Planar Dual Readout Calorimetry Studies
Progress Report

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Modivation: High Resolution Jet Calorimetry for the ILC

- Jets = hadrons + photons. In a calorimeter photons are measured quite well, hadrons are measured poorly.
- Proposed ways to improve:
  - 'if that hurts – do not do THAT' (a.k.a. PFA): reduce the role of a hadron calorimeter to a relatively minor one of measuring n,Ko only
  - Try to understand why hadrons are measured poorly and try to eliminate/reduce the fluctuations
- Both methods (as it turnes out require rather good understanding of the hadron calorimetry/showers)

Goals of This Study

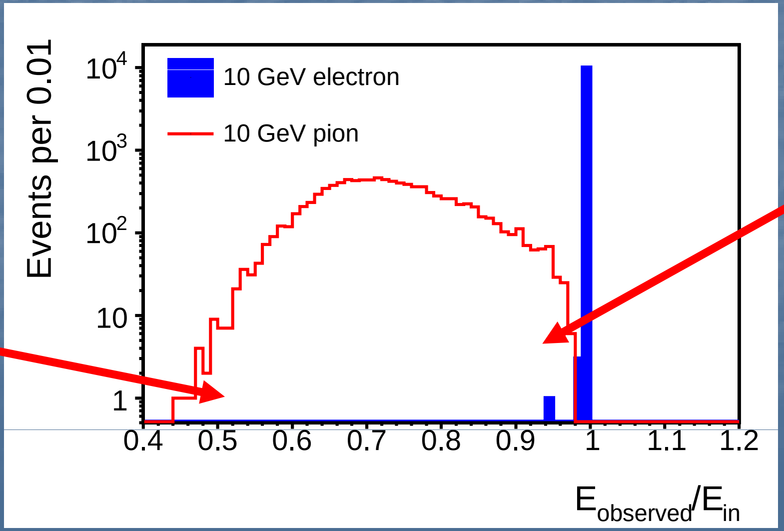
- Systematic studies of contributions to energy resolution of high precision dual readout calorimeters:
  - Sampling frequency
  - Active detectors: materials and thickness
  - Detection mechanism: scintillation/Cherenkov
- Investigate performance of compensating dual readout calorimeters and its dependence 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 (fluctuations 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

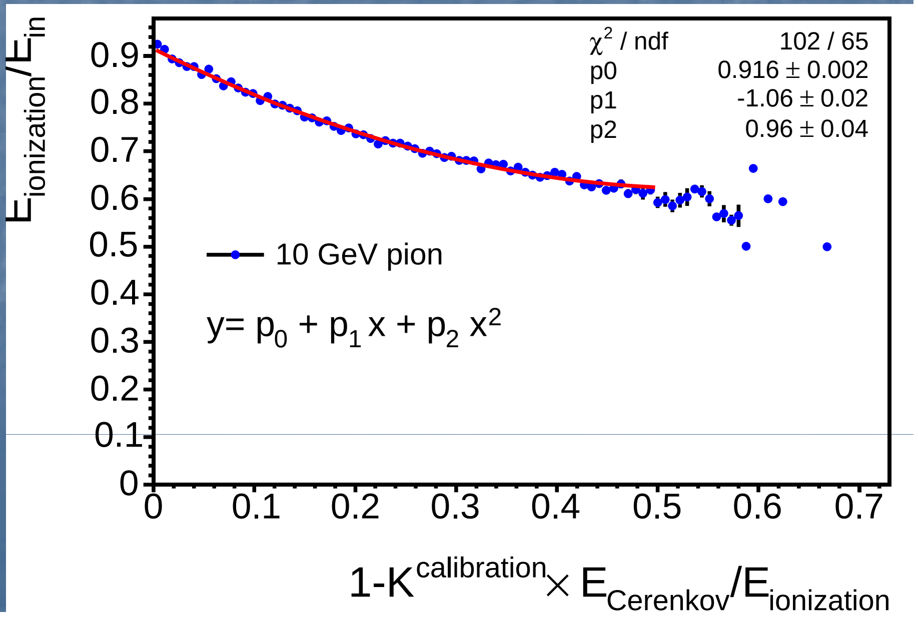
Path to High Precision Hadron Calorimetry: Compensate for the Nuclear Energy Losses

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

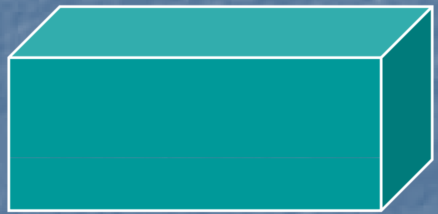
• 'EM' shower: relativistic electrons, relatively large amount of Cherenkov light

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

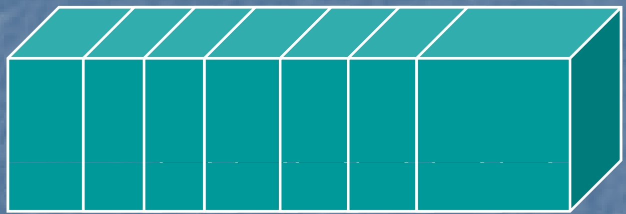


Program of Studies (software)

- Systematic step-by-step approach

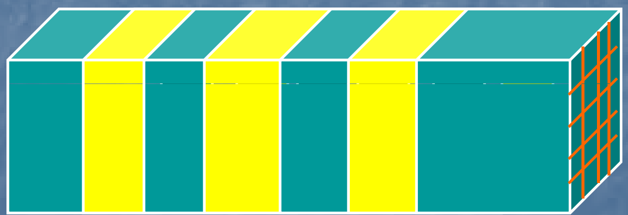


Large homogeneous calorimeter



Longitudinally segmented calorimeter (all lead glass, serated functions)

Longitudinally segmented calorimeter (plastic scintillator)



Transversely and longitudinally segmented calorimeter (different materials)

Large Homogeneous Calorimeter (Total Absorption)

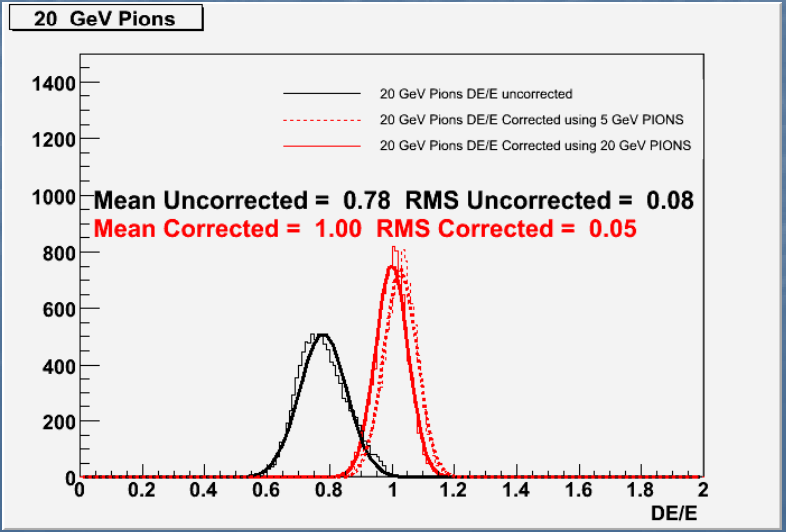
- Simulation of homogeneous scintillation/cherenkov calorimeter (stand-alone GEANT4)
- Studies of compensating calorimetry with a homogenous calorimeter:
  - compensation algorithm
  - Single particles, linearity response, e/π
  - Jets

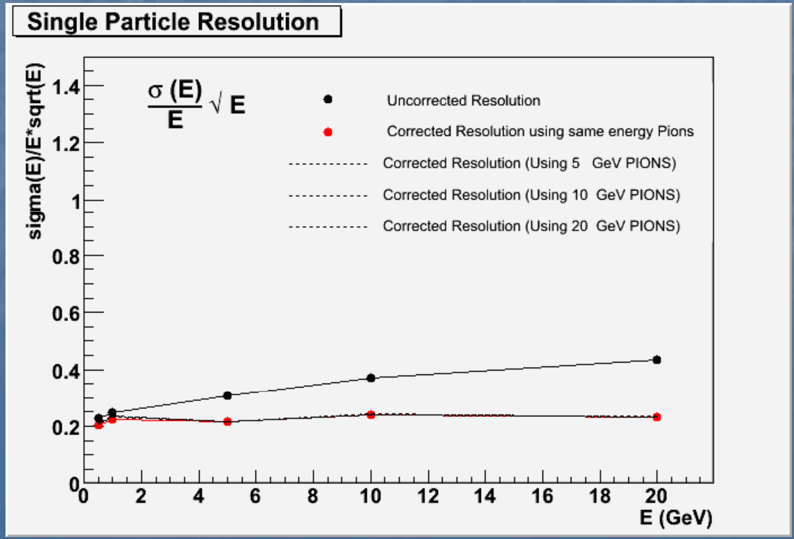
Cherenkov-assisted Calorimetry at Work: Single Particle Case

- 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 charged hadron energy resolution $\Delta E/E=0.25/\sqrt{E}$
- Scales with energy like $1/\sqrt{E}$ (no 'constant term')
- Linear response





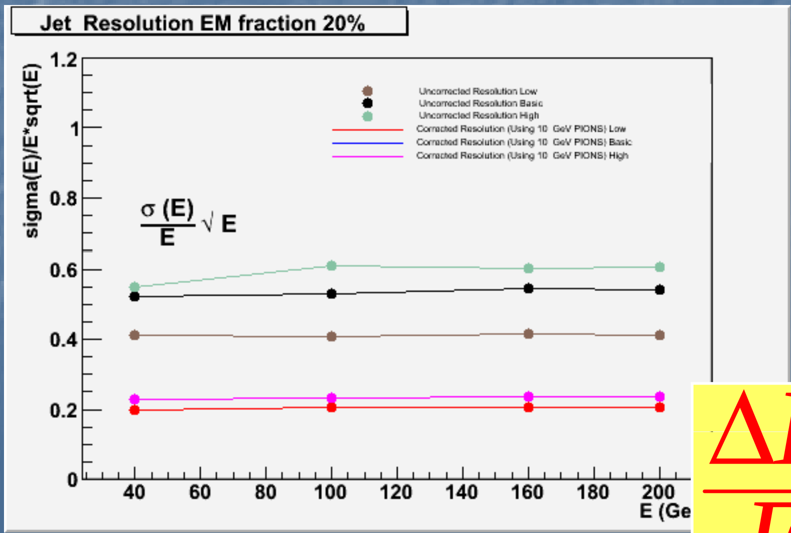
Measuring jets (== ensembles of particles)

Jet fragmentation (in)dependence

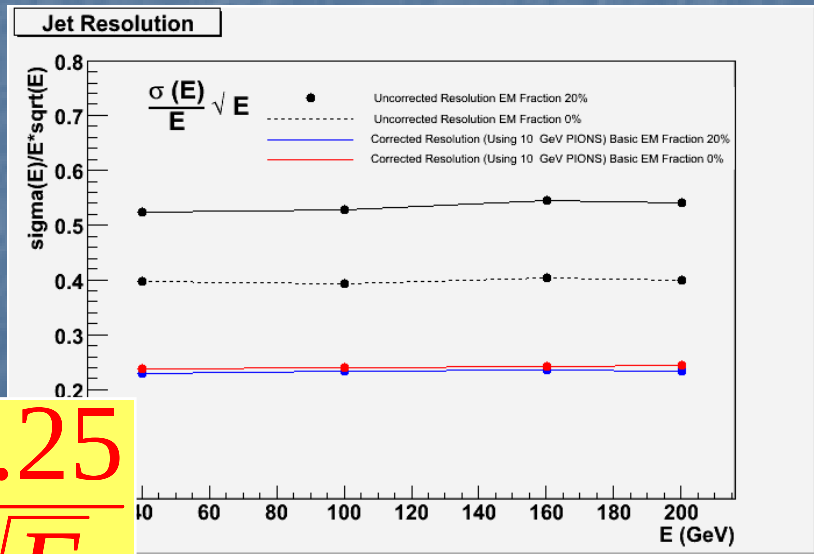
- Resolution of Cherenkov-corrected energy measurement is nearly independent of the jet fragmentation
- Resolution (and the response) of the uncorrected energy measurement dependent on the jet composition

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



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



Homogeneous Detector Summary

- Excellent resolution for electrons/hadrons/jets. No segmentation (transverse or longitudinal) required, but..
- Possible as desired by other physics requirements as long as all detector volumes have the same material and provide both Cherenkov and scintillation information. It is wise to keep the number of segments close minimum nceseeary

Homogeneous Detector Implementation

- High density (SF57: 5.7 g/cm^3) lead glass blocks doped with cerium? P-TP? POPOP?
- Read out with GM-APD's (with or without WLS fiber) – this is the enabling technology
- Cherenkov/scintillation separation by timing
- Early section (for example) 1 x 1 x 5 cm fingers
- Late section (for example) 10 x 10 x 10 cm cubes

Dual Readout Hardware Issues

- Scintillation doping (cerium? organic activator?) Northwestern Polytechnical University, Xian
- Cost effective production of lead glass plates Shanghai Xinhu Glass Co., LTD. Notice old encouraging results of cast/extruded lead glass (Grannis et al)
- Light collection/yield (especially Cherenkov):
  - Started lab measurements
  - Forward Calorimetry R&D for TESLA (R. Dollan Diplomaarbeit)
- Optimization of the structure of the EM 'section' (test beam module)
-

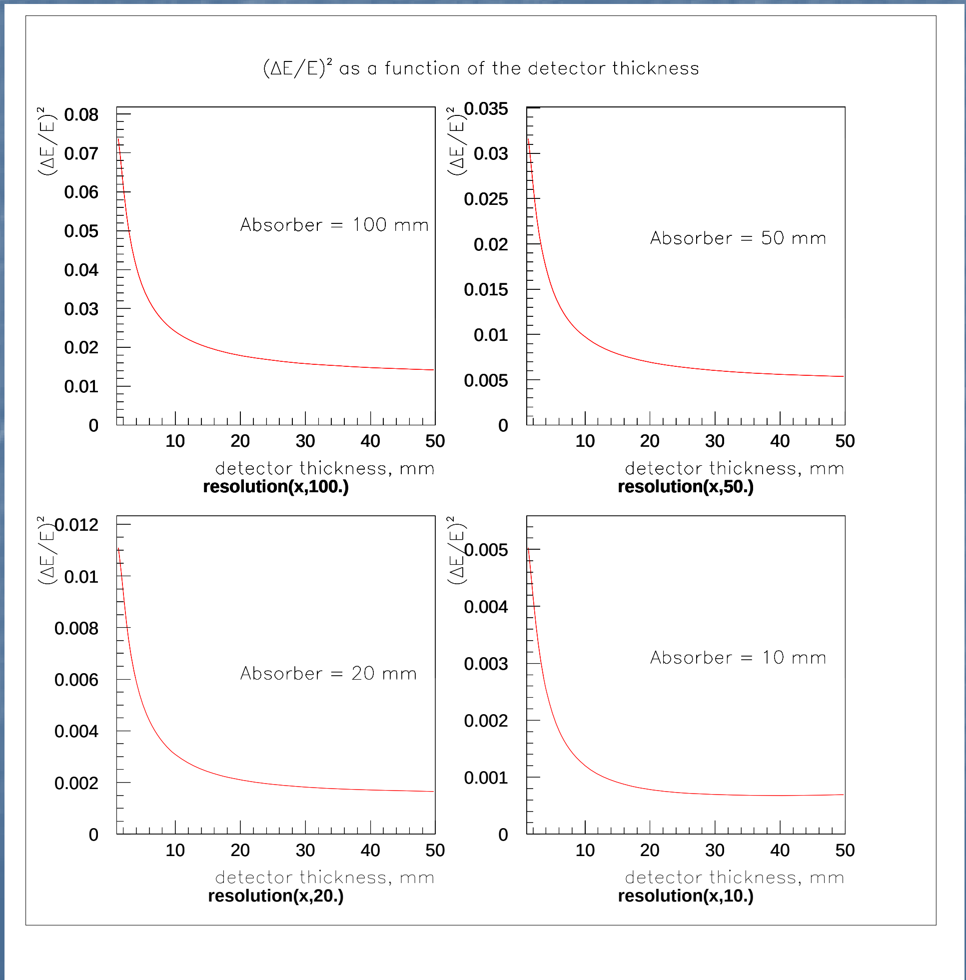
Longitudinally Segmented (Sampling) Calorimeter. Glass Scintillator

- 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

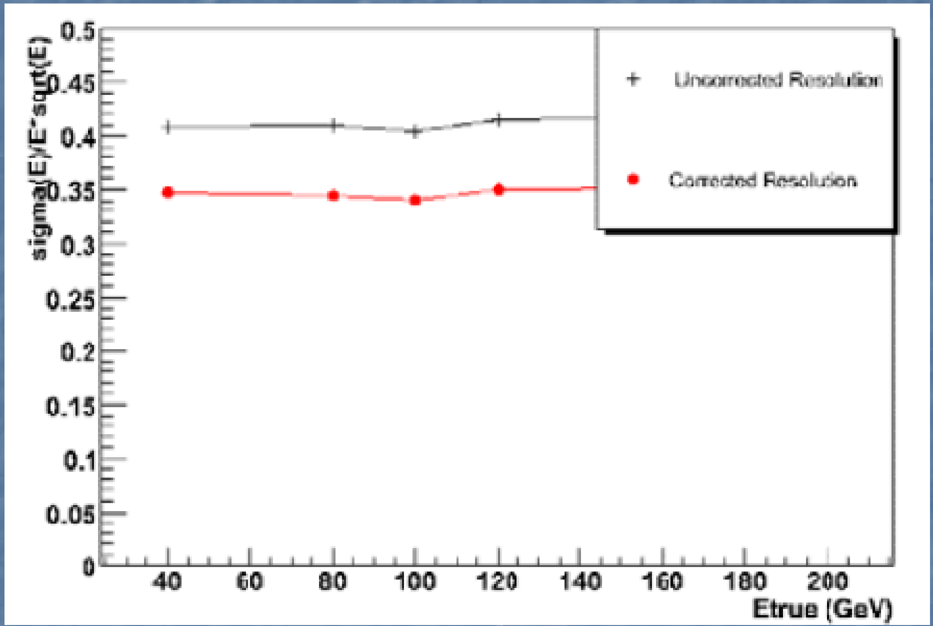
  - Contributions to the energy resolution from the geometrical factors
  - Compensation algorithm
  - Resolution and linearity, single particles
  - Resolution and linearity, jets
  - Optimization of the readout granularity

Sampling calorimeter - sampling fluctuations



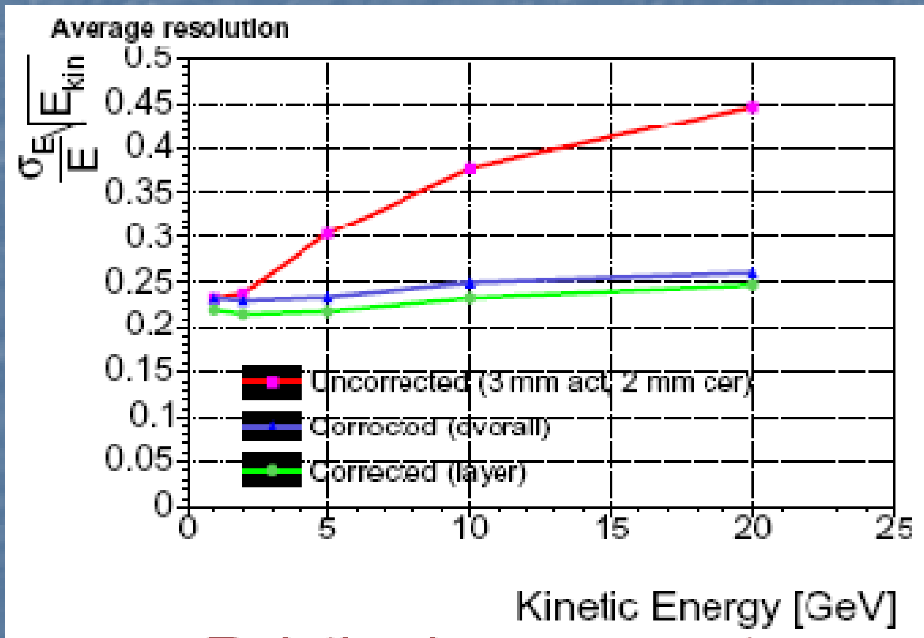
- Energy resolution depends on sampling frequency
- Energy resolution depends on sampling fraction
- Energy resolution depends on absolute thickness on the active layer

Step 1: energy measurement/correction based on total amount of light



- Cherenkov/scintillation light corresponds to different physical signals - dilution
- Good jet energy resolution attainable
- Even in the presence of significant structural (dead) materials
- Example shown:
  - 30 mm scintillator
  - 2 mm Cherenkov
  - 18 mm structural

Step 2: local correction



- Correction based on a local Ch/sc ratio. Still diluted as no transverse segmentation/significant dilution
- Some ~7% improvement of the resolution
- Further improvement expected with transverse segmentation
- Example shown: single particles, 3 mm scintillator, 2 mm Cherenkov

Next Step: Plastic scintillator

- Combination of neutron-based and Cherenkov-based compensation

Advantages of a 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

Dual Readout vs PFA?

- It is becoming more and more difficult to hide the fact that the 'confusion' term is a killer for the PFA $1.4 \times 0.9^4 = 0.92$
- The confusion term is likely related to the 'shower size'
- Hadron shower as seen with Cherenkov light has very small lateral extent (at the expense of the energy resolution. Perfect match for the PFA) (Very forward quartz fiber calorimeter of CMS is a good illustration)
- Dual readout calorimeter offers an unique combination of excellent energy resolution and the PFA capabilities. These two methods of attaining the energy resolution are largely uncorrelated.

Studies and Characterization of Silicon Photodetectors (Enabling Technology)

- This are very promising new detectors
- Enabling seamless light collection and measurement in volume
- but they are still in their infancy
- Thorough characterization/understanding effort is necessary
- With feedback to producers to optimize the performance

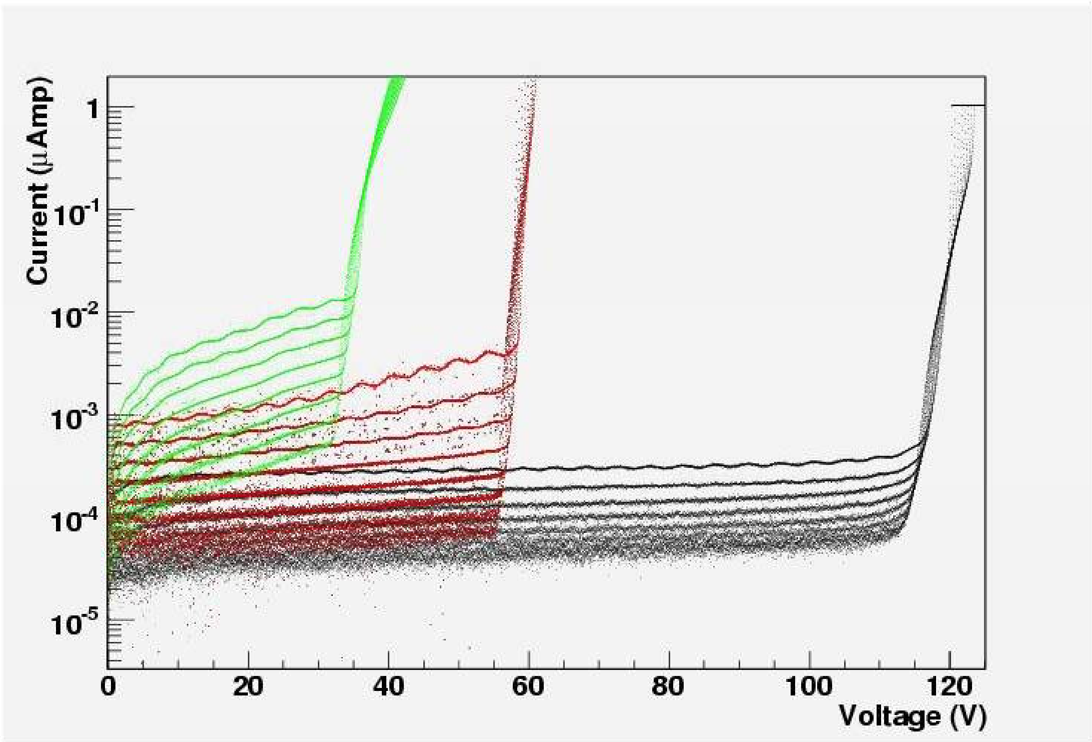
Goals

- 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..)

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

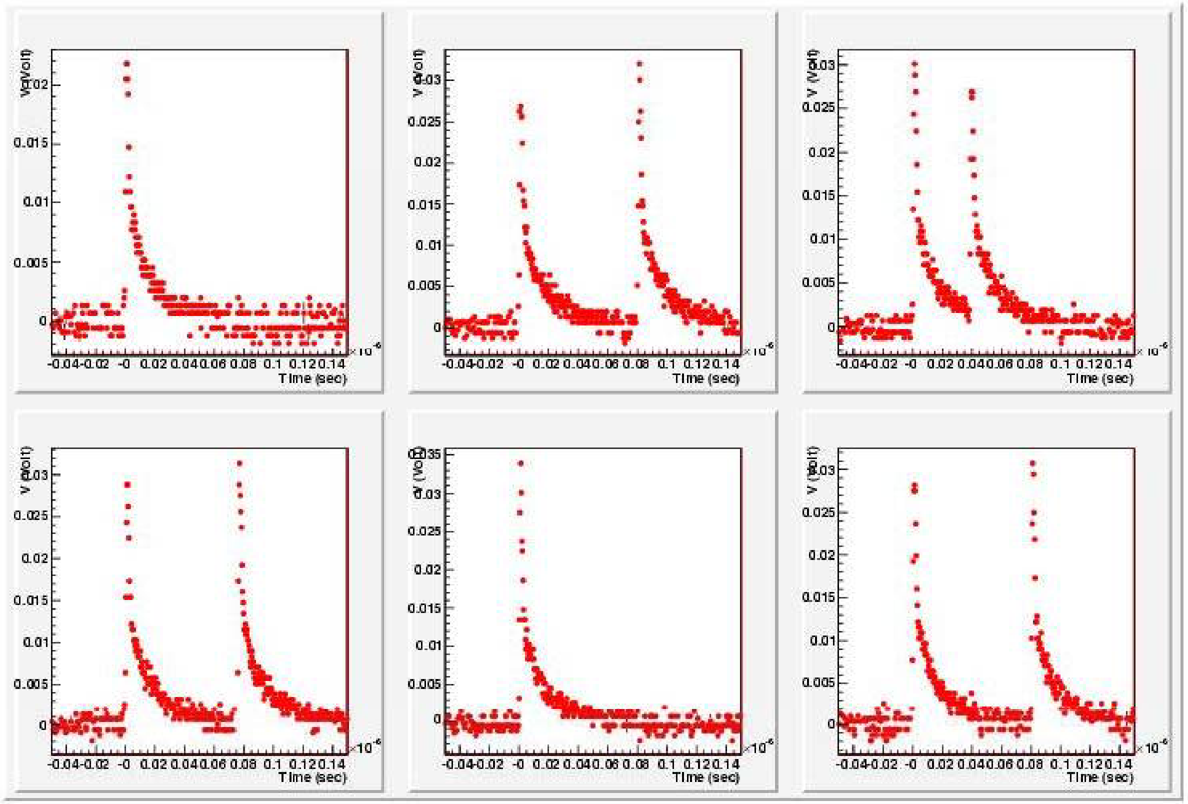


- Different detectors have quite different operating point
- Dark current and the operating point depend on temperature

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) …

Examples of Real Pulses



- Afterpulses and/or cross-talk
- ~ 5-10% (depending on voltage)
- Time constant of tens of nanoseconds
- This is a potential problem if timing of the signal is of interest (fast/slow component)

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