ATLAS Diamond Pixel Modules

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For the RD42 Collaboration

Outline:

- Diamonds in HEP
- Trackers for IBL (ATLAS) and sLHC
- scCVD and pCVD pixel modules
- Irradiation Studies
- Summary

The RD42 Collaboration

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78 participants

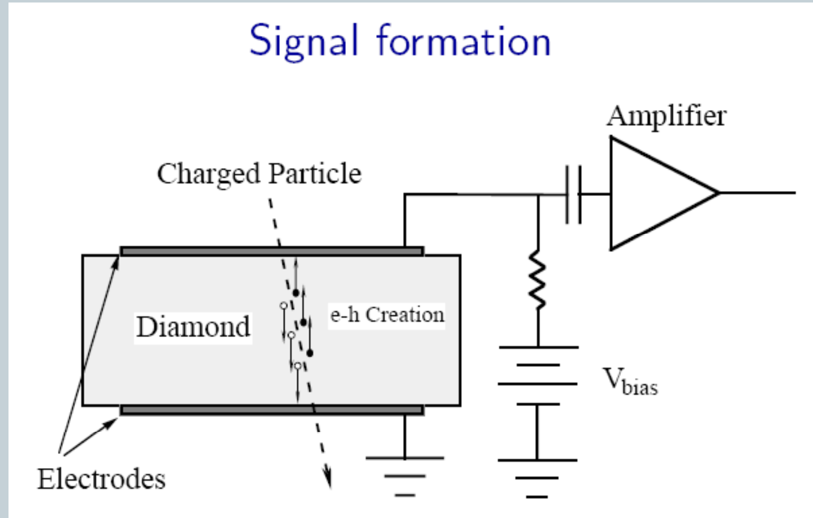
24 institutes

Diamond for Particle Tracking

Properties of diamond

- Radiation hard
- Low capacitance
- Small leakage current
- Room temperature operation
- Fast signal collection time
- High thermal conductivity

Disadvantage: Smaller signal than Si



Parameter of Interest: Charge Collection Distance

$$Q = \frac{d}{t} Q_0$$

Q: collected charge
Q_o: ionized charge
d: charge collection distance
t: thickness of the diamond

$$d = (\mu_e \tau_e + \mu_h \tau_h) E$$

E: average electric field
μ_e, μ_h: mobility of electrons/holes
τ_e, τ_h: lifetime of electrons/holes

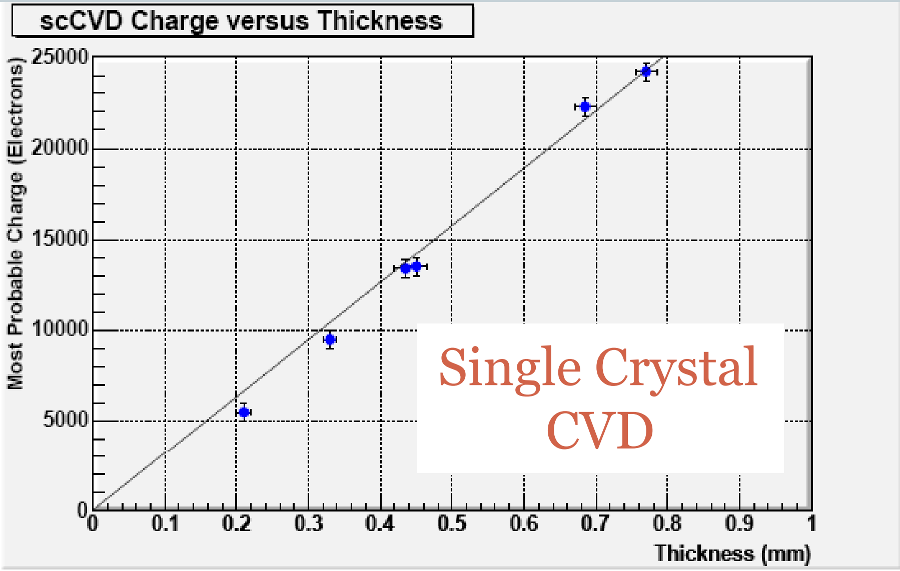
Experimentally:

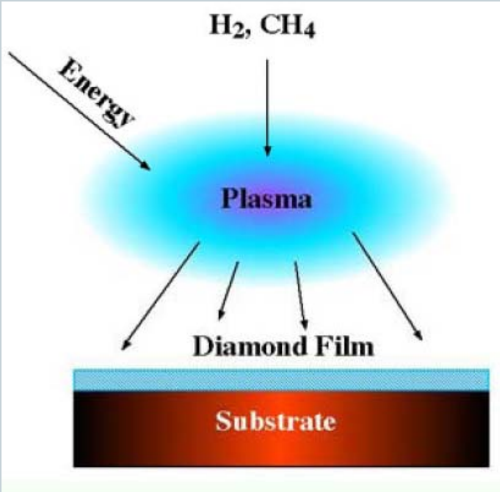
$$\bar{d} = \frac{\langle Q \rangle \;\; [e]}{36 \;\; e/\mu\mathrm{m}}$$

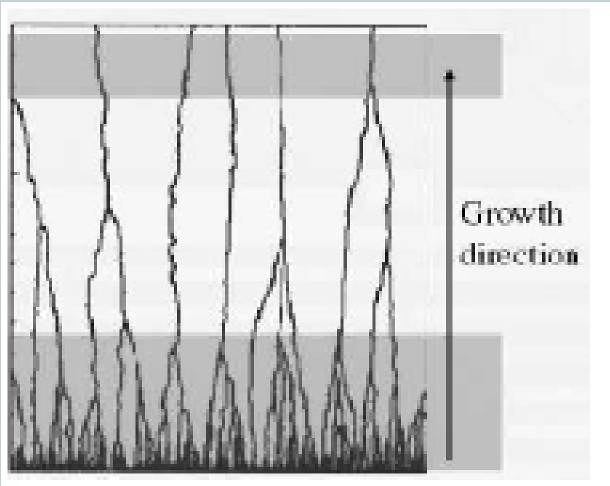
Fabrication of Diamond Sensors

Chemical Vapor Deposition

- Microwave growth reactor
- Diamond growth copies substrate
  - pCVD → several crystal seed centers
  - scCVD → single crystal substrate (limited to ~1 cm²)
- Best pCVD material is grown thick ~2mm
- Polishing and thinning can improve charge collection distance





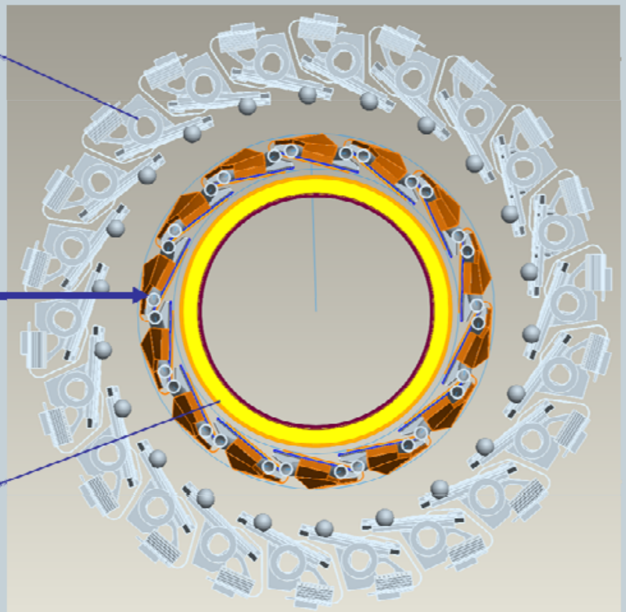


Metallization of Diamond

- No doping necessary
- Metal contacts applied by sputtering or evaporation
- Contacts can be applied as pads, strips or pixels

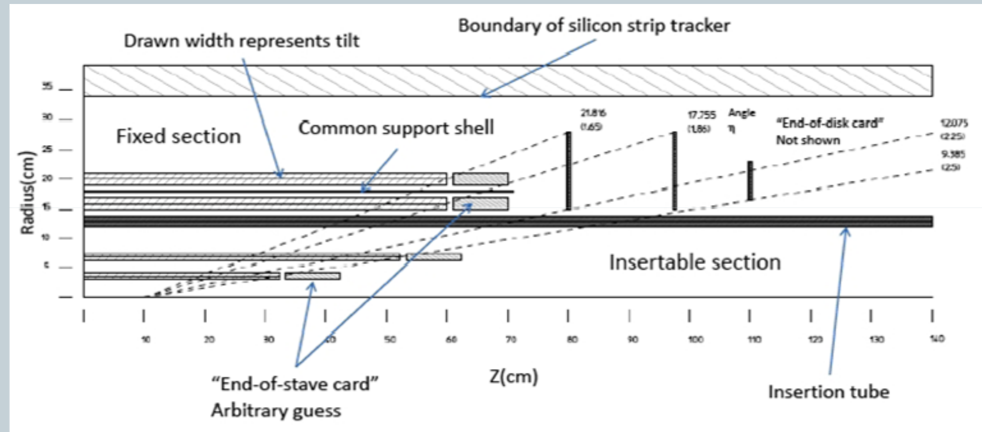
ATLAS upgrade: IBL & sLHC

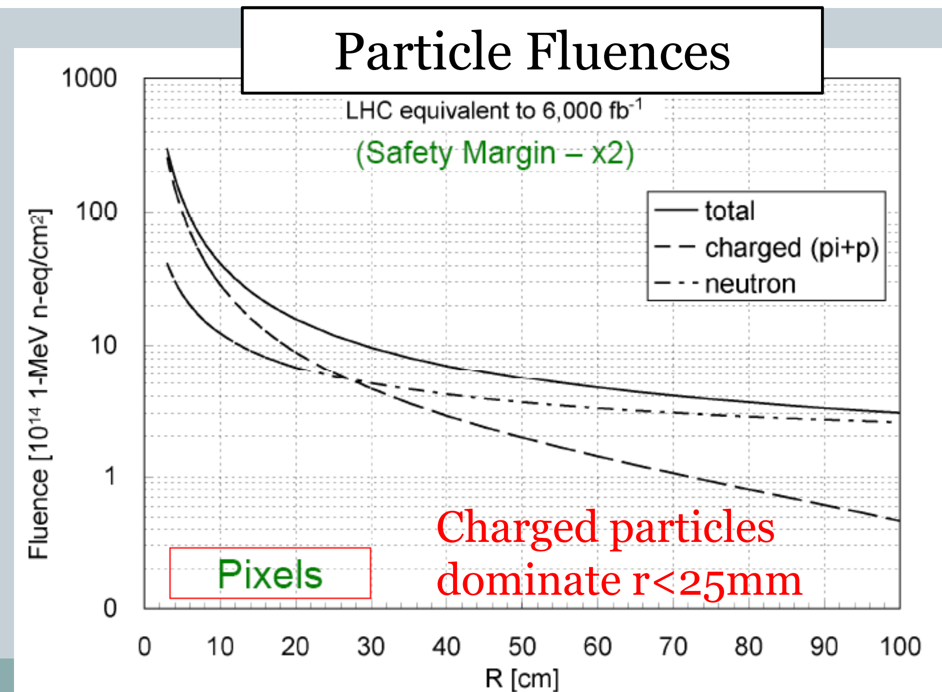
Inner B-Layer for ATLAS Phase I upgrade



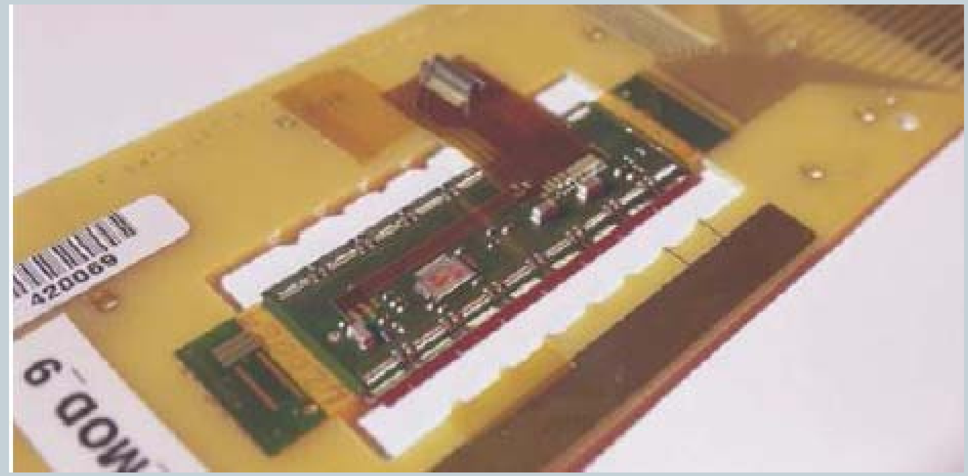
	Current Design (mm)	Phase I (proposed) (mm)
Beam aperture (10σ)	14	14
Alignment	2.6	2.6
Construction and deflection	2.6	2.6
Stability during run, and between alignments	9.8	5.8
Physical radius of pipe	29	25

sLHC Inner Detector Strawman





Diamond Pixel Modules

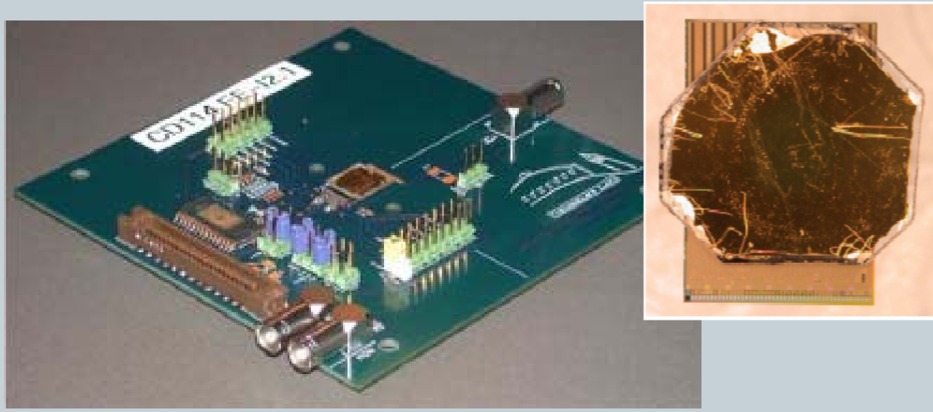


- 16 FE chip and single FE chip devices produced
- ATLAS pixel FE (FE-I3) and support electronics
- Bump-bonded at IZM (Berlin), dressed and tested in Bonn
- Typical operating parameters for FE-I3:

  threshold ~1450e-1600e   Noise ~ 140e

  Peaking time ~22ns   Overdrive ~800e

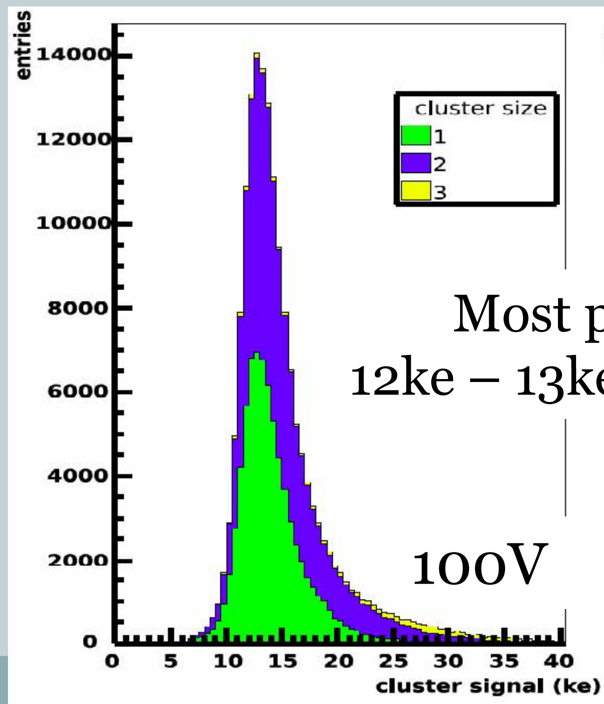
scCVD Diamond Pixel Module

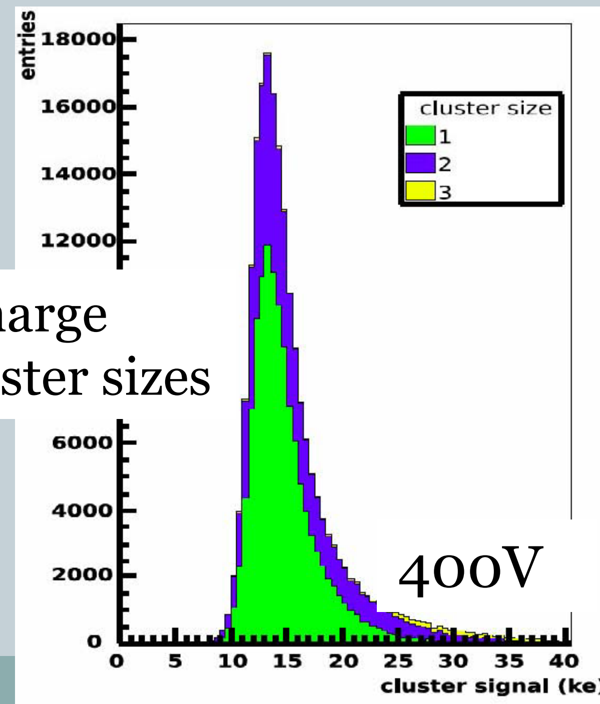


395μm thick scCVD diamond

- Sensor is ~10mm x ~10mm
- Constructed in Fall 2006
- 2200/2880 bump-bonded pixels
- 50x400μm
- Data taken at CERN: 120GeV pions

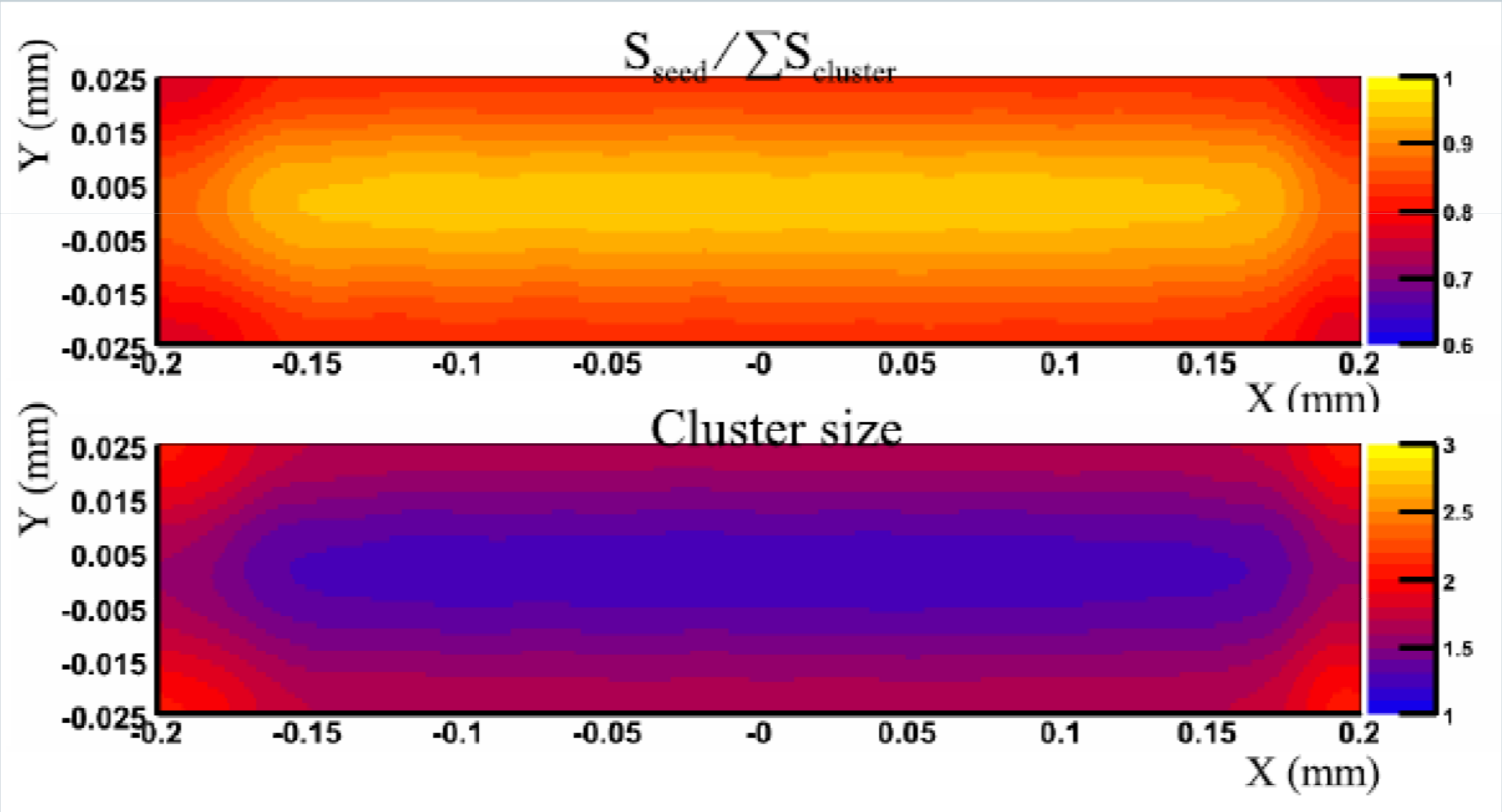
Cluster Signal





Most probable charge
12ke – 13ke for all cluster sizes

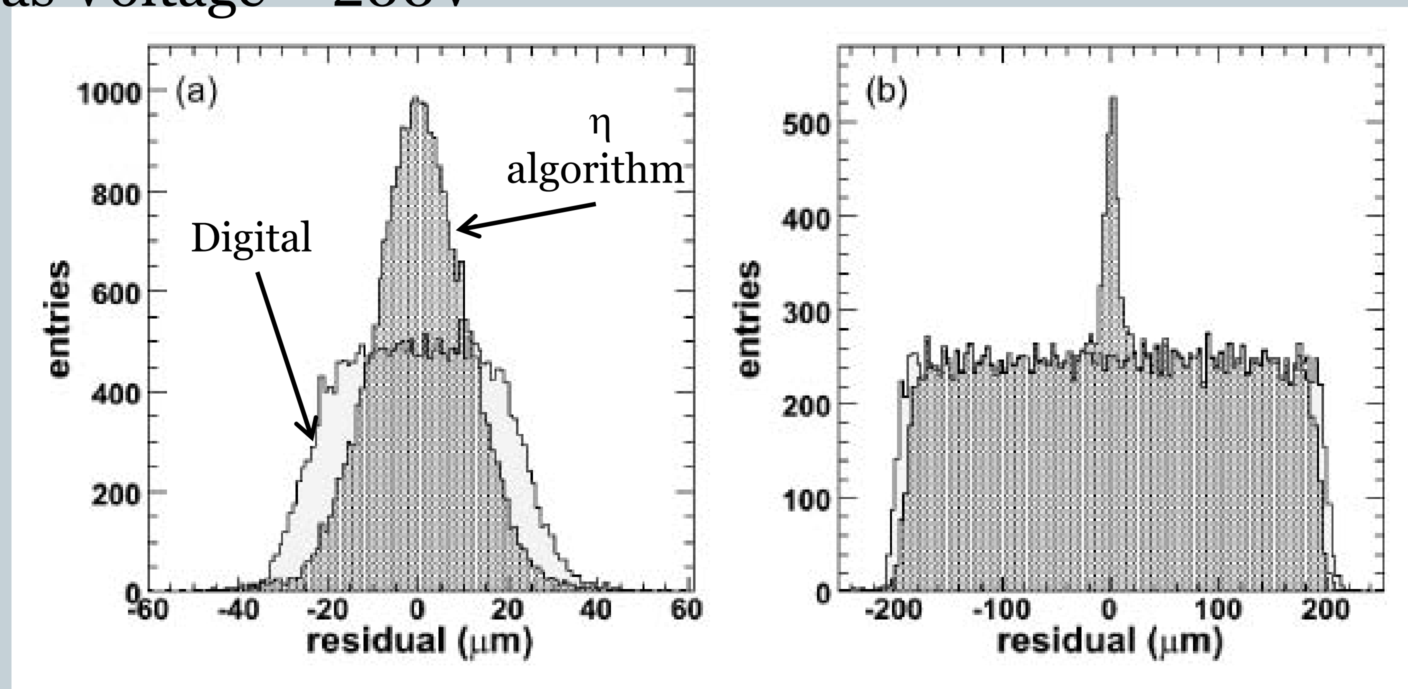
Charge Sharing



- Use tracking to predict hit position inside a pixel
- Bias and Threshold dependant
- Charge sharing and Cluster signal as expected

scCVD Module Resolution

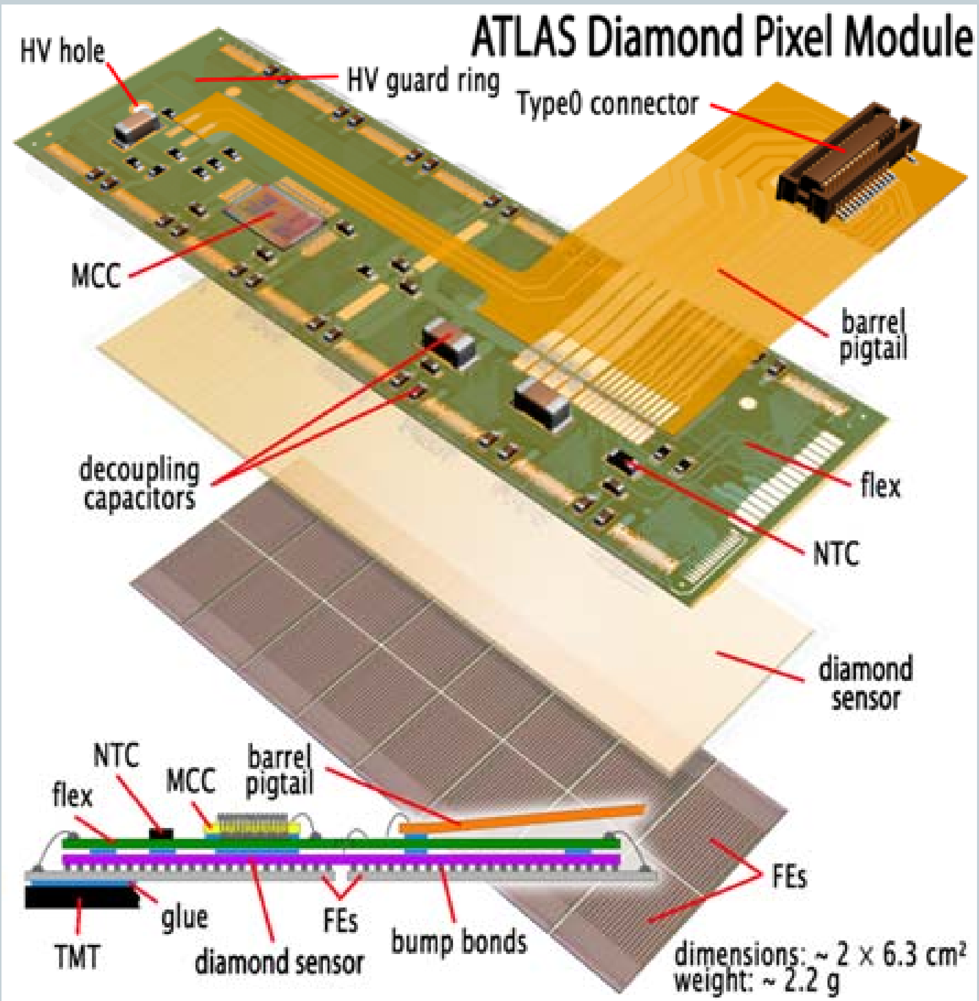
Bias Voltage = 200V

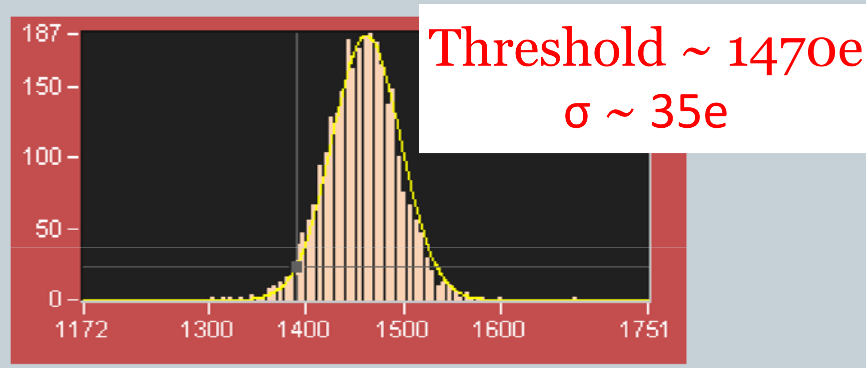


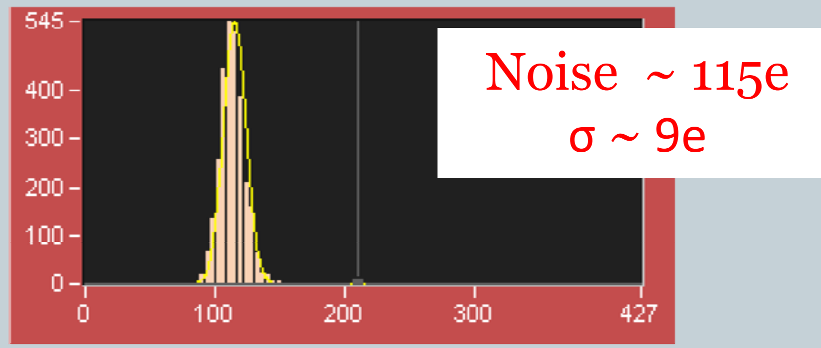
Measured resolution = 8.9 μm ±0.1 μm

- Normal incident tracks
- Signal/Threshold ~8
- Typical ATLAS silicon module resolution ~10 μm
- Lower Threshold → better resolution

Diamond Pixel Modules, ATLAS electronics







- pCVD sensor, ~800μm thick
- 16 ATLAS FE-I3 chips
- 61 mm x 16.5 mm active area
- 46k pixels, 50μm x 400(600) μm

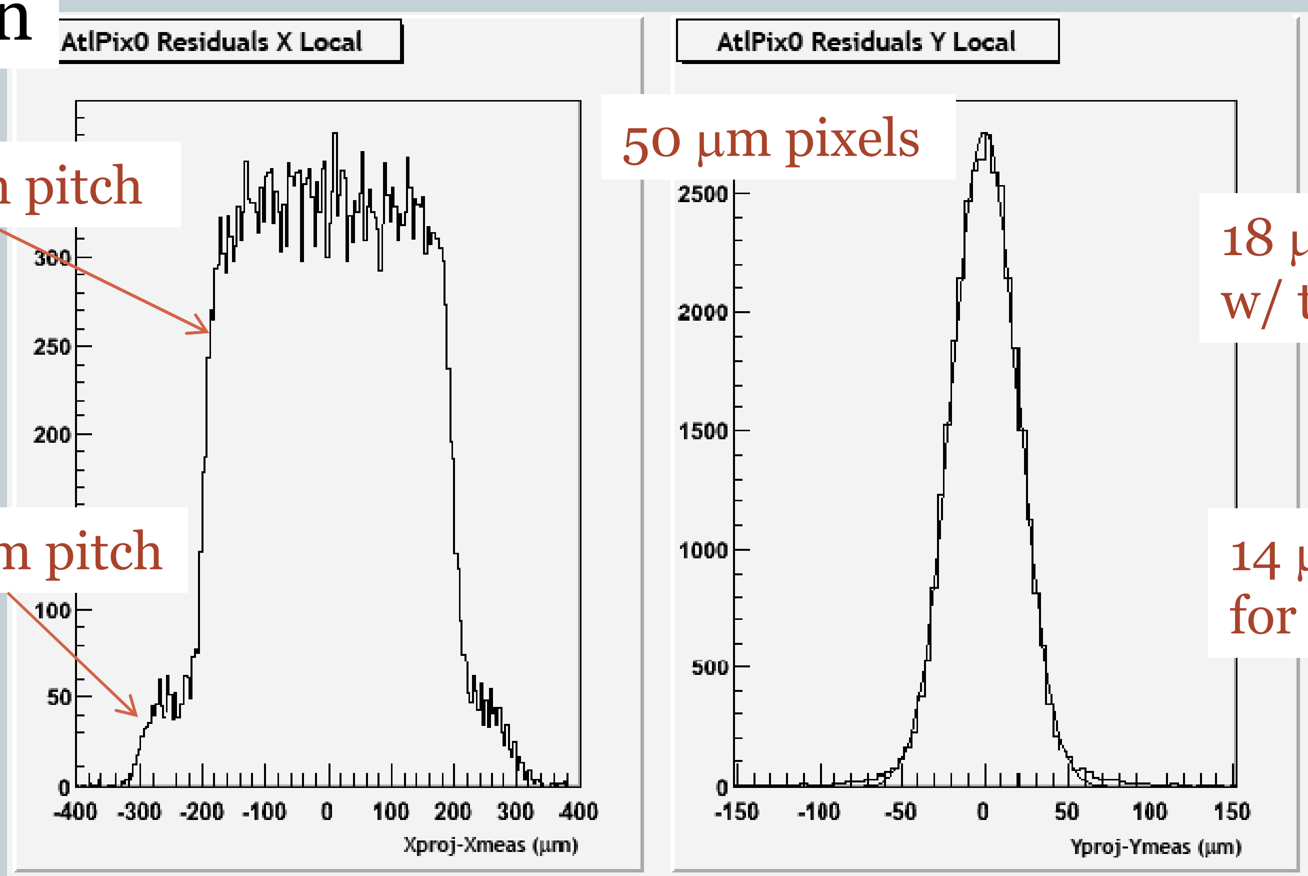
Full ATLAS Diamond Pixel Module

Resolution

400 μm pitch

600 μm pitch

50 μm pixels



18 μm residual w/ telescope

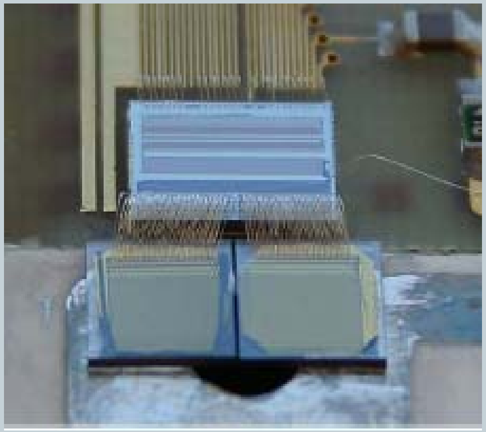
14 μm residual for diamond

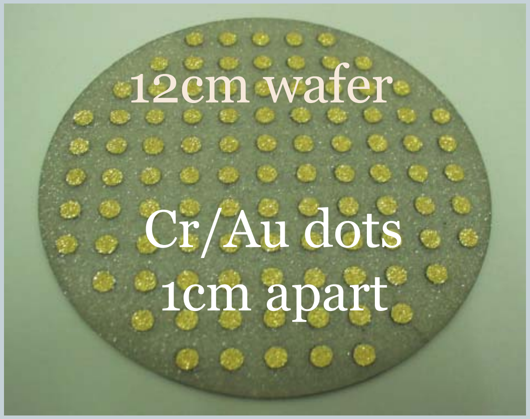
Residual with telescope ~ 18 μm

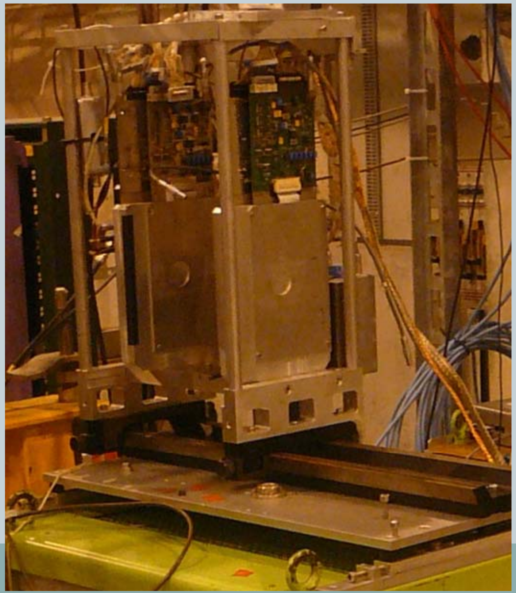
Remove telescope contribution ~14 μm

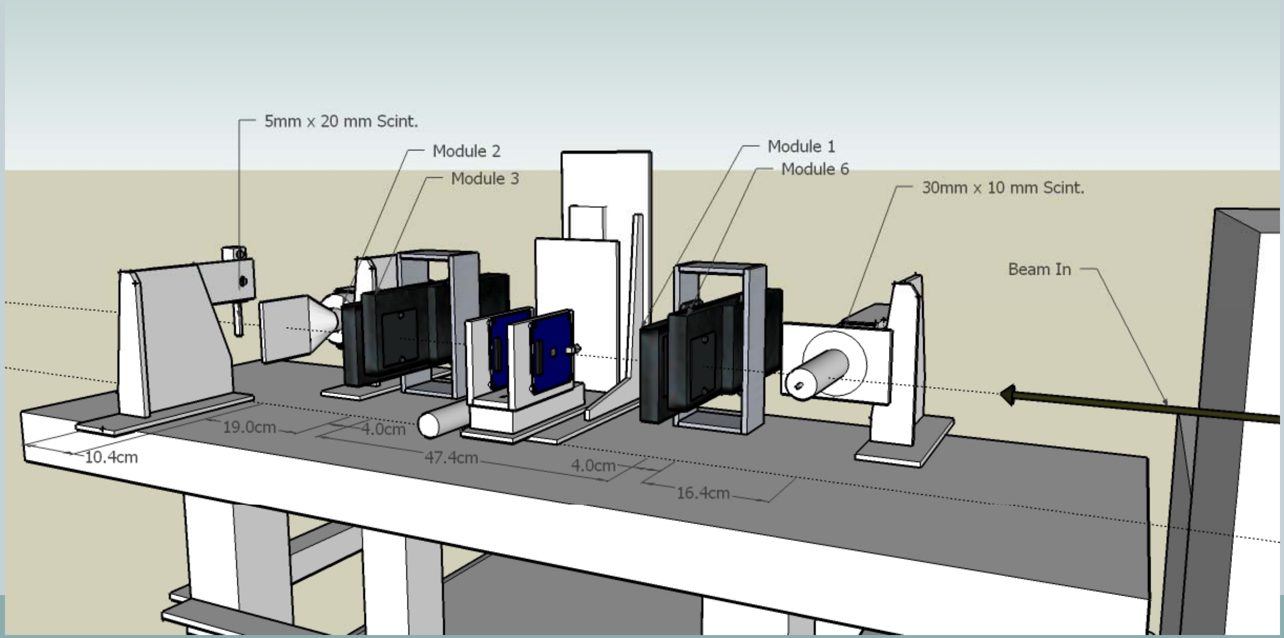
Radiation Hardness Studies

- Lab Characterization: Source tests
- Test beams: pads, strips and pixels
- Irradiations:
  - 24GeV protons -> Cern SPS
  - 70 MeV protons -> Sendai
  - 25 MeV protons -> Karlsruhe
  - Neutrons ->Ljubljana

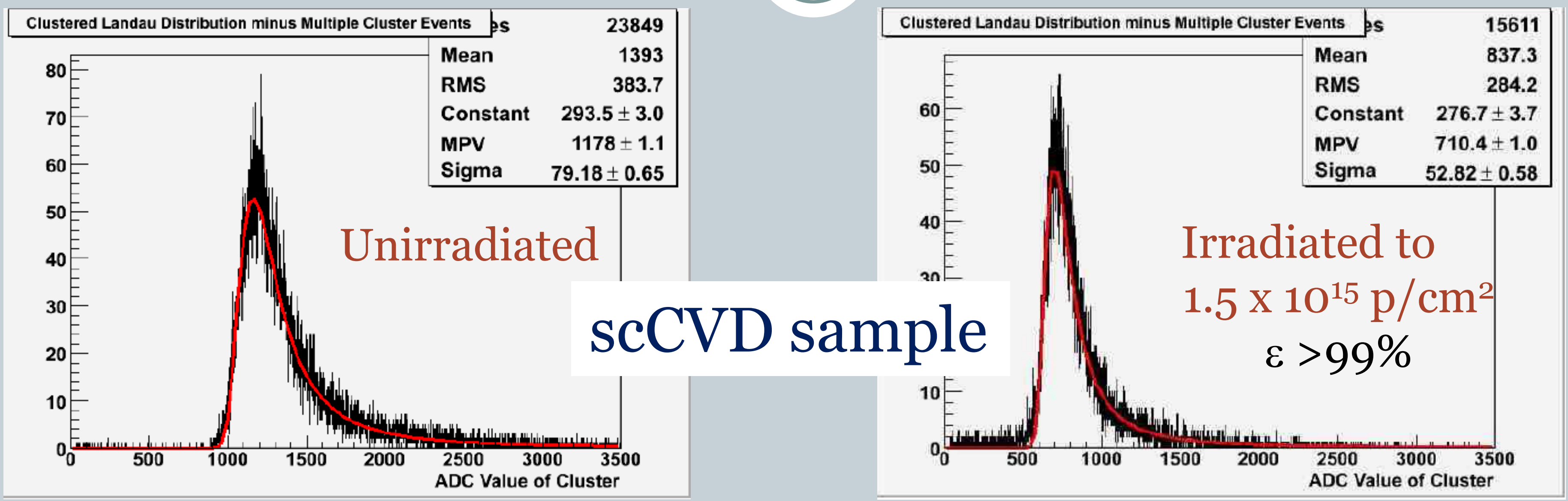


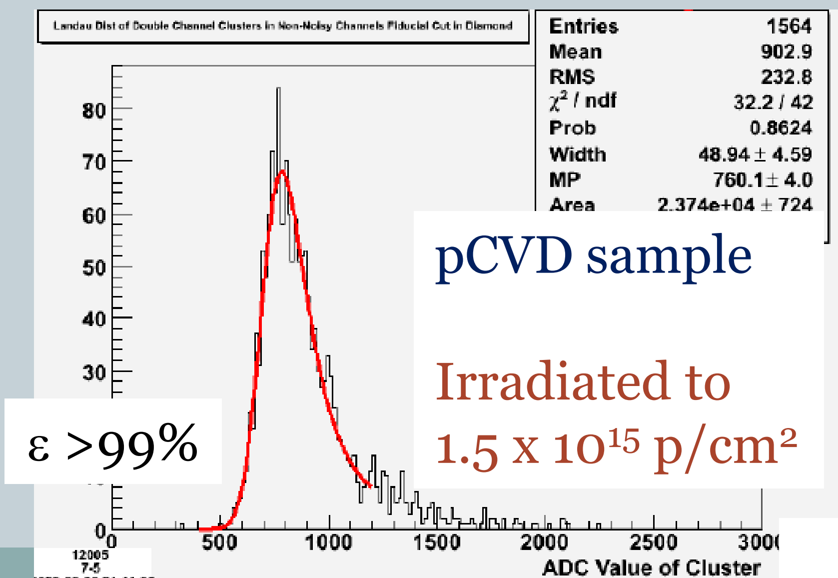






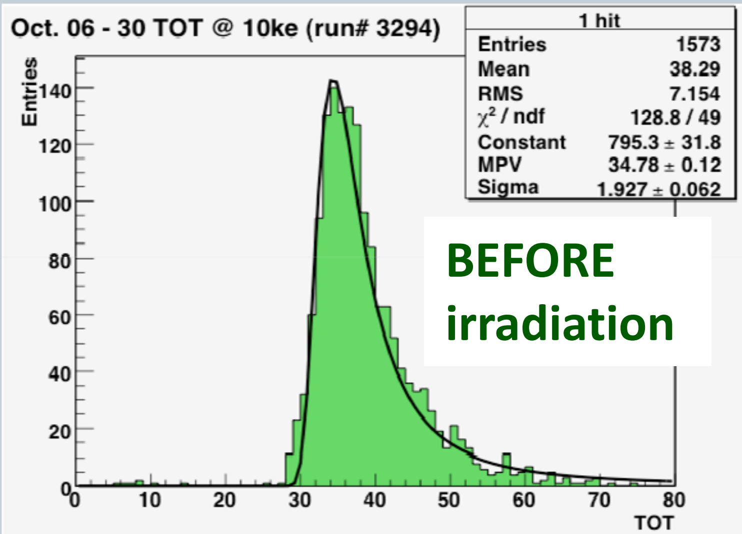
Irradiation Studies

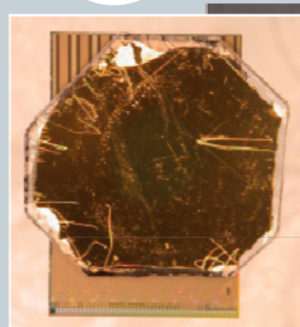


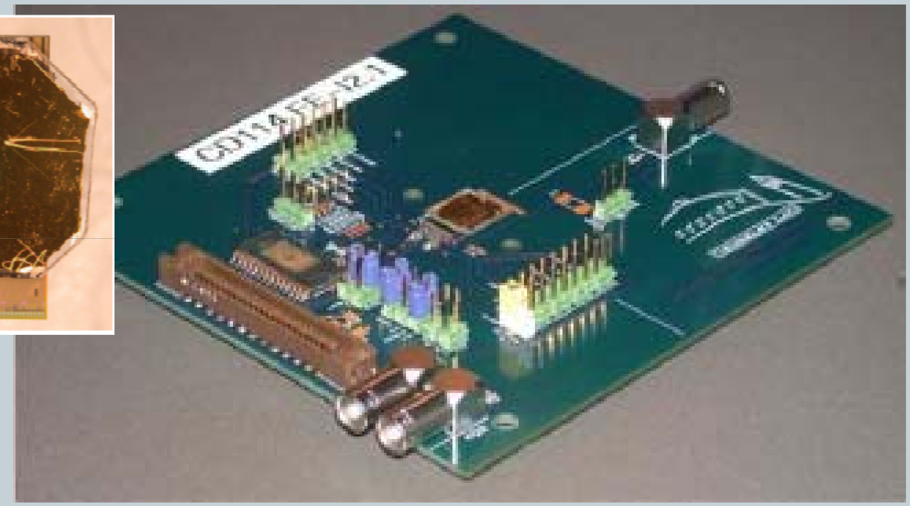


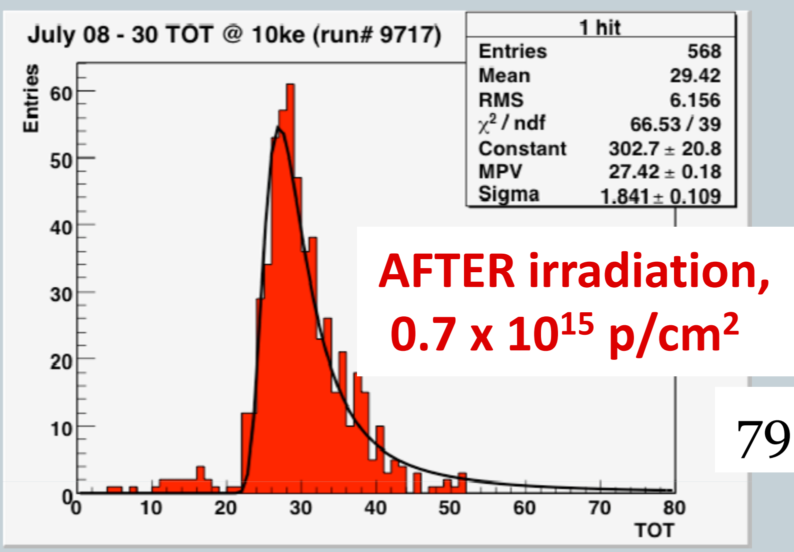
- Narrow distributions before and after Irradiation
- Diamond is irradiated without electronic (except for Pixel devices)
- Studies performed with many pCVD & scCVD samples
- Diamonds irradiated up to ~18 x 10^{15} p/cm^2

Irradiation Studies: scCVD Pixel Module



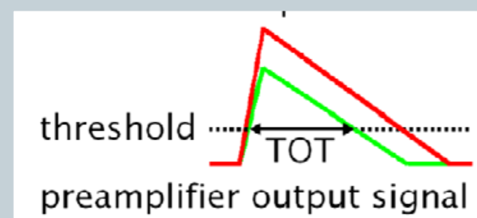






- scCVD diamond pixel module, 395 μm thick
- Both the sensor and electronics were irradiated

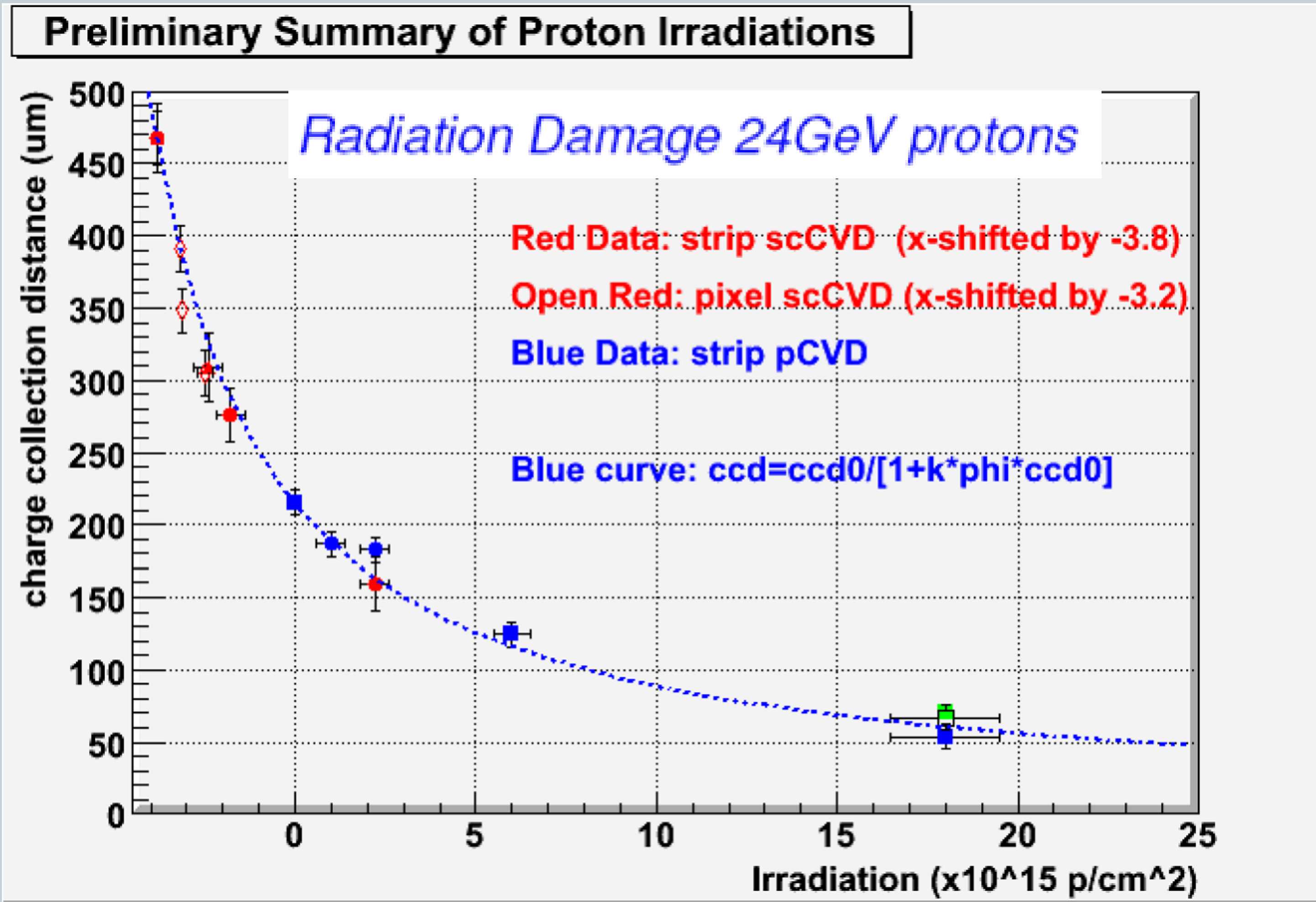
79% of Unirradiated



Time over Threshold
- measured in 25ns clock cycles

A. La Rosa, 2008

Proton Irradiation Summary -- Preliminary



pCVD and scCVD diamond follow the same damage curve:
$1/ccd = 1/ccd_0 + k\,\phi$.

Research Plans

Diamond R&D approved by ATLAS for LHC Upgrade R&D

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

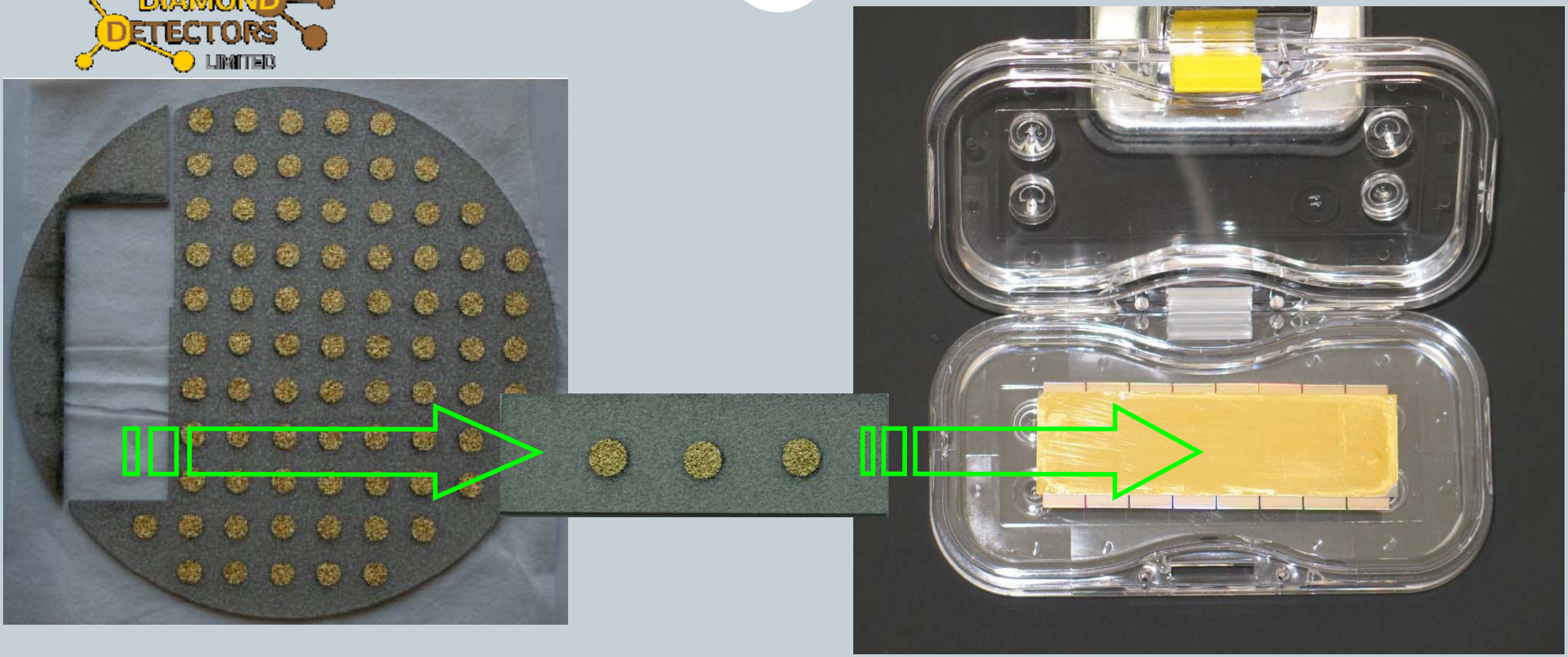
ATLAS project	Diamond Pixel Modules for the High Luminosity ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	*Institute Document No.*	*Created:* 15/05/2007	*Page:* 1 of 14
		Modified: 21/12/2007	*Rev. No.:* 1.8

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 1.8×10^{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

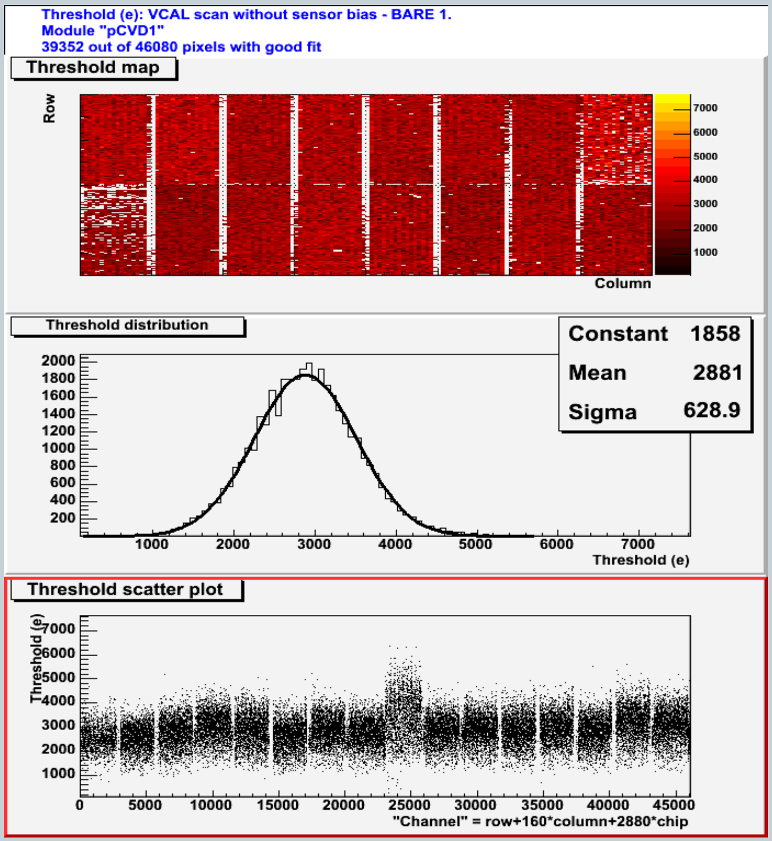
Industrialization: 2nd Full Pixel Module



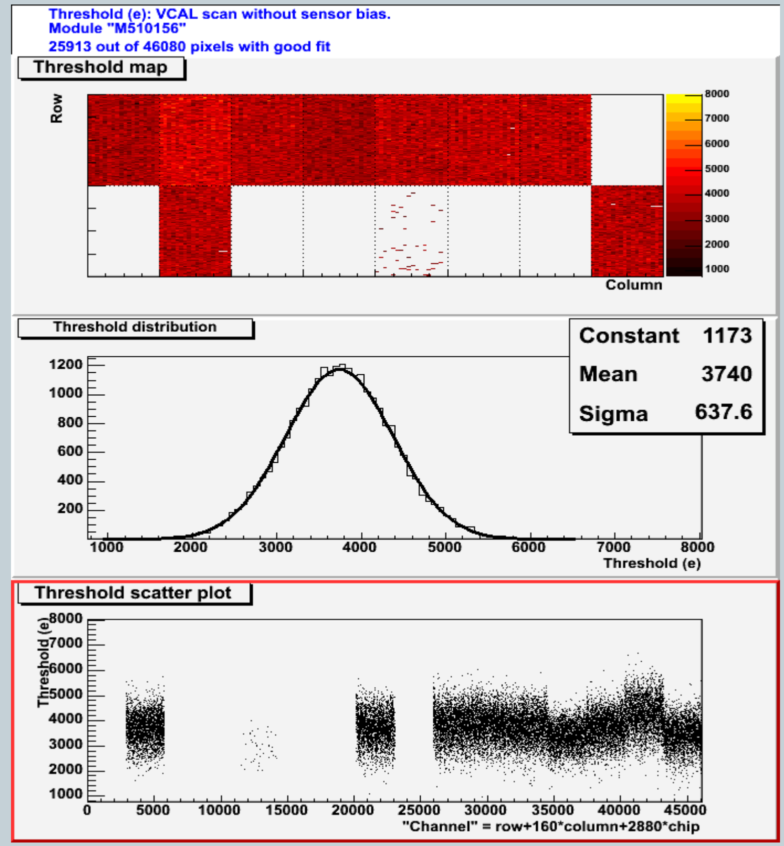
- All steps from polished sensor to bump bonding performed at IZM
- Bump-bonded sent to Bonn for dressing: flex, services
- 1st module to be built by industry

2nd Full Pixel Module: Damage

Before Applying 10 V



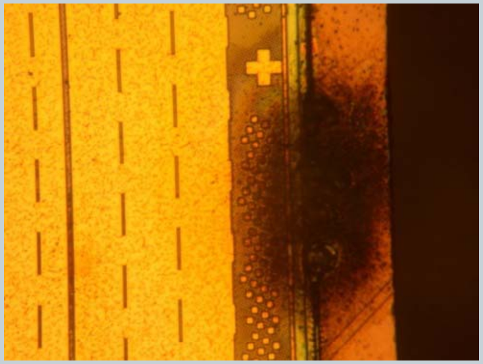
After Applying 10 V

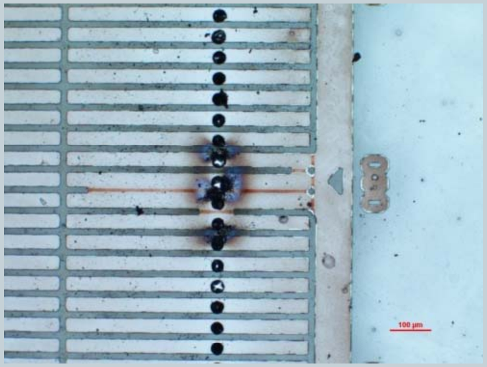


- Edge of diamond left metalized

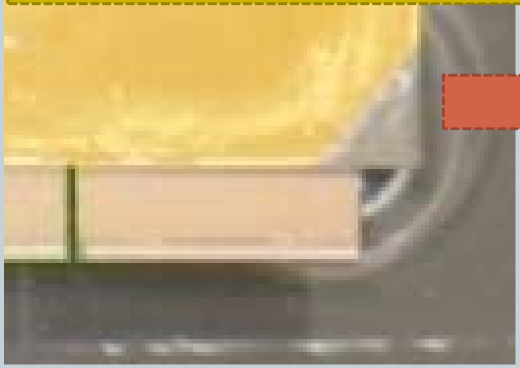
Industrialization: Damage

- Diamond edge was left metalized→ Module shorted out with 10V bias
- 7/16 FE chips were damaged
- Returned to IZM for re-build
  - visible damage to FE chips
  - All FE chips replaced
  - Diamond cleaned, re-metalized
  - Improved edge treatment

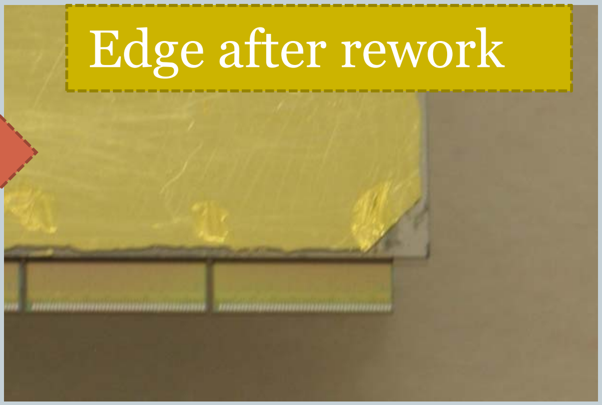




Edge before rework



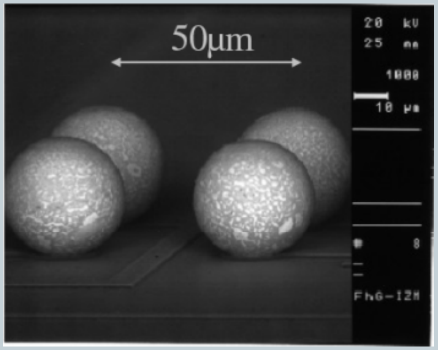
Edge after rework

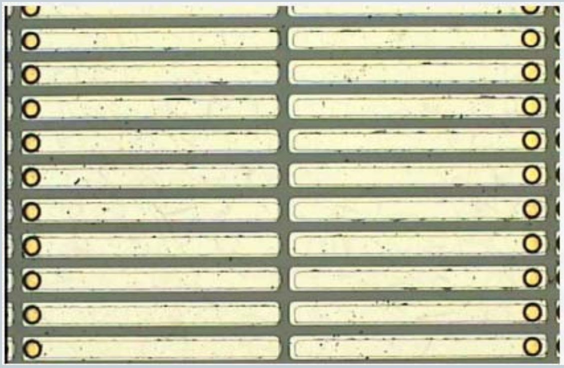


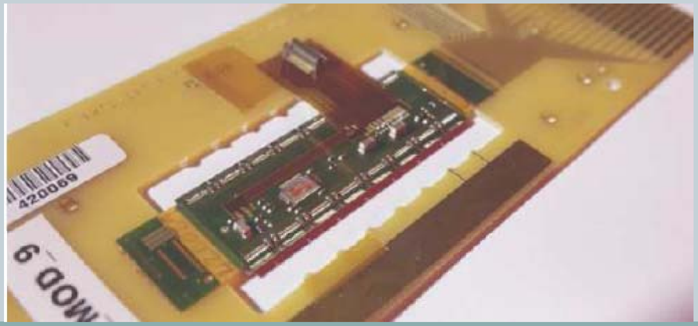
Successful rebuild -> recycling diamond sensors works
Module is currently in test beam at CERN

Diamond Module Plans

- Re-test ATLAS pixel modules at CERN – Done
- Continue irradiations of pCVD and scCVD diamonds
  - Map out damage curves for many particle types and energies
  - Status: In Progress!
- Industrialization of module production – In progress
  - 1st module produced in industry
  - Currently in Test beam at CERN
- Produce 5-10 Modules – Ongoing
  - 4-16 Chip FE-I3 modules to be built
  - 4-1chip FE-I4 modules: waiting for FE-I4
- Testing Modules
  - Beam tests of production modules
  - Test radiation hardness of produced modules







Extra/Backup

Charge & Resolution vs. Bias Voltage

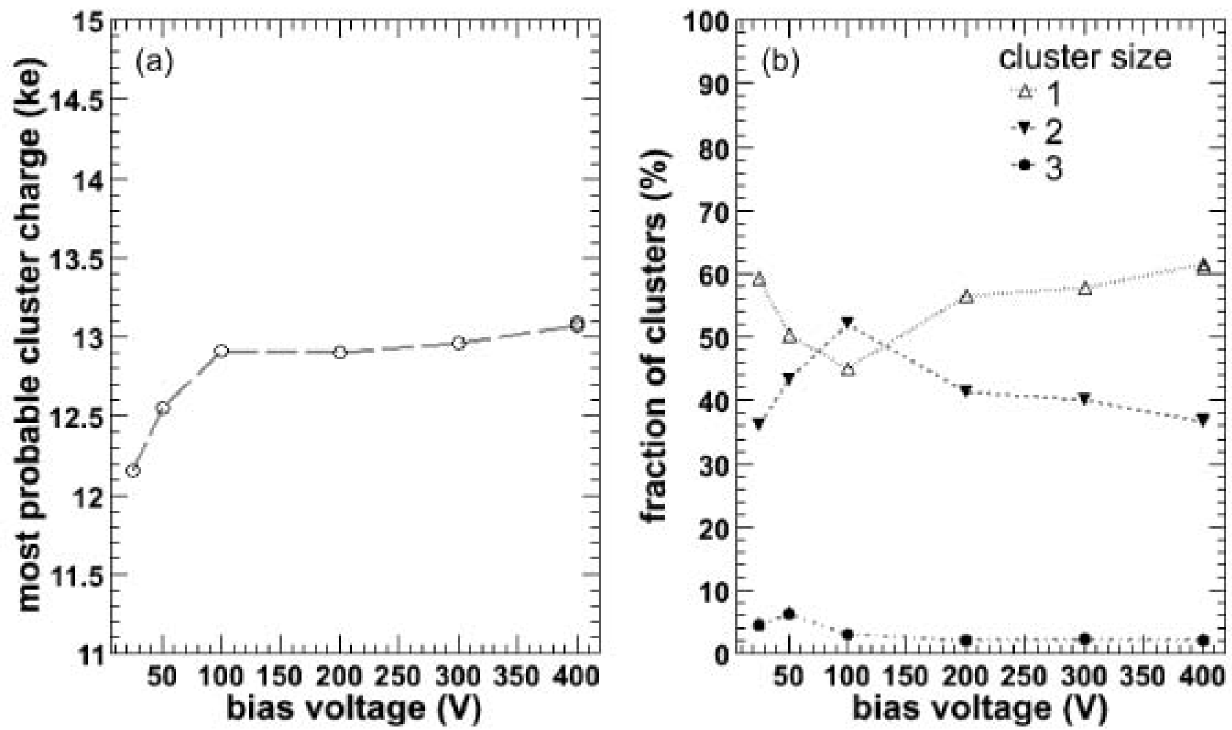
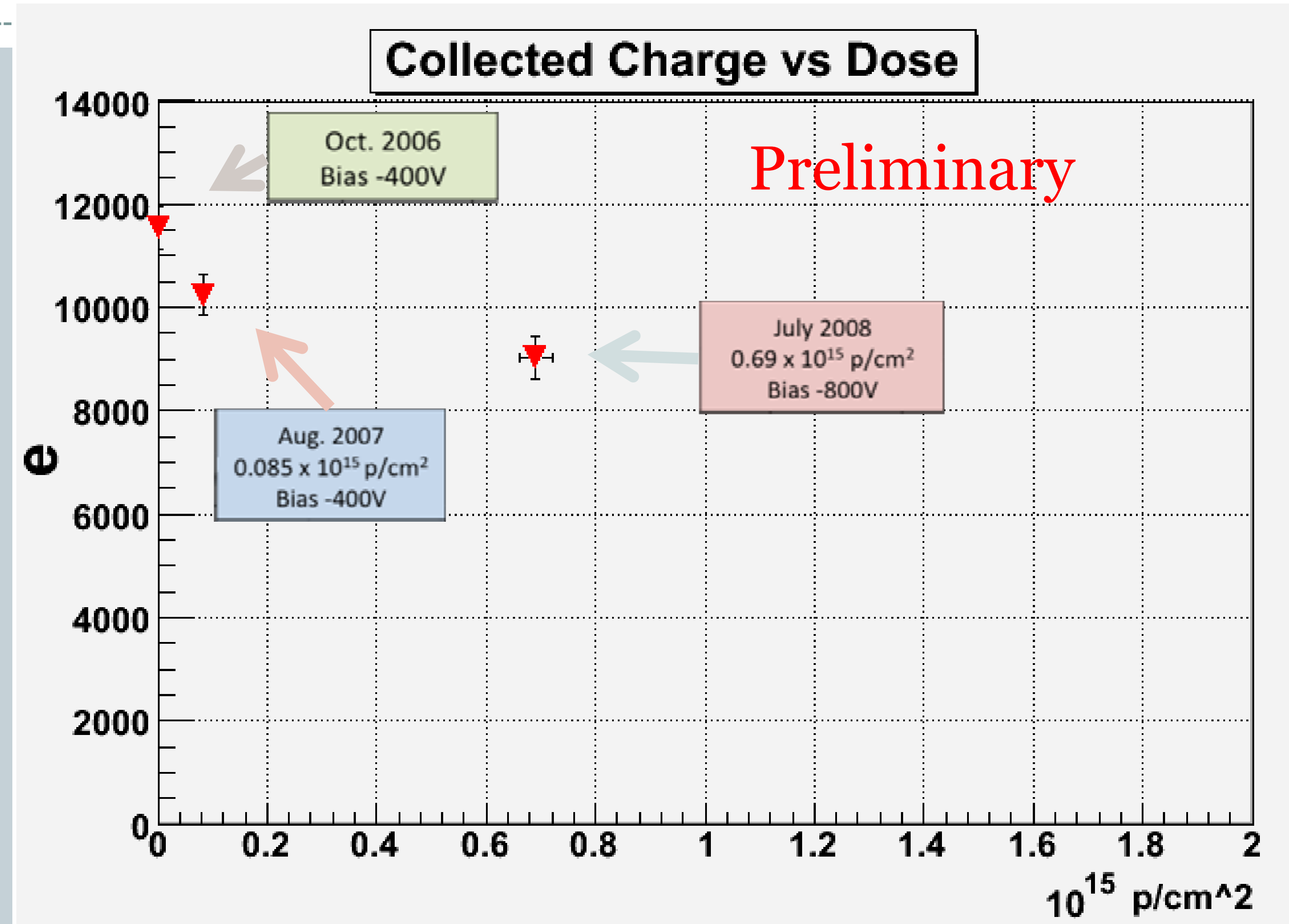


Fig. 5. Most probable values of the charge distribution (a) and fractions of charge cluster sizes (b) as a function of the bias voltage.

- Full charge collected for biases >0.25 V/μm

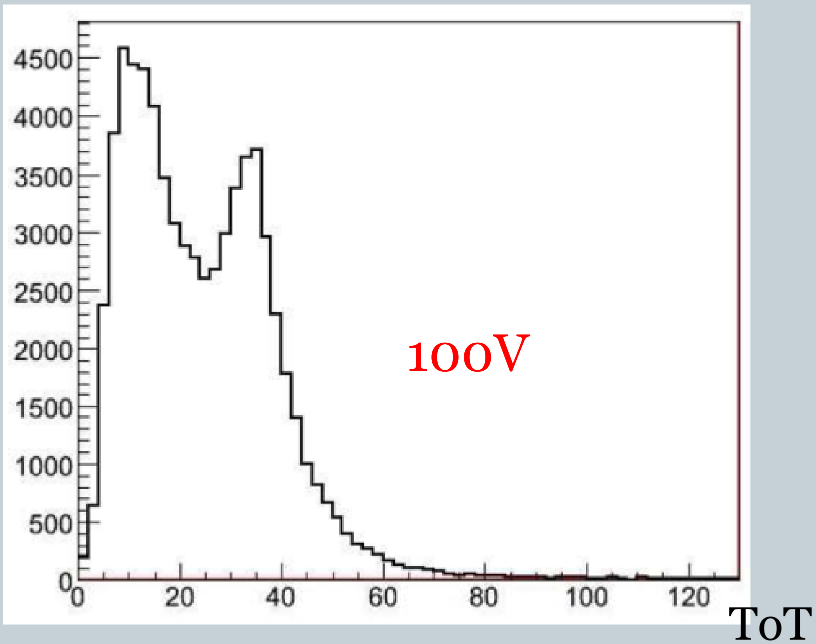
Collected Charge vs. Dose

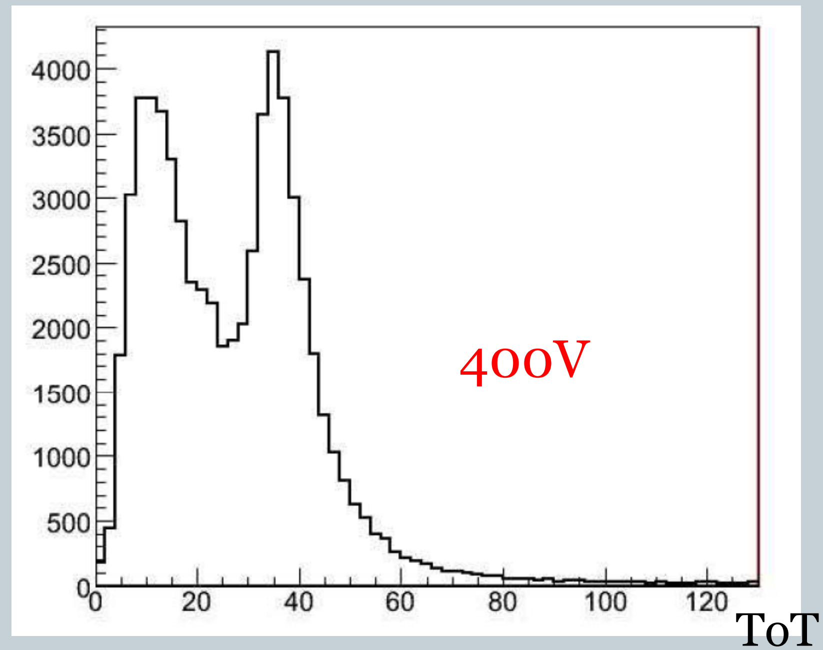


• Both diamond and electronics irradiated

ToT & Charge Sharing

October 2006

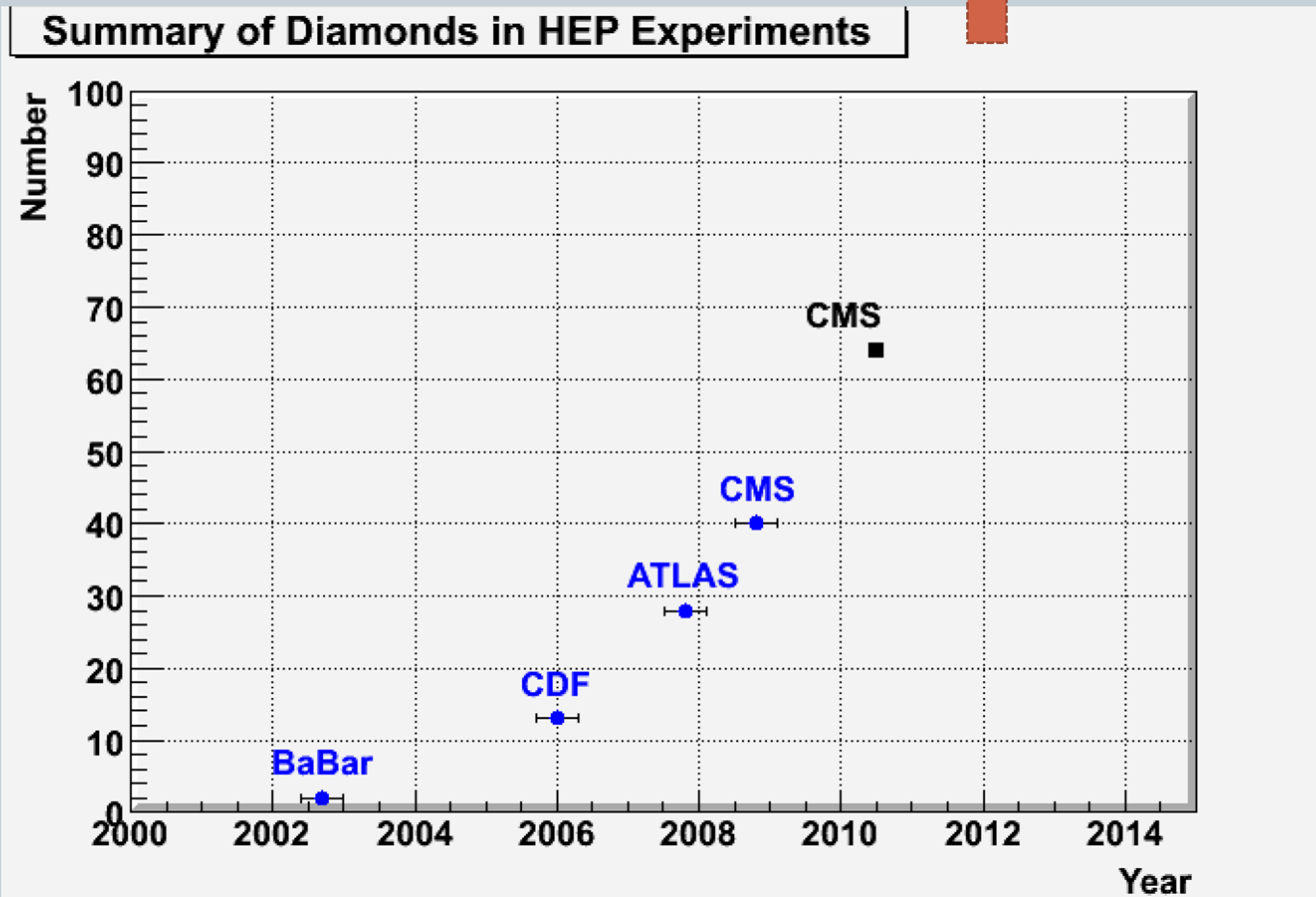




- Raw ToT values per hit, “online” plots → no tracking yet
- Global ToT calibration: 30ToT = 10ke
- One hit and multiple hit events visible
- Charge sharing decreases as bias voltage increases

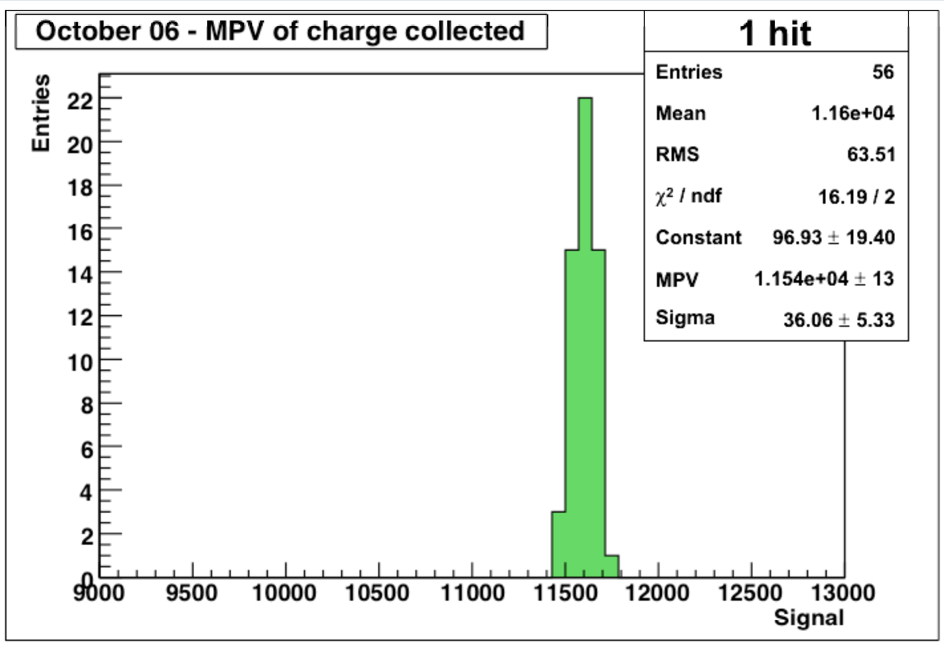
Diamonds in HEP Experiments

IBL - ATLAS?



Irradition Results: Charge Collected

BEFORE irradiation



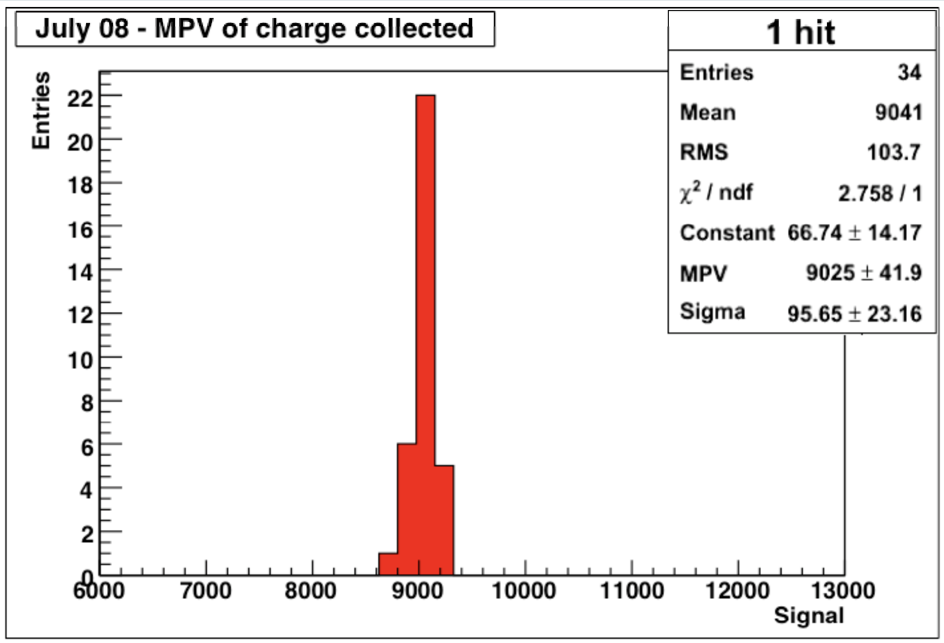
MPV of Charge Collected: ≈ 11540e

MPV of TOT : ≈34.6

Bias: – 400 V

Th= ~1700e

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



MPV of Charge Collected: ≈ 9025e

MPV of TOT : ≈27.6

Bias: – 800V

Th= ~1470e

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

Properties of Diamond and Silicon

Property	Diamond	4H-SiC	Si
Band Gap [eV]	5.5	3.3	1.12
Breakdown field [V/cm]	10^7	4×10^6	3×10^5
Resistivity [Ω-cm]	$>10^{11}$	10^{11}	2.3×10^5
Intrinsic Carrier Density [cm^{-3}]	$<10^3$		1.5×10^{10}
Electron Mobility [$cm^2V^{-1}s^{-1}$]	1800	800	1350
Hole Mobility [$cm^2V^{-1}s^{-1}$]	1200	115	480
Saturation Velocity [km/s]	220	200	82
Mass Density [g cm^{-3}]	3.52	3.21	2.33
Atomic Charge	6	14/6	14
Dielectric Constant	5.7	9.7	11.9
Displacement Energy [eV/atom]	43	25	13-20
Energy to create e-h pair [eV]	13	8.4	3.6
Radiation Length [cm]	12.2	8.7	9.4
Spec. Ionization Loss [MeV/cm]	4.69	4.28	3.21
Ave. Signal Created/100 μm [e]	3600	5100	8900
Ave. Signal Created/0.1% X_0 [e]	4400	4400	8400

Advantages:

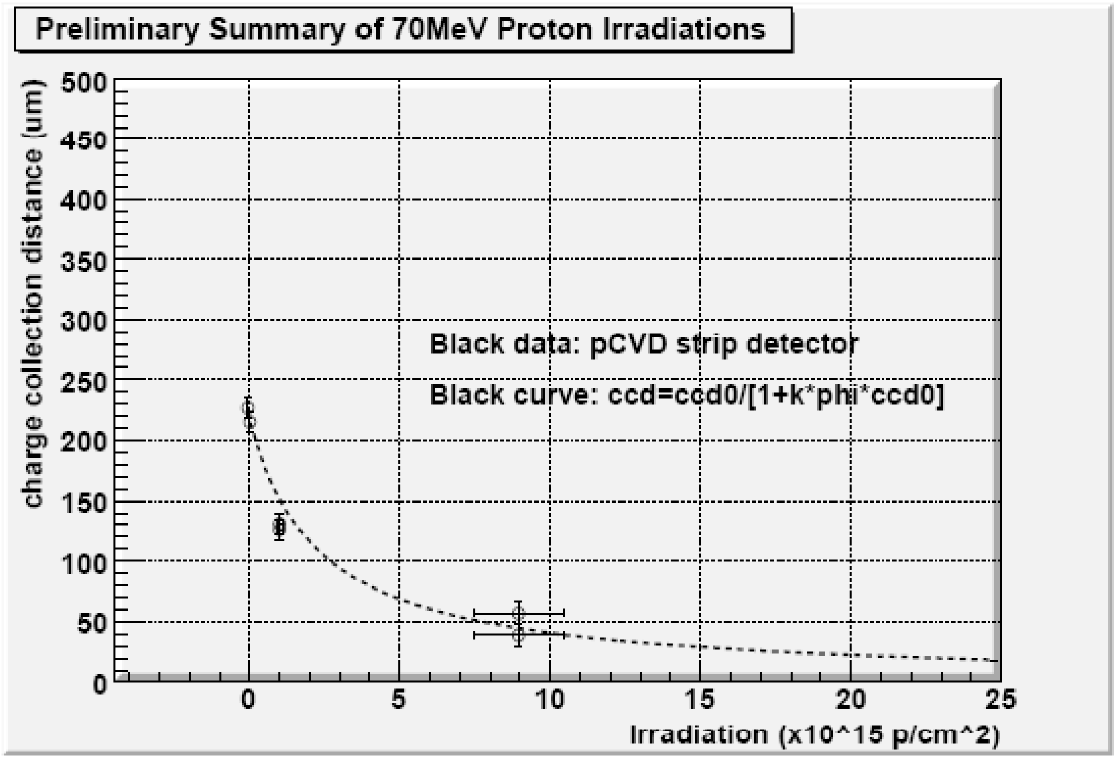
- Low leakage current
- No doping necessary
- Radiation hard
- Low capacitance
- High thermal conductance
- Room temperature operation
- High Mobility/fast signal collection

Disadvantages:

- 50% signal of Si for the same radiation length

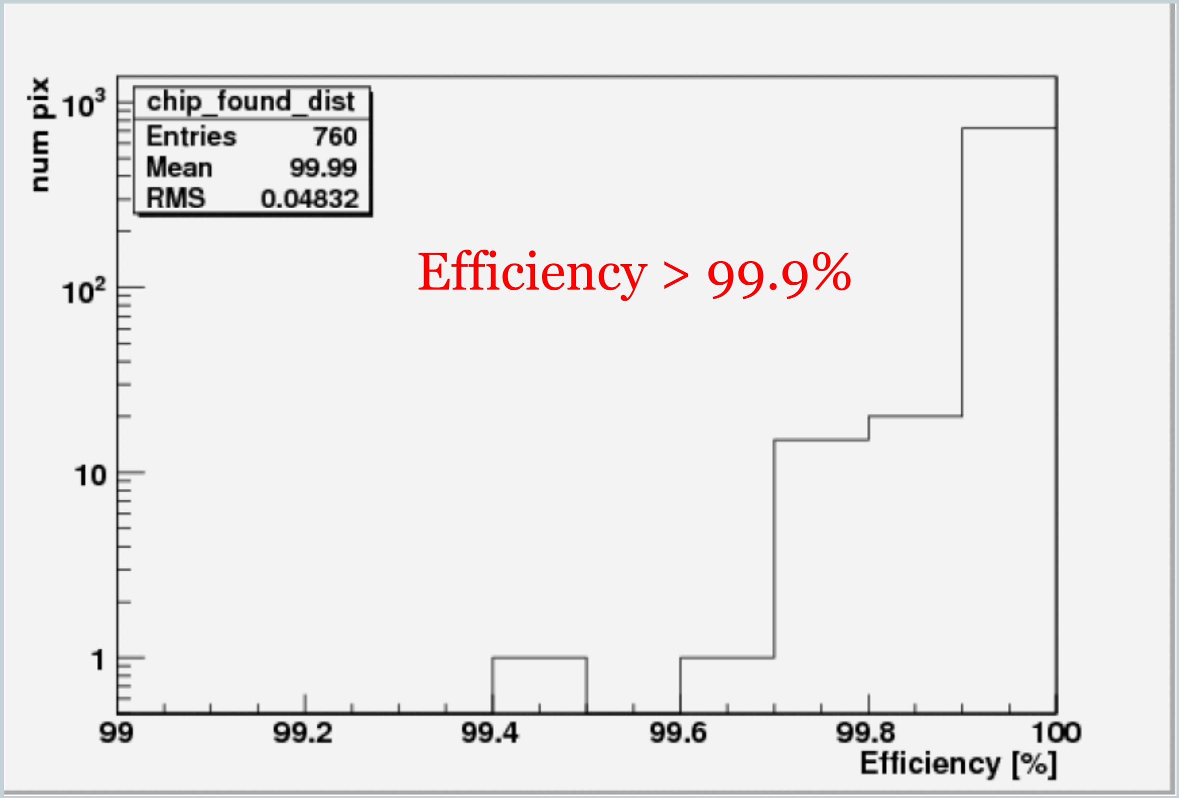
Work in Progress 2009:

- Irradiations already performed awaiting test beam:
  - Sendai - $10^{15}, 10^{16}$ 70MeV protons/cm^2
  - Ljubljana - 10^{16} neutrons/cm^2
- Irradiations in progress:
  - Karlsruhe - 25MeV protons



In diamond 70MeV protons have ~3x larger damage constant than 24GeV

Transparent Efficiency



- Predict hit position with telescope (~5 μm resolution at diamond)
- Look within 100 μm of the prediction