Detectors

DLSR workshop – “Technologies” session

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Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Another ‘new’ generation of light sources…

Can detectors be ***‘the’*** game changer?

- Obviously not (or may be yes?), but the game can’t change if all the players don’t advance (together)

Outline

Spectroscopy:

- Very high-energy-resolution X-ray detectors
- High-speed spectroscopic X-ray detectors

Imaging*:

- Good spatial resolution
- Dynamic range
- Fast and “smart”

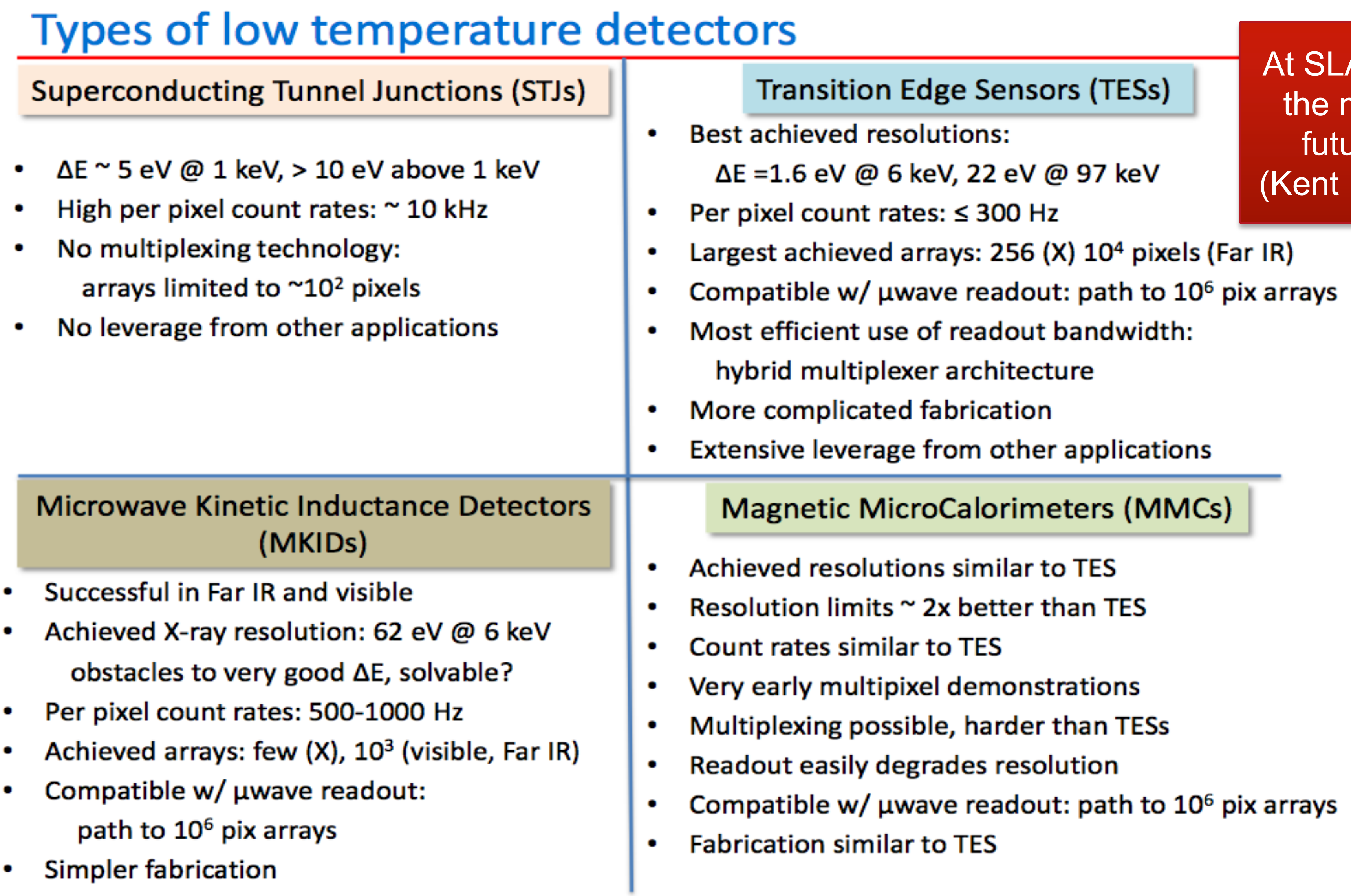
Other common needs:

- Large solid angle (large area)
- Efficiency
  - Good entrance window for soft x-rays
  - High stopping power material for hard x-rays
- Radiation tolerant
- Easy to use

* The talk doesn’t cover detectors based on indirect conversion (aka scintillator)

Joel Ullom – NIST
DOE - BES Detector Workshop 2012

Spectroscopy: very high-energy resolution



Types of low temperature detectors

At SLAC in the near future (Kent Irwin)

Superconducting Tunnel Junctions (STJs)

- ΔE ~ 5 eV @ 1 keV, > 10 eV above 1 keV
- High per pixel count rates: ~ 10 kHz
- No multiplexing technology:
  arrays limited to ~10^2 pixels
- No leverage from other applications

Transition Edge Sensors (TESs)

- Best achieved resolutions:
  ΔE =1.6 eV @ 6 keV, 22 eV @ 97 keV
- Per pixel count rates: ≤ 300 Hz
- Largest achieved arrays: 256 (X) 10^4 pixels (Far IR)
- Compatible w/ μwave readout: path to 10^6 pix arrays
- Most efficient use of readout bandwidth:
  hybrid multiplexer architecture
- More complicated fabrication
- Extensive leverage from other applications

Microwave Kinetic Inductance Detectors (MKIDs)

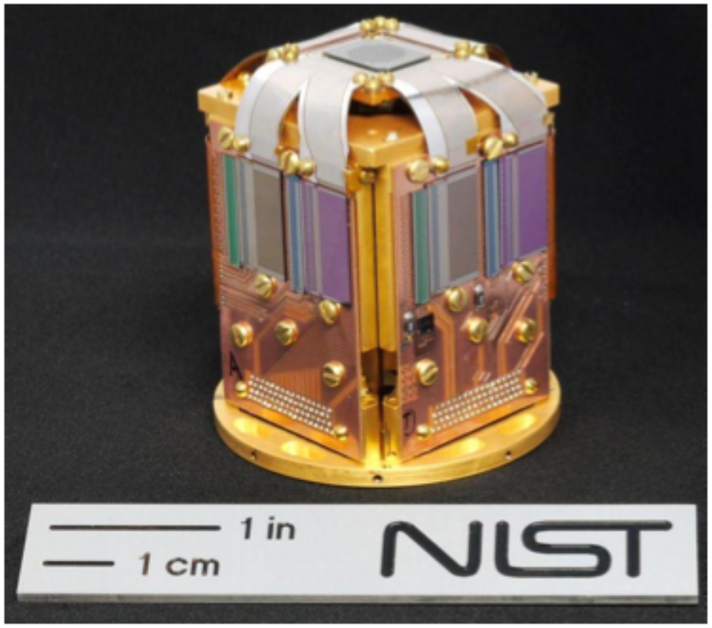
- Successful in Far IR and visible
- Achieved X-ray resolution: 62 eV @ 6 keV
  obstacles to very good ΔE, solvable?
- Per pixel count rates: 500-1000 Hz
- Achieved arrays: few (X), 10^3 (visible, Far IR)
- Compatible w/ μwave readout:
  path to 10^6 pix arrays
- Simpler fabrication

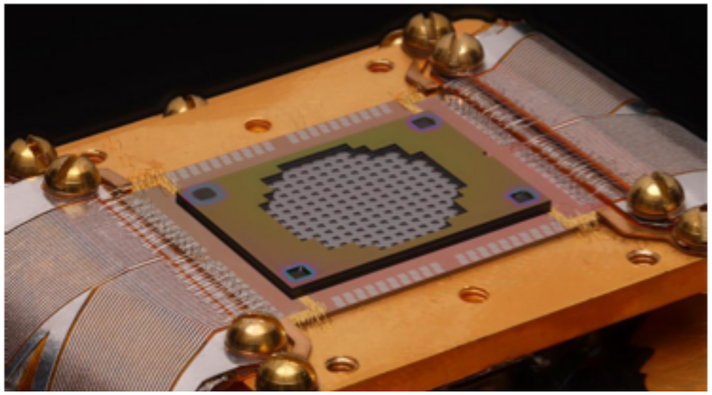
Magnetic MicroCalorimeters (MMCs)

- Achieved resolutions similar to TES
- Resolution limits ~ 2x better than TES
- Count rates similar to TES
- Very early multipixel demonstrations
- Multiplexing possible, harder than TESs
- Readout easily degrades resolution
- Compatible w/ μwave readout: path to 10^6 pix arrays
- Fabrication similar to TES

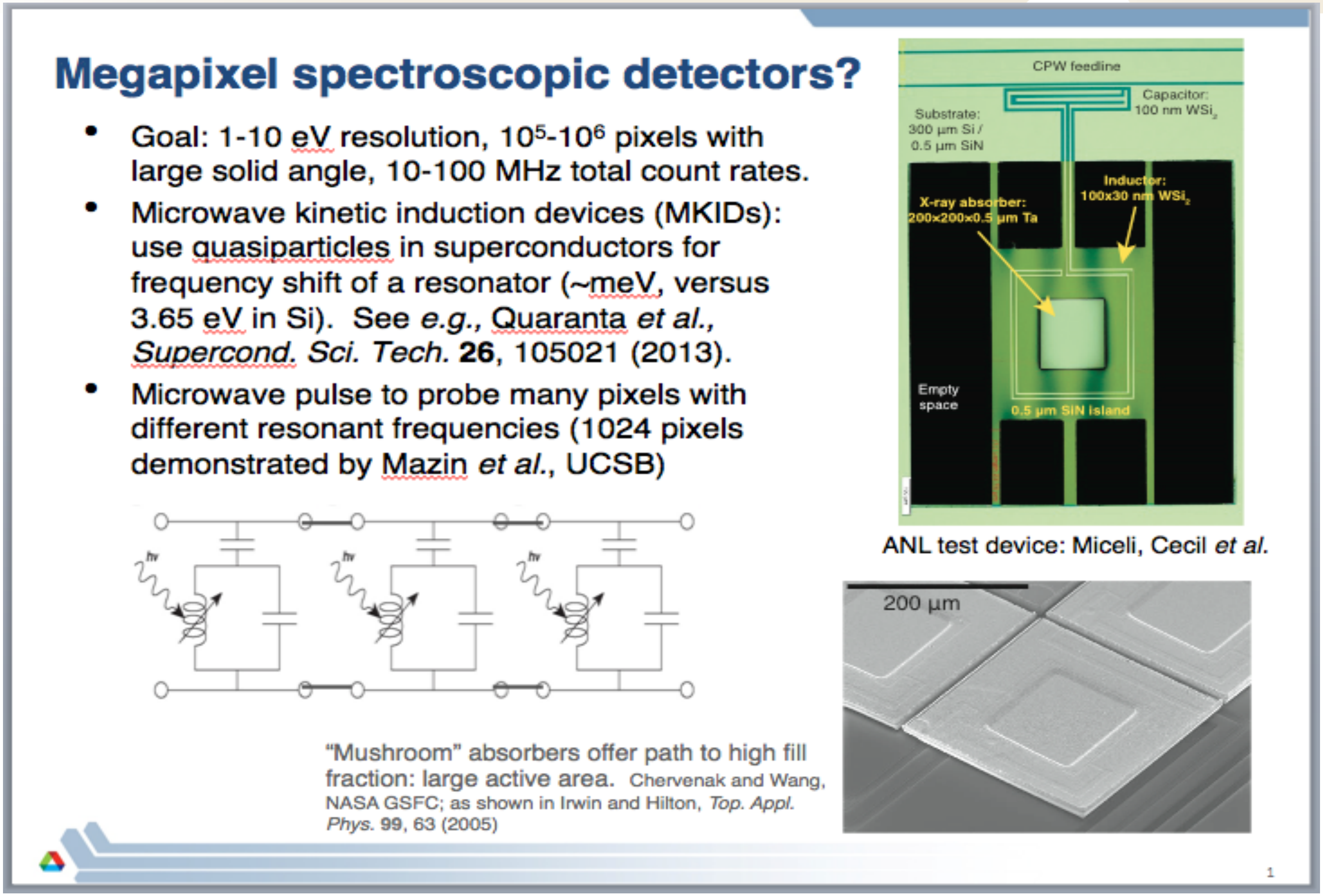
Spectroscopy: very high-energy resolution

- TES X-ray spectrometer that can accommodate 256 pixels deployed to National Synchrotron Light Source (spectrometer paid for by NIST)
- 40 pixels now, 160 in FY13





Spectroscopy: very high-energy resolution



Megapixel spectroscopic detectors?

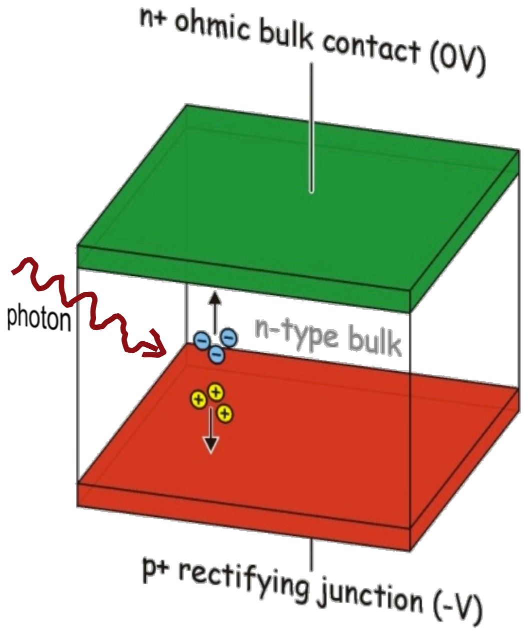
- Goal: 1-10 eV resolution, 10^5-10^6 pixels with large solid angle, 10-100 MHz total count rates.
- Microwave kinetic induction devices (MKIDs): use quasiparticles in superconductors for frequency shift of a resonator (~meV, versus 3.65 eV in Si). See *e.g.*, Quaranta *et al.*, *Supercond. Sci. Tech.* **26**, 105021 (2013).
- Microwave pulse to probe many pixels with different resonant frequencies (1024 pixels demonstrated by Mazin *et al.*, UCSB)

ANL test device: Miceli, Cecil *et al.*

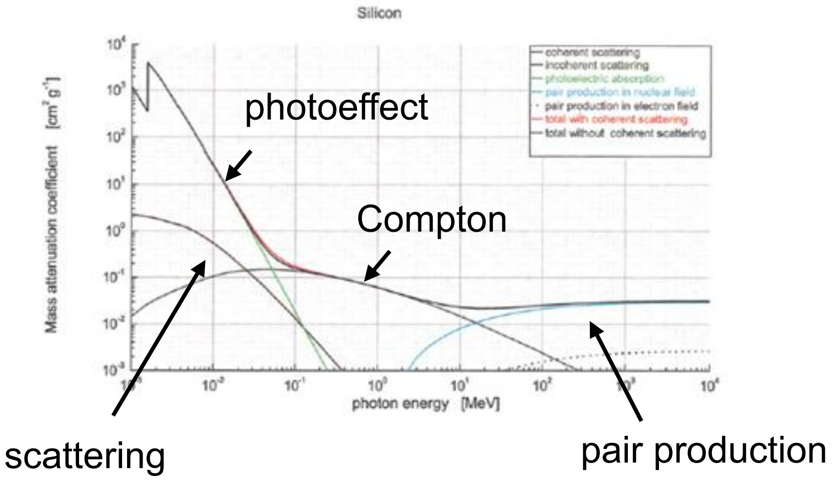
"Mushroom" absorbers offer path to high fill fraction: large active area. Chervenak and Wang, NASA GSFC; as shown in Irwin and Hilton, *Top. Appl. Phys.* 99, 63 (2005)

Silicon: Fano-limited energy resolution

Silicon is an excellent material for direct conversion



PIN diode scheme

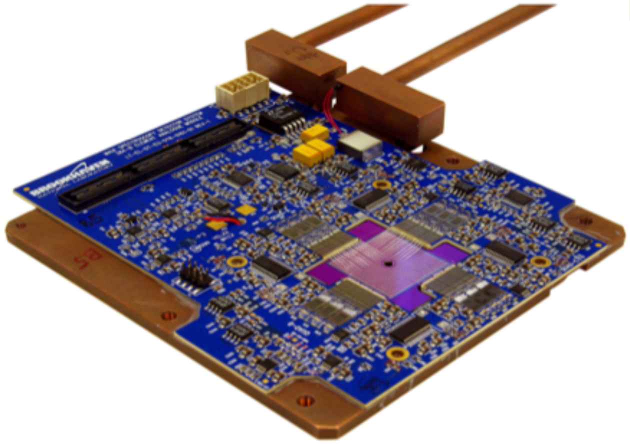


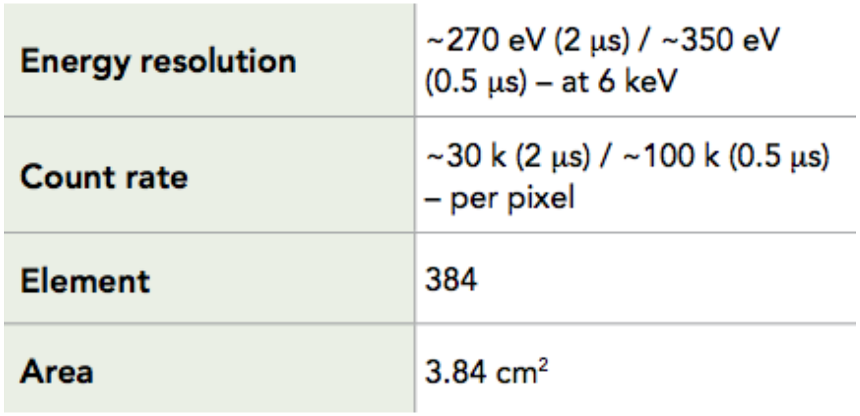
- Below ca. 40keV photoeffect dominates in silicon
- $N_{\text{e-h pairs}} = E_{\text{x-ray}} / 3.65\text{eV}$
- Variance: $\sigma = \sqrt{(F \times N)}$
  - Fano factor: F= 1 pure Poisson process
    F= 0.115 - 0.117 for silicon

5.9keV (Fe^{55}) → 1616 e$^-$ mean → 13.7 e$^-$ sigma → 50.2eV sigma → 118eV FWHM

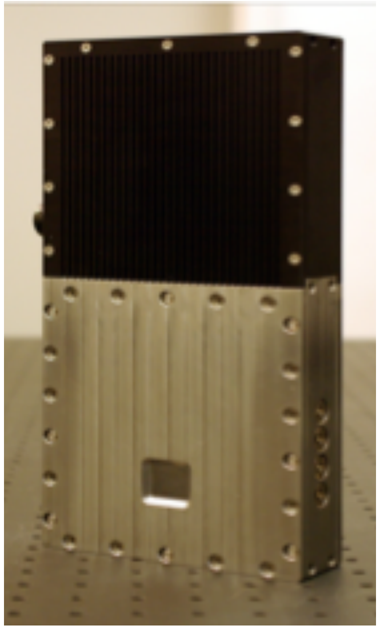
/3.65 *3.65 *2.35

High-speed spectroscopic detectors: Maia (BNL - CSIRO)





Energy resolution	~270 eV (2 μs) / ~350 eV (0.5 μs) – at 6 keV
Count rate	~30 k (2 μs) / ~100 k (0.5 μs) – per pixel
Element	384
Area	3.84 cm^2



Large solid angle (1.2sr) and real-time processor

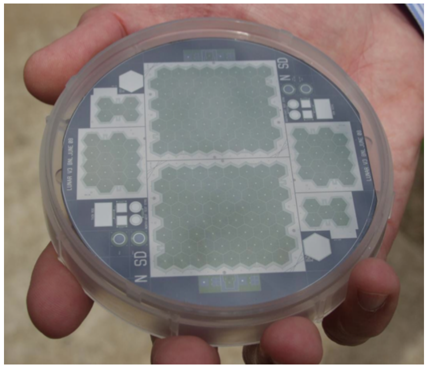
Photon event (Peak height, Time-over-Threshold, detector number)

FPGA performs high-speed computation (Dynamic Analysis for deconvolution) and generates elemental maps (photon-by-photon) in real time

Obvious future path with SDDs

Can hybrid pixel array detectors play a role?

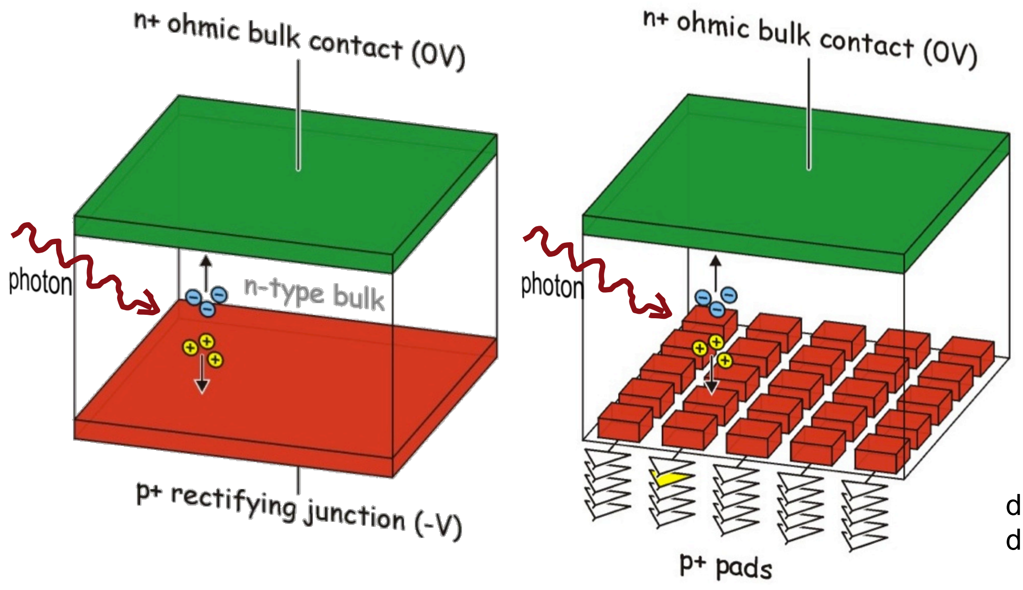
HEXID (Hyperspectral Energy-resolving X-ray Imaging Detector, BNL) - Other low noise detectors (e.g. ePix100, Moench)



Rehak *et al*., Nucl. Inst. Meth. A624 (2010) 260

Silicon: time and spatial resolution

Initial charge cloud generated by the photoelectric – delta electron is very small <<1um



$\sigma=\sqrt{2Dt}$

sigma of charge cloud due to diffusion

$D=\mu KT/e$

diffusion coefficient

$t=d/v$

drift time trough the detector bulk

$v=\mu E$

drift velocity

$E=V/d$

electric field

Diffusion is often the dominant effect

for 200V ca. 10ns drift time and 8.5um sigma
95% of the generated charge confined within a cloud of 34um diameter
(assuming generation at one side of 500um detector and collection at the other side)

In reality the charge collection is often much slower,
especially when big amounts of charge are generated at once (like at FELs)

Small pixel size and fast readout

Medipix/Timepix based detectors:

55 um x 55 um pixel size, 256 x256 pixel per chip

- Maxipix (ESRF) – 320kpixel / 1400 frames/s, 290 us readout dead time
- EXCALIBUR (Diamond and RAL STFC) – 3Mpixel / 1000 frames/s
- Lambda (DESY) – 768kpixel / 750 frames/s (2000 frames/s under development) no readout dead time

etc.

Good spatial resolution + low noise = better spatial resolution

At single photon rates interpolation may give 1 um position resolution
Spectral information can be available by summing cluster charges

So far scientific CCDs (e.g. pnCCD-MPI/HLL, fCCD -LBNL)

Now low noise integrating pixel array detectors are being developed: ePix 100 (SLAC) and Moench (PSI)

ePix 100

50 um x 50 um pixel, low noise (<50 e^- - MEASURED!) up to 1000 frames / s

Fixed gain - 100 8 keV photon

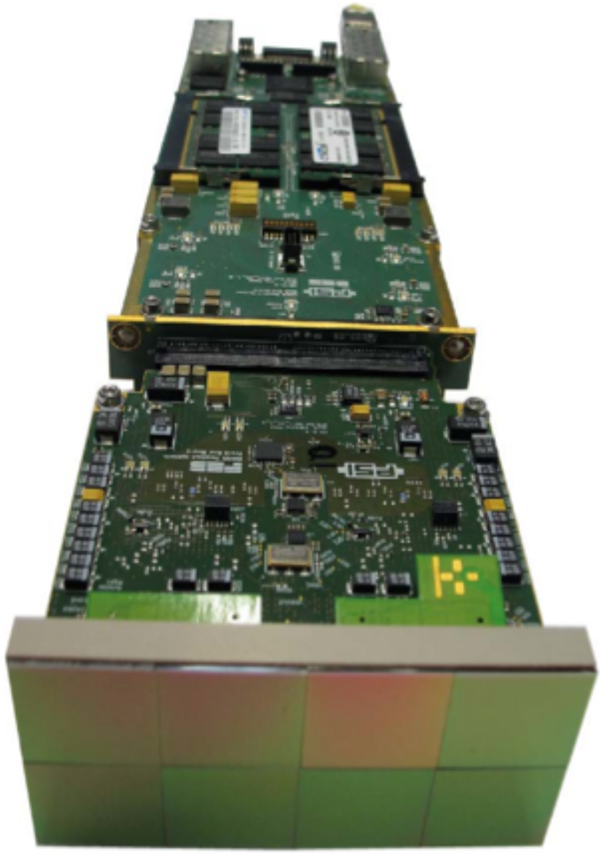
MOENCH

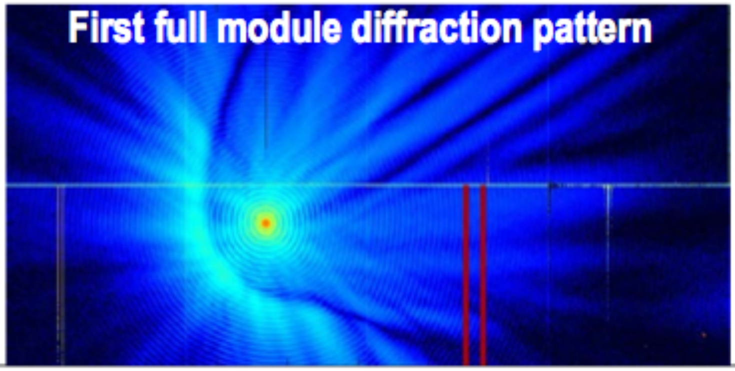
25um x 25um pixel, low noise (goal to achieve < 40 e^- - not there yet)

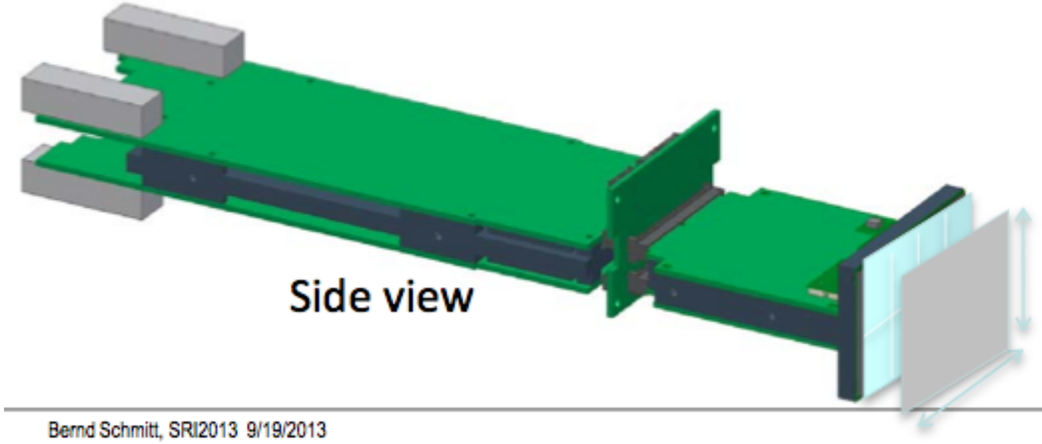
Different implementation with fixed gain and gain switching - from 15 12 keV photons up to 600 12 keV photons

Eiger, the next generation pixel detector

- Single photon counting pixel detector
- Sensitive area of 38 X 77 mm^2
- Pixel size 75 μm
- 524k pixel module
- Dead time free mode of operation
- Maximum frame rates
  - 23 kHz in 4 bit mode
  - 12 kHz in 8 bit mode
  - 8 kHz in 12 bit mode
- 8 GB of memory on a module
- Two 10 GbE data links per module

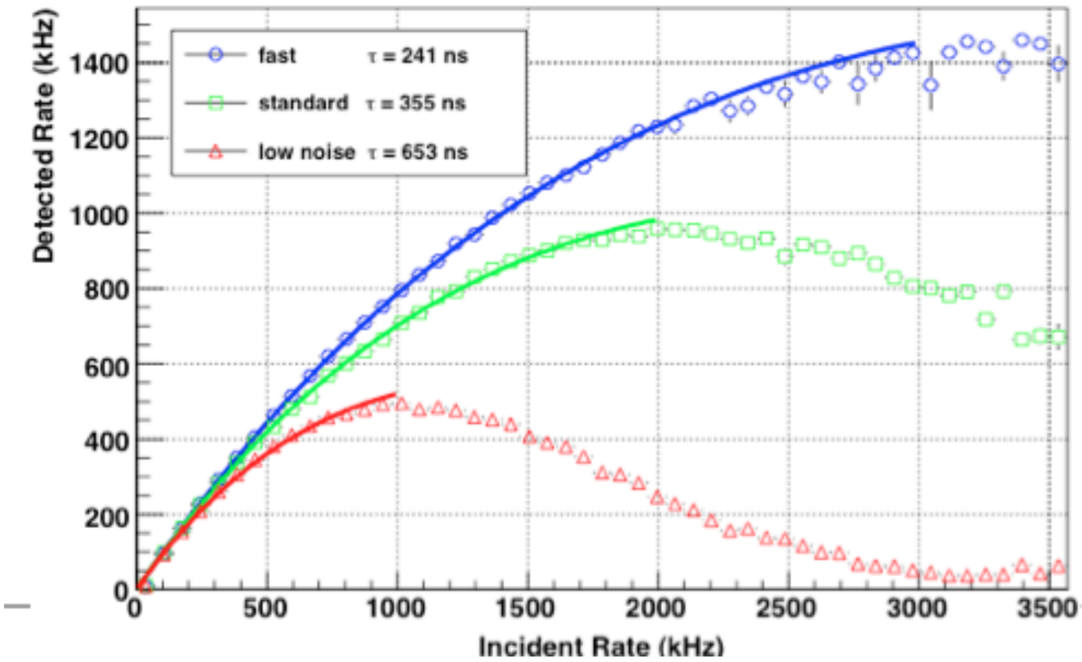


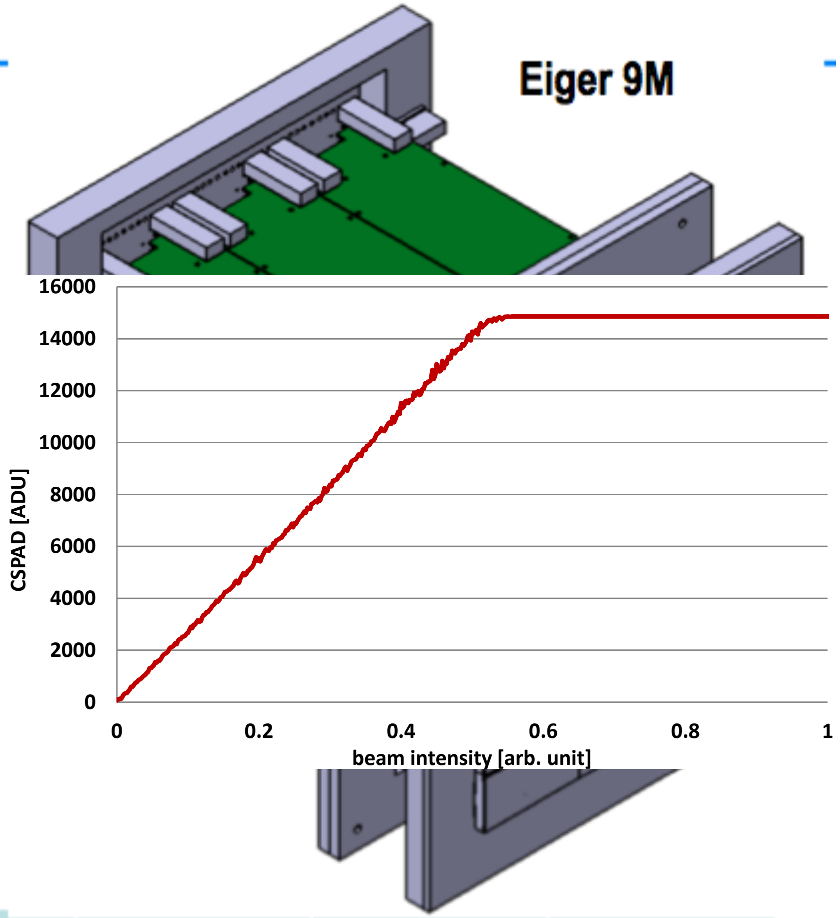

First full module diffraction pattern


Side view

Eiger systems

500k single module





	Number of pixels	On board storage (frames/4 bits)	Data rate[1] @ 12 kHz	Data rate[2] @ 1kH	Data rate[3] @ 100 Hz	Data rate[4] @ 10 Hz
Module	524 k (512 x 1024)	~32,740	50.3 Gb/s	6.29 Gb/s*	839 Mb/s*	168 Mb/s*
9M Detector	9.44 M (3072x3072)	~32,740	906 Gb/s	113 Gb/s	15.1 Gb/s*	3.02 Gb/s*

1) 8 bit, equivalent to ~4@23 kHz and 12@8 kHz. 2) 12 bit. 3) 16 bit. 4) 32 bit. *) Foreseeable continuous storage rates (~20 Gb/s).

Dynamic range: the gain game?

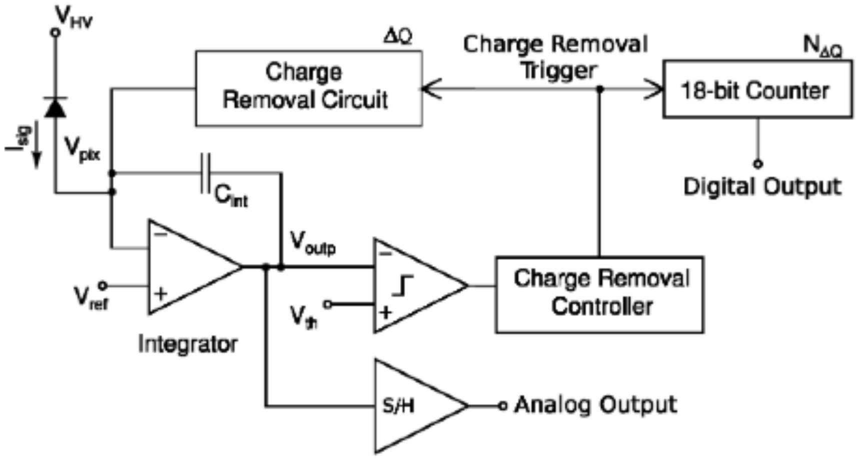
MMPAD: range extension

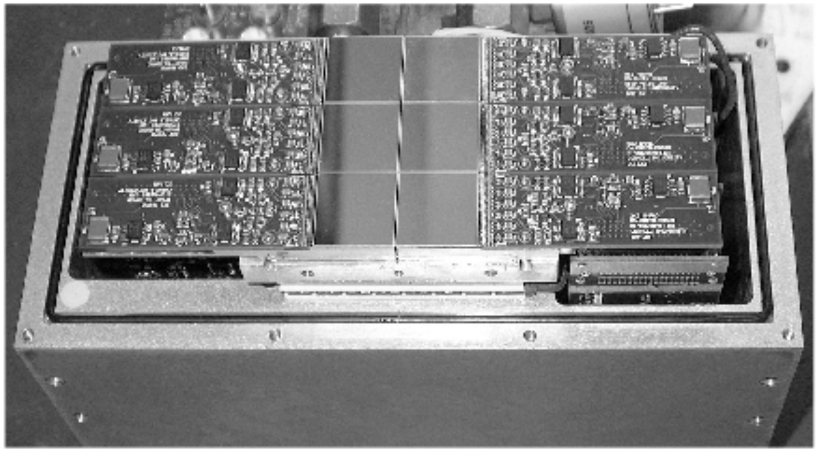
AGIPD, JUNGFRAU, ePix 10k: gain switching

LPD: multiple gains

Mixed-Mode Pixel Array Detector (MMPAD)

Cornell University and Area Detector System Corporation





150 um x 150 um, up to 200 photons arriving simultaneously, up to 4.7 10 ^{7} 8keV full well, 0. 86 ms read time, > 400 e$^-$ noise, up to 1100 Hz (computer memory) and 200 Hz for continuous storage to disk.

M. Tate *et al.* Journal of Physics: Conference Series **425** (2013) 062004

Dynamic range: the gain game?

MMPAD, AGIPD, LPD, JUNGFRAU, ePix 10k, etc.

JUNGFRAU (PSI)

3 gains automatic switching

10^4 12 keV photons

75 um x 75 um pixel (4 cm x 8 cm sensor)

2000 frames/s

120 e^- noise

B. Schmitt – SRI 2013

Dynamic range: the gain game?

AGIPD (DESY, University of Hamburg, University of Bonn and PSI)

3 gains automatic switching

10^4 12.4 keV photons

200 um x 200 um pixel

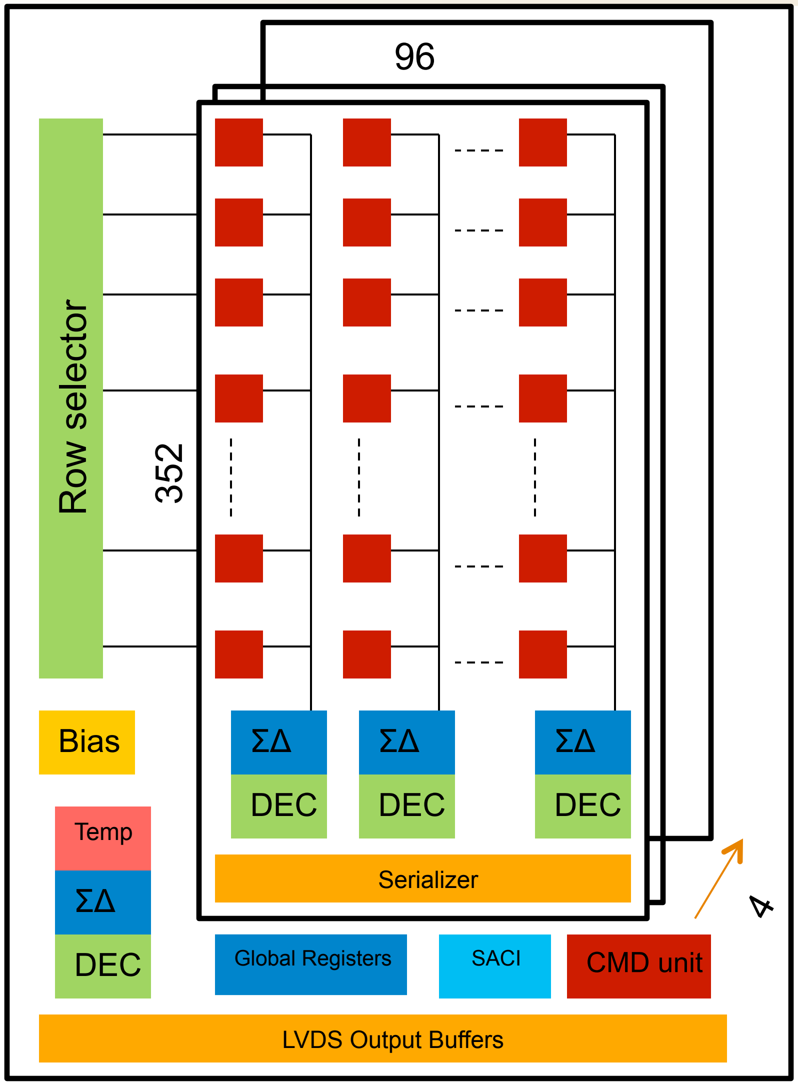
352 image storage at 4.5 MHz

readout and digitization in 99.4 ms

noise estimated better than 400 e^- in a 64 x 64 pixel

J. Becker *et al.* arXiv:1303.2523 2013

ePix 10K (SLAC)



	ePix100	**ePix10k**
Mode of Operation	INT	INT-with Auto-ranging
Technology	0.25 µm	0.25 µm
Pixel size	50x50 µm^2	100x100 µm^2
Array	352x384	176x192
Full Size	Full Reticule	Full Reticule
Frame rate	120Hz (480Hz)	120Hz (960Hz)
Range	220ke$^-$	22Me$^-$
Effective ENC	<100e$^-$ (50e$^-$)	<350e$^-$ (120e$^-$)
FE Gain	6.5µV/e$^-$	6.5µV/e$^-$,64nV/e$^-$
Polarity	positive	positive
Filtering	LP + cds	LP + cds
Required ADC res	14 bits	14 bits
S/N	44	8.8
Supply	2.5V	2.5V
DC Power cons.	< 15µW/pix	< 15µW/pix
Power pulsing	Yes	Yes
Rad Hard by Design	Enclosed layout only	Enclosed layout only

Pixel Matrix: fully analog. Different designs for each detector variants

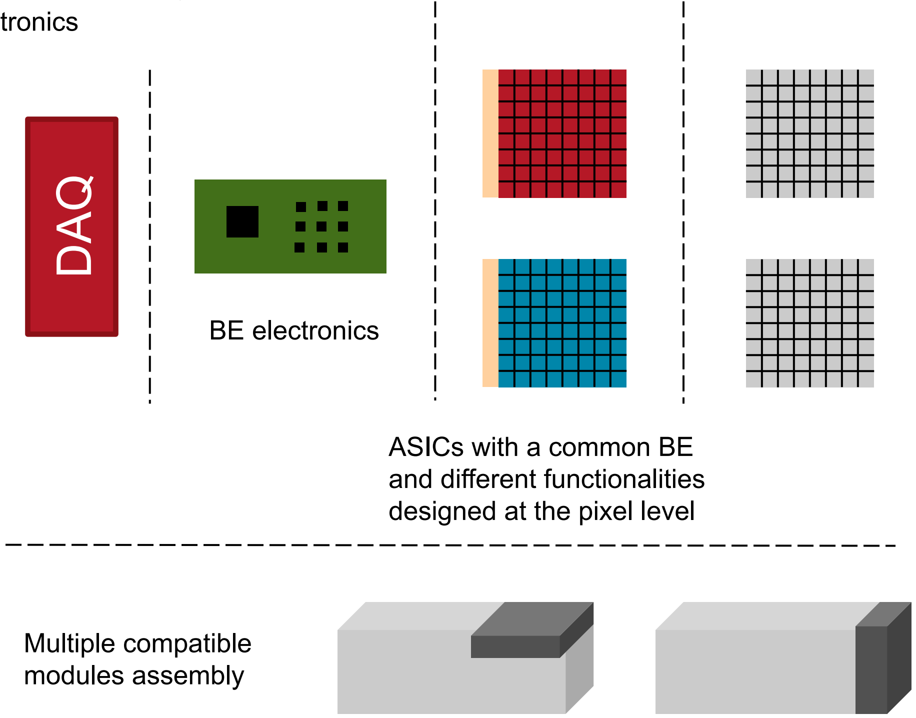
- Pre-amplifies signals
- Filters signals
- samples signals (with CDS)

Balcony (ePix platform):

- Controls Configuration
- Controls Acquisition and Readout
- Performs Analog to Digital Conversion
- Provides Calibration and Monitoring support

Modularity and scalability: SLAC approach

- Cameras require a top down design approach using common platforms.
- The platform is defined by standardized interfaces and communication protocols between the various components of the detector
- A minimum set of key components has multiple variants (ASIC and assemblies)



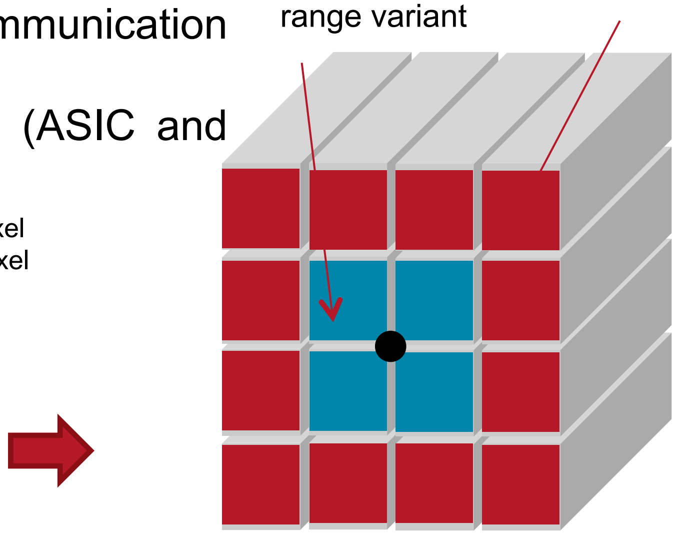
Standard communication protocol between DAQ and BE electronics

Standard configuration and communication protocol with minimum I/Os between ASIC and BE electronics.

Sensors with different pixel size to match different pixel implementations

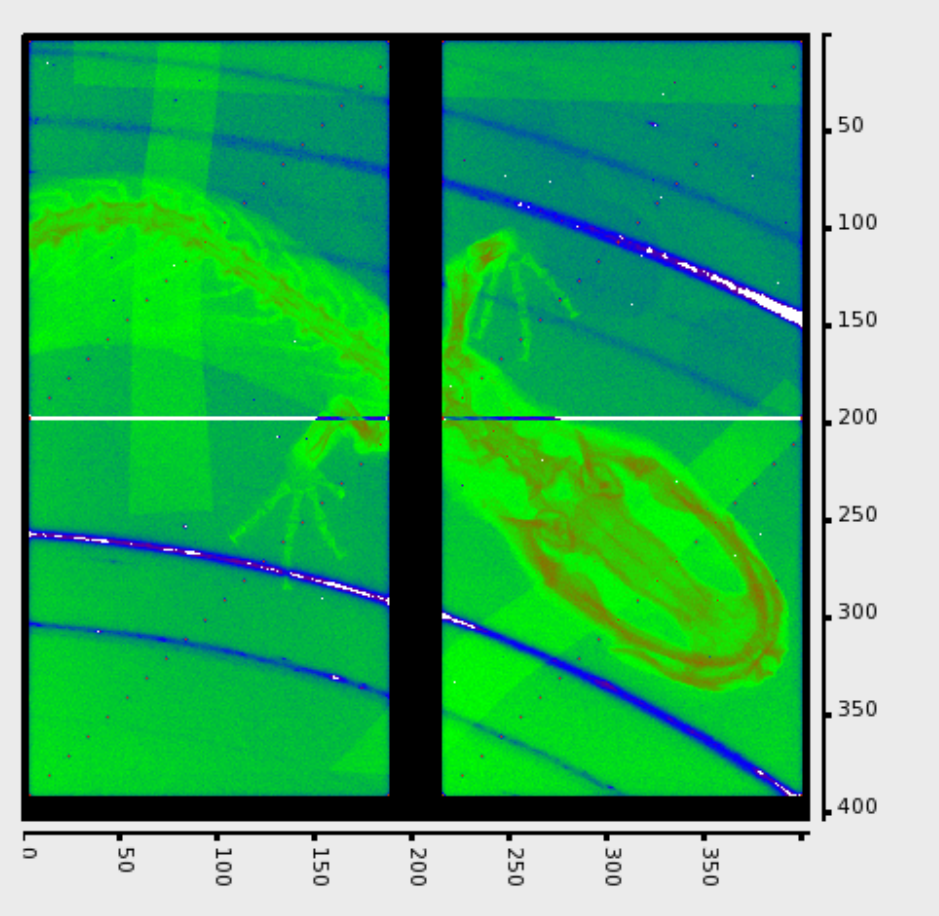
ASICs with a common BE and different functionalities designed at the pixel level

Multiple compatible modules assembly



- Several variants of ASIC/sensor combinations with a common communication BE up to the DAQ.
- Variants can be housed in several module assembly
- Facilitates integration of one or multiple detectors into a combined camera of various sizes and shapes (rectangular planes, curved arcs)
- Combinations can even include modules with different functionalities

Virtually unlimited



Combining single-photon counting with signal integration can reach larger dynamic ranges (CSPAD 140k)

How smart is smart enough?

Implementing some ‘sort of’ on-chip processing

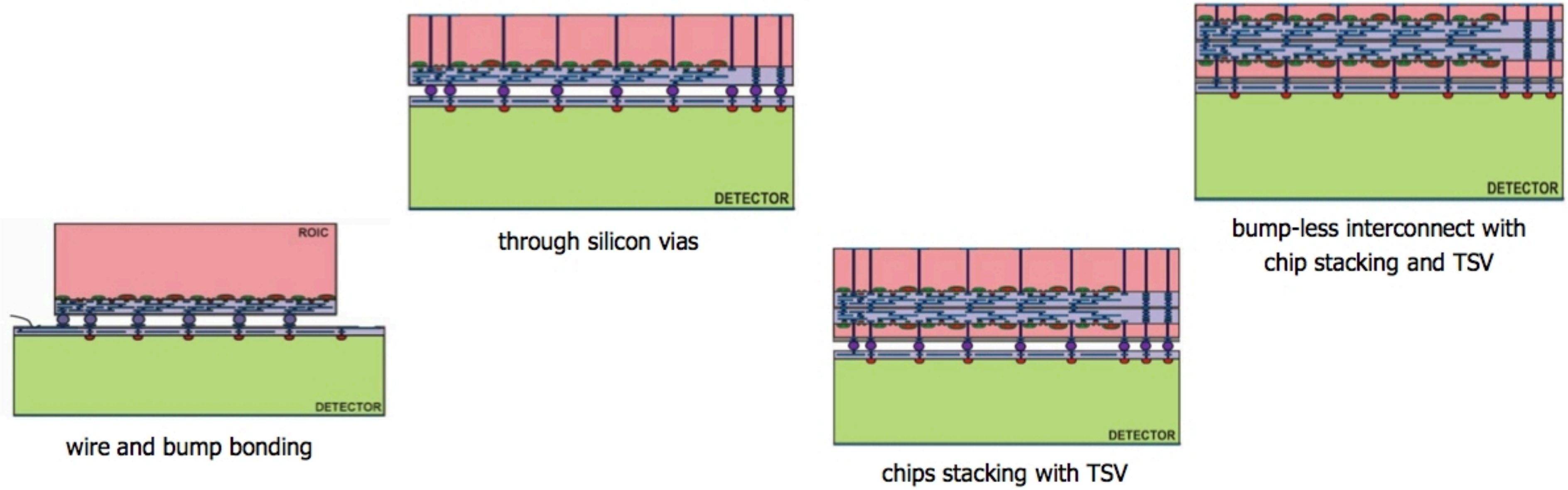
It requires **advanced interconnects techniques**:

- Increase number of transistor per pixel
- Enable heterogeneous integration
- Needed also for faster detectors
    - Higher I/O parallelization
    - Lower parasitic capacitance
    - Structured and hierarchical power distribution

Advanced interconnects

Interconnect techniques: from wire bonding to 3D.

In the recent past, a variety of wafer bonding techniques has found novel applications, particularly in the IC community, and are now attracting attention from the detector community as well.



wire and bump bonding

through silicon vias

chips stacking with TSV

bump-less interconnect with chip stacking and TSV

Interconnection schemes

Vertically Integrated Photon Imaging Chip

BNL – Fermilab (3D – IC consortium run)

Technology: 2 wafers with Cu-Cu thermocompresion BI by Tezzaron, **CHRT 130 nm** (6 metal layer) is supplemented by insertion of **TSV (6 um deep, min space 3.8 um)** after completion of FEOL

Geometry: 64 × 64 array of **80x80 μm2 pixels,** 5120 × 5120 μm2 active surface (Die size 5.5 × 6.3 mm2) **1st tier – analog part**, **2nd tier – digital part**,

Analog part: Architecture of single pixel: **CSA + shaper + discriminator** (trimming and testing options) Optimized for **8 keV X-ray** photons (up to 3 × 8 keV with Si detector), Shaping time **tp=250 ns, ENC <150 e-**, pwr ~**25 uW** / analog pixel

Digital part: Two modes of operation: 1) timed readout of hits acquired at low occupancy (**address and hit count, 10 μs frame readout time**) 2) **imaging** (two 5 bit-long counters / pixel accumulates hits occuring in each time slot, readout uses sparsification mechanism but no readout of addresses) **Dead timeless operation** (operation divided into time slots: hits arriving in time Δtn-1 are read out in Δtn while simultaneously new hits are being acquired in time Δtn). **Sparsified data readout** based on priority encoder circuit (binary tree) with automatic binary-coded generation of hit pixel addresses. **Hit pixel address readout only**.

VIPIC sees x-rays

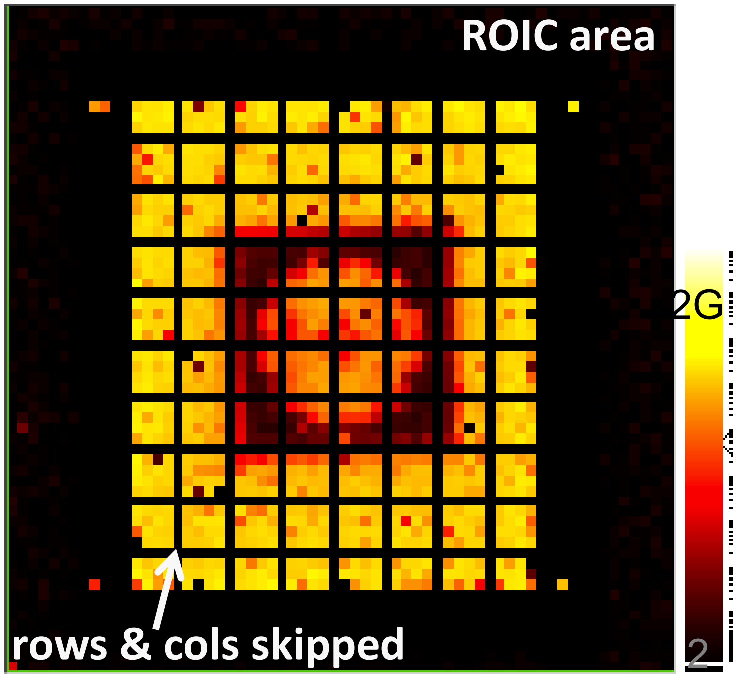


Fig. 5. Transmission radiogram of a small W mask (2.5×2.5 mm^2) placed atop of the sensor back-side illuminated and fully depleted.

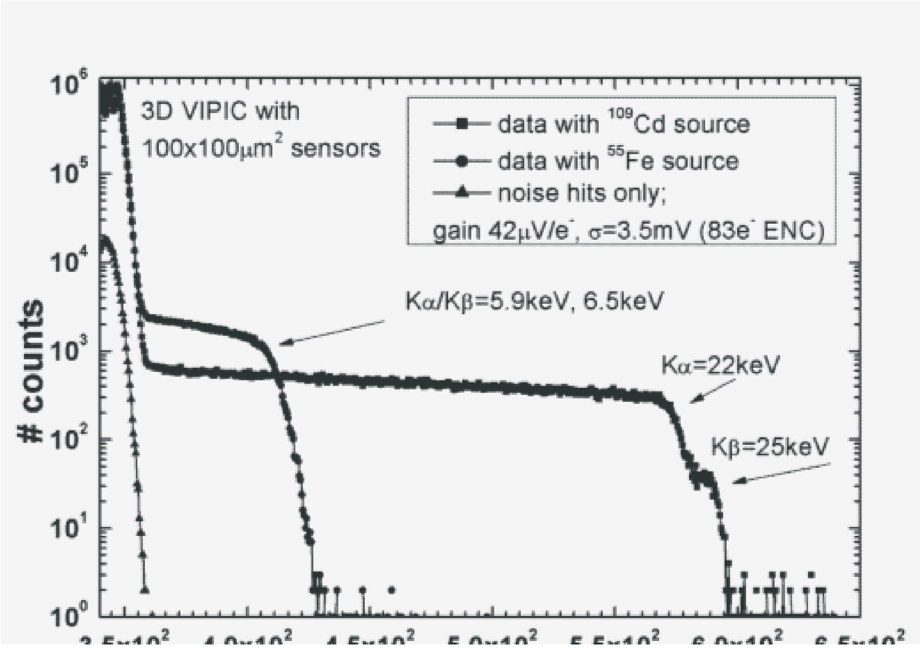


Fig. 6. Selected results of the threshold scans for a single pixel with no source and flat field exposures using ^{109}Cd, ^{55}Fe sources.

G. Deptuch *et al.* accepted for publication IEEE TNS

CMOS imagers

SOPHIAS (Riken, Japan)

Fully-Depleted SOI, 5.5-7keV, 30 um x 30 um, 1.92 Mpixel,100 e- (~1 keV), 7Me$^-$ maximum signal, 60 Hz (multiple gain)

T. Hatsui, International Image Sensor Workshop (IISW), Snowbird, Utah, USA, June 12-16, 2013.

PERCIVAL (RAL, DESY and Elettra)

back-thinned to access its primary energy range of 0.25-1 keV, 25 um x 25 um, 16 Mpixel, single-photon, 1 to ~ 10^5 (500eV), 120 Hz (gain switching)

http://photon-science.desy.de/research/technical_groups/detectors/projects/percival/index_eng.html

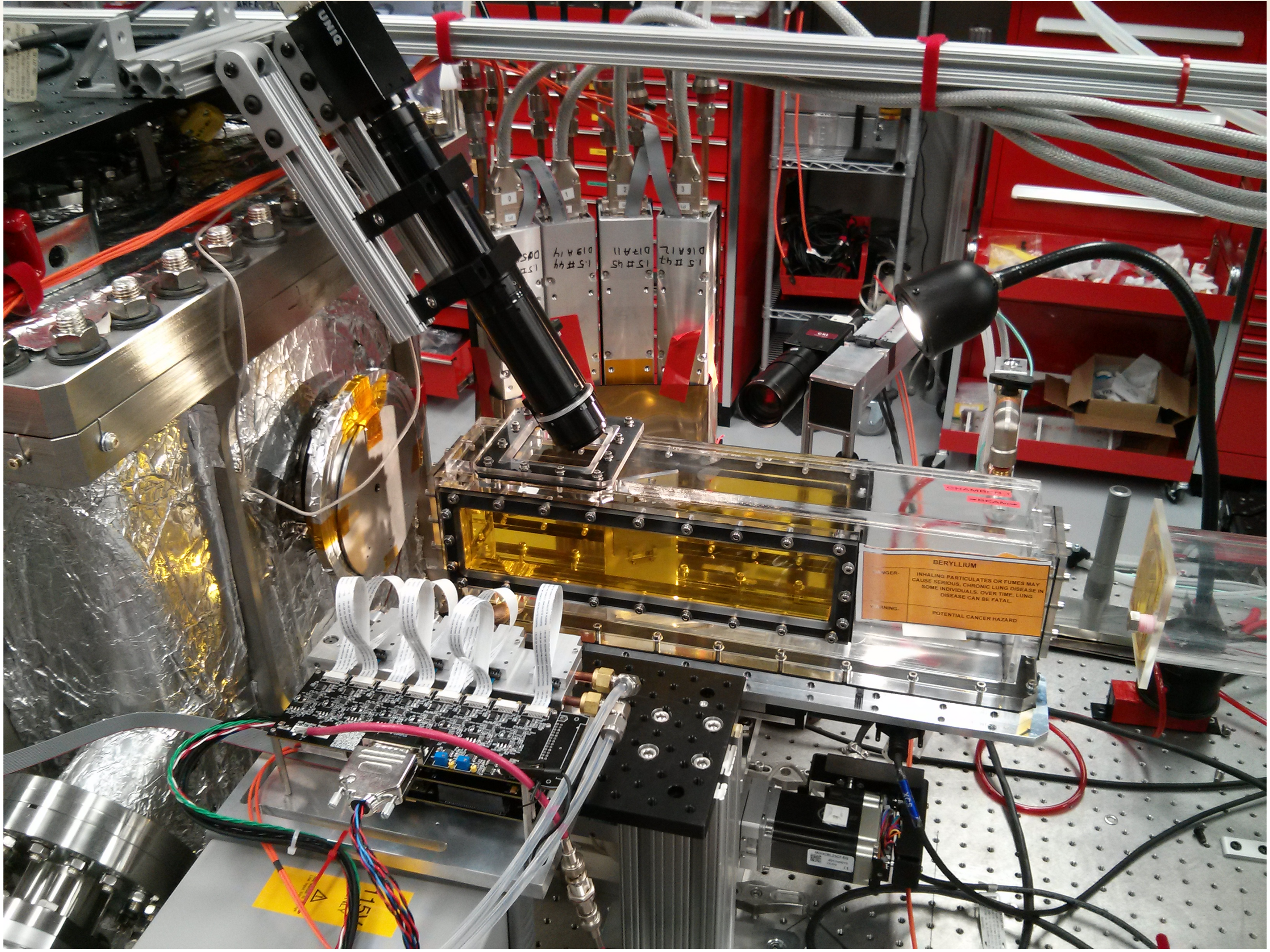
A few things to keep in mind

- low detector capacitance is important for noise performance
- low noise performance needs lots of power
- high speed per channel kills the noise performance

- high dynamic range, many pixels and high framerates push on the Information Generation Rate (IGR)
  - for a given technology there is a practical limit on the IGR in a given area !
  - high IGR densities are more prone to crosstalk problems
  - if one demands to much one has to do R&D to push the FOM in our field
  - there might be some room to push on thermo-mechanical packaging to harvest improvements

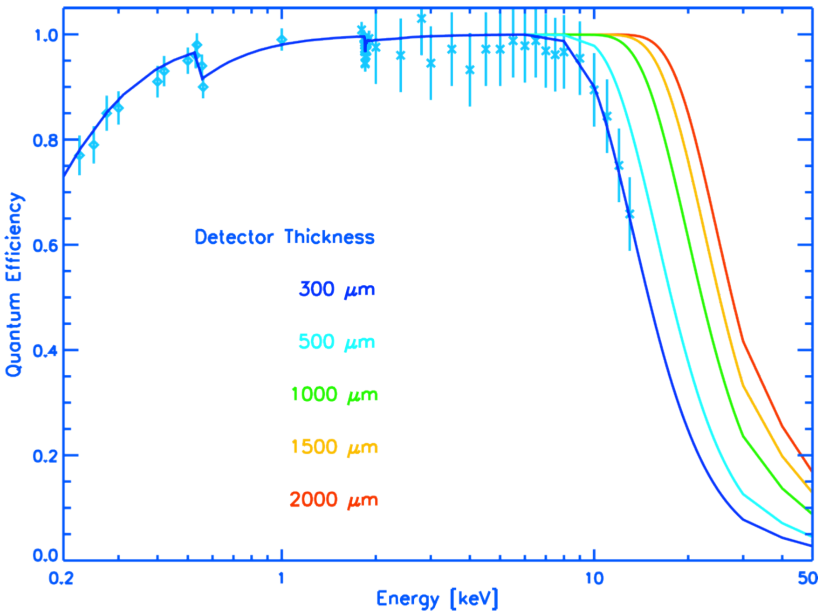
Gapless: WidePIX (IEAP CTU Prague) – 6.5Mpixel / edgeless (VTT/ Advacam)
TSV : Medipix3 – Leti (CEA, France)

Another type of high density



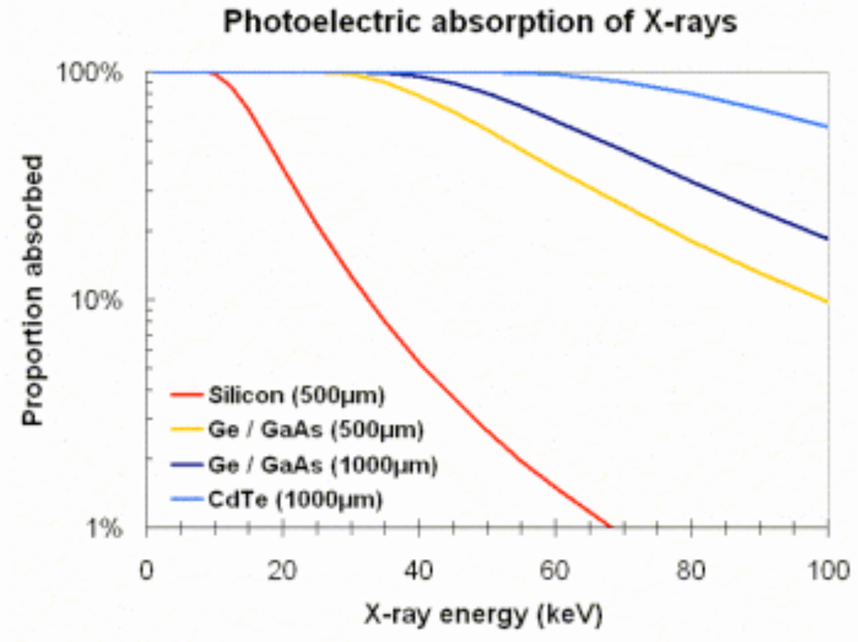
Silicon limitation – other sensor materials

Thicker silicon sensors



From: J. Treis, MPI, Pixel 2008

Other semiconductors for direct detection



http://hasylab.desy.de/instrumentation/detectors/e74464/e106206/index_eng.html

- *Small improvement*
- *High depletion voltage*
- *Parallax*

- *Germanium (‚faster than Si‘)*
- *GaAs (‚faster than Si‘)*
- *CdTe, CdZnTe*

Ge, GaAs, CdTe and CdZnTe

Material	Si	Ge	CdTe	$Cd_{1-x}Zn_xTe$ (x=10%)	GaAs
Atomic number	14	32	48, 52	48, 30, 52	31,33
Density [g/cm^3]	2.33	5.33	6.20	5.78	5.32
Bandgap [eV]	1.12	0.67	1.44	1.6	1.43
Pair creation energy [eV]	3.6	2.9	4.43	4.6	4.2
$\mu_e\tau_e$ [cm^2/V]	>1	>1	10^{-3}	10^{-3}-10^{-2}	10^{-5}
$\mu_h\tau_h$ [cm^2/V]	~1	>1	10^{-4}	10^{-5}	10^{-6}
Resistivity [Ωcm]	10^4	50	10^9	10^{10}	10^7

Material	Si	Ge	CdTe	$Cd_{1-x}Zn_xTe$ (x=10%)	GaAs
Pair creation energy [eV]	3.6	2.9	4.43	4.6	4.2
Fano Factor	0.115	0.13	0.11	0.089	0.10
Standard deviation [eV] (@ 20keV)	~ 91	~ 87	~ 99	~ 91	~ 92
FWHM [eV] (@ 20keV)	~ 213	~ 204	~ 232	~ 213	~ 215

- Ongoing effort in Europe: Within ‘high-Z’ framework; Some detectors with CdTe (Pixirad, Medipix); Attempts also with GaAs and Ge (DESY)
- Still some material and technological limitations

DOE – BES Detector workshop

Agenda:

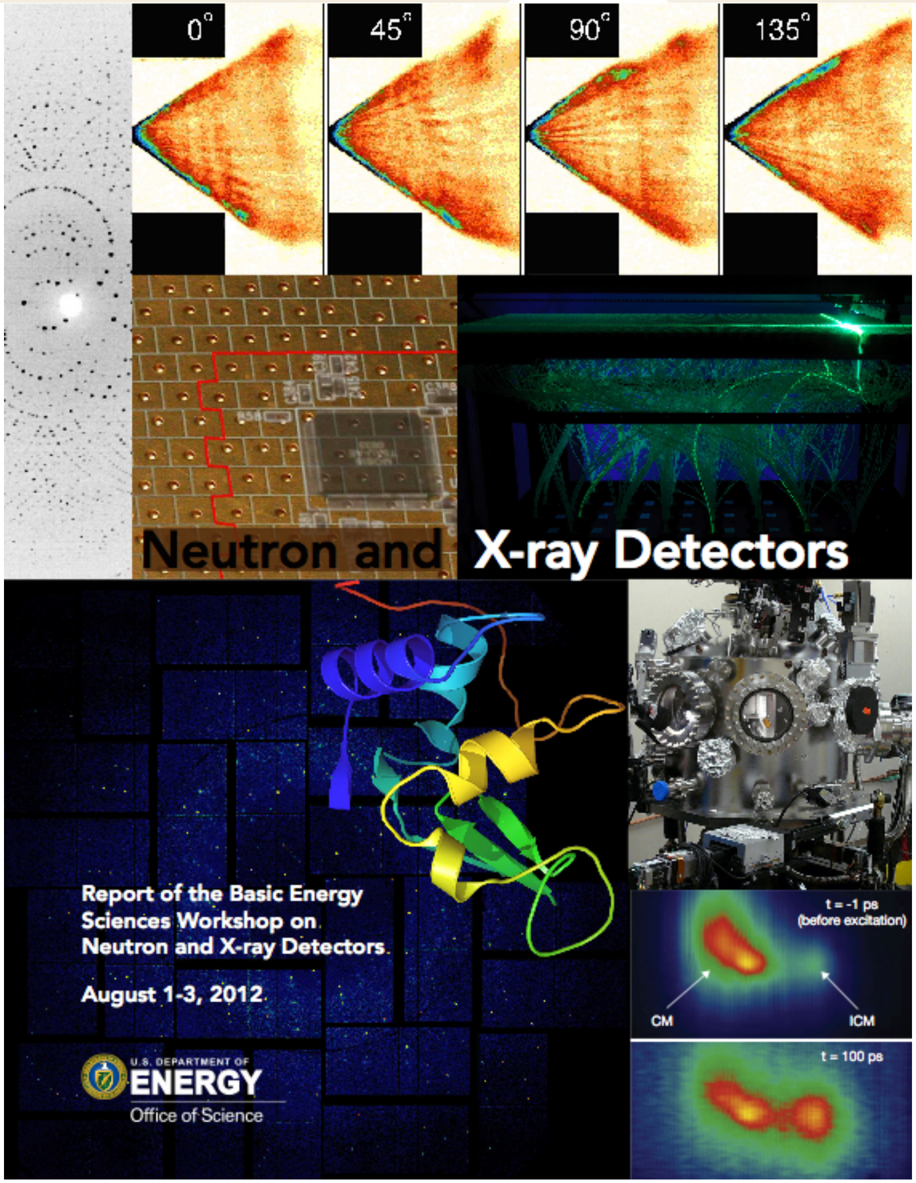
http://www.orau.gov/detector2012/

Report:

http://science.energy.gov/~/media/bes/pdf/reports/files/NXD_rpt_print.pdf

Presentations:

https://portal.slac.stanford.edu/sites/conf_public/nxd2012/Pages/default.aspx



Neutron and X-ray Detectors

Report of the Basic Energy Sciences Workshop on Neutron and X-ray Detectors

August 1-3, 2012

U.S. DEPARTMENT OF ENERGY
Office of Science