Diamond (Radiation) Detectors Are Forever!

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Outline of the Talk

- **Introduction to Diamond**
- **Recent Results**
- **Applications**
- **Summary**

Introduction

Motivation: Tracking Devices Close to Interaction Region of Experiments

Use at the LHC/SLHC (or similar environments e.g. BaBar, Belle):

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

→ Inner tracking layers must survive! → what does one do?

→ Annual replacement of inner layers perhaps?

Look for a Material with Certain Properties:

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

Material Presented Here:

- Polycrystalline Chemical Vapor Deposition (pCVD) Diamond
- Single Crystal Chemical Vapor Deposition (scCVD) Diamond

On Behalf of RD42:

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

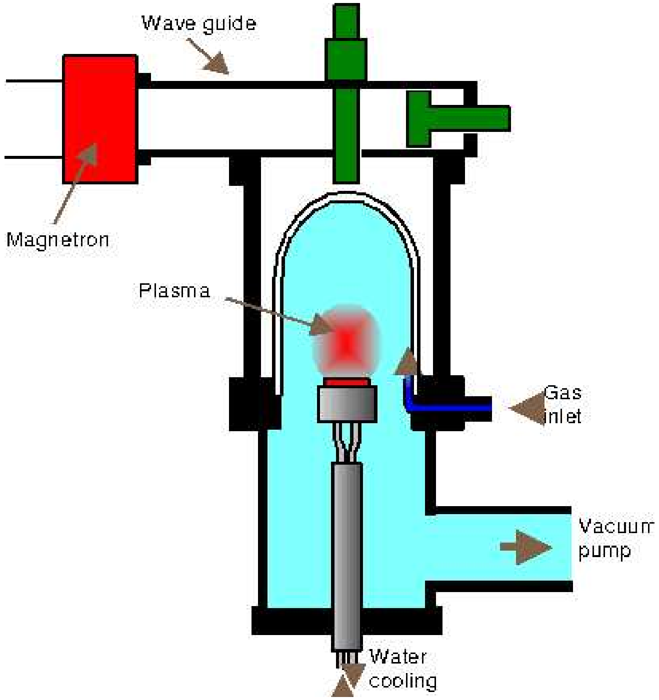
Comparison of Various Materials

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

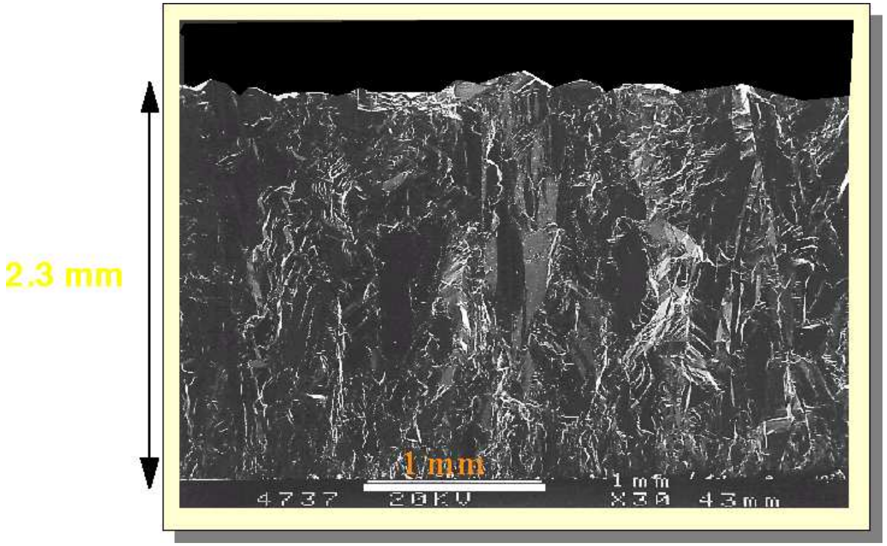
→ Low dielectric constant - low capacitance
→ Large bandgap - low leakage current
→ Large energy to create an eh pair - small signal

Diamond Growth:

Micro-Wave Reactor Schematic



Edge View of pCVD diamond

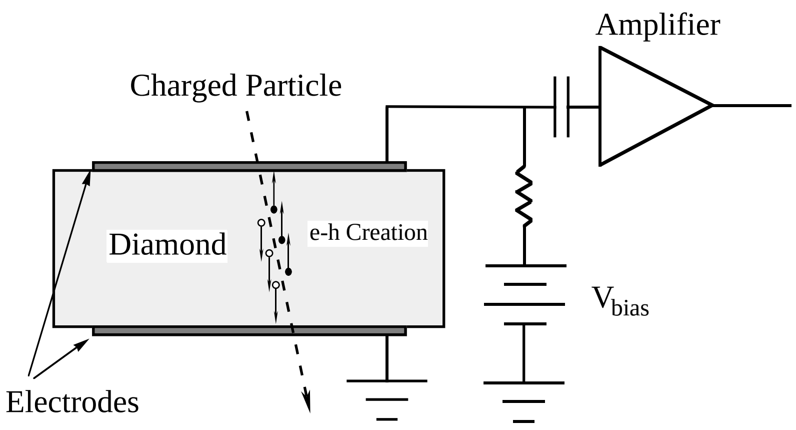


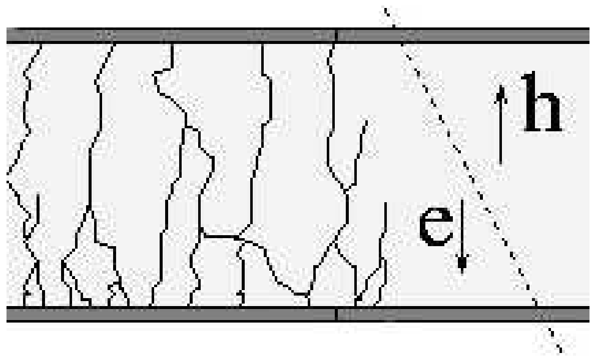
(Courtesy of Element Six)

- Diamonds are “synthesized” from a plasma
- The diamond “copies” the substrate

Characterization of Diamond:

Signal formation





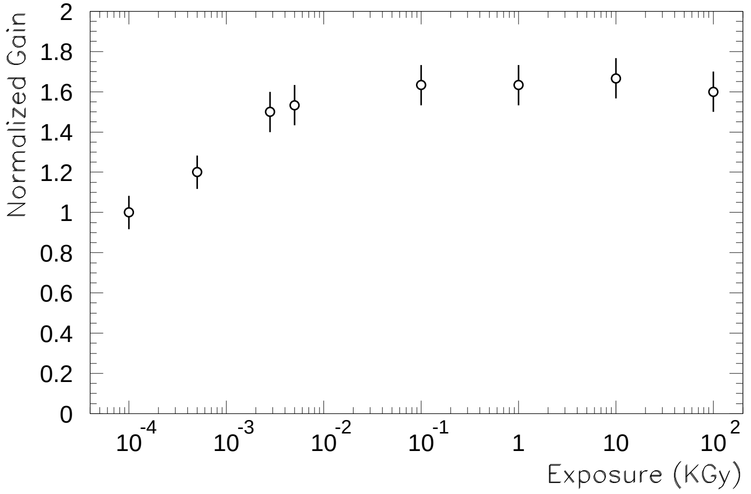
- Q=$\frac{d}{t}$Q$_0$ where d = collection distance = distance e-h pair move apart
- d=$(\mu_e\tau_e + \mu_h\tau_h)$E
- d=μEτ

  with $\mu = \mu_e + \mu_h$

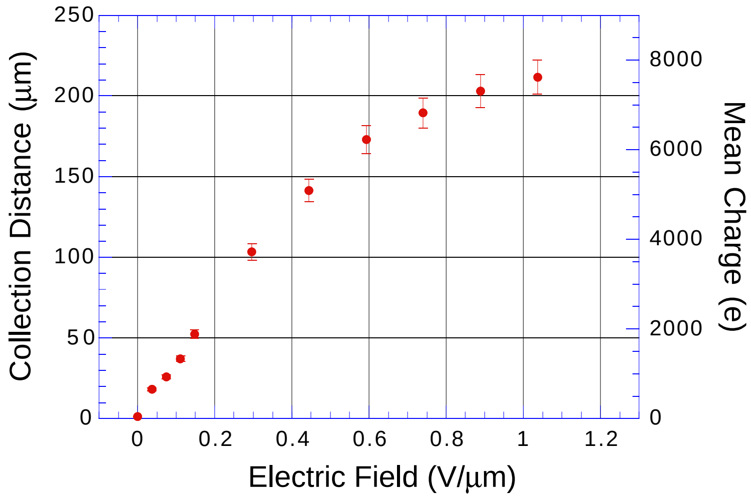
  and $\tau = \frac{\mu_e\tau_e + \mu_h\tau_h}{\mu_e + \mu_h}$

Diamond Properties:

Signal formation



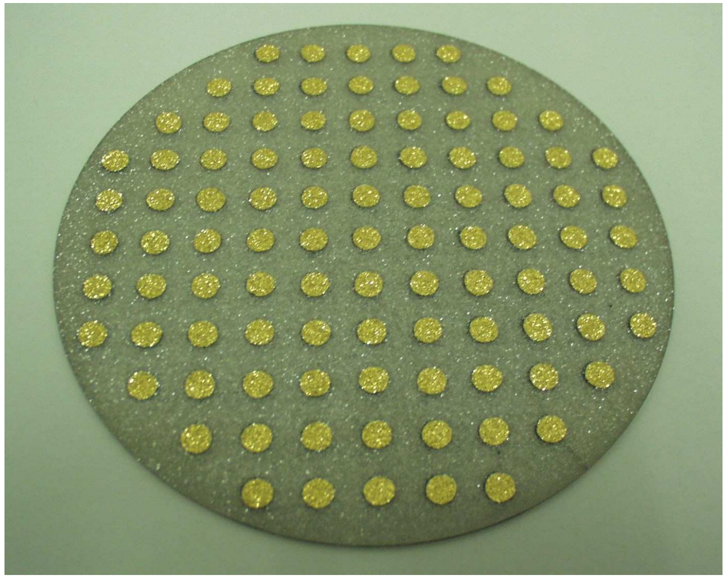
Signal versus applied electric field



- Contacts on both sides - structures from μm to cm
- Contacts typically: Cr/Au or Ti/Au or Ti/W $\longrightarrow$ non-carbide formers
- Polycrystalline CVD diamond typically "pumps" by a factor of 1.5-1.8
- Usually operate at 1V/μm $\longrightarrow$ drift velocity saturated
- Test Procedure: dot $\longrightarrow$ strip $\longrightarrow$ pixel on same diamond!

Recent polycrystalline CVD (pCVD) diamond.

(Courtesy of Element Six)



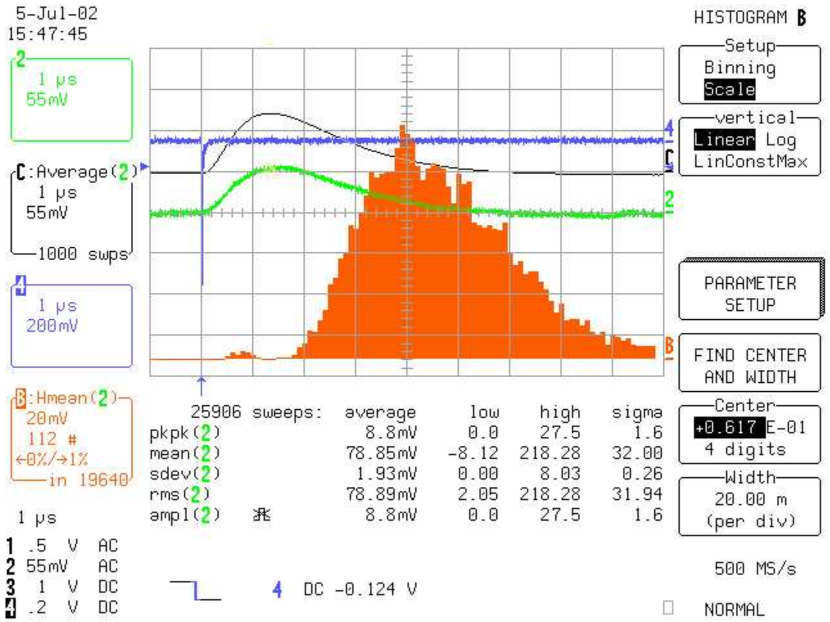
Left: Enhanced surface of pCVD diamond
Right: Recent pCVD wafer ready for test - Dots are 1 cm apart

Wafers can be grown >12 cm diameter, >2 mm thickness.

Diamond

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

Research Program Diamond Measured with a ^{90}Sr Source:

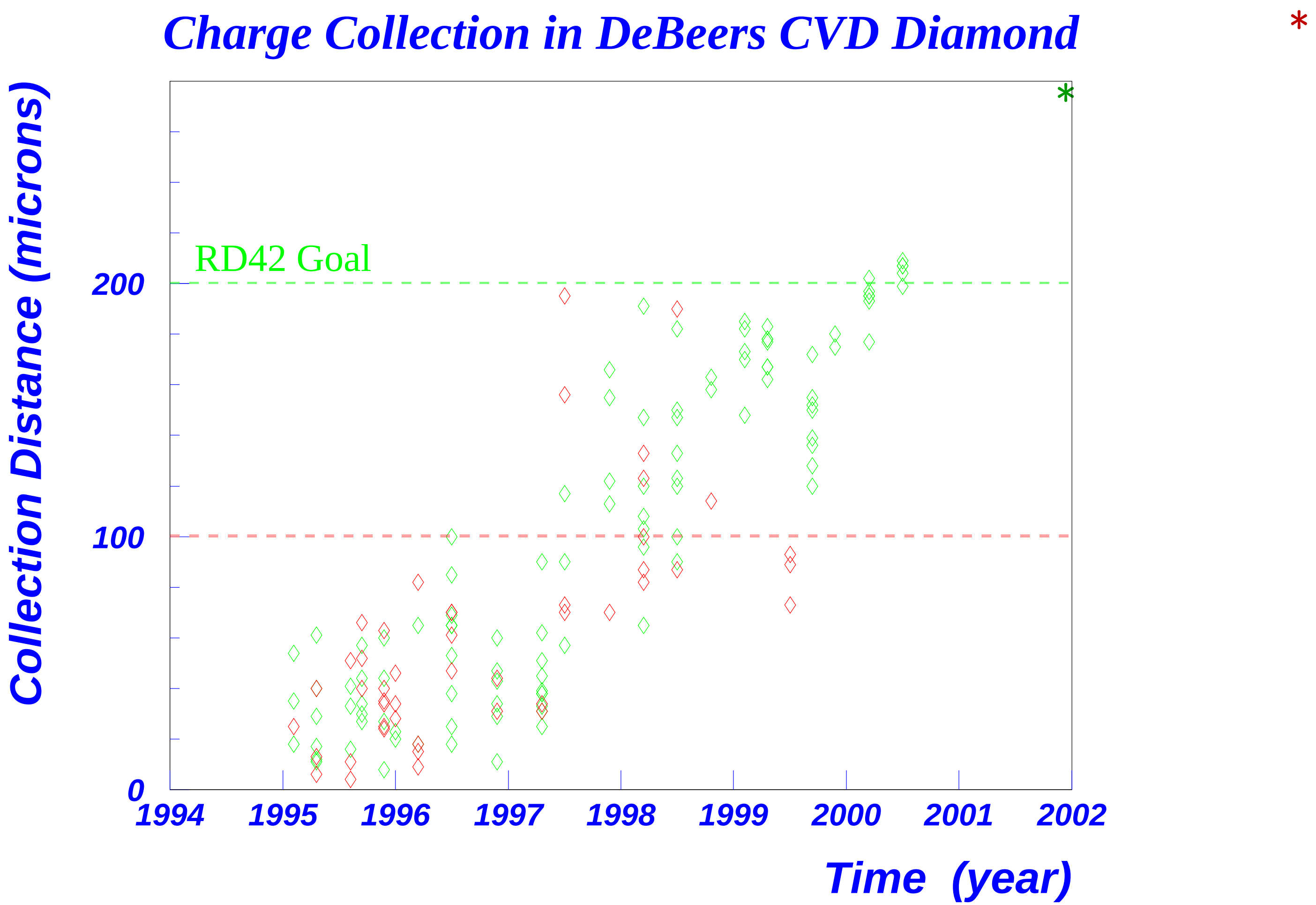


- System Gain = 124 e/mV
- Q_{MP} = 7600e (62mV)
- Mean Charge = 9800e (79mV)

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

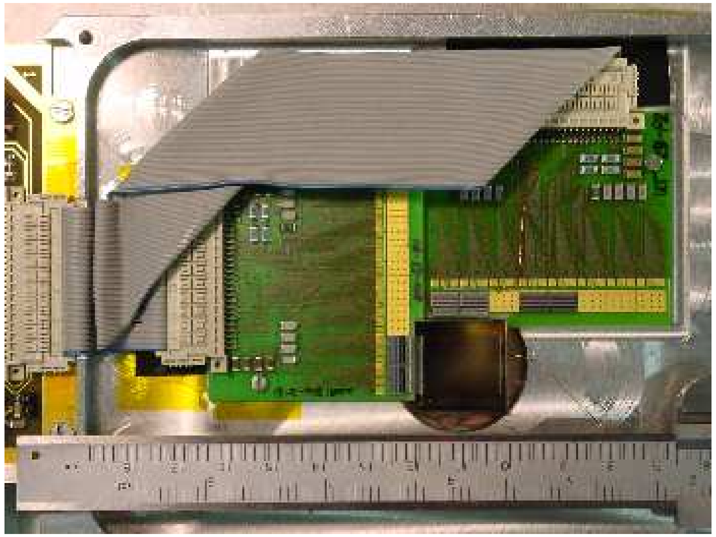
The Research program worked!

History of Diamond Progress

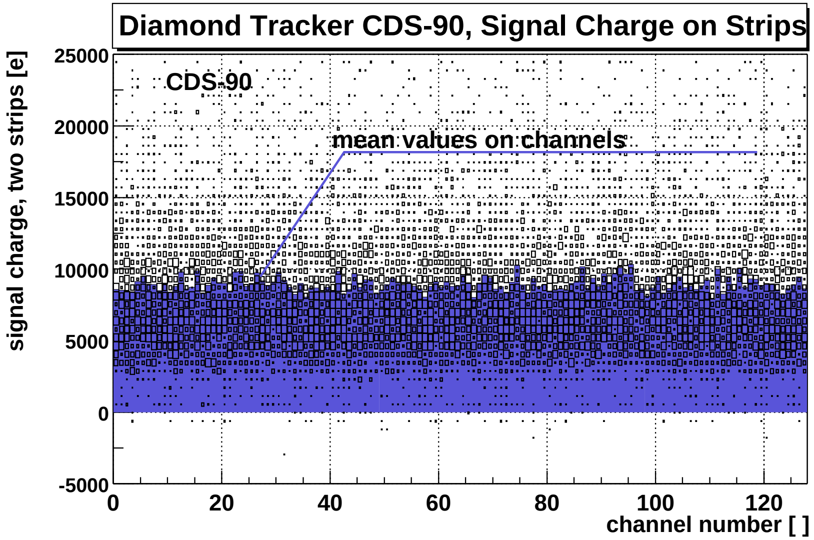


Diamond Tracking Planes:

Photo of Two Diamond Tracking Planes



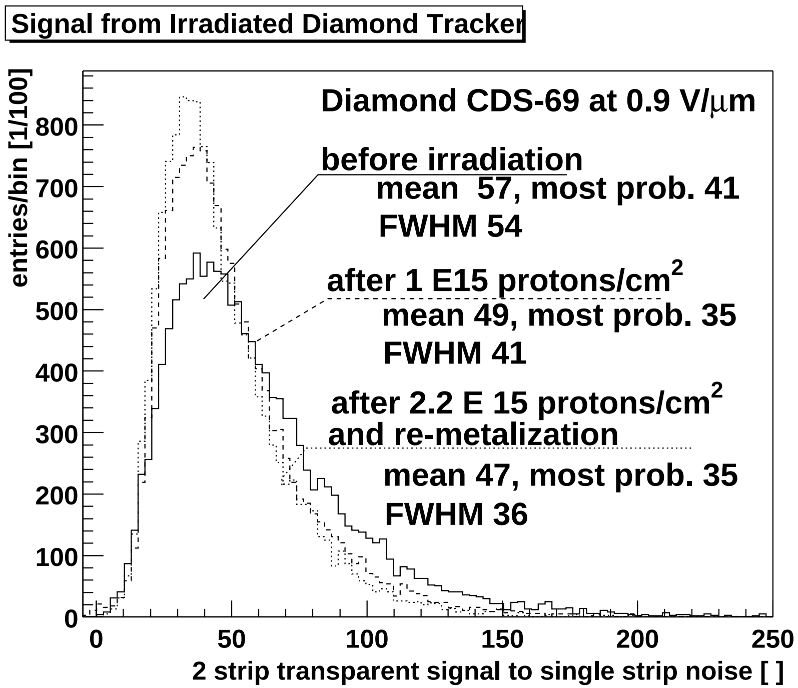
PH Distribution on each Strip



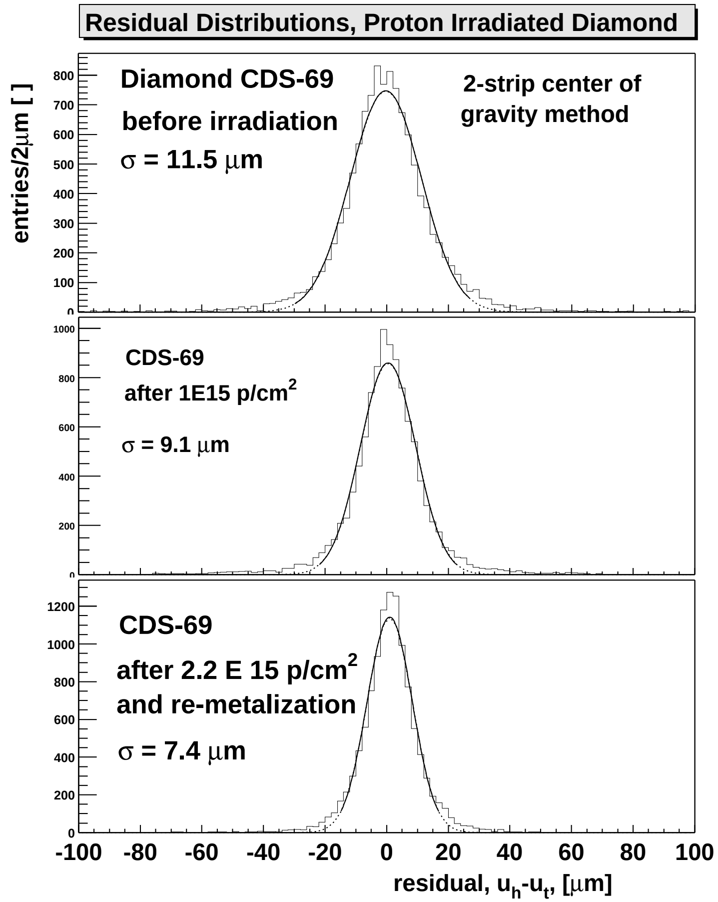
- Use same electronics as Silicon
- Uniform signals on all strips $\longrightarrow$ new metalisation
- Pedestal separated from "0" on all strips
- 99% of entries above 2000 e
- Mean signal charge $\sim$ 8640 e $\longrightarrow$ new metalisation
- MP signal charge $\sim$ 6500 e

Proton Irradiation Studies with Trackers:

Signal to Noise



Resolution

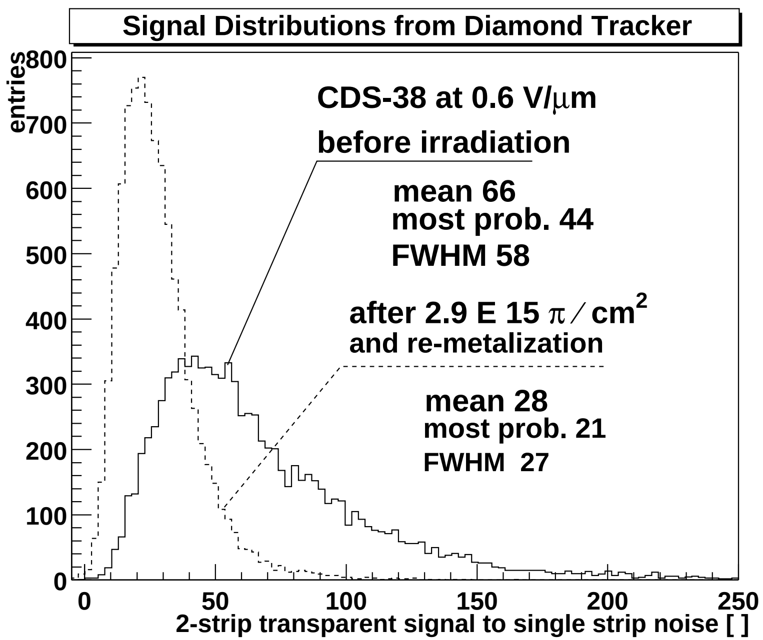


- Dark current decreases with fluence
- S/N decreases at $2 \times 10^{15}/\text{cm}^2$
- Resolution improves at $2 \times 10^{15}/\text{cm}^2$

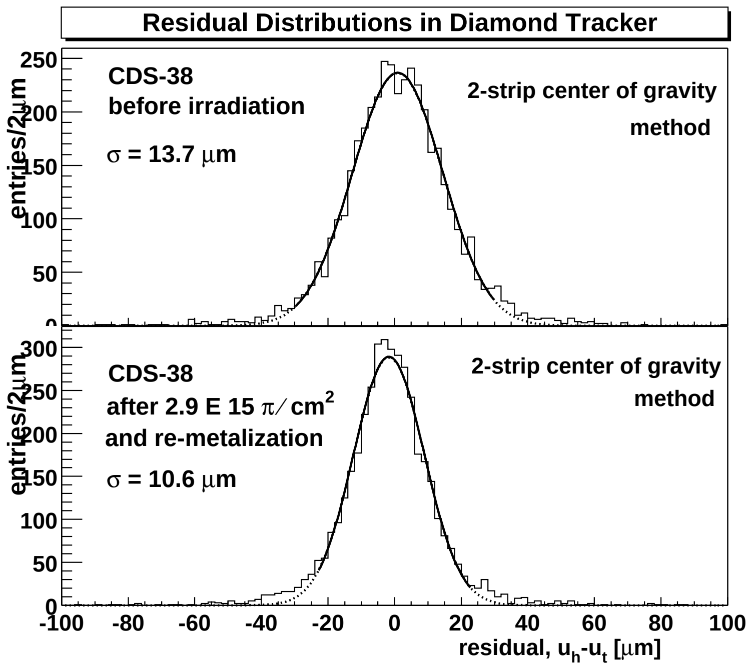
Irradiation to 10^{16} protons/cm^2 presently underway!

Pion Irradiation Studies with Trackers:

Signal to Noise

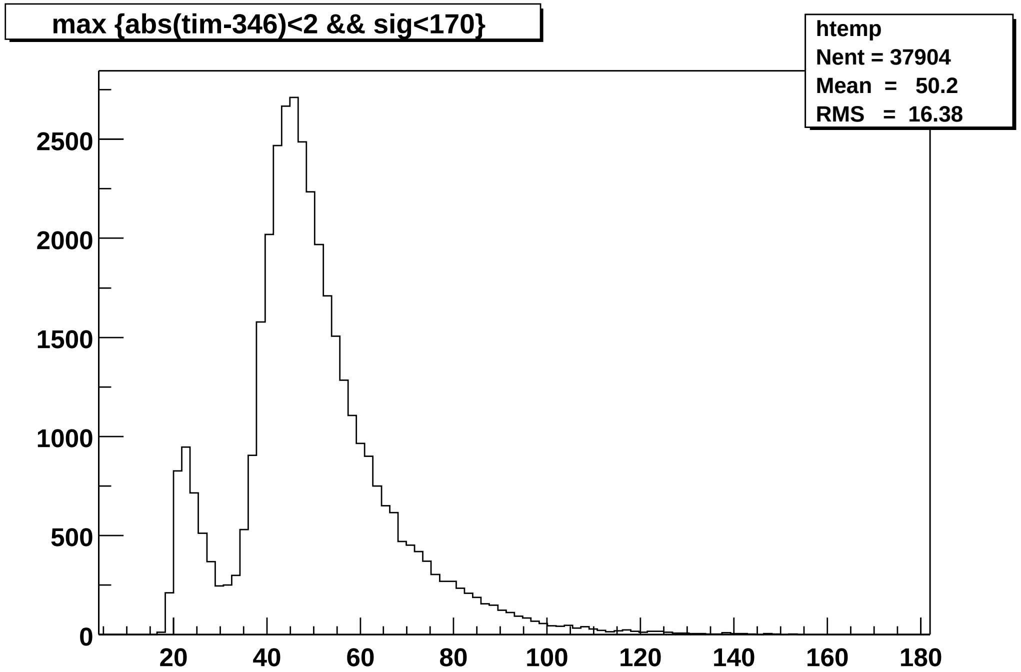


Resolution



- 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

Radiation Hard Diamond Tracking Modules:



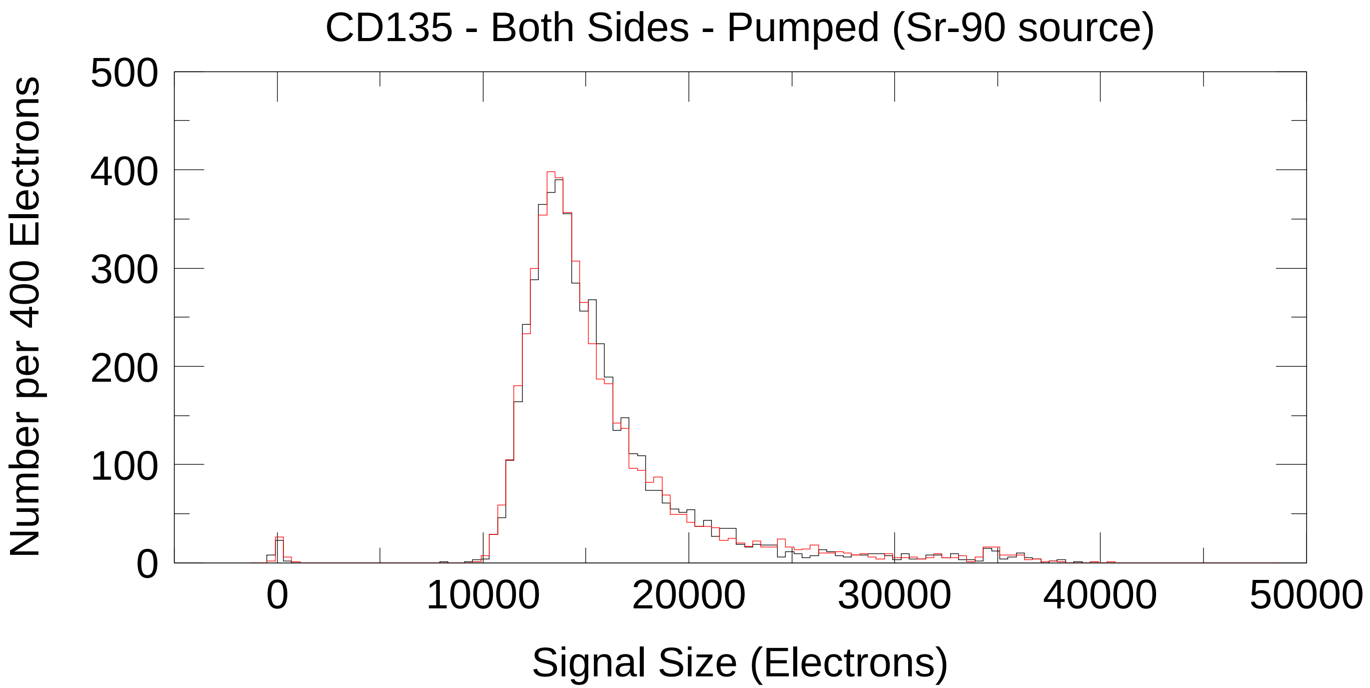
- Large (2cm $\times$ 4cm) Module constructed with new metalisation
- Fully radiation hard SCTA128 electronics $\rightarrow$ 25ns peaking time
- Tested in a ^{90}Sr $\rightarrow$ ready for beam test and irradiation
- Charge distribution cleanly separated from the noise tail $\rightarrow$ S/N $>$ 8/1

New Type of CVD Diamond: Single Crystal CVD Diamond

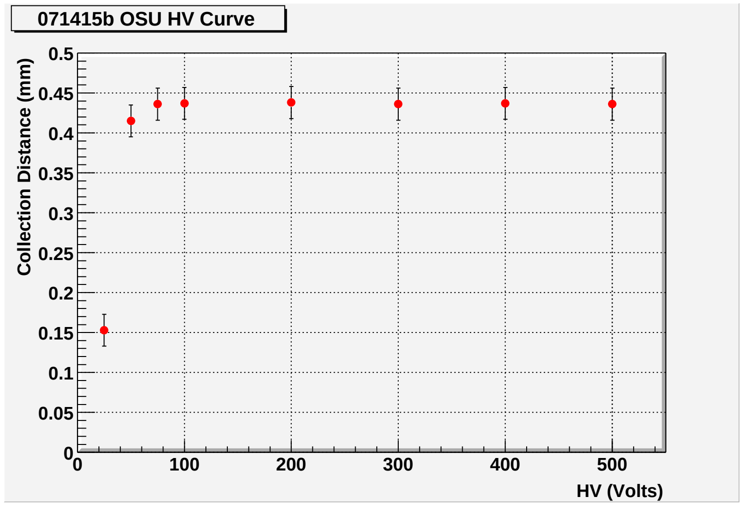
Could we make a CVD diamond with improved characteristics?

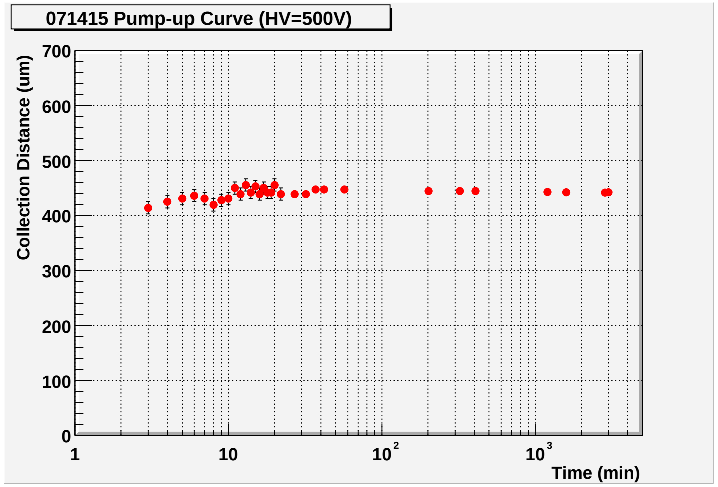
- Remove the grain boundaries, defects, charge trapping etc.
- Lower operating voltage.
- Eliminate pumping.

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



HV and Pumping Characteristics



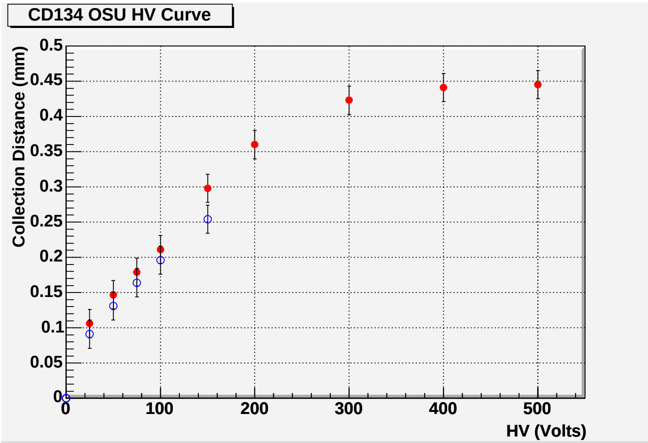


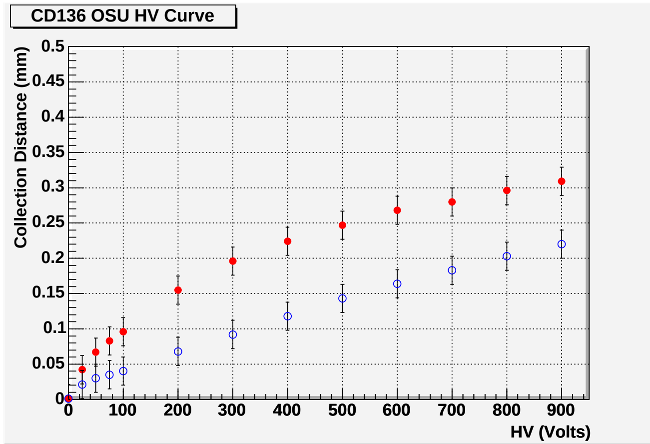
- High quality scCVD diamond collects all the charge at E=0.2V/μ!
- High quality scCVD diamond does not pump!

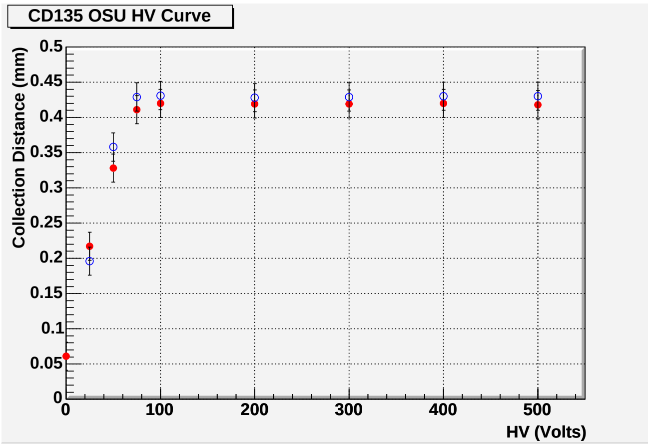
But...

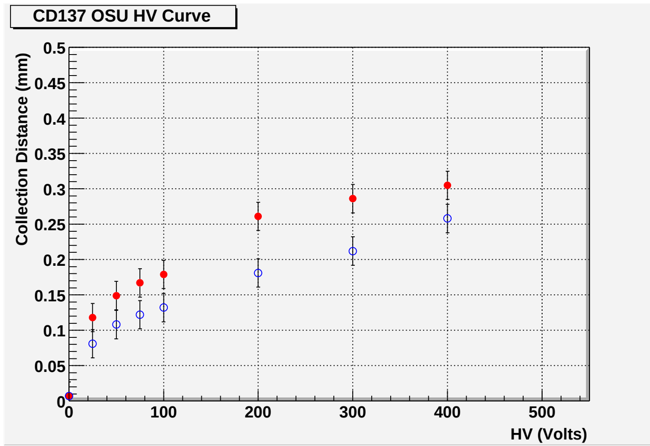
Single Crystal CVD Diamond

But for Other Diamonds





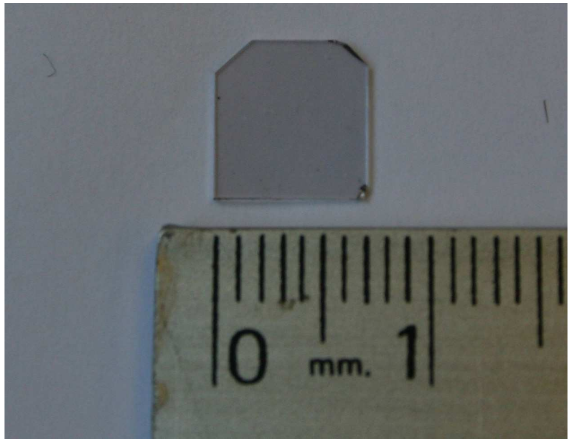




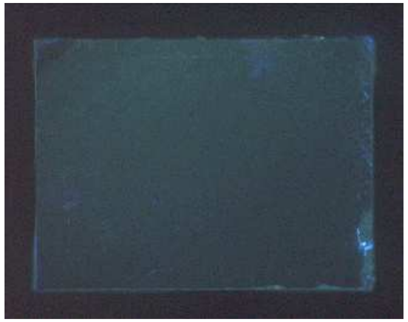
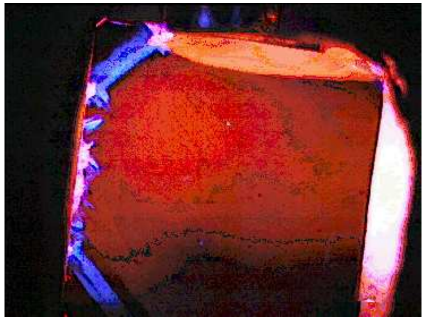
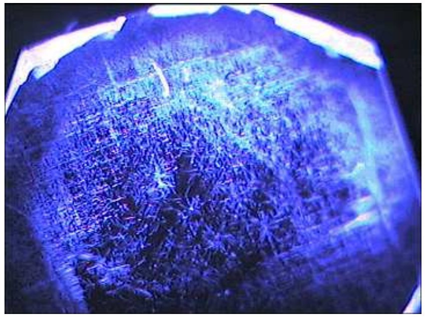
Not that easy to make!

Largest scCVD Diamond:

- Began with 4mm × 4mm
- Today 7mm × 7mm
- Well on our way to 8mm × 8mm sizes!



Impurities, Defects and Dislocations: Photo-Luminescence Measurements

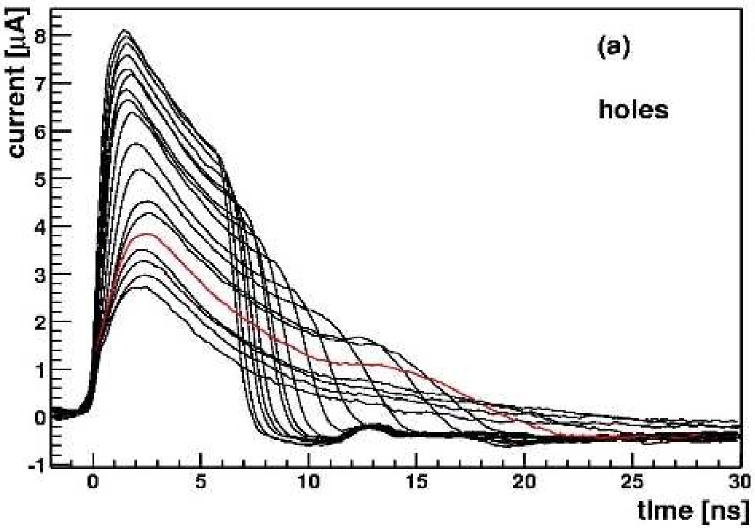




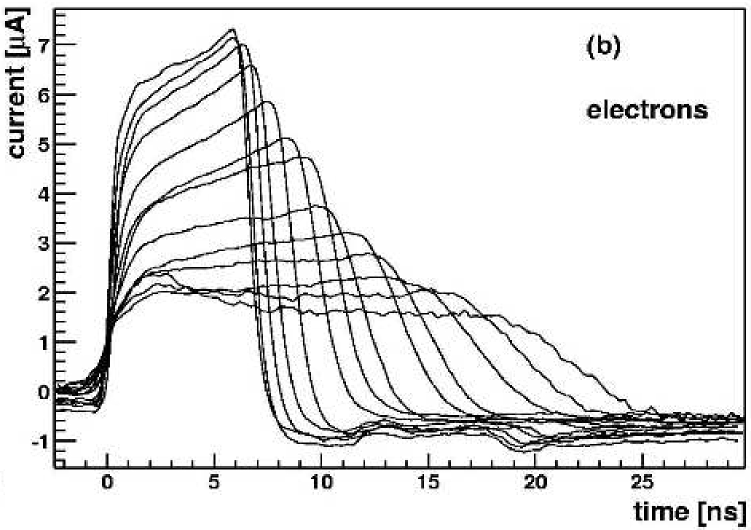
Left Image: High purity, no nitrogen, no dislocations.
Middle Image: Contains nitrogen - NV centre, 575 nm PL.
Right Image: Contains dislocations, broad band blue PL.

May be able to unravel the compexity of the CVD process!

Charge Collection Properties: Transient Current Measurements (TCT)

- Measure charge carrier properties separately for electron and holes
- Use α-source (Am241) to inject charge
  - penetration $\approx$ 14 μm (thickness of diamonds $\approx$ 470 μm)
  - use positive and negative applied voltage
- Amplify ionization current





Extracted parameters: Transit time, velocity, lifetime, space charge, pulse shape, charge.

Preliminary Results: saturated velocity $v_e = 96$ km/s, $v_h = 141$ km/s
lifetimes $\approx$ 34 ns $>>$ transit time (charge trapping not the issue)

Applications

CVD Diamond Used or Planned for Use in Several Fields

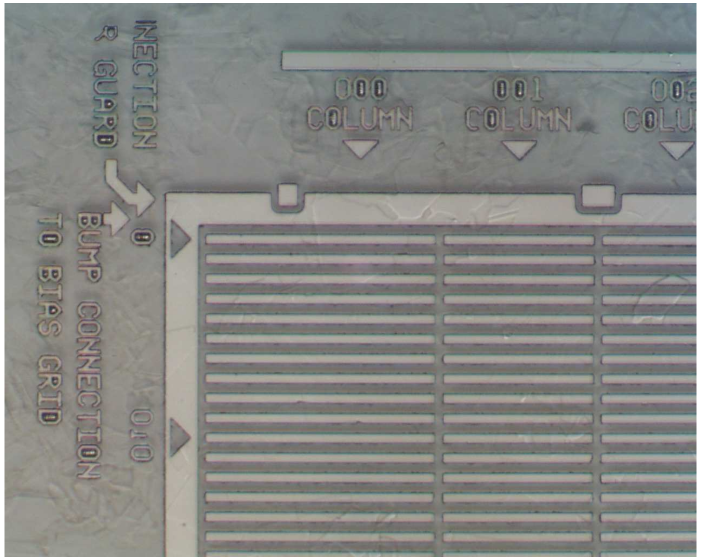
- High Energy Physics
- Heavy Ion Beam Diagnostics
- Sychrotron Radiation Monitoring
- Neutron and α Detection

Applications Discussed Here

- Pixel Detectors
  ATLAS, CMS
- Beam Monitoring
  BaBar
  Belle
  ATLAS
  CMS

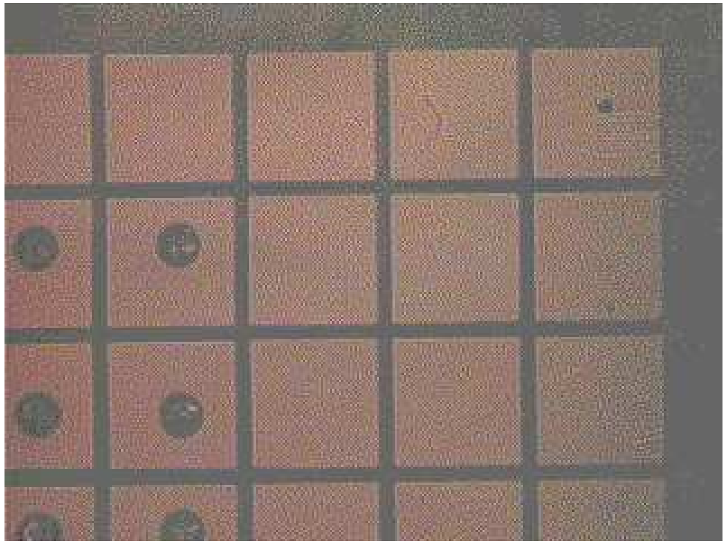
Diamond Pixel Detectors

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)



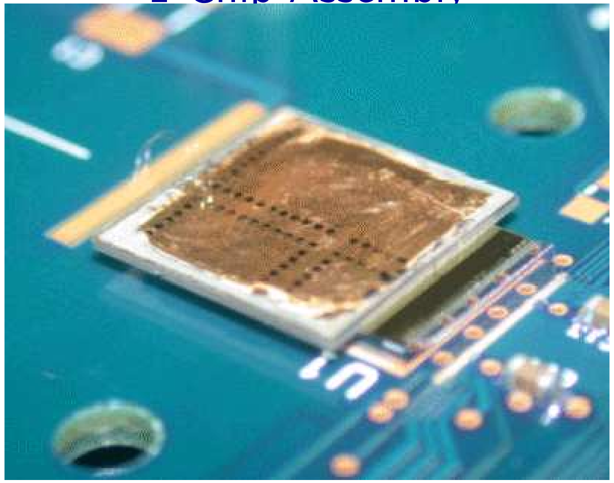
- CMS pixel pitch $125\mu m \times 125\mu m$
- Metalization: Ti/W
- Indium bumping at UC Davis

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

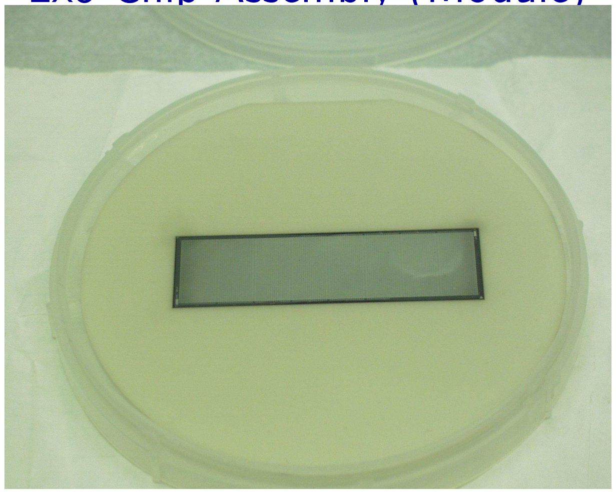
New radiation hard chips produced this year.

Results from an ATLAS pixel detector

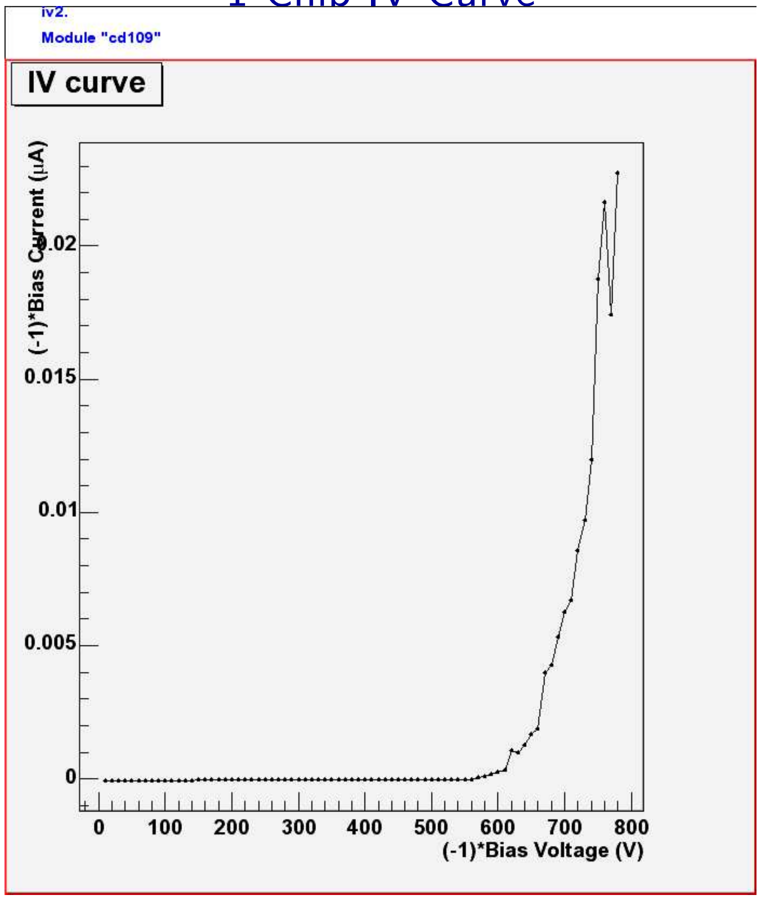
1 Chip Assembly



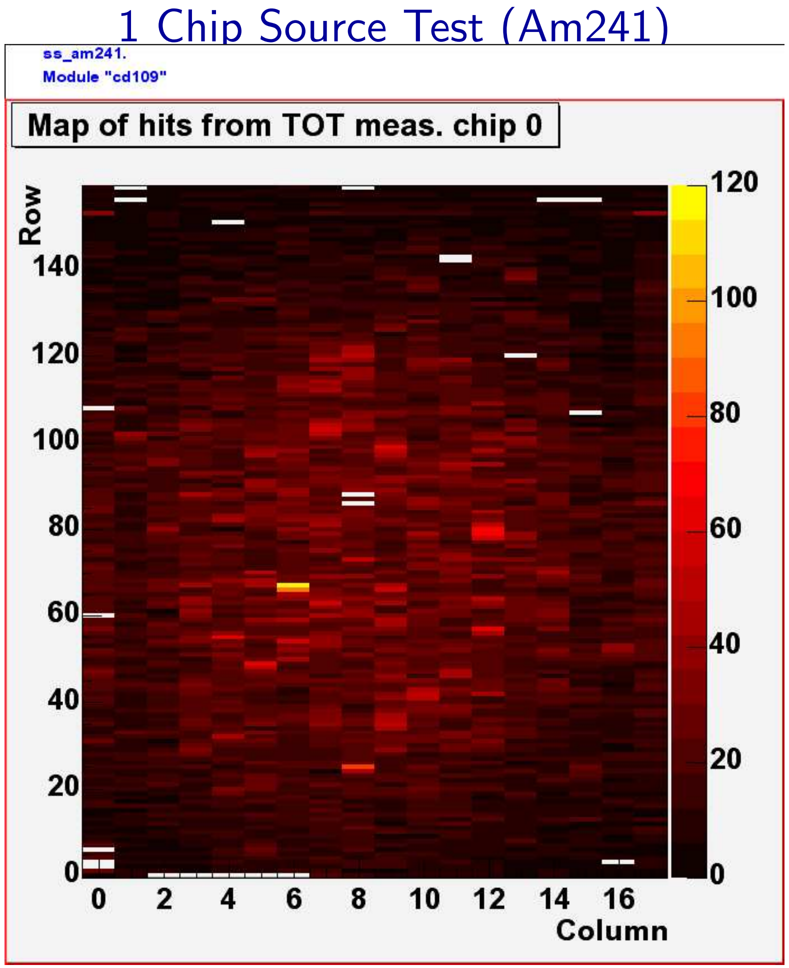
2x8 Chip Assembly (Module)

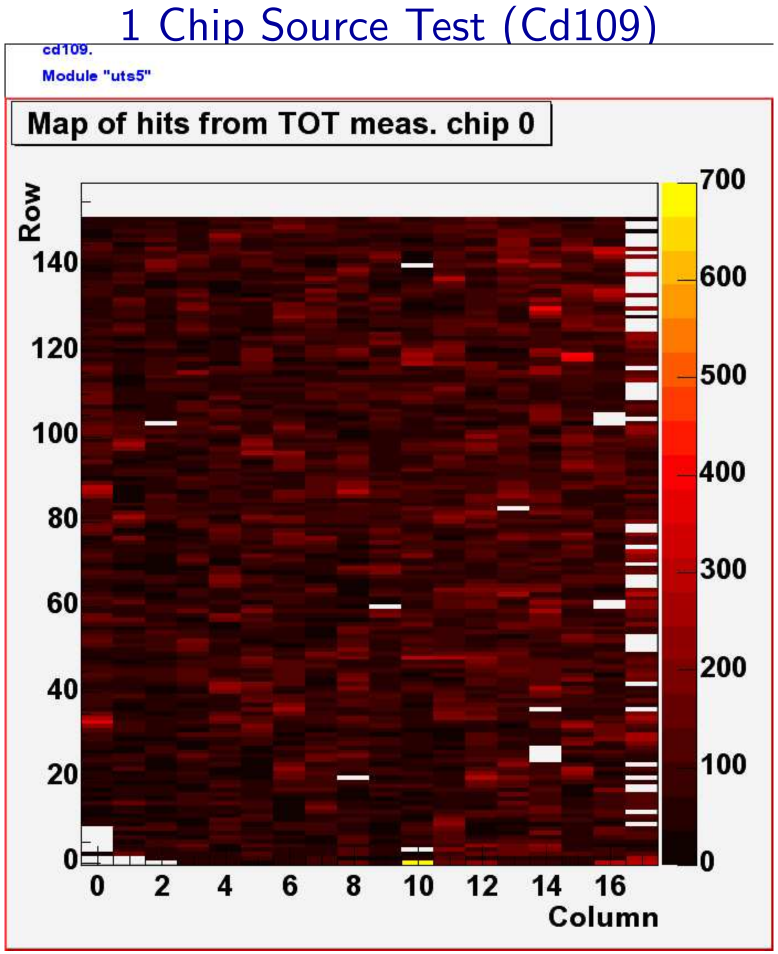


1 Chip IV Curve



Results from an ATLAS pixel detector

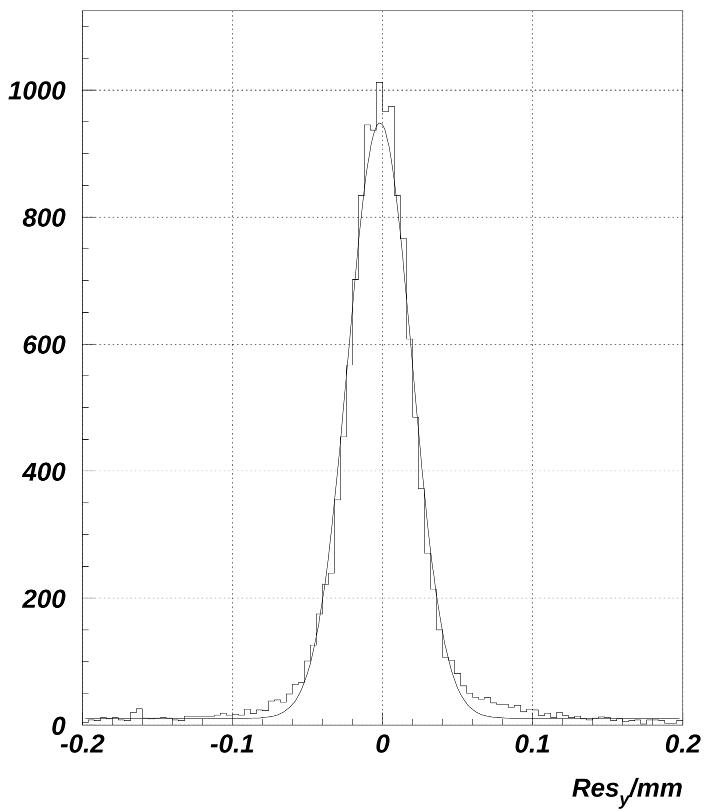




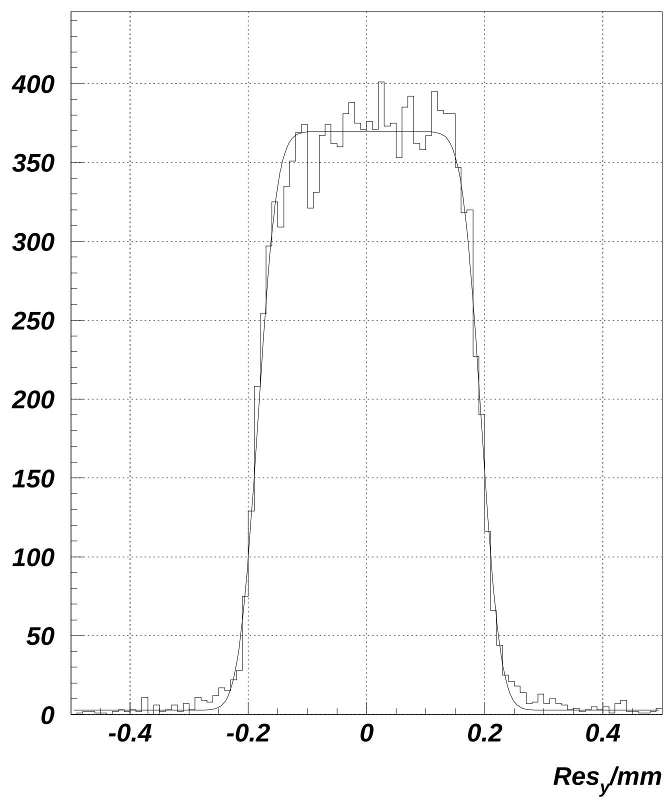
Americium 241 deposits $\approx$ 4600e
Cadmium 109 deposits $\approx$ 1600e

Results from an ATLAS pixel detector

1 Chip Beam Test (x-Resolution)

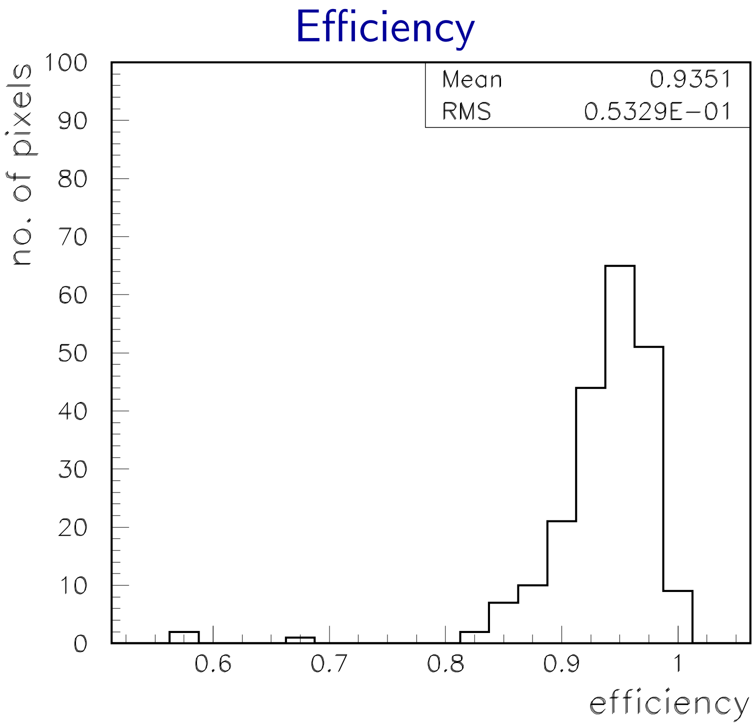


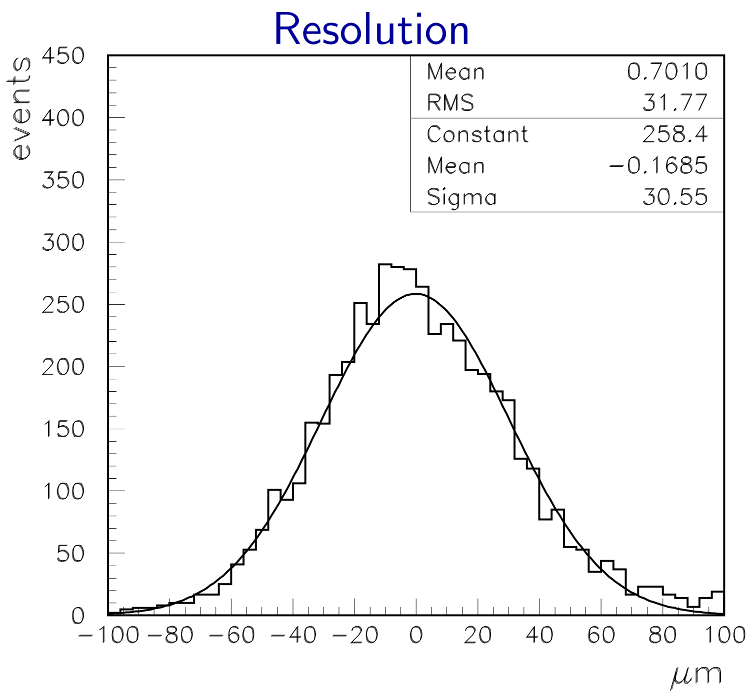
1 Chip Beam Test (y-Resolution)



Pitch is 50μm $\times$ 400μm
Spatial Resolution $\approx$ pitch/$\sqrt{12}$

Results from a CMS pixel detector



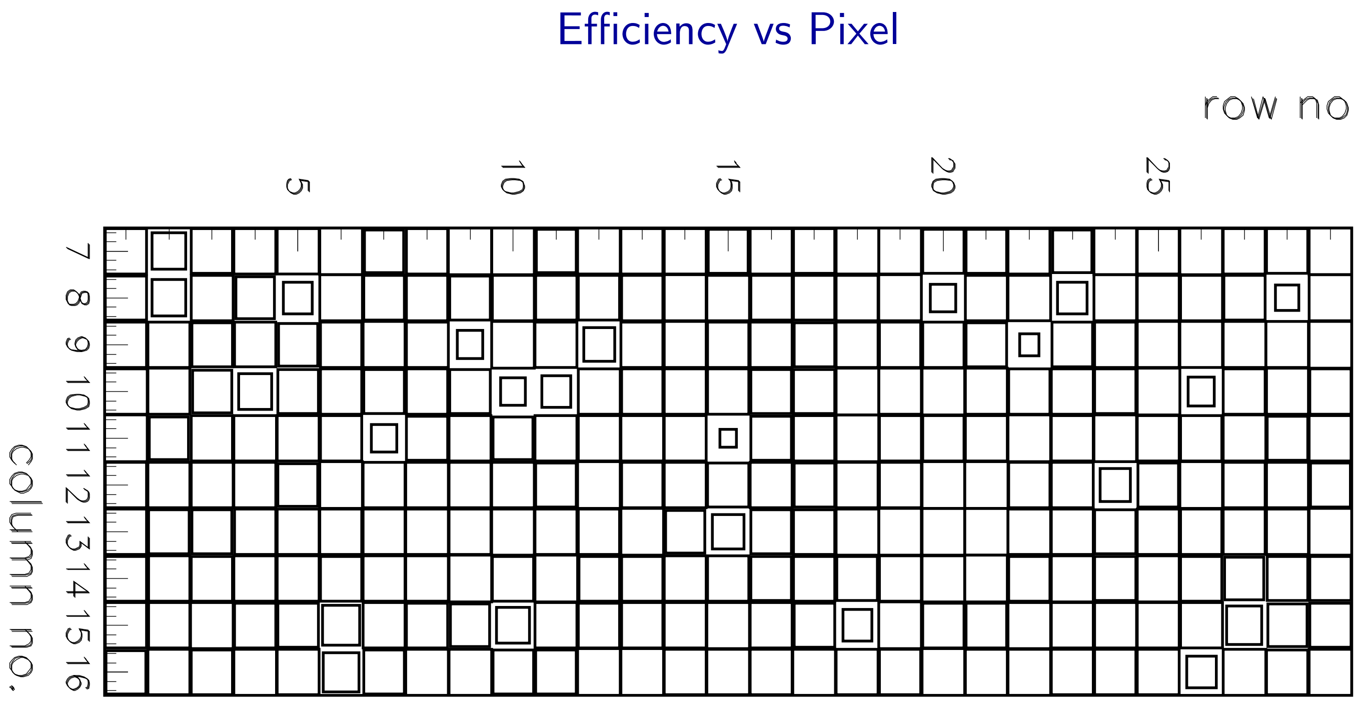


- Results with 200μm collection distance diamond

  Efficiency $\sim$ 94%

  Spatial resolution $\sim$ 31μm for 125μm pitch

Results from a CMS pixel detector



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

Radiation Monitoring - New Application - BaBar, Belle, ATLAS, CMS

Motivation:

→ Radiation monitoring crucial for Si operation/abort system of BaBar, Belle, LHC

→ Abort beams on large current spikes

→ Measure calibrated daily and integrated dose

Style:

- DC current or Slow Readout
- Requires low leakage current
- Requires small erratic dark currents
- Allows simple measuring scheme

- Examples: BaBar, Belle, CMS

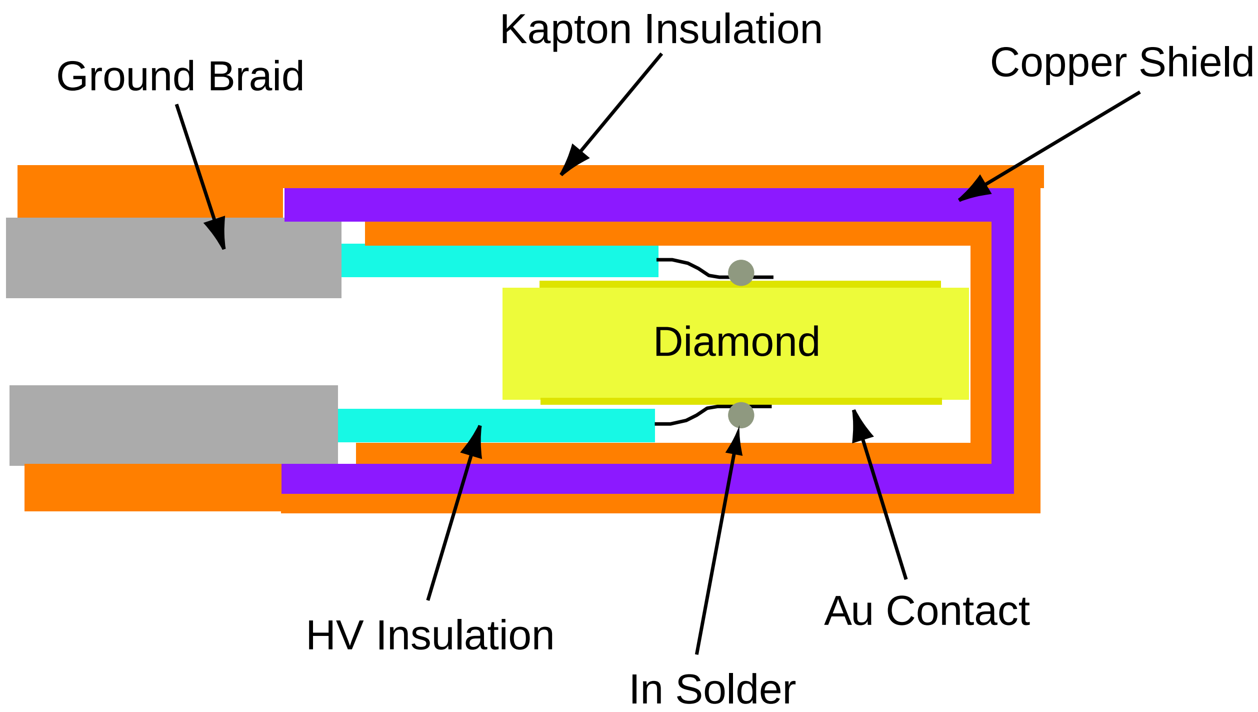
- Single Particle Counting
- Requires fast readout (GHz range)
- Requires low noise
- Allows timing correlations

- Example: ATLAS

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:

- → 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 PIN diodes will not last past 2005

Photo of BaBar Prototype Devices

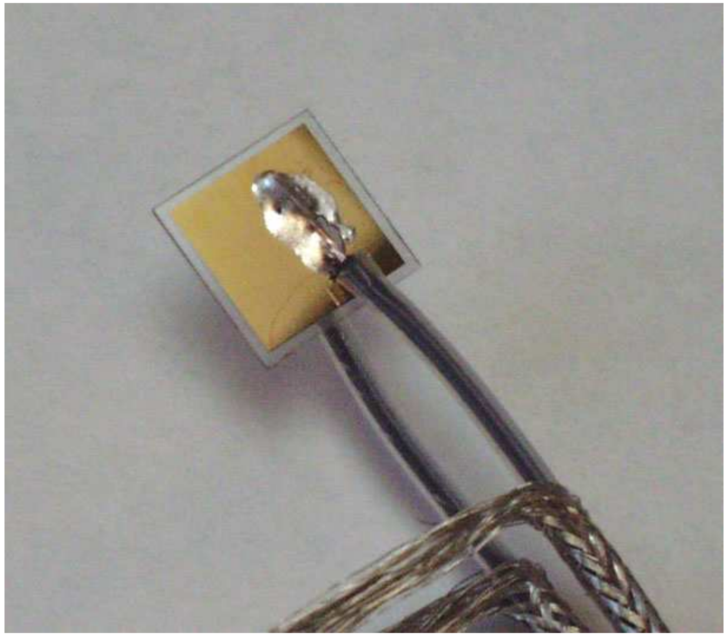
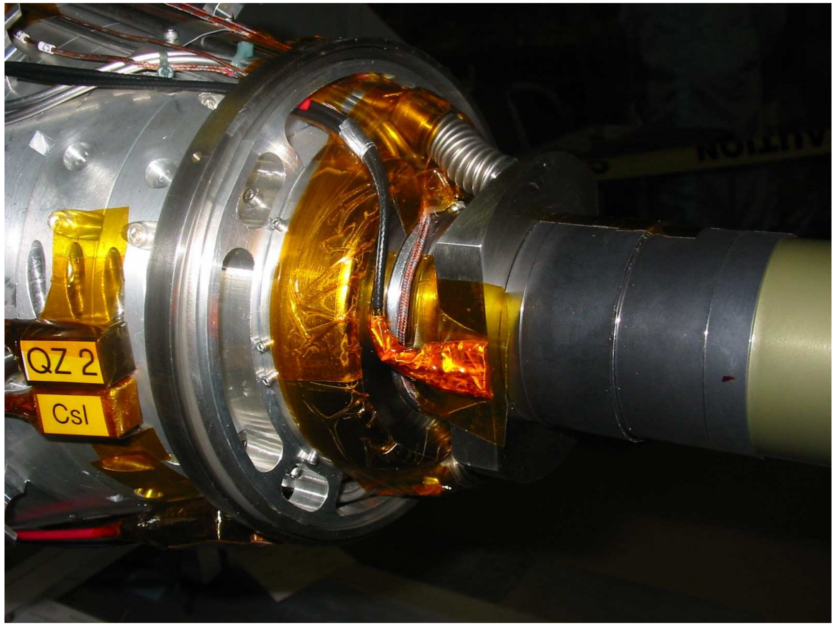


Photo of Installed BaBar Device



BaBar device inside the silicon vertex detector.

The BaBar/Belle Diamond Radiation Monitor Prototypes:

Photo of Belle Prototype Device

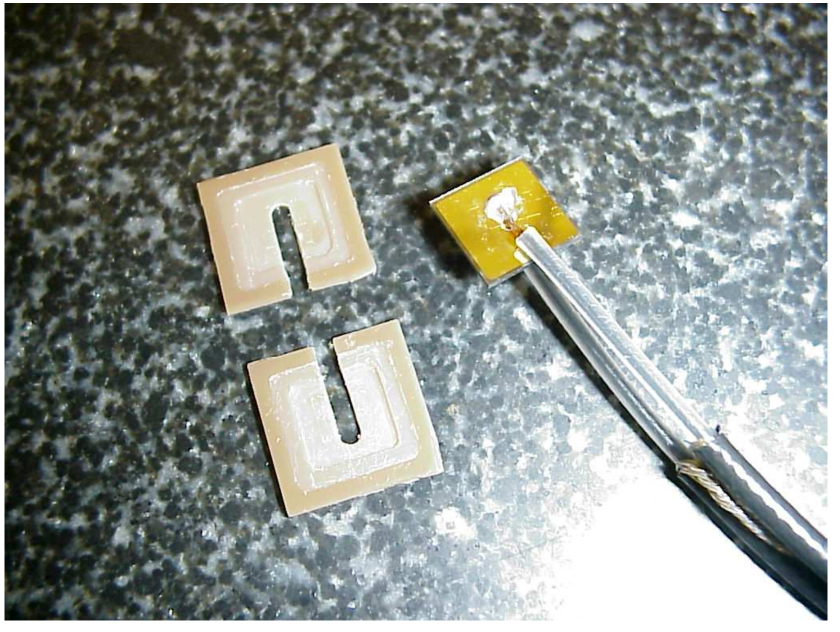
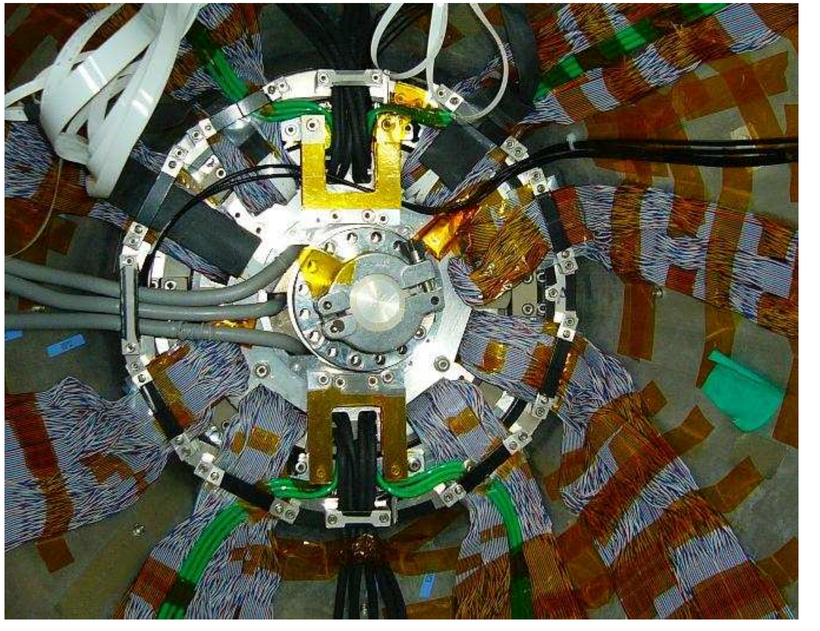


Photo of Installed Belle Device

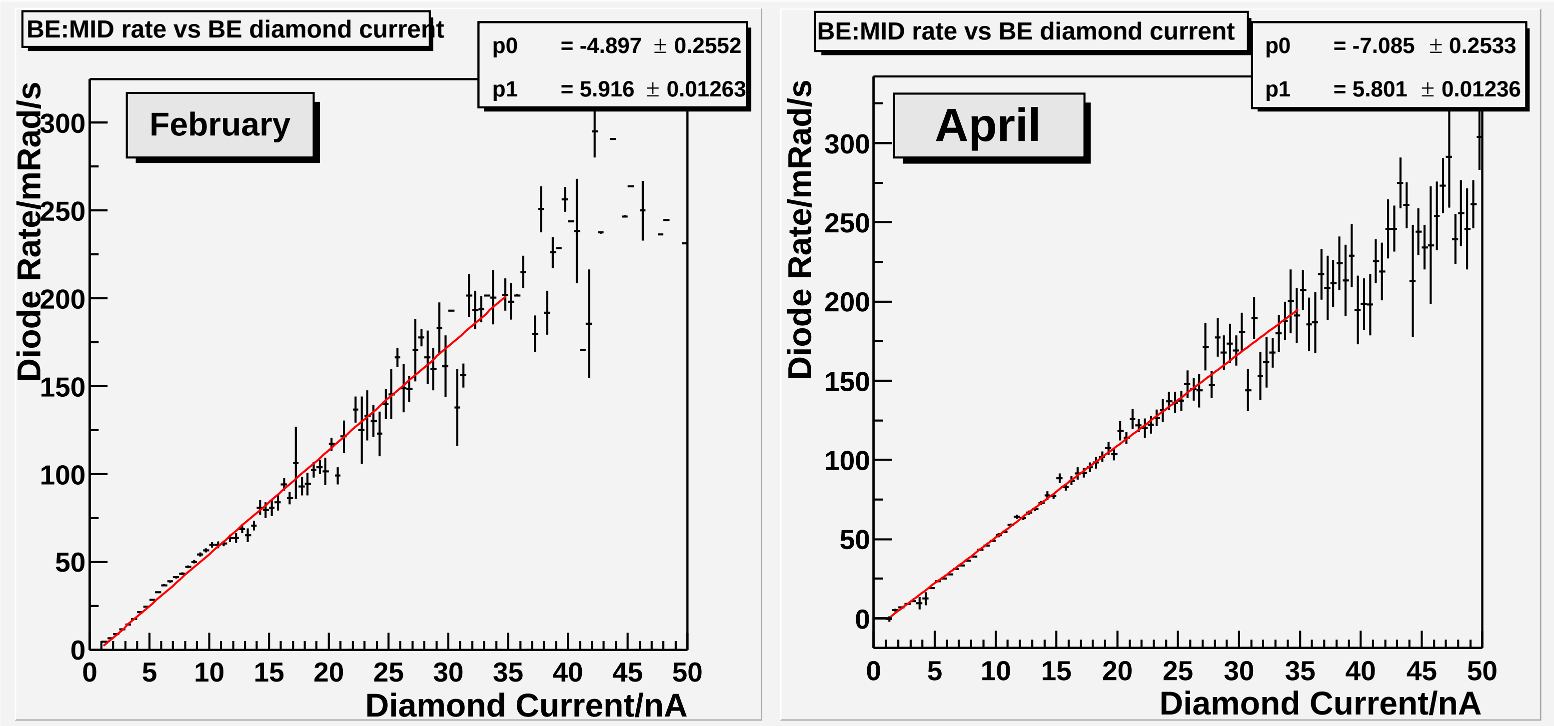


Belle device just outside the silicon vertex detector.

Radiation Monitoring

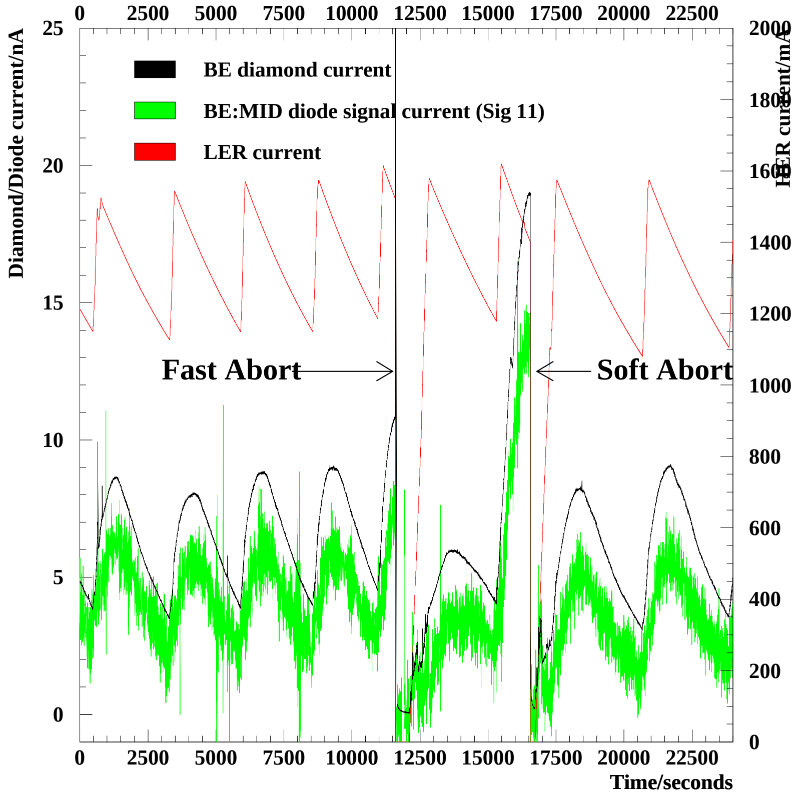
Results on Calibration in BaBar:

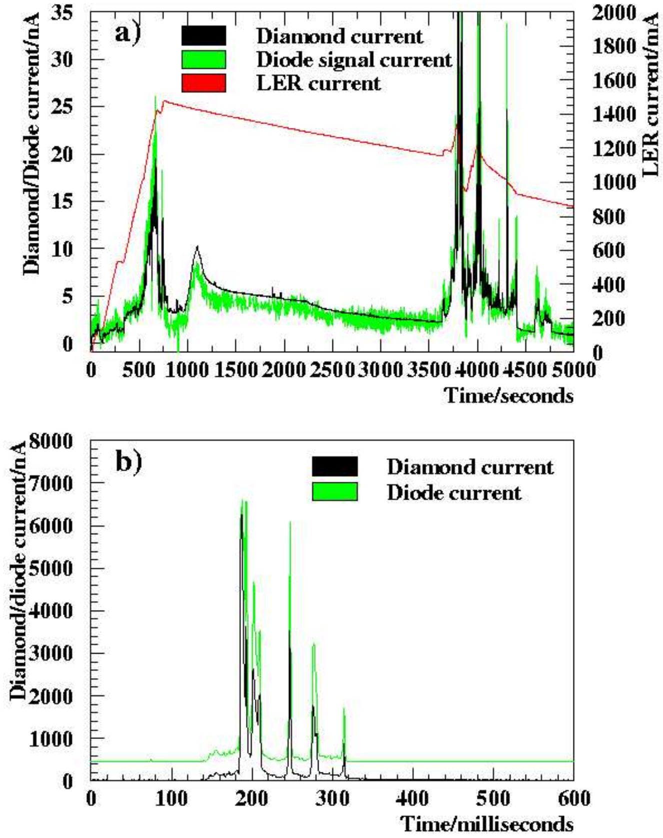
- In BaBar during injection relative to silicon diodes: 5.9mrad/nC (Feb)
- In BaBar during injection relative to silicon diodes: 5.8mrad/nC (Apr)
- Correlation coefficient unchanged over several months



Calibration repeatable over many months

Data Taking in BaBar:

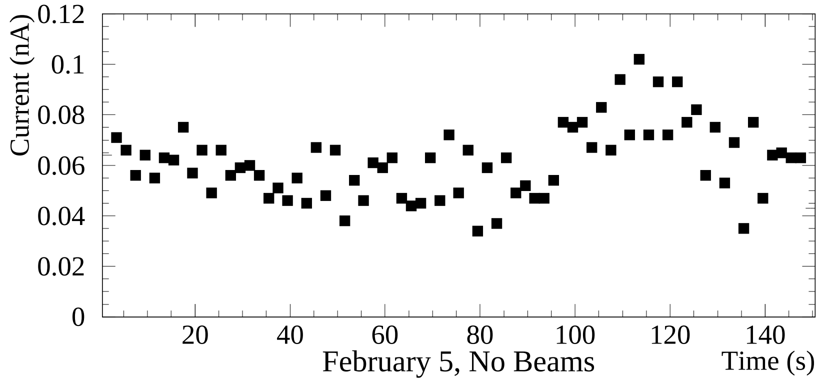


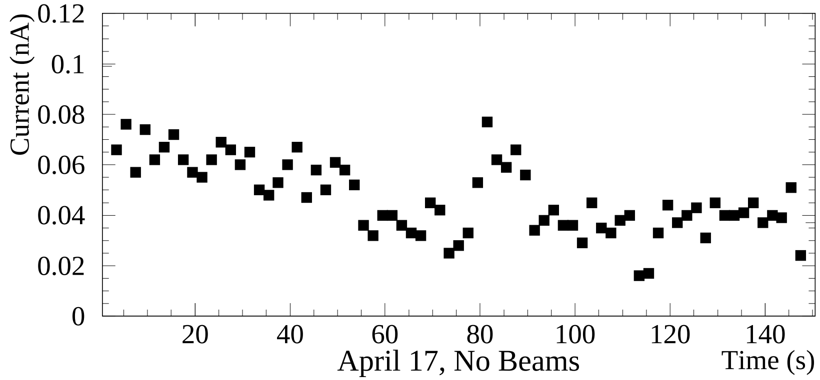


System operating for 18 months in BaBar and works well!

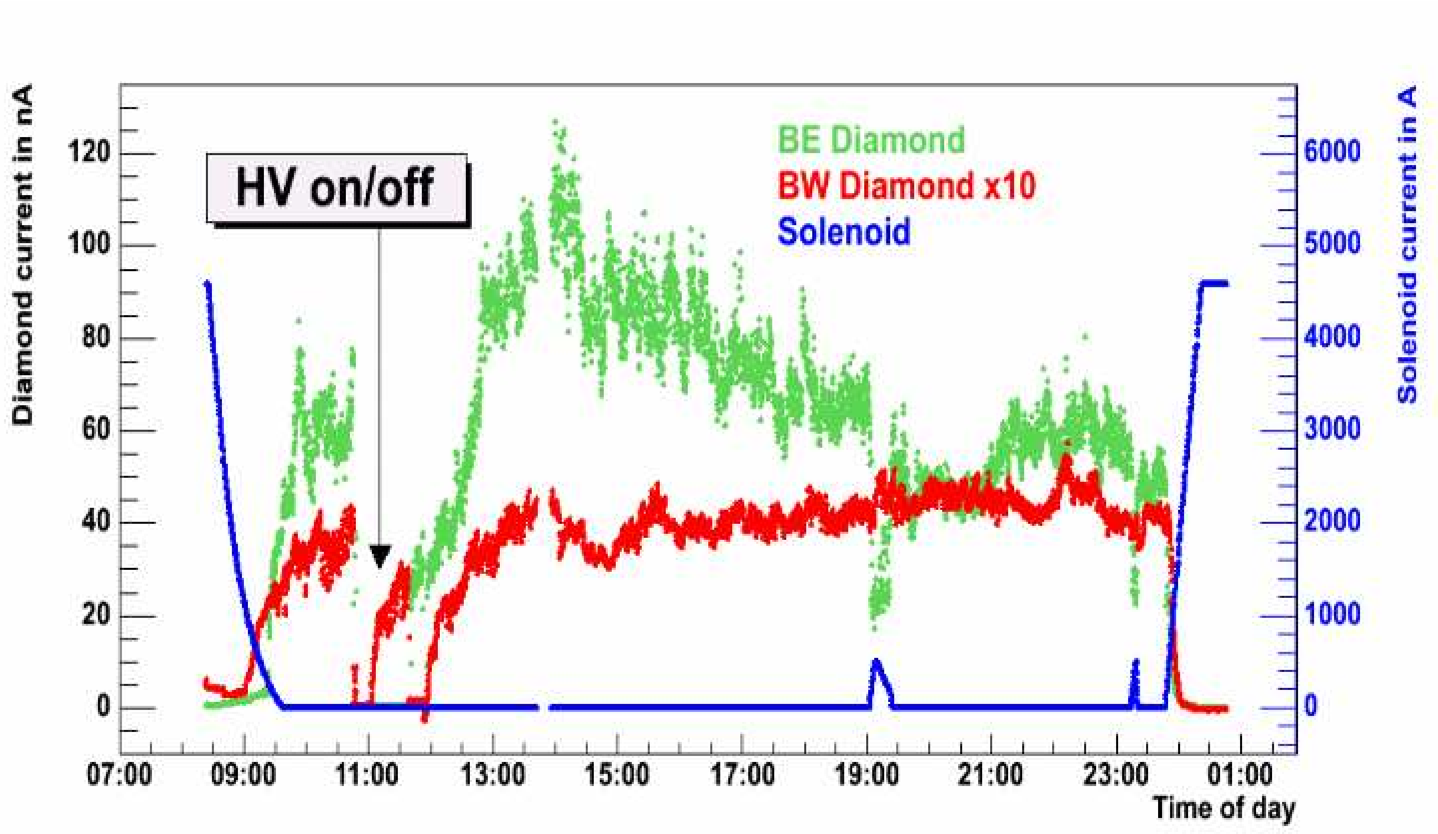
Leakage Current in BaBar

- Diamonds have received 250kRad ^{60}Co plus 750kRad 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





Discovery of Erratic Dark Currents

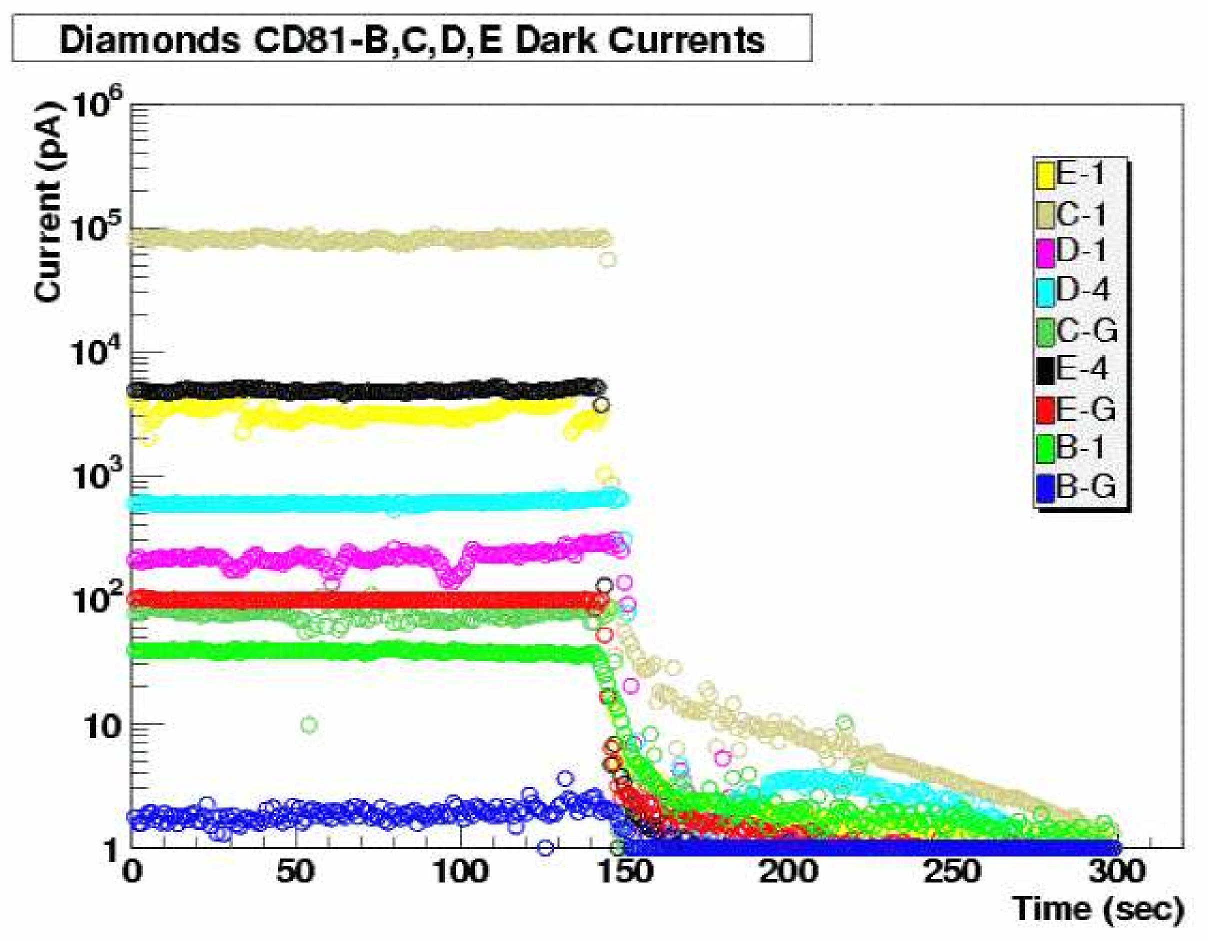


It is observed the diamond current increases as the magnetic field goes off.

This happens every time the field goes off in BaBar

The Eratic Dark Currents have been reproduced in the laboratory!

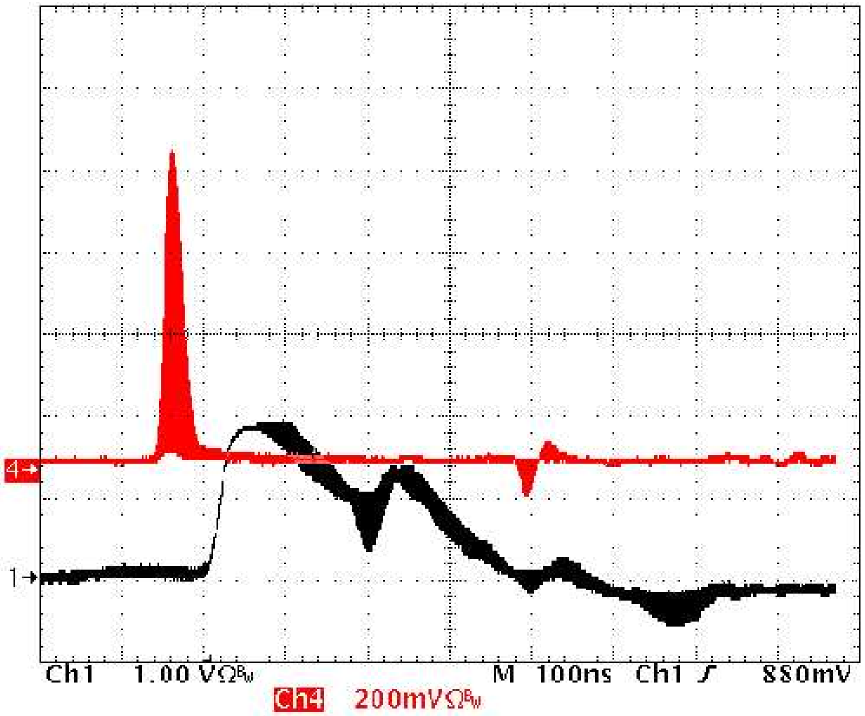
Discovery of Erratic Dark Currents



Eratic Dark Currents go away every time the magnetic field is turned on!
Origin is still a mystery

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



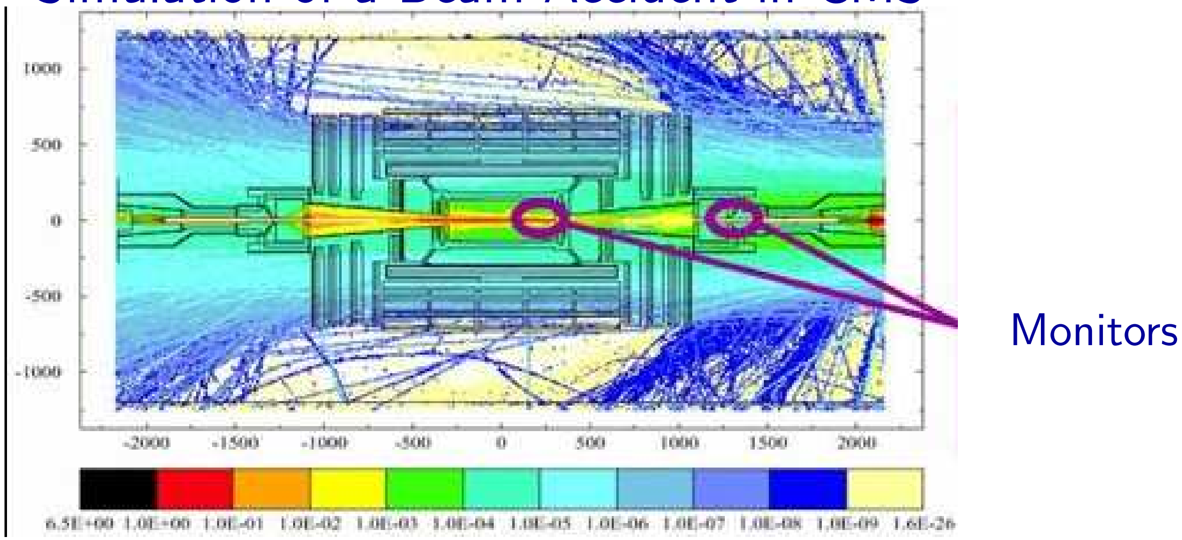
Diamond is fast enough (< 20 ns) $\rightarrow$ now used in BaBar abort system

Installation of full diamond system possible in summer 2005

The CMS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Test beam emulating beam accident - unsynchronised beam abort - 10^{12} protons lost in 260 ns in CMS
- Worst case 100x unsynchronised beam abort over several turns - protection requires early detection
- Possible location in the CMS detector:

Simulation of a Beam Accident in CMS

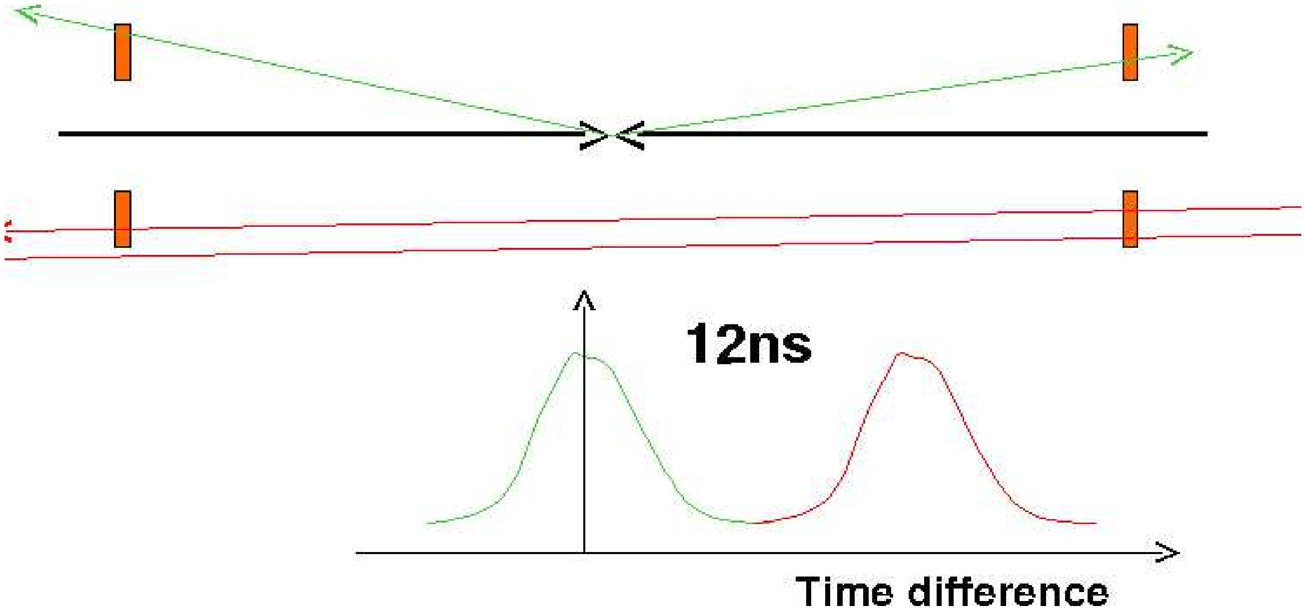


Radiation Monitoring

The ATLAS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Time of flight measurement to distinguish collisions from background
- Located behind pixel detector forward disks in pixel support tube
- Possible ATLAS scenario:

Beam Condition Monitor in ATLAS



Summary

CVD Diamond as Radiation Tolerant Detectors

- High Quality pCVD diamond (ccd up to 275 μm) are readily available in large sizes
  - 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
- Radiation Tests show tolerance up to 2×10^{15}/cm^2
  - 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
- Present pCVD diamonds should surpass performance of silicon at around 10^{15}p/cm^2

scCVD Diamonds May Overcome the Limitation of pCVD Material

- Full signal collection at E<<1V/μm
- Long charge lifetime
- Very little trapping- uniform detector

Many Applications Benefit from use of Diamond

- Beam Monitoring Now - BaBar, Belle
- Strip or Pixel detectors for the future

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 $\rightarrow$ Now

  With Pions:

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