Radiation Hardness Studies of Polycrystalline & Single-crystal Chemical Vapor Deposition Diamond for High Luminosity Tracking Detectors

Harris Kagan
Ohio State University

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Outline of the Talk

- **Introduction**
- **Radiation Hardness Studies with Trackers**
- **Diamond Pixel Modules**
- **Plans**
- **Summary**

The RD42 Collaboration

D. Asner[22], M. Barbero[1], V. Bellini[2], V. Belyaev[15], E. Berdermann[8], P. Bergonzo[14], M. Bruzzi[5], V. Cindro[12], G. Claus[10], S. Chatterji[22], M. Cristinziani[1], S. Costa[2], R. D'Alessandro[6], W. de Boer[13], I. Dolenc[12], P. Dong[20], W. Dulinski[10], V. Eremin[9], R. Eusebi[7], F. Fizzotti[18], H. Frais-Kölbl[4], A. Furgeri[13], K.K. Gan[16], M. Goffe[10], J. Goldstein[21], A. Golubev[11], A. Gorišek[12], E. Griesmayer[4], E. Grigoriev[11], F. Hügging[1], H. Kagan[16,◇], R. Kass[16], G. Kramberger[12], S. Kuleshov[11], S. Lagomarsino[6], A. Lo Giudice[18], I. Mandic[12], C. Manfredotti[18], C. Manfredotti[18], A. Martemyanov[11], M. Mathes[1], D. Menichelli[5], S. Miglio[5], M. Mikuž[12], M. Mishina[7], S. Mueller[13], P. Olivero[18], G. Parrini[6], H. Pernegger[3], M. Pomorski[8], R. Potenza[2], S. Roe[3], M. Scaringella[5], D. Schaffner[20], C. Schmidt[8], S. Schnetzer[17], T. Schreiner[4], S. Sciortino[6], S. Smith[16], R. Stone[17], C. Sutera[2], M. Traeger[8], W. Trischuk[19], C. Tuve[2], J. Velthuis[21], E. Vittone[18], R. Wallny[20], P. Weilhammer[3,◇], N. Wermes[1]

◇ Spokespersons

[1] Universität Bonn, Bonn, Germany
[2] INFN/University of Catania, Italy
[3] CERN, Geneva, Switzerland
[4] Fachhochschule für Wirtschaft und Technik, Wiener Neustadt, Austria
[5] INFN/University of Florence, Florence, Italy
[6] Department of Energetics/INFN Florence, Florence, Italy
[7] FNAL, Batavia, U.S.A.
[8] GSI, Darmstadt, Germany
[9] Ioffe Institute, St. Petersburg, Russia
[10] IPHC, Strasbourg, France
[11] ITEP, Moscow, Russia
[12] Jožef Stefan Institute, Ljubljana, Slovenia
[13] Universität Karlsruhe, Karlsruhe, Germany
[14] CEA-LIST Technologies Avancees), Saclay, Gif-Sur-Yvette, France
[15] MEPHI Institute, Moscow, Russia
[16] The Ohio State University, Columbus, OH, U.S.A.
[17] Rutgers University, Piscataway, NJ, U.S.A.
[18] University of Torino, Italy
[19] University of Toronto, Toronto, ON, Canada
[20] UCLA, Los Angeles, CA, USA
[21] University of Bristol, Bristol, UK
[22] Carleton University, Carleton, Canada

68 Participants

22 Institutes

Motivation

- 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
- Disadvantage: Smaller signal

Priorities (ATU-RD-MN-0012):

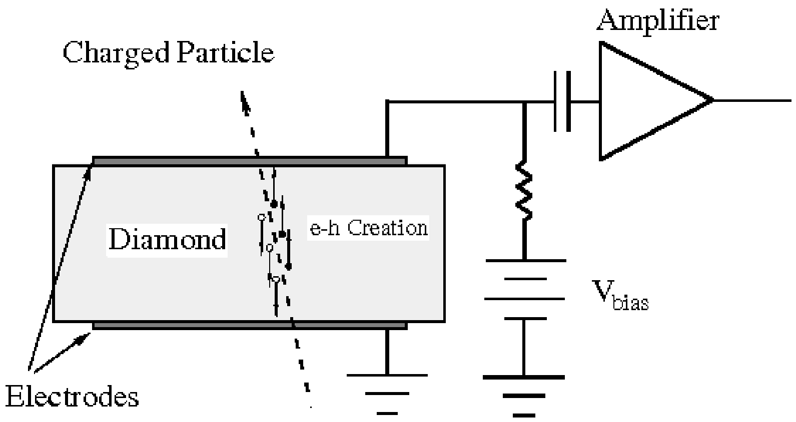
- Radiation hardness tests of the highest quality pCVD and scCVD diamond
- Beam tests results to characterize quality
- Development of new manufacters
- Module preparation

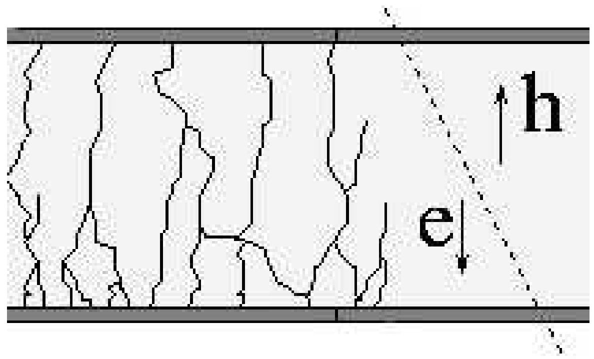
These points will be addressed in this talk.

- *See also:* F. Hügging poster at this meeting
- *Reference* → http://rd42.web.cern.ch/RD42

Characterization of Diamond:

Signal formation





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

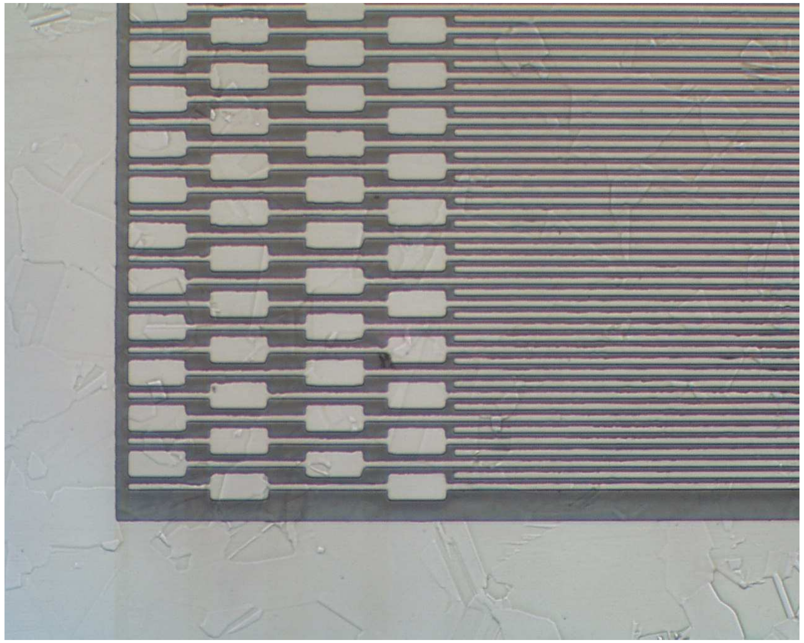
  with $\mu = \mu_e + \mu_h$

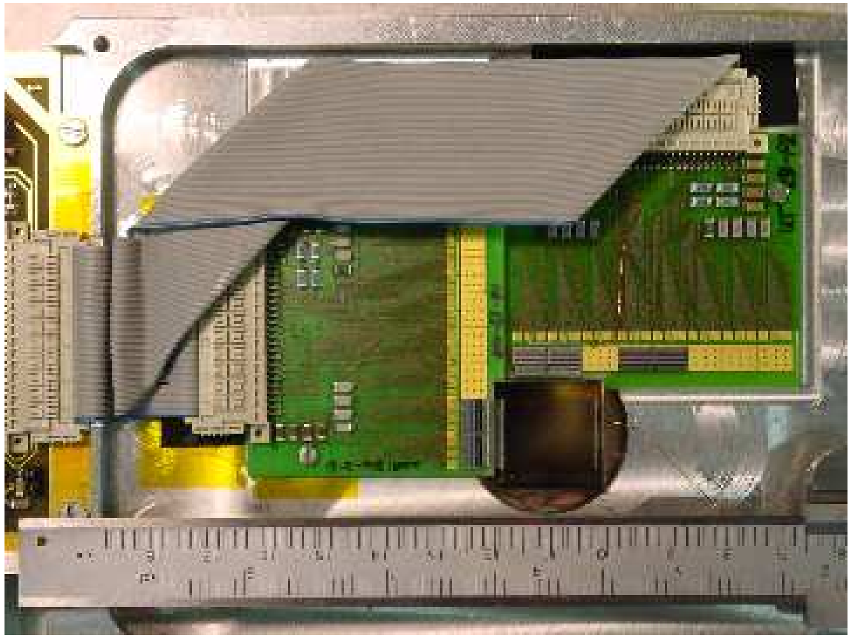
  and $\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$

Radiation Hardness

- binding energy
- displacement energy
- elastic, inelastic, total cross section

pCVD Diamond Trackers:

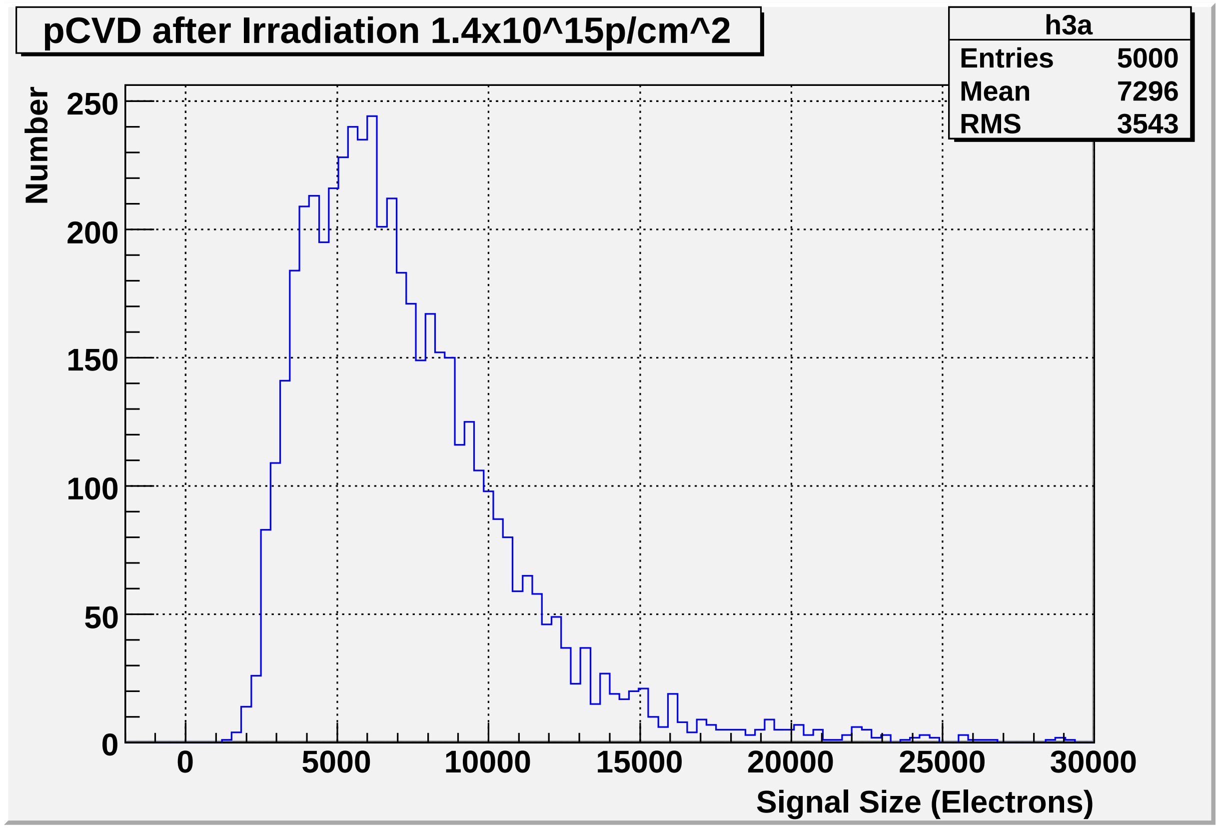




- Patterning the diamond $\longrightarrow$ pads, strips, pixels!
- Successfully made double-sided devices; could be made basically edgeless.
- Use trackers (strip and pixel) in radiation studies - charge and position.

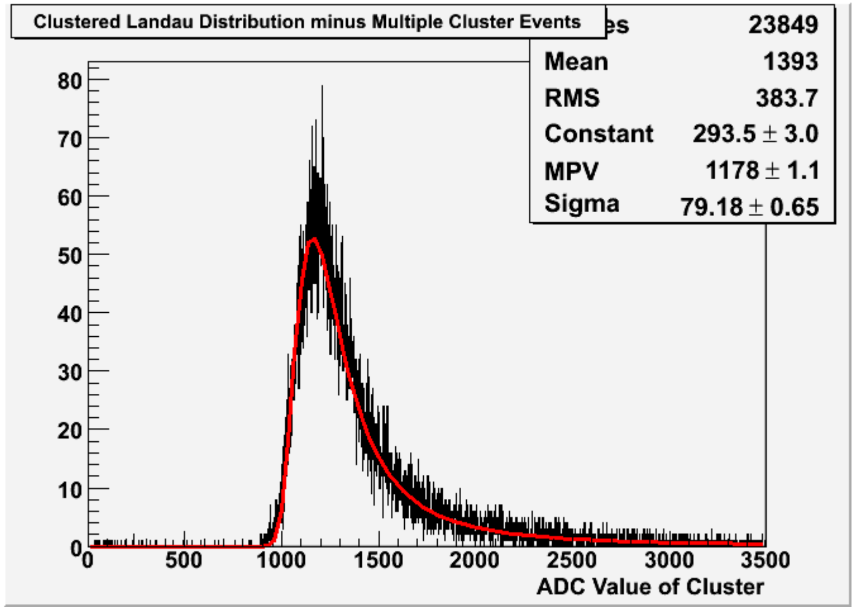
pCVD Diamond After Irradiation

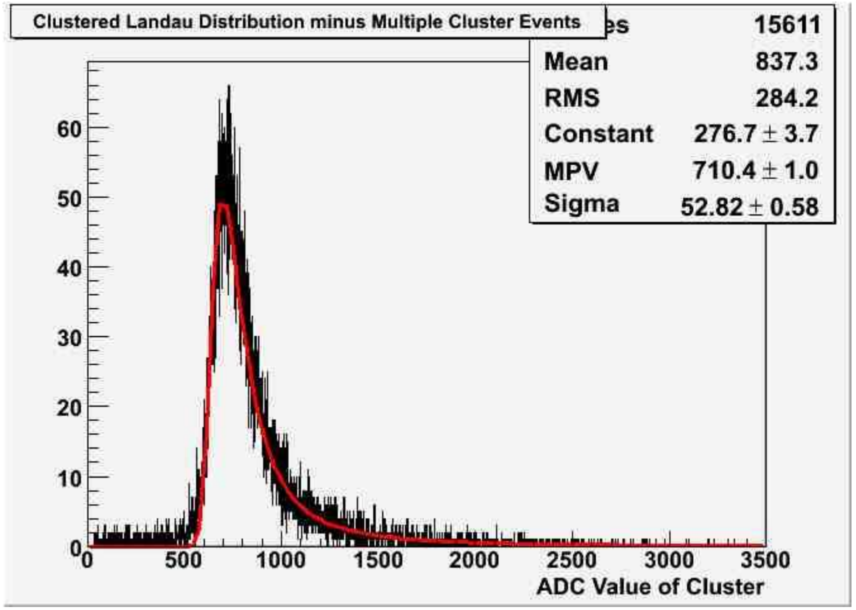
Polycrystalline CVD (pCVD) Diamond irradiated to 1.4x10^{15}p/cm^2



- Application is pixel detectors
- In-time thresholds are $\sim$ threshold (1450e) plus overdrive (800e)
- PH distributions after 1.4x10^{15}p/cm^2 $\rightarrow \epsilon > 99\%$.

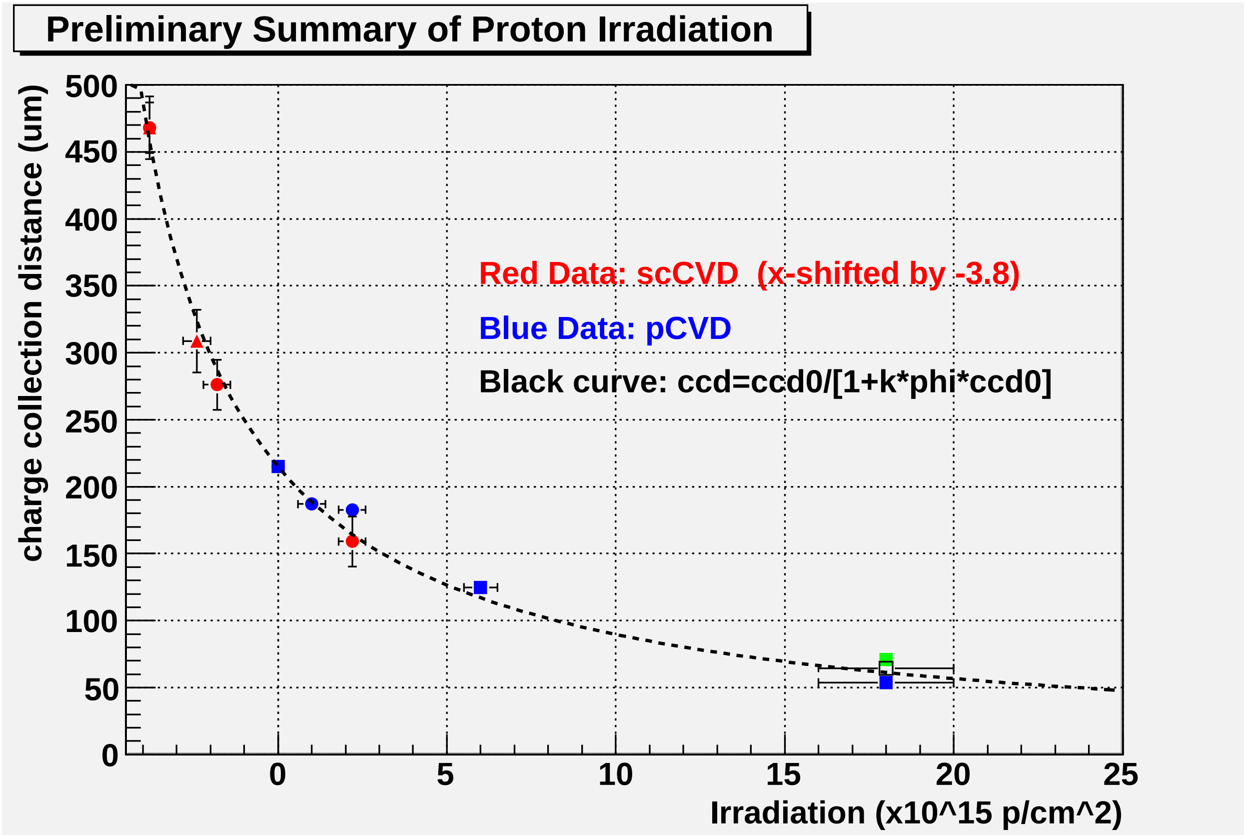
Single Crystal CVD (scCVD) Diamond irradiated to 1.5x10^{15} p/cm^2





- PH distributions look narrow before and after irradiation
- In-time thresholds are $\sim$ threshold(1500e) + overdrive(800e)
- PH distributions after 1.5x10^{15}p/cm^2 $\rightarrow \epsilon > 99\%$.

Proton Irradiation Summary - preliminary:



Preliminary summary of proton irradiation results for pCVD (blue) and scCVD diamond (red) at E=1V/μm up to 1.8×10^{16} p/cm^2 ($\sim$500Mrad).

pCVD and scCVD diamond follow the same damage curve:

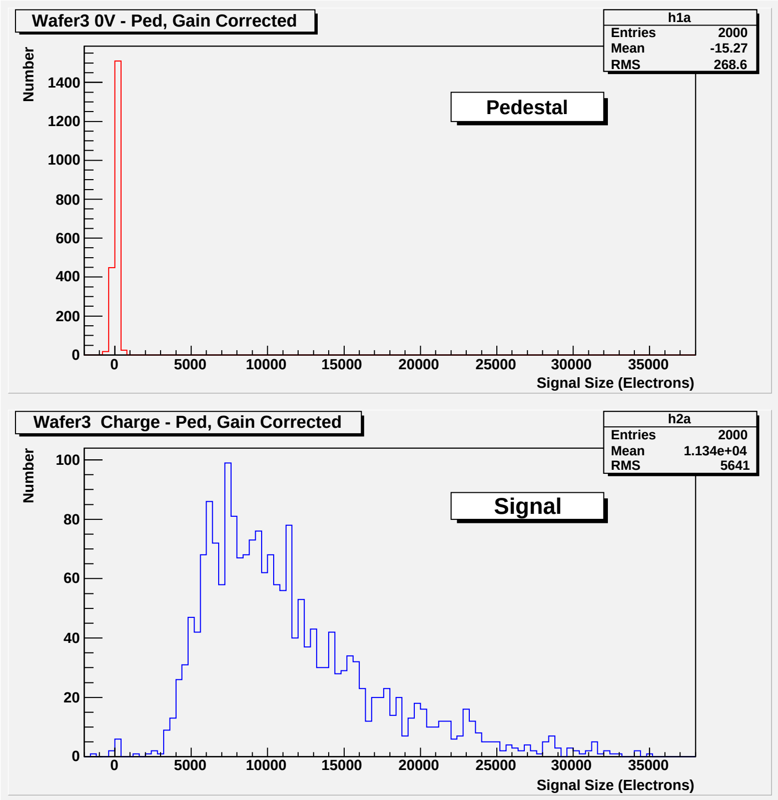
$$1/\text{ccd} = 1/\text{ccd}_0 + \text{k}\ \phi.$$

CVD Diamond Material Status

- collection distance
- polycrystalline, single crystal
- new manufacturers

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

- Contacts on both sides - structures from μm to cm
- Usually operate at E=1-2V/μm
- Test Procedure: dot $\longrightarrow$ strip $\longrightarrow$ pixel on same diamond!

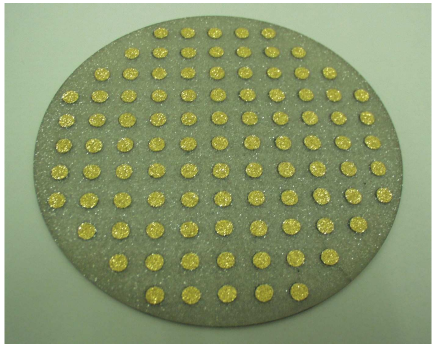
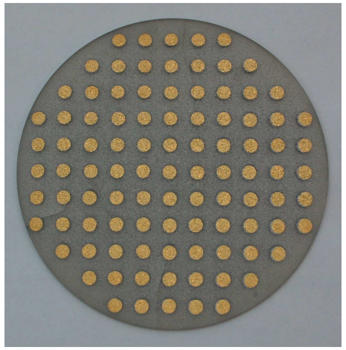


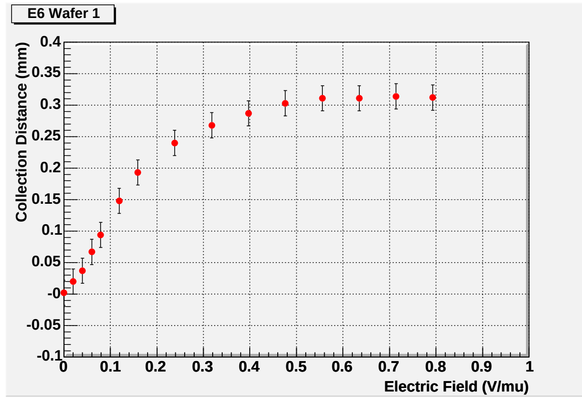
- Q_{MP} = 8500-9000e
- Mean Charge = 11300e

- Source data well separated from 0
- Collection Distance now $\approx$ 300μm
- Most Probable Charge now $\approx$ 9000e
- 99% of PH distribution above 4000e
- FWHM/MP $\approx$ 0.95 — Si has $\approx$ 0.5
- Four wafers grown with this quality; two in progress

Material Status - pCVD Diamond

Recent Polycrystalline CVD Diamond



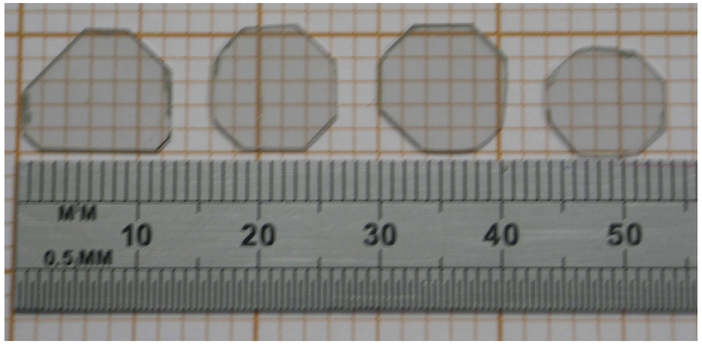
Left: Recent pCVD wafers ready for test - Cr/Au dots are 1 cm apart
Right: Collection distance from a dot in the pCVD wafer

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

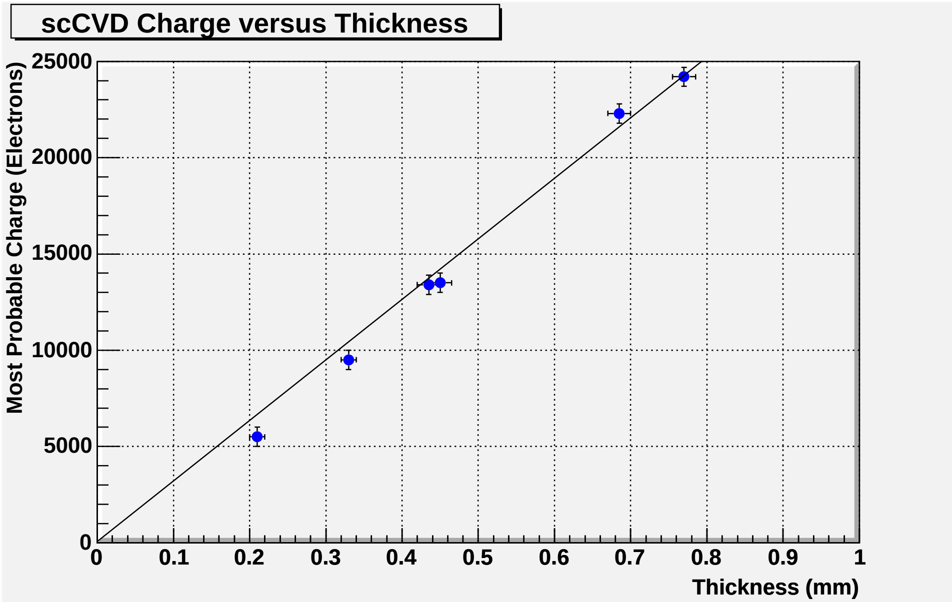
Wafer collection distance now typically 250μm (edge) to 310μm (center).

Material Status - Single Crystal CVD Diamond

Recent Single Crystal CVD Diamond



scCVD Diamond Most Probable Charge versus Thickness

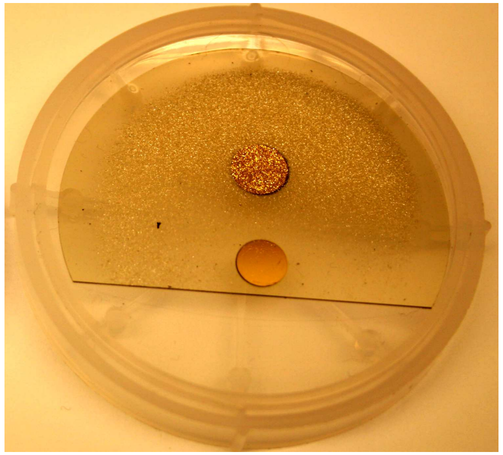


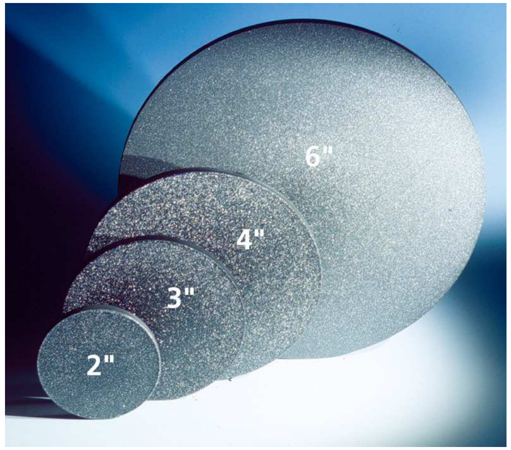
- High quality scCVD diamond can collect full charge for thickness 880μm

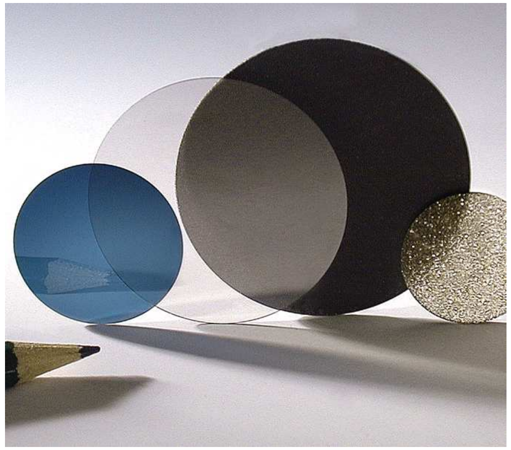
New Manufacturers Developing Detector Grade Diamond

Status:

RD42 has begun working with two companies (Germany, US) to develop detector grade diamond material





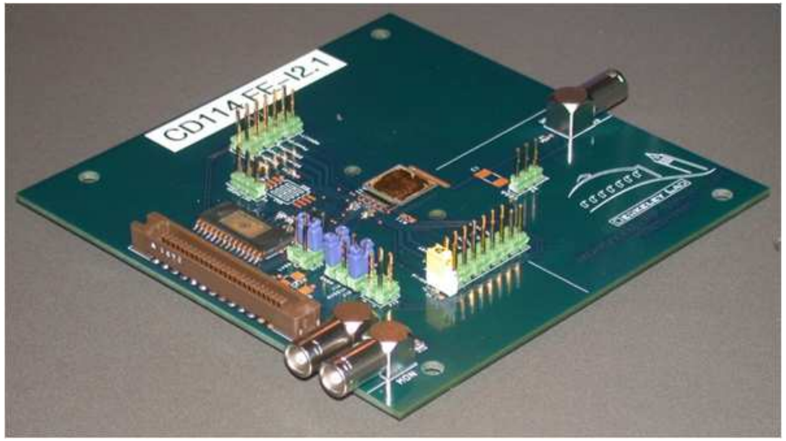


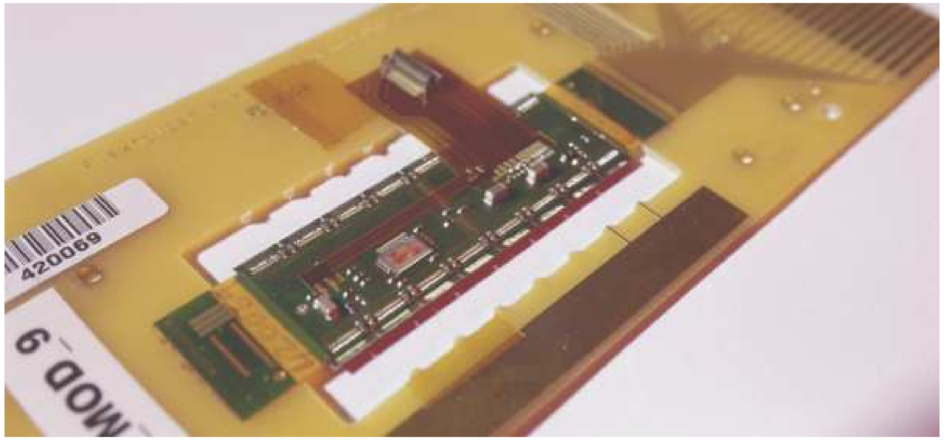
- First samples from companies show charge collection distance $\sim 100 \mu m$

pCVD and scCVD Pixel Detectors

- signal
- noise, threshold, overdrive
- charge sharing, signal over threshold

ATLAS diamond pixel modules



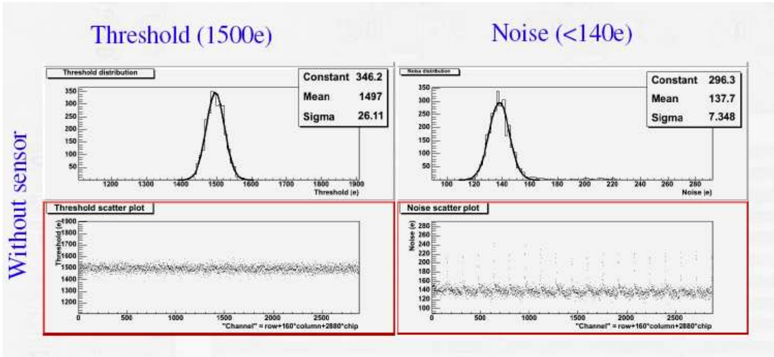


- Single chip and full modules bump-bonded at IZM (Berlin), constructed and tested in Bonn
- Operating parameters (FE-I3): Peaking Time 22ns, Noise 140e,Threshold 1450-1550e, Threshold Spread 25e, Overdrive 800e

ATLAS Diamond Pixel Detectors

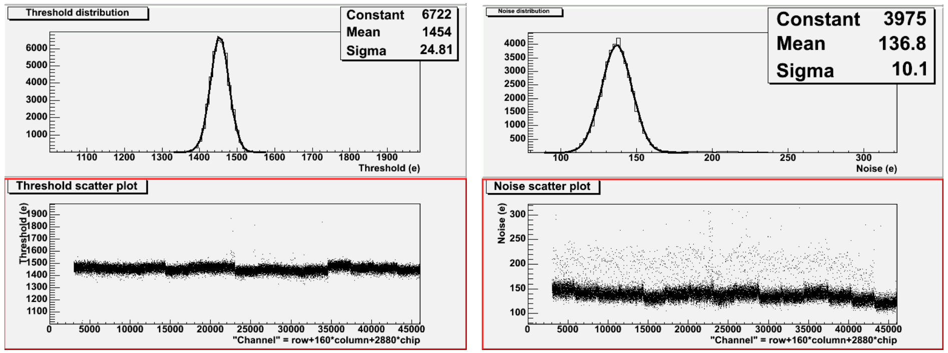
The ATLAS pixel module - Noise, Threshold

Bare Chips

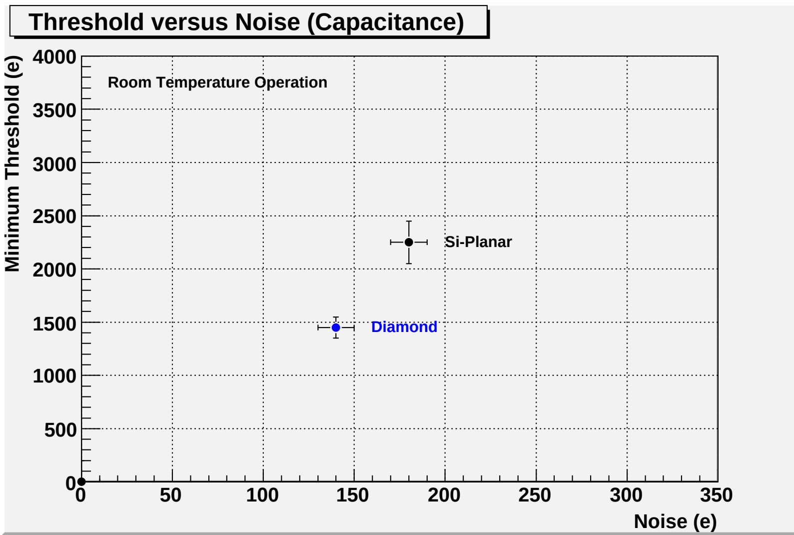


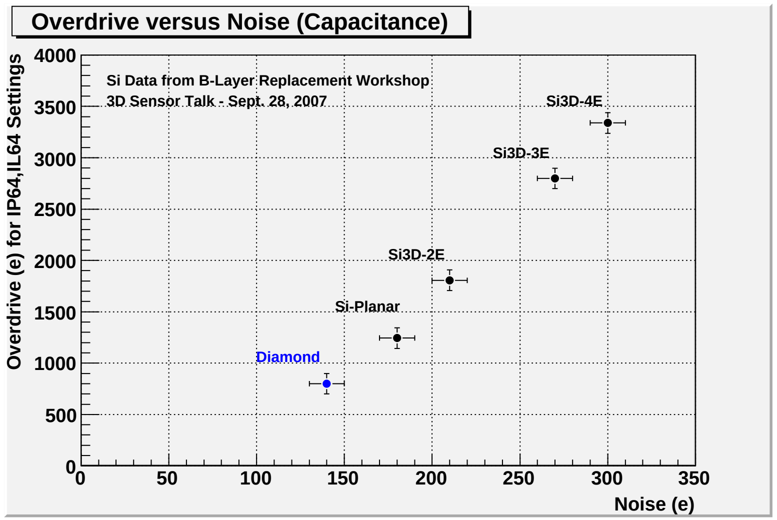
Noise $\sim 140e$, Mean Threshold $1500e$, Threshold Spread $\sim 25e$.

with Diamond Detector

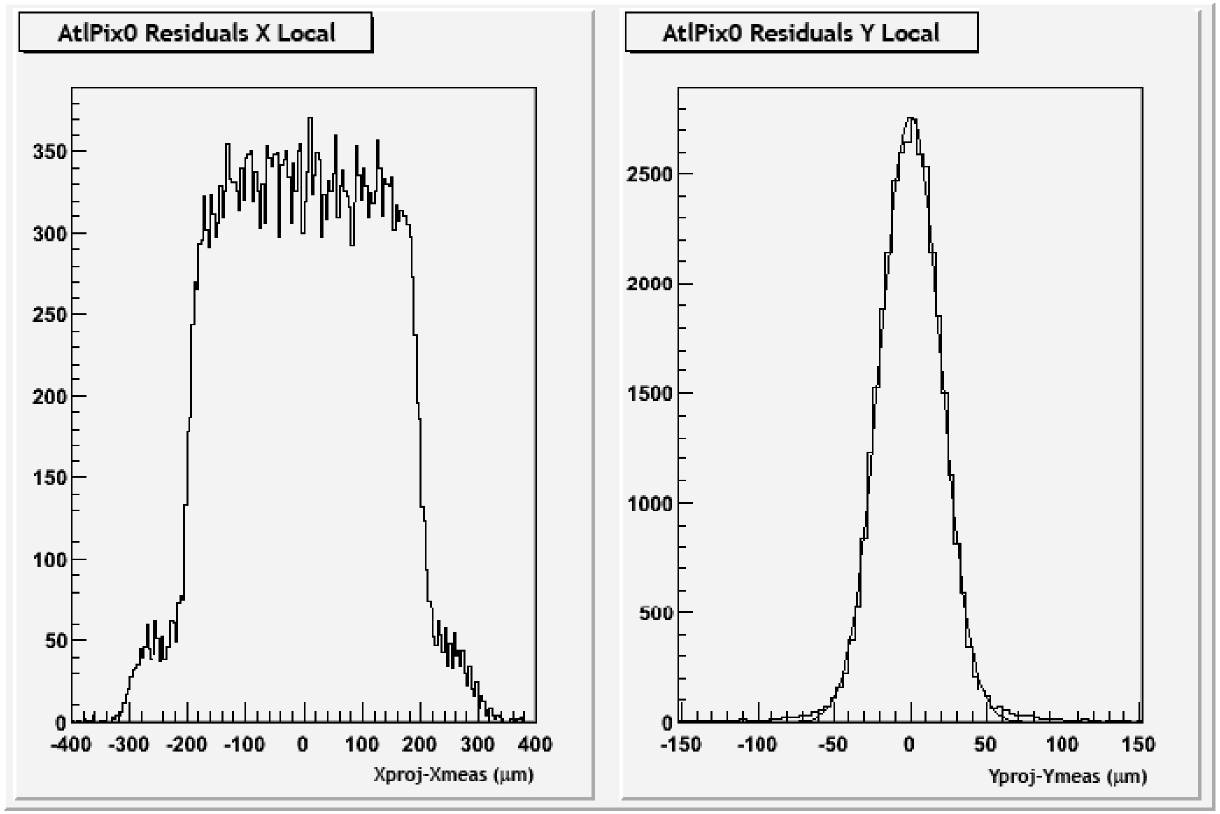


Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$.



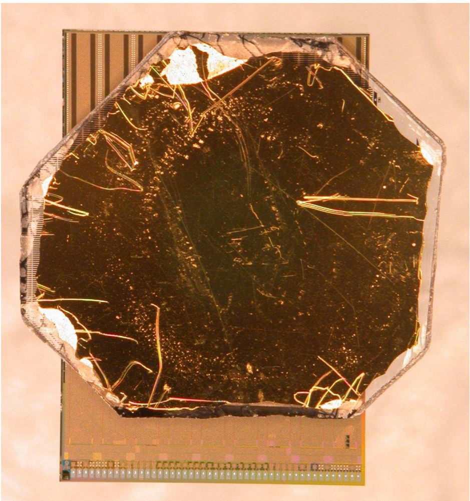


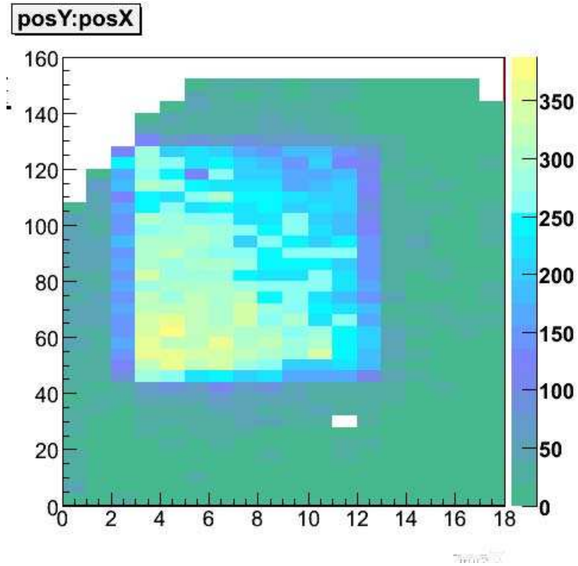
The full ATLAS diamond pixel module - Resolution

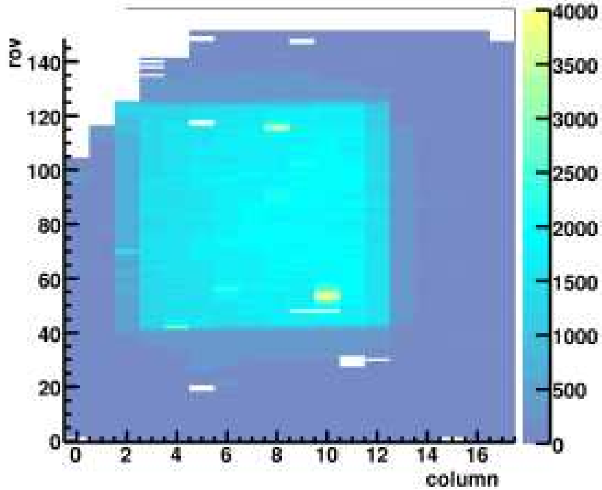


- Excellent correlation with telescope
- Residual $\sim 18\mu$m - remove telescope tracking contribution $\rightarrow 14\mu$m.

The First scCVD ATLAS diamond pixel detector

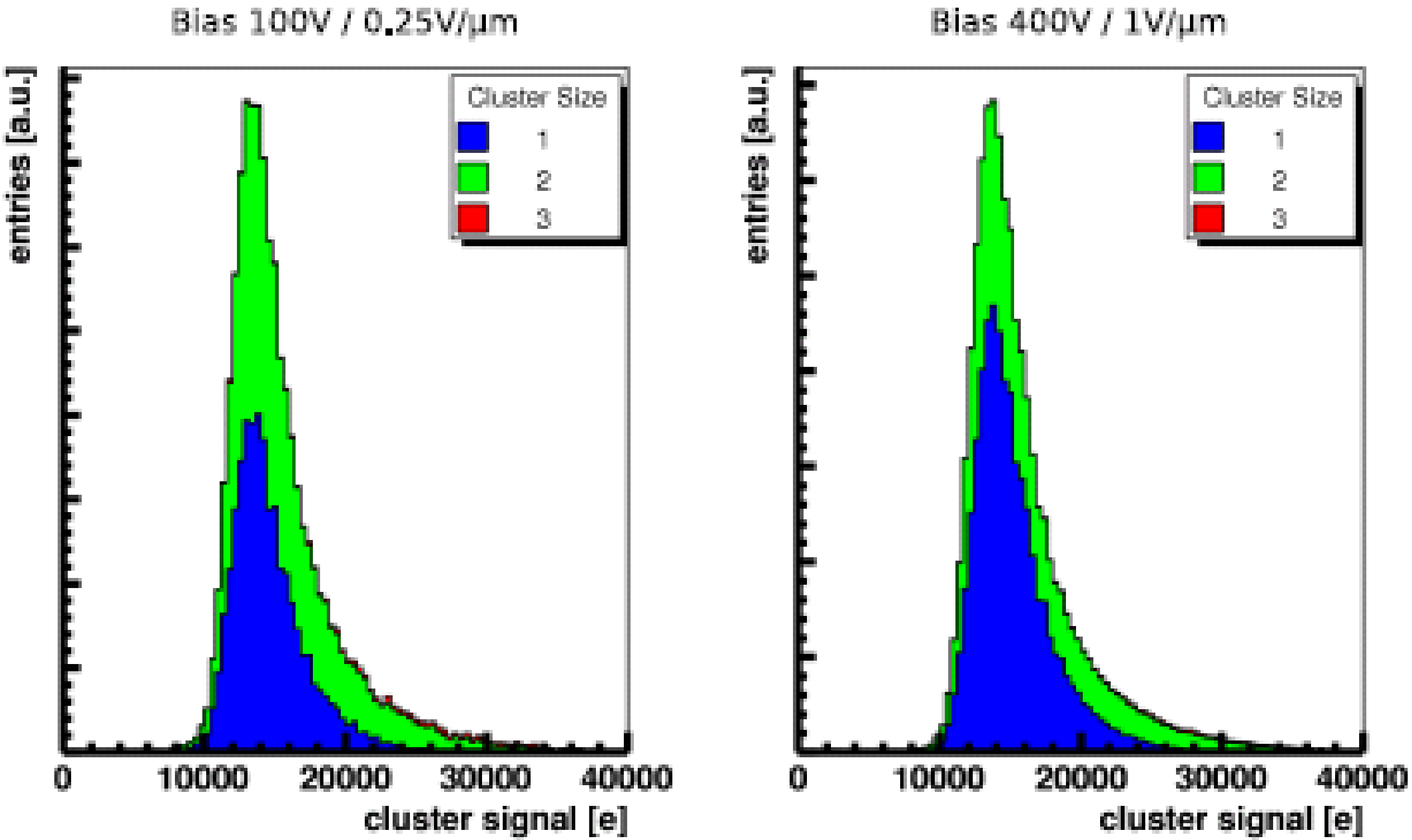






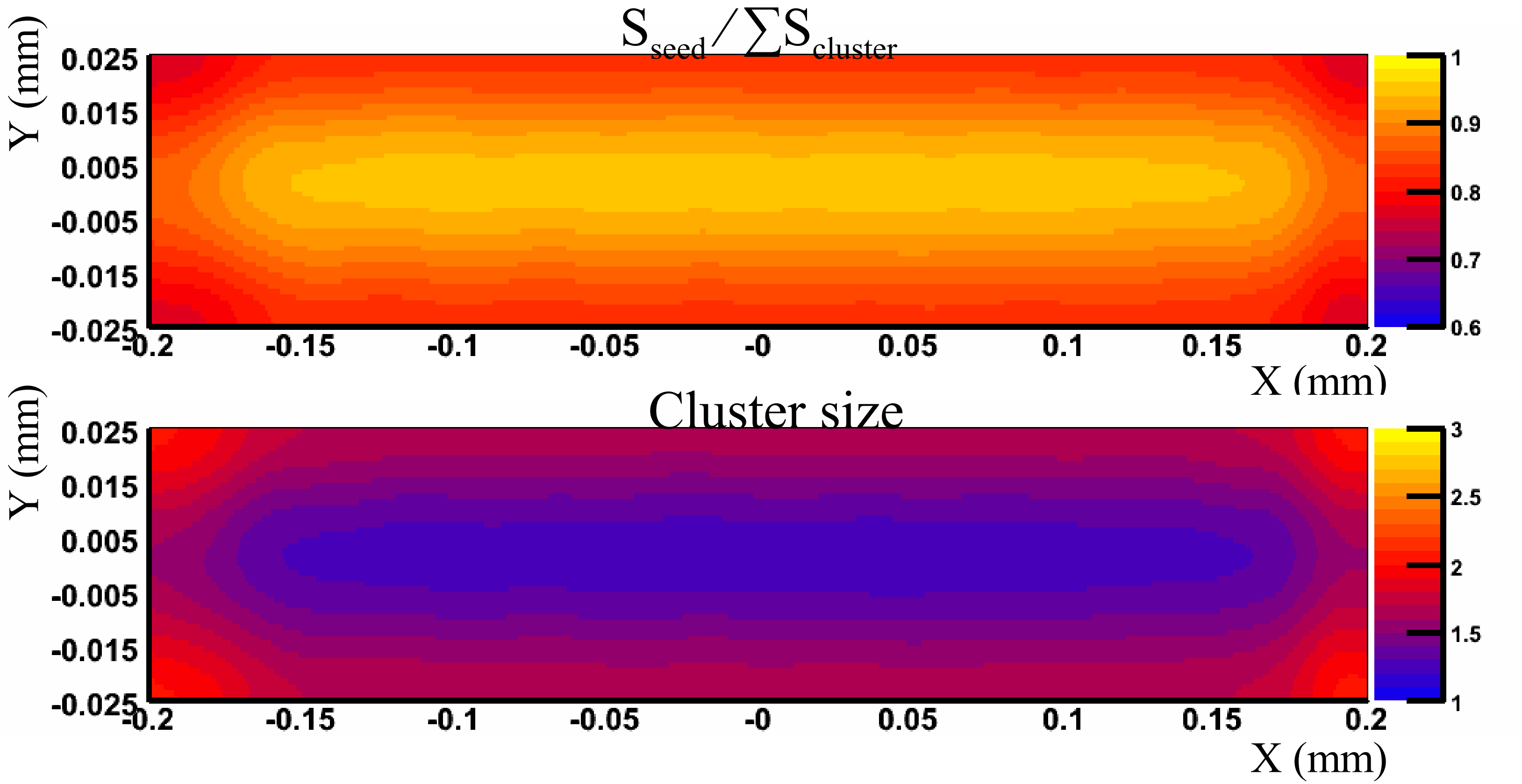
- The hitmap plotted for all scintillation triggers with trigger in telescope.
- The raw hitmap looks goods - $\sim$ 1 dead pixel

scCVD ATLAS diamond pixel detector - Cluster Signal



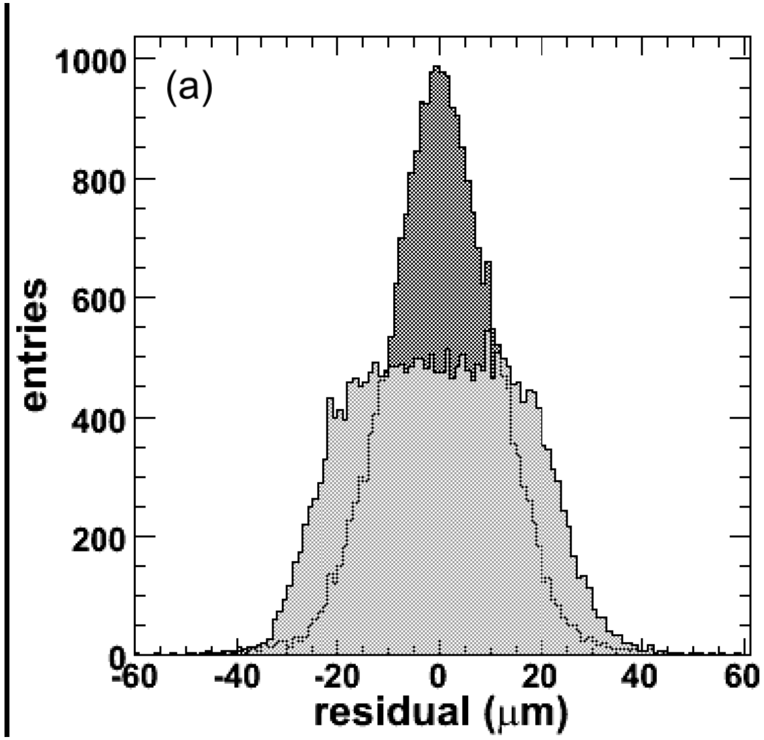
- As voltage is raised → more 1-hit clusters

scCVD ATLAS diamond pixel detector - Charge Sharing



- Charge sharing as expected
- Cluster signal as expected

scCVD diamond pixel detector - Position Resolution (1-Strip and 2-Strip η)

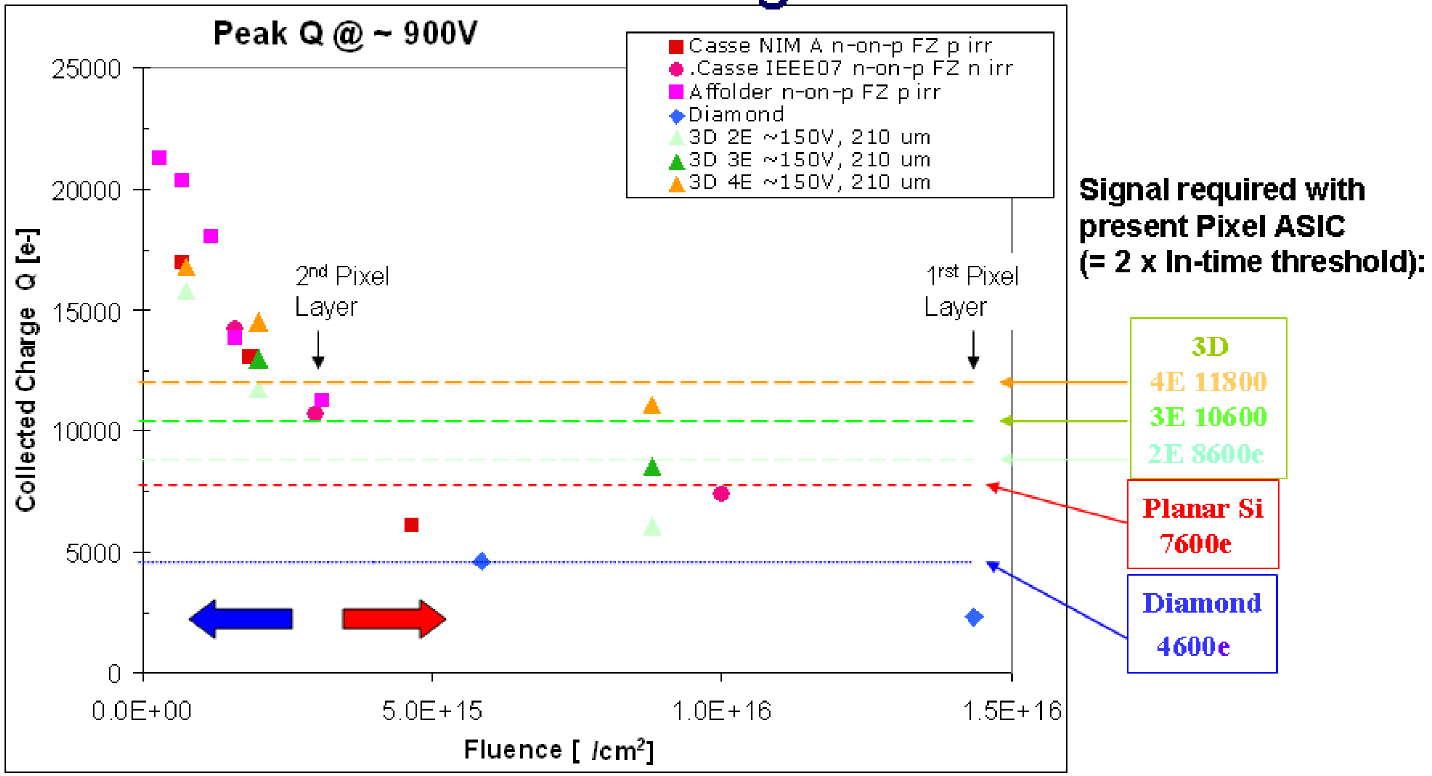


- Plot contains all scintillator triggers with "track" trigger in telescope
- The pixel detector hits correlate well with the telescope hits
- Residual $\sim 9\mu$m (η algorithm) - after removing telescope tracking

Radiation Hardness Comparison

Signal/2x In-time Threshold (from H. Sadrozinski Jun08 ATLAS talk):

Pixel S/N -> Signal/Threshold



Need to optimize FEE

Marginal performance for innermost Pixel Layer

Plans

On the bases of these results ATLAS officially approved Upgrade R&D on Diamond Pixel Detectors

Proposing Institutes:

- Carleton University (Canada)
- University of Toronto (Canada)
- University of Bonn (Germany)
- Jožef Stefan Institute (Slovenia)
- CERN
- Ohio State University (US)

- Submitted May 2007
- Approved Feb 2008
- Technical Decision 2010

ATLAS project	Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	*Institute Document No.*	*Created: 15/05/2007*	*Page: 1 of 14*
		Modified: 21/12/2007	*Rev. No.: 1.8*

Abstract

The goal of this proposal is to construct diamond pixel modules as an option for the ATLAS pixel detector upgrade. This proposal is made possible by progress in three areas: the recent reproducible production of high quality polycrystalline Chemical Vapour Deposition diamond material in wafers, the successful completion and test of the first diamond ATLAS pixel module, and the operation of a diamond after irradiation to 1.8x10^{16} p/cm^2. In this proposal we outline the results in these three areas and propose a plan to build 5 to 10 ATLAS diamond pixel modules, characterize their properties, test their radiation hardness, explore the cooling advantages made available by the high thermal conductivity of diamond and demonstrate industrial viability of bump-bonding of diamond pixel modules. Based on availability and size polycrystalline Chemical Vapour Deposition diamond has been chosen as the baseline solution. The use of single crystal Chemical Vapour Deposition diamond is reserved as a future option if the manufacturers can attain sizes in the range 16mm x 16mm.

Reference → ATU-RD-MN-0012, EDMS ID: 903424

Irradiation Plans

- **Irradiation of diamond pixel modules at CERN**
  - Done - single chip $\rightarrow 10^{15}$p/cm^2
  - Done - full module $\rightarrow 10^{14}$p/cm^2
  - In Progress - full module $\rightarrow 10^{15}$p/cm^2
  - Status - data being analyzed
- **Irradiation of pCVD diamonds**
  - Done (Japan) - 1 10^{15}p/cm^2, 2 10^{16}p/cm^2
  - Done (CERN) - 1 1.8×10^{16}p/cm^2
  - In Progress (CERN) - 1 3×10^{16}p/cm^2
  - Status - data being analyzed, awaiting test beam
- **Irradiation of scCVD diamonds**
  - Done (CERN) - 1 1.4×10^{15}p/cm^2
  - Done (Japan) - 1 2.5×10^{15}p/cm^2
  - In Progress (CERN) - 1 2.8×10^{15}p/cm^2
  - Status - data being analyzed, awaiting test beam

Plans

- **Move Metalization to Industry**

  Cleaner facilties

  Metalization and bumping done at one facility

  Status - Done

- **Produce 3-10 Modules in Industry**

  Evaluate production process

  Full measure of efficiency, noise, etc.

  Status - In Progress

- **Test of Modules**

  Beam test of production modules

  Radiation hardness test of production modules

  Status - In Progress

- **Construct Pixel Modules with Irradiated Diamond**

  Status - In Progress

- **Design Diamond Specific Pixel Module Support**

  Reduce material, increase heat spreading

  Status - In Progress

Summary

- **Further Progress in Charge Collection**
  - pCVD - 300 μm collection distance diamond attained in wafer growth
  - pCVD - FWHM/MP $\sim$ 0.95 – Working with manufacturers to increase uniformity
  - scCVD - Full charge collection, fast, large signals, Larger size?
  - New manufacturers arriving
- **Radiation Hardness of Diamond Trackers**
  - Using trackers allows a correlation between S/N and Resolution
  - Dark current decreases with fluence
  - With protons - pCVD and scCVD have same damage curve
    - E=1V/μm: 15% S/N loss at 2.2×10^{15}/cm^2, 33% signal at 1.8×10^{16}/cm^2
- **Diamond Pixel Detectors**
  - Successfully tested a complete ATLAS pCVD module and scCVD module
    - Excellent correlation for both between telescope and pixel data - stable op
    - pCVD $\rightarrow$ digital resolution; scCVD $\rightarrow$ 9μm resolution
  - Diamond R&D Approved by ATLAS for LHC Upgrade R&D