PPD Review,
Fermilab,
August 2, 2010

HIGH RESOLUTION CALORIMETRY R&D: PROTOTYPES AND LABORATORY STUDIES

Perspective

- Working assumption: a decisive demonstration of high resolution calorimetric technique must include a test beam study of a full scale prototype. This is probably ~5 year, $10-12M proposition. Given the scale of the project:
- Is it really worth it? Can some intermediate size module do? Probably not. Can one prove it without? Only in a rational world.
- It is important to examine thoroughly the case and to optimize the test beam module to minimize/eliminate the risk of a failure. This will require various small/medium scale prototypes to test various ingredients of the simulation and to test various technical elements/solutions (this talk)
- It is important to develop adequate solutions for the front-end electronics (Paul Rubinov)
- It is important to initiate and carry out a search for new and inexpensive optical media. A success on this front can reduce the cost of the full scale prototype by a big factor (Marcel Demarteau)

Areas Requiring Studies with Prototypes and Test Setups

- Cherenkov/scintillation light detection and separation with compact photodetectors
- light collection, uniformity, crystal size and shape dependence
- Photodetectors characterization
- Calibration of the crystals/photodetectors response
- Characterization and evaluation of newly developed scintillating materials
- Response of scintillating crystals to slow heavy particles
- Cherenkov light production and detection, fluctuations, in hadronic showers

T-1004 Total Absorption Dual Readout Calorimetry R&D

- Fermilab, Caltech, University of Iowa, Argonne National Laboratory, Fairfield University, CERN, INFN Trieste/Udine, INFN Roma, Shinshu University and University of Cyprus
- EM calorimeter with different crystals, different photodetectors, different geometries. Calibration of a segmented calorimeter. Position and angle measurement.
- Single crystal exposure. Different crystals, different photodetectors, different geometries, different surface treatment, different filters. Separation of Cherenkov and scintillation. Light collection, uniformity. Cherenkov light yield, Angular dependence of the Cherenkov signal.

Two Components of the Test Beam Program

- EM calorimeter with different crystals, different photodetectors, different geometries. Calibration of a segmented calorimeter. Position and angle measurement.
- Single crystal exposure. Different crystals, different photodetectors, different geometries, different surface treatment, different filters. Separation of Cherenkov and scintillation. Light collection, uniformity. Cherenkov light yield, Angular dependence of the Cherenkov signal.
- Phase 1 principal participants: Burak Bilki and Ugur Akgun(Iowa), Diego Cauz and Giovanni Pauletta (Udine), Fotios Ptochos (Cyprus), Erik Ramberg, Paul Rubinov, Hans Wenzel and Adam Para (Fermilab

EM Calorimeter, version 1.0

- PbWO4 crystals (Iowa), former CMS test beam calorimeter
- 7 x 7 crystals array, read out via light guides and PMT's. Beam along the crystal axis
- Crystals of varied quality (yellowness), check the energy resolution as a function of the crystal quality
- Future developments:
  - equip with SiPM's, check the energy resolution SiPM vs PMT
  - Couple PMT's directly , rotate by 90 degrees, 6 x 9 matrix, study the position and angle measurement


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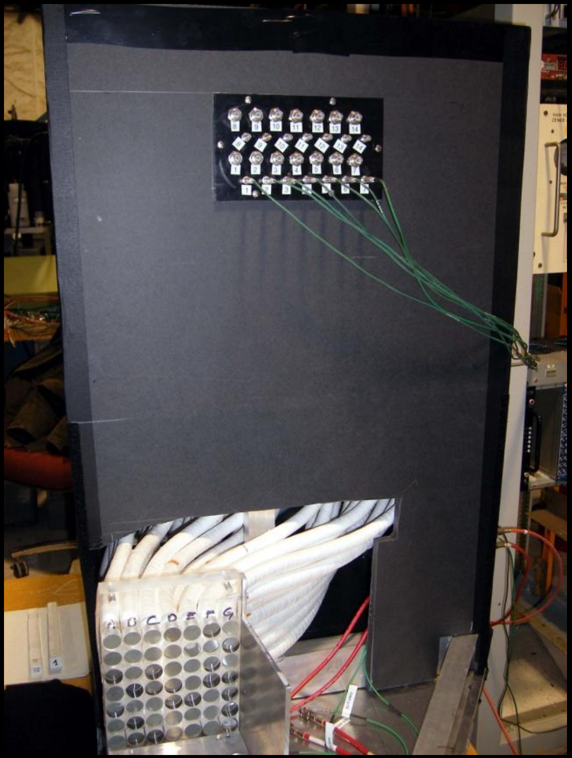

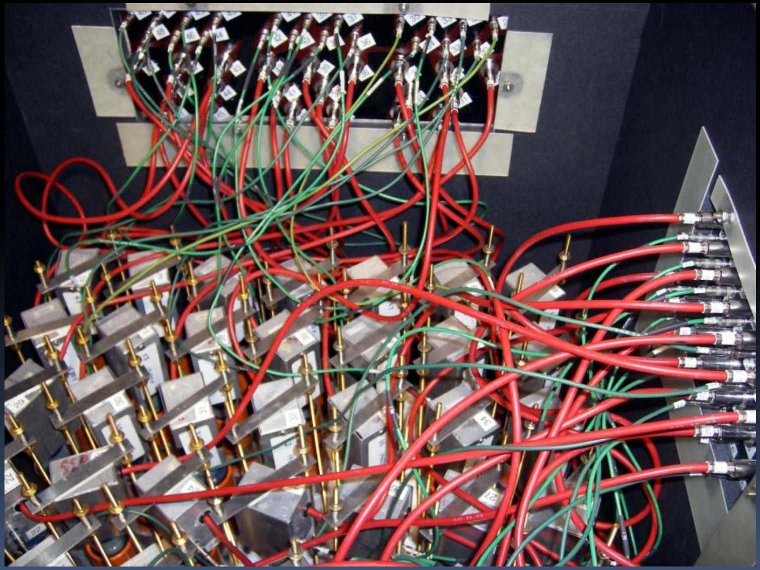


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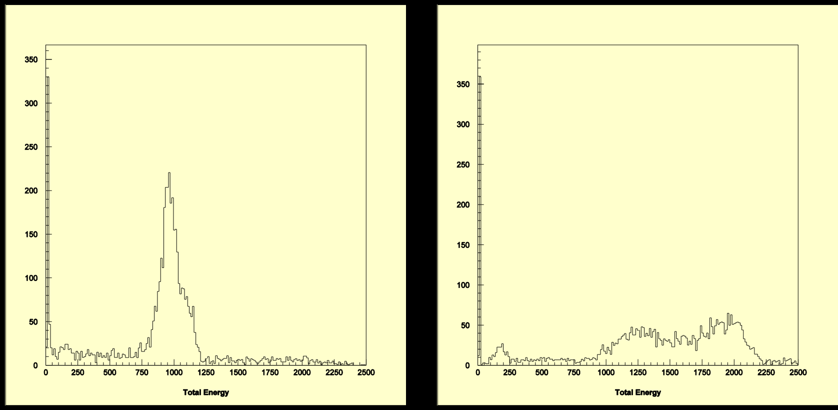
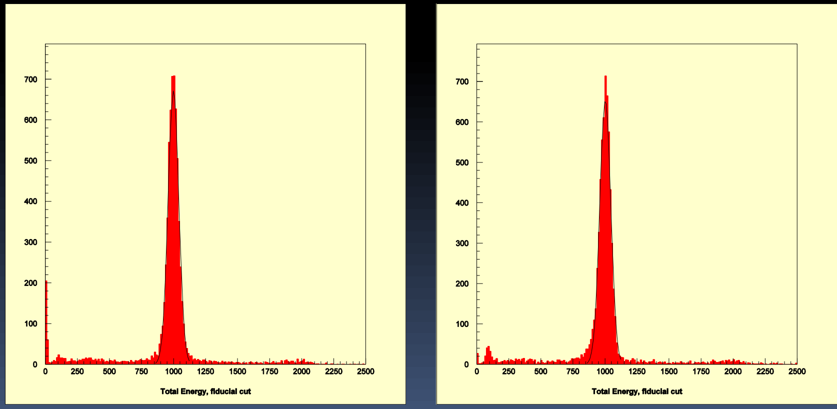
Cross Calibration of a Segmented Calorimeter

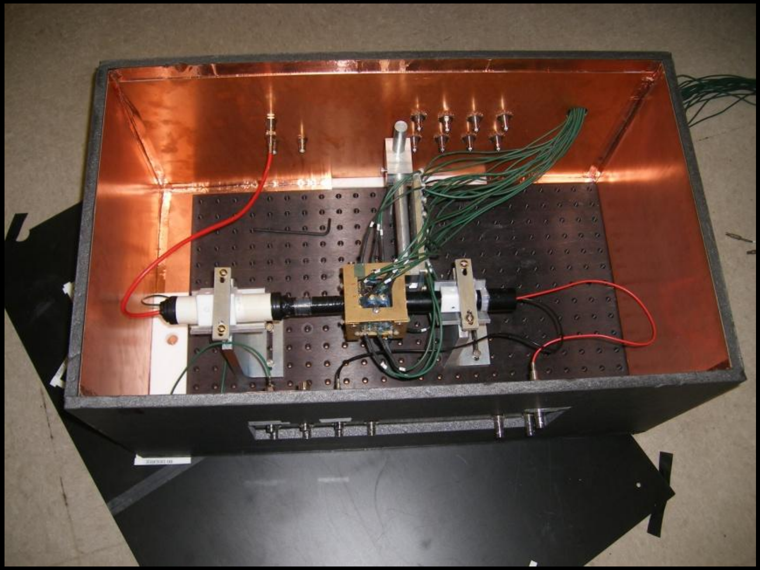
- Segmented crystal calorimeter involves large number of independent detector volumes which need to be inter-calibrated
- This is always a pain, but at least straightforward in principle (T1004 test beam: upper row the response of collection of crystals before inter-calibration, bottom row – after inter-calibration)
- Energy resolution of $\Delta E/E$=4.3% at 4 GeV, limited by the beam energy spread

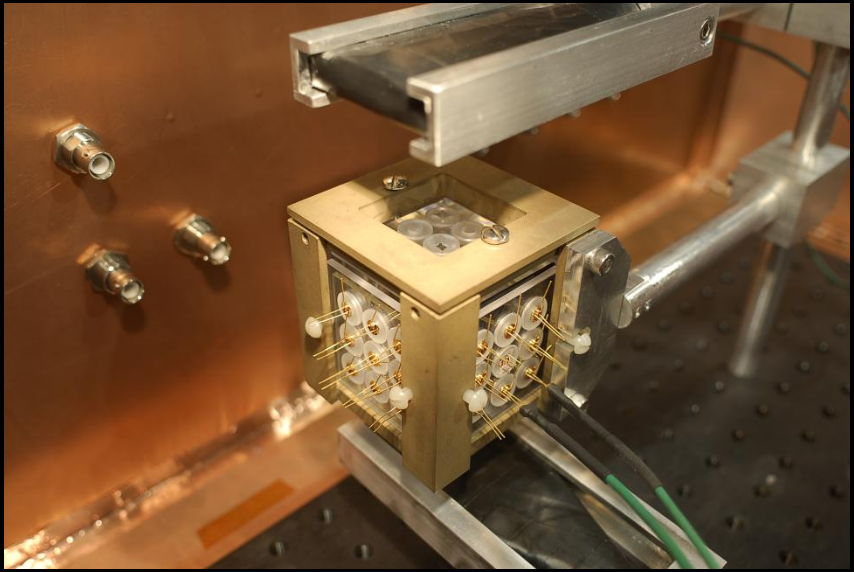


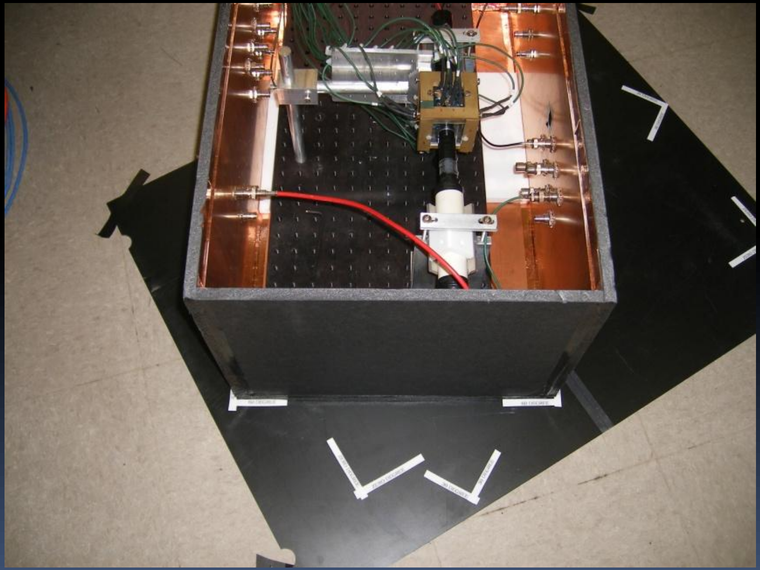
Before calibration



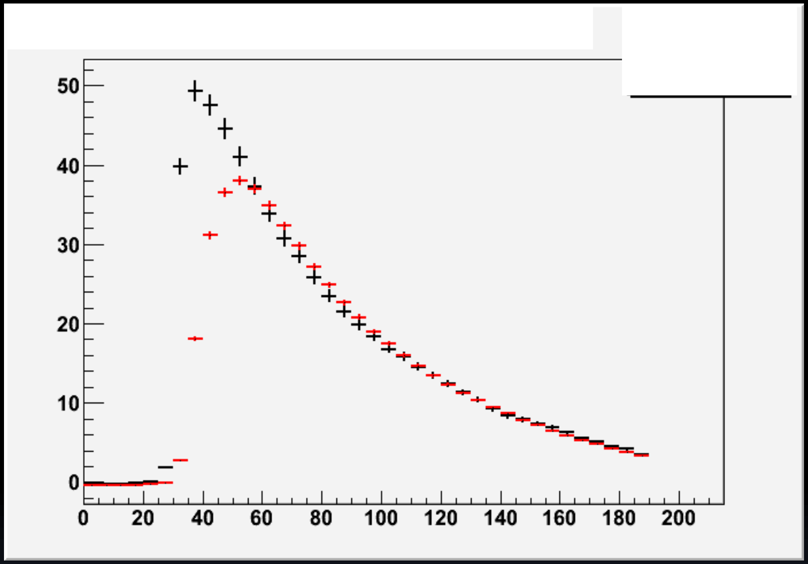
After calibration







Single BGO Crystal Studies, 120 GeV Proton Beam



- Several types of SiPM's
- UG11 (UV) filters and 'visible light' filters
- Red points: visible light filter: scintillation only
- Black points: UV filter: Cherenkov + residual scintillation
- Both signals normalized to each other at 'late' times

- BGO scintillation has slow turn-on, peak intensity occurs at ~ 50 nsec
- Clear indication for a prompt component (Cherenkov)
- Reddy Pratap Gandrajula (Iowa) : Cherenkov mostly in a single spot
- Yannis Makris, Savvas Kyriacou (Cyprus) : in accordance with simulation

Forthcoming Runs of T-1004

- Single crystal studies:
  - BGO crystal, more SiPM's (types, and sizes)
  - Rotational stage (angular dependence)
  - Different crystal surface treatments
  - PbF_2 crystal (Cherenkov only)
- EM Calorimeter (PbWO4)
  - Remove the lightguides, couple the PMT's directly (1/2" ZEUS PMT's from Argionne)
  - New CW bases and digitizers (Sten Hansen)
  - Add SiPM readout (IRS SiPM's from Trieste/Udine)

Single Crystal(s): Further Studies

- Evaluation of newly developed crystals/glasses, feedback to the developers
- Detailed tests of the optical simulation part of the dual readout calorimetry simulation:
  - Different geometries
  - Different sizes
  - Different optical properties (Scintillation/Cherenkov, refractive index, surface treatments)
- Relative calibration of different crystals
- Test beam studies
- Cosmic rays hodoscope: using MINERVa scintillator planes and MINERVa readout. Under commissioning. Need space to establish crystal evaluation facility.

Further Calorimetric Studies

- EM-size (10 x 10 x 30 cm) calorimeters, BGO and PbF_2, dual readout and Cherenkov only. PMT and SiPM readouts.
- Three silicon strips layers to demonstrate the spatial resolution (position, angle, close tracks resolution)
- (several) single crystals with all sides equipped for Cherenkov detection embedded in a large block of absorber to provide experimental information on the angular distribution of the observed Cherenkov light INSIDE HADRON SHOWERS

Photodetectors

- Dual readout calorimeter requires a compact, inexpensive photodetectors capable of operating in magnetic fields
- SiPM's (MPPC's, PPD's) are attractive candidates, at ;east for the scintillation component.
- Cherenkov signal may require further development of the SiPM's. Inexpensive MCP's (Argonne/Chicago) may be another possibility
- SiPM's are still in their infancy and systematic studies are necessary to understand their behavior and optimize their operating conditions.
- These studies are also necessary for the development of the suitable readout electronics.

'Silicon Photomultipliers' a.k.a. Pixelized Photon Detectors (PPD)

- Novel, very attractive photodetectors:
  - Compact
  - Inexpensive
  - Insensitive to magnetic field
  - Low operating voltage
- But.. They have very little to do with photomultpliers. They are, in fact, solid state versions of RPC's.
- There are several variants of these devices with different operational characteristics
- There is very limited body of experience with their operation, optimization of the operating point, calibration and monitoring

Standard Model of the PPD

- There are at least two parameters strongly affecting the response of the PPD to a light signal: temperature and bias voltage
- The principal effect is the variation of the breakdown voltage with temperature. At the fixed overvoltage the dependence of the response with temperature is greatly reduced
- Given an incoming photon:
  - $P_{av}(T,V)$ = probability that an incoming photon will start an avalanche. Amplitude of the single avalanche signal is well defined, but depends on V and T.
  - A random avalanche due to a thermal electron may accompany the photon induced signal at a random time, with probability dependent on temperature and voltage $R_{dark}(T,V)$

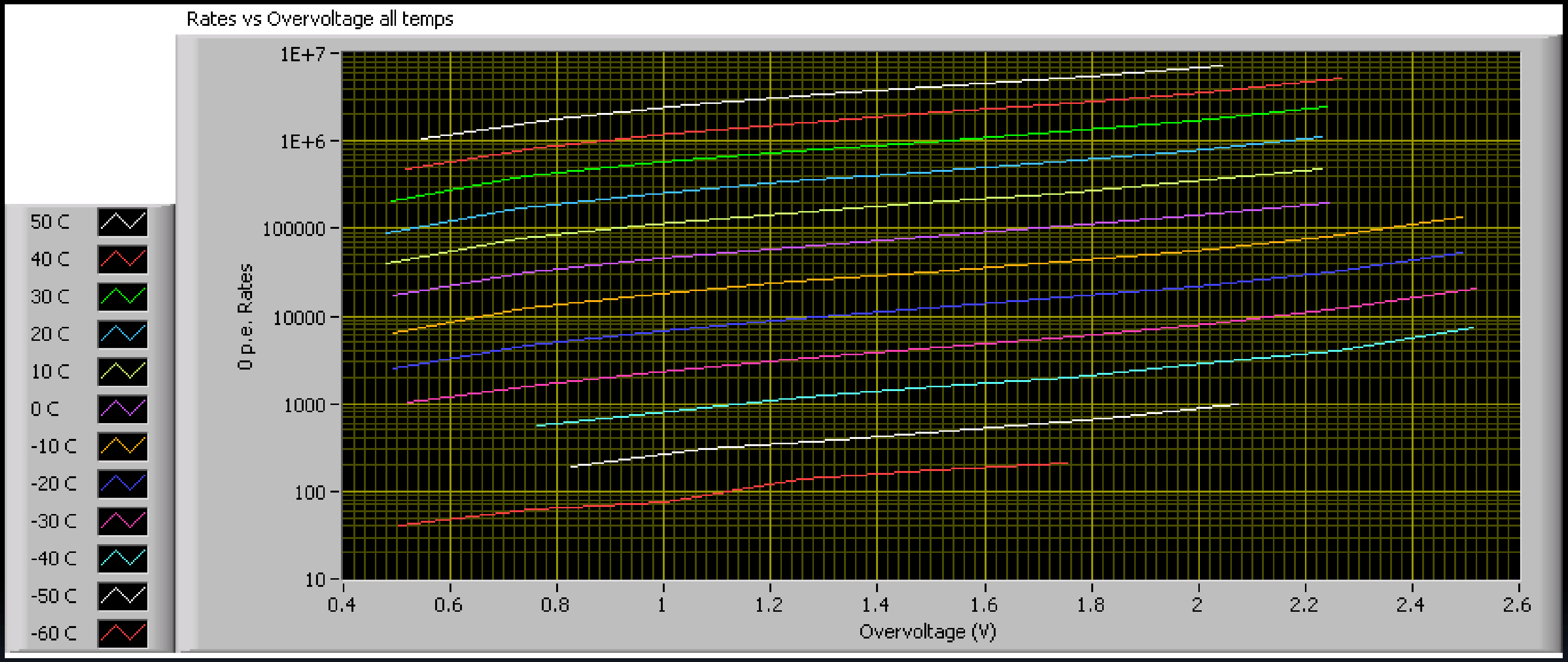
Standard Model of the PPD II

- For every produced avalanche (independent of its origin ➔ beware of non-linearities)
  - $P_{ap}(T,V,t-t_0)$ = probability that an avalanche at time t_0 will lead to another avalanche at time t. The amplitude of this avalanche is suppressed by a factor $F_{sup}(t-t_0)$
  - $P_{xtalk}(T,V)$ = probability that an avalanche in a pixel will induce an avalanche in a neighboring pixel (optical cross-talk). This additional avalanche occurs at 'the same' time as the parent avalanche
- In an application where the precise measurement of the light intensity is necessary all these factors: $P_{av}(T,V)$, $R_{dark}(T,V)$, $P_{ap}(T,V,t-t_0)$, $F_{sup}(t-t_0)$, $P_{xtalk}(T,V)$ must be known to model the response of the detector and to interpret the measured signal in terms of the number of photons.
- Goals of the R&D project: develop the methodology to identify and measure the parameters affecting the response as a function of relevant variables.

PPD Testing Setup

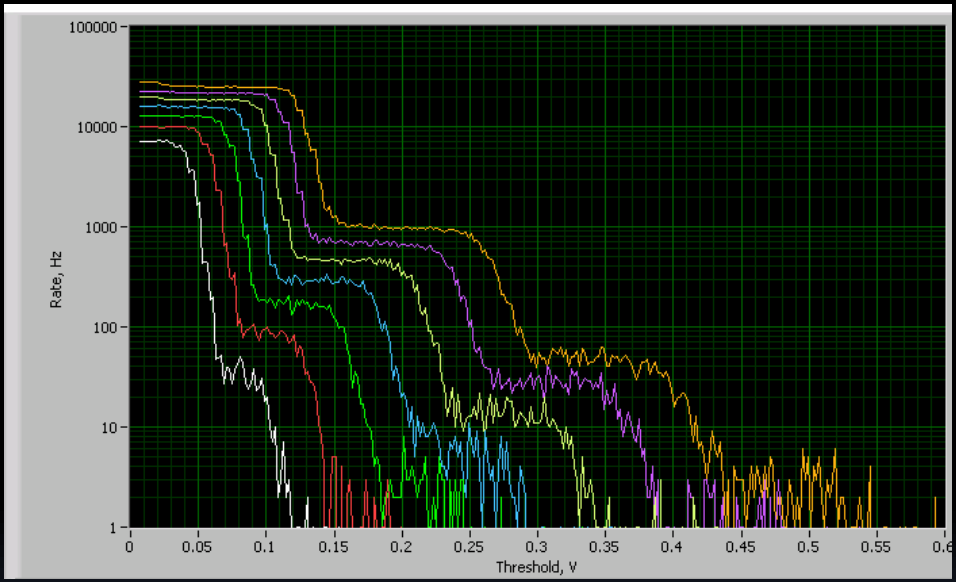
- Real estate: SiDet
- Equipment:
  - Temperature chamber (acquired)
  - Fast laser 635 nm (acquired)
  - 4 Keithley 2400 source-meters (SiDet infrastructure/borrowed)
  - Two Tektronix 3054 scopes (borrowed/SiDet infrastructure)
  - HP53131A counter (borrowed)
  - MITEQ amplifiers (500/1000 MHz, 30/60 dB)
  - 4 PC computers (SiDet infrastructure/recovered from surplus)
  - Several dark boxes allowing for simultaneous measurements, as allowed by the measuring infrastructure
- Labview data acquisition infrastructure allowing for simultaneous, but independent measurement
- Few selected results shown

Dark Counts Rates



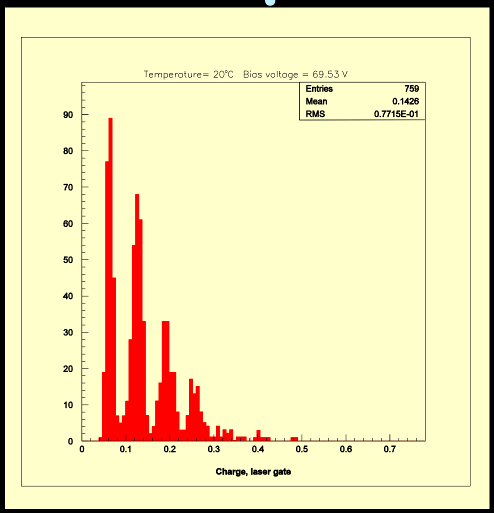
Dark count rates vary by many orders of magnitude in an approximately exponential fashion as a function of bias voltage and temperature.

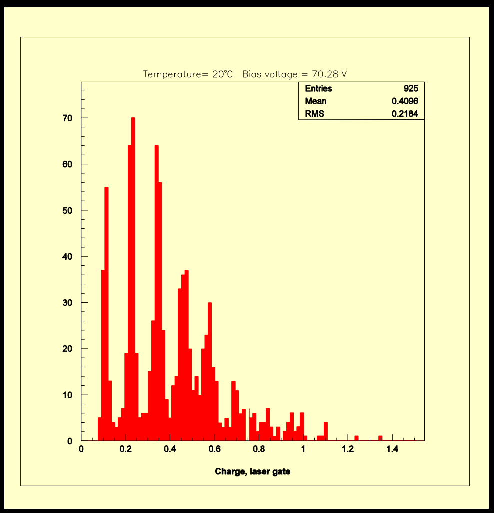
Cross Talk Measurement

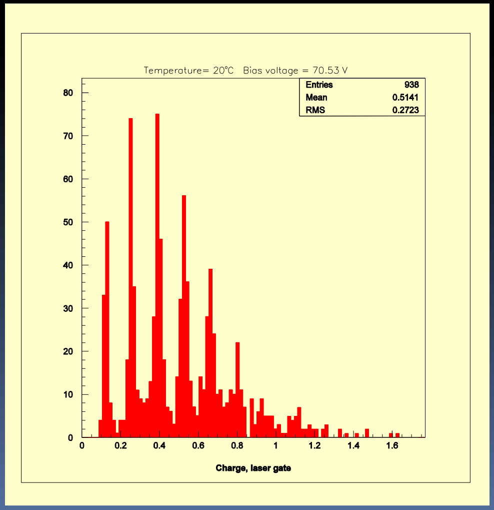


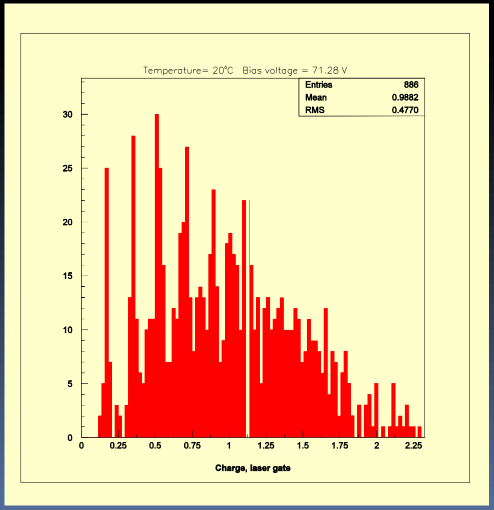
- Given the dark current rates, the rate of accidental coincidences of two thermally-induced avalanches is very low
- The primary source of pulses with double (tripple) height is the optical cross talk from the primary avalanche
- The ratio of rates of double-to-single avalanche pulses is a direct measurement of cross-talk probability at a given bias voltage and temperature.

Bias Voltage Dependence of the Response







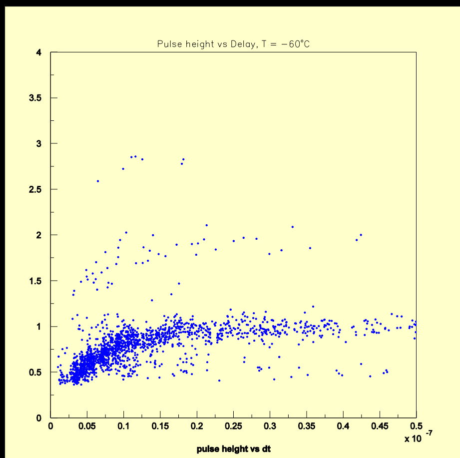


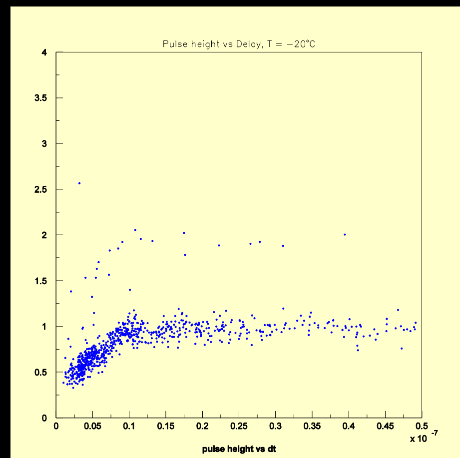
- Response of the detector at T=20C to the laser light with the bias voltage increasing within the range of 1.75 V
- Huge variation of the response

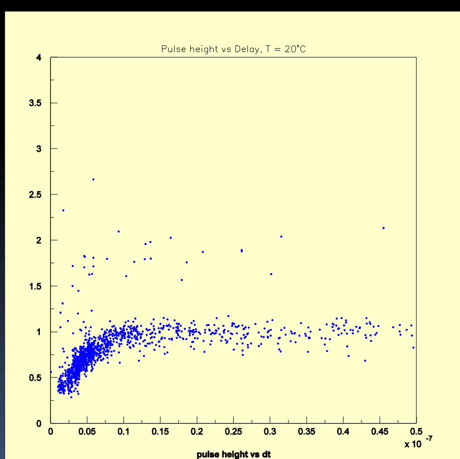
The same laser light intensity!

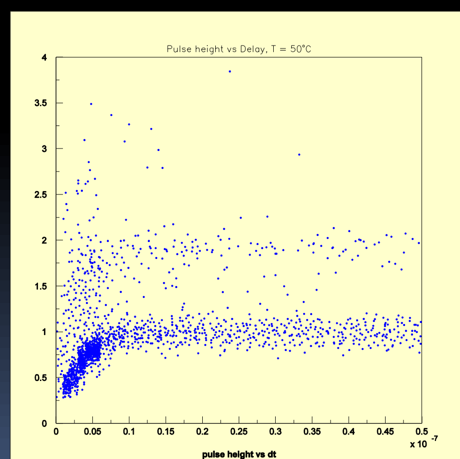
Need a calibration prescription to yield the same measurement in all cases

Amplitude of Afterpulses



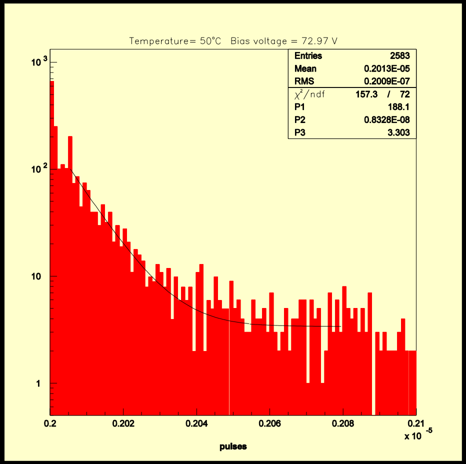


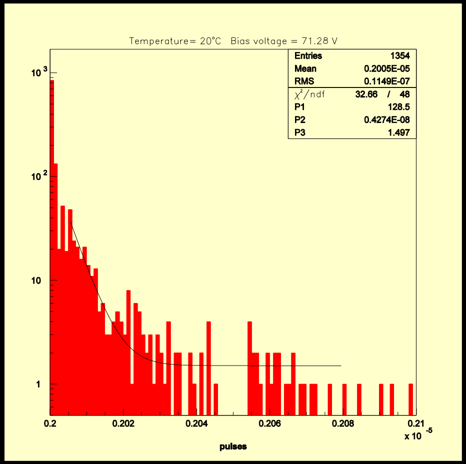


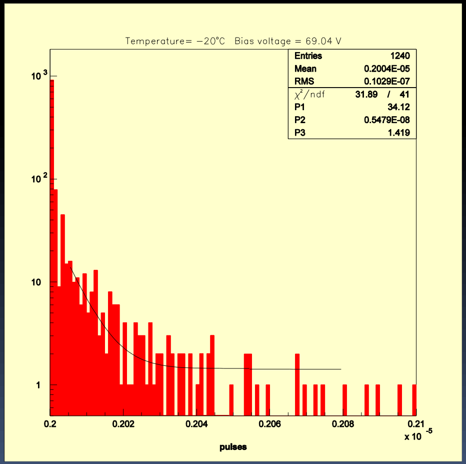


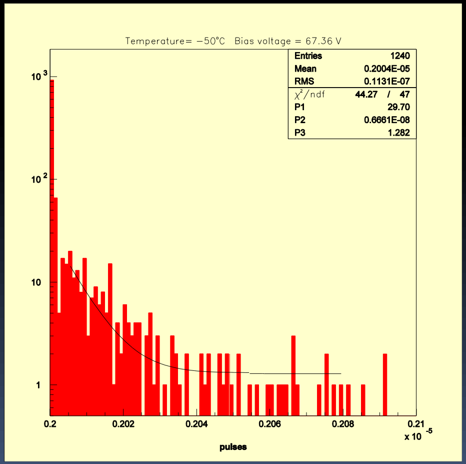
- Amplitude of a pulse is shown as a function of time since the previous pulse
- Examples of data shown at different temperatures
- Clear evidence of the reduction of the pulse height during the pixel recovery time
- Recovery time varies with temperature (as the result of the variation of the value of quenching resistor)

Afterpulses within 100 nsec gate









- Studies limited by statistics (DAQ rate of the scope)
- Data at different bias voltages summed at fixed temperature
- Decay time fit at different temperatures: gives the time constant and the overall rate
- Examples shown here: -50C, -20C, 20C, 50C

Collaborative Efforts

- MOU with CNRS/IN2P3 with the proposed common program of the characterization of the photodetectors
- Studies at LAL extend the studied temperature range down to -110^{o}C
- Common set of methods and tools (DAQ, data analysis and data processing)
- Common centralized database of the waveform data planned at Fermilab
- TRIUMF: simulation program for the SIPM's performance
- DELFT University: discussions

Further Studies of SiPM's at Fermilab

- Study the intensity dependence of the observed signals (saturation) as a function of the operating conditions
- Study the spectral characteristics of response
- Absolute quantum efficiency (use non-linear crystals down-conversion technique a la DES?)
- Need more space and more equipment

Hadronic Response of Crystals?

- Mechanisms of scintillation light production in inorganic scintillators by hadrons (low and high energy) are surprisingly poorly known/understood.
- A significant fraction of hadron shower energy is deposited by slow heavy particles (protons, nuclear fragments)
- It is important to understand the response of crystals to these slow particles and to evaluate the impact of a possible saturation no the resulting hadron energy resolution.
- These studies may require a dedicated exposure to very low energy protons and light/heavy nuclei beams. Such studies can be carried out, perhaps, at the JINR, Dubna