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

RD42 Status Report

Harris Kagan, Ohio State University

LHCC Presentation
Nov. 19, 2008, CERN

Outline of the Talk

- **Introduction - 2008 LHCC Milestones**
- **Radiation Hardness Studies with Trackers**
- **Pixel Module Studies**
- **Material and Manufacturing Developments**
- **RD42 Plans and Request**

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], M. Cristinziani[1], S. Costa[2], R. D'Alessandro[6], W. de Boer[13], D. Dobos[3], I. Dolenc[12], 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. La Rosa[3], 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], J. Moss[16], S. Mueller[13], P. Olivero[18], G. Parrini[6], H. Pernegger[3], M. Pomorski[14], 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

70 Participants

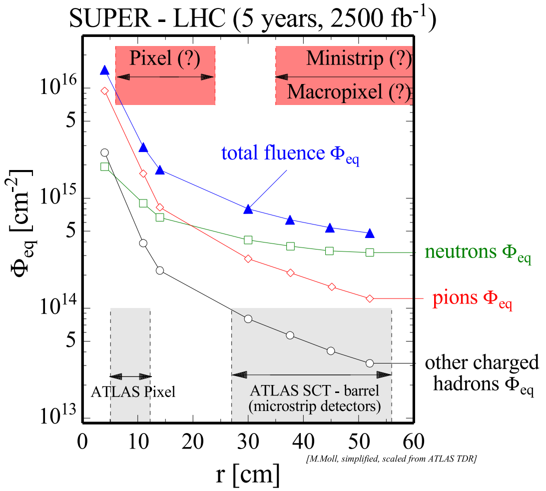
22 Institutes

New groups joined RD42 from: Carleton University

Motivation: Tracking Devices Close to Interaction Region of Experiments

Scale is $\sim 10^{16}$ *cm*$^{-2}$

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:

- Radiation hardness tests of the highest quality pCVD and scCVD diamond
- Pixel module development
- Beam tests results
- Manufacturing and Module Developments

- *Reference* → http://rd42.web.cern.ch/RD42

2008 LHCC Milestones

Priorities of Research in 2008 (LHCC 2008-005)

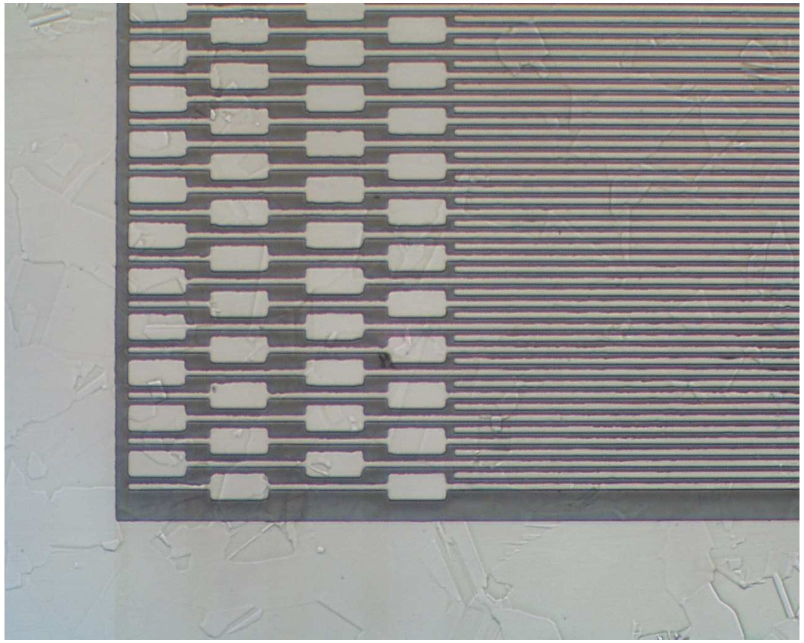
- Test the radiation hardness of the highest quality pCVD and scCVD diamond.
- Develop diamond pixel modules useful at the LHC. Industrialization of the process.
- Beam tests with diamond pixel trackers and pixel detectors.
- Continue the development of pCVD and scCVD diamond material. Develop additional suppliers.
- Continue the development of systems for beam monitoring for the LHC.

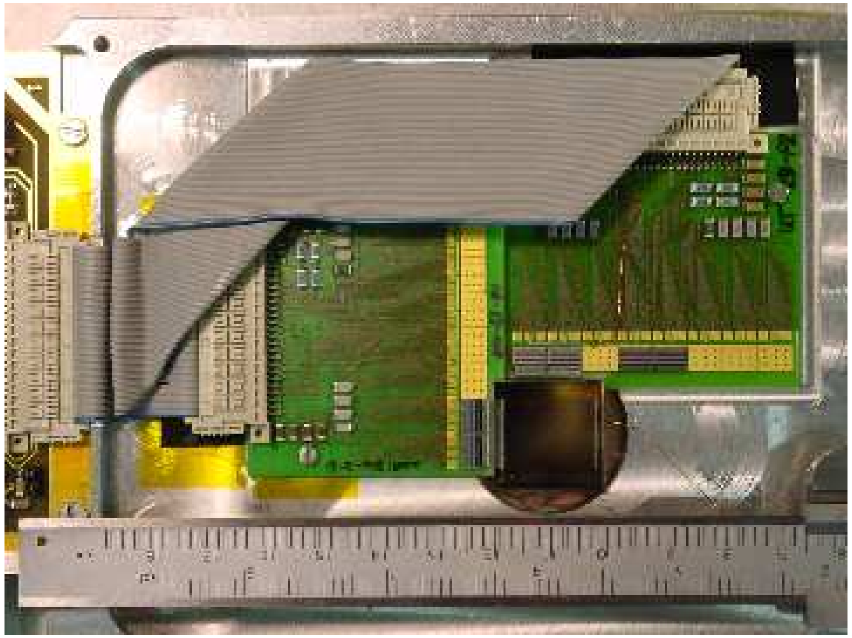
These points will be addressed in this talk.

Radiation Hardness

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

pCVD Diamond Trackers:

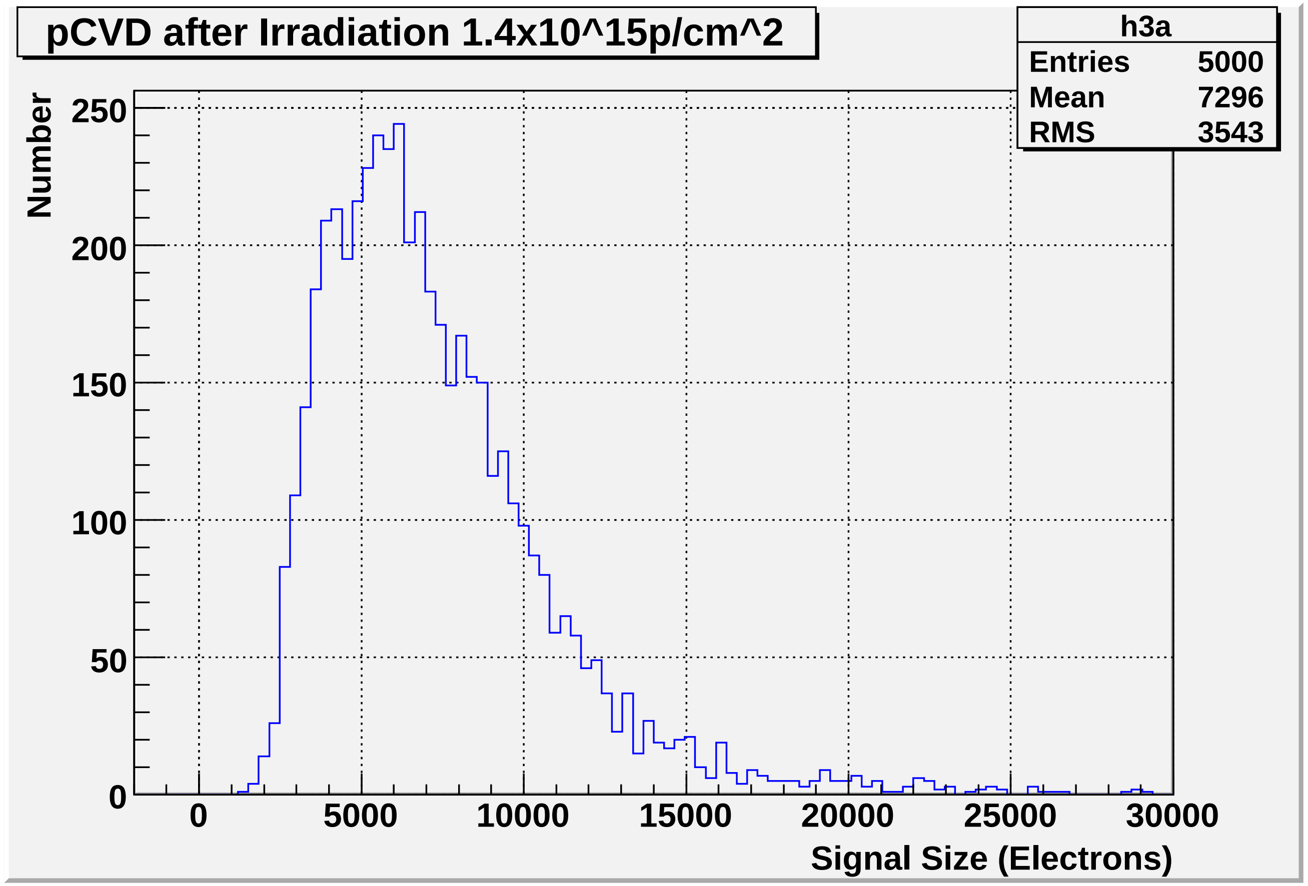




- Patterning the diamond → pads, strips, pixels!
- Successfully made double-sided devices; edgeless ok.
- Use trackers (strip or pixel) in radiation studies - charge and position.

pCVD Diamond After Irradiation

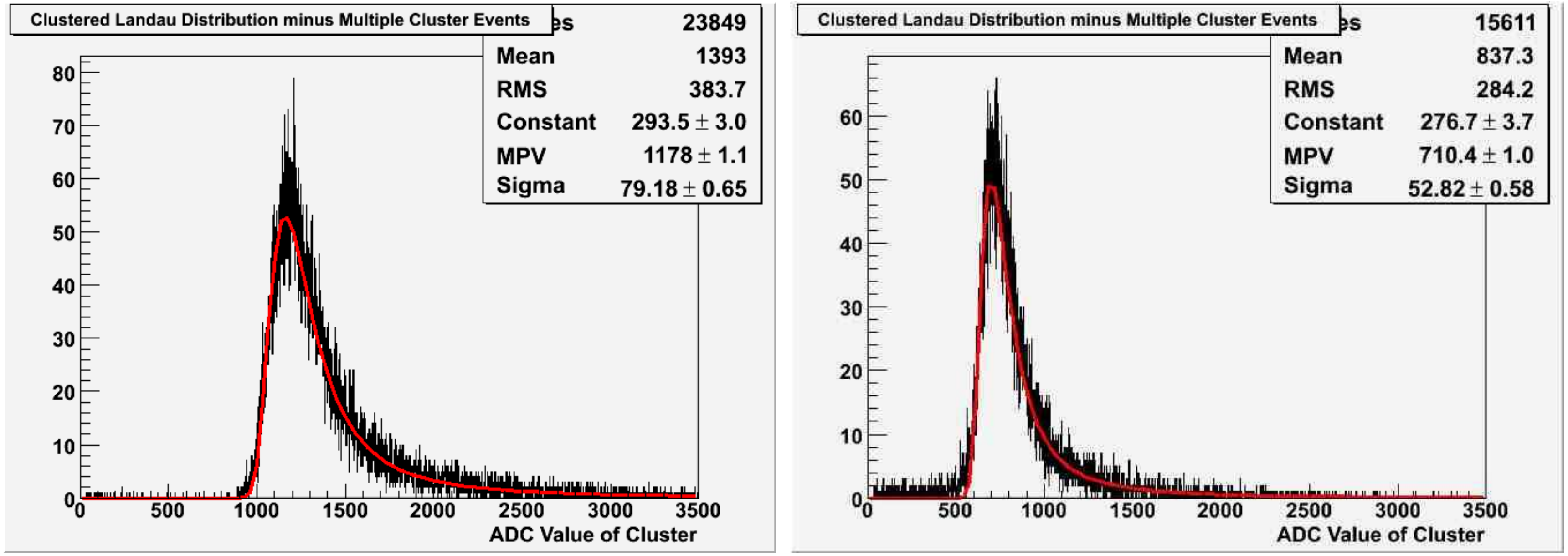
Polycrystalline CVD (pCVD) Diamond irradiated to 1.4x10^{15}



- Application is pixel detectors
- At the LHC, thresholds are $\sim$ Noise (1400e) plus overdrive (800e)
- PH distributions look good after irradiation of 1.4x10^{15}p/cm^2.

scCVD Diamond After Irradiation

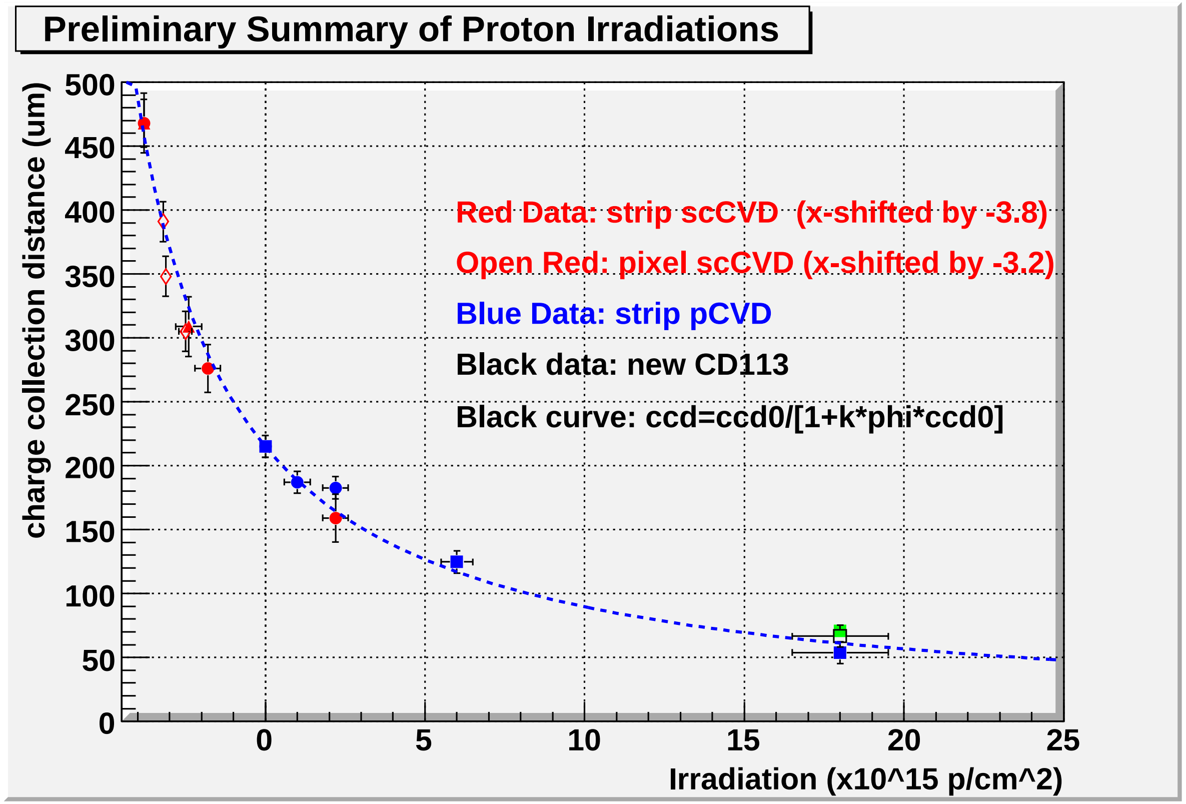
Single Crystal CVD (scCVD) Diamond irradiated to $1.5x10^{15}$



- PH distributions look narrow before and after irradiation
- PH distributions after $1.5x10^{15}$p/cm^2 $\rightarrow \epsilon > 99\%$.
- Calibration: 750ADC $=$ 10,000e

Proton Irradiation Summary - This Year:

New results from pixel modules - diamond and electronics irradiated!



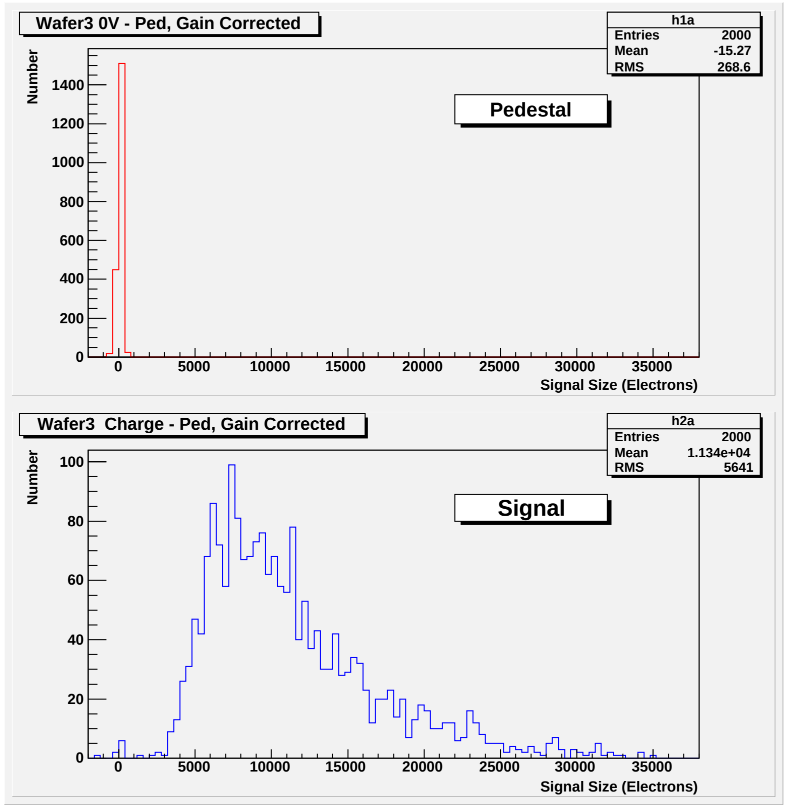
Irradiation results up to 1.8×10^{16} p/cm^2 (∼500Mrad).
pCVD and scCVD diamond follow the same damage curve:
$1/\text{ccd}=1/\text{ccd}_0 + \text{k}\ \phi$.

CVD Diamond Material Status

- collection distance
- polycrystalline, single crystal
- new manufacturers

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

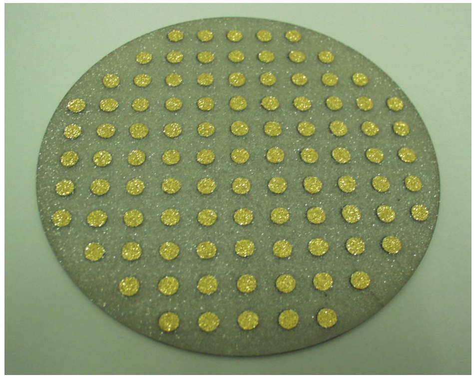
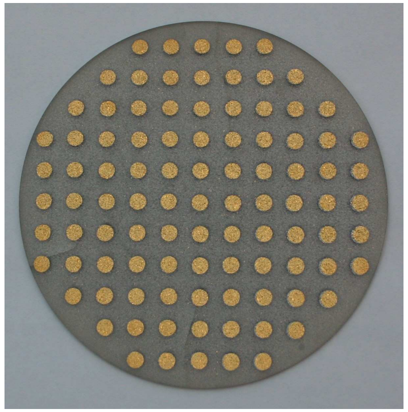
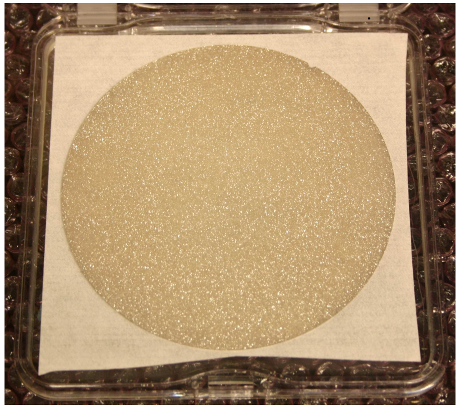
- Contacts on both sides - structures from μm to cm
- Usually operate at E=1-2V/μm
- Test Procedure: dot $\rightarrow$ strip $\rightarrow$ pixel on same diamond!



- 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
- Six wafers grown with this quality

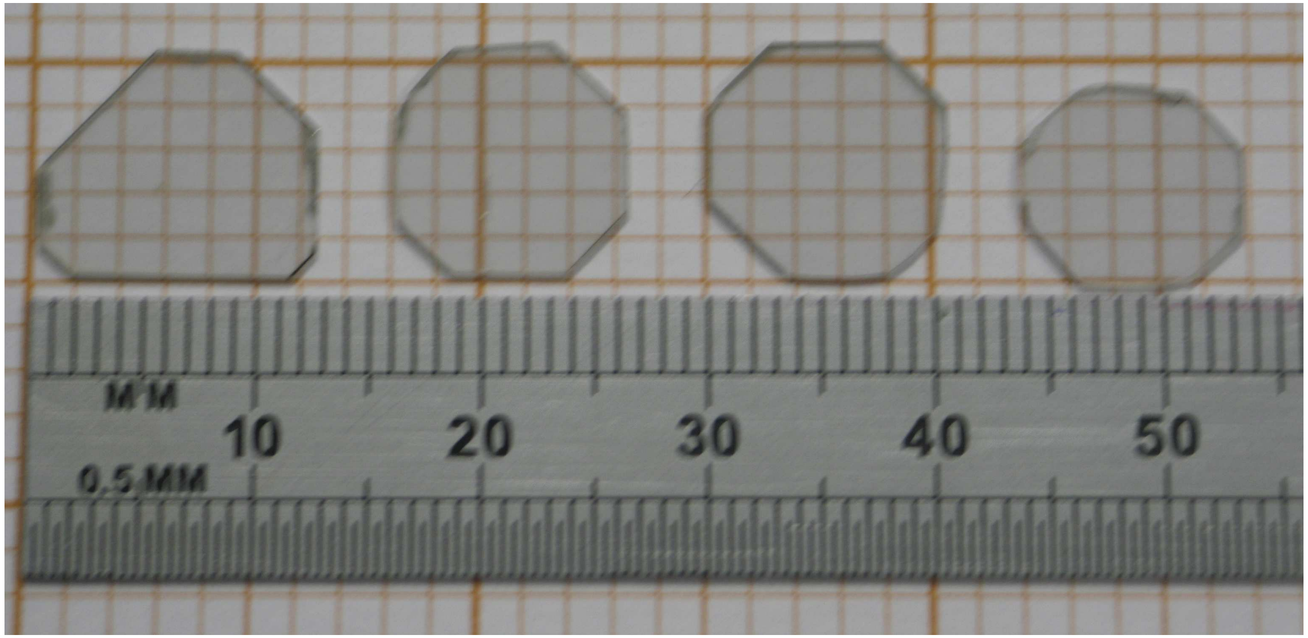
Recent Polycrystalline CVD Diamond

Recent pCVD wafers ready for test - Cr/Au dots are 1 cm apart

- New wafers continually being produced.
- Wafer collection distance now typically 250μm (edge) to 310μm (center).
- Contract for material with ccd $>$ 275μm.

Recent Single Crystal CVD (scCVD) Diamond



RD42 continues to develop and test this material.

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

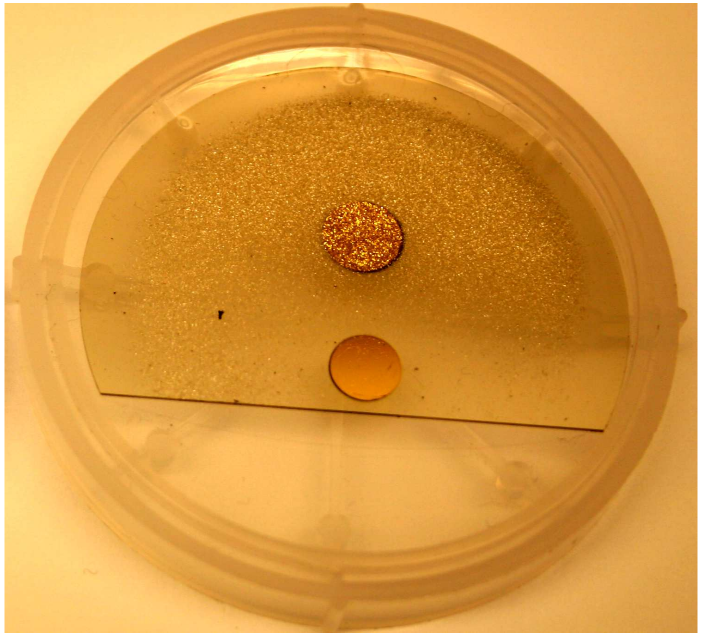
Largest scCVD diamond grown $\approx$ 14 mm $\times$ 14 mm.

First results from irradiated scCVD pixel module.

New Manufacturers Developing Detector Grade Diamond

Status:

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



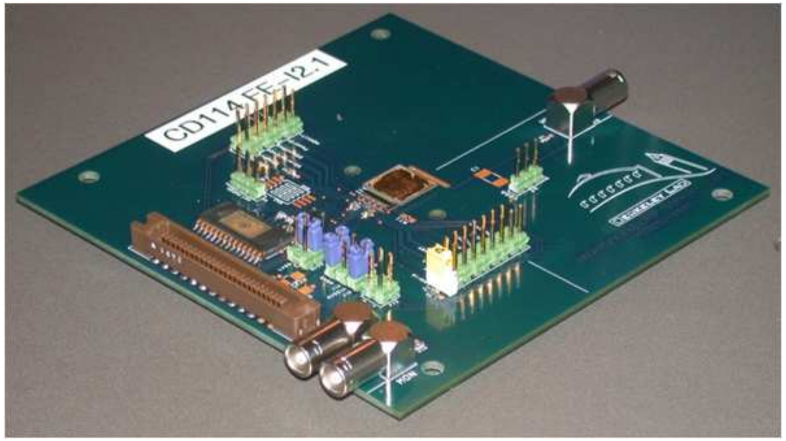
- First samples from companies show charge collection distance $\sim 100\mu m$
- RD42 is working with these manufacturers
- Work in progress on both pCVD and scCVD.

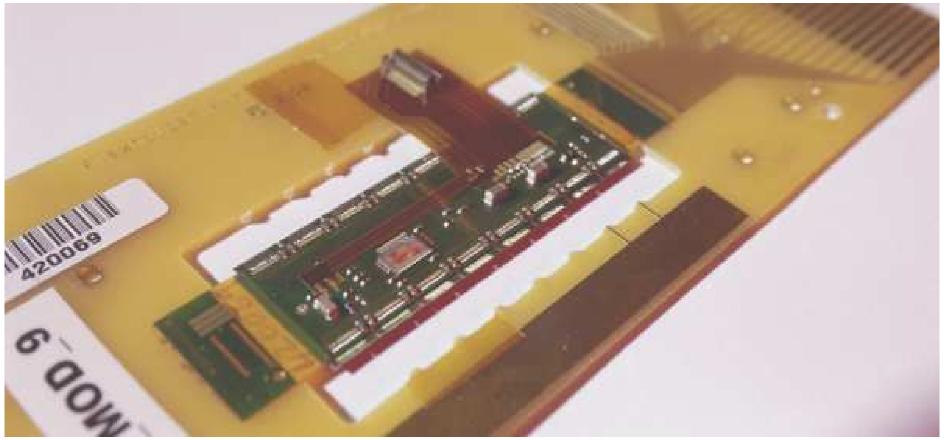
pCVD and scCVD Pixel Detectors

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

ATLAS Diamond Pixel Detectors

Recall: Full 1 Chip and 16 chip ATLAS diamond pixel modules

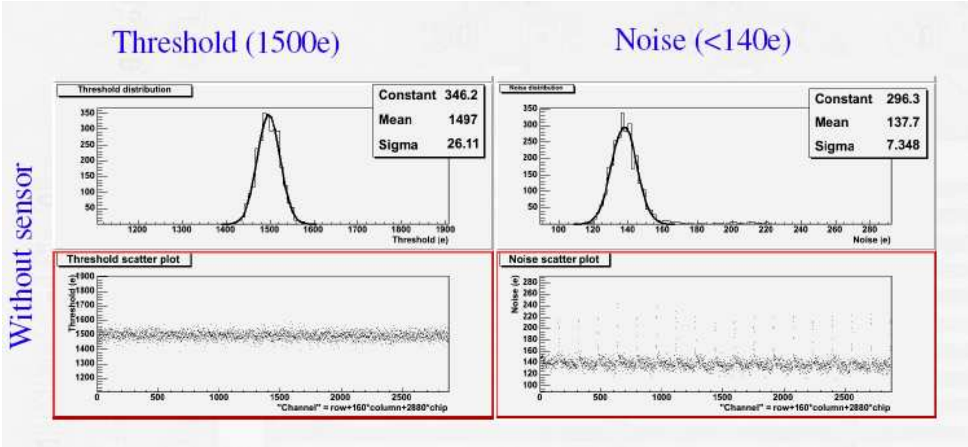




- Single-chip and 16-chip modules bump-bonded at IZM (Berlin), constructed and tested in Bonn
- Operating parameters (FE-I3): Peaking Time 22ns, Noise 140e,Threshold 1450-1550e, Threshold Spread 25e, Overdrive 800e

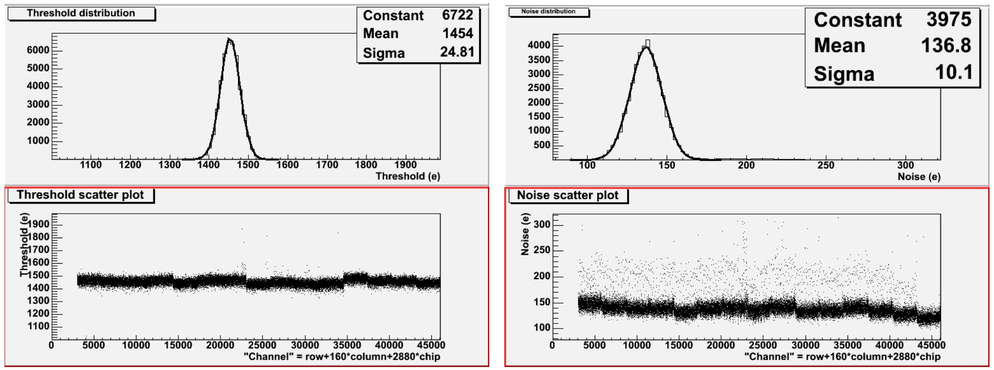
The ATLAS pixel module - Threshold, Noise

Bare Chips



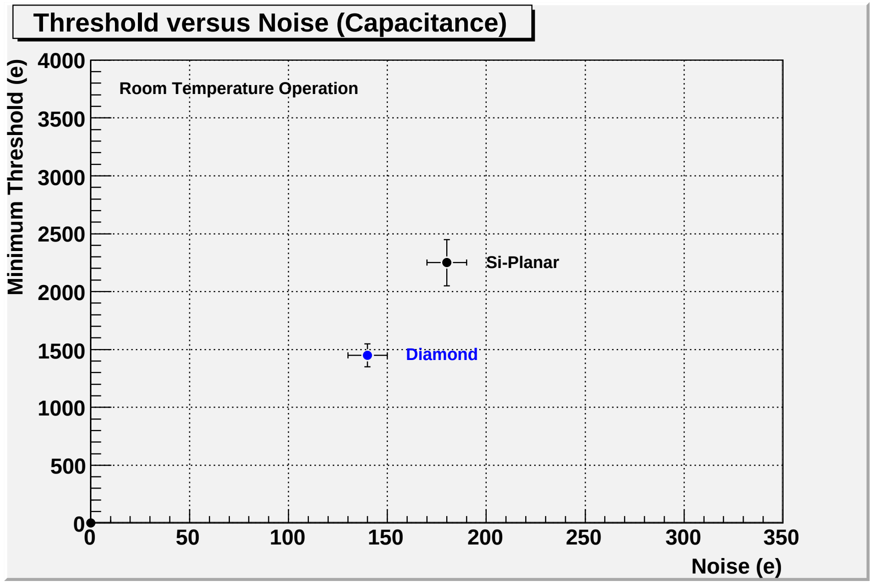
Noise $\sim 140e$, Mean Threshold $1500e$, Threshold Spread $\sim 25e$.

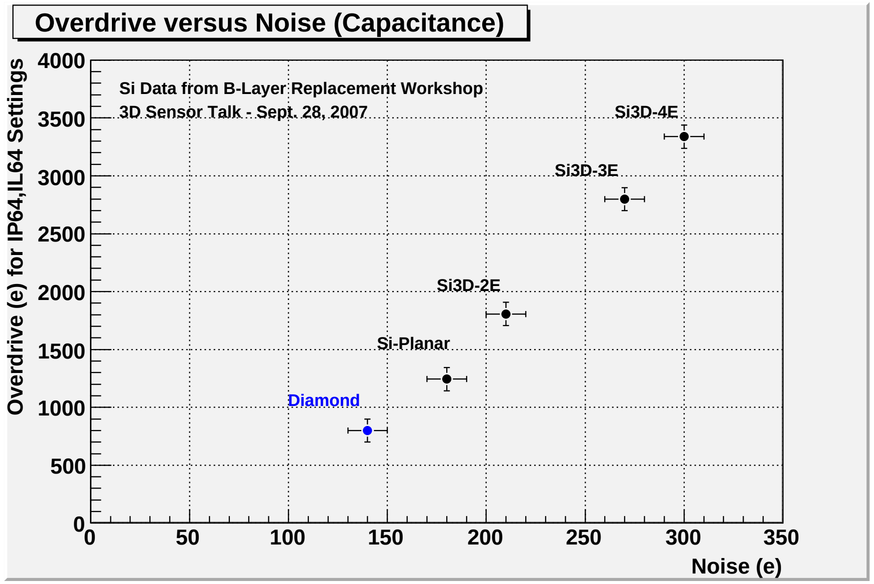
with Diamond Detector



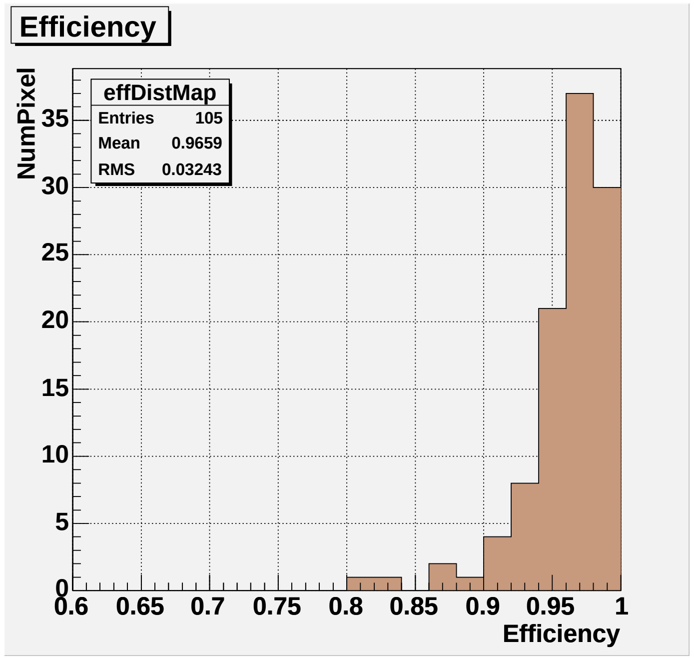
Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$.

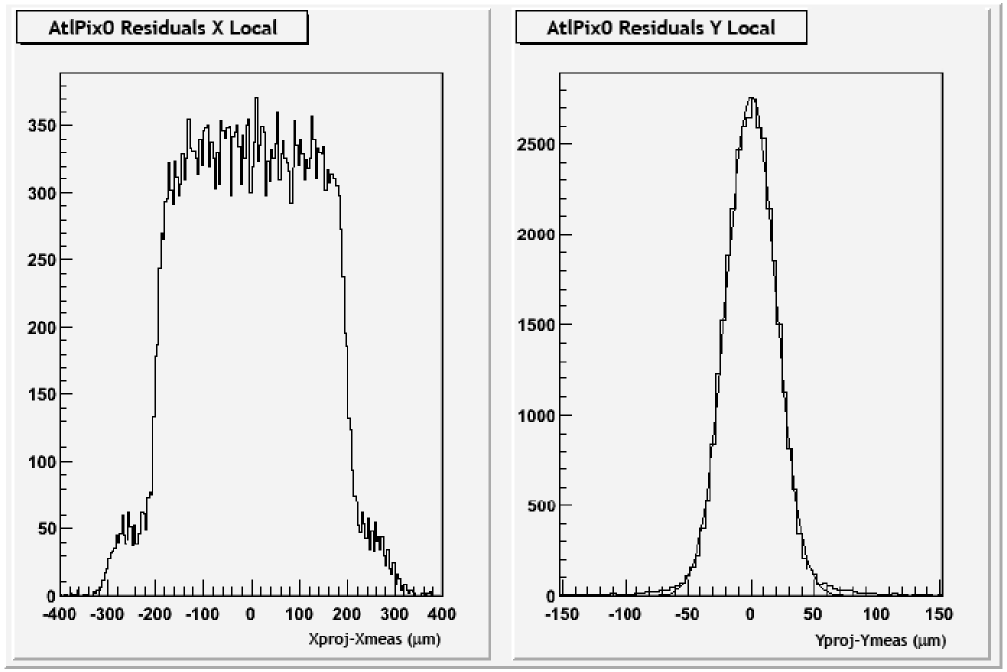
The ATLAS pixel module - Threshold, Overdrive vs Noise





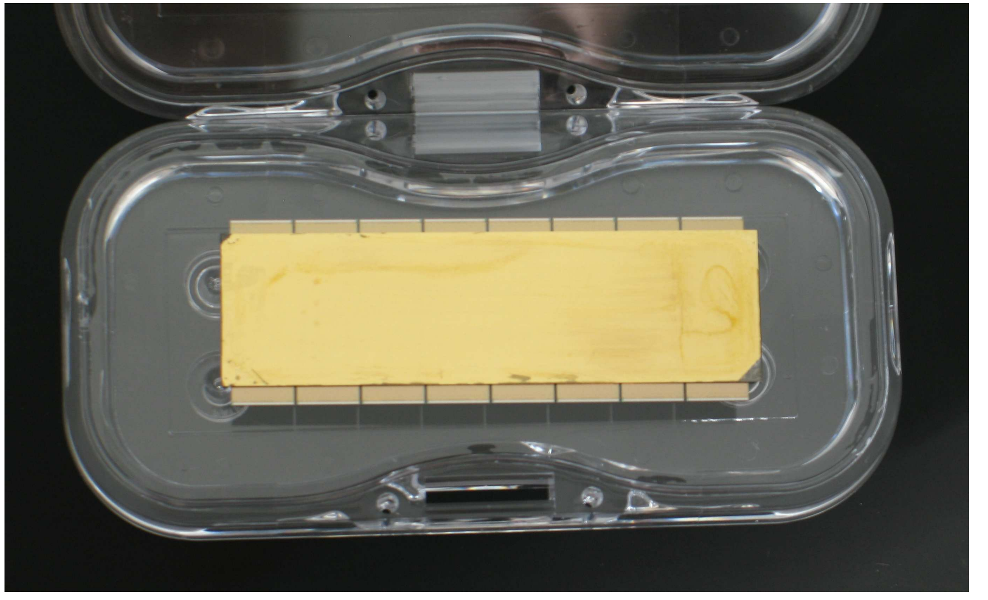
Recall: Full ATLAS diamond pixel module - Efficiency, Resolution





- Excellent correlation with telescope, efficiency $> 97\%$
- Residual $\sim 18\mu$m - remove telescope tracking contribution $\rightarrow 14\mu$m.

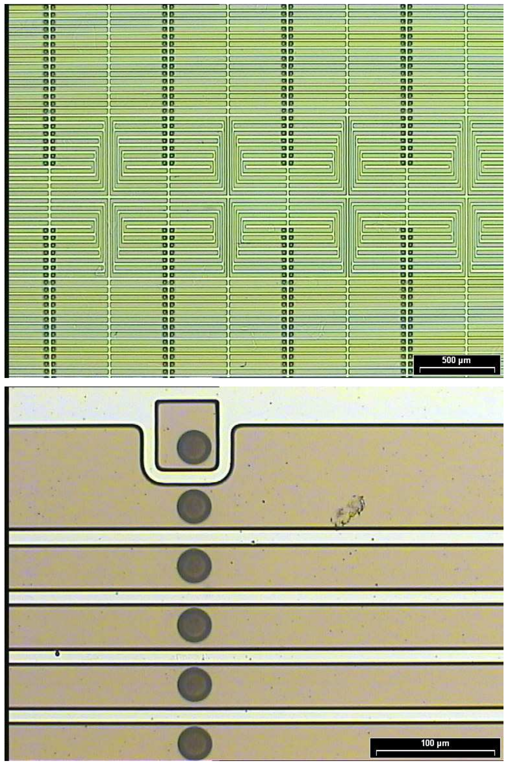
New: First Full Diamond Pixel Module Made in Industry



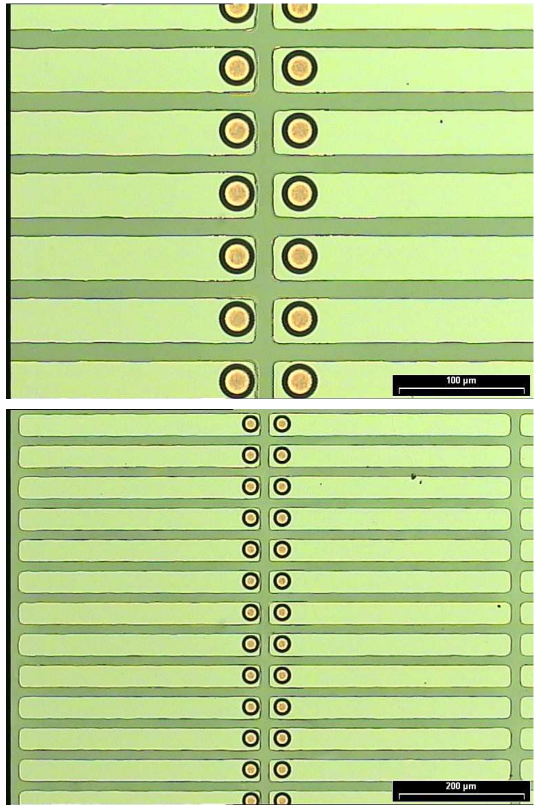
- Begin with a raw diamond wafer → characterize
- Cut out detector → characterize
- Clean → IZM in Berlin
- Receive finished, metalised, bump-bonded module!

New: First Full Diamond Pixel Module Made in Industry

Diamond sensor pixel metallisation



Status after elelctroplating of pad metallisation and lithography for pixel metallisation patterning

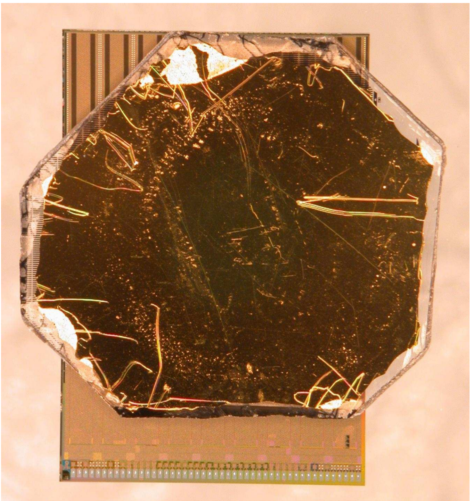


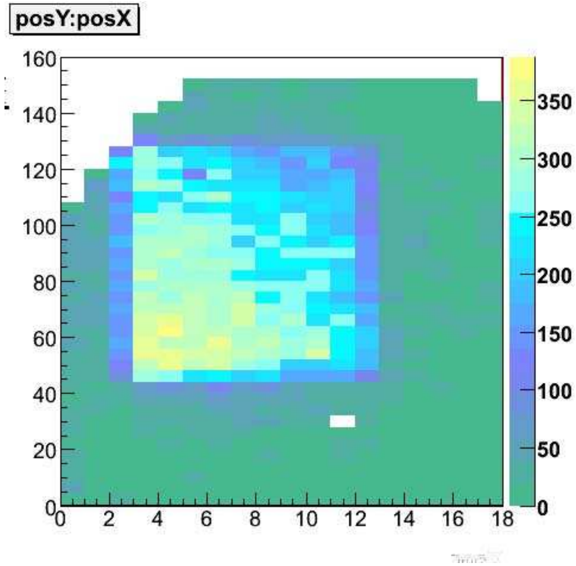
result after pixel metallisation patterning

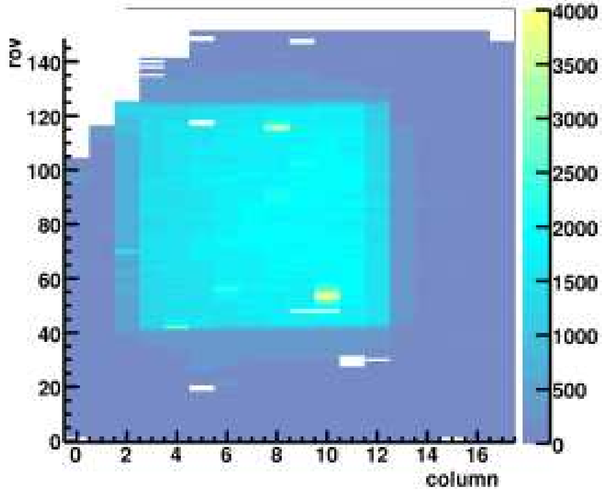
Fraunhofer Institut Zuverlässigkeit und Mikrointegration

ATLAS Diamond Pixel Detectors

The First scCVD ATLAS diamond pixel detector

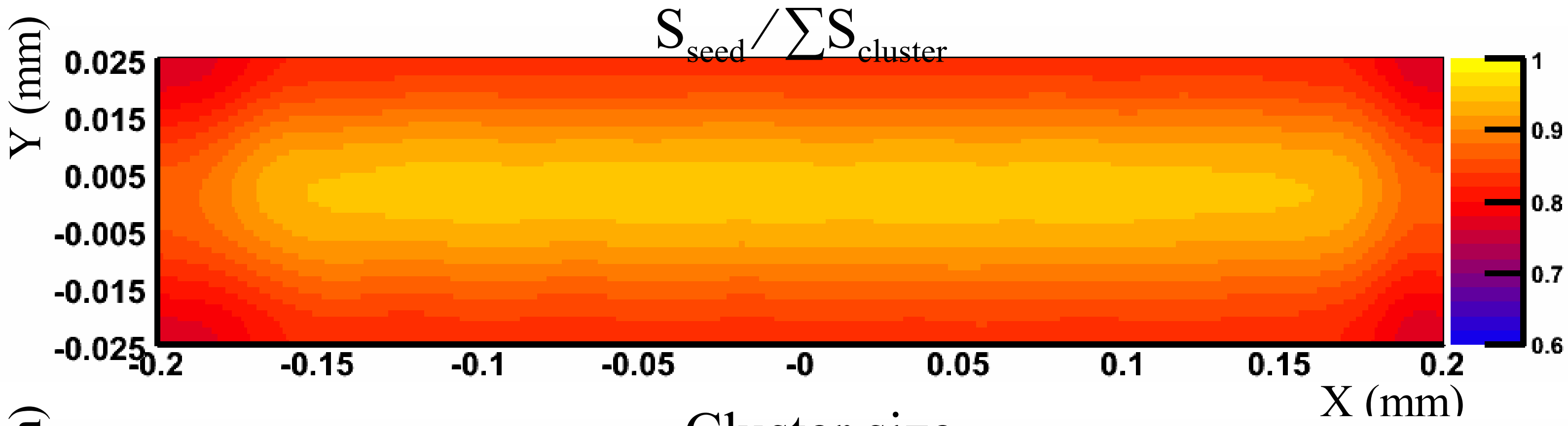


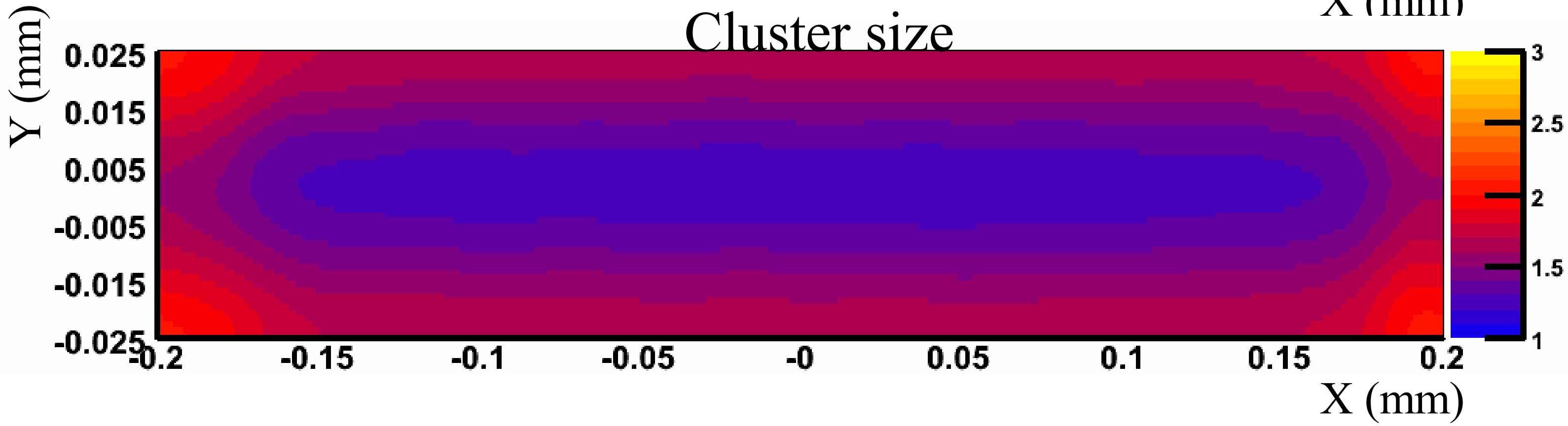




- The hitmap plotted for all scintillation triggers with trigger in telescope.
- The raw hitmap looks goods - $\sim$ 1 dead pixel

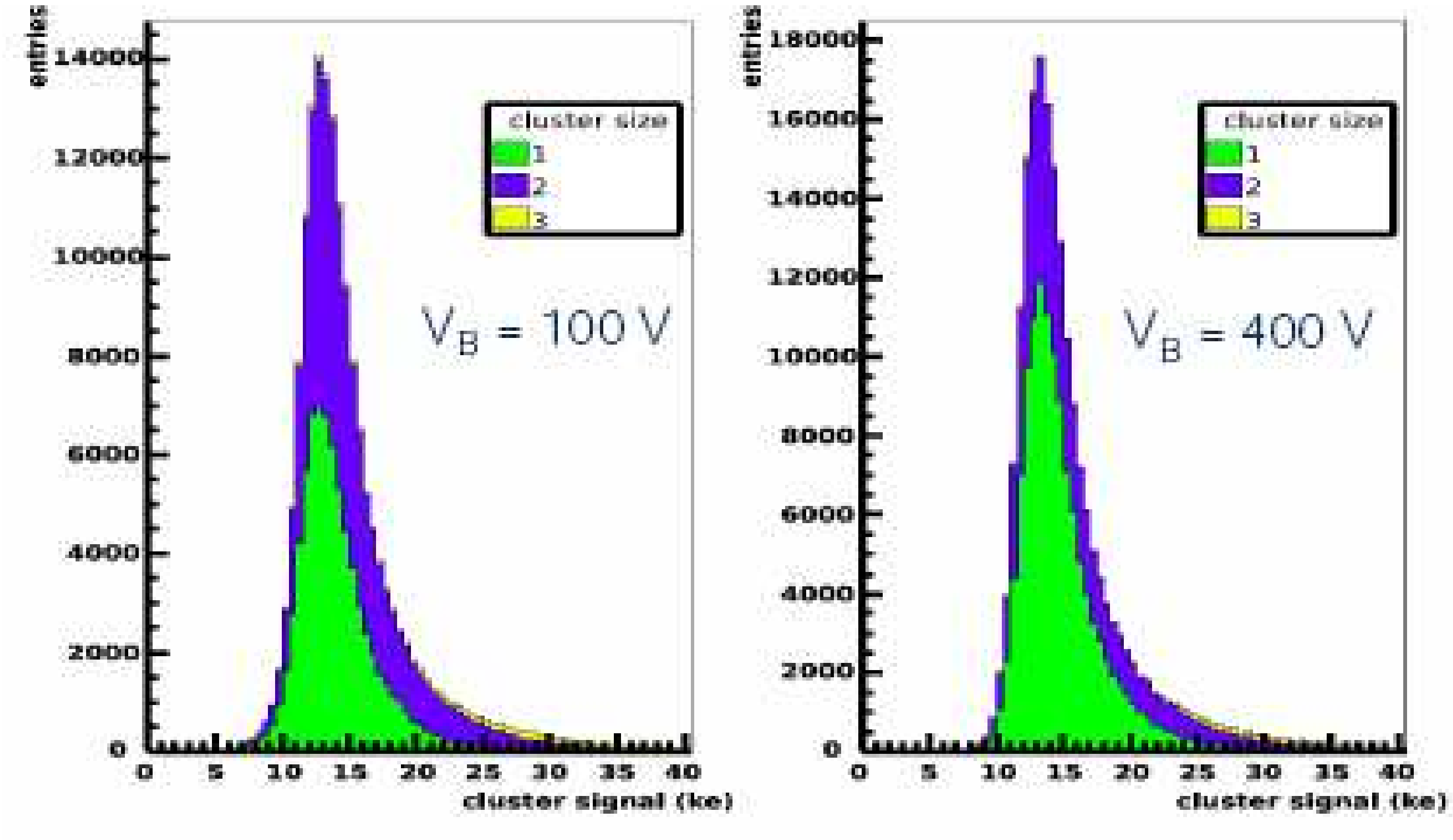
Last Year: The First scCVD ATLAS diamond pixel detector - Charge Sharing





- 25 μm pixel is located at Y $= \pm$ 0.0125 mm
- Charge sharing as expected

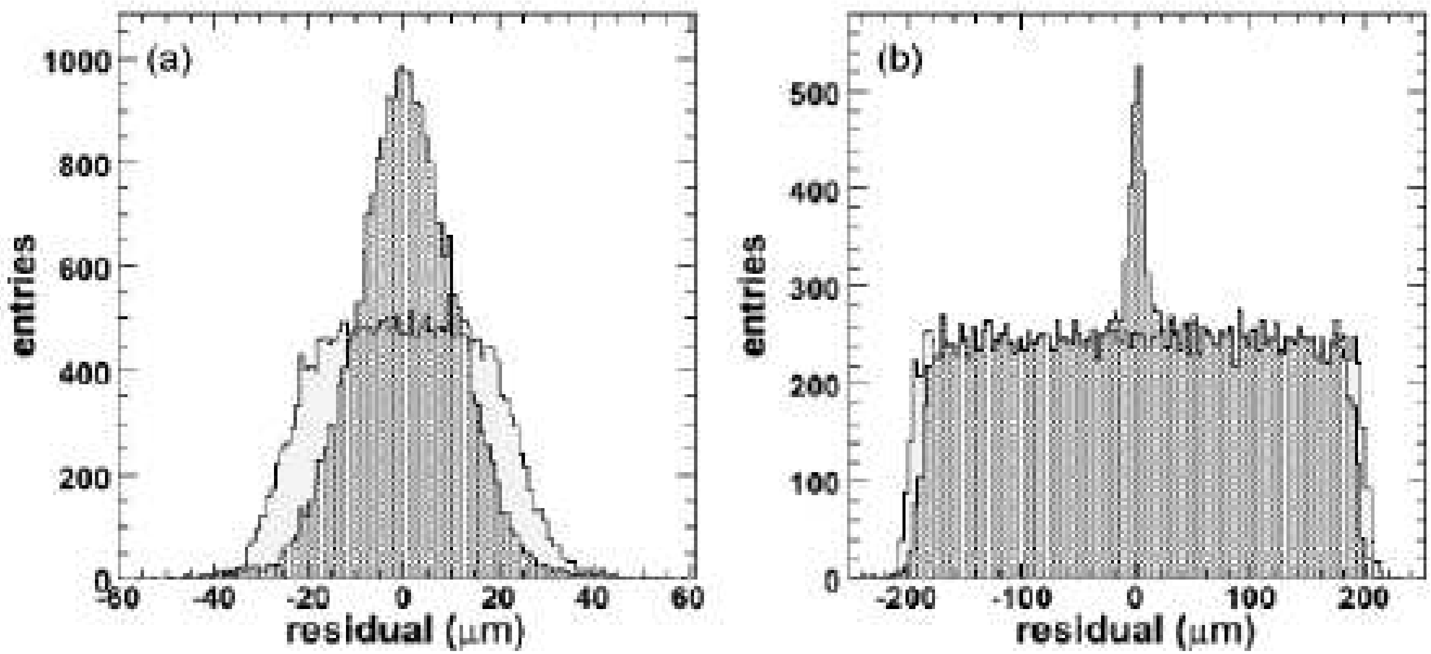
New This Year: Cluster Signal



- As voltage is raised → more 1-hit clusters
- Cluster signal as expected

ATLAS Diamond Pixel Detectors

New This Year: Spatial Resolution (1-pixel and 2-pixel η)

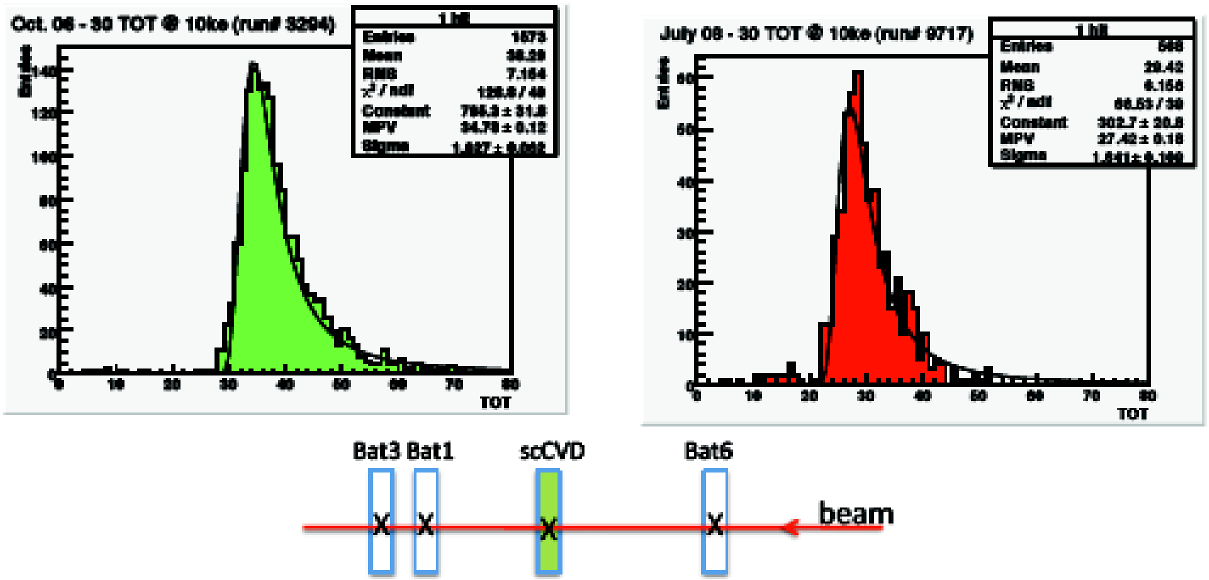


- Plot contains all scintillator triggers with "track" trigger in telescope
- Diamond pixel resolution 8.9μm for normal incidence
- Lower threshold $\rightarrow$ more charge sharing observed $\rightarrow$ better spatial resolution.

New This Year: Irradiated scCVD Diamond Pixel Module

TOT comparison (Oct.06 – Jul08)

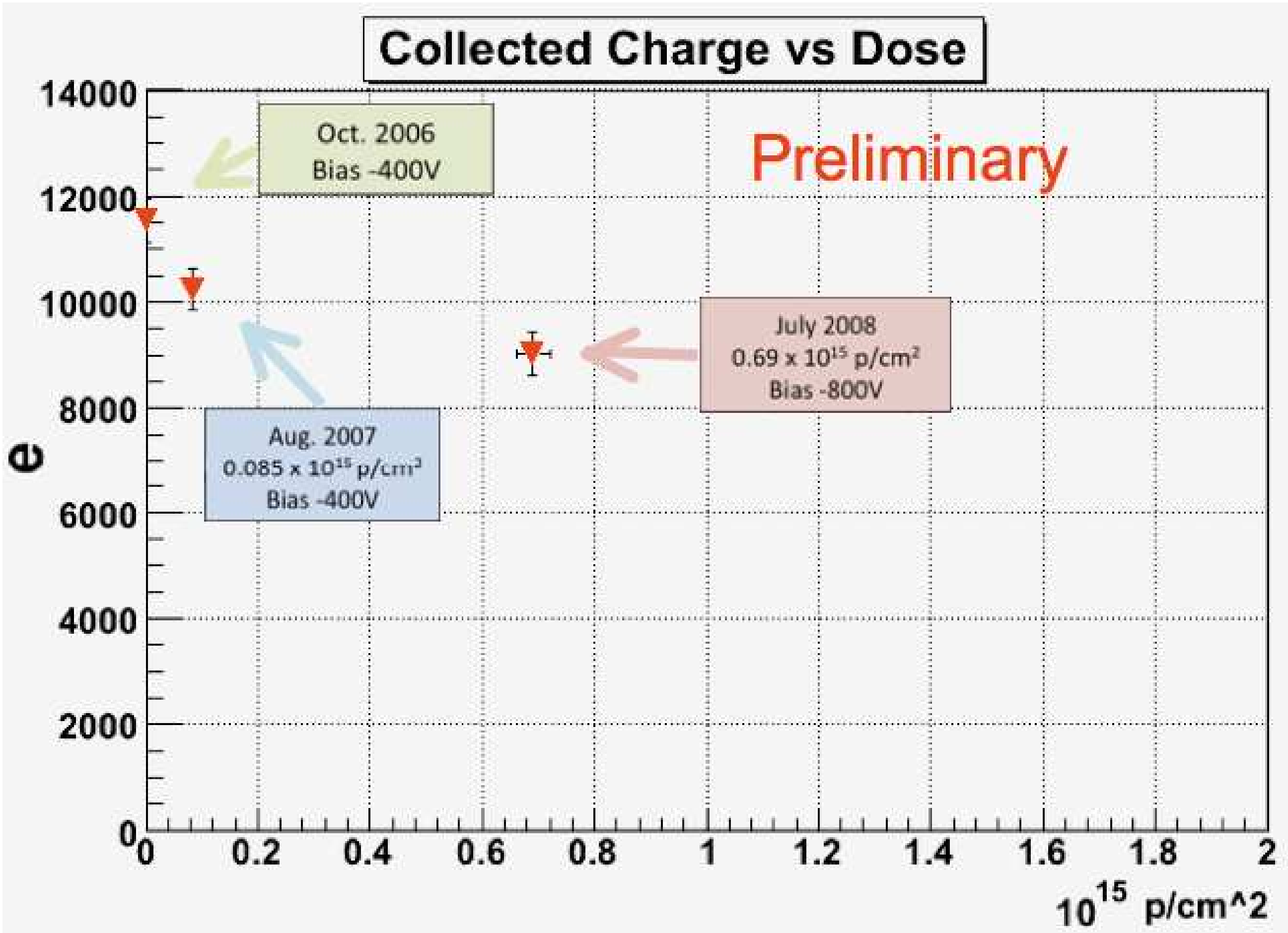
BEFORE irradiation **AFTER irradiation (f_T= 0.7 x 10^{15} p/cm^2)**



Only data from events with a single hit in each of the telescope planes are selected.

- Full scCVD module irradiated - electronics and diamond.
- Tested in CERN test beams

New This Year: Irradiated scCVD Diamond Pixel Module



- Full scCVD module irradiated - electronics and diamond.
- Data falls on expected damage curve!

Next Steps

On the basis 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

From Last Year: Next Steps Checklist

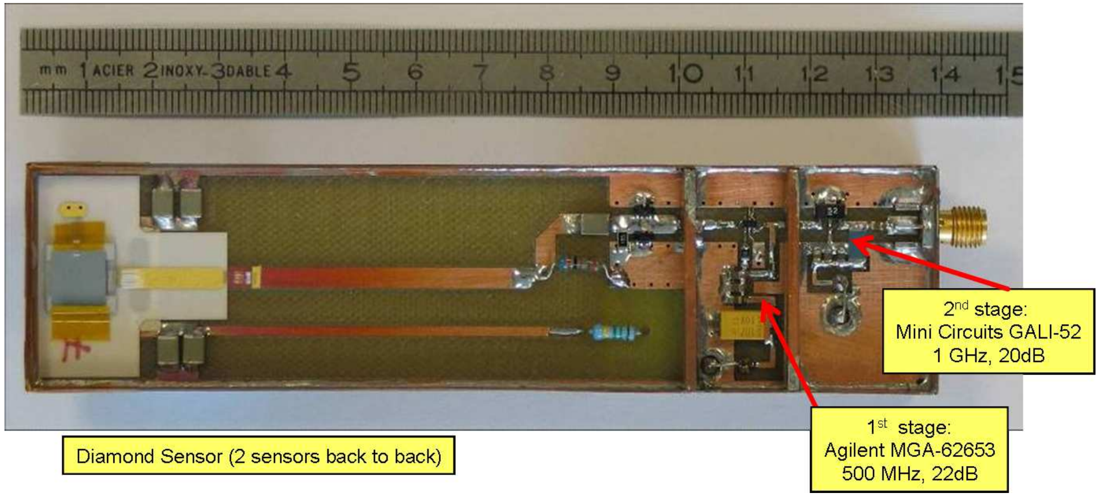
- **Re-Test ATLAS Pixel Module at CERN - Done**
  - Done - data being looked at → Thesis
- **Irradiate scCVD and pCVD diamonds - Done**
  - pCVD to 2×10^{16} and scCVD to 2×10^{15}p/cm^2
- **Irradiate scCVD pixel modules (chip and detector) - Done**
  - Up to $\sim 10^{15}$
- **Move Metalization to Industry - Done**
  - Cleaner facilties
  - Metalization and bumping done at one facility
  - This should be easy ... IZM is interested
- **Produce 3-10 Modules - ongoing**
  - Evaluate production process
  - Full measure of efficiency, noise, etc.
- **Test of Modules - beginning**
  - Beam test of production modules
  - Radiation hardness test of production modules

→ Much progress made!!!

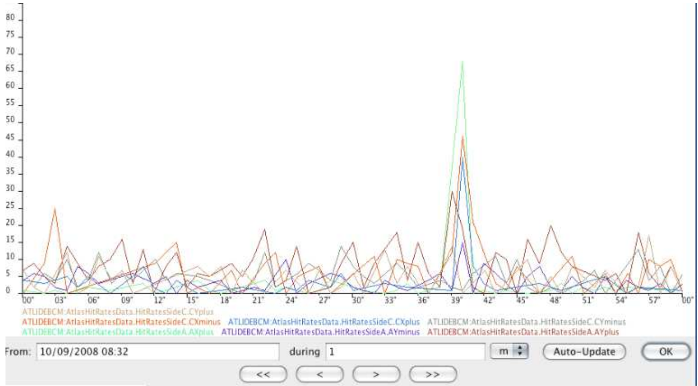
Beam Condition Monitoring

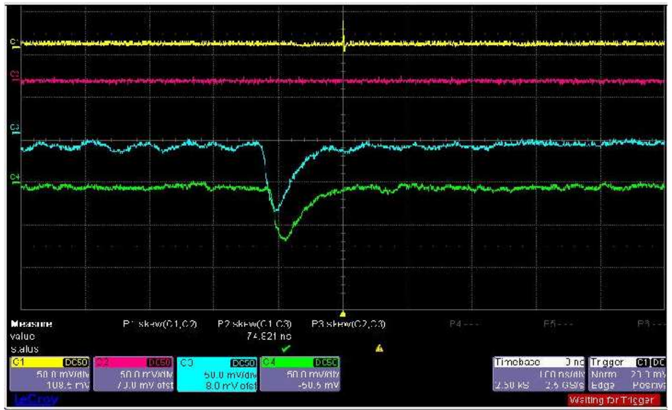
- current measurement
- single particle counting
- monitoring, protection

All LHC experiments have diamond Beam Condition Monitors



All saw First Beams





RD42 helped make this happen!!! → This work is a huge success for RD42!

Proposed Research for RD42

- **Radiation Hardness of Diamond Trackers and Pixel Detectors**
  - Continue tracker and pixel irradiations in the next year,
  - Use pCVD and scCVD
- **Pixel Detector Modules**
  - Test Industrial Modules (IZM).
  - Construct two additional modules - funded by ATLAS R&D?
- **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:

Why Support RD42

- Lots of generic work to be done - n-, π-irradiations, development of new manufacturers, sample procurement, test beams
- Central facilities for all experiments → this worked for BCM's
- CERN People in RD42 - D. Dobos, A. la Rosa, H. Pernegger, S. Roe

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
  - → test beam time

RD42 and CERN play a critical role in diamond detector development