CVD Diamond Radiation Sensors For Application In Very High Radiation Environments

Seminar presented at University of Geneva

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RD42 Collaboration: 28 institutes on joined development of CVD diamond detectors

http://rd42.web.cern.ch/rd42/

Industrial Partner:
Element Six Ltd

H. Murphy, D. Twitchen, A. Whitehead
(Element Six, UK)

RD42 Collaboration:

Goal: Development of Diamond as a Detector Material

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Institutes from HEP, Heavy Ion Physics, Hadron Therapy Centers and Solid State Physics

Still growing: new groups joined in 2004 and 2005

Desy-Zeuthen, Ioffe Institute St. Petersburg, Fachhochschule fuer Technik, Vienna, ITEP Moscow

IN THIS TALK I WILL PRESENT AN OVERVIEW AND SOME RECENT RESULTS

Content of this presentation:

1. INTRODUCTION AND SOME BASIC FACTS ON CVD DIAMOND
2. POLYCRYSTALLINE CVD DIAMOND (pCVD)
   - Charge Collection, Results from Irradiations, Applications: the ATLAS Pixel Module, Beam diagnostics and Monitoring with Diamonds
3. SINGLE CRYSTAL CVD DIAMONDS (sCVD)
   - Charge Collection, Charge Carrier Properties via TCT

Introduction

Attraction of Semiconductor Sensors for Radiation Detection and for Tracking

For modern detectors in particle physics (and in particular close to the interactions region of colliders) detectors need to …

❖Have fast signals and be able to tolerate high rates
- High drift velocity and short drift path

❖Ionization is localized and can achieve very high segmentation

❖Are free standing with an absolute minimum of “dead” material

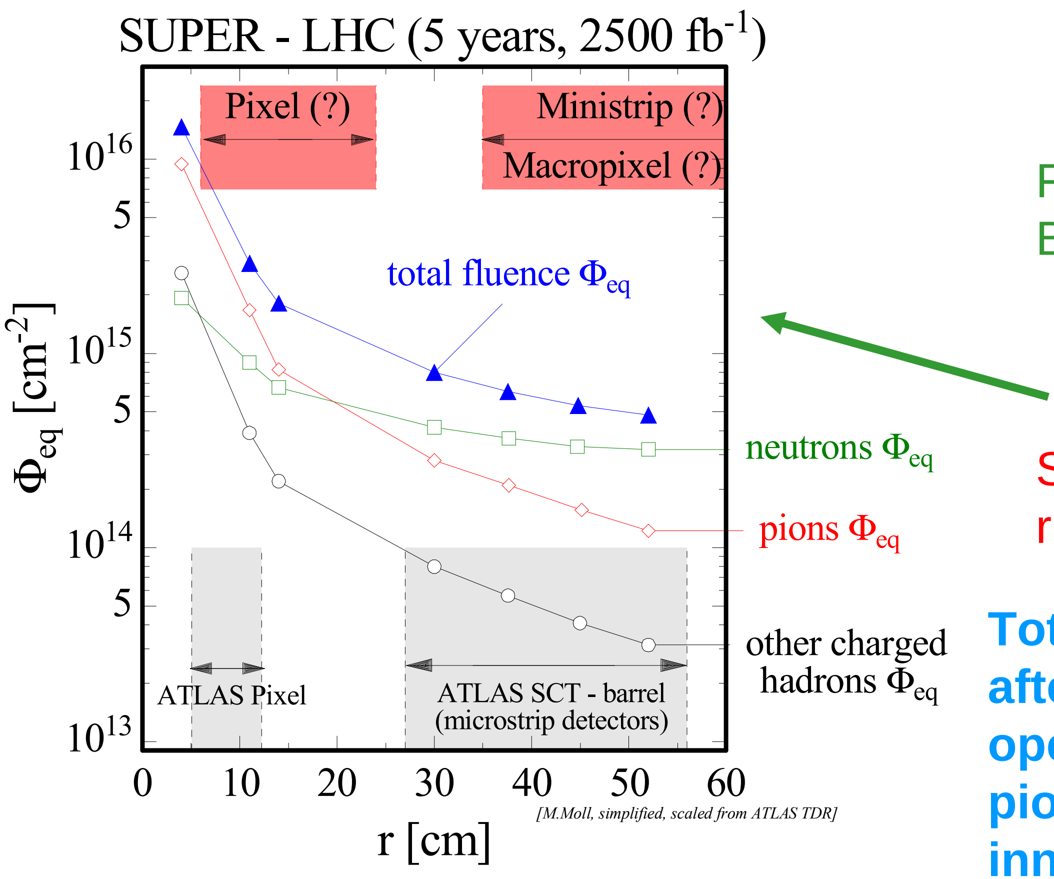
❖Are relatively radiation hard and easy to operate
- to survive many years of operation without access or replacement: in colliders, in space,….

The central tracking detectors of present and future collider facilities use nearly only semi-conductor detectors (Silicon)
Many astrophysics detectors in orbit have silicon trackers: GLAST, AMS,…

Challenge for future detectors: Development of Radiation Detectors for Future Hadron and Linear Colliders which can survive long enough severe radiation environments without bad performance deterioration.

What do we expect:

What are the radiation environments to be expected after initial LHC running: SEVERE!!



From M. Moll Pixel2005 Bonn

Scenario for 5 years running SLHC

Total fluence expected after 5 years of operation: ~ 10^{16} pions/cm^2 at the innermost radius of LHC interaction regions

Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to 10^{35} $cm^{-2}s^{-1}$ ("Super-LHC").

Challenges:

- **Radiation hardness up to 10^{16} cm^{-2} required**
- **Fast signal collection** (Going from 25ns to 10 ns bunch crossing ?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

For silicon detectors and other materials (except diamond) this is done in **RD39** and **RD50**.

One way to go: Make Silicon Detectors more radiation-hard :

Main adverse effects in Si after irradiation:

1. Bulk (Crystal) damage due to Non Ionizing Energy Loss ("NIEL"): **displacement damage, built up of crystal defects –**

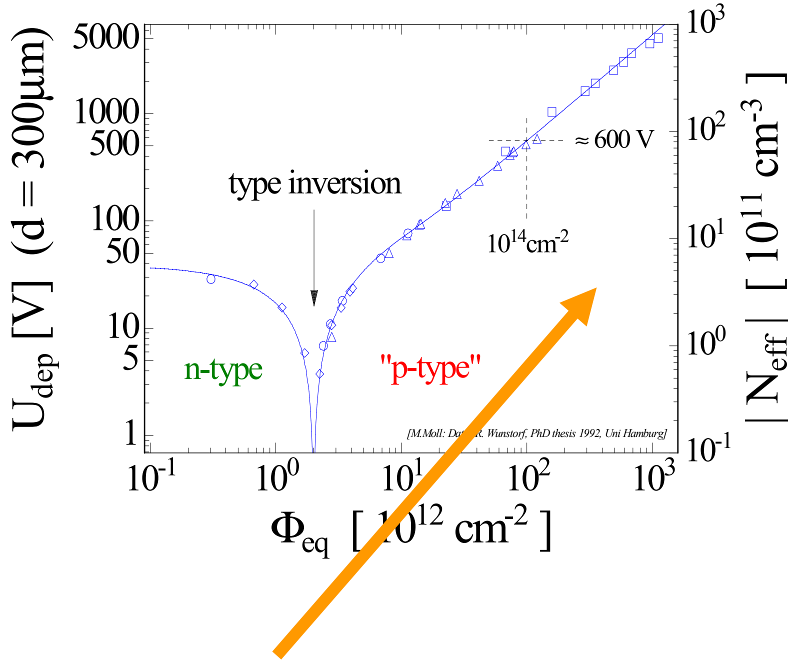
- Change of **effective doping concentration (higher depletion voltage, under- depletion)**
- Increase of **leakage current (increase of shot noise, thermal runaway)**
- Increase of **charge carrier trapping (loss of charge)**

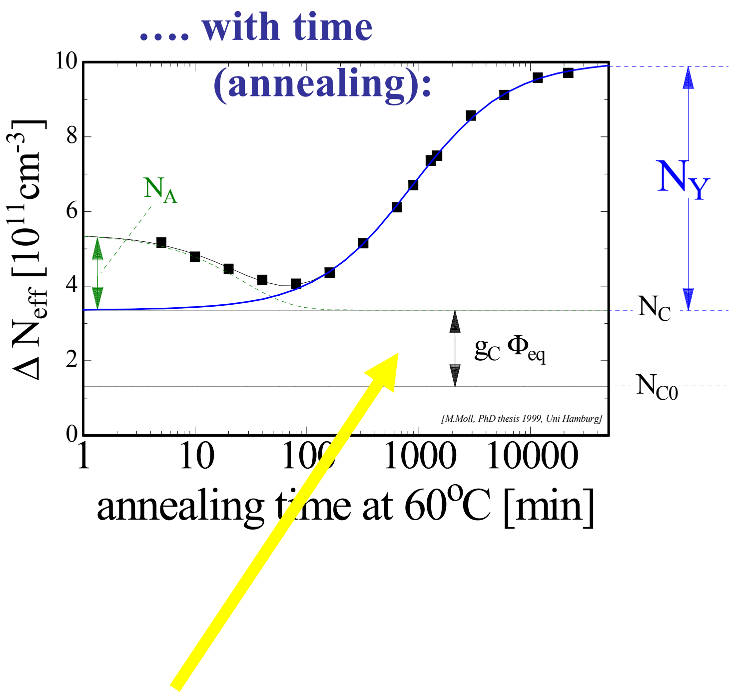
2. **Surface damage due to Ionizing Energy Loss (IEL)**

- **accumulation of positive charge in the oxide (SiO_2) and the Si/SiO_2 interface –**

affects: interstrip capacitance (noise factor), breakdown behavior, …

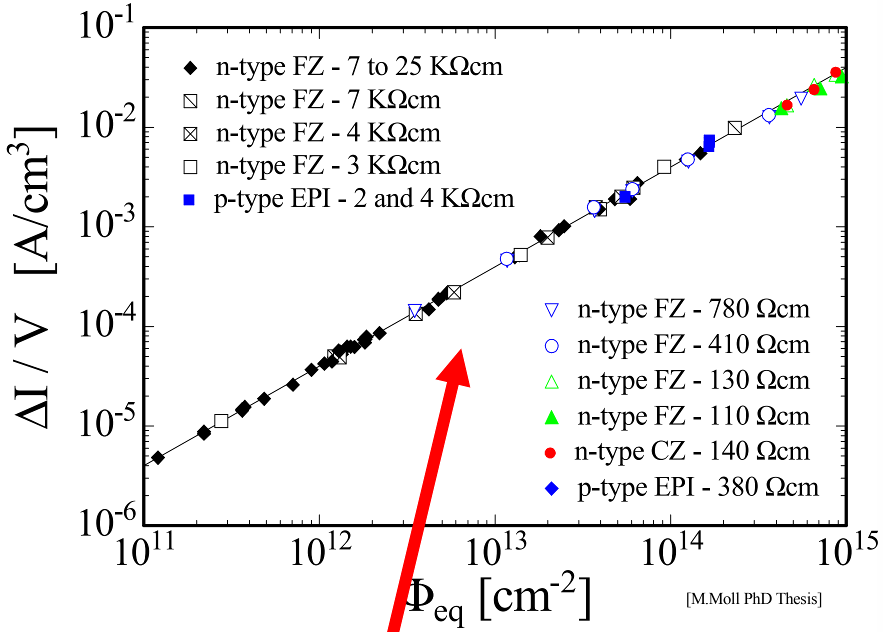
What happens in physical terms to a silicon detector (equivalently to other semiconductor detectors) which stays for a long time in an high radiation environment:





The effective doping concentration (n-) changes and eventually becomes p-doping (type inversion) ➔ increasing voltage of full depletion

Moreover: this process goes on with time when irradiation stopped



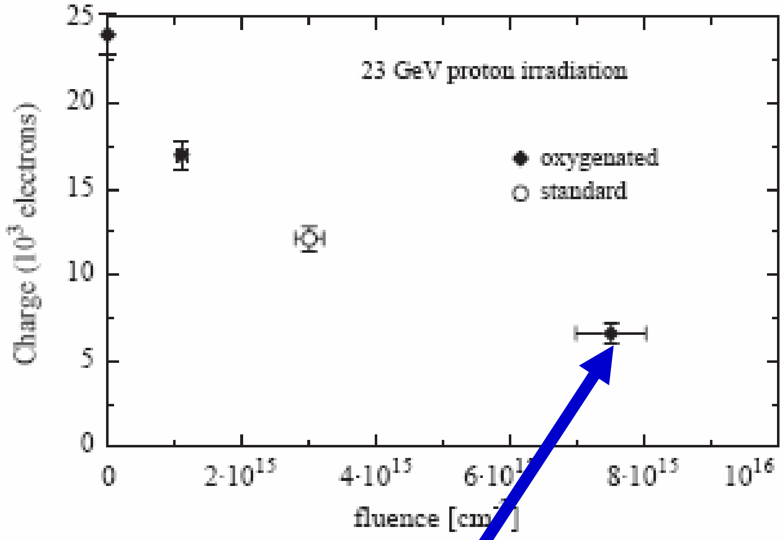


Fig. 2. Collected charge as a function of the 23 GeV proton fluence for standard and oxygenated n-in-p miniature micro-strip detectors (source: Ru106, chip: SCT128A-40 MHz, 800–900 V applied to irradiated devices, measured at −20 °C) [25].

The leakage current goes up by orders of magnitude with a total fluence of 10^{15} cm^{-2}

Charge trapping energy levels inside the band gap are created which eat up the electron hole pairs when drifting across the detector before they can be fully collected ➔ 70% charge loss at 8 10^{15}

Remedies for Silicon:

Material engineering

Device engineering

Change of detector operational conditions

Maybe new materials:

4H-SiC, 6H-SiC, GaN, GaAs, CZT, a-Si(H), ….CVD Diamond

So far lots of progress to improve radiation hardness of Si based sensors

However to get enough charge after irradiation and not to have the signal dominated by noise: quite extreme running conditions required (in Silicon case):

Low temperatures, very high bias voltage,…….

In this situation it is interesting to study CVD diamond as a detector material; at least for the areas with the highest integrated radiation fluxes

Basic material constants of CVD diamond in comparison

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

New Results on this ...

Important Properties of CVD diamond for Tracking:

GOOD

Both electron and hole mobilities are high, signal collection fast
At E = 1 V/µm high → Diamond v_d= 1.67 x 10^7 cm/sec
Drift velocities v_d → Silicon v_d = 3.8 0 x 10^6 cm/sec

Load capacitances of sensor 2.1 times lower than for Si (lower dielectric constant epsilon)

Diamond has 1.3 times less radiation length compared with Si

"Good" CVD Diamond is an insulator (high band gap) with resistivity greater than 10^{14} Ωcm.
Leakage current: I_{leak} ~ 1 -10 pA/squcm for a 500µm thick sample.

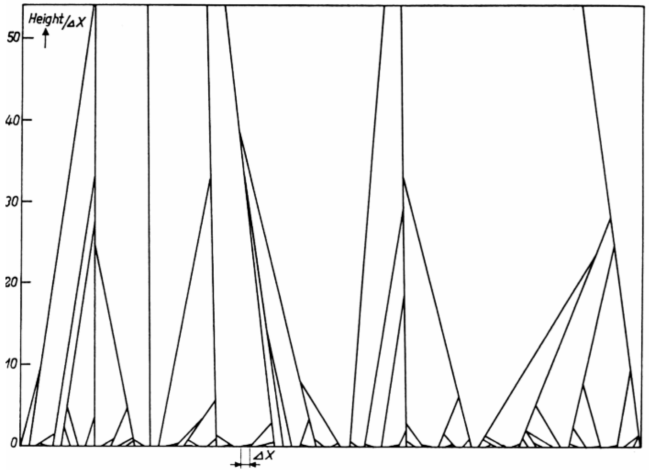
→ Low load capacitances are limiting electronic noise

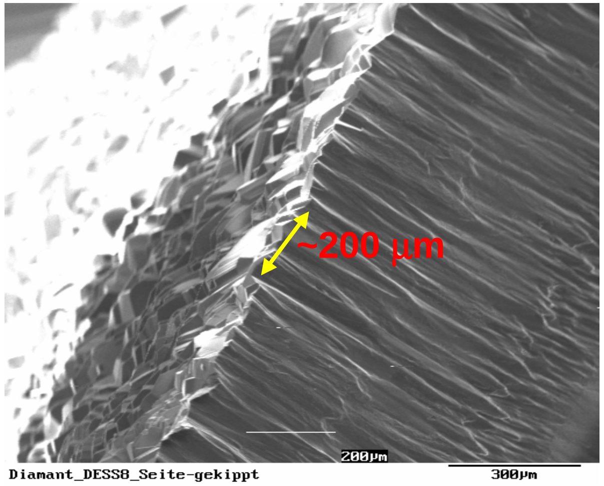
NOT SO GOOD, but maybe possible to live with

The **generated charge** in diamond is **3600** electron- hole pairs per 100 μm compared with **10600** electron hole pairs in Si.
Slightly more favorable when one compares **generated charge per .3% of radiation length (typical silicon sensor thickness)**:

Diamond:	~13900 mean charges	in 361 μm
Silicon:	~26800 mean charges	in 282 μm

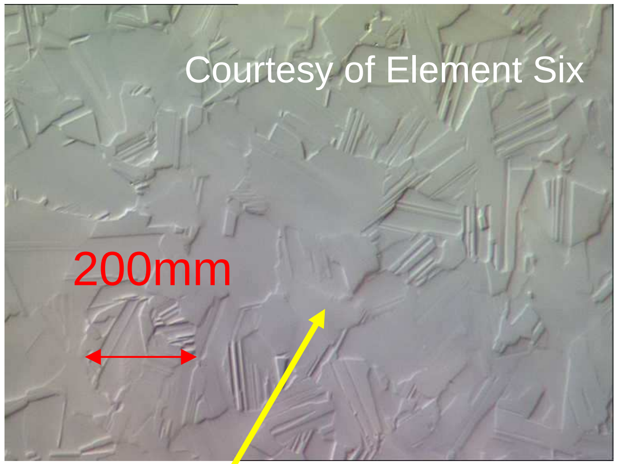
Lifetime of both holes and electrons is smaller than the transit time at 1V/μm (in un-irradiated silicon lifetime is 10's of ms): signal loss in bulk by trapping in non-irradiated material





The Material: single crystals a few micron across at substrate side up to a few 100 µm across on top of growth side (~500 to 800 µm thick)

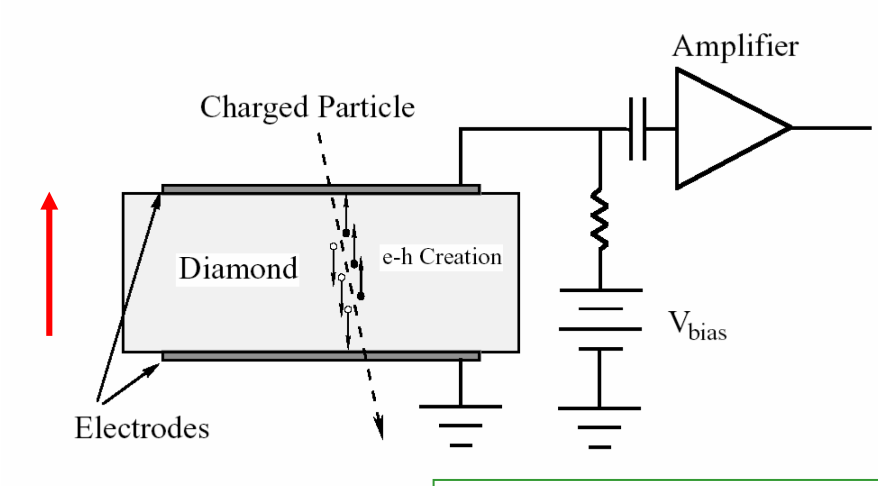
Deposited by Chemical Vapor Deposition in Microwave plasma



Polished growth side

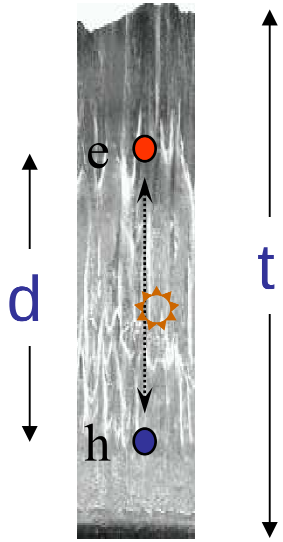
Charge Collection and Radiation Hardness of pCVD Diamond

Principle of detector operation



Electric field

Growth-Side



Substrate-Side

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

$$d = \mu E \tau$$ "collection distance"

$$\varepsilon = Q / Q_0$$ collection efficiency

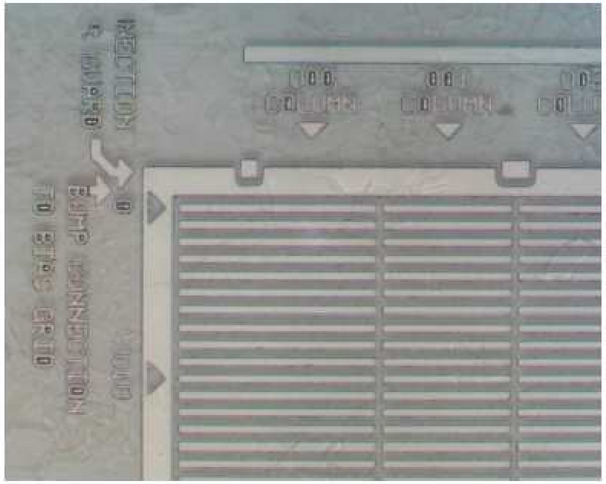
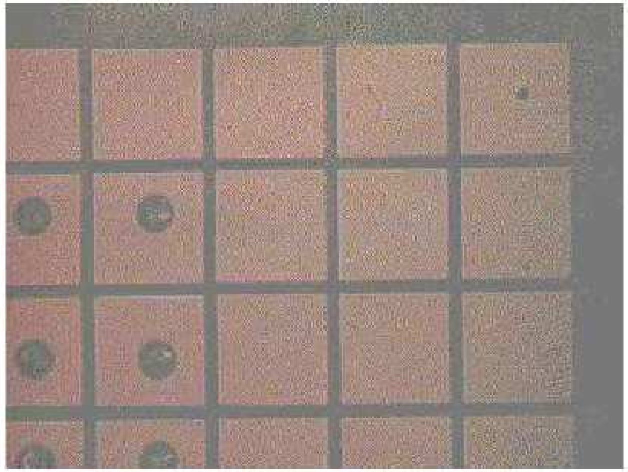
μ and τ are "effective" mobility and lifetime

$$\mu = \mu_e + \mu_h$$

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

Examples of Detectors made in RD42

•Diamond Pixel Detectors for ATLAS and CMS

ATLAS FE/I Pixels (Al)	CMS Pixels (Ti-W)
	

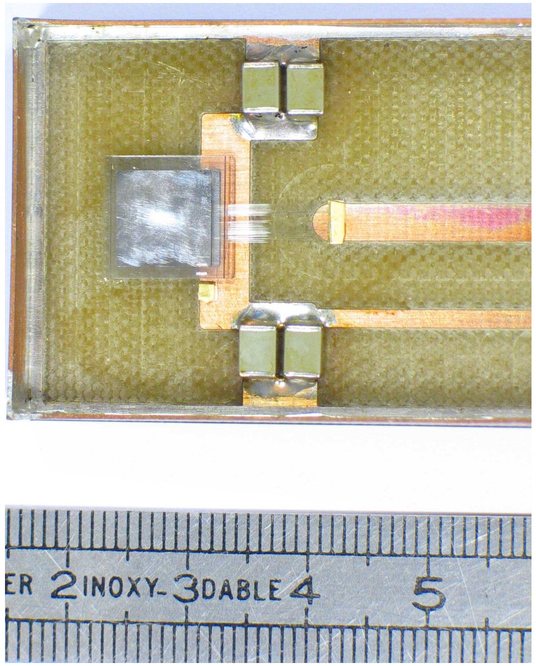
- ✦ Atlas pixel pitch $50\mu m \times 400\mu m$
- ✦ Over Metalisation: Al
- ✦ Lead-tin solder bumping at IZM in Berlin

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

→ Bump bonding yield ≈ 100 % for both ATLAS and CMS devices

New radiation hard chips produced this year.

Diodes for ATLAS Beam Conditioning Monitor

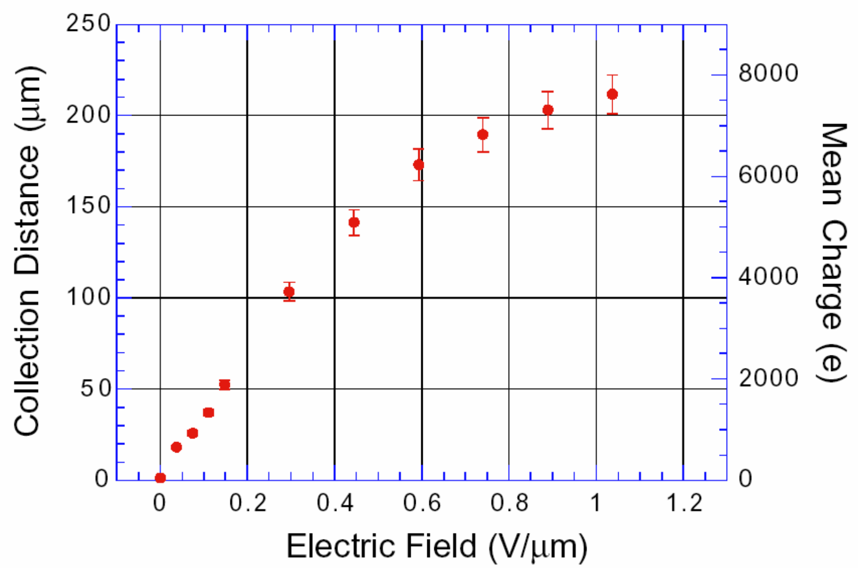


Charge Signal versus applied Field

Saturation above 1 V/mm.

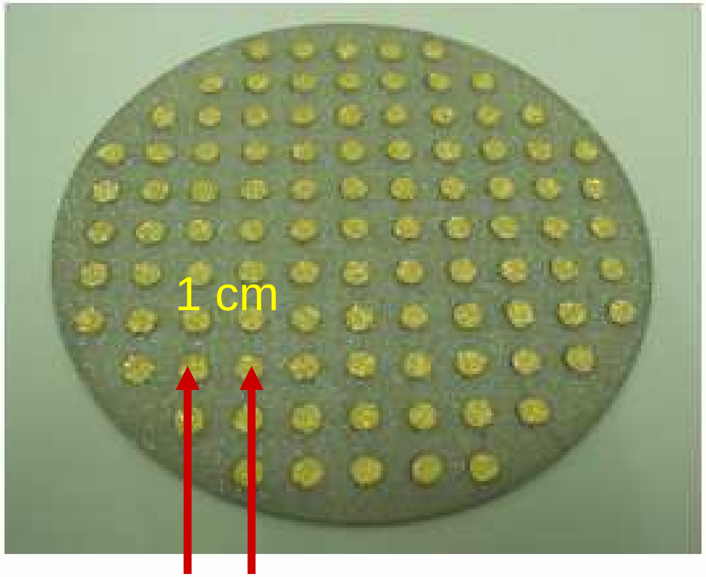
Shape governed by mobility μ(E) dependence.

Metallization typically
is a carbide former plus over-metal like
Cr/Au
Ti/Au
Ti/Pt/Au
Ti/W
New better process used recently: Non carbide former
Results are very regular

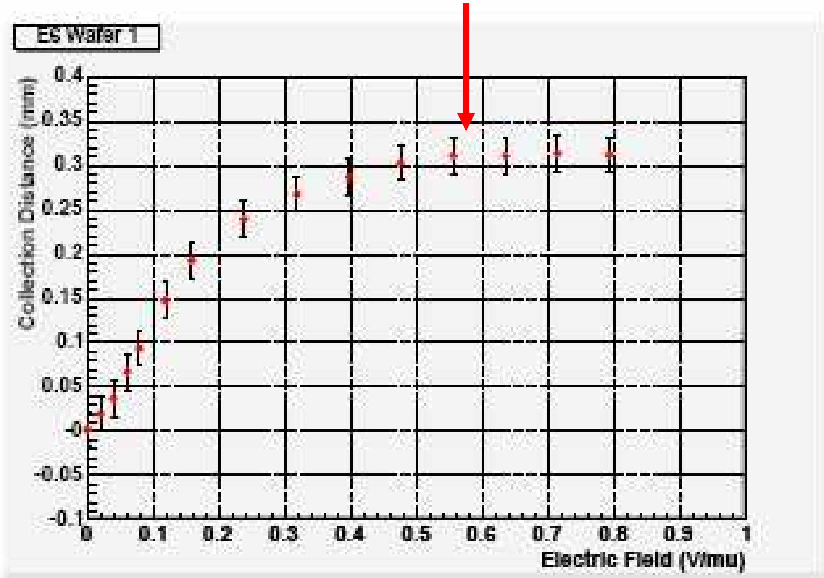


A particular effect is "priming" in pCVD diamonds: When a sample is first biased with a e. g. field of 1 V/micron and with radiation impinging the collected charge will increase with time in average by ~60% after 30 to 60 mins

Recent polycrystalline CVD (pCVD) diamond.



Approaching saturation velocity



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

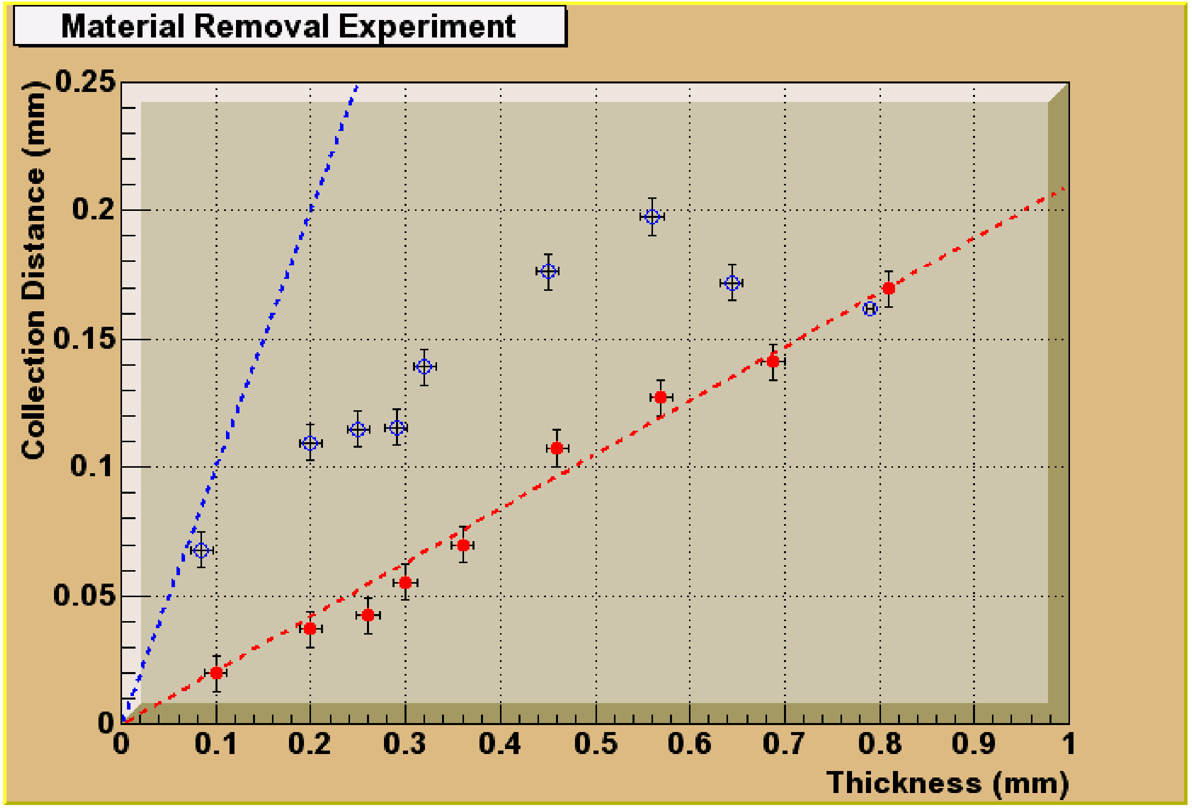
Wafers can be grown >12 cm diameter, >2 mm thickness.

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

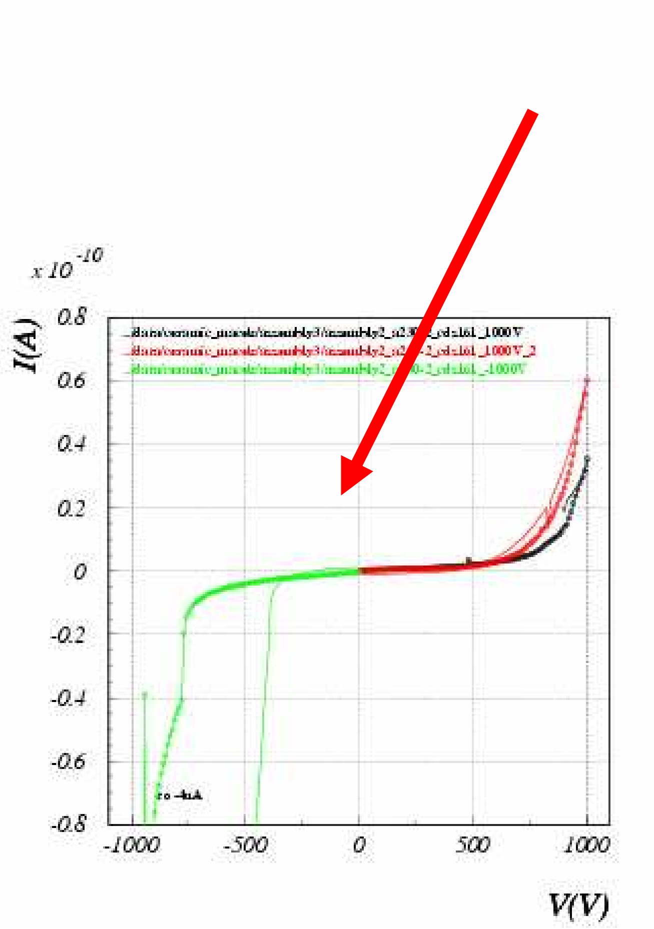
Collection Distance

	-5	-4	-3	-2	-1	0	1	2	3	4	5
5				295	283	214	270	255			
4			1	279	285	290	259	275	208		
3		276	287	305	252	274	262	275	205	249	
2	272	276	285	294	209	272	277	235	280	226	175
1	262	205	214	282	283	281	280	248	234	266	271
0	255	282	291	278	238	1	253	257	291	291	277
-1	226	262	154	264	213	255	266	276	272	281	286
-2	232	246	265	240	252	255	256	240	266	271	256
-3		261	264	219	187	244	199	227	228	251	
-4			253	239	216	222	210	273	202		
-5				195	125	179	196	117			

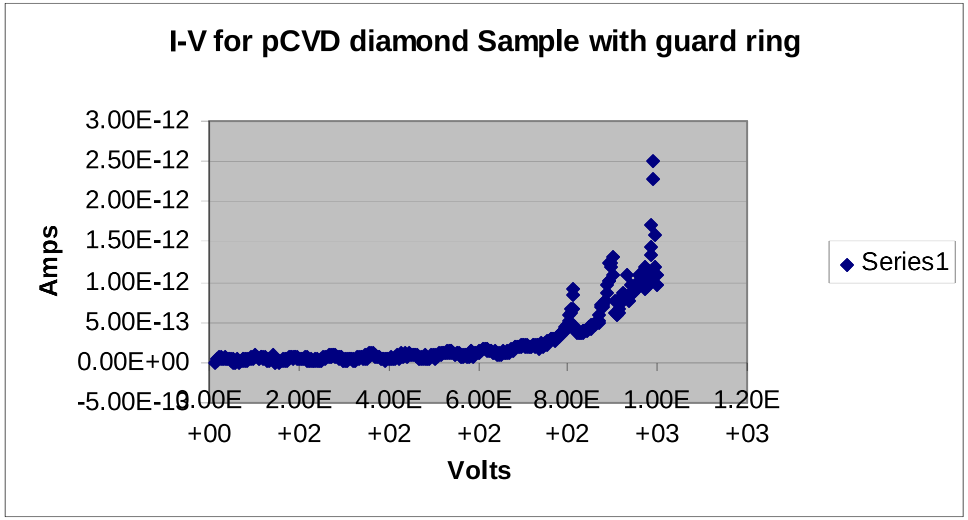
Thinning Experiment



Leakage Current in pCVD Diamonds for ATLAS Beam Monitoring System

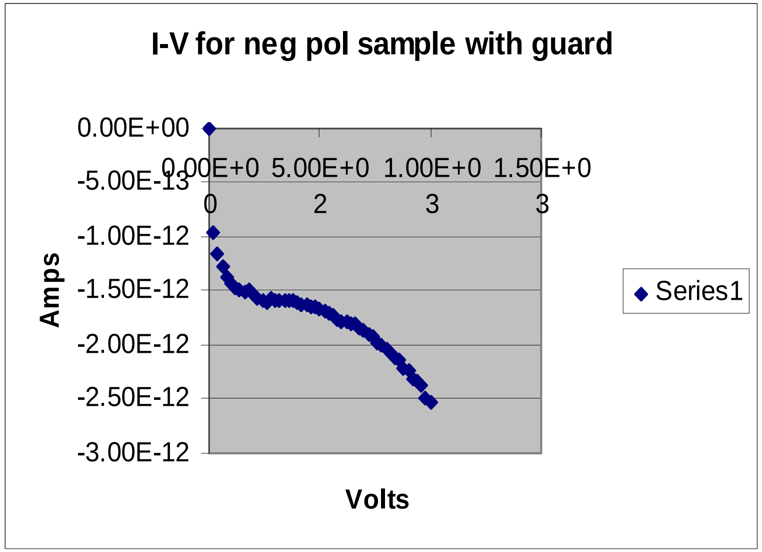


Leakage currents in 1/10 pA region up to +- 500 V (No guard ring on this devices)



Leakage current for a very recent pCVD Diamond samples with Guard ring around dot

Positive Polarity



Leakage current for pCVD Diamond samples with Guard ring around dot Negative Polarity

Radiation Hardness Measurements

Summary on Irradiation Studies done over last few years

Studied with Protons, Neutrons and Pions on pCVD Strip Detectors

Fluences of 2-3 10^{15} particles/cm^2

Generally decrease of leakage current with dose observed.

Resolution of Strip detectors gets better with fluence.

300 MeV Pions damage more than 27 GeV protons.

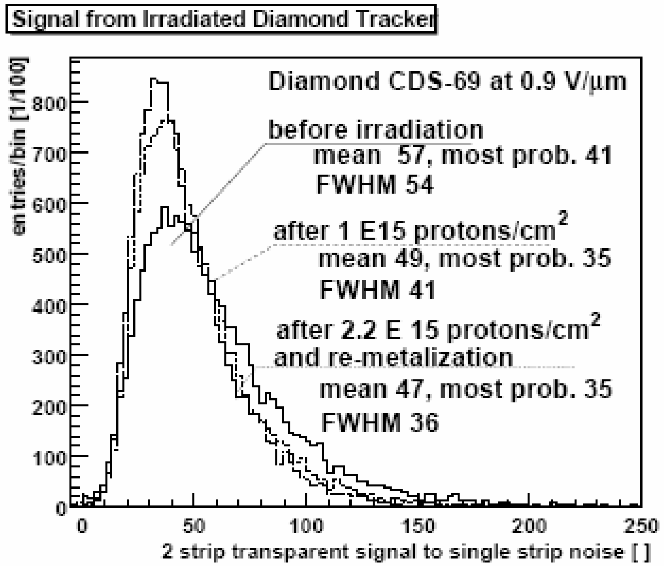
- ➔50% loss of S/N at 2.9 x 10^{15} pions/cm^2.
- ➔15% loss of S/N at 2.2 x 10^{15} protons/cm^2

No loss seen for EM radiation up to 10MGy.
(Behnke et al., Nucl.Instrum.Meth. A489 (2002) 230-240.)

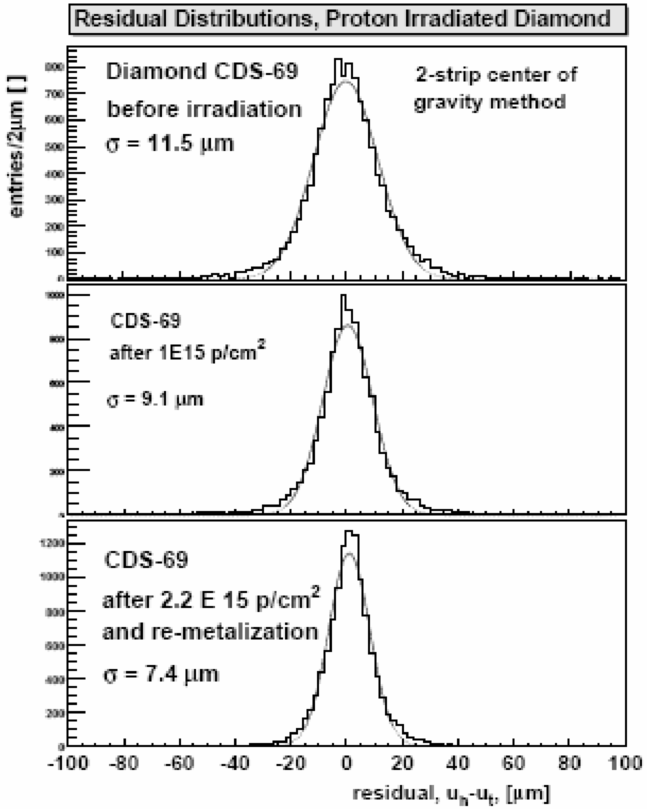
Sample CDS-69 had originally ~ 160μm ccd, 520 μm thick

Proton Irradiation - previously:

Signal to Noise



Resolution



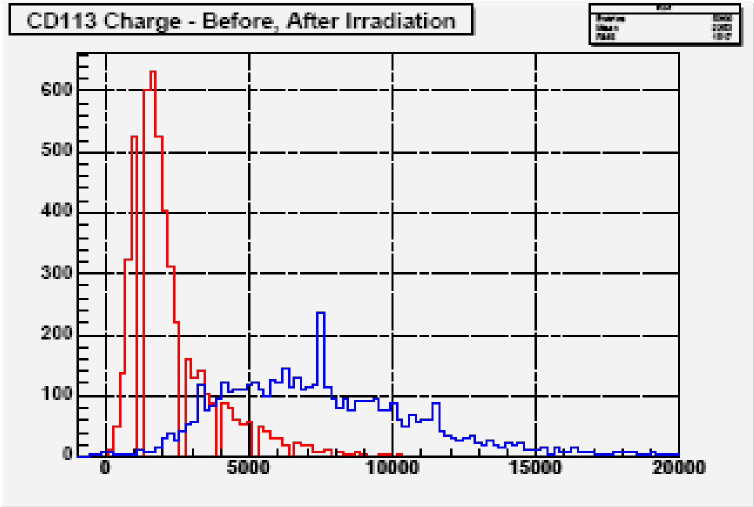
- Data taken over a period of 2 years
- Dark current decreases with fluence
- 15% loss of S/N at $2.2 \times 10^{15}/cm^2$
- Resolution improves 35% at $2.2 \times 10^{15}/cm^2$

Irradiation with protons up to ~2 x 10^{16} !

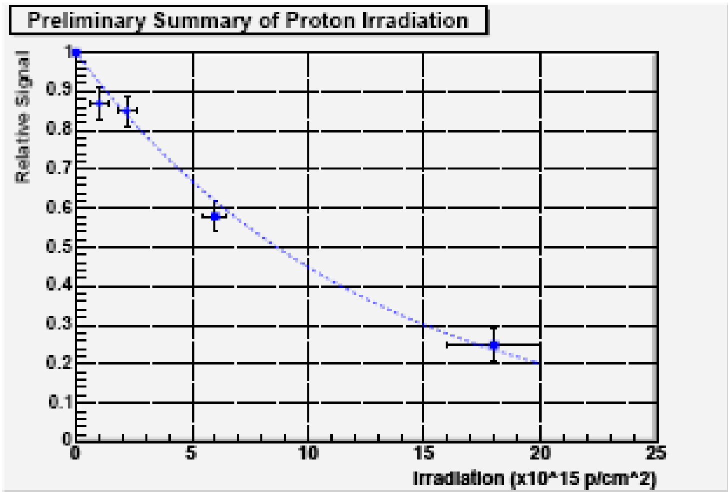
Sample: t = 490 μm, ccd = 225μm

Proton Irradiation - new:

Pulse Height



Sumary

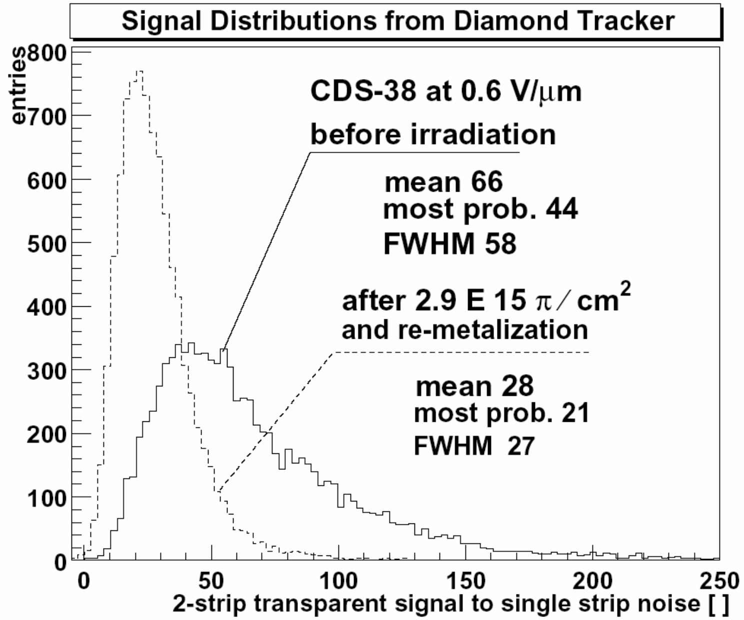


Left: Pulse height distributions before (blue curve) and after (red curve) the irradiation to 18×10^{15} p/cm^2 (~500Mrad)

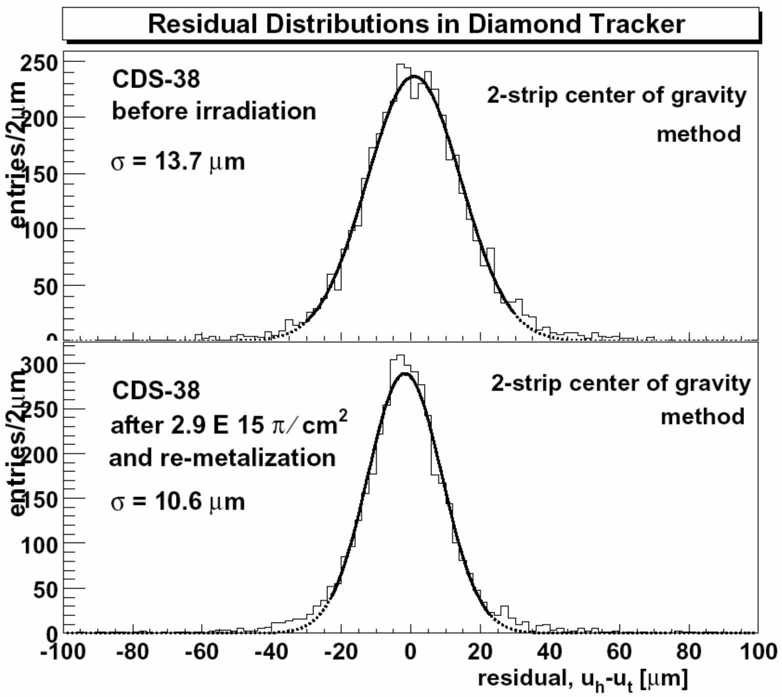
Right: Summary of proton irradiation results for pCVD diamond at fixed V

Results from Irradiations with pions

Landau Distribution before and after irradiation



Spatial Resolution



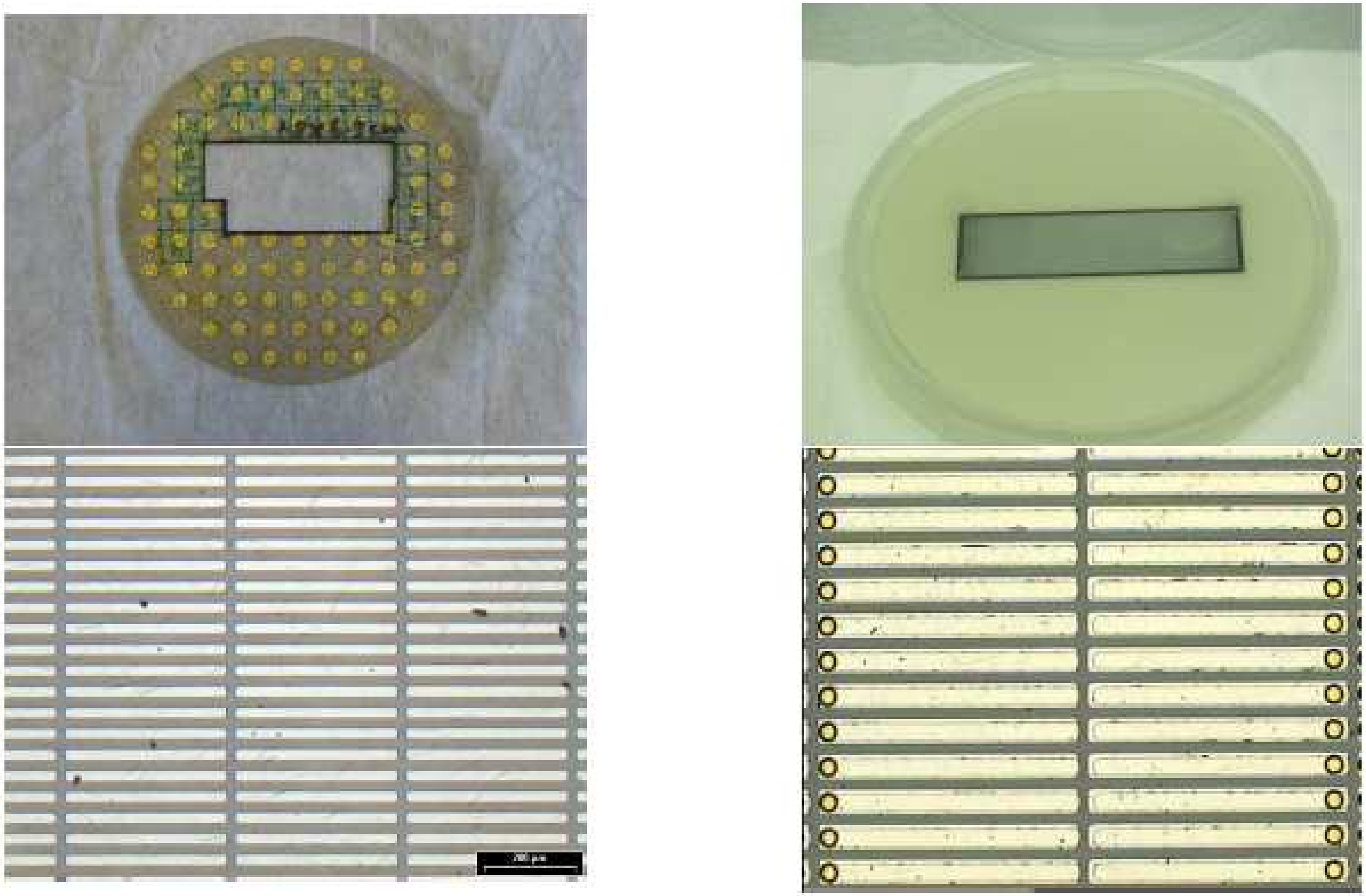
52% loss of S/N at 2.9 1015 p/cm2

Some Applications

A full ATLAS Pixel Module with pCVD Diamond

Most of this done by the Bonn Pixel group in RD42:
M. Mathes, F.Huegging, J. Weingarten, N Wermes
and H. Kagan (OSU)

Constructing a full ATLAS Diamond Pixel Module - new:



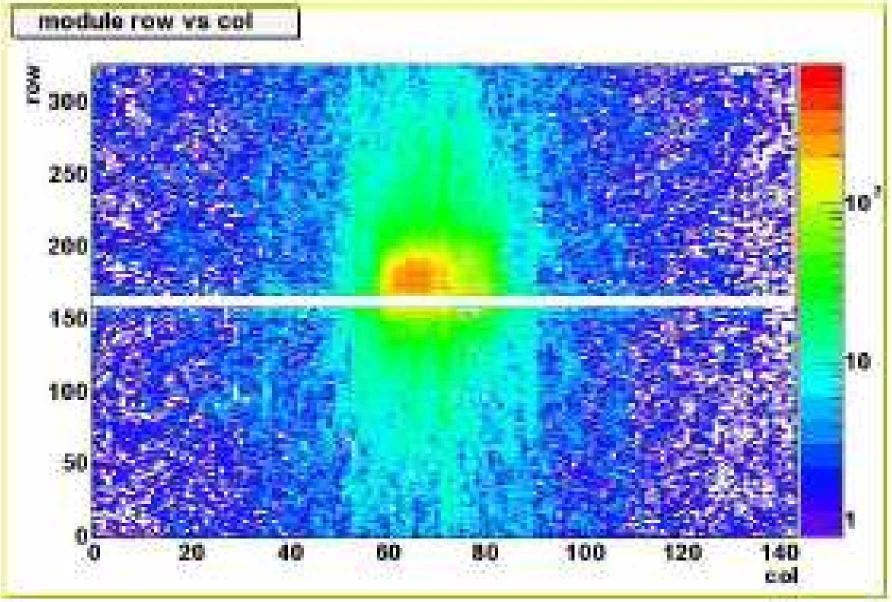
Various stages of making a module

Very short test in the high energy ATLAS test beam at CERN

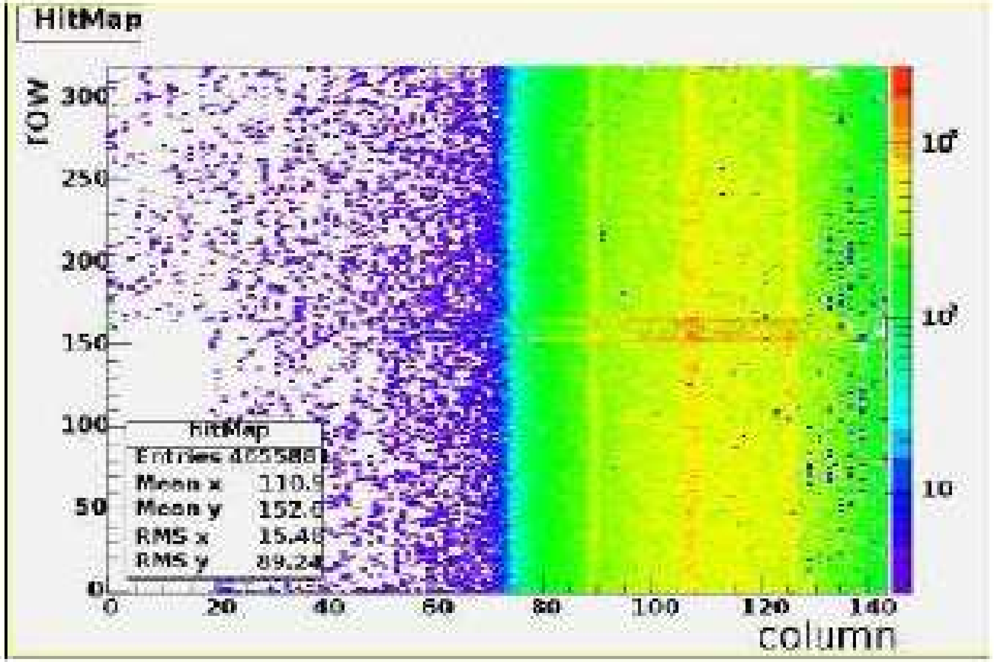
Module equipped with 16 fully radhard IBM readout chips

Beam profile

All channels are working



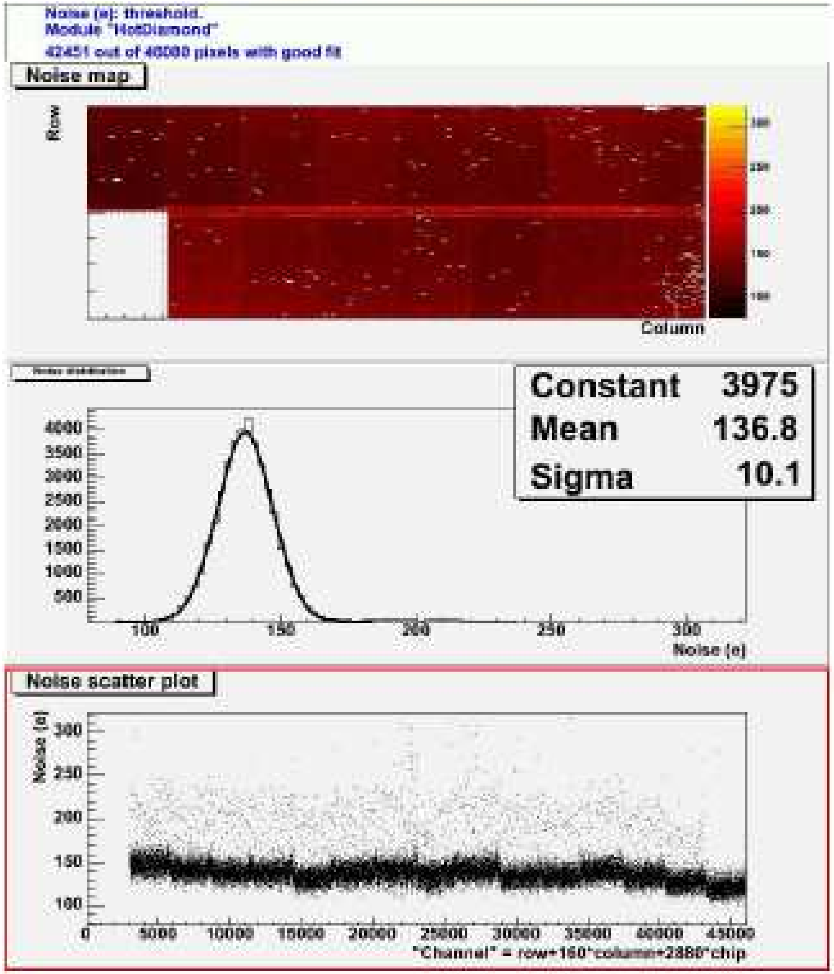
The full diamond pixel module at DESY - Hitmap

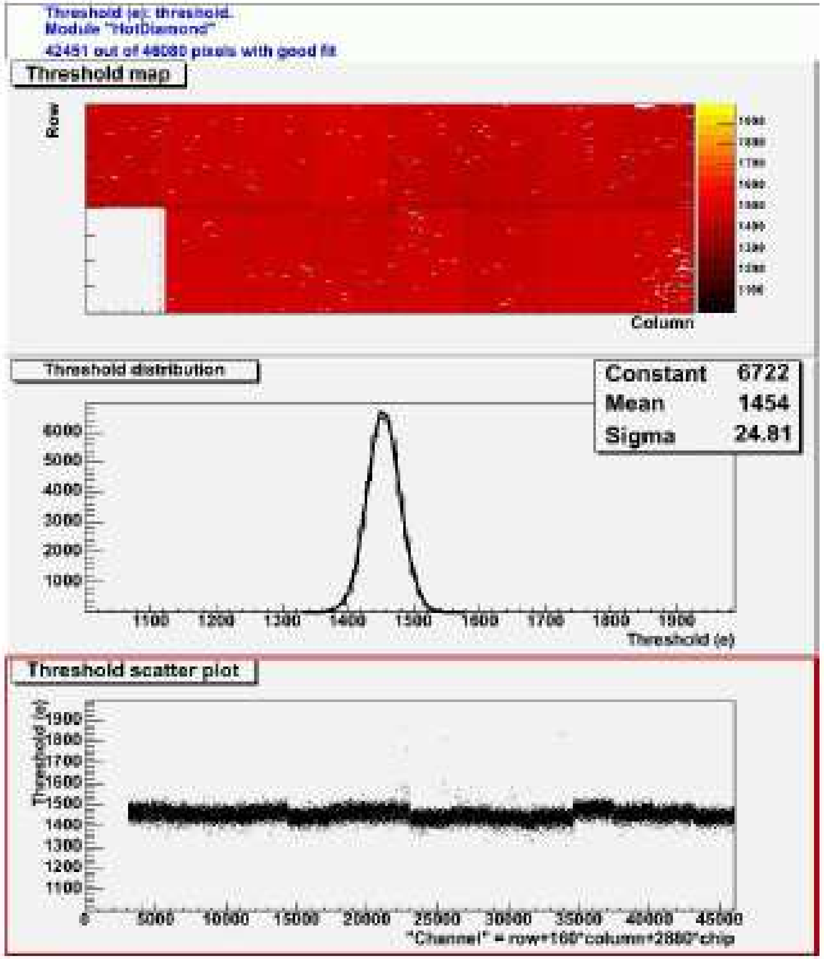


Analysis in Progress.

Hitmap looks good - can easily see scintillator edge.

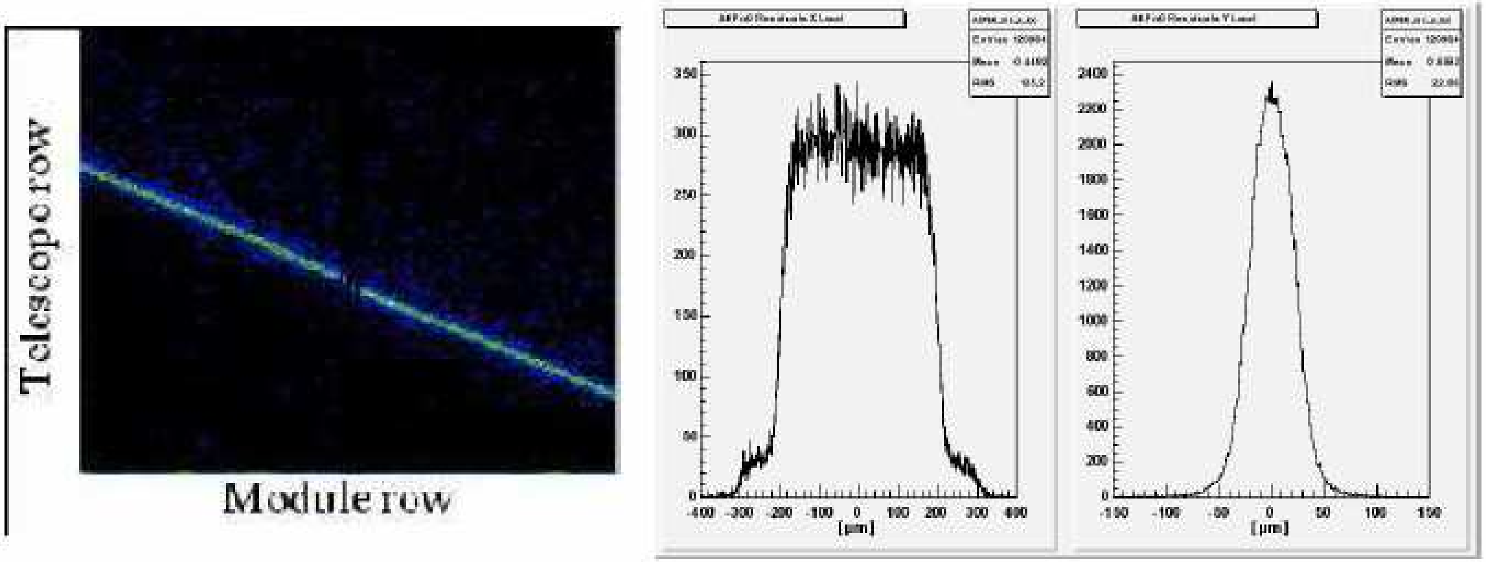
The full ATLAS diamond pixel module - Noise, Threshold





Results - Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$.

The full ATLAS diamond pixel module - Correlation, Resolution



Excellent correlation with telescope

Resolution dominated by multiple scattering.

Preliminary residual $\sim 23\mu m$ - includes contribution from multiple scattering.

Beam Diagnostics and Monitoring with pCVD Diamonds

Beam Diagnostics & Monitoring with Diamonds (ATLAS, CMS, CDF, Belle, BaBar)

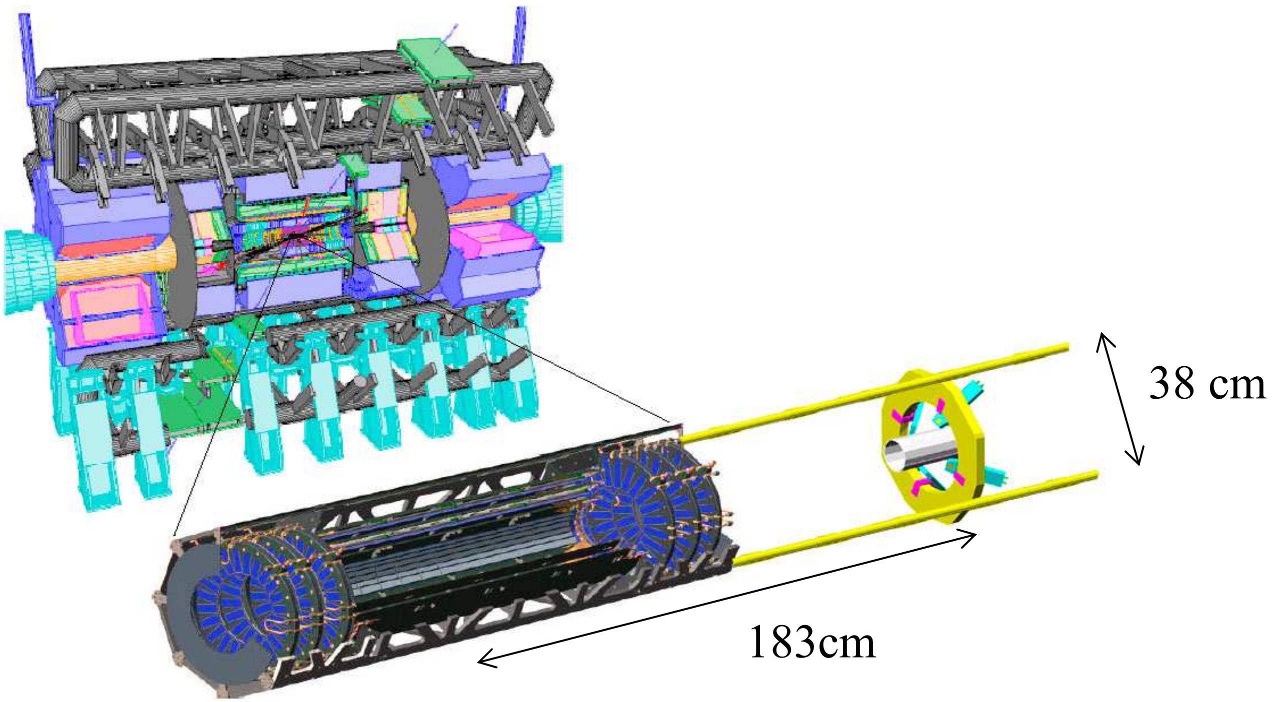
- Common Goal: measure interaction rates & background levels in high radiation environment
- Input to background alarm & beam abort

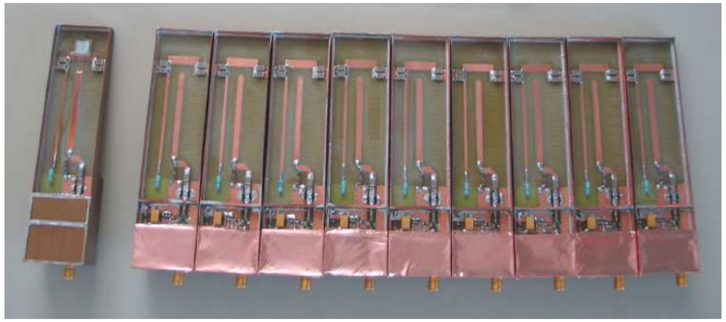
- "DC current"
  - Uses beam induced DC current to measure dose rate close to IP
  - Benefits from very low intrinsic leakage current of diamond
  - Can measure at very high particle rates
- Simple DC (or slow amplification) readout
- Examples:
  - BaBar
  - Belle, CDF
  - Similar method planned for CMS

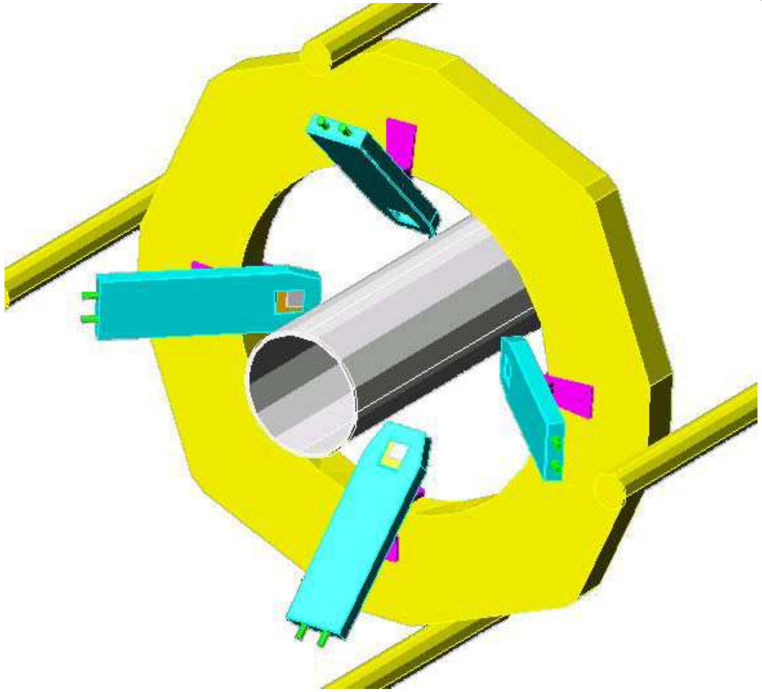
- Single particle counting
  - Counts single particles
  - Benefits from fast diamond signal
  - Allows more sophisticated logic coincidences, timing measurements
  - Used at high particle rates up to
- Requires fast electronics (GHz range) with very low noise
- Examples
  - Atlas Beam conditions monitor

ATLAS Beam Conditions Monitor @ LHC

- 4 BCM stations on each side of the Pixel detector
  - Mounted on Pixel support structure at z = +/- 183.8 cm and r = 7 cm
  - Each station: 1cm^2 detector element + Front-end analog readout



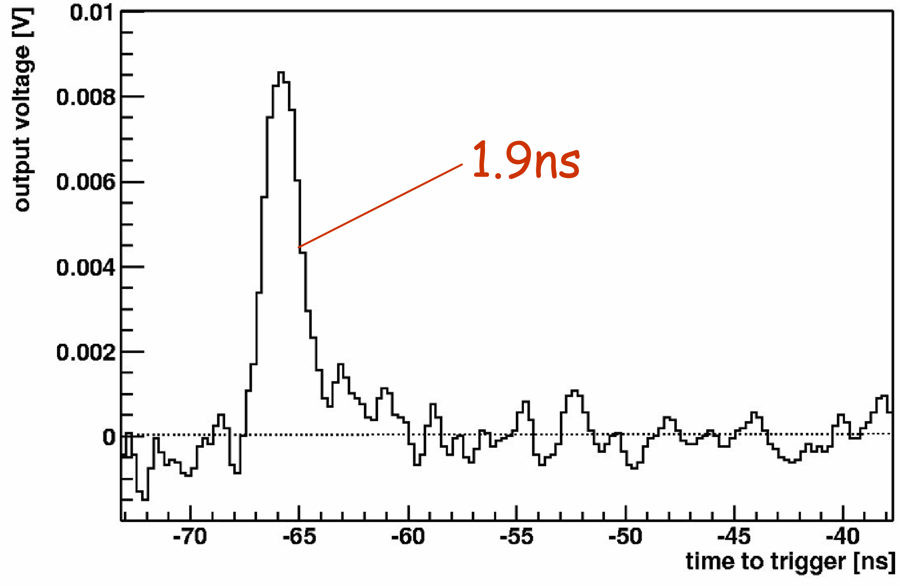




Ten ATLAS BCM Modules with double sensor mounting and GHz readout ready for mounting

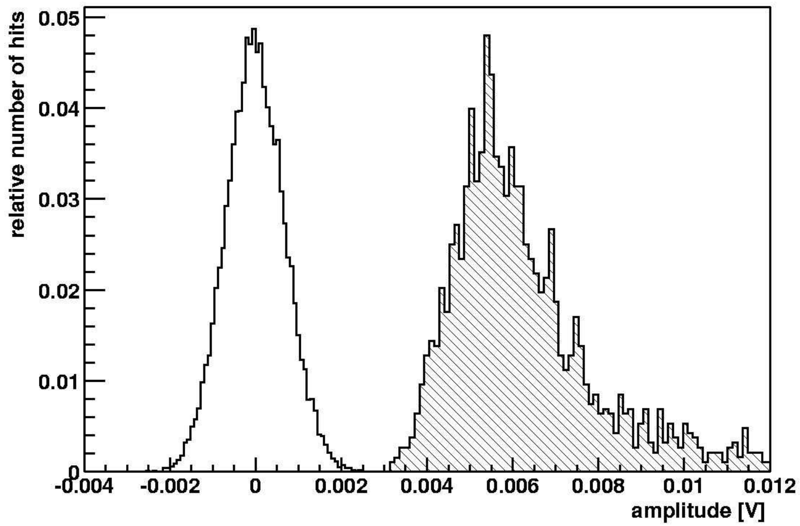
CVD diamonds and fast amplifiers at ATLAS

- Benefits from very fast signal in diamond
- radiation hard and requires no cooling



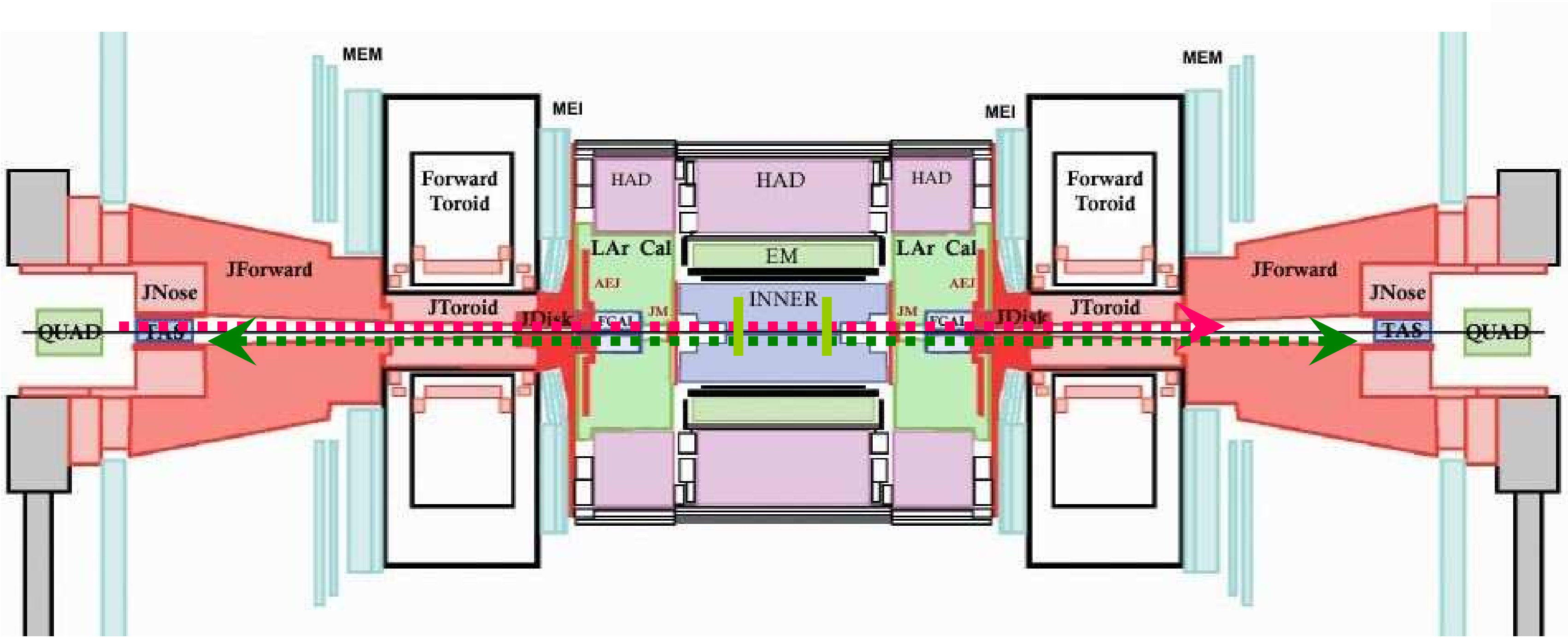
MIP signal distribution:
Average signal = 6.3mV
S_{mp} = 5.2mV
SNR_{mp} ~ 8:1

- Single MIP time response:
  - After 16m analog readout
- Rise-time: 0.9 ns
- Pulse width : 2.1ns

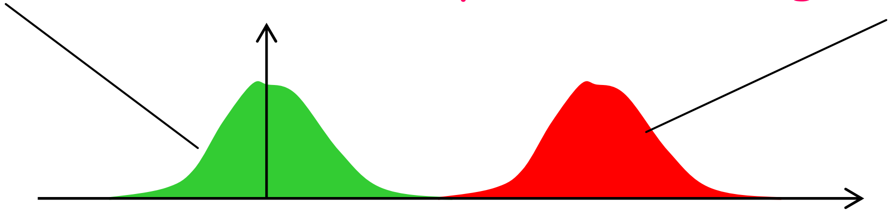


Timing of background vs. interactions

- Distinguish collisions from background through time-of-flight measurement
  Measure number of charged particle/cm2 using analog pulse height



Interactions: Δt = 0, 25, … ns Upstream background: $\Delta t = 2z/c$ = 12ns

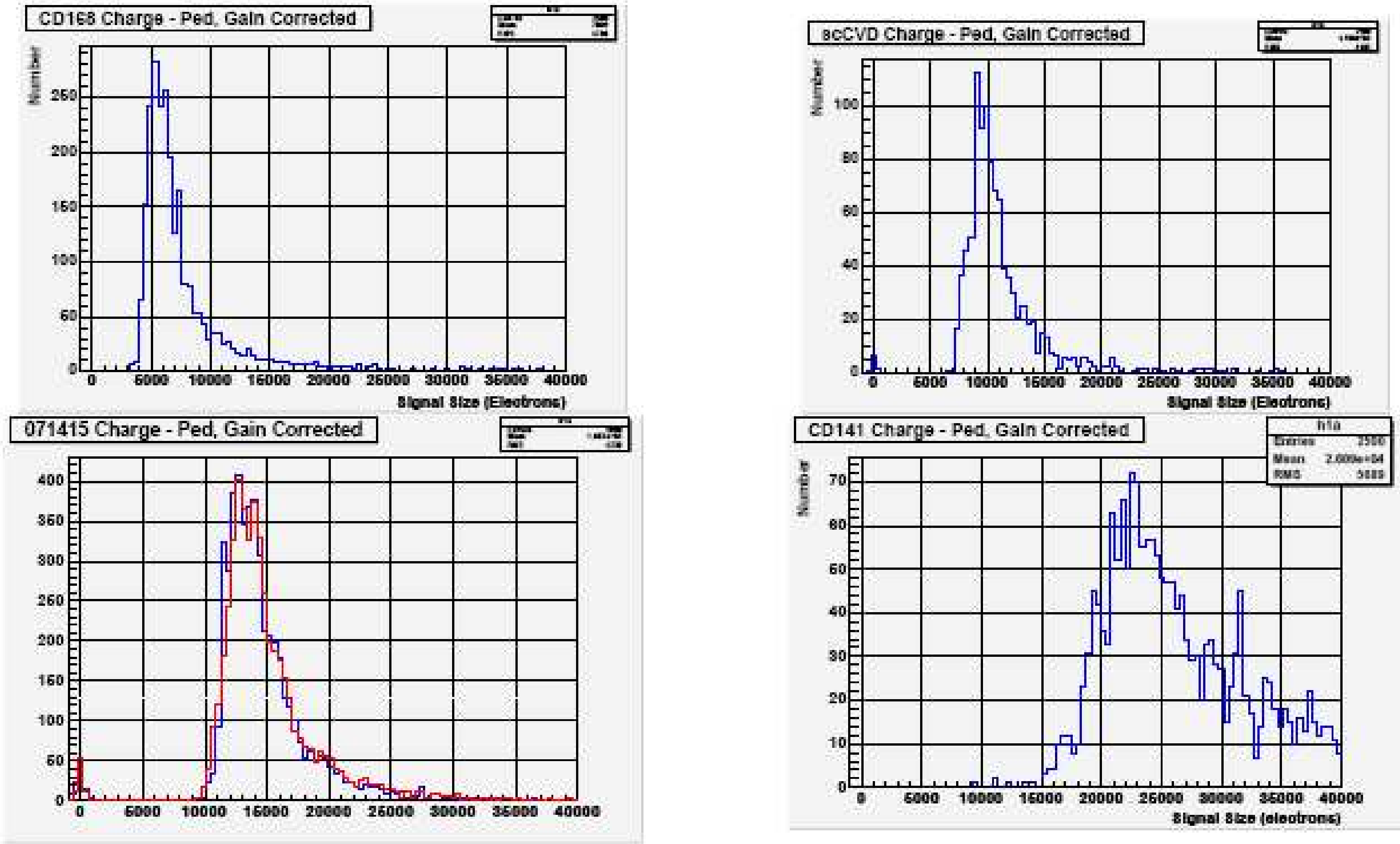


Normal operation flux
1-2 MIPs/cm2/BCO

Single Crystal CVD Diamonds

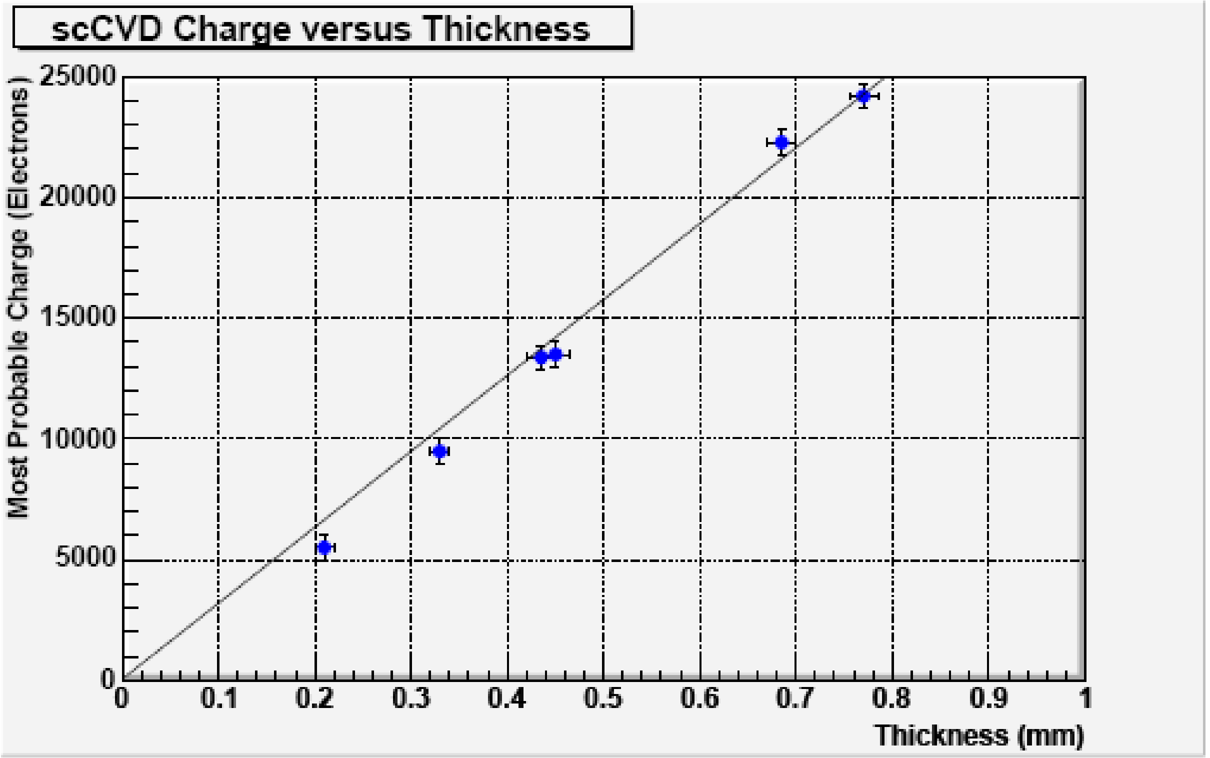
Some first results on charge collection and carrier properties

Recent single crystal CVD (scCVD) diamond.



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

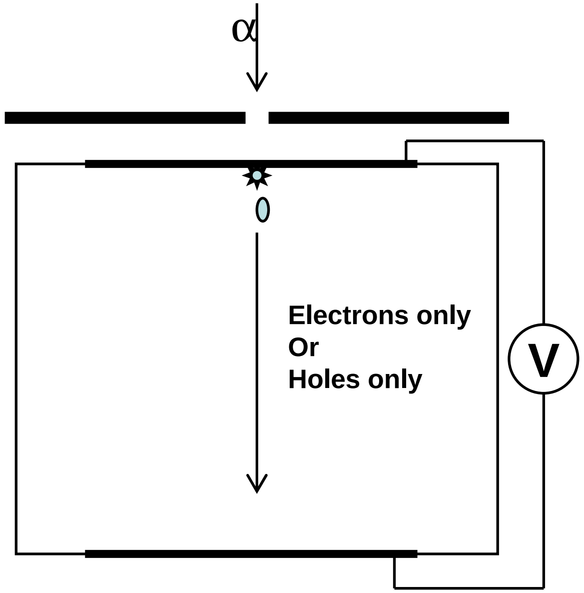
Recent single crystal CVD (scCVD) diamond.



Most Probable charge versus thickness

Charge carrier properties in Single Crystals

- Measure charge carrier properties important for signal formation
  - electrons and holes separately
- Use α-source (Am 241) to inject charge
- Injection
  - Depth about 14µm compared to 470µm sample thickness
  - Use positive or negative drift voltage to measure material parameters for electrons or holes separately
  - Amplify ionization current

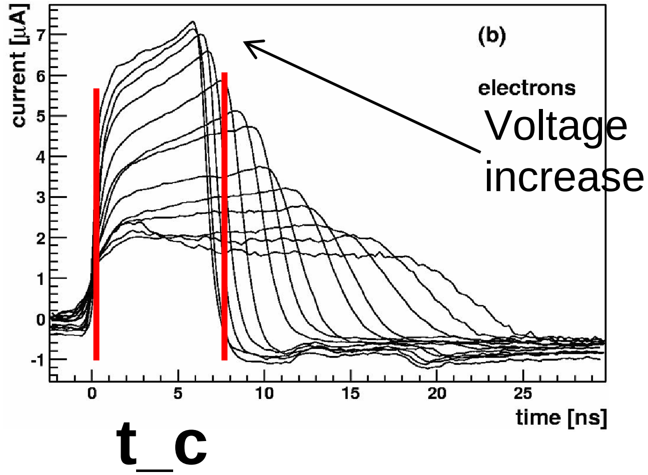


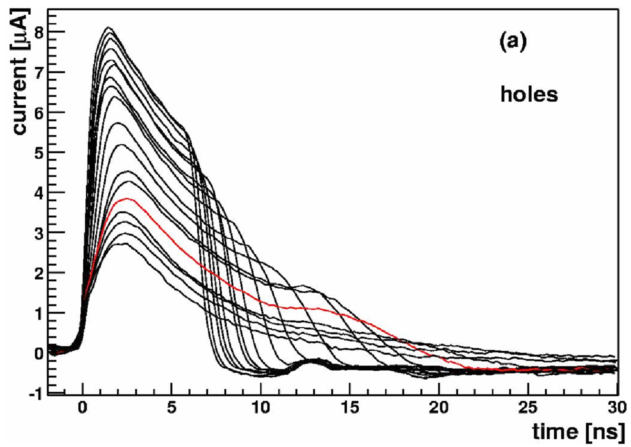
The pulse shape of the induced current is recorded
(**T**ransient **C**urrent **T**echnique)

Ionization current in a sCVD sample

- **Drift time and mobility**
- **Charge Lifetime**
- **Internal electrical field**

- Transit time of charge cloud
  - Signal edges mark start and arrival time of drifting charge cloud
- Two effects determine the shape **during** the drift
  - Charge trapping during drift if any
  - Space charge : decrease of current for holes / increase for electrons with time





$$i_{e,h}(t) \propto e^{\frac{t}{\tau_{eff_{e,h}}} - \frac{t}{\tau_{e,h}}}$$

$$\tau_{eff_{e,h}} = \frac{\epsilon\epsilon_0}{e_0\mu_{e,h}|N_{eff}|} \approx \frac{\epsilon\epsilon_0 t_c V}{e_0 d^2 |N_{eff}|}$$

The measured drift velocity

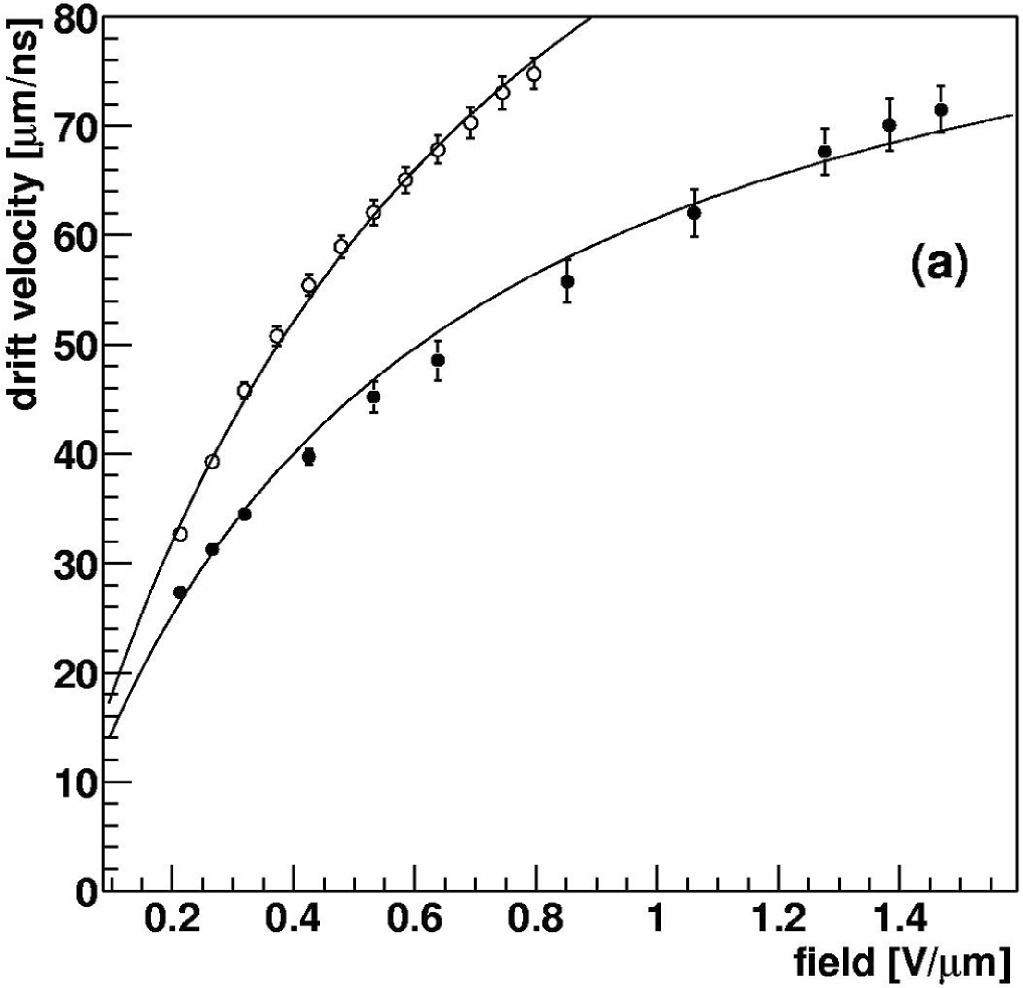
- Average drift velocity for electrons and holes

$$v_{dr_{e,h}}(E) = d/t_c$$

- Extract μ_0 and saturation velocity

$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_s}}$$

μ_0 for this sample:
  - Electrons: 1714 cm2/Vs
  - Holes: 2064 cm2/Vs
- Saturation velocity:
  - Electrons: 0.96 10^7 cm/s
  - Holes: 1.41 10^7 cm/s



The “effective mobility”

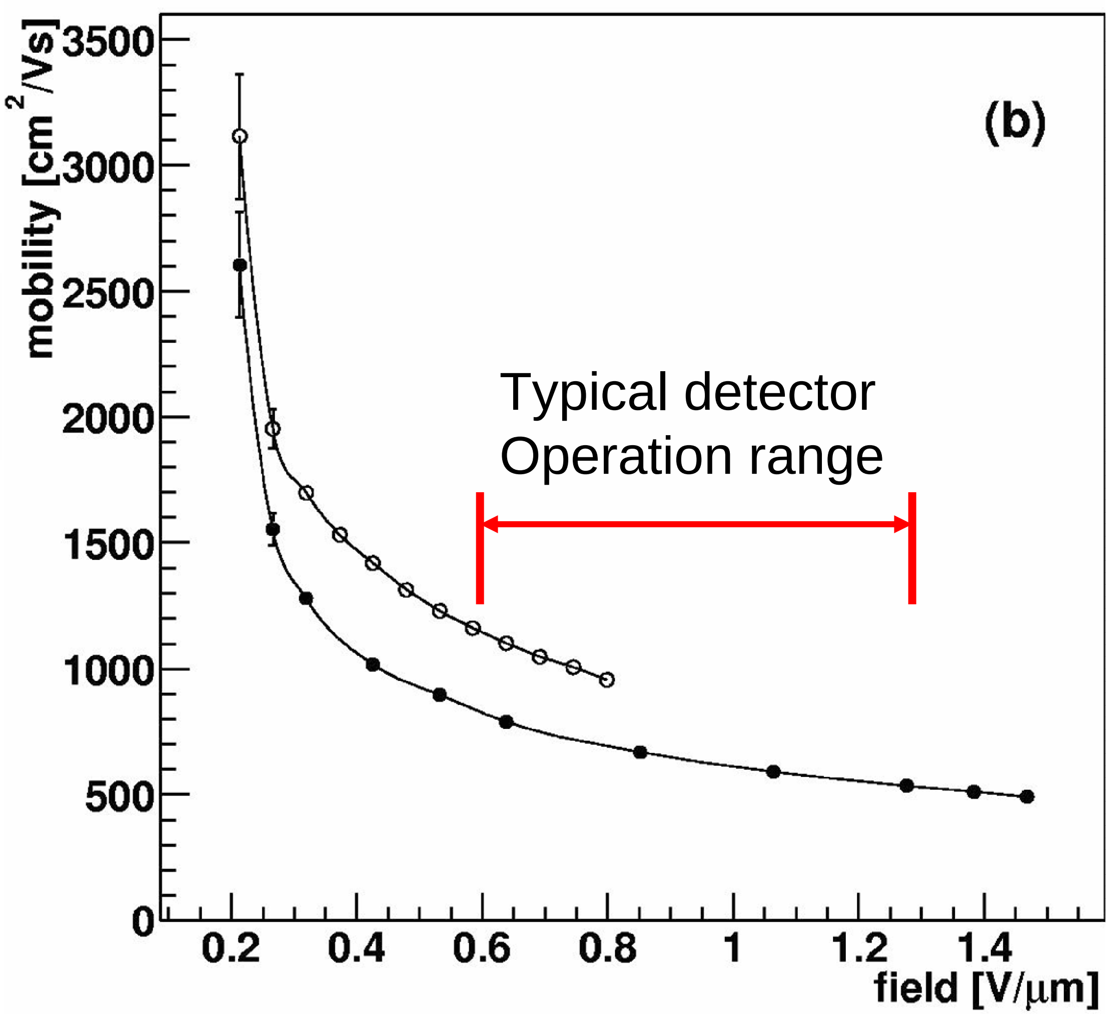
- Deduce a calculated mobility from the measured velocity (normally mobility is defined only at low fields with linear relation between field and velocity)

- Taking space charge into account:

$$\mu_h = -\frac{d^2}{2t_c V_c} \ln\left(\frac{V + V_c}{V - V_c}\right)$$

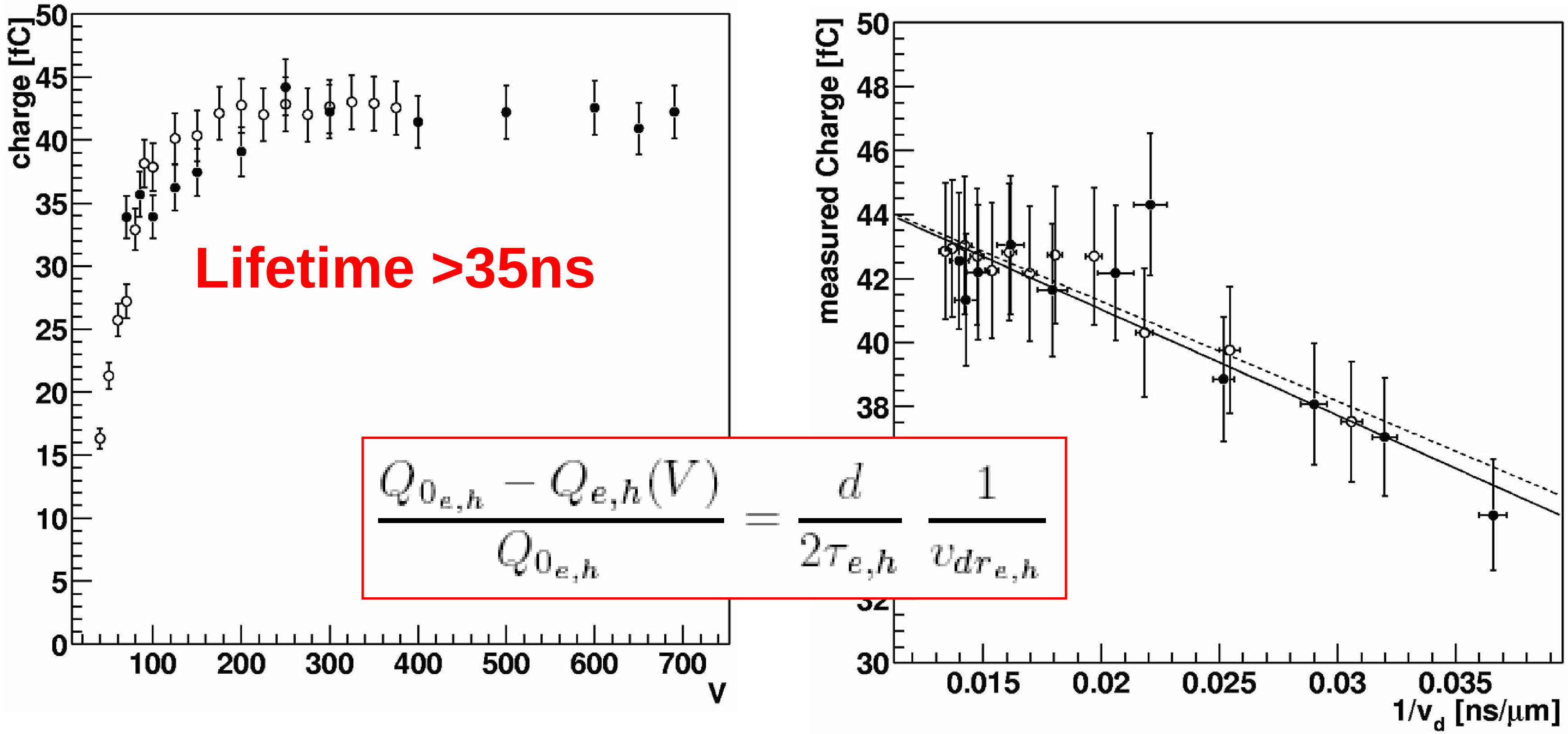
$$\mu_e = -\frac{d^2}{2t_c V_c} \ln\left(\frac{V - V_c}{V + V_c}\right)$$

- Normal operation in region close to velocity saturation



Preliminary carrier lifetime measurements

- Extract carrier lifetimes from measurement of total charge



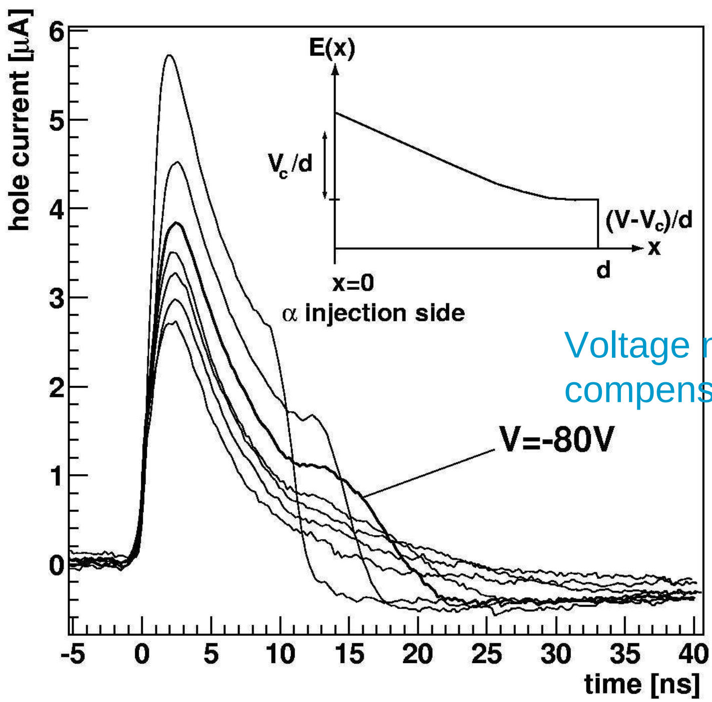
$$\frac{Q_{0_{e,h}} - Q_{e,h}(V)}{Q_{0_{e,h}}} = \frac{d}{2\tau_{e,h}} \frac{1}{v_{dr_{e,h}}}$$

Charge trapping doesn't seems to limit signal lifetime -> full charge collection (for typical operation voltages and thickness)

Net effective space charge

» TCT probes the internal field configuration

- Allows precise measurement of space charge if present
- On this sample e.g.
  - Signal decrease due to decreasing electrical field
  - Negative space charge $N_{eff} = - 2.8 \times 10^{11}\ cm^{-2}$



Voltage necessary to compensate for N_{eff}

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 works in 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 diamond module
  - Bump bonding yield $\approx$ 100 %

  Analyzing Module data from DESY
  - Excellent correlation between telescope and pixel data
  - Noise, Threshold, Efficiency, Resolution look good

- ✦ **Beam Conditions Monitoring**
  - Application of diamond successful in BaBar, Belle, CDF
  - Successfully tested ATLAS BCM prototypes
    - ◦ have met all of the ATLAS specs
  - ATLAS diamond BCM system in production (10 modules)
  - ATLAS diamond BCM installation in Fall 05/Winter 2006

- ➢ First results obtained with single crystal CVD diamonds :
  - Full charge collection in material up to 1mm thick
  - Mobility of electrons and holes measured with TCT; very high hole mobility
  - Carrier lifetimes are bigger than 40 nsec ➔ full charge collection

CVD Diamond is very promising material for Radiation Detectors up to fluences where other solid state detectors will no more have required performance using acceptable service and running conditions