Studies of Silicon Photodetectors for Scintillator-based Hadron Calorimetry at the International Linear Collider

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BEAUNE 05

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Outline

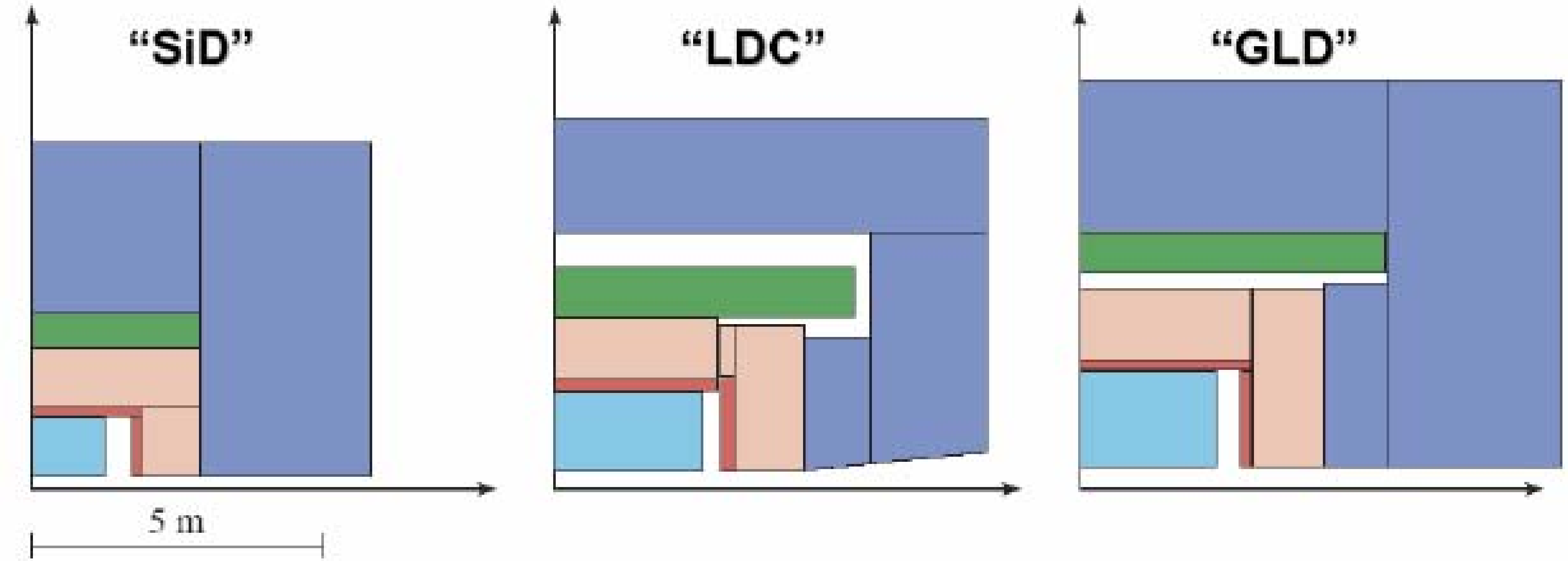
- Motivation: the intended application
- The device: the Metal/Resistor/Semiconductor photodiode (MRS)
- Determination of Working point: bias voltage, threshold, temperature
- Linearity of response
- Stress tests: magnetic field, exposure to radiation
- Tests with scintillator using cosmic rays and radioactive source
- Summary

Motivation

A scintillator-based Hadron Calorimeter for the proposed International Linear Collider

- Excellent 3-d imaging for separation of showers in jet of particles: "Particle-Flow Algorithms" for $\Delta E/\mathrm{GeV} \approx 0.3\sqrt{(E/\mathrm{GeV})}$
- Barrel: $R_{in} \approx 150$ cm, $R_{out} \approx 250$ cm, $L \approx 600$ cm
- ~35 layers of ~0.5 cm thick, 4-25 cm^2 scintillating cells $\Rightarrow O(10^6)$
- Must be
  - sensitive to Minimum Ionizing Particles,
  - able to operate inside strong (~5 T) magnetic field,
  - highly hermetic,
  - cost effective ($\lesssim$\$30M).

The ILC Detector Concepts

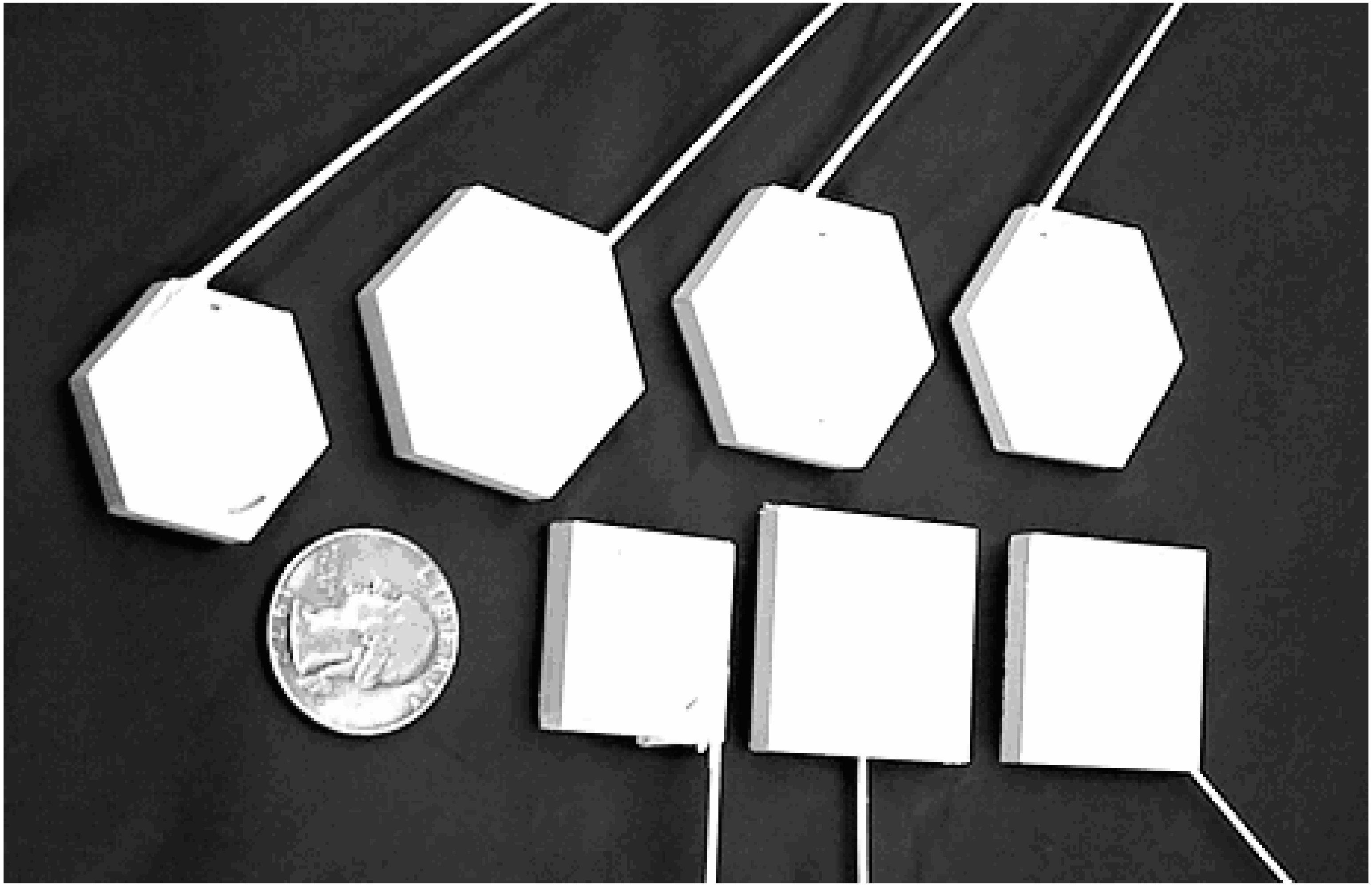


- Main Tracker
- EM Calorimeter
- Had Calorimeter
- Cryostat / Solenoid
- Iron Yoke / Muon System

- SiD: Silicon Detector — SiD: $B R^2$
  - Small, 'all' silicon
- LDC: Large Detector Concept — LDC: $B R^2$
  - TPC based
- GLD: Global Large Detector — GLD: $B R^2$

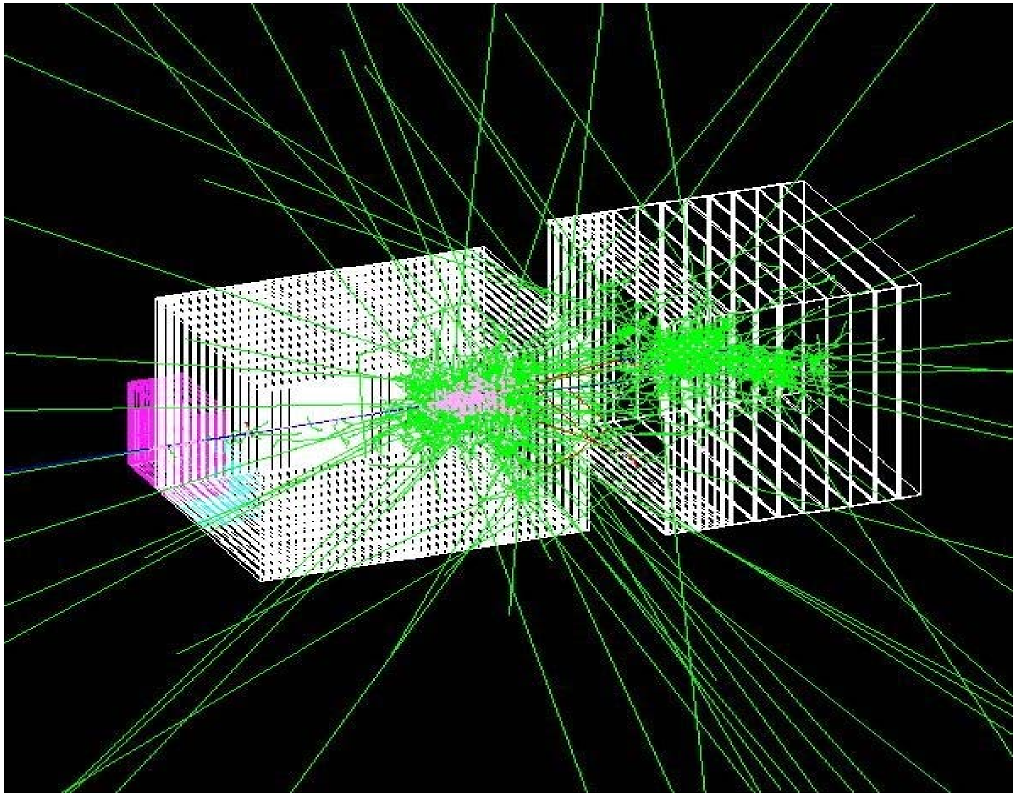
Small Scintillating cells for the ILC HCal

- Different cell & groove shapes with extruded and cast scintillators

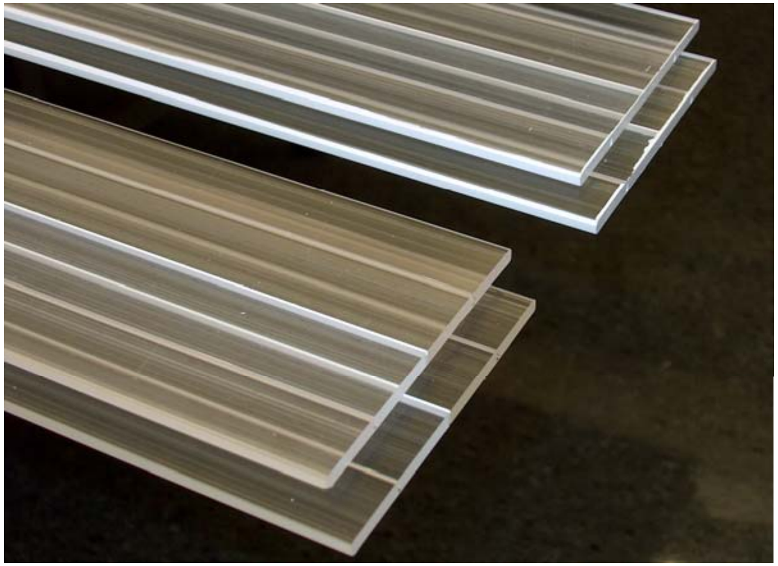


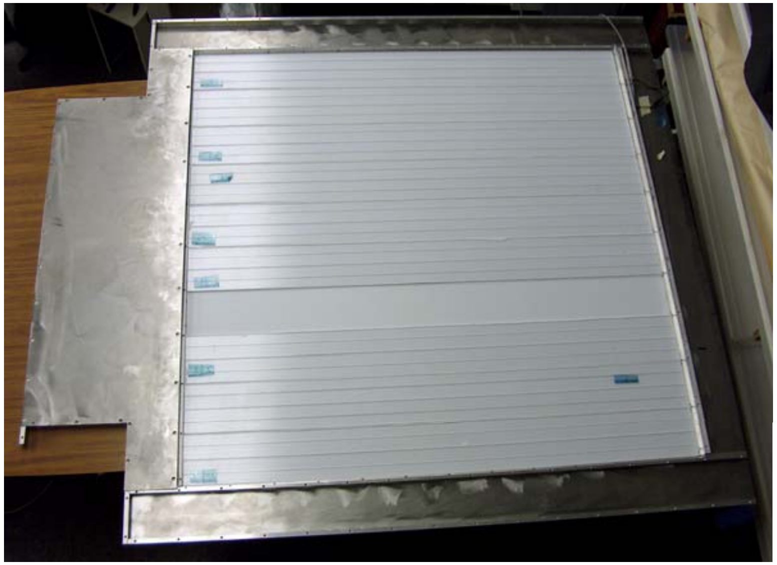
The Tail-Catcher/Muon Tracker for the CALICE test beam module

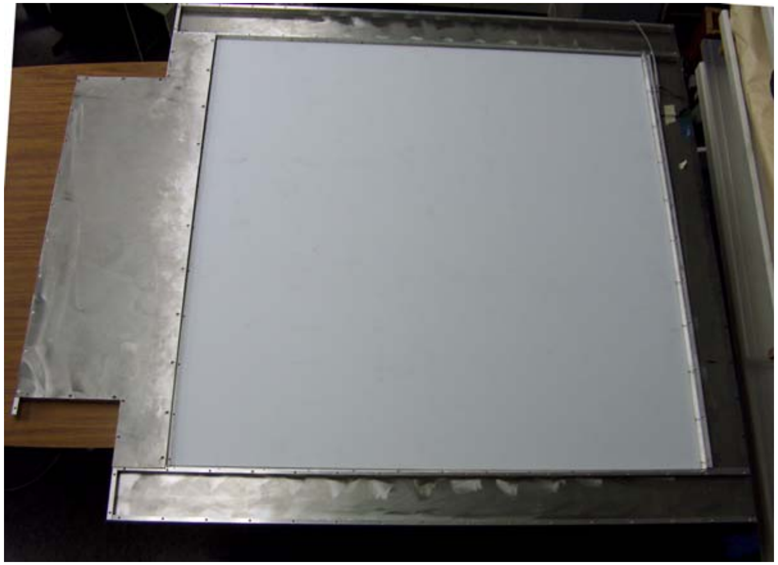
- “Fine” section (8 layers): 2 cm thick steel
- “Coarse” section (8 layers): 10 cm thick steel
- 5mm thick, 5cm wide extruded scintillator strips
- 1.2 mm-diameter Kuraray Y11 fibers
- Tyvek/VM2000 wrapping
- Alternating x-y orientation
- Si photodetectors (SiPM)
- Common readout w/ Hcal
- Along beam: 142 cm
- Height: 109 cm
- Weight: ~10 ton

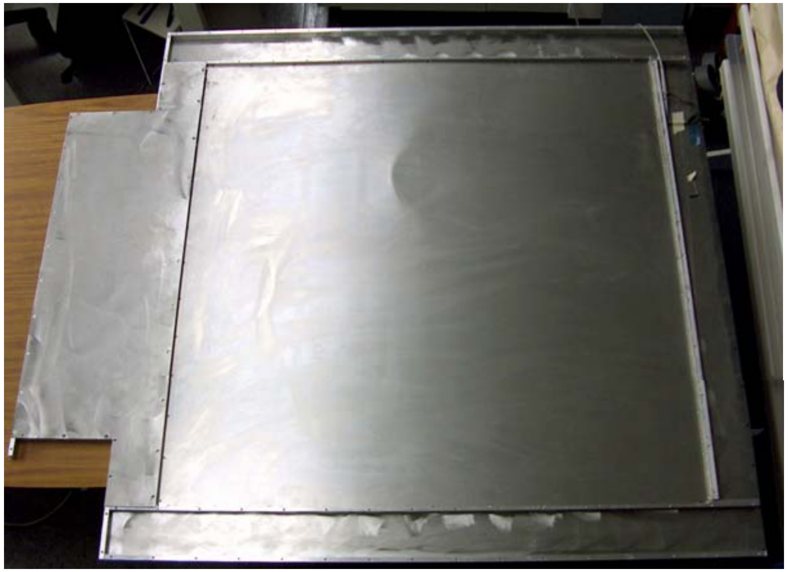


CALICE TB TCMT layer assembly

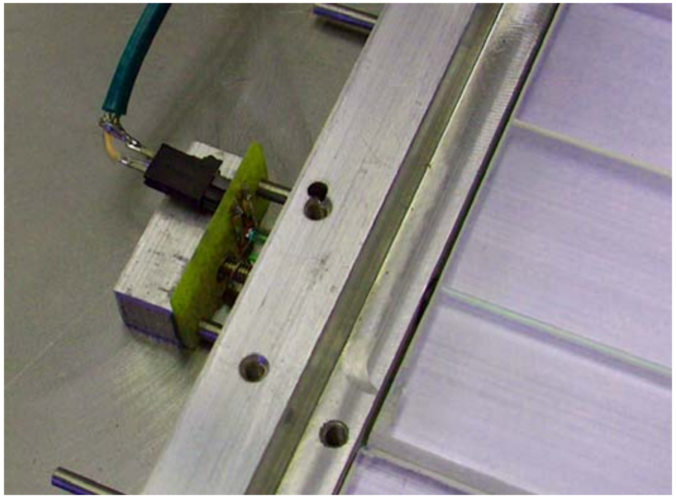


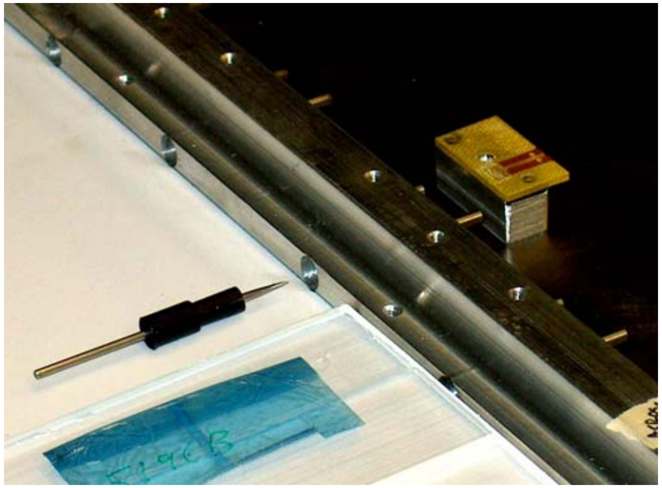


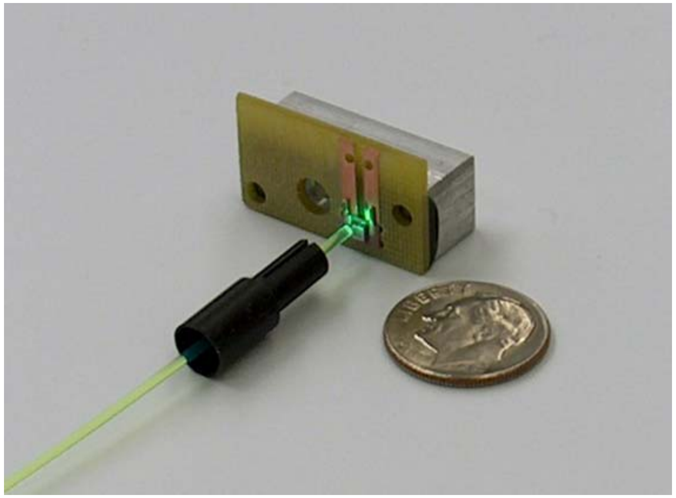




CALICE TB TCMT layer assembly



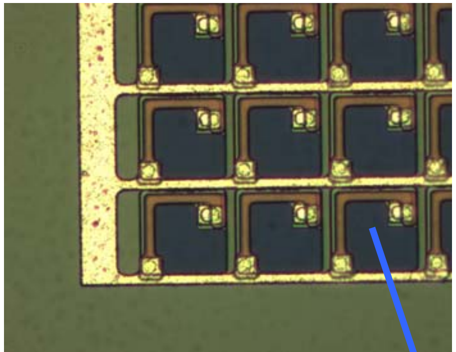


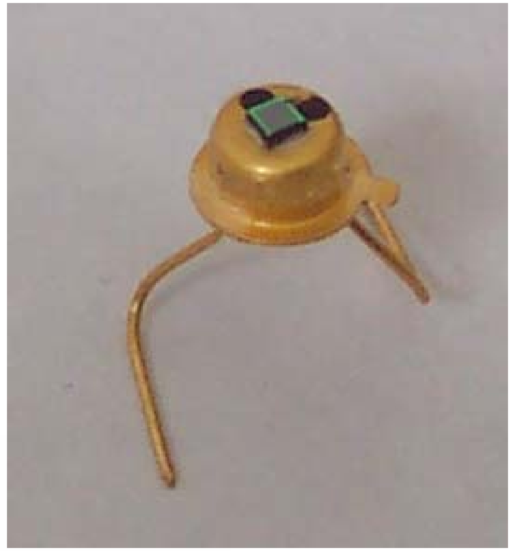


The Metal/Resistor/ Semiconductor Photodiode (MRS)

- From the Center of Perspective Technologies & Apparatus (CPTA),
- Multi-pixel solid-state devices with every pixel operating in the limited Geiger multiplication mode & sensitive to single photon,
- ~1500 pixels on 1 mm x 1 mm sensor,
- Avalanche quenching achieved by resistive layer on sensor,
- Detective QE of up to 25% at 500 nm,
- Good linearity (within 5% up to 2200 photons)
- Immune to magnetic field,
- Radiation-tolerant.

Metal Resistive Semiconductors (MRS)





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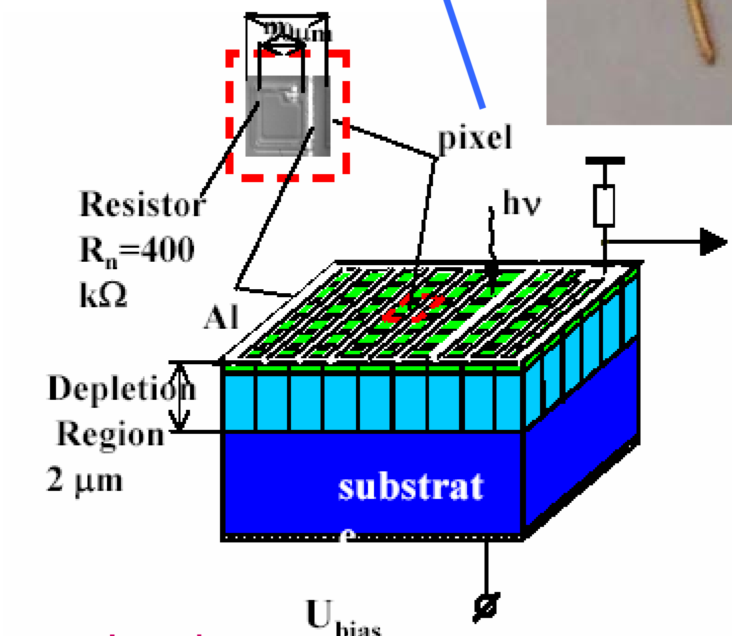
Center of Perspective
Technologies &
Apparatus (CPTA)



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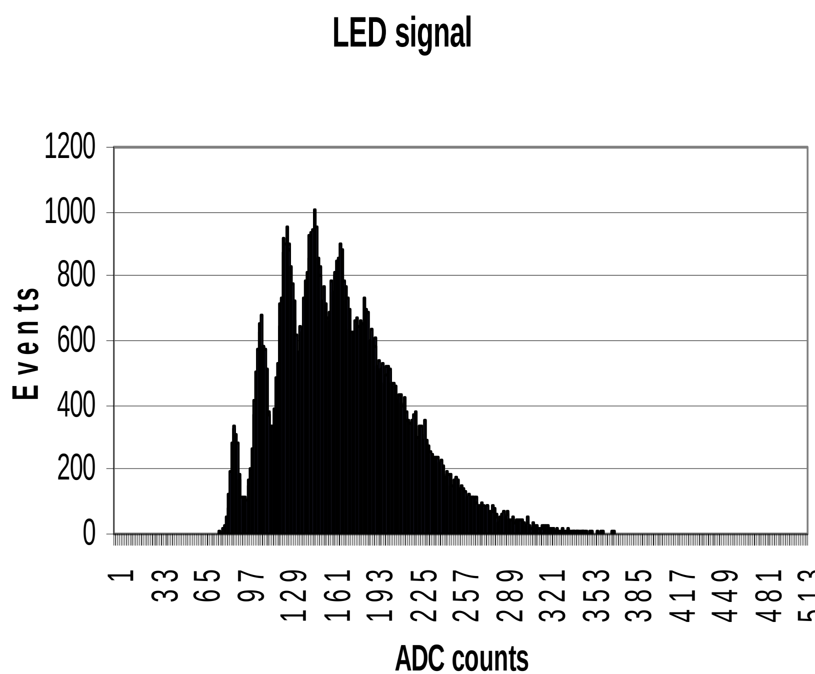
Typical pulseheight spectrum

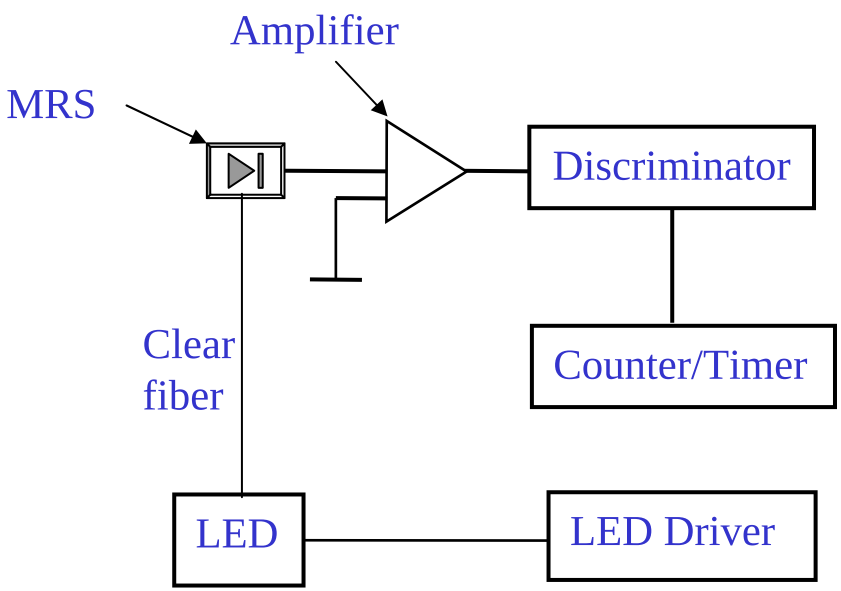


The Test Suite

- Threshold characteristics,
- Noise frequency,
- Dependence of signal amplitude on bias voltage & temp,
- Linearity of response,
- Stability over time,
- Single photoelectron separation with LED,
- Response to light produced in scintillator by cosmic ray muons and radioactive source,
- Effects of magnetic field & radiation dose,
- Sensitivity to fiber-sensor alignment

Working Point Determination

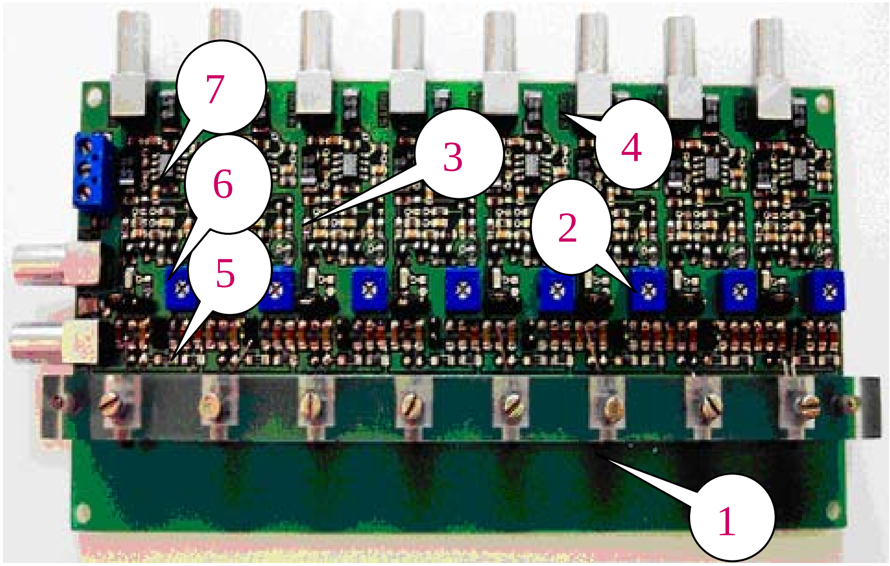
The set-up



Green LED, 510 nm peak

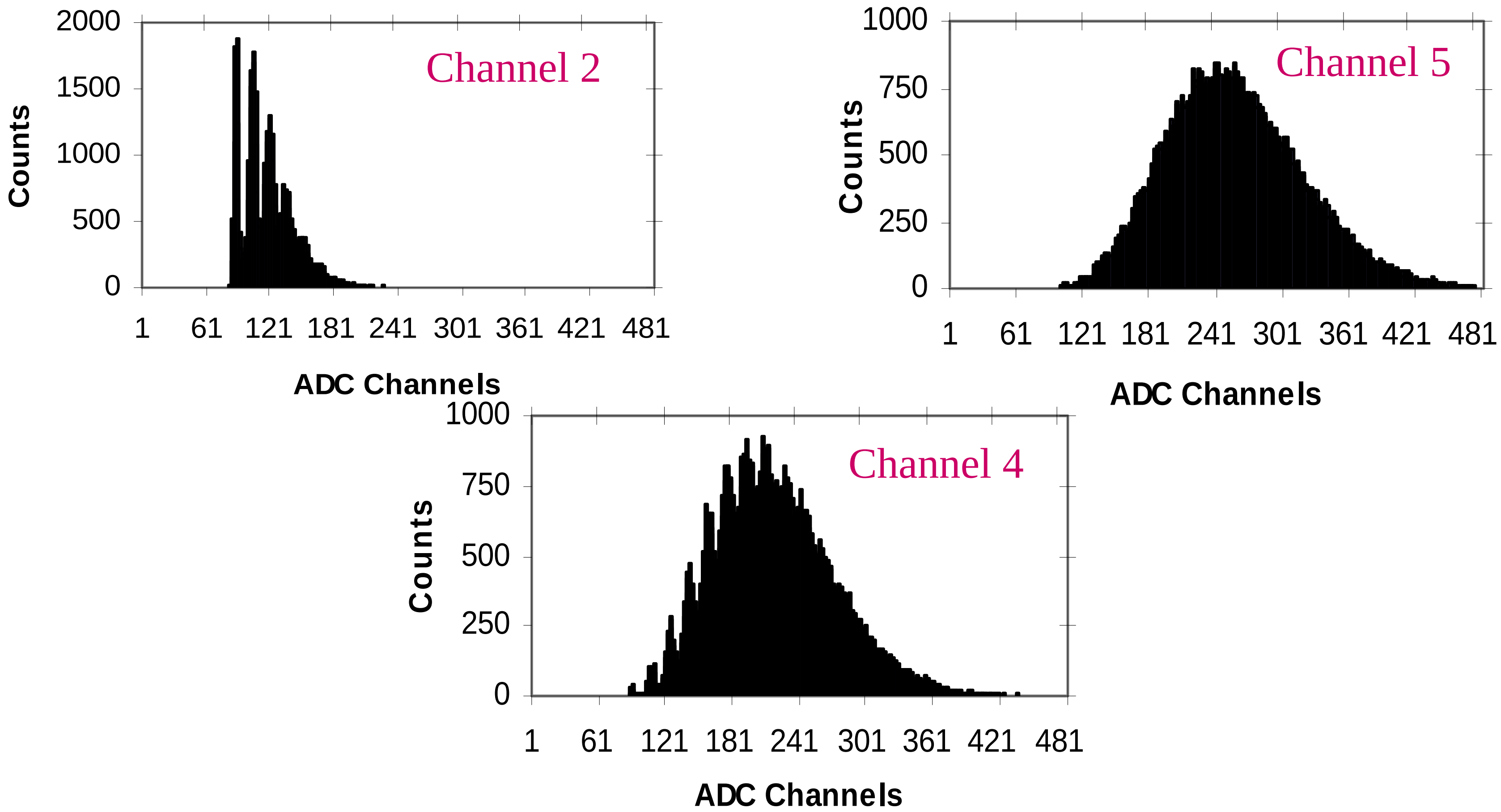
Pulsed with ~10 ns @ ~150 Hz

The 8-channel board



1. MRS sensor,
2. Bias voltage tuner,
3. Preamplifier,
4. Signal output
5. Bias voltage input,
6. Test signal input,
7. Preamplifier power

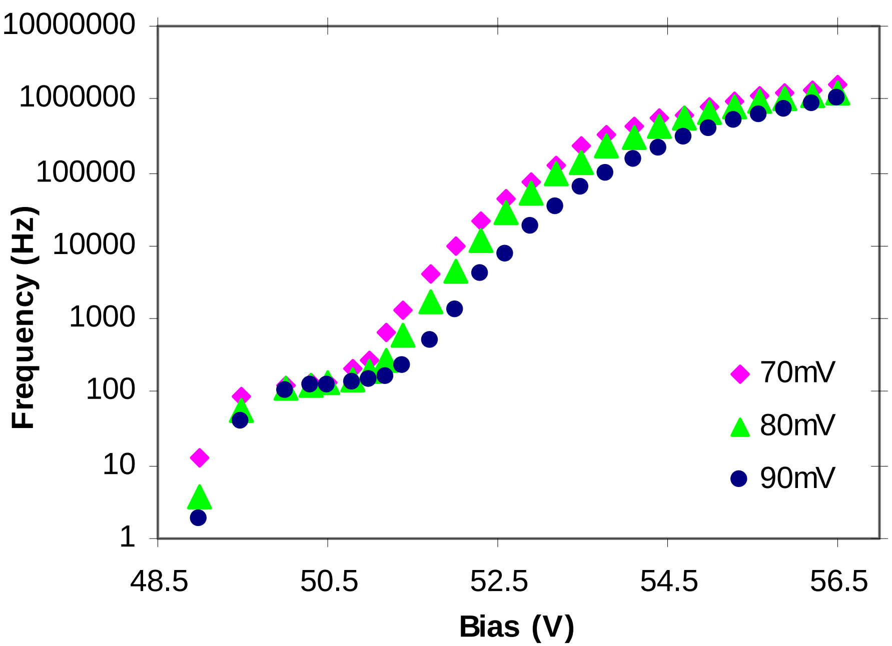
Working point determination (contd.)

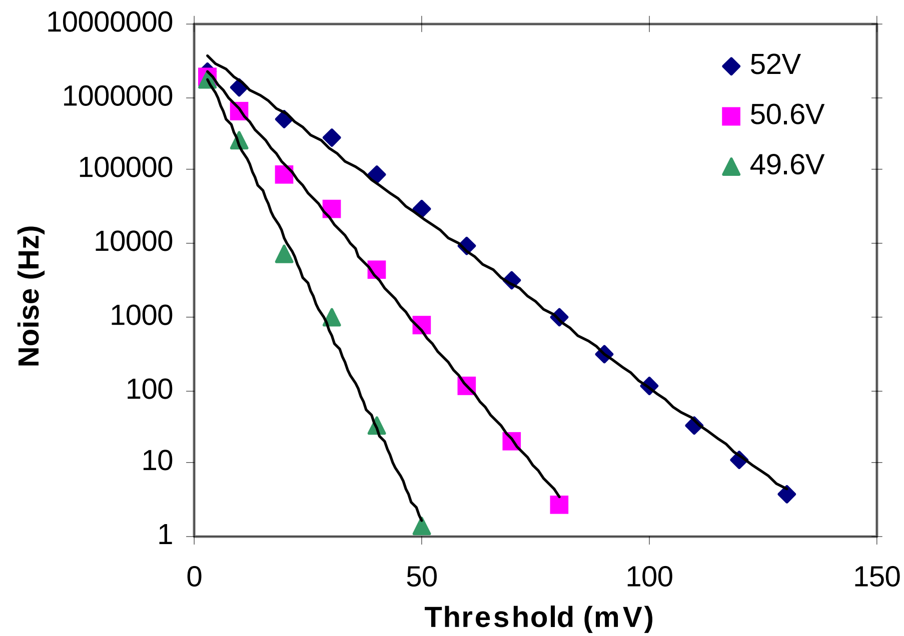


- The MRS is to able to separate single photoelectrons
- Different response under identical setup

⇒ working point must be determined for each channel individually

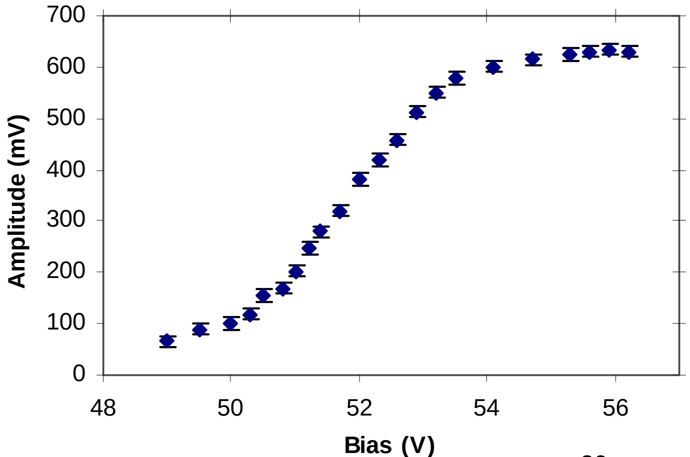
Noise Rate vs. Bias Voltage & Threshold

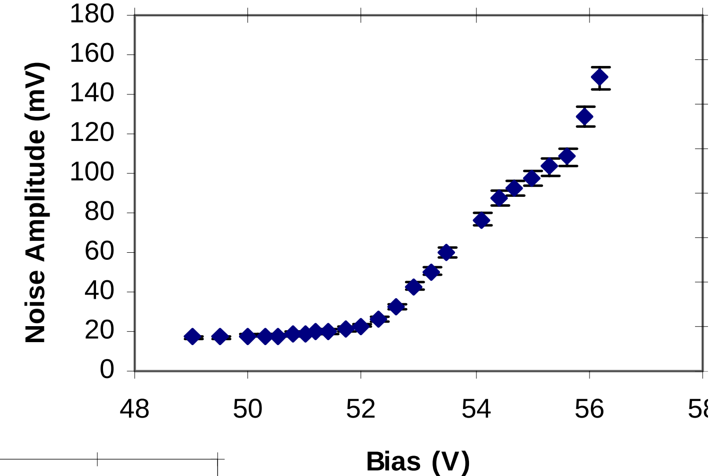


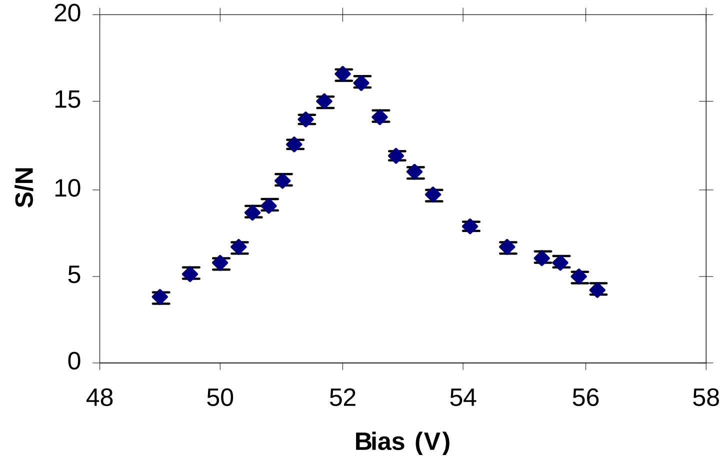


- The right end of the plateau region in the Figure on left is optimal for our purpose.
- For thresholds in the range of 80±10 mV and bias voltage in 50.0±0.5 V, the dark noise is well under control.

Signal & Noise Amplitudes vs. Bias Voltage

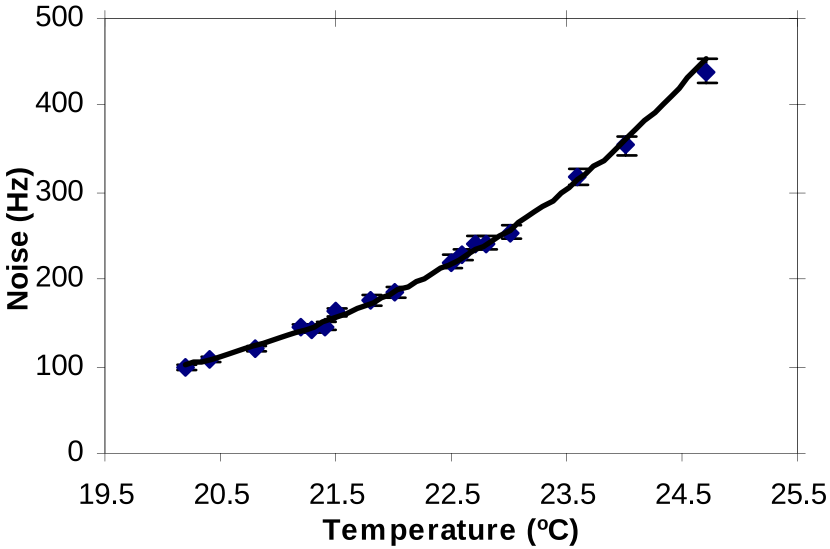


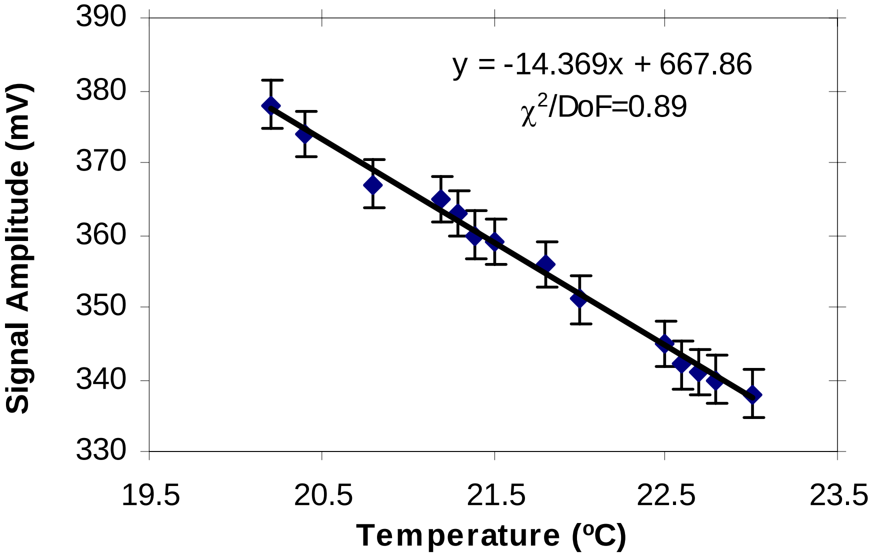




- For this particular device S/N peaks at $V_{bias} \approx 52$ V
- Sharp peaking in S/N $\Rightarrow$ working point must be found for each piece.

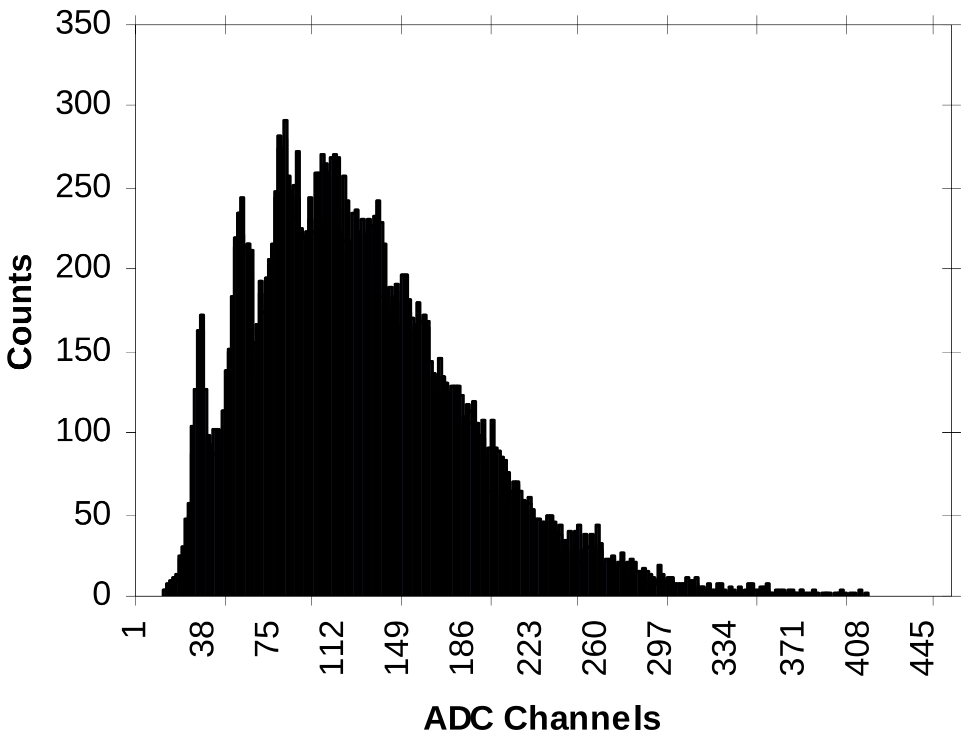
Temperature Dependence





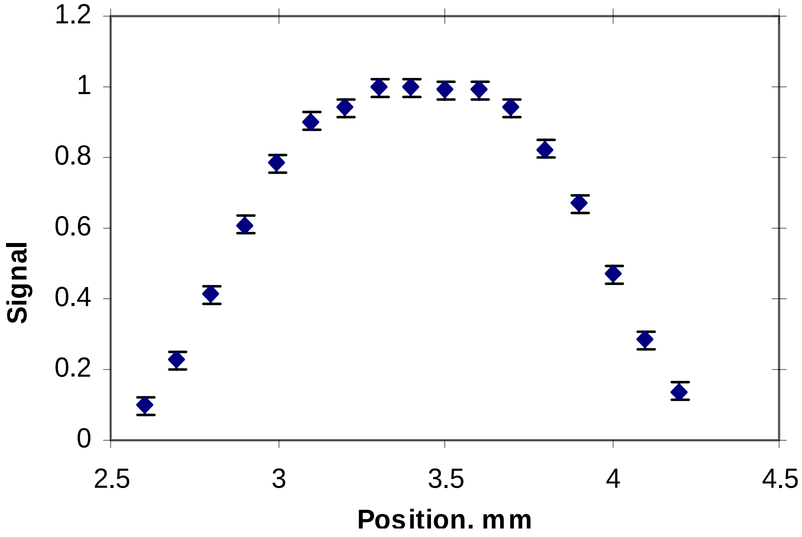
- Bias = 51.3 mV, threshold = 80 mV
- Loss in signal amplitude with increase in T ≈ 3.5%/ ˚C

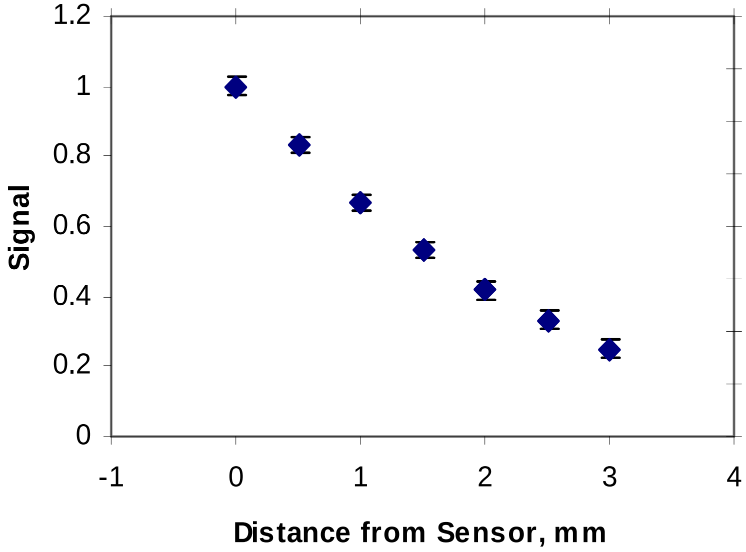
Calibration test

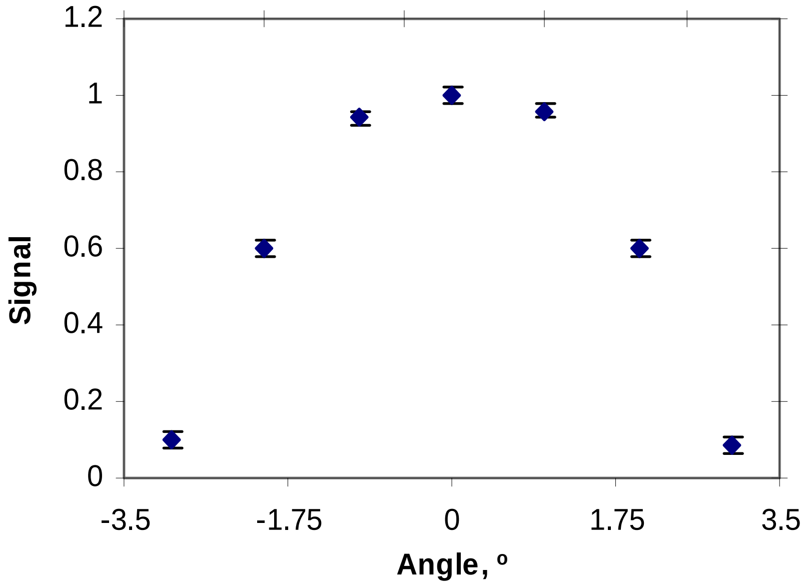


- Blue LED (450 nm) to simulate light from scintillator,
- Light delivered to MRS using green WLS fiber,
- First few PE peaks are easily discernible and uniformly separated $\Rightarrow$ good linearity (at the low end, at least).

Fiber Positioning on MRS







Optimal fiber–sensor mating is crucial.

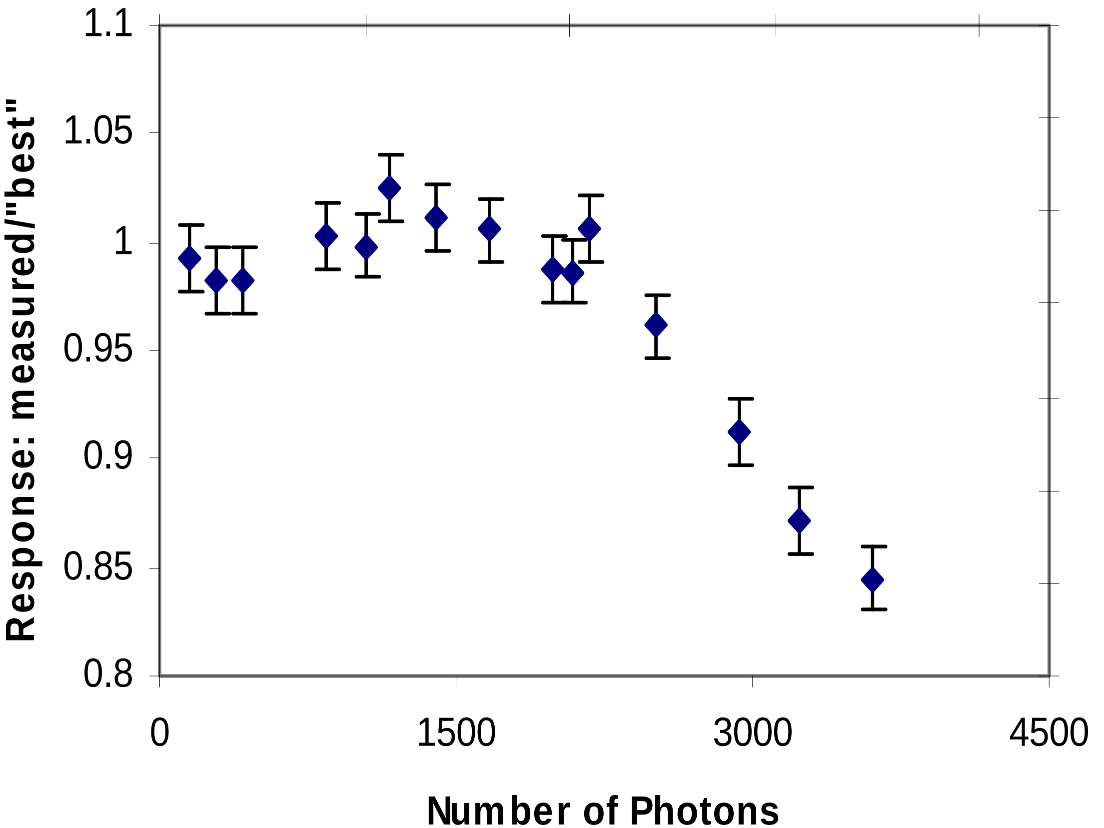
Linearity of Response

Since the response of an individual pixel is not proportional to n_γ, (unless it has had time in between to recover), non-linearity is expected when the detector receives a large number of photons.

Deviation reaches 5% (10%) at $n_\gamma \approx 2200$ (3000) or, $n_{PE} \approx 550$ (750).

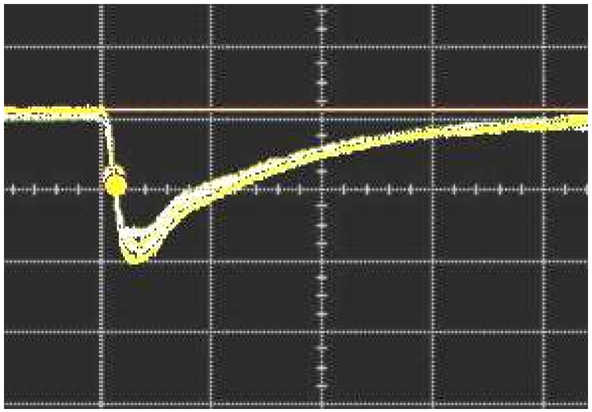
One MIP $\approx$17 PE

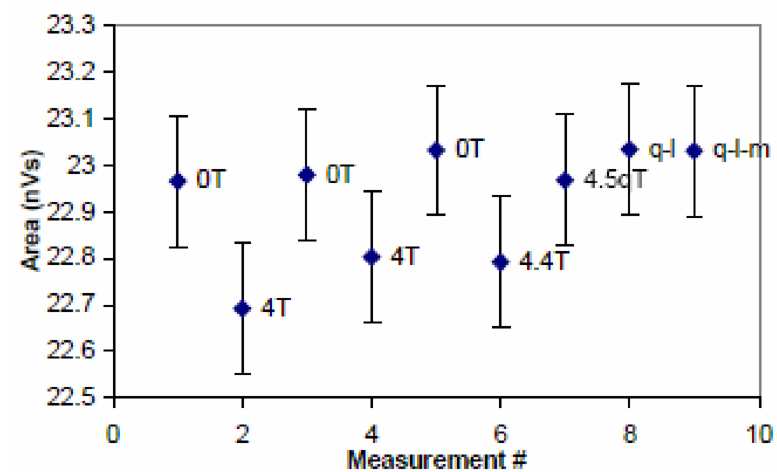
$\Rightarrow$ up to 32 MIPs can be measured within 5% linearity.

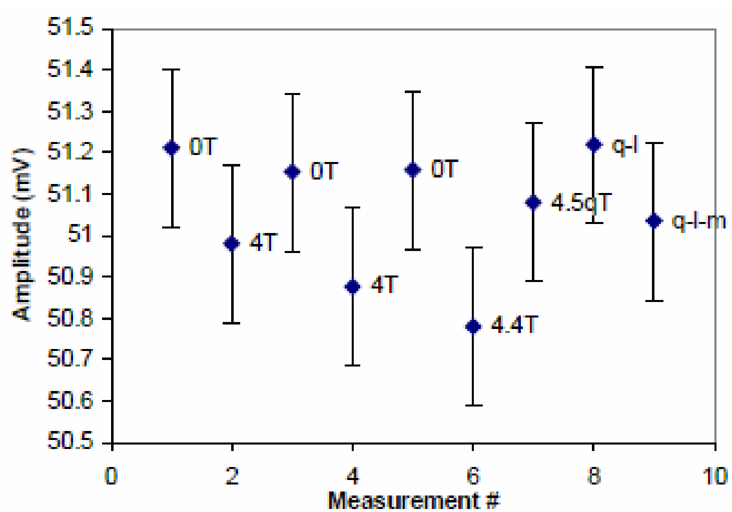


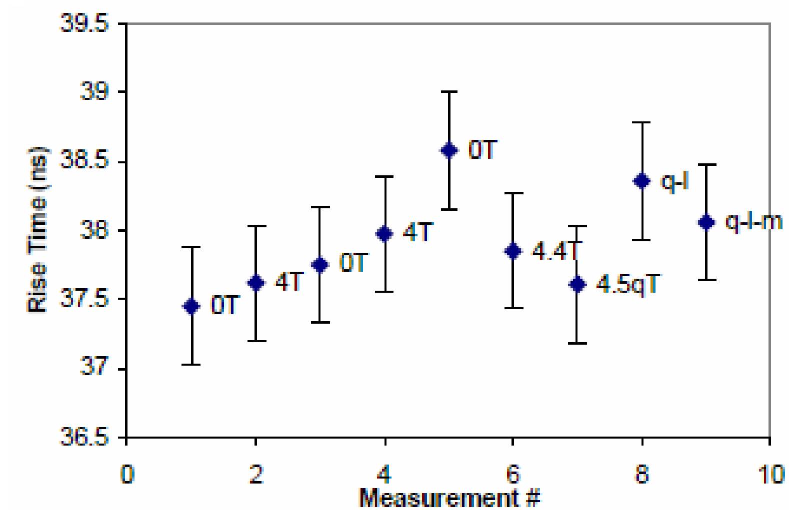
Stress Tests: Effect of Mag. field

No significant effect of fields up to 4.4 T and quenching at 4.5T:



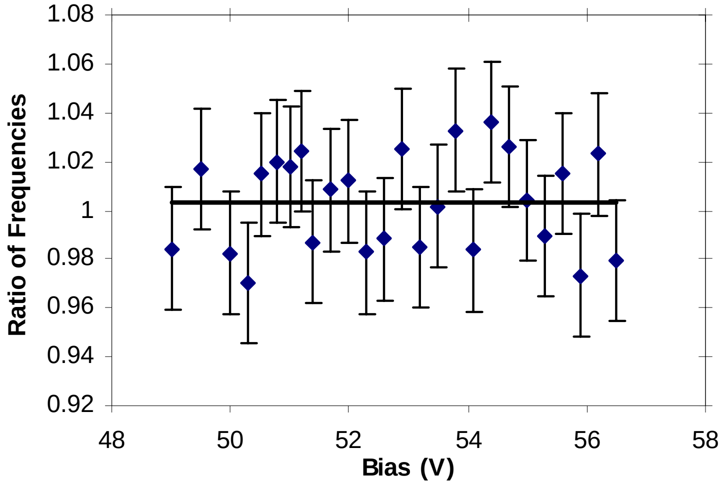


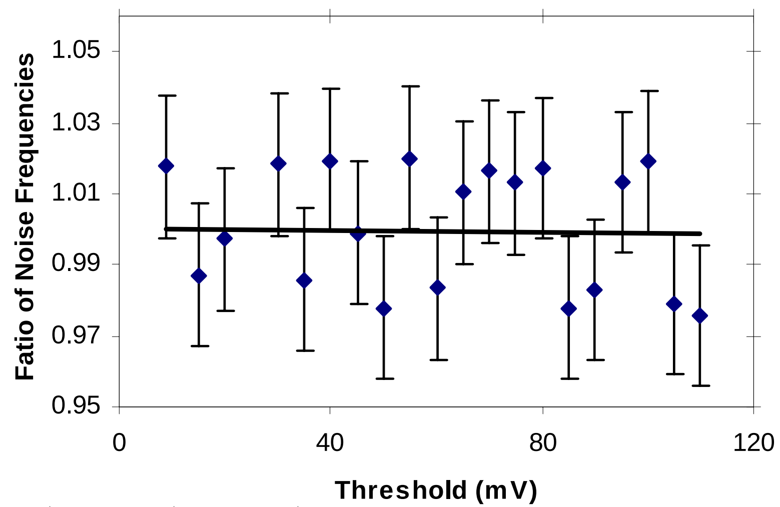


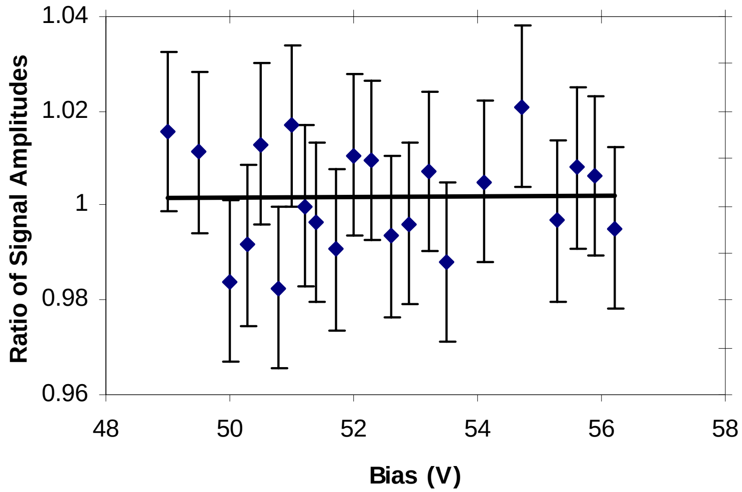


Stress Tests: Effect of Irradiation

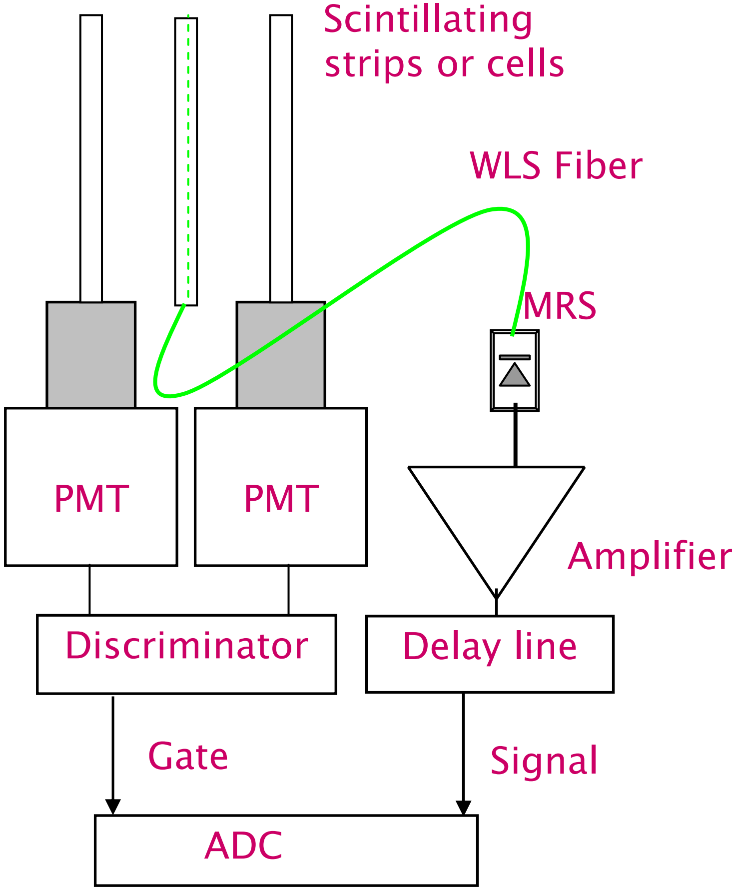
- No detectable damage from 1 Mrad of γ:



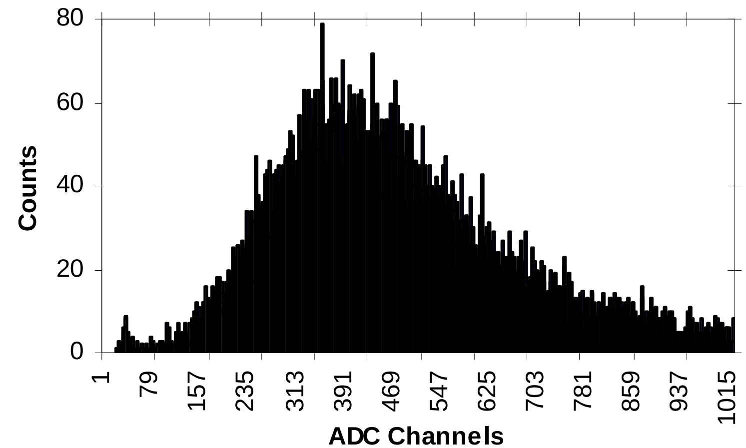




Cosmic Ray & Radioactive Source Tests



CR muons:



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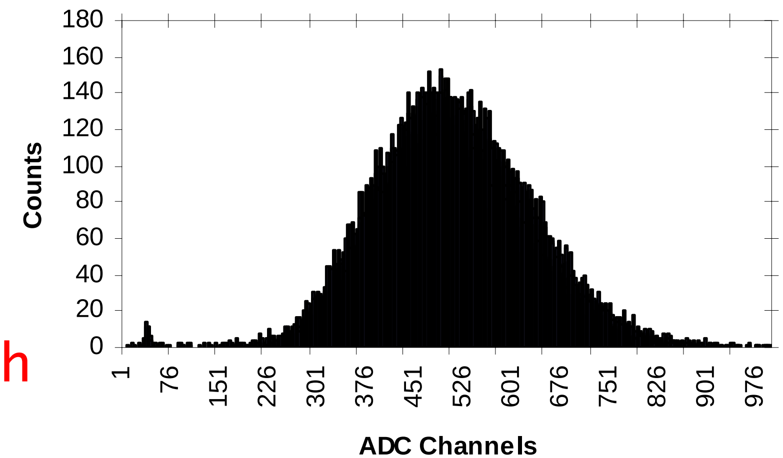

1 MIP taking the shortest path through 5 mm thick cell/strip ⇒ 14–17 PE

Summary

We have conducted a set of measurements to illustrate the potential use of Si photodetectors in High Energy Collider experiments in general, and for hadron calorimetry at the ILC in particular.

- Good MIP sensitivity, strong signal (gain ~O(10^6),
- Fast: Rise time $\approx$ 8 ns, Fall time $<$ 50 ns, FWHM $\approx$ 12 ns (w/ amp)
- Very compact, simple operation (HV, T, B,…),
- Each sensor requires determination of optimal working point,
- Noise is dominated by single photoelectron: a threshold to reject 1 PE reduces the noise by a factor of ~2500,
- The devices operate satisfactorily at room temperature (~22 °C). Cooling reduces noise and improves gain,
- Not affected by magnetic field (tested in up to 4.4 T + quench),
- No deterioration of performance from 1 Mrad of γ irradiation.

Thank you!

For further details,

- See NIM A vol. 545, issue 3 (2005), p 727-737
- Visit http://nicadd.niu.edu/
- Contact Dr. Victor Rykalin: rykalin@fnal.gov