Scintillator/WLS Fiber Readout with Geiger-mode APD Arrays

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Overview

- Motivation
- Silicon Avalanche Photodiode basics
- aPeak GPD device characterization
- 7-pixel cluster measurements with MINOS-type bars
- Recent single pixel measurements (temperature)
- Future plans
- Summary

Motivation

- WLS readout of scintillator strips basic component of several existing detectors (MINOS, CMS-HCAL); option for LC muon/calorimeter systems

- Geiger-mode Avalanche photodiodes (GPDs)
  - Pros: Large pulse (~volt); high quantum efficiency; relatively fast; compact; low mass; low voltage operation (~10s volts); modest physical plant; magnetic field insensitive; compatible with CMOS -> cheap?
  - Cons: High dark count rate; small pixels (13-150 microns); unproven.

- Several developers in past few years
  - SiPM: Dolgoshein et al.
  - MCP: Hamamatsu
  - **GPD: aPeak**

Device Characterization

Characterization measurements first performed at aPeak.
Evaluated with cosmics and LED excitation of WLS at CSU.

Typical configuration:

- Green (550 nm) LED, 150 ns pulse@10 kHz
- ~7-10 photons/pulse
- Active quench circuit (< 1 μsec output pulse width) – several versions

Basic Measurements:

- Dark Count Rate, DCR
- Detection Efficiency, DE = (Illuminated Rate - Dark Rate)/10 kHz
  - In cosmic ray measurements DE determined from hodoscope triggers
- Temperature dependence

Interpreting Detection Efficiency

Number of photons detected:

$$n_d = QE * A * N_\gamma$$

- N_γ is the number photons incident on the photodetector
- $QE*A$ is an effective single photon detection efficiency.

From Poisson statistics, the probability for n_d to fluctuate to 0 is given by:

$$P(0;n_d) = e^{-n_d}$$

So we define a Detection Efficiency for a digital device,

$$\boxed{DE = (1 - e^{-n_d}) = (1 - e^{-QE*A*N_\gamma})}$$

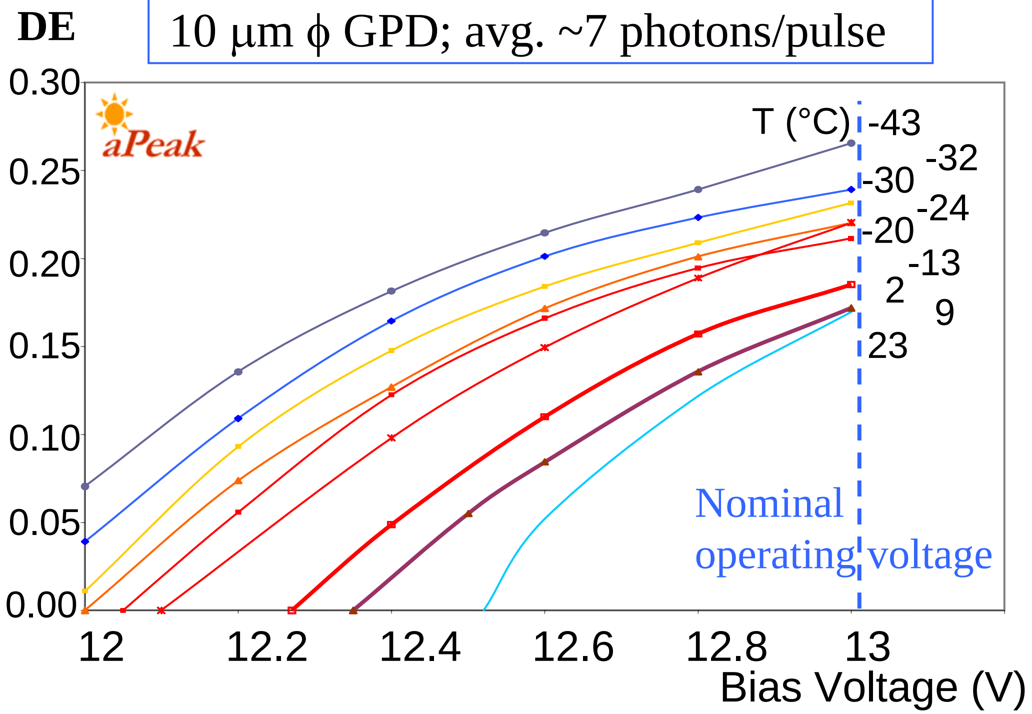
Characterize the effect of high DCR on detection efficiency with a correction for GPD signal quench time f_q and DCR:

$$\boxed{DE_{eff} = DE\,(1 - f_q * DCR)}$$

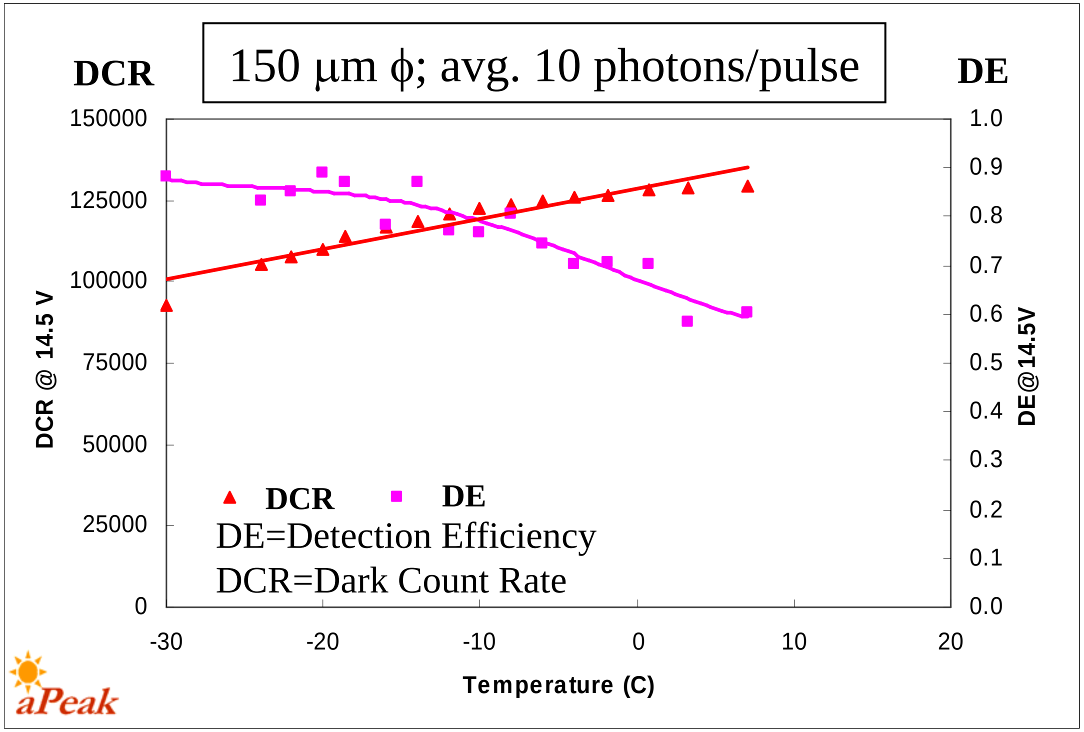
Device Characteristics (1)

Room temp. operation: 21,600 hours (3 years) without degradation

10 μm ϕ GPD; avg. ~7 photons/pulse



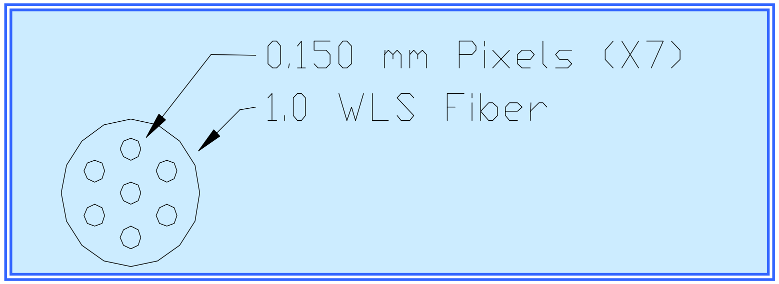
Device Characteristics (2)



One sample 150 μm GPD at 20°C has DCR~375 kHz, f_q, $DE\sim0.50$ for $\langle N_\gamma \rangle \sim 10$

$\Rightarrow QE*A \sim 0.069;\ f_q*DCR \sim 0.23$

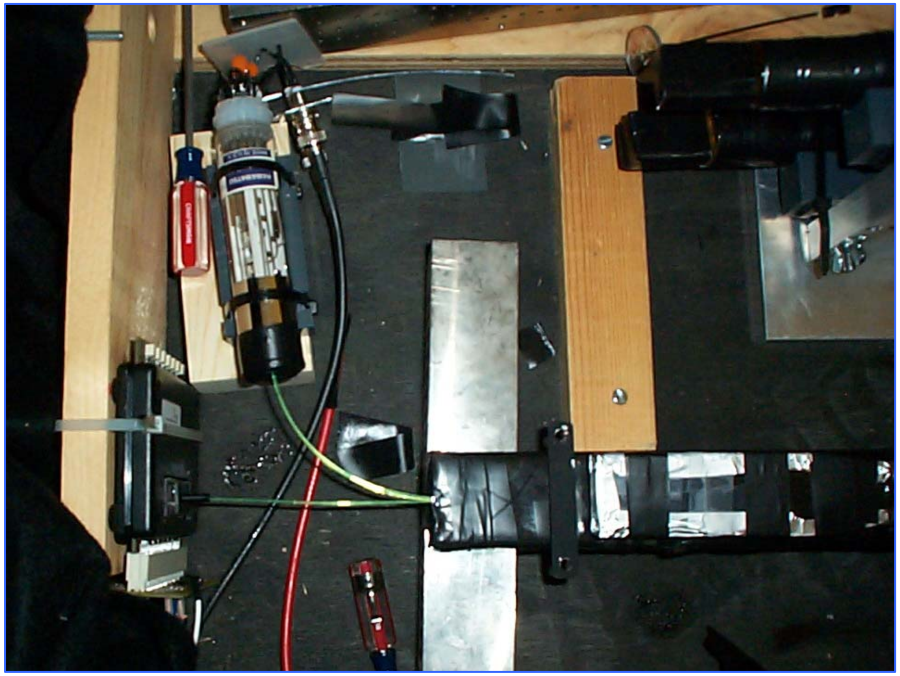
7-pixel GPD cluster

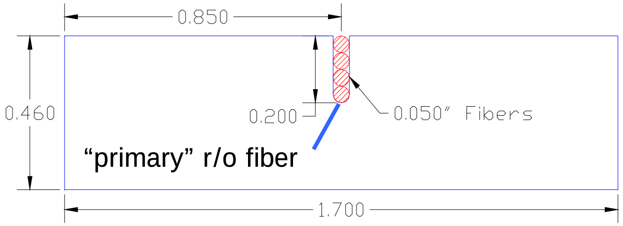


- Seven 150 μm GPDs under 800 μm footprint; two clusters on chip
- Clear fiber bonded to each cluster
- Active GPDs 16-23% of fiber area
- Active Quenching Circuit (AQC) somewhat unstable – output pulses vary in amplitude even above turn-on
- Measure Detector Efficiency on cosmics test bed at CSU

GPD Scintillator/Fiber Test Bed

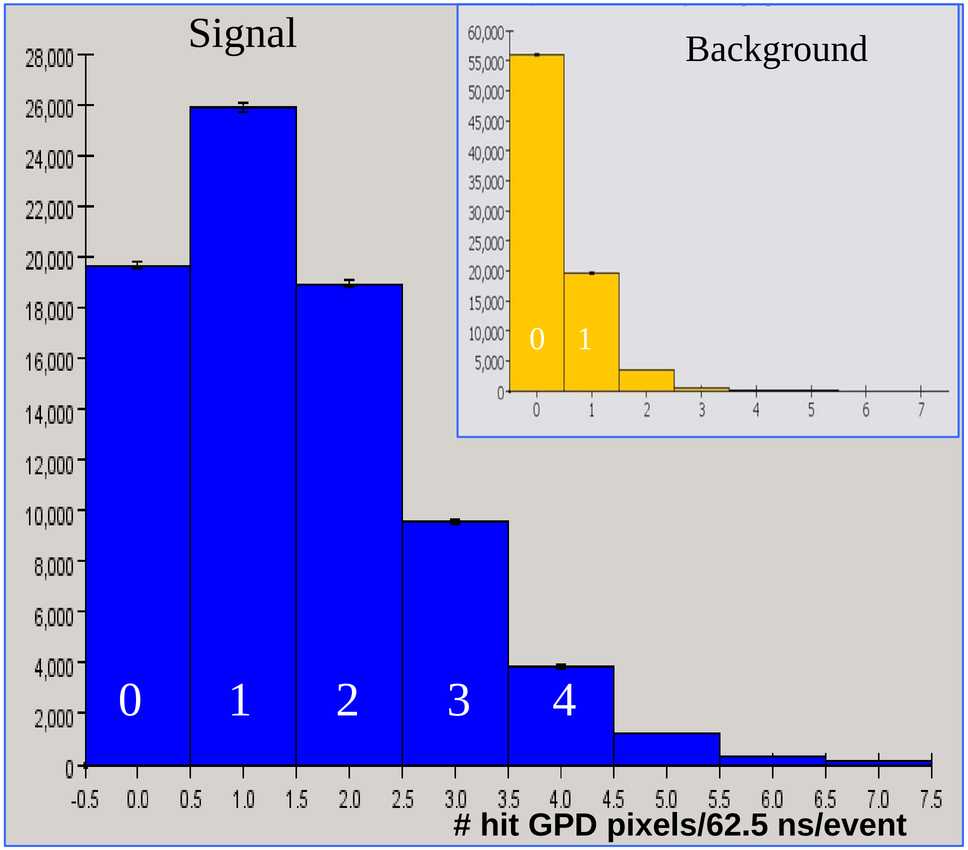
- Scintillator hodoscope for cosmics
- SLAC modification of MINOS scint/WLS (Y-11) fiber: 4 x 1.2 mm fiber readout
- *Primary* (bottom) WLS fiber provides ~50% of total ~ 110 γ/event
- Remaining three fibers are attached to the face of a PMT (Hamamatsu R2658) for monitoring
- Primary spliced to clear fiber glued to one GPD cluster
- 1.7-2.4 photons/event onto each pixel (depending on distribution in the fiber)
- With QE*A=0.069 from 550 nm LED measurements, expect DE/pixel~0.11-0.15





GPD Cluster: pixel hit distribution

- Single hit TDC r/o of each pixel
- Count # hit pixels within 62.5 ns signal window each event
- DCR determined for each pixel before/after run (stable)
- DCR crosscheck in 62.5 ns period before signal window ("Background" insert)



- Distribution used to calculate cluster DE
  - one or more pixels w/ true signal hit
  - measured DCR to correct for background
  - DCR-dependent uncertainty
- Pixel-pixel crosstalk "low" (under study)
  - may increase pixel packing fraction

Cluster Detection Efficiency

For a cluster to register a true signal, we require only that any one of the pixels has a true signal hit. However, we must account for the situation that the cluster has two or more hits and correct for the probability that these are entirely due to background hits.

Calculate the background contribution bin-by-bin using factor: $f_{bkg} = N_{bkgd} / N_{events}$

where N_{bkgd} is the estimated total number of background hits during signal time window

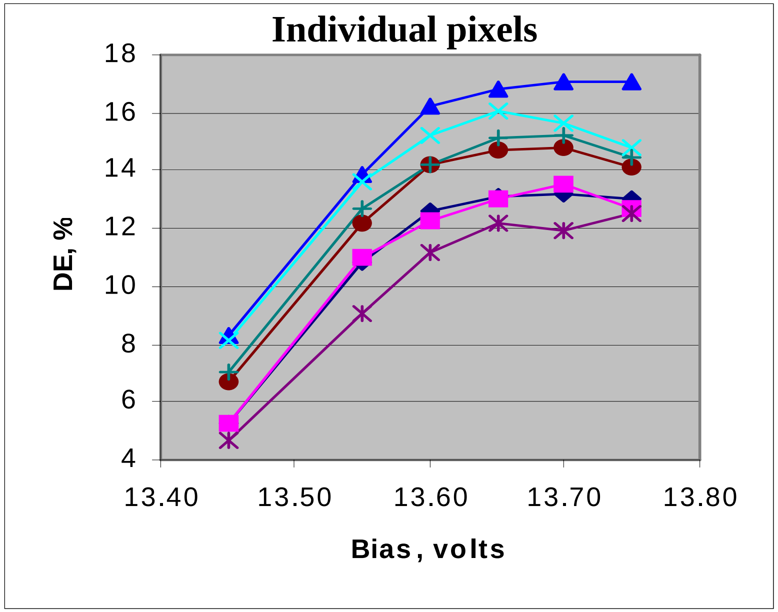
(using DCR) and N_{event} is the total number of selected events.

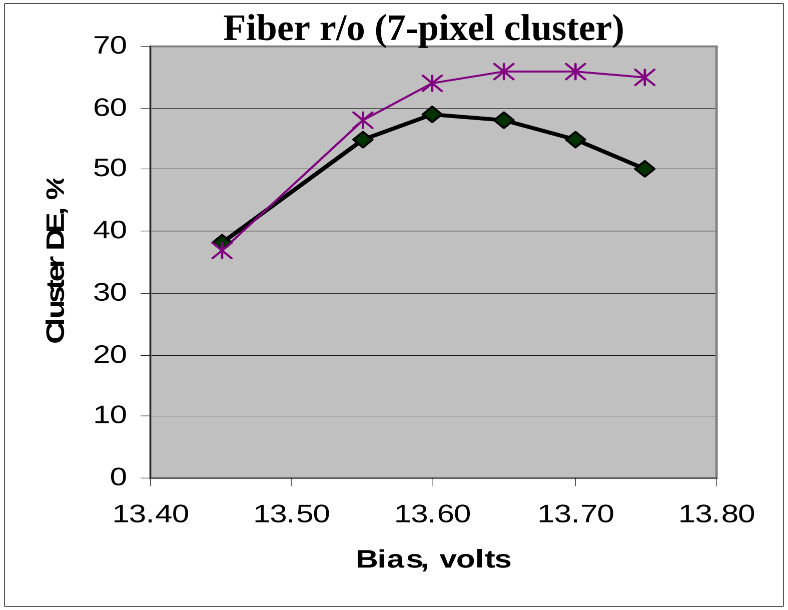
For example, in the histogram bin for two hits, the probability for both of the pixels to be due to random background is $f_{bkgd}{}^{2}$

So background corrected number of bin entries is $N_{2-corr} = (1 - f_{bkgd}{}^{2}) * N_{2-entries}$

So the cluster detection efficiency is : $(N_{1-corr} + N_{2-corr} + N_{3-corr} + ...) / N_{events}$

Cluster Detection Efficiency



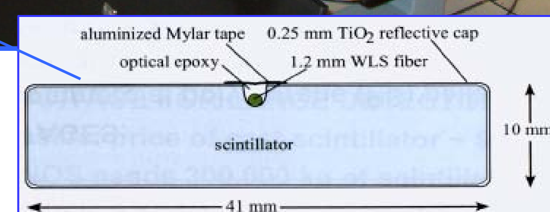


- Avg. pixel DE~14%; close to prediction
- QE*A~0.07
- Significant variation among pixels; contribution from photon distribution
- Difficult to calculate effect of large DCR w/ single hit TDC

- Thick line is estimate from data correcting for DCR; thin line assumes DCR has smaller effect on DE
- 65% cluster DE consistent with 15 photons/cluster or 2.2 photons/pixel

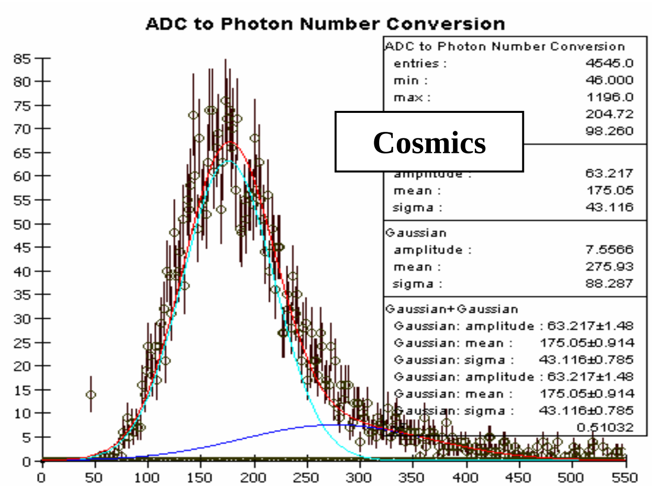
New Cosmics Test Bed

- New MINOS scintillator bar and WLS fiber w/ micropolish from FNAL
- **Many thanks to Gene et al.!**
- ~145 photons/CR
  (close to bar near end)
- New dark box & support frames
- Used to test new square
  162μm x 162μm single pixel



Cosmic Ray Yield

Calibrated PMT (EMI 911B) w/ cosmic rays

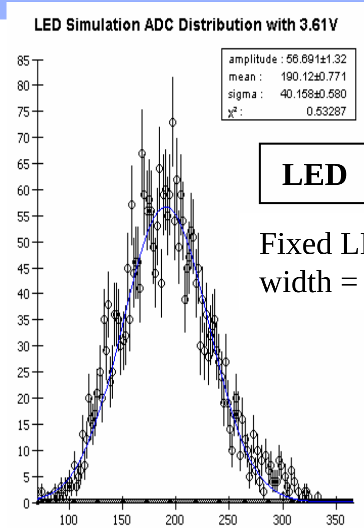


1 bin ~ 1.13 photons

- N_{avg}=145 photons
- 5 photons expected on 162µm □ GPD

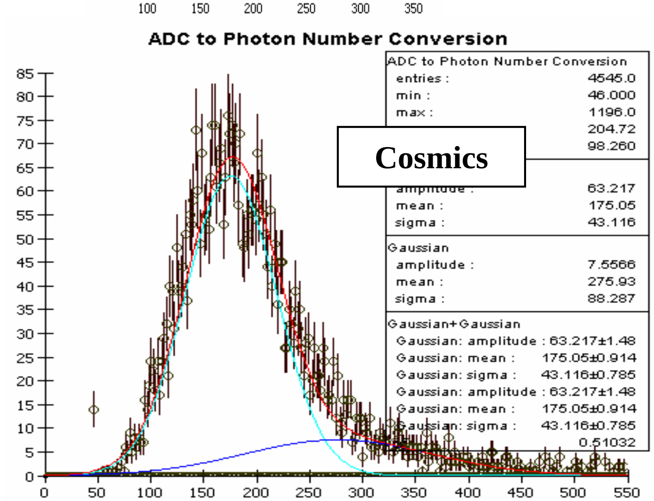
Cosmic Ray Yield : LED simulation

Calibrated PMT (EMI 911B) w/ cosmic rays & LED



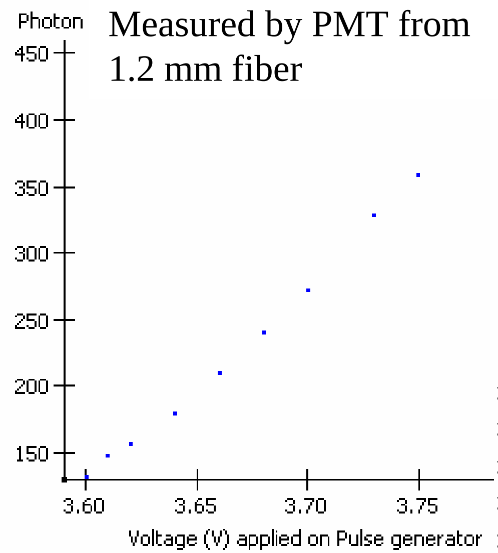
LED

Fixed LED pulse width = 35 ns



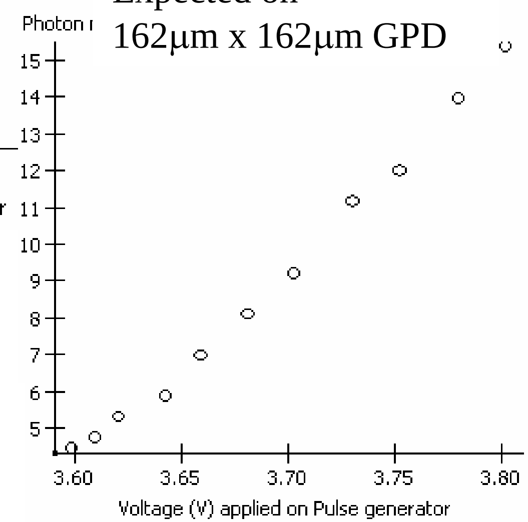
Cosmics

1 bin ~ 1.13 photons



Measured by PMT from 1.2 mm fiber

 # photons is a calibrated function of pulse generator voltage



Expected on 162µm x 162µm GPD

- N_{avg}=145 photons
- 5 photons expected on 162µm □ GPD

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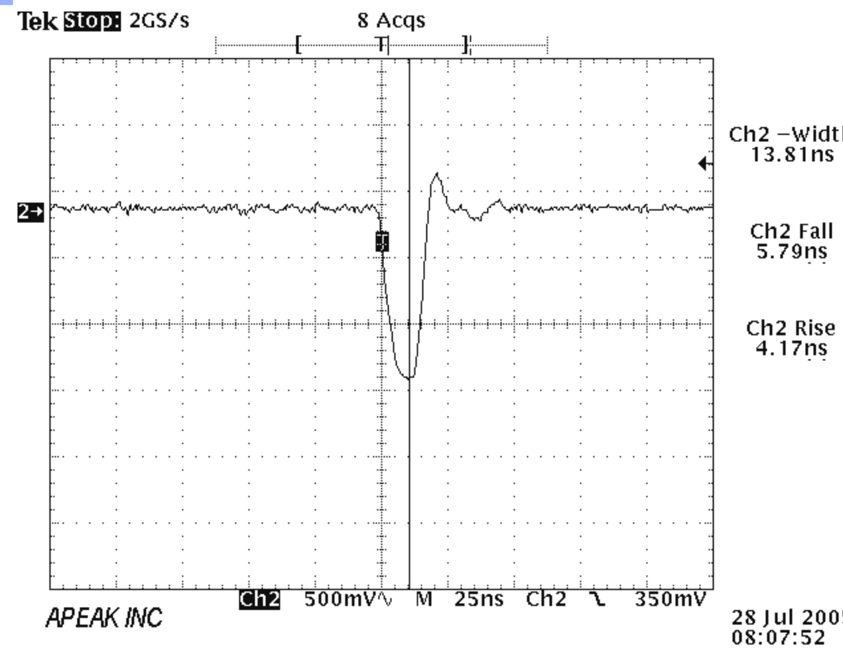
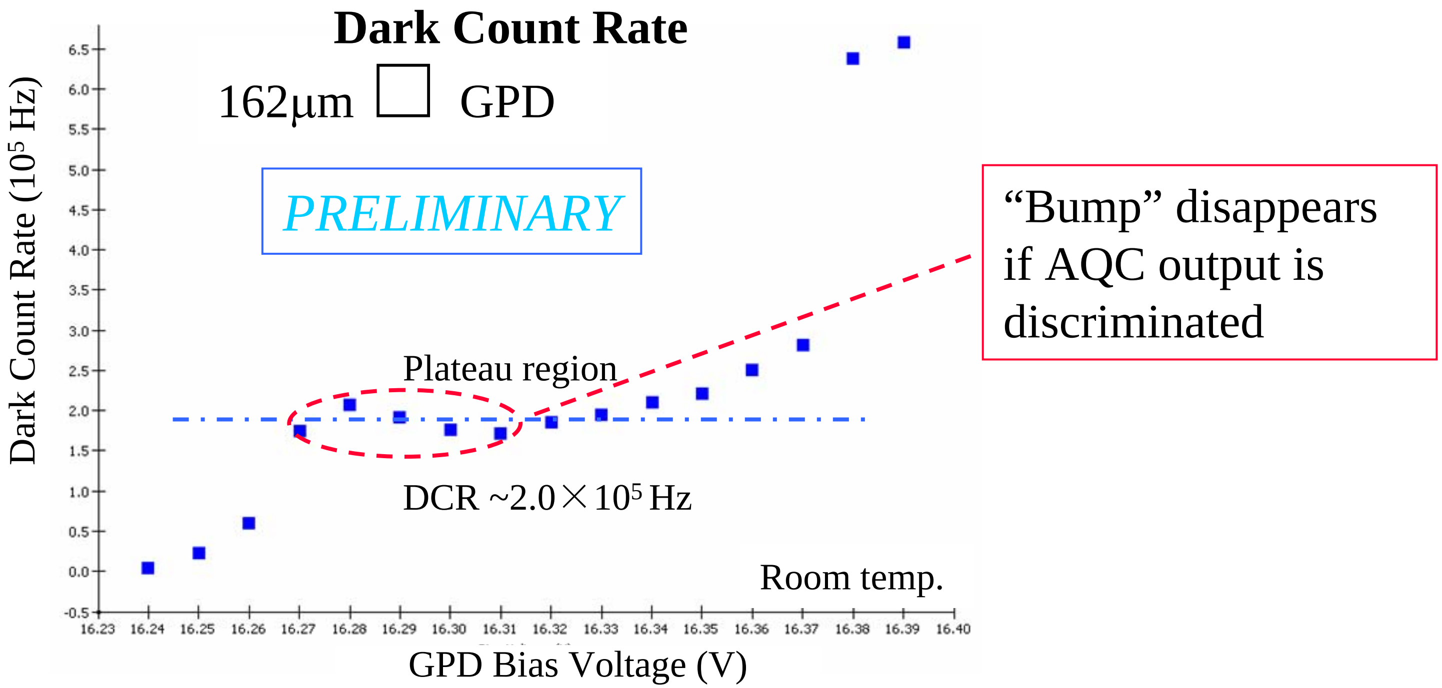
New aPeak Active Quenching Circuit



- AQC8X-MCM : Active Quenching Circuit Multi-Chip module in QFP ceramic package
  - output drives NIM directly
  - AQC operates at 3.5 V
- Width broader for optimal GPD detection efficiency (~110 ns)

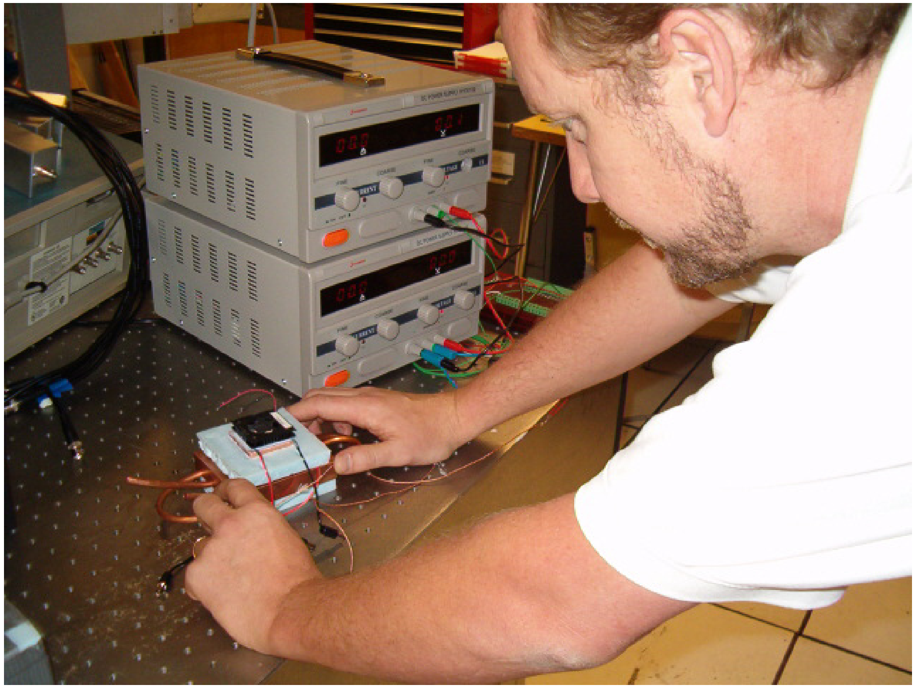
162μm □ GPD



- Plateau region 16.28 – 16.37 V has stable pulses: 110 ns wide with -1V amplitude
- With AQC8 the DE degradation factor ~ 0.98 in plateau region

New GPD Temperature Controller

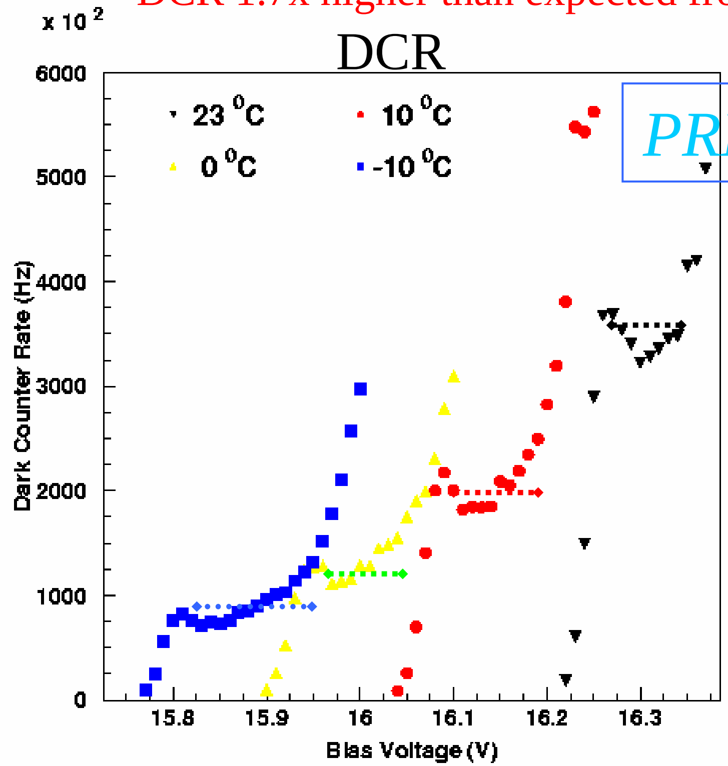
- Peltier junction refrigerator (photo - outside of insulating and dark box)
- Programmable control & monitoring (LabView)
- Range: to -20°C
- Stability ±0.2°C



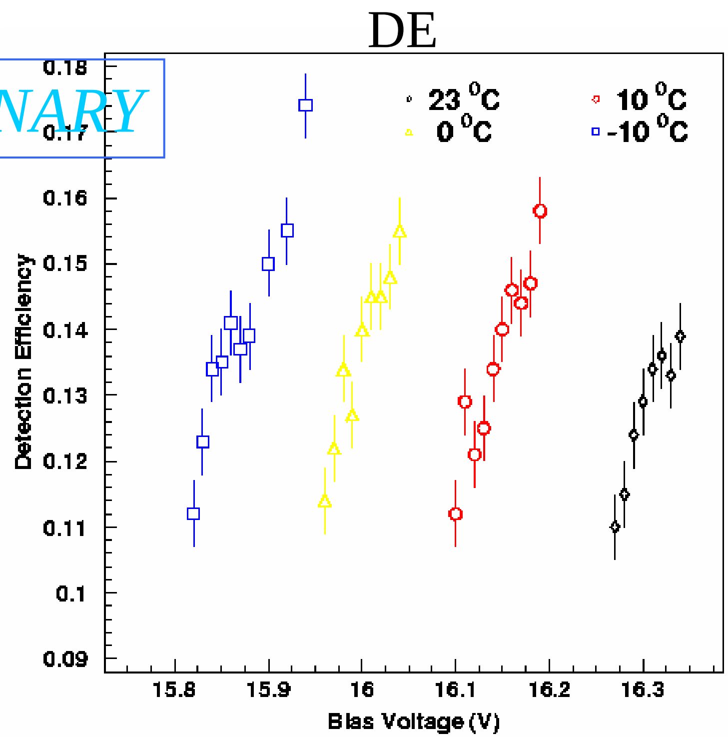
Temperature Effects

162μm ☐ GPD

DCR 1.7x higher than expected from earlier measurements– suspect light leaks



PRELIMINARY



- Temperature dependence of GPD operating bias voltage ≈ 0.013 V/° C
- Operating plateau width ≈ 0.100 V

- GPD coupled to 60 cm length of Y-11 fiber
- Excited by LED flasher set for 1 CR-equivalent

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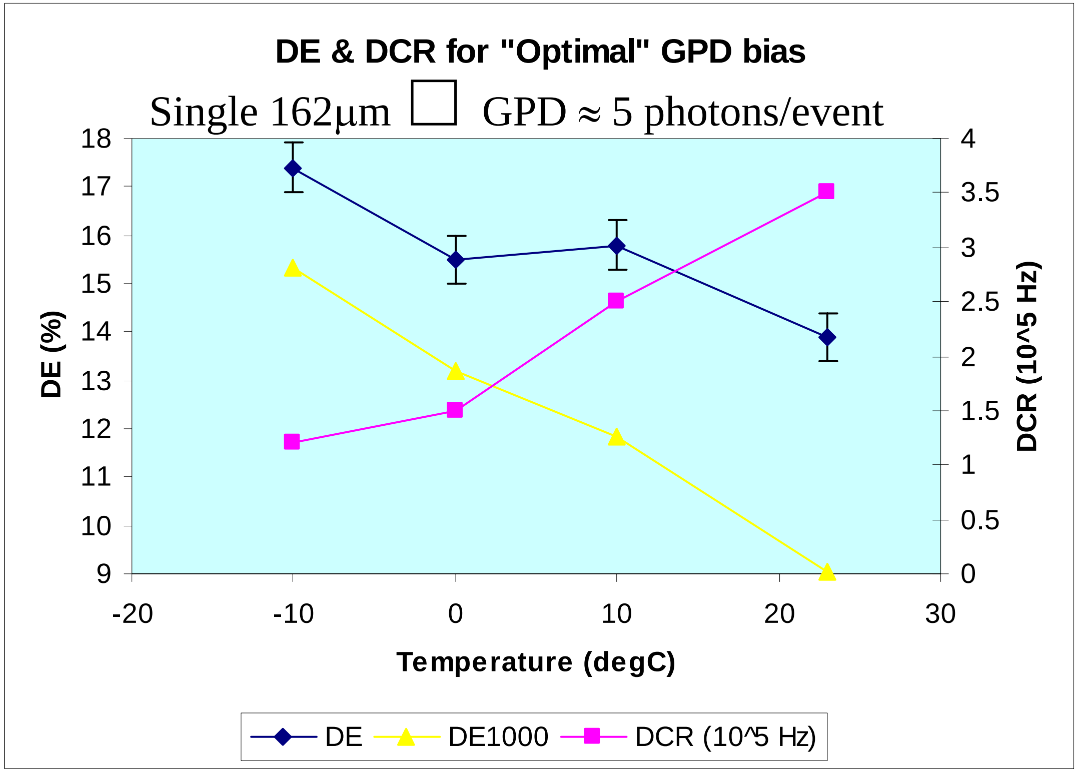
DE/DCR Summary



PRELIMINARY

- Lower QE*A than 150 μm ◯ pixels not understood
- Measurements ongoing…
- 3x3 array expected soon

- DE – measured detection efficiency
- DE1000 – effective DE if the quenching time is 1000 ns (typical of unquenched devices)

aPeak/CSU SBIR Goals

1. Increase the detection efficiency (to > 95% for "MINOS bars") by:
   - Decreasing the reset time;
   - Setting the optimal operation temperature; and
   - Improving the optical coupling to the scintillation fiber.
2. Develop GPD arrays architecture for dual tracking and calorimetry operation
3. Improve the timing performance
4. Develop compact and improved interface electronics (active quenching circuitry and drivers) with:
   - Integrated bias control to compensate for process variations
   - Additional amplification stage with improved stability
   - Signal multiplexing in cluster.
5. Identify failure mechanisms and extract lifetime
6. Develop 64 channel GPDs to readout 1.2 mm diameter WLS fiber bundles in scintillator strip configuration.
   - Demonstrate performance on CSU setup
   - *Validate performance and functionality in beamline at Fermilab.*
7. Performance versus Cost Analysis

Deliverable (late 2006):

Ten 64 channel GPDs (incl. AQC and driver electronics) to read out 640 WLS fibers.

Summary

- Another potential source for pixelated Si photodetector for WLS or scintillating fiber readout
- Feature faster reset for high rate applications – effective detection efficiency depends on f_q*rate
- CMOS technology should provide cheap, reliable high volume production – not demonstrated yet
- aPeak very motivated – offers flexible design, fast turn-around
- Single pixel readout demonstrated with MINOS bars
- Single output for GPD clusters planned
- Photon counting configuration w/ small diameter pixel possible
- Another year before firm conclusions
- Hope to have ten 64 channel GPDs (incl. AQC and driver electronics) to read out 640 WLS fibers by later next year