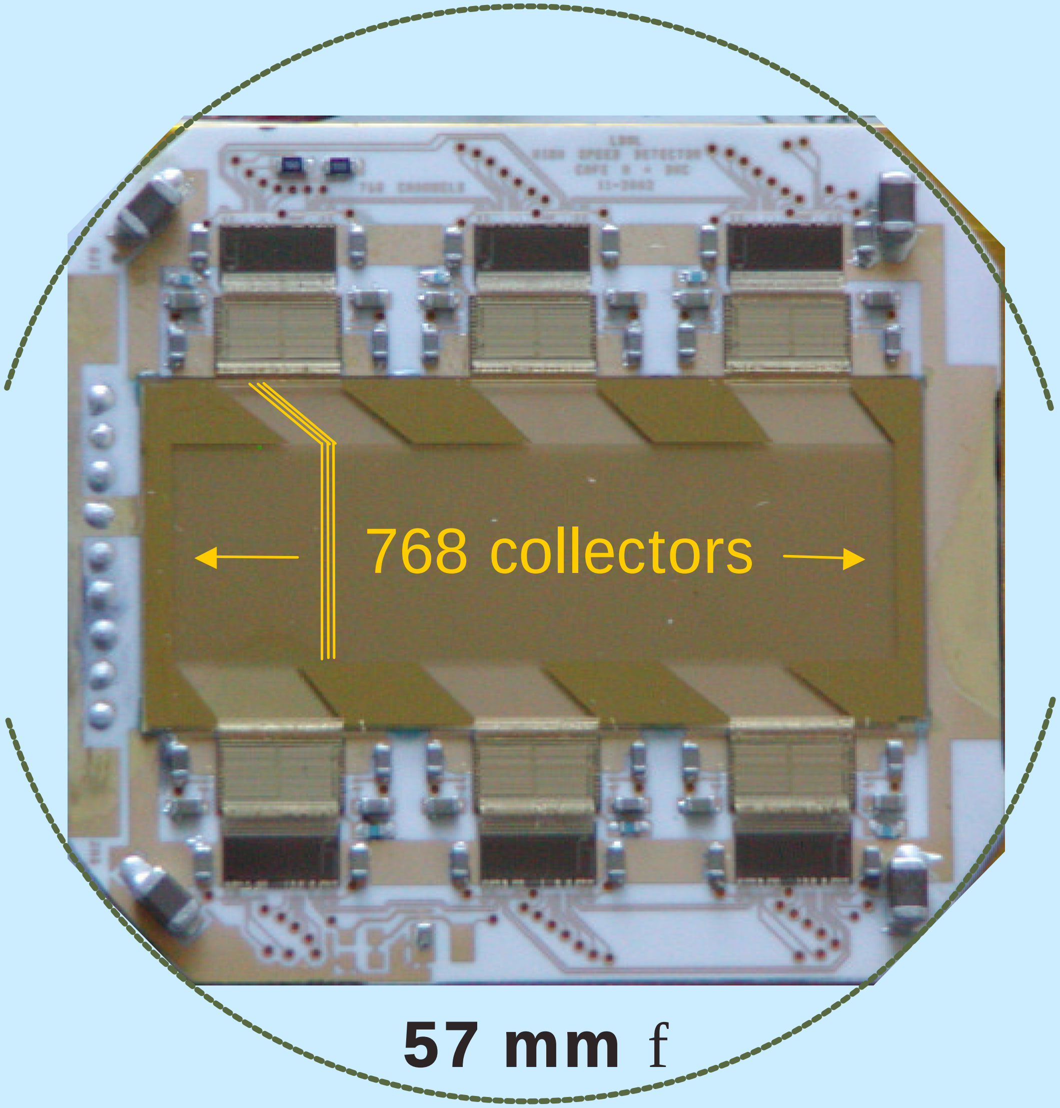


Microchannel
plates

Bussat et al.,
Poster 10.46

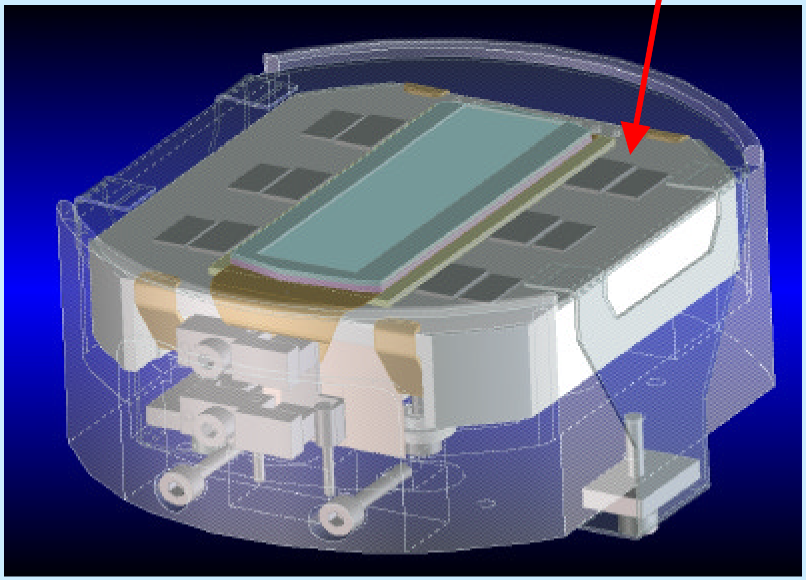
Detector Hybrid

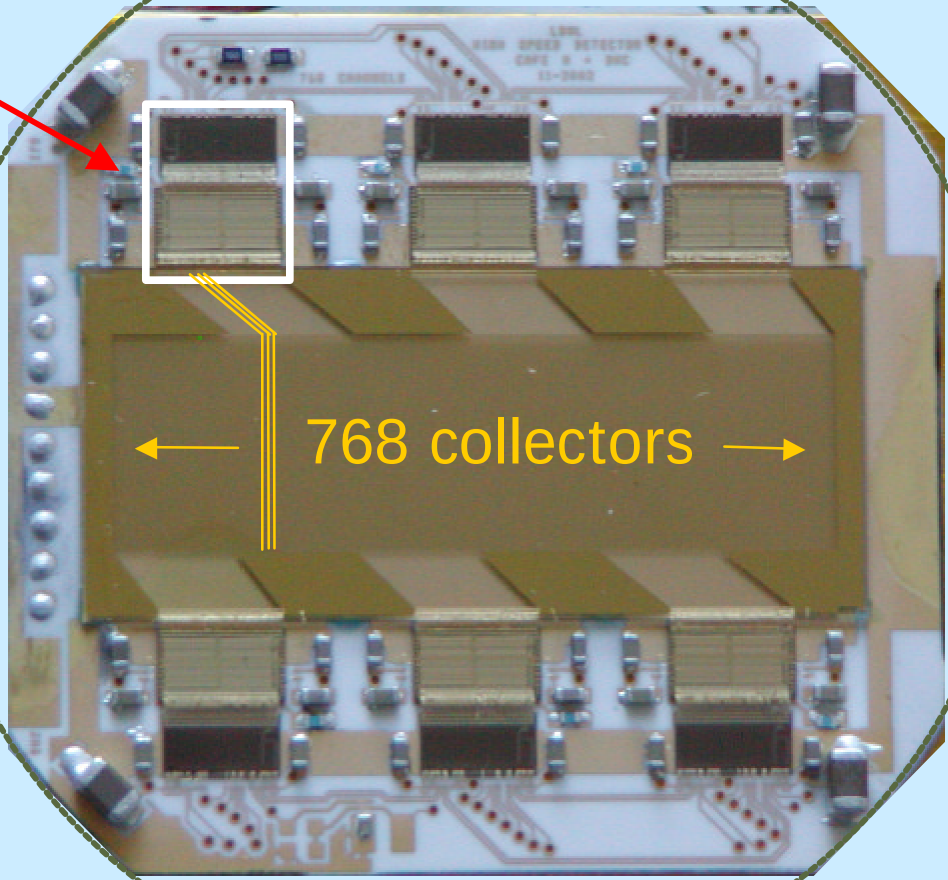




Detector Hybrid

Custom Integrated Circuits





57 mm f

Custom Integrated Circuits

CAFE-M, analog front end:

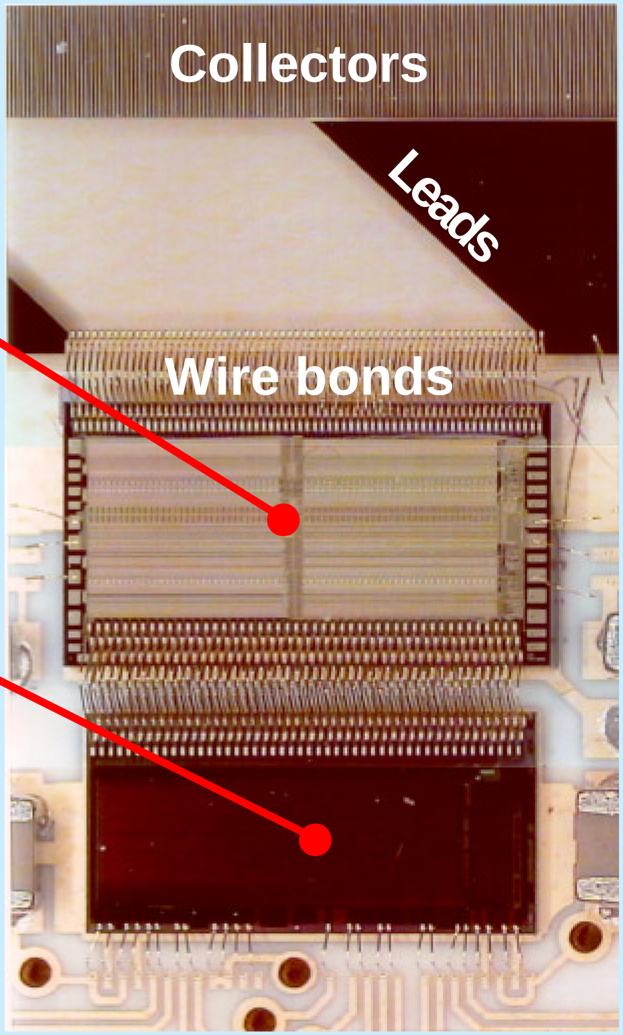
Gain at the Comparator	100	mV/fC
Peaking Time	25	ns
Output Pulse Amplitude	100	mA
Double Pulse Resolution (Qs=4 fC)	50	ns
Time Walk (Qs=1.25 - 10 fC)	< 15	ns
Supply Voltage	3.5	V
Power Dissipation per Channel	1.2 - 1.8	mW
Number of Channels	128	

Includes calibration pulse generator

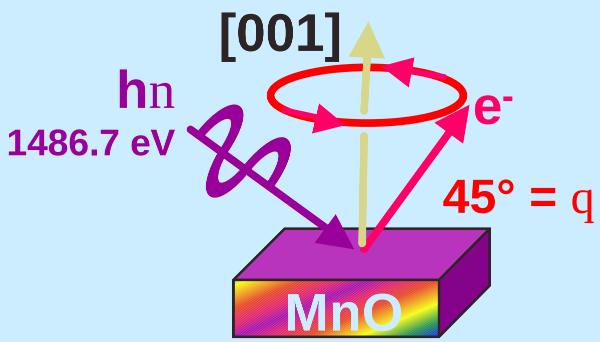
BMC (Buffered Multichannel Counter):

Counter sizes (selectable)	4,8,12,16,24-bit	
Maximum counting frequency	>2	MHz/channel
Serial link operating frequency	>40	MHz
Supply Voltage	3.3	V
Power Dissipation (total)	45	mW
Number of Channels	128	

Includes dual 8-bit DAC for CAFE-M control & internal test functions

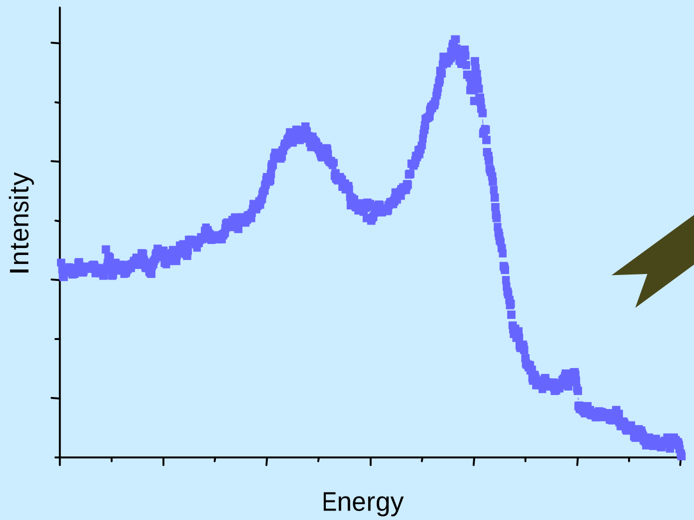


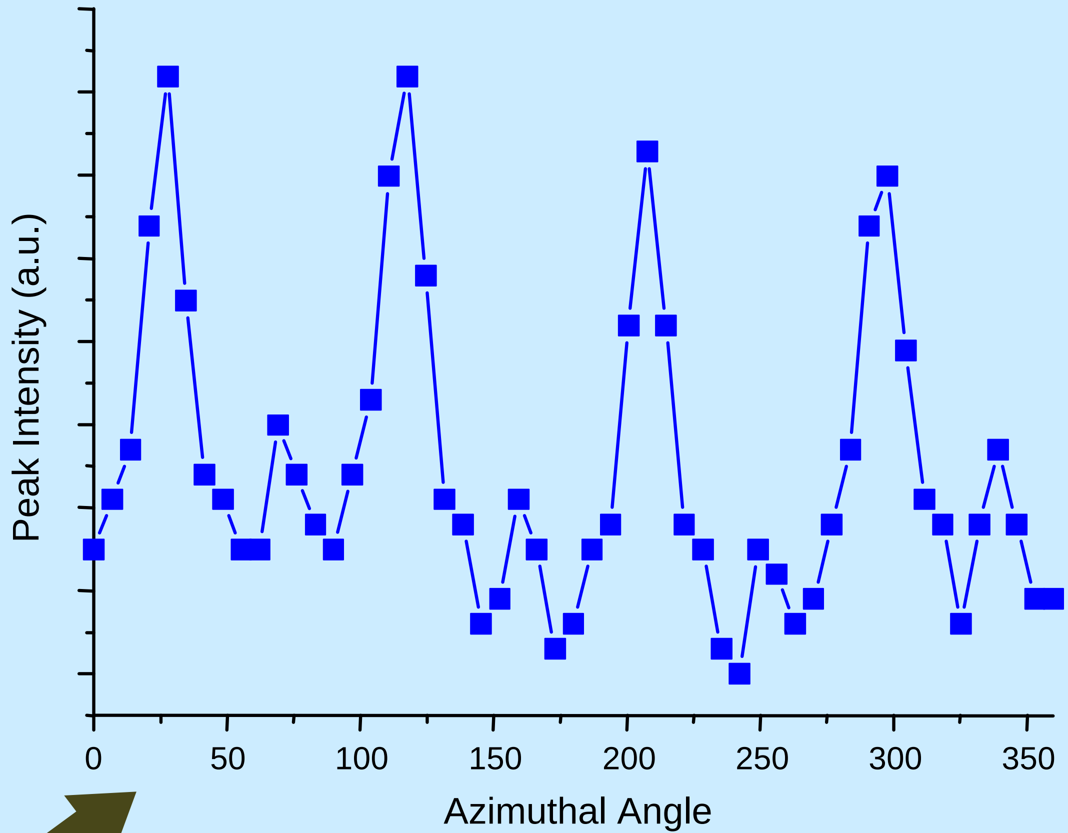
Some First Data: Photoelectron Diffraction



Mn 2p Spectrum

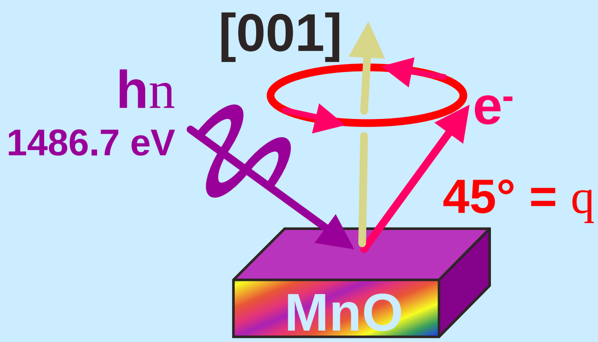
(Pass Energy 500 eV)





In 1 minute

Some First Data: Photoelectron Diffraction



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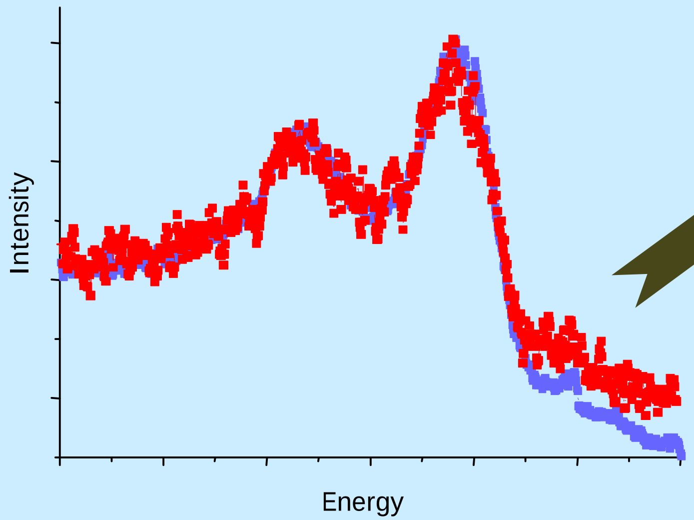
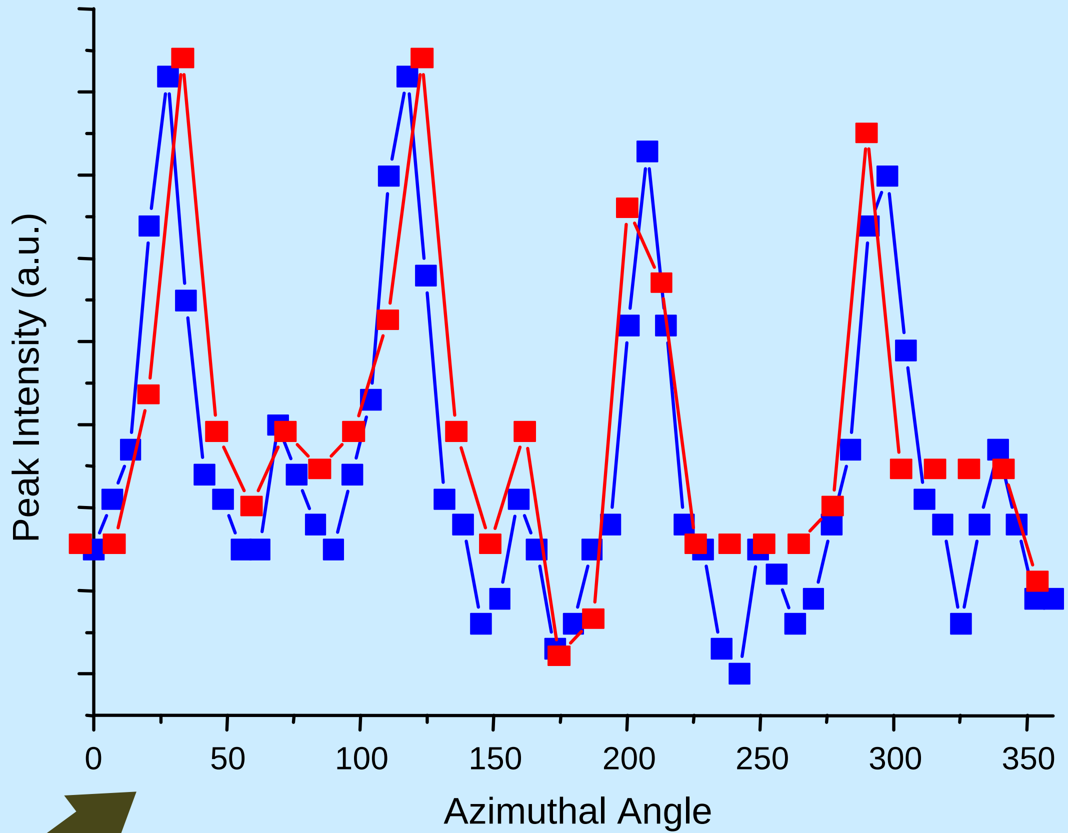


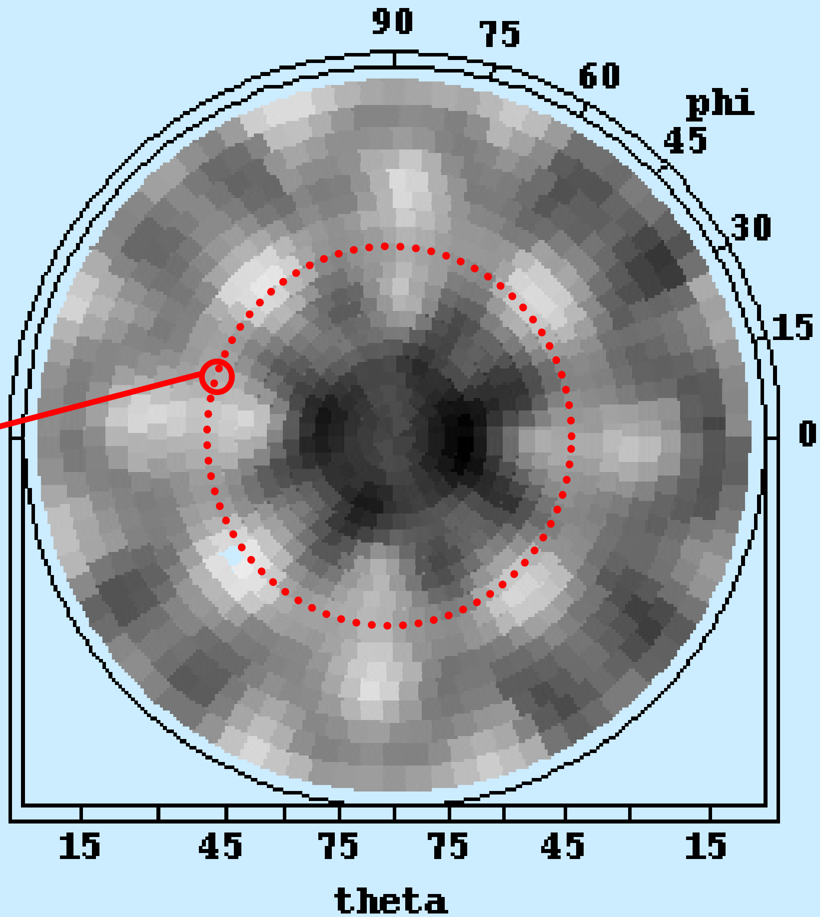


In 1 minute

In 5 seconds

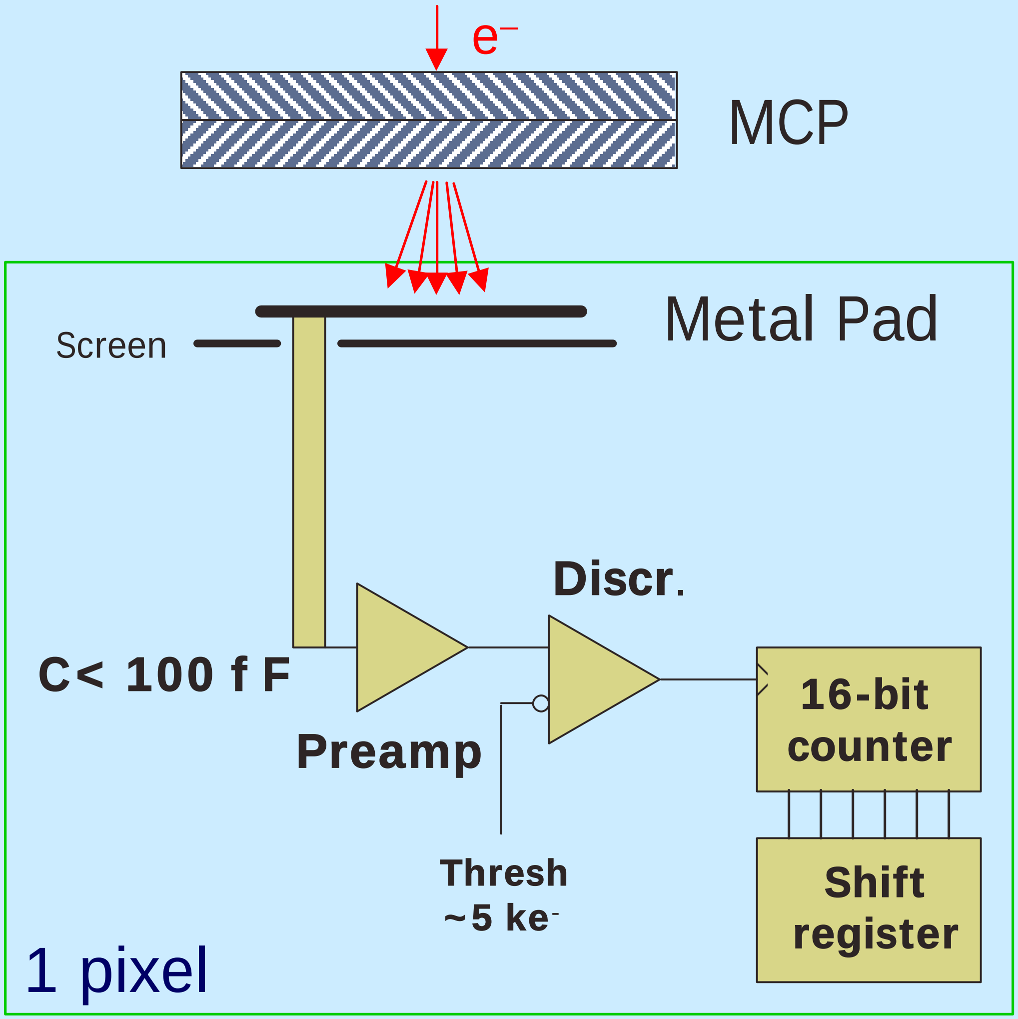
...and Photoelectron Holography

Cf. data from prior slide at θ=45°



MnO(001), Mn 2p emission, 848 eV
Conventional x-ray tube (Al K_a)
~1200 spectra, 1.5 s/spectrum

2-D Version of *ALS* High-Speed Detector for Spatially-Resolved Spectroscopy of Electrons and Soft x-rays

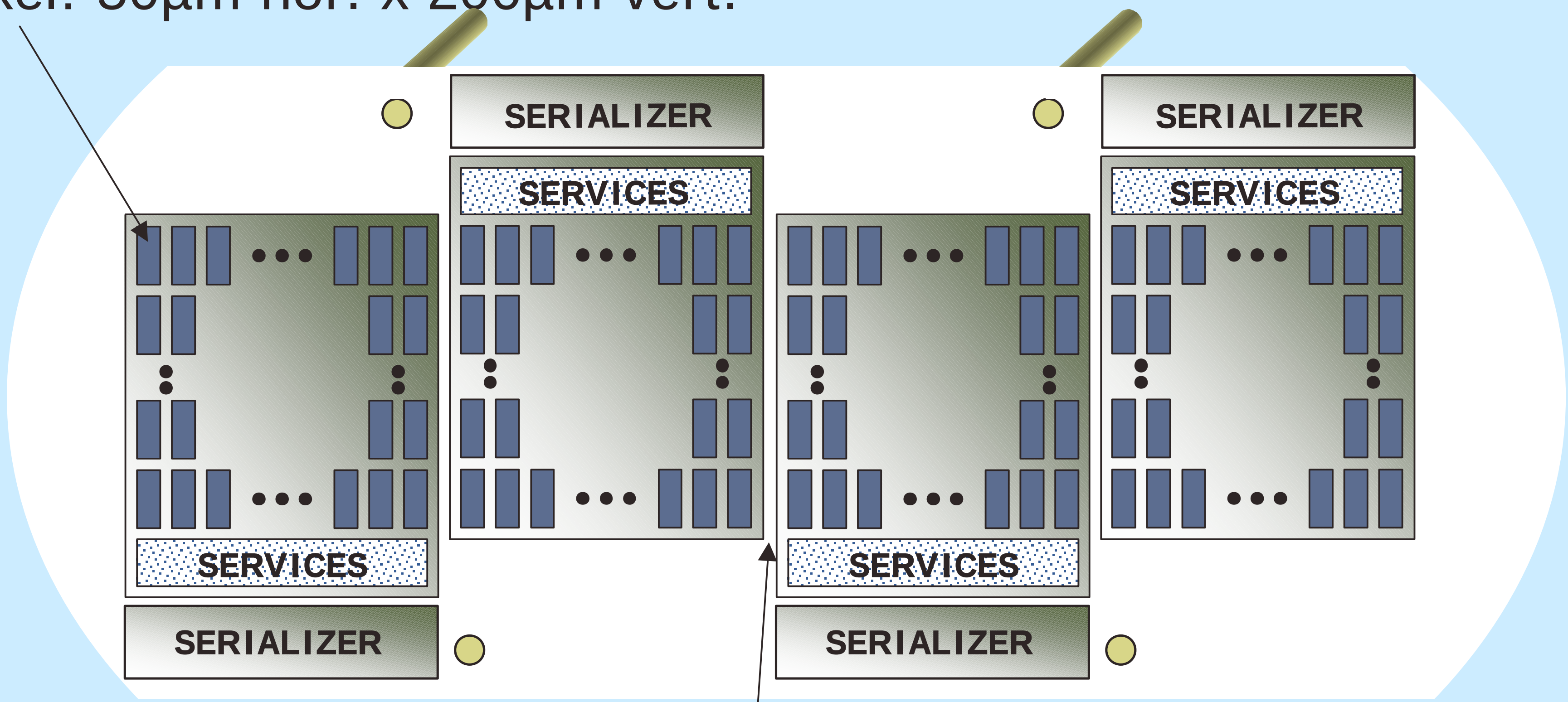


- Monolithic detector
- Top layer of ASIC metalization serves as (pixellated) collector
- 10k pixels/chip
- Up to 20 MHz/pixel
- Gigabit link
  ⇒ 100 Mbytes/s
  ⇒ 200 μs to read out system

2-D Version of *ALS* High-Speed Detector

Active area: 4 x 1 cm^2, 40k pixels, integrated rate ~10^{12} hits/s

Pixel: 50µm hor. x 200µm vert.



Gap: ≥200µm

← ~ 1cm →

Applications: angle-resolved photoemission ® *E* vs. *k* ,
x-ray emission spectroscopy & inelastic scattering

Inside a Pixel--Detailed Architecture

- C_{IN} ~ 70 fF (pad)
- Q_{THR} ~ 5k e–
- ~1300 transistor/pixel
- CMOS 0.25µm
  - *50µ x 200µ pixels*
  - *13M transistor/chip*

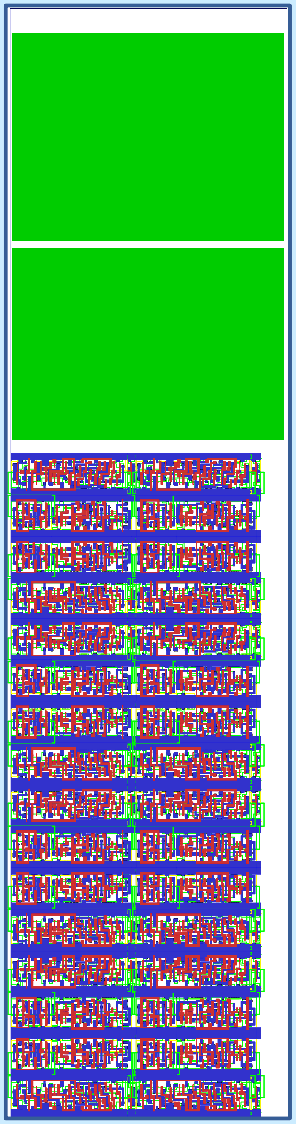
--or--

- CMOS 0.13µm
  - *50µ x 50µ pixels*
  - *55M transistor/chip*

Test Pulse

Preamp Discriminator

Digital part (16-bit counter, shift register ...)



Envelope: 50µm x 200µm

Multi-Purpose Mega-Pixel Detector Platforms

- Several groups are leveraging their HEP experience to make pixellated detectors
- Use similar techniques: mosaics of modules consisting of sensor arrays bump-bonded to readout ICs
- Platform: focus on system aspects (interchangeable sensor and ultimately readout IC)

- Proposed 1st Detector:
  - *Encode as much info. as possible, even if not at ultimate resolutions:*
    - *Position*
    - *Energy*
    - *Arrival time*
  - *1024 x 1024 pixels*

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  - *Encode as much info. as possible, even if not at ultimate resolutions:*
    - *Position*
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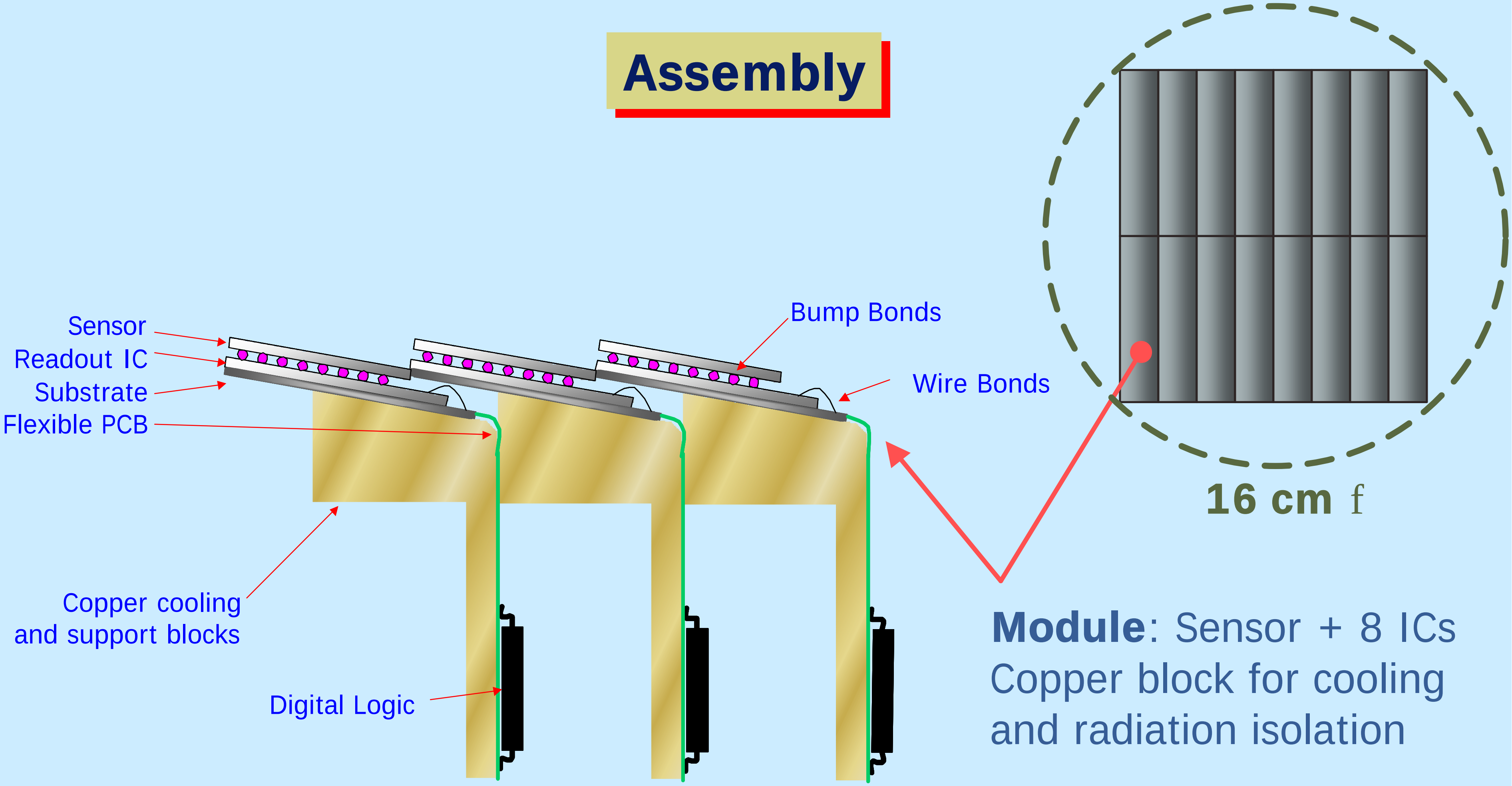
  → *Measure (x, y, t, E) for* ***each*** *photon*

  - *1024 x 1024 pixels*

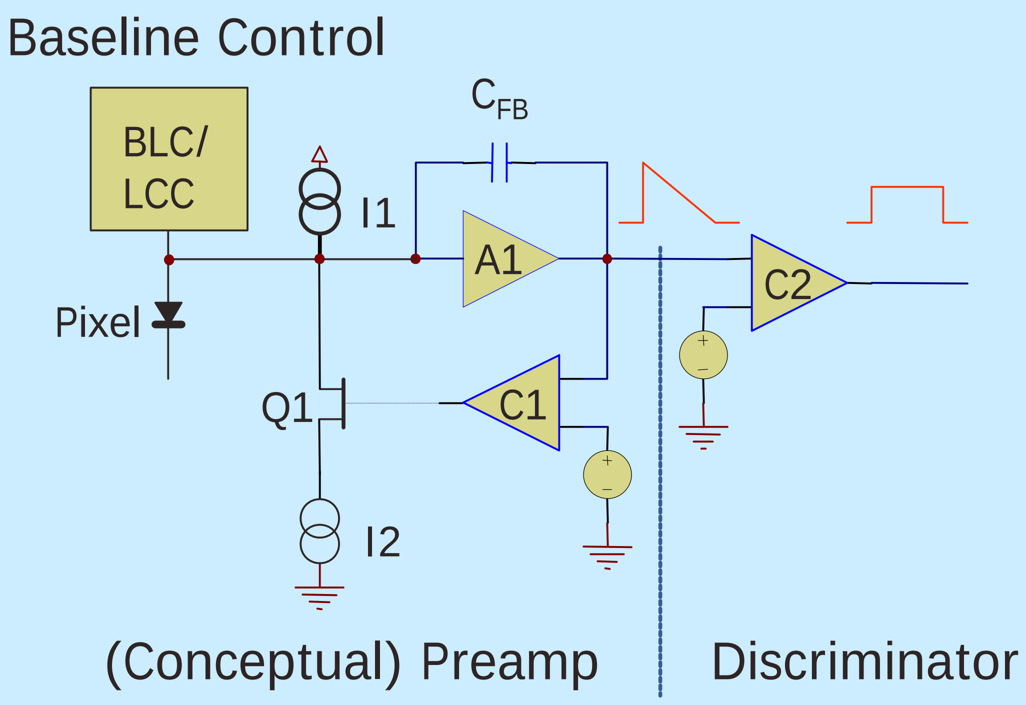
Assembly



Module: Sensor + 8 ICs
Copper block for cooling and radiation isolation

- MPix detector = 2 x 16 modules - 32 k pixels per module
- Modules are independent - any size detector possible
- Rad-Hard techniques for sensors and custom readout IC (other logic is shielded by copper cooling blocks)

Based on *ATLAS* front-end



- The preamp integrates the deposited charge on C_{FB}, and then discharges C_{FB} with a constant current
- This produces, ideally, a triangular pulse - whose width is proportional to the charge deposited
- The discriminator following the preamp converts the analog (triangular) pulse into a variable-width "digital" pulse

- Each pixel has a small analog front-end, followed by digital storage and logic

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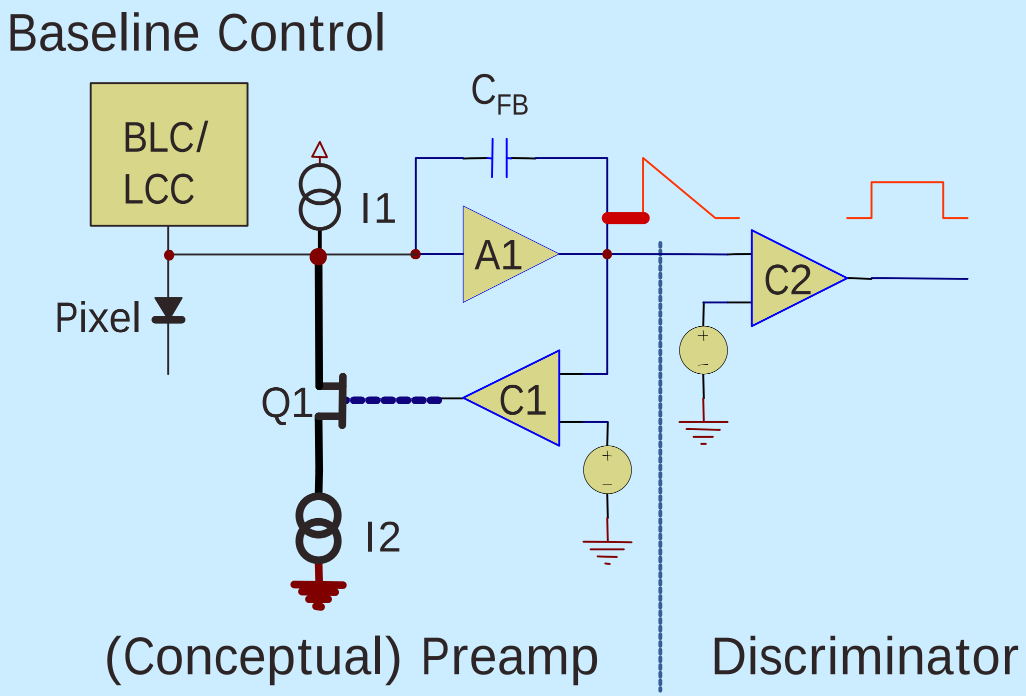

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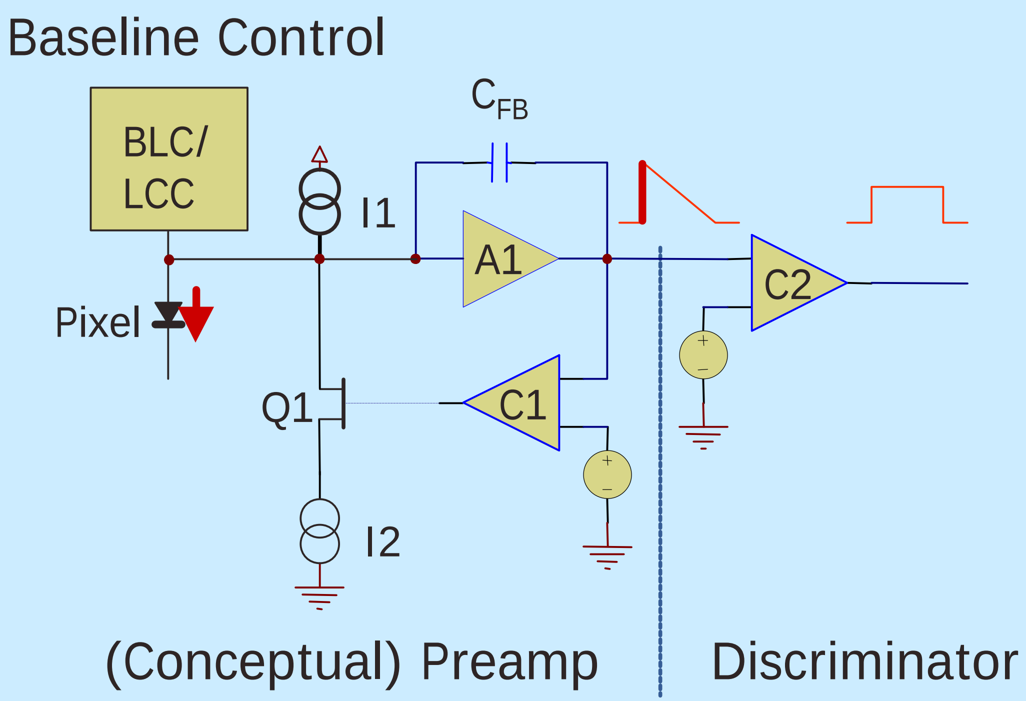

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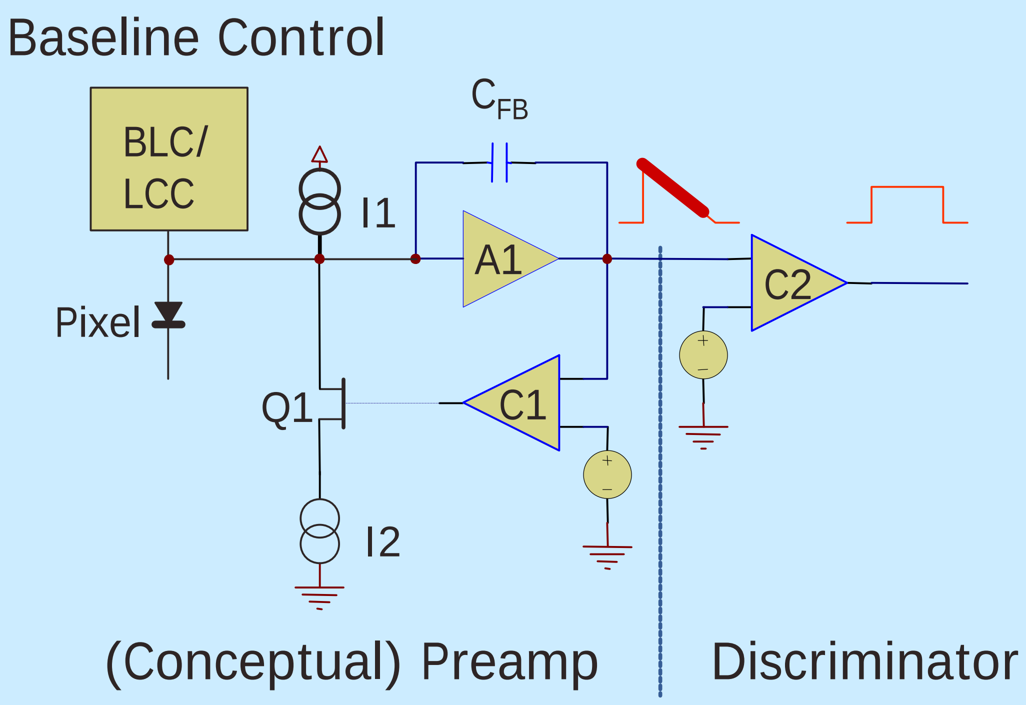

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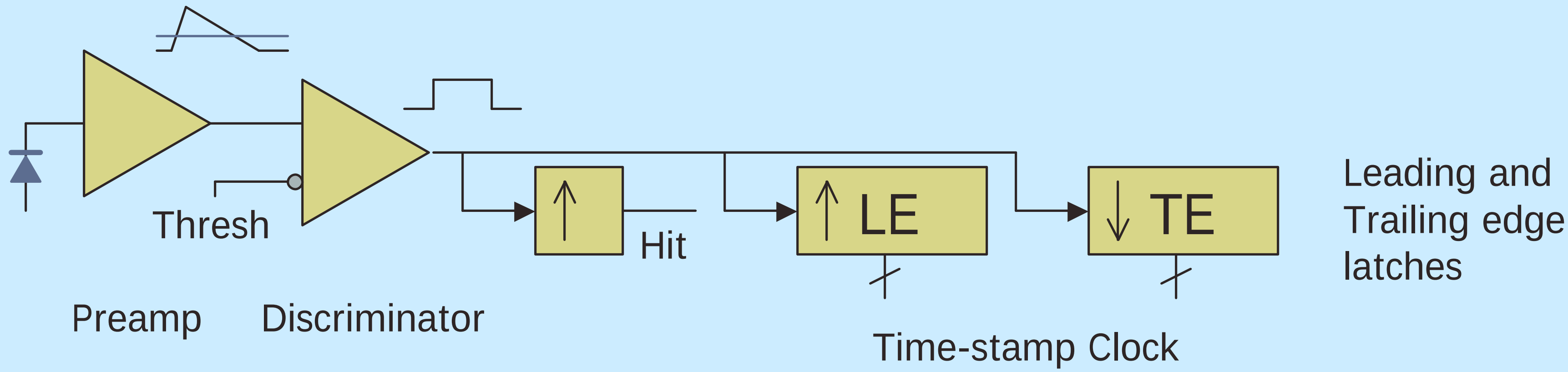
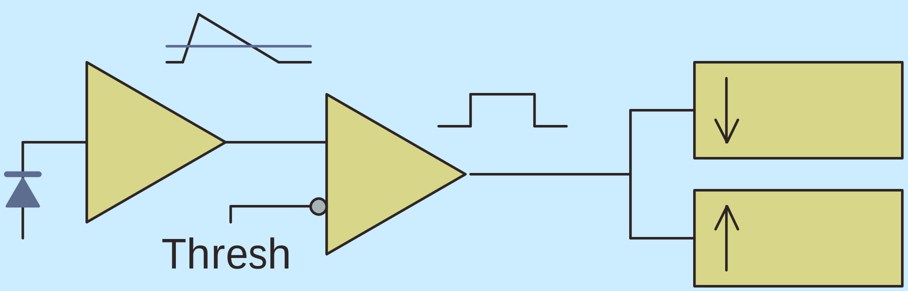
Pixel Information



- Each pixel contains 2 n-bit latch/registers, both of which have a high-speed time-stamp clock as their input.
- When a hit occurs, the LE latch records the value of the time-stamp clock on the leading edge of the discriminator output (thus tagging the photon arrival time). The TE latch records the value of the time-stamp clock on the trailing edge
- E ∝ Q ∝ TOT *(**T**ime **O**ver **T**hreshold)* = TE - LE

Proposed Version--Overall Specifications

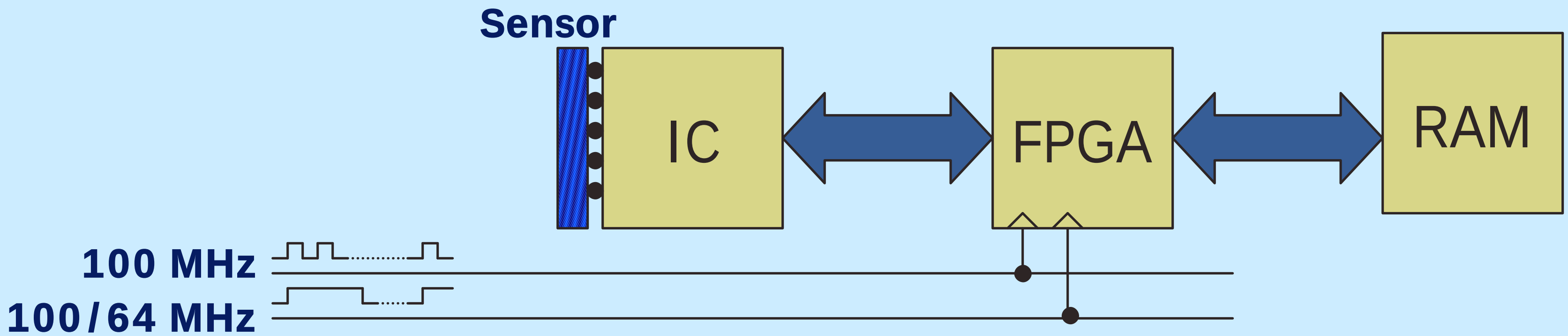
- 1024 x 1024 pixels, 150 µm x 150 µm
- 64 x 64 per chip - several chips in the system
- 100 MHz time-stamp clock
- Variable discharge current to tune energy resolution vs speed
  - ***"Fast" mode, 100 ns return to baseline,***
    ~3 bit resolution $= \Delta(h\nu)/h\nu \approx 1/8$
  - ***"Slow" mode 1 µs return to baseline,***
    ~6 bit resolution $= \Delta(h\nu)/h\nu \approx 1/64$
- Threshold 500 e^-
- Noise σ~100 e^- (Γ~1 keV in Si)



Preamp **Discriminator** **Leading and Trailing Edge (LE and TE) latches**

- Arrival time = LE
- ADC = TOT = TE-LE

Operation



- Logic+RAM per readout IC
- A “hit” consists of geographic address, arrival time and energy
  Many ways to process this data
- Time stamping at 100 MHz Þ photon arrival time known to 10 ns/Ö12 = 3 ns
- Energy quantization tuned to desired readout rate - few hundred eV to few keV
- Rate limited to ~1 MHz/pixel at 2% occupancy ® 20 GHz counting rate overall
- (x, y, t, E) - could be better in any quantity, but get <u>all</u> of them, and performance can be tuned to optimize one or more quantities
- No existing pixellated x-ray detector with the above capabilities

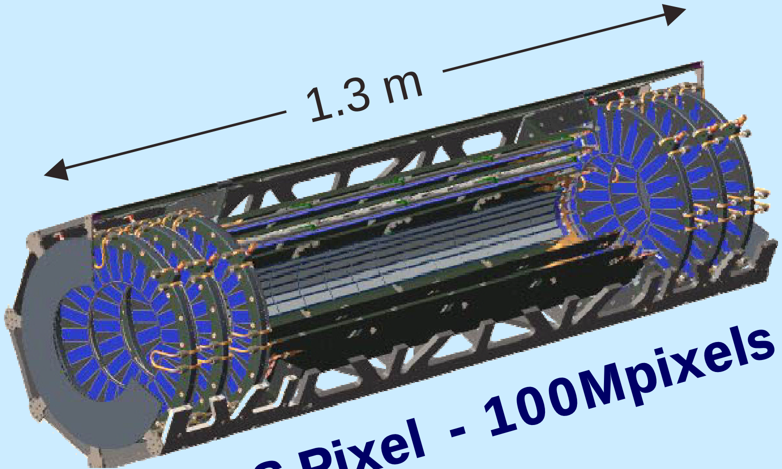
Usage Examples

- Data flows out of each of the 256 readout ICs at a rate of up to 100 MB/s. The data are of the form

	Optional, programmable Δt	Optional, programmable ΔE
Geographic Address	**Arrival Time**	**Charge**

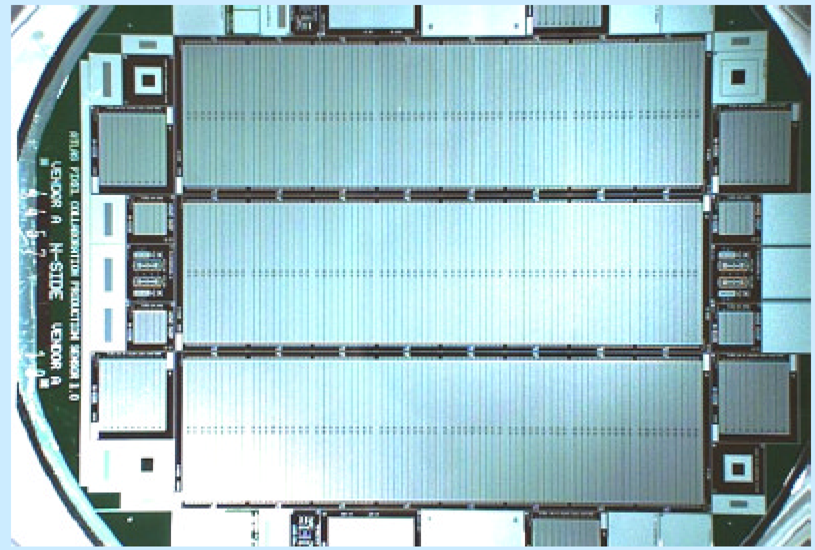
- The backend FPGA performs digital processing on the data, and store/buffer the results in RAM. Examples
  - *Histogram (x, y) only - like conventional counting pixels*
  - *2D Histogram: (x, y) vs. E*
  - *Time-resolved studies: (x, y, E) knowing t to £ 10 ns*
    e.g. time autocorrelation per pixel; temporal correlations between pixels or groups of pixels, …

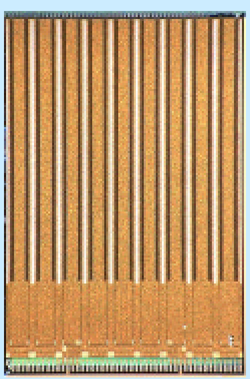
Large-Scale Pixel Detectors are Complex Systems ® HEP experience



ATLAS Pixel - 100Mpixels

100 mm wafer with 3 Si sensors

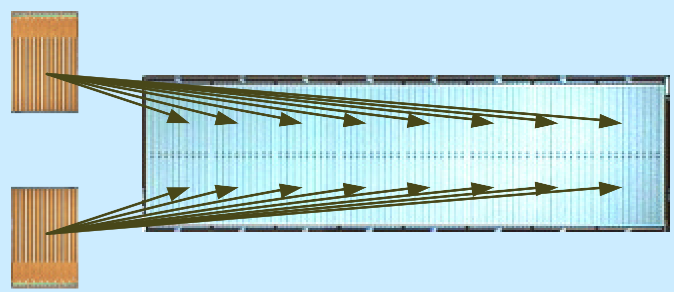


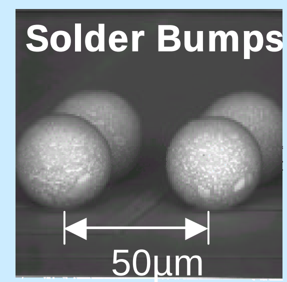


Readout ICs

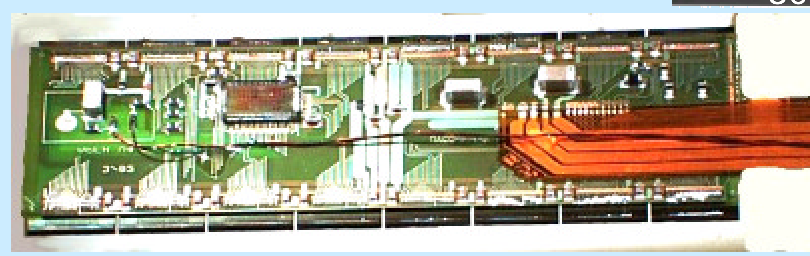
18x160 pixels

Readout



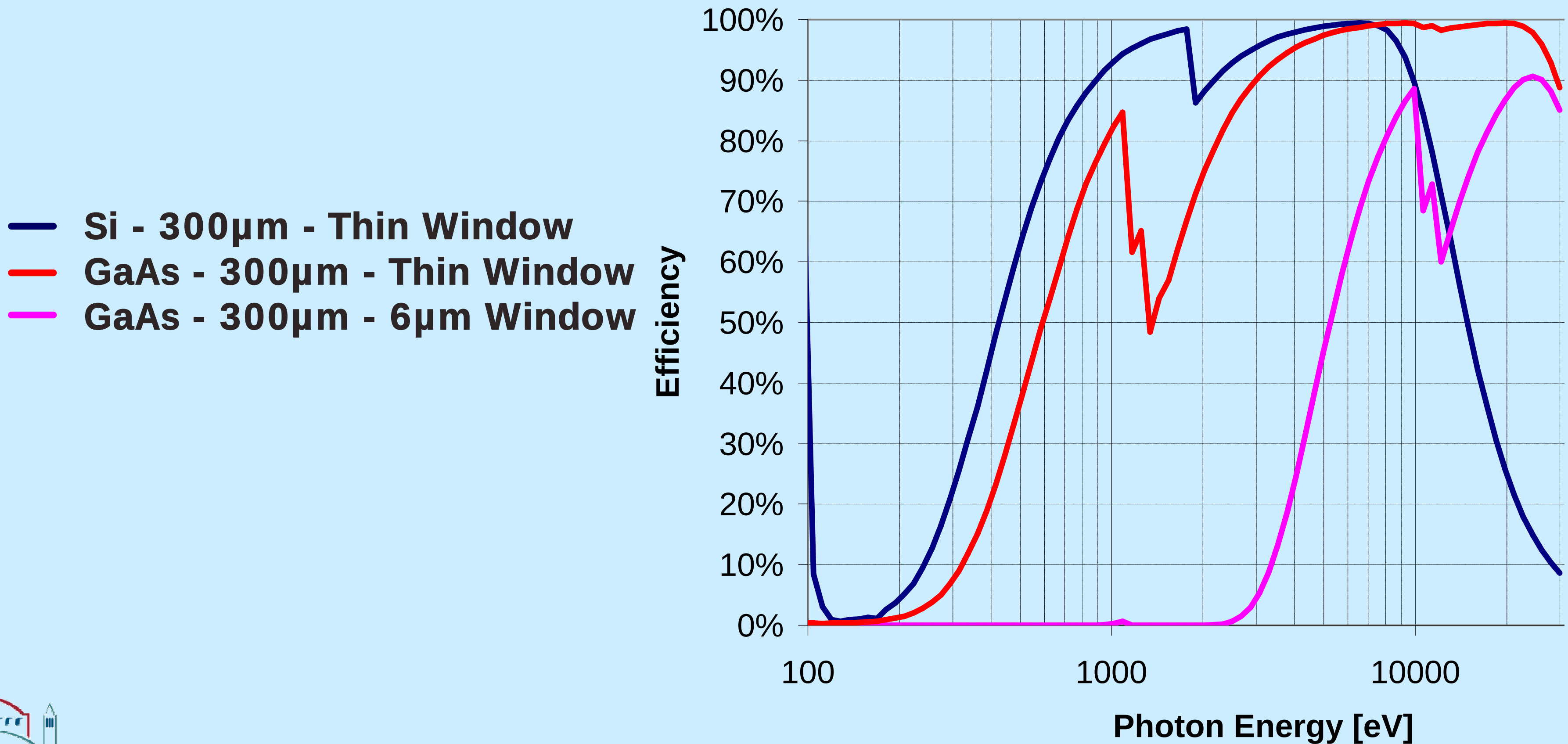


A “module” is 1 sensor with 2x8 bump-bonded chips



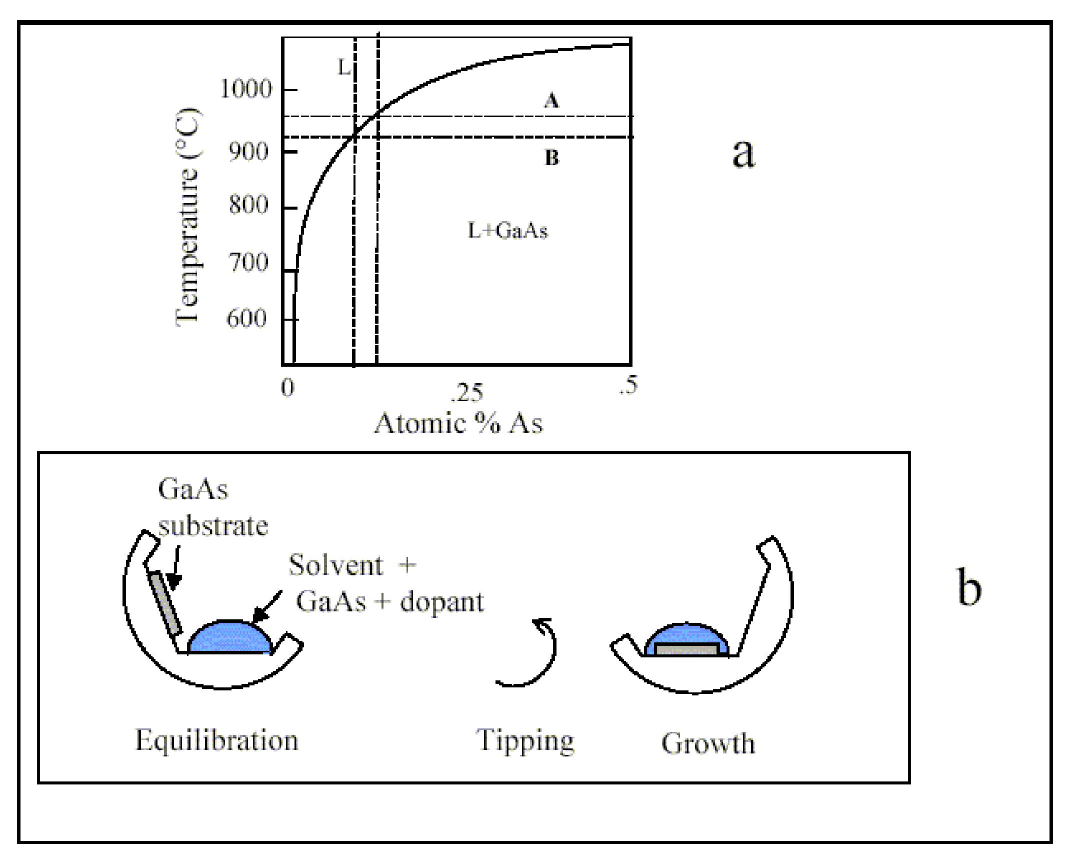
Sensors

- Initial version will use silicon sensors
- In order to go to higher energy, target GaAs pixels
  - *Much work already done in demonstrating GaAs pixels*
  - *Some specific developments for large, hybrid pixel detectors needed*



LBNL GaAs Program

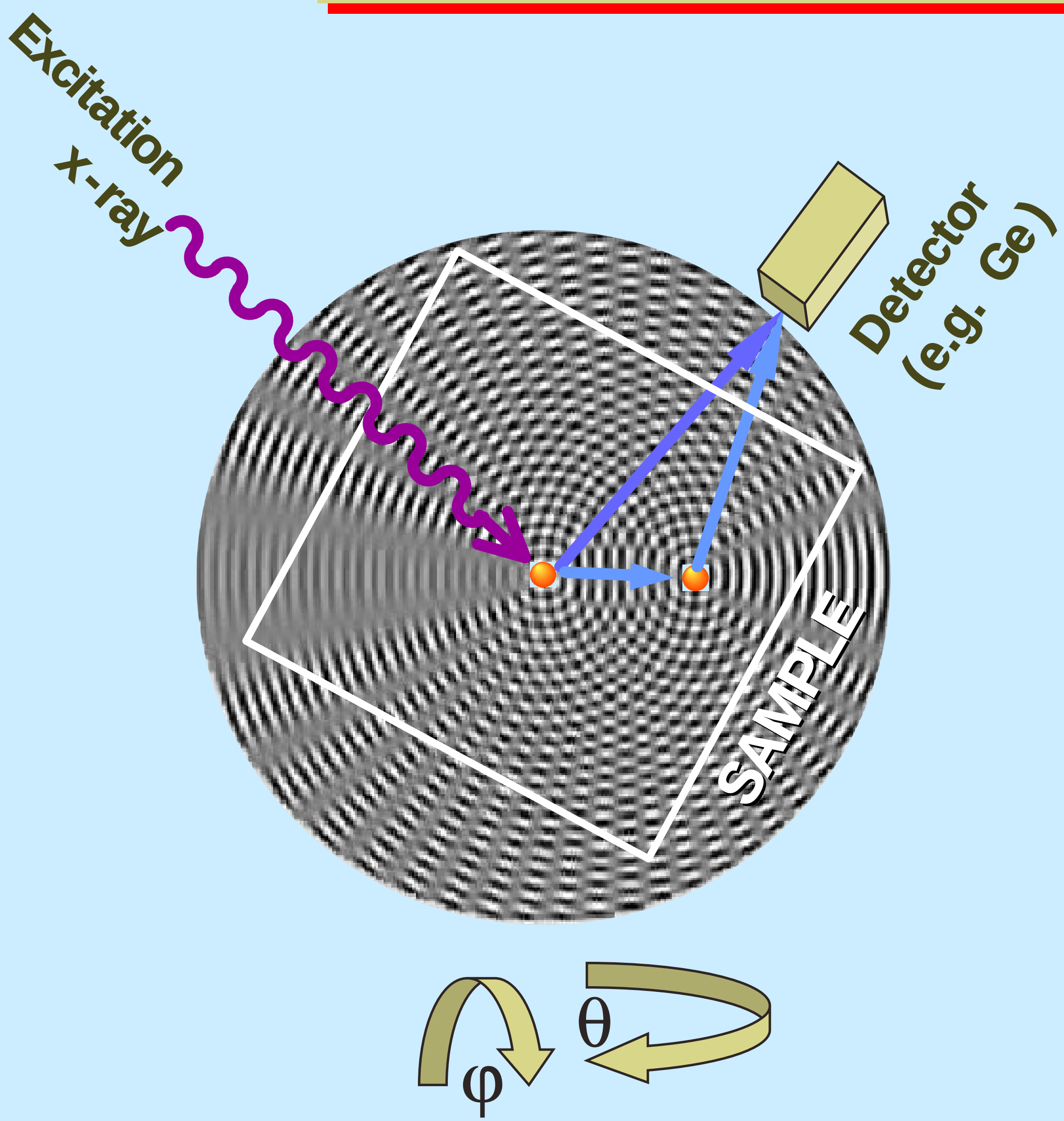
- Low temperature liquid phase epitaxial growth
- Achieves thick detectors
- Achieves low impurity concentration (low leakage current)



Schematic of LPE growth in a graphite crucible. GaAs is dissolved in Ga at elevated temperature and equilibrated. The solution is "tipped" onto the GaAs substrate and then cooled. After growth, the solution is tipped off

E. Haller, J. Beeman et al…

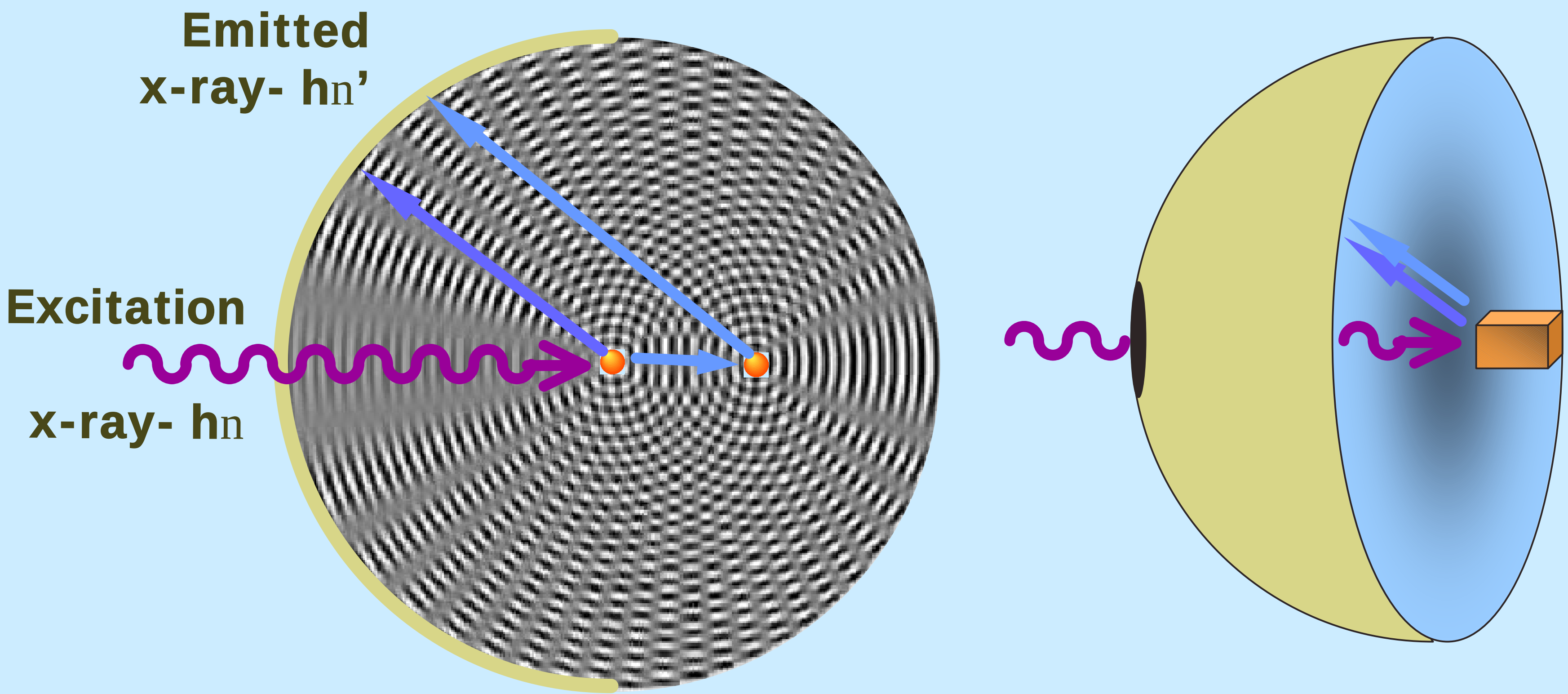
X-ray Fluorescence Holography



Current Method

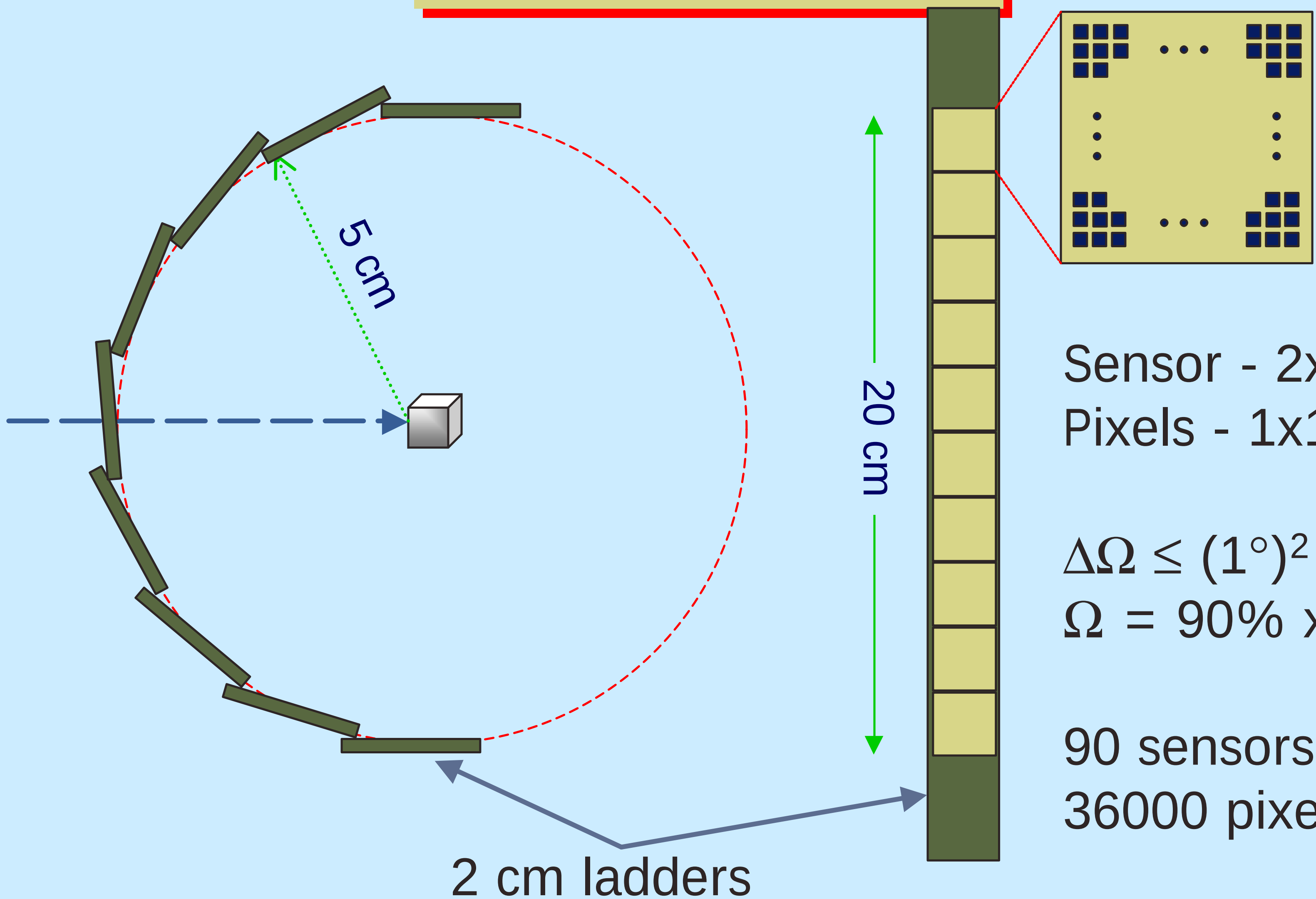
- Fixed, single-element detector
- Rotate sample in θ,φ
- Hologram in hours

XFH (or EXAFS) with Pixellated Detector



Large area pixel detector (Ω ~ 2π, $\Delta\Omega$ small, GHz rate)
$\rightarrow$ Hologram in minutes/seconds

XFH / EXAFS Detector



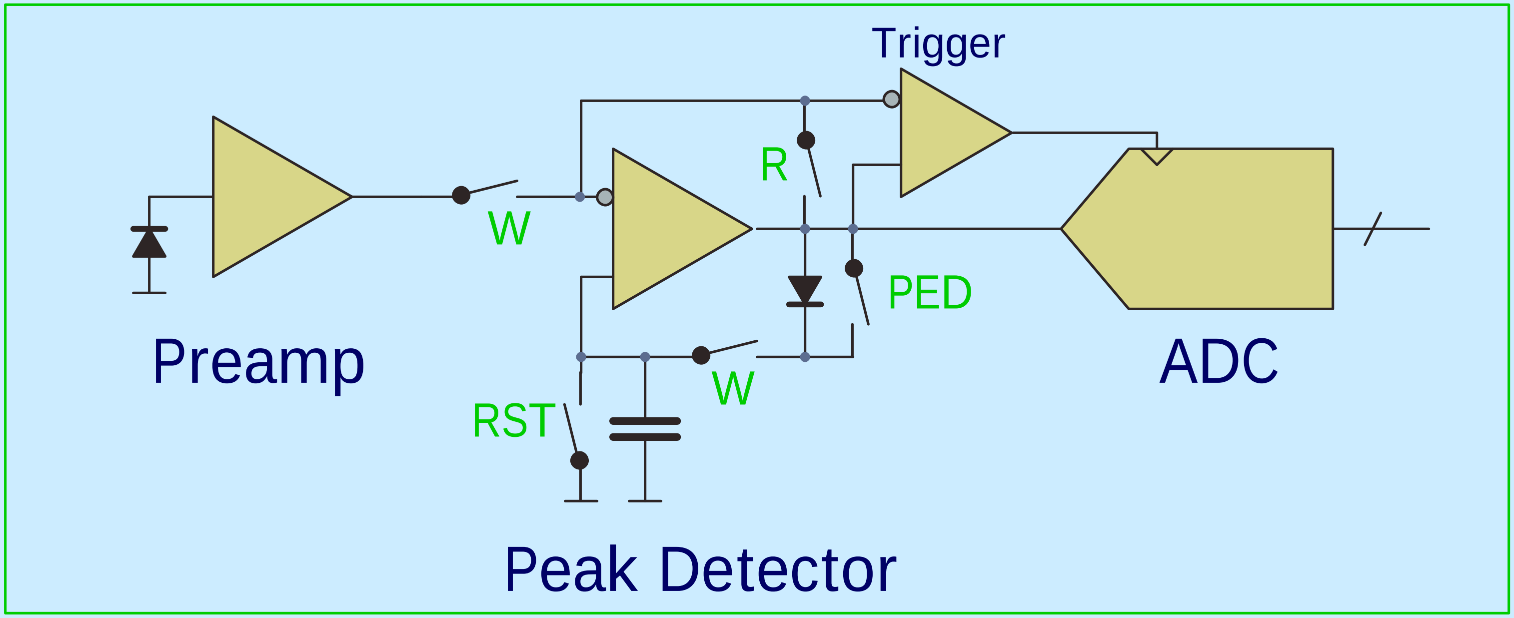
Sensor - 2x2 cm^2
Pixels - 1x1 mm^2

$\Delta\Omega \leq (1^\circ)^2$
$\Omega = 90\% \times 2\pi$

90 sensors
36000 pixels

Applications: Holograms in seconds or single XFEL pulse, Ultrahigh-speed EXAFS; Simplified version for XRD in single FEL pulse

Inside a Pixel



- 200-300 eV FWHM
- Adjustable shaping times
- 50 kHz / pixel
- 8-bit ADC / pixel
- Pedestal measurement mode

Readout format

Time	Addr	ADC

- ADC value
- Geographical address
- Time stamp

Summary and Roadmap

MCP-based: **Current 1D** → **Very Fast 1D** (x)→(E) — **PES, XES/RIXS, NEXAFS**

MCP-based: **Current 1D** → **Fast 2D** (x, y)→(E, θ) — **ARPES, XES/RIXS**

Solid State 2D:

- 150 μ Pixels: **Si Multi Purpose** (**150 μ Pixel Platform**)
  - → **GaAs Multi Purpose**
  - → **Modified Si Sensor, Modified readout IC**
  - (x, y, t, E) — **XRD, XFH, PCS, Speckle**
- 1 mm Pixels: **Si Multi Purpose** (**1 mm Pixel Platform**) — **Slower, better DE/E** (x, y, t, E) — **XFH, EXAFS, XRD**