Improved X-ray vision: Advanced Detectors for Synchrotron Radiation

D. Peter Siddons

NSLS,

Brookhaven National Laboratory,

Upton NY 11973

BNL Collaborators for SR Detector Development

- **Silicon detectors:**
  - **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).**
- **Gas detectors:**
  - **Tony Kuczewski, readout electronics and user interface (NSLS).**
  - **Graham Smith, Bo Yu, gas detector design (Inst. Div.).**
- **CZT detectors**
  - **Edson Kakuno (Univ. Fed. Parana, Brazil)**
  - **Giuseppe Camarda (NSLS)**
- **Technical help**
  - **John Triolo, Gene Von Achen (Inst.) , Denis Poshka (NSLS)**

Outline

- SR motherhood
- Silicon spectroscopy detector
- Curved high-speed proportional PSD
- CZT-based arrays
- Avalanche photodiode package

What's the problem?

- SR sources have increased their brightness by 10^n, but our detector systems haven't changed.
- Physical limits of samples are beginning to become apparent, so inefficient experiments cannot be compensated for by building bigger sources.
- Experiment designs need to become more sophisticated, particularly in photon utilization.

A new phenomenon: big little science

- There are two ‘camps’ of experimental science
  - Big
    - Large teams of scientists working collaboratively to perform an experiment which needs massive resources, and typically uses a large machine (SLAC, CERN, FERMILAB, RHIC etc.)
  - Little
    - Typically one or two scientists, performing experiments in a single room with table-top equipment, usually at a University or College.
  - Usually the two never interact

Until Synchrotron Radiation

- Uses a large particle accelerator to produce light
- ‘light’ means more than just the stuff you can see.

So that's the 'big-little' thing.

- SR has forced "little" scientists to learn how to work in a "big science" environment.
- SR is produced by a large accelerator which operates with an antisocial schedule
- Building and running a beamline is more than one person can handle alone, so collaborations get bigger
- Altogether a different sociology to University or College life.

Different sociology

- Different culture to HEP:
  - Physically small-scale experiments.
  - Small experiment teams
  - Low-budget (follows from first two points)
  - Wide range of science studied
  - Often, SR experiments are only part of a larger program.
  - Instrumentation development typically not rewarded by science funding agencies.

So why bother?

- SR is a fantastic source of radiation, in many regions of the spectrum it is irreplaceable.
  - It extends from IR to ‘gamma rays’
  - It is naturally highly collimated
  - It has a well-defined polarization
  - It is extremely intense
  - It is extremely bright
  - It is pulsed

So what can we do?

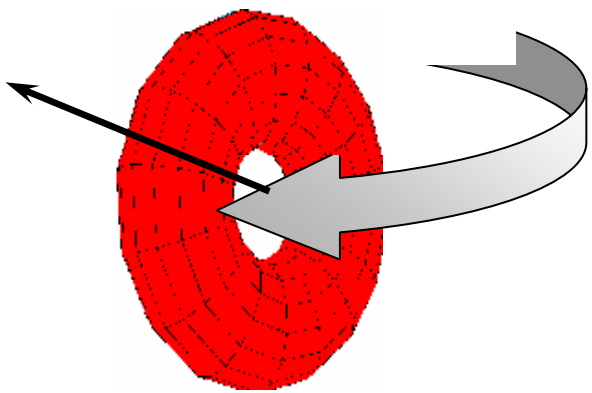
- Work with instrumentation experts to design better experiments.
- Press for funding to be made available for such developments.

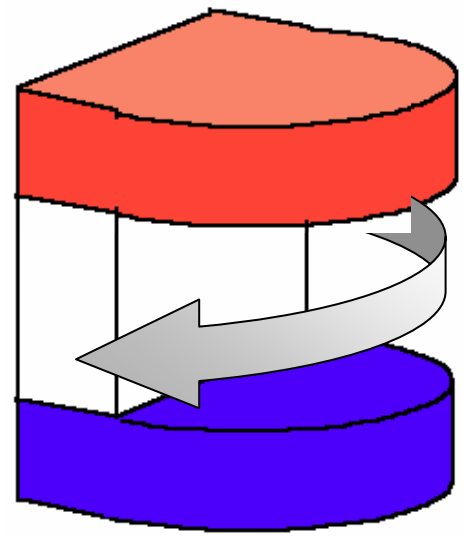
Advanced Detectors for Synchrotron Radiation

- Most detector systems in use at SR facilities are general-purpose simple devices, quite inadequate and inefficient.
- For many experiments, further increasing the source power to make up for the detector inefficiencies is no longer viable: *radiation damage* is becoming significant.
- We need a national effort to develop advanced detectors which make optimal use of modern technology to allow full utilization of the current sources.

Low velocity electron (v << c) . .

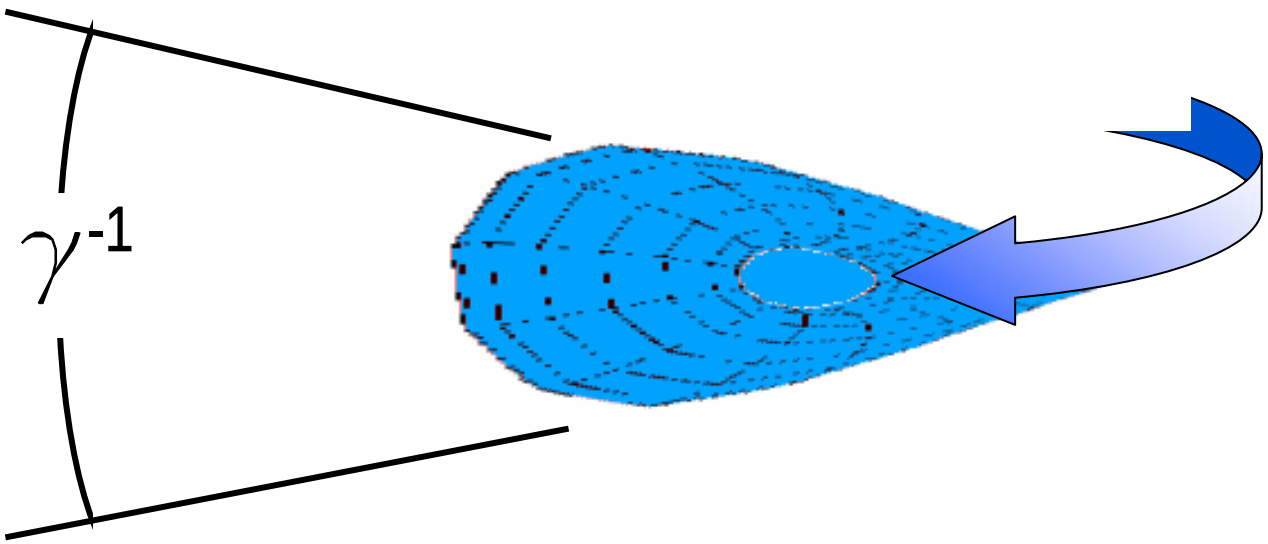
- Electron experiences centripetal acceleration
- Emitted radiation has dipole pattern



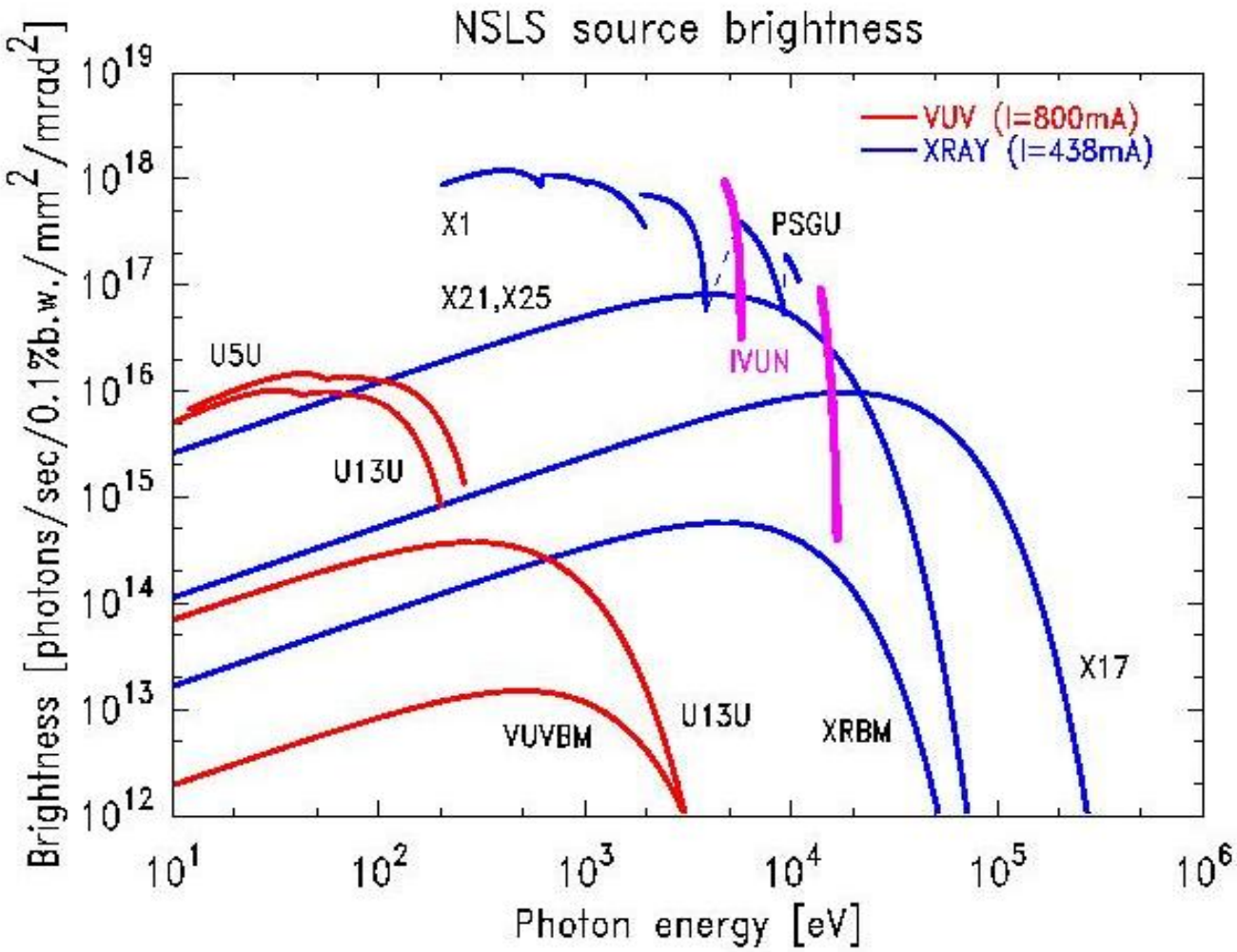


High velocity electron (v ~ c) . . .

- Relativistic effects take hold . . .
  - Emitted power dramatically increased
  - Spectrum shifts to significantly higher energies
  - Pattern strongly forward directed



Spectrum from NSLS beamlines



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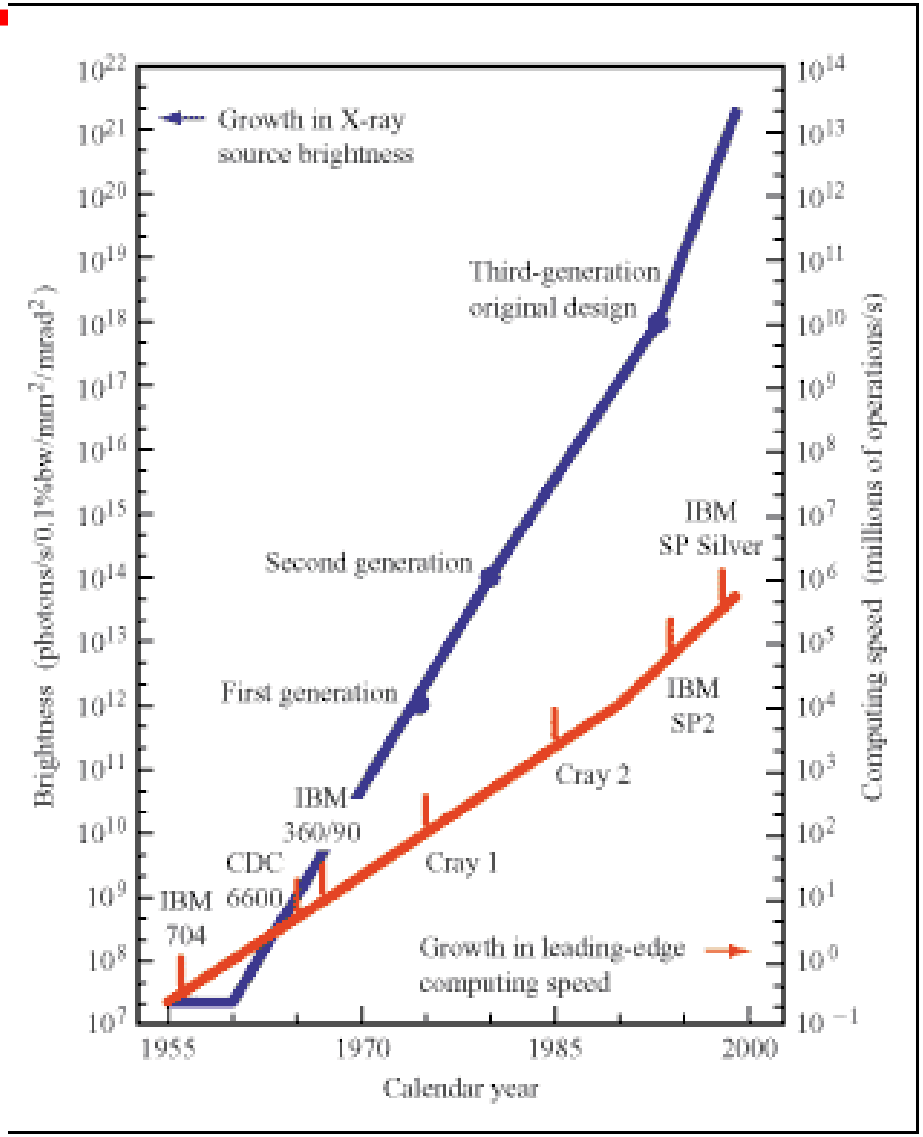
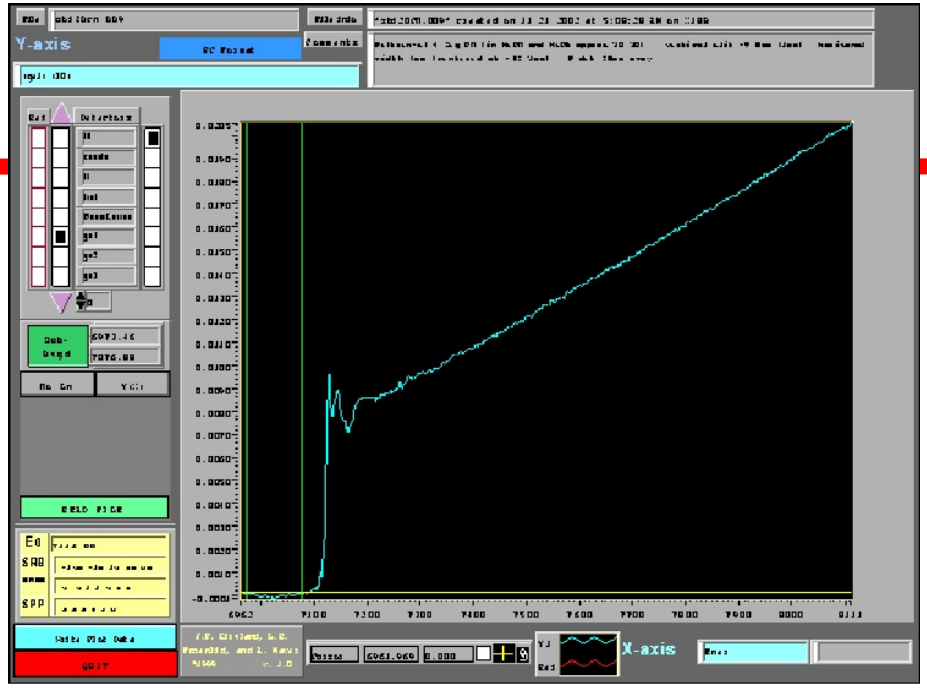
Growth in SR brightness with time

- Essentially no growth in conventional x-ray machines.
- Growth is faster than Moore's law!



The problem

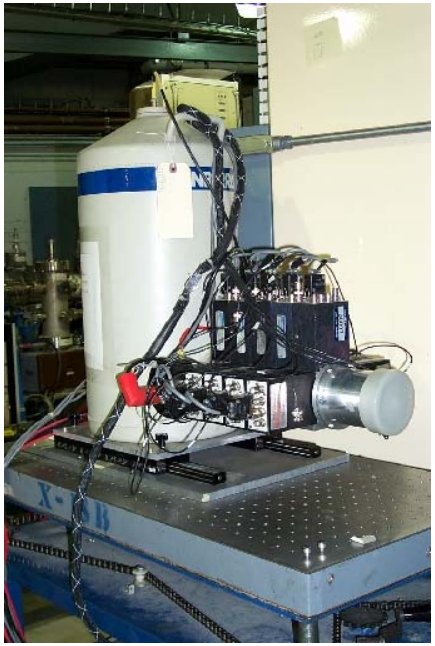


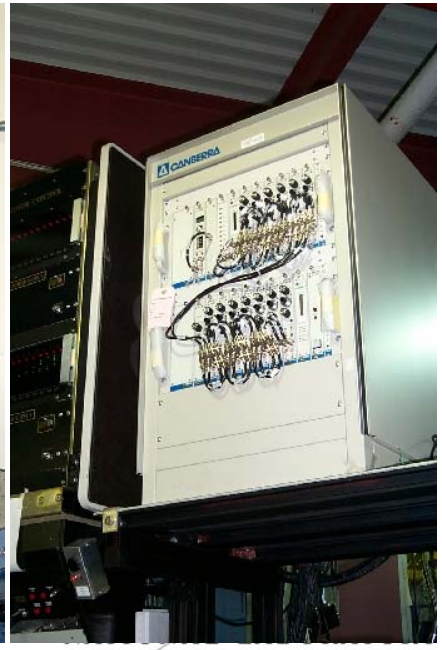
Spectroscopy:

- High rates
- S/N
- Coverage

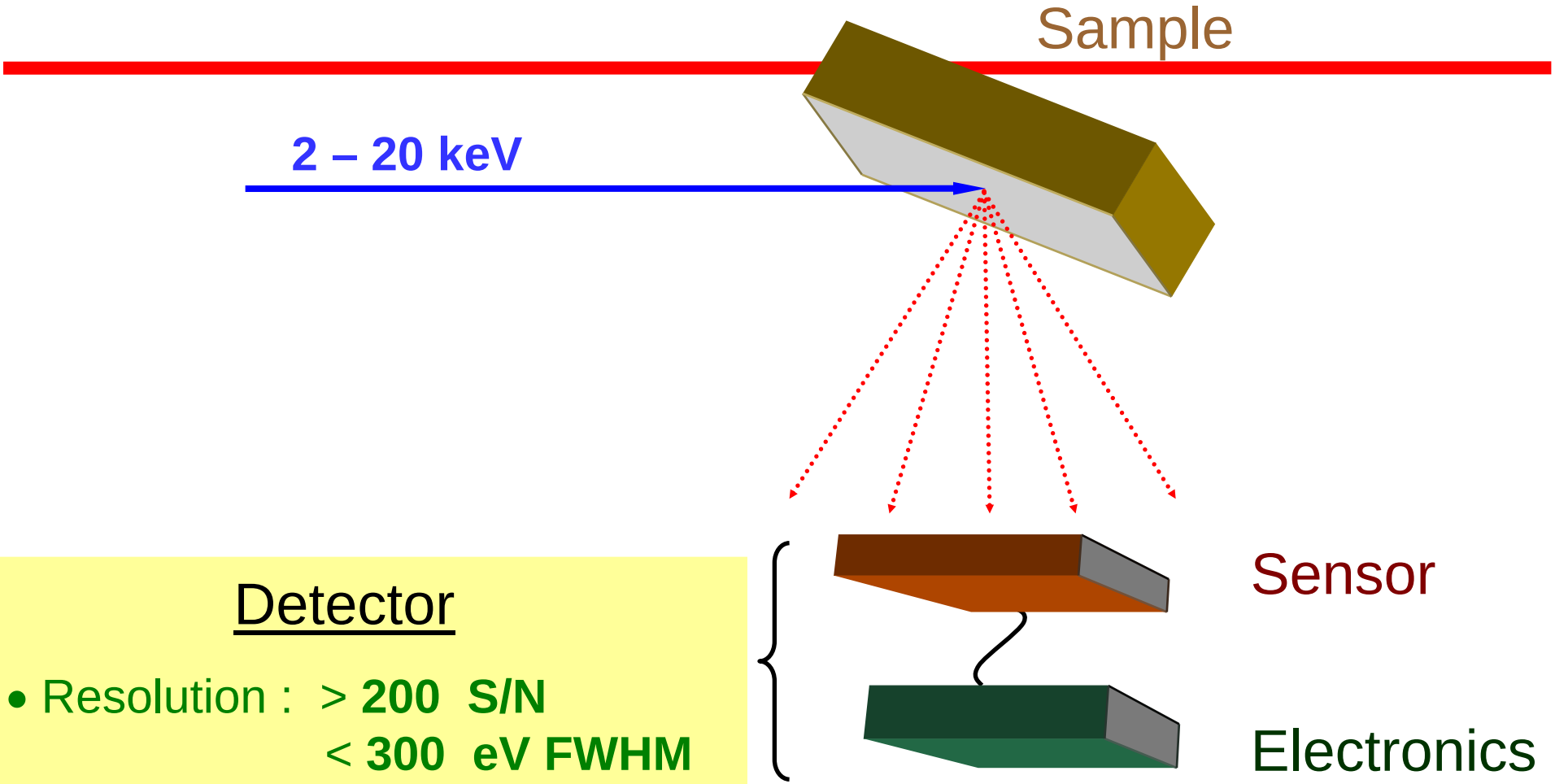
Diffraction:

- Resolution
- Speed
- Coverage
- High energies





Typical fluorescence EXAFS spectroscopy geometry



Detector

- Resolution : > **200 S/N**
  < **300 eV FWHM**
- Rate : > **10 MHz/cm^2**
  > **100 kHz/pixel**
- Spectroscopy (energy windows)

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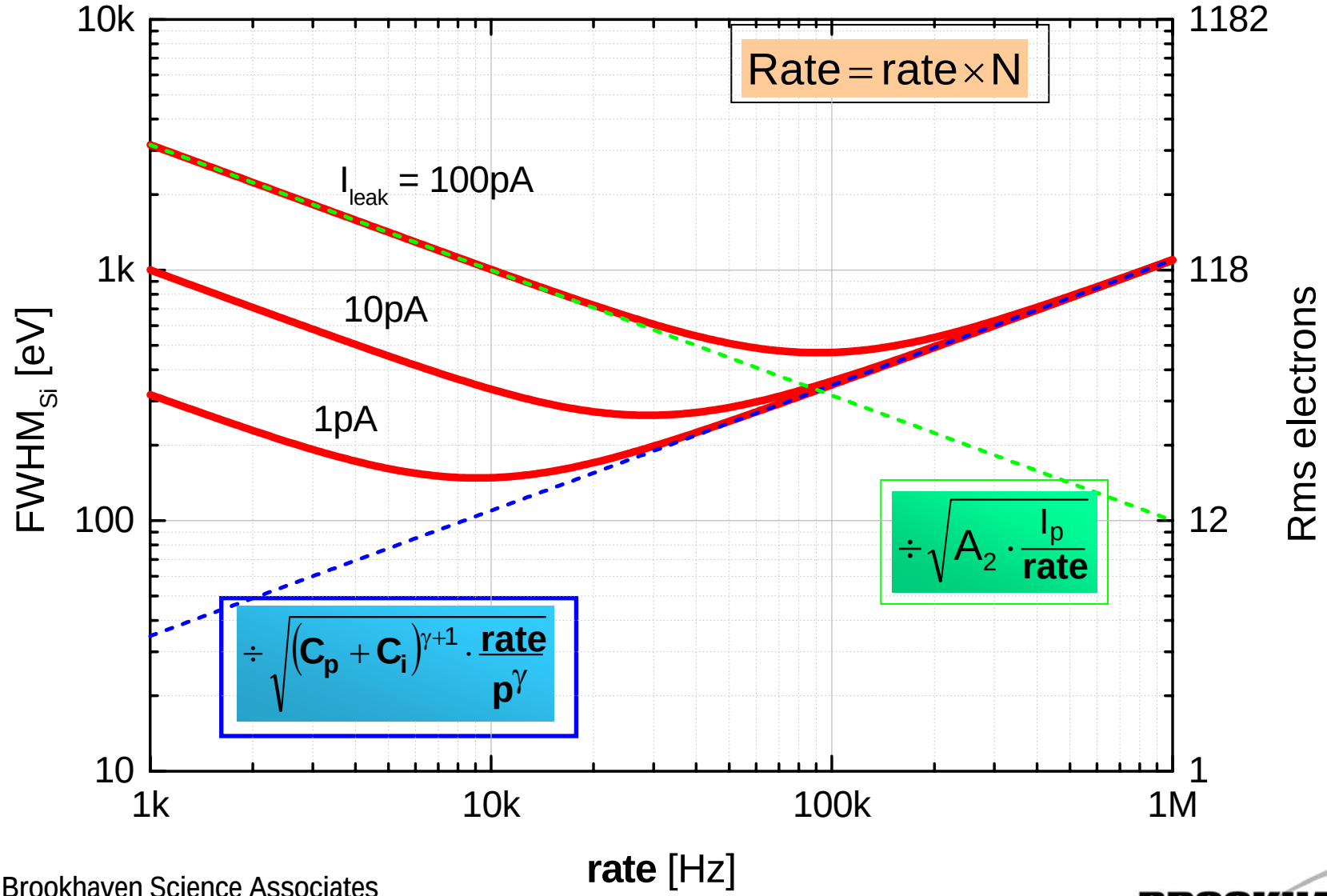
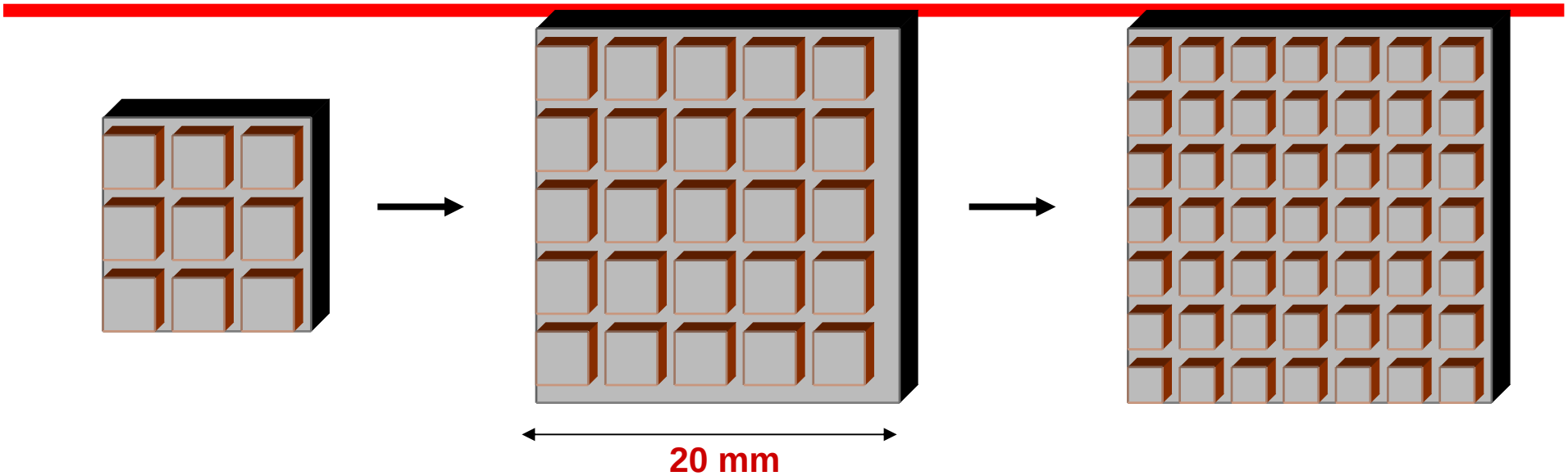
Resolution vs Rate



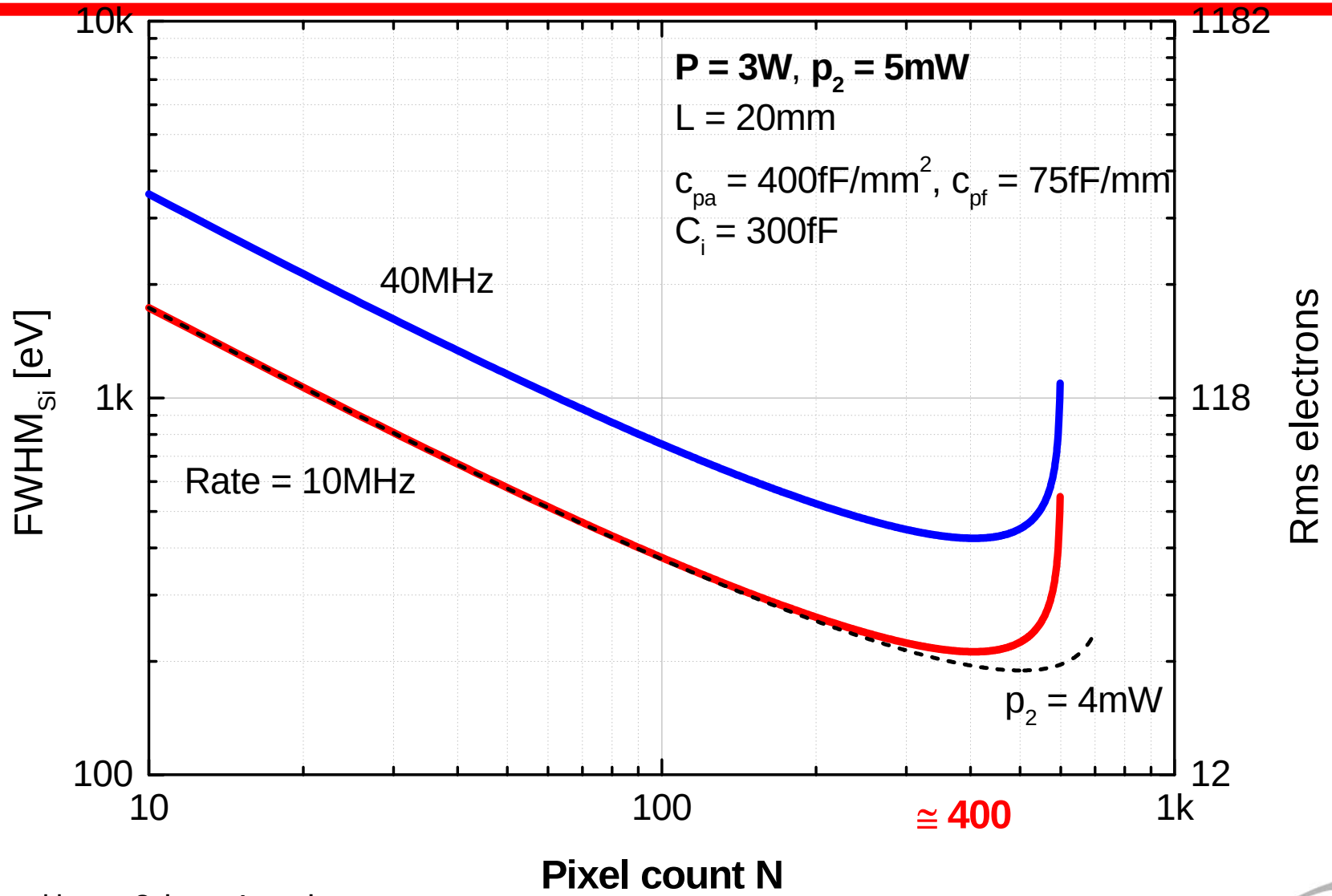
Optimum pixellation



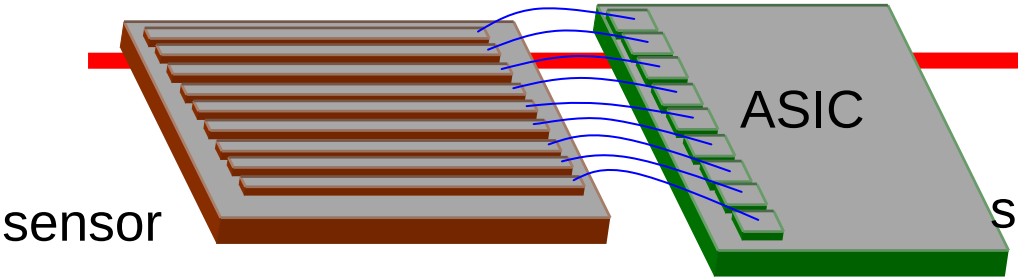
$$ENC^2 \div \left(C_p(N) + C_i\right)^{\gamma+1} \frac{\frac{Rate}{N}}{\left(\frac{P}{N} - p_2\right)^{\gamma}}$$

- charge sharing (≈20μm/side) and trapping (gap/side) : empirical

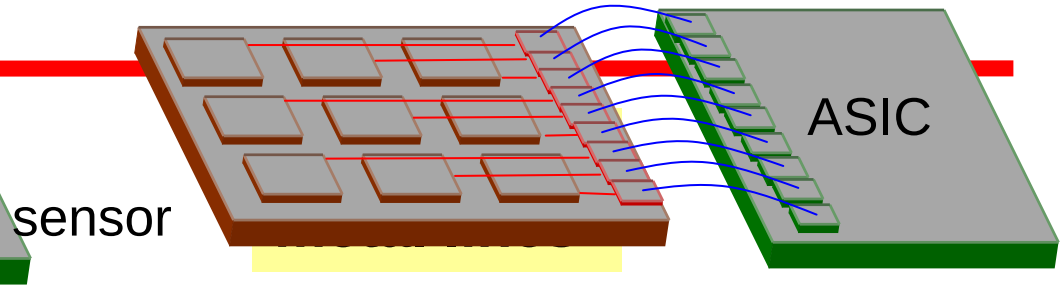
Optimum pixellation



Interconnecting pixel to front-end electronics

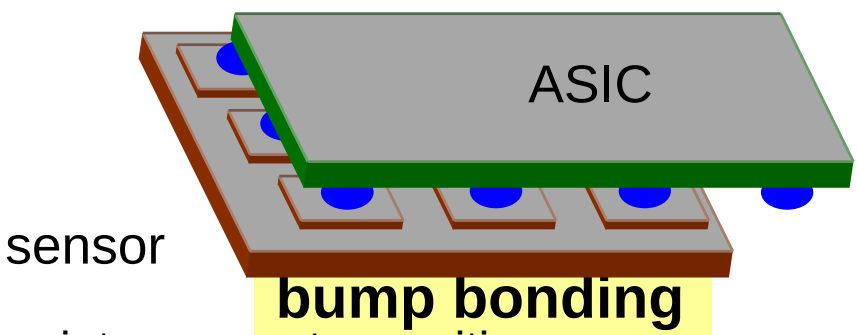


+ interconnect parasitic
+ bond length
- fringe capacitance
- <u>charge sharing and trapping</u>

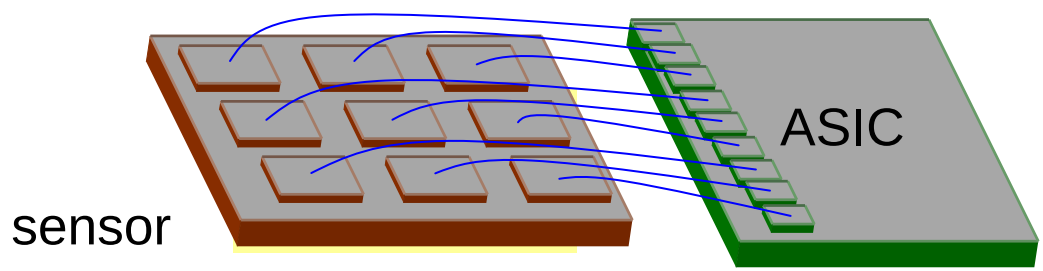


+ bond length
- interconnect parasitic
- <u>dielectric losses</u>

6mm×10µm, Si_3N_4 (ε_r=6.5,$tan(\delta)\approx$1m), 3µm,
δ**C_i≈1.2pF**
δ**$FWHM_{loss}$**$= 8.5/q\cdot\sqrt{(2kTC_i tan(\delta))}\approx$ **180eV**



+ interconnect parasitic
- <u>constraint on ASIC area and layout</u>
- fluorescence from Pb (Sn/Pb/Ag)
- illumination from segmented side



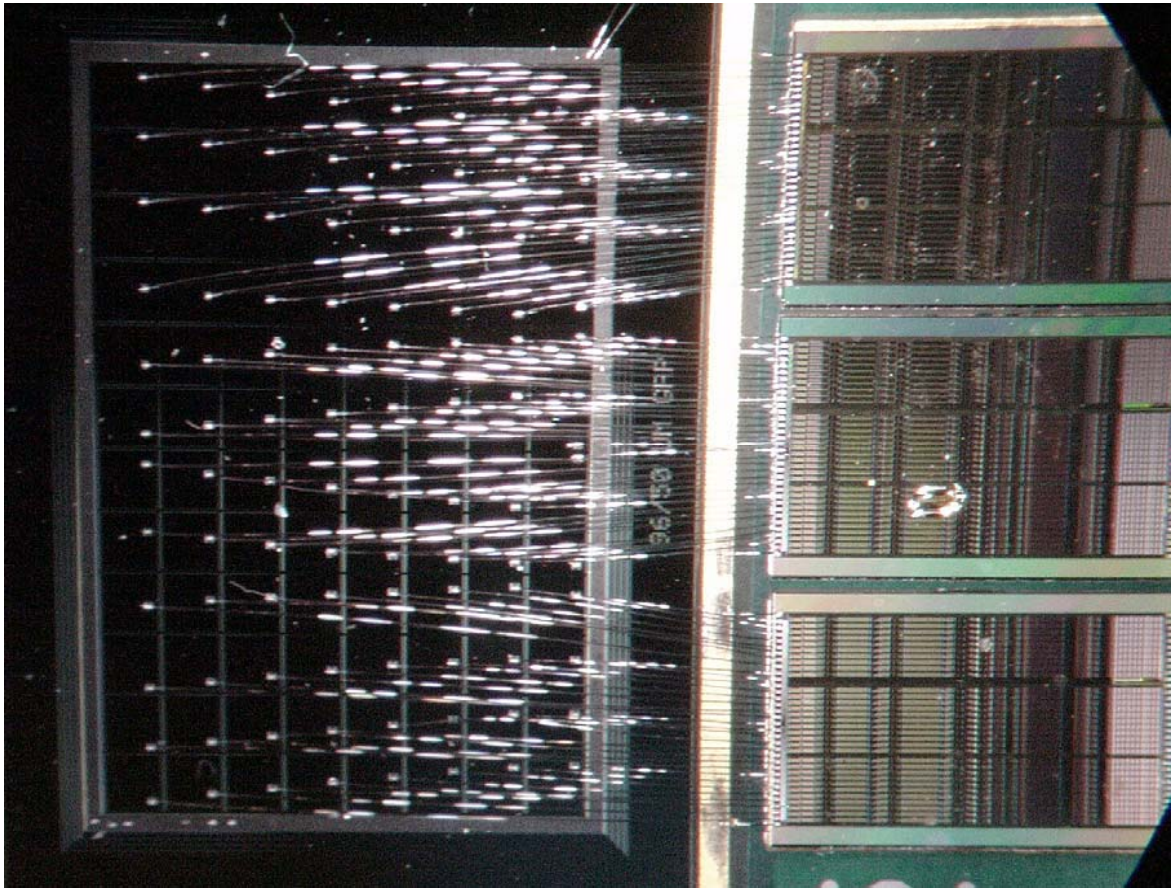
+ dielectric losses
± interconnect parasitic
- bond length

One quadrant with ASICS

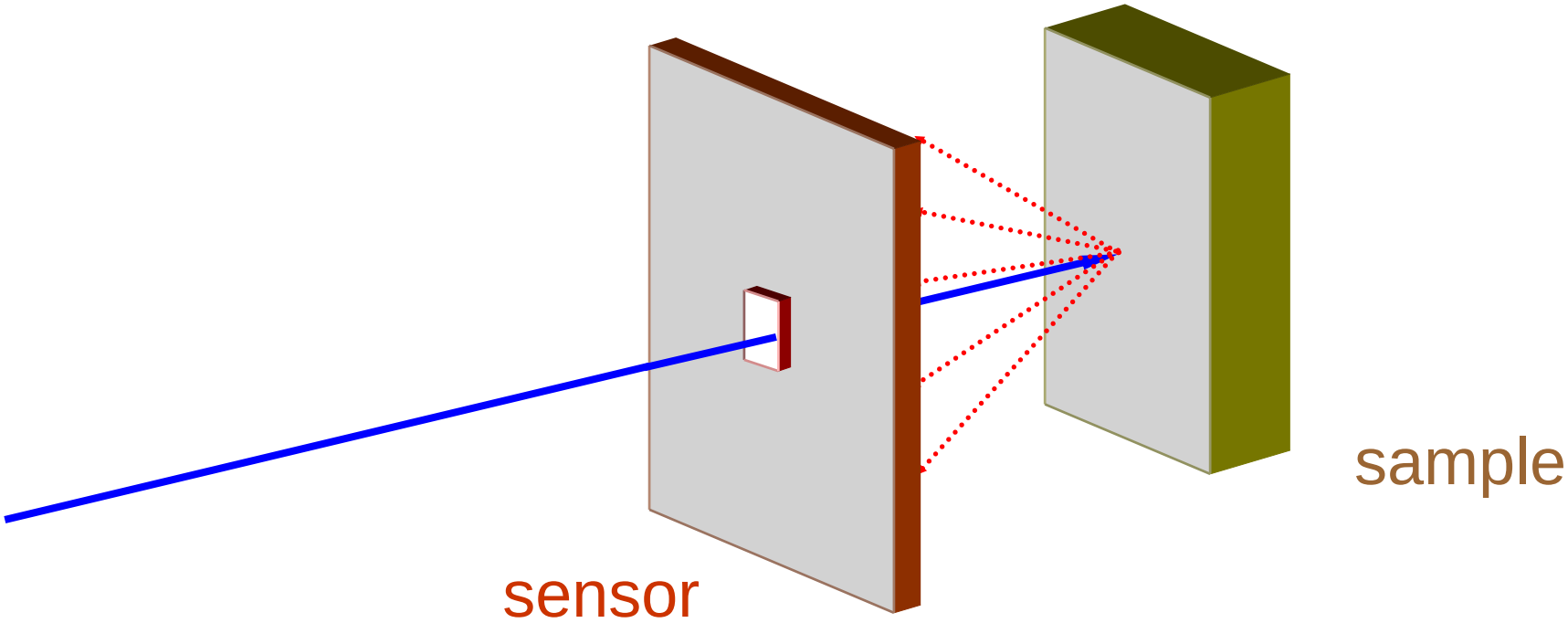
96 pads wire-bonded to 3 ASICS.

The long bonds are rather fragile, but this approach provided least parasitic capacitance.

Each ASIC provides 32 channels of low-noise analog/digital processing.



Beam through

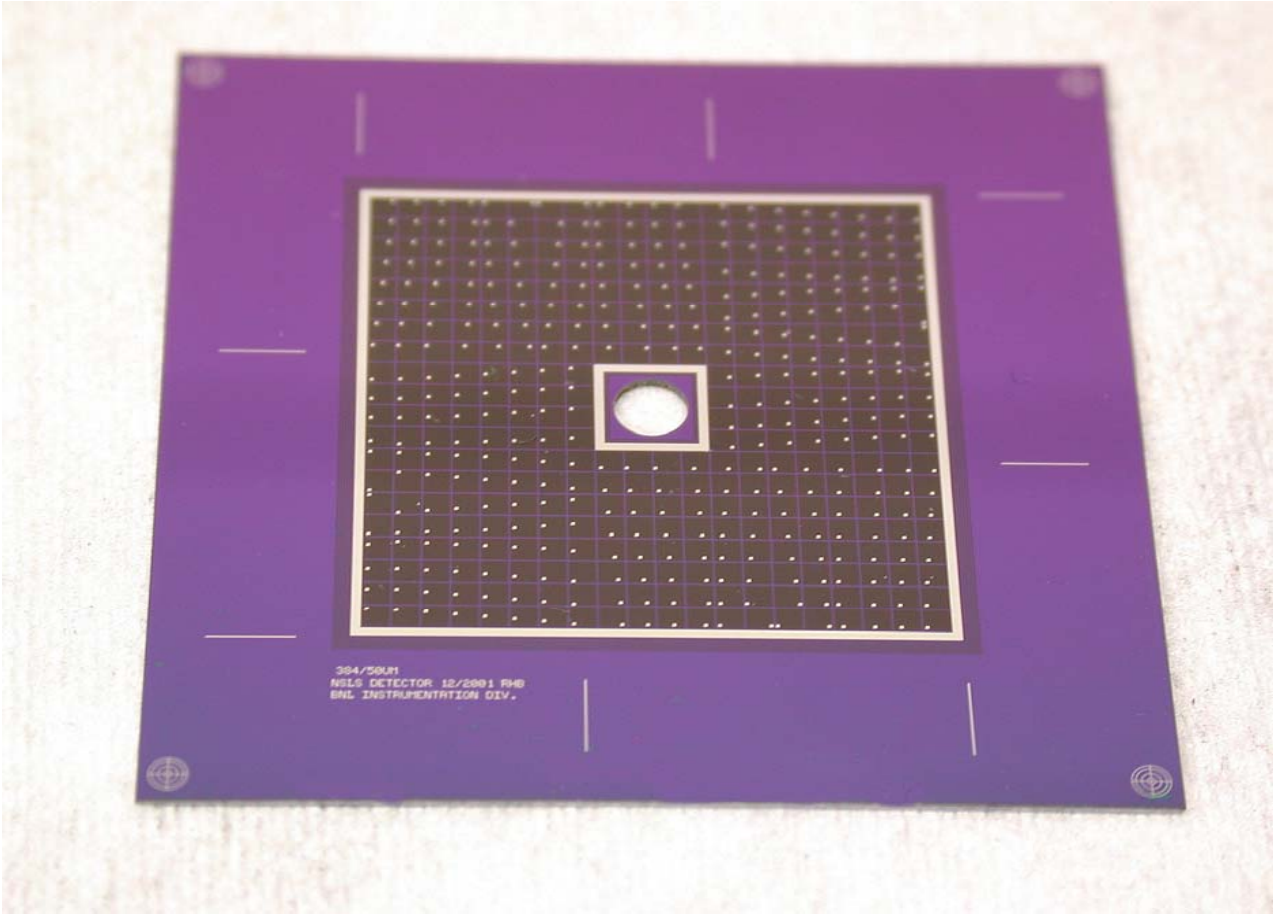


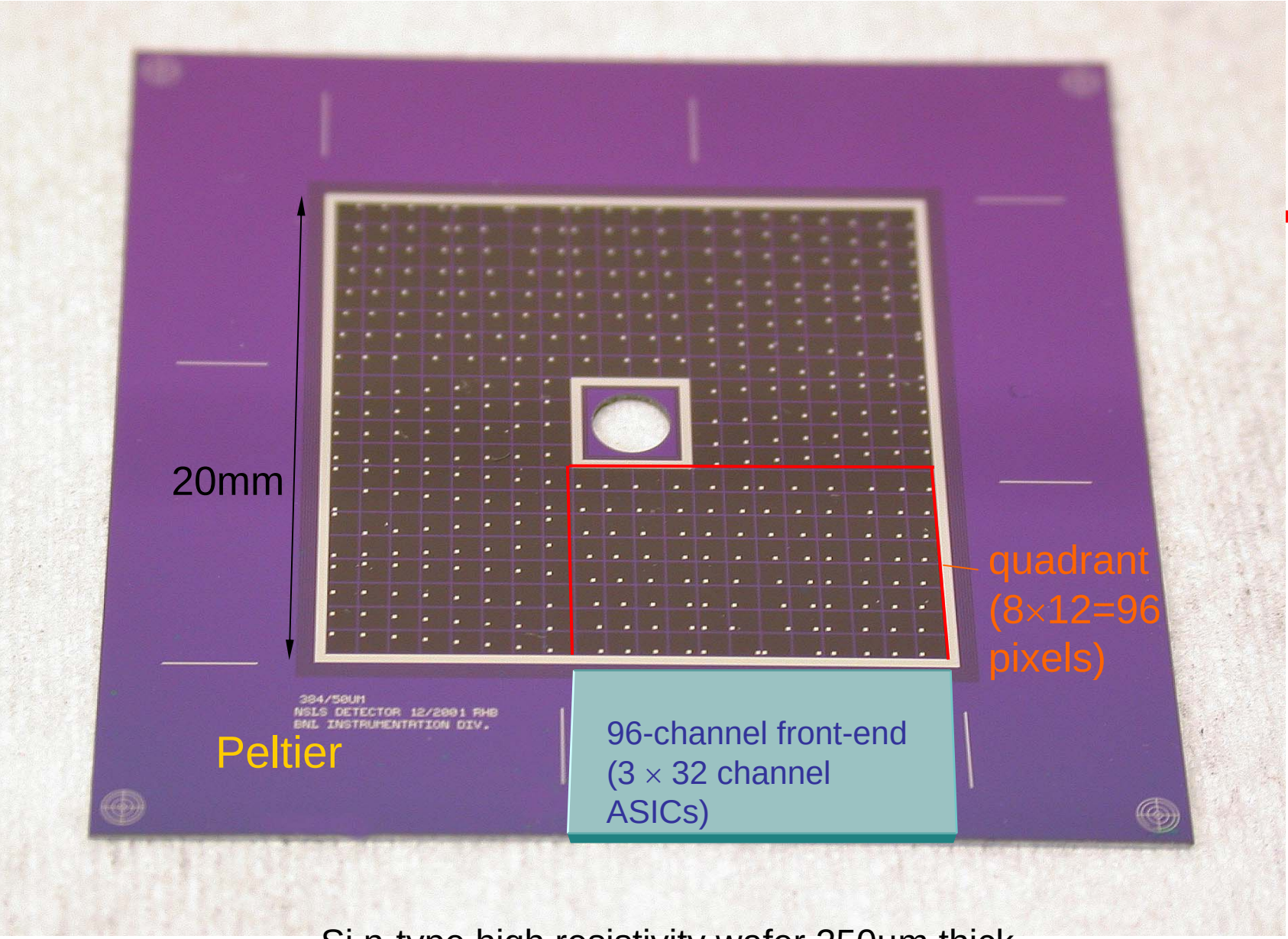
High-rate multi-element detector for fluorescence measurements

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 custom ASICS designed by BNL Instrumentation.



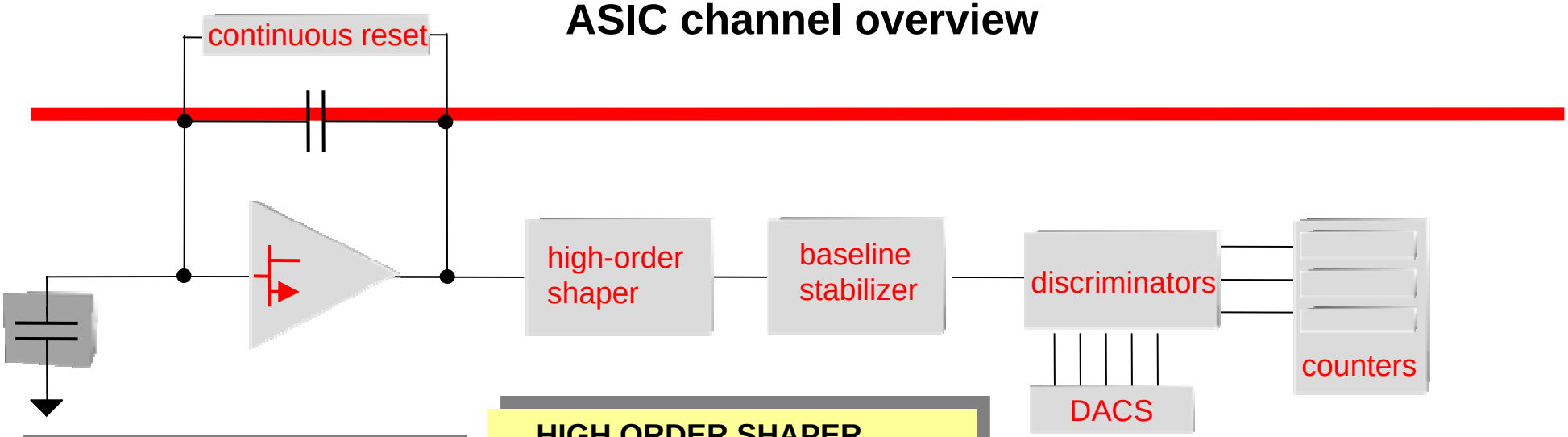


Si n-type high resistivity wafer 250µm thick,

N = 384 p^+ ≈1mm×1mm pixels, C_p ≈ 700-1000fF

gaps 10µm, 30µm, 50µm

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

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

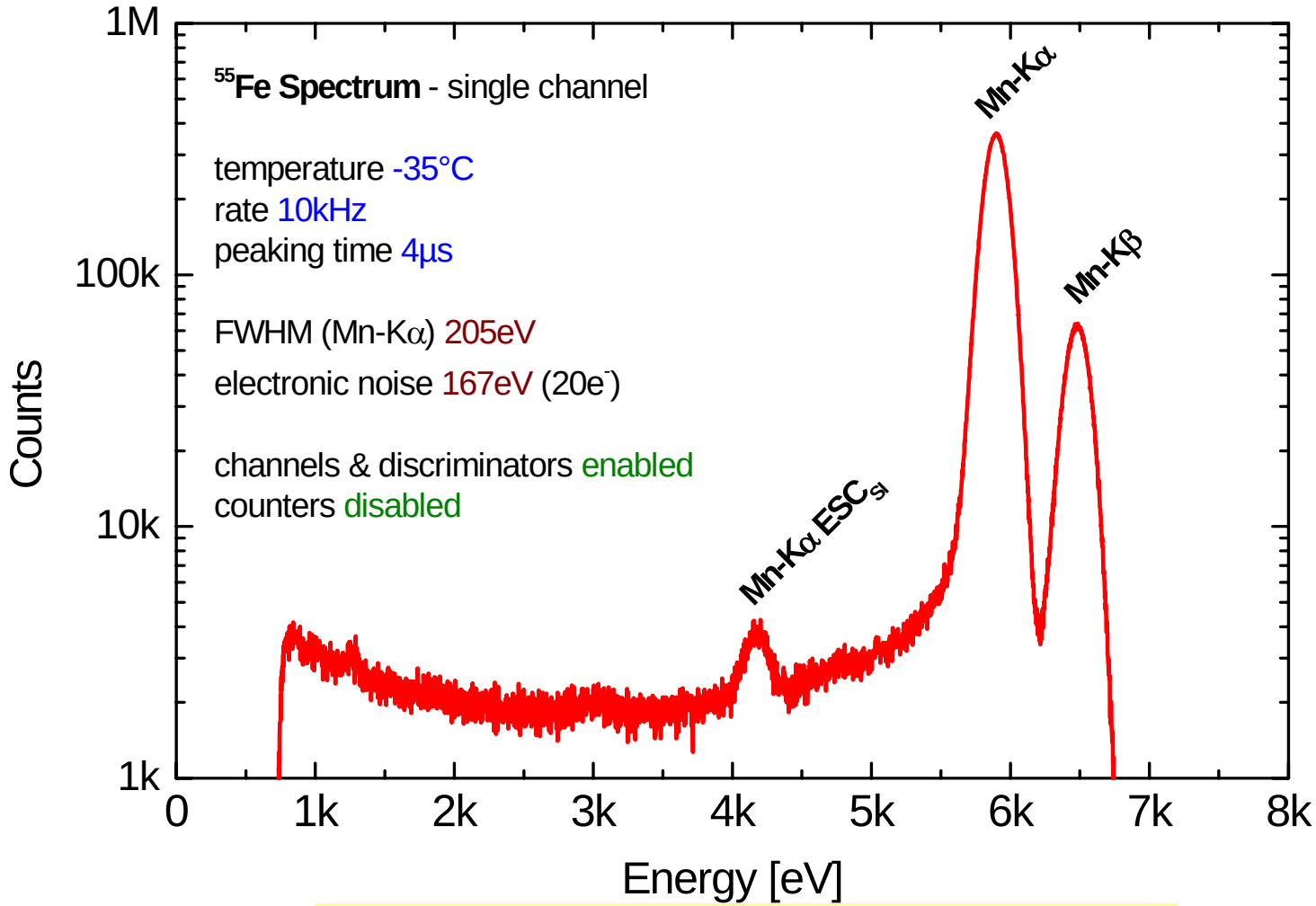
DISCRIMINATORS
- five comparators
- 1 threshold + 2 windows
- four 6-bit DACs (1.6mV step)
- dispersion (adj) < 2.5e$^-$ rms

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

≈ 3 mW

≈ 5 mW

^{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

ASIC overview

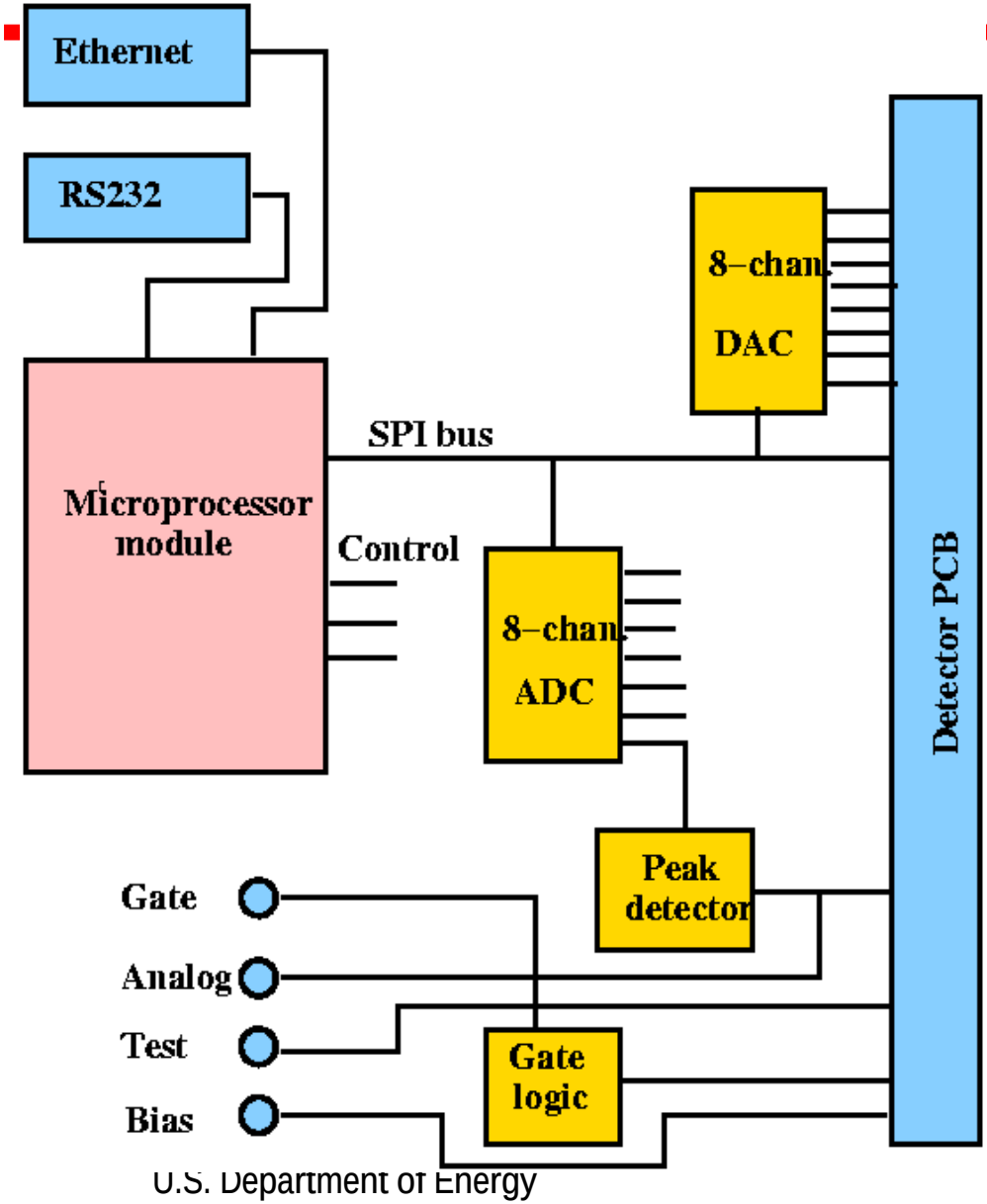
Technology	CMOS 0.35µm 3.3V 2P4M
Size	≈ 3.6 × 6.3 mm^2
# MOSFETs	≈ 180,000
# Channels	32
power / channel	≈ 8 mW
# Discriminators	three / channel (1 thr., 2 win.)
threshold adjustment	four 6-bit DACs (1.6mV step)
threshold dispersion (adj)	≈ 2.5 electrons rms
# Counters	three / channel
bits per counter	24
Gain (settable)	750, 1500 mV/fC
Peaking time (settable)	0.5, 1, 2, 4 µs
ENC @ 1µs	≈ 14 + 12/pF electrons rms
ENC @ 4µs	≈ 11 + 6/pF electrons rms

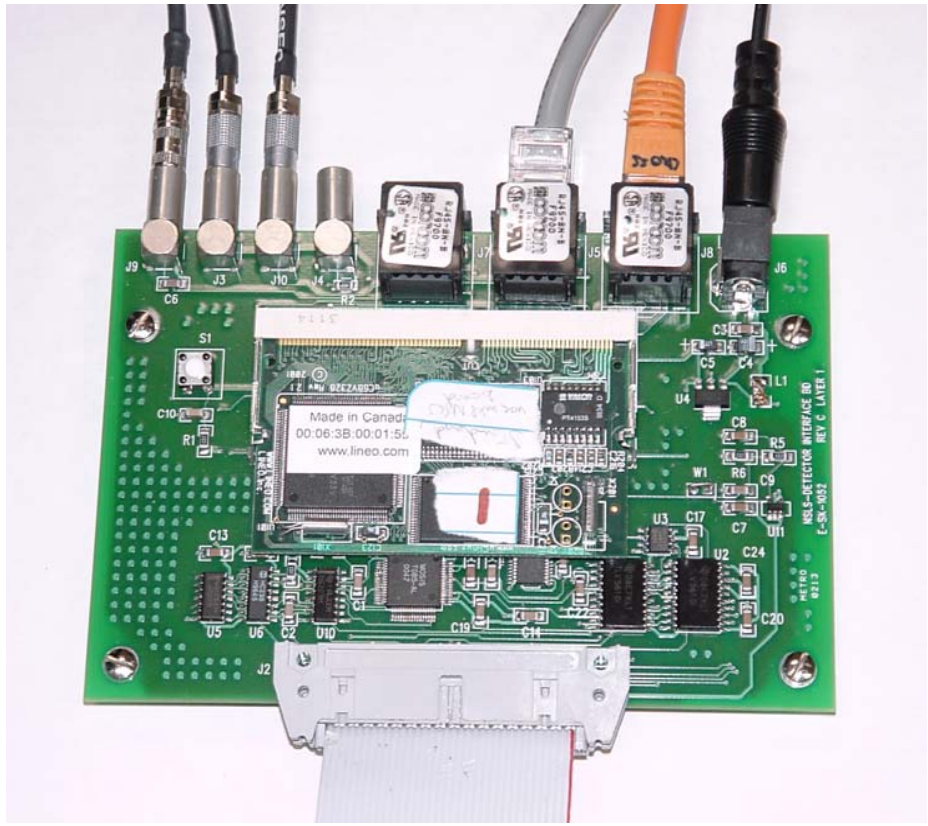
- self adaptive continuous reset
- high order shaper
- band-gap referenced output baseline
- output baseline stabilizer (BLH)
- test capacitors
- analog out and pixel leakage monitors
- plug & play (fully self biasing)
- serial interface
  - counters readout
  - gain / peaking-time setting
  - monitors & test enable
  - channel masking
  - DACs setting
- token or chip-select mode

ASIC photo

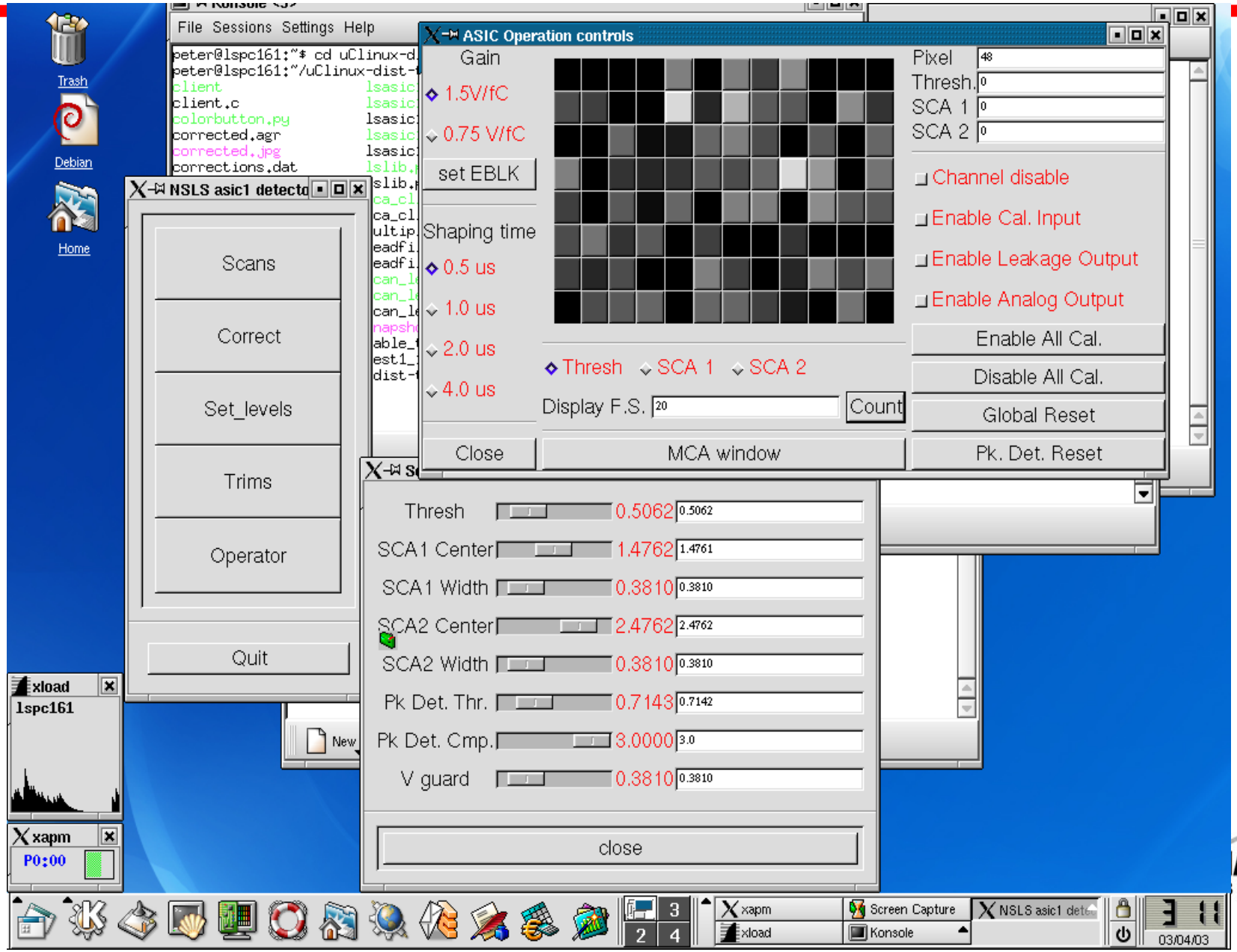
32 channels, 3.6 × 6.3 mm²

Readout

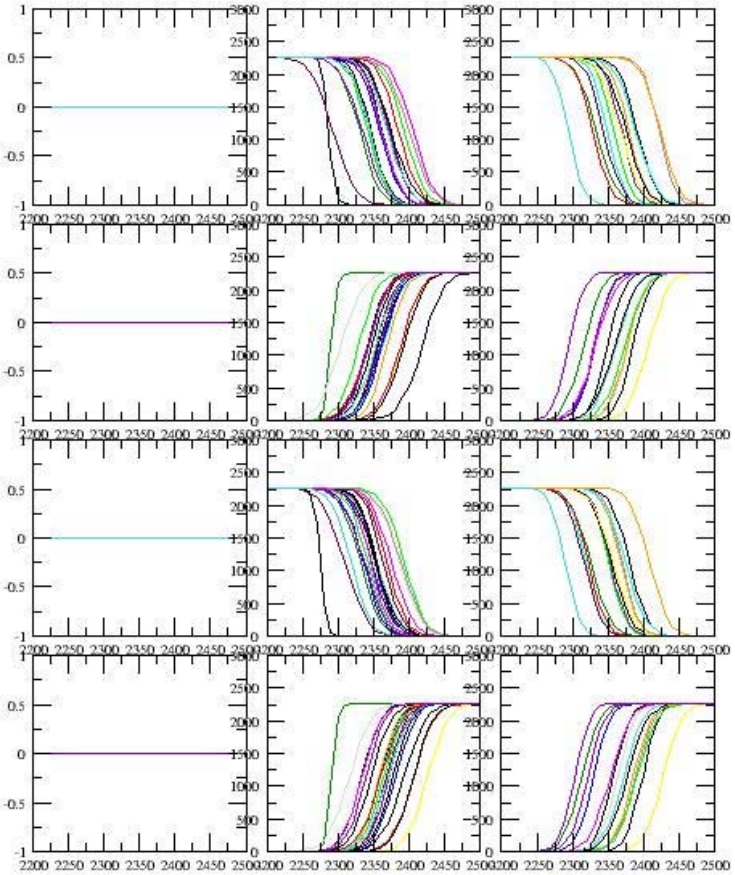

Ethernet
RS232
Microprocessor module
SPI bus
Control
8–chan DAC
8–chan ADC
Peak detector
Gate logic
Detector PCB
Gate
Analog
Test
Bias

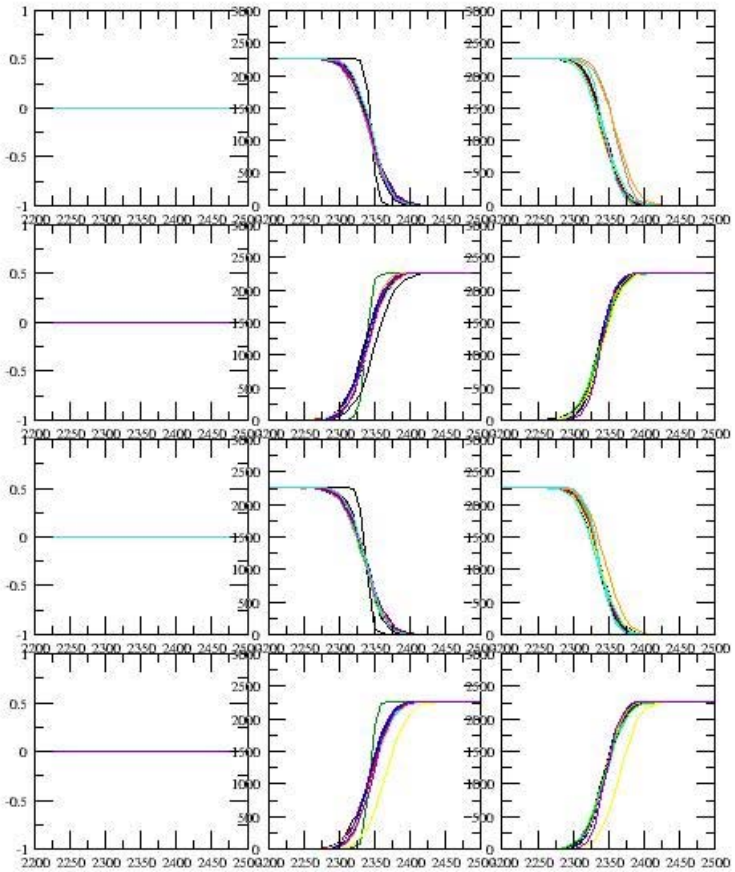


BNL detector software



Automatic threshold equalization

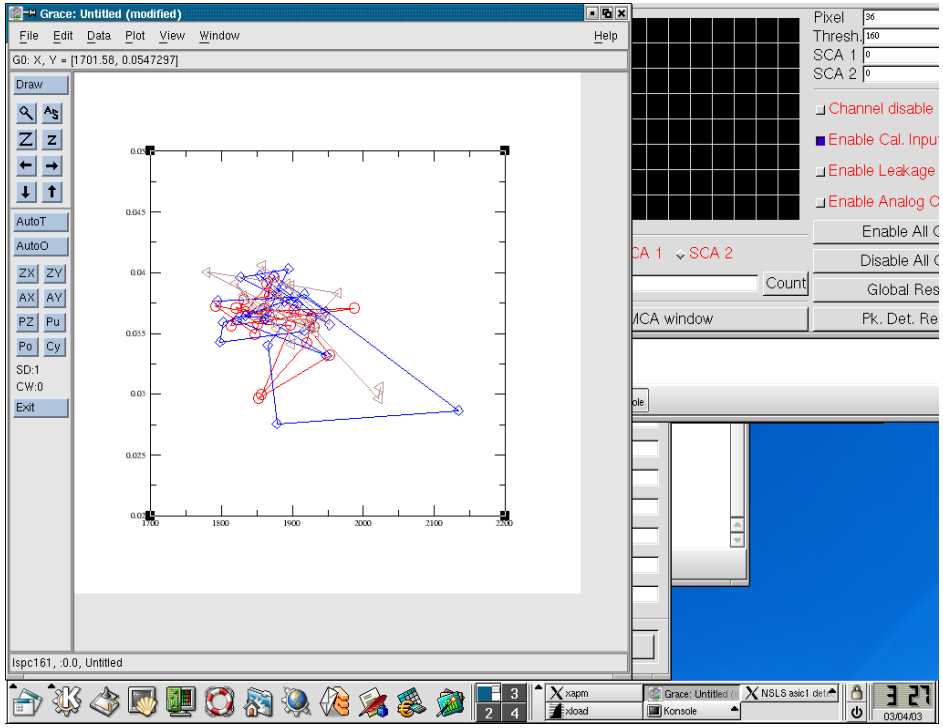


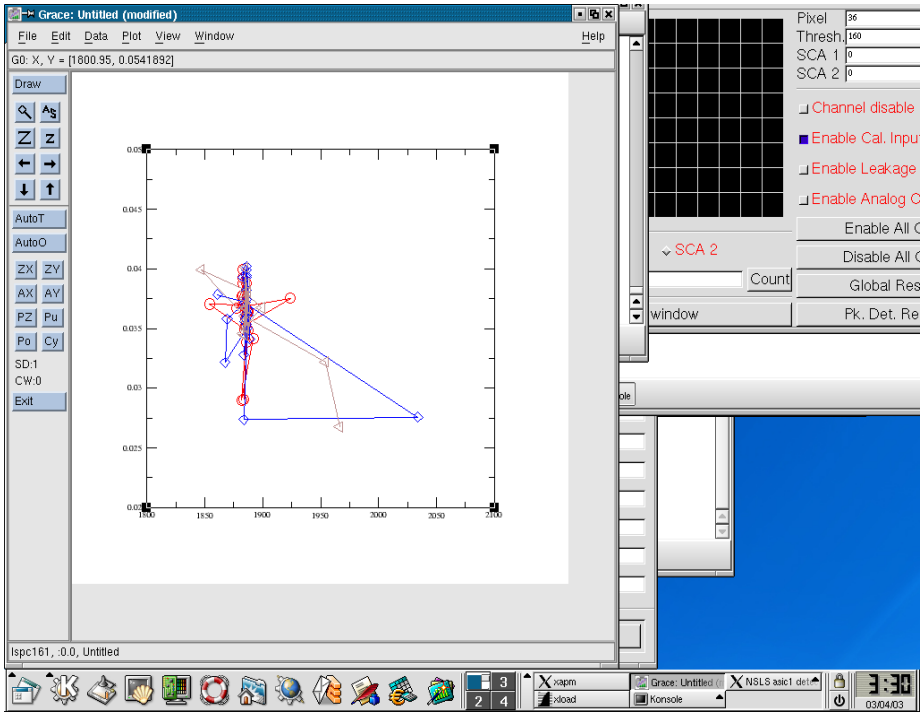


before correction $\sigma \approx 170e^{-}$ ***rms***

after correction $\sigma \approx 2.5e^{-}$ ***rms***

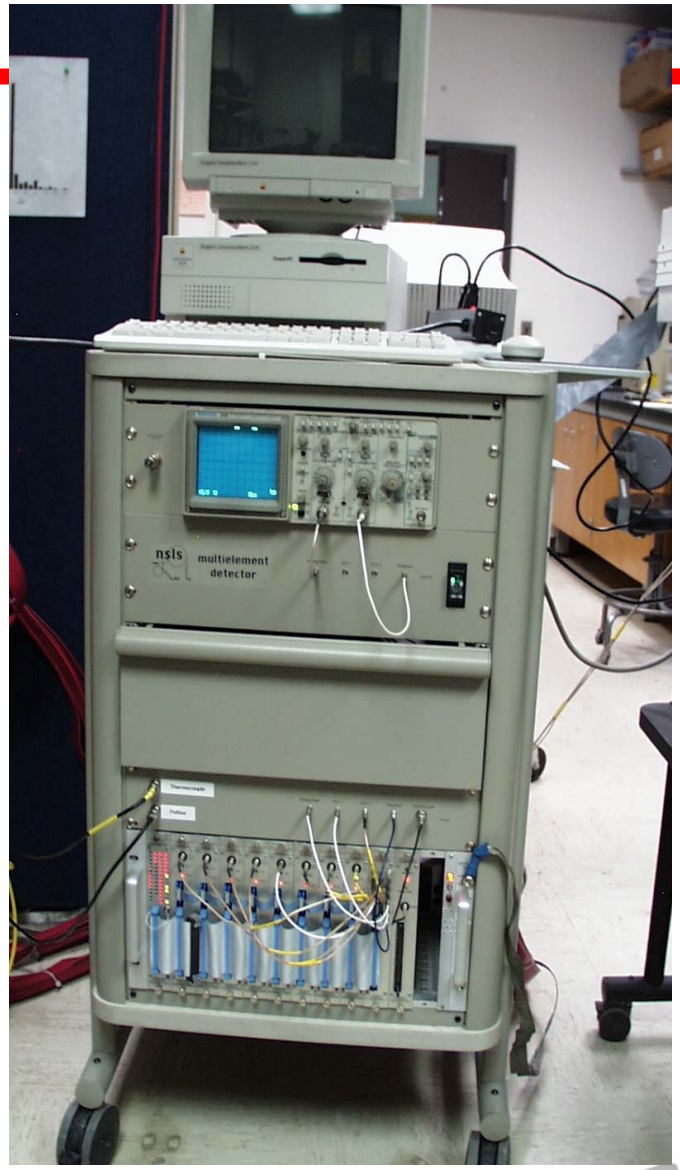
Correction map





Current EXAFS detector

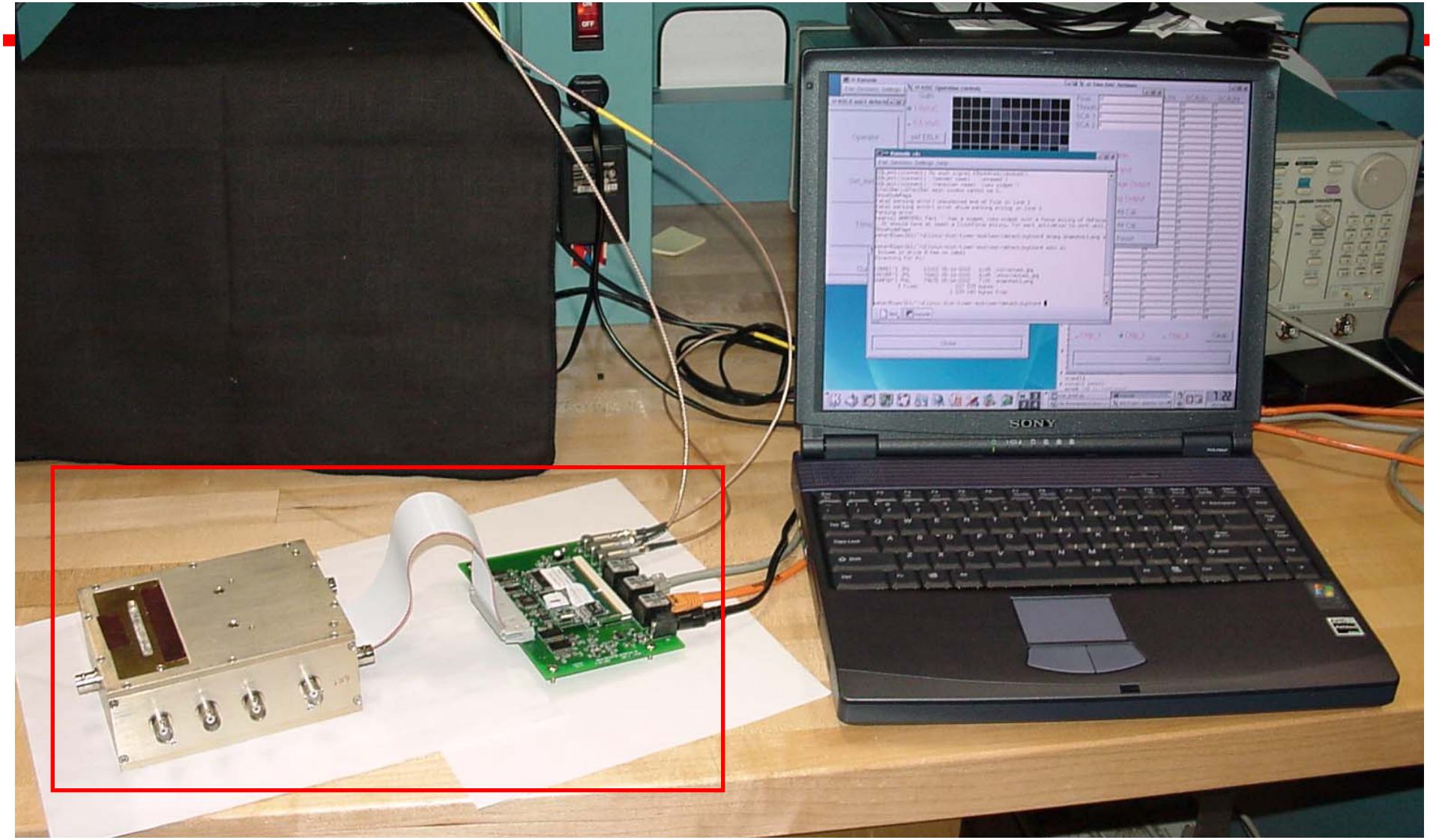
head - preamplifiers



rack – shapers...

≈100 channels, > 350 eV, < 1 MHz

New EXAFS detector



≈ 400 channels, < 300 eV, > 10MHz

Problems with first ASIC run (and solutions)

Significant # of channels don't work (~30%)

- Due to process problem. MOSIS solved.

Switching any control bit causes whole chip to be disabled for ~3 sec.

- SPI chain was unbuffered on chip, so all channels were disabled then re-enabled. Re-enable needs 3 sec. Buffering added

BLH fails for negative pulses.

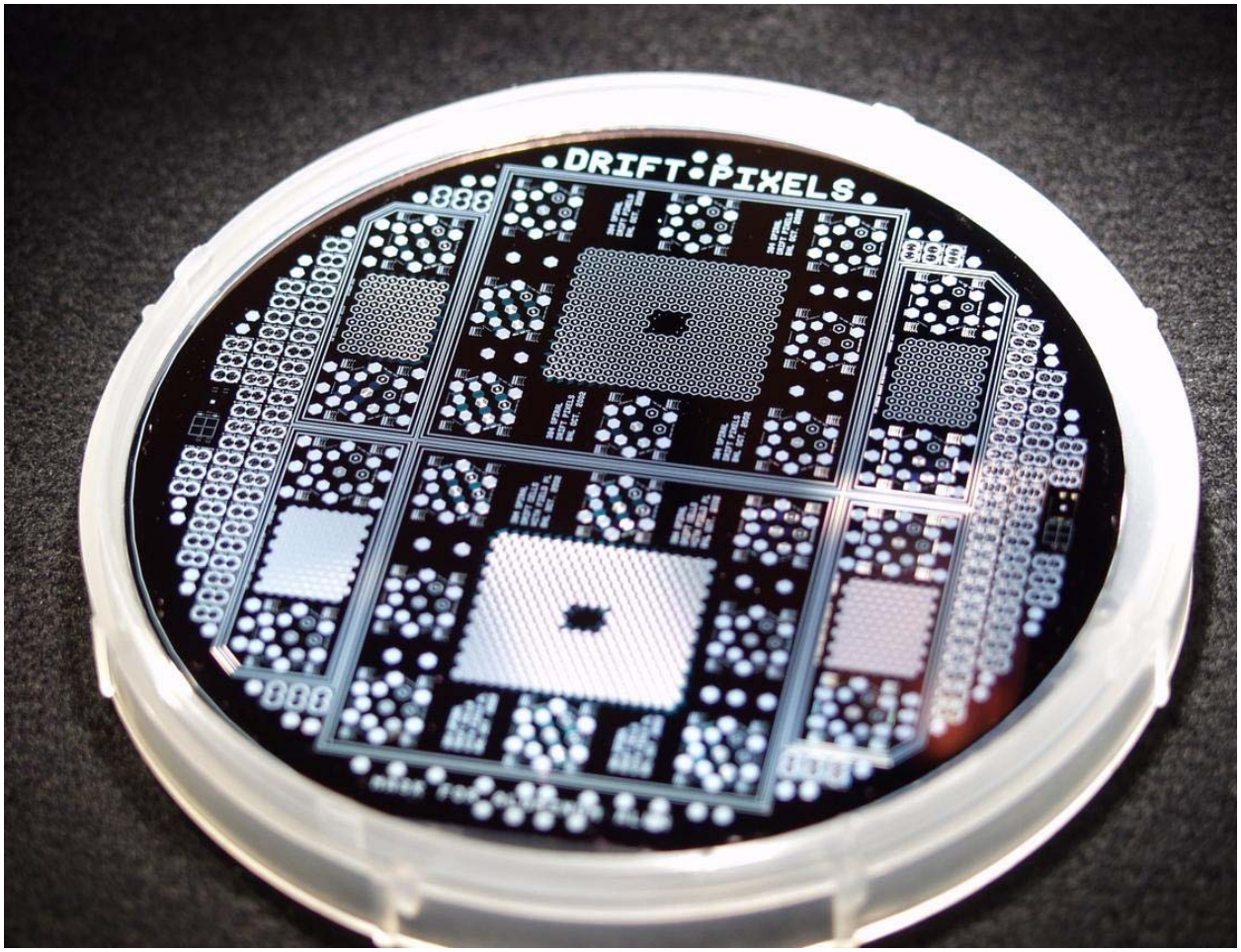
- Any undershoot (e.g. during overload recovery) causes baseline shift for a significant time. Due to asymmetric behavior of BLH. Added symmetry components. Simulations shows problem and suggests fix will be successful.

Second run just arrived. All bugs seem to be fixed ☺

Drift-Detector Array

Drift-detectors give large area while keeping low capacitance by ‘drifting’ charge through bulk of silicon to a small collector electrode.

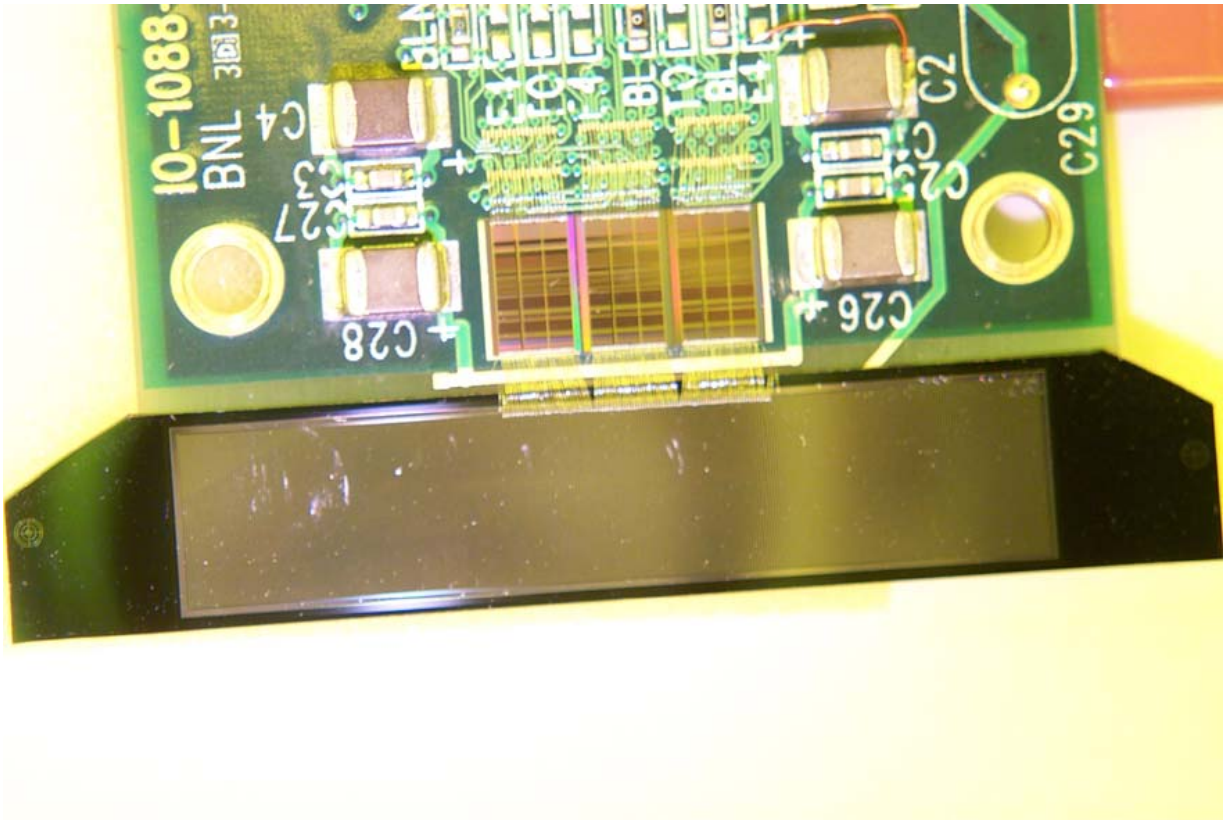
Wafer has 96- and 384-element arrays.



Non-spectroscopic applications

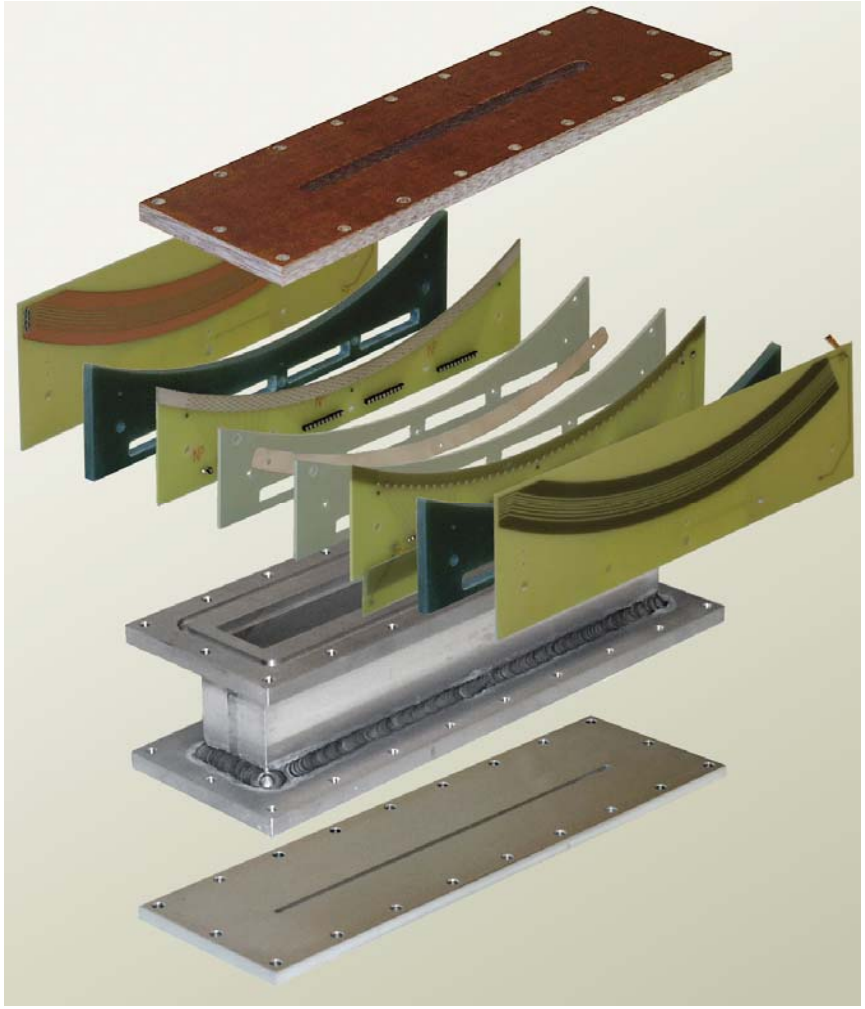
0.1mm strip-shaped pixels form a 1-D position sensing detector with energy resolution.

Useful for diffraction and scattering experiments.



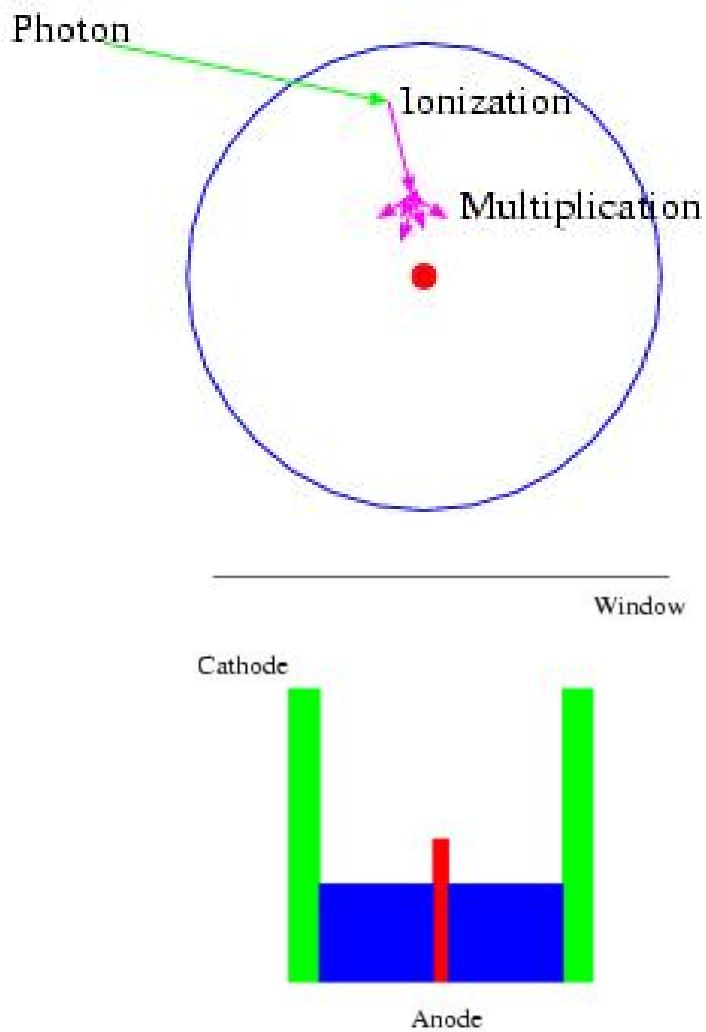
Curved proportional counter for rapid powder diffraction.

- Gas proportional position sensitive detectors are thick, and hence prone to parallax smearing of position resolution.
- Radial geometry solves this problem, but curved wire-based detectors are difficult to manufacture.
- We developed a blade detector which can operate in the proportional regime, and a highly parallel readout scheme capable of acquiring position events at several MHz.



Proportional counters

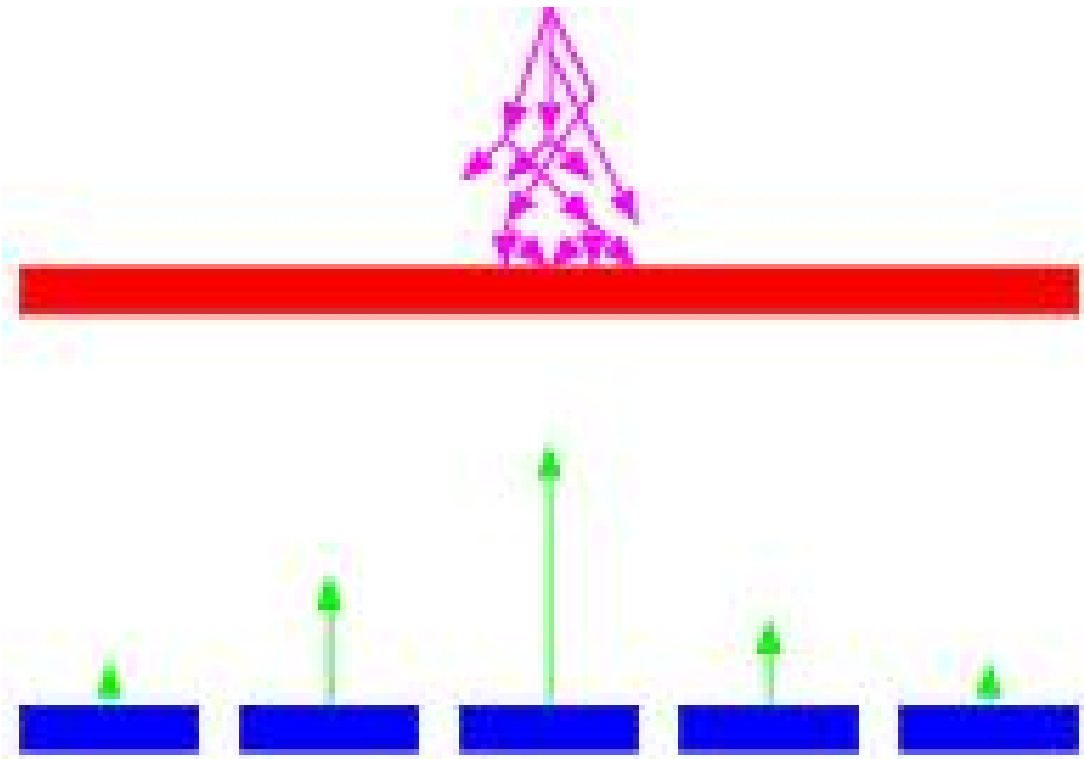
- Uses controlled avalanche multiplication of electrons in a gas
- Avalanche occurs in high-filed region near center thin wire
- Edge of blade acts like wire, but can be curved
- Signals read out from segmented cathodes



Segmented cathode readout

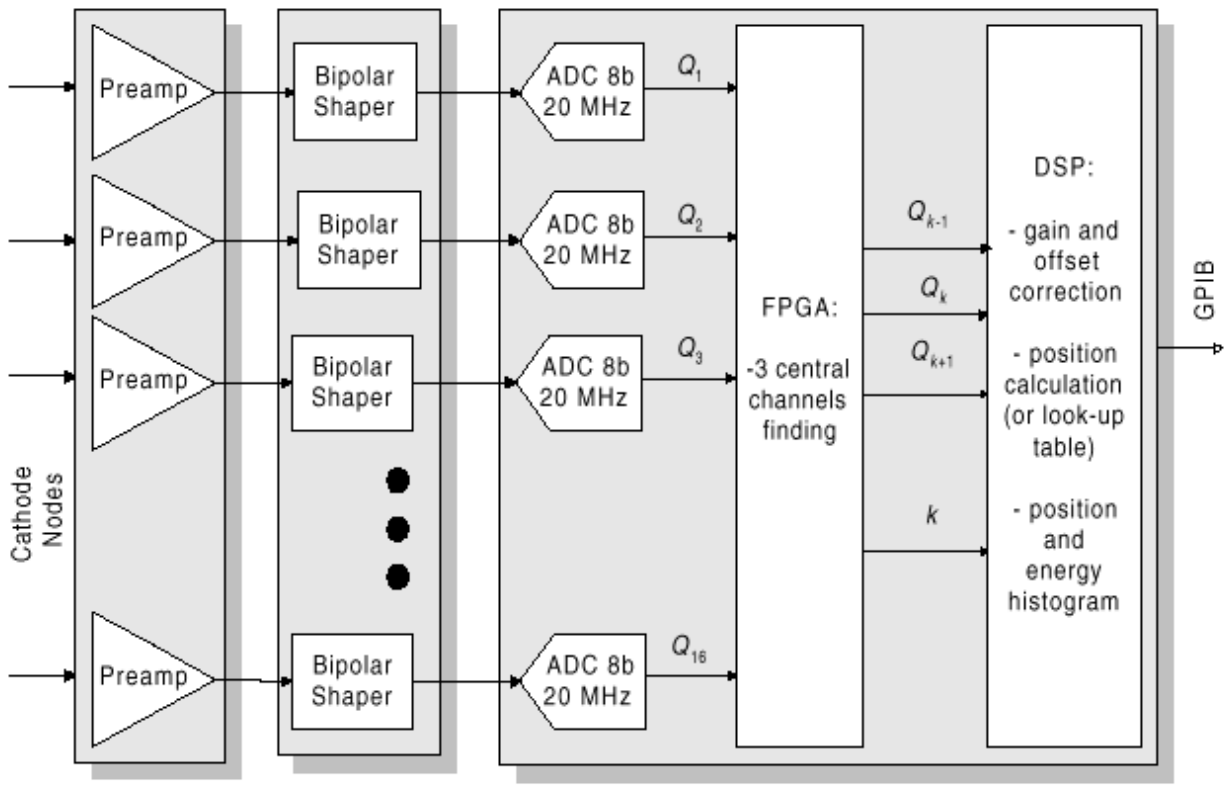
Charge induced on cathodes is measured for each segment

Charge pattern is interpolated to find event position



Pad readout schematic

- Each cathode pad has individual preamp, shaper and ADC
- Inputs are digitized continuously at 20MHz
- FPGA takes all digital data and detects ‘events’.
- DSP takes ‘events’ and computes a position.

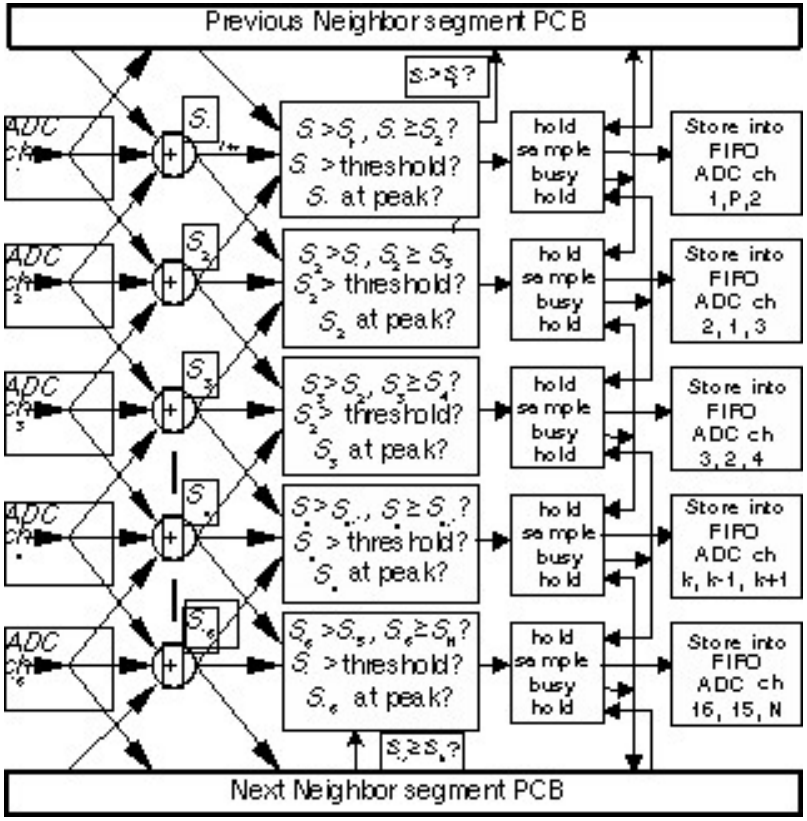


Readout electronics

The heart of the readout system is a large FPGA implementing event triggers and peak identification at high speed.

Qualifying events are passed as 3 8-bit numbers to a DSP for interpolation to identify the peak centroid.

FIFO's de-randomize the events, allowing each DSP to handle about 1.5M events/sec.



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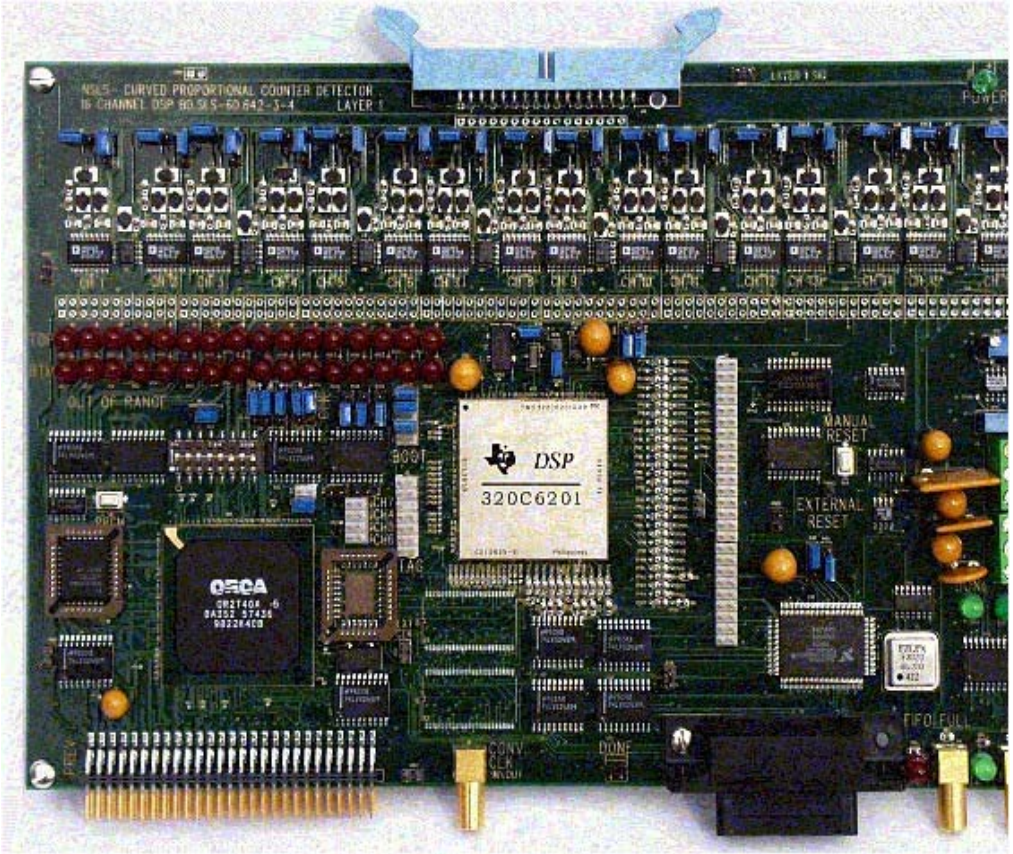
Readout Electronics

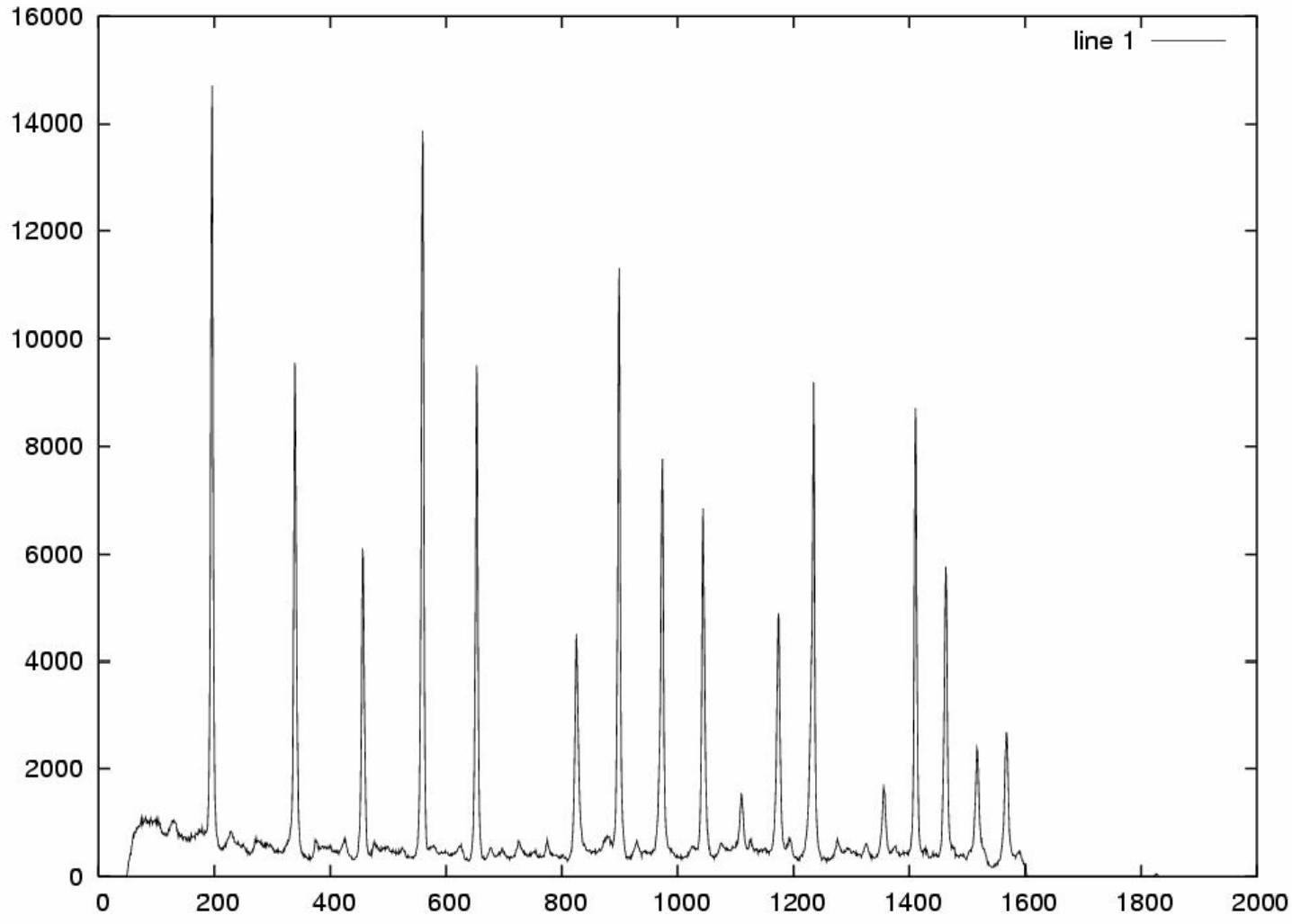
This PCB carries 16 20MHz 10-bit ADC's, an FPGA and a DSP system.

Three such boards form a complete detector.



Example diffraction pattern

- Test pattern. LaB6 0.3mm capillary. X14B beamline, 17keV
- 1 second acquisition, total counts in pattern ~800k
- Xe-Co2, 2 atm.



High-Z arrays

- Trend in condensed matter diffraction is to higher energy photons
- Silicon becomes transparent at ~12keV.
- Need to have similar capability in some higher-Z material
  - Custom shaped arrays
  - Integrated readout system
- LDRD funding
  - Able to fabricate small CZT arrays using a lithographic process
  - The performance of our individual elements is as good as that of commercial single detectors in this material.
- BNL's Instrumentation Division has developed suitable readout IC's for CZT-based detectors.

CZT detector fabrication

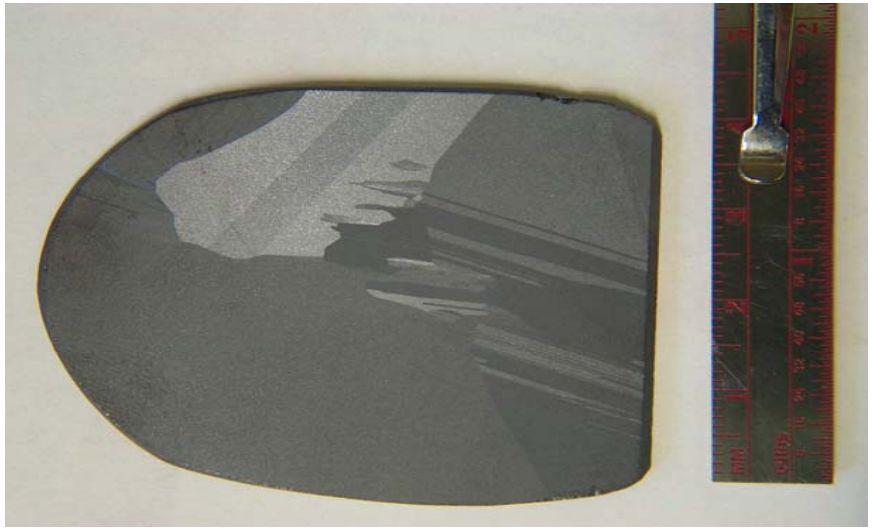
The as-received wafer is polycrystalline with large, clearly visible grains.

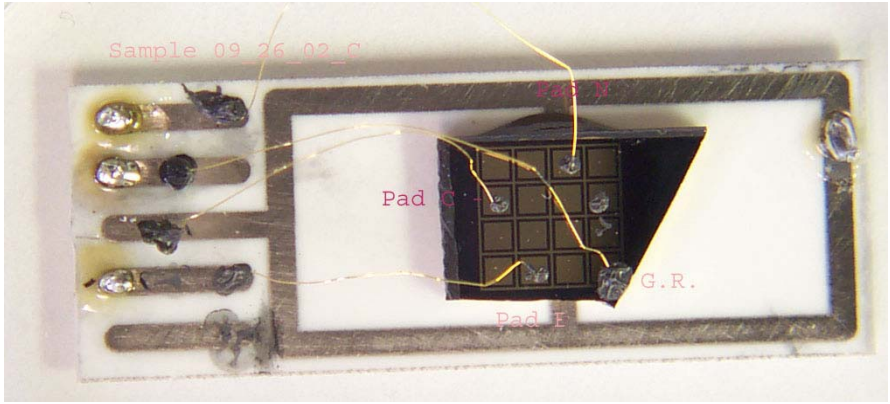
Single-grain regions are selected from the slice for detector fabrication.

The surface of the selected piece is lapped, polished and etched.

Gold patterns are formed using a selective chemical deposition process.

Wires are bonded from the detector to the test fixture.





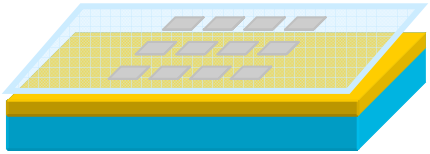
Fabrication Process

Photoresist

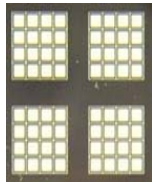
(a)

CZT sample

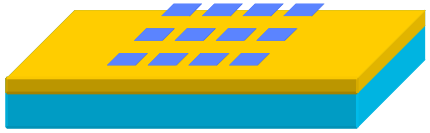
(b)



Bright-field mask



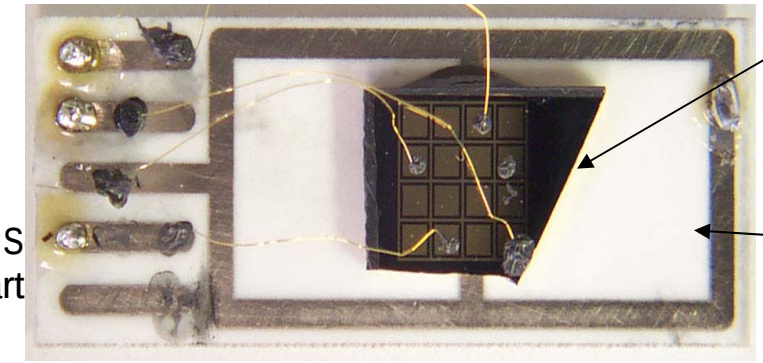
(c)



Sample UV-exposed & developed

(d)

Sample with electroless gold contacts

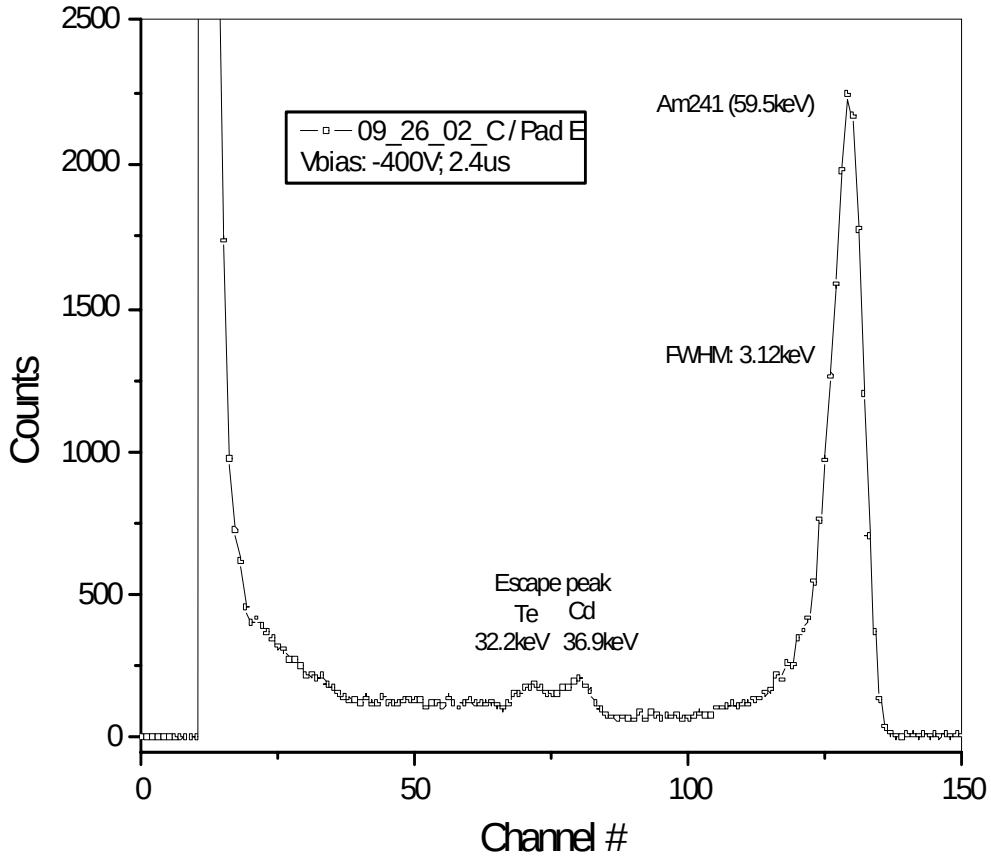


Mounted Detector
Onto Ceramic board

1mm x 1mm pad performance

This level is typical for detectors of similar construction reported in the literature.

We still need to develop a wire bonding technique which will allow us to connect to smaller devices such as 0.1mm pitch strips.



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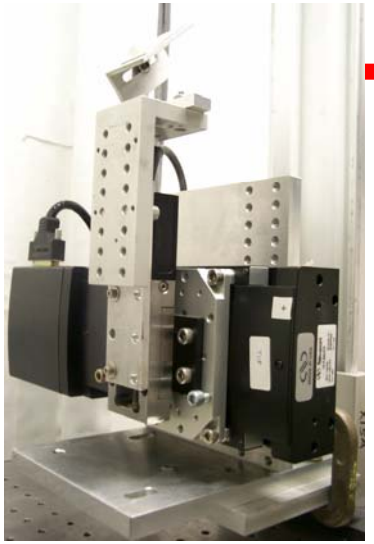
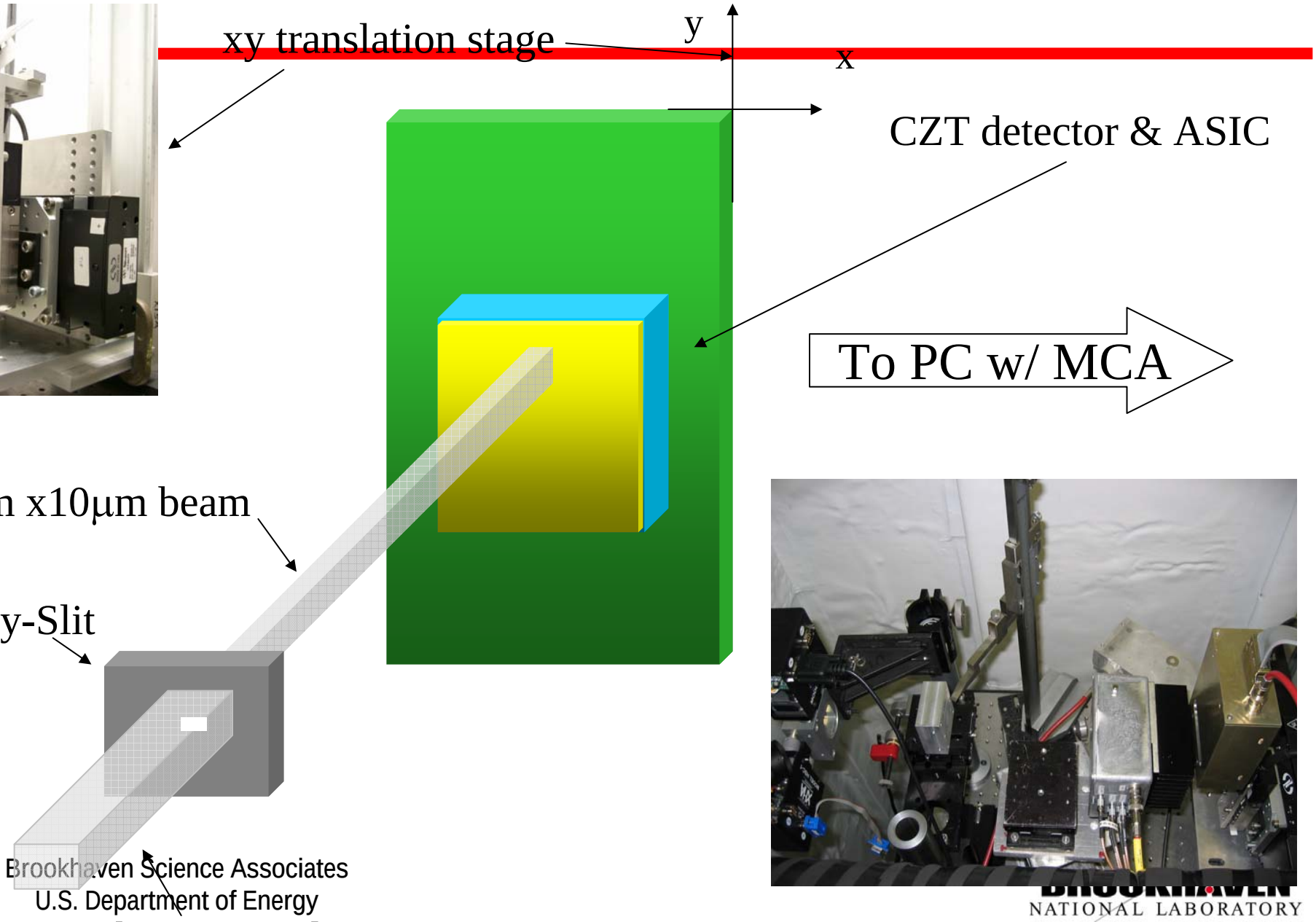
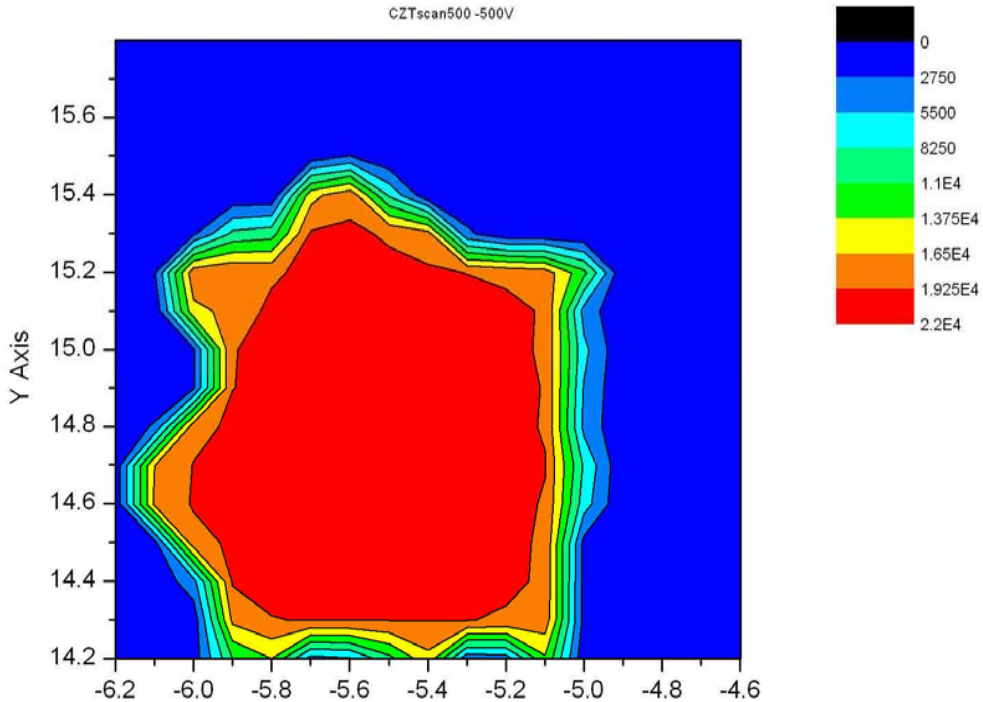
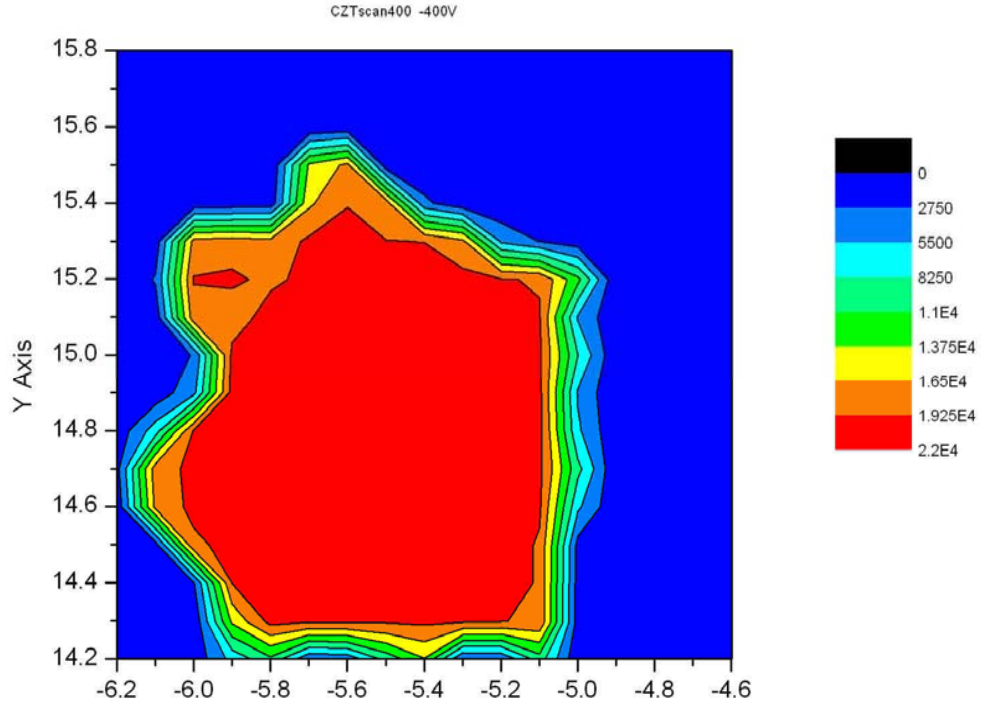
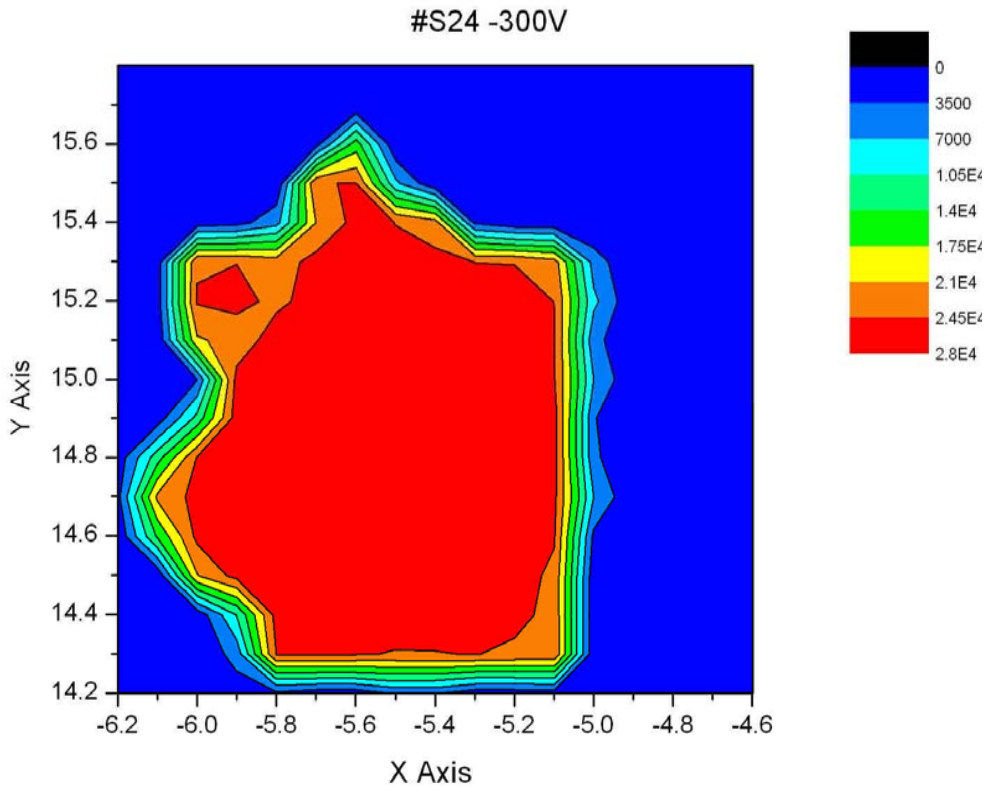
Micron-scale detector mapping

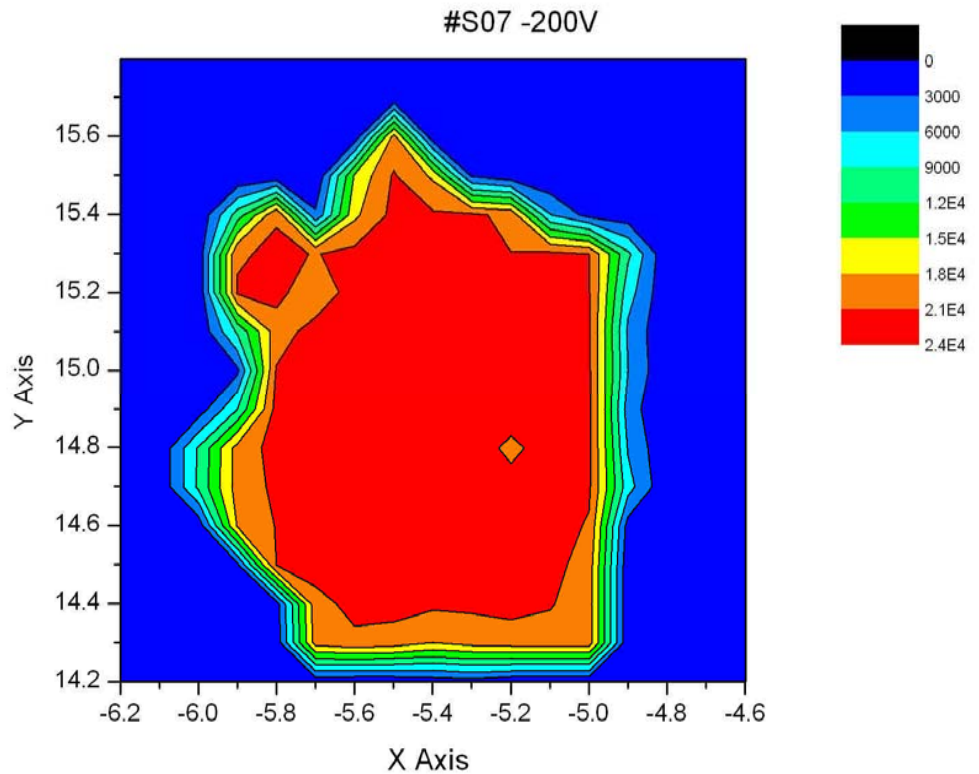


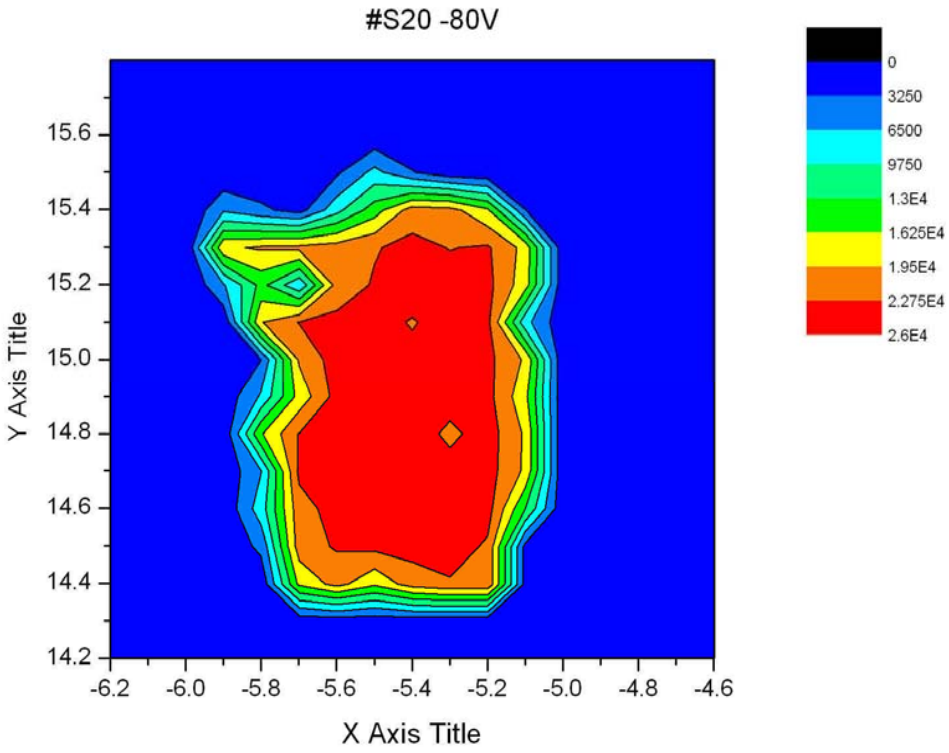


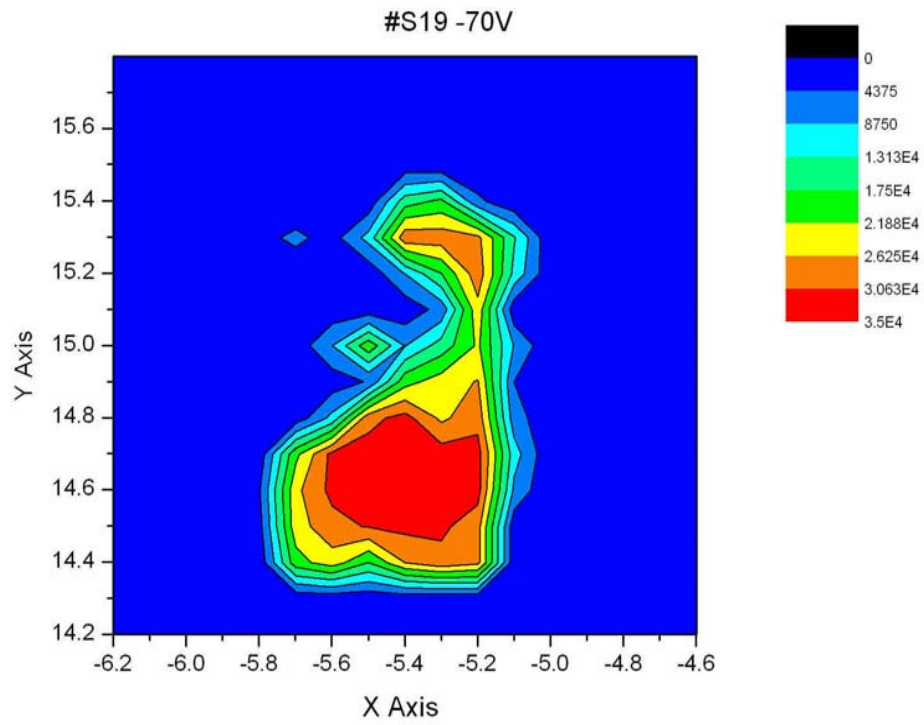

CZTscan500 -500V
Y Axis
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
0
2750
5500
8250
1.1E4
1.375E4
1.65E4
1.925E4
2.2E4

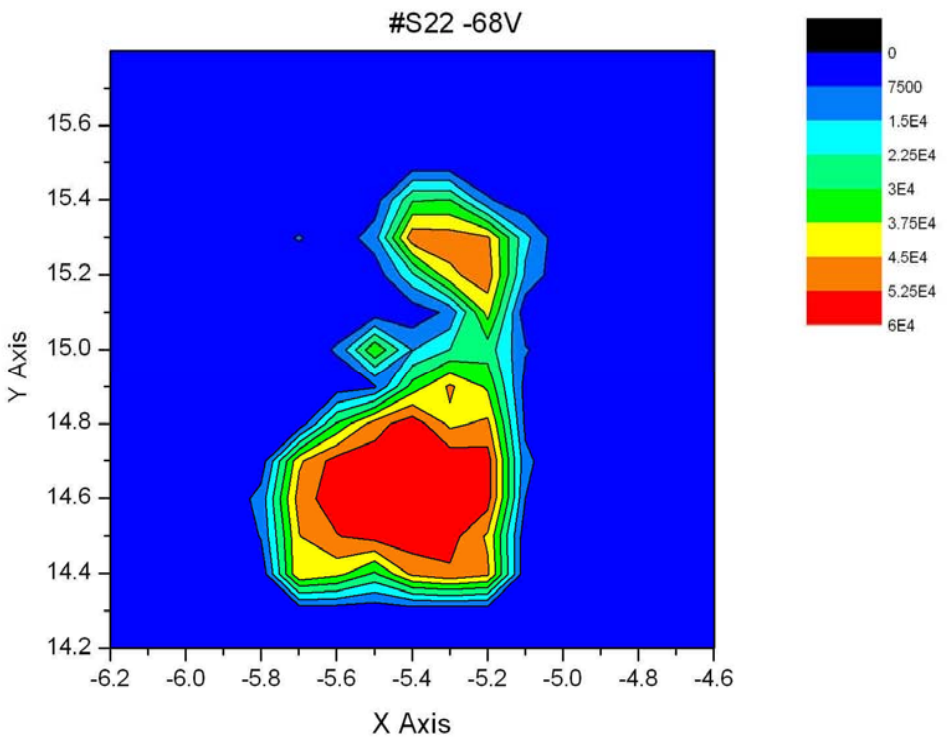

CZTscan400 -400V
Y Axis
15.8
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
0
2750
5500
8250
1.1E4
1.375E4
1.65E4
1.925E4
2.2E4

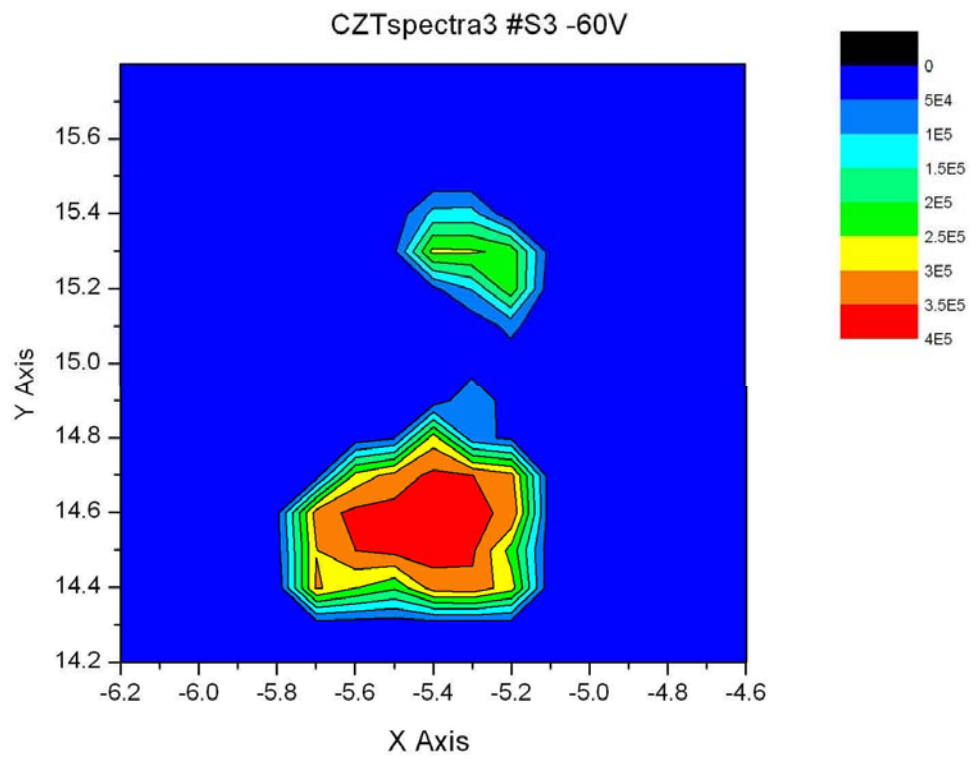

#S24 -300V
Y Axis
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
X Axis
0
3500
7000
1.05E4
1.4E4
1.75E4
2.1E4
2.45E4
2.8E4


#S07 -200V
Y Axis
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
X Axis
0
3000
6000
9000
1.2E4
1.5E4
1.8E4
2.1E4
2.4E4

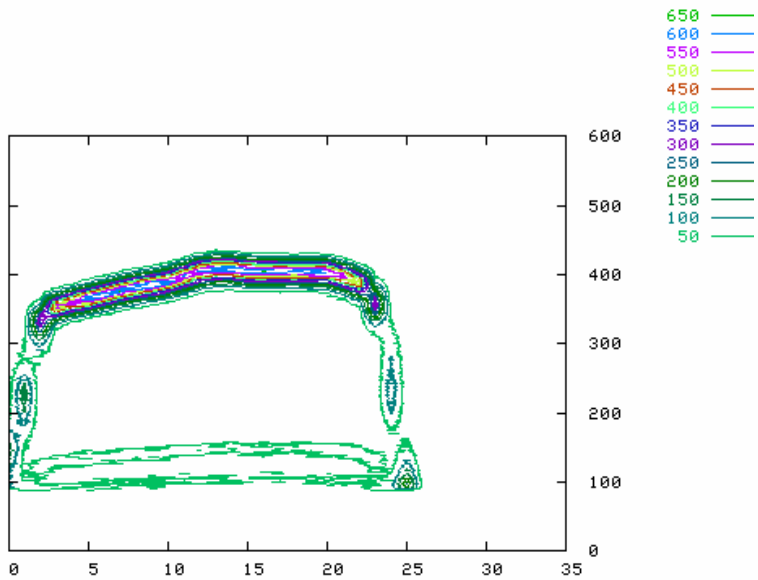

#S20 -80V
Y Axis Title
X Axis Title
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
0
3250
6500
9750
1.3E4
1.625E4
1.95E4
2.275E4
2.6E4

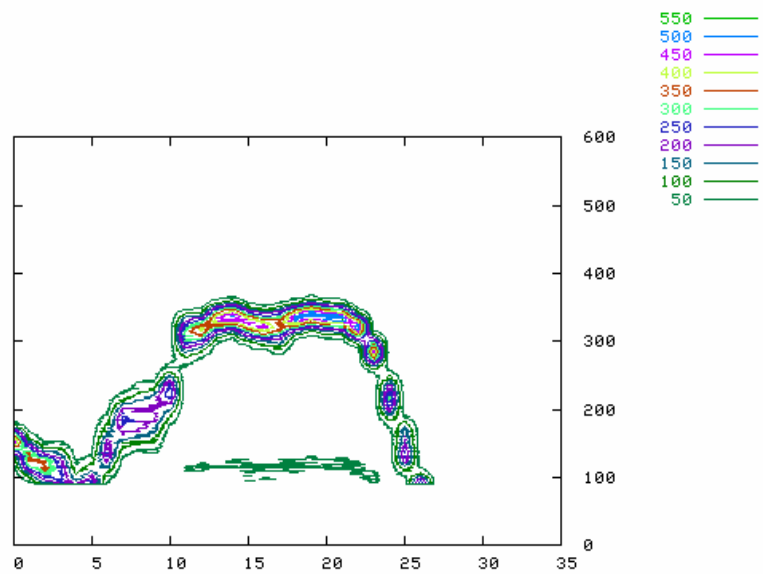

#S19 -70V
Y Axis
X Axis
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
0
4375
8750
1.313E4
1.75E4
2.188E4
2.625E4
3.063E4
3.5E4


#S22 -68V
Y Axis
X Axis
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
0
7500
1.5E4
2.25E4
3E4
3.75E4
4.5E4
5.25E4
6E4

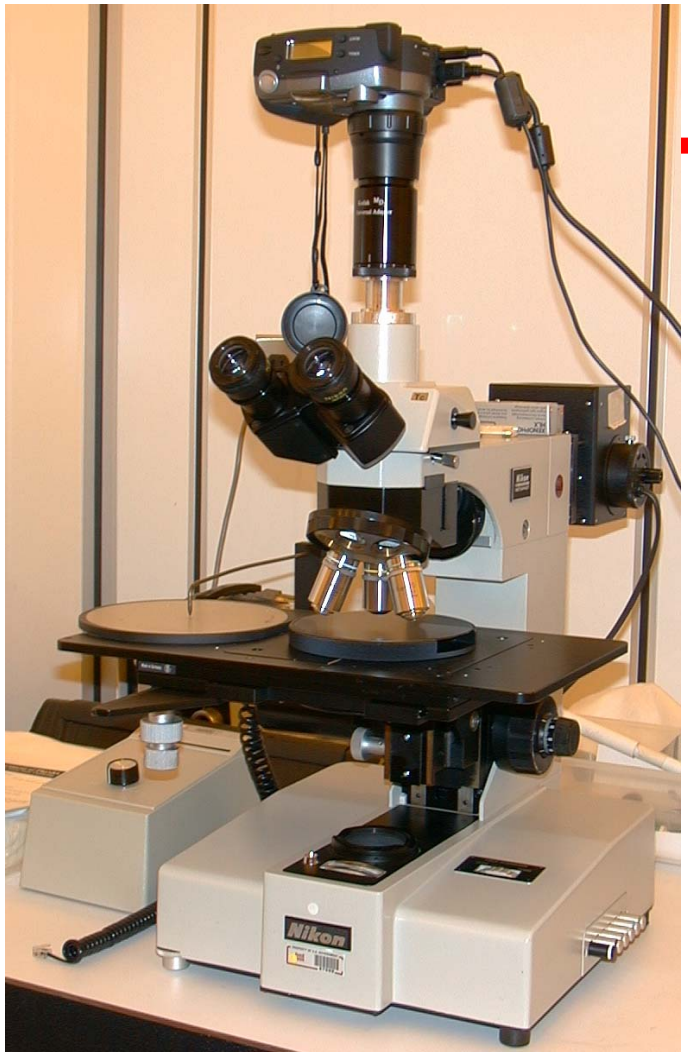

CZTspectra3 #S3 -60V
Y Axis
X Axis
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
-6.2
-6.0
-5.8
-5.6
-5.4
-5.2
-5.0
-4.8
-4.6
0
5E4
1E5
1.5E5
2E5
2.5E5
3E5
3.5E5
4E5

2D Contour Map



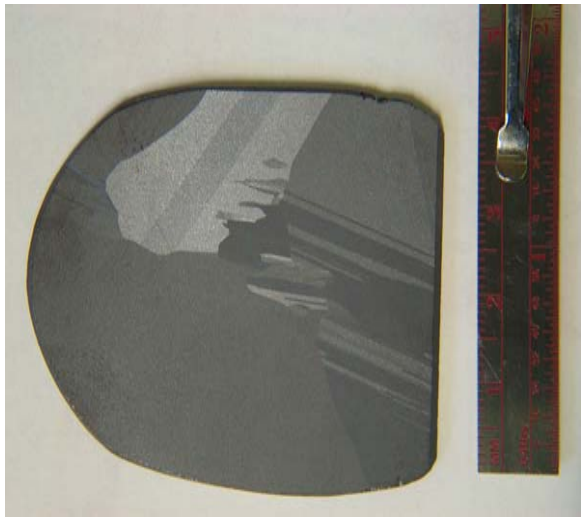


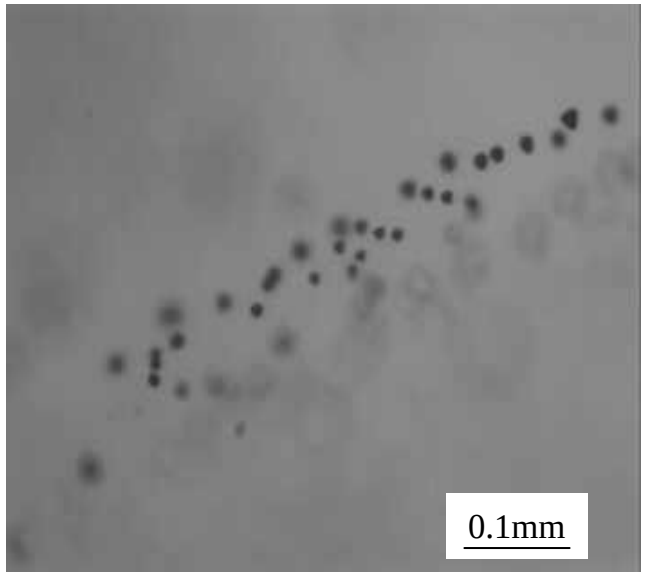
IR transmission Microscopy



IR microscopy used to:

- Detect non uniformities
  - Grain boundaries
  - Te precipitates approximate dimensions: 10 μm
- Align the CZT pixellated detector to the print circuit board





IR Microscope | Yinnel Tech wafer | IR Microscopy Image

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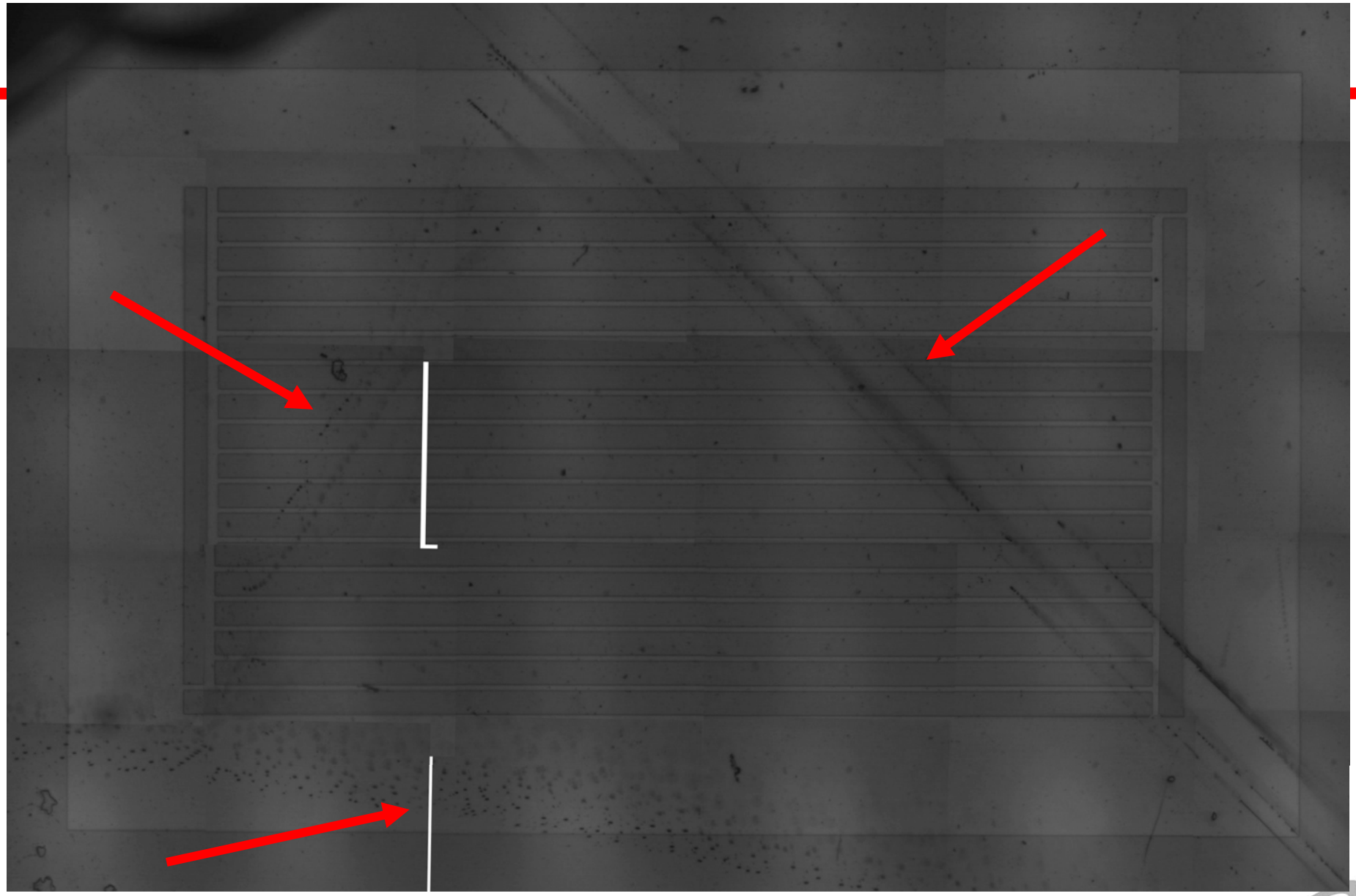
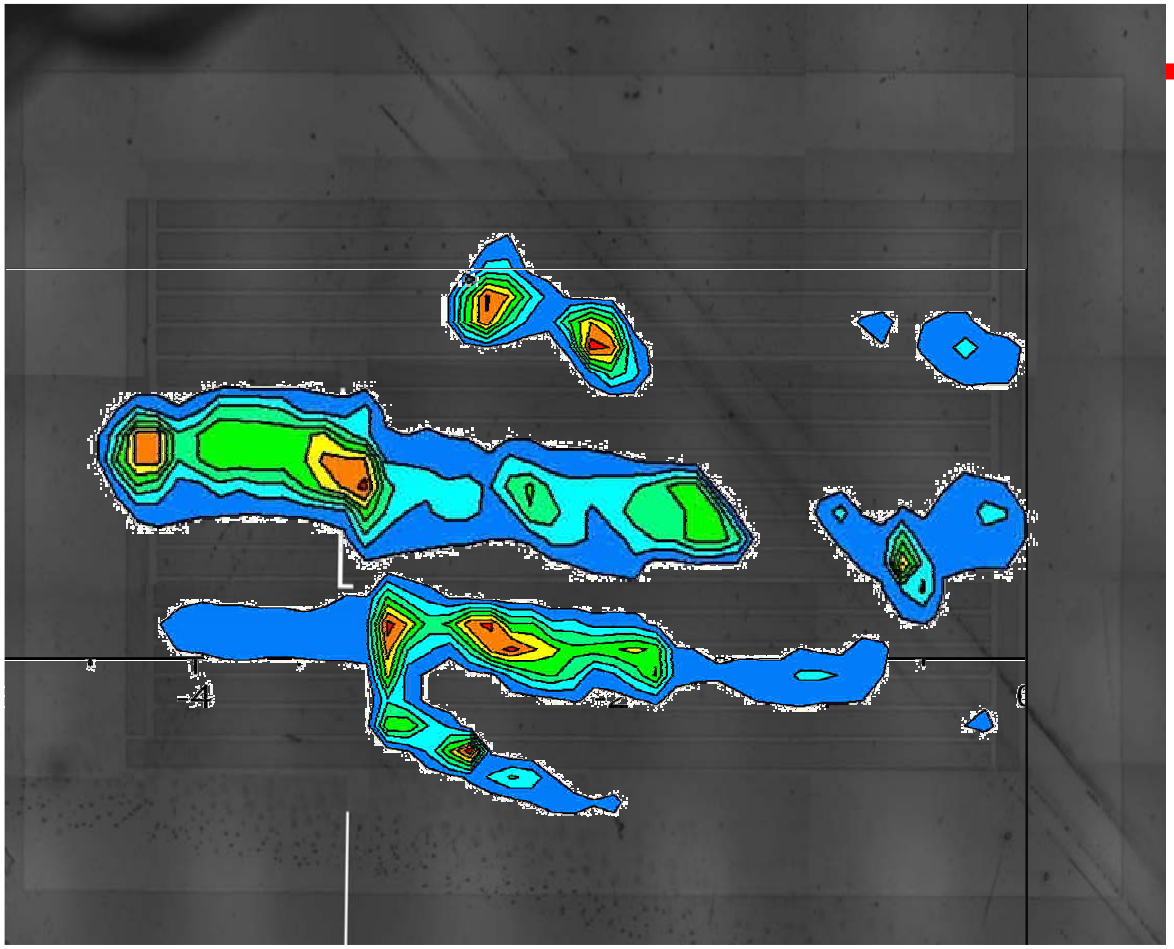
IR Transmission Microscopy



Sample B, top surface

Micron-scale detector mapping



Counts distribution sample B, V = -200V

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Avalanche photodiode detector for high dynamic range point counting.

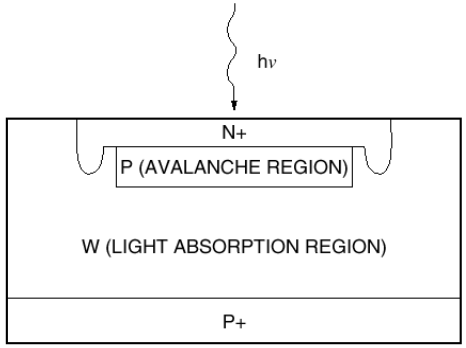
- Many experiments still use NaI-phototube detectors for point-counting situations. These have a count-rate limit of around 100KHz.
- It is therefore frequently necessary to attenuate beams in order to bring the count rate into the linear range of such a detector.
- Integrating detectors have significant disadvantages and a serious noise penalty at low rates.
- Avalanche photodiodes have become quite reliable, and have capabilities above 10^7 Hz, with similar energy discrimination to NaI.
- We have adapted an existing design to make it user-proof.

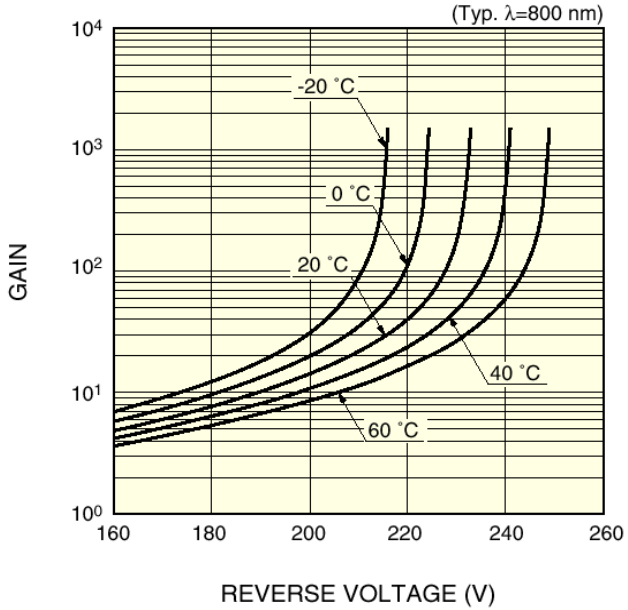
Avalanche photodiodes for x-ray detection

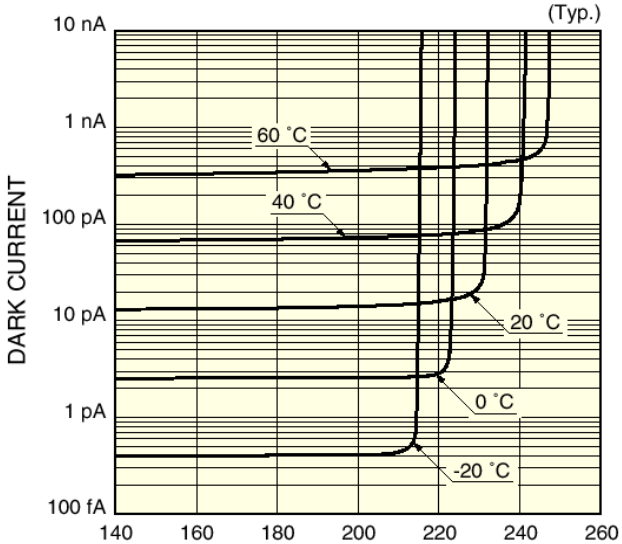
Use special doping profile to create high-field region in a reverse-biased silicon diode.

Energetic collisions of photo-generated carriers produces carrier multiplication.

Device is intrinsically unstable!







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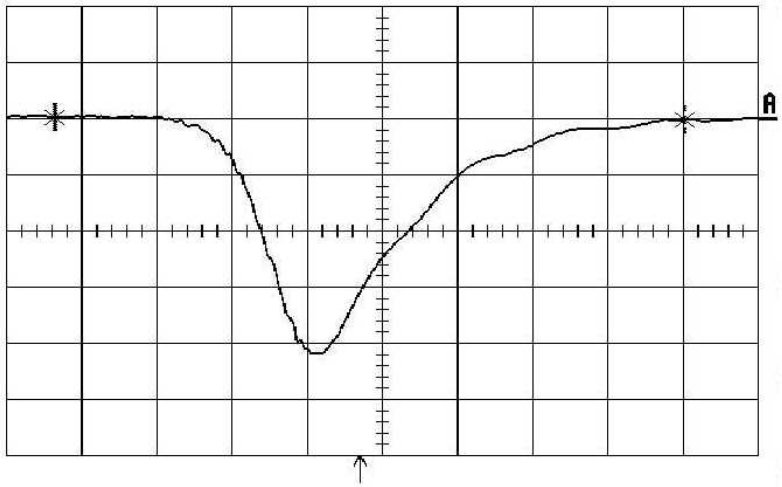
APD detector head

APD Detector Head Specifications:

- **Pulse height resolution ~30% up to 10 MHz (measured at 9 KeV)**
- **Efficiency ~ 50% (measured at 10 KeV compared to NaI)**
- **Maximum rate - ~10 MHz unipolar, ~100 MHz bipolar (with external circuitry)**
- **Rise time (10 – 90%) t_r ~ 1.8 nSec.**
- **Fall time ~ 5.5 nSec.**
- **Width (FWHM) ~ 3.8 nSec.**
- **Output ~ -430 mV for 9 keV X-rays with 370 V bias**
- **Maximum output -2.5 V into 50 W**
- **Diode gain @ 370 V ~ 200, amplifier gain at 100 MHz ~ 60 dB**



Averaged one photon output signal from APD detector head
With 9 KeV X-rays.
Horizontal = 2 nSec/Div., Vertical = 100 mV/Div.

NIM service module

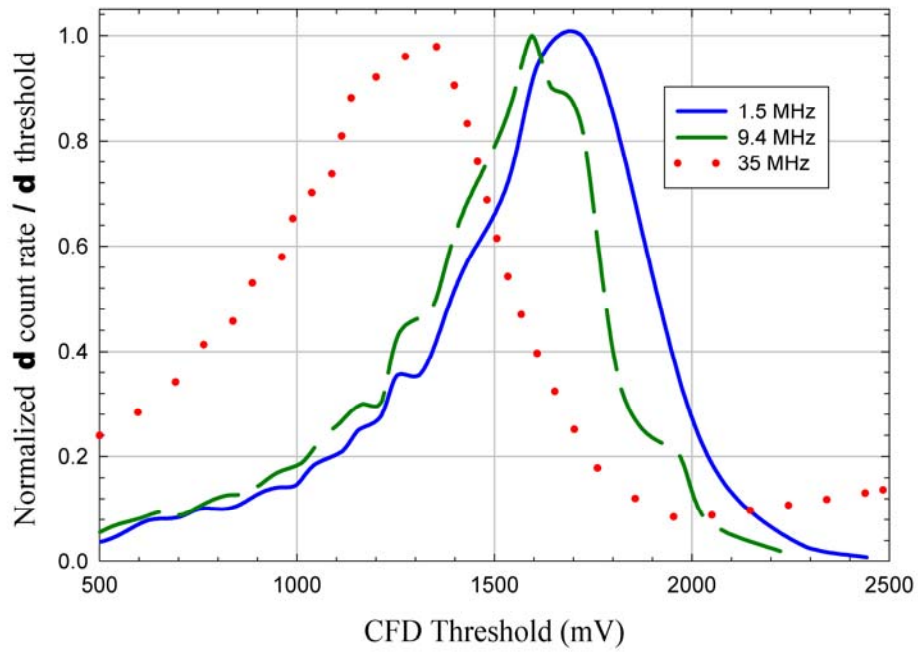
NIM Module Specifications:

SCA / CFD

- **Input impedance 50 W**
- **Timing resolution: ~ 60 pSec. (FWHM)**
- **Input thresholds lower and upper level: 0 – -2.5 V**
- **Fixed input delay: t_d = 2 nSec., t_d > 2/3 * t_r for true constant fraction**
- **TTL output into 50 W**
  - **Rise time – 2.2 nSec.**
  - **Fall time – 3.5 nSec.**
  - **Width (FWHM)– 6.2 nSec.**
  - **Maximum rate ~ 100 MHz**

HV APD bias output 0 – 400 V

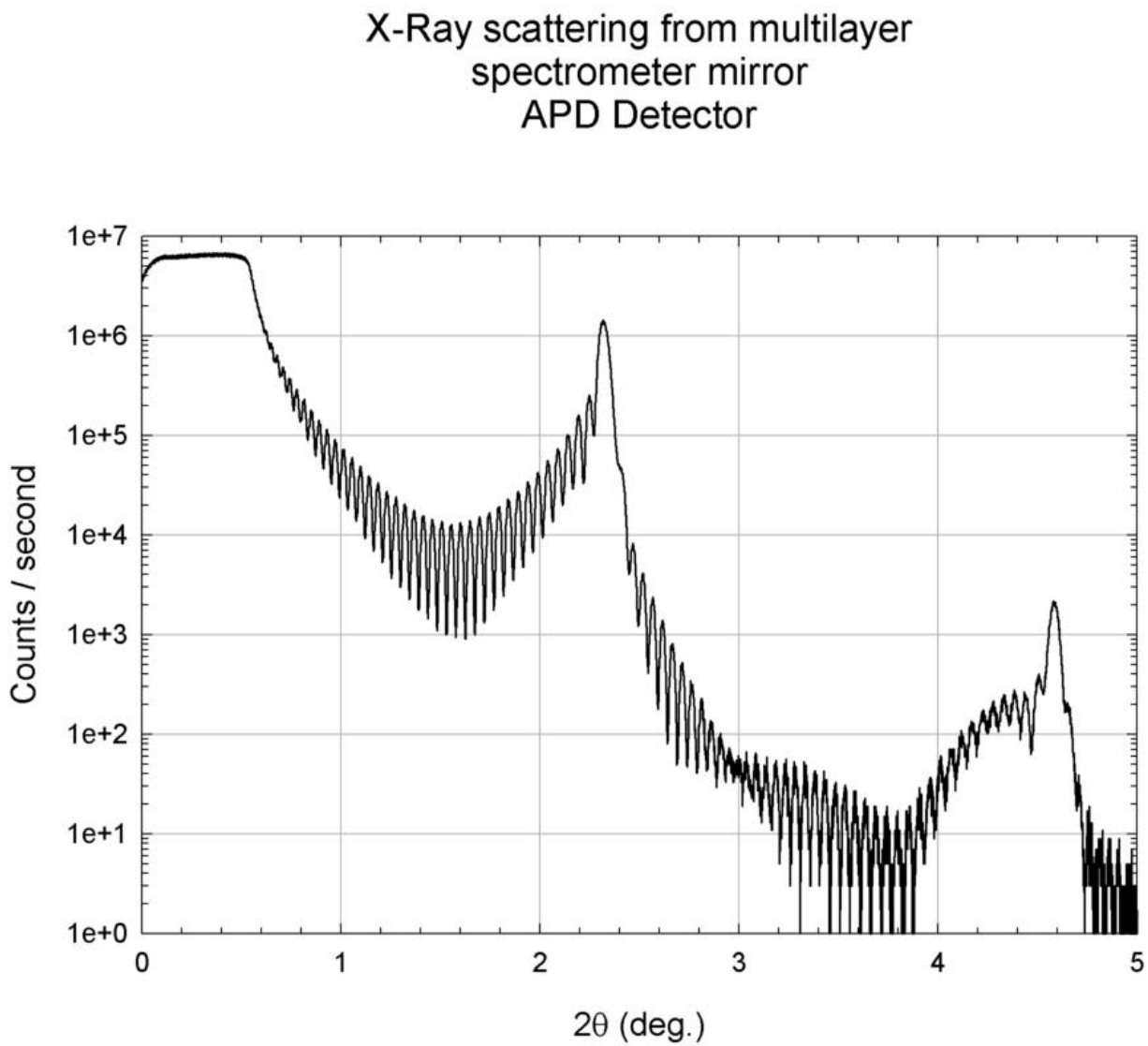
HV trip point 0 – 30 mA



Reflectivity of Mo/Si multilayer

These data were collected without any attenuators.

Maximum rate is limited by NSLS 50MHz bunch rate.



Summary

We are able to leverage our small in-house team by working collaboratively with BNL's Instrumentation Division.

Our role is to define the detector need, to steer the design specifications so that we arrive at a practical design, and to generate user interfaces (both software and hardware) which allow scientists to use our detectors productively.

We have begun an effort to bring CZT technology into BNL's toolkit.