



Recent Developments in Diamond Tracking Devices

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Outline of the Talk

- ❖ Introduction
- ❖ Tracking Studies
- ❖ Diamond Pixel Detectors
- ❖ Radiation Hardness Studies
- ❖ Radiation Monitoring - a new application
- ❖ Summary and RD42 Plans



The RD42 Collaboration



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◇ Spokespersons

Institutes from HEP, Heavy Ion Physics, and Solid State Physics



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?

Diamond Properties:

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

Tracking Detector Implementation:

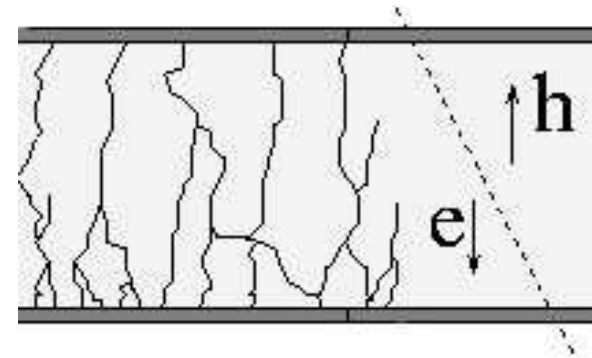
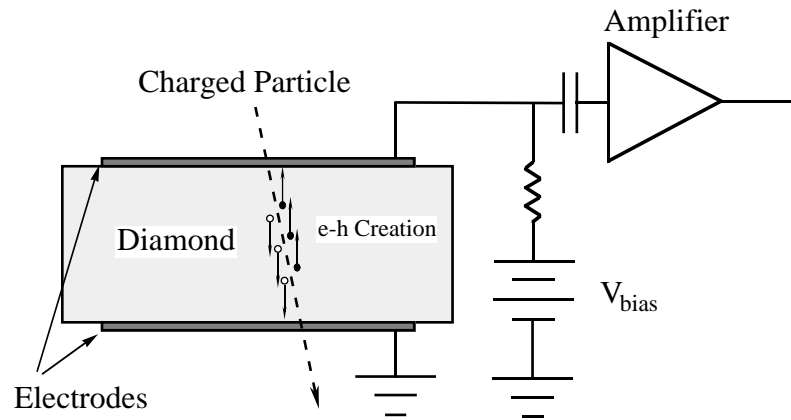
- ❖ Based on Chemical Vapor Deposition (CVD) Diamond
- ❖ Material goes Beyond Silicon in Radiation Hardness
- ❖ Signal Size and Uniformity?
- ❖ Performance of Trackers?
- ❖ Pixel Detector Performance?
- ❖ Radiation Hardness?

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

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

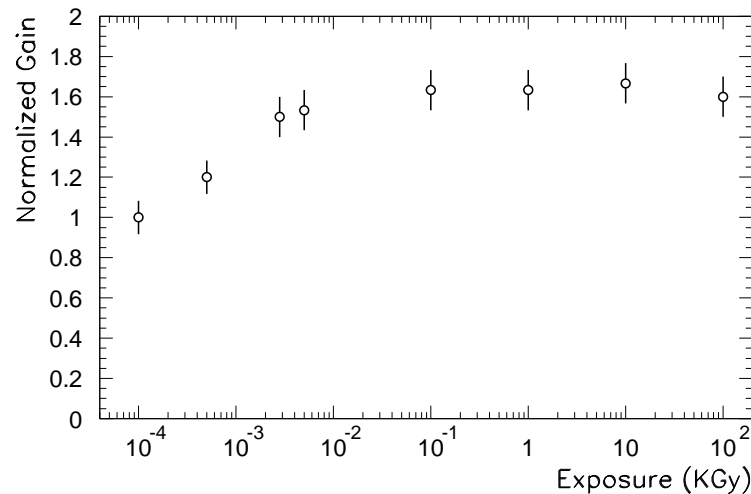
- ❖ $d = \mu E \tau$

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

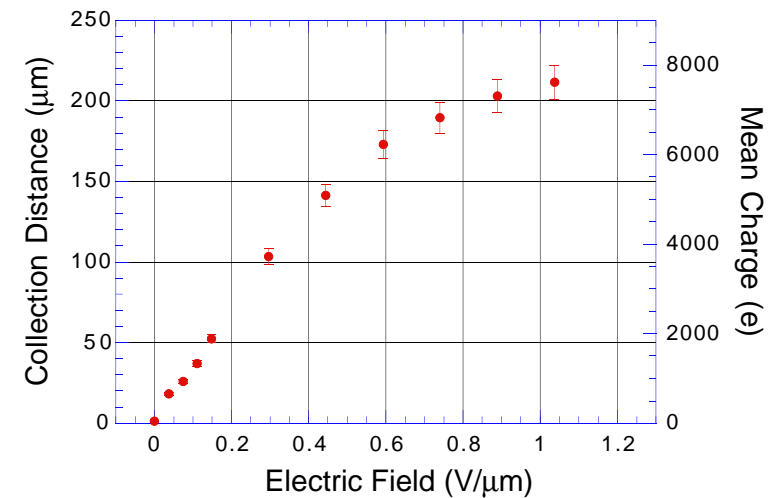


Diamond Properties:

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 $1V/\mu m$ → drift velocity saturated
- ❖ Test Procedure: dot → strip → pixel



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



(Courtesy of Element Six)

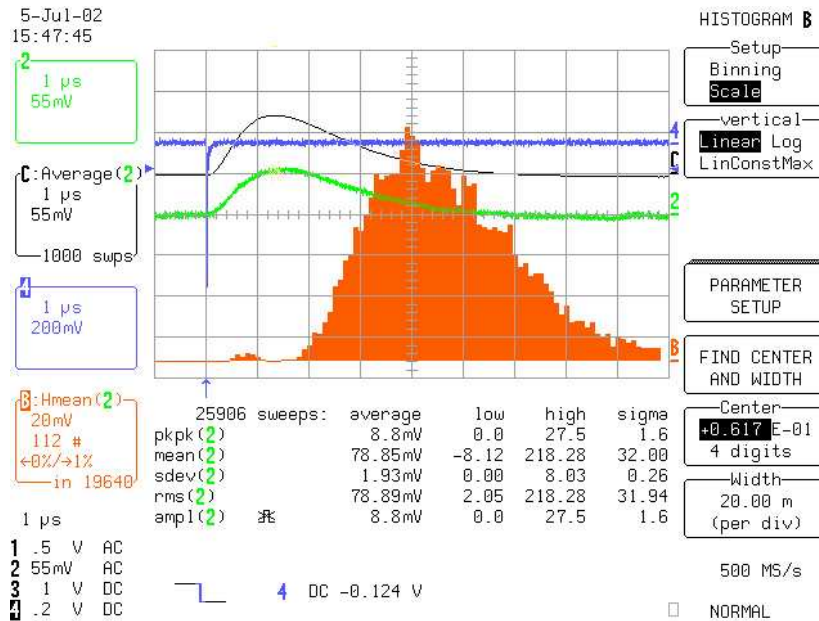


Introduction



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

Latest Diamonds Measured with a ⁹⁰Sr Source:



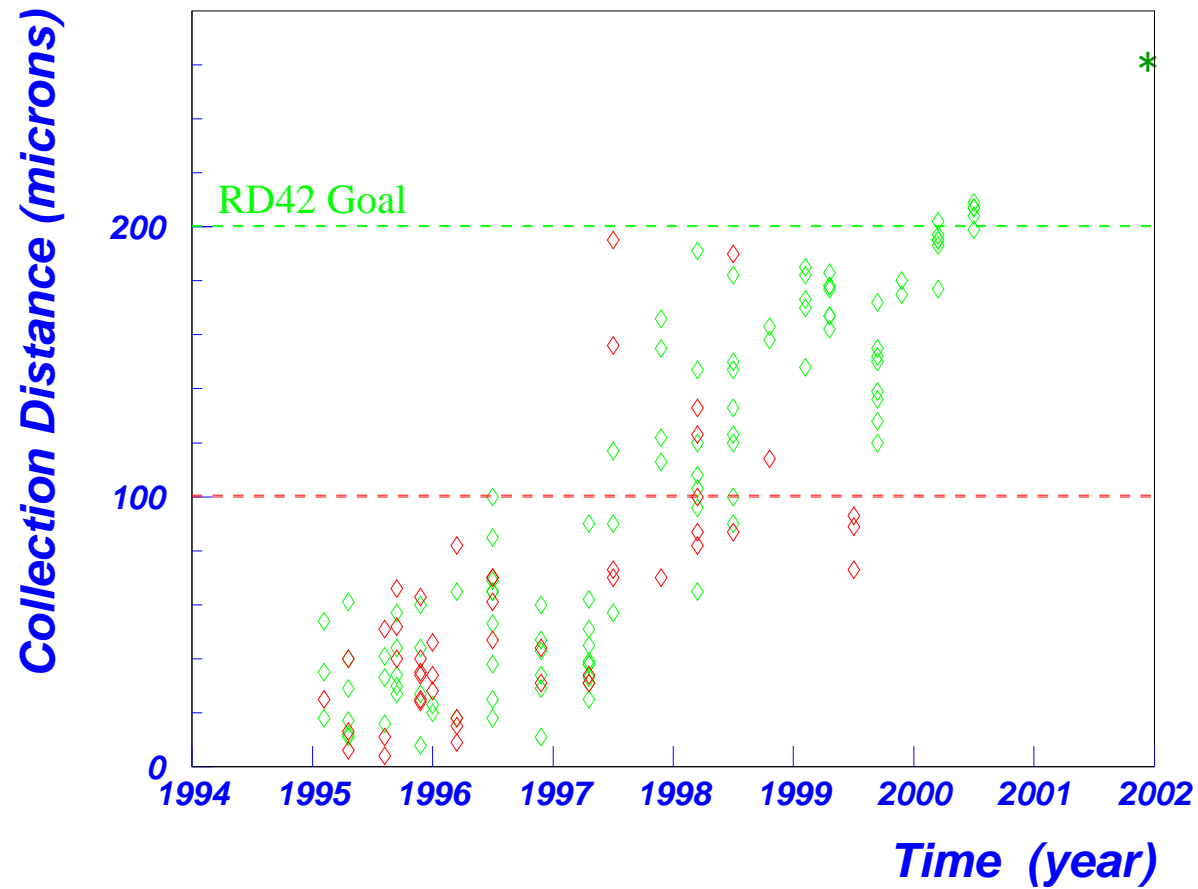
- ❖ System Gain = 124 e/mV
- ❖ $Q_{MP} = 62\text{mV} = 7600e$
- ❖ Mean Charge = 79mV = 9800e
- ❖ Source data well separated from 0
- ❖ Collection Distance now 275 μ m
- ❖ Most Probable Charge now $\approx 8000e$
- ❖ 99% of PH distribution now above 3000e
- ❖ FWHM/MP ≈ 0.95 — Si has ≈ 0.5
- ❖ This diamond available in large sizes

The Research program worked!



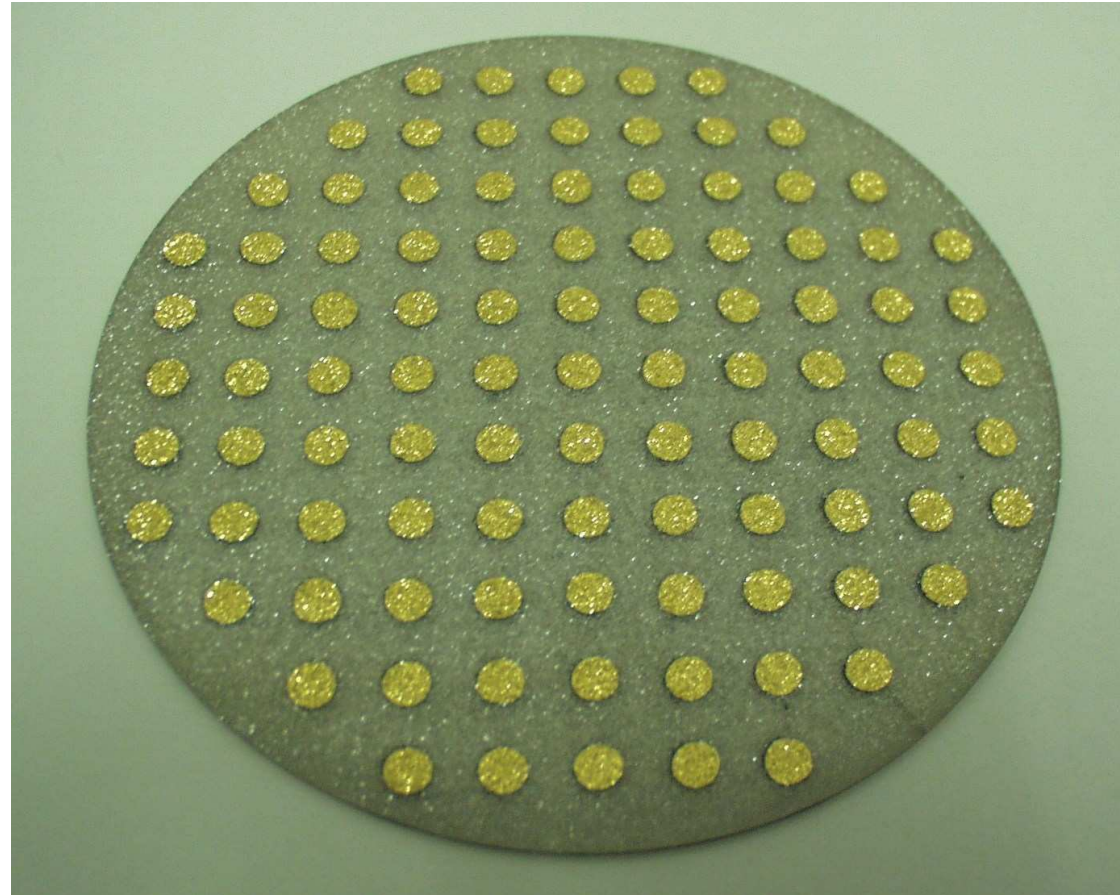
History of Diamond Progress

Charge Collection in DeBeers CVD Diamond



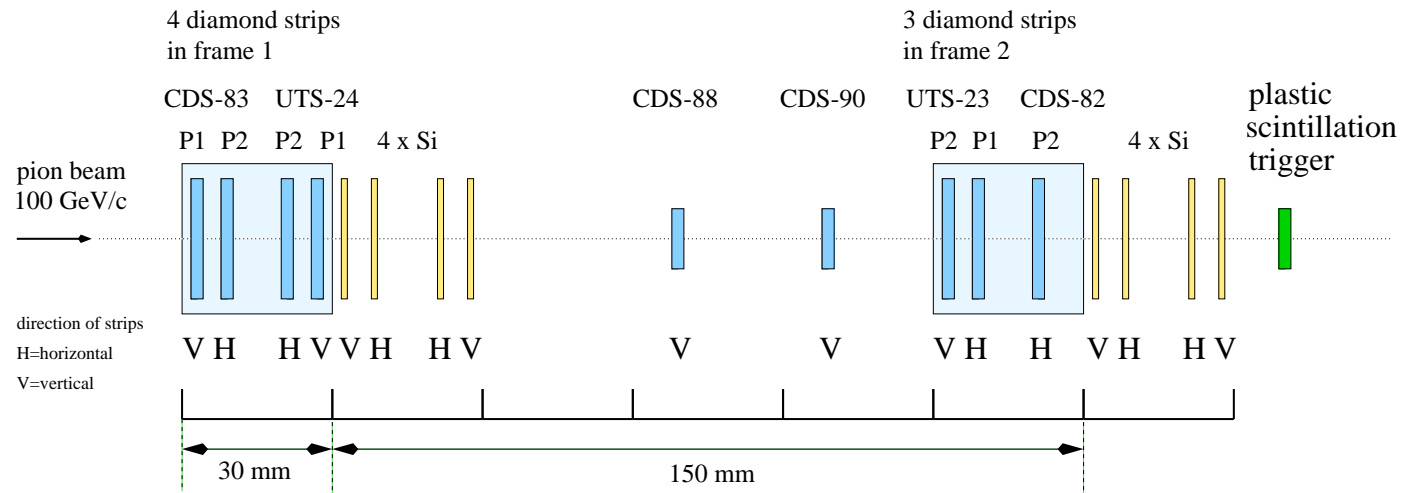


Recent pCVD diamond wafer ready for test:





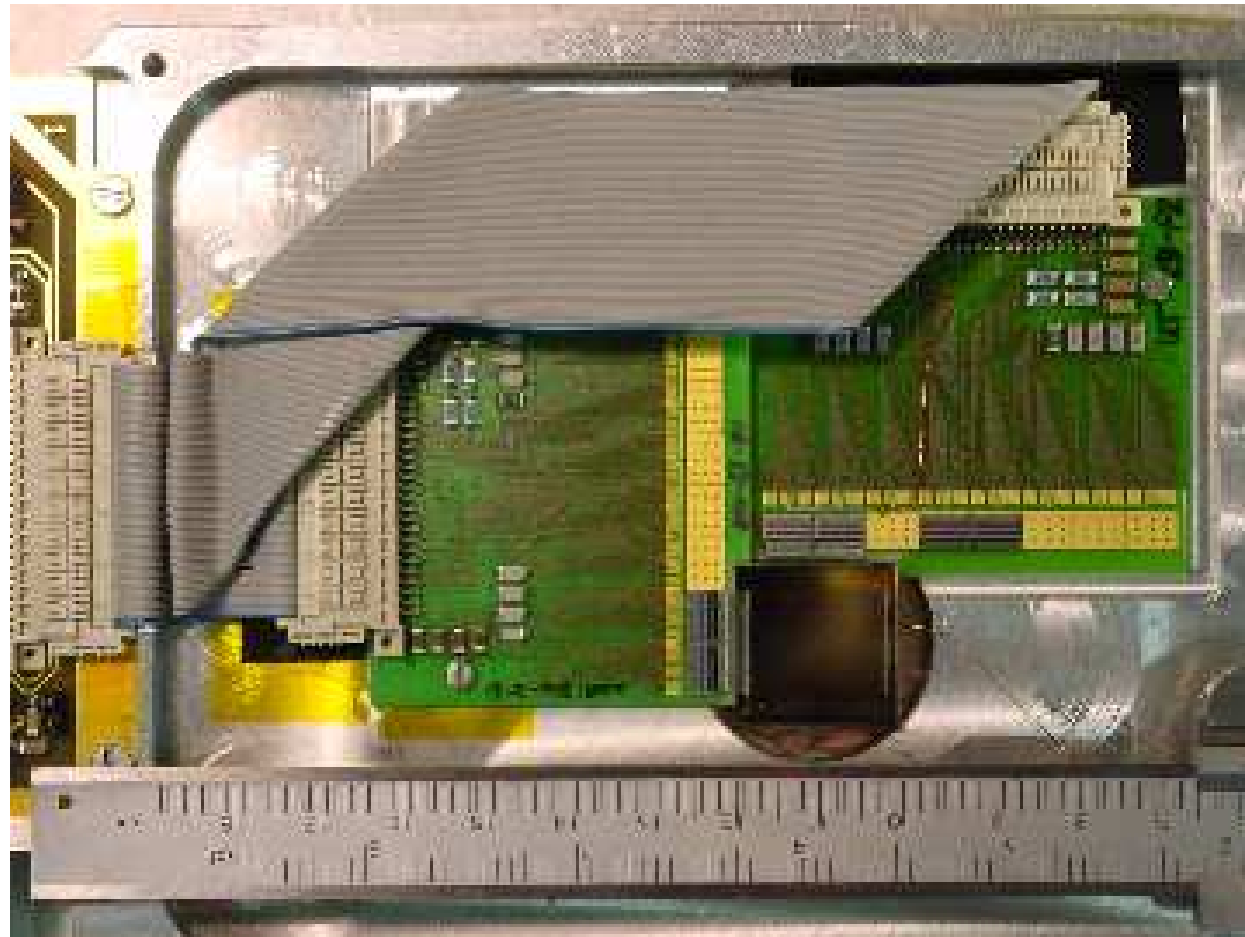
CERN Testbeam Setup for Diamond Telescope:



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

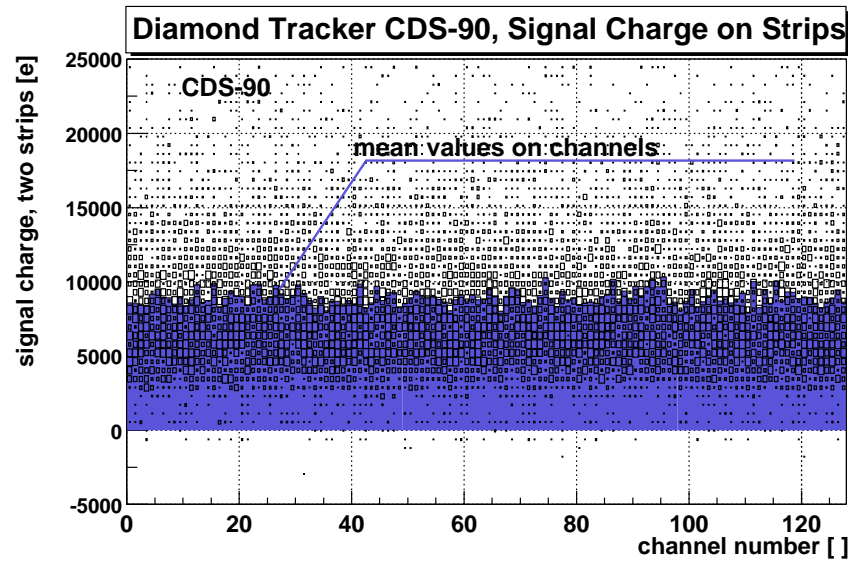


Photograph of Two Planes of the Telescope:

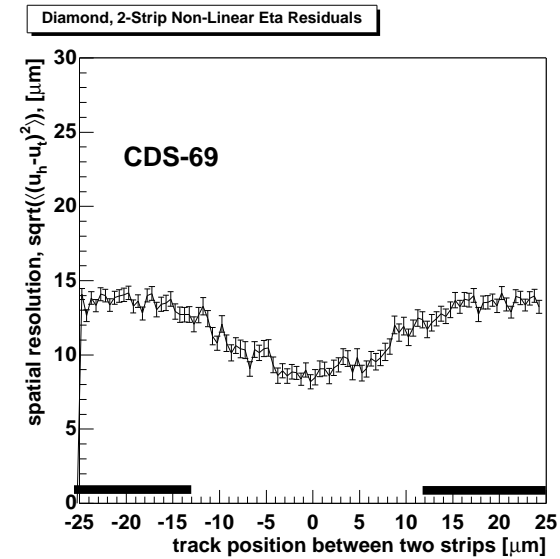




PH Distribution on each Strip



Residual versus Track Position

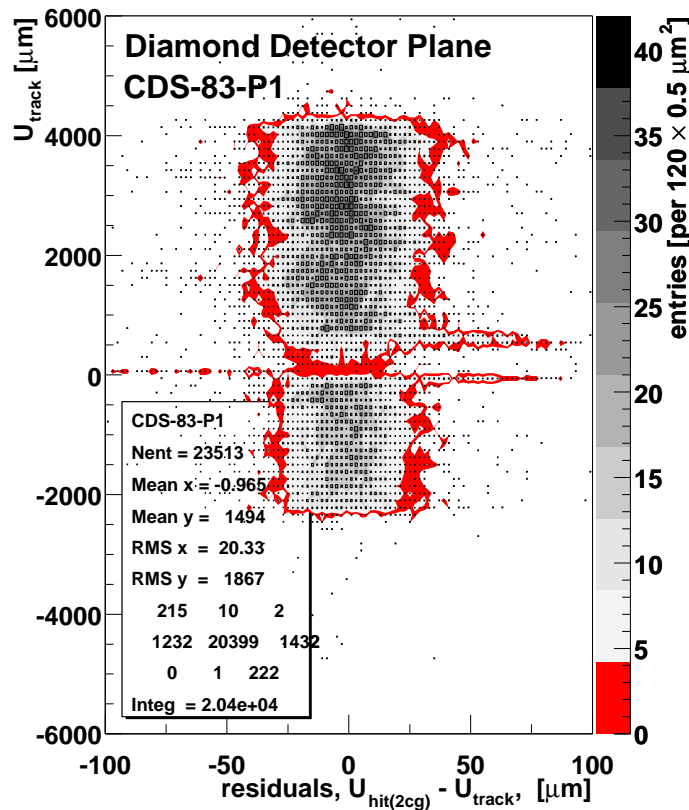


- ◆ Uniform signals on all strips → new metalisation
- ◆ Pedestal separated from “0” on all strips
- ◆ 99% of entries above 2000 e
- ◆ Mean signal charge ~ 8640 e → new metalisation
- ◆ MP signal charge ~ 6500 e

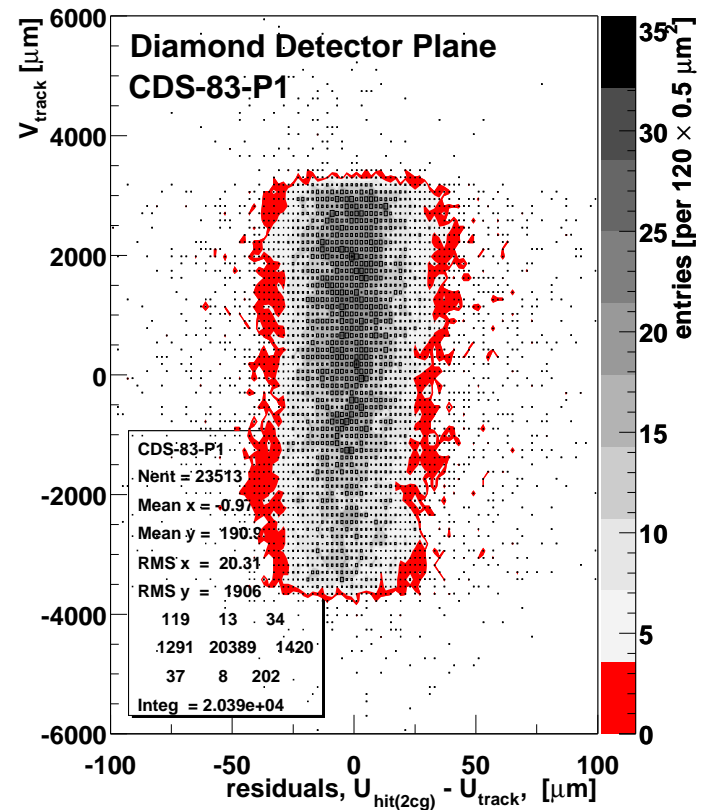


Residuals

Residuals perpendicular to Strips



Residuals along Strips

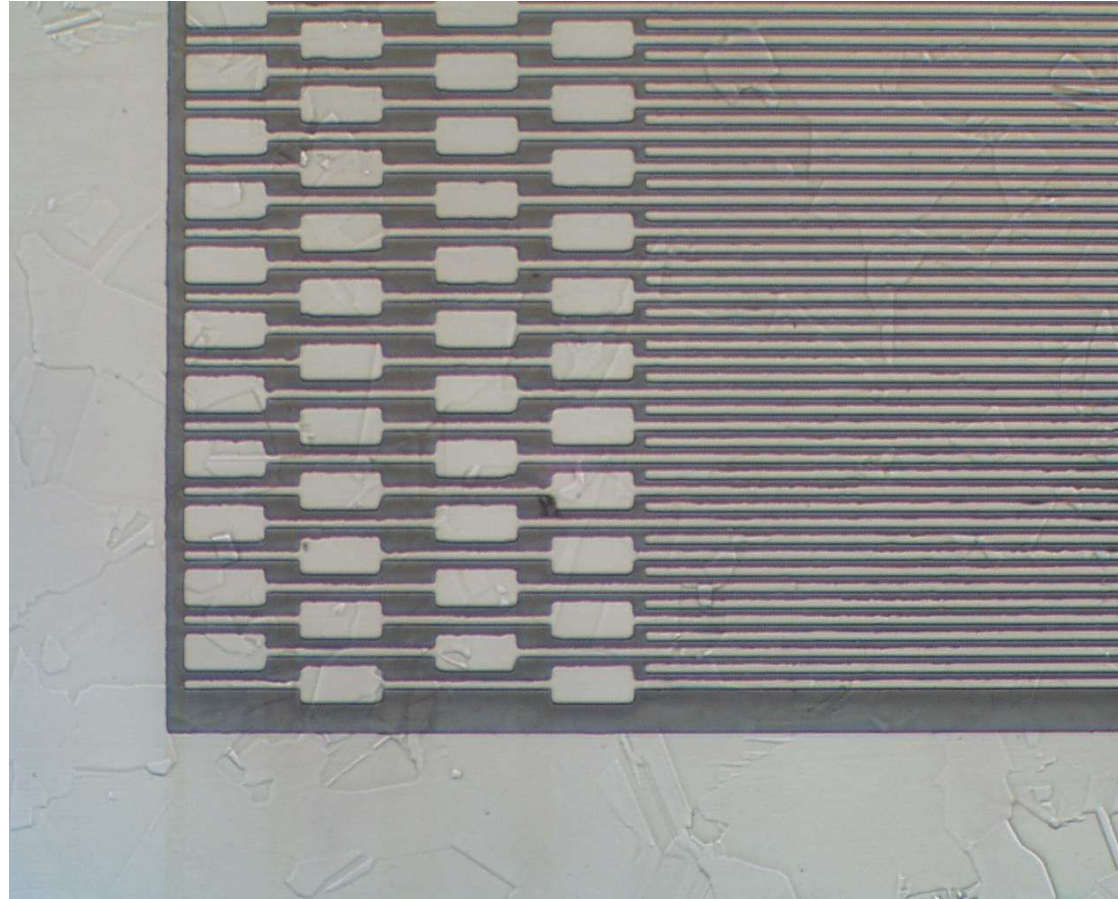




Recent Tracking Studies



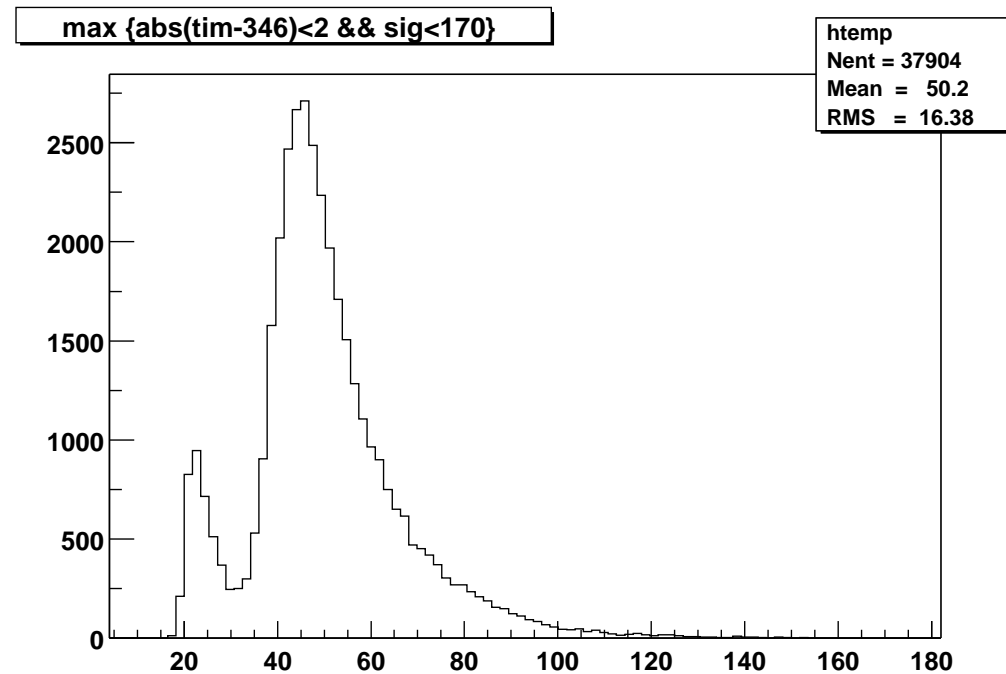
Next advance → take advantage of charge sharing:



Use intermediate strips to force charge sharing.



Radiation Hard Diamond Tracking Modules:



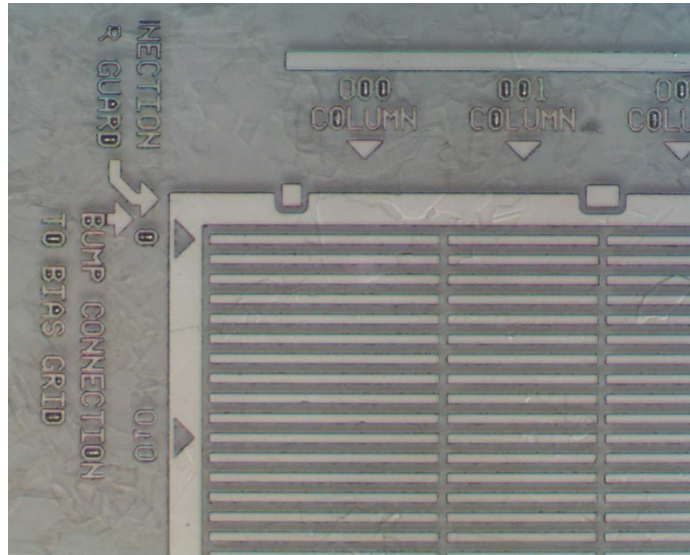
- ❖ Large (2cm × 4cm) Module constructed with new metalisation
- ❖ Fully radiation hard SCTA128 electronics → 25ns peaking time
- ❖ Tested in a ^{90}Sr → ready for beam test and irradiation
- ❖ Charge distribution cleanly separated from the noise tail → $S/N > 8/1$
- ❖ Efficiency will be measured in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



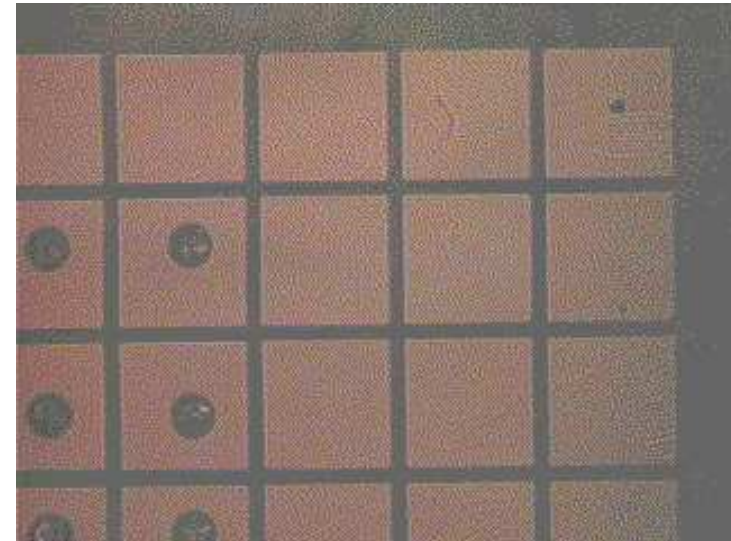
Diamond Pixel Detectors



ATLAS FE/I Pixels (Al)



CMS Pixels (Ti-W)



- ❖ Atlas pixel pitch $50\mu\text{m} \times 400\mu\text{m}$
- ❖ Over Metalisation: Al
- ❖ Lead-tin solder bumping at IZM in Berlin
- ❖ CMS pixel pitch $125\mu\text{m} \times 125\mu\text{m}$
- ❖ Metalization: Ti/W
- ❖ Indium bumping at UC Davis

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

New radiation hard chips produced this year.

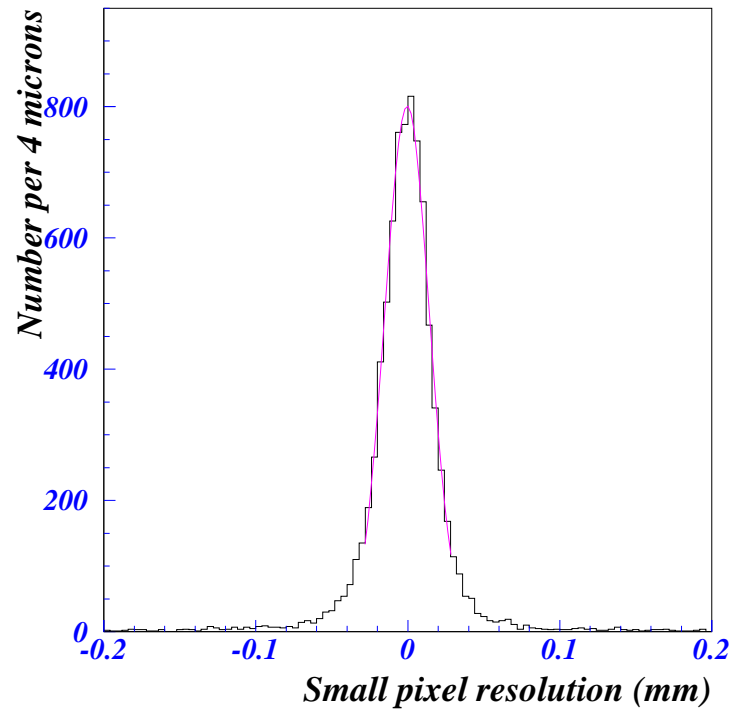


Diamond Pixel Detectors

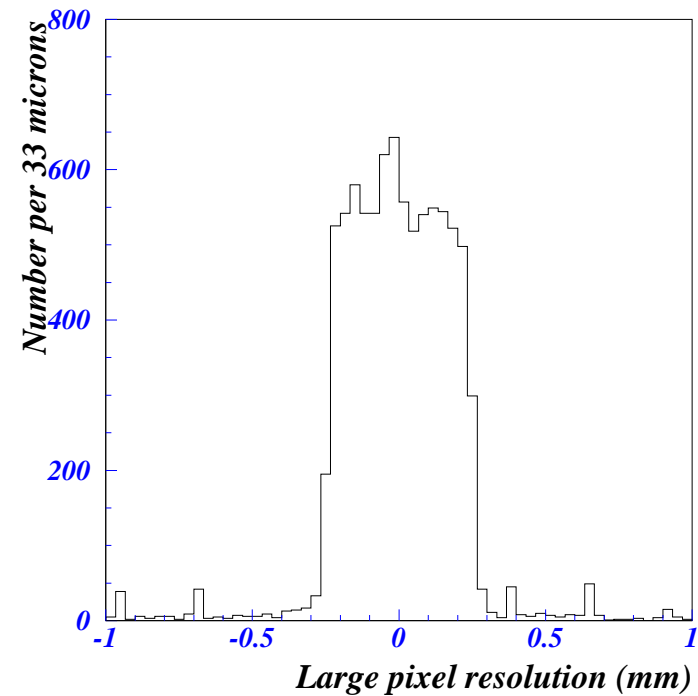


Results from an ATLAS pixel detector

Spatial Resolution – Short Direction



Spatial Resolution – Long Direction



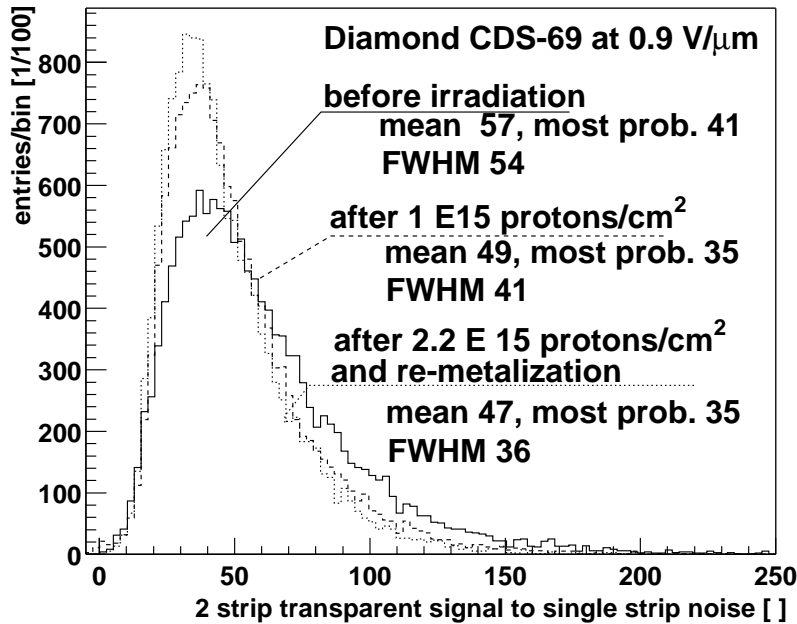
❖ Excellent correlation between beam telescope and pixel tracker data!



Proton Irradiation Studies with Trackers:

Signal to Noise

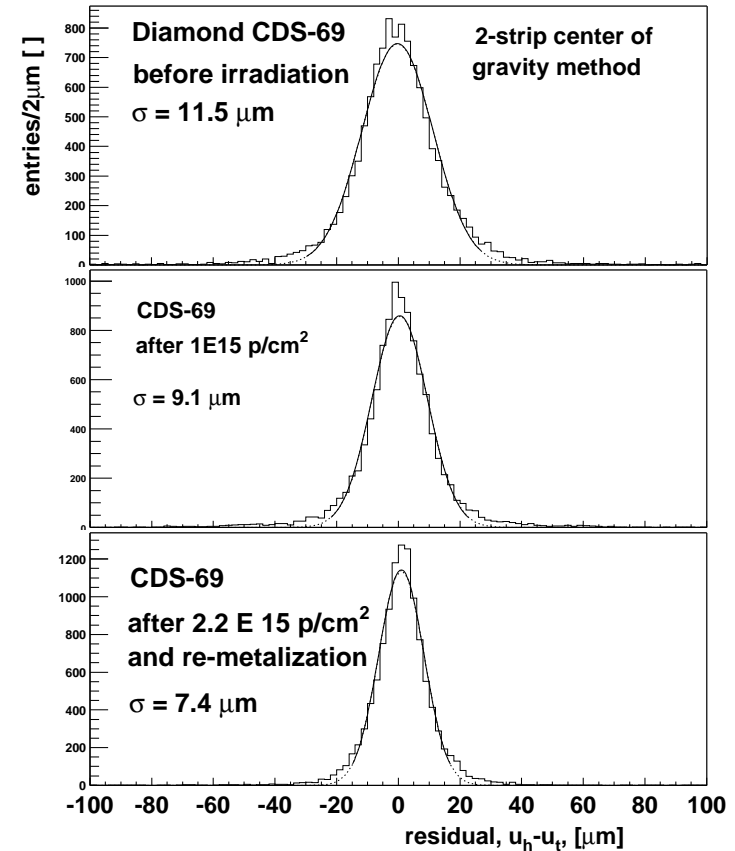
Signal from Irradiated Diamond Tracker



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

Resolution

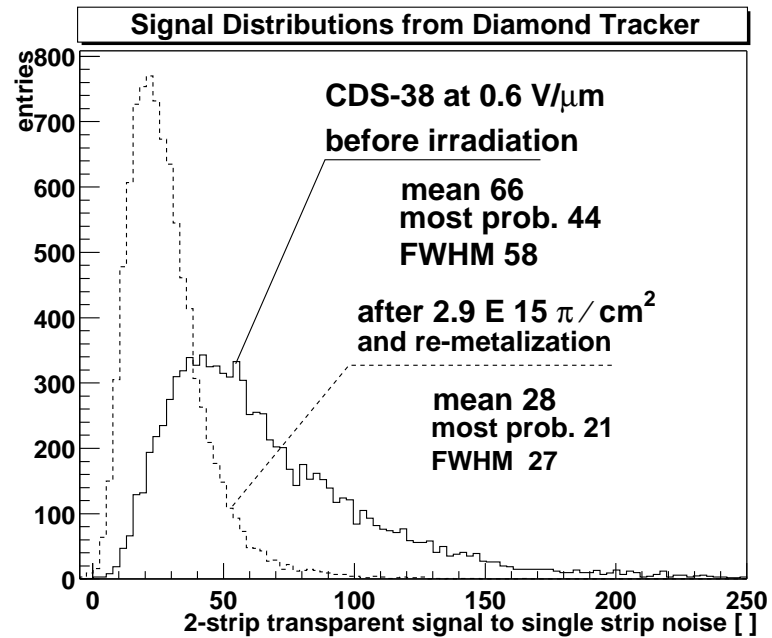
Residual Distributions, Proton Irradiated Diamond



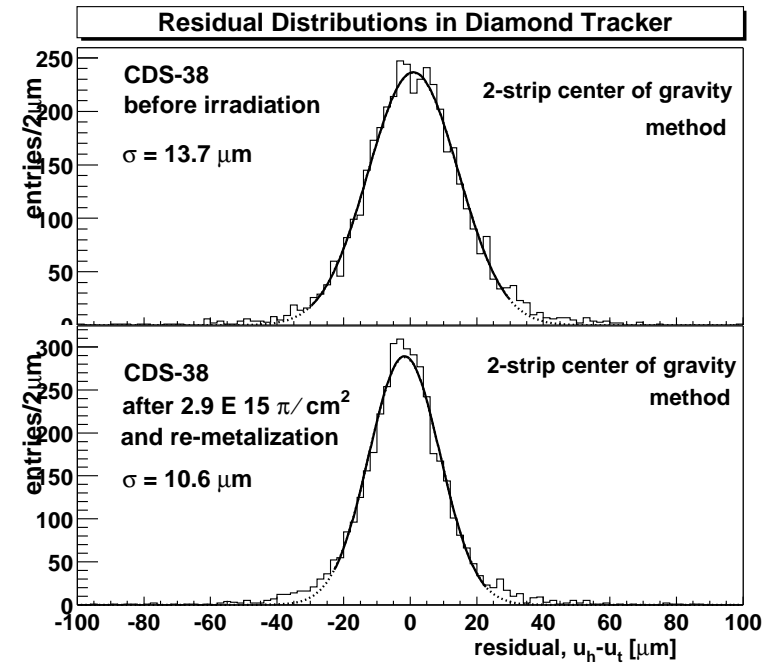


Pion Irradiation Studies with Trackers:

Signal to Noise



Resolution



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



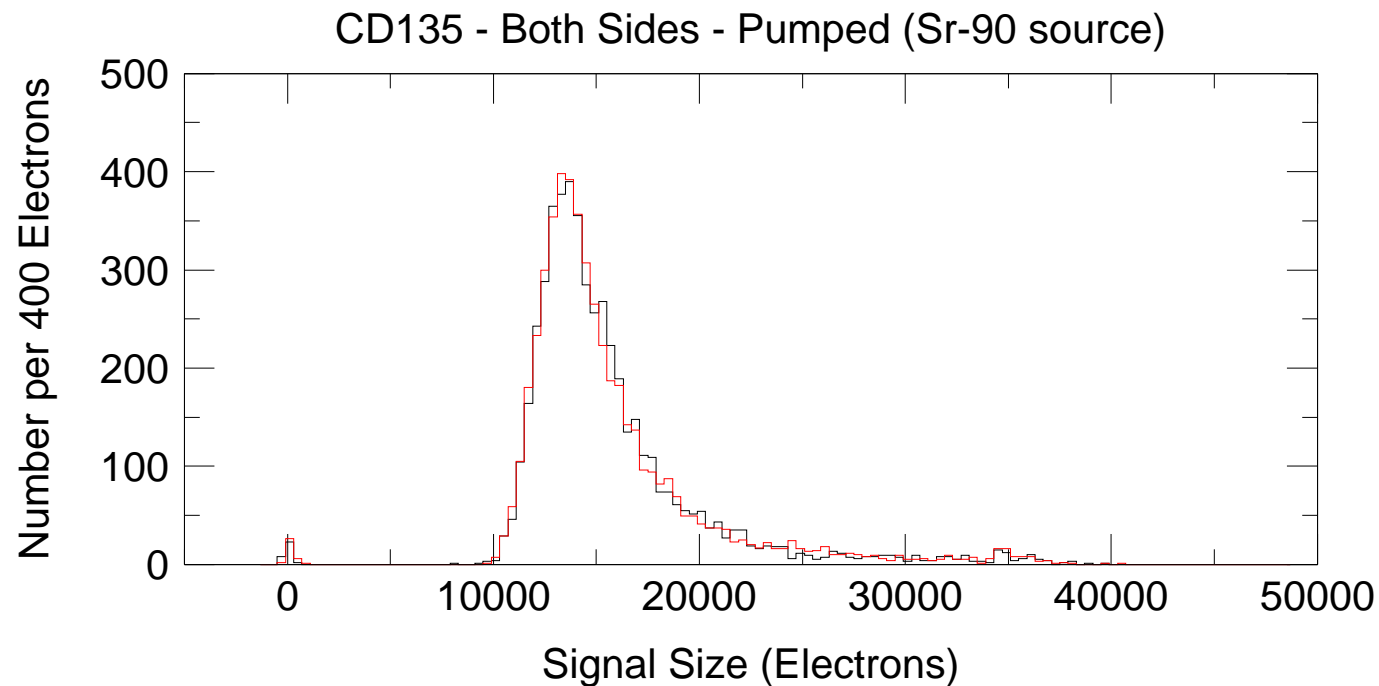
The Future: Single Crystal CVD Diamond



Could we make a CVD diamond with improved characteristics?

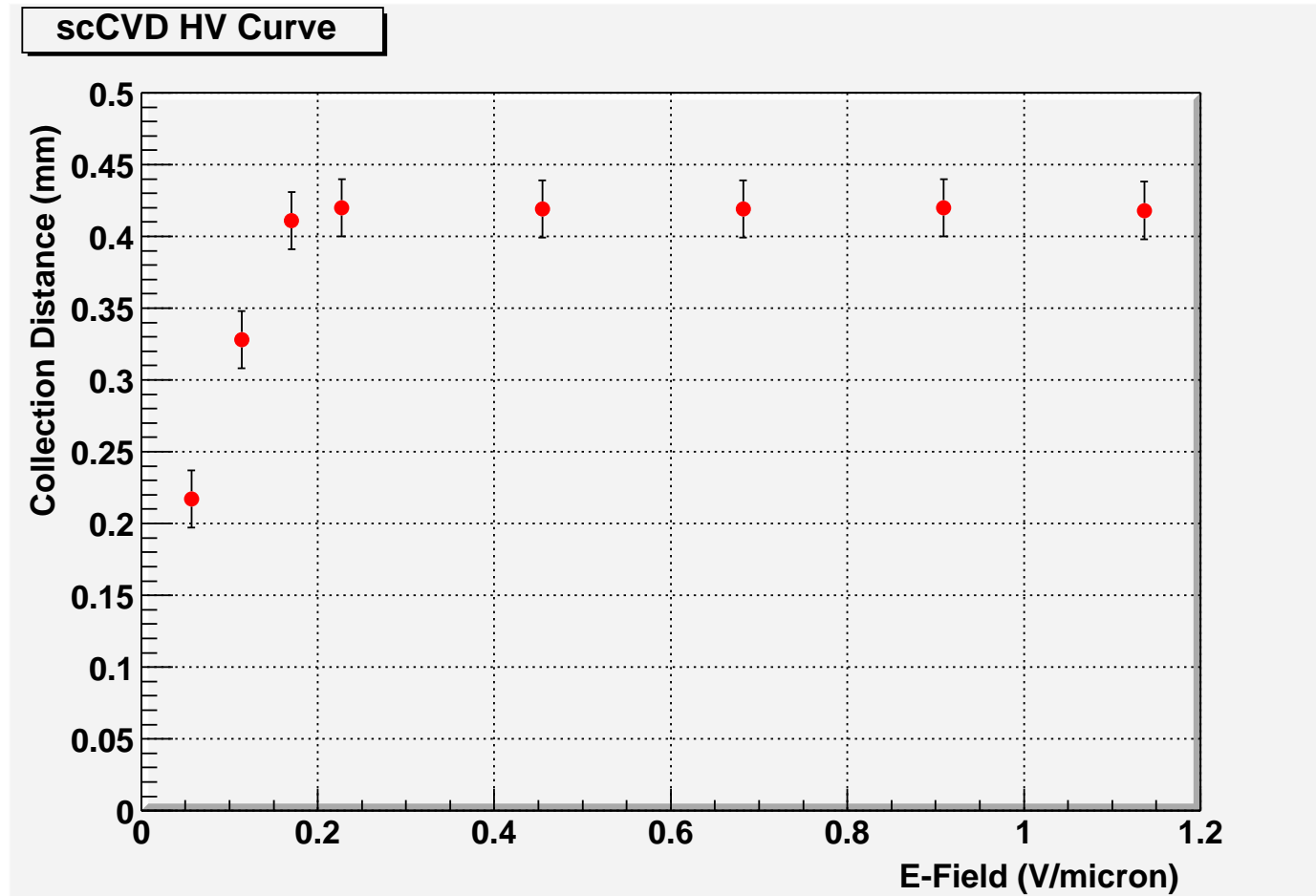
- ❖ Remove the grain boundaries, defects, etc.
- ❖ Lower operating voltage.
- ❖ Eliminate pumping.

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





HV characteristics



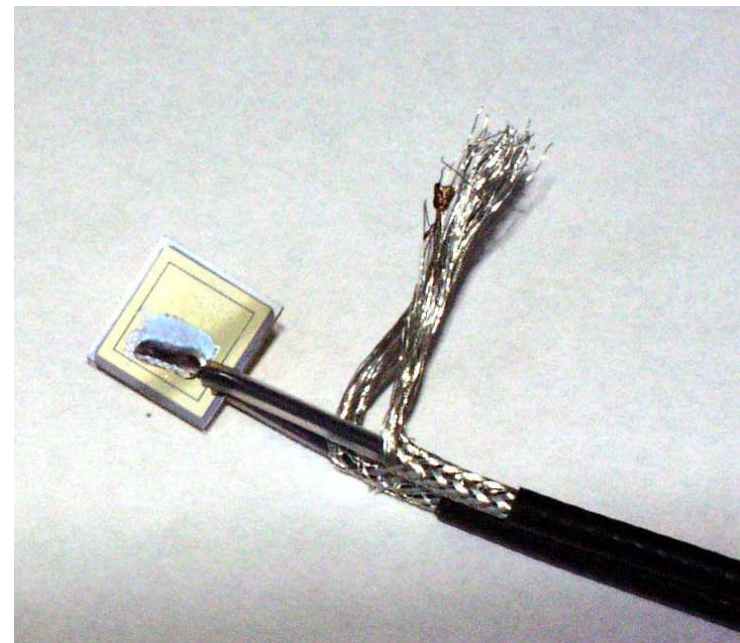


Radiation Monitoring - A New Application



Motivation:

- SVT monitoring crucial for silicon operation/abort system
- Abort beams on large current spikes
- Measure calibrated daily and integrated dose
- Presently use silicon PIN diodes at 50V, leakage current increases 2nA/krad
- After 100fb^{-1} signal $\approx 10\text{nA}$, noise $\approx 1\text{-}2\mu\text{A}$
- Large effort to keep working, system will not last past 2004-05





The BaBar Diamond Radiation Monitor Prototypes:

- ❖ Package must be small to fit in allocated space
- ❖ Package must be robust
- ❖ Package of choice - shown below

Schematic View

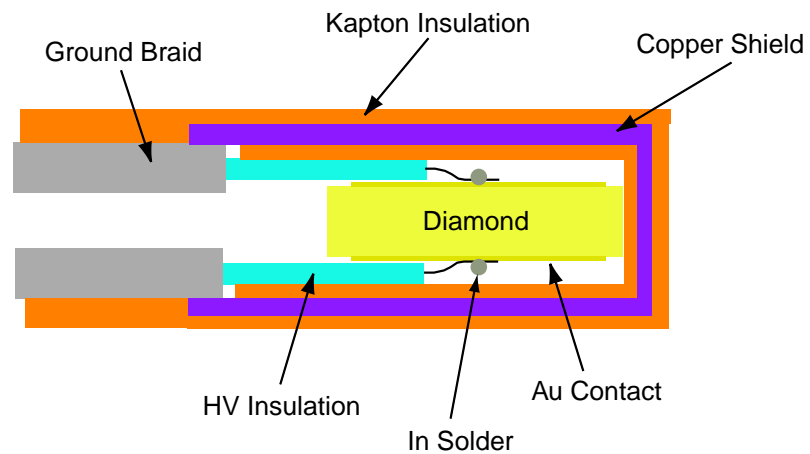
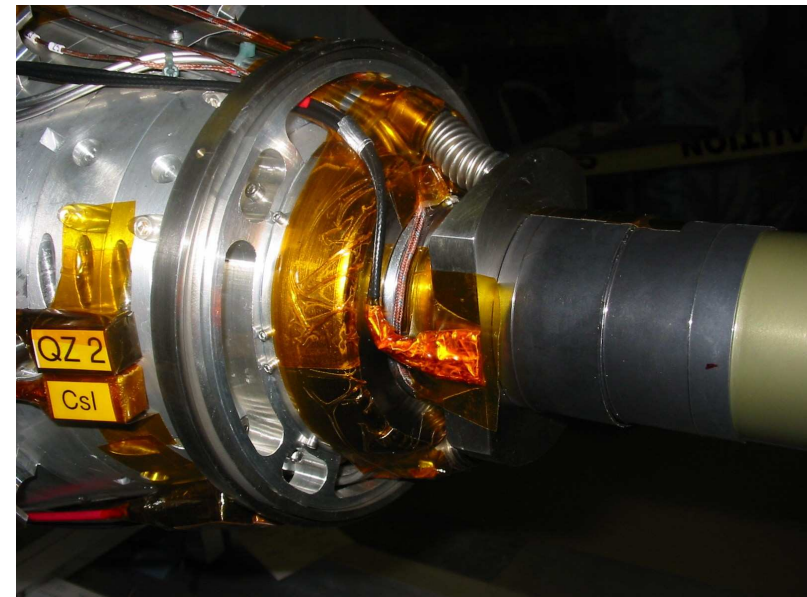


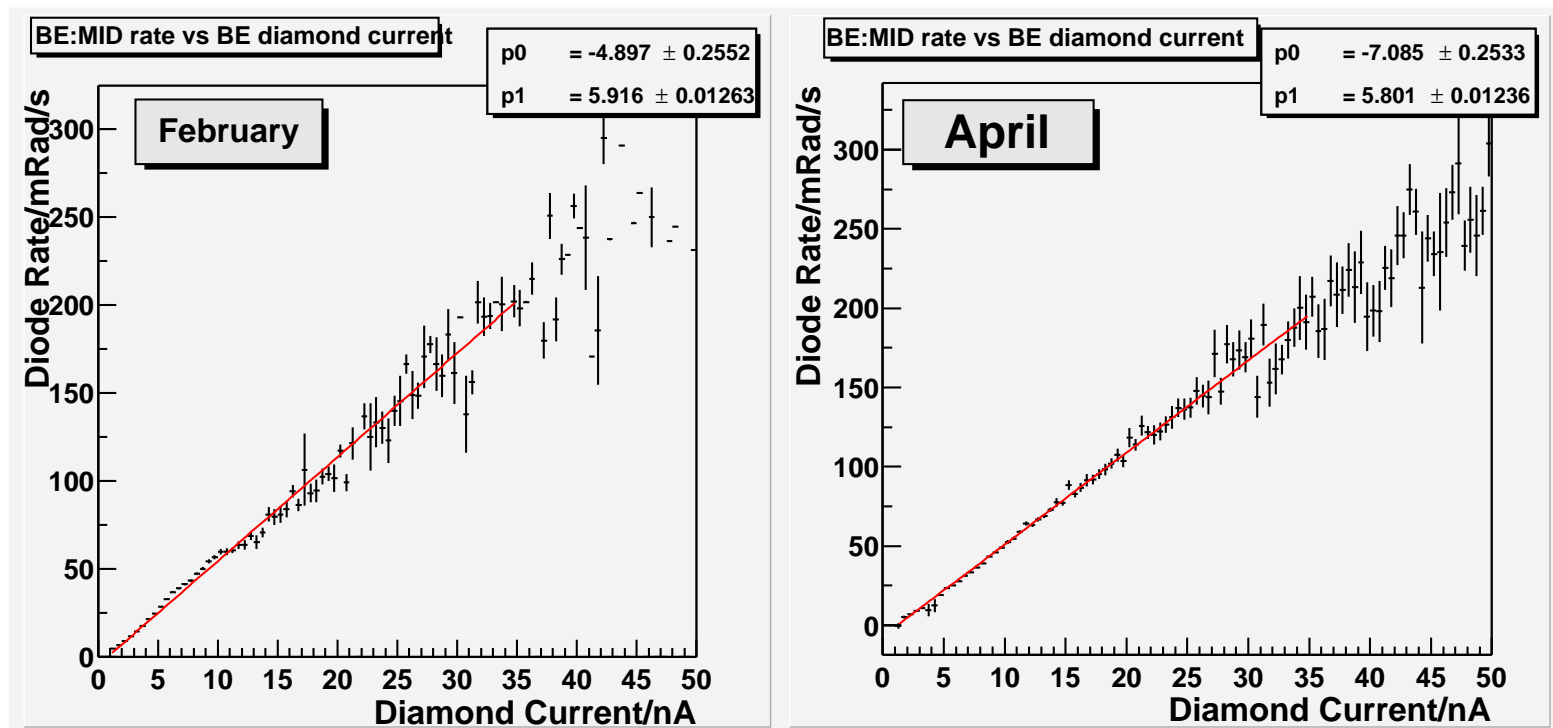
Photo of Installed Device





Calibration:

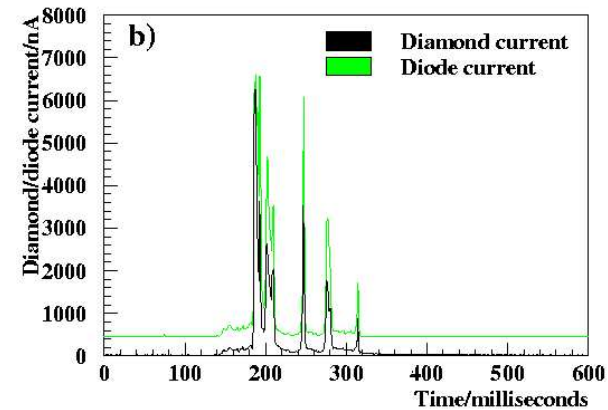
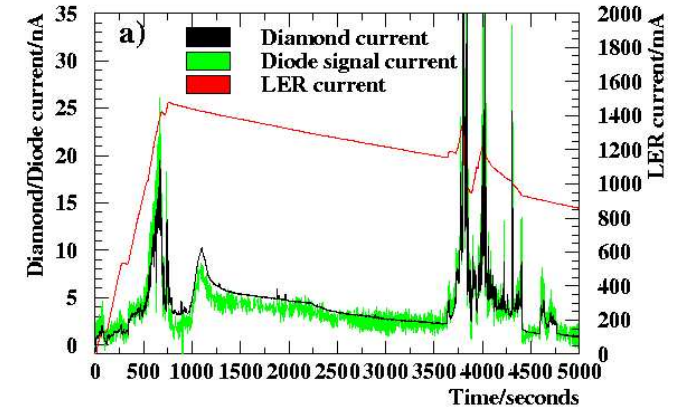
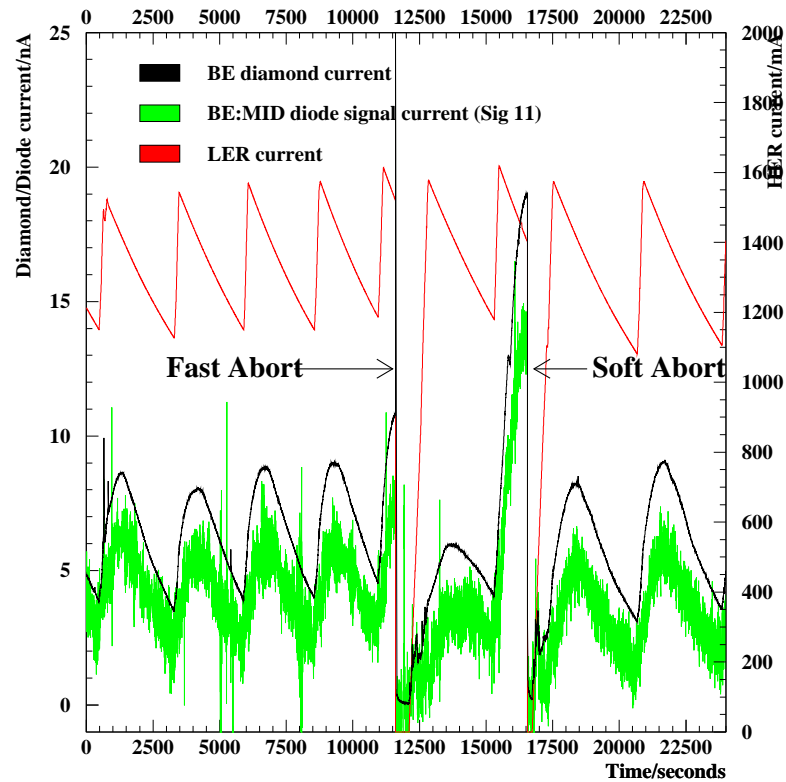
- ◆ In BaBar during injection relative to silicon diodes: 5.9mrad/nC (Feb)
- ◆ In BaBar during injection relative to silicon diodes: 5.8mrad/nC (Apr)
- ◆ Correlation coefficient unchanged over several months



Calibration repeatable but so far limited by systematics



Data Taking:

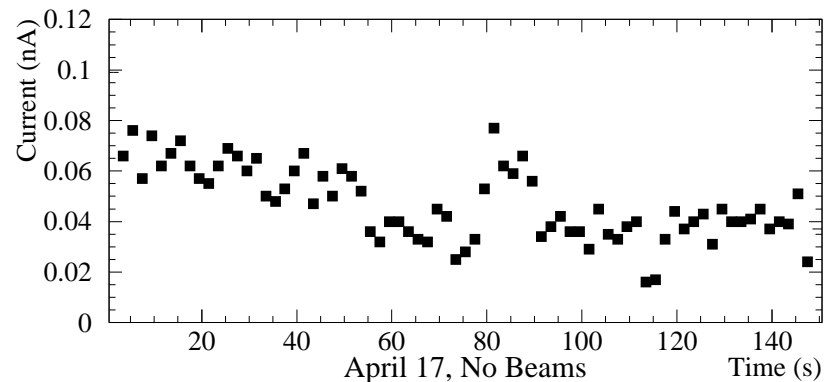
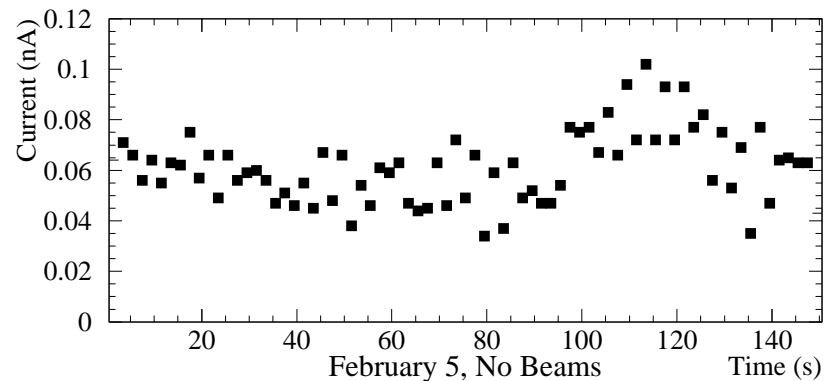


System operating for 4 months and works well!



Leakage Current

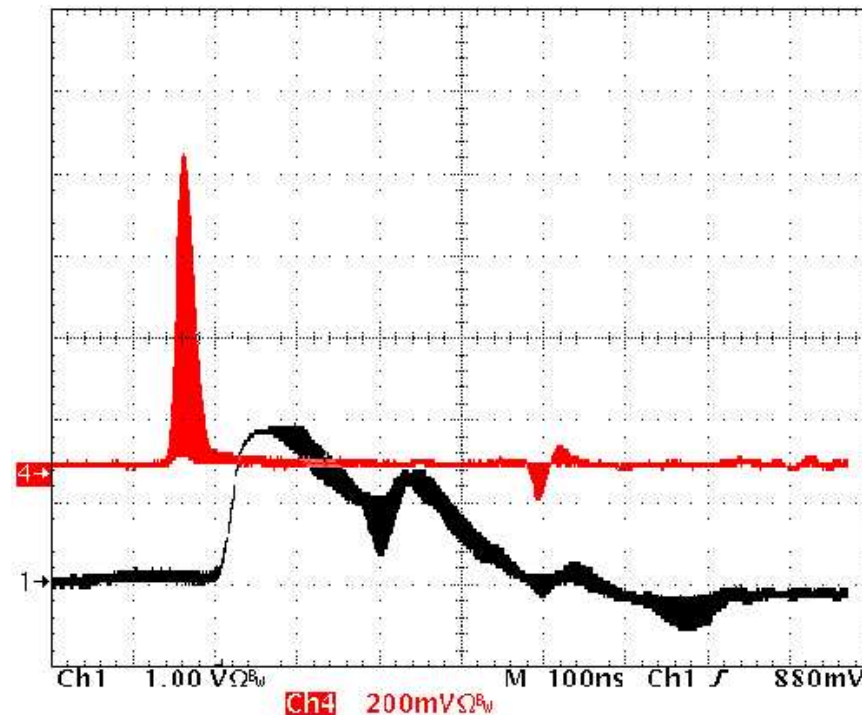
- ◆ Diamonds have received 250kRad ^{60}Co plus 250kRad while installed
- ◆ No observed change in leakage current ($<0.1\text{nA}$) or fluctuations (30pA)
- ◆ Data directly from SVTRAD system
- ◆ Electronic noise ($\approx 0.5\text{nA}$) subtracted off





Very Fast Time Scale (ns)

- ❖ 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



❖ Charge Collection

270 μm collection distance diamond attained in pCVD research contract

MP signal $\approx 8000 e$

99% of charge distribution above 3000 e

FWHM/MP ~ 0.95 – Working with manufacturers to increase uniformity

This diamond process now in production reactors

Single crystal CVD diamond is here: $>450 \mu\text{m}$ collection distance attained

MP signal $\approx 13000 e$

99% of charge distribution above 10000 e

FWHM/MP ~ 0.30

❖ Tracking Results

Operated a 7 plane telescope with 50 μm pitch detectors

Attained high efficiency and tracking precision of 10-20 μm

A rad-hard module with DMILL electronics was constructed with S/N=8/1

Source tests indicate high efficiency at 40 MHz

Beam test and irradiation \rightarrow **this summer!**

Constructed first diamond detector with intermediate strips \rightarrow **test this July!**



❖ Radiation Hardness of Diamond Trackers

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

All tests will be repeated with more trackers and the latest pCVD and scCVD diamonds

❖ Diamond Pixel Detectors

Successfully tested ATLAS and CMS pixel patterns

- Bump bonding yield $\approx 100\%$
- Excellent correlation between telescope and pixel data
- Reasonable spatial resolution attained

Radiation hard chips have arrived and work

Single chip and module tests this summer

More progress this Summer



Future Plans for RD42



❖ Charge Collection

Continue research program to improve pCVD material:
collection distance $\rightarrow 300\mu\text{m}$ ($\bar{Q} = 10,800e$)
 \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:

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

With Pions:

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

With Neutrons:

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

❖ 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