Spectroscopic Multi-element Ge Detectors: Status

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BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science U.S. DEPARTMENT OF ENERGY

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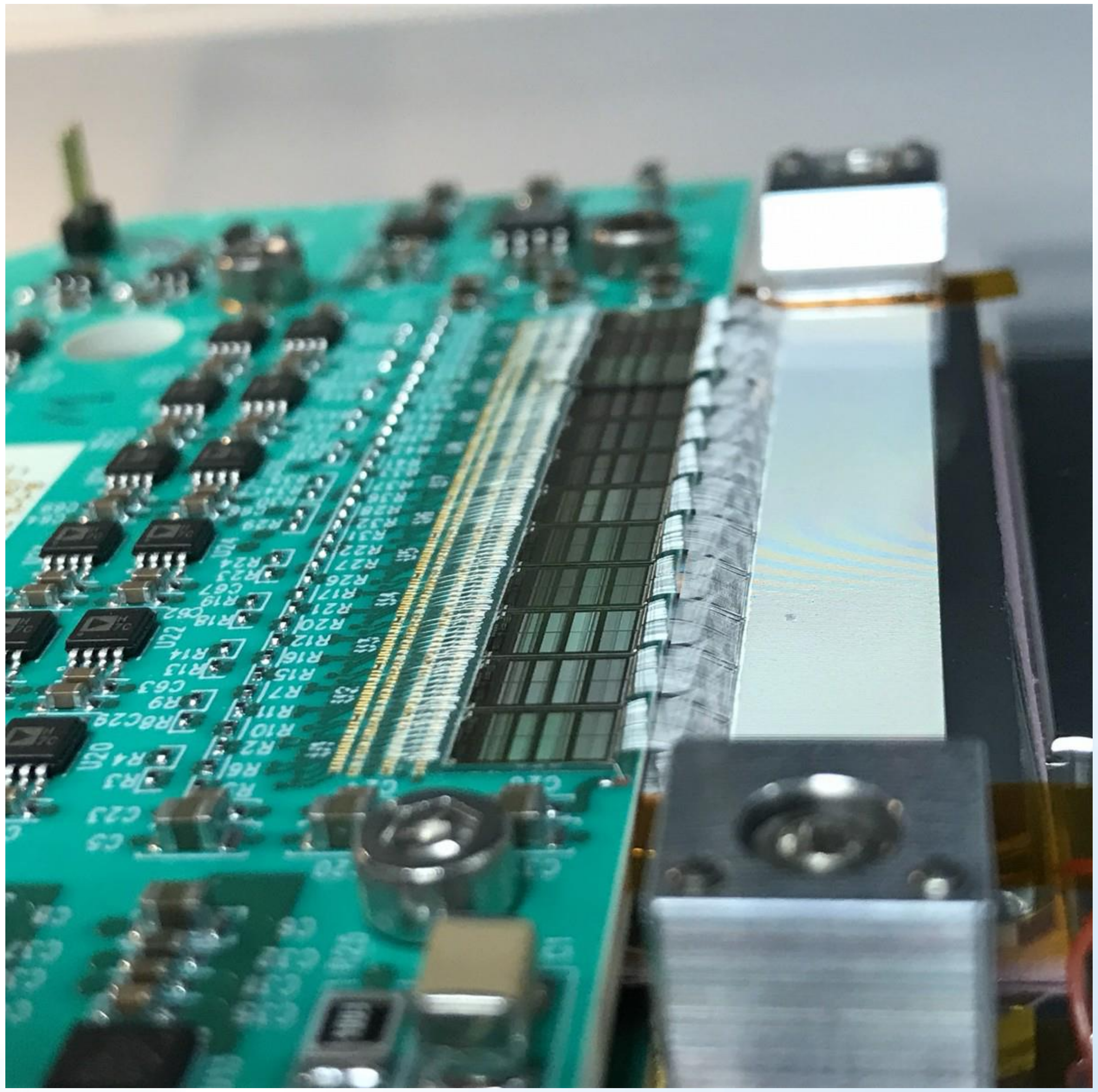
Outline

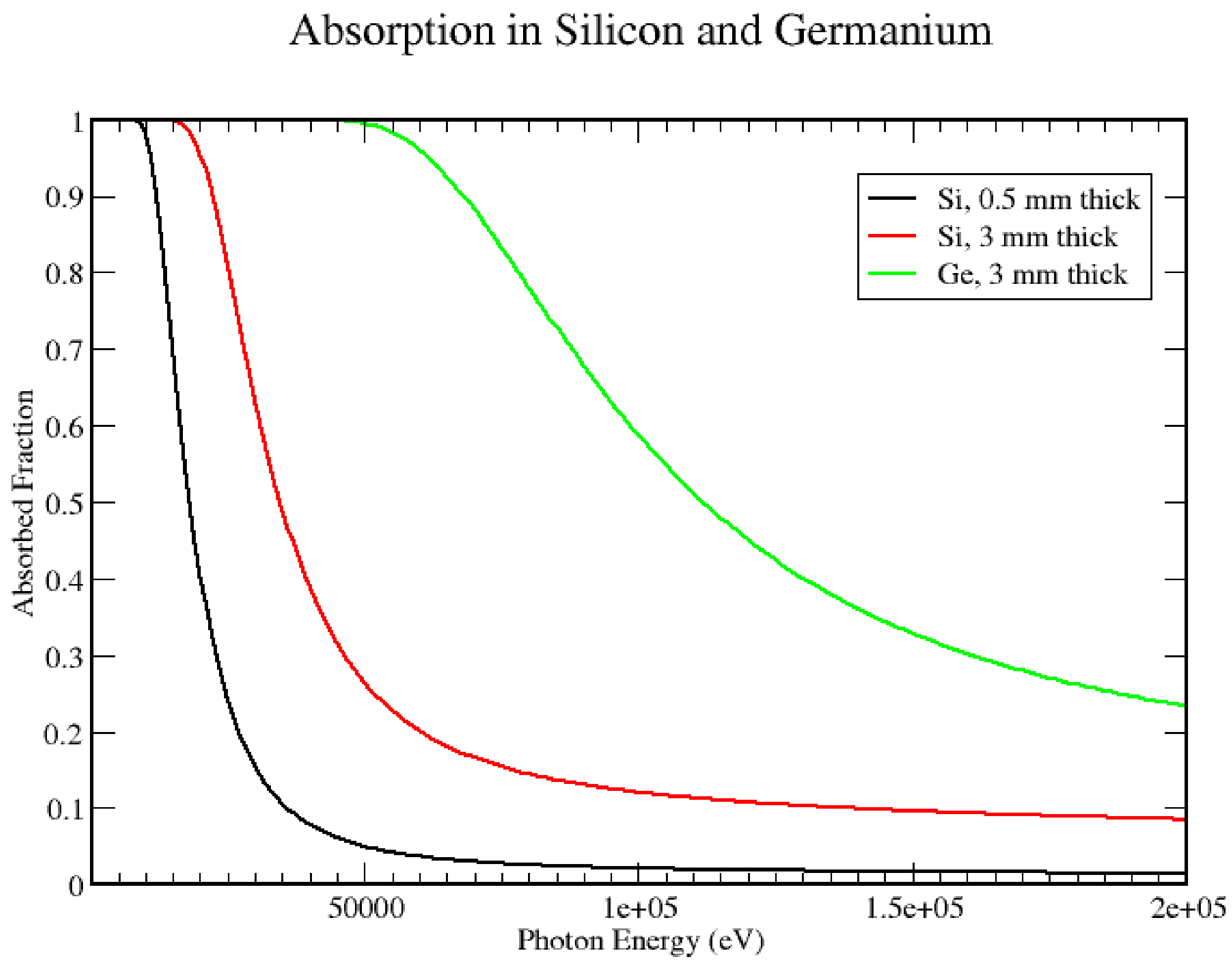
- ➢ Why Germanium
- ➢ Detector System
  - ✓ Sensor
  - ✓ ASIC (MARS)
  - ✓ Readout electronics (GeRM)
- ➢ Ge Detector at APS:
  - 64-strip
  - 192- strip
- ➢ Ge detector at NSLS II
  - 384-strip at XPD



Why Germanium?

High-quality/detector grade wafers commercially available
-Fully depleted sensors with few mm thick wafer at modest depletion voltages possible

High Z gives good efficiency at high energies



Germanium properties

- Band gap is much smaller than silicon
- More charge per photon -> better resolution
- More leakage current at room temperature -> need to be cryo-cooled for detector applications.
- Old technology; large crystals, thermally diffused junctions − detectors tiled.

How does it compare with other high z material

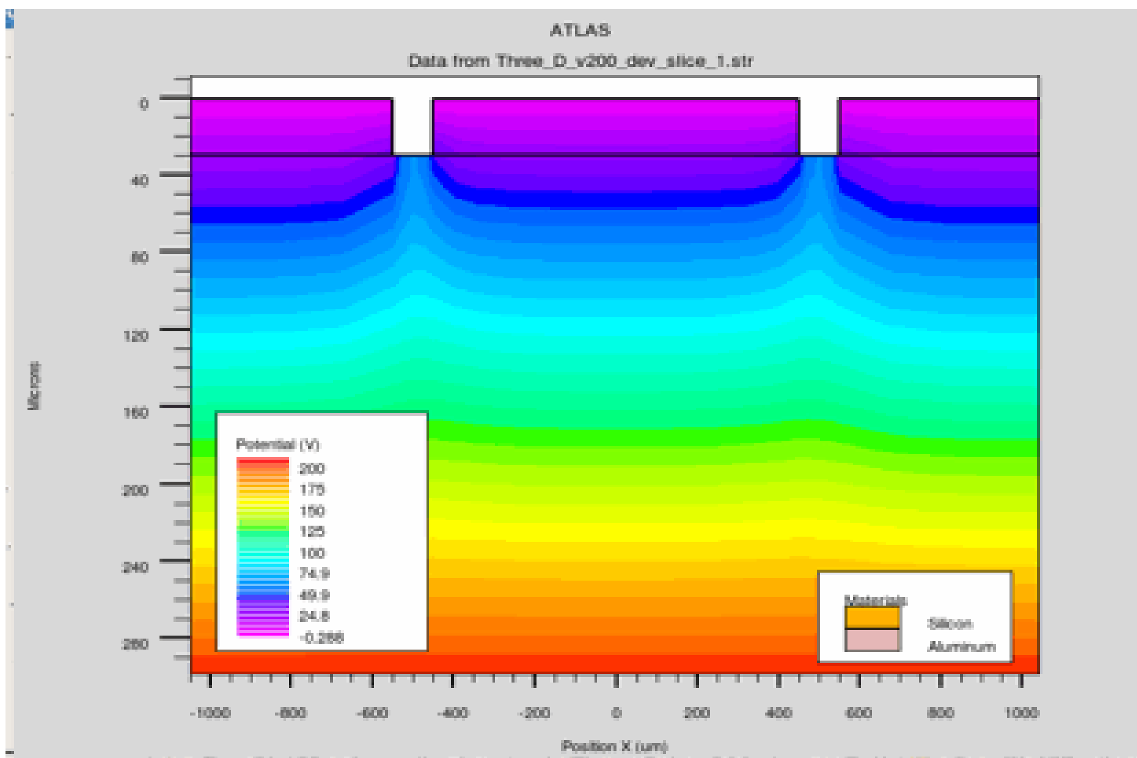
Semi-conductor	E_{gap} [eV]	μ_h / μ_e [cm^2/Vs]	ρ [Ω cm]	Density [g/cm^3]	Z	ε [eV]
Si	1.12	480 1350	2.3×10^5	2.33	14	3.6
Ge	0.67	1900 3900	47	5.33	32	2.9
CdTe	1.44	100 1100	1×10^9	5.85	48,52	4.43
CdZnTe	1.6	100 1000	5×10^{11}	5.81	48,30,52	4.6

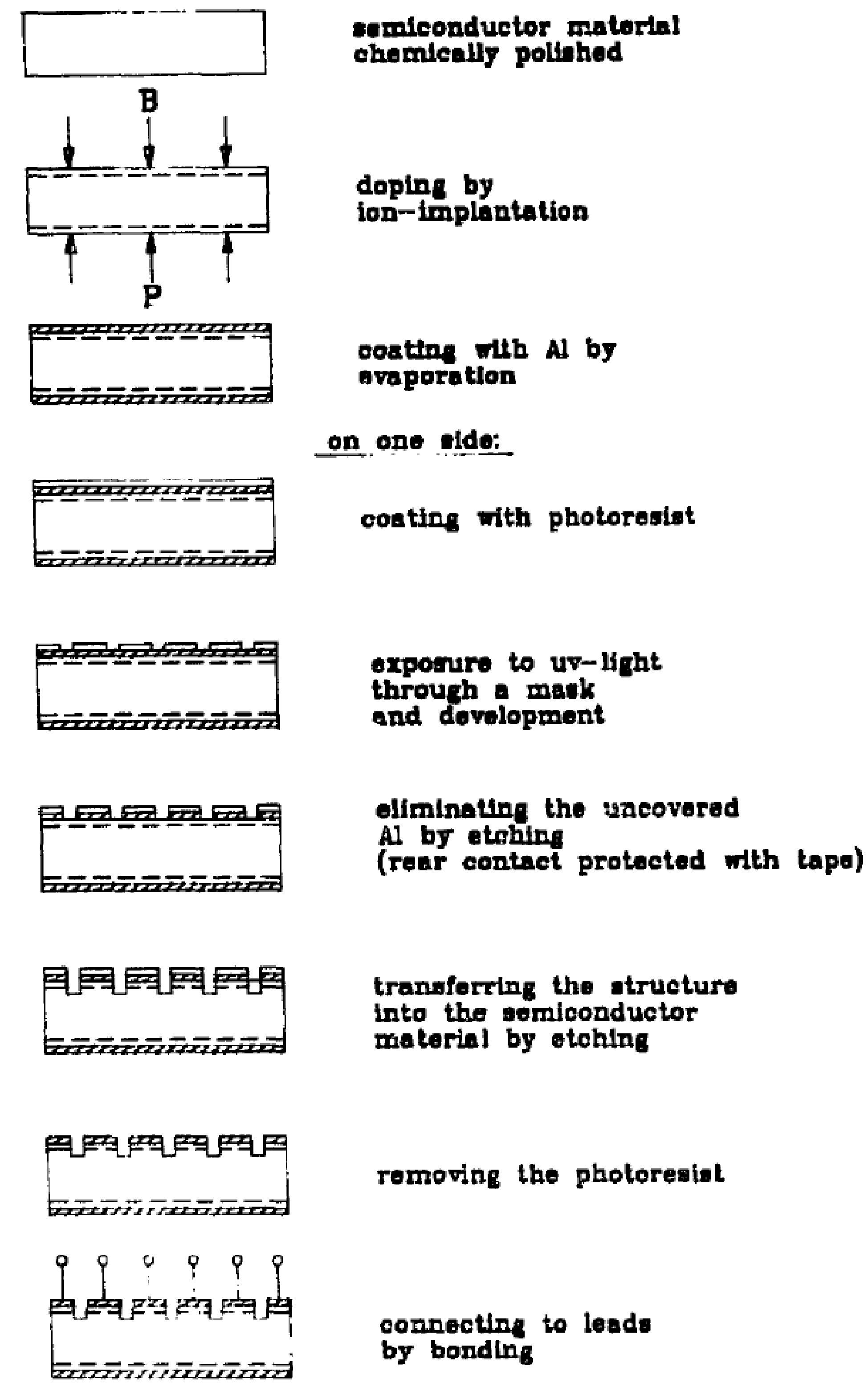
Wide Band Gap → Room Temperature
High Atomic Number → High Stopping Power

Monolithic Germanium Process Issues

- Technology not as mature as Si
- Key to devices (and detectors) are field oxides
- GeO_x is unstable (water-soluble, volatile), unlike SiO_2
- High K dielectrics are likely candidates
- Semiconductor industry is interested in Ge as high-speed deep submicron material

Isolation with trenches

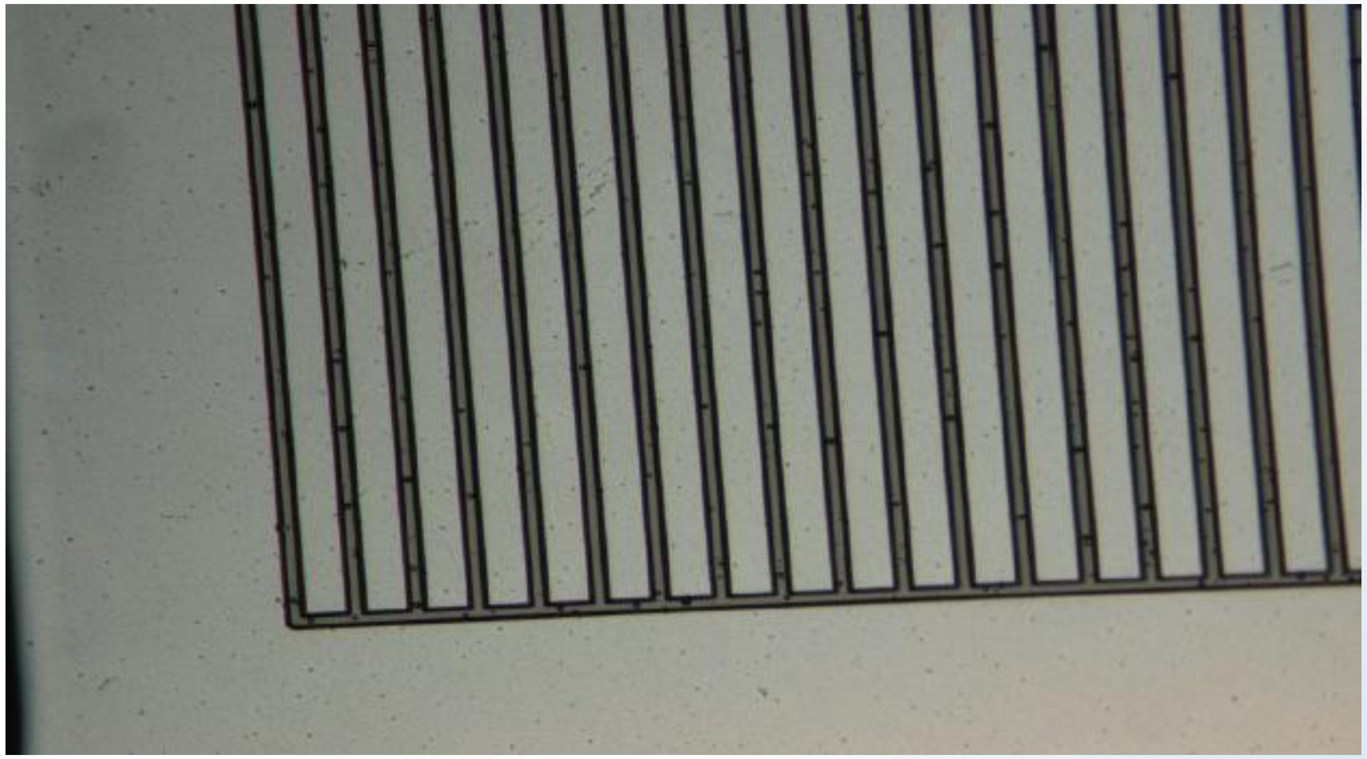




A.Hamacher et al. Nucl.Ins. Meth.Phys. Res. **A295**, 128 (1990)

Ge Sensor

- P-type layer formed by ion implantation.
- N-type contact formed by diffusion.
- Implanted layer formed into pixels by etching trenches between them.
- Pixels become electrically isolated upon full depletion.



ASIC: MARS, a new spectroscopy chip

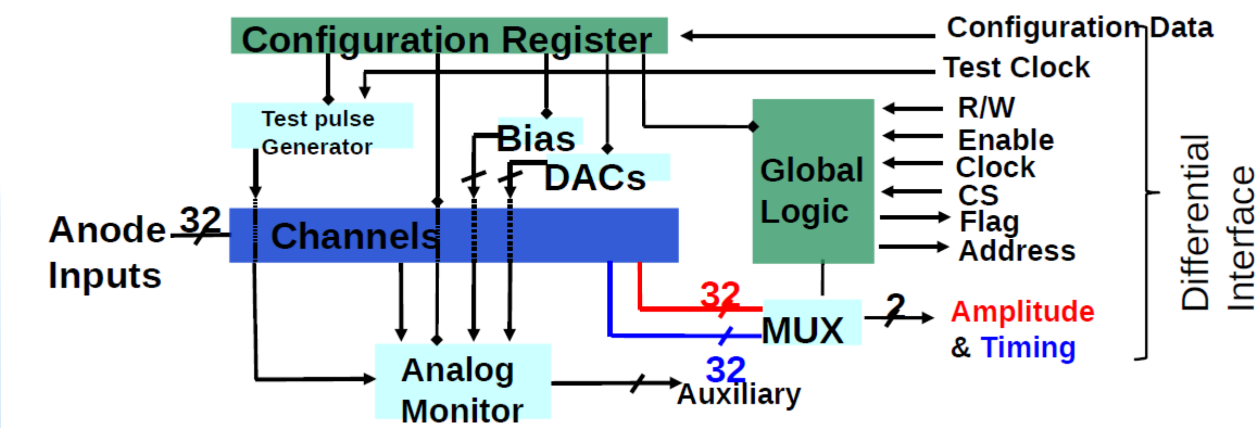
MARS has 32 low-noise channels, each with its own peak detector and timing circuitry

– Charge-sensitive preamplifier capable of reading electrons or holes, with 4 gain settings from 3600mV/fC to 600mV/fC (12.5keV – 75keV F.S.)

– Shaper with 4 time constants from 0.25 us to 2 us.

– Per-channel peak detector and timing generator. Timing generator can measure time-over-threshold (for pileup detection) or time-of-arrival (for detecting charge-shared events)

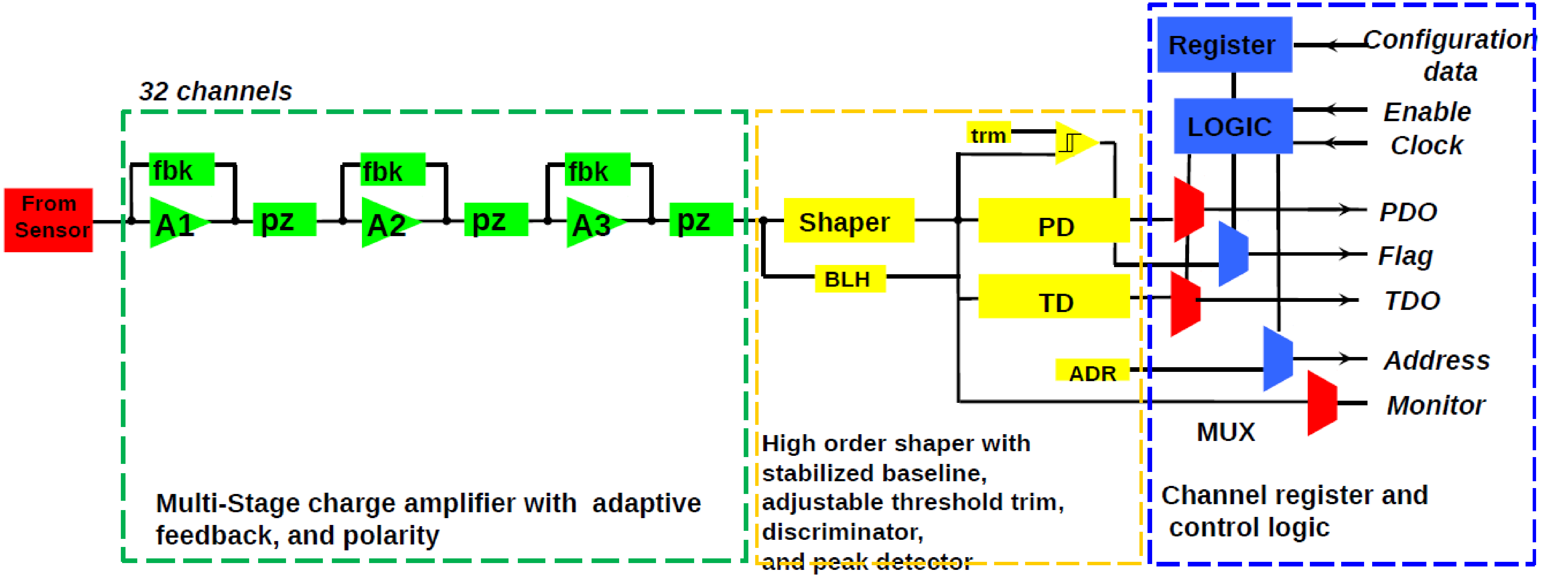
– All external signals are fully differential to preserve the system's low noise



32 readout channels

- Amplitude and timing measurement per channel
- LVDS interface, analog differential outputs
- Test pulse generator
- Multiplexed analog monitors

Channel Architecture



- Processes electrons or holes from photodiodes or SDDs
- Front-end optimized for 50 fF, DC coupling, adaptive to leakage (100 fA to 1nA)
- Gain: 0.6,1.2, 1.8, and 3.6 V/fC (60keV to 10keV full-scale)
- Peaking time: 0.25, 0.5, 1, and 2 μs (5th order complex conjugate poles)
- Peak detector and time-to-amplitude converter per channel
- 3.2 mW/channel

Readout electronics: GeRM

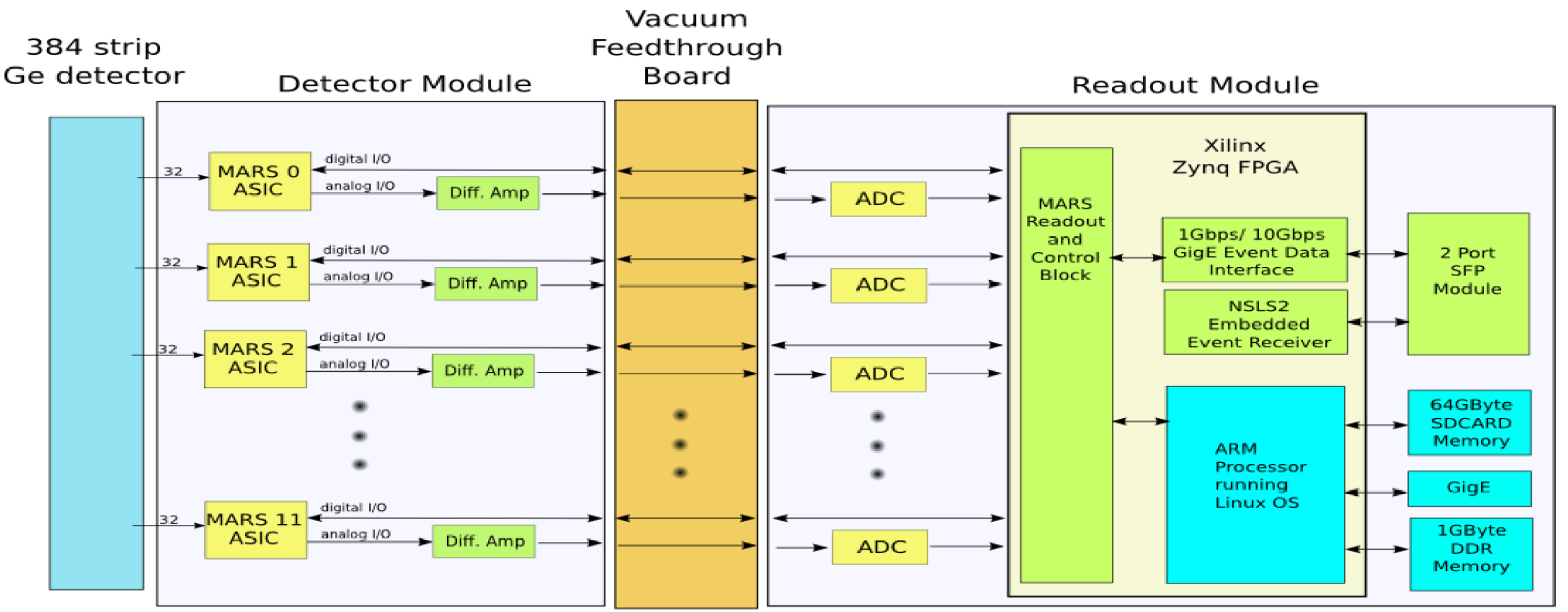
To read out these ASICs we have developed a toolkit based on an advanced FPGA series from Xilinx, the Zynq SOC.

We have two basic configurations

– A simple system based on a commercial Zynq system module, the Picozed. Due to I/O pin limitations, that system multiplexes the outputs from the ASICs, similar to the setup used in Maia. Three ASICs are read out by two ADCs (one each for amplitude and time).

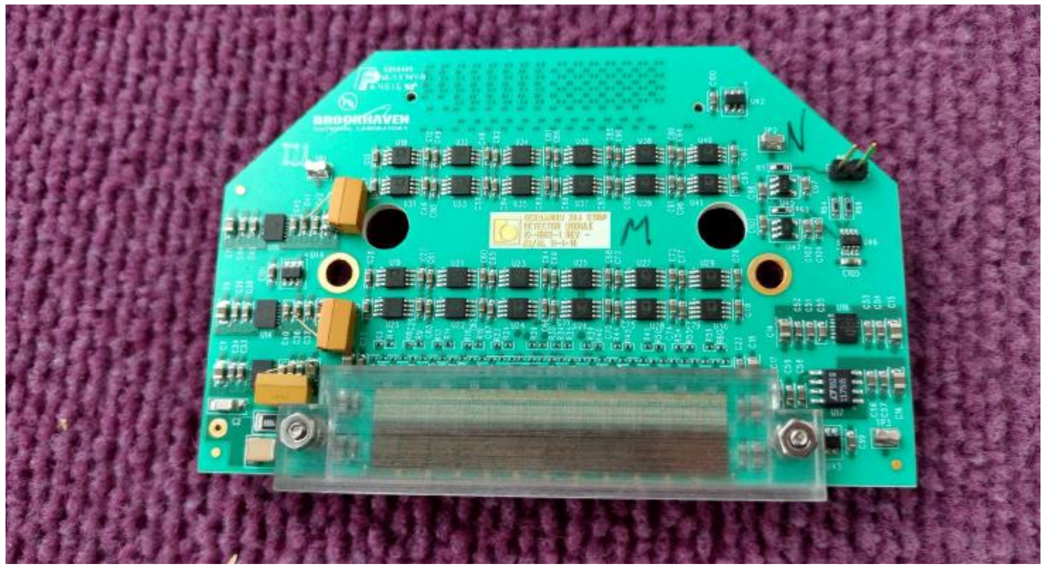
– An extended system which accepts outputs from up to 12 ASICs, each with a dedicated ADC pair, for a total of 24 ADC channels. This system was designed from scratch, and uses a larger FPGA.

GeRM Hardware Block Diagram



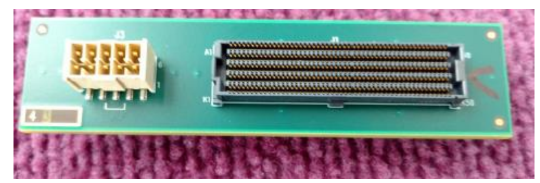
GeRM Hardware

Detector Module



- In Vacuum board, connects via 384 wire bonds to the Germanium Detector.
- 12 custom MARS (Multi-element Amplifier and Readout System) ASICs
- Each MARS ASIC handles 32 strips.
- Programmable threshold, with channel trims.
- Outputs the strip address plus Peak Detector (PD) and Time Detector (TD) analog outputs
- JFET Amplifiers buffer the analog PD and TD.
- All Digital I/O from the MARS ASIC is differential and connects directly to the Readout Board.
- 10 Digital I/O pairs per ASIC, 240 signal traces total

Vacuum Feed- through

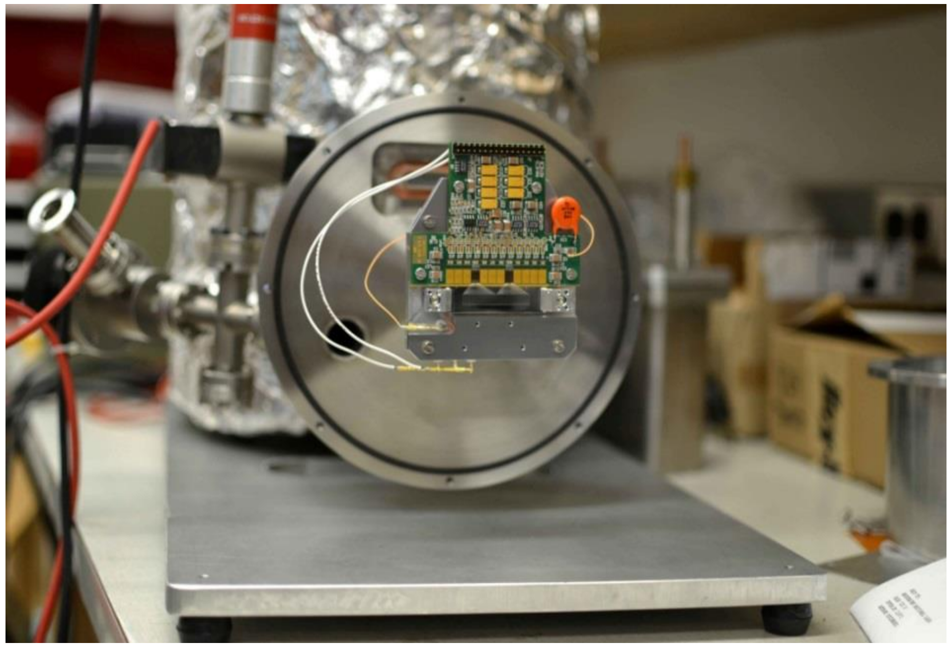


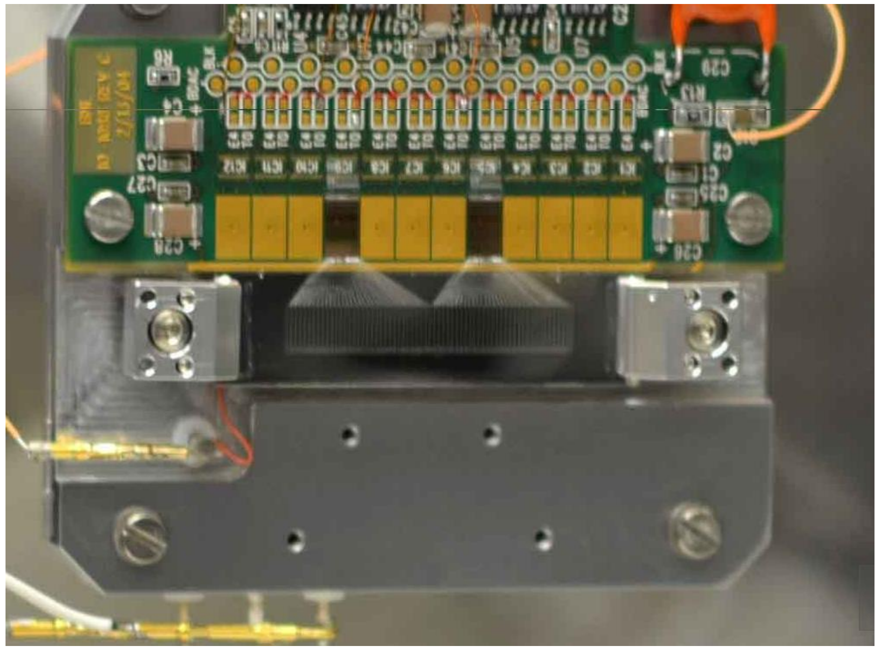
- 166 differential pair connections
- 500 pin Samtec SEAF8-10-50 connector
- 6 power connections

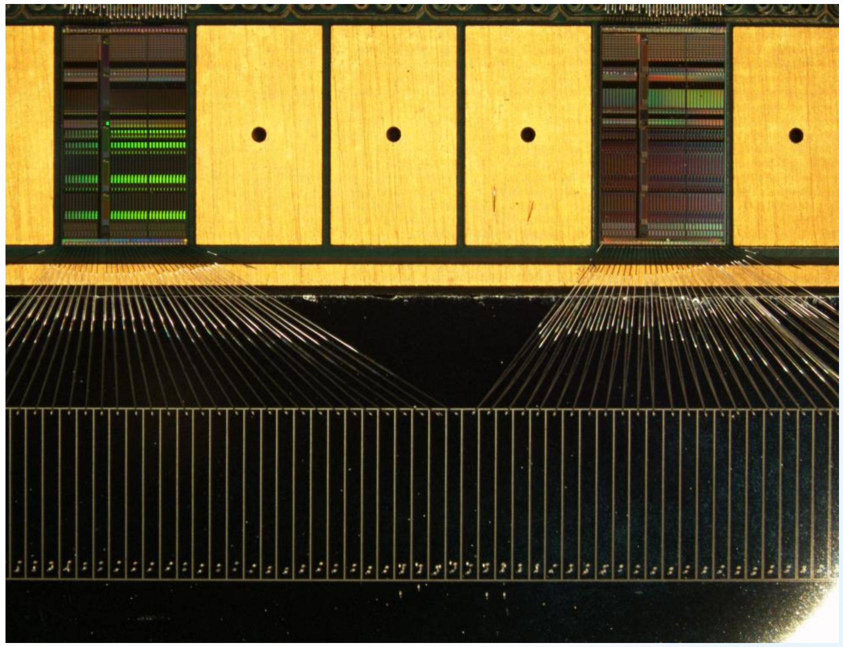
Readout Module

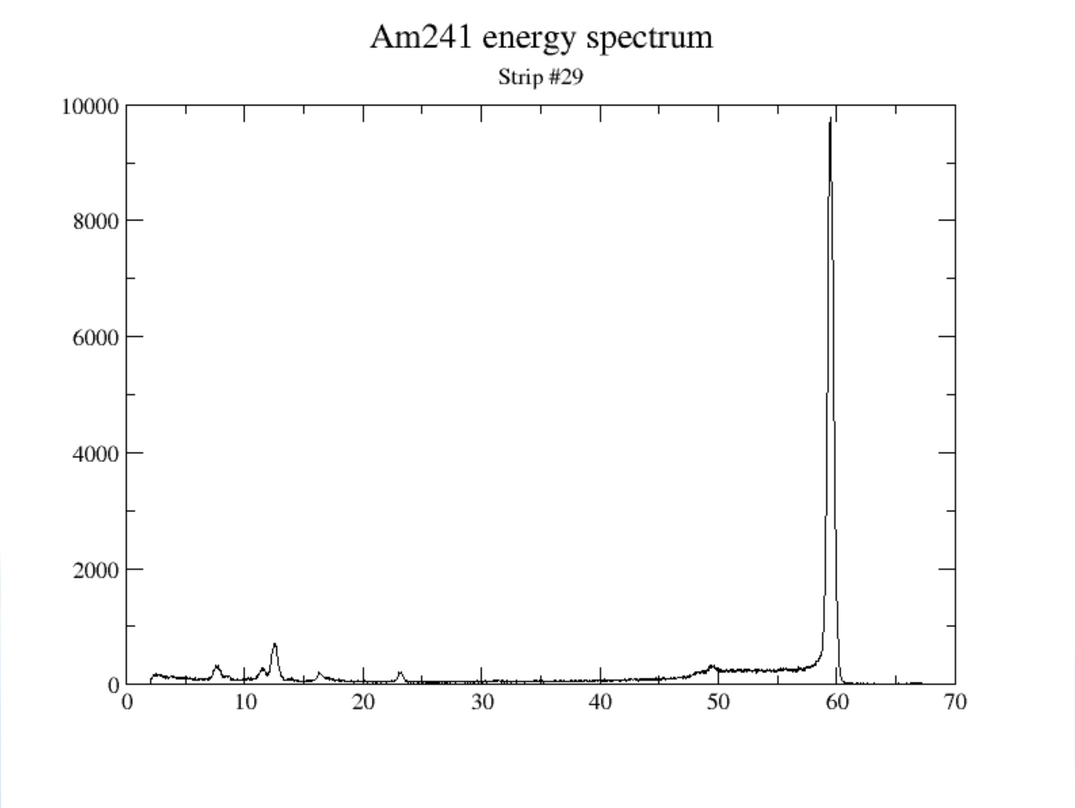
- Full parallel readout and control of 12 MARS ASICS.
- > 20M events / sec.
- Xilinx Zynq 7045 FPGA.
- FPGA programmable fast logic
- dual-core ARM A9 processor
- Debian Linux OS
- 24 x 14-bit ADC's to digitize PD and TD)
- Gigabit Ethernet using TCP/IP and ZeroMQ protocol
- Embedded NSLS-II event receiver
- synchronization and time-stamping of data

Multi-element Germanium prototype: The Past



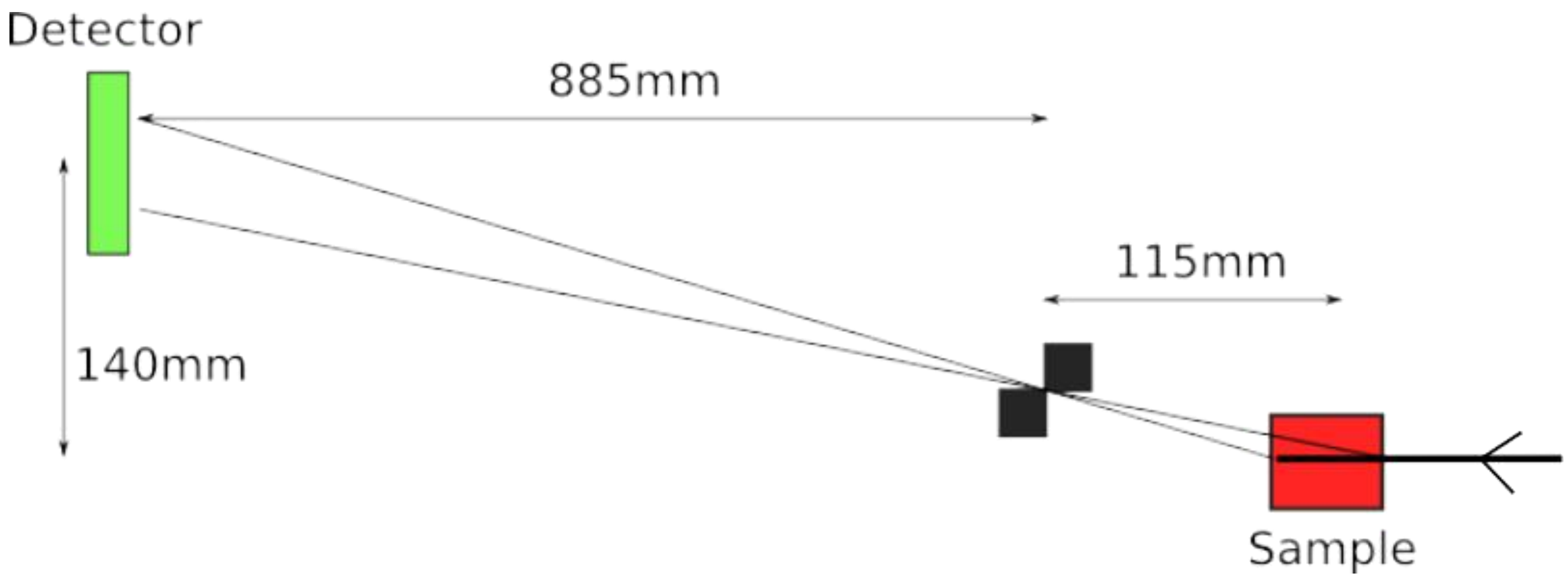


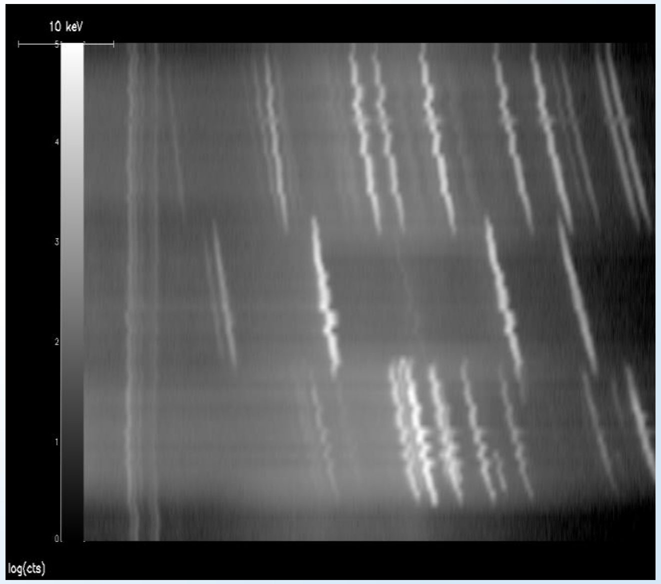




Energy resolution:
~450eV @ 60keV

64 Element Ge strip for EDX Experimental Set up



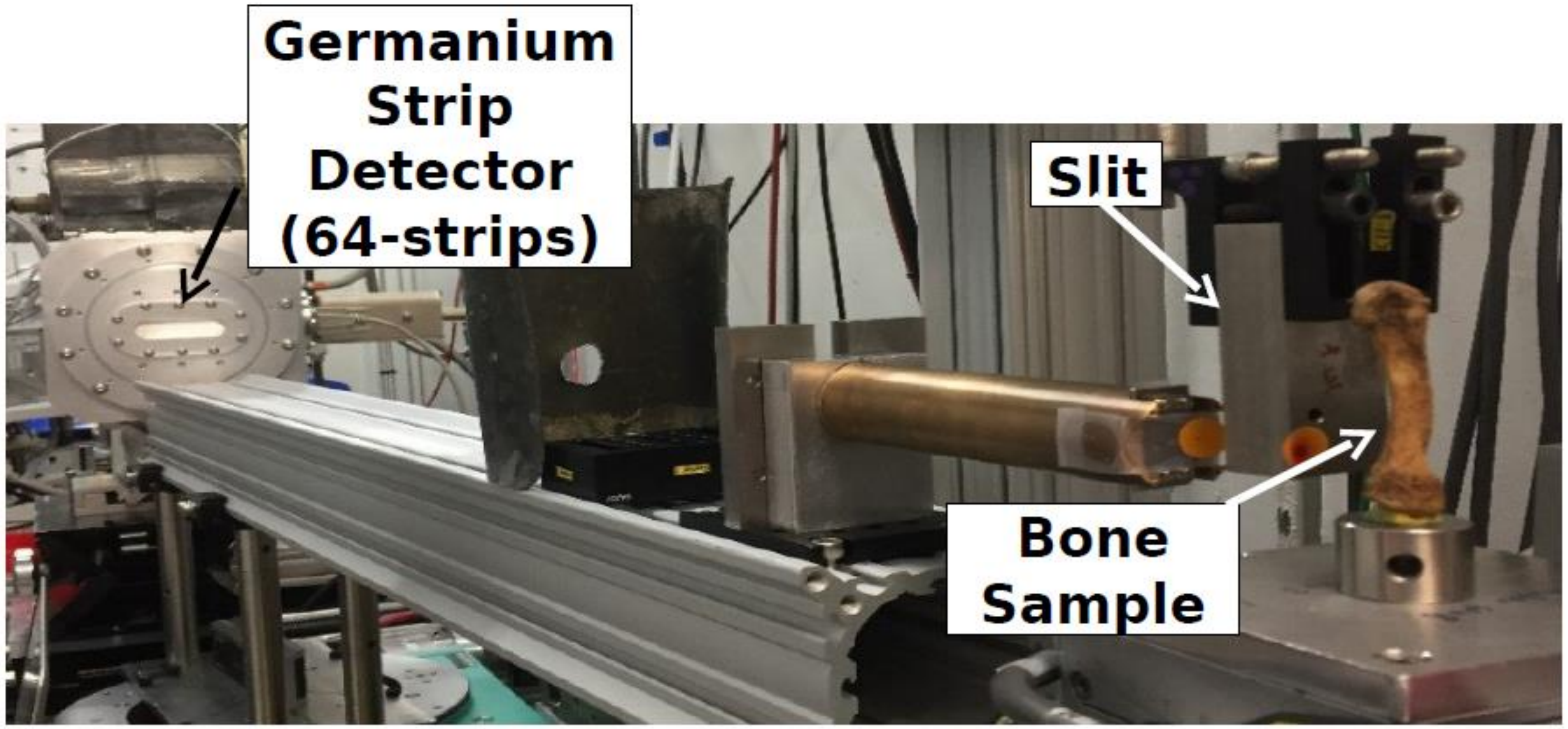


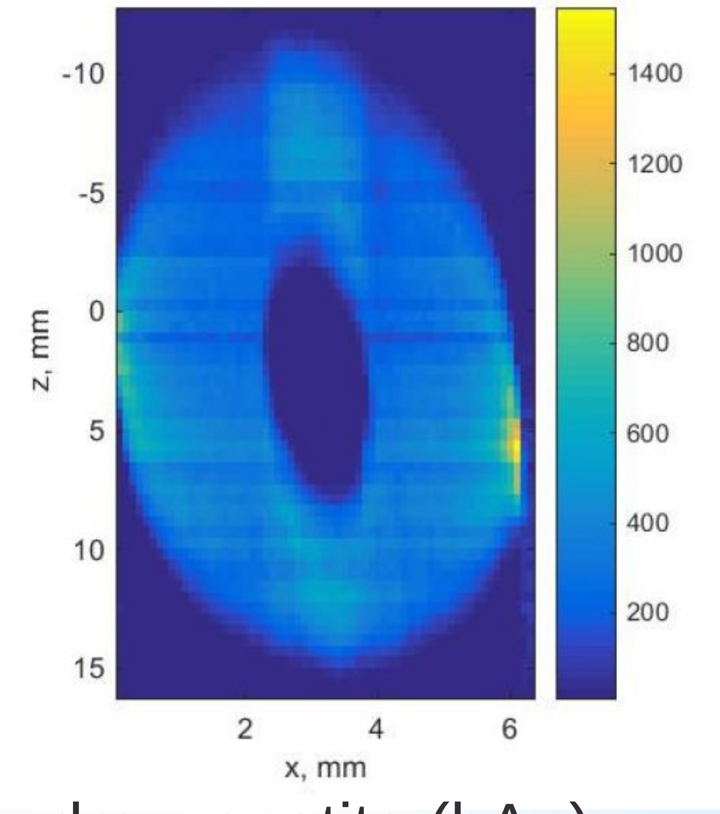
- 100um white beam enters from right
- Slit projects scattered beams onto strip detector
- Each detector element collects spectra (i.e. diffraction pattern) from one region of sample.

A.K. Rumaiz, T. Krings, D.P. Siddons, A.J. Kuczewski, D. Protic, C. Ross, G. De. Geronimo and Z. Zhong, IEEE Trans. Nucl. Sci., 61, 3721 (2014)

Reworked 64 element Ge at APS 6-BM

Energy dispersive diffraction imaging





- The energy dispersive real space reconstruction of a hydroxyapatite (hAp) bone phantom is shown to the left.
- Several diffraction peaks were reconstructed and peak intensity from one is shown here (hAp 004 reflection).
- The shape including empty central region is correctly reconstructed.
- Peak centers from each phase present can also be reconstructed to yield strain information.

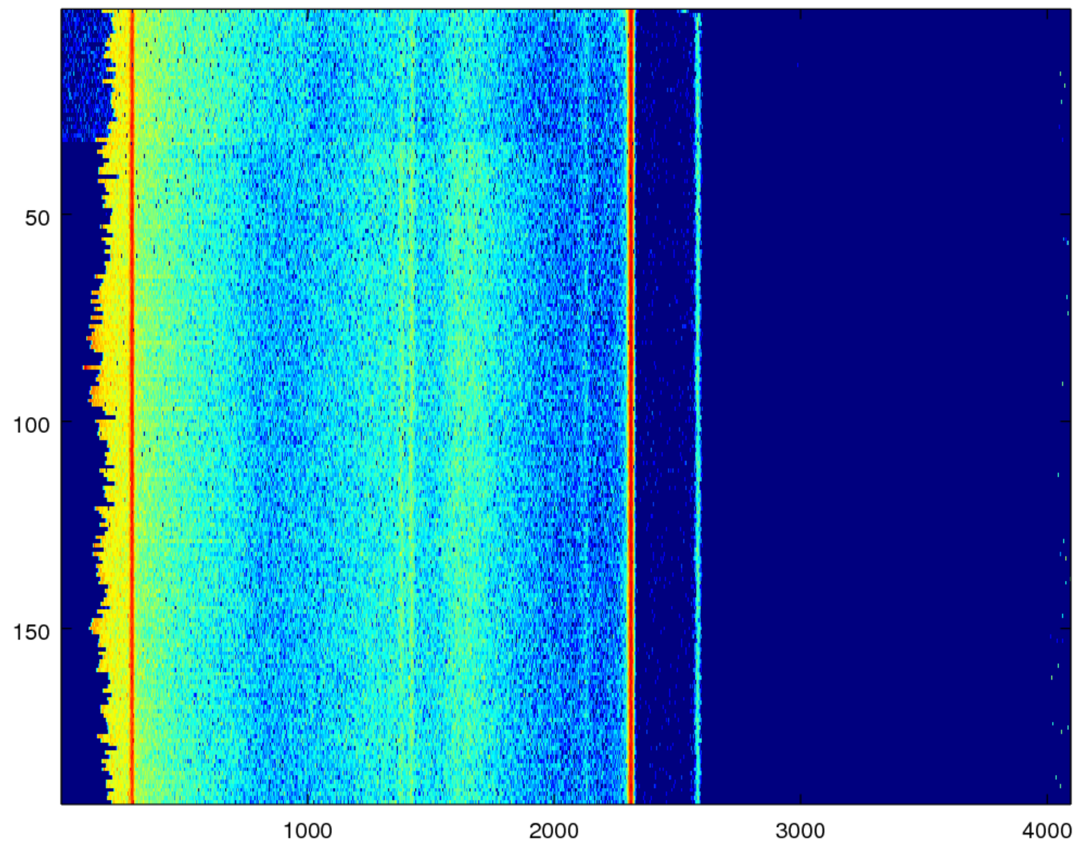
S R Stock et. al, Proc SPIE 10391, 103910A (2017)

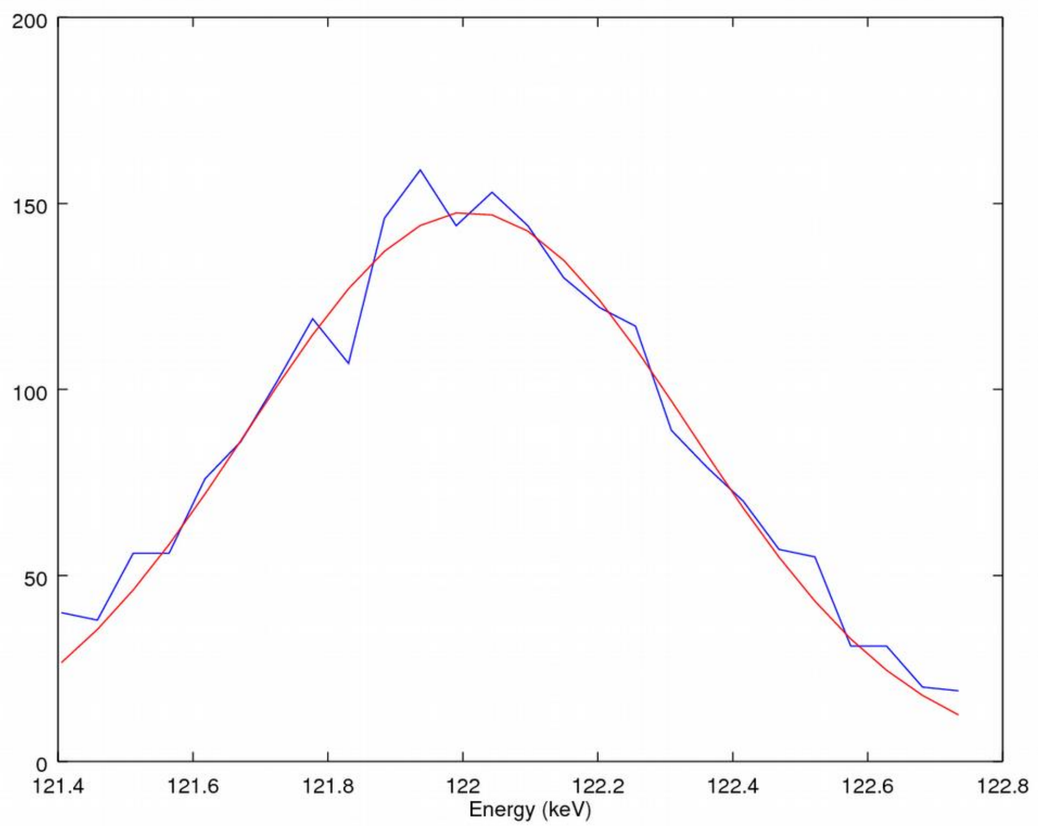
APS192-element detector for EDX: The present

- 192 strips, each 250um x 8mm
- Uses same in-vacuum PCB as 384-strip device
- Uses HE-MARS chip to give 200keV capability
- Populate every other chip.

$_{57}$Co spectra from 192-strip detector

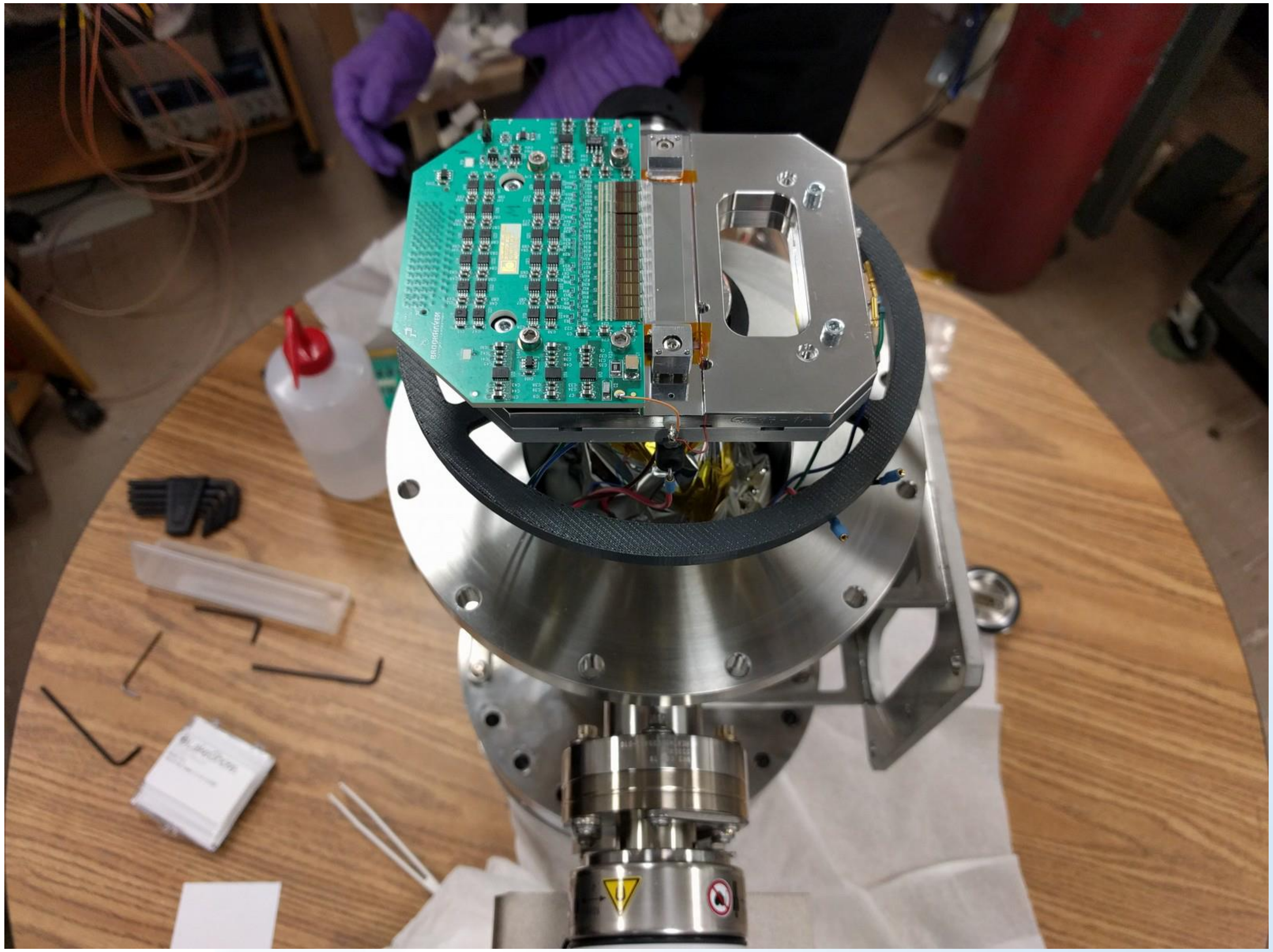
- All channels working equally well
- Resolution at 122keV = 770eV (Fano limit ~510eV)





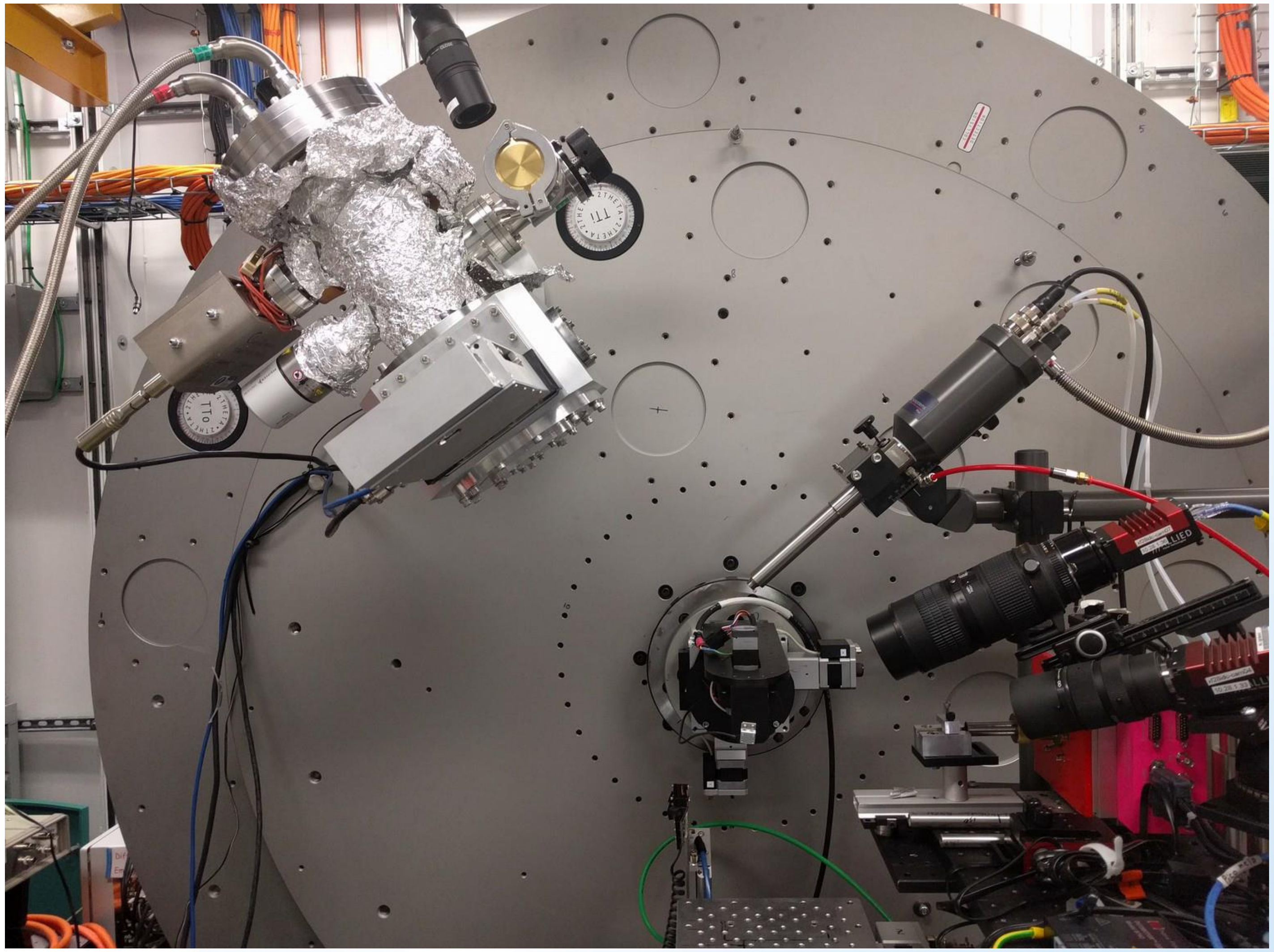
384-element detector: XPD beamline

- For this application we built a 384-strip detector
  - 384 strips, 0.125 mm x 8mm
  - 3mm thick
  - 12 ASICs with full parallel readout



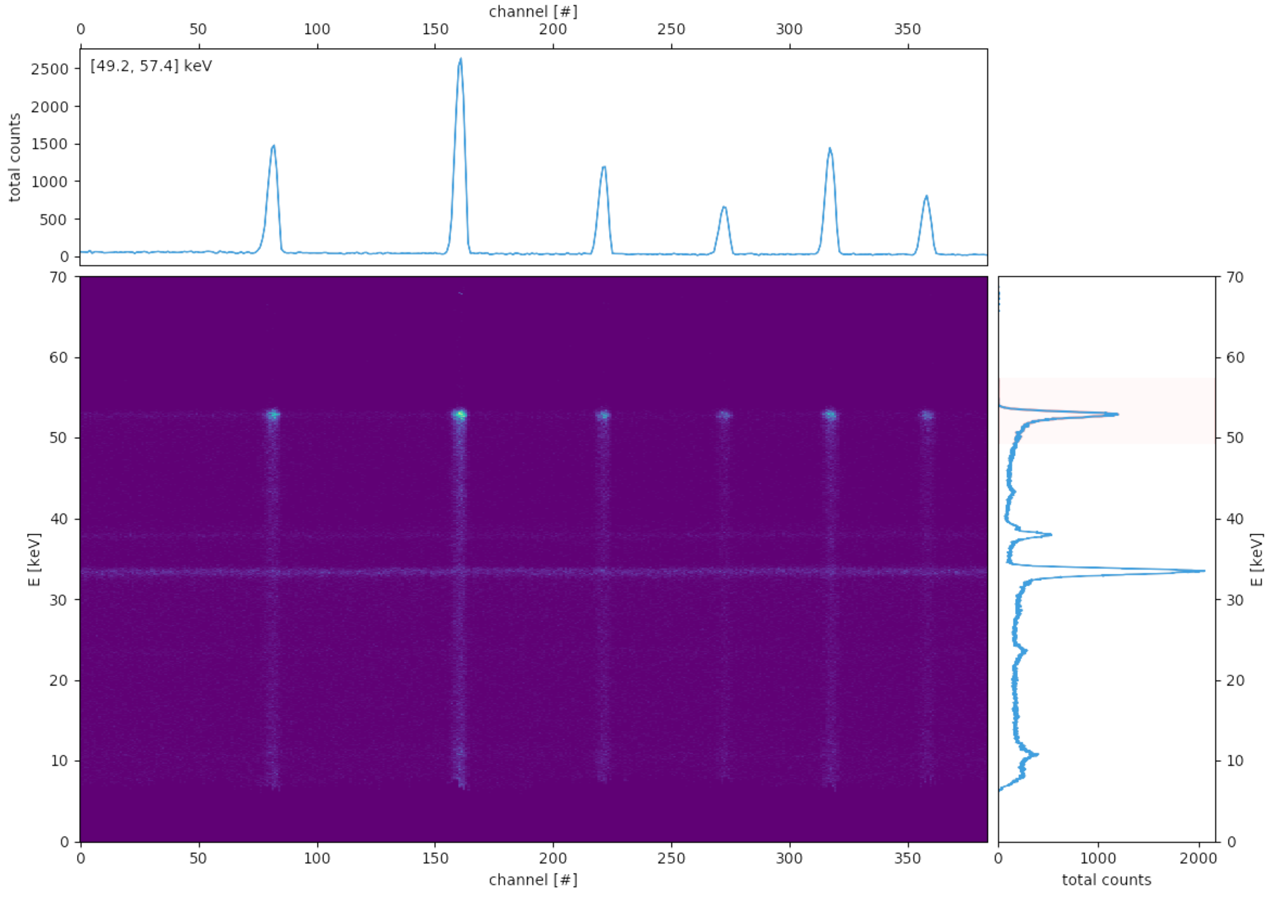
Detector system at XPD beamline

The detector was designed to mount on the large goniometer in the NSLS-II Powder Diffraction beamline (XPD). It can be easily mounted on one of several locations on either of the two outer circles of the goniometer. It uses a closed cycle cryostat, so can operate in any orientation and needs no LN_2.



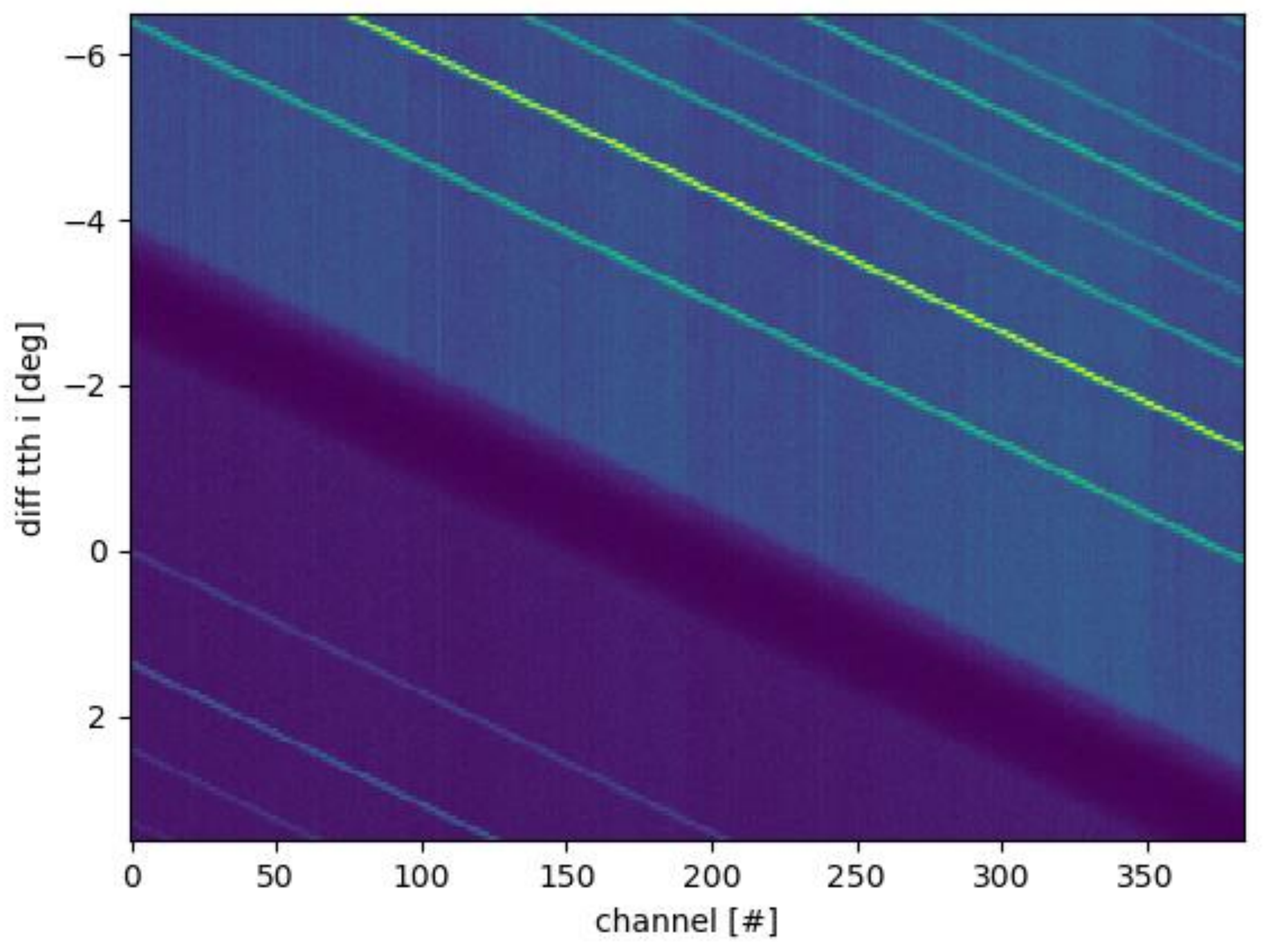
First Data from XPD

- As a first test we took standard samples LaB_6.
- The X-axis is detector strip number.
- the Y-axis is photon energy in keV.
- the color represents the intensity.
- The right hand curve is the energy spectrum of the beam integrated over all strips. Note the strong BaKa/Kb fluorescence lines.
- The curve at the top represents the integral along the energy axis enclosed by the pink rectangle on the right, I.e. the diffraction pattern.

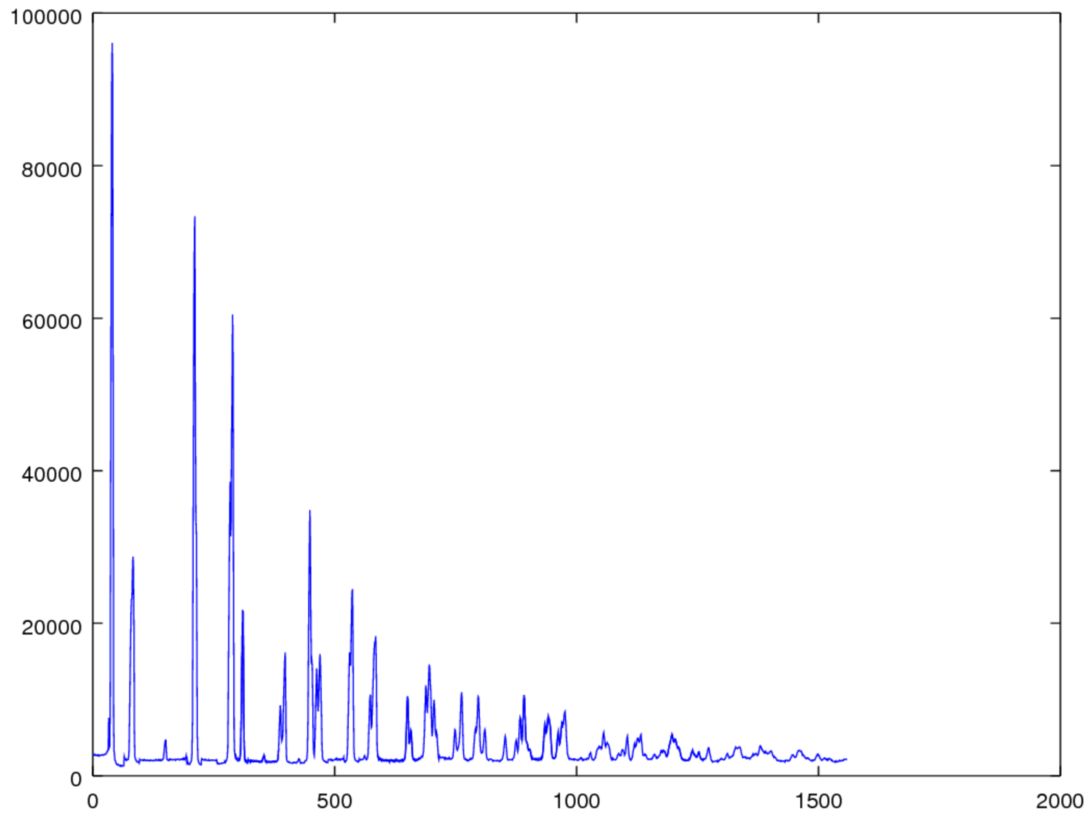


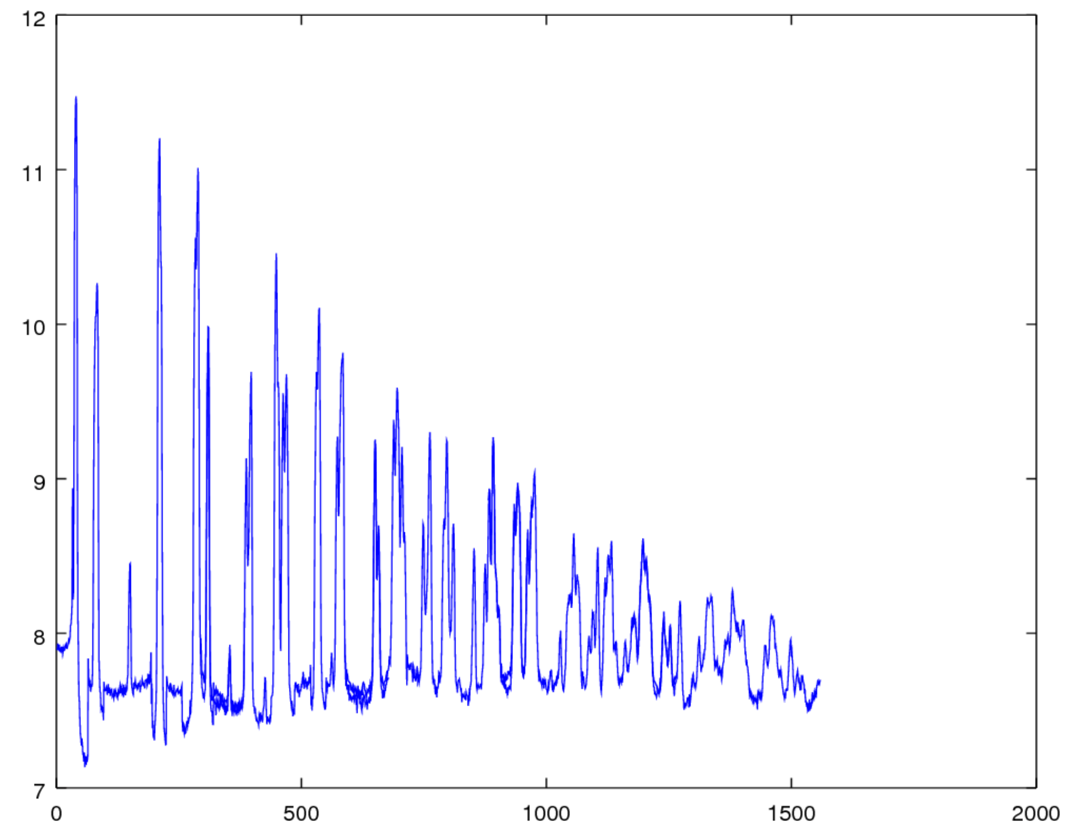
Angle Calibration

- The correspondence between Bragg angle and strip number depends on the distance of the detector from the sample, and so must be carefully estimated.
- Using the goniometer 2-theta motion, we stepped the detector through the diffraction pattern, recording the intensities at each step.
- The figure shows the traces of the Bragg peaks walking across the detector.
- The slope of these lines gives directly the angle calibration of the detector.



Wide data range





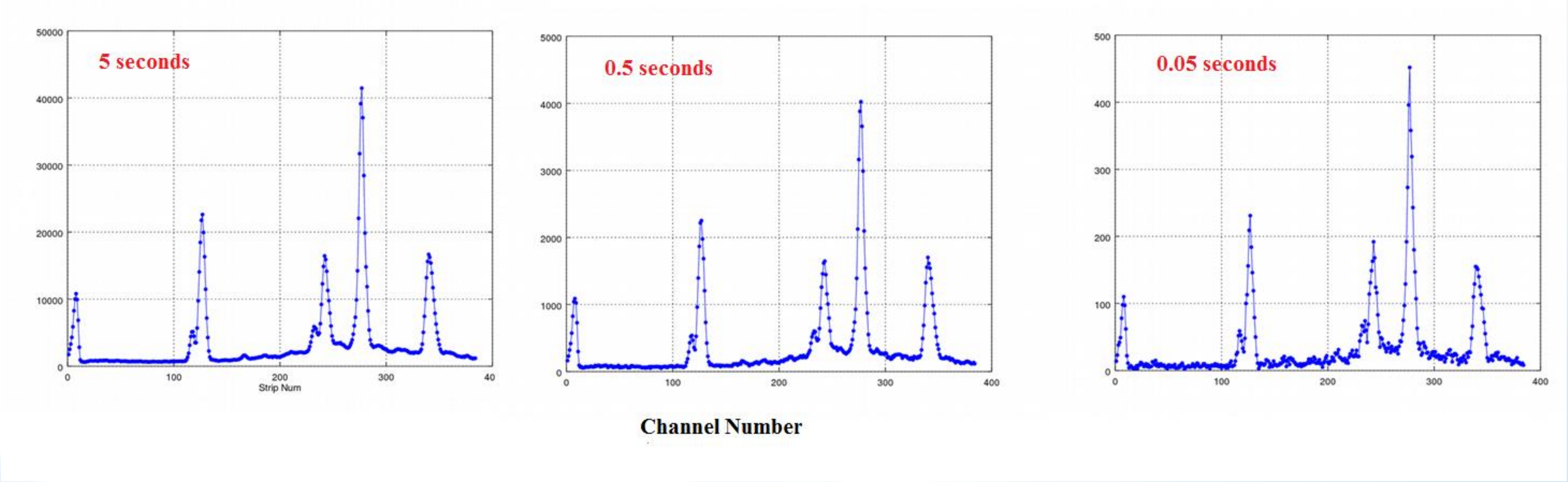
Longer scan of BaTiO3 sample by stepping the 2-theta axis in 5 degree steps and merging the resulting data to give 30 degrees total (~0.5A resolution).

Left-hand side is linear plot

Right hand side is log plot to bring out the high-angle data

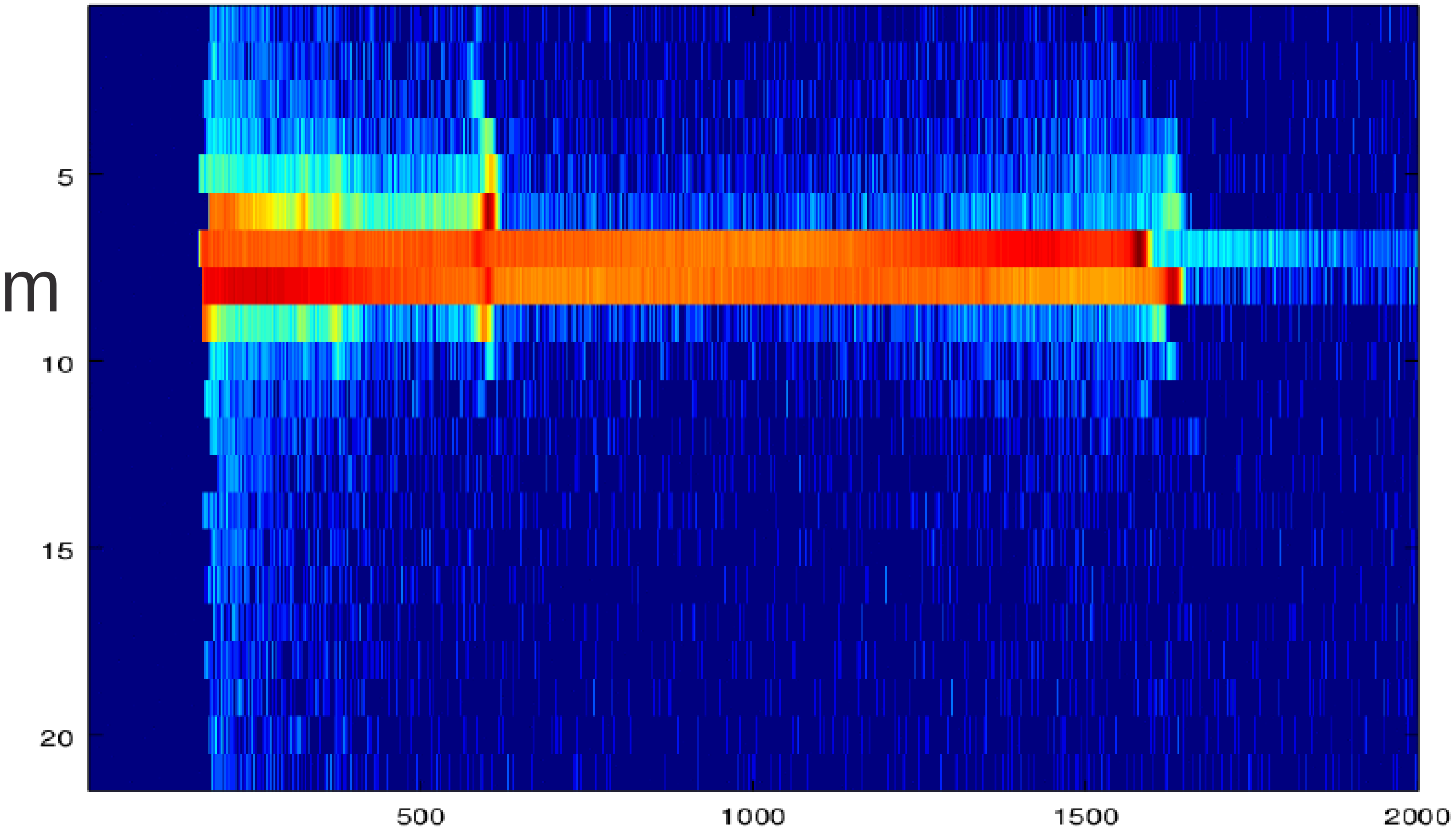
Time-resolved measurements

- Every photon is timestamped with 40ns resolution.
- Data is stored as a stream of photon records
- Any size time slice can easily be extracted from this data. Below are three views extracted from the same data



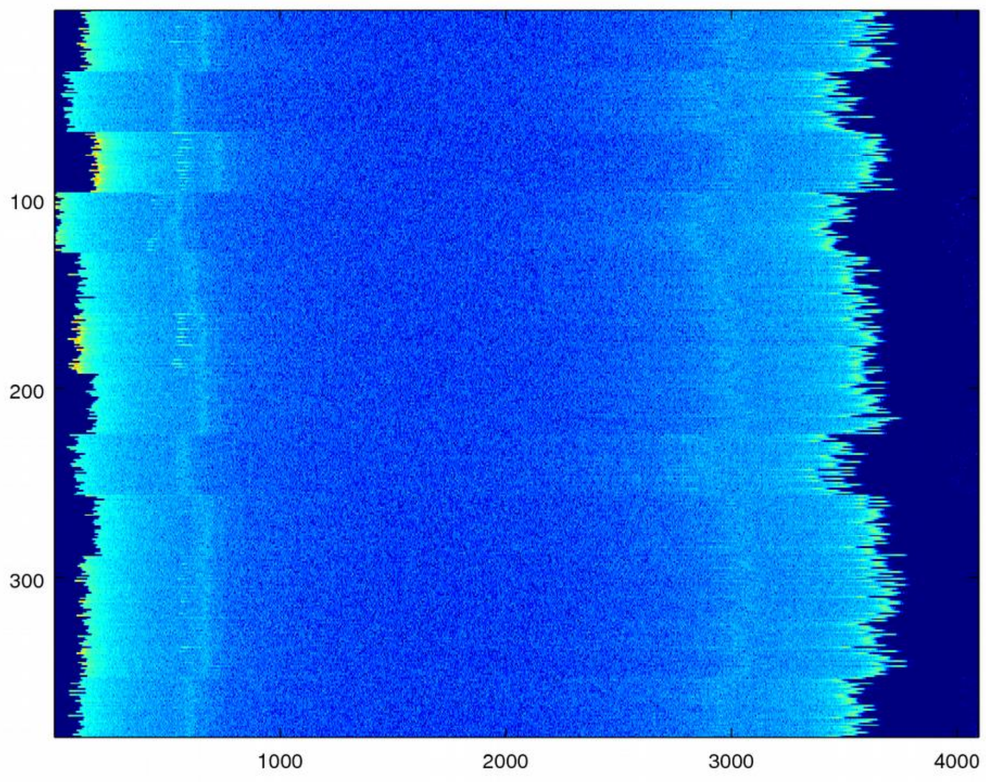
Charge-sharing in the strip detector

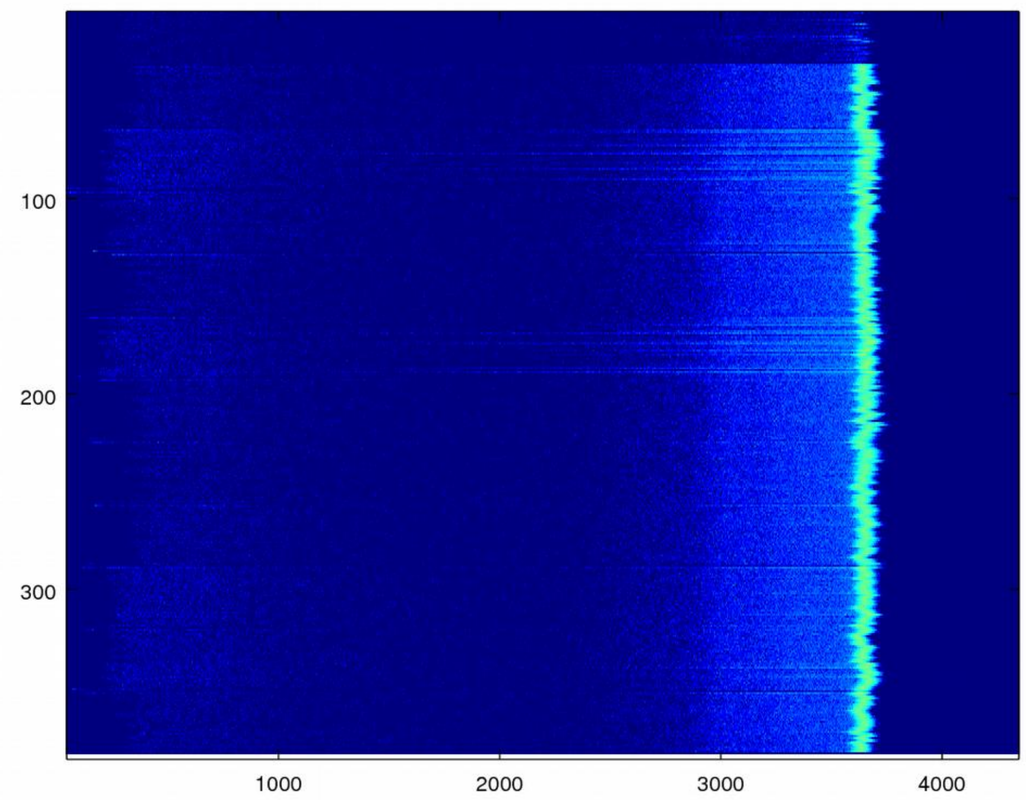
Using a pinhole, prepare a Monochromatic beam ~10um in size.
Scan several strips
to look at charge sharing behavior.



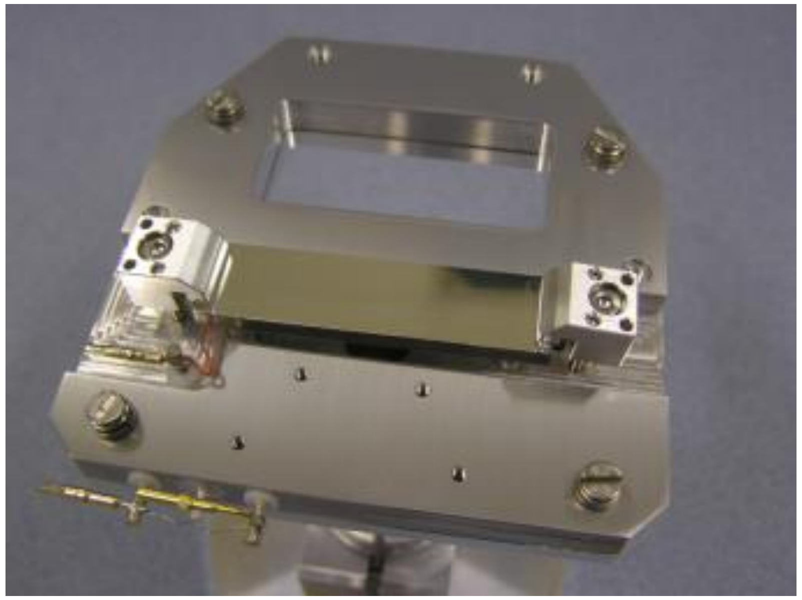
Charge-sharing Algorithm

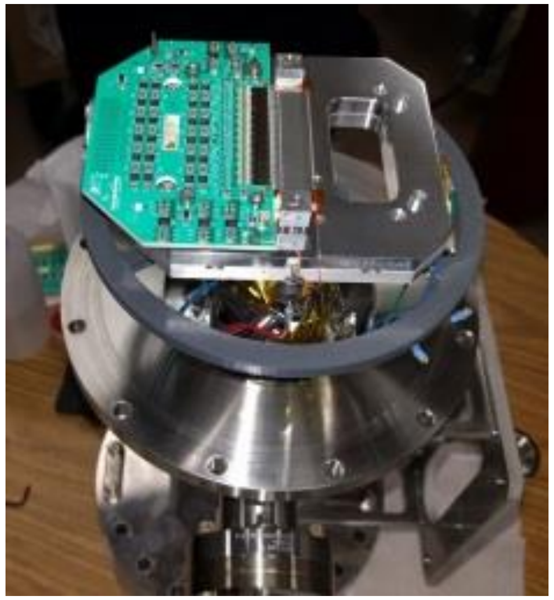
- Photons arrive sequentially; build a FIFO pipeline
- Compare first one with its predecessors and look for same timestamp.
- If a match, add the charges and remove one of the events from the stream.

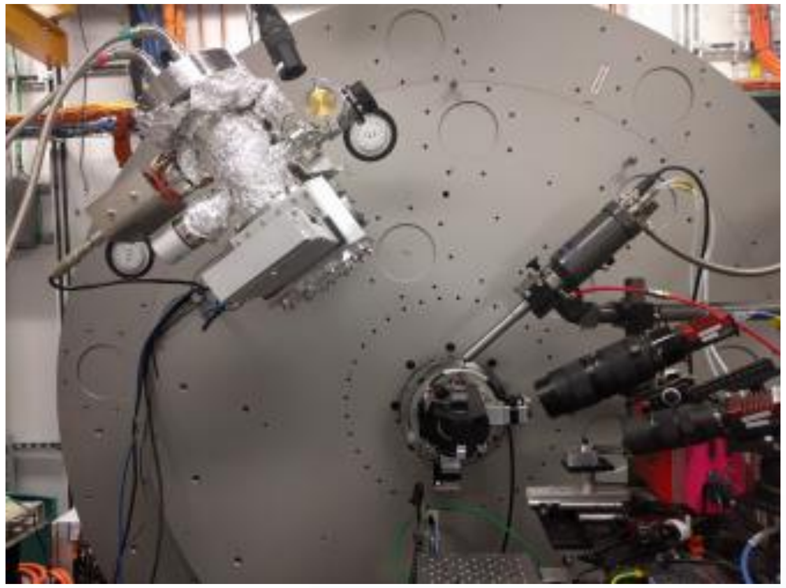




"Large" Ge strip detector: Future







Larger arrays: assembling multiple sensors into a common cryostat:
- Larger angle range without motion for time-resolved diffraction
- Orthogonal detectors for EDX strain tensor measurements

Improved software:
- Refine charge-sharing algorithm
- Position interpolation; better spatial resolution
- User interface improvements

Conclusions

- Germanium is the best-performing high-Z semiconductor and large-scale detectors with spectroscopic quality can be fabricated.
- Closed-cycle refrigerators ease the burden of cryo-cooling the sensors.
- We have developed a toolkit to allow detectors with small pixels and a large element count to be readily constructed.
- The high level of integration allows compact systems to be built which can be, for example, mounted on a diffractometer.
- Modern embedded computing systems allow flexible interfacing to sophisticated hardware.