Planar Dual Readout Calorimetry Studies
Progress Report

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Motivations/Goals

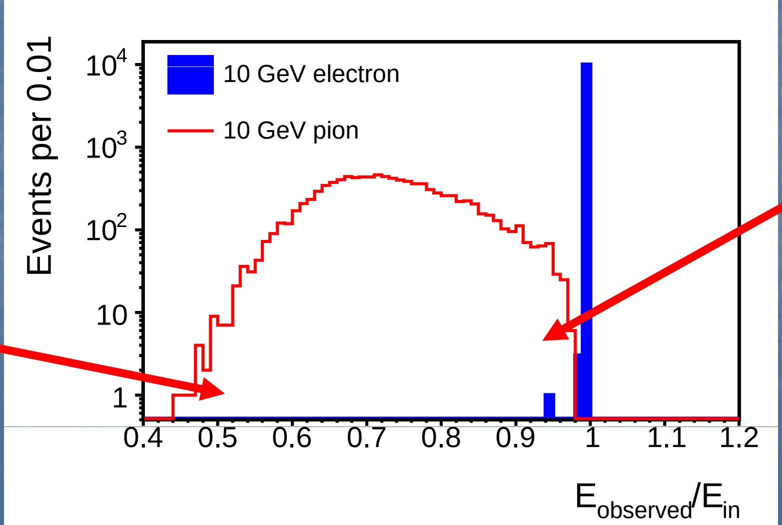
- Systematic studies of contributions to energy resolution of high precision sampling calorimeters:
  - Sampling frequency
  - Active detectors: materials and thickness
  - Detection mechanism: scintillation/Cherenkov
- Investigate performance of compensating dual readout calorimeters and its dependence on the calorimeter design and segmentation
- Investigate performance of the dual readout calorimeter as an electromagnetic calorimeter
- Investigate the production of low-cost lead glass tiles
- Study and characterize the performance of Geiger-mode Avalanche PhotoDiodes

Total Absorption Calorimeter

- Electrons/photons interact with atomic electrons. Total energy of the incoming particle is converted into detectable kinetic energy of electrons
- Hadrons interact with nuclei. They break nuclei and liberate nucleons/nuclear fragments. Even if the kinetic energy of the resulting nucleons is measured, the significant fraction of energy is lost to overcome the binding energy. Fluctuations of the number of broken nuclei dominates fluctuations of the observed energy
- Excellent energy resolution for electrons/photons
- Relatively poor energy resolution for hadrons (constant with energy, $e/\pi > 1$)

Large number of broken nuclei:

- large number of slow neutrons
- Small fraction of energy in a form of π^0's



Very few broken nuclei:

- Small number of slow neutrons
- Large fraction of energy in a form of π^o's

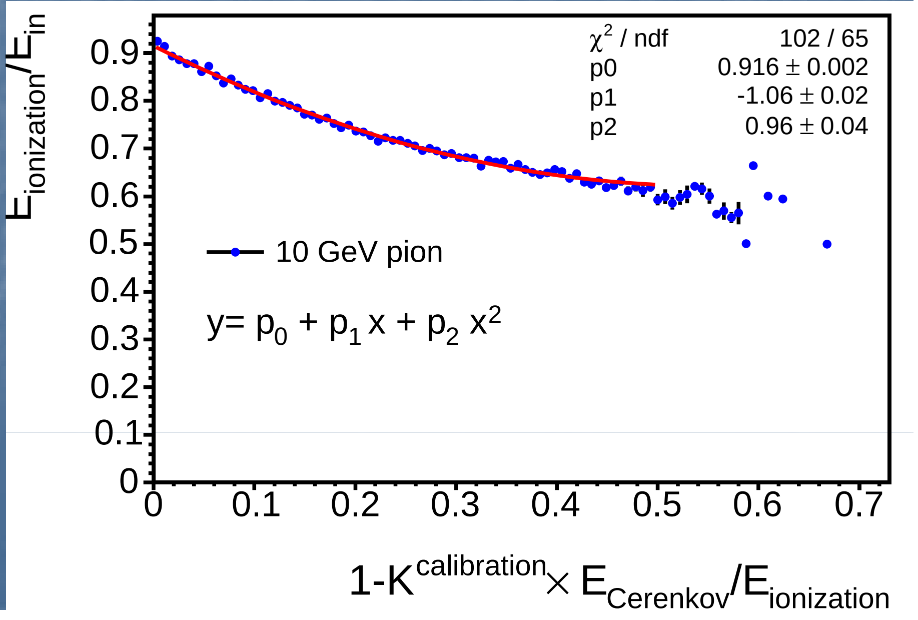
Path to High Precision Hadron Calorimetry: Compensate for the Nuclear Energy Losses

- Compensation principle: $E = E_{obs} + k^*N_{nucl}$
- Two possible estimators of N_{nucl}:
  - $N_{nucl} \sim N_{slow\ neutrons}$
  - $N_{nucl} \sim (1-E_{em}/E_{tot})$

Cherenkov-assisted hadron calorimetry: $E_{em}/E_{tot} \sim E_{Cherenkov}/E_{ionization}$

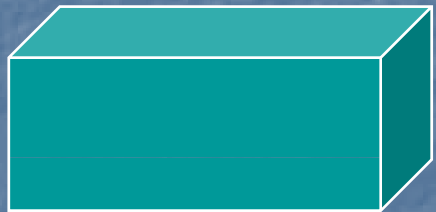
• 'EM' shower: relativistic electrons, relatively large amount of Cherenkov light

•'hadronic' shower – most of the particles below the Cherenkov threshold

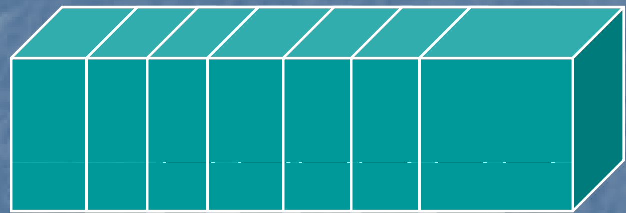


Program of Studies (software)

- Systematic step-by-step approach

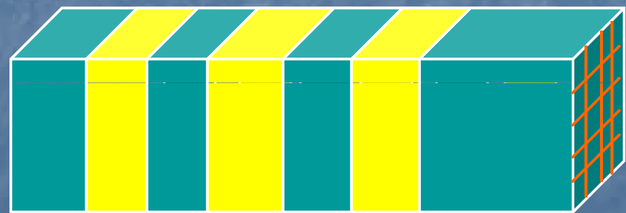


Large homogeneous calorimeter



Longitudinally segmented calorimeter (same material)

Longitudinally segmented calorimeter (several materials)



Transversely and longitudinally segmented calorimeter (different materials)

Large Homogeneous Calorimeter (Total Absorption)

- Simulation of homogeneous scintillation/cherenkov calorimeter (stand-alone GEANT4)
- Studies of compensating calorimetry with a homogenous calorimeter:
  - compensation algorithm
  - Single particles, linearity response, e/π
  - Jets

Cherenkov-assisted Calorimetry at Work: Single Particle Case

- Use the $E_{Cherenkov}/E_{ionization}$ ratio to 'correct' the energy measurement

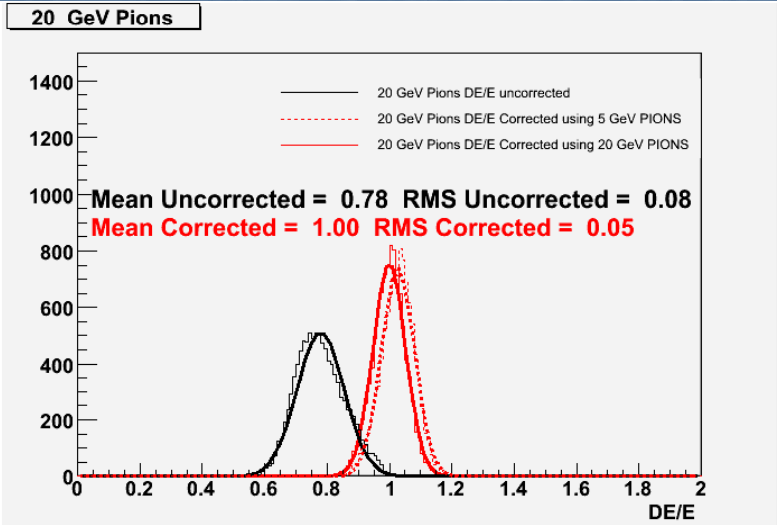
• Corrected pion shower energy = pion energy ("e/π"=1)

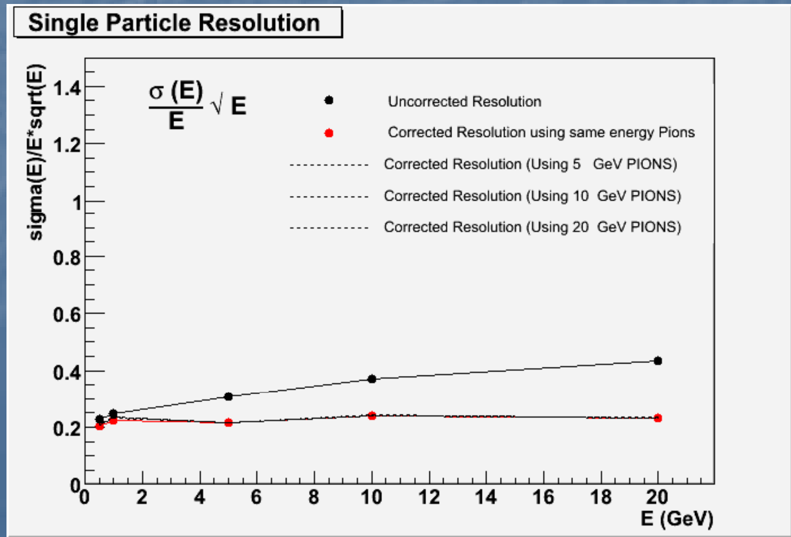
• Correction function independent of the actual shower energy

• Single particle energy resolution ΔE/E=0.25/√E

• Scales with energy like 1/√E (no 'constant term')

• Linear response





Measuring jets (== ensembles of particles)

Jet fragmentation (in)dependence

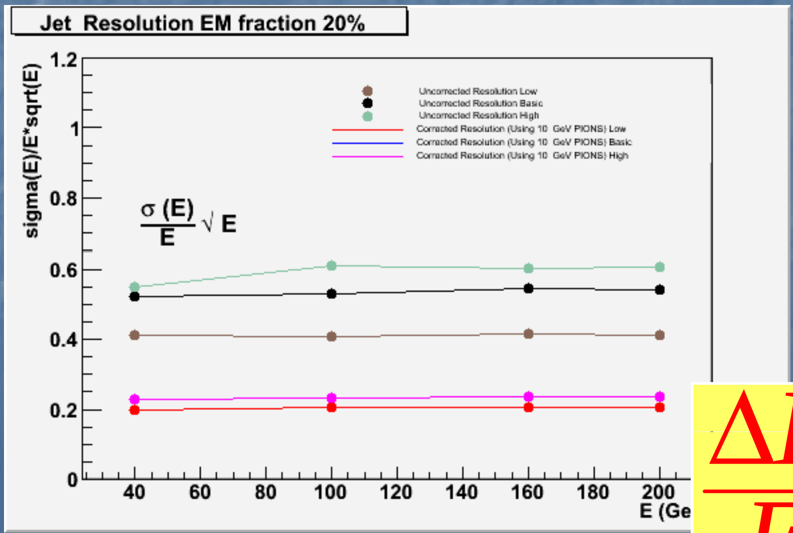
• Resolution of Cherenkov-corrected energy measurement is nearly independent of the jet fragmentation

• Resolution (and the response) of the uncorrected energy measurement dependent on the jet composition

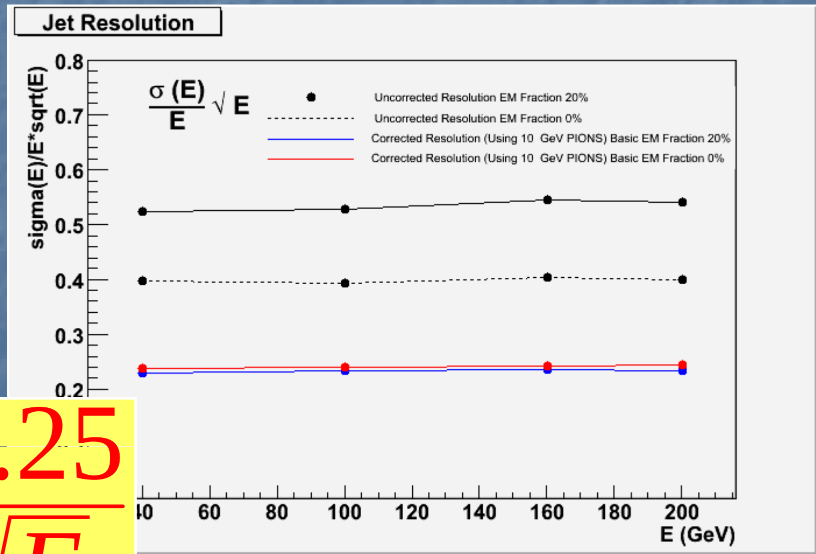
Fluctuations of EM fraction of jets

• Do not contribute to the jet energy resolution for Cherenkov-corrected measurement

• Dominate the jet energy resolution in the uncorrected case



$$\frac{\Delta E}{E} \leq \frac{0.25}{\sqrt{E}}$$



Longitudinally Segmented (Sampling) Calorimeter. Uniform Material

- Uniform medium: no ambiguities in sampling fraction definitions, no particle/energy dependence of sampling fractions.
- Lead glass as a material, 10000 layers 1 mm thick.
- Combinations of layers treated as ‘scintillator’, ‘cherenkov’ and ‘structural’ material

  - Contributions to the energy resolution from the geometrical factors
  - Compensation algorithm
  - Resolution and linearity, single particles
  - Resolution and linearity, jets
  - Optimization of the readout granularity

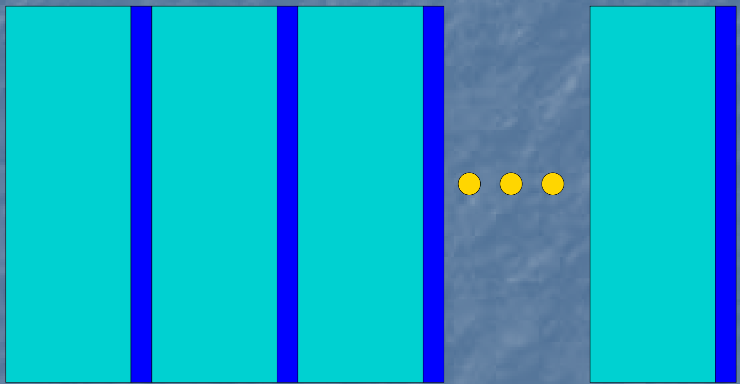
Next Step: Transverse Segmentation

- Sampling calorimeter, uniform medium, longitudinal and transverse segmentation (SLIC?)
  - Compensation algorithm: use local scintillation/Cherenkov ratio to correct the energy measurement of the 'hadronic' component
  - Optimize of transverse and longitudinal segmentation
  - Single particles resolution and linearity
  - Jets
  - Scintillating glass as an implementation

Next Step II: Different Materials

- Sampling fractions: neutrons, electrons and photons
- Combination of neutron-based and Cherenkov-based compensation
- Material choices: plastic scintillator or scintillating glass?
  - Compensation algorithm
  - Optimization of segmentation
  - Single particles, resolution and linearity
  - jets

Practical Implementation of a Cherenkov-assisted Hadron Calorimeter



Alternating layers of:

- lead glass to read out Cherenkov light
- scintillator to measure (sampled) ionization energy loss

- Lead glass and scintillator light read out with WLS fiber. Enabling technology: silicon photodetector
- Longitudinal and transverse segmentation, as required by physics driven considerations, relatively easy
- Thin layer of structural material (steel?) may be necessary for support
- Ultimate hadron energy resolution likely dominated by sampling fluctuations (thickness of lead glass). Optimization in progress.

Advantages Planar Calorimeter in Comparison with Fiber Based Dual Readout

- Very good energy resolution for electrons (using lead glass, nearly 100% sampling fraction), hence…
- Uniform calorimeter (the same structure for EM/Hadron section)
- Easy transverse and longitudinal segmentation
- High yield/detection efficiency of the Cherenkov photons

Studies and Characterization of Silicon Photodetectors (Enabling Technology)

- Static characterization: I-V curves, temperature dependence
- 'Dark' measurements (as a function of temperature, overvoltage, thresholds)
  - Rates
  - Gain
  - Afterpulsing and cross-talk
- Characterization of the detector response to a calibrated low intensity light source (0.1 – 1000 photons) as a function of operating conditions (temperature, voltage)
- Micro-pixel studies of the detector response over the front face of the detector (uniformity of gain, cross-talks, detection efficiency)

Goals

- Develop a complete characteristics of the detector response. Identify relevant variables.
  - For example: is $G(T,V) = G(\Delta V)$, with $V_{brkd} = V_{brkd}(T)$?
- Try to relate some of the characteristics to the detector design and construction
  - For example inter- and intra micro-pixel response uniformity
- Develop algorithm for readout strategy and calibration procedure (integration time, cross-talk, after-pulses, etc..)

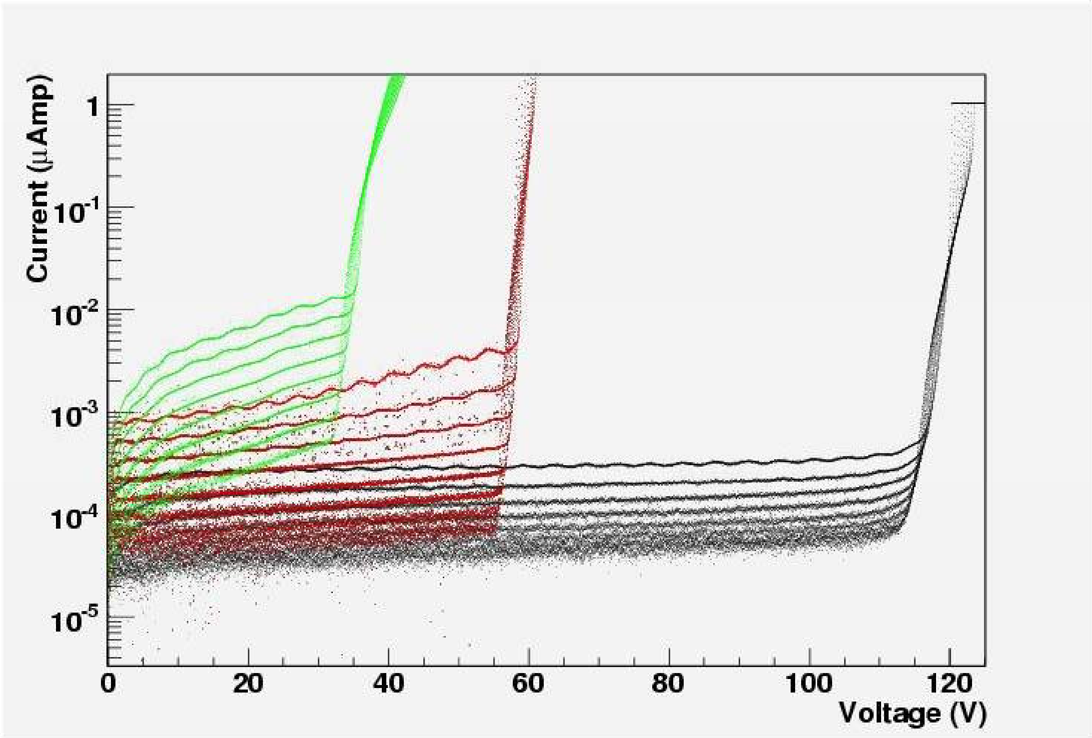
Detector Samples

- Existing
  - Hamamatsu (100, 50 and 25 μ micropixels)
  - IRST (several designs)
  - CPTA
  - Mehti
  - Dubna (two designs)
- Forthcoming
  - SensL
  - Others?

Step 1: Database of Static Characteristics

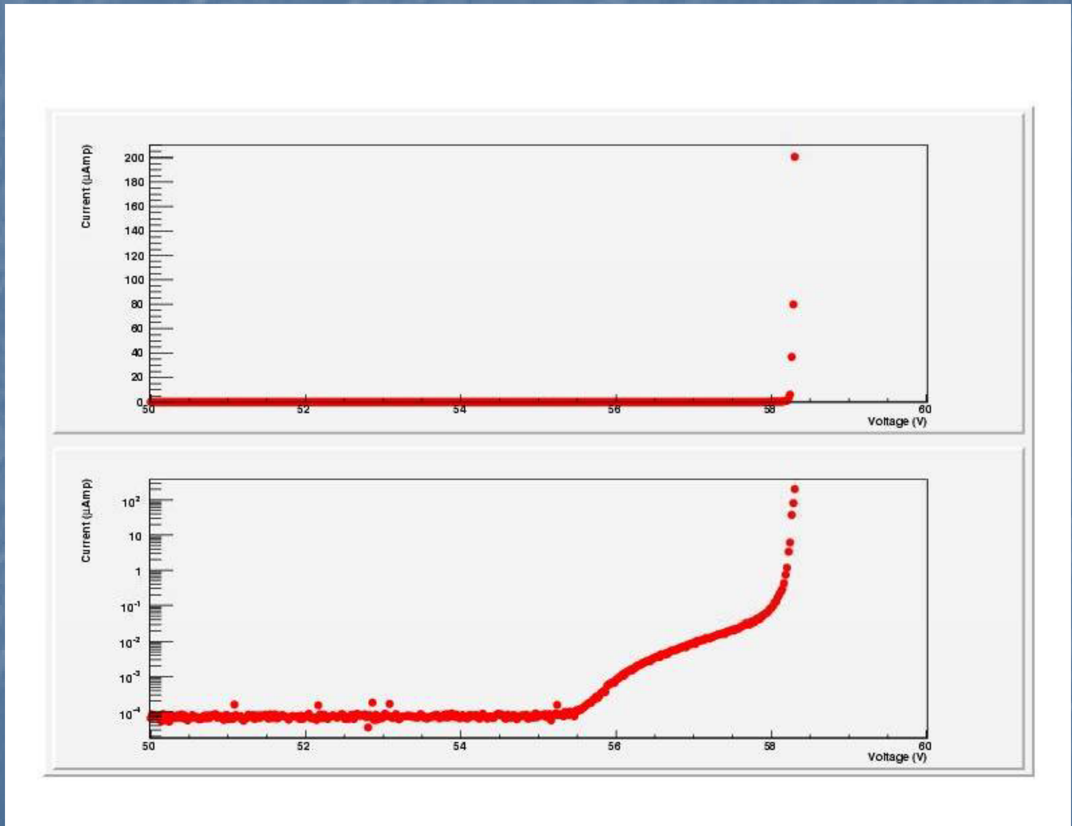
- Develop a procedure for imaging of the detector samples (SiDET facility)
- Develop an automated procedure for static characterization (breakdown voltage, resistance) as a function of the operating temperature
  - Keithley 2400 source-meter
  - Dark box
  - Peltier cold plate
  - Labview controls/readout
- Create a database of the samples, enter the static and image data

I-V Characteristics at Different Temperatures



- Different detectors have quite different operating point
- Dark current and the operating point depend on temperature

Breakdown Voltage: a Knee on the I-V plot?

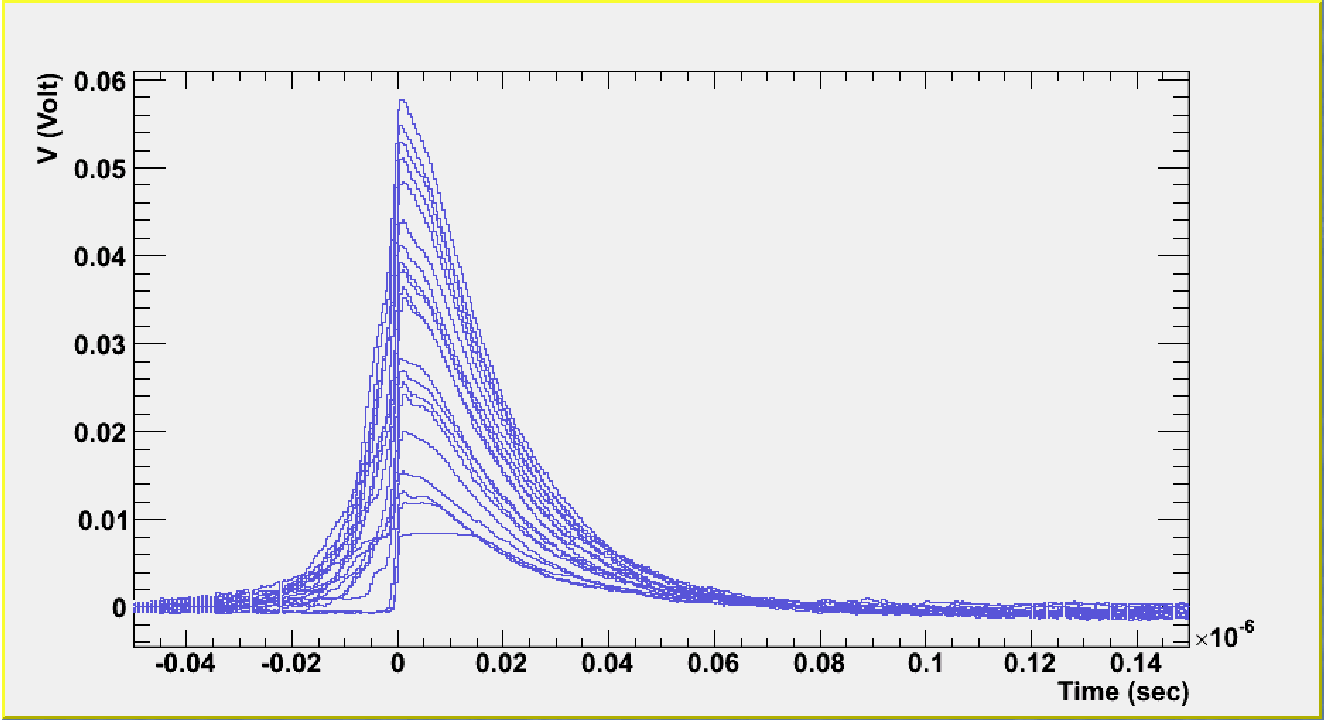


- Linear or logarithmic plot (derivative)?
- What is the shoulder on the IV log plot?
- Different pixels break-down at different voltages??
- Is it related to the resolution/width of the single electron peak??

Step 2: 'Dark Measurements' (no external light signal)

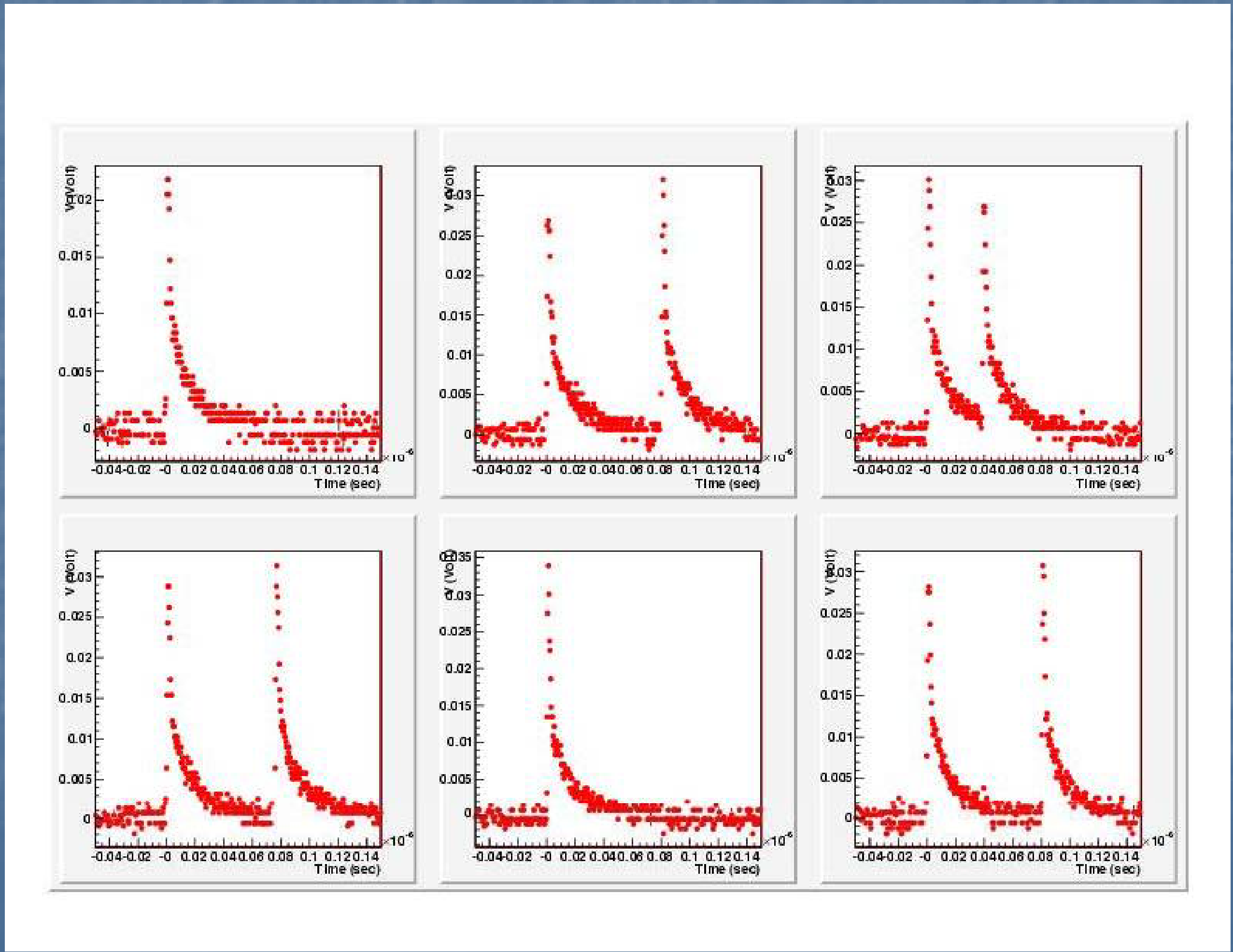
- Readout strategy:
  - Trans-conductance amplifier (MITEQ amplifiers: AU-2A-0159, AU-4A-0150, AM-4A-000110)
  - Controlled temperature:
    - Peltier creates too much of a noise
    - Chiller-based setup under construction
  - Tektronix 3000 series digital scope (5 GHz)
  - LabView DAQ and analysis program
  - Root-based analysis environment
- Dynamical characteristics of the detectors (Later: as a function of the operating temperature).
  - Rate (as a function of threshold, voltage and temperature)
  - Gain = (Charge of a single avalanche)/e (as a function of threshold, voltage and temperature)
- Examples follow (at the 'room' temperature) …

Average Pulse Shapes for Different Thresholds



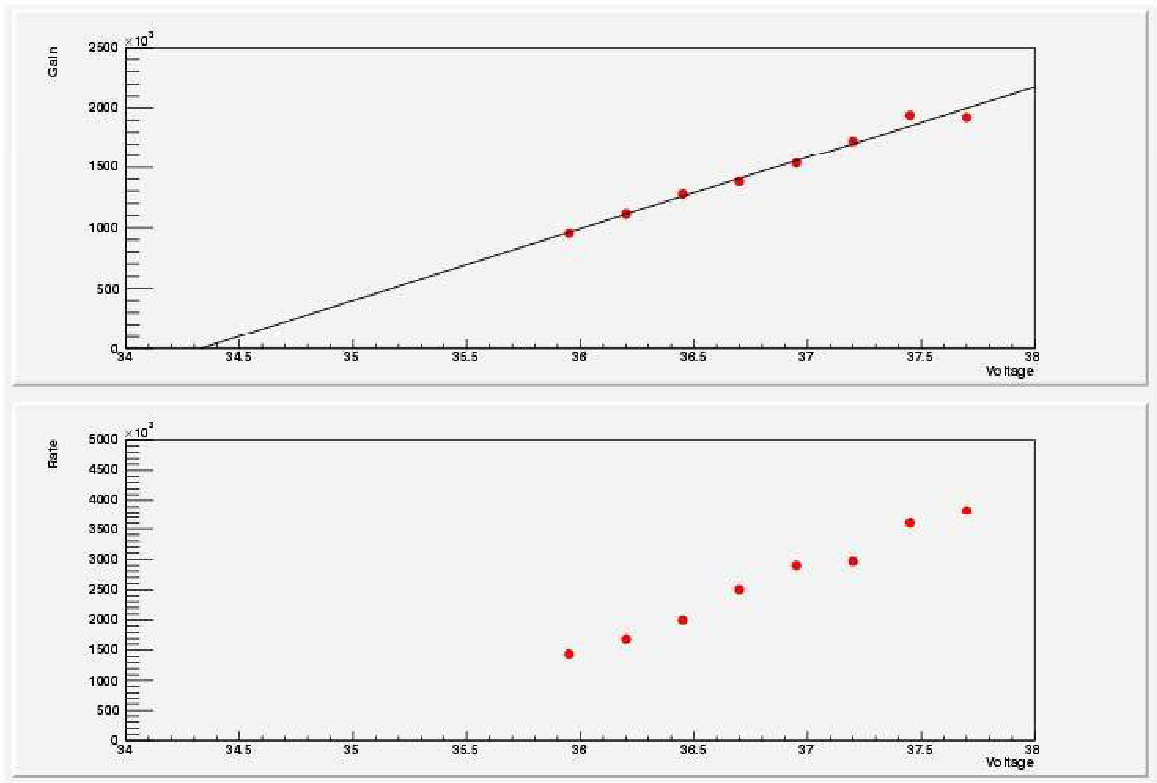
- But… average does not necessarily represent the real pulses

Examples of Real Pulses

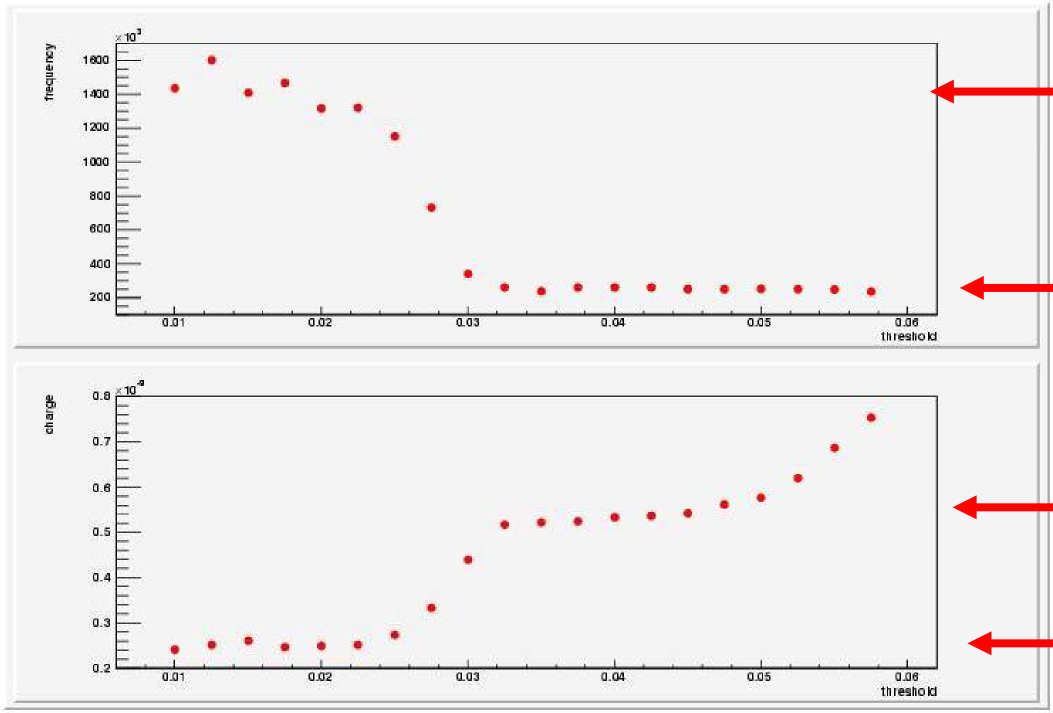


- Afterpulses and/or cross-talk
- ~ 5-10% (depending on voltage)
- Time constant of tens of nanoseconds

Gain and Rate as a Function of Voltage



Rate and Charge as a Function of Trigger Threshold



Single avalanche

Double avalanche

Double avalanche

Single avalanche

Step 3: Characterization of the Detector Response to a Calibrated Light Pulse

- Light source (under construction):
  - Short pulse duration (<1 nsec)
  - Absolute light calibration (modified scheme of P. Gorodetzky)
  - Variable light intensity (0.1 – 1000 photons)
- Readout and analysis scheme (as before)
- As a function of voltage and temperature:
  - PDE
  - Linearity of the 'prompt' response (~5 nsec gate)
  - The rate, time and amplitude distribution of 'follow-up' pulses (as a function of the light intensity)

Step 4: Microscopic Studies of the Photodetector (Planned)

- Focused (calibrated) light source, 2-3 μ spot size (Selcuk C.)
- Microstage (<1 μ stepping accuracy)
- Dark box containing the detector, focusing lenses and the stage
- Readout as before
- Spatial characteristics of the photodetector, intra and inter-micro pixel variation of:
  - Gain
  - PDE
  - Afterpulses
  - Cross-talk