Diamond Pixel Modules

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for the RD42 Collaboration

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Outline of the Talk

- **Introduction**
- **Radiation Hardness Studies with Trackers**
- **Pixel Module Studies**
- **Material and Manufacturing Developments**
- **Summary**

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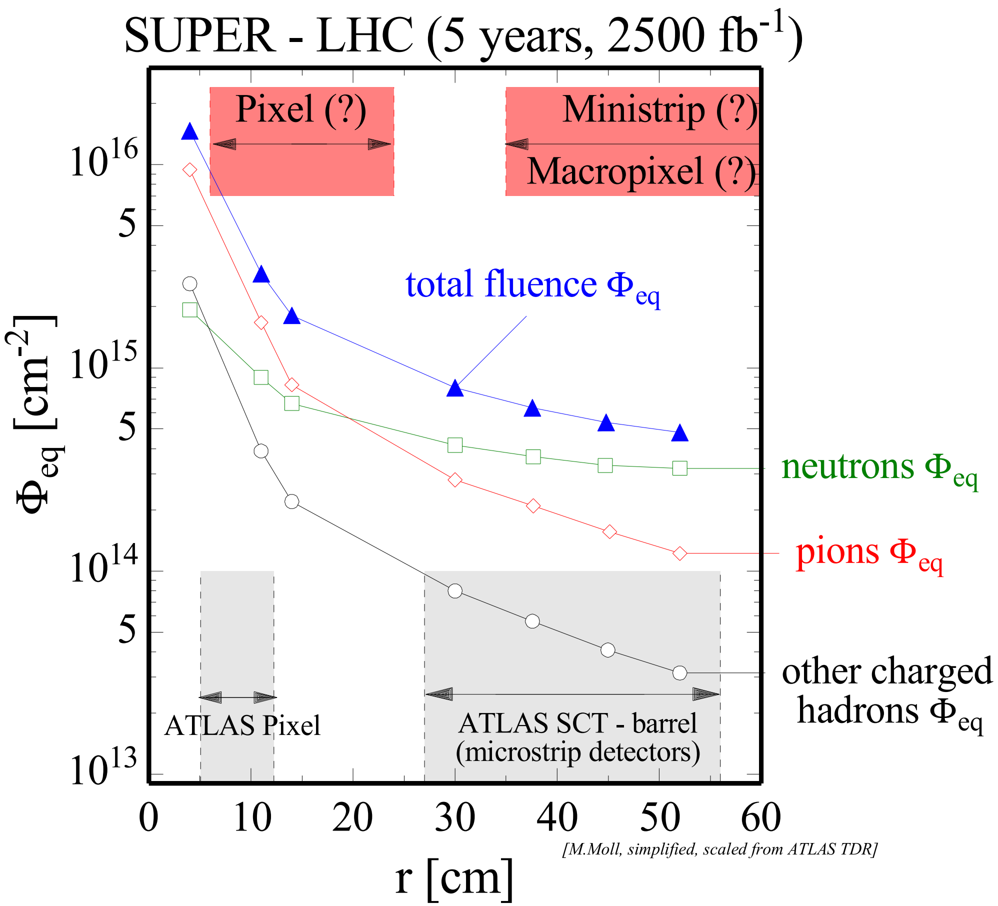
22 Institutes

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

Scale is $\sim 10^{16}$ cm^{-2} → Annual replacement of inner layers perhaps? → No



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:

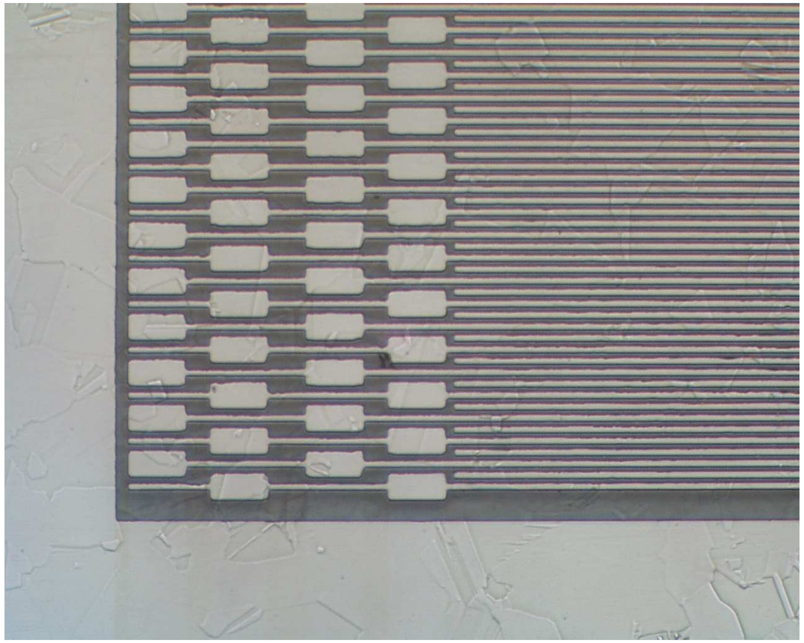
- Radiation hardness tests of the highest quality pCVD and scCVD diamond
- Beam tests results to characterize quality
- Pixel Module preparation
- Manufacturing Developments
- See also talk by A. Gorišek - ATLAS Diamond BCM and BLM

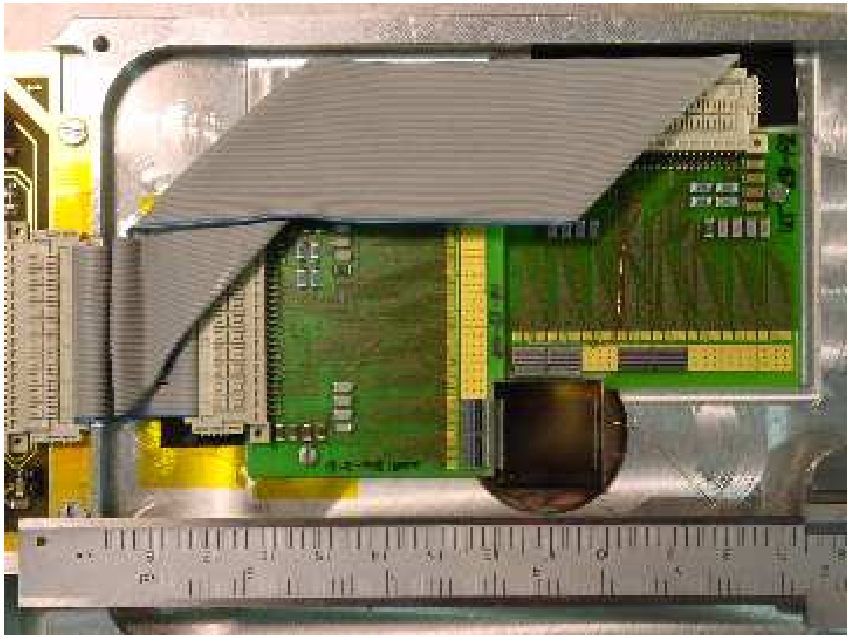
- *Reference* → http://rd42.web.cern.ch/RD42
- *Diamonds supplied by/in collaboration with Diamond Detector Ltd./Element Six Ltd.*

Radiation Hardness

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

pCVD Diamond Trackers:

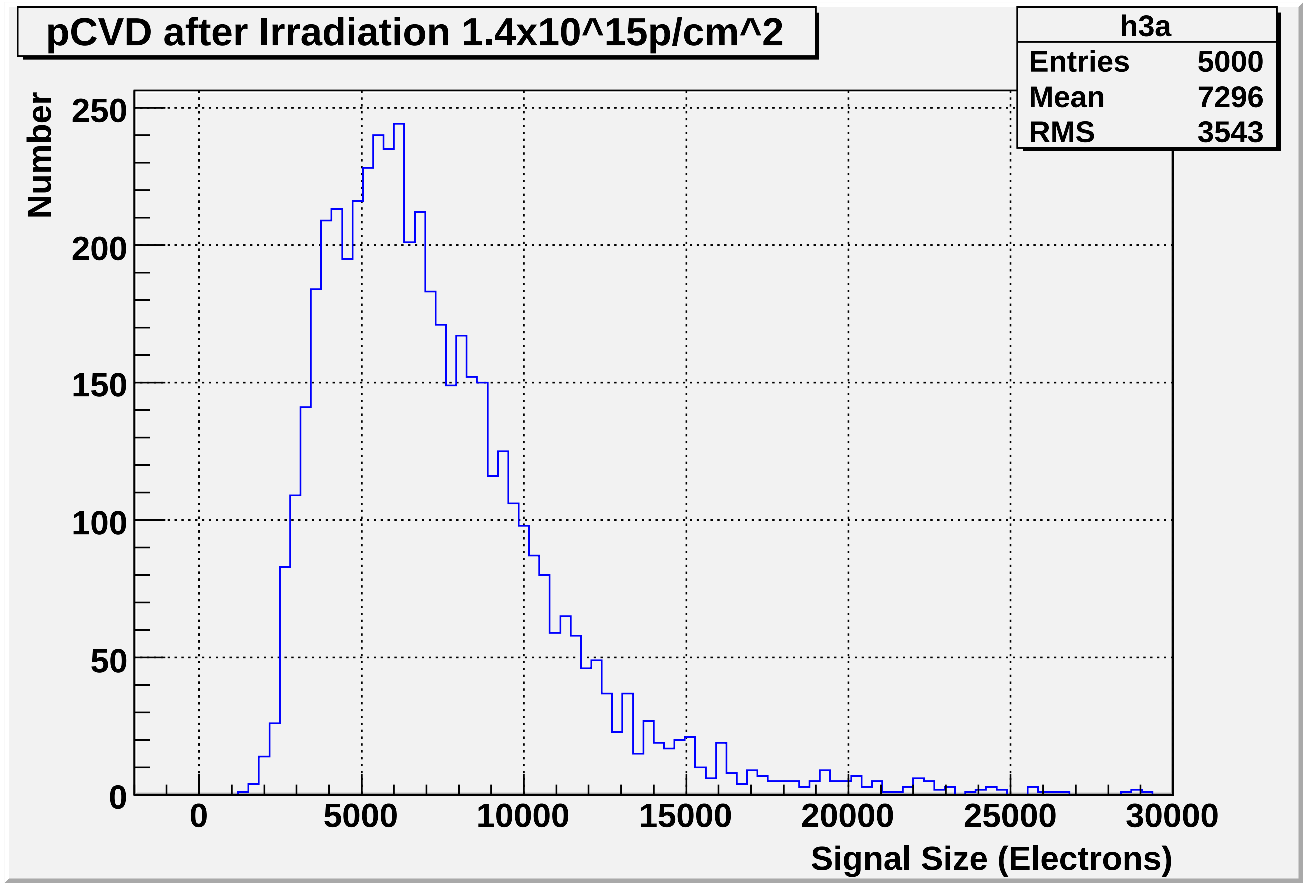




- Patterning the diamond → pads, strips, pixels!
- Successfully made double-sided devices; could be made edgeless.
- Use trackers (strip or pixel) in radiation studies - charge and position.

pCVD Diamond After Irradiation

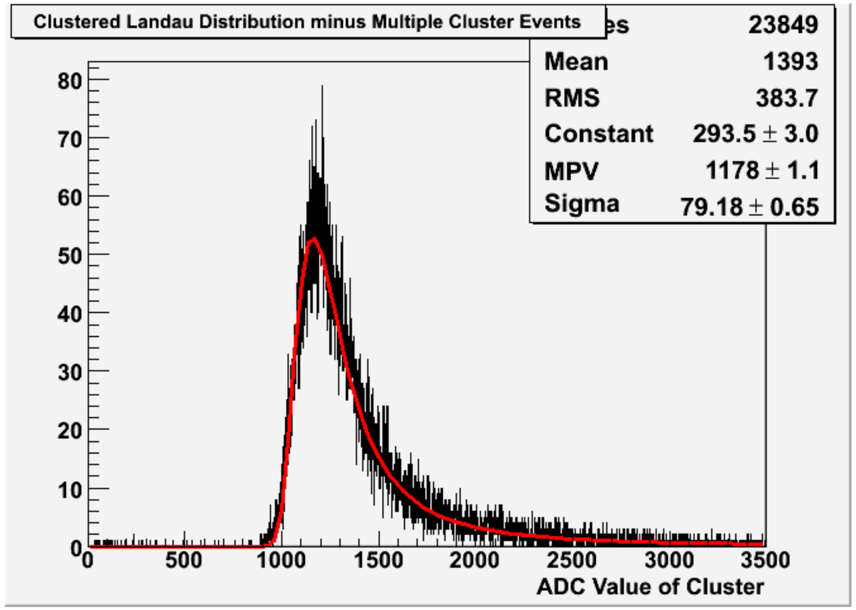
Polycrystalline CVD (pCVD) Diamond irradiations at 1.4x10^{15}

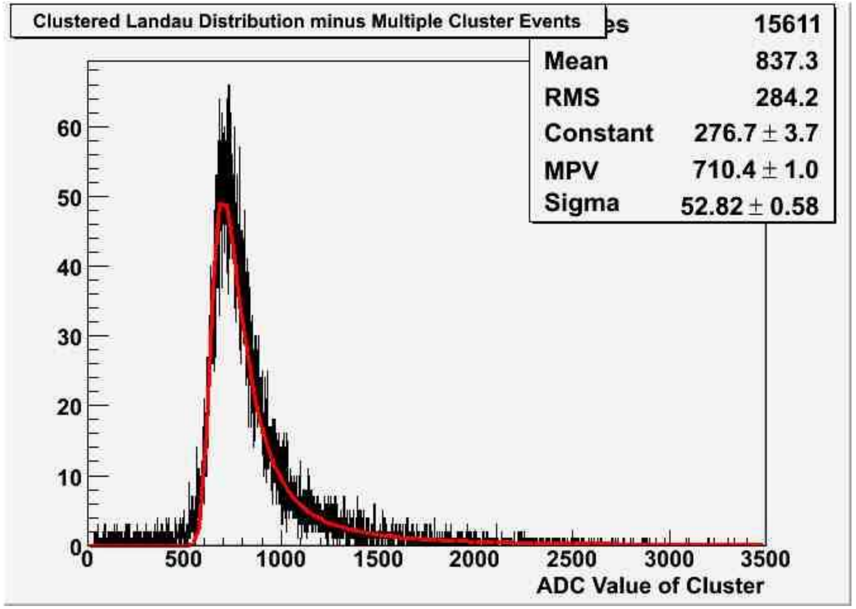


- Application is pixel detectors
- At LHC (FE-I3), Thresholds are $\sim$ noise(1400e) plus overdrive(800e)
- PH distributions look good after irradiation of 1.4x10^{15}p/cm^2.

scCVD Diamond After Irradiation

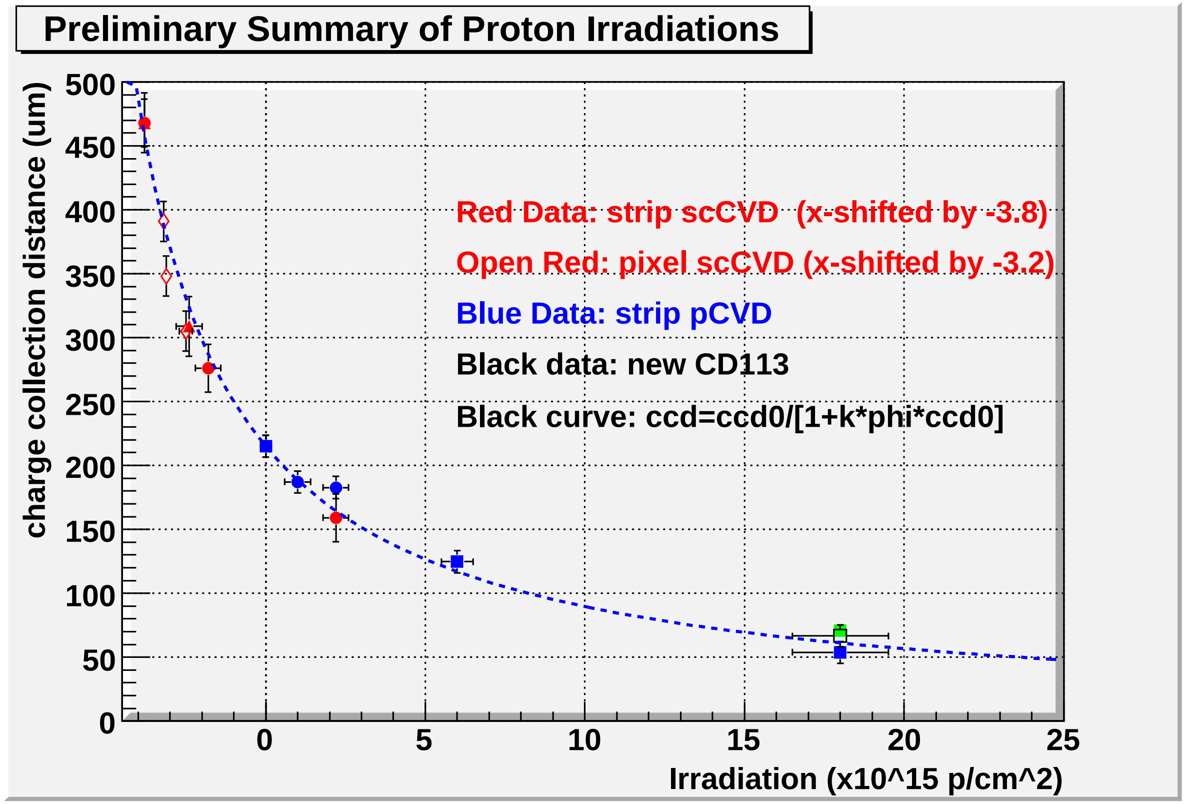
Single Crystal CVD (scCVD) Diamond irradiations at 1.5x10^{15}





- PH distributions look narrow before and after irradiation
- PH distributions after 1.5x10^{15}p/cm^2 $\rightarrow \epsilon > 99\%$.

24GeV Proton Irradiation Summary 2009:



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

Work in Progress 2009:

- Irradiations already performed awaiting test beam:
  - Sendai - 1×10^{16} 70MeV protons/cm^2
  - Ljubljana - 1×10^{16} neutrons/cm^2
- Irradiations in progress:
  - Karlsruhe - 25MeV protons

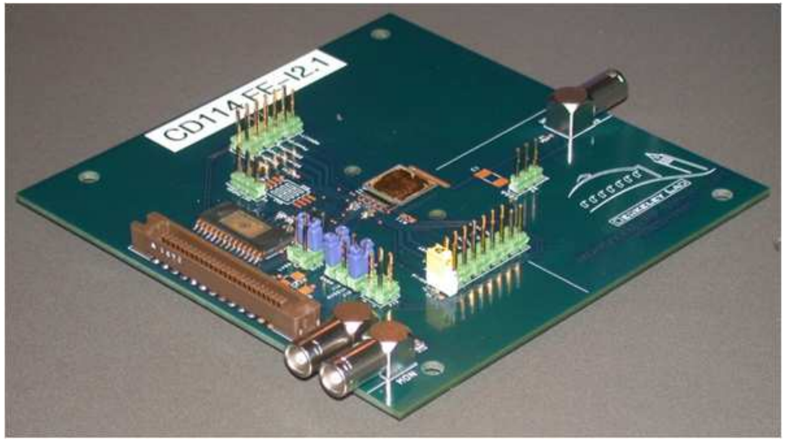
In diamond 70MeV protons have $\sim$3x larger damage constant than 24GeV

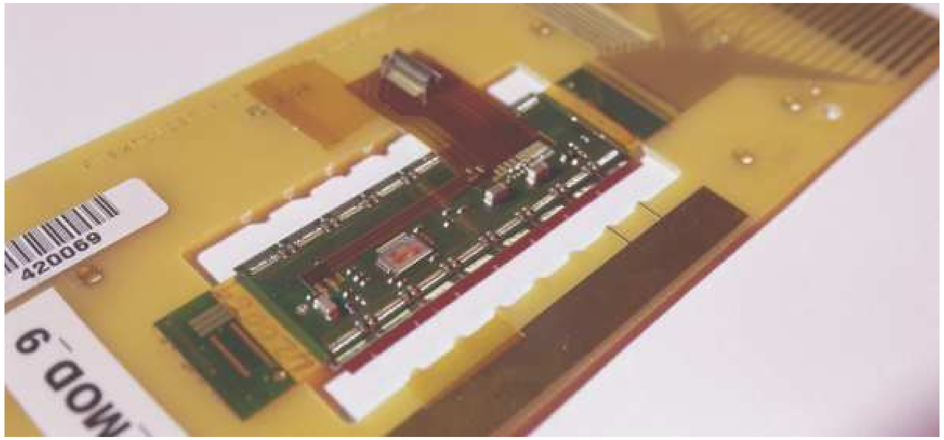
pCVD and scCVD Pixel Detectors

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

ATLAS Diamond Pixel Detectors

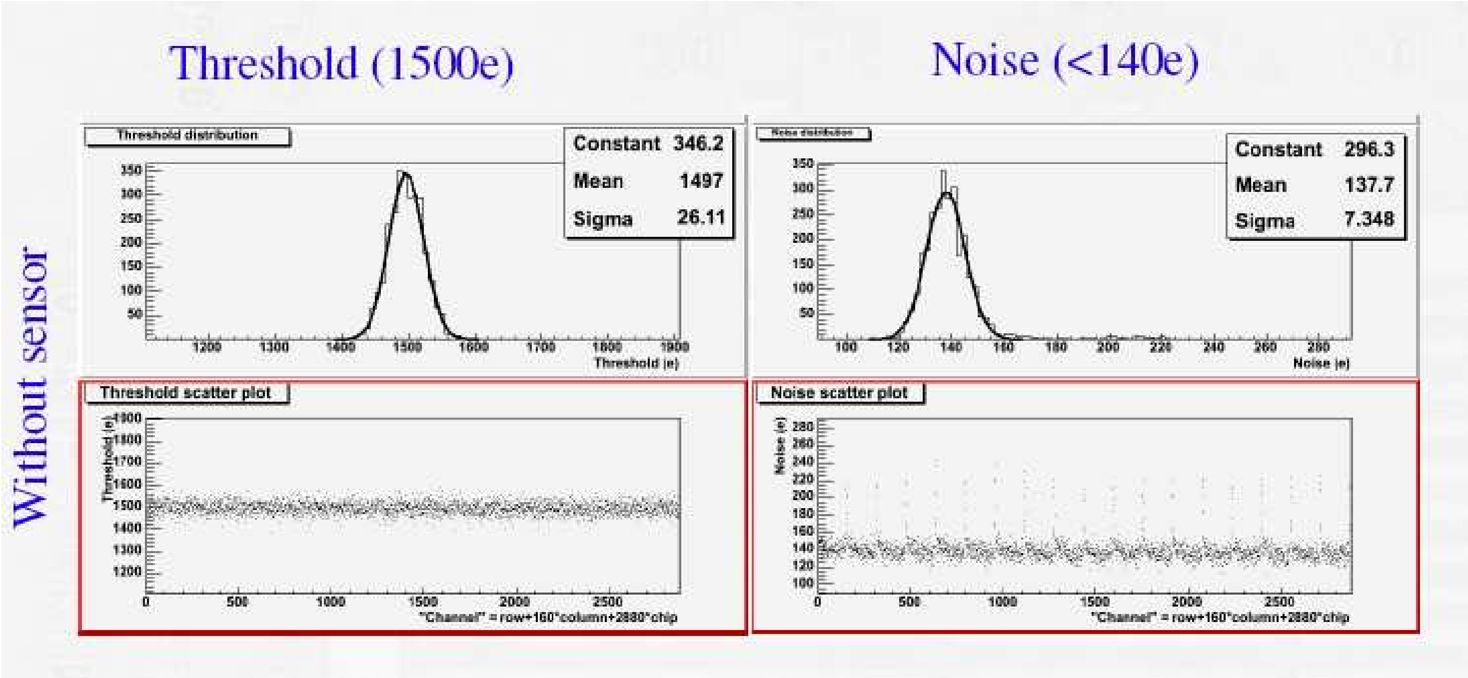
Recall: Full 16 Chip and 1 chip ATLAS diamond pixel modules





- 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

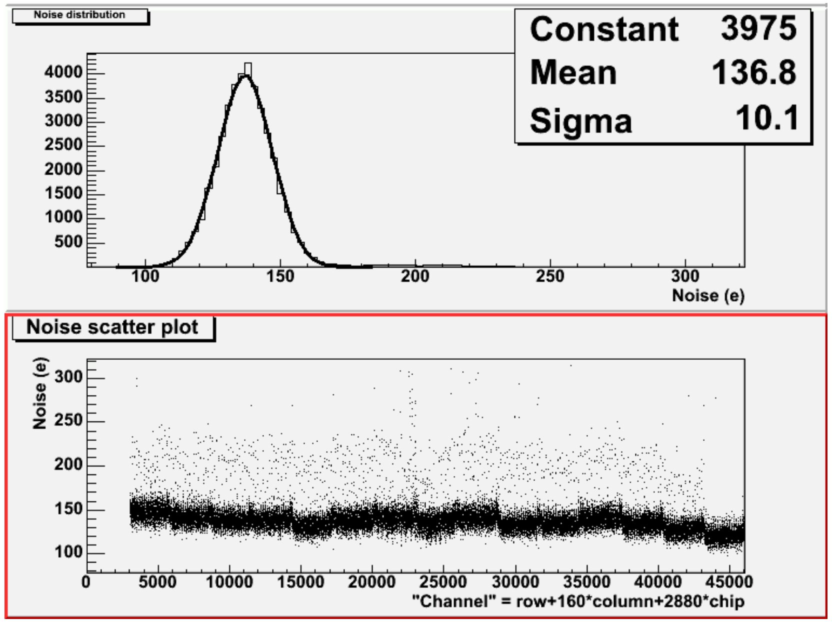
The ATLAS pixel module - Bare Chip, No Detector - Noise, Threshold

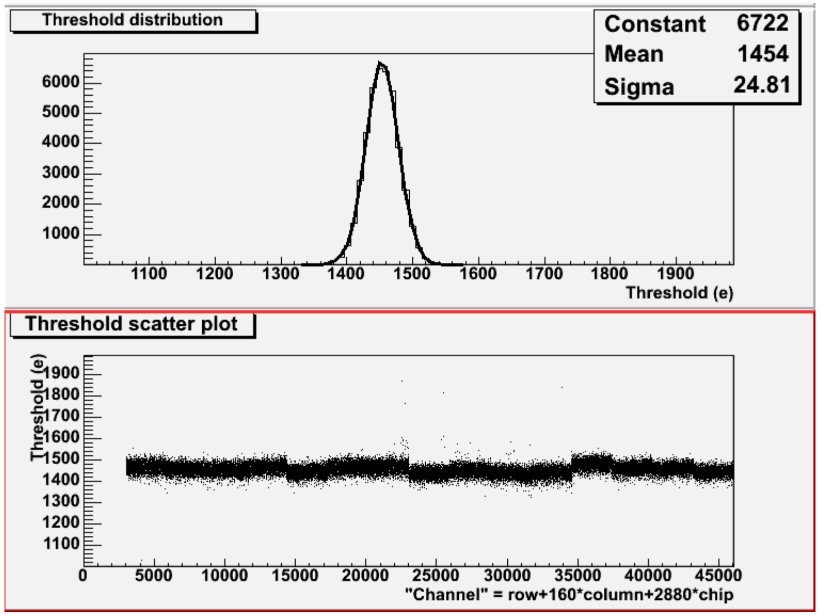


Results: Bare Noise $\sim 140e$, Bare Mean Threshold $\sim 1500e$,
Bare Threshold Spread $\sim 25e$.

ATLAS pCVD Diamond Pixel Detectors

The full ATLAS diamond pixel module - Noise, Threshold

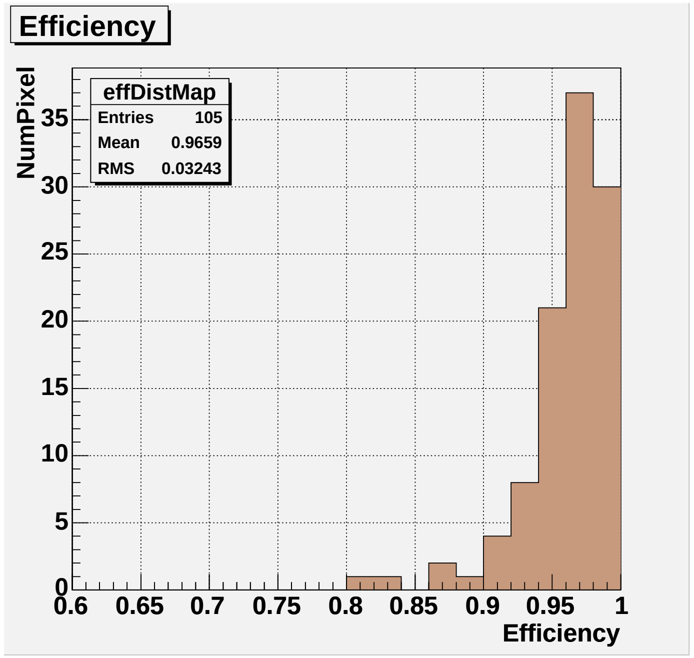


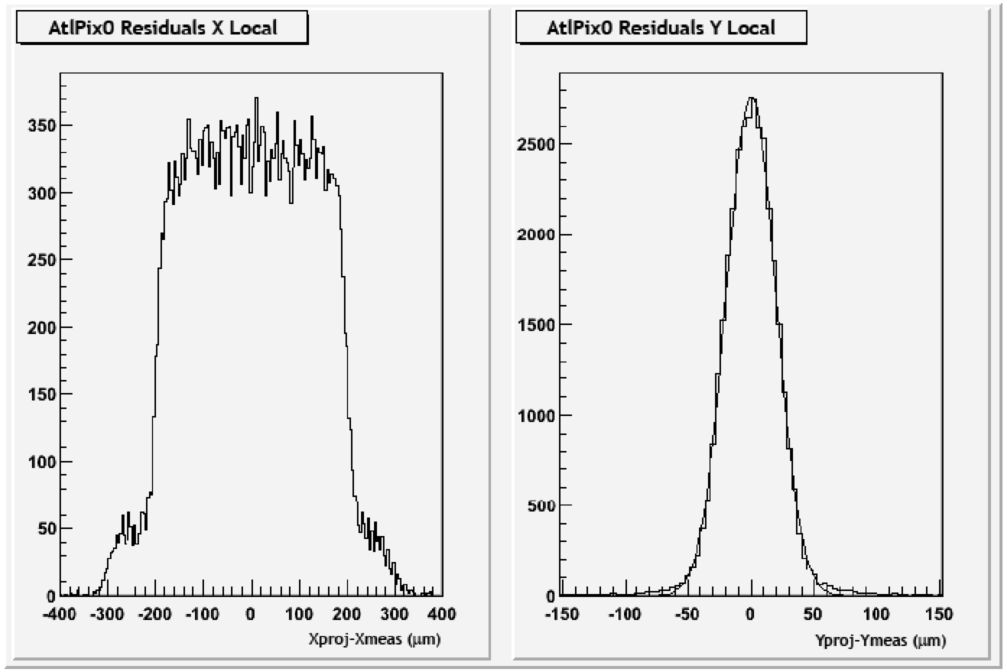


Results: Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$.
Noise, threshold, threshold spread do not change from bare chip.

$\rightarrow$ Advantage of low capacitance, no leakage current

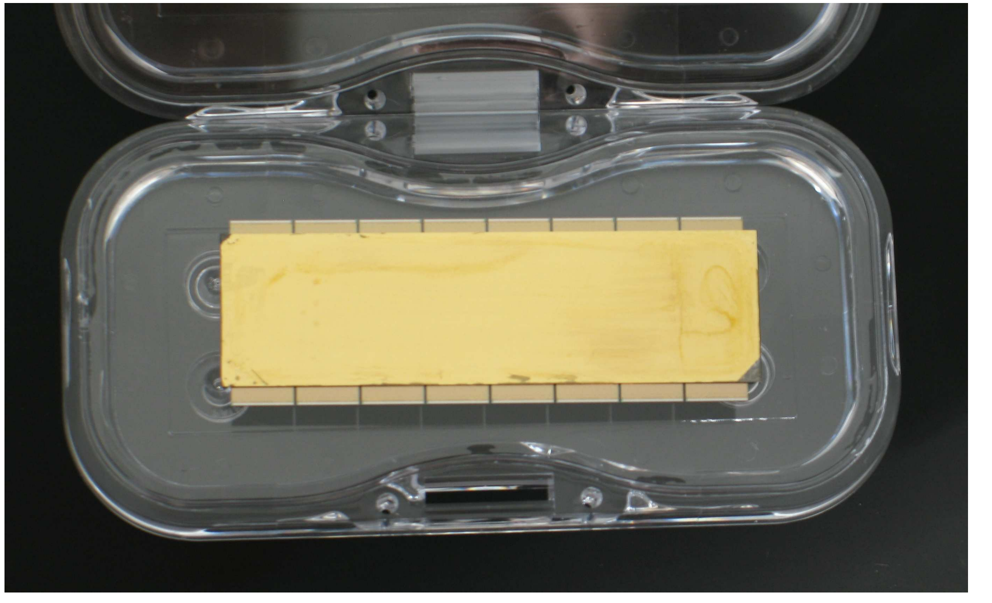
Recall: Full ATLAS diamond pixel module - Efficiency, Resolution





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

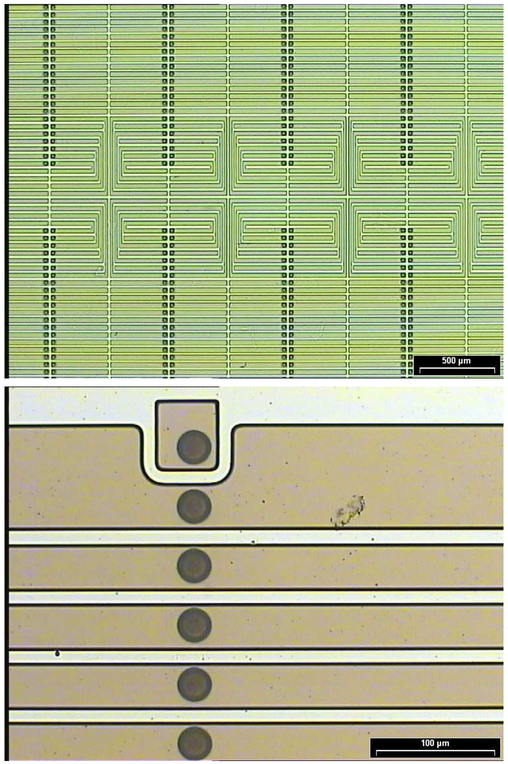
New: First Full Diamond Pixel Module Made in Industry



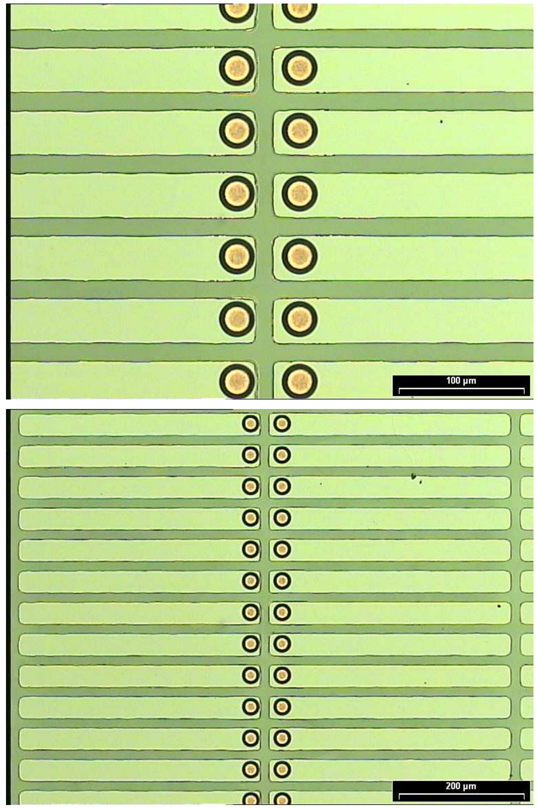
- Begin with a tested raw diamond
- Clean $\rightarrow$ IZM in Berlin
- Receive finished, metalised, bump-bonded module!

New: First Full Diamond Pixel Module Made in Industry

Diamond sensor pixel metallisation



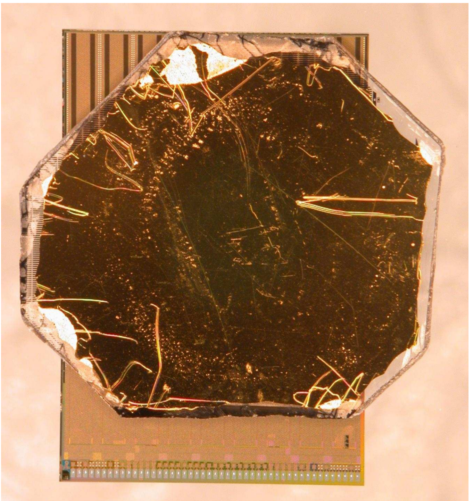
Status after elelctroplating of pad metallisation and lithography for pixel metallisation patterning

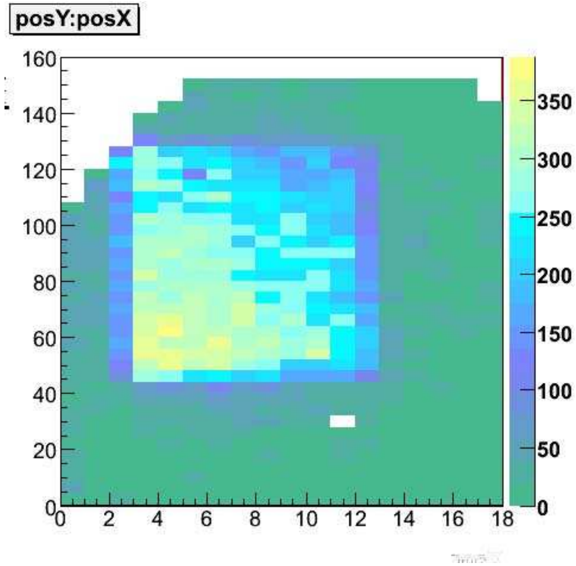


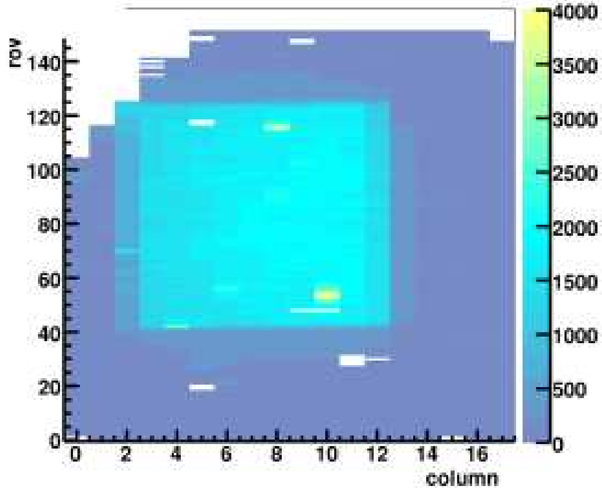
result after pixel metallisation patterning

Fraunhofer Institut Zuverlässigkeit und Mikrointegration

The First scCVD ATLAS diamond pixel detector

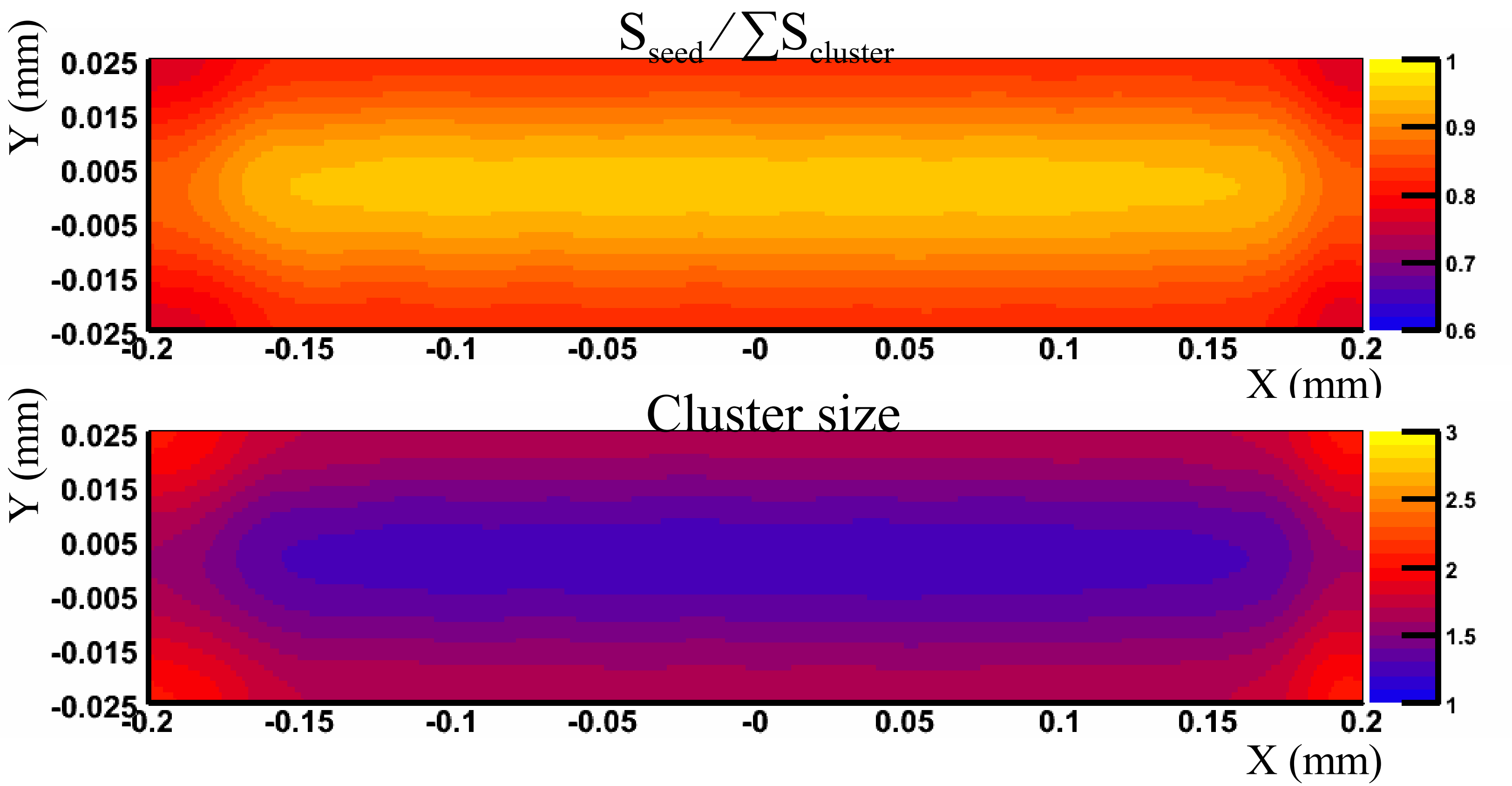






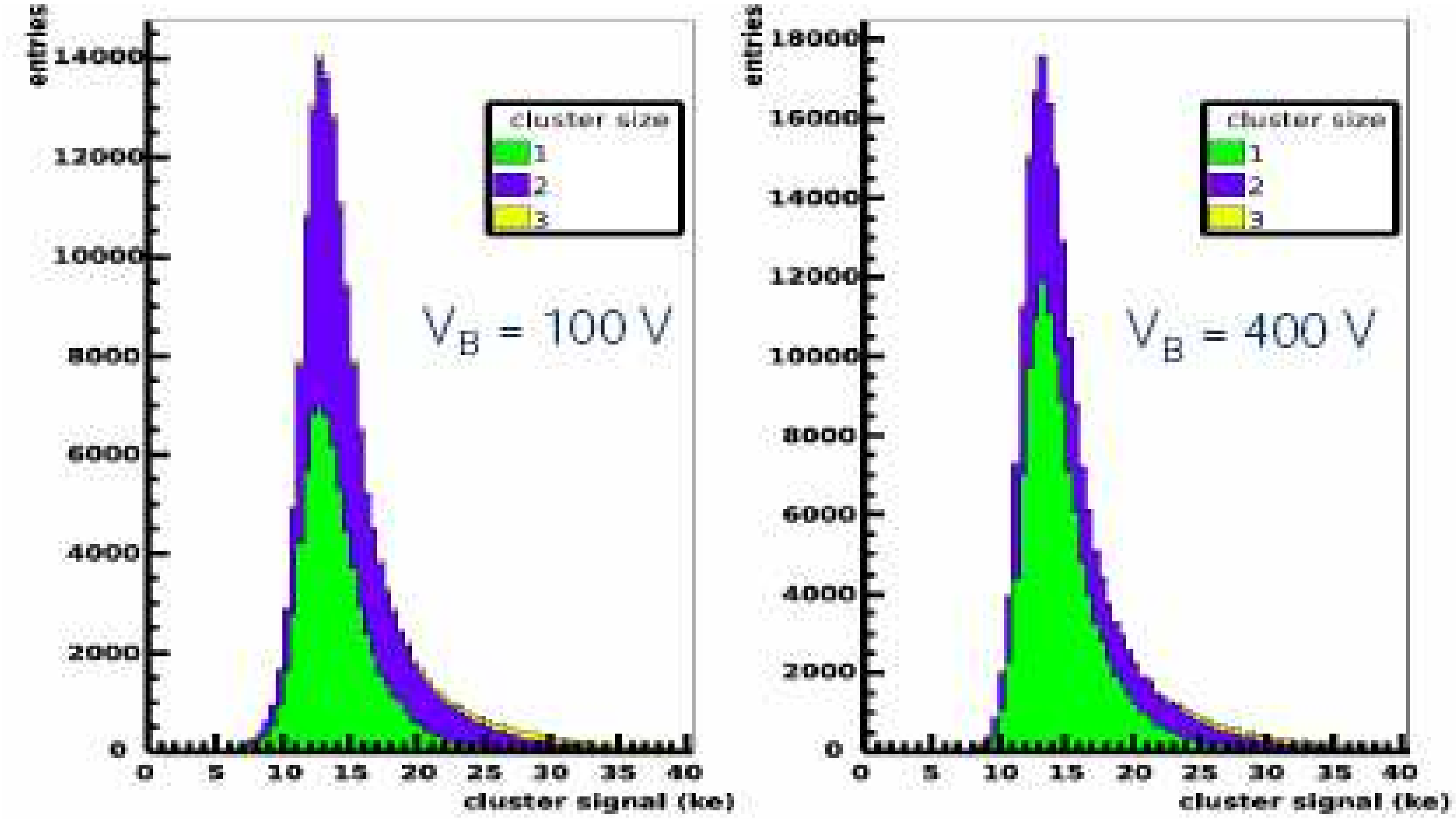
- The hitmap plotted for all scintillation triggers with trigger in telescope.
- The raw hitmap looks goods - $\sim$ 1 dead pixel

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



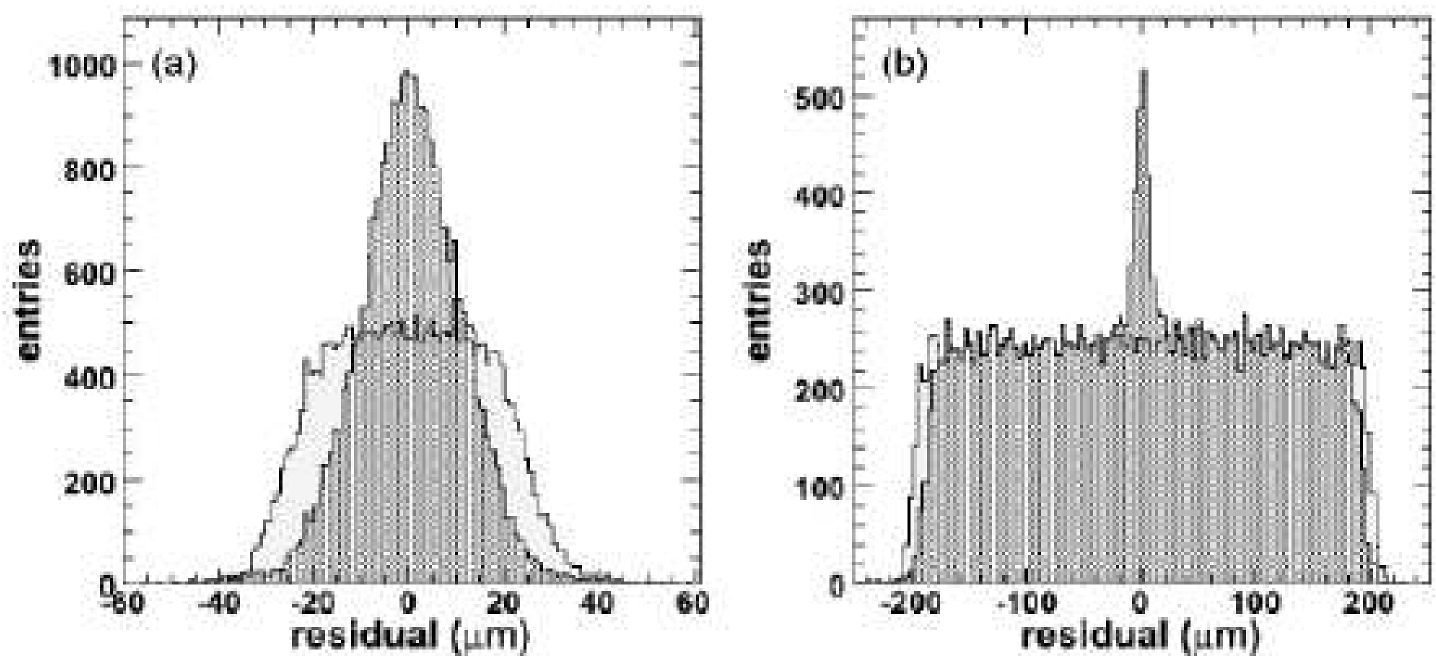
- Charge sharing as expected

New This Year: Cluster Signal



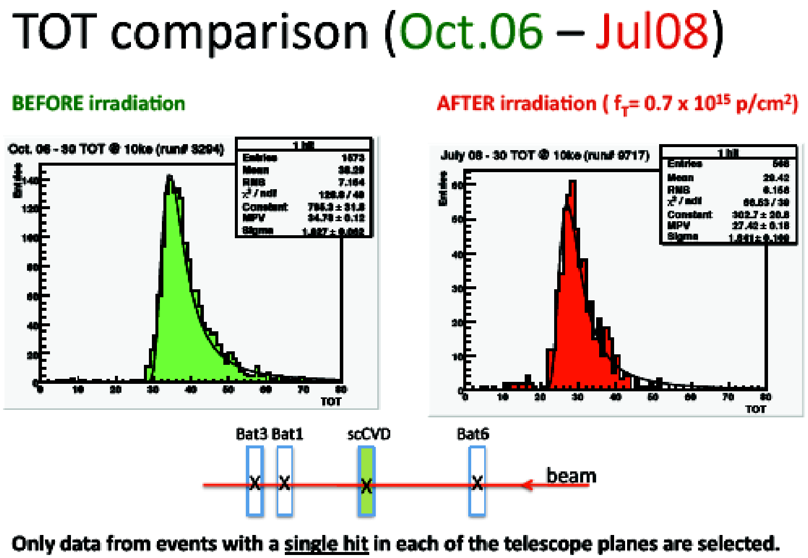
- As voltage is raised → more 1-hit clusters
- Larger drift speed → less lateral diffusion
- Cluster signal as expected

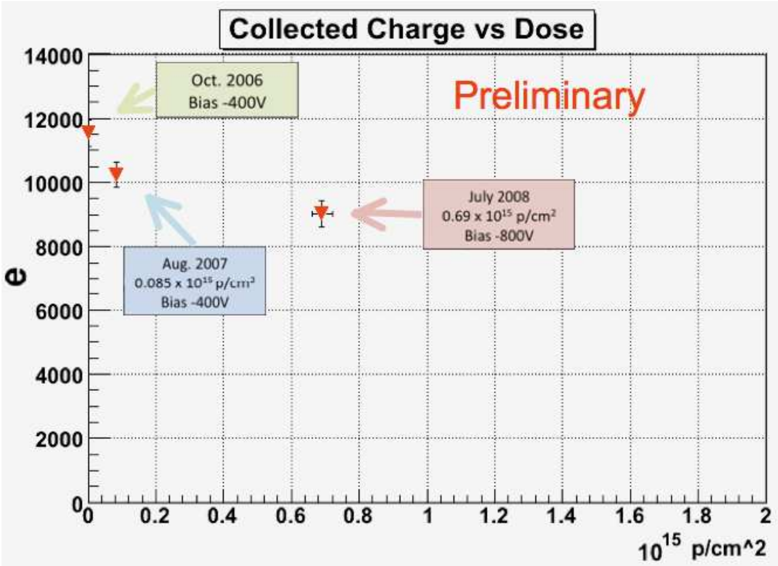
New This Year: Spatial Resolution (1-pixel and 2-pixel η)



- 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





- Full 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

Next Steps Checklist

- **Re-Test ATLAS Pixel Module at CERN - Done**
  - Data analysis → 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 5-10 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

→ Progress on many fronts!!!

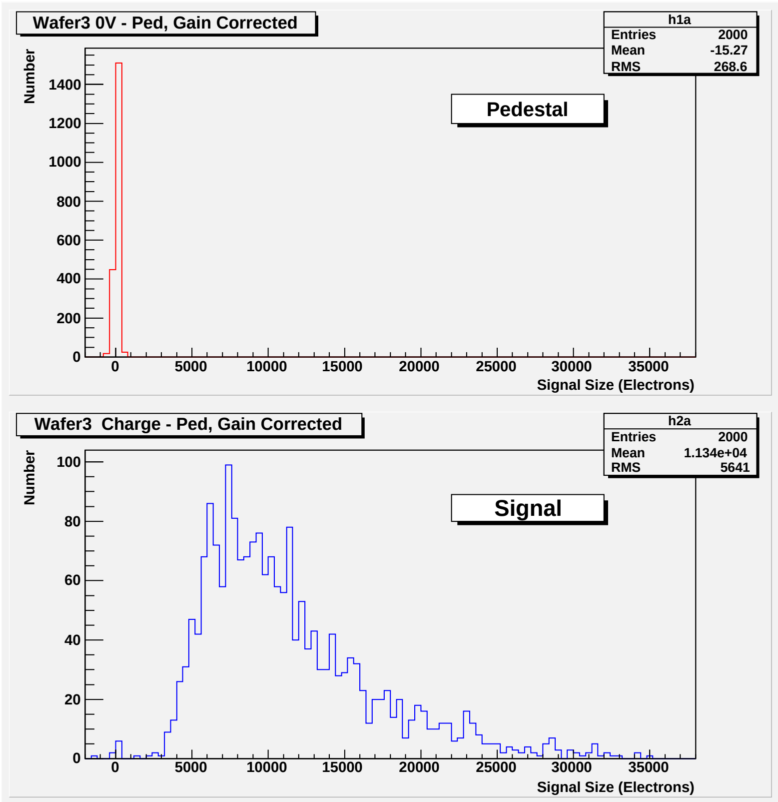
CVD Diamond Material Status

- collection distance
- polycrystalline, single crystal
- new manufacturers

Material Status - Polycrystalline CVD Diamond

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

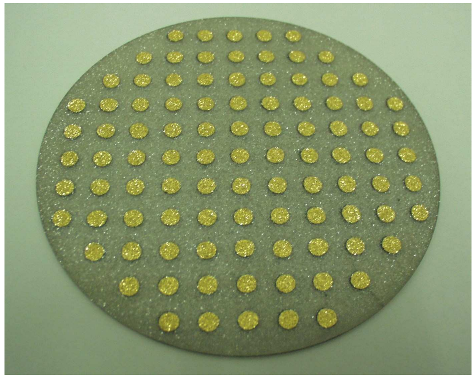
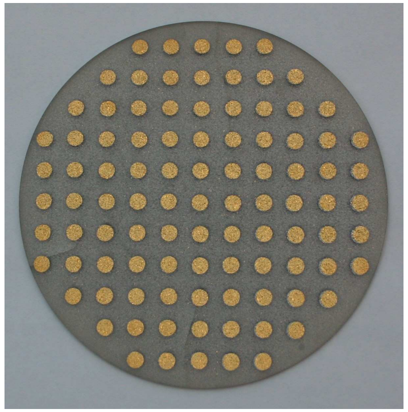
- Contacts on both sides - structures from μm to cm
- Usually operate at E=1-2V/μm
- Test Procedure: dot $\longrightarrow$ strip $\longrightarrow$ pixel on same diamond!

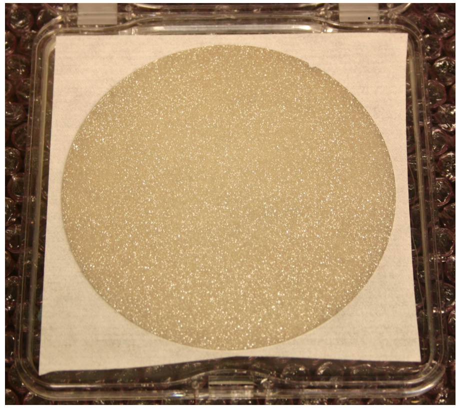


- Q_{MP} = 8500-9000e
- Mean Charge = 11300e

- Source data well separated from 0
- Collection Distance now ≈ 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

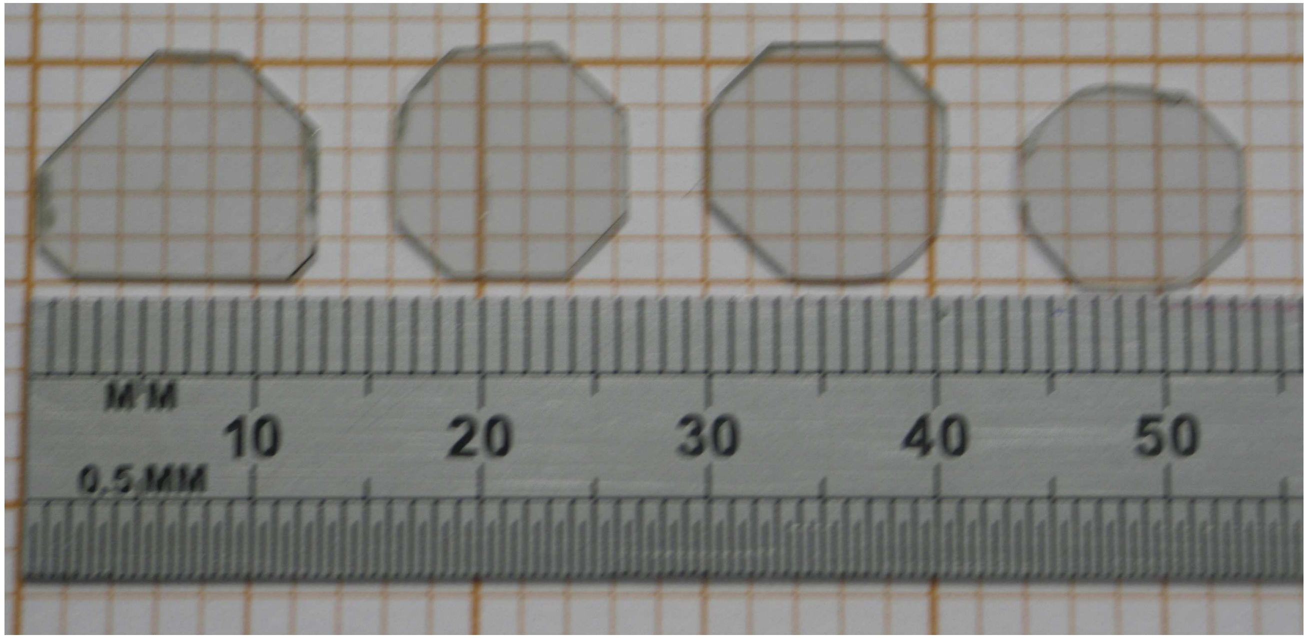


Recent pCVD wafers ready for test - Cr/Au dots are 1 cm apart

- New wafers continually being produced.
- Wafer collection distance now typically 250μm (edge) to 310μm (center).
- Contract for material with ccd $>$ 275μm $\rightarrow$ 300μm.
- Samples available by contacting DDL

Material Status - Single Crystal CVD Diamond

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.

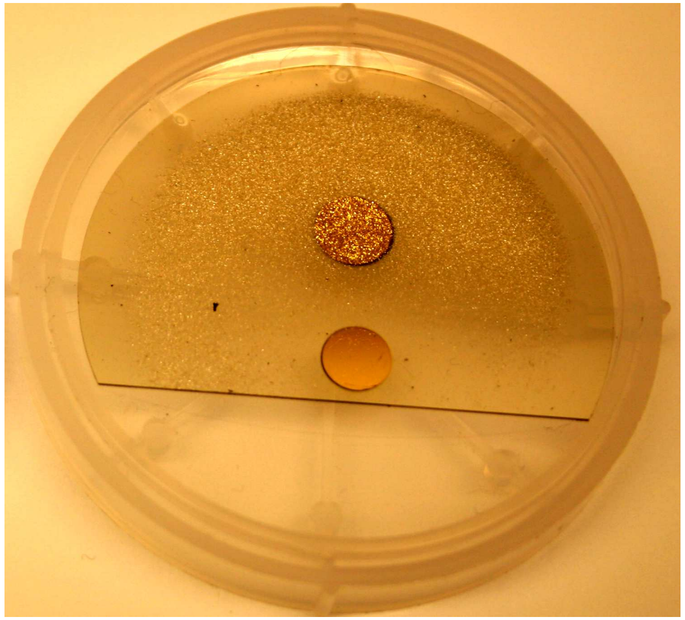
Largest scCVD diamond grown $\approx$ 14 mm $\times$ 14 mm.

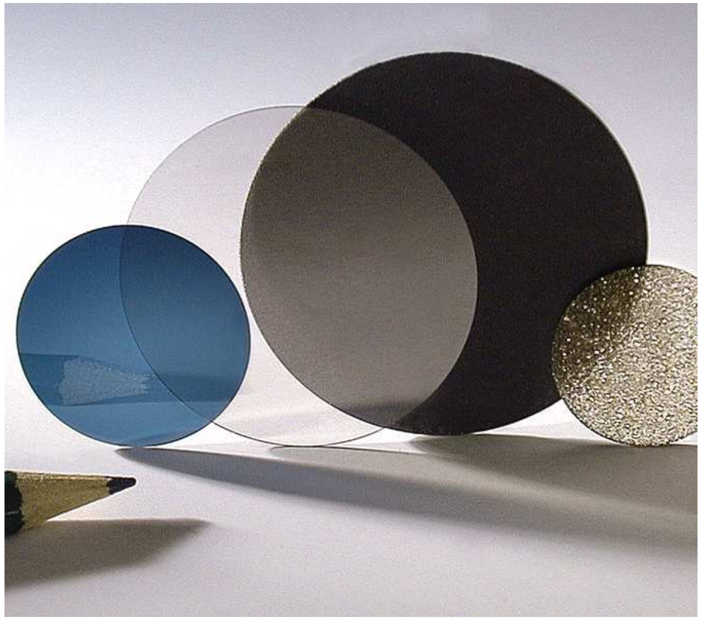
First results from irradiated scCVD pixel module.

Material Status: Additional Manufacturers

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$100μm
- RD42 is working with these manufacturers on both pCVD and scCVD

Summary

- **Radiation Hardness of Diamond Trackers**

  Using trackers allows a correlation between S/N and Resolution

  With Protons:

  - Dark current decreases with fluence
  - pCVD and scCVD have same damage curve

- **Diamond Pixel Detectors**

  Successfully tested a complete ATLAS pCVD module and scCVD module

  Five full pCVD modules in production

  Diamond R&D Approved by ATLAS for LHC Upgrade

- **Further Progress in Charge Collection**

  pCVD - 320 μm collection distance diamond attained in wafer growth

  pCVD - 275-325 μm collection distance for modules

  scCVD - Full charge collection, fast, large signals, Getting larger?

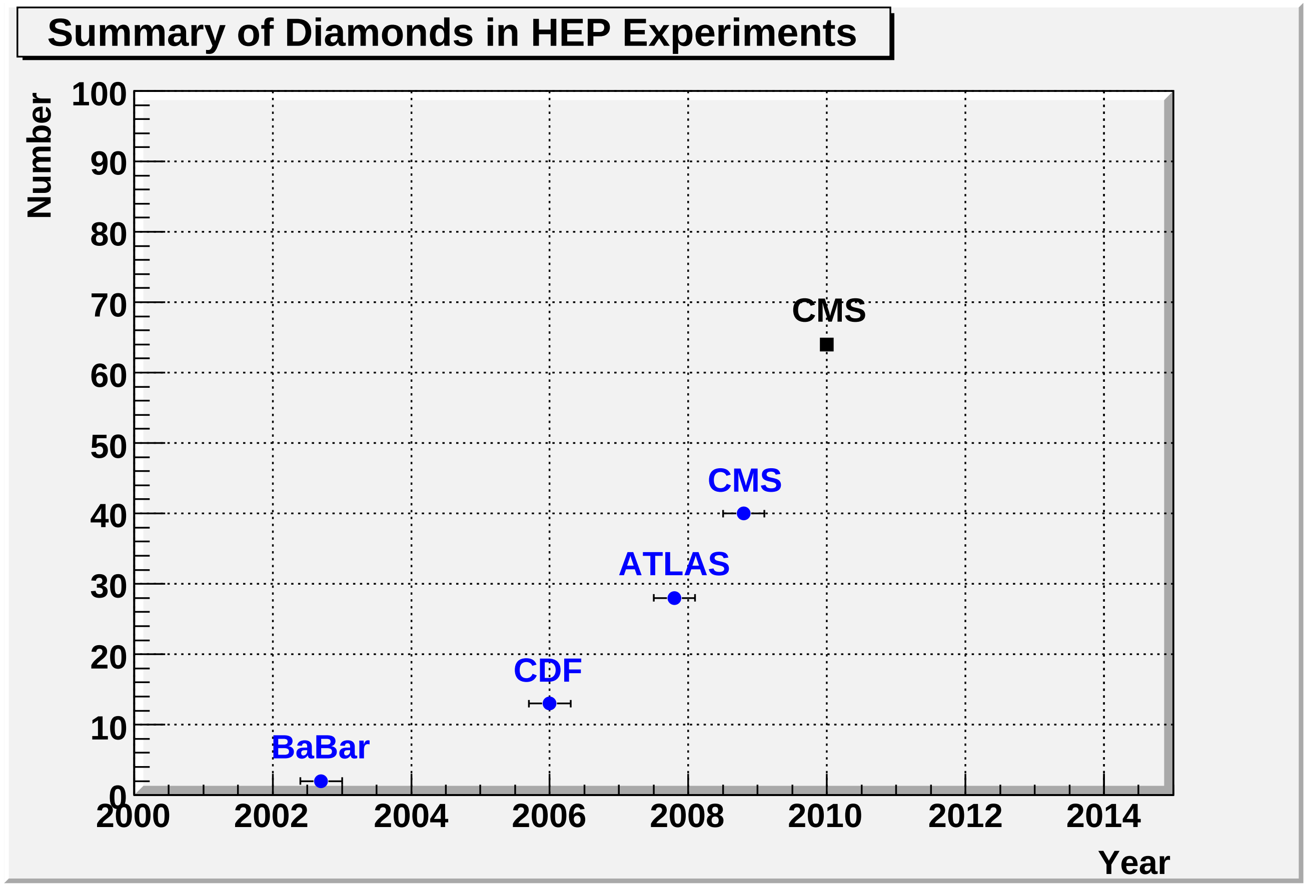
- **Beam Conditions Monitoring**

  see A. Gorišek Talk on ATLAS diamond BCM and BLM

  Application of diamond successful in BaBar, CDF, Alice, ATLAS, CMS, LHCb.

Summary

CVD Diamond Used in High Energy Physics Experiments



Blue data installed; black data planned.
Diamond use is on the rise!