Development of CVD Diamond Tracking Detectors for Experiments at High Luminosity Colliders

RD42 Status Report

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LHCC Presentation
Jan. 31, 2007, CERN

Outline of the Talk

- **Introduction - 2006 LHCC Milestones**
- **Diamond Pixel Modules**
- **Radiation Hardness Studies with Trackers**
- **Beam Position Monitoring Studies**
- **Summary**
- **RD42 Plans and Request**

The RD42 Collaboration

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58 Participants

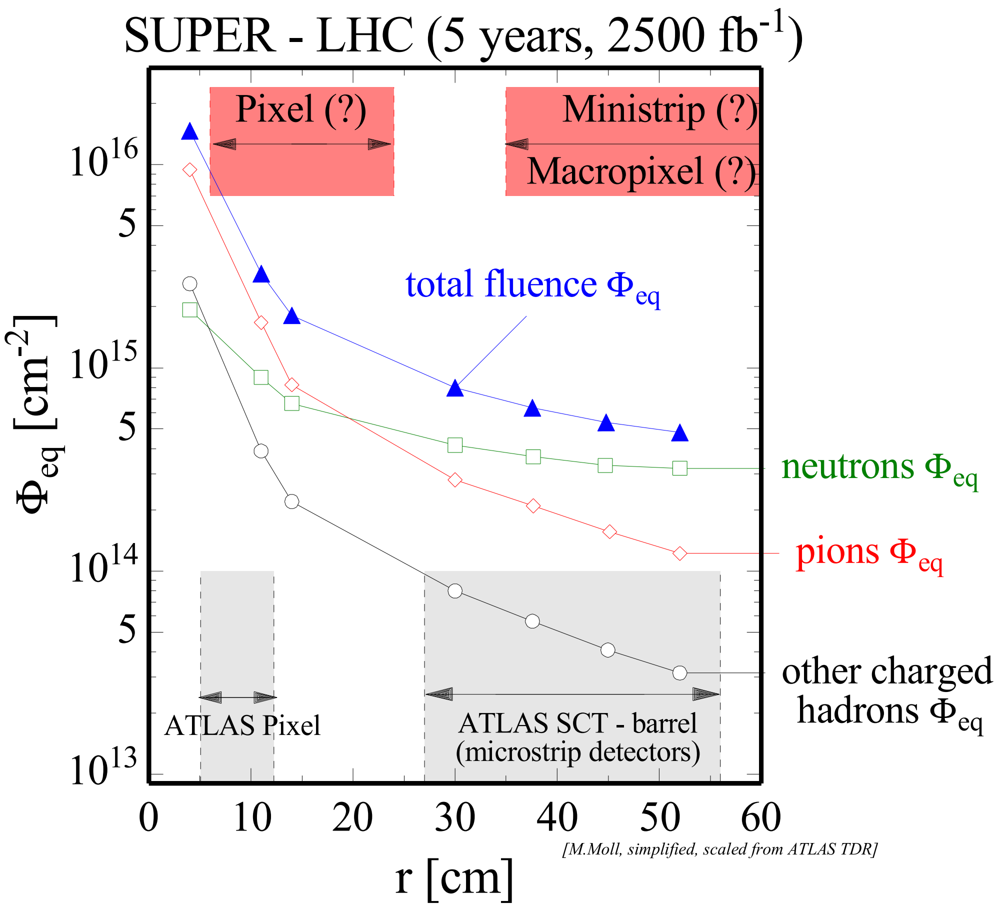
21 Institutes

Detectors in BaBar, Belle, CDF, ATLAS; planned DESY, CMS, ALICE, LHCb

New groups joined RD42 from: Ljubljana, MEPHI Institute Moscow, ITEP Moscow, UCLA
Some groups left

Motivation: Tracking Devices Close to Interaction Region of Experiments at the SLHC

Scale is $\sim 10^{16}$ cm^{-2} $\rightarrow$ annual replacement of inner layers perhaps?



Introduction

Motivation: Tracking Devices Close to Interaction Region of Experiments

Look for a Material with Certain Properties:

- Radiation hardness (no frequent replacements)
- Low dielectric constant → low capacitance
- Low leakage current → low readout noise
- Good insulating properties → large active area
- Room temperature operation, Fast signal collection time → no cooling

Presented Here:

- Polycrystalline Chemical Vapor Deposition (pCVD) Diamond
- Single Crystal Chemical Vapor Deposition (scCVD) Diamond
- ATLAS pCVD Diamond Pixel Module
- ATLAS scCVD Diamond Pixel Module
- CDF pCVD diamond Beam Conditions Monitoring system
- ATLAS pCVD diamond Beam Conditions Monitoring system

- *Reference* → http://rd42.web.cern.ch/RD42
- *Diamonds supplied by and in collaboration with Element Six Ltd.*

Priorities of Research in 2006

- Develop diamond pixel modules useful at the LHC by ATLAS and CMS
- Pursue the development of single crystal CVD (scCVD) diamond material
- Test the radiation hardness of the highest quality pCVD and scCVD diamond
- Continue the development of systems for beam monitoring for the LHC
- To strengthen the collaboration with future LHC applications

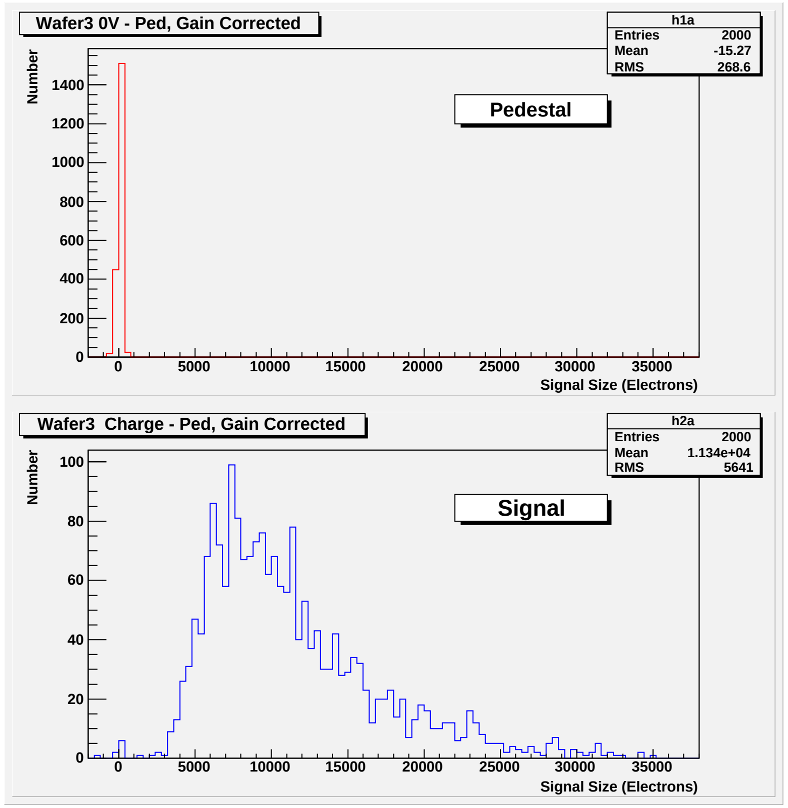
These points will be addressed in this talk.

CVD Diamond Properties

Properties - Polycrystalline CVD Diamond

Latest Material: pCVD Diamond Measured with a ^{90}Sr Source

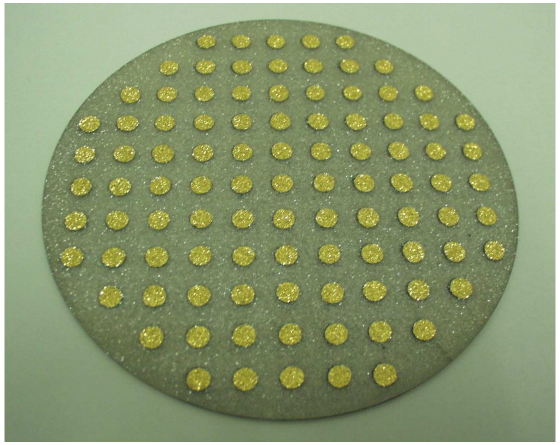
- Contacts on both sides - structures from μm to cm
- Usually operate at E=1V/μm
- Test Procedure: dot $\rightarrow$ strip $\rightarrow$ pixel on same diamond!

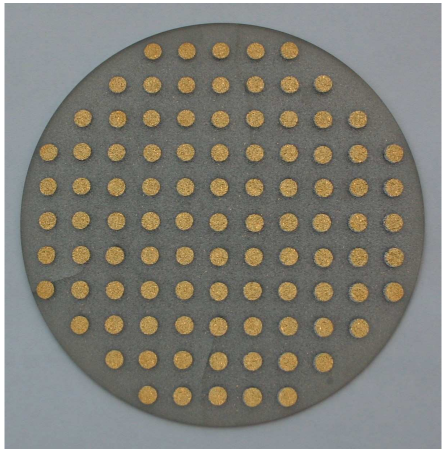


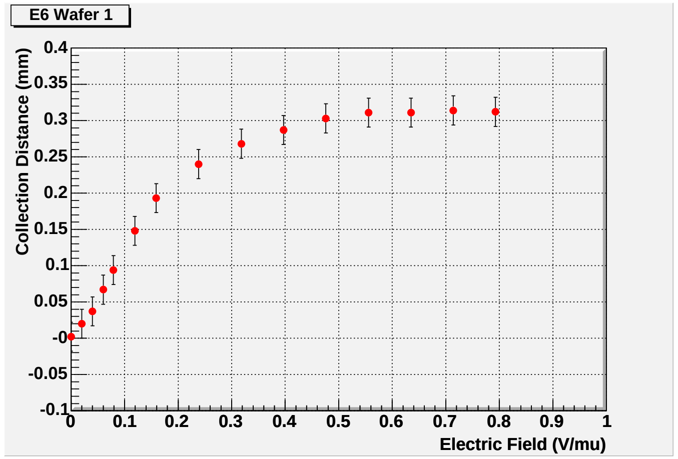
- Q_{MP} = 8500-9000e
- Mean Charge = 11300e

- Source data well separated from 0
- Collection Distance now ≈ 300μm
- Most Probable Charge now ≈ 9000e
- 99% of PH distribution above 4000e
- FWHM/MP ≈ 0.95 — Si has ≈ 0.5
- This diamond available in large sizes

Recent Polycrystalline CVD Diamond







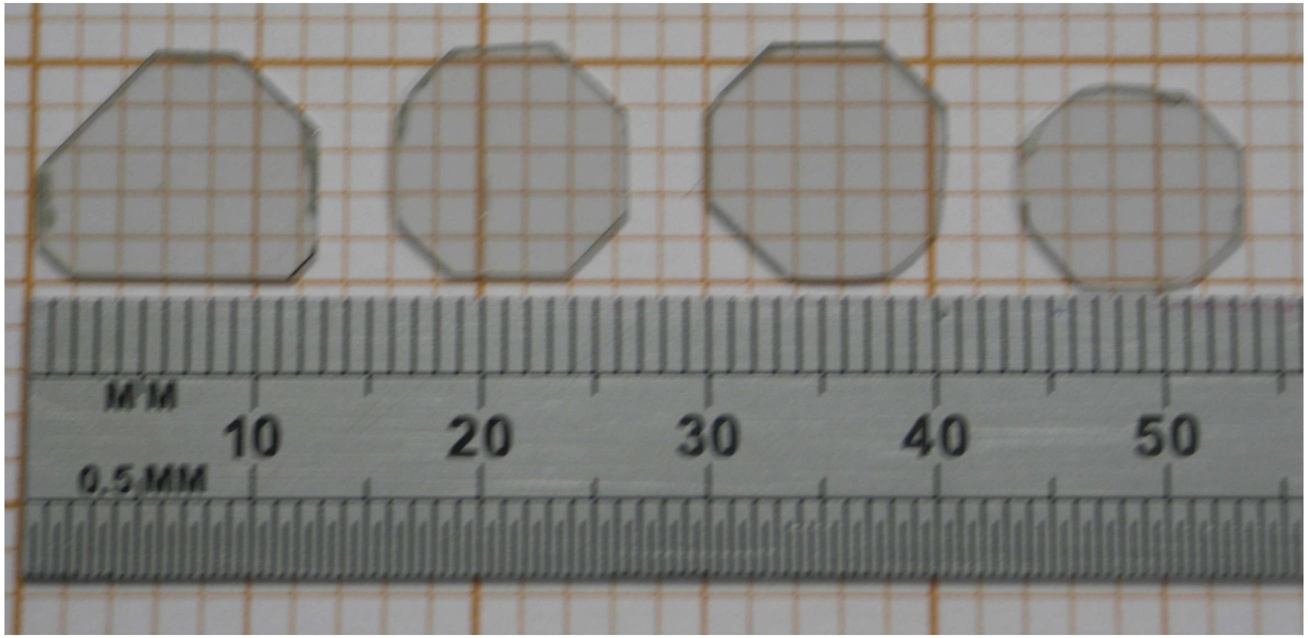
Left: Recent pCVD wafers ready for test - Cr/Au dots are 1 cm apart
Right: Collection distance from a dot in the pCVD wafer

pCVD diamond wafers can be grown >12 cm diameter, >2 mm thickness.

Wafer collection distance now typically 250μm (edge) to 310μm (center).

Properties - Single Crystal CVD Diamond

Recently Single Crystal CVD (scCVD) Diamond has been Fabricated



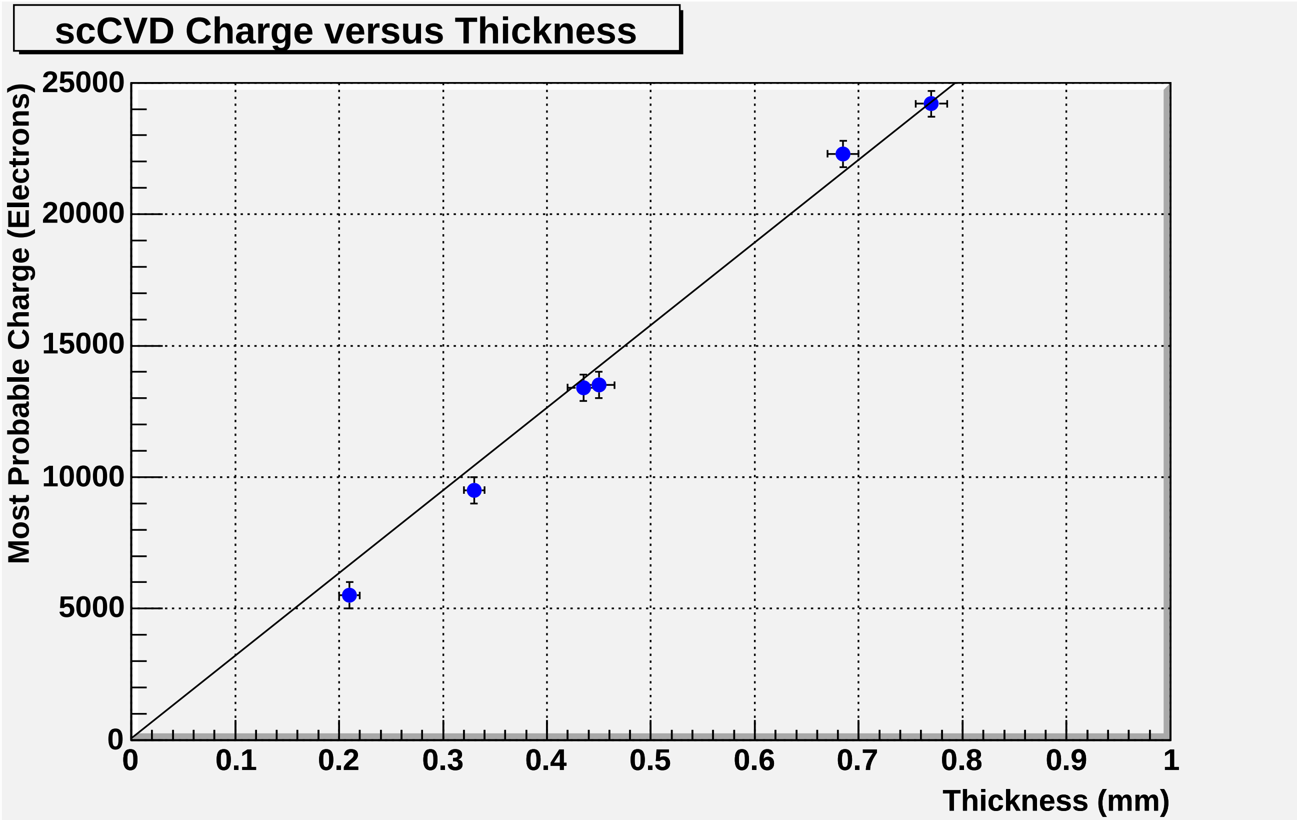
RD42 has a research contract with Element Six to develop this material.

scCVD diamond can be grown $\approx$ 10 mm $\times$ 10mm, >1 mm thickness.

Largest scCVD diamond grown $\approx$ 14 mm $\times$ 14 mm.

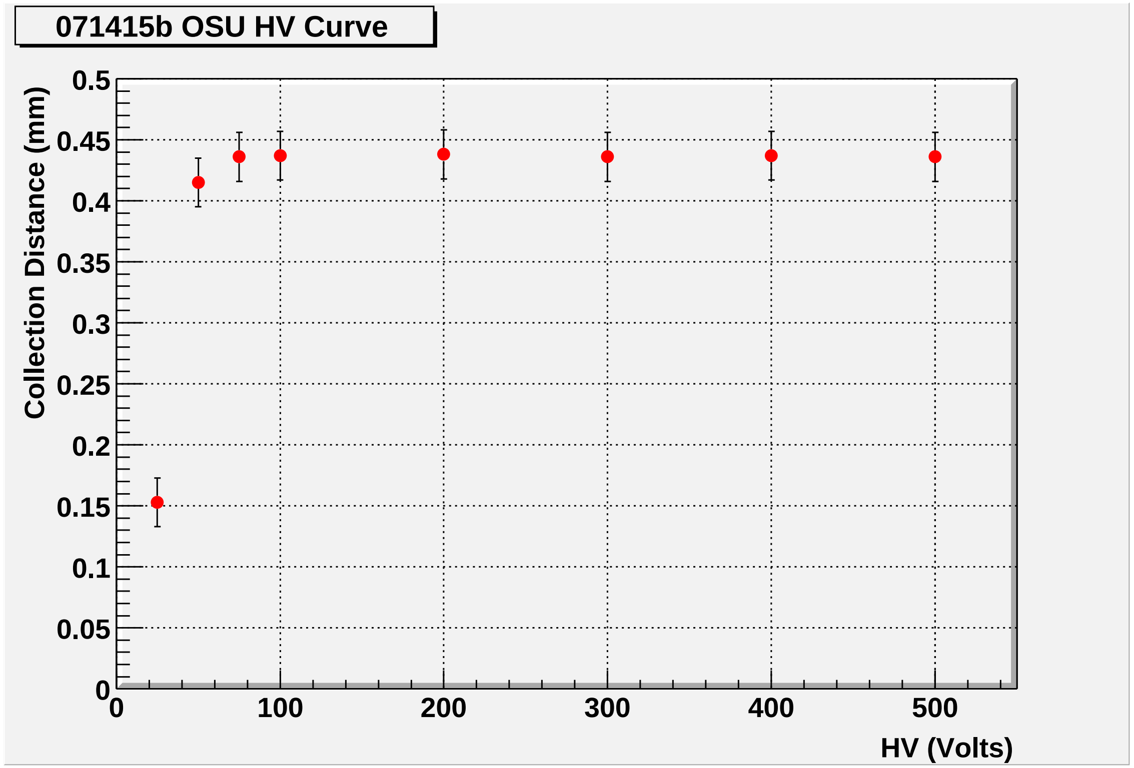
Properties - Single Crystal CVD Diamond

scCVD Diamond Most Probable Charge versus Thickness



- High quality scCVD diamond can collect full charge for thickness 880μm
- Width of landau distribution is $\approx 1/2$ that of silicon, $\approx 1/3$ that of pCVD diamond

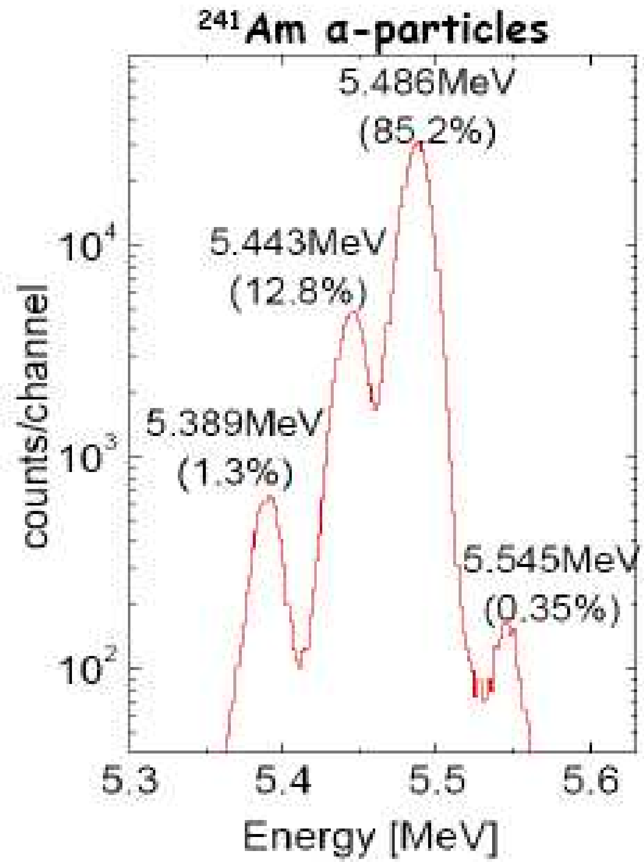
HV Characteristics



- High quality scCVD diamond collects all the charge at E=0.2V/μ!
- High quality scCVD diamond does not pump!

Properties - Single Crystal CVD Diamond

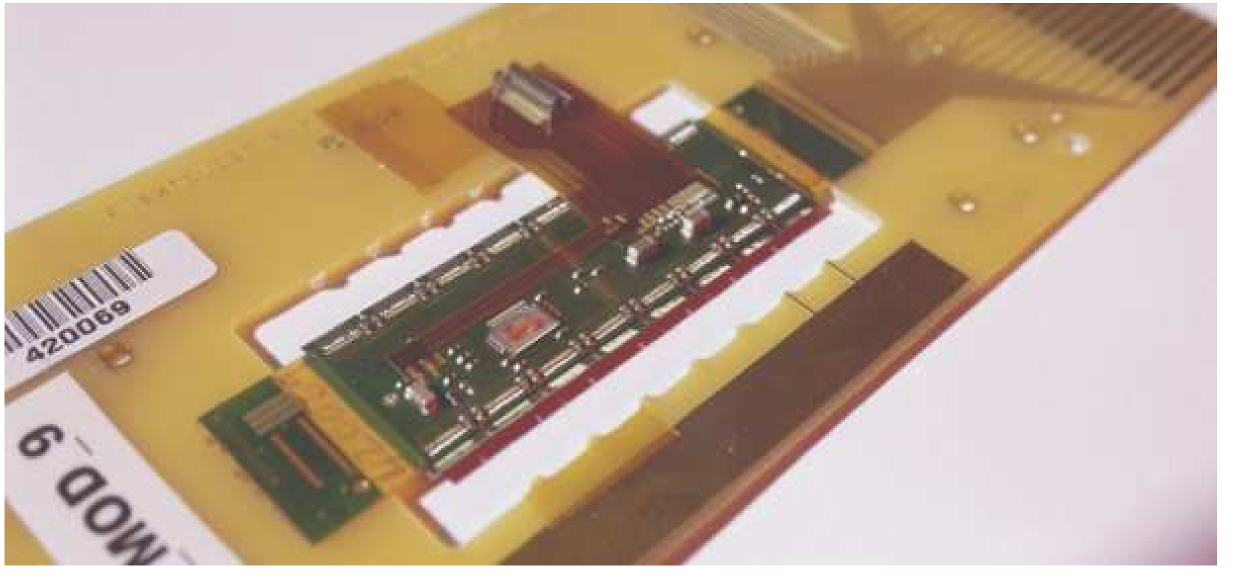
Energy Resolution:



- FWHM: 17keV @ 5.4MeV → spectroscopic material

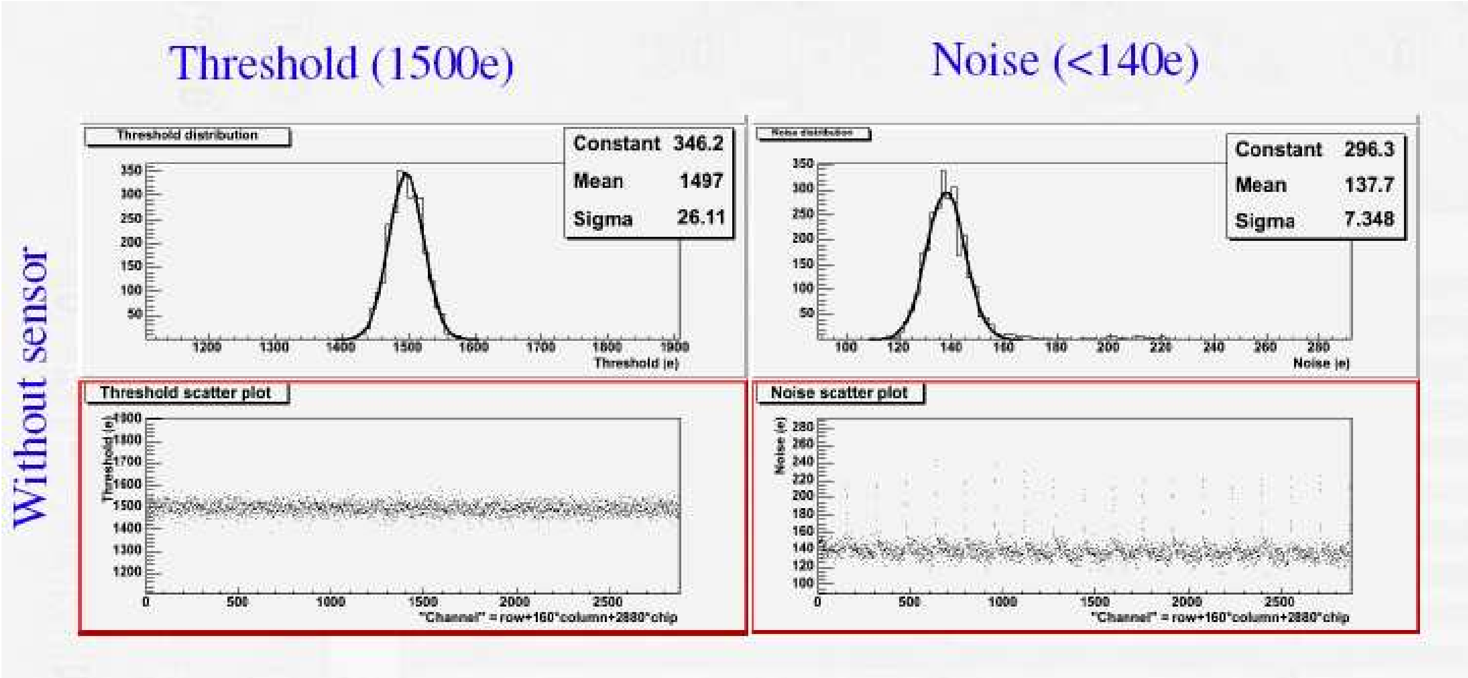
pCVD and scCVD Pixel Detectors

A full 16 Chip ATLAS diamond pixel module



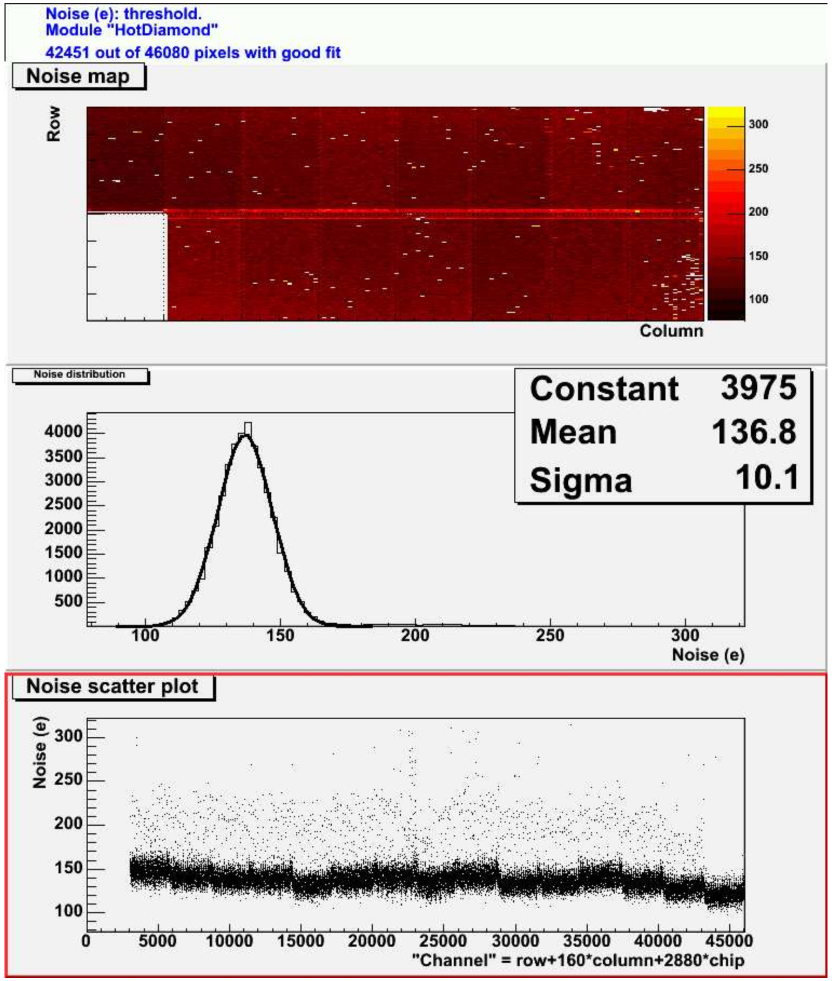
- Module tested in Bonn

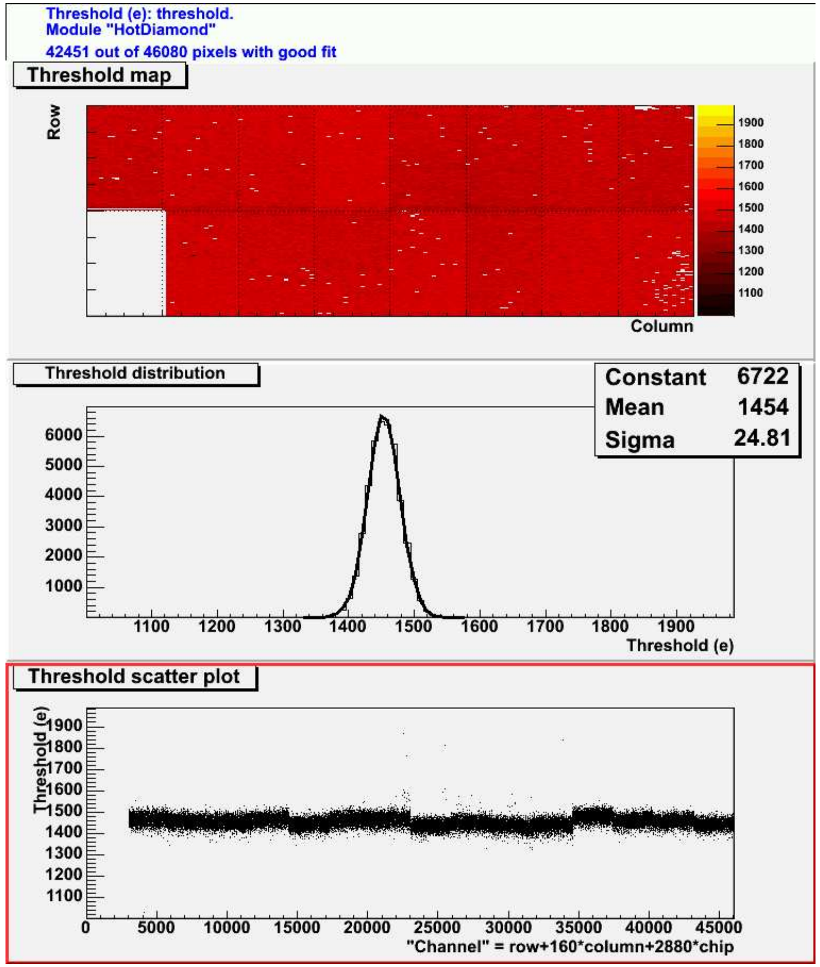
The ATLAS pixel module - Bare Chip, No Detector - Noise, Threshold



Results: Bare Noise $\sim 140e$, Bare Mean Threshold $\sim 1500e$,
Bare Threshold Spread $\sim 25e$.

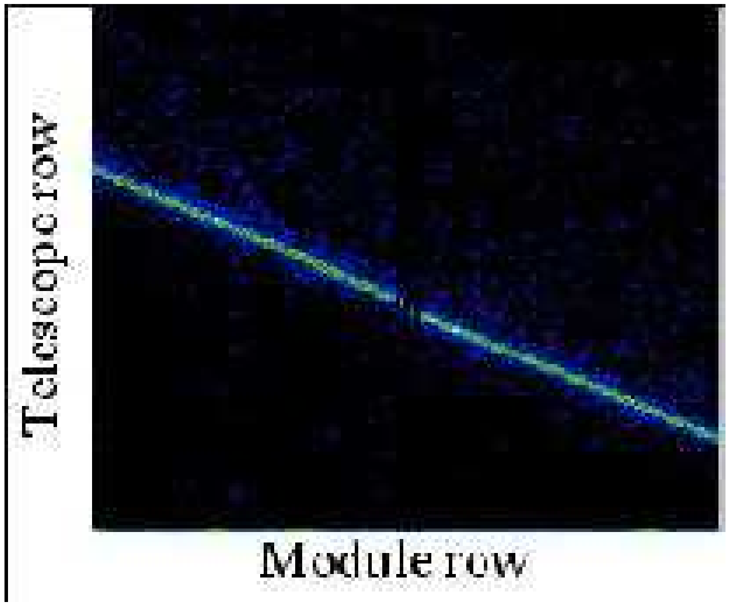
The full ATLAS diamond pixel module - Noise, Threshold

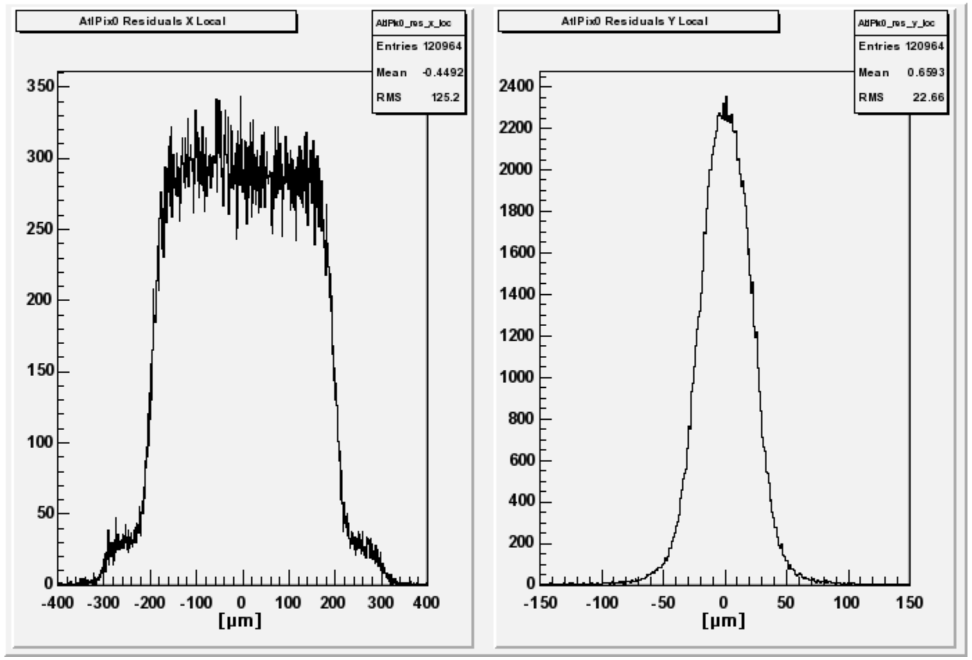




Results: Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$.
Noise, threshold, threshold spread do not change from bare chip.

The full ATLAS diamond pixel module - Correlation, Resolution



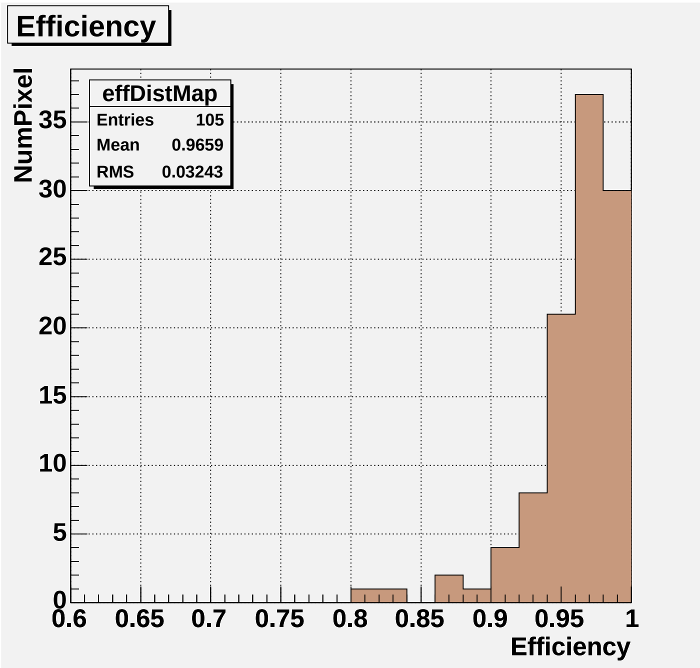


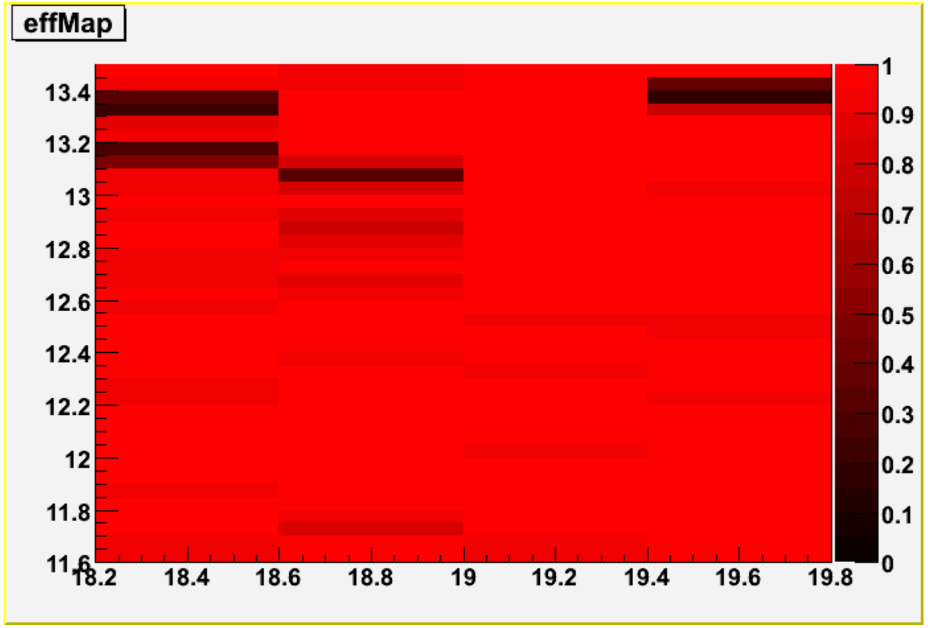
Excellent correlation with telescope

Resolution dominated by 6 GeV electron multiple scattering.

Preliminary residual $\sim 23\mu$m - includes contribution from multiple scattering.

The full ATLAS diamond pixel module - Efficiency (New Analysis)

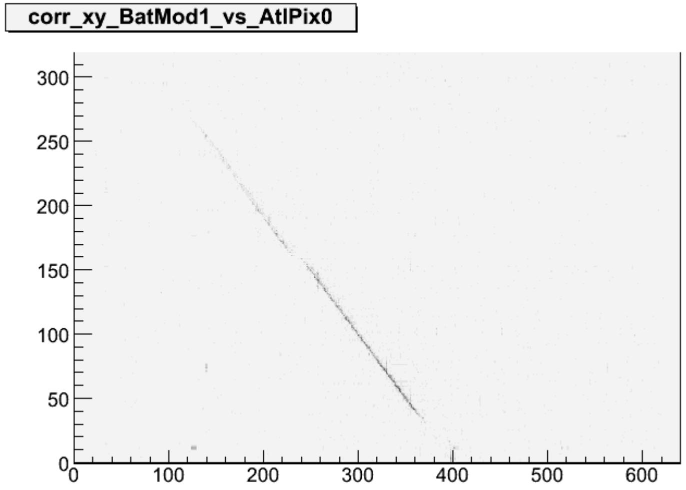


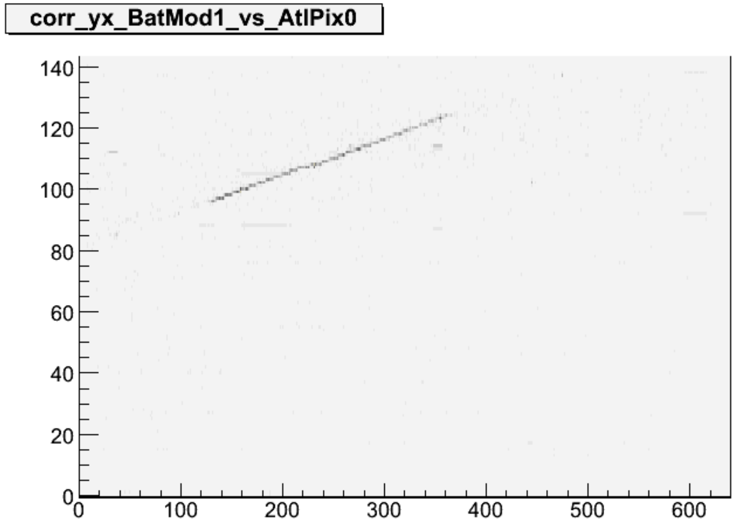


Preliminary efficiency >97.5%

- still need to correct tracking errors, multiple scattering.
- still need better fiducial region.

November 2006 Test Beam - CERN
The full ATLAS diamond pixel module - Position Correlation



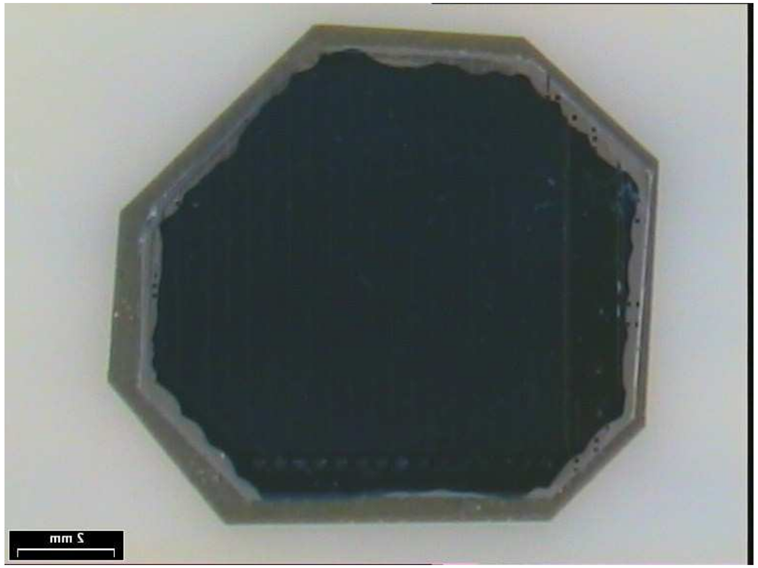


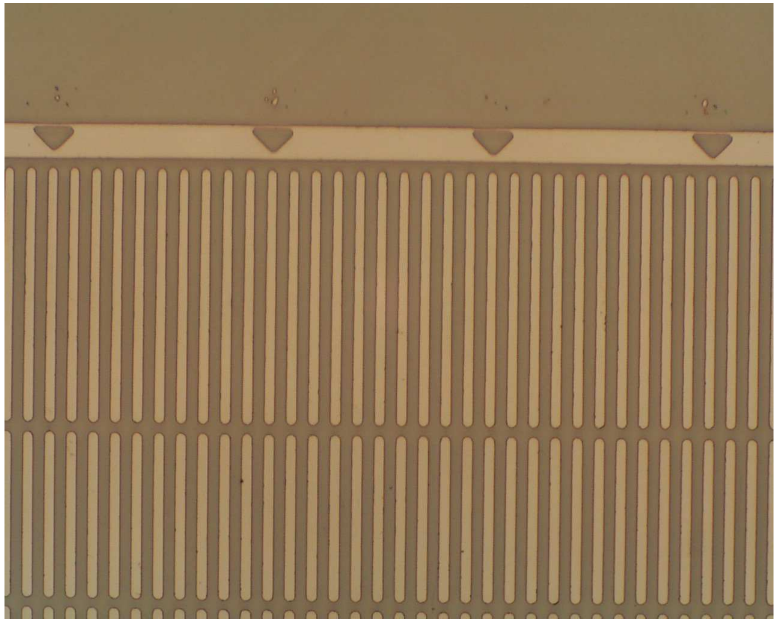
Plot contains all scintillator triggers with telescope trigger → good efficiency

Online results for correlation with telescope hits → good resolution

ATLAS Diamond Pixel Detectors

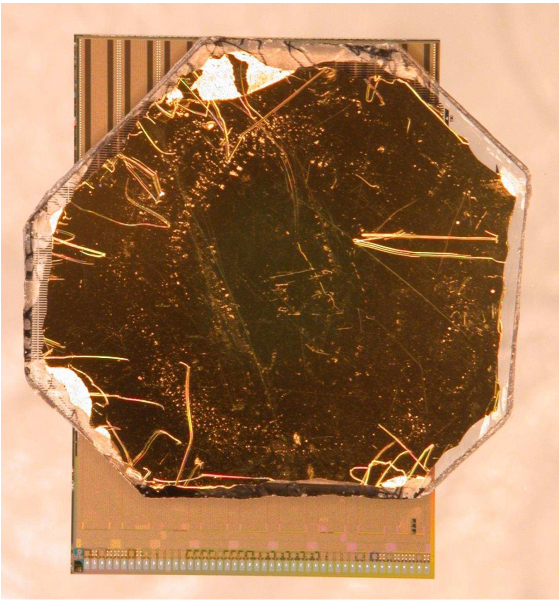
The First scCVD ATLAS diamond pixel detector

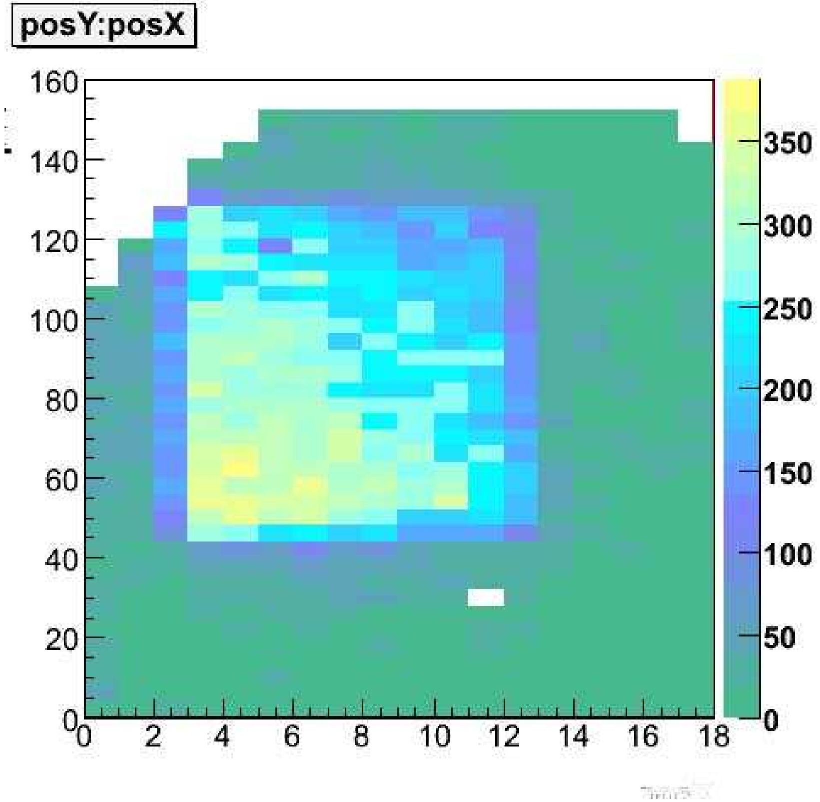




- The first device → odd shaped but looks good

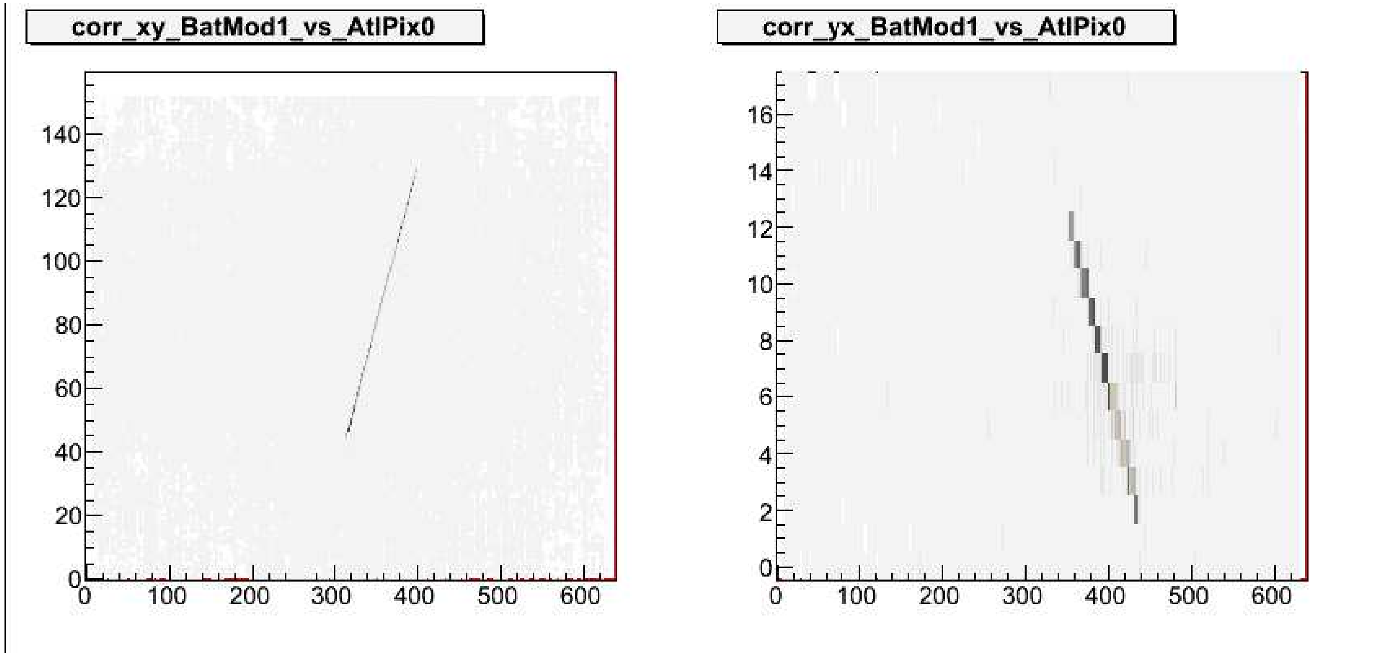
The First scCVD ATLAS diamond pixel detector





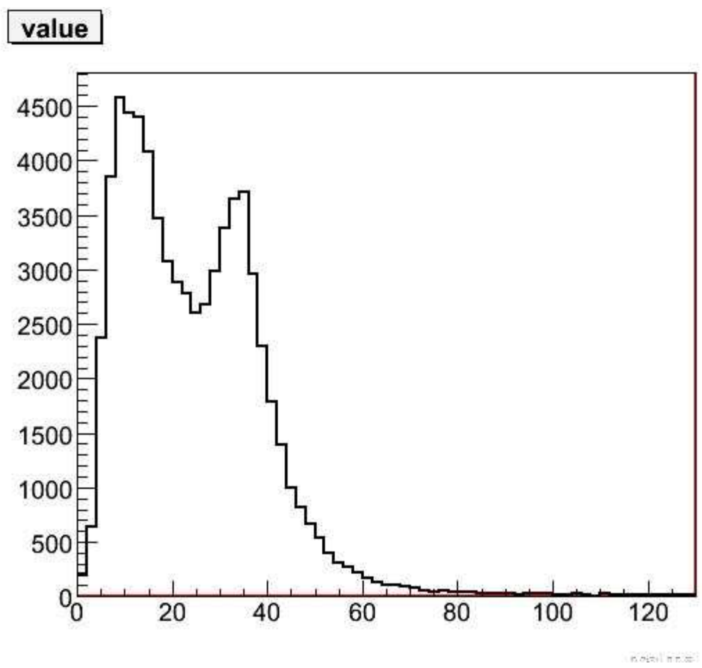
- The hitmap plotted for all scintillation triggers with trigger in telescope.
- The raw hitmap looks goods - $\sim$ 1 dead pixel

The First scCVD ATLAS diamond pixel detector - Position Correlation

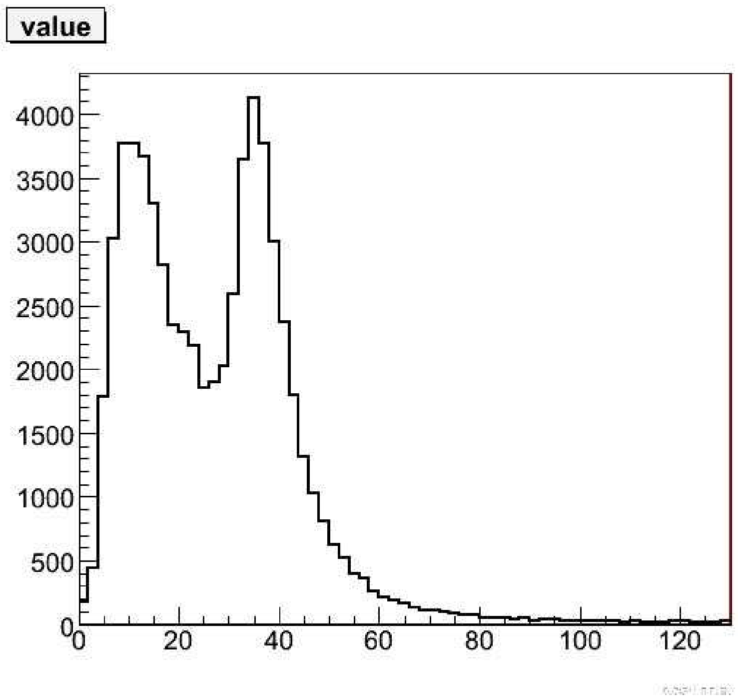


- Plot contains all scintillator triggers with "track" trigger in telescope
- The pixel detector hits correlate well with the telescope hits

The First scCVD ATLAS diamond pixel detector - Pulse Height



100V

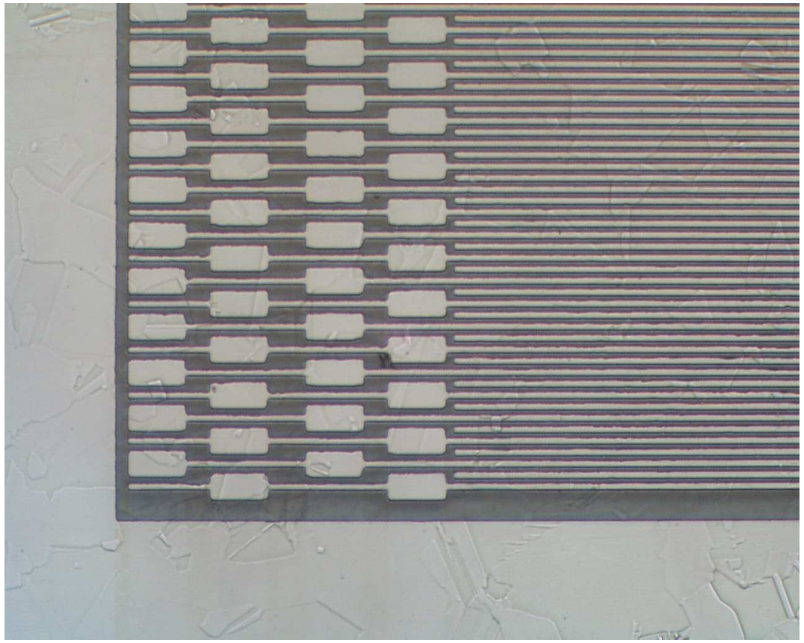


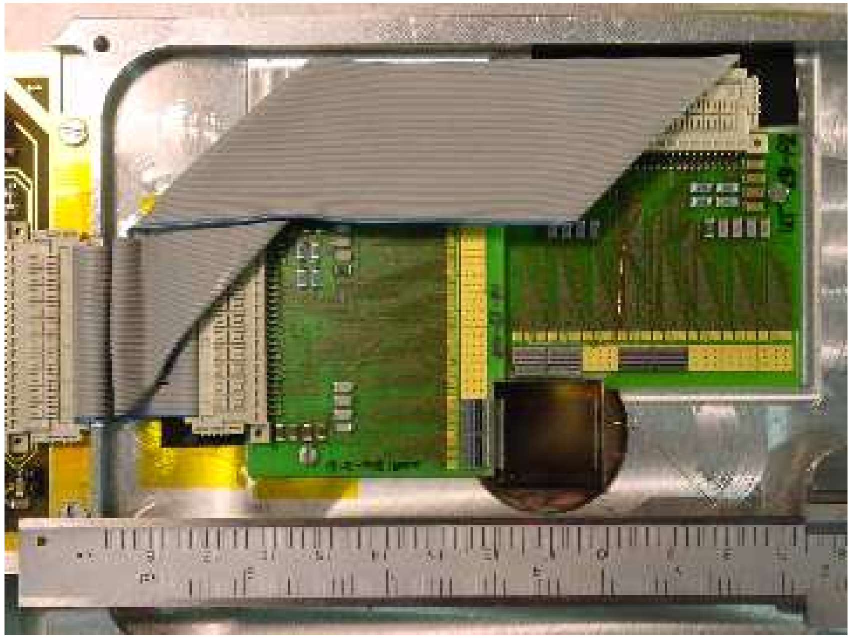
400V

- Use Time Over Threshold to get Pulse Height
- 30 TOT counts $\sim$ 10,000e
- Two peaks: single pixel hit events (higher), multi-pixel hit events (lower)

Radiation Hardness

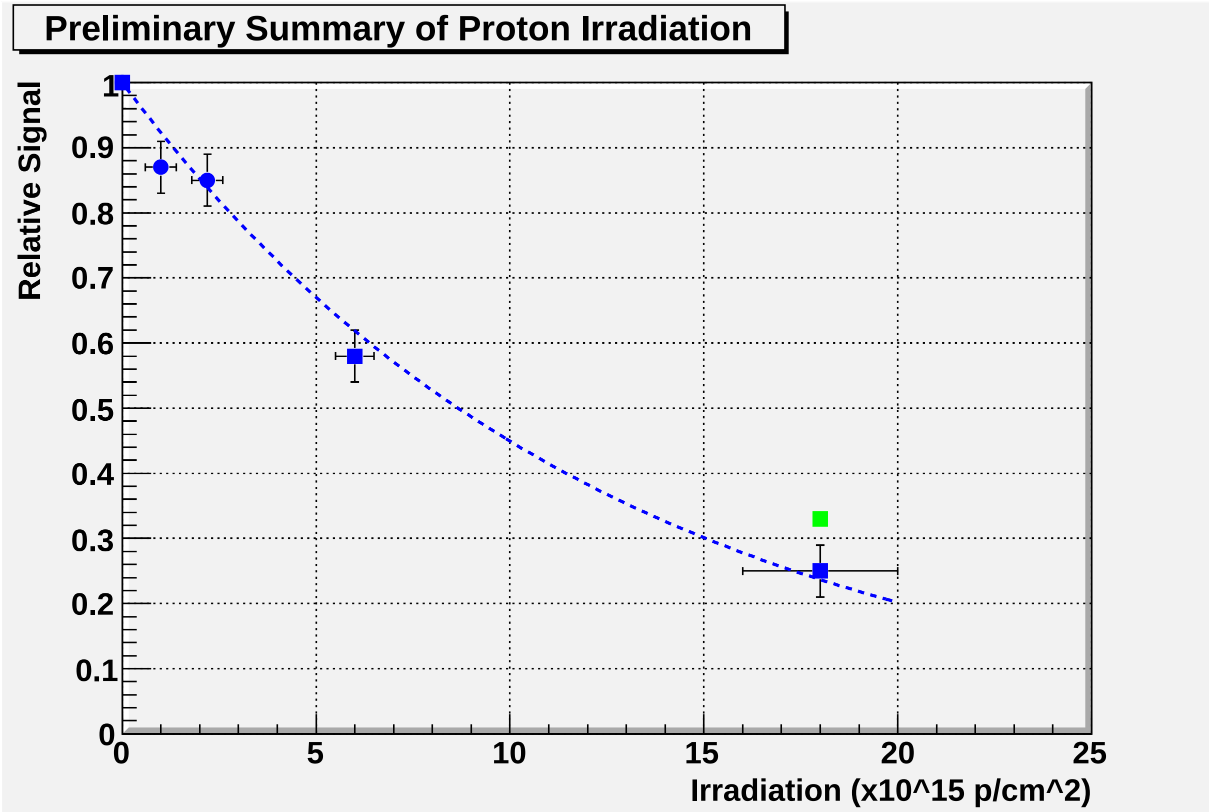
pCVD Diamond Trackers:





- Patterning the diamond → pads, strips, pixels!
- Successfully made double-sided devices; could be made basically edgeless.
- Use trackers in radiation studies - charge and position.

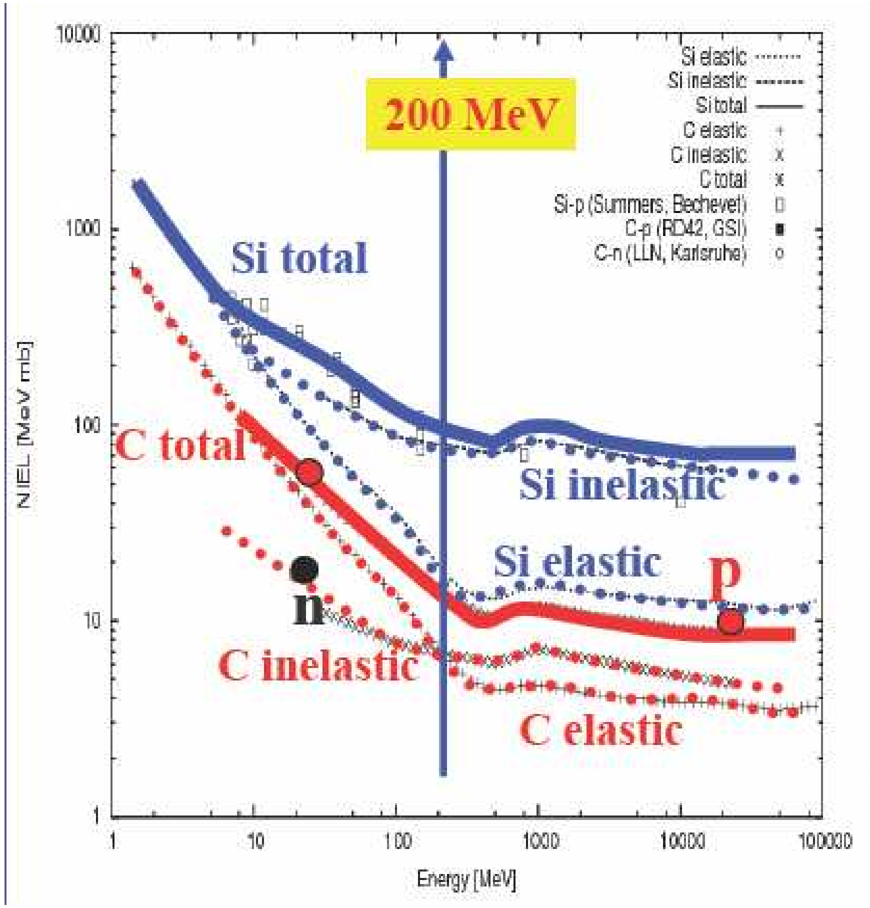
Proton Irradiation - now:



Summary of proton irradiation results for pCVD diamond at E=1V/μm and E=2V/μm (green square) after 1.8×10^{16} p/cm^2 (~500Mrad)

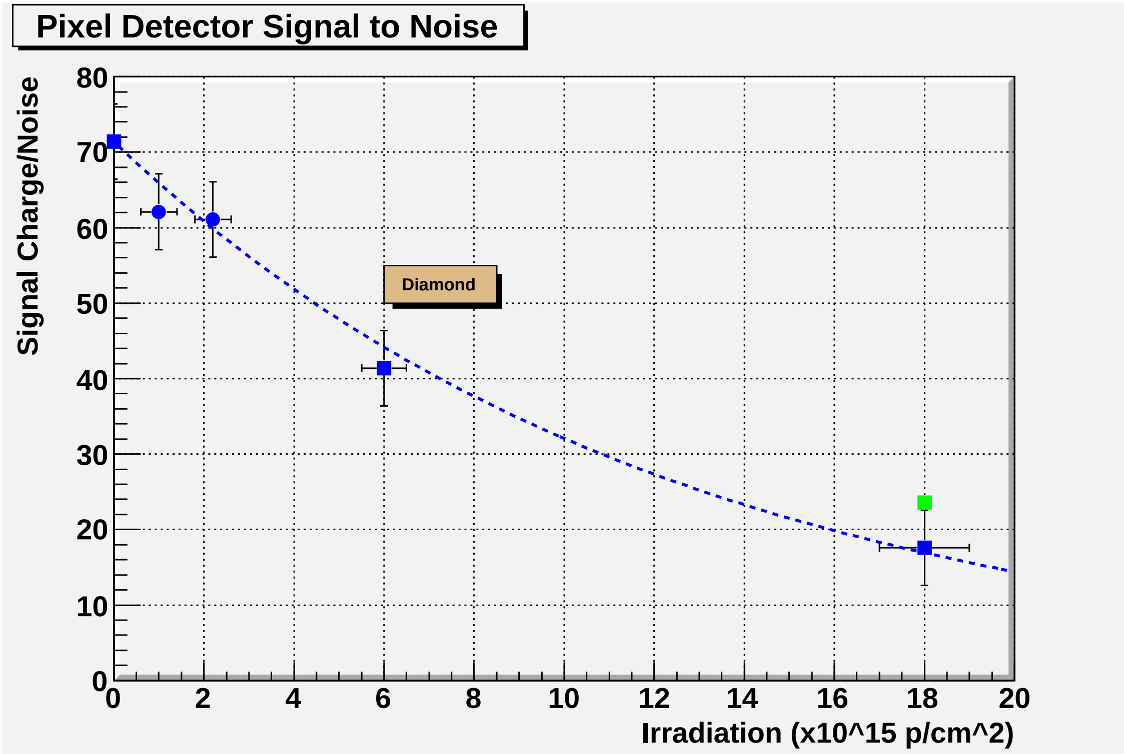
Radiation Hardness Studies with pCVD Trackers

Irradiation Results and NIEL:



- Data for Diamonds seems to follow NIEL.
- At all energies diamond more radiation hard than silicon.

Proton Irradiation - Signal Charge/Noise:



Measured in November Test Beam

- Diamond ATLAS pixel detector noise 140e (low C, low I)
- Silicon ATLAS pixel detector noise 180e
- 3D Silicon ATLAS pixel detector noise 310e
- Silicon signal larger by factor of 2 (3D data from C. Da Via-Vertex06)

Next Steps

- **Re-Test ATLAS Pixel Module at CERN**

  Done - data being looked at → Thesis

- **Irradiate scCVD and pCVD diamonds**

  pCVD to 2×10^{16} and scCVD to 2×10^{15}p/cm^2

- **Irradiate pCVD pixel modules (chip and detector)**

  Up to $\sim 10^{16}$

- **Move Metalization to Industry**

  Cleaner facilties

  Metalization and bumping done at one facility

  This should be easy ... IZM is interested

- **Produce 3-10 Modules**

  Evaluate production process

  Full measure of efficiency, noise, etc.

- **Test of Modules**

  Beam test of production modules

  Radiation hardness test of production modules

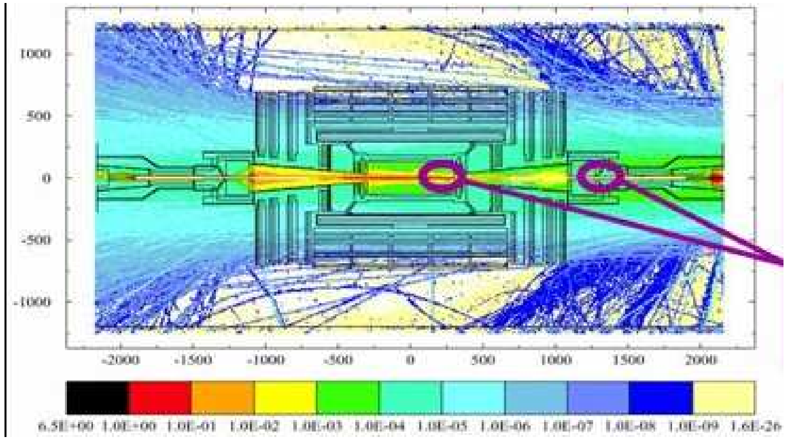
Beam Condition Monitoring

Motivation:

→ Radiation monitoring crucial for Si operation/abort system

→ Abort beams on large current spikes

→ Measure calibrated daily and integrated dose



Style:

- DC current or Slow Readout
- Requires low leakage current
- Requires small erratic dark currents
- Allows simple measuring scheme

- Examples: BaBar, Belle, CDF

- Single Particle Counting
- Requires fast readout (GHz range)
- Requires low noise
- Allows timing correlations

- Example: ATLAS

The CDF Diamond Radiation Monitors:

Photo of CDF Prototype Devices

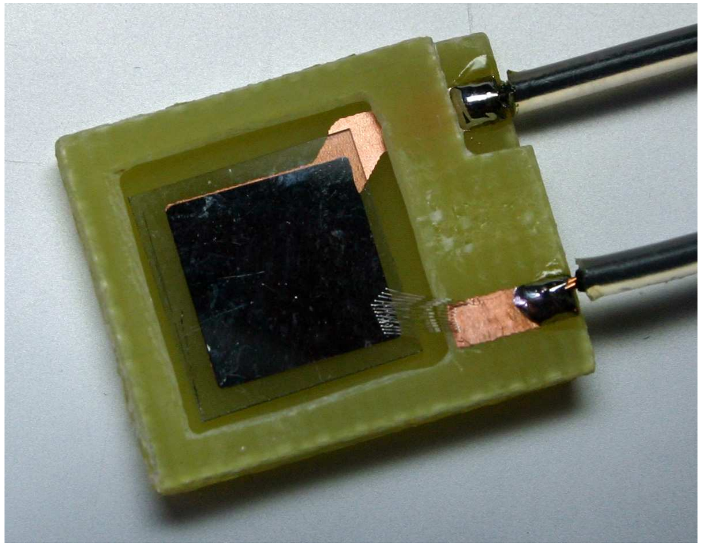
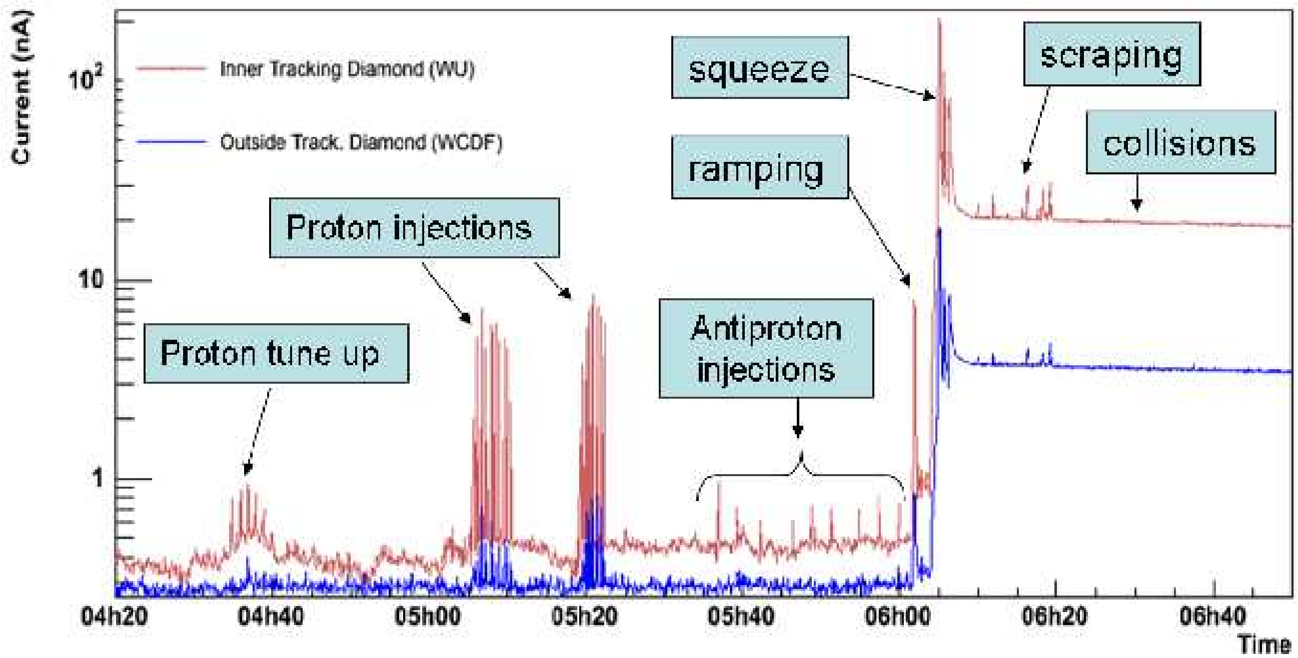


Photo of Installed CDF Device

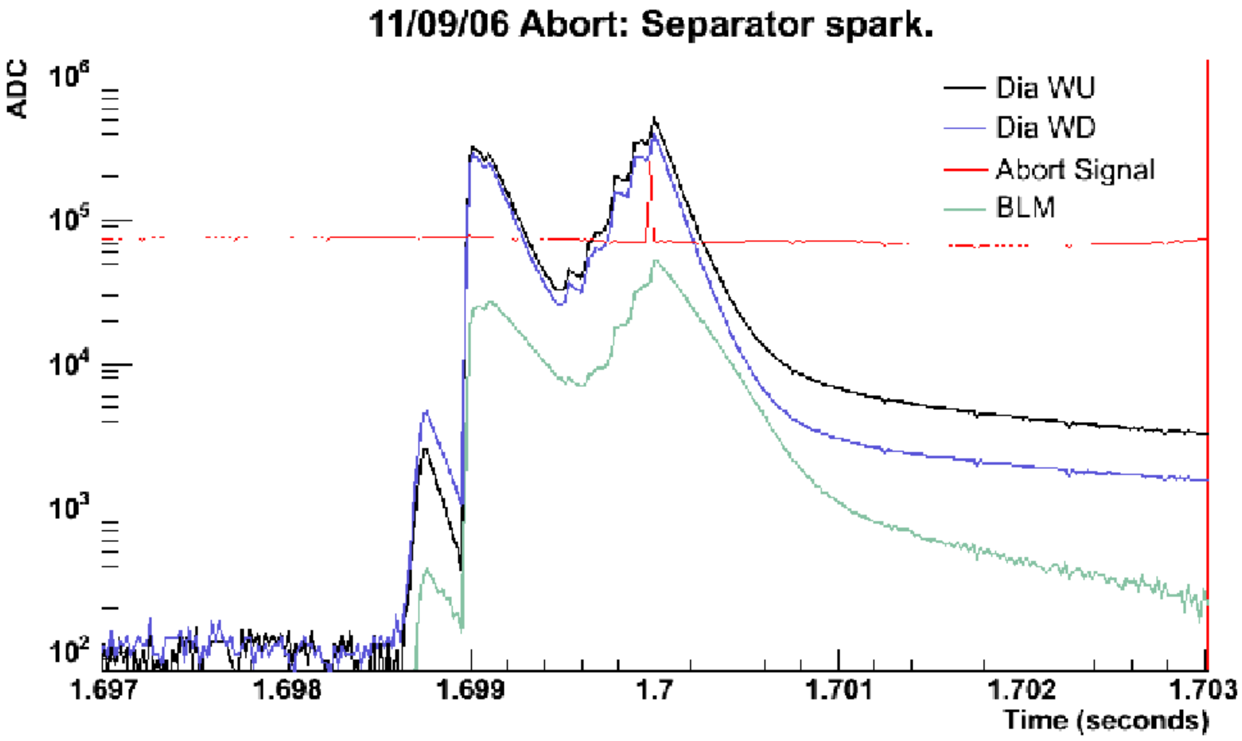
- The installed CDF device has thirteen diamonds
- Eight inside CDF - four per side
- Five outside the experiment at calibration stations near Beam Loss Monitors (BLM's)

Data Taking in CDF:



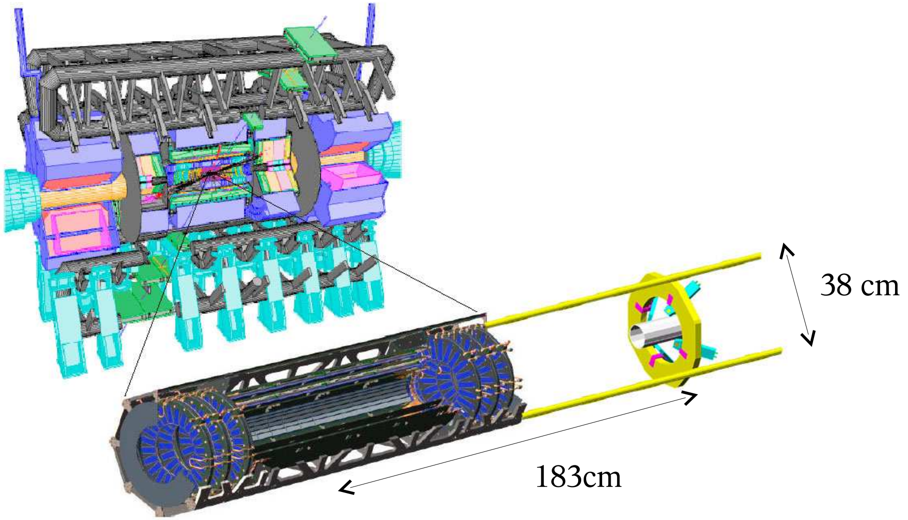
- *Two diamonds operating in CDF since Fall 2004.*
- *Full system installed - June 2006!*
- *Inside detector is the place to be by an order of magnitude!*

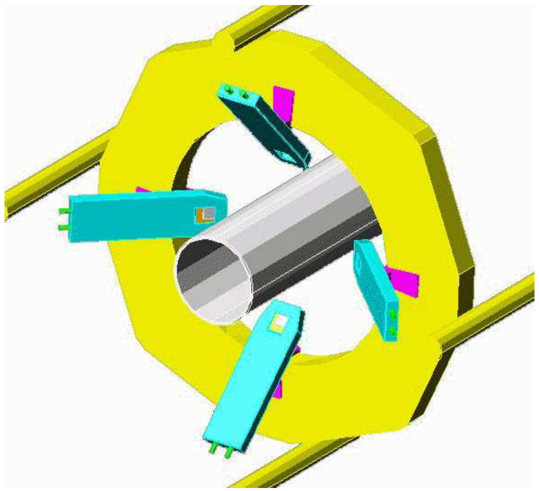
Beam Abort in CDF:

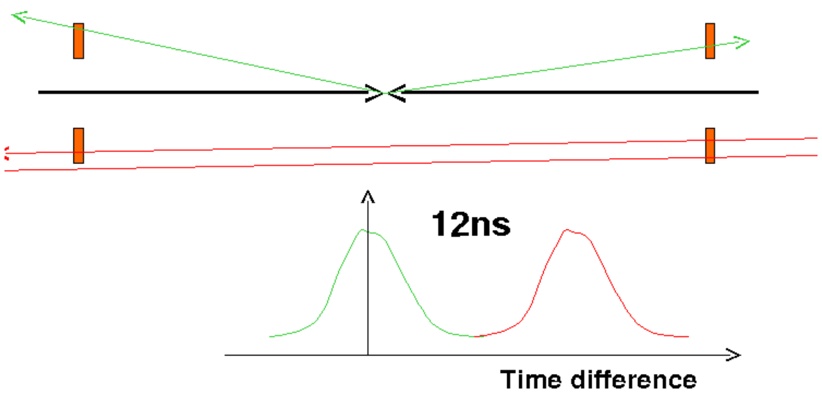


- *Both diamonds respond quicker than BLM and abort signal.*

Idea: Time of flight measurement to distinguish collisions from background

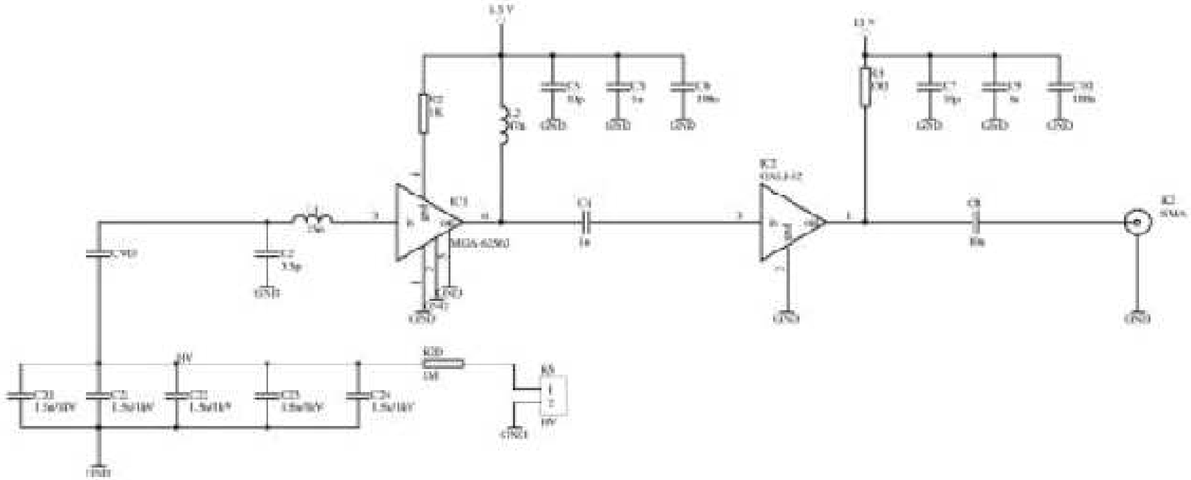


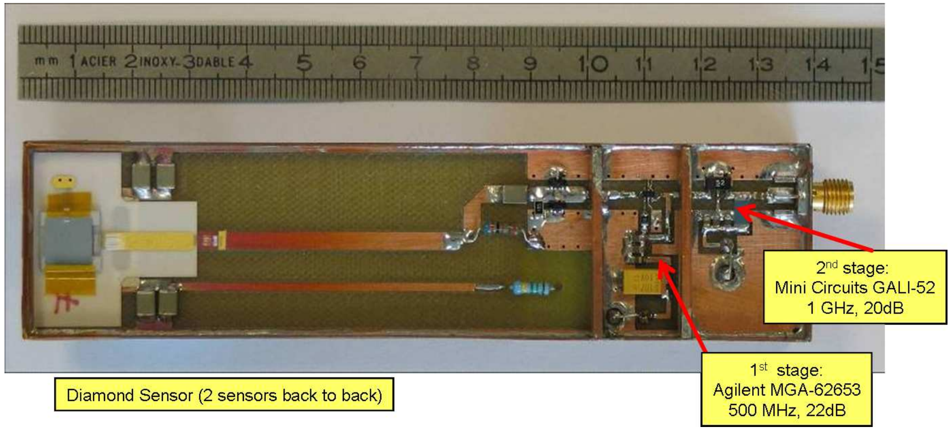


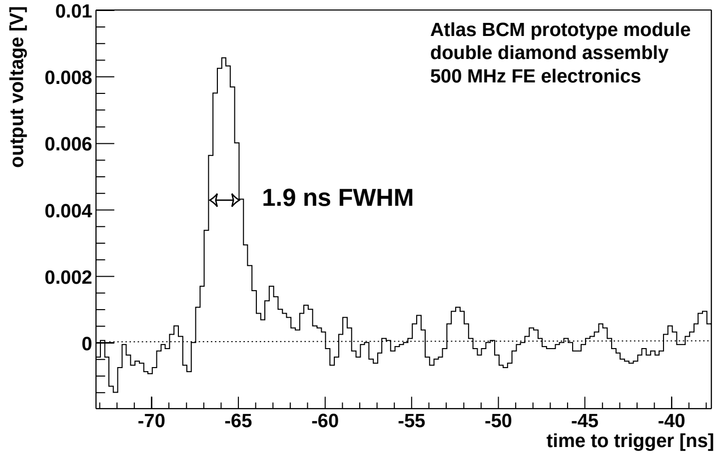


ATLAS Beam Condition Monitor

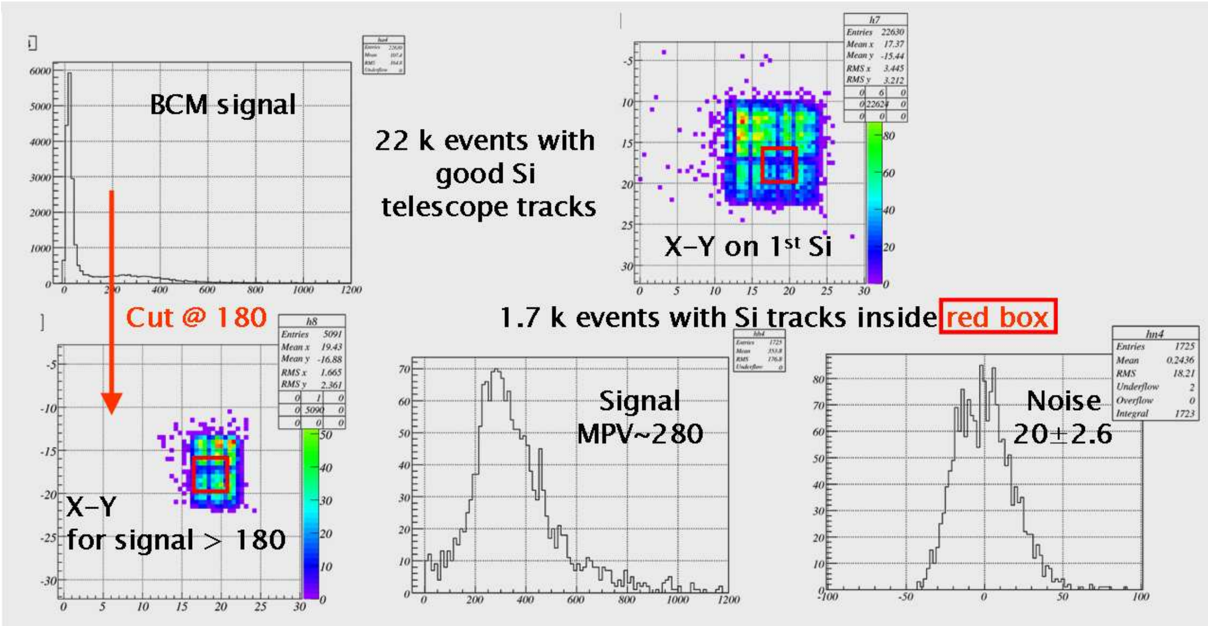
Testbeam Results:

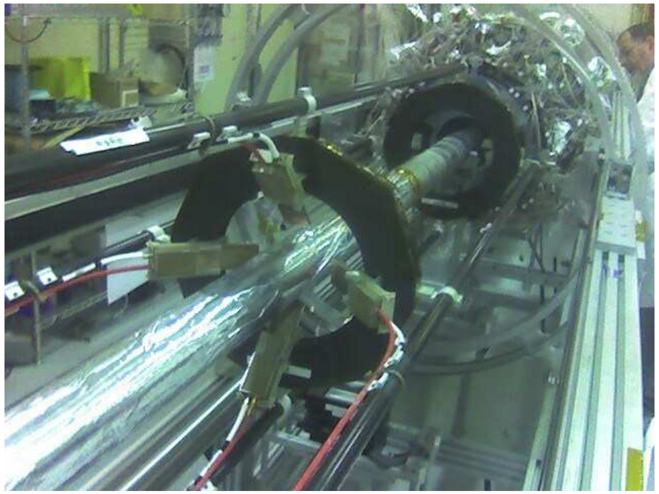


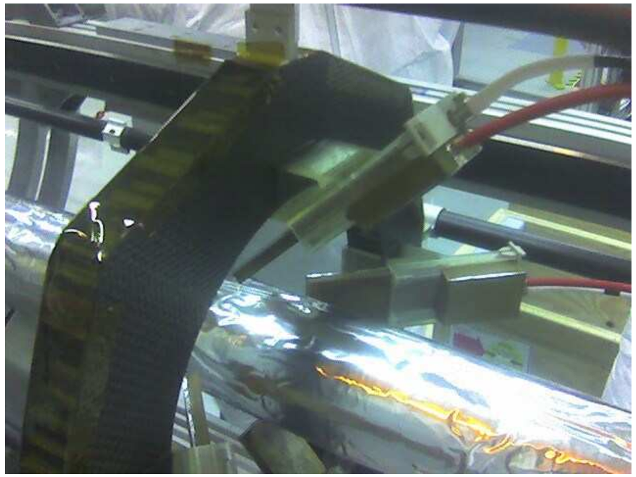




Final Testbeam Results:







Summary

- **Further Progress in Charge Collection**

  300 μm collection distance diamond attained in wafer growth

  FWHM/MP $\sim$ 0.95 – Working with manufacturers to increase uniformity

  This diamond process has been moved to production reactors

  Single Crystal diamonds look quite attractive for special applications

  Have scCVD research contract in operation until 2007

- **Radiation Hardness of Diamond Trackers**

  Using trackers allows a correlation between S/N and Resolution

  With Protons:

  - Dark current decreases with fluence
  - E=1V/μm: 15% S/N loss at 2.2×10^{15}/cm^2, 25% signal at 1.8×10^{16}/cm^2
  - E=2V/μm: 33% signal at 1.8×10^{16}/cm^2
  - Resolution improves 35% at 2.2×10^{15}/cm^2 (measured 4 yrs ago)

- **Diamond Pixel Detectors**

  Successfully tested a complete ATLAS module and scCVD module

  - Bump bonding yield $\approx$ 100 %
  - Excellent correlation between telescope and pixel data - stable operation

  Awaiting results from Nov beamtest on irradiated single chip devices

Summary

- **Beam Conditions Monitoring**

  Application of diamond successful in BaBar, CDF

  ATLAS diamond BCM installed in January 2007

Significant progress in the last year

- # RD42 Request to CERN/LHCC

  RD42 is supported by many national agencies:

  → continuation of official recognition by CERN critical

  → 50kCHF from CERN/ 150kCHF from outside CERN

  RD42 requires access to CERN facilities:

  → maintain the present 20 m^2 of lab space (test setups, detector prep, ...)

  → maintain present office space

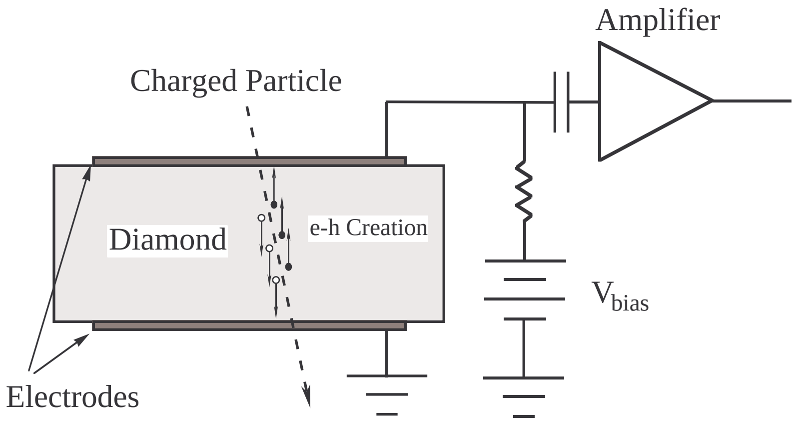
Proposed Research for RD42

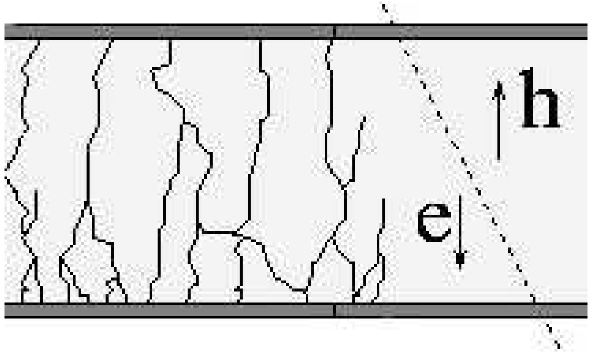
- **Radiation Hardness of Diamond Trackers and Pixel Detectors**
  - Continue tracker irradiations in the next year, add pixel irradiations
  - Use pCVD and scCVD
- **Pixel Detector Modules**
  - Transfer technology to industry (IZM).
  - Construct two additional modules.
- **Beam Tests with Diamond Trackers and Pixel Detectors**
  - Complete test of ATLAS diamond pixel modules
  - Irradiation of one ATLAS diamond pixel module
- **Diamond Characterization**
  - Continue research program to improve material in progress:
    - collection distance $\rightarrow$ 325μm ($\bar{Q} = 11,700e$)
    - $\rightarrow$ improved uniformity
    - $\rightarrow$ identification of trapping centers
    - compare scCVD with pCVD

Additional Transparencies

Characterization of Diamond:

Signal formation





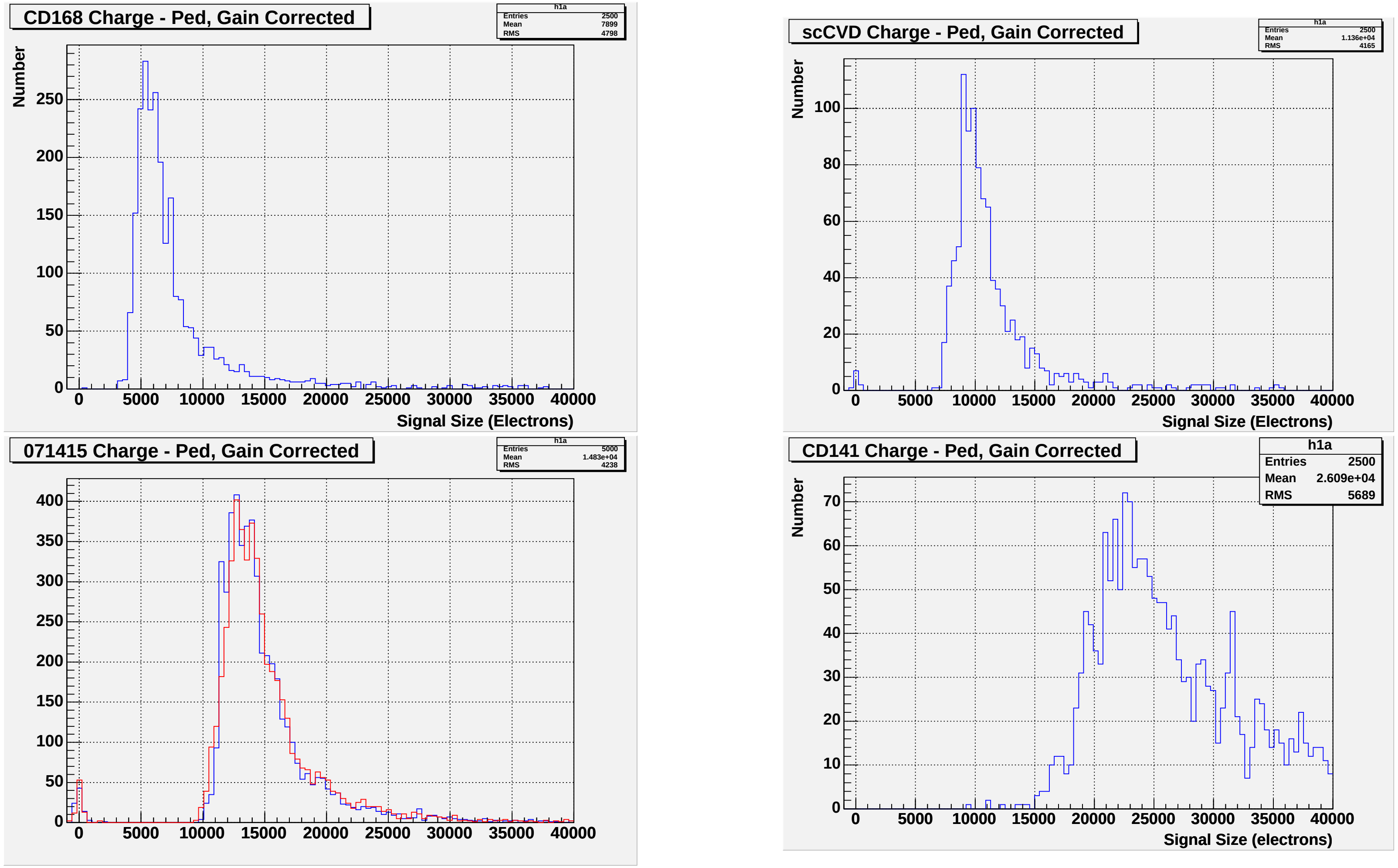
- $Q = \frac{d}{t} Q_0$ where d = collection distance = distance e-h pair move apart
- $d = (\mu_e \tau_e + \mu_h \tau_h) E$
- $d = \mu E \tau$

  with $\mu = \mu_e + \mu_h$

  and $\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$

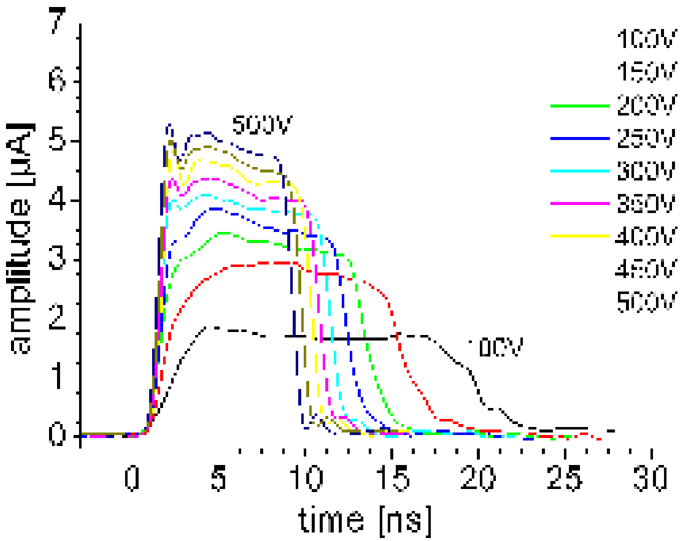
Properties - Single Crystal CVD Diamond

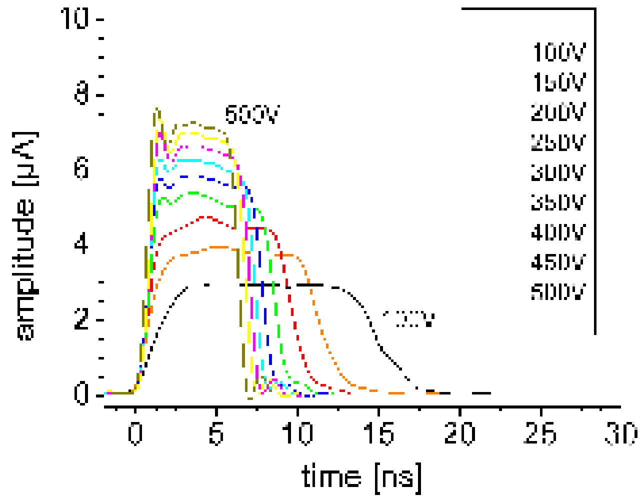
scCVD Diamond Measured with a ^{90}Sr Source:



Pulse height spectrum of various scCVD diamonds (t=210, 320, 435, 685 μm)

Drift Velocity and Lifetime:





- Average drift velocity for electrons and holes: $v_{e,h} = d/t_c$
- Extract μ_0 and saturation velocity: $v = \frac{\mu_0 E}{1+\mu_0 E/v_s}$
- For this sample

  $\mu_{0_e} = 1714$ cm^2/Vs $\quad v_{s_e} = 0.96 \times 10^7$ cm/s = 96 km/s

  $\mu_{0_h} = 2064$ cm^2/Vs $\quad v_{s_h} = 1.41 \times 10^7$ cm/s = 141 km/s
- From the drift velocity deduce the lifetimes > 35 ns $\rightarrow >>$ transit time so charge trapping not the issue