Development of CVD Diamond Tracking Detectors for Experiments at High Luminosity Colliders

RD42 Status Report

Harris Kagan, Ohio State University

LHCC Presentation

Feb. 2, 2005, CERN

Outline of the Talk

- **Introduction - 2004 LHCC Milestones**
- **Diamond Properties**
- **Radiation Hardness Studies with Trackers**
- **Pixel Results**
- **Beam Position Monitoring Studies**
- **Summary**
- **RD42 Plans and Request**

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

New groups joined RD42 from:

DESY-Zeuthen, St. Petersburg, Fachhocchschule für Wirtschaft und Technik-Vienna

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

2004 LHCC Milestones

Priorities of Research in 2004

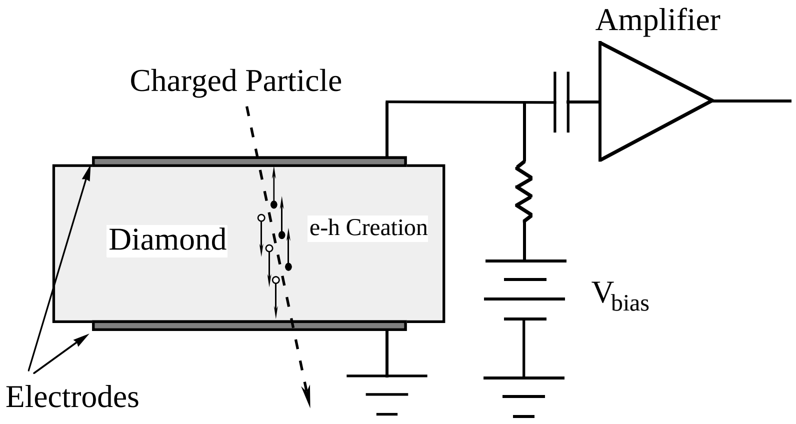
- Improve the charge collection distance of polycrystalline CVD (pCVD) material above 250 μm
- Pursue the development of single crystal CVD (scCVD) diamond material
- Test the radiation hardness of the highest quality pCVD and scCVD diamond
- Develop devices useful at the LHC by ATLAS and CMS
- Continue the development of systems for beam monitoring for the LHC

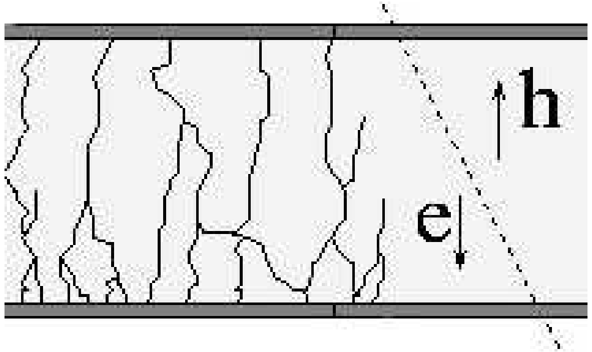
These points will be addressed in this talk.

Diamond Properties

Characterization of Diamond:

Signal formation





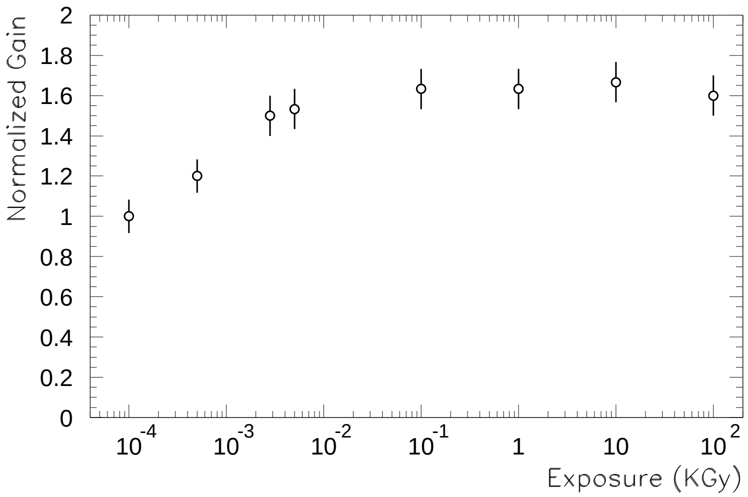
- $Q=\frac{d}{t}Q_0$ where d = collection distance = distance e-h pair move apart
- $d=(\mu_e\tau_e + \mu_h\tau_h)E$
- $d=\mu E\tau$

  with $\mu = \mu_e + \mu_h$

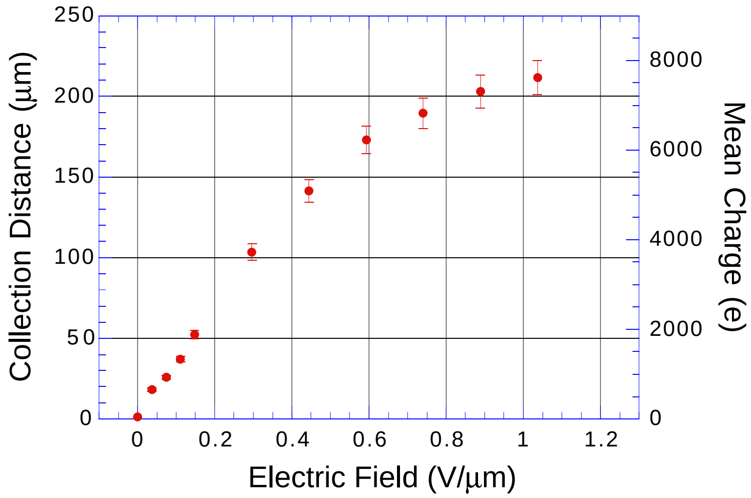
  and $\tau = \frac{\mu_e\tau_e+\mu_h\tau_h}{\mu_e+\mu_h}$

Diamond Properties:

Signal formation

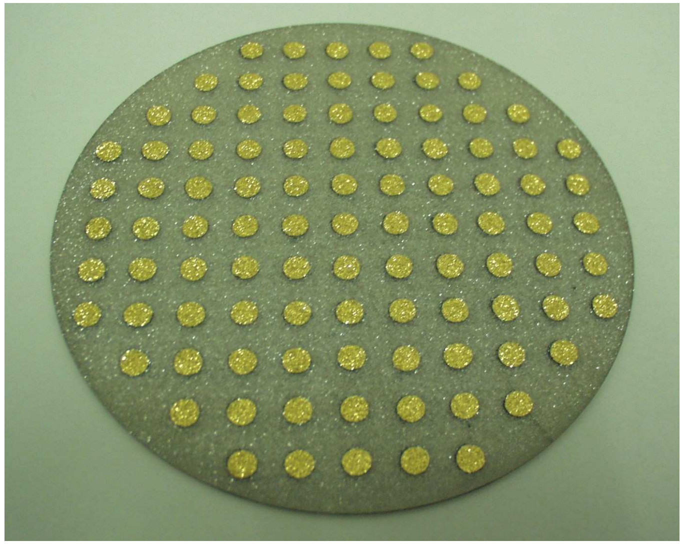


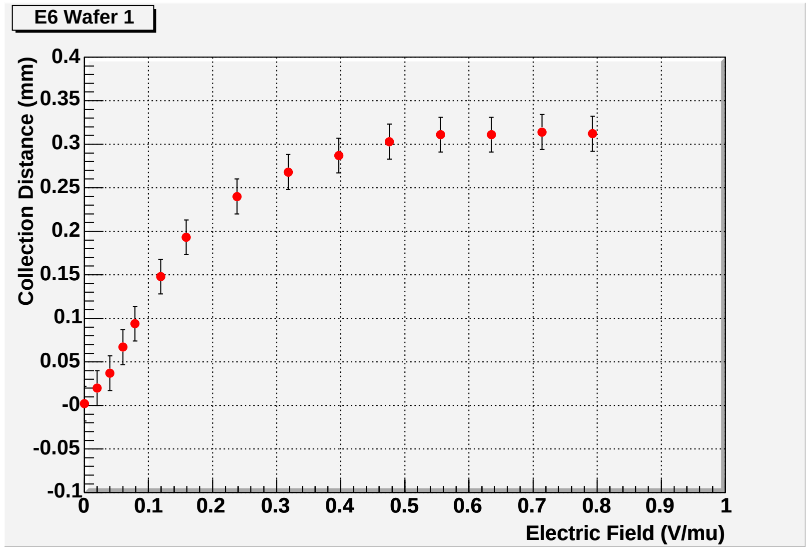
Signal versus applied electric field



- 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.





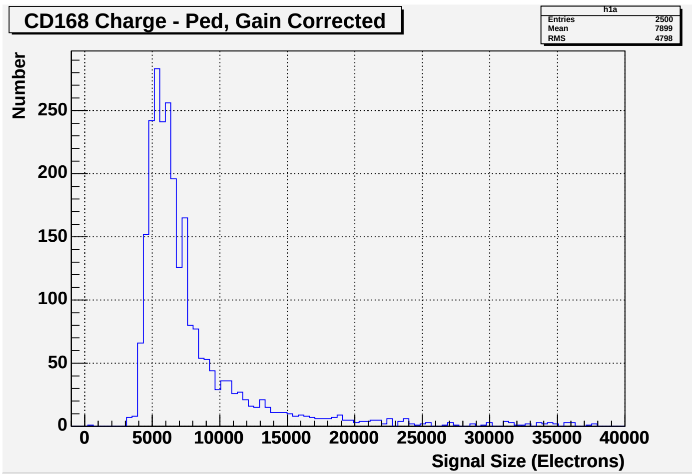
Left: Recent pCVD wafer ready for test - Dots are 1 cm apart
Right: Collection distance from a dot in the pCVD wafer

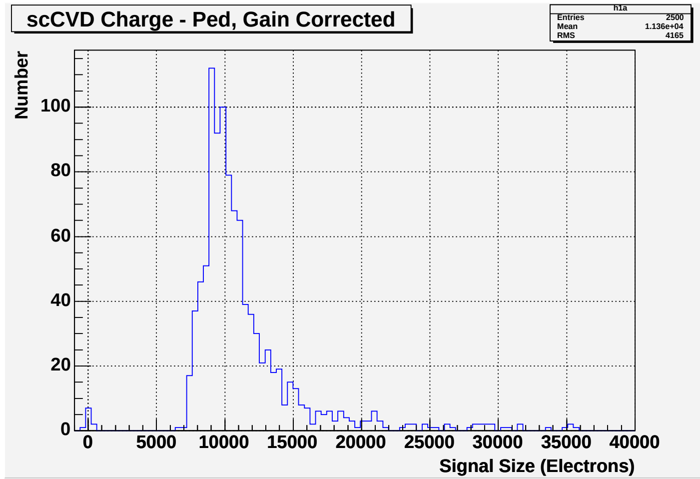
Results of Research Program:

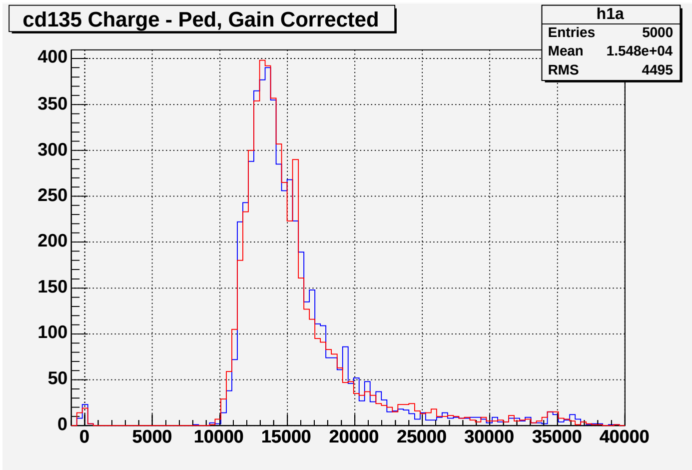
Wafers can be grown >12 cm diameter, >2 mm thickness.

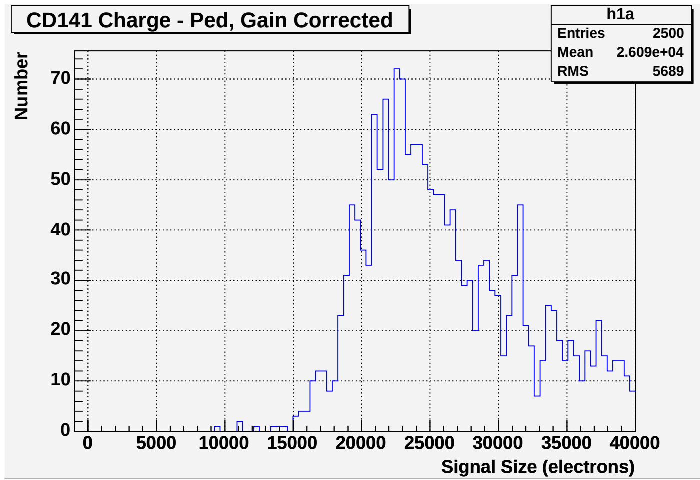
Collection distance of this wafer 200μm (edge) to 310μm (center).

Recent single crystal CVD (scCVD) diamond.







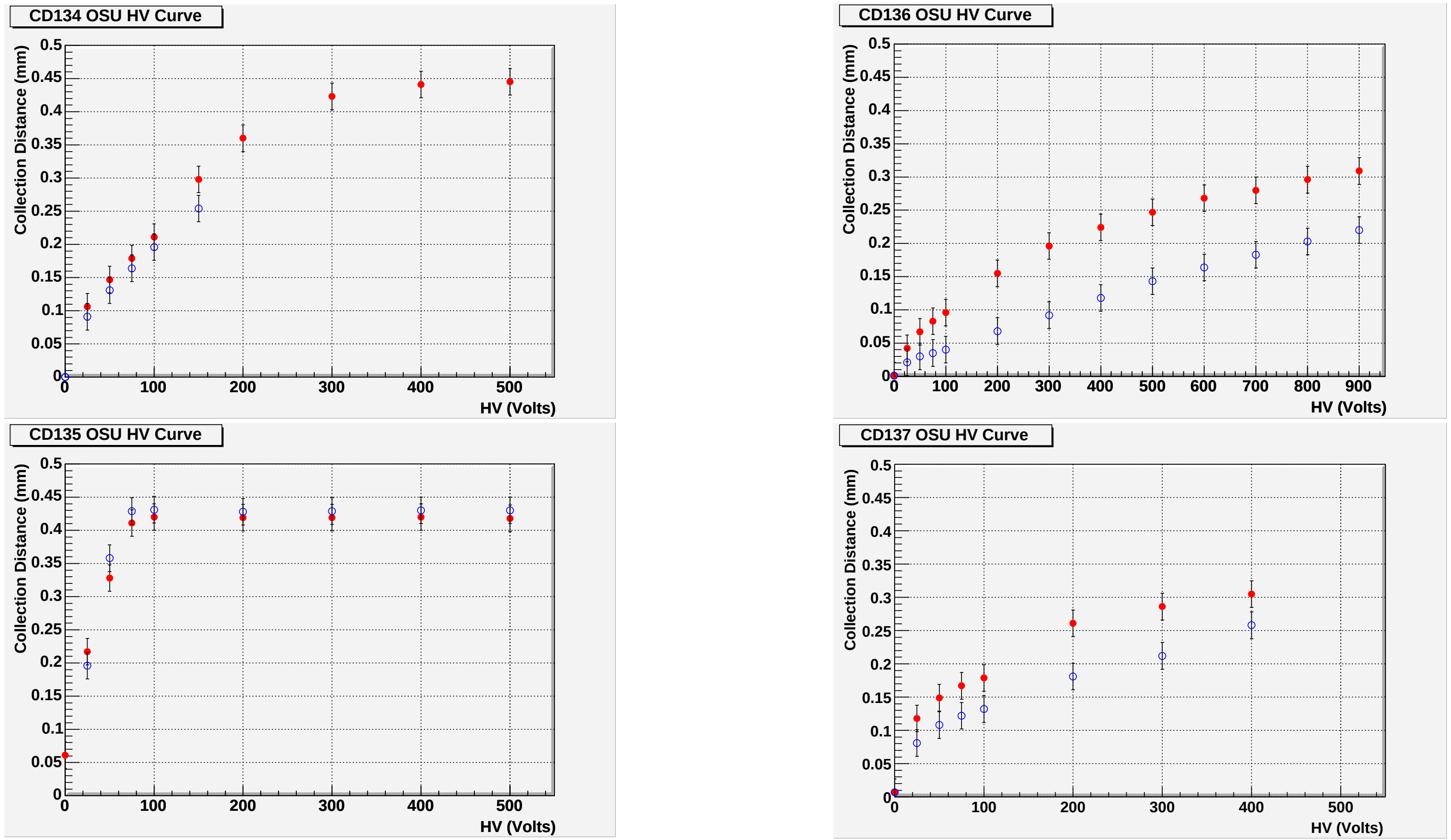


New Research Program

Pulse height spectrum of various scCVD diamonds (t=210, 320, 435, 685 μm)

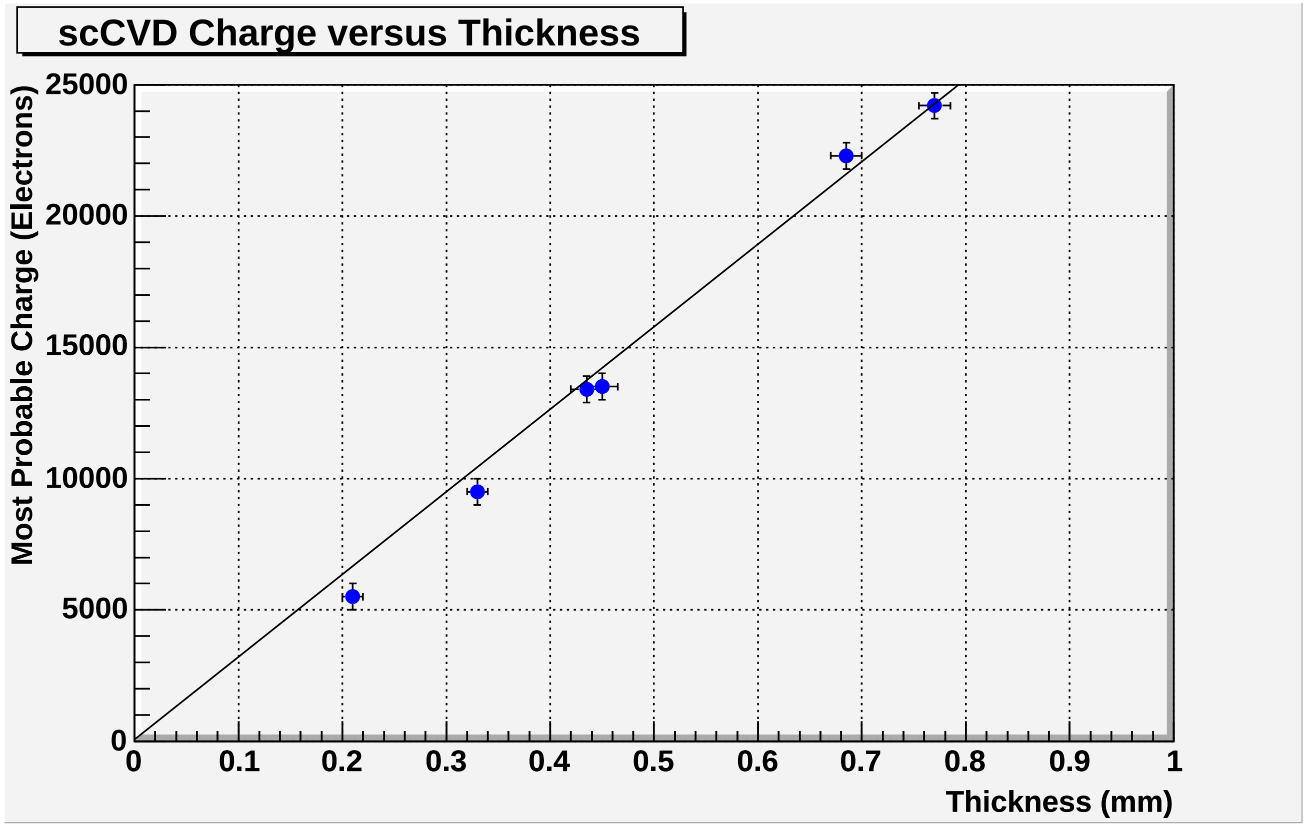
Diamond Properties

But along the way



Not that easy to make!

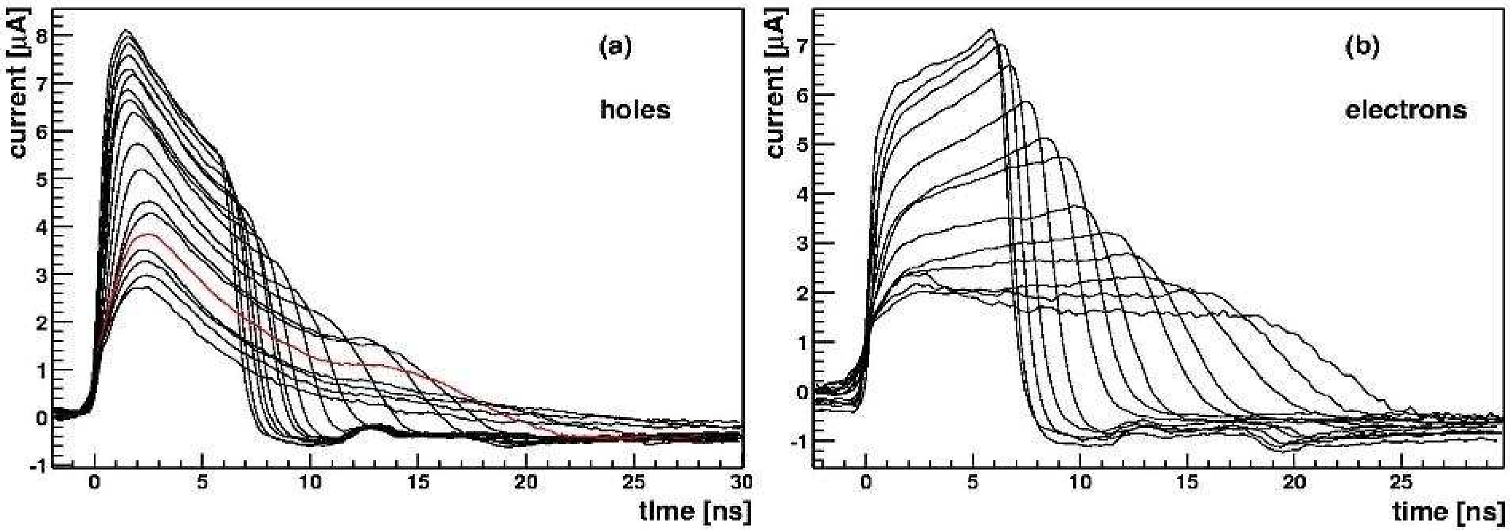
Recent single crystal CVD (scCVD) diamond.



Most Probable charge versus thickness

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



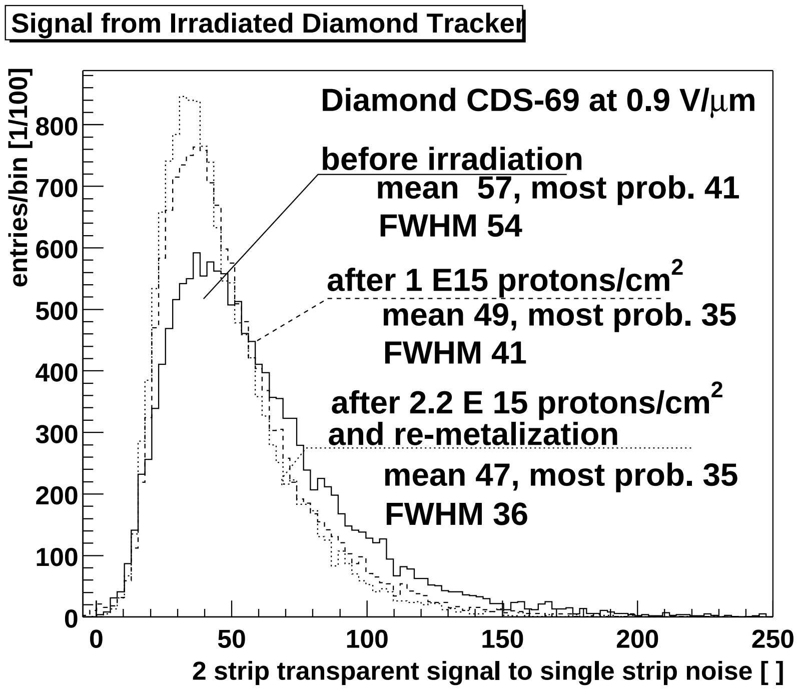
Extracted parameters: Transit time, velocity, lifetime, space charge, pulse shape, charge.

Preliminary Results: saturated velocity $v_e = 96$ km/s, $v_h = 141$ km/s

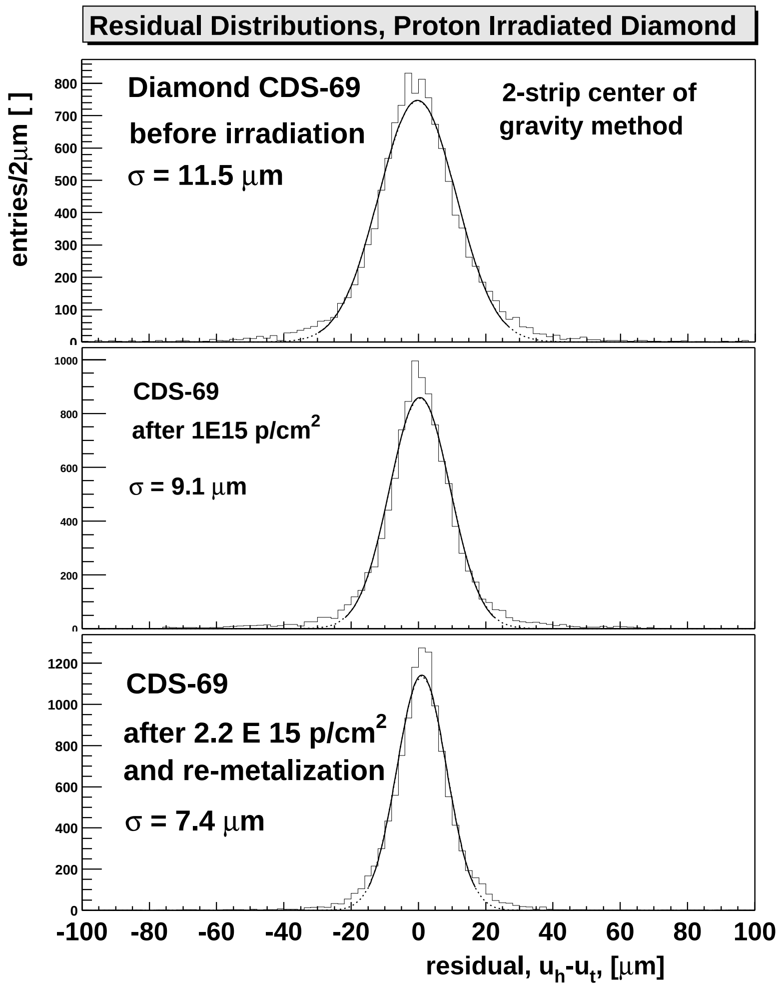
lifetimes $\approx$ 34 ns >> transit time (charge trapping not the issue)

Proton Irradiation - previously:

Signal to Noise



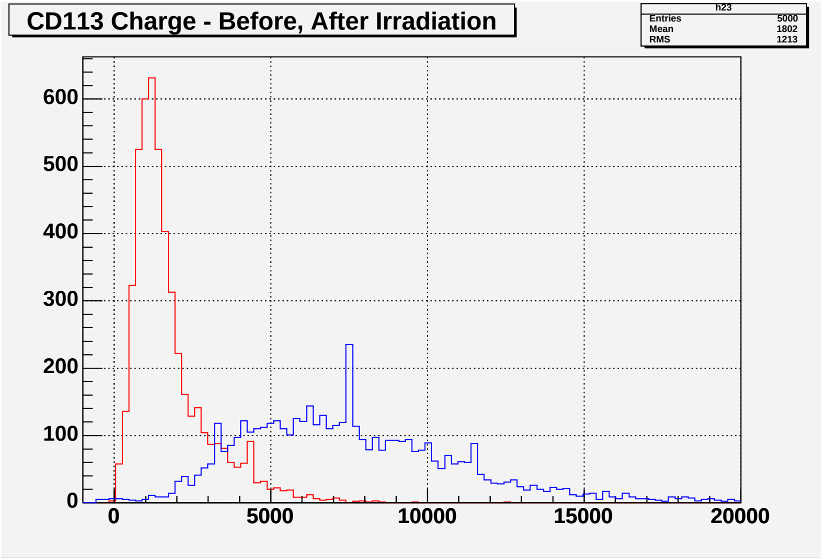
Resolution



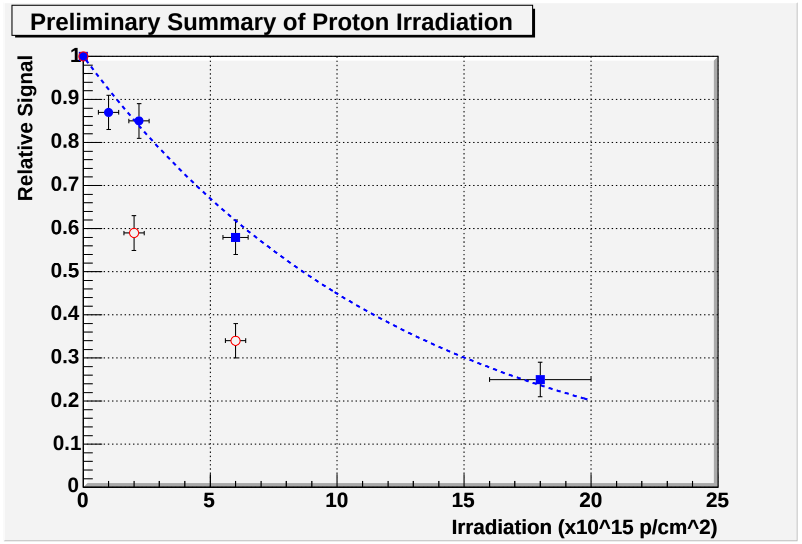
- Data taken over a period of 2 years
- Dark current decreases with fluence
- 15% loss of S/N at $2.2 \times 10^{15}/\text{cm}^2$
- Resolution improves 35% at $2.2 \times 10^{15}/\text{cm}^2$

Proton Irradiation - new:

Pulse Height



Sumary



Left: Pulse height distributions before (blue curve) and after (red curve) the irradiation to 20×10^{15} p/cm^2 (500Mrad)

Right: Summary of proton irradiation results for pCVD diamond (filled points) and first scCVD diamond (open points)

Applications

CVD Diamond Used or Planned for Use in Several Fields

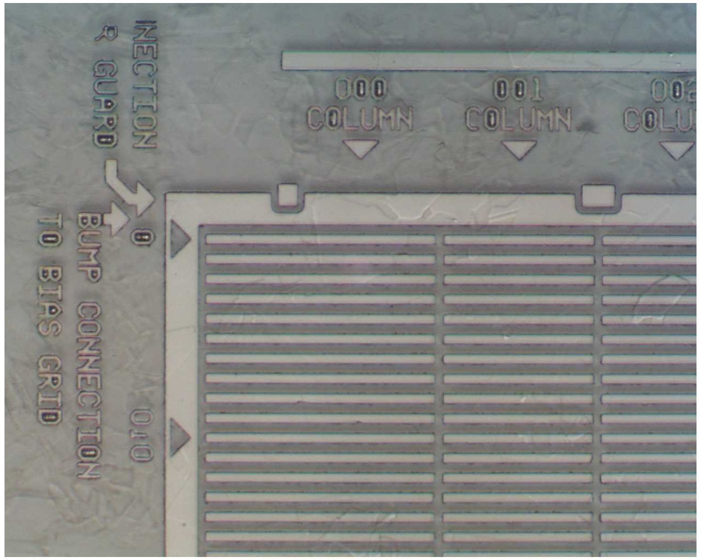
- High Energy Physics
- Heavy Ion Beam Diagnostics
- Sychrotron Radiation Monitoring
- Neutron and α Detection

Applications Discussed Here

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

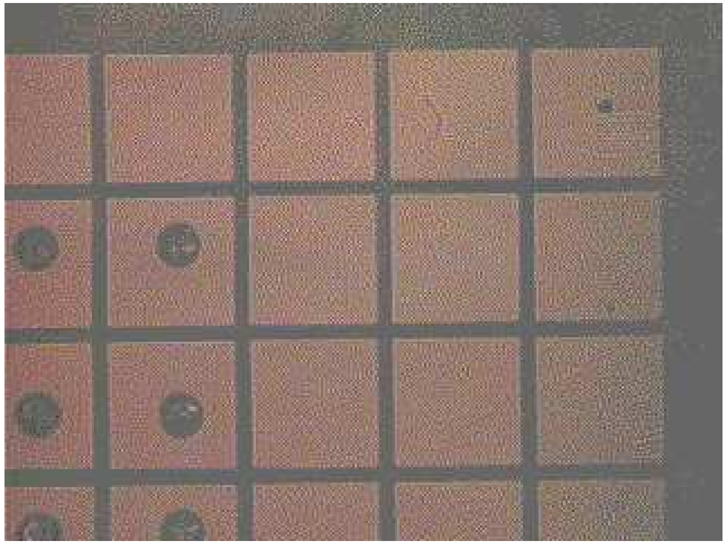
Diamond Pixel Detectors

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)



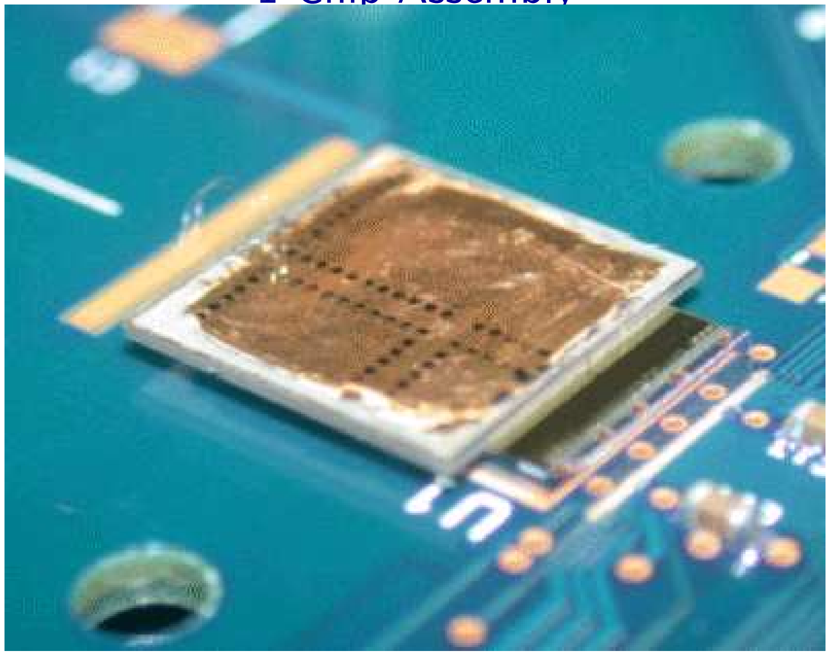
- CMS pixel pitch $125\mu m \times 125\mu m$
- Metalization: Ti/W
- Indium bumping at UC Davis

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

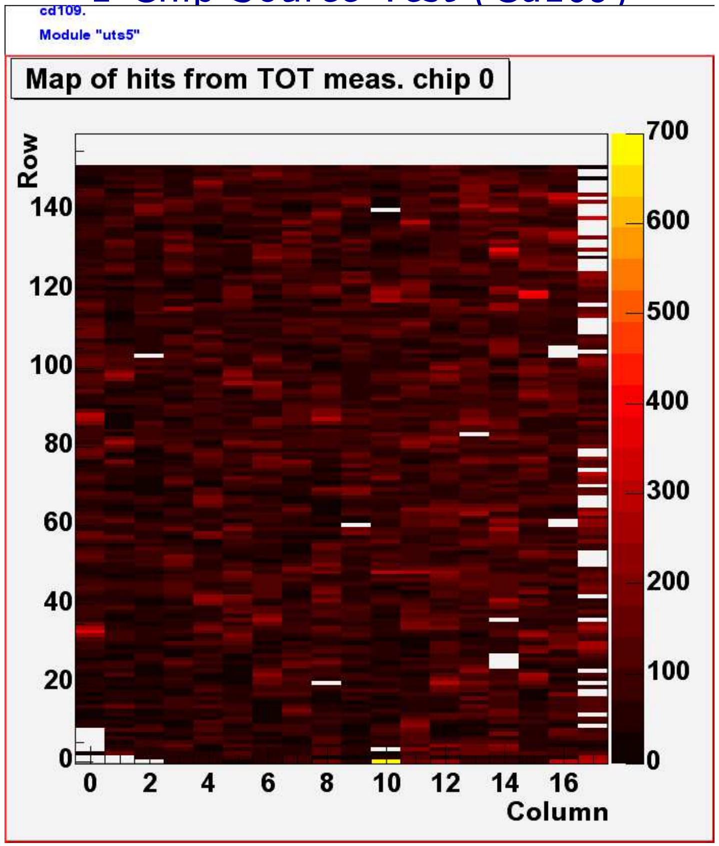
Radiation hard chips produced last year.

Results from a single chip ATLAS pixel detector

1 Chip Assembly

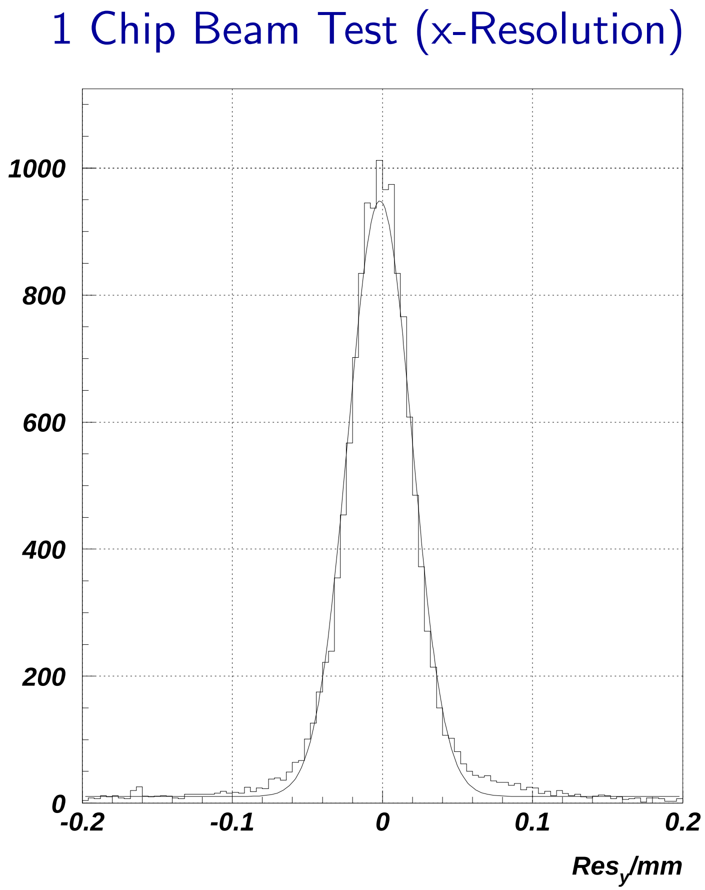


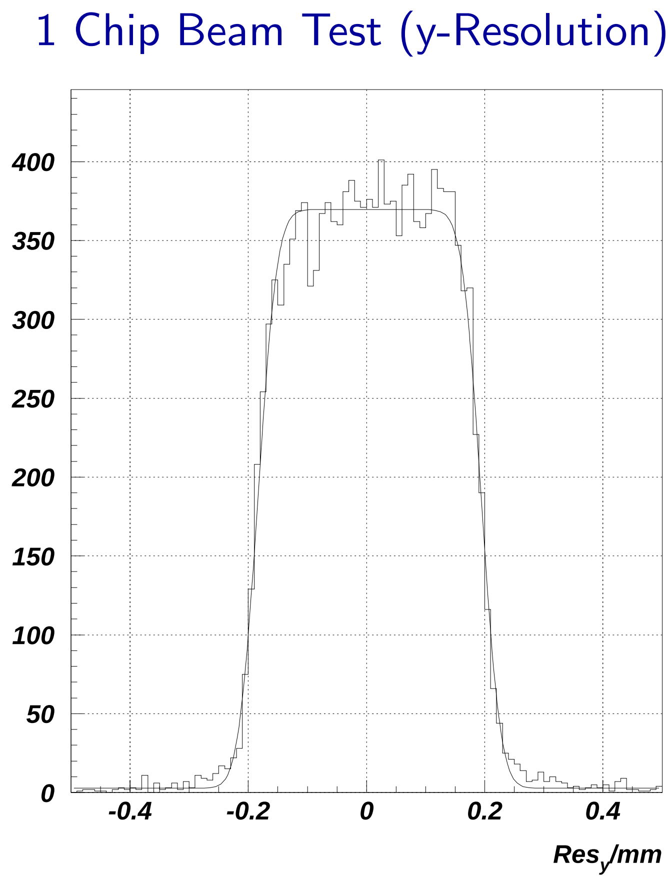
1 Chip Source Test (Cd109)



Cadmium 109 deposits $\approx 1600e$

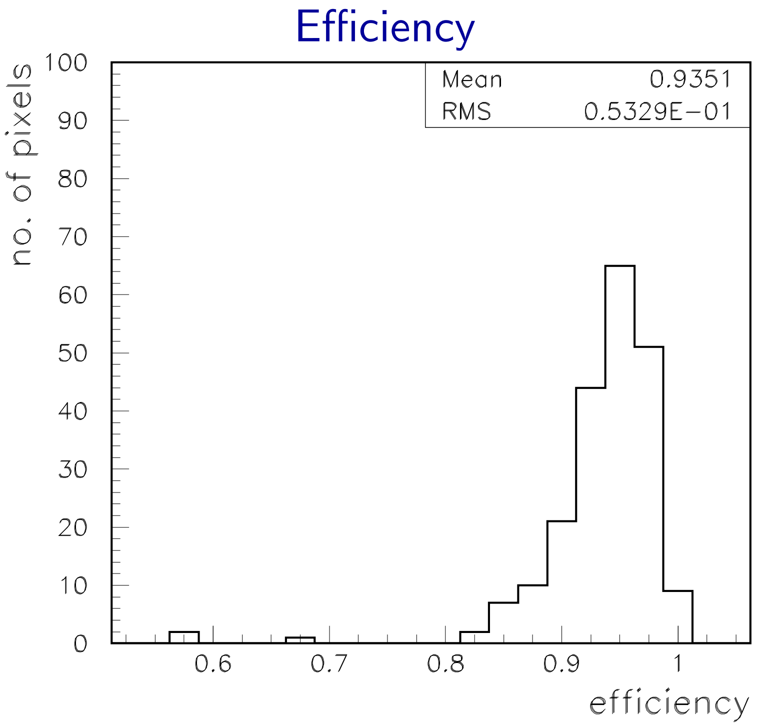
Results from a single chip ATLAS pixel detector

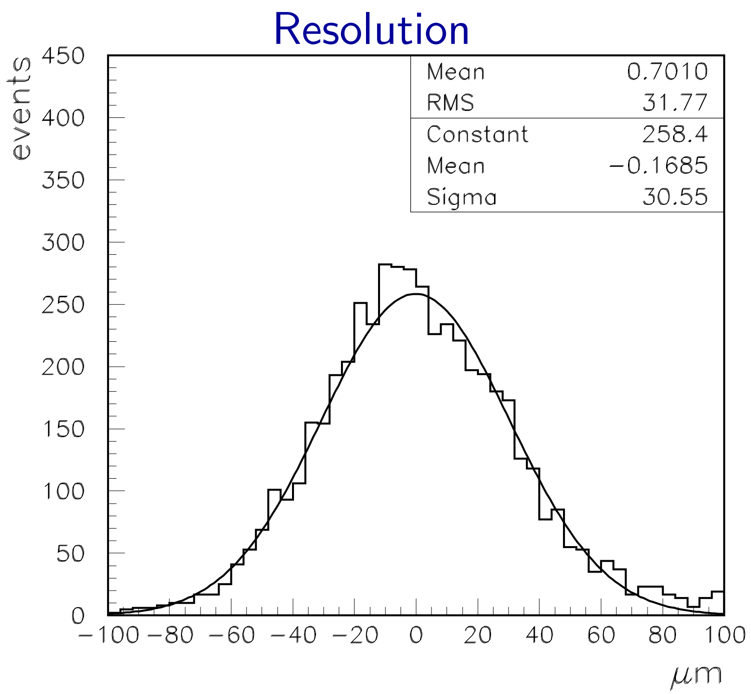




Pitch is 50μm $\times$ 400μm
Spatial Resolution 12μm; Efficiency 98%

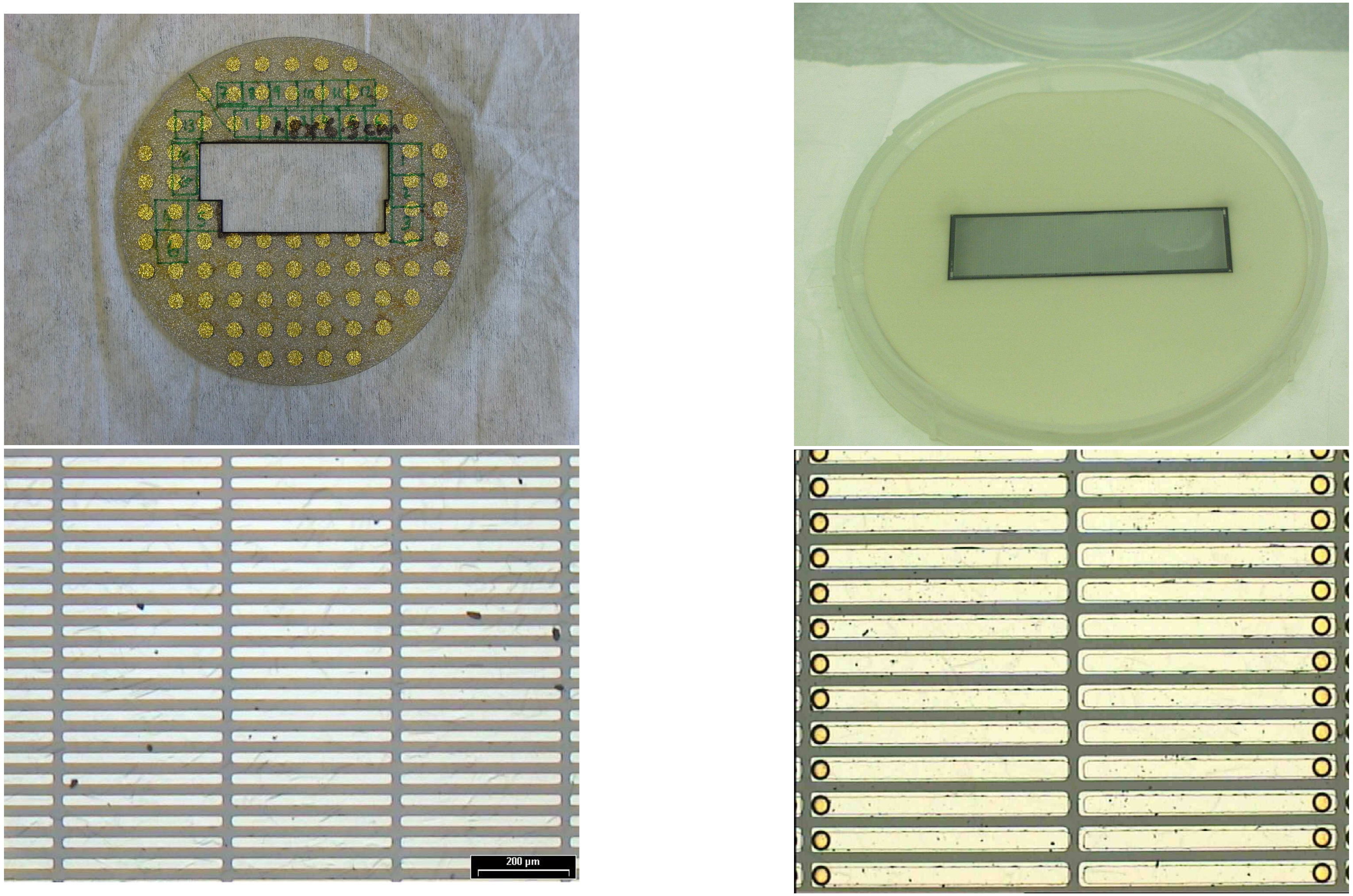
Results from a single chip CMS pixel detector





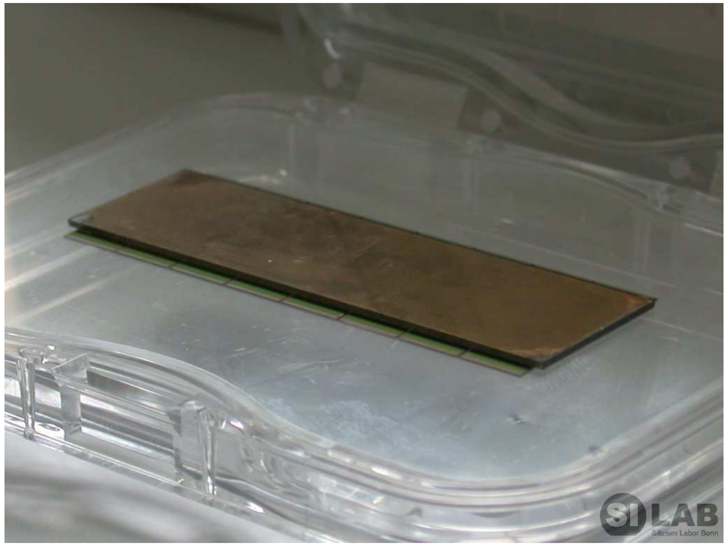
- Results with 200μm collection distance diamond
  - Efficiency $\sim$ 94%
  - Inefficient pixels due to bump bonding and/or electronics - shown in pulser tests
  - Spatial resolution $\sim$ 31μm for 125μm pitch

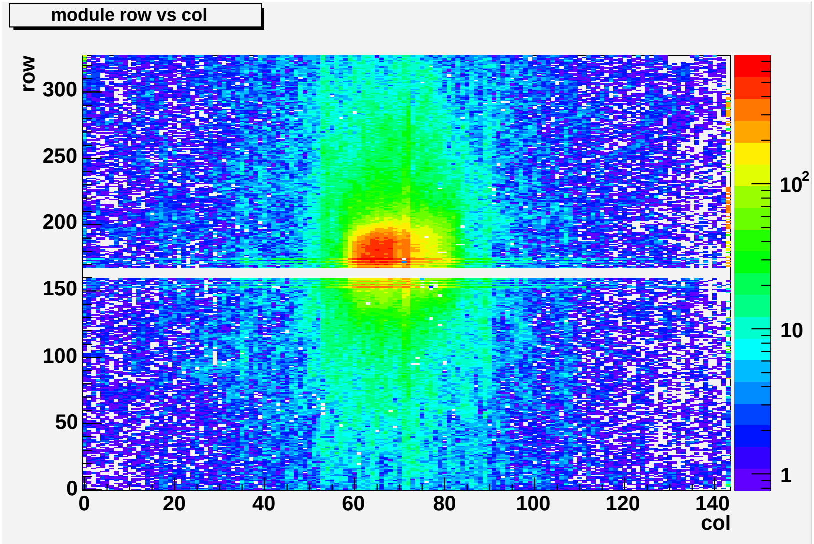
Constructing a Full ATLAS pixel module



Various stages of making a module

The Full 16 Chip ATLAS pixel module





The diamond ATLAS pixel module test was cut short. (Non-ATLAS R&D?)

Excellent first results for a 4 hr run.

Module is now being tested at DESY.

Radiation Monitoring - BaBar, Belle, CDF, ATLAS, CMS

Motivation:

→ Radiation monitoring crucial for Si operation/abort system of 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, CDF, CMS

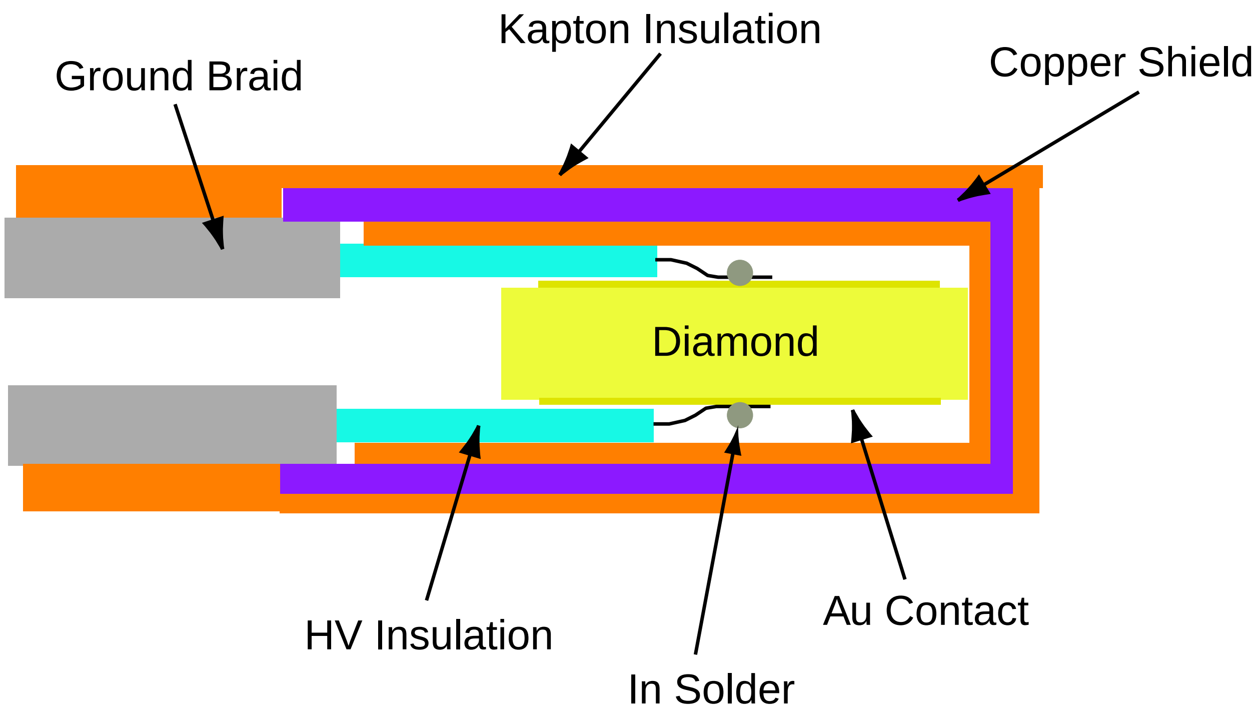
- Single Particle Counting
- Requires fast readout (GHz range)
- Requires low noise
- Allows timing correlations

- Example: ATLAS

The BaBar/Belle/CDF Diamond Radiation Monitor Prototypes:

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

Schematic View



The BaBar/Belle/CDF Diamond Radiation Monitor Prototypes:

→ BaBar/Belle/CDF presently use silicon PIN diodes

→ Leakage current increases 2nA/krad

→ Large effort to keep working, BaBar PIN diodes will not last past 2005

Photo of BaBar Prototype Device

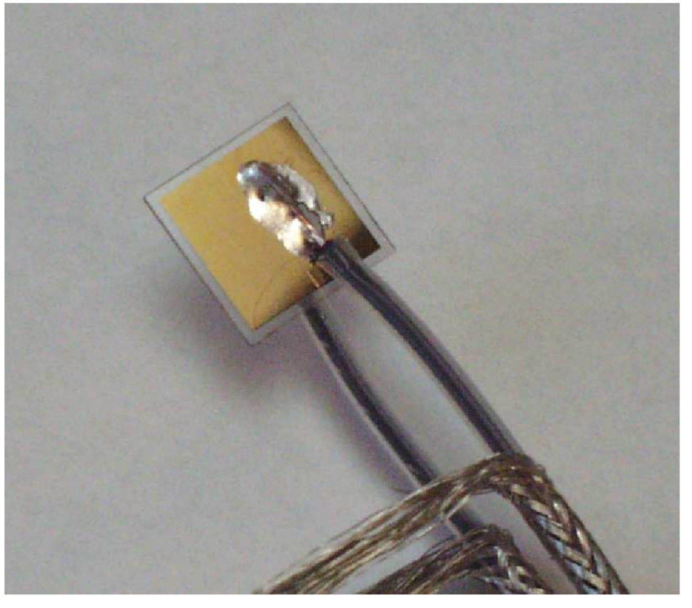
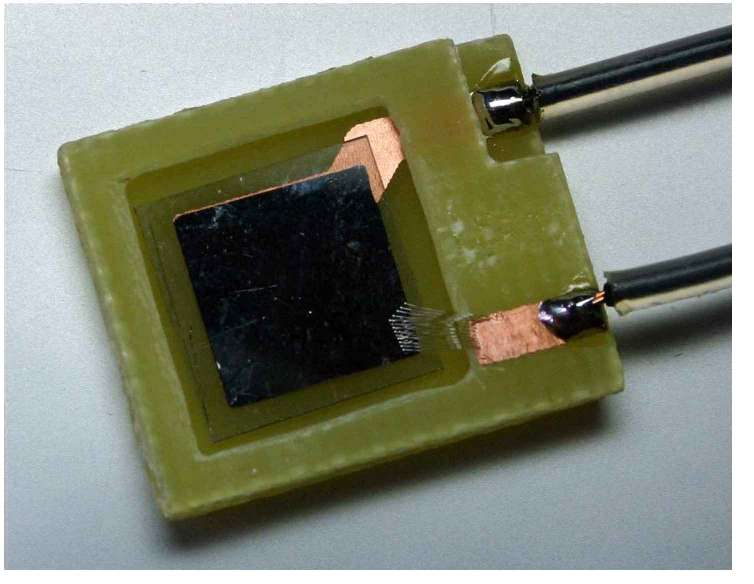
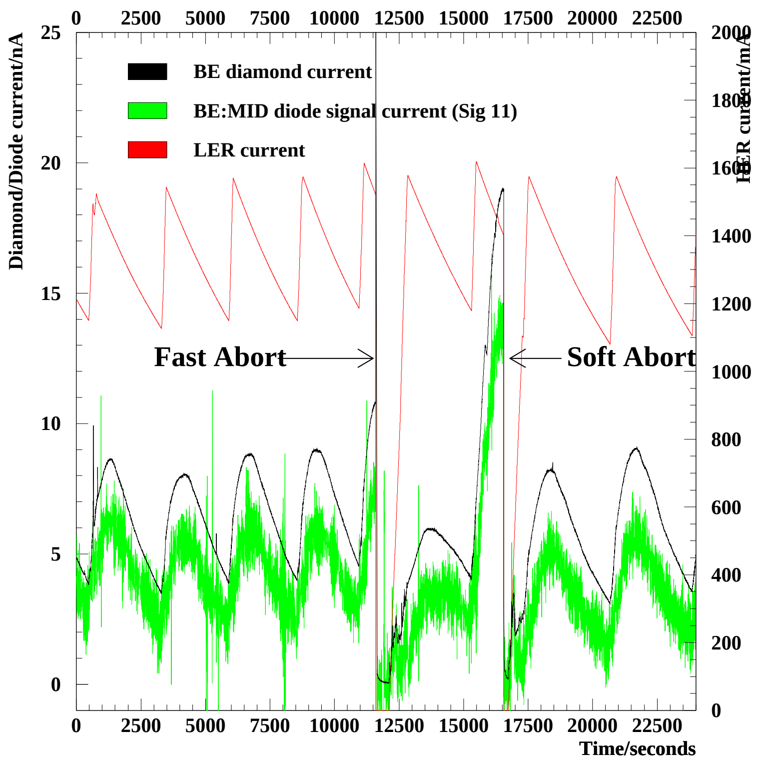


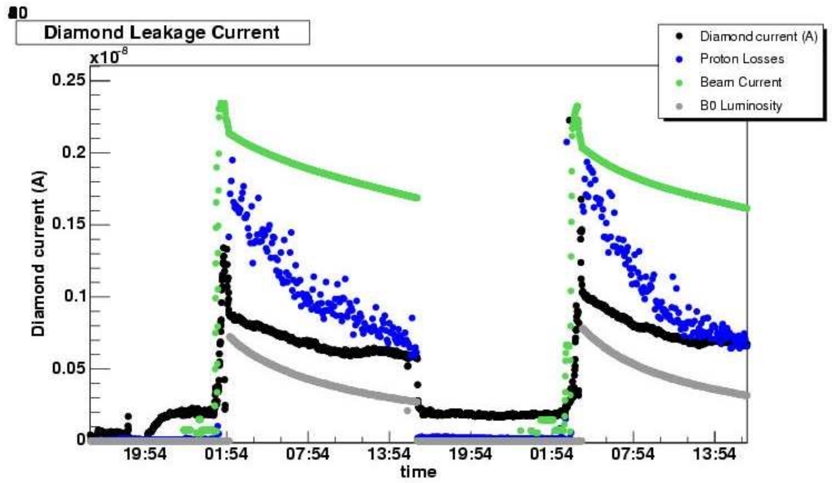
Photo of CDF Prototype Device



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

Data Taking in BaBar, CDF:





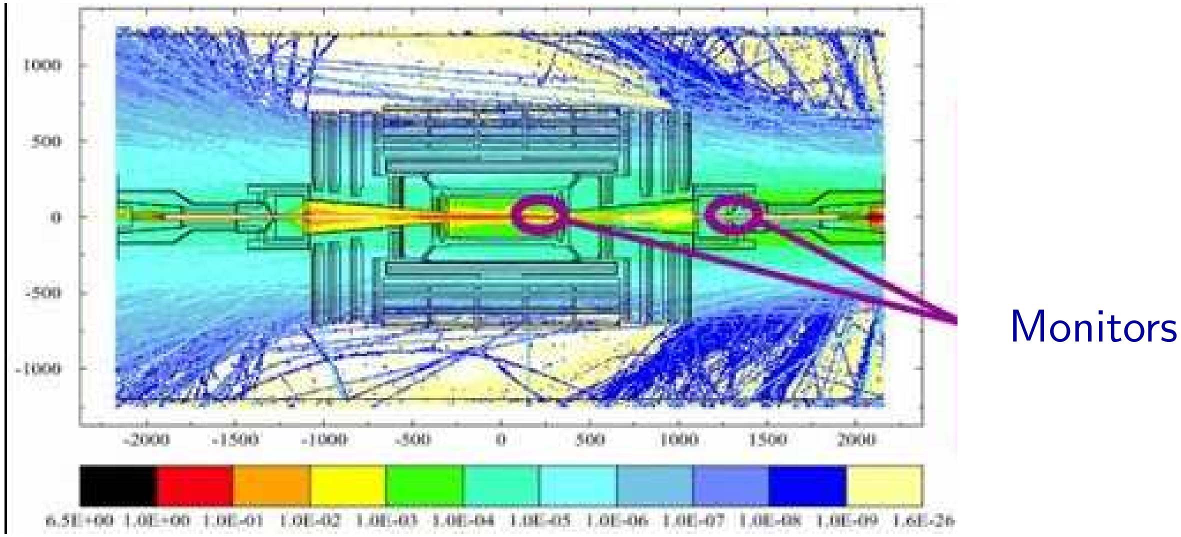
System operating for 18 months in BaBar and works well!
Installation of full system in Winter 2006

System operating for 1 month in CDF and works well!

The CMS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Successful 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:

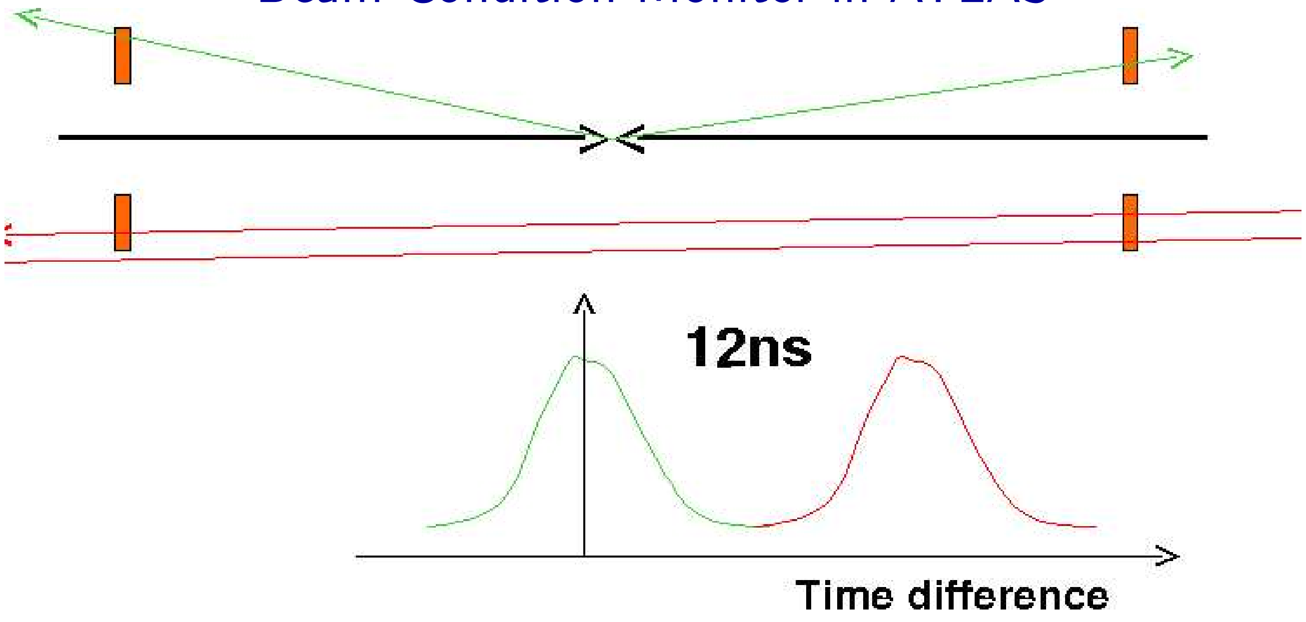
Simulation of a Beam Accident in CMS



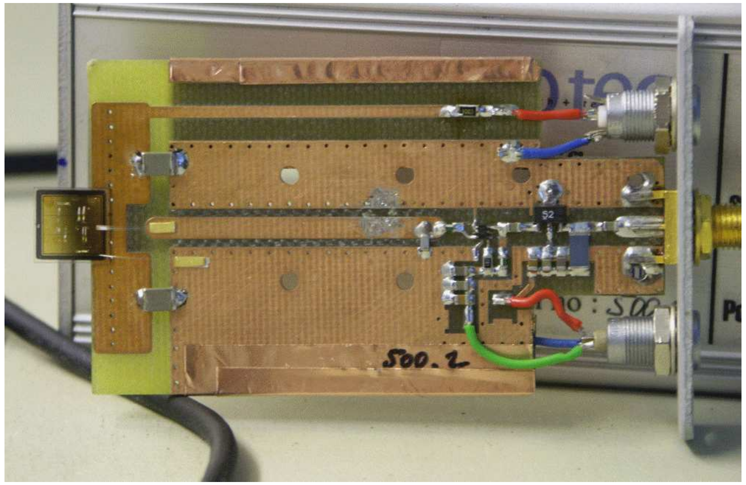
The ATLAS Diamond Radiation Monitor Program:

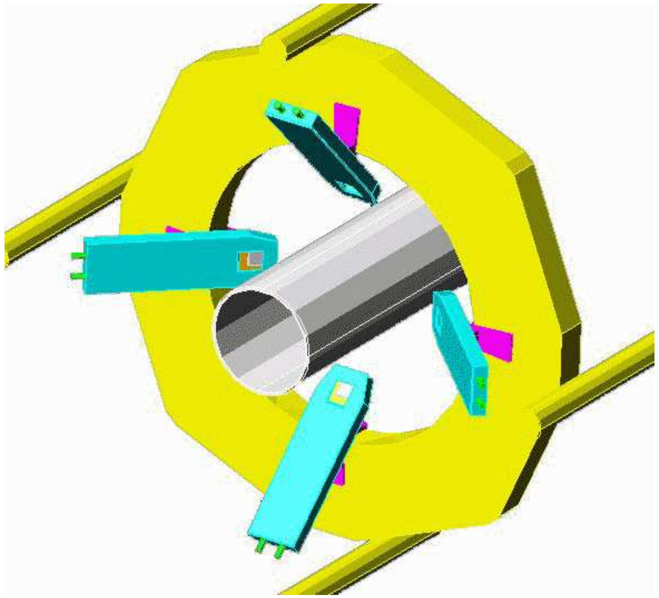
- Diamond activity has begun!
- Time of flight measurement to distinguish collisions from background
- Located behind pixel detector forward disks in pixel support tube
- Possible ATLAS scenario:

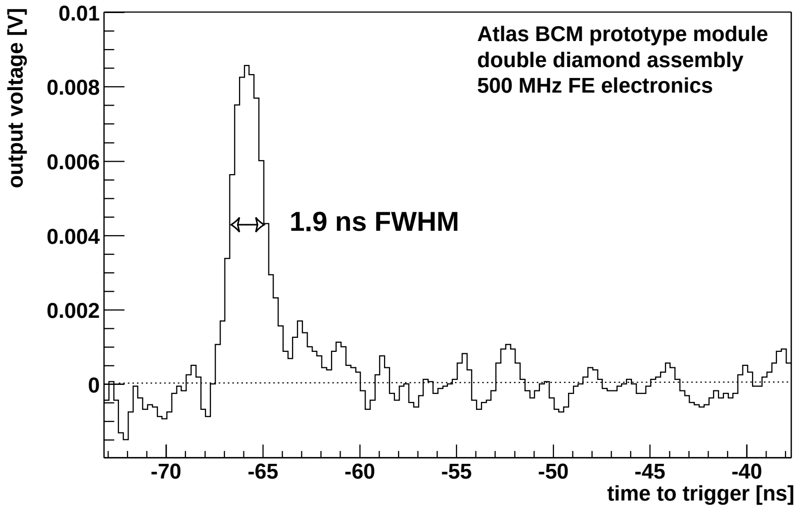
Beam Condition Monitor in ATLAS



The ATLAS Diamond Radiation Monitor Program:







- Use 2 diamonds to double S/N
- System meets all ATLAS specs
- System will be installed in Fall 05

Summary

- **Further Progress in Charge Collection**

  300 μm collection distance diamond attained in wafer growth

  FWHM/MP $\sim$ 0.95 – Working with manufacturers to increase uniformity

  This diamond process has been moved to production reactors

  Single Crystal diamonds look quite attractive

  Have scCVD research contract in operation until 2006

- **Radiation Hardness of Diamond Trackers**

  Using trackers allows a correlation between S/N and Resolution

  With Protons:

  - Dark current decreases with fluence
  - 15% loss of S/N at 2.2×10^{15}/cm^2, 25% signal at 20.0×10^{15}/cm^2
  - Resolution improves 35% at 2.2×10^{15}/cm^2

- **Diamond Pixel Detectors**

  Successfully constructed a complete ATLAS module

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

  Awaiting results on irradiated single chip devices

Summary

- **Beam Conditions Monitoring**

  Application of diamond successful in BaBar, CDF

  Successfully tested ATLAS and CMS BCM prototypes

  ◦ have met all of the ATLAS specs

  ATLAS diamond BCM installation in Fall 2005

Significant progress in the last year

- **RD42 Request to CERN/LHCC**

  RD42 is supported by many national agencies:

  → continuation of official recognition by CERN critical

  → 55kCHF from CERN/ 250kCHF from outside CERN

  RD42 requires access to CERN facilities:

  → maintain the present 20 m^2 of lab space (test setups, detector prep, ...)

  → maintain present office space

Proposed Research for RD42

- **Charge Collection**

  Continue research program to improve material in progress:
  - collection distance → 325μm ($\bar{Q} = 11,700e$)
  - → improved uniformity
  - → identification of trapping centers
  - compare scCVD with pCVD

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

  Continue tracker irradiations in the next year, add pixel irradiations

  With protons, pions, neutrons

  Use pCVD and scCVD

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

  Complete test of the first full ATLAS diamond pixel module

- **Beam Condition Monitors**

  Continue development of BCM's, work with ATLAS group to complete its BCM

- **Material Research**

  → CERN, Florence, OSU, Rome