Semiconductor Detectors for a Strong Field QED facility

Just saw the specification Document

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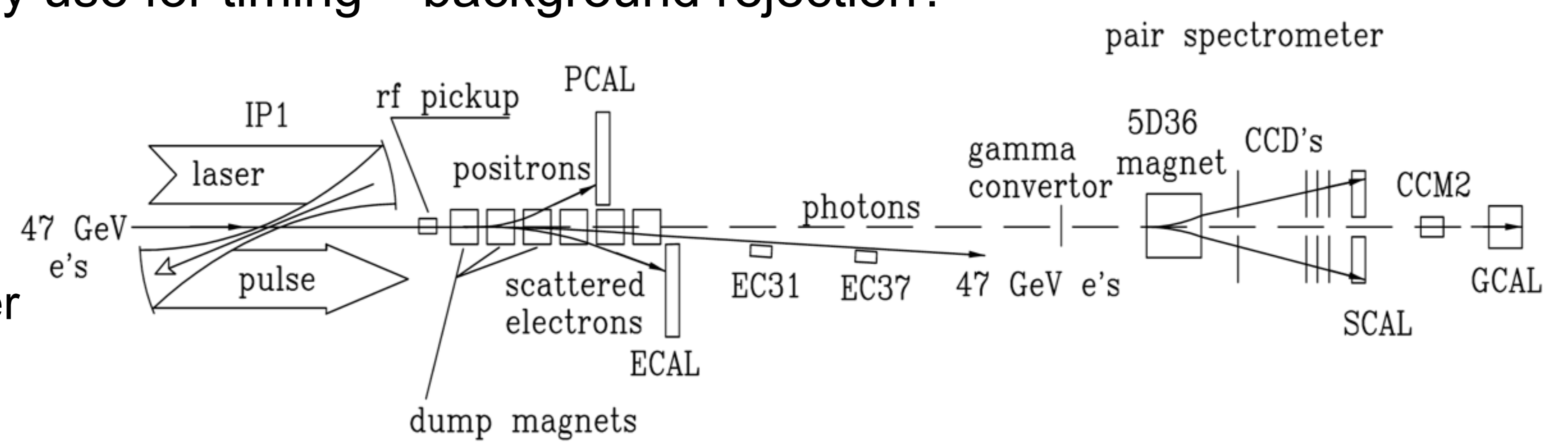
What's needed?

- Appears to be a wide range of potential experimental parameters, which may evolve over time
- Looks like a very creative, fun community!
- Still the types of possible measurements seem limited:
  - Vertexing
  - Magnetic spectrometer
  - Calorimeters
  - Any use for timing – background rejection?

E144 used calorimeters and a spectrometer



Bamber et al.Phys Rev D, (1999)

Other Considerations

- Very low pulse repetition rate likely below 10 Hz
  - Makes things MUCH easier
  - Benefit from detector development for FELs
- Radiation damage may be a big challenge
- Anything that would generate an EMP?
- Entire apparatus in vacuum?

Imaging detectors in Matter in Extreme Conditions (MEC) instrument vacuum chamber at LCLS

Sealed in metal to withstand EMP

Hart et al. 2012

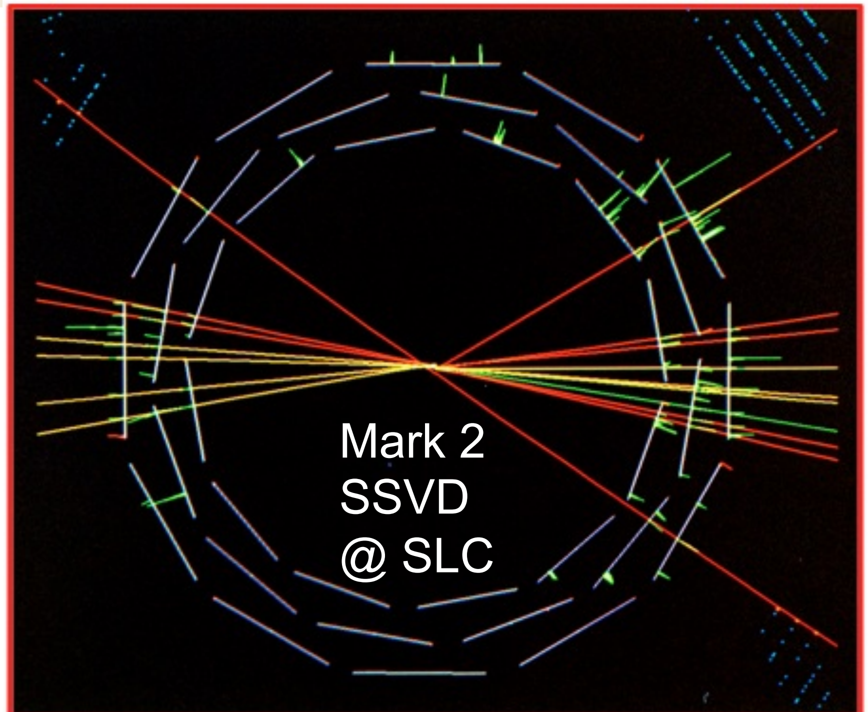
What's needed in vertexer or tracker?

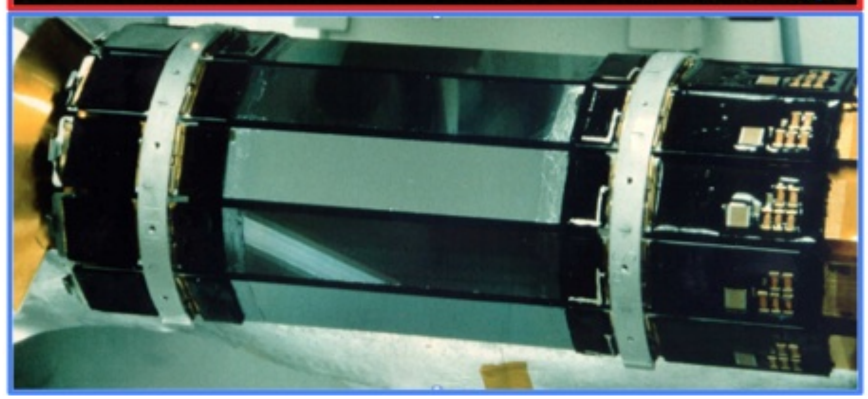
- First layer as close to IP as feasible
- Low Mass
  - Loss of trajectory information due to multiple scattering
  - Ancillary structures for cooling, power, etc.
- Pixel size = spatial resolution
- Signal-to-noise

Heavy Photon Search Tracker
Adrian et al. 2018

Hybrid Designs

- Dominant paradigm for LHC, synchrotron, and XFEL
- Sensor and circuitry on separate silicon substrates
- Combined with flip-chip interconnects
- Or wire bonded
- Pros:
  - Allows complex circuitry
  - Sensor flexibility
- Cons:
  - Two chips tends to double the mass



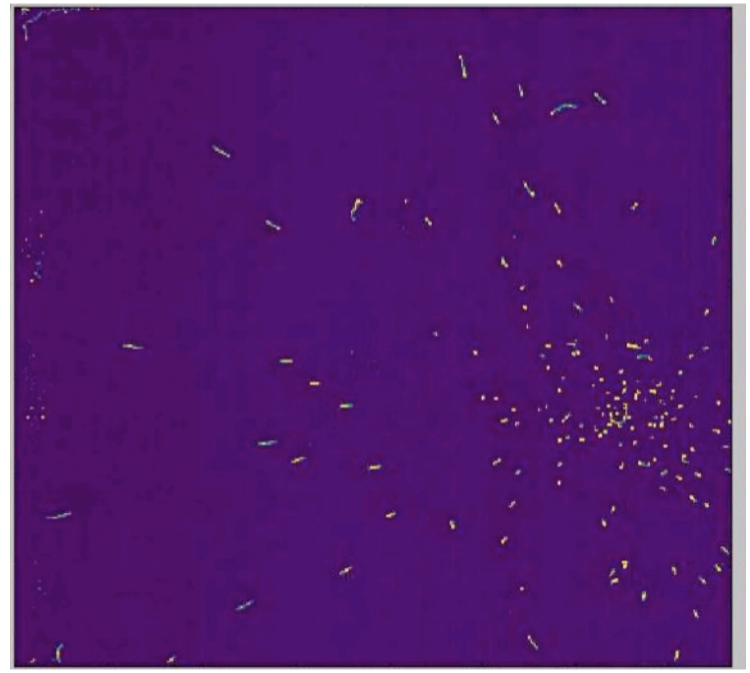


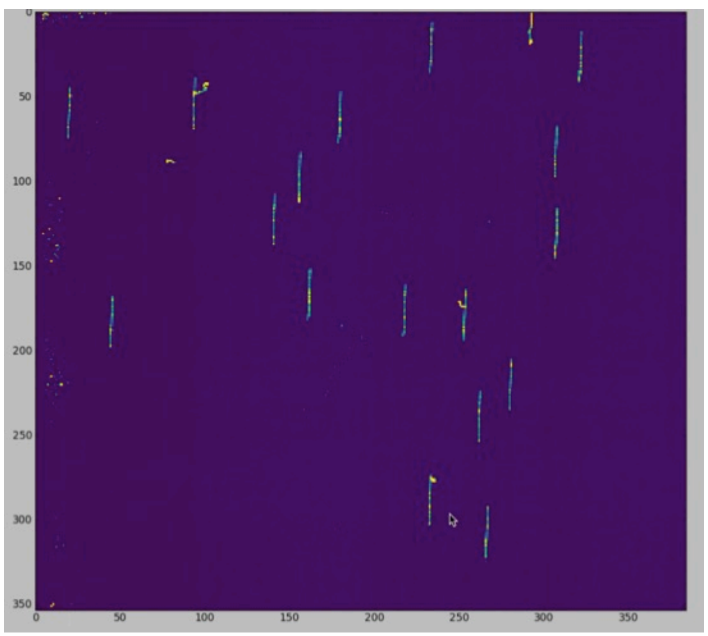
Jacobsen et al. 1990

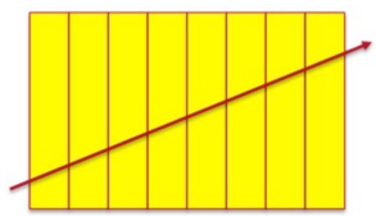
Hybrid LCLS Detector in End Station A

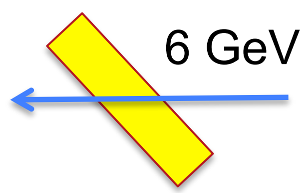
SLAC End Station A with 6 GeV electrons from LCLS primary beam

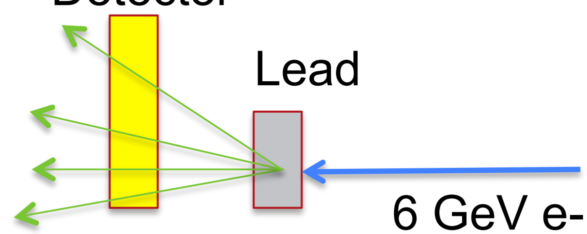
- ePix (also planed use at EuXFEL)
- 50 μm pixels
- Low noise (i.e. 50 e-)
- S/N for a mip ~ 800
- Already in FEL's DAQ







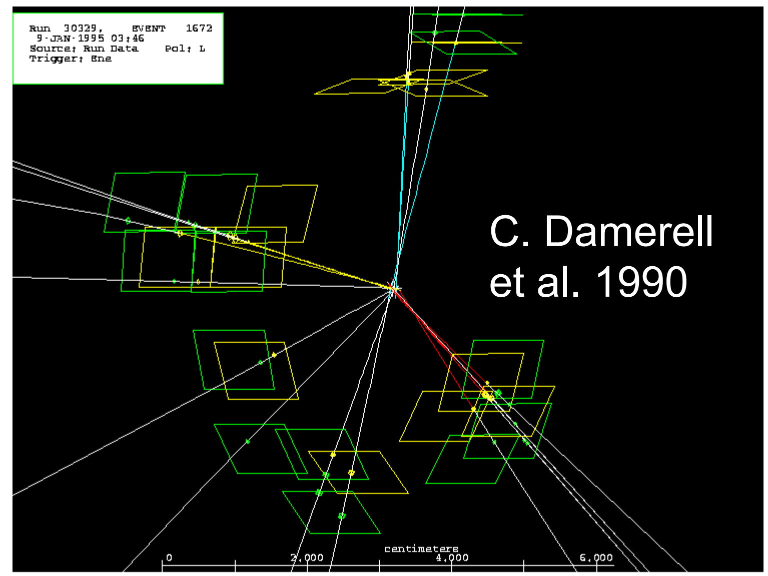




Blaj et al. 2016

CCDs

- Circuitry outside active area = lower mass
- Low noise = thinner = low mass
- Tend to be radiation damaged
- Skipper CCD < 1 electron rms (Holland et al.)
- Low power in active area = low mass
- SLD @ linear collider used a CCD vertexer (Damerell et al.)

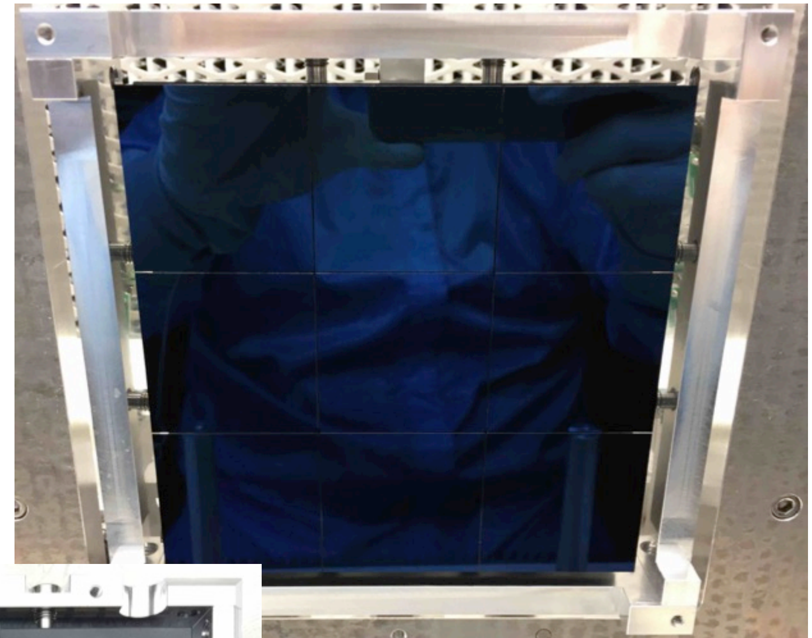


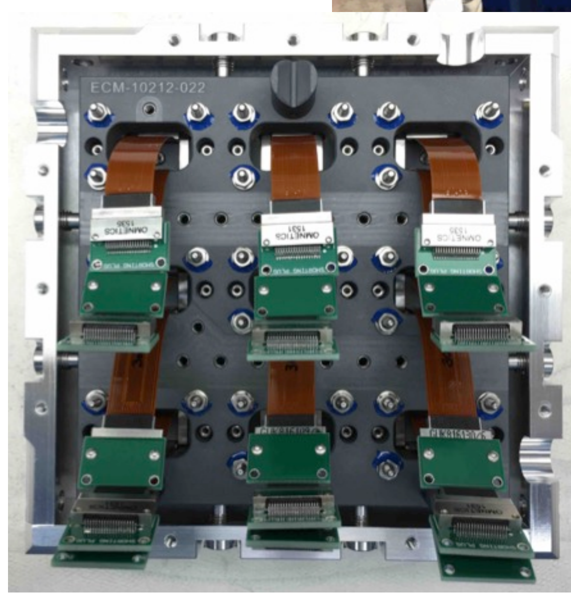
- Used in E144 magnetic spectrometer

LSST

SLAC

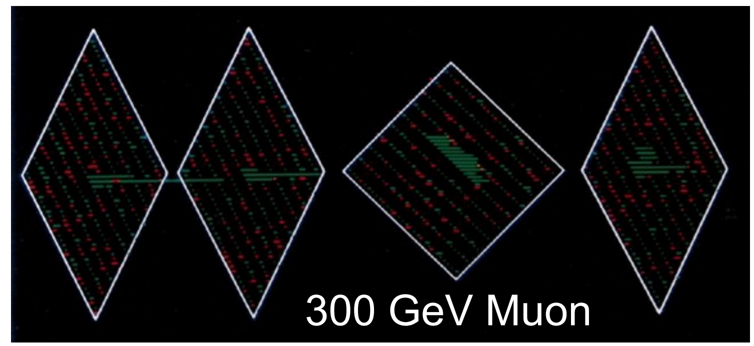
- 3 Gigapixels – largest digital camera
- Edge buttable
- 10 e- noise
- 5 um PSF
- Full depletion
- 100 microns thick
- Thin entrance window

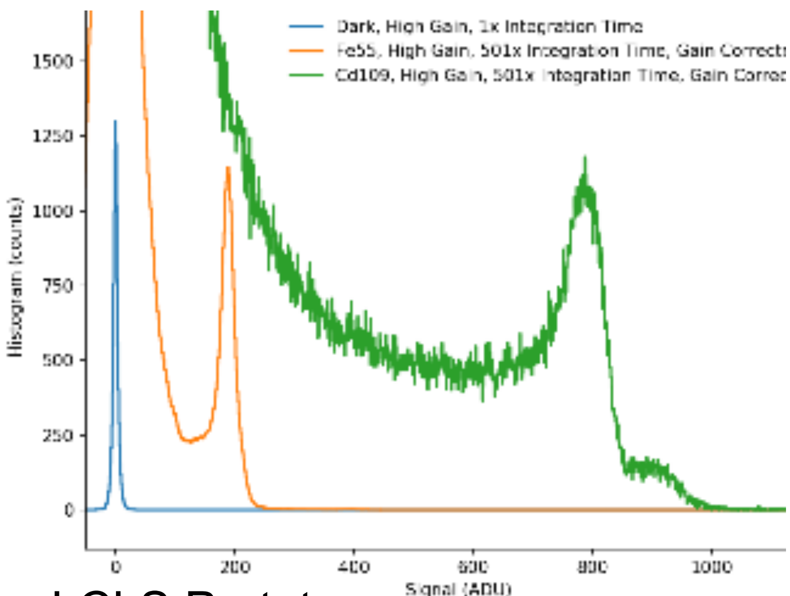




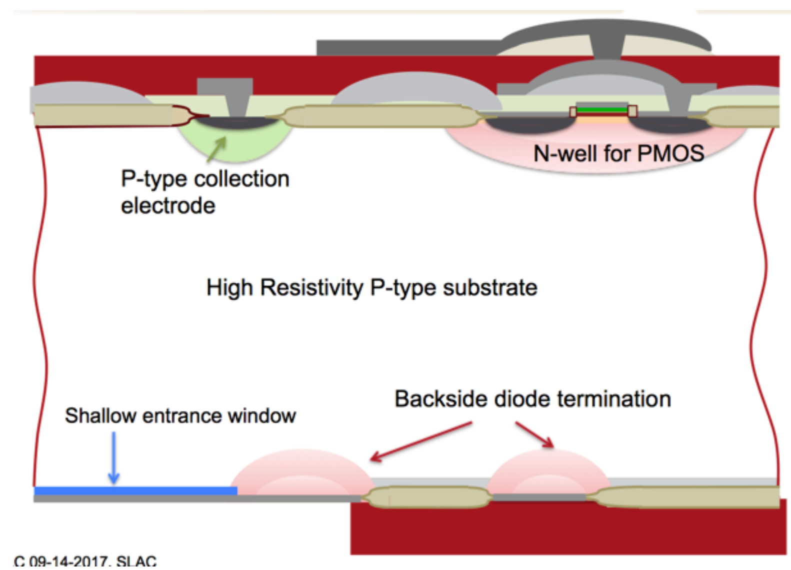
Monolithic CMOS Image Sensors

- Sensor and circuitry combined in same silicon substrate
- Dominant technology for digital cameras in cell phones
- First ionizing radiation CMOS imager for Superconducting Super Collider
- Aggressively being pursued for LHC
- Can be fully depleted
- Low C = Low noise



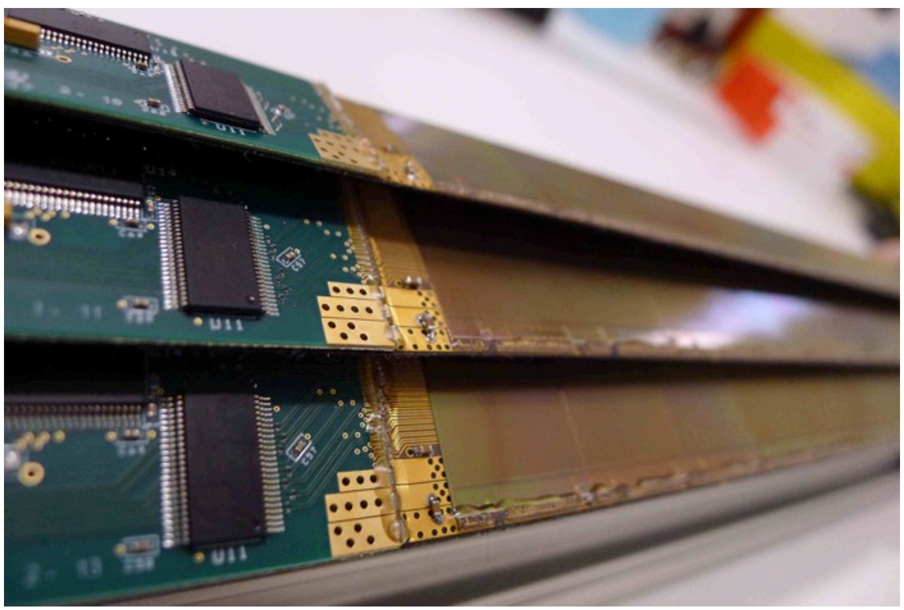


LCLS Prototype

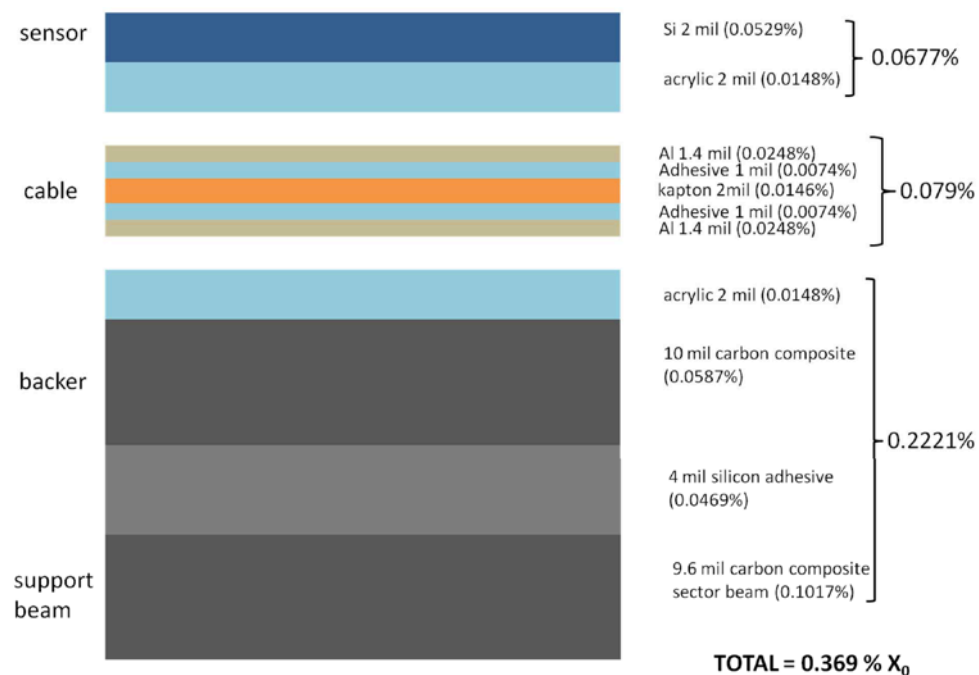


STAR Tracker at RHIC

- CMOS monolithic active image sensors
- Thinned to 50 microns to reduce scattering
- 350 megapixels
- Less than 0.4% R.L.



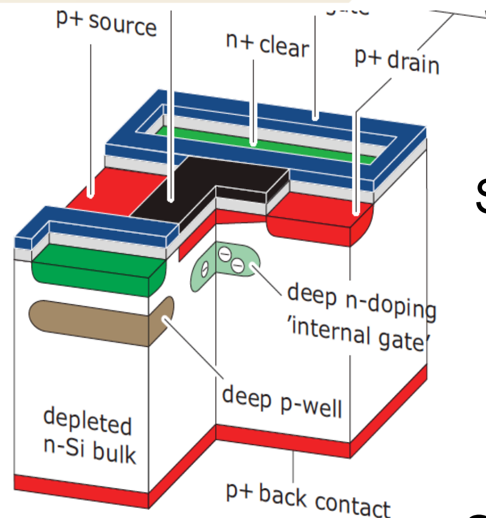
Radiation Length of active area



NOTE: Does not include sector tube side walls

B Factories Examples

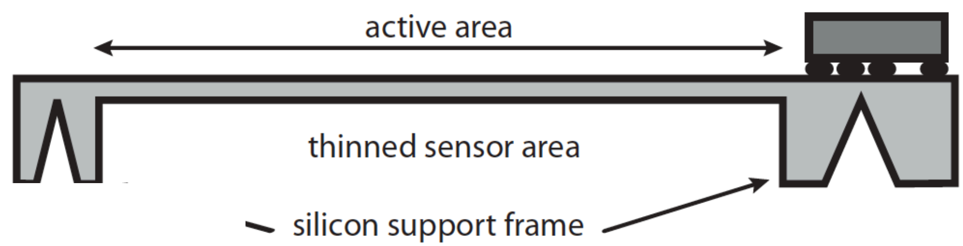
- SuperKEKB – Belle II
- DEPFET based
- Example of a specialized monolithic device

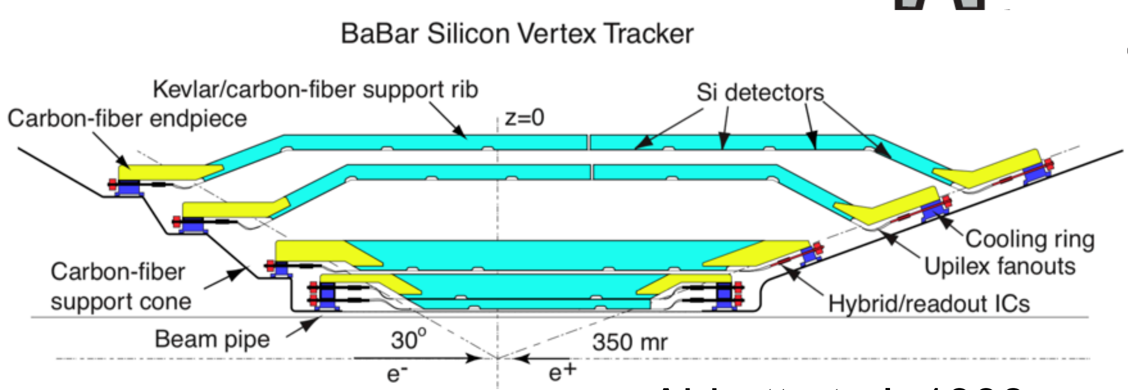


Schiek et al. 2018

- BaBar at PEP II
- Double-sided silicon strips

Simon et al. 2010

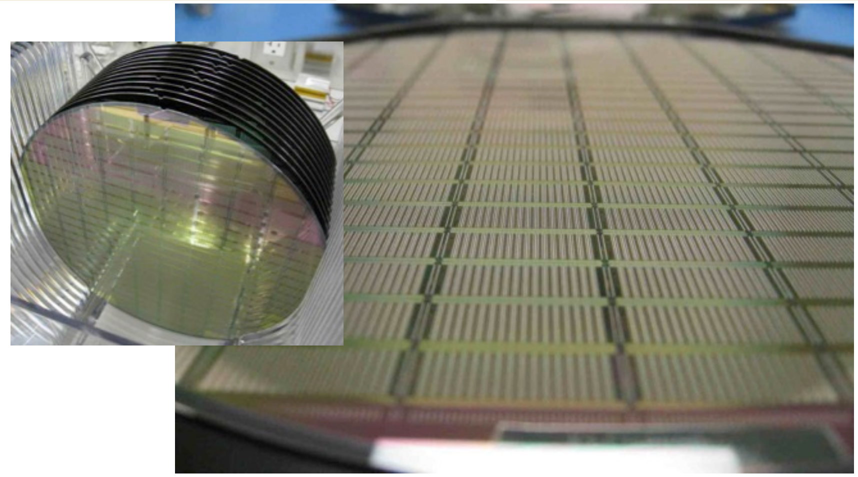




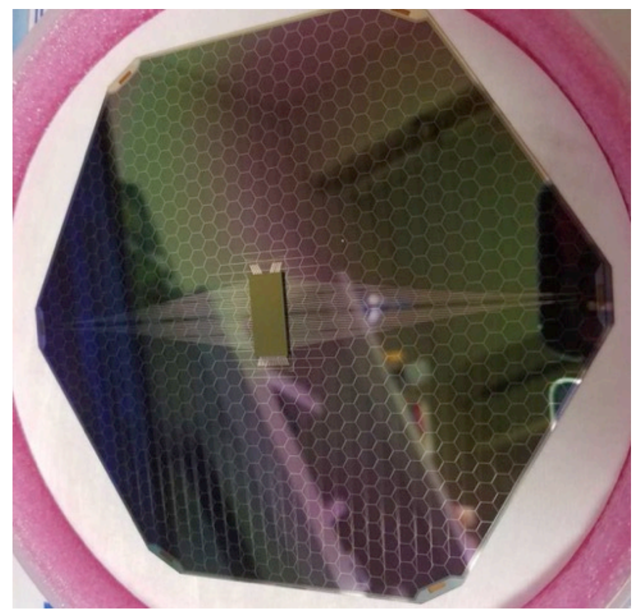
Abbott et al. 1998

Semiconductor Detectors for Calorimetry

- Needed
  - Modest spatial resolution
  - High dynamic range
- Auto-ranging = high dynamic range
- W-Silicon Geometry
  - SLAC E144
  - Fermi-LAT
  - Kpix for SiD
    - Multi-purpose
    - Bump bonded to sensor
- Auto-ranging detectors for XFELs: AGIPD, LPD, ePix10K
- Dynamic range in a cm2 area between 1 and 10^7

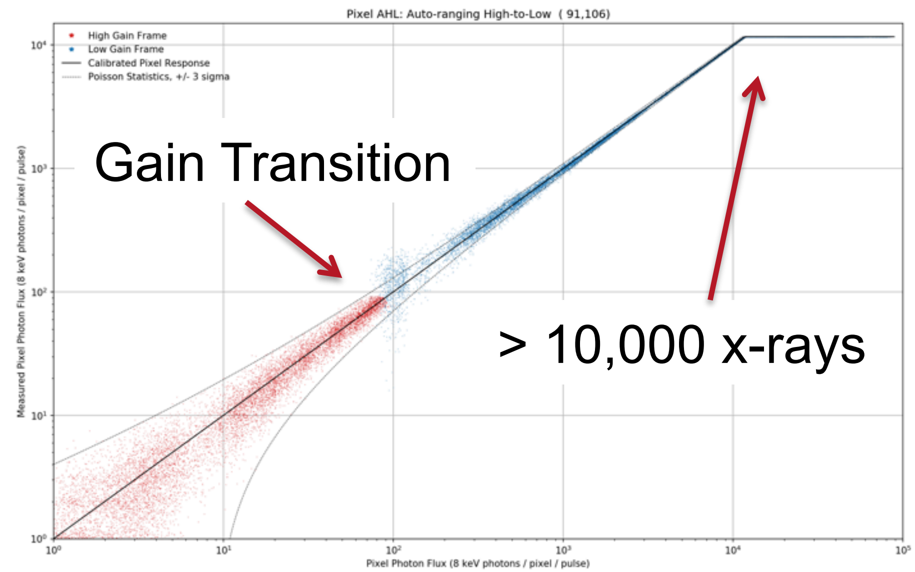


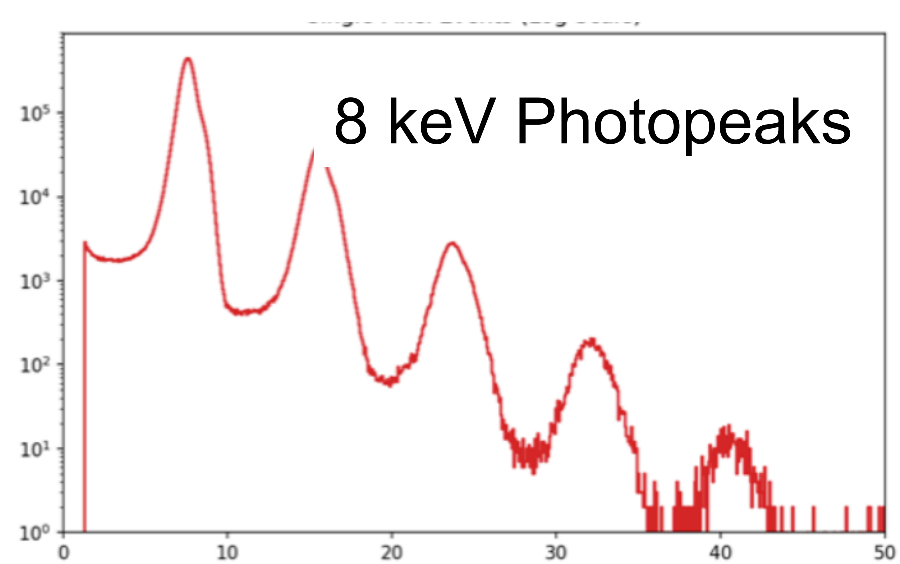
D. Freytag et al., *IEEE Nucl. Sci. Symp. Conf. Rec. (2008) 3447*



ePix10k Auto-Ranging Example

- Developed for LCLS FEL
- Every pixel automatically selects appropriate gain level on a pulse-by-pulse basis
- Similar to KPix, AGIPD, LPD
- 70 electrons of noise in high gain
- Maximum signal of 80 MeV (20 million electrons) per pixel per pulse in low gain





Dragone et al. 2014

Three Regimes

- One – low intensity
- Less than 10^5 electrons per event
- Can track every electron/positron
- Can use existing detector components or slightly modified ones
- Still need to correlate hits across planes
- CCDs, Monolithic, or Hybrid

Three Regimes

- Two – moderate intensity
- Less than 10^8 electrons per event
- Taking integrated images of the charged particle trajectories
- Can use an autoranging hybrid detector: ePix10K, AGIPD ..
- Might want to redesign to optimze well depth versus noise
- Thin sensor to increase well depth
- Still able to resolve at single particle level
- Hybrid with 1-10 megapixels per plane

Three Regimes

- Three – high intensity
- Above ~10^8 electrons per event
  - Depends on spatial distribution of electrons
- Taking integrated images of the charged particle trajectories
- No ability to sense a single track
- Radiation damage becomes worrisome
- Can use an autoranging hybrid/CMOS detector: ePix10K, AGIPD ..
- But with low-efficiency transducer/sensor
- Perhaps an indirect scheme – scintillator and take an optical image of it.

Conclusions

- Very difficult to individually track 10^{10} electrons per pulse
  - CMOS imager may be only option for this
  - Very thin, low noise, small pixels
  - Computation would be formidable – probably not viable
- Probably have to record integrated image – still challenging
- Low repetition rate eases DAQ aspects
- Radiation damage may limit lifetime of detector
- For low rates vertex, tracking, magnetic spectrometer, & calorimetry all similar to existing systems
- Would 100 ps timing reject backgrounds?
- FEL detectors are designed for similar time structure
- Funding could be major constraint