Next generation microprobes: Detector Issues and Approaches

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Outline

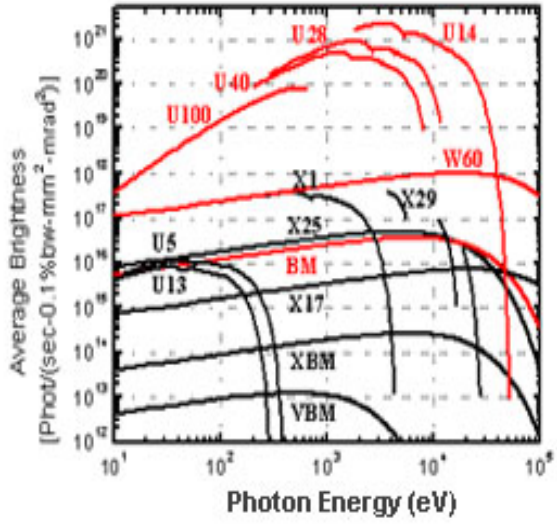
- Why do we need new detectors?
- What detectors will have most impact?
- BNL development initiatives
  - Spectroscopy
  - Diffraction
  - Speckle

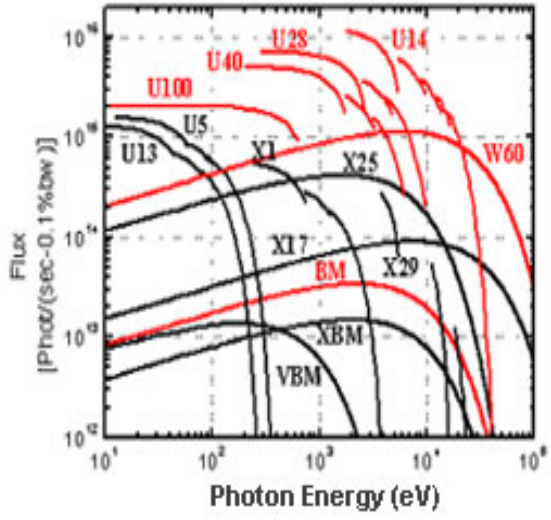
BNL Collaborators for silicon detector development

- **Zheng Li , Pavel Rehak, Wei Chen, Rolf Beuttenmuller, detector elements (Inst. Div.).**
- **Paul O'Connor, Gianluigi De Geronimo, ASIC design (Inst. Div).**
- **Peter Siddons, Tony Kuczewski, computer and user interface (NSLS)**
- **Technical assistance:**
  - **John Triolo, Don Pinelli (Inst.) ,**
  - **Denis Poshka, Tony Lenhard, Shu Cheung, Rick Greene (NSLS)**

NSLS-II

- A new 3rd-generation source at BNL
- 3GeV, 600m circumference.
- 24 TBA cells
- 5m straights
- 1.5nm-rad/0.008nm-rad
- Green-field site adjacent to NSLS
- 2012 ops.





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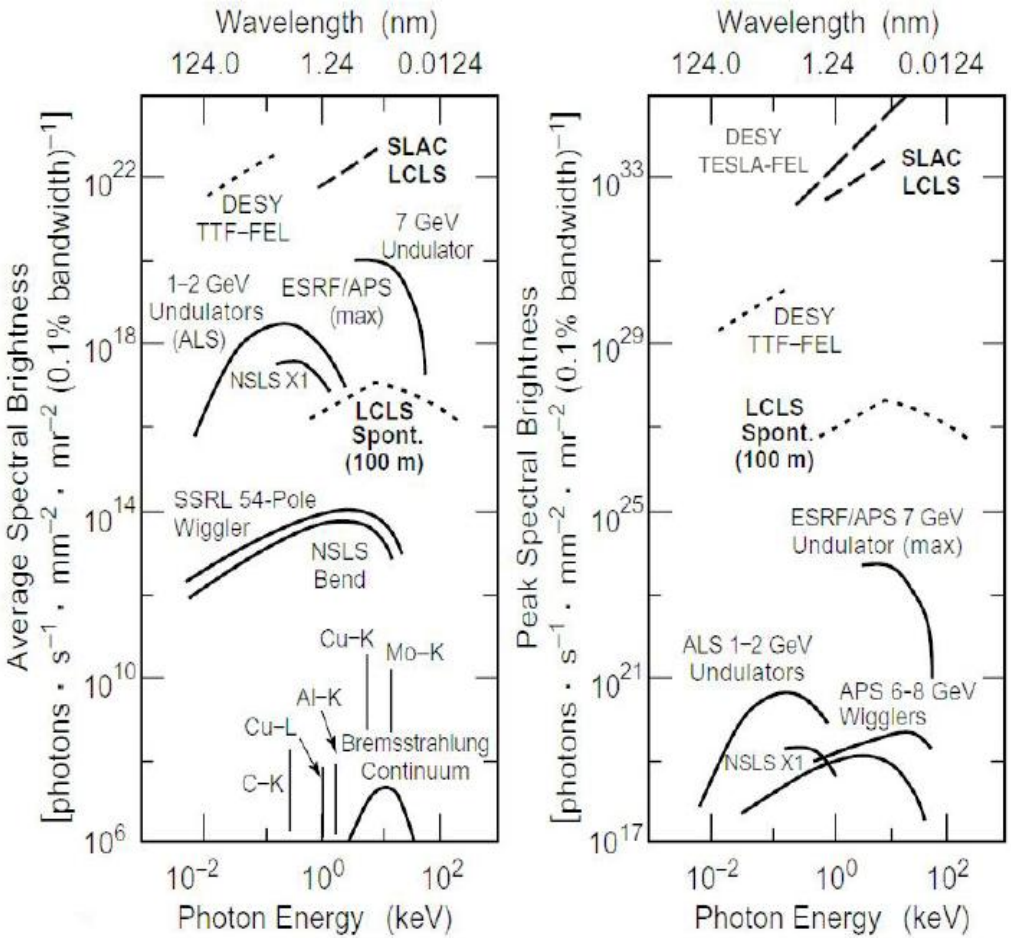
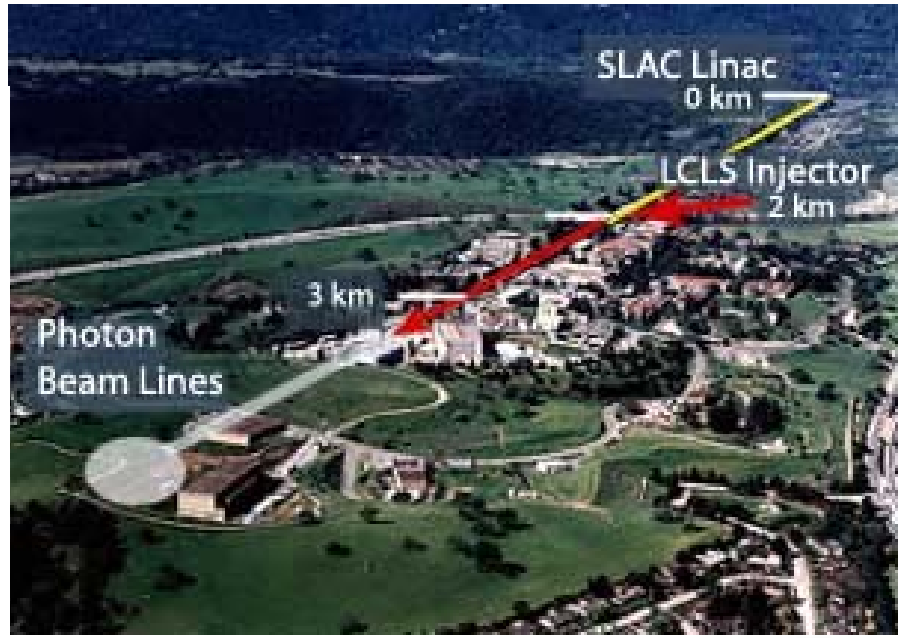
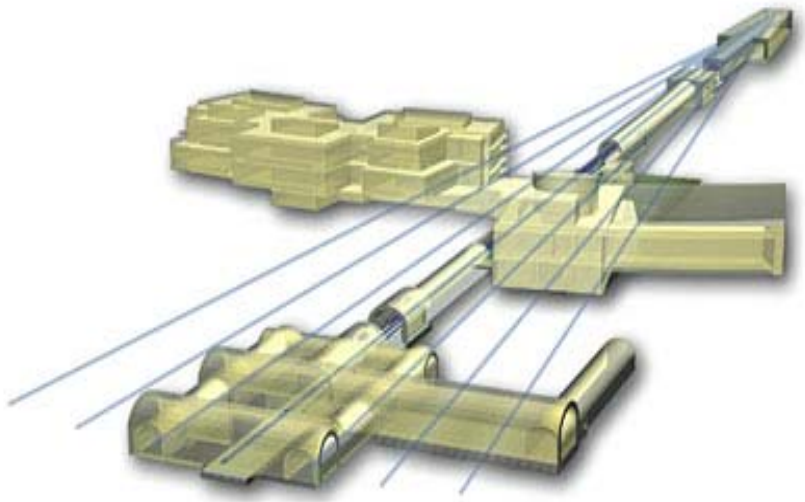
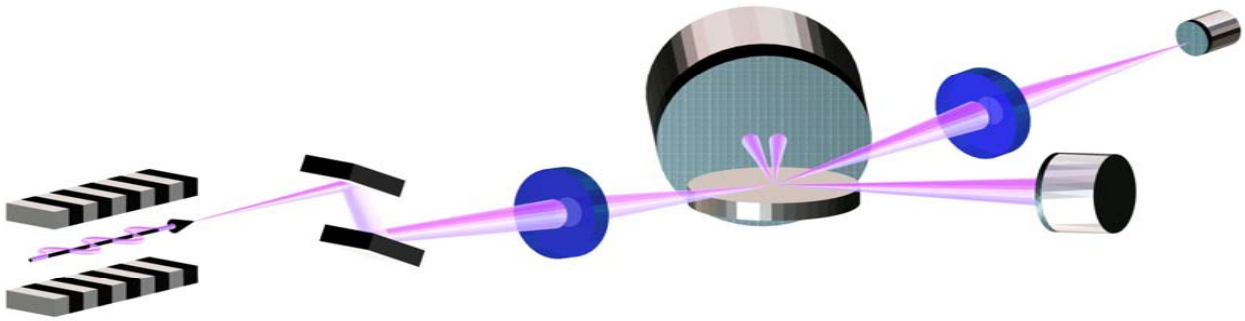
LCLS


Wavelength (nm)
124.0
1.24
0.0124
Average Spectral Brightness
[photons · s^{-1} · mm^{-2} · mr^{-2} (0.1% bandwidth)$^{-1}$]
10^{22}
10^{18}
10^{14}
10^{10}
10^{6}
SLAC LCLS
DESY TTF-FEL
7 GeV Undulator
1-2 GeV Undulators (ALS)
ESRF/APS (max)
NSLS X1
LCLS Spont. (100 m)
SSRL 54-Pole Wiggler
NSLS Bend
Cu-K
Mo-K
Al-K
Cu-L
Bremsstrahlung Continuum
C-K
10^{-2}
10^{0}
10^{2}
Photon Energy (keV)
Wavelength (nm)
124.0
1.24
0.0124
Peak Spectral Brightness
[photons · s^{-1} · mm^{-2} · mr^{-2} (0.1% bandwidth)$^{-1}$]
10^{33}
10^{29}
10^{25}
10^{21}
10^{17}
DESY TESLA-FEL
SLAC LCLS
DESY TTF-FEL
LCLS Spont. (100 m)
ESRF/APS 7 GeV Undulator (max)
ALS 1-2 GeV Undulators
APS 6-8 GeV Wigglers
NSLS X1
10^{-2}
10^{0}
10^{2}
Photon Energy (keV)


SLAC Linac
0 km
LCLS Injector
2 km
3 km
Photon
Beam Lines



Generic microprobe schematic

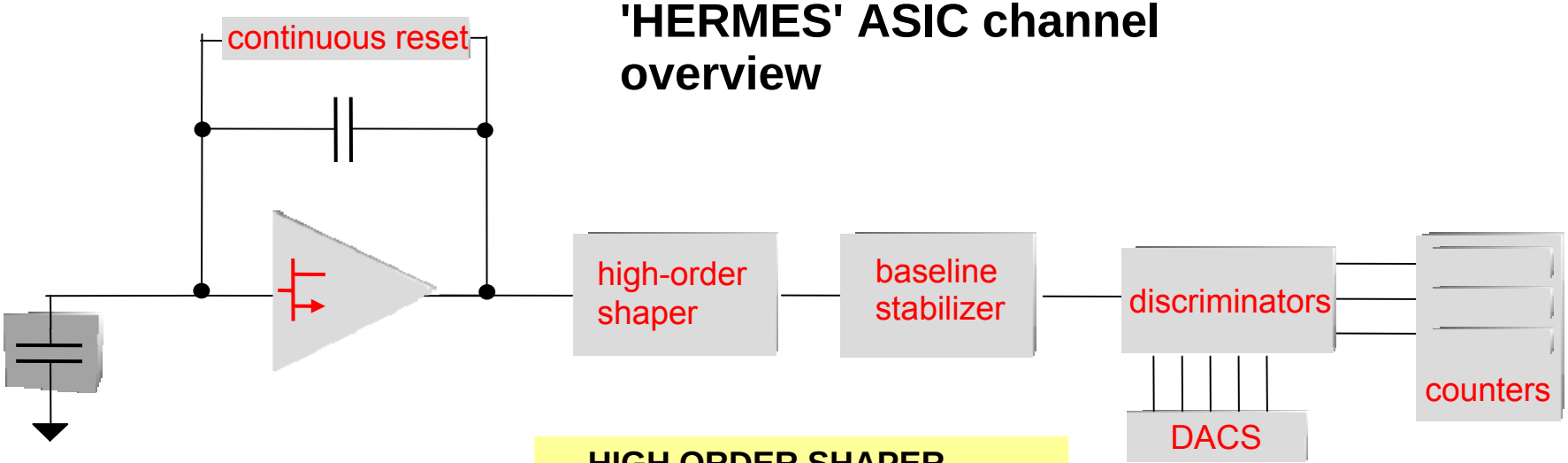


- Includes facilities for
  - fluorescence (multi-element detector)
  - diffraction (fast readout area detector)
  - microscopy (full-field ZP microscope)

Next-generation x-ray microprobe spectroscopy detector

- Continuous-scan sample rastering
  - rapid image acquisition
  - Collaboration with CSIRO /Australian Light Source
- 400 element full-spectrum back-scatter detector array
  - <200eV resolution @ 4us
  - >100kHz @ 0.5us
- Real-time quantitative multi-elemental mapping
  - Fast per-photon processing, detector response and spectral modeling

'HERMES' ASIC channel overview



INPUT p-MOSFET
- optimized for operating region
- NIM A480, p.713

CONTINUOUS RESET
- feedback MOSFET
- self adaptive 1pA - 100pA
- low noise < 3.5e$^-$ rms @ 1μs
- highly linear < 0.2% FS
- US patent 5,793,254
- NIM A421, p.322
- TNS 47, p.1458

≈ 3 mW

HIGH ORDER SHAPER
- amplifier with passive feedback
- 5th order complex semigaussian
- 2.6x better resolution vs 2nd order
- TNS 47, p.1857

BASELINE STABILIZER (BLH)
- low-frequency feedback, BGR
- slew-rate limited follower
- DC and high-rate stabilization
- dispersion < 3mV rms
- stability <2mV rms @ rt×tp<0.1
- TNS 47, p.818

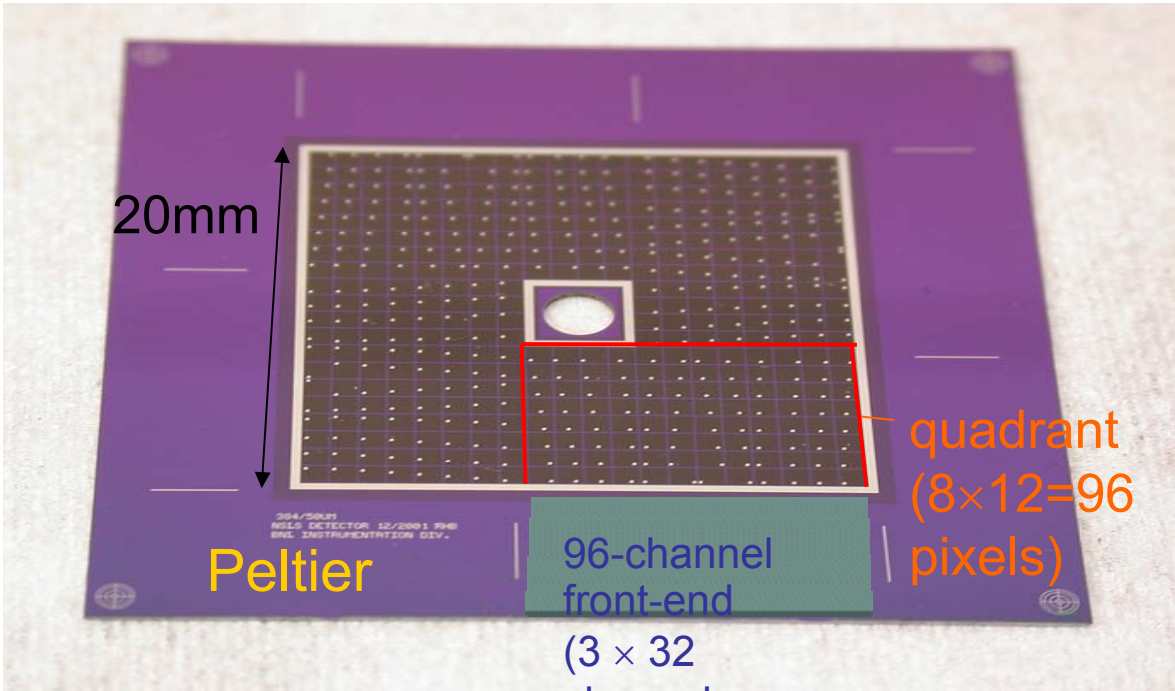
DISCRIMINATORS
- five comparators
- 1 threshold + 2 windows
- four 6-bit DACs (1.6mV step)
- dispersion (adj) < 2.5e$^-$ rms

COUNTERS
- three (one per discriminator)
- 24-bit each

≈ 5 mW

High-rate multi-element detector for fluorescence measurements

- 398-element silicon pad array for absorption spectroscopy and/or x-ray microprobes.
- Central hole for incident pump beam to allow close approach to sample.
- Uses 12 ASICS.
- Peltier cooled to -35 deg. C.



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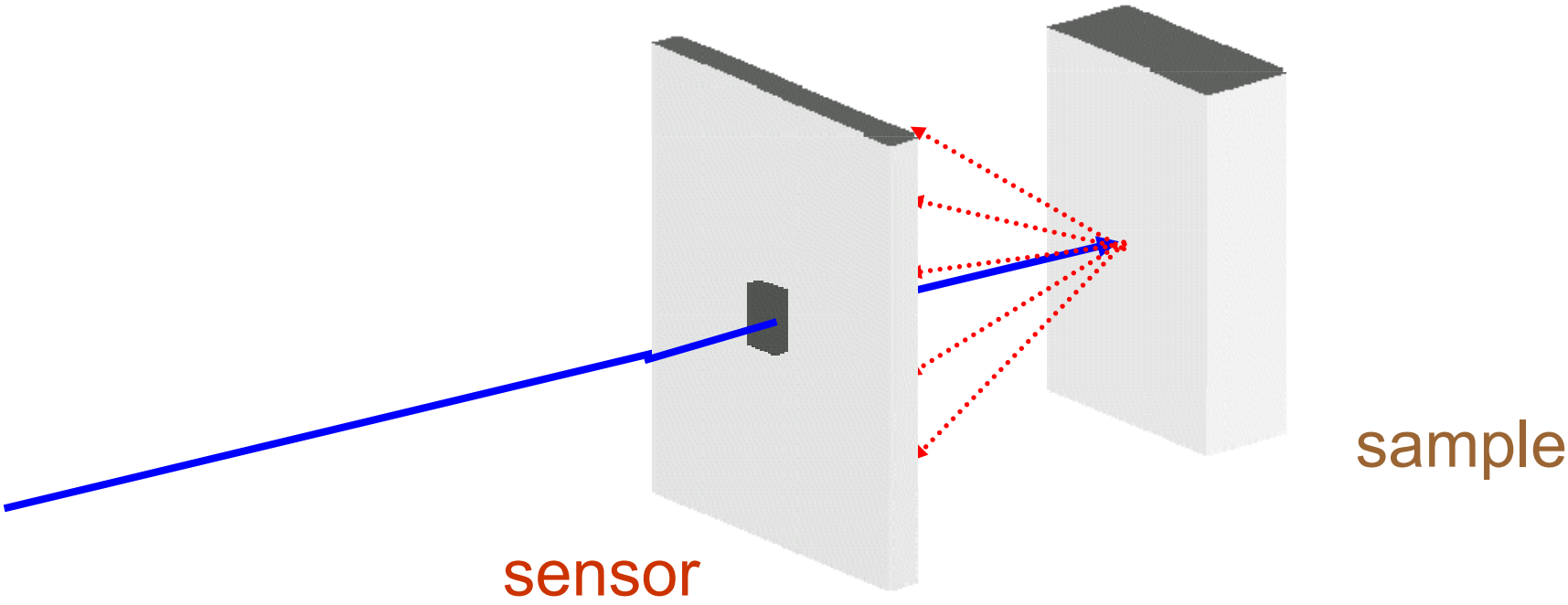
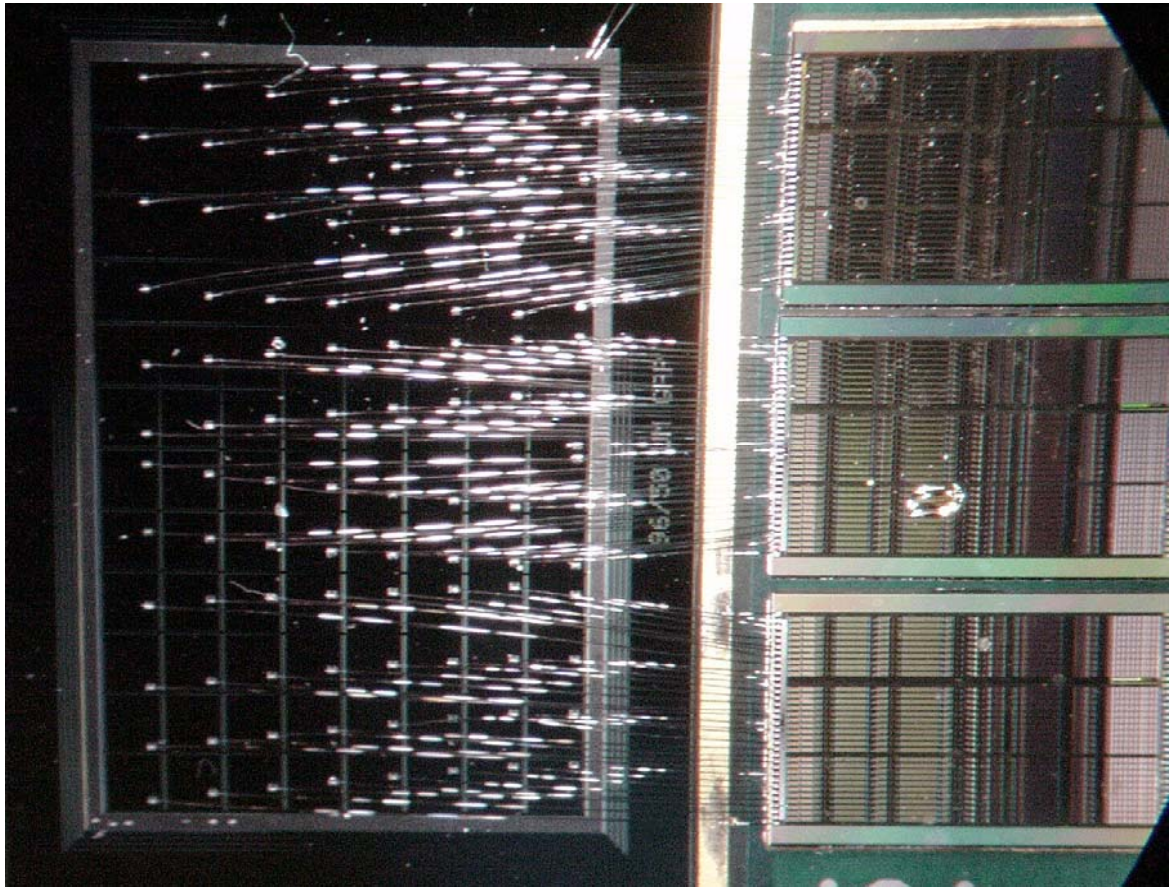
Backscattering geometry for microprobes



One quadrant with ASICS

- 96 pads wire-bonded to 3 ASICS.
- The long bonds are rather fragile, but this approach provided least parasitic capacitance.
- Each ASIC provides 32 channels of low-noise analog/digital processing.
- ASIC appears to have 100% yield (no bad channels to date).



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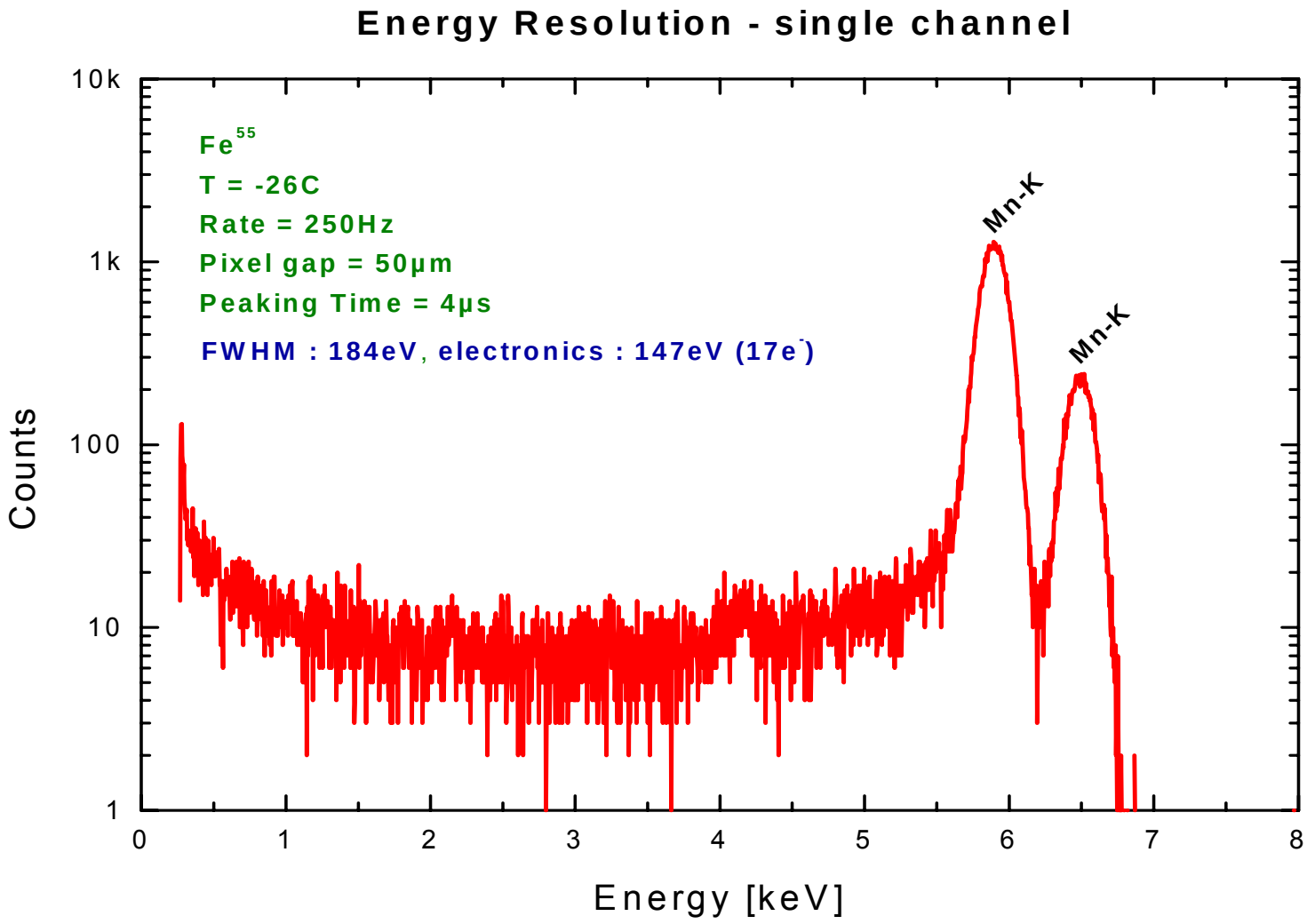
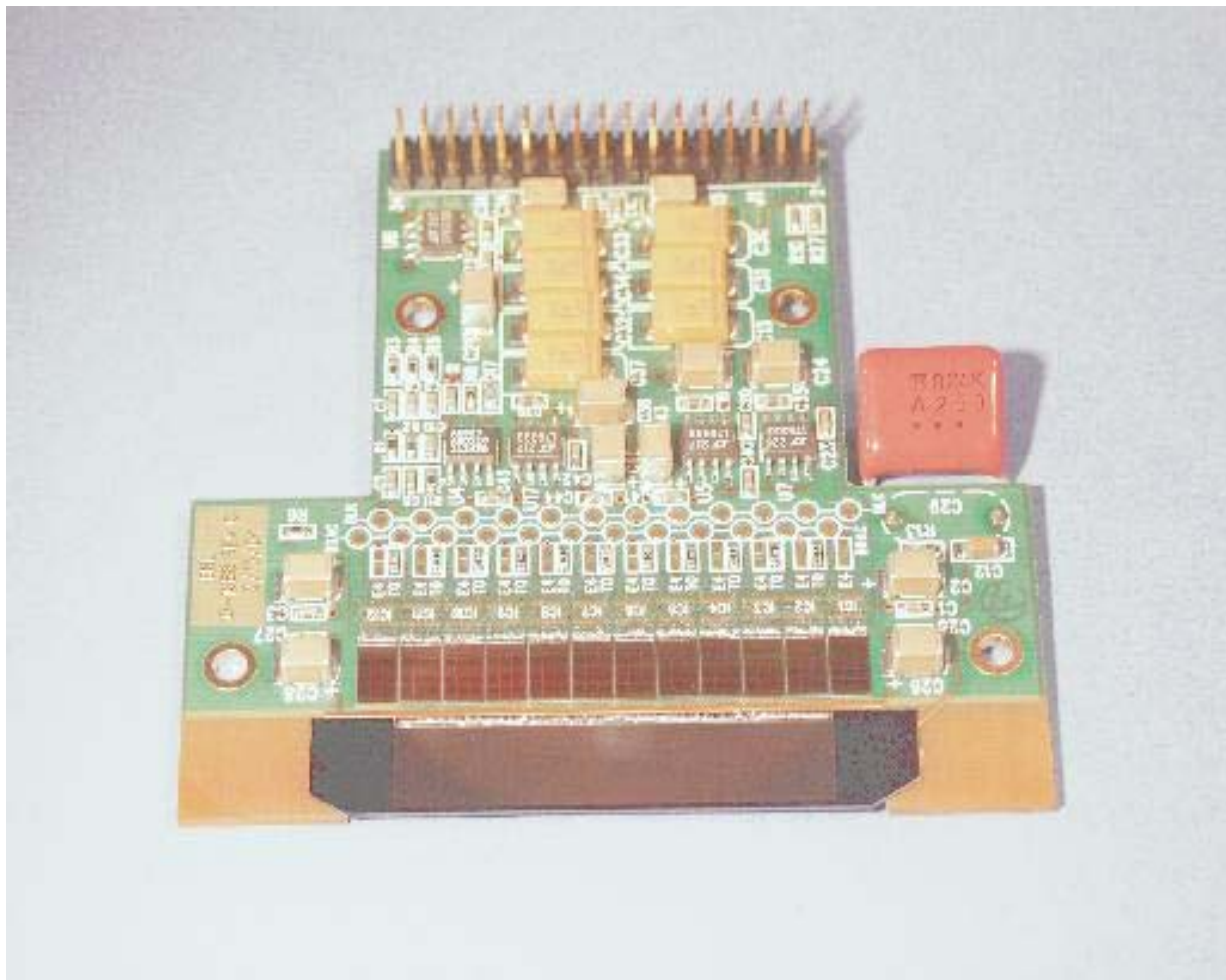
^{55}Fe spectrum



50µm-gap, $C_p \approx 700$fF, $C_{i\text{-bond}} \approx 50\text{-}200$fF, $C_{i\text{-pad}} \approx 220$fF

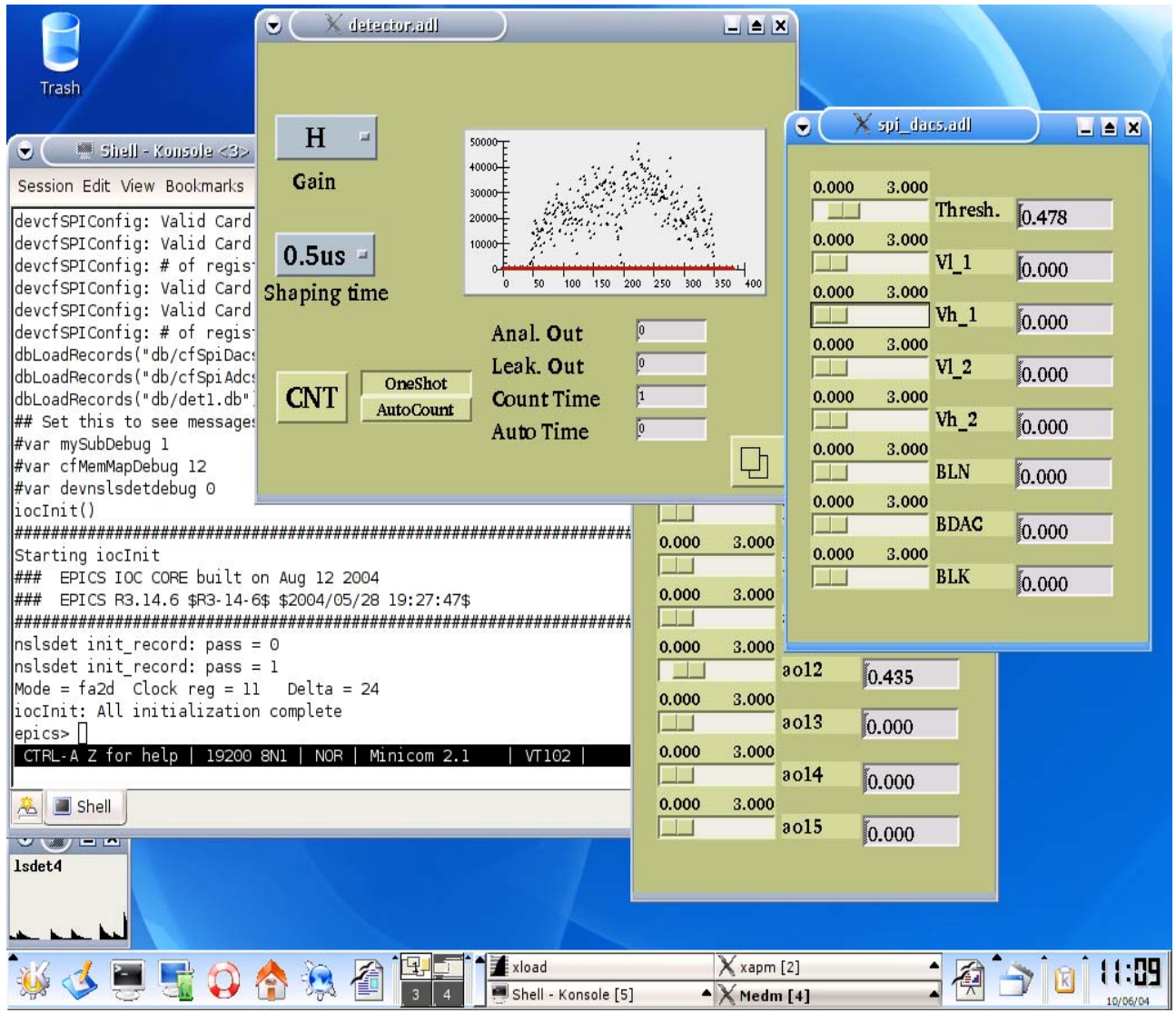
Non-spectroscopic applications

- Strip-shaped pixels form a 1-D position sensing detector with energy resolution (~350eV).
- 320 strips on 0.125mm pitch -> 40mm total length
- Strips 8mm long
- Useful for diffraction and scattering experiments.



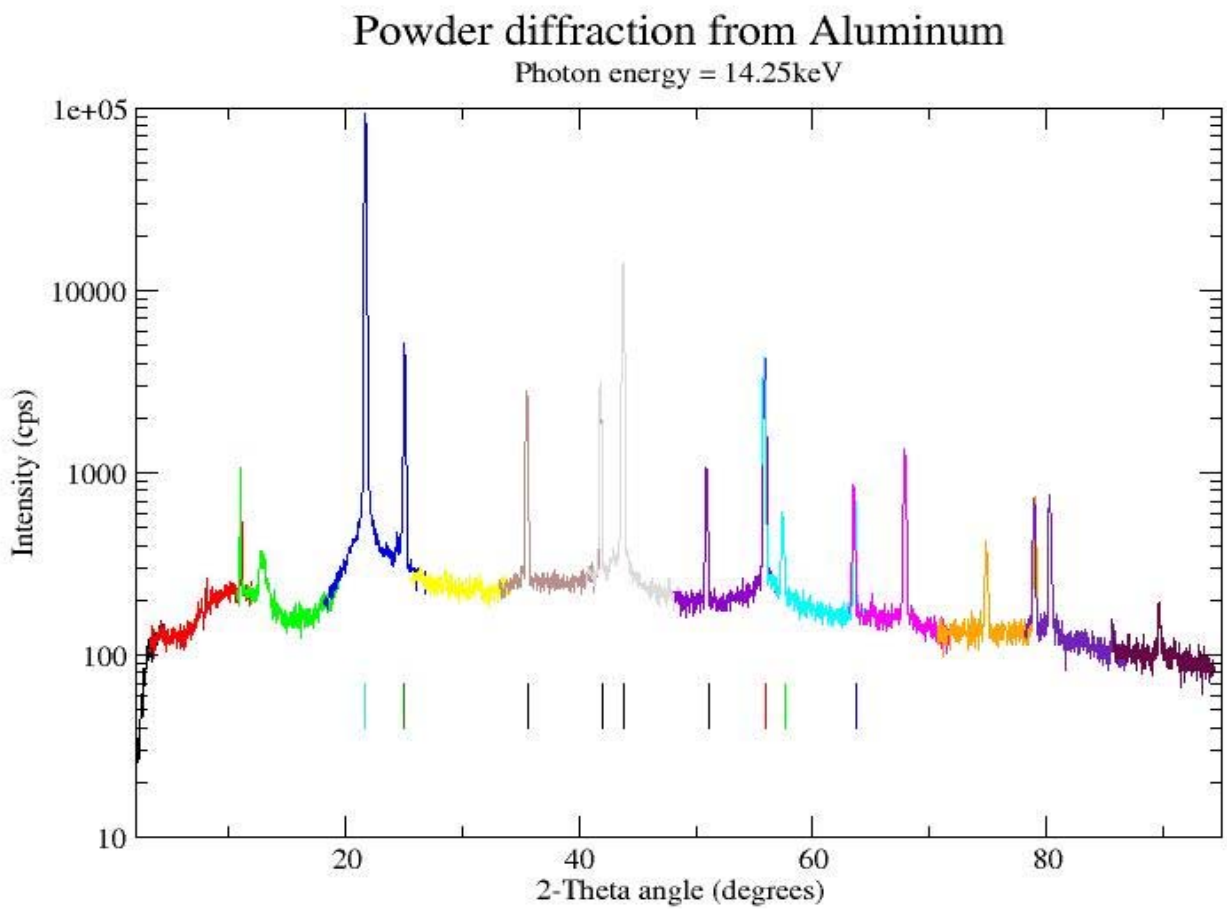
MEDM user interface

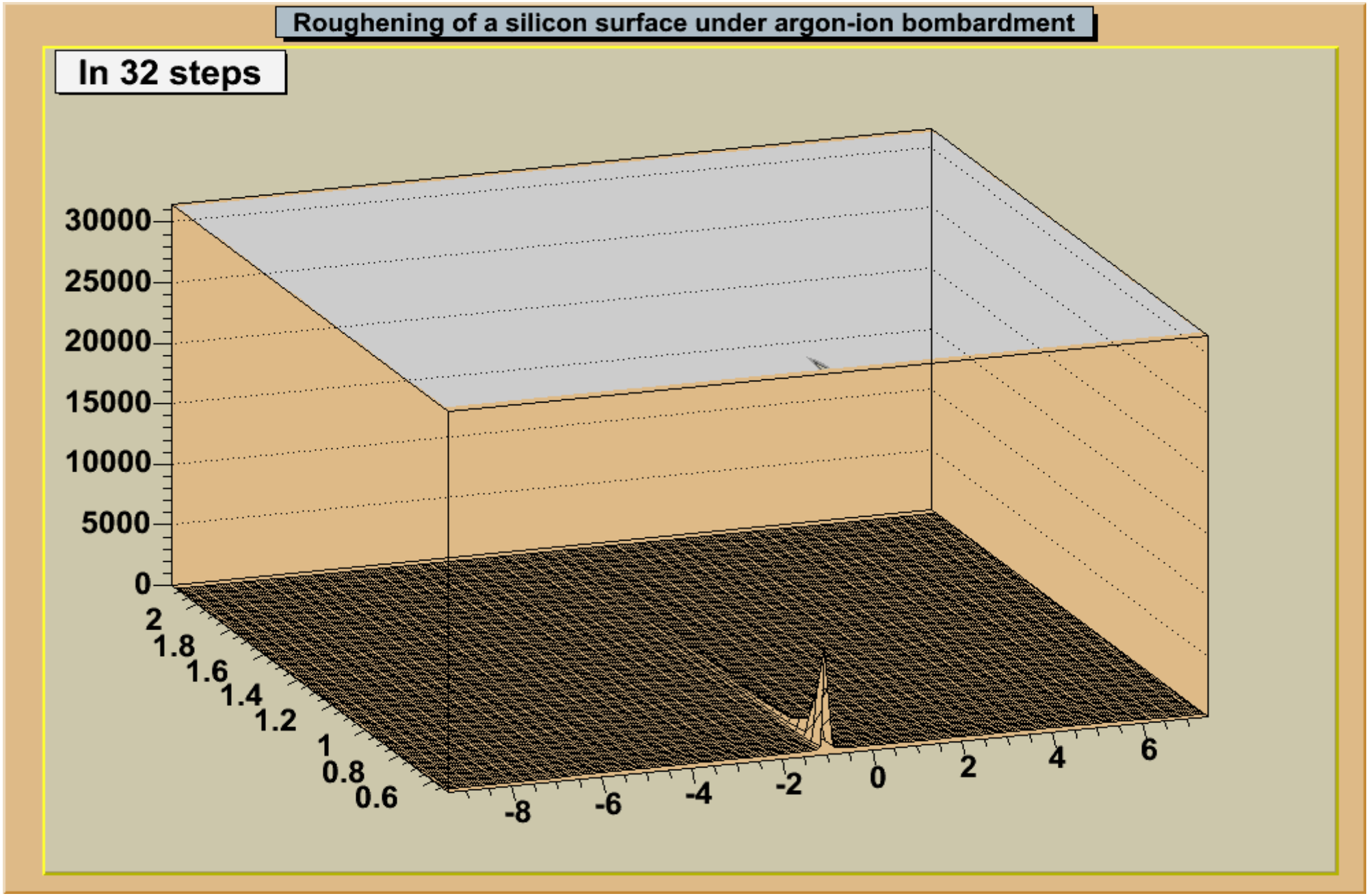
- SOFTWARE IS IMPORTANT!!!
- Standard EPICS facilities allow quick GUI development, much easier than conventional GUI toolkits.
- Device looks very similar to the standard EPICS scaler device, but with many more channels and additional detector control functionality.
- Thresholds set via on-board DACs accessed as 'ao' records.



Powder diffraction

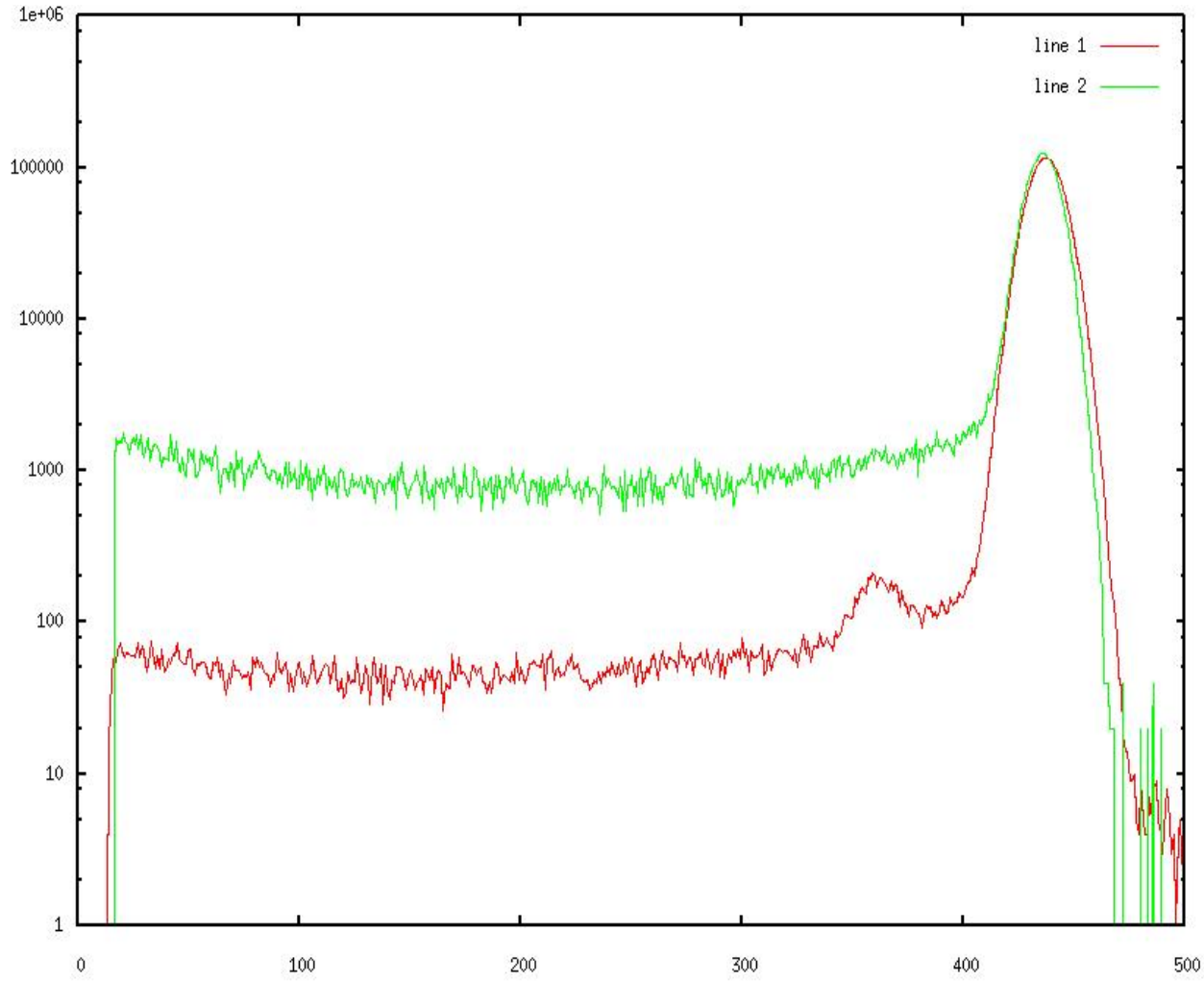
- Detector length = 40mm
- Sample-detector distance = 263mm
- -> 8.7 degrees coverage, 0.03 degrees / strip.
- 13 measurements spaced 7.5 degrees apart, each 1 second count time.
- Total 20 sec. scan.




Roughening of a silicon surface under argon-ion bombardment
In 32 steps
30000
25000
20000
15000
10000
5000
0
2
1.8
1.6
1.4
1.2
1
0.8
0.6
-8
-6
-4
-2
0
2
4
6

Charge-sharing

- Pinhole collimator measurements:
  - Green curve near edge of pixel
  - Red curve at center of pixel
- Primarily a geometrical problem
  - Absorption mask to cover gaps
  - 'Trenching' to physically separate pixels, at least on entrance side.

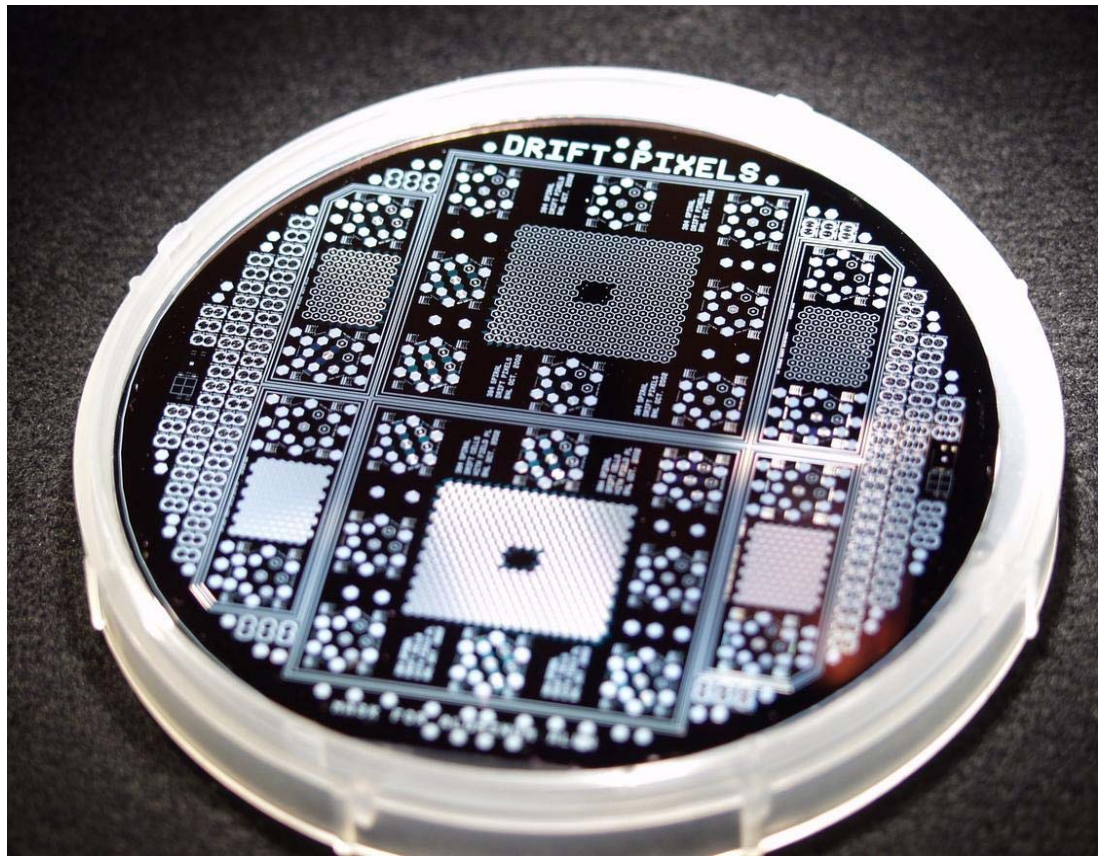


Next step

- Try to replace pad detectors with drift detectors.
- Work towards a system providing full spectrum per channel, instead of hardware windows
  - Same low-noise analog front-end
  - Integrate BNL Peak-detect / derandomizer module, modified for time-over-threshold mode (pileup rejection).
  - Fast ADC + FPGA + CPU to process data
  - Real-time processing

Detector array

- Mult-element array
  - **400-element drift detector array**
    - Drift detector provides improved resolution at high rates
  - Central hole for incident beam
- Multi-channel ASIC
  - 32 channels
  - <200eV resolution
  - Pileup rejection circuit



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Quantitative PIXE Real-time Imaging and its Application to Imaging using the Synchrotron X-ray Microprobe

Chris Ryan[1], Barbara Etschmann[1], Stefan Vogt[2], Jörg Maser[2], Cathy Harland[2]

[1] CSIRO Exploration and Mining, Clayton VIC, Australia

[2] Advanced Photon Source, Argonne National Laboratory, Argonne IL, USA

Work supported by:

U.S. Department of Energy, Office of Basic Energy Sciences

Australian Synchrotron Research Project

Real-time Elemental Imaging ...

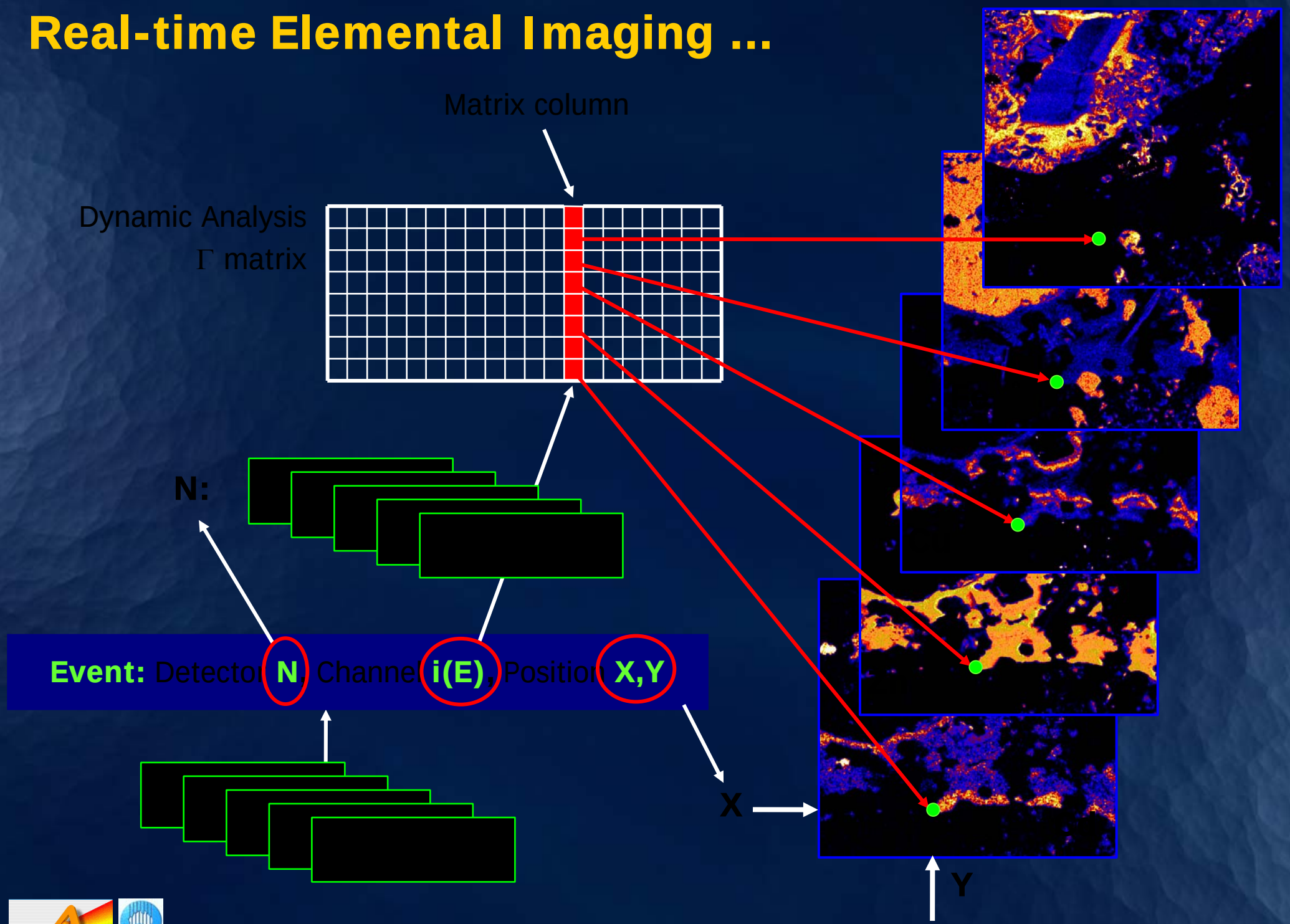
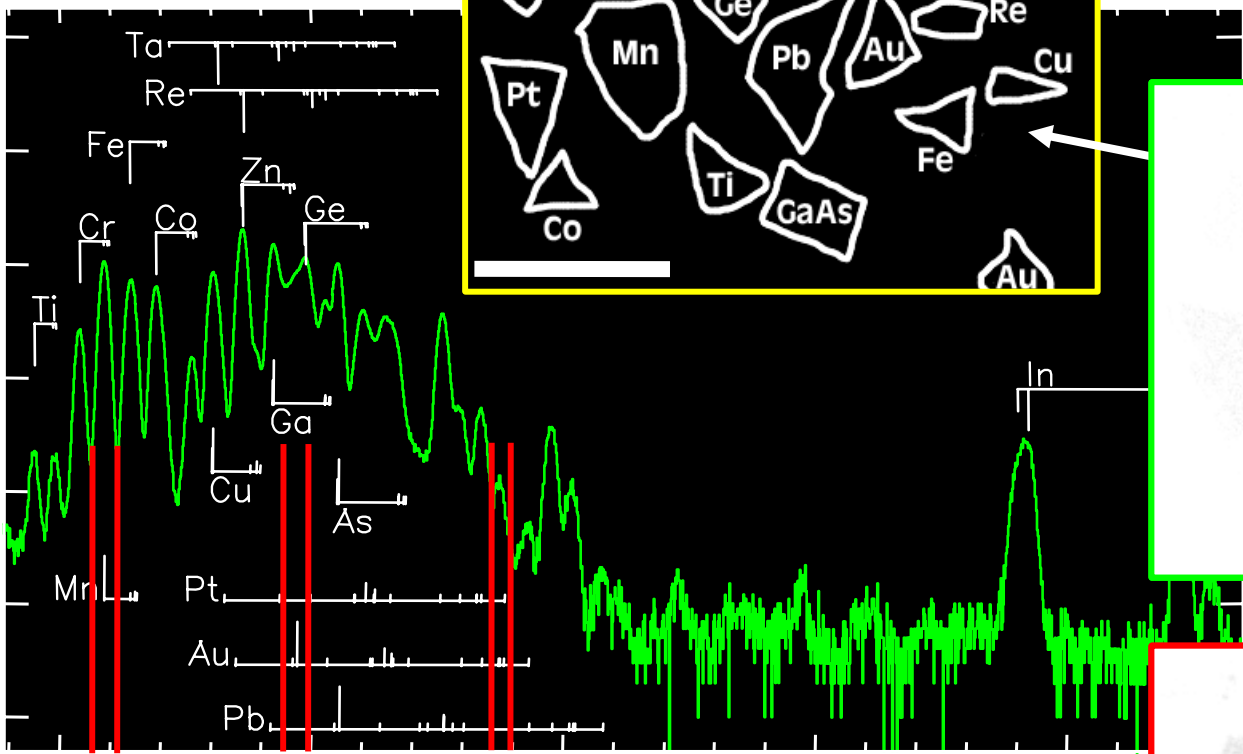
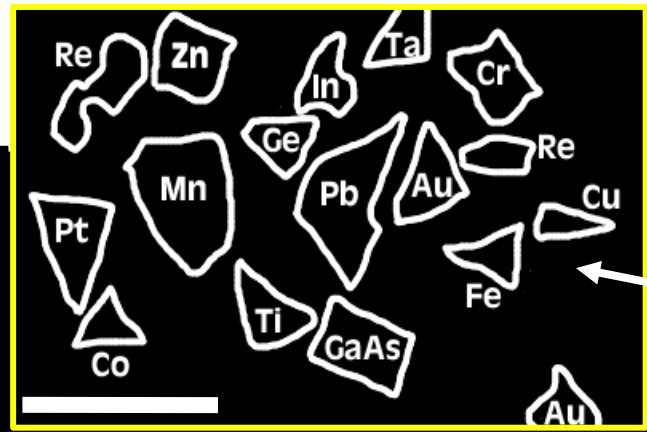


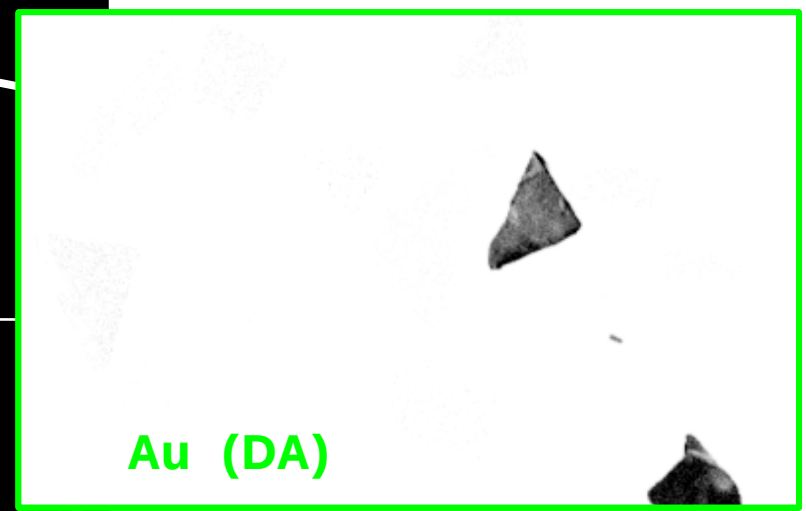
Illustration of Dynamic Analysis using PIXE

3 MeV protons

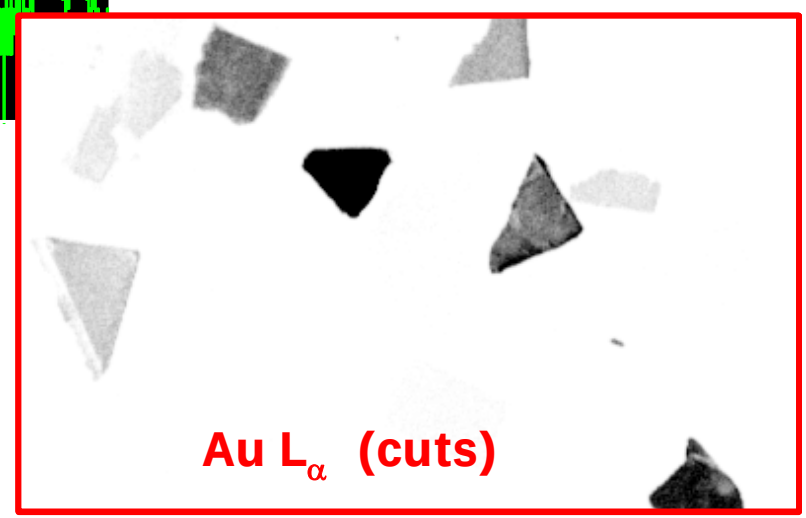




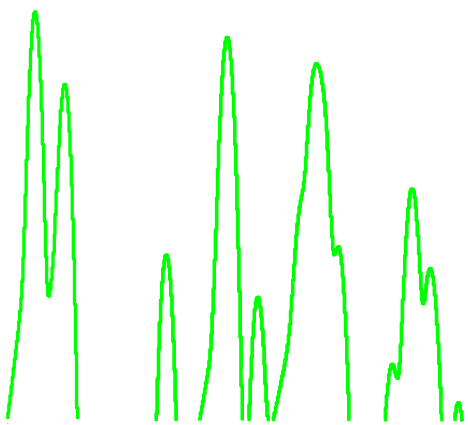
Map



Au (DA)

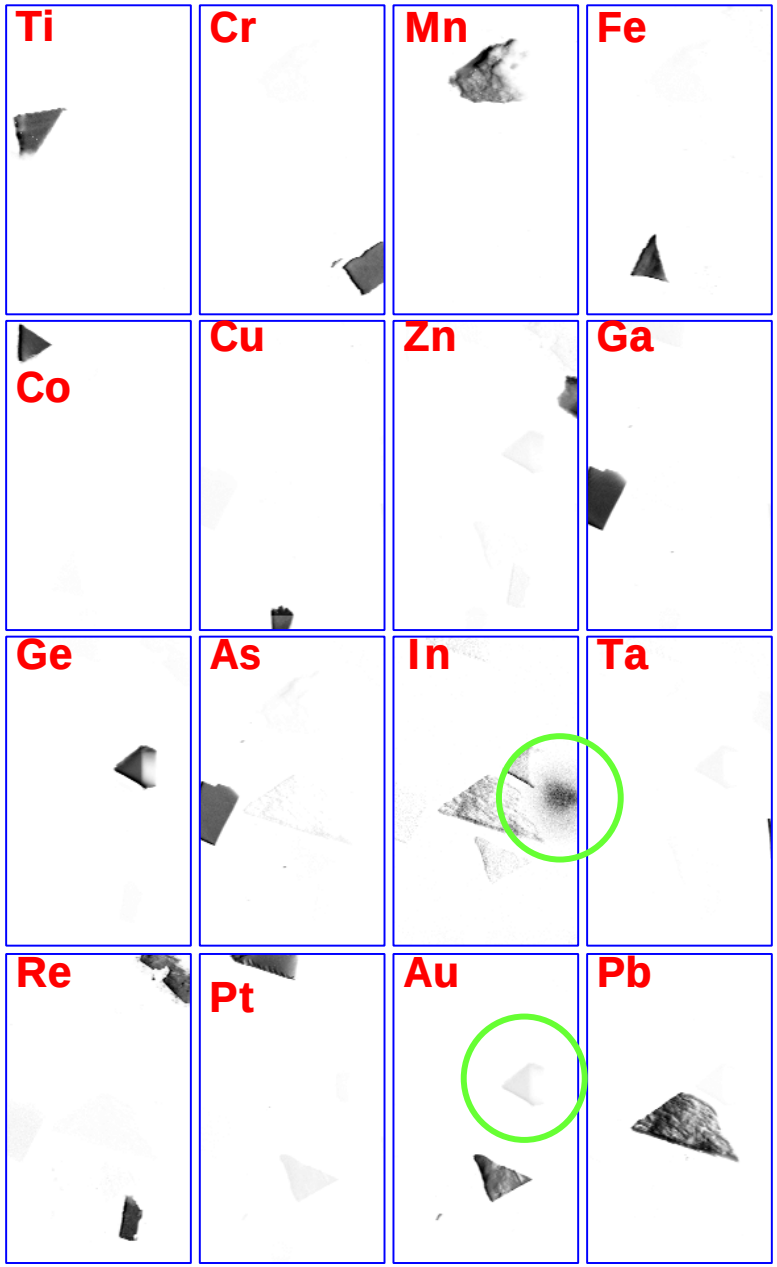


Au L_α (cuts)

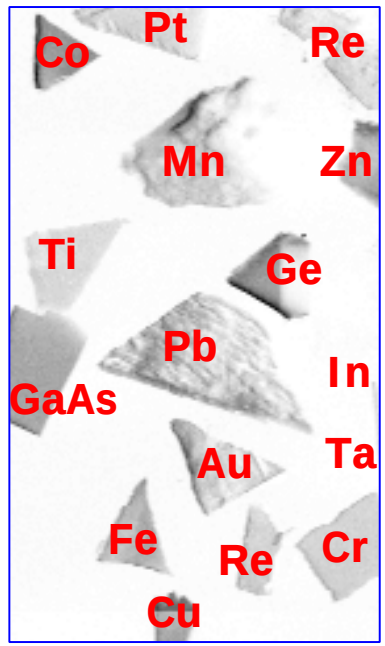


Test of Dynamic Analysis using SXRF

Dynamic Analysis

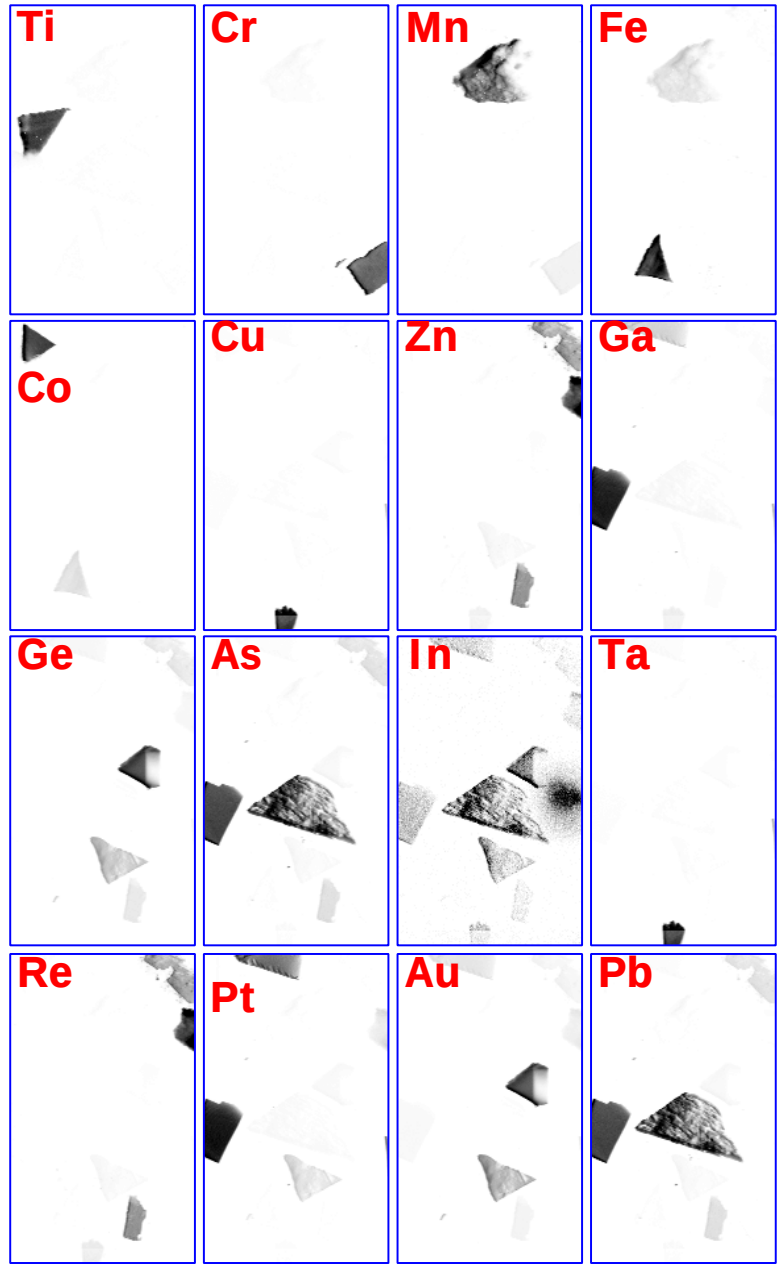


Map



16.1 keV photons

Simple Energy Cuts



1ms readout active-matrix area detector

- Fully pixellated detectors are complicated
- Hybrid (bump-bonded) devices add fabrication difficulties
- Monolithic devices built on high-resistivity silicon provide simplest structure
  - No bump-bonding
  - Simplest structure is active-matrix type
    - row-by-row parallel readout
    - N readout channels instead of N x N
  - Need to provide low-resistivity layer to fabricate readout structures

Pixel structure

- Low-resistivity layer is formed by deep implant.
- JFET switches are fabricated in this layer
- Charge is produced by photoionization
- Electrons collect under pixel (switch is OFF)
- Charge is read out by turning transistor ON, connecting stored charge to a buss-bar, and read out by a charge-sensitive amplifier.

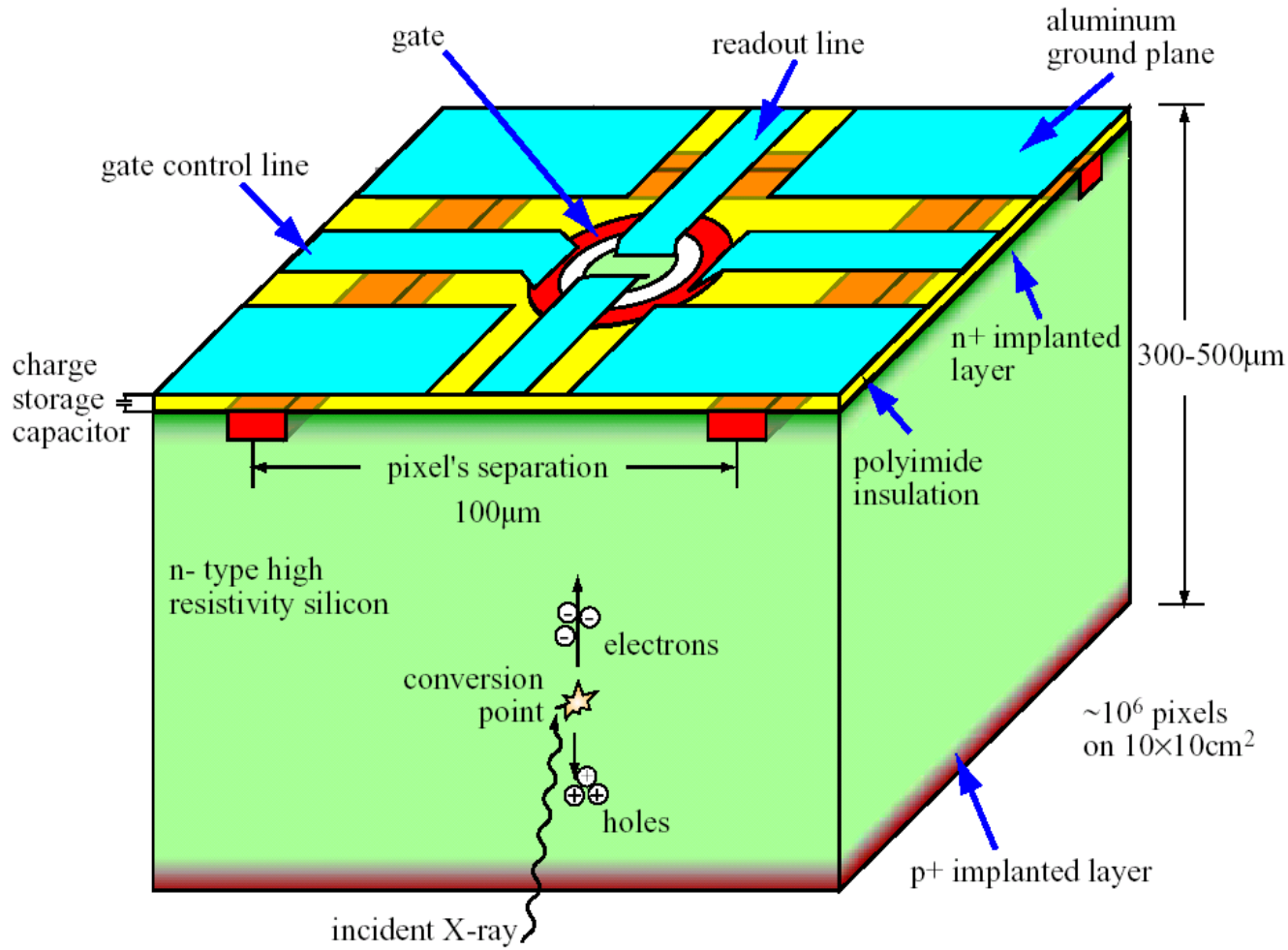


Figure 6. One pixel from an Active Matrix Pixel detector array. The device is fabricated by forming a low-resistivity silicon layer suitable for JFET switching devices on top of high-resistivity silicon optimized for detector fabrication. The JFET transistors formed in this layer are used to row-sequentially switch the collected charge into column output amplifiers.

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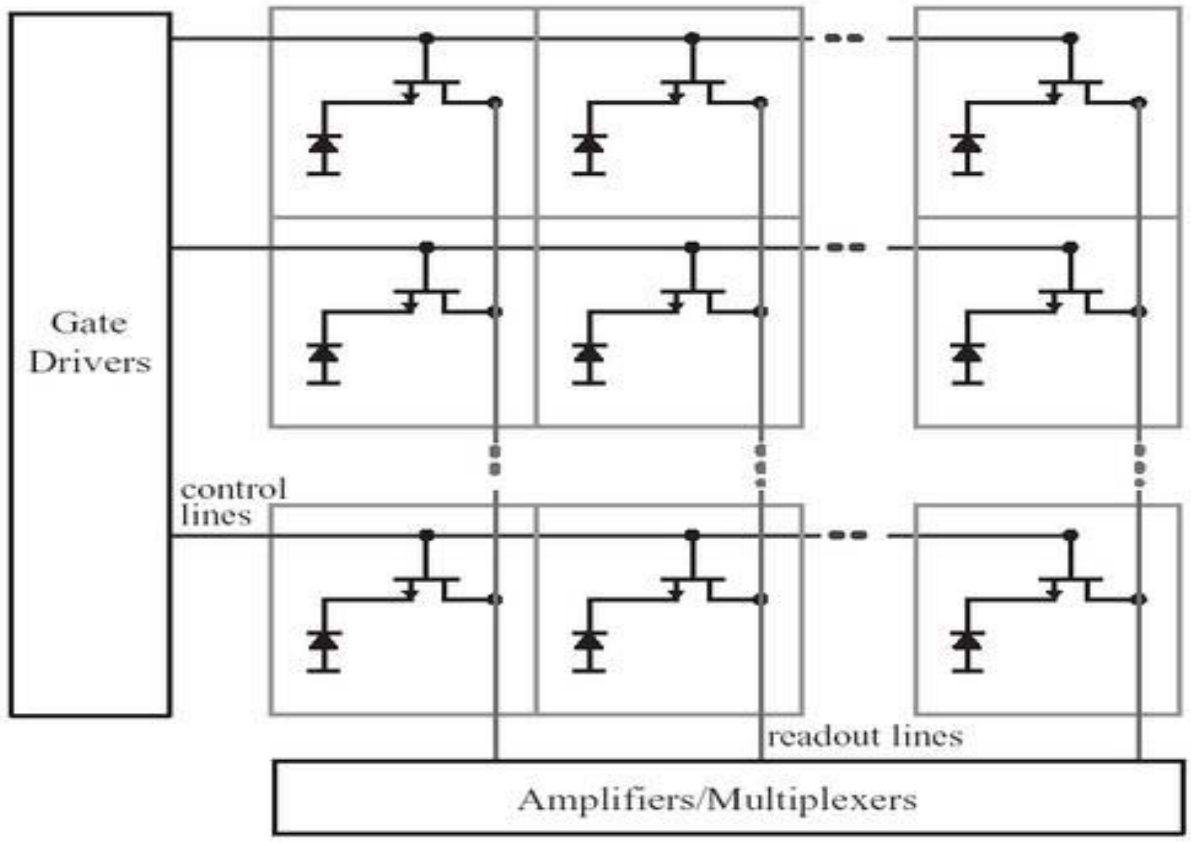
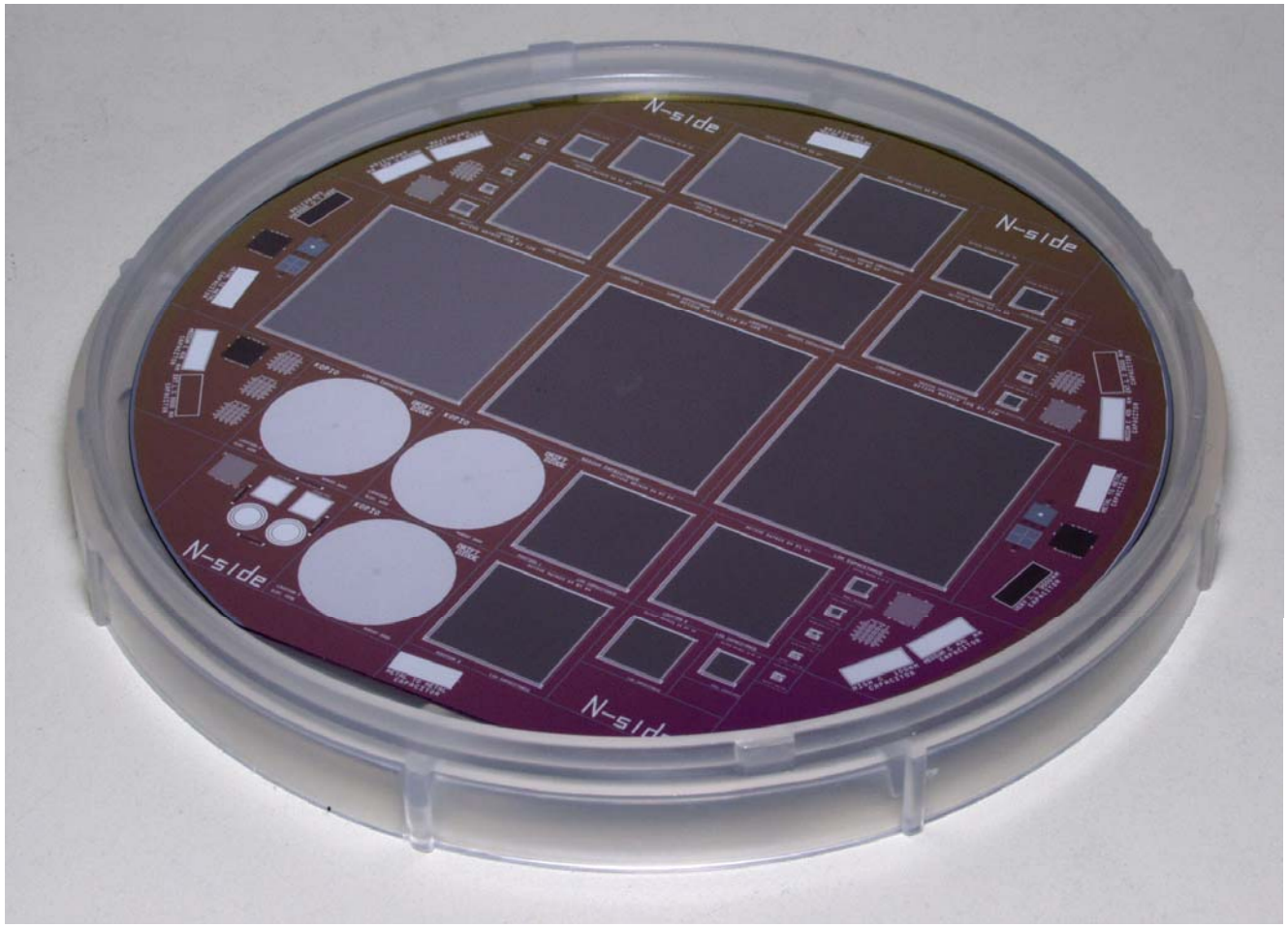
Active matrix readout

- Charge stored in diode capactance (switches off)
- Readout amplifier/ADC on each column
- Switches turned on sequentially row-by-row
- Charge read out and digitized
- 1us per row => 1ms for 1000 rows.
  - 8-channel 40MHz/channel ADC chip exists
  - 32 chips, each ADC multiplexed among 4 columns
  - 2Gb/s data rate



View of a completed wafer



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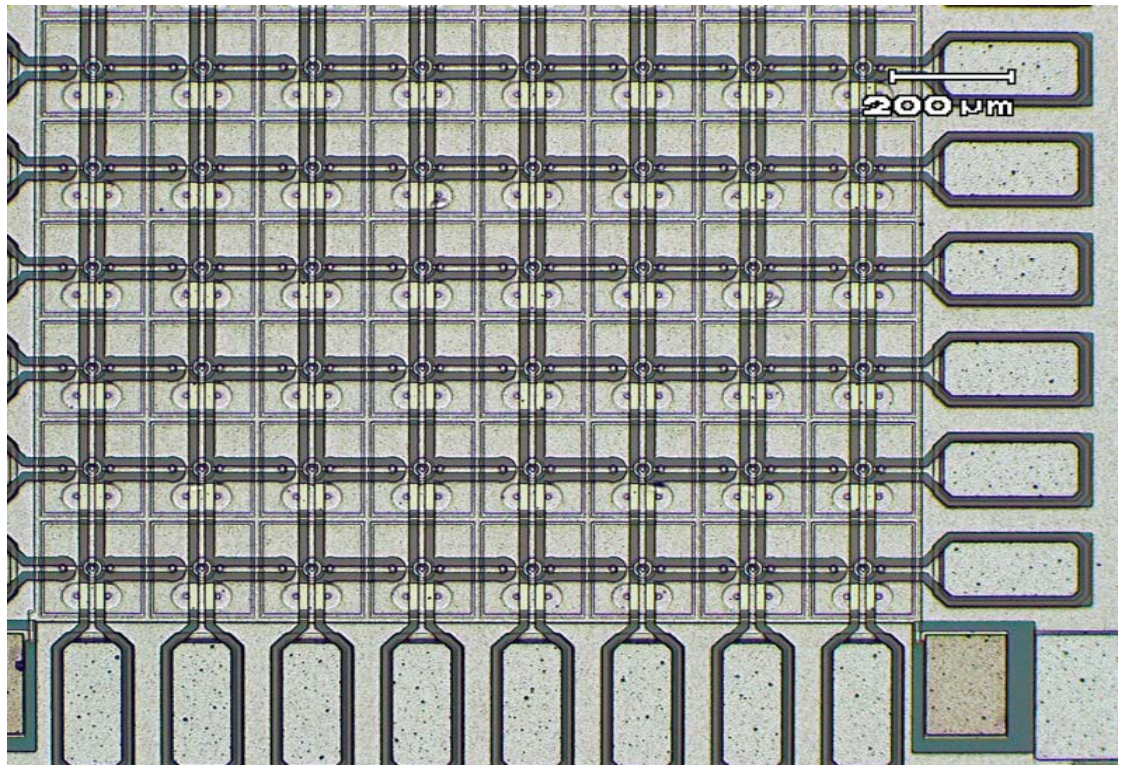
Prototype device

- Part of an 8 x 8 pixel test device
- 180 um square pixels



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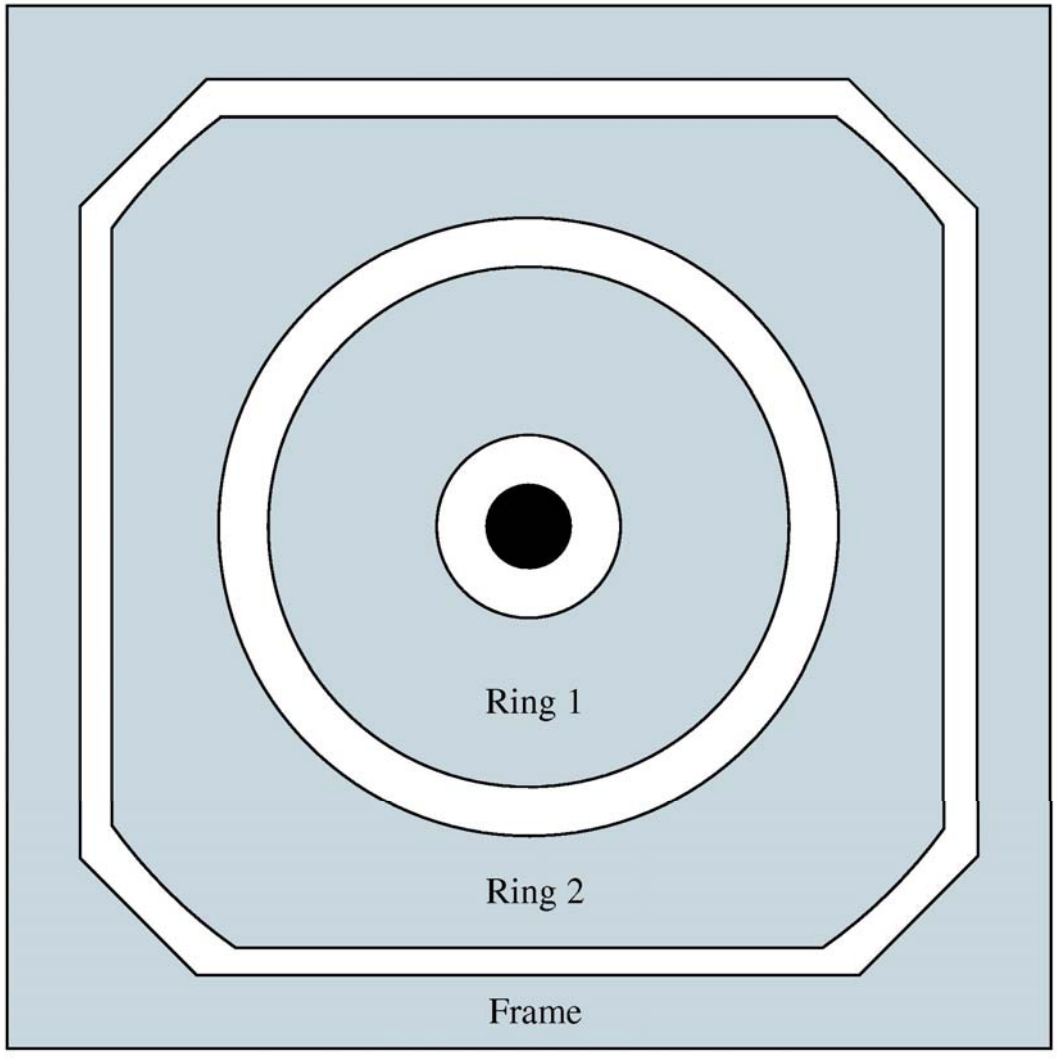
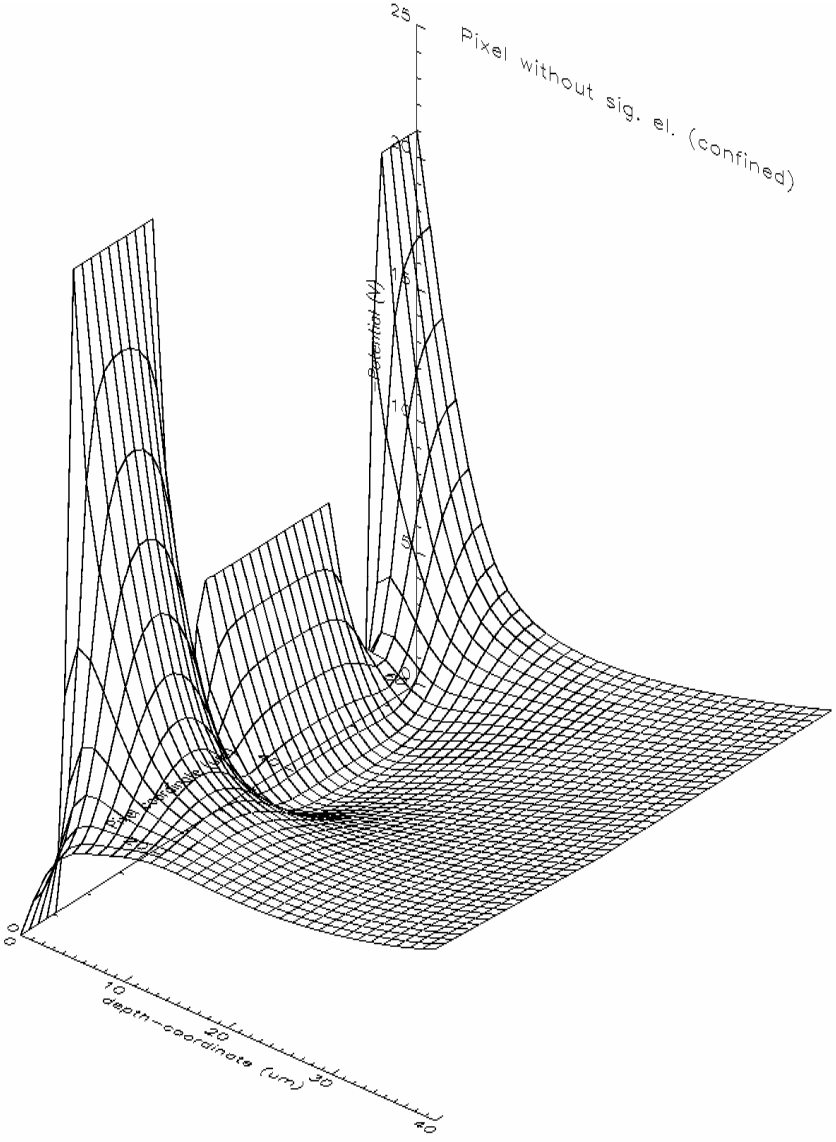
Alternative small-pixel structure

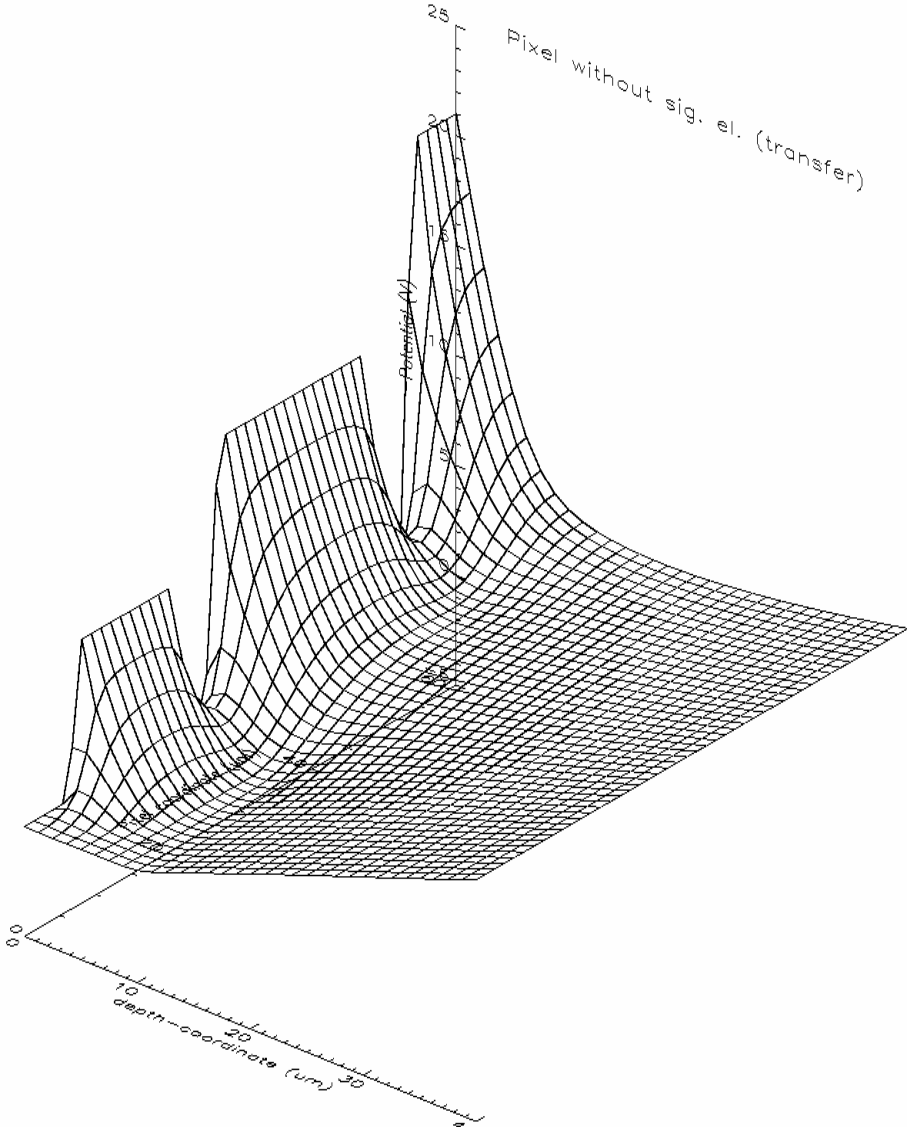
- Small pixels are difficult with transistor switch
- Charge can be stored in potential well and released in a controlled way, similar to drift detectors.
- This 'charge pump' technology is ideal for speckle applications.

Top view of a pixel with a charge pump single transfer



Charge pumping (no transistor)





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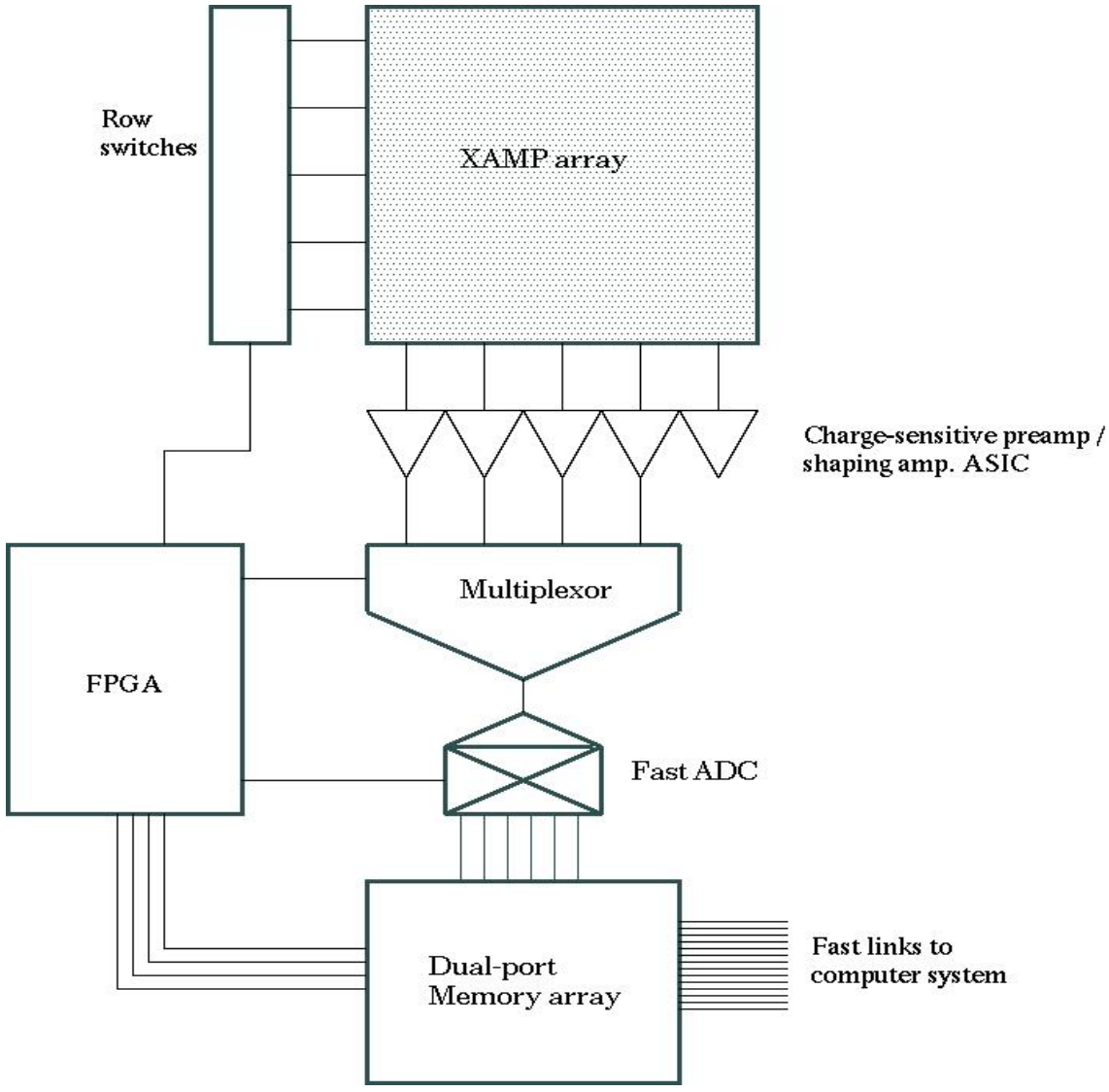
Readout system

- Row-by-row readout, 1us/row
- 32 Fast (>20MHz) 8-channel ADC's multiplexed e.g. x4 = 1024
- 2Gb/s
- Data streamed through FPGA to fast memory and terabyte disk store.



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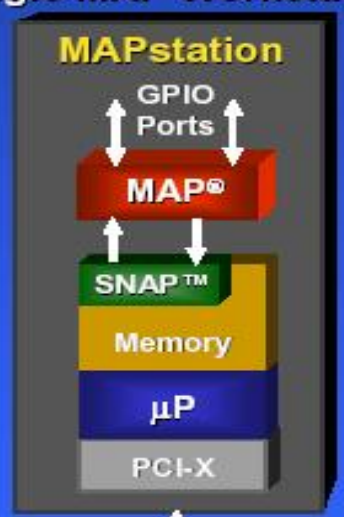
SRC MAPstation™

SRC-6 uses standard external network connections

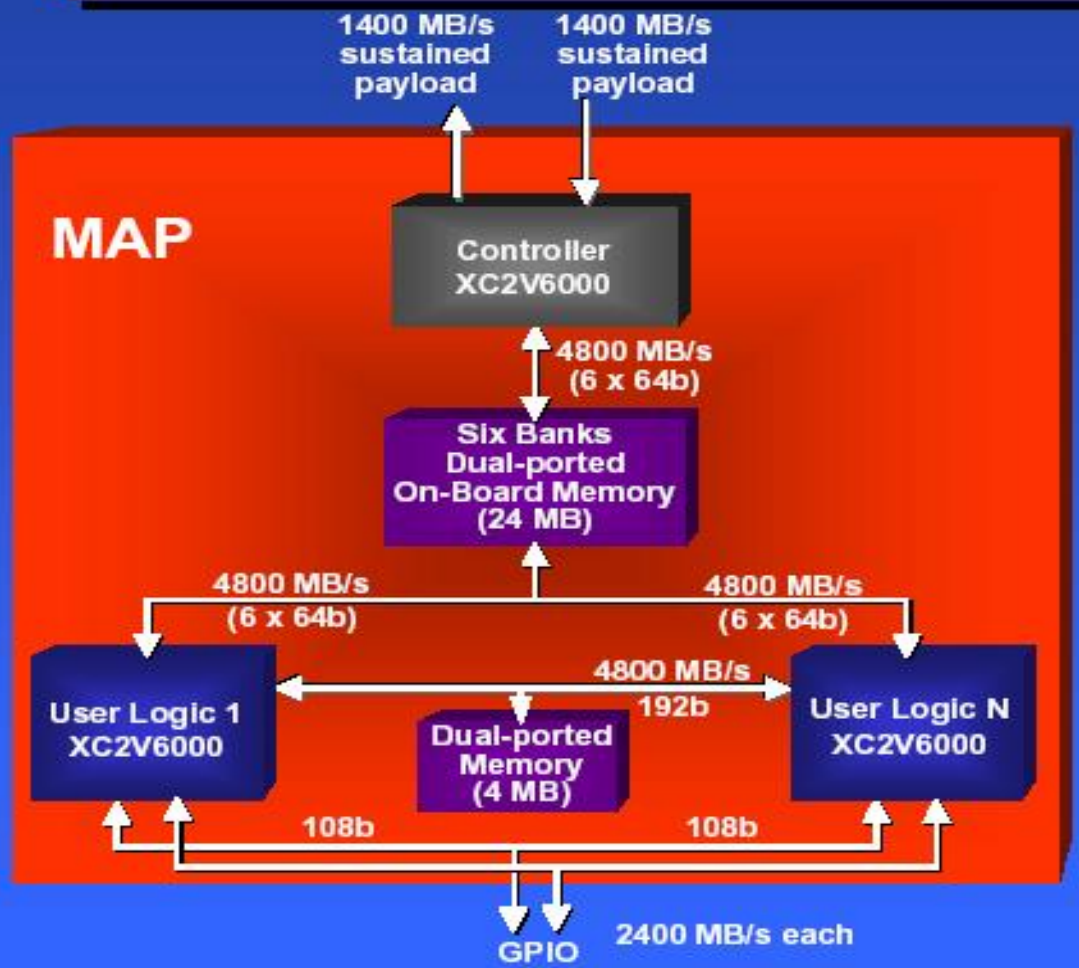
Single MAP Workstation



MAPstation Configurations

 www.srccomputers.com

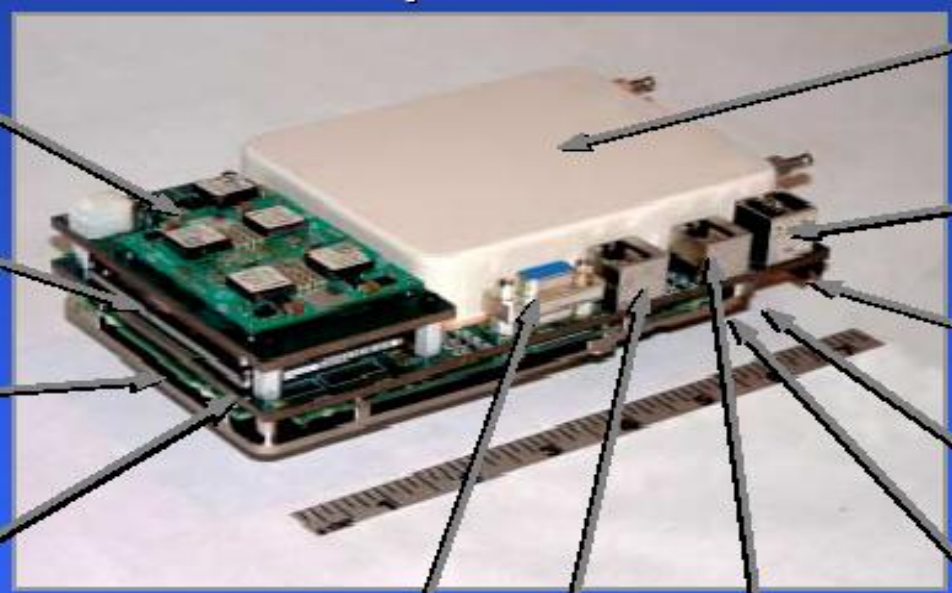
MAP® Implementation



- Direct Execution Logic (DEL) made up of one or more User Logic devices
- Control circuits allow explicit control of memory prefetch and data access
- Multiple banks of On-Board Memory maximizes local memory bandwidth
- GPIO ports allow direct MAP to MAP chain connections or direct data input
- Multiple DMA engines support
  - Distributed SRAM in User Logic
    - 264 KB @ 844 GB/s
  - Block SRAM in User Logic
    - 648 KB @ 260 GB/s
  - On-Board SRAM
    - 28 MB @ 9.6 GB/s
  - Microprocessor Memory
    - 8 GB @ 1400 MB/s

Embedded Compact MAP® System

Top View



Overall dimensions are 1.6 inches H x 4.5 inches D x 7.5 inches W

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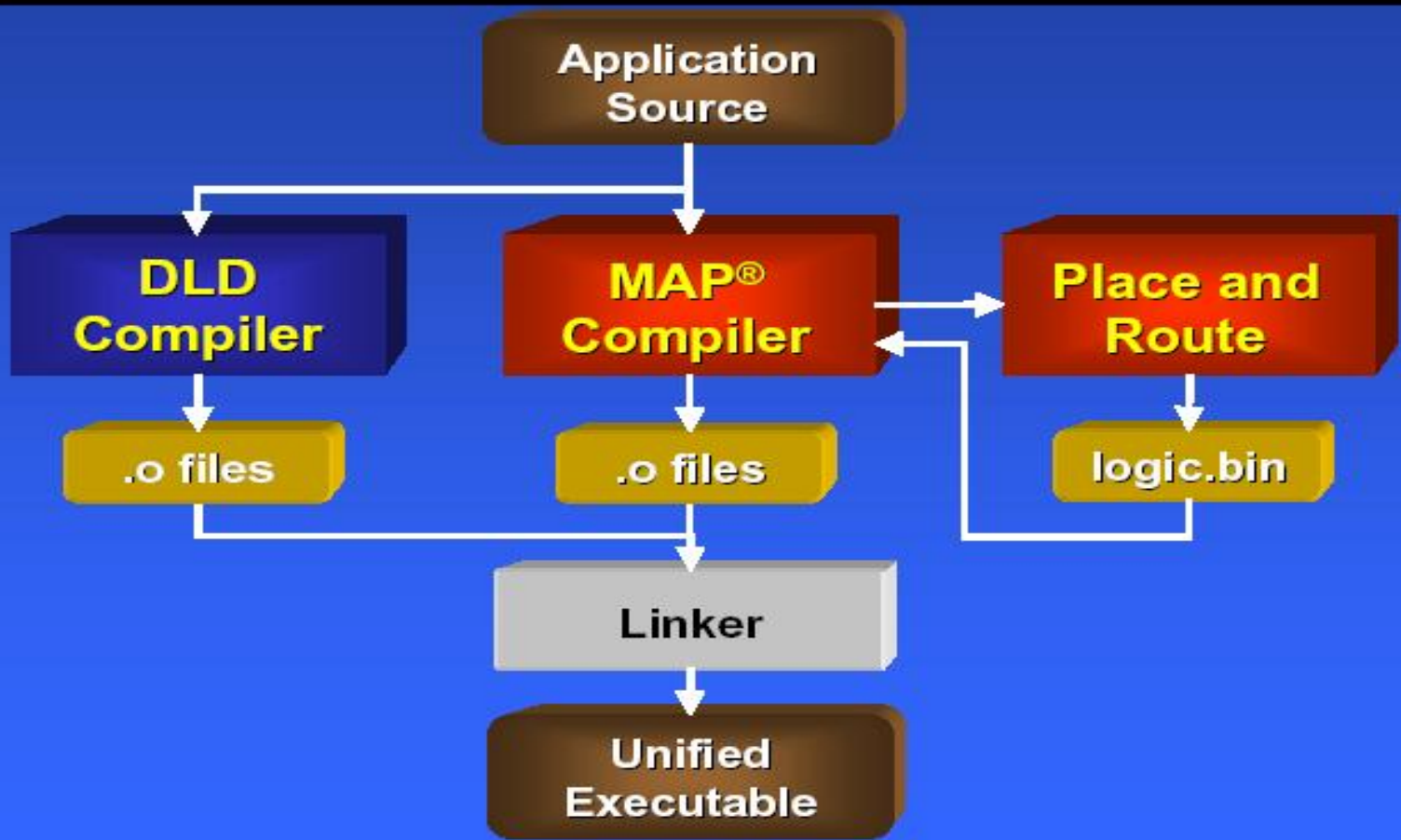
Compilation and Linking



Summary

- A path to satisfying the needs of current and next-generation microprobes exists
  - Spectroscopy
  - Diffraction
  - Speckle
- The demand for higher-performance instruments is clear
  - Higher rate capability
  - Better throughput
  - better utilization of photons
  - Better (and real-time) analysis
- It will take all of us to push hard if anything is to happen.