Non-Silicon Solid State Detectors

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42nd INFN Eloisatron Workshop
Oct. 1, 2003 - Erice, Italy

Outline of the Talk

- Introduction
- Status of Diamond Research
- Status of Silicon Carbide Research
- Radiation Monitoring - a new application
- The Future
- Summary

Introduction

Motivation: Tracking Devices Close to Interaction Region of Experiments

LHC + SLHC Issues:

→ Inner tracking layers must survive!

→ Inner tracking layers must provide high precision tracking to tag b, t, Higgs, . . .

→ Annual replacement of inner layers perhaps?

Material Properties:

- Radiation hardness
- Low dielectric constant → low capacitance
- Low leakage current → low readout noise
- Room temperature operation, Fast signal collection time → no cooling

Material Presented Here:

- Chemical Vapor Deposition (CVD) Diamond
- Silicon Carbide

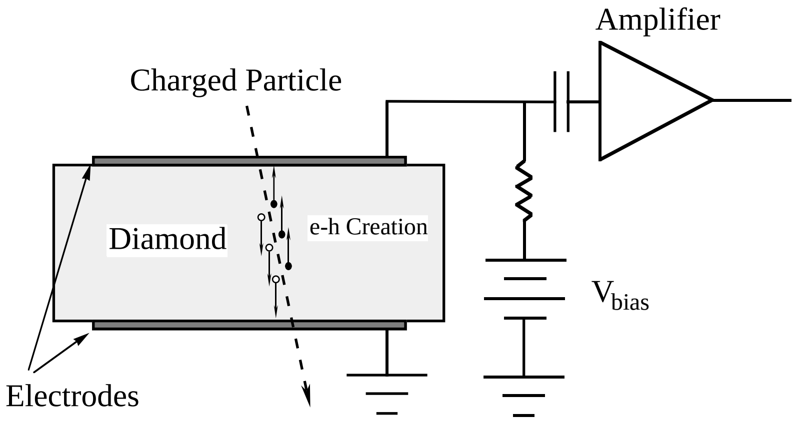
Reference → http://rd42.web.cern.ch/RD42
→ http://rd50.web.cern.ch/RD50

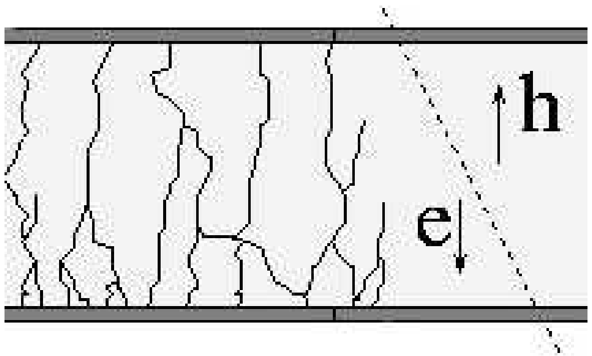
Comparison of Various Materials

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

Characterization of Diamond:

Signal formation





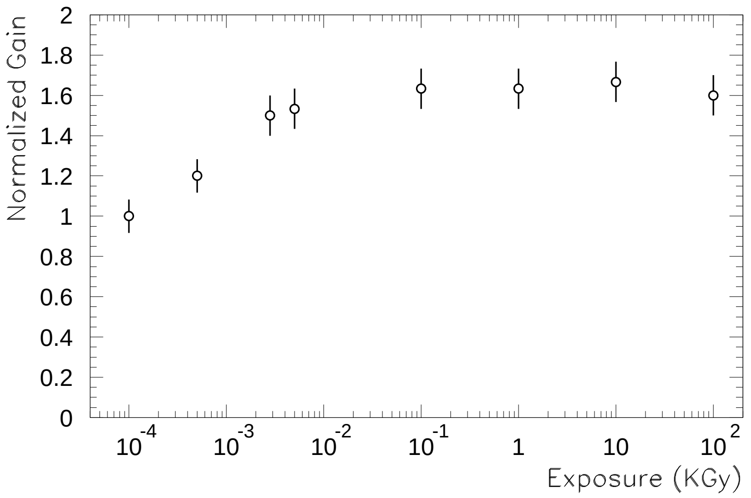
- Q=$\frac{d}{t}Q_0$ where d = collection distance = distance e-h pair move apart
- d=$(\mu_e\tau_e + \mu_h\tau_h)$E
- d=μEτ

  with $\mu = \mu_e + \mu_h$

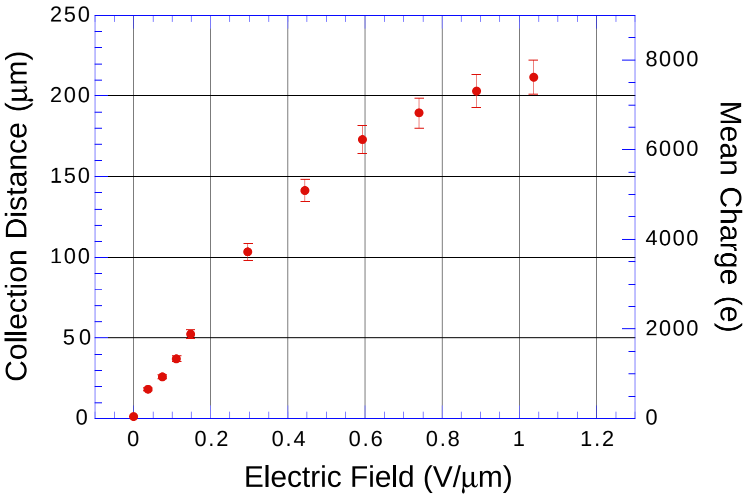
  and $\tau = \frac{\mu_e\tau_e+\mu_h\tau_h}{\mu_e+\mu_h}$

Diamond Properties:

Signal formation



Signal versus applied electric field



- Metalization was typically Cr/Au or Ti/Au or Ti/W → new
- Polycrystalline CVD diamond typically "pumps" by a factor of 1.5-1.8
- Usually operate at 1V/μm → drift velocity saturated
- Test Procedure: dot → strip → pixel

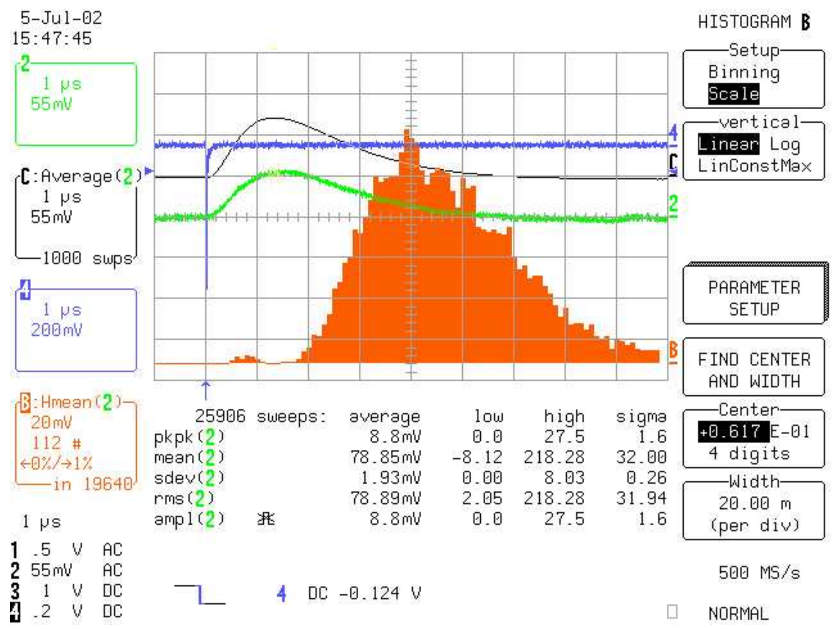
Growth side of a recent polycrystalline CVD (pCVD) diamond.

(Courtesy of Element Six)

Diamond

In 2000 RD42 entered into a *Research Program* with Element Six to increase the charge collected from pCVD diamond.

Latest Diamonds Measured with a ^{90}Sr Source:

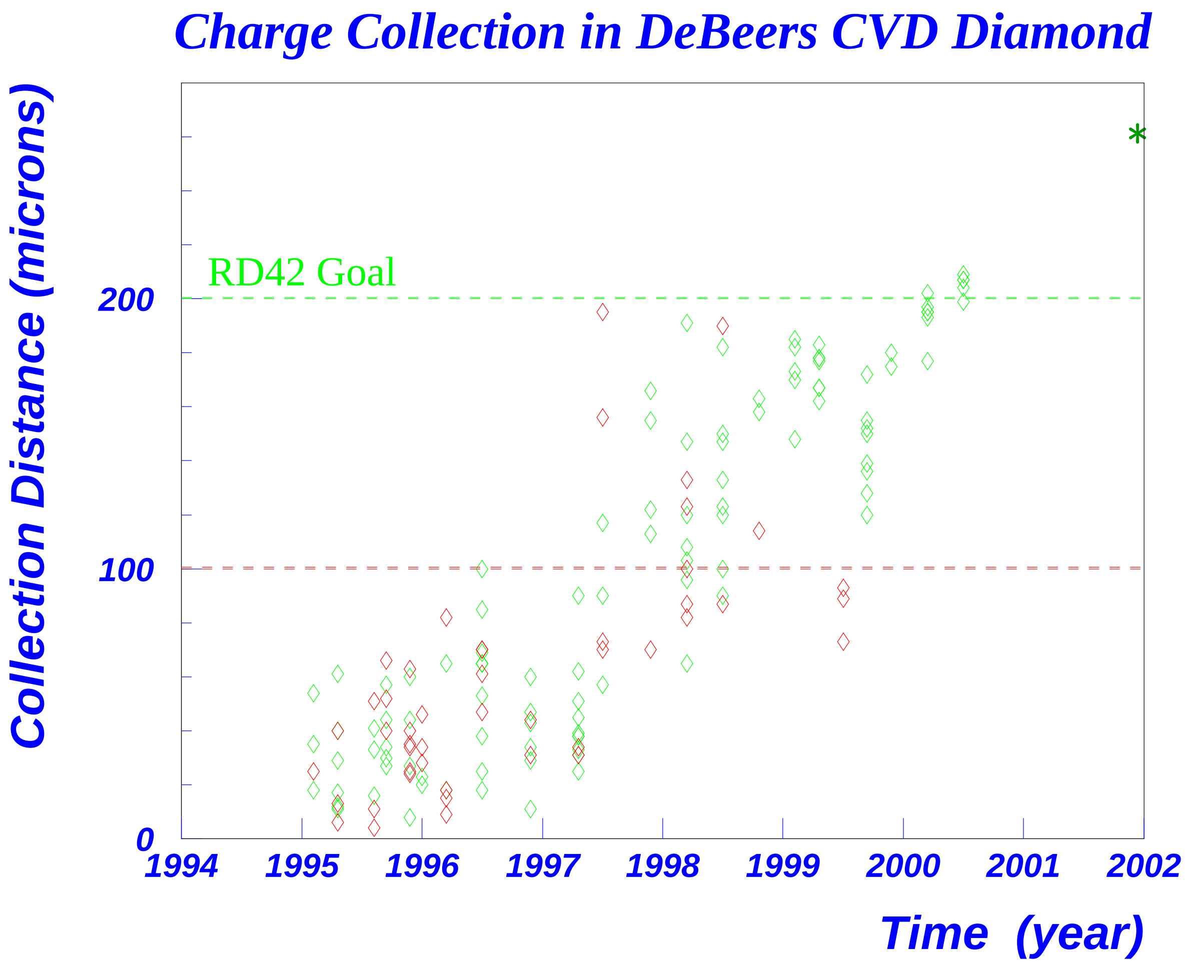


- System Gain $= 124\ e/\text{mV}$
- Q_{MP} = 62mV = 7600e
- Mean Charge = 79mV = 9800e

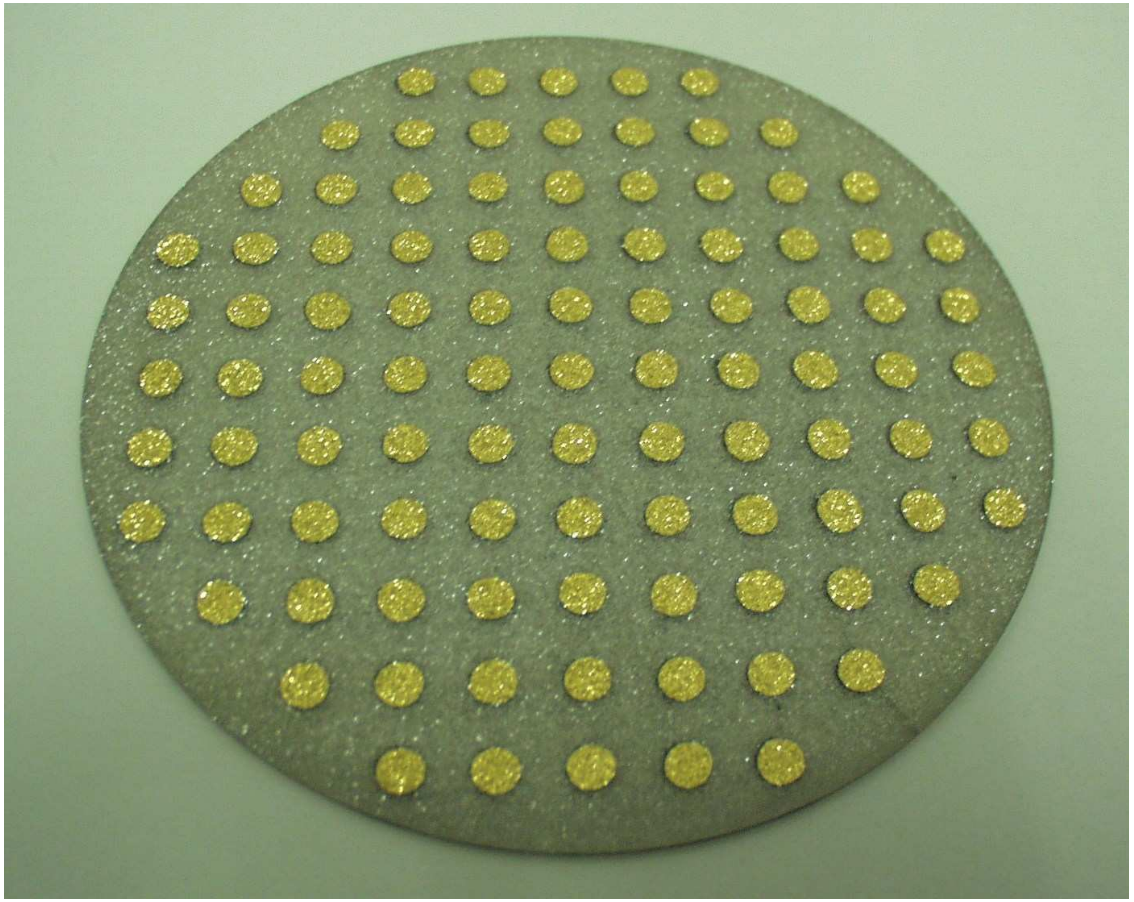
- Source data well separated from 0
- Collection Distance now 275μm
- Most Probable Charge now $\approx$ 8000e
- 99% of PH distribution now above 3000e
- FWHM/MP $\approx$ 0.95 — Si has $\approx$ 0.5
- This diamond available in large sizes

The Research program worked!

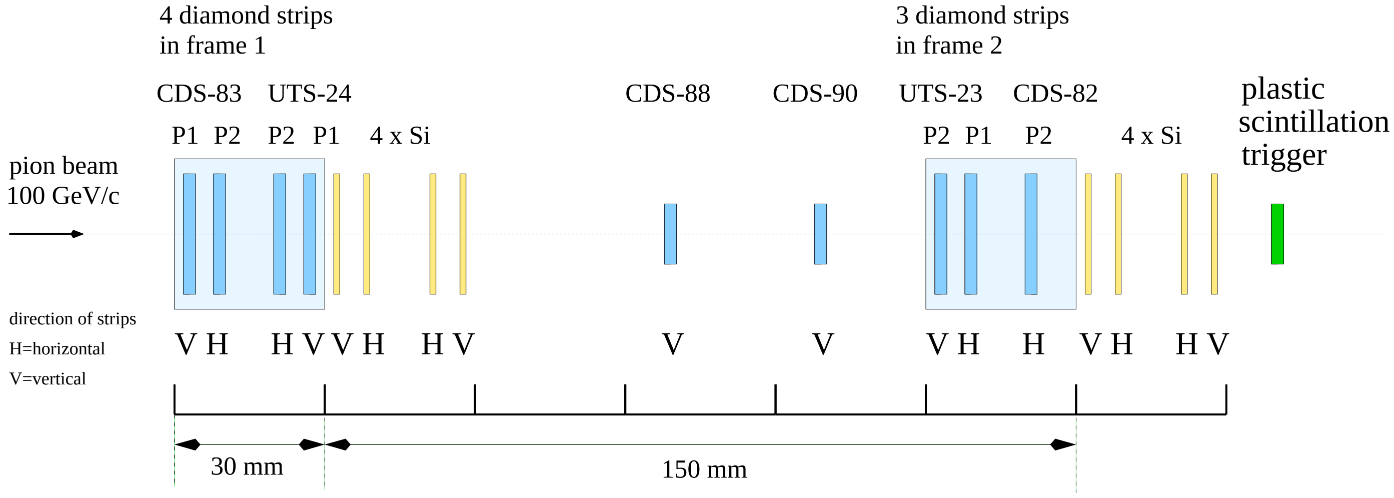
History of Diamond Progress



Recent pCVD diamond wafer ready for test:

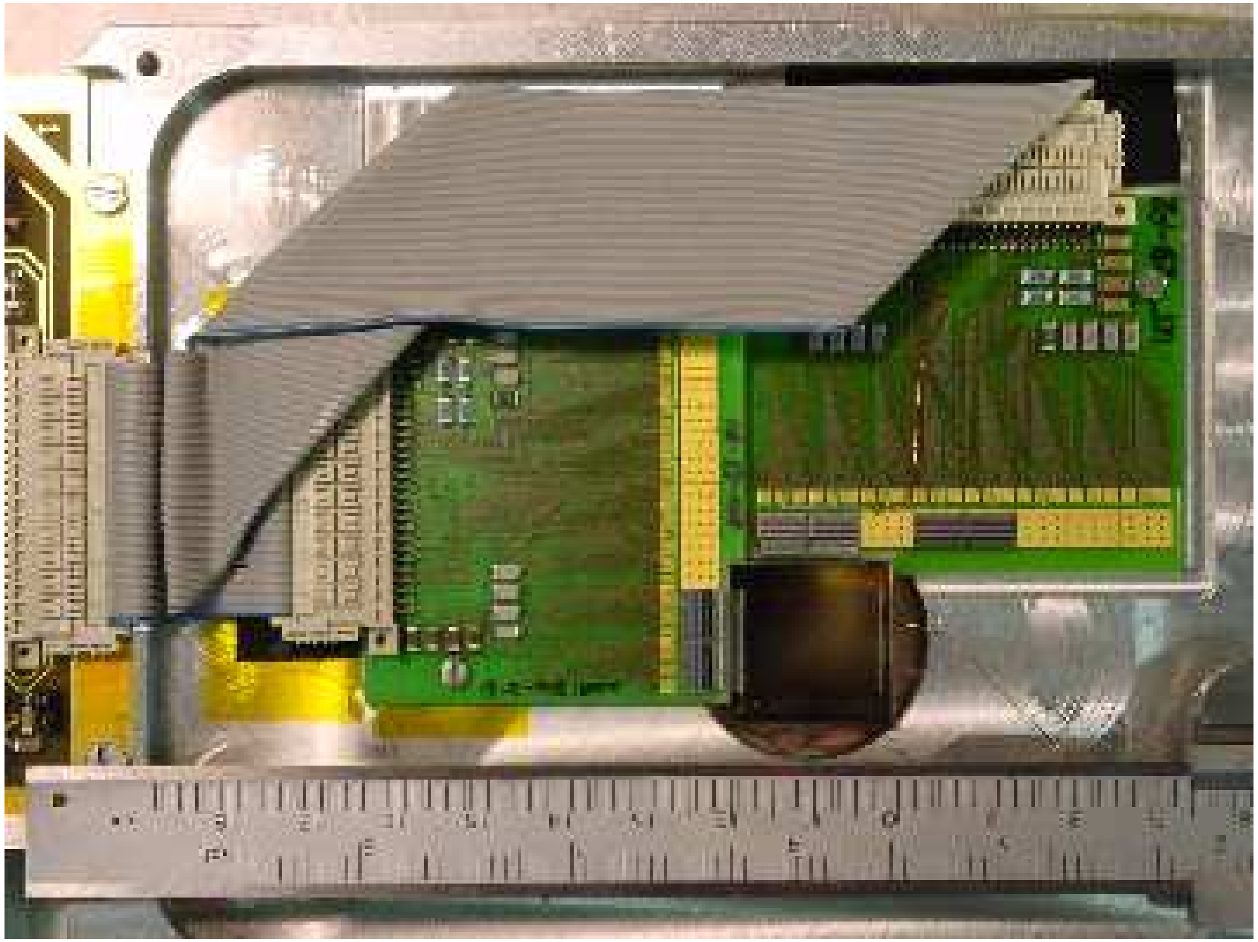


CERN Testbeam Setup for Diamond Telescope:



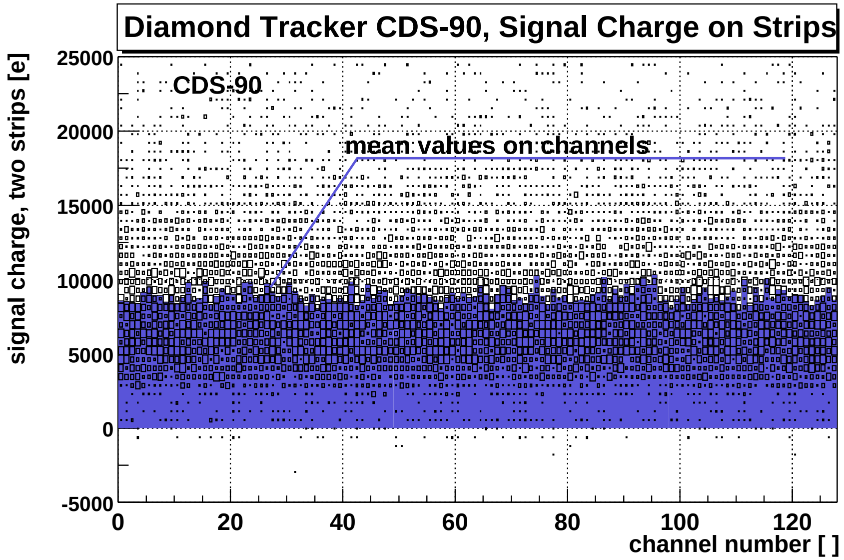
- 100 GeV/c pion/muon beam
- 7 planes of CVD diamond strip sensors each 2cm $\times$ 2cm
- 50μm pitch, no intermediate strips $\rightarrow$ new metalisation procedure
- 2 additional diamond strip sensors for test
- Several silicon sensors for cross checks
- Strip Electronics (2 μsec) $\rightarrow$ ENC $\approx 100e + 14e/$pF

Photograph of Two Planes of the Telescope:

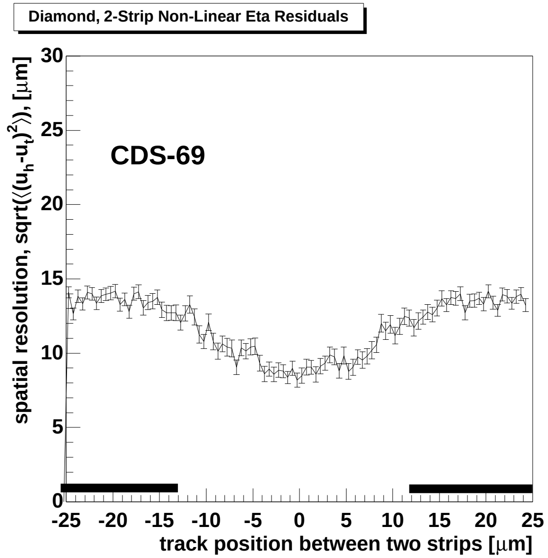


Diamond - Tracking Studies

PH Distribution on each Strip

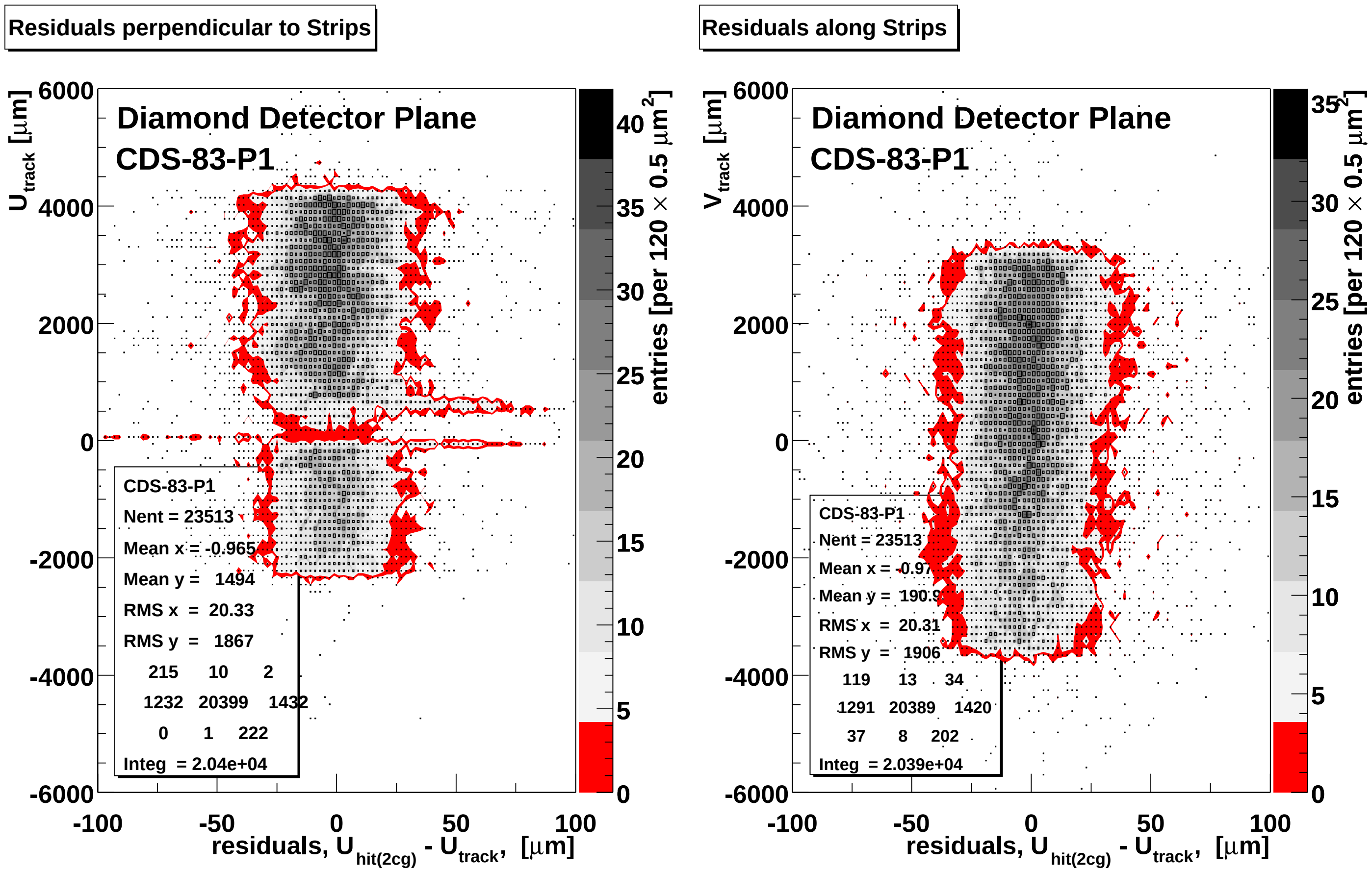


Residual versus Track Position

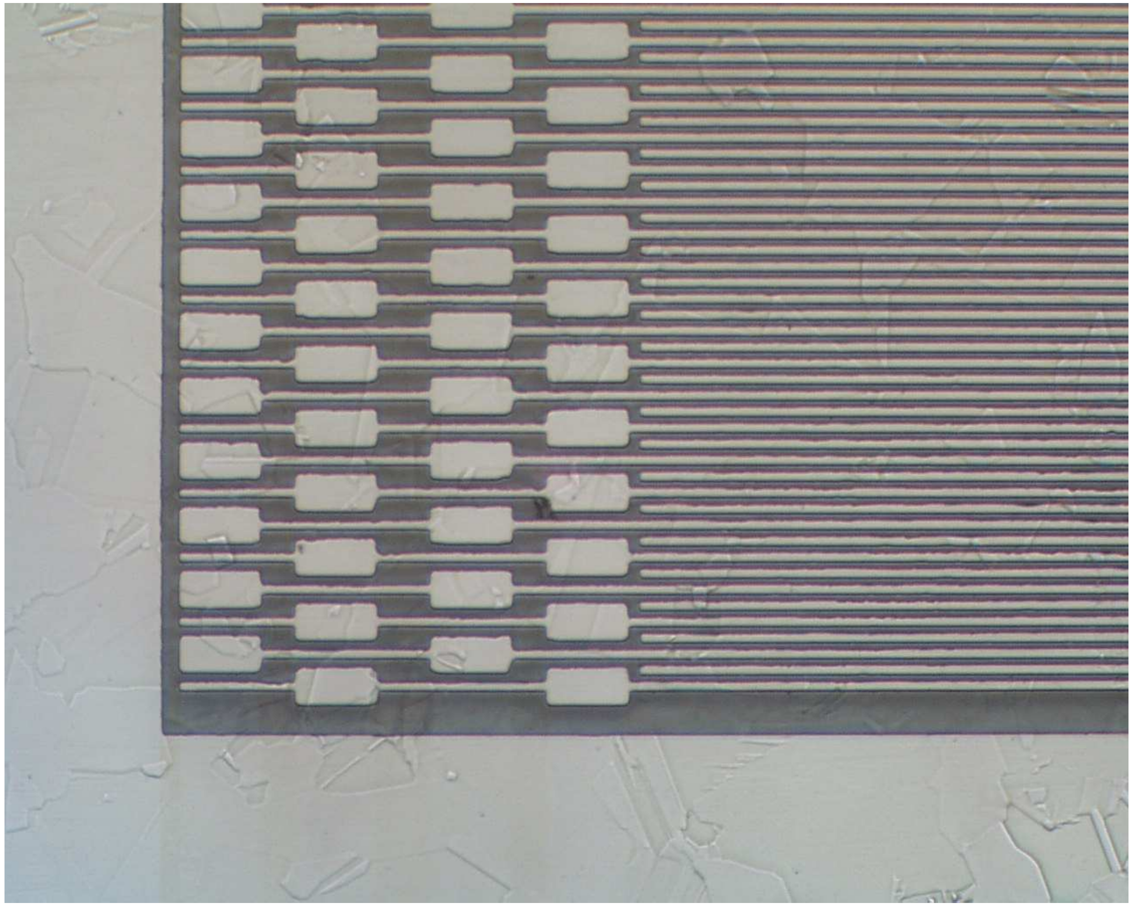


- Uniform signals on all strips $\longrightarrow$ new metalisation
- Pedestal separated from "0" on all strips
- 99% of entries above 2000 e
- Mean signal charge $\sim$ 8640 e $\longrightarrow$ new metalisation
- MP signal charge $\sim$ 6500 e

Residuals

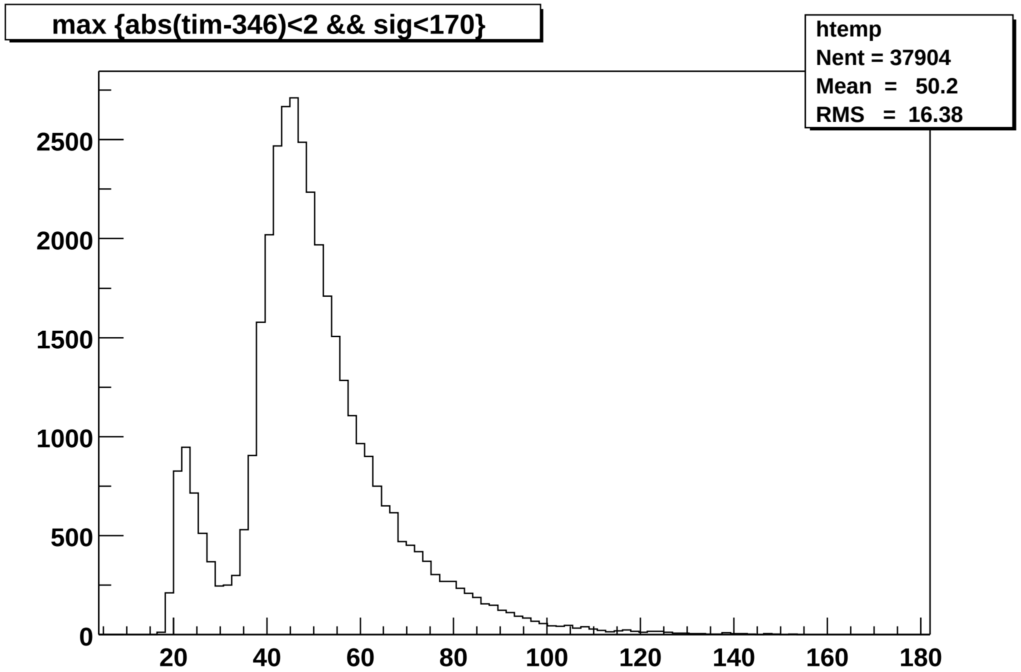

Residuals perpendicular to Strips
Diamond Detector Plane
CDS-83-P1
CDS-83-P1
Nent = 23513
Mean x = -0.965
Mean y = 1494
RMS x = 20.33
RMS y = 1867
215 10 2
1232 20399 1432
0 1 222
Integ = 2.04e+04
U_track [µm]
entries [per 120 × 0.5 µm^2]
residuals, U_hit(2cg) - U_track, [µm]
Residuals along Strips
Diamond Detector Plane
CDS-83-P1
CDS-83-P1
Nent = 23513
Mean x = -0.97
Mean y = 190.9
RMS x = 20.31
RMS y = 1906
119 13 34
1291 20389 1420
37 8 202
Integ = 2.039e+04
V_track [µm]
entries [per 120 × 0.5 µm^2]
residuals, U_hit(2cg) - U_track, [µm]

Next advance → take advantage of charge sharing:



Use intermediate strips to force charge sharing.

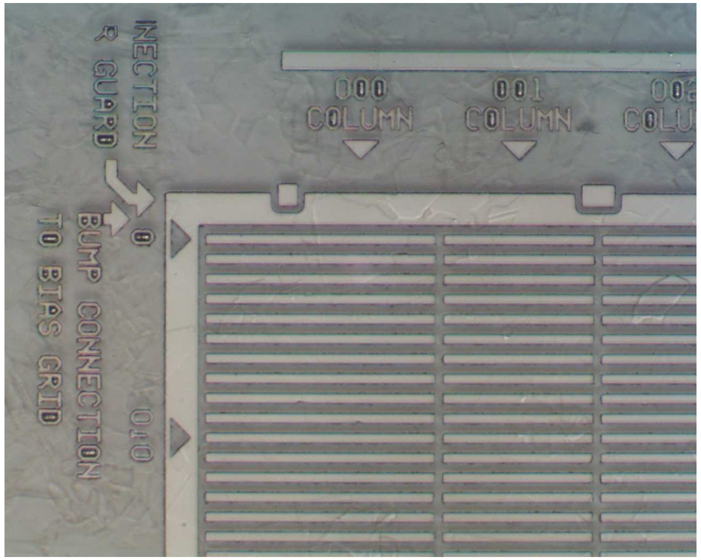
Radiation Hard Diamond Tracking Modules:



- Large (2cm × 4cm) Module constructed with new metalisation
- Fully radiation hard SCTA128 electronics → 25ns peaking time
- Tested in a ^{90}Sr → ready for beam test and irradiation
- Charge distribution cleanly separated from the noise tail → S/N > 8/1
- Efficiency will be measured in test beams at 40 MHz clock rate

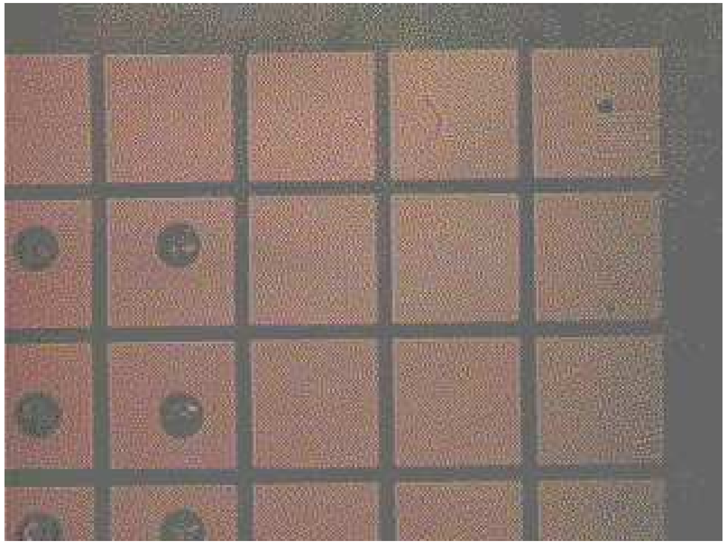
Diamond Pixel Detectors

ATLAS FE/I Pixels (Al)



- Atlas pixel pitch $50\mu m \times 400\mu m$
- Over Metalisation: Al
- Lead-tin solder bumping at IZM in Berlin

CMS Pixels (Ti-W)

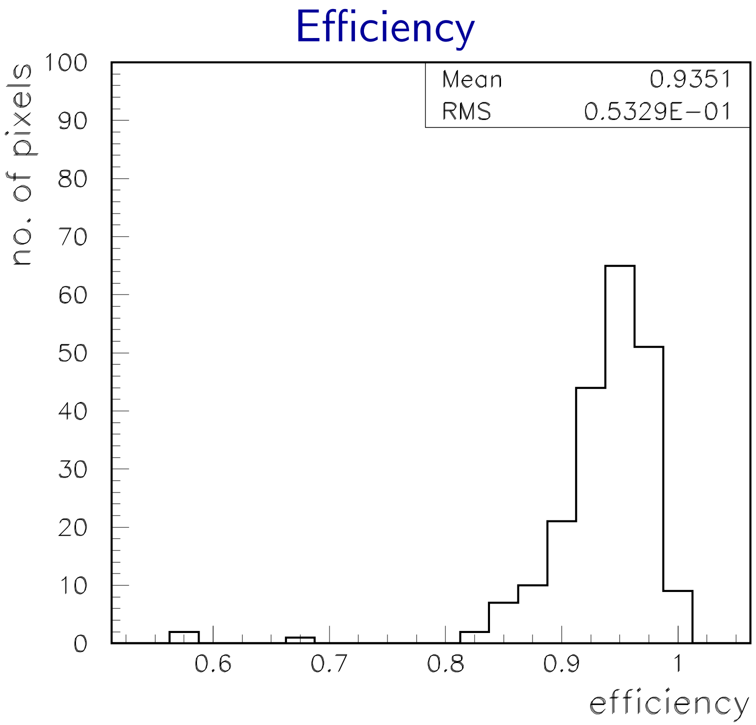


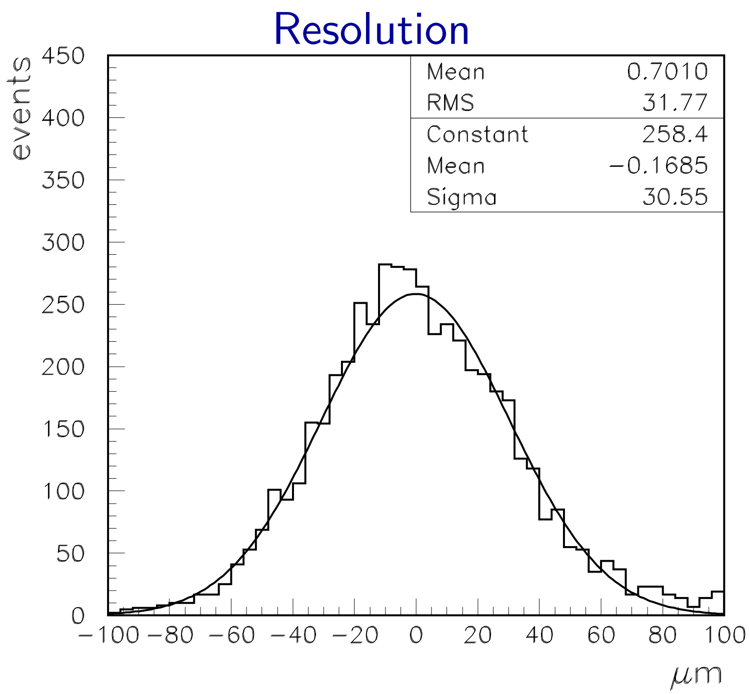
- CMS pixel pitch $125\mu m \times 125\mu m$
- Metalization: Ti/W
- Indium bumping at UC Davis

$\rightarrow$ Bump bonding yield $\approx$ 100 % for both ATLAS and CMS devices

New radiation hard chips produced this year.

Results from a CMS pixel detector

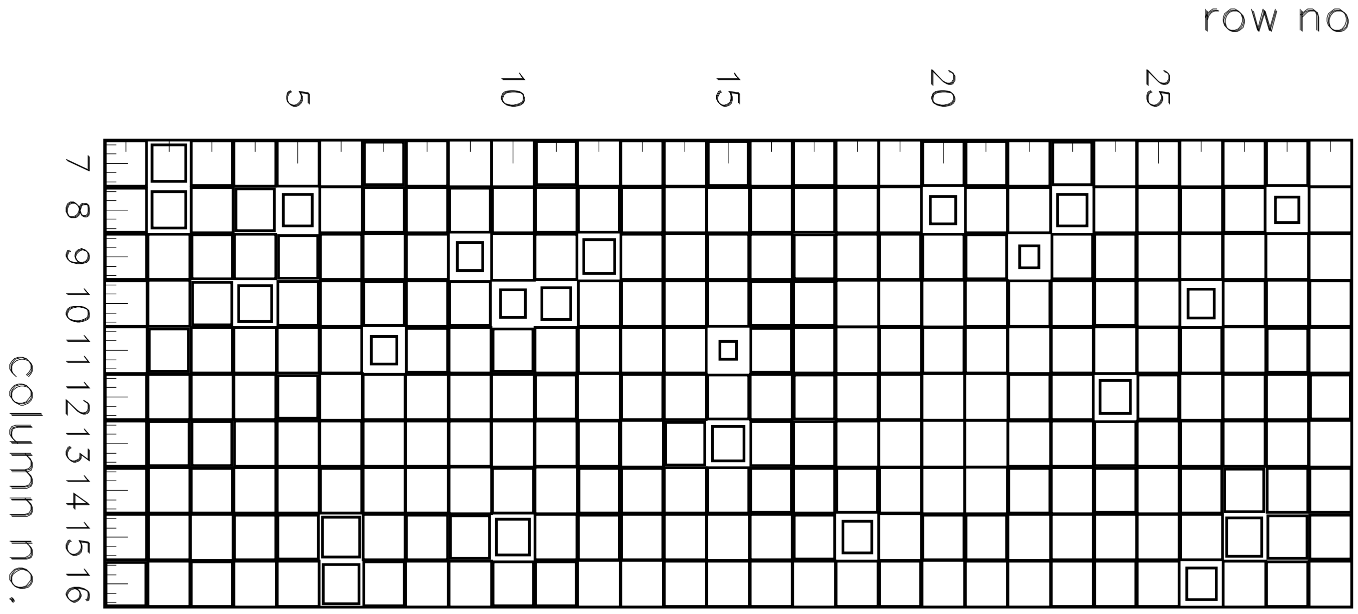




- Results with 200μm collection distance diamond
  - Efficiency $\sim$ 94%
  - Spatial resolution $\sim$ 31μm for 125μm pitch

Results from a CMS pixel detector

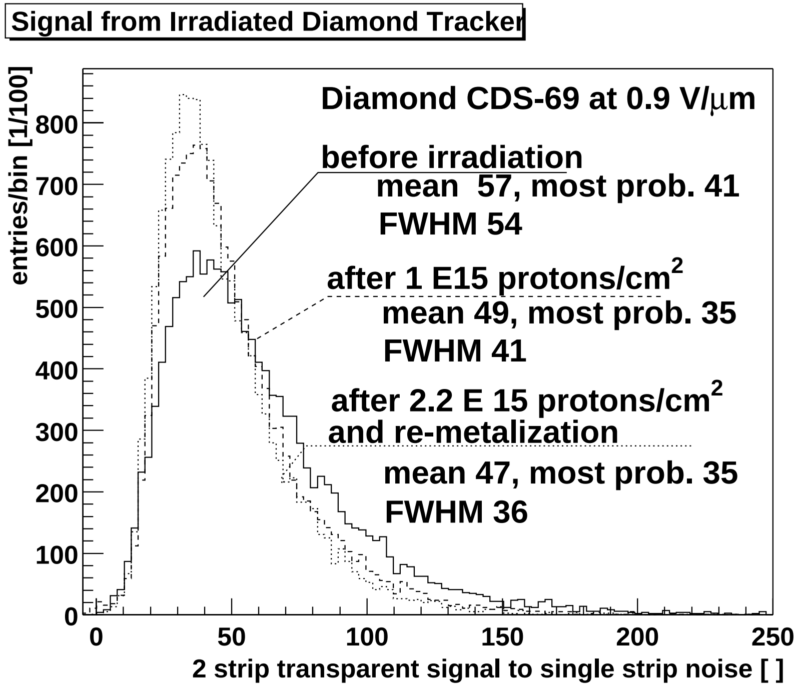
Efficiency vs Pixel



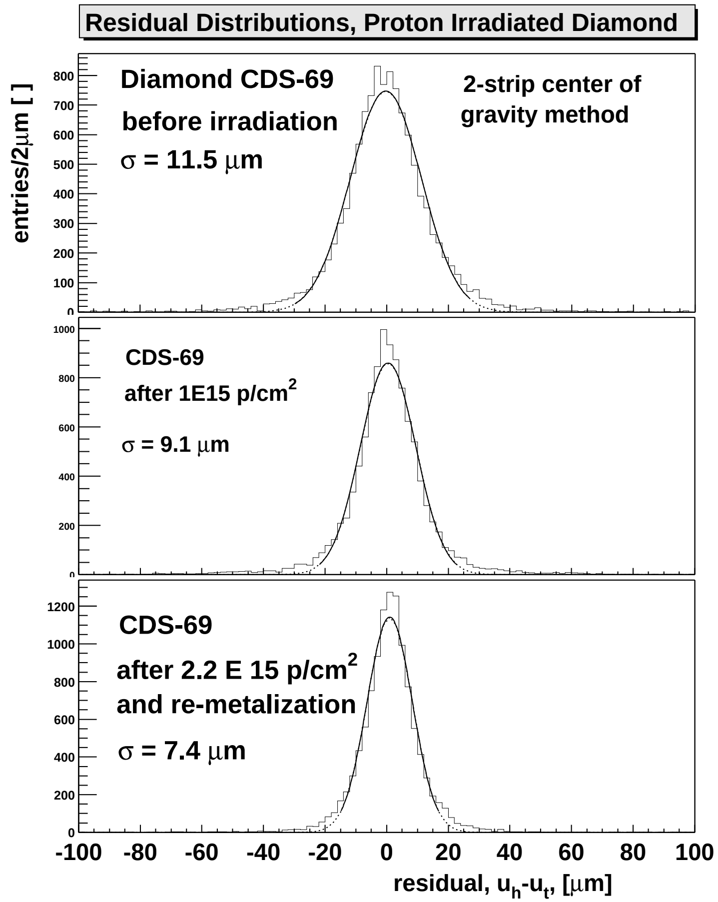
- Inefficient pixels due to bump bonding and/or electronics - shown in pulser tests
- Excellent correlation between beam telescope and pixel tracker data!

Proton Irradiation Studies with Trackers:

Signal to Noise



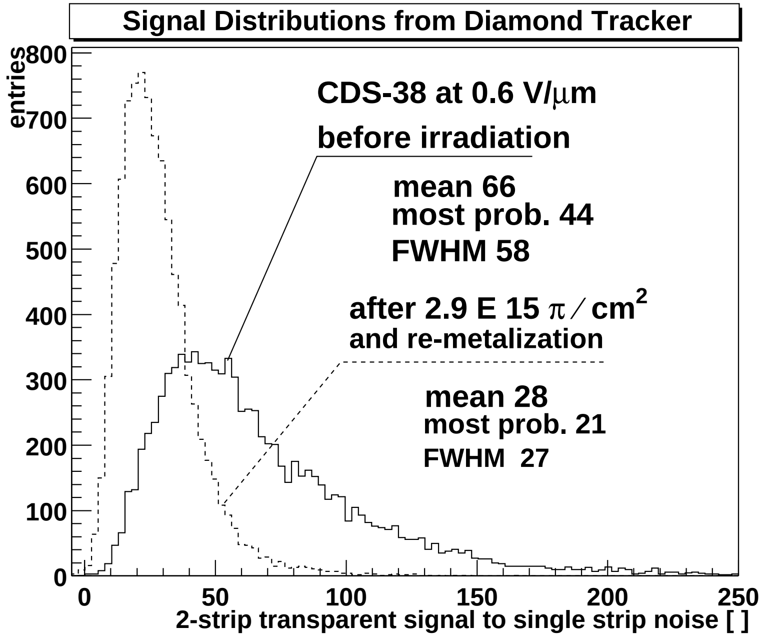
Resolution



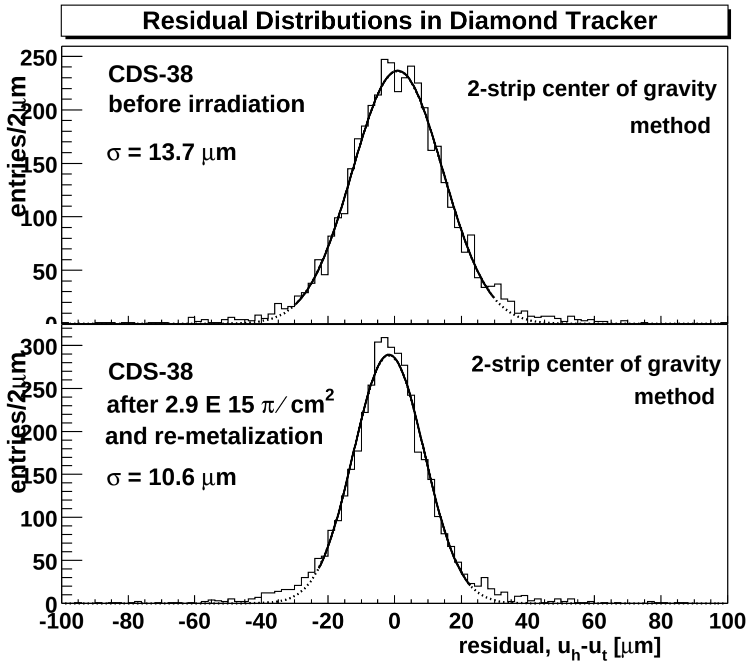
- Dark current decreases with fluence
- S/N decreases at $2 \times 10^{15}/\text{cm}^2$
- Resolution improves at $2 \times 10^{15}/\text{cm}^2$

Pion Irradiation Studies with Trackers:

Signal to Noise



Resolution



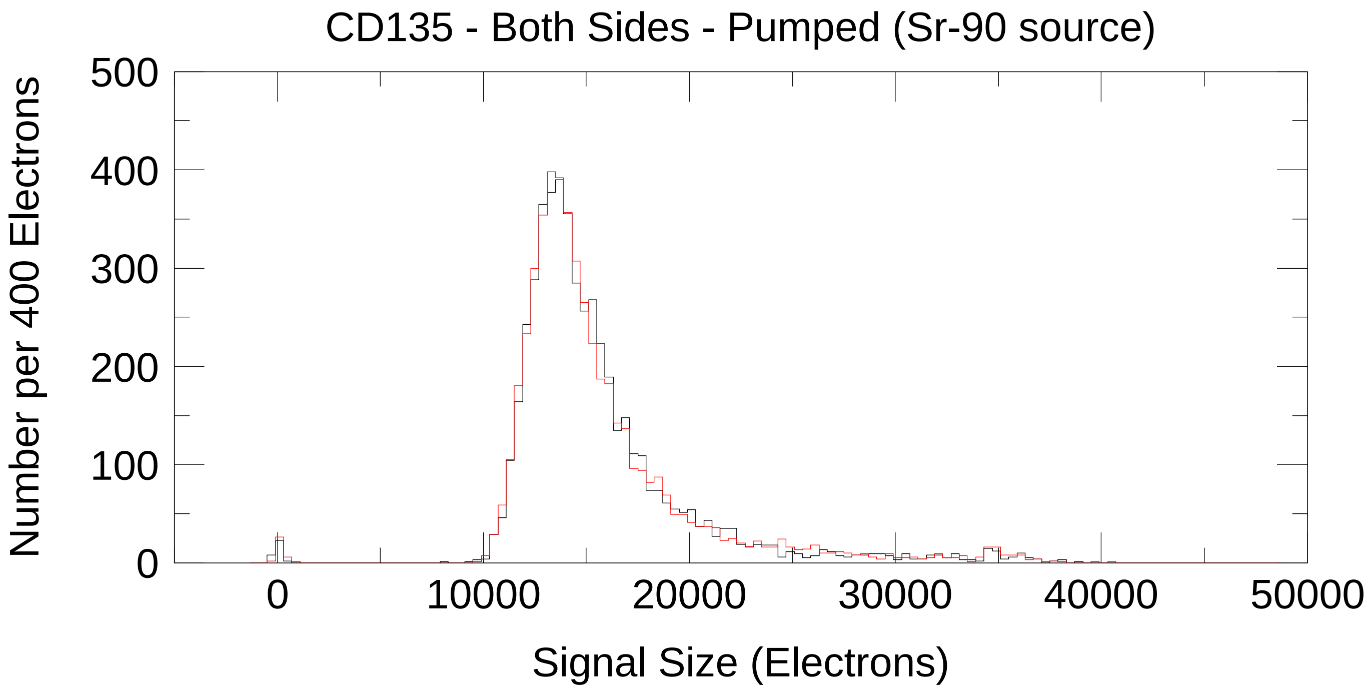
- Dark current decreases with fluence
- 50% loss of S/N at 2.9×10^{15}/cm^2
- Resolution improves 25% at 2.9×10^{15}/cm^2

Diamond Future: Single Crystal CVD Diamond

Could we make a CVD diamond with improved characteristics?

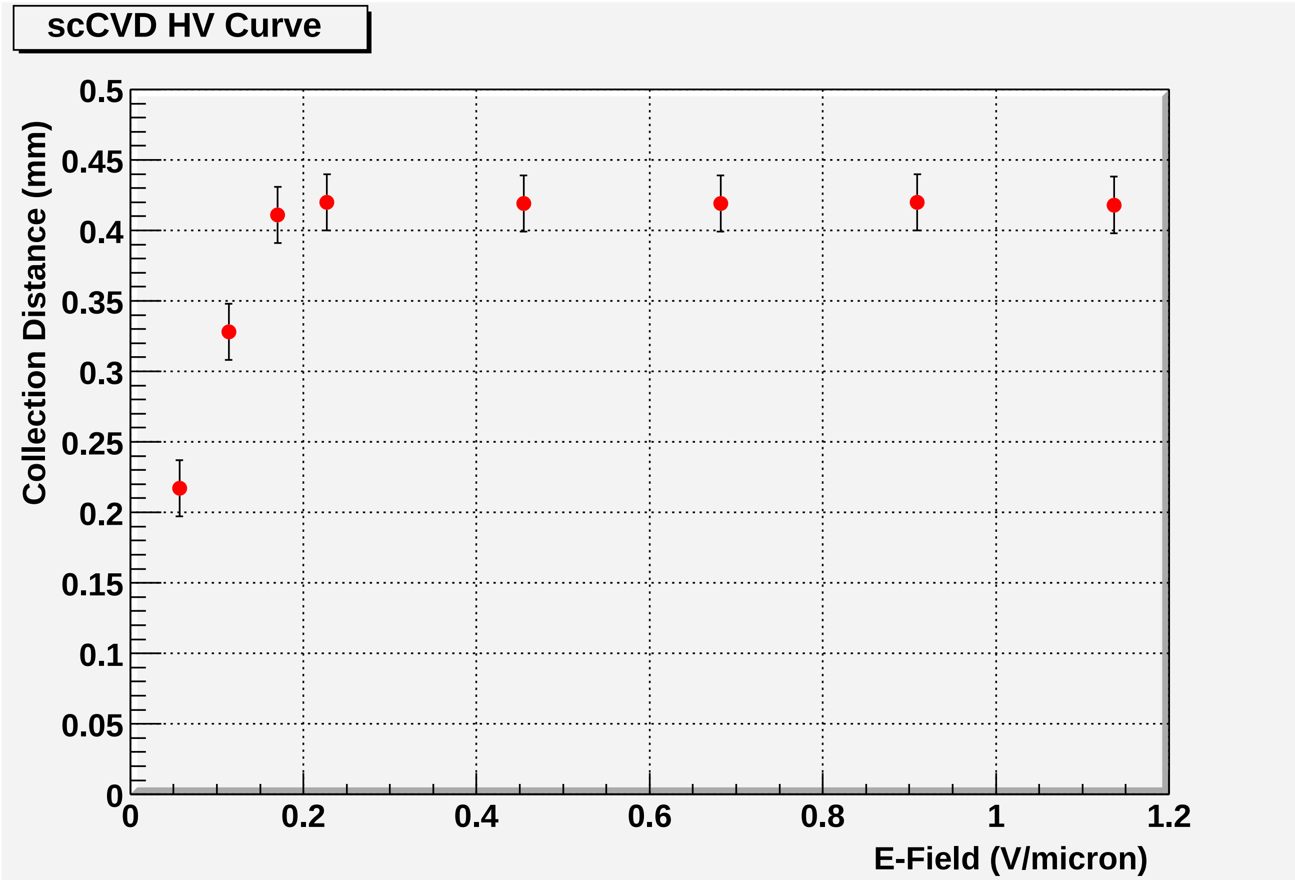
- Remove the grain boundaries, defects , etc.
- Lower operating voltage.
- Eliminate pumping.

This is single crystal CVD (scCVD) diamond: [Isberg *et al.*, Science 297 (2002) 1670].



Single Crystal CVD Diamond

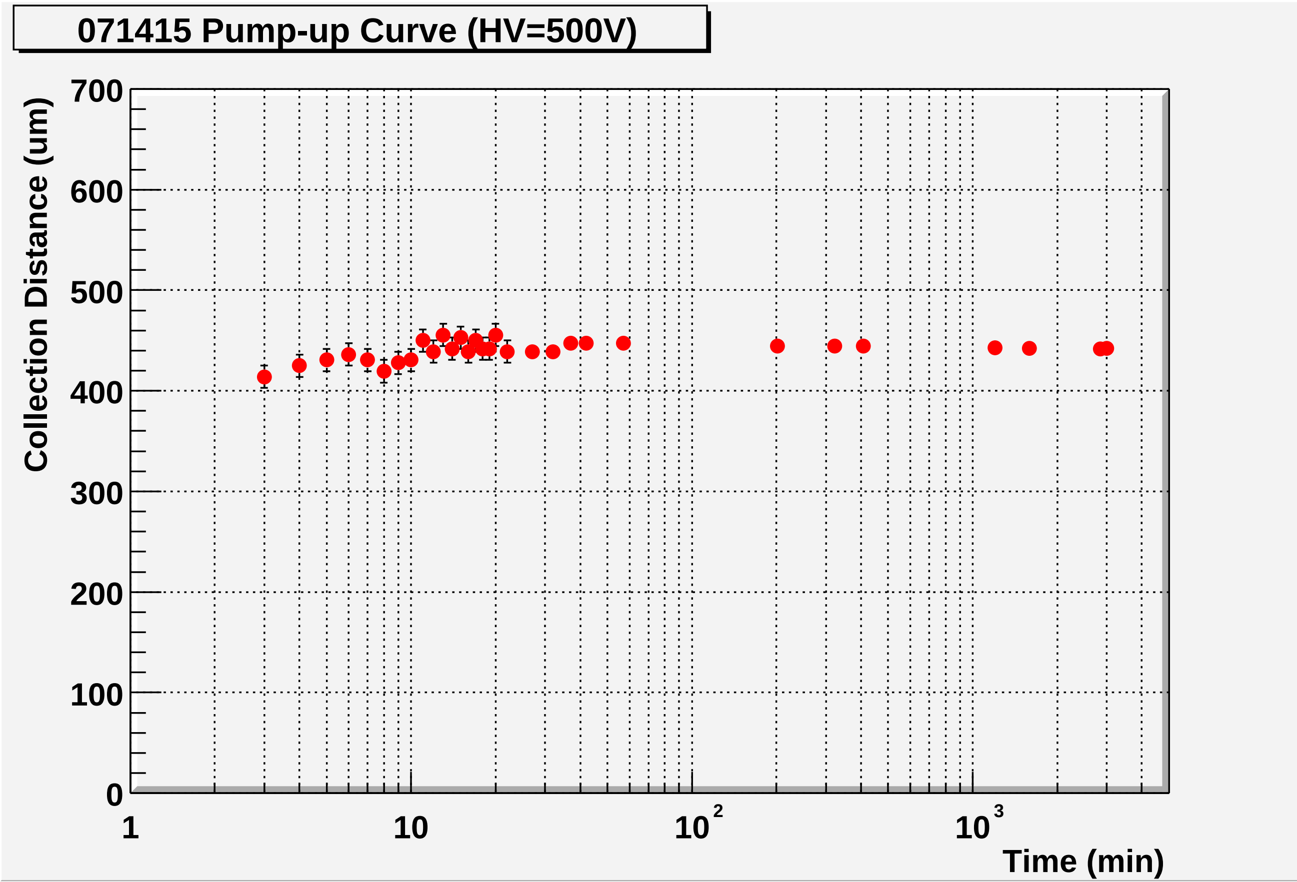
HV characteristics



High quality scCVD diamond collects all the charge at E=0.2V/μ!

Single Crystal CVD Diamond

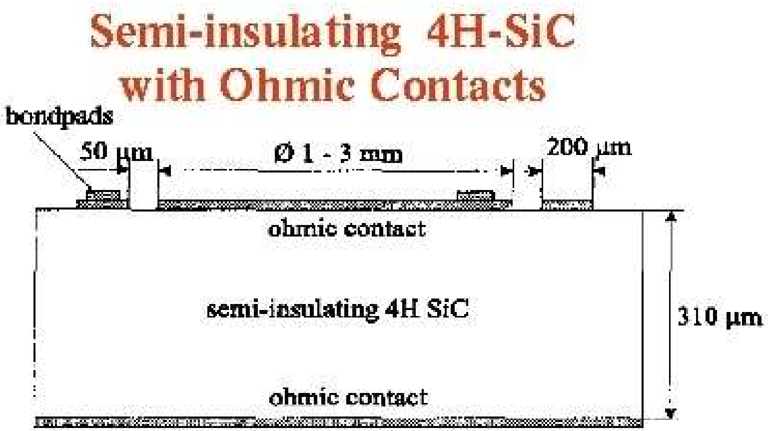
Pumping characteristics

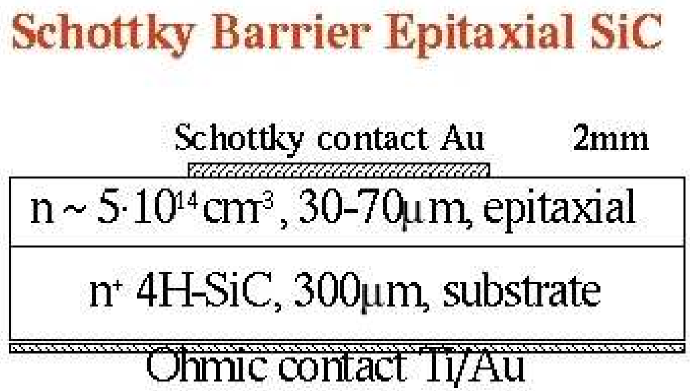


High quality scCVD diamond does not pump!

Structures in 4H-SiC:

The properties of silicon carbide are in some sense the geometric mean between silicon and diamond. As a result one hopes to take advantage of the strengths of both. Two types of SiC structures have been studied:

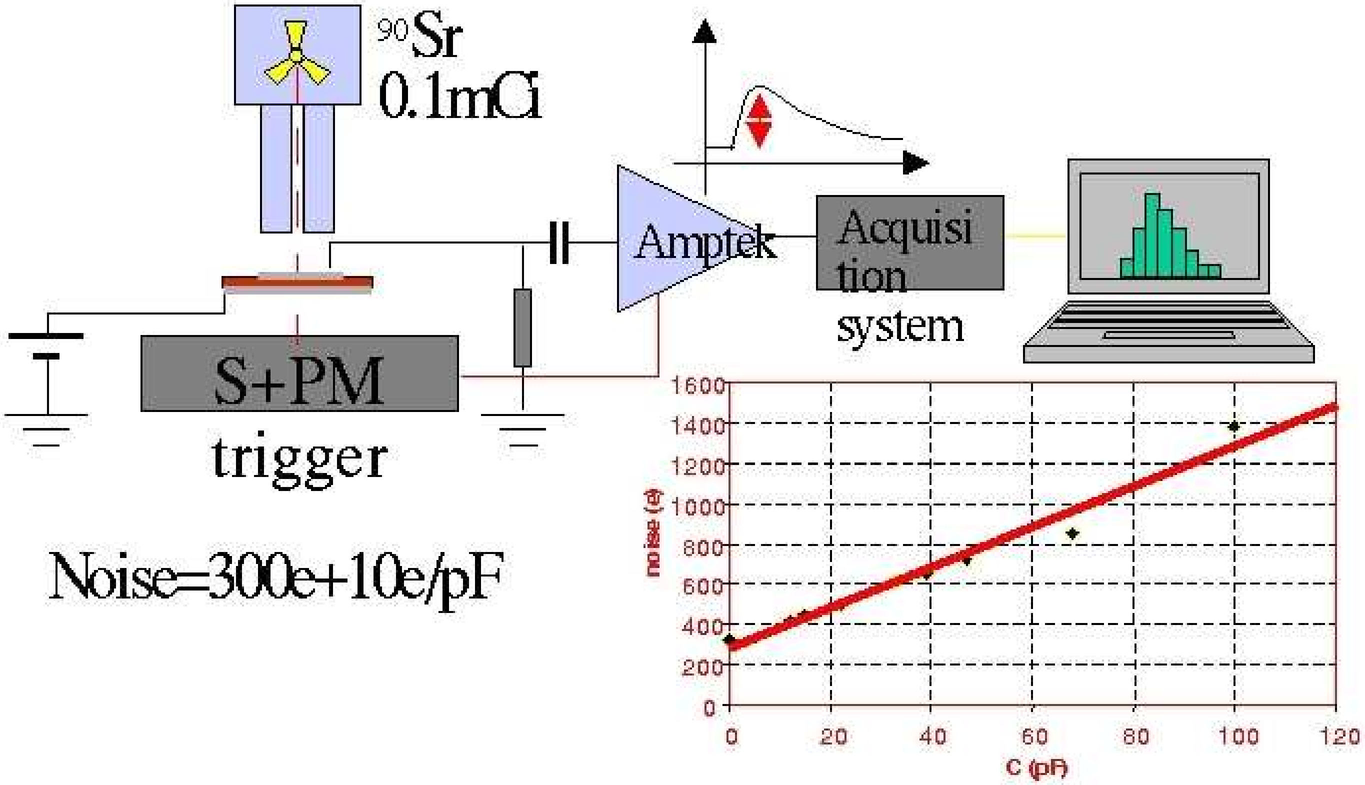




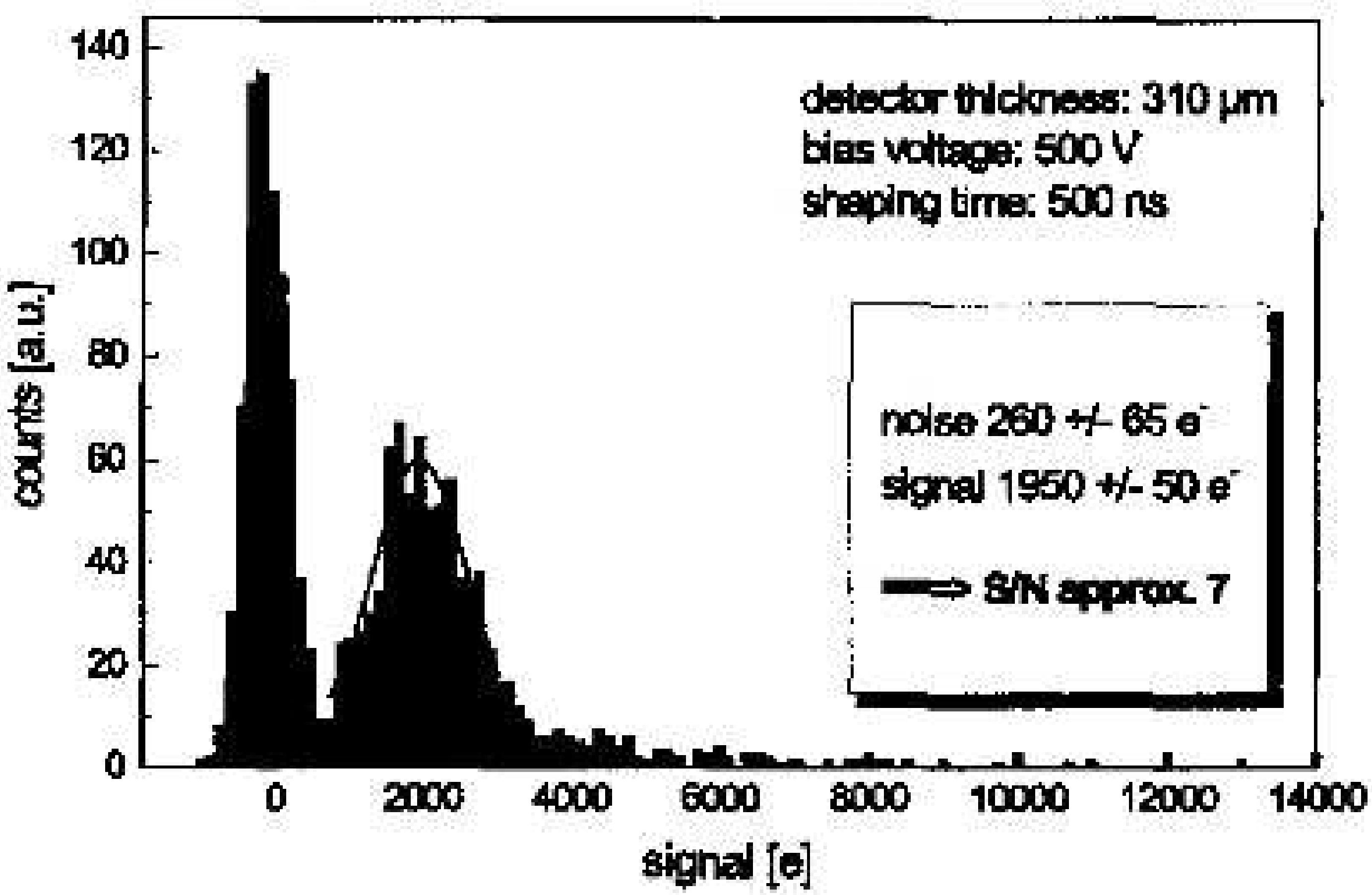
In Semi-Insulating material the charge collection depends on native defects; Epitaxial material has low native defects but only exists in thin layers.

Characterization of SiC:

Source Setup

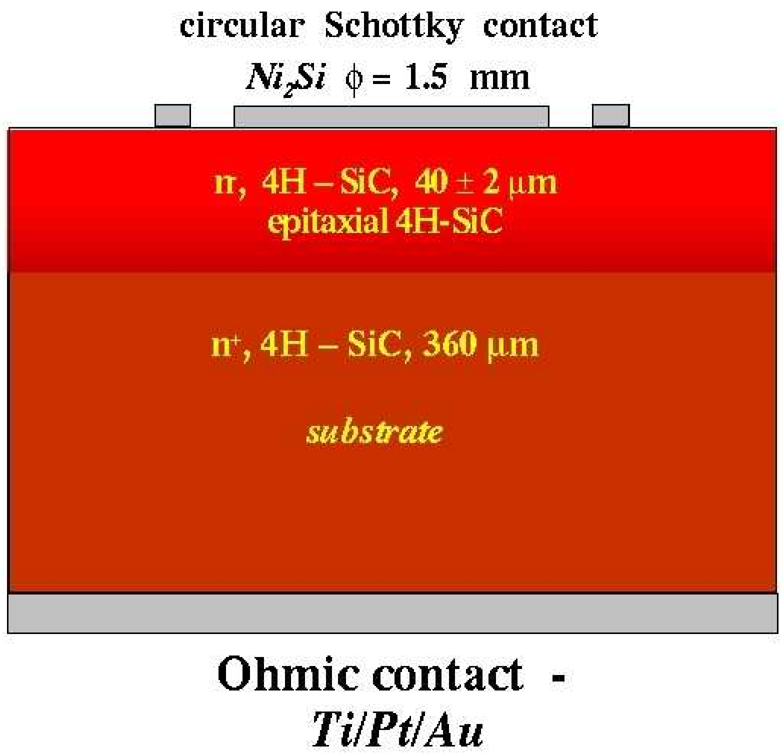


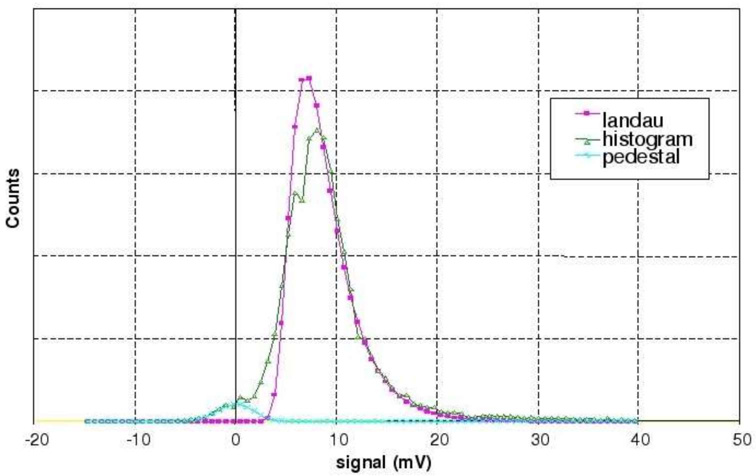
Charge Distributions from Semi-insulating 4H-SiC:



Semi-insulating SiC works but has problems with defects, full charge collection and stability.

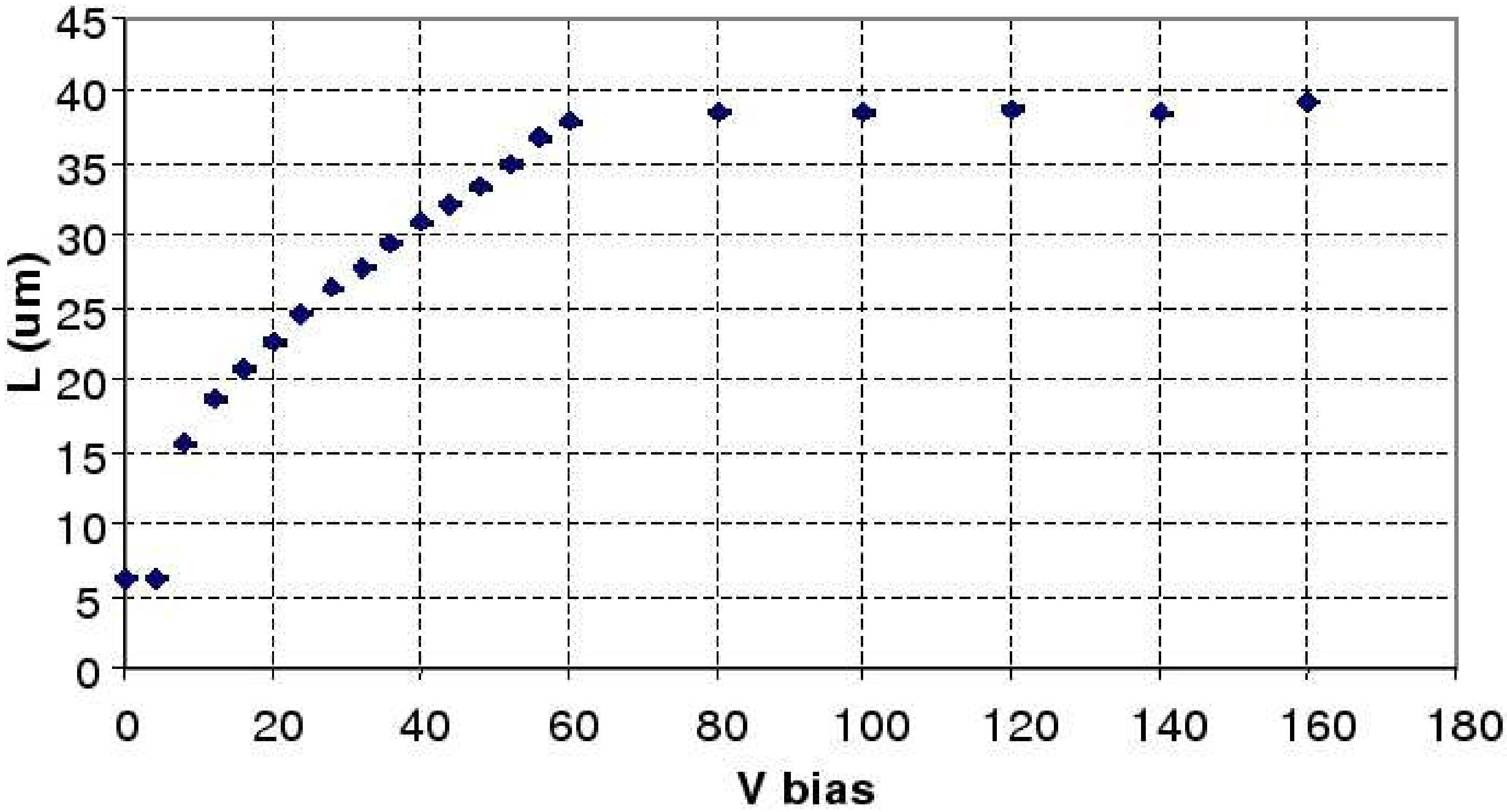
Charge Distributions from Epitaxial 4H-SiC:





Signal to Noise of 7:1 attained with Epitaxial SiC. Signal just separated from the pedestal.

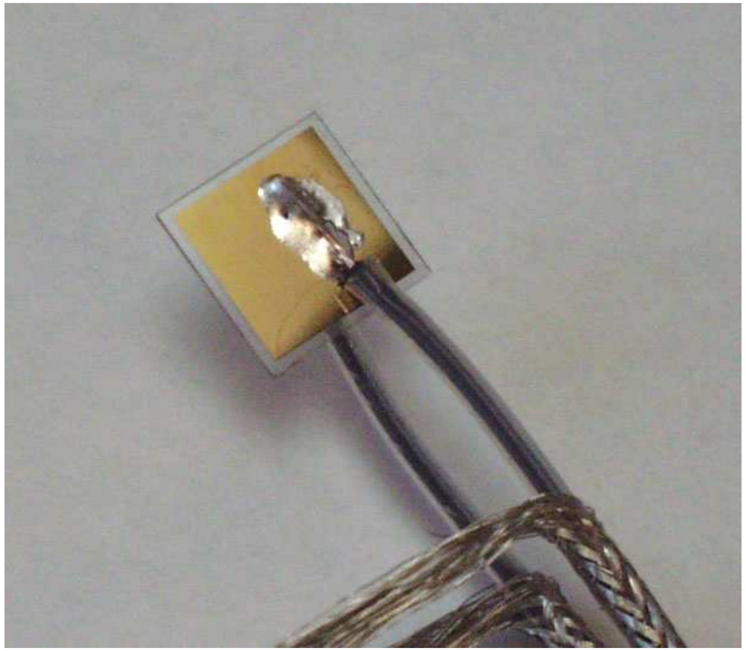
Charge Distributions from Epitaxial 4H-SiC:

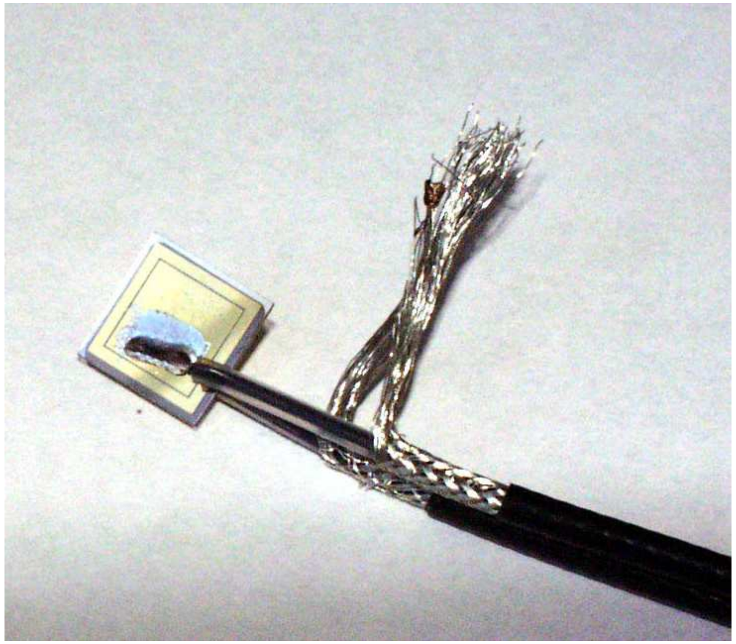


Epitaxial SiC has been shown for thin layers to collect all the charge at electric fields of $\sim 1.5\mathrm{V}/\mu\mathrm{m}$.

Motivation:

- → Radiation monitoring crucial for silicon operation/abort system
- → Abort beams on large current spikes
- → Measure calibrated daily and integrated dose
- → BaBar/Belle presently use silicon PIN diodes, leakage current increases 2nA/krad
- → After 100fb^{-1} signal≈10nA, noise≈ 1-2μA
- → Large effort to keep working, BaBar/Belle PIN diodes will not last past 2004-05

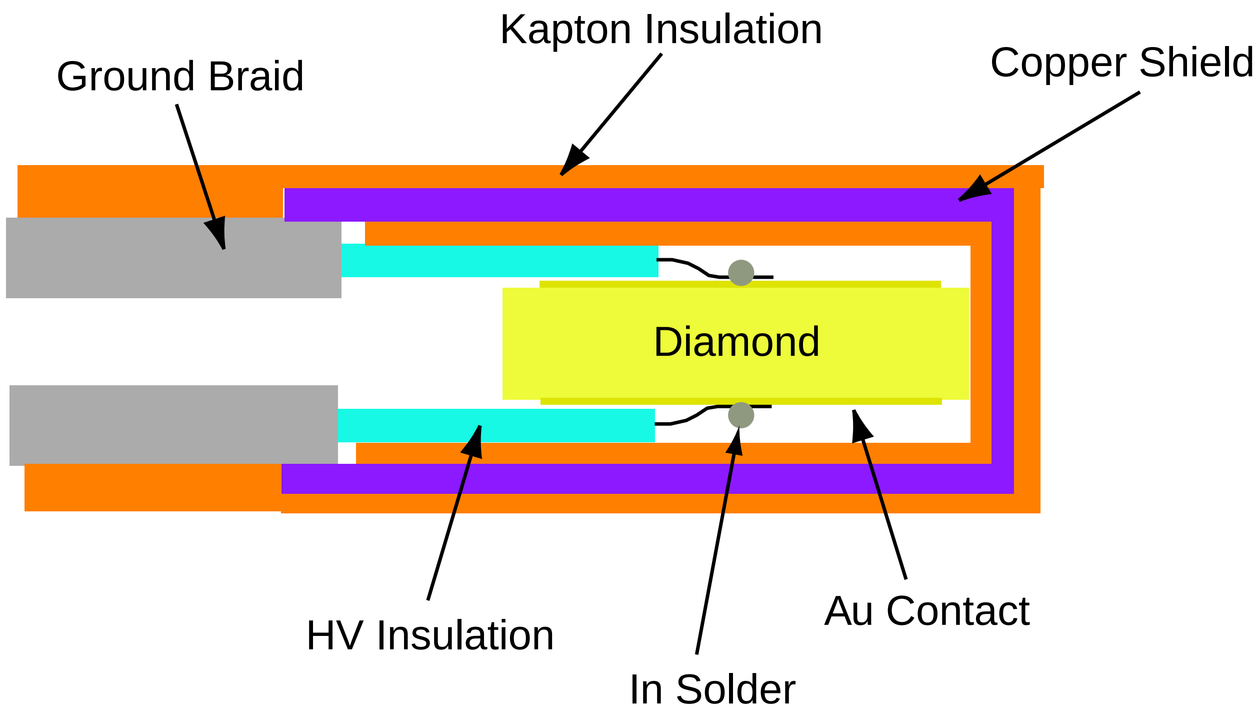




The BaBar/Belle Diamond Radiation Monitor Prototypes:

- Package must be small to fit in allocated space
- Package must be robust

Schematic View



The BaBar/Belle Diamond Radiation Monitor Prototypes:

Photo of Belle Prototype Device

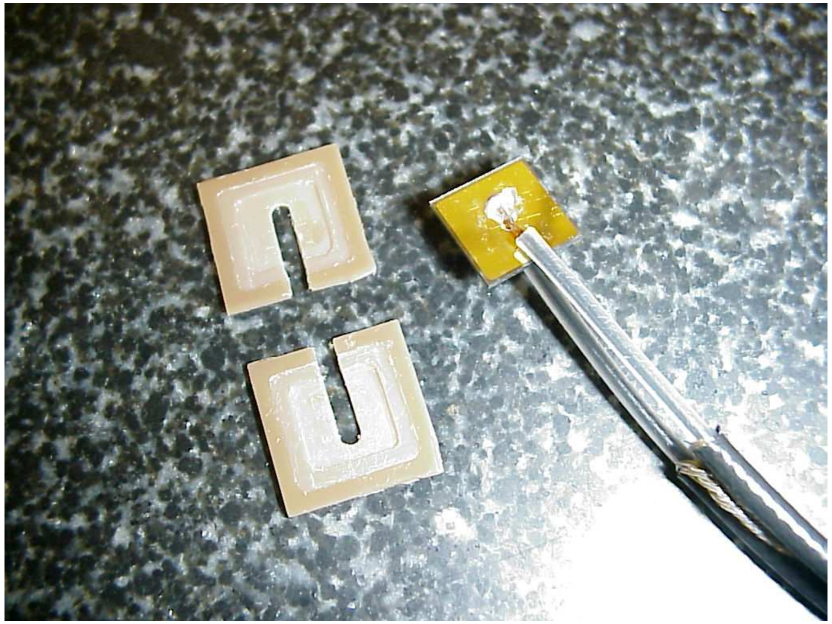


Photo of Packaged Belle Prototype

The BaBar/Belle Diamond Radiation Monitor Prototypes:

Photo of Installed BaBar Device

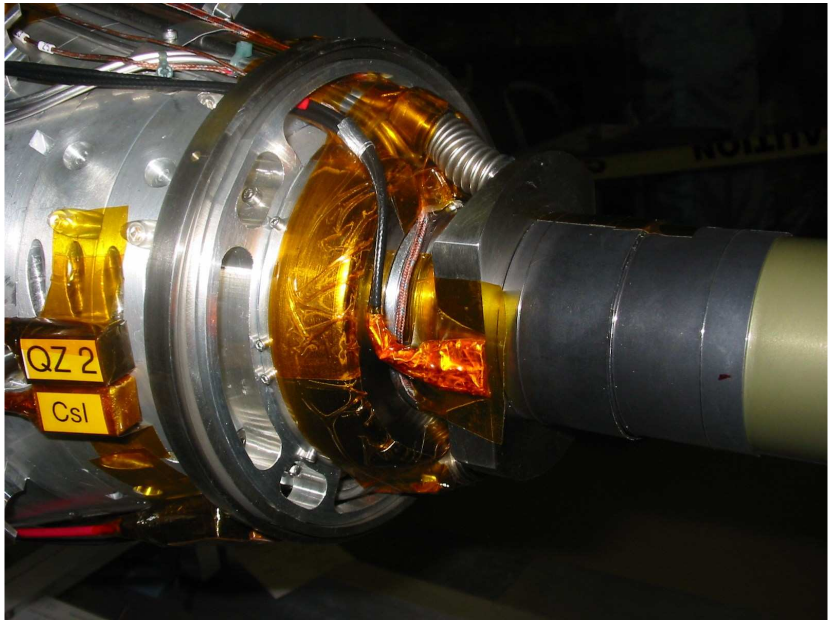
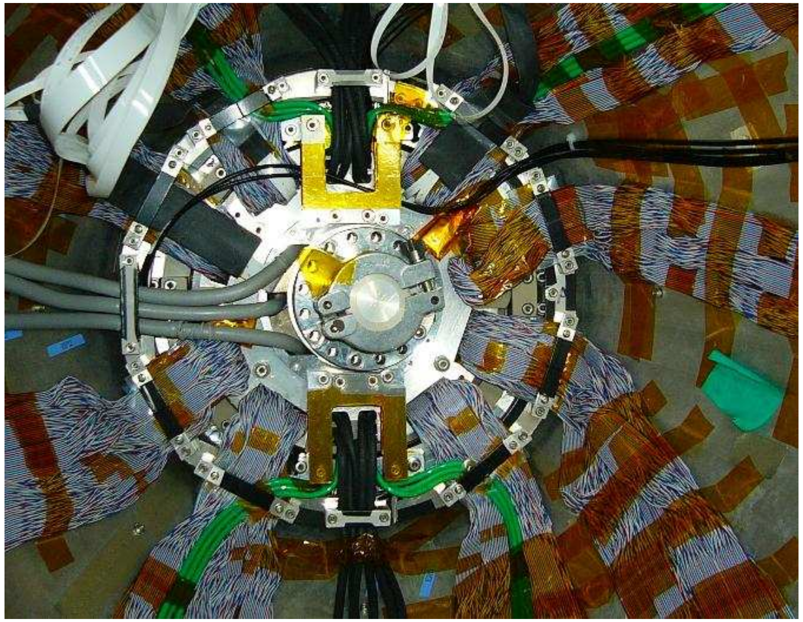


Photo of Installed Belle Device

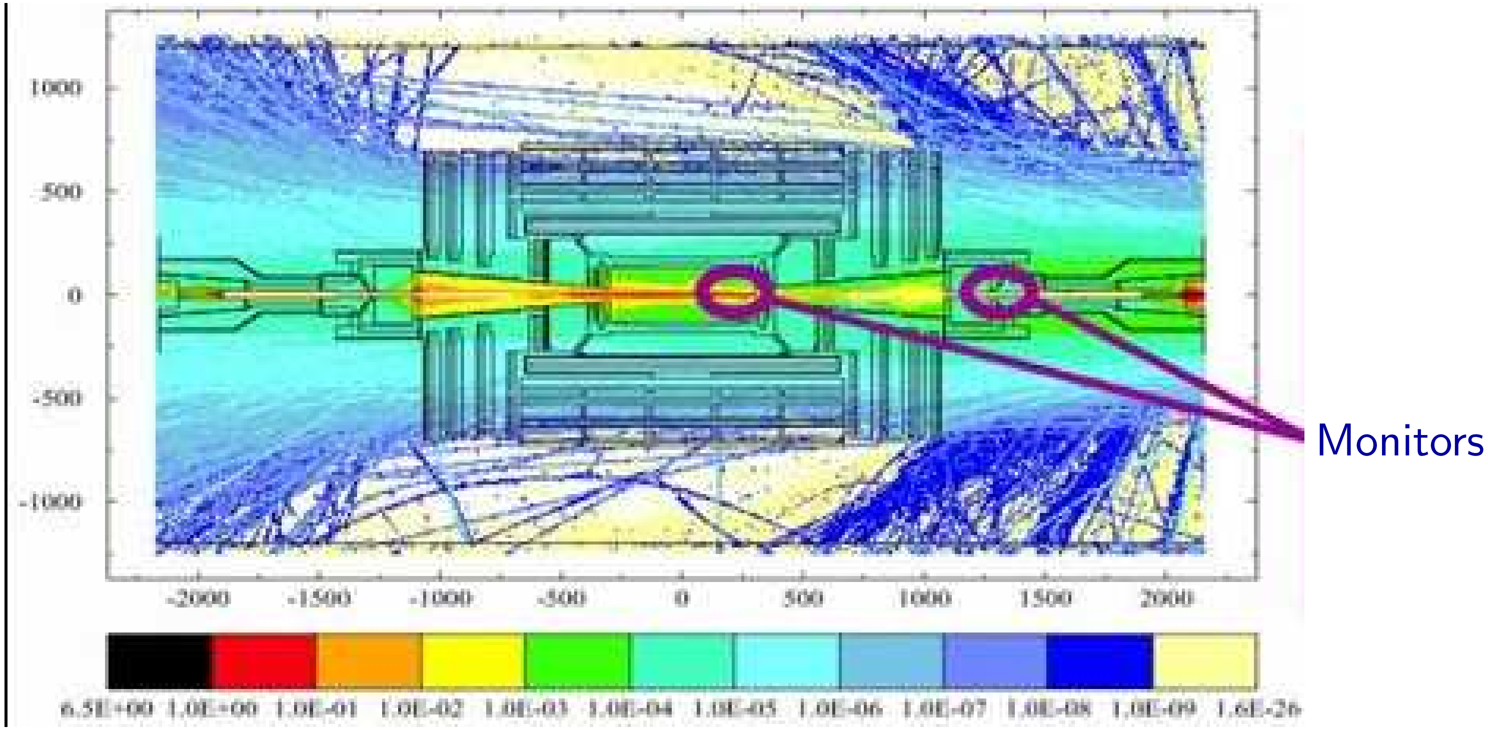


BaBar device inside the silicon vertex detector.
Belle device just outside the silicon vertex detector.

The CMS Diamond Radiation Monitor Program:

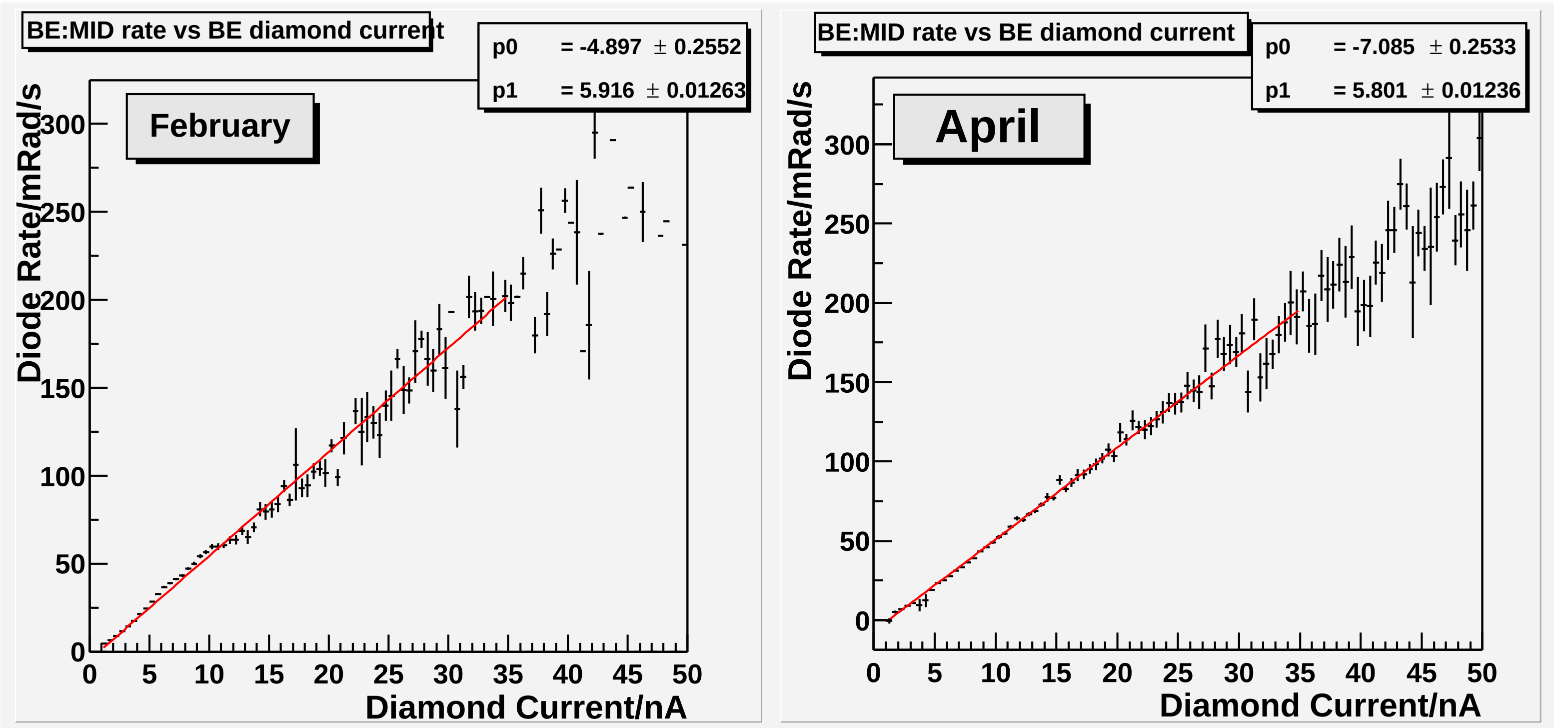
- Diamond activity has begun!
- Test beam emulating beam accident in Autumn 2003
- Possible location in the CMS detector:

Simulation of a Beam Accident in CMS



Results on Calibration in BaBar:

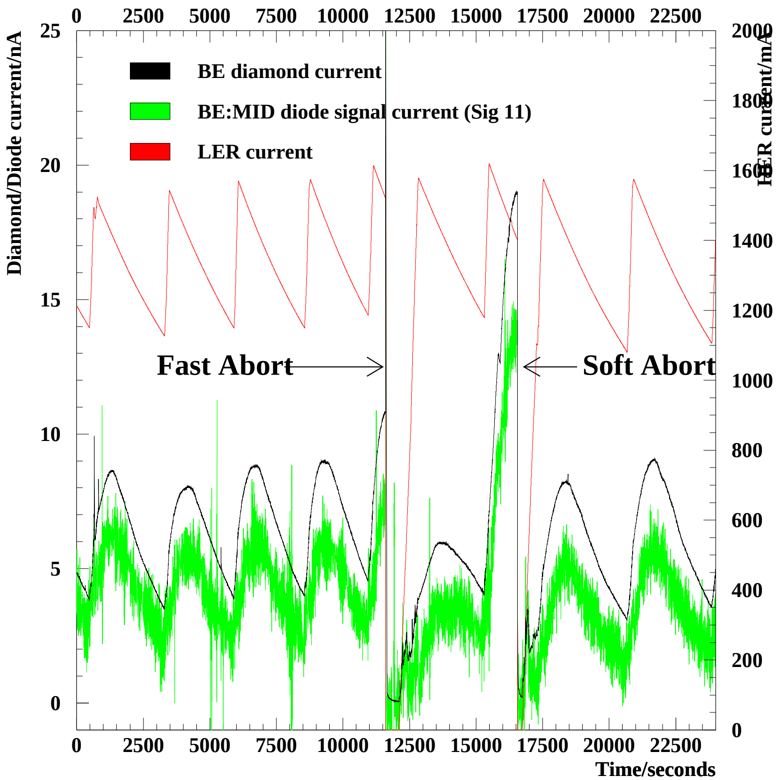
- In BaBar during injection relative to silicon diodes: 5.9mrad/nC (Feb)
- In BaBar during injection relative to silicon diodes: 5.8mrad/nC (Apr)
- Correlation coefficient unchanged over several months

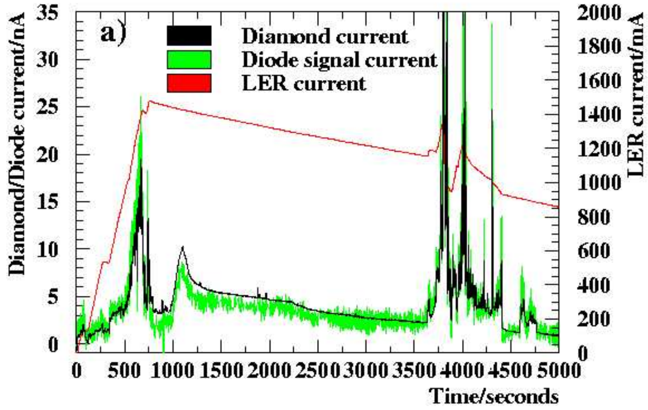


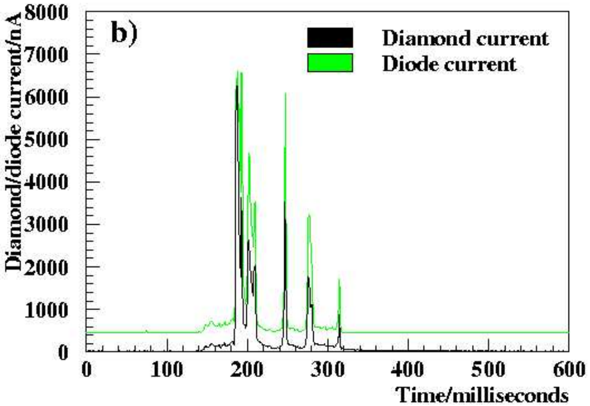
Calibration repeatable but so far limited by systematics

Radiation Monitoring

Data Taking in BaBar:



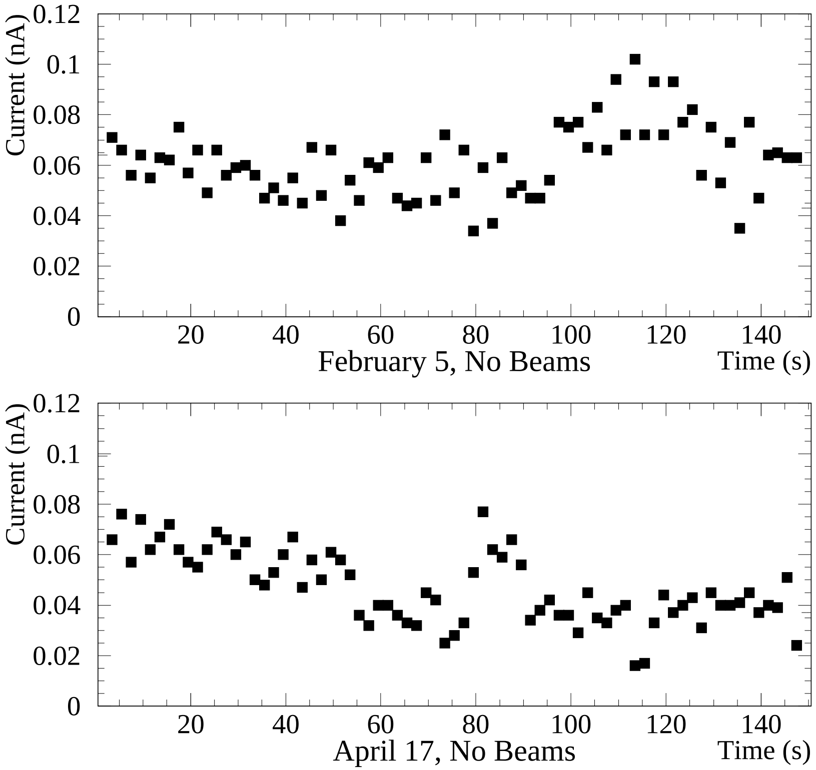




System operating for 4 months in BaBar and works well!

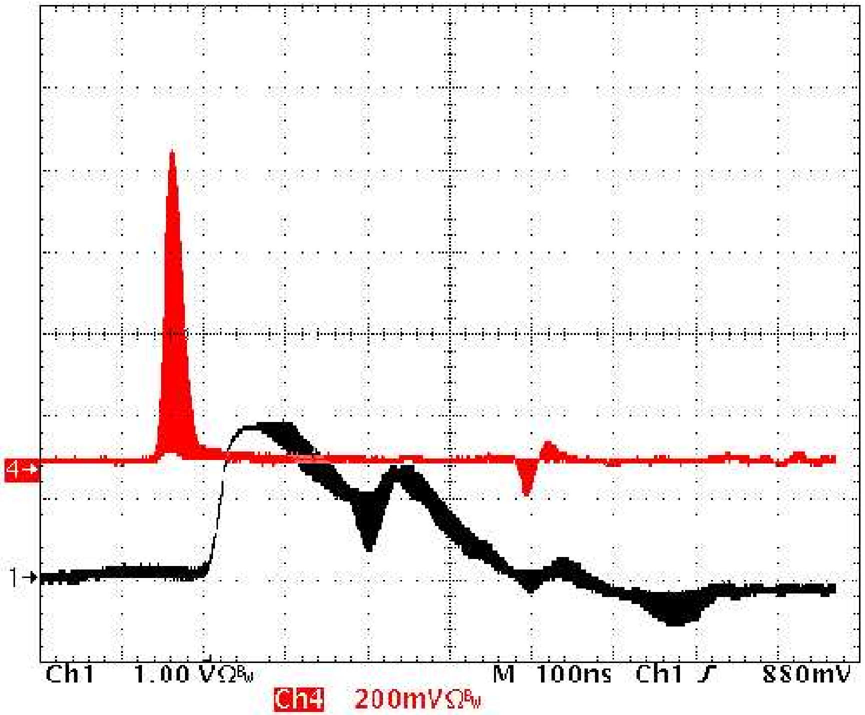
Leakage Current in BaBar

- Diamonds have received 250kRad ^{60}Co plus 250kRad while installed
- No observed change in leakage current (<0.1nA) or fluctuations (30pA)
- Data directly from BaBar SVTRAD system
- Electronic noise ($\approx$ 0.5nA) substracted off



Very Fast Time Scale (ns) in BaBar

- Use a fast amplifier to look at PIN-diode and diamond signals
- Trigger on the PIN-diode signal
- Look at fast spikes: red = diamond, black = PIN-diode



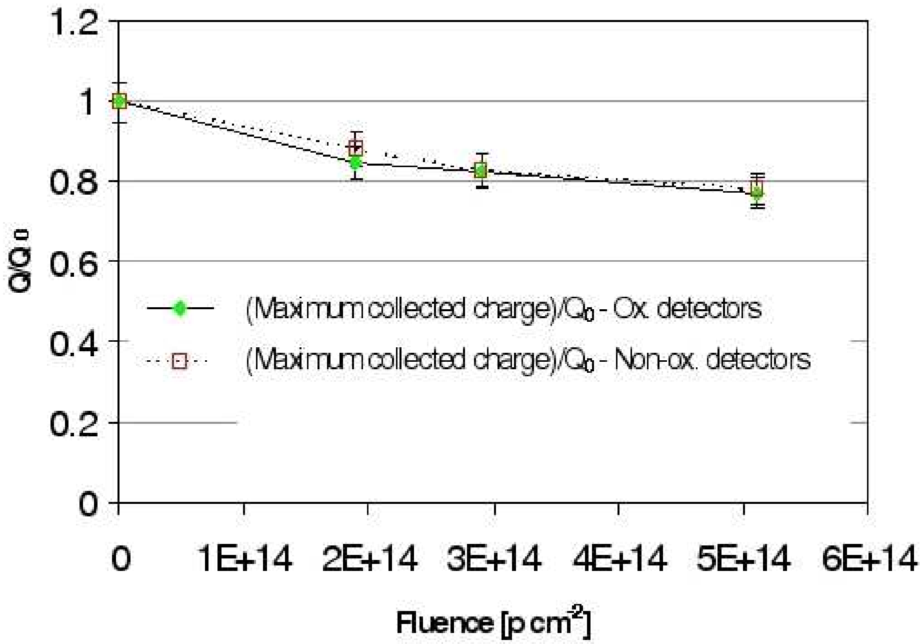
Diamond is fast enough for Fast Abort

An attempt at final packaging

Ceramic Package

The Future

- Diamond and silicon carbide have very promising futures
- Diamond work is being pursued by RD42 pCVD → scCVD
- SiC work is being pursued by RD50 epi layers → 100μm
- Present pCVD diamonds should surpass the performance of present silicon at around 10^{15}p/cm^2
- Semi-insulating SiC will require lots of engineering



Data: Gianluigi Casse: 1st Workshop on Radiation hard semiconductor devices for high luminosity colliders; CERN; 28-30 November 2002

Summary

- **Charge Collection in Diamond**

  270 μm collection distance diamond attained in pCVD research contract
  MP signal $\approx$ 8000 e
  99% of charge distribution above 3000 e
  Attained S/N=60/1 with 2μs shaping time; 8/1 at 25ns
  FWHM/MP $\sim$ 0.95 – Working with manufacturers to increase uniformity
  This diamond process now in production reactors

  Single crystal CVD diamond is here: $>$450 μm collection distance attained
  MP signal $\approx$ 13000 e
  99% of charge distribution above 10000 e
  FWHM/MP $\sim$ 0.30

- **Charge Collection in Silicon Carbide**

  40 μm collection distance epitaxial SiC attained
  Full charge collection at E $\sim$ 1.5V/μm
  Attained S/N of 7/1 with 2μs shaping time using a source
  Wafer diameters up to 3 cm and thicknesses up to 100μm soon
  Tracking devices now being fabricated

Summary

- **Radiation Hardness of Large Bandgap SemiConductors**

  Using trackers allows a correlation between S/N and Resolution

  - Dark current decreases with fluence
  - Some loss of S/N with fluence
  - Resolution improves with fluence

  Tests must be repeated with more trackers and latest pCVD and scCVD diamonds and Epitaxial 4H-SiC

- **Radiation Monitoring**

  Successfully tested BaBar and Belle devices

  CMS performing tests this summer

Radiation monitoring should lead to the development of the next level radiation hard devices

Future Plans for RD42

- **Charge Collection**

  Continue research program to improve pCVD material:

  collection distance $\rightarrow$ 300μm ($\bar{Q} = 10,800e$)

  $\rightarrow$ improved uniformity

  $\rightarrow$ identification of trapping centers

  Begin research program on scCVD diamond

- **Radiation Hardness of Diamond Trackers and Pixel Detectors**

  Continue tracker irradiations this year, add pixel irradiations

  With Protons:

  $\rightarrow 5 \times 10^{15}$/cm^2

  With Pions:

  $\rightarrow 5 \times 10^{15}$/cm^2

  With Neutrons:

  $\rightarrow 5 \times 10^{15}$/cm^2

- **Beam Tests with Diamond Trackers and Pixel Detectors**

  $\rightarrow$ trackers with intermediate strips, SCTA128 electronics

  $\rightarrow$ pixel detectors with ATLAS and CMS radhard electronics now available!

  $\rightarrow$ construct the first full ATLAS diamond pixel module

- **Material Research**

  $\rightarrow$ Florence, OSU, Paris, Rome

Future Plans for RD50

Goals: Define optimal materials and device structures to ensure best radiation tolerance.

- **Defect Engineering of Si**

  Oxygen, Oxygen dimmers, etc

- **New Materials**

  SiC, GaN

- **New Geometries**

  3D, thin detectors

- **Defect Modeling and Device Simulation**

Detectors should (soon) be able to handle the highest luminosities of the SLHC!