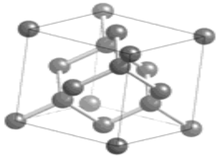


Status of the Development of Polycrystalline and Single Crystal CVD Diamond Detectors

RD42 Collaboration

Peter Weilhammer

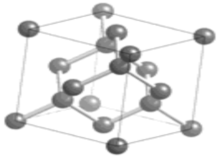
INFN Perugia and CERN

RD42 Collaboration: 24 institutes for 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

W. Adam[1], E. Berdermann[2], W. de Boer[20], F. Bogani[4], E. Borchi[5], M. Bruzzi[5], C. Colledani[6], P. D'Angelo[8], W. Dabrowski[9], W. Dulinski[6], B. van Eijk[11], V. Ermin[24], F. Fizzotti[12], H. Frais-Kölbl[22], C. Furetta[8], K.K. Gan[13], N. Ghodbane[10], E. Griesmayer[22], E. Grigoriev[20], F. Hartjes[11], J. Hrubec[1], F. Huegging[19], H. Kagan[13,◇], J. Kaplon[14], R. Kass[13], K.T. Knöpfle[15], W. Lange[23], M. Krammer[1], A. Logiudice[12], R. Lu[12], L. mac Lynne[7], C. Manfredotti[12], M. Mathes[19], D. Menichelli[5], S. Meuser[19], M. Mishina[16], L. Moroni[8], J. Noomen[11], A. Oh[14], M. Pernicka[1], L. Perera[7], H. Pernegger[14], R. Potenza[21], J.L. Riester[6], S. Roe[14], A. Rudge[14], S. Sala[8], M. Sampietro[17], S. Schnetzer[7], S. Sciortino[5], H. Stelzer[2], R. Stone[7], C. Sutera[21], W. Trischuk[18], C. Tuve[21], B. Vincenzo[21], P. Weilhammer[14,◇], N. Wermes[19], W. Zeuner[10]

◇ Spokespersons

[1] HEPHY, Vienna, Austria
[2] GSI, Darmstadt, Germany
[4] LENS, Florence, Italy
[5] University of Florence, Italy
[6] LEPSI, IN2P3/CNRS-ULP, Strasbourg, France
[7] Rutgers University, Piscataway, U.S.A.
[8] INFN, Milano, Italy
[9] UMM, Cracow, Poland
[10] II.Inst. für Exp. Physik, Hamburg, Germany
[11] NIKHEF, Amsterdam, Netherlands
[12] Univerity of Torino, Italy
[13] Ohio State University, Columbus, OH, U.S.A.
[14] CERN, Geneva, Switzerland
[15] MPI für Kernphysik, Heidelberg, Germany
[16] FNAL, Batavia, U.S.A.
[17] Polytechnico Milano, Italy
[18] University of Toronto, Toronto, Canada
[19] Universität Bonn, Bonn, Germany
[20] Universität Karlsruhe, Karlsruhe, Germany
[21] University of Roma, Italy
[22] FWT, Wiener Neustadt, Austria
[23] DESY-Zeuthen, Zeuthen, Germany
[24] Institute for Semiconductor Studies, St. Petersburg, Russia

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

Still growing – new groups joined RD42 during last 18 months:

DESY Zeuthen

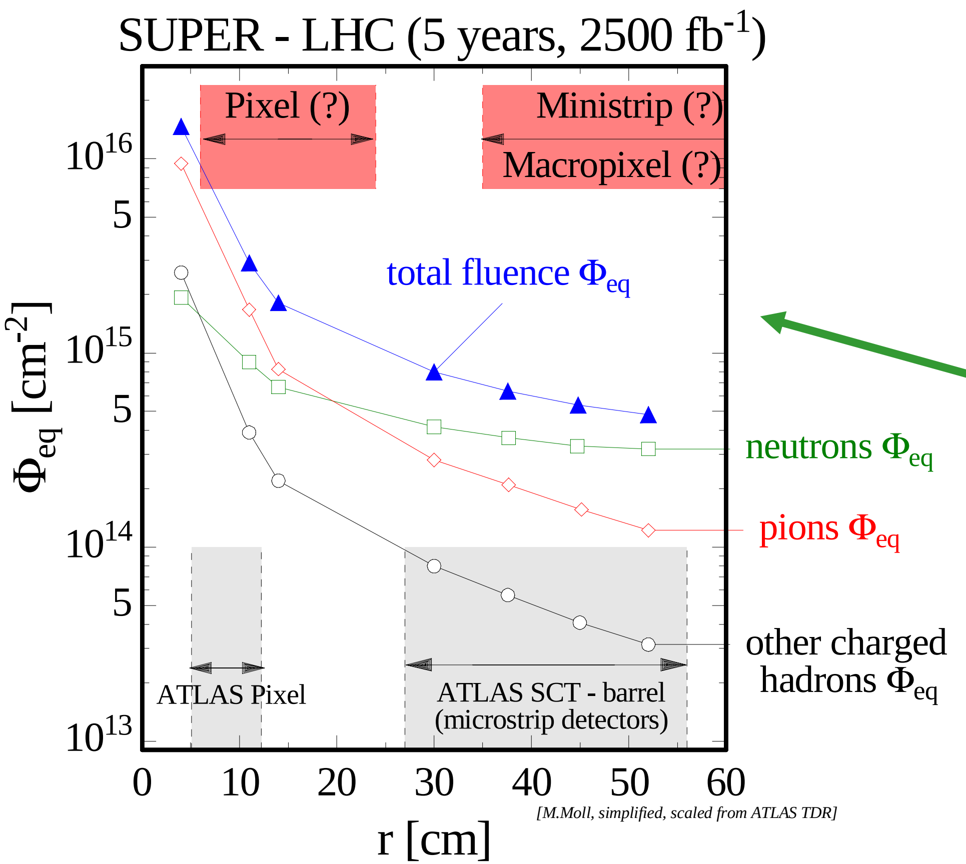
St. Petersburg

Fachhochschule fuer Wirtschaft und Technik-Vienna

ITEP Moscow

Josef Stefan Institute Ljubljana

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



From M. Moll Pixel2005 Bonn

Scenario for 5 years running SLHC

Radiation Hardening of Silicon Detectors:

Main adverse effects after irradiation: (M. Moll, Pixel2005, Bonn)

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**)**

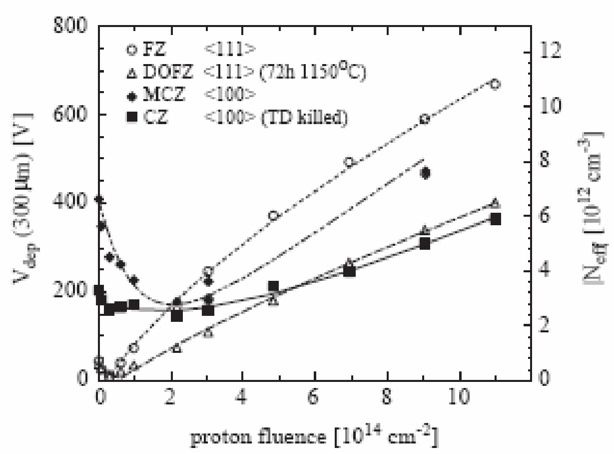


Fig. 1. Comparison of standard (FZ) and oxygenated (DOFZ) Float Zone silicon with Czochralski (CZ) and Magnetic Czochralski (MCZ) silicon detectors in a CERN irradiation scenario with 23 GeV protons [13].

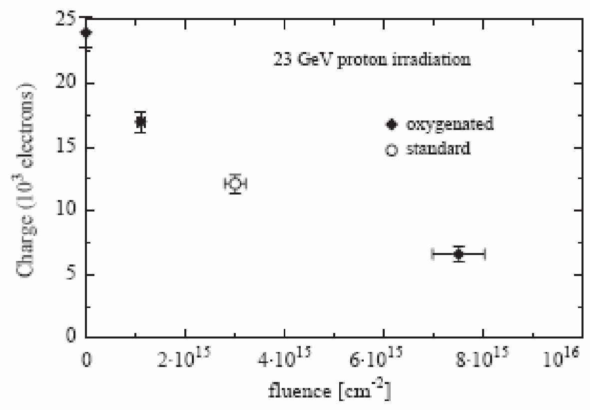


Fig. 2. Collected charge as a function of the 23 GeV proton fluence for standard and oxygenated n-in-p miniature micro-strip detectors (source: Ru^{106}, chip: SCT128A–40 MHz, 800–900 V applied to irradiated devices, measured at −20 °C) [25].

Remedies for Silicon:

Material engineering

Device engineering

Change of detector operational conditions

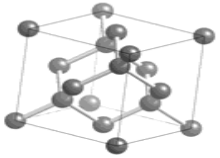
Maybe new materials:

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

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

Low temperatures, very high bias voltages,…….

In this situation it is a challenge to continue studies of CVD diamond as a detector material; in particular for application in environments with the highest integrated radiation fluxes



Important Properties of CVD diamond for Tracking:

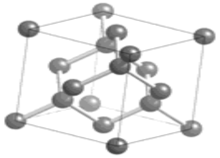
GOOD

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

Load capacitances of sensor 2.1 times lower than for Si because of low ε.
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} ~ 100 pA/cm^2 for a 500μm thick sample.

➔ Low load capacitances are reducing electronic noise



NOT SO GOOD,

but maybe compensated by good properties

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**:

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 (now comparable to) at 1V/mm (in un-irradiated silicon lifetime is 10’s of ms): signal loss in bulk by trapping

AN OVERVIEW AND SOME RECENT RESULTS

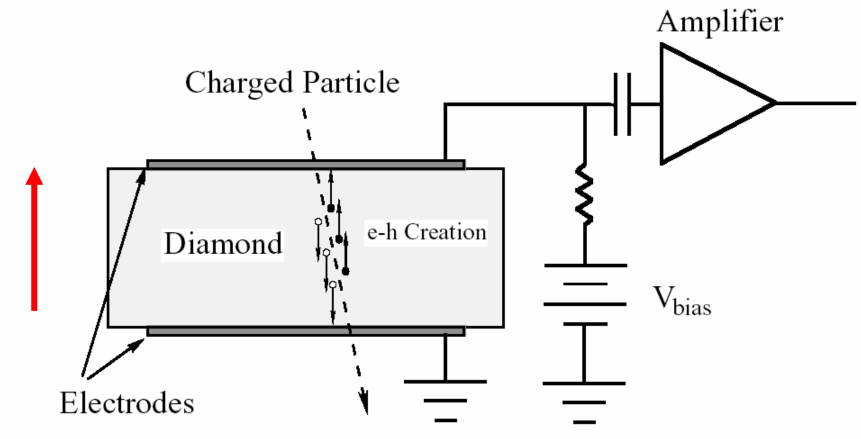
Content of this presentation:

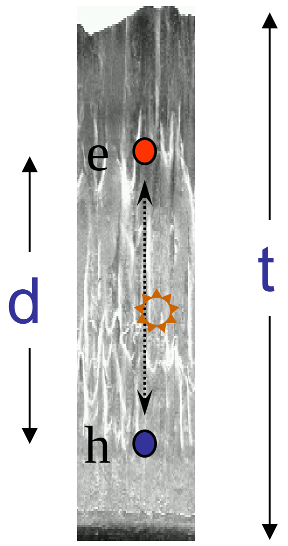
1. **POLYCRYSTALLINE CVD DIAMOND (pCVD)**
    - **Charge Collection, Results from Irradiations, the ATLAS Pixel Module, Beam diagnostics and Monitoring with Diamonds**
2. **SINGLE CRYSTAL CVD DIAMONDS (sCVD)**
    - **Charge Collection, Charge Carrier Properties via TCT**
3. **SOME APPLICATION**
    - **The ATLAS Pixel Module, Beam Diagnostics and Monitoring with Diamonds**

Charge Collection and Radiation Hardness of pCVD Diamond

Principle of detector operation

Electric field





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

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

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

μ and τ are "effective" mobility and lifetime

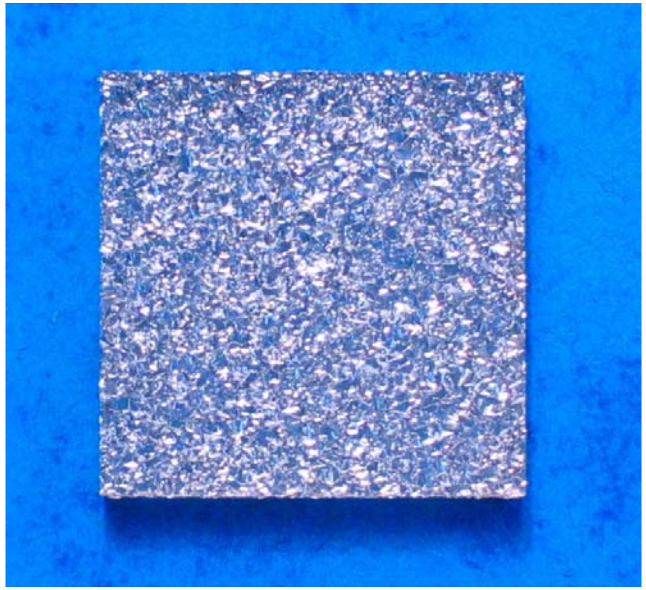
$$\mu = \mu_e + \mu_h$$

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

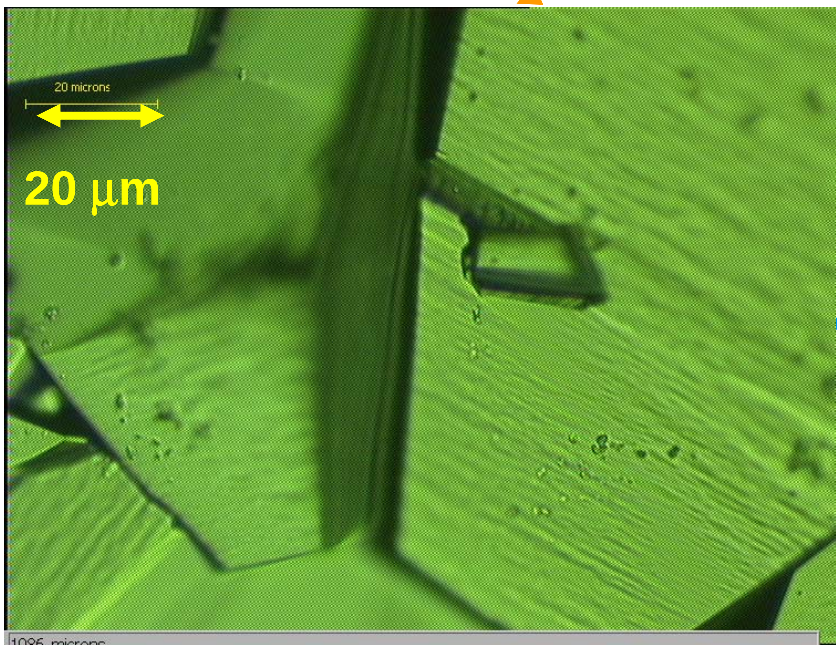
State of the art pCVD material

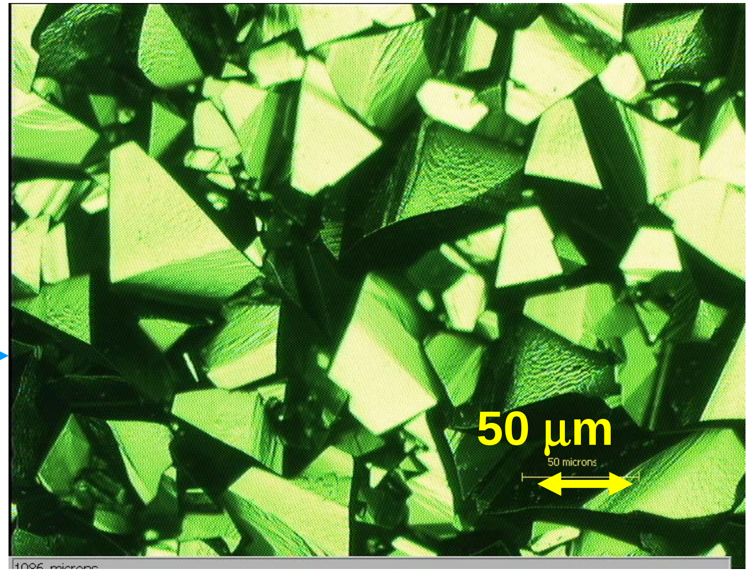
1.1 mm thick

Photo of Sample

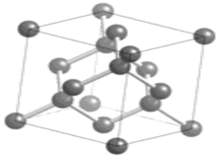


Growth side

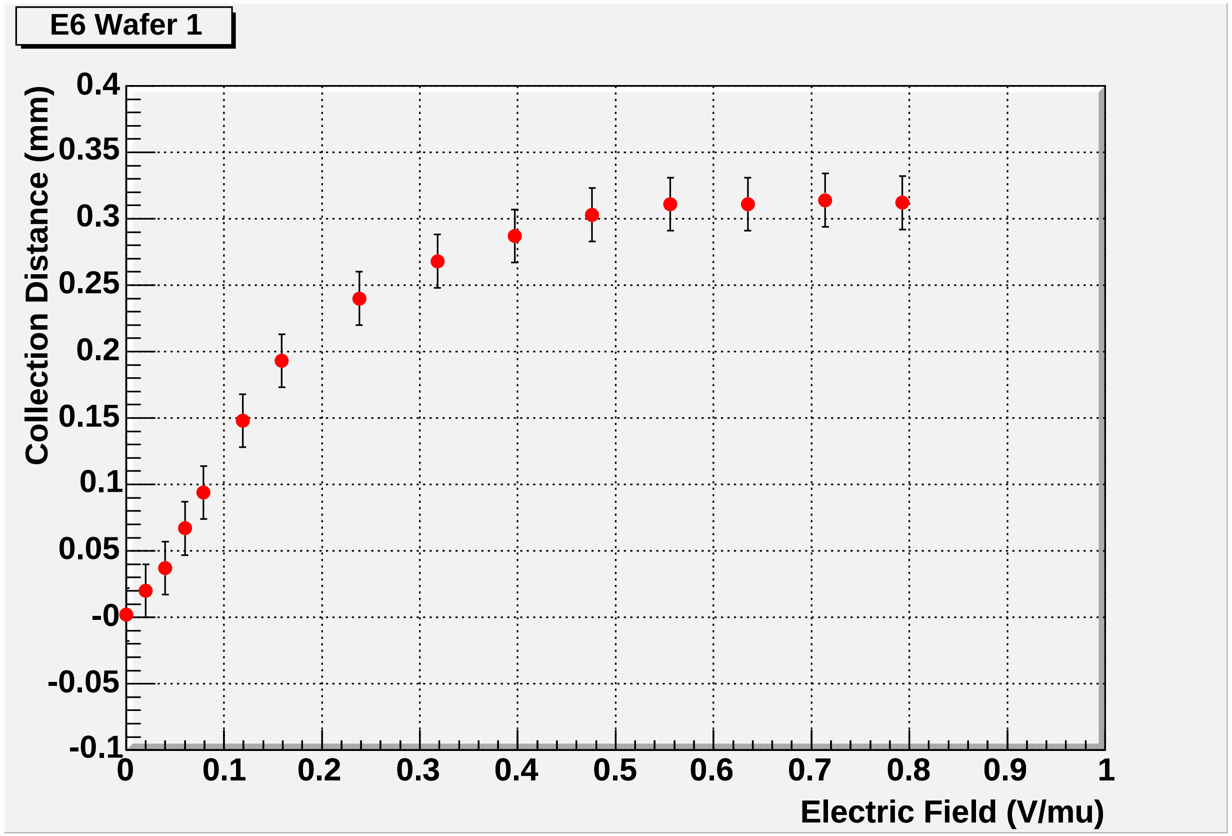




What Charge Collection Distance can one get



Saturation Velocity of carriers reached at ~ .7 V/µm

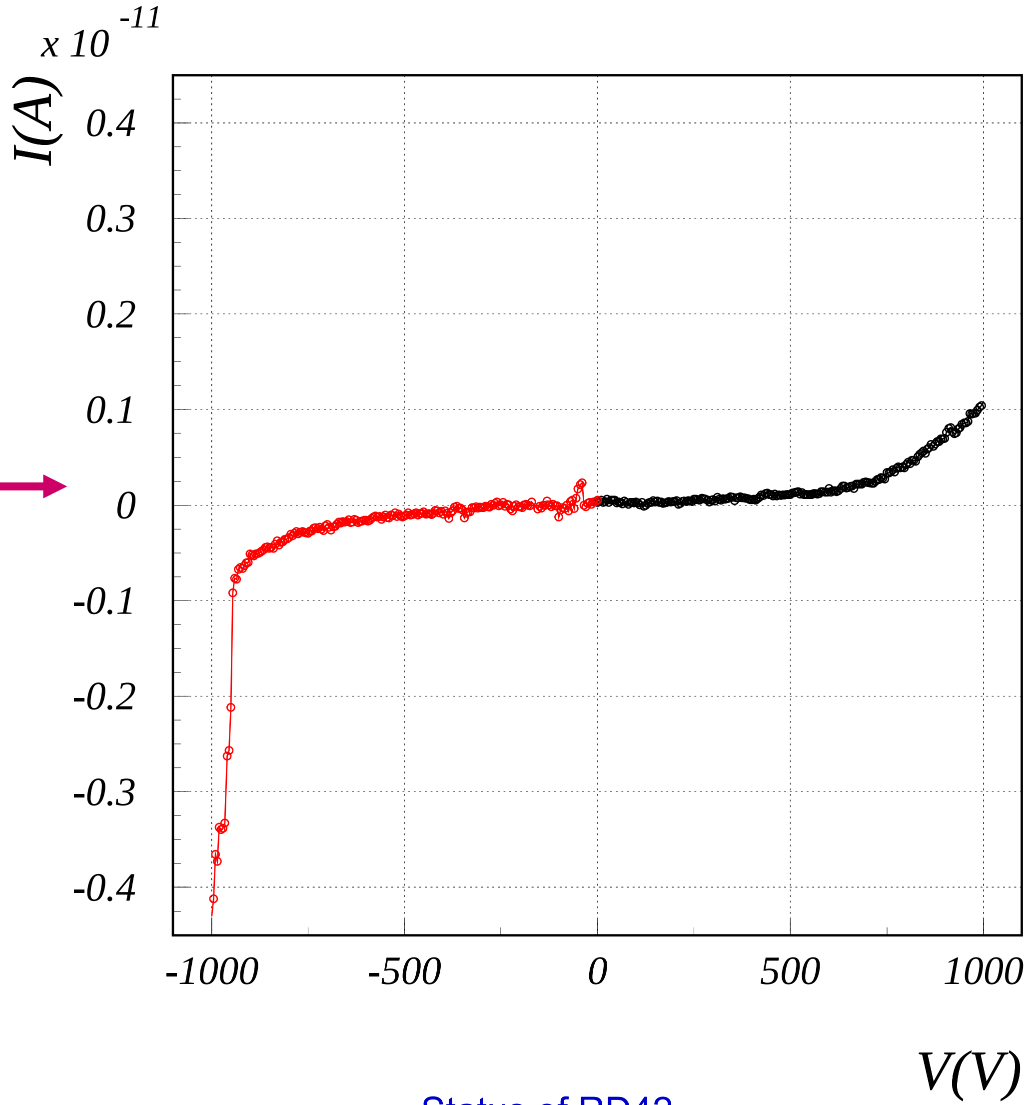


Charge Collection Distance of such samples

^{90}Sr Source

300µm **~11000 eh pairs mean**

I-V Curve for a pCVD Sample



~0.01 pA

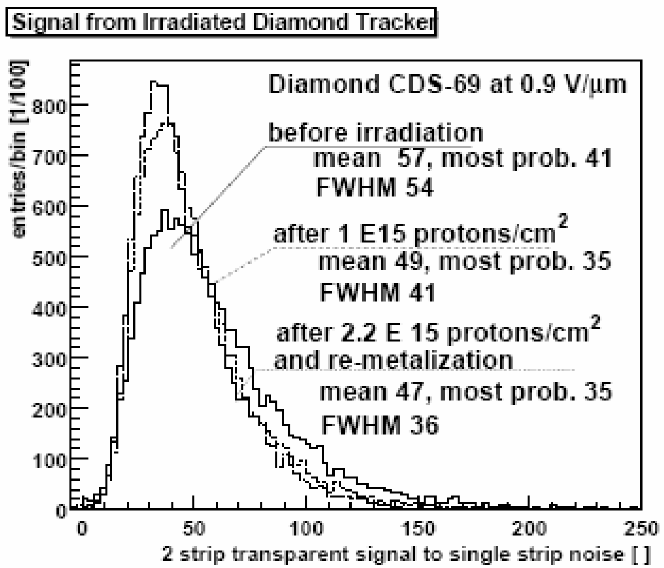
~ pA

History of Radiation Hardness Measurements with pCVD Diamonds

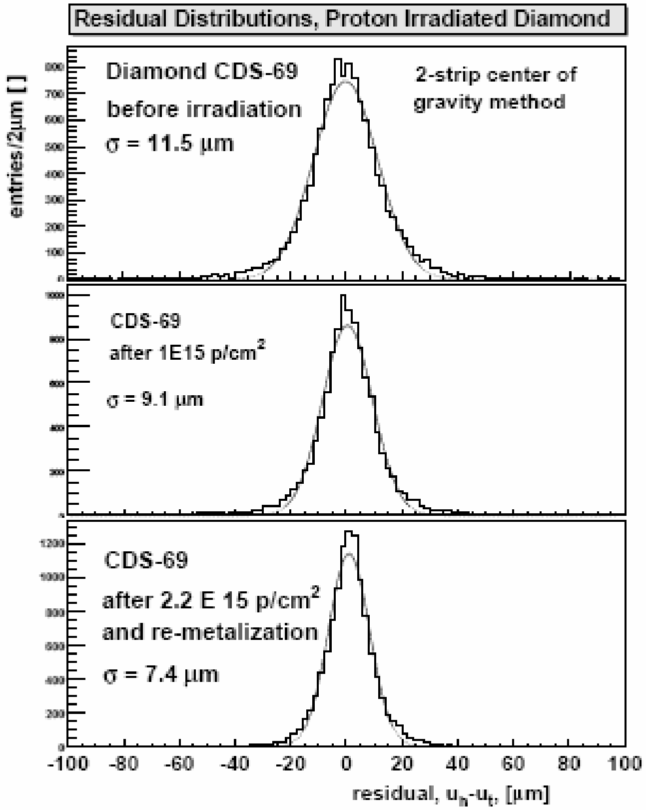
Sample CDS-69 had originally ~ 160μm ccd, 520 μm thick

Proton Irradiation - previously:

Signal to Noise



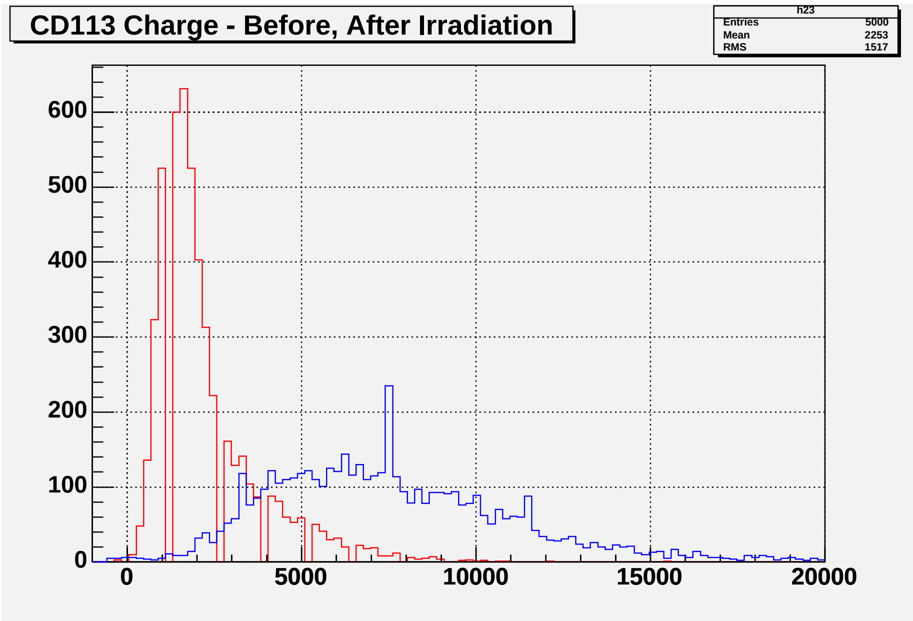
Resolution

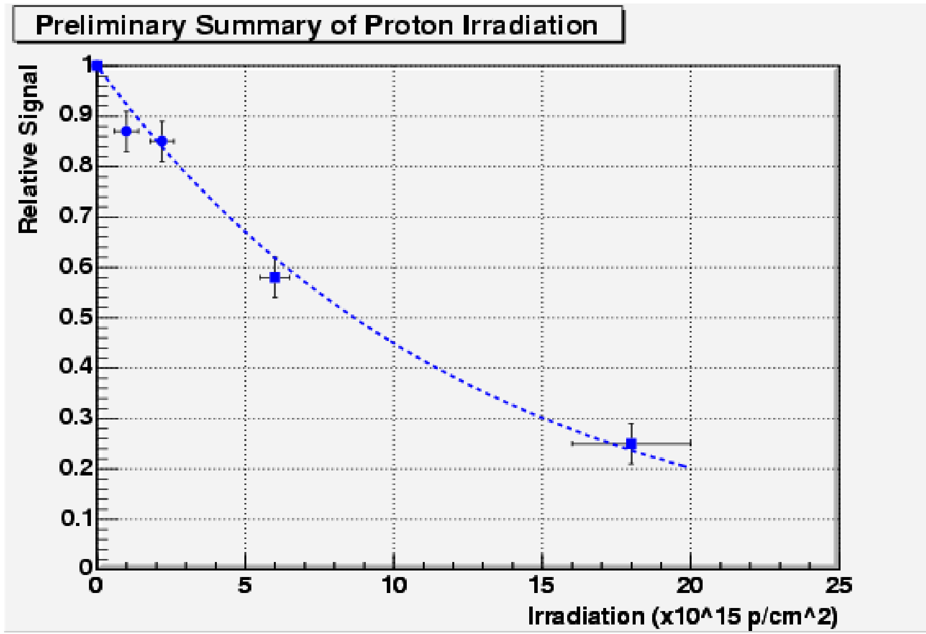


- Data taken over a period of 2 years
- Dark current decreases with fluence
- 15% loss of S/N at $2.2 \times 10^{15}/cm^2$
- Resolution improves 35% at $2.2 \times 10^{15}/cm^2$

Irradiation with protons to 1.8 x 10^{16} p/cm^2 (~500Mrad)

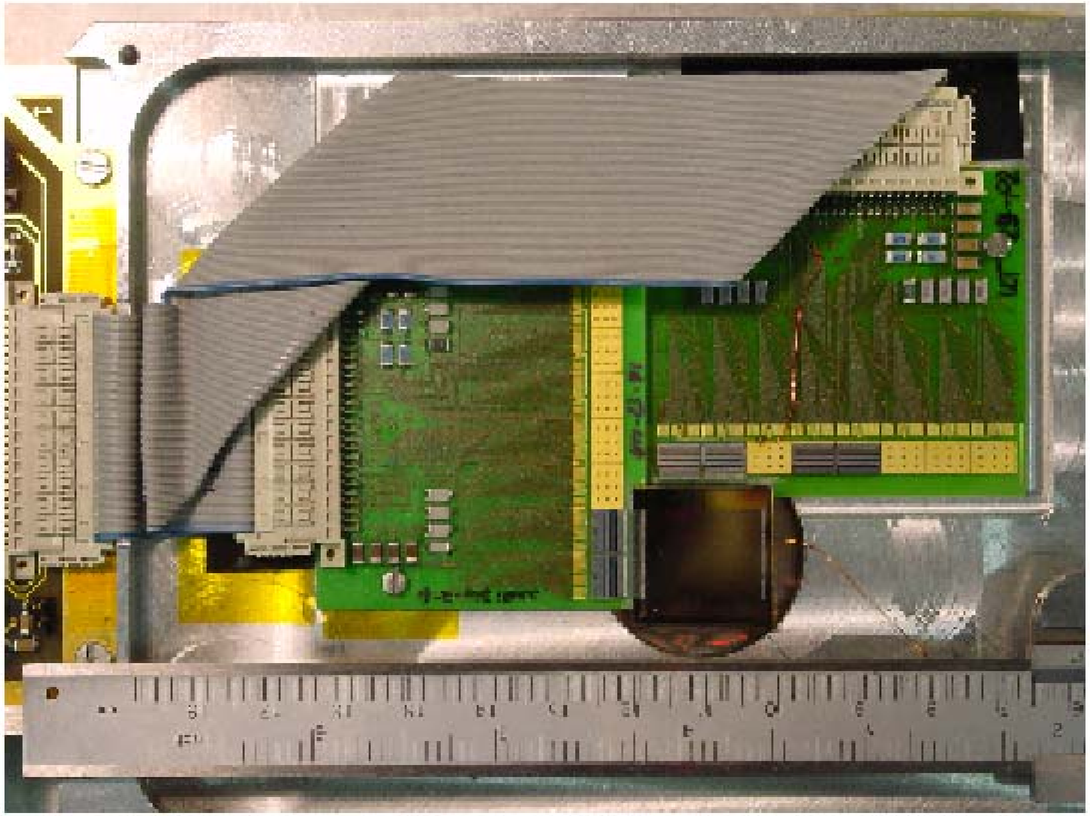
Relative charge as function of fluence at fixed field



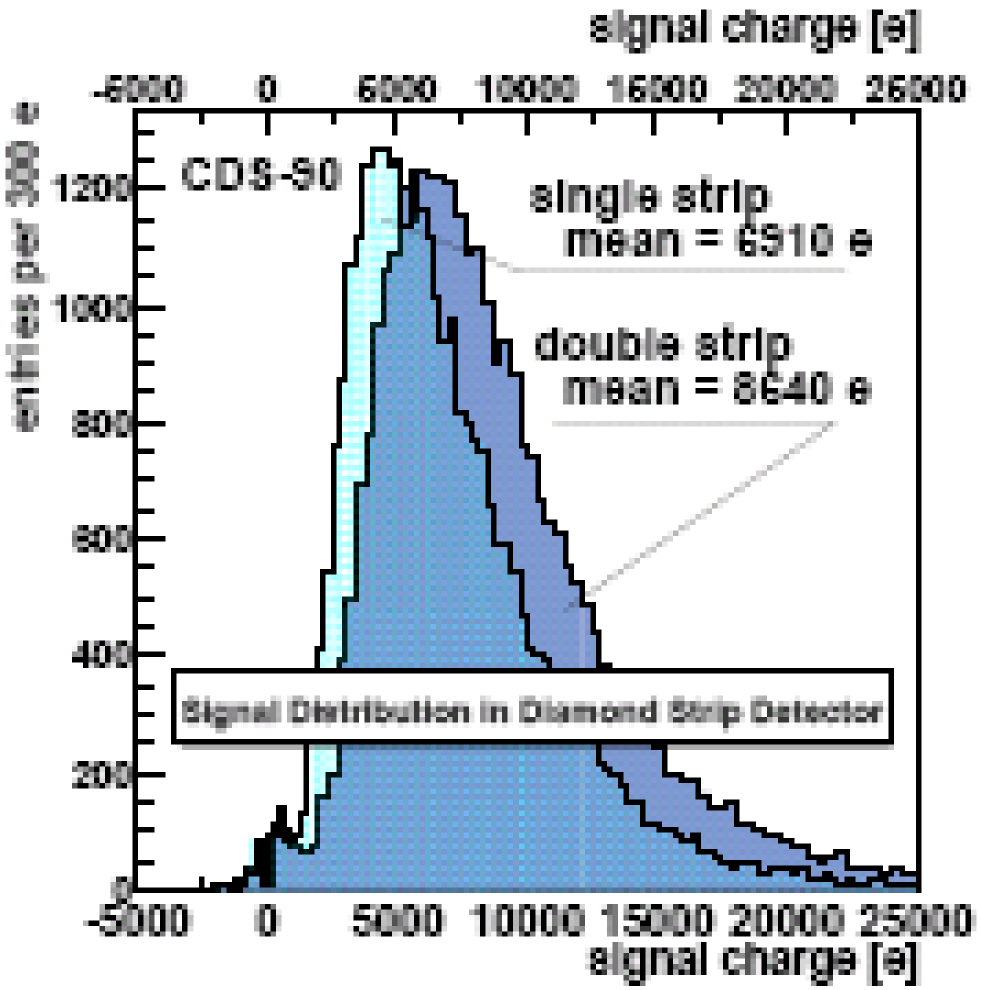


Sample CD113: t= 490 µm, CCD = 225 µm

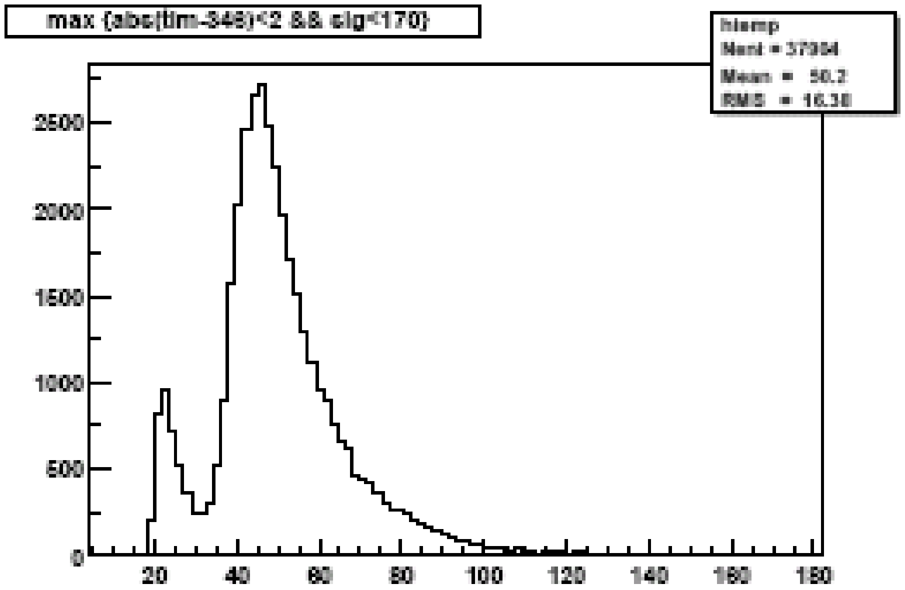
A Double-sided Strip Detector



Orthogonal strips on opposite side of sample, 50 μm strip pitch

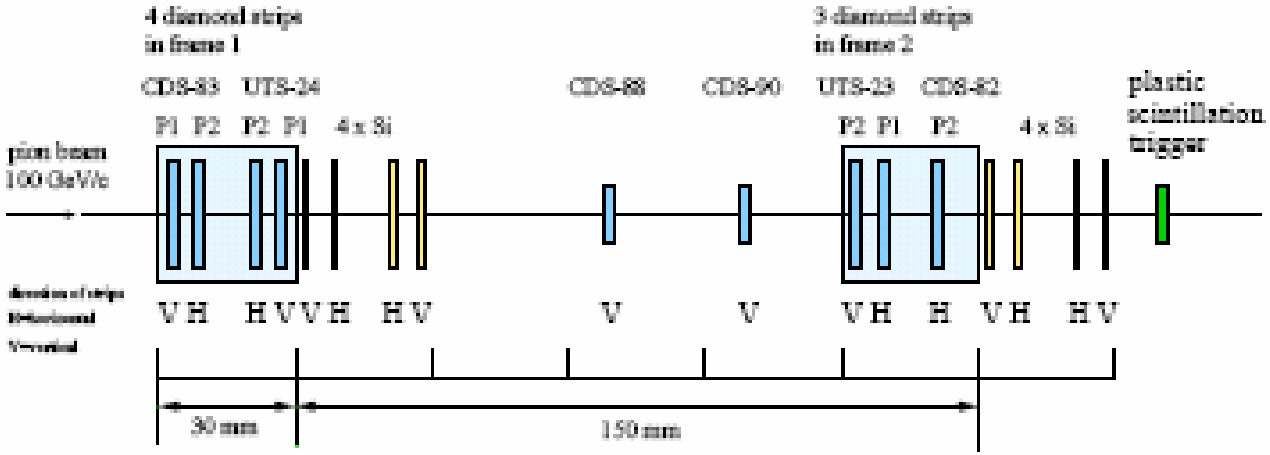

signal charge [e]
-5000 0 5000 10000 15000 20000 25000
entries per 300 e
0 200 400 600 800 1000 1200
CDS-90
single strip
mean = 6910 e
double strip
mean = 8640 e
Signal Distribution in Diamond Strip Detector
-5000 0 5000 10000 15000 20000 25000
signal charge [e]

Radiation Hard Diamond Tracking Modules:



- Module constructed with fully radiation hard SCTA128 electronics
- Tested is a ^{90}Sr → ready for beam test and irradiation
- Charge distribution cleanly separated from the noise tail
- Efficiency will be measured in test beams at 40 MHz clock rate

CERN Testbeam Setup:



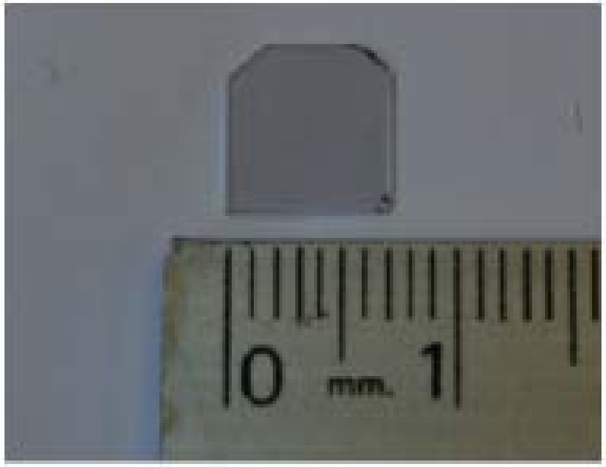
- 100 GeV/c pion/muon beam
- 7 planes of CVD diamond strip sensors each 2cm × 2cm
- 50μm pitch, no intermediate strips
- 2 additional diamond strip sensors for test
- several silicon sensors for cross checks
- Strip Electronics (2 μsec)

  ENC $\approx 100e + 14e/\mathrm{pF}$

Single Crystal CVD Diamonds

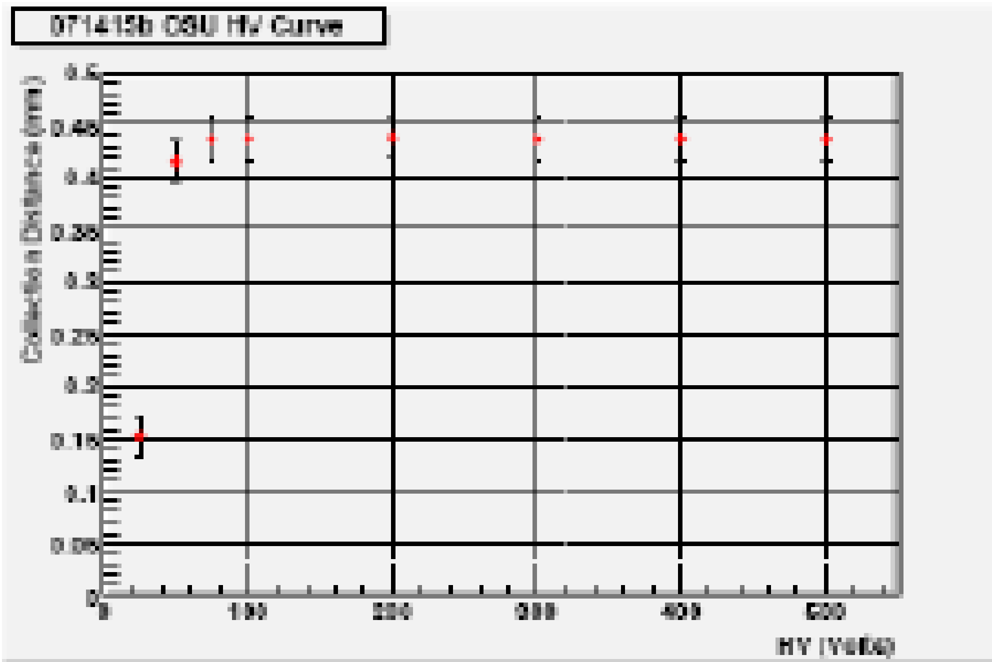
Summary of results on charge collection and carrier properties

Single Crystal CVD Diamond Samples



- Rd 42 has research contract with Element6 to further develop this material
- scCVD can be grown at present to ~ 1cm x 1 cm size, ~ 1mm thick
- Biggest sample fabricated was 14 mm x 14 mm

Collected charge for a scCVD sample

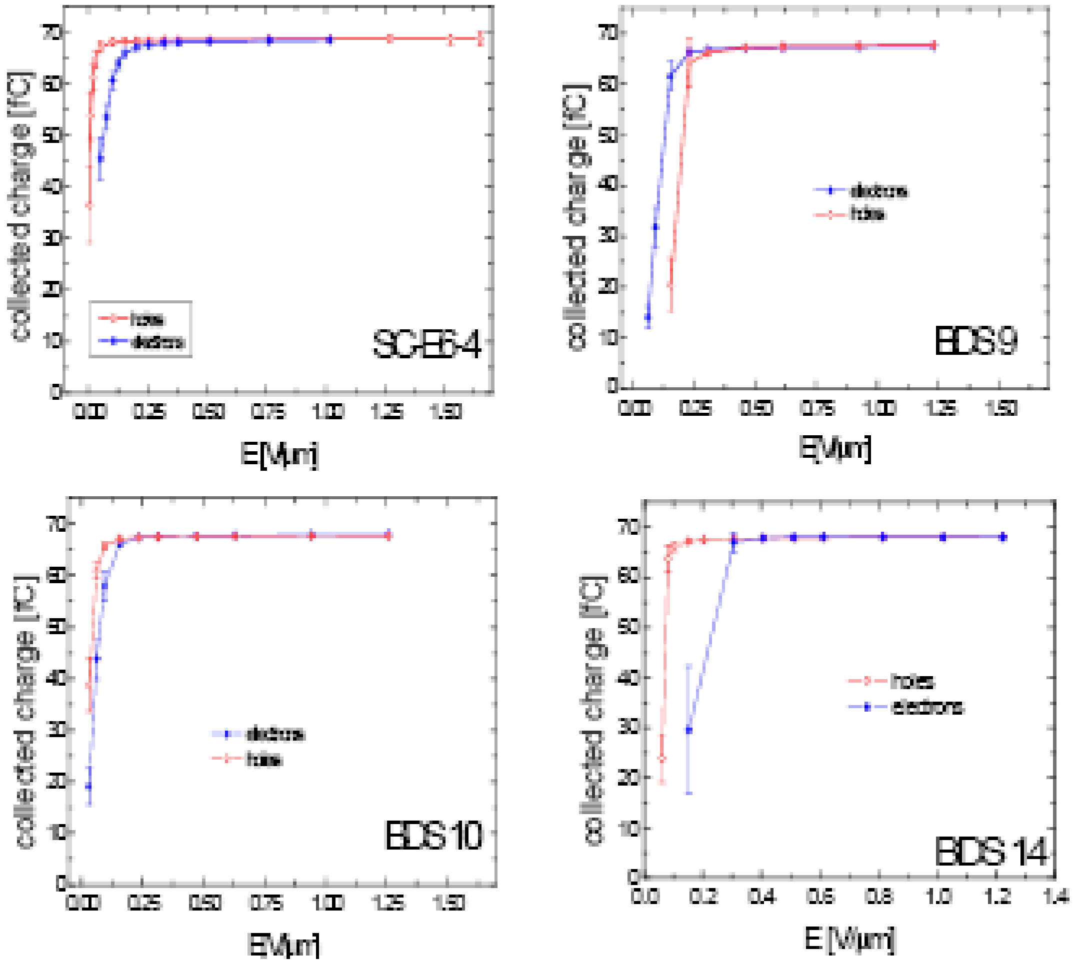


Sample is ~435 micron thick

- Single Crystal CVD collects all created charge at ~0.2 V/µm
- Single crystal CVD does not "pump"

Collected Charge measured on Samples in GSI

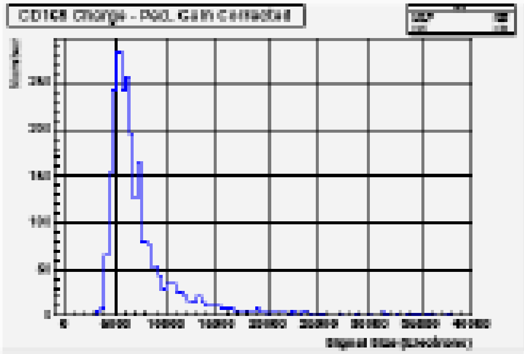
Charge from integration of current pulses (see below) shows that charge collection is complete above 0.35 V/µm for both holes and electrons

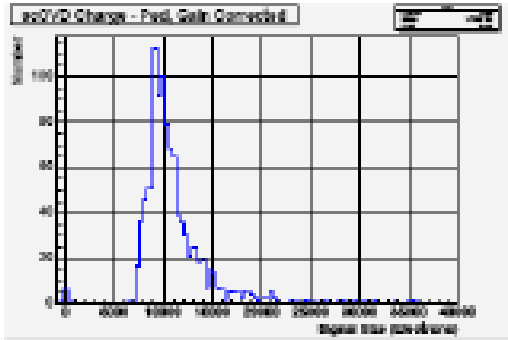


A w value of 12.8 eV/(eh)pair is derived from this

Pulse Height Spectrum with ^{90}Sr Source from 4 scCVD samples with different thicknesses

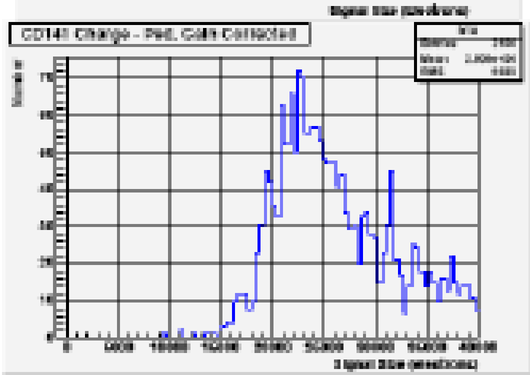
t = 210µm



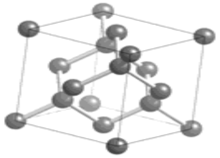


t = 320µm

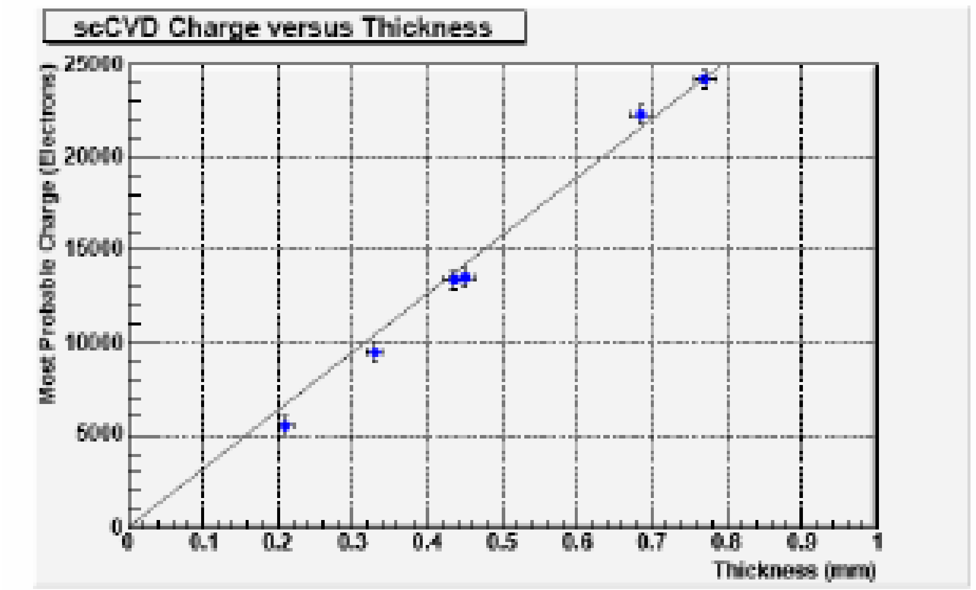
t = 435 µm



t = 685 µm

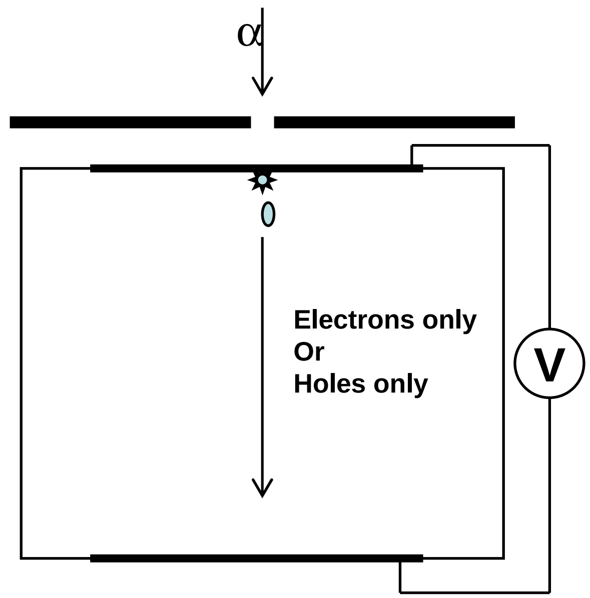


Most probable charge versus thickness of samples



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

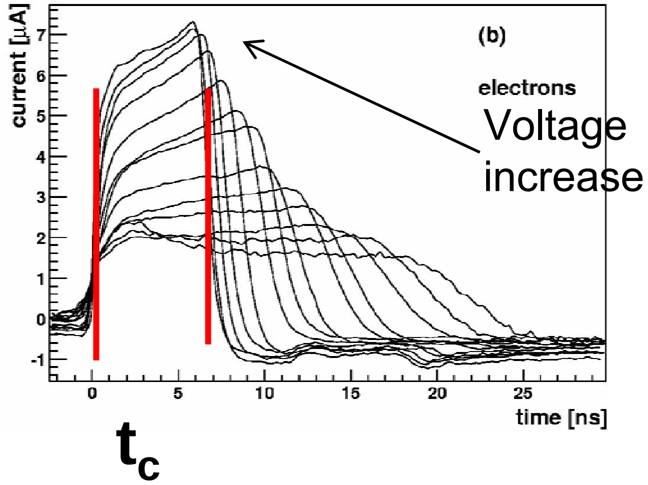


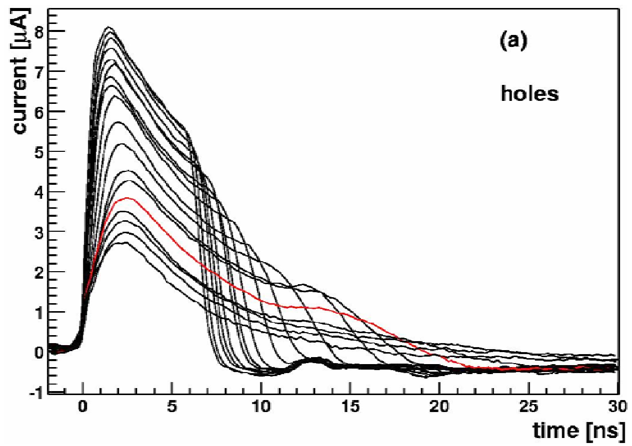
The pulse shape of the induced current is recorded
(**T**ransient **C**urrent **T**echnique)

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 for this sample
  - Charge trapping during drift if any
  - Space charge : decrease of current for holes / increase for electrons with time





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

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

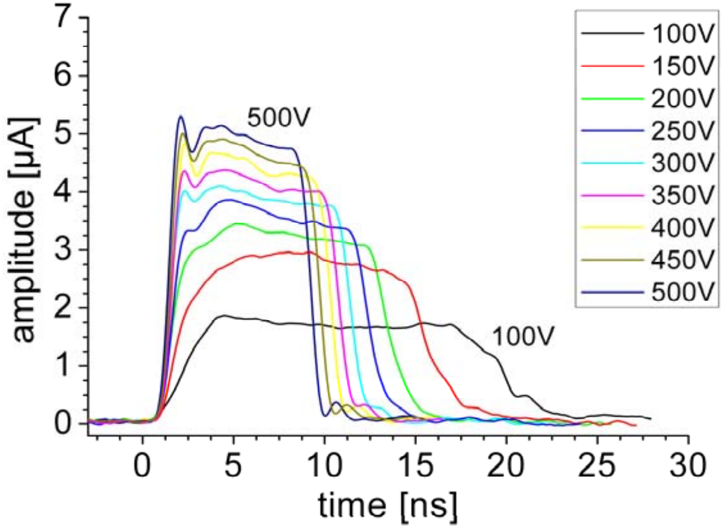
Another Single Crystal Sample from E6

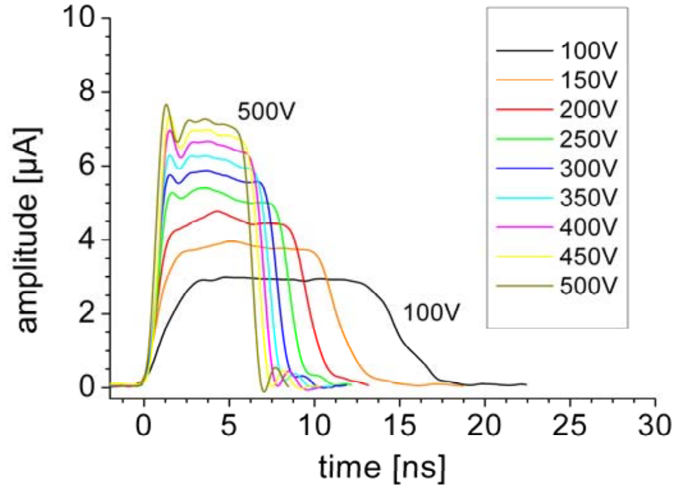
(measured in Bonn)

Indicates that the electric field in this sample is uniform➔ no space charge!

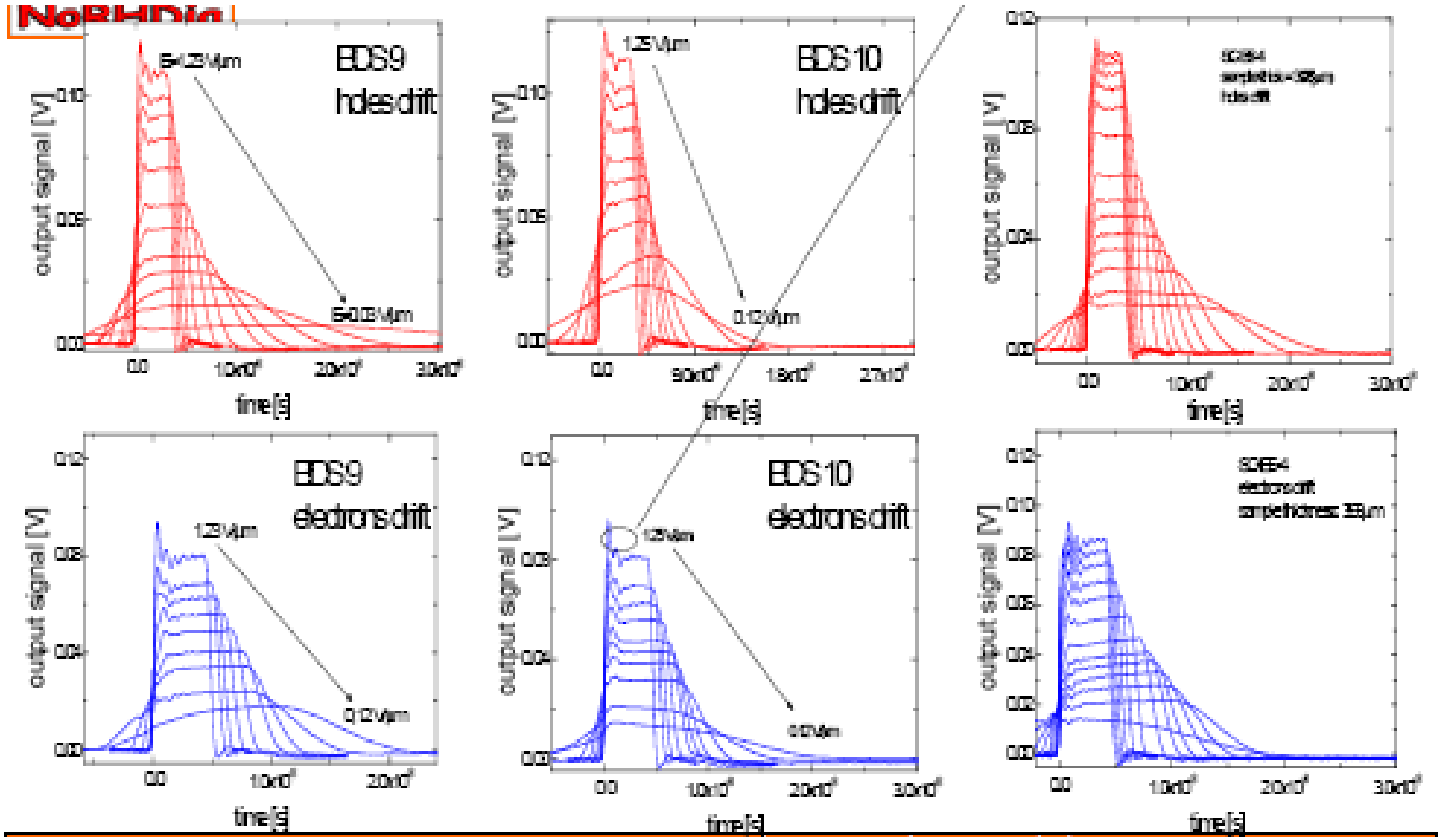
Electrons

Holes





Six more samples from E6 measured in GSI: also uniform electric field observed; This seems to be the normal case in Element6 scCVD samples



The measured drift velocity

- Average drift velocity for electrons and holes

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

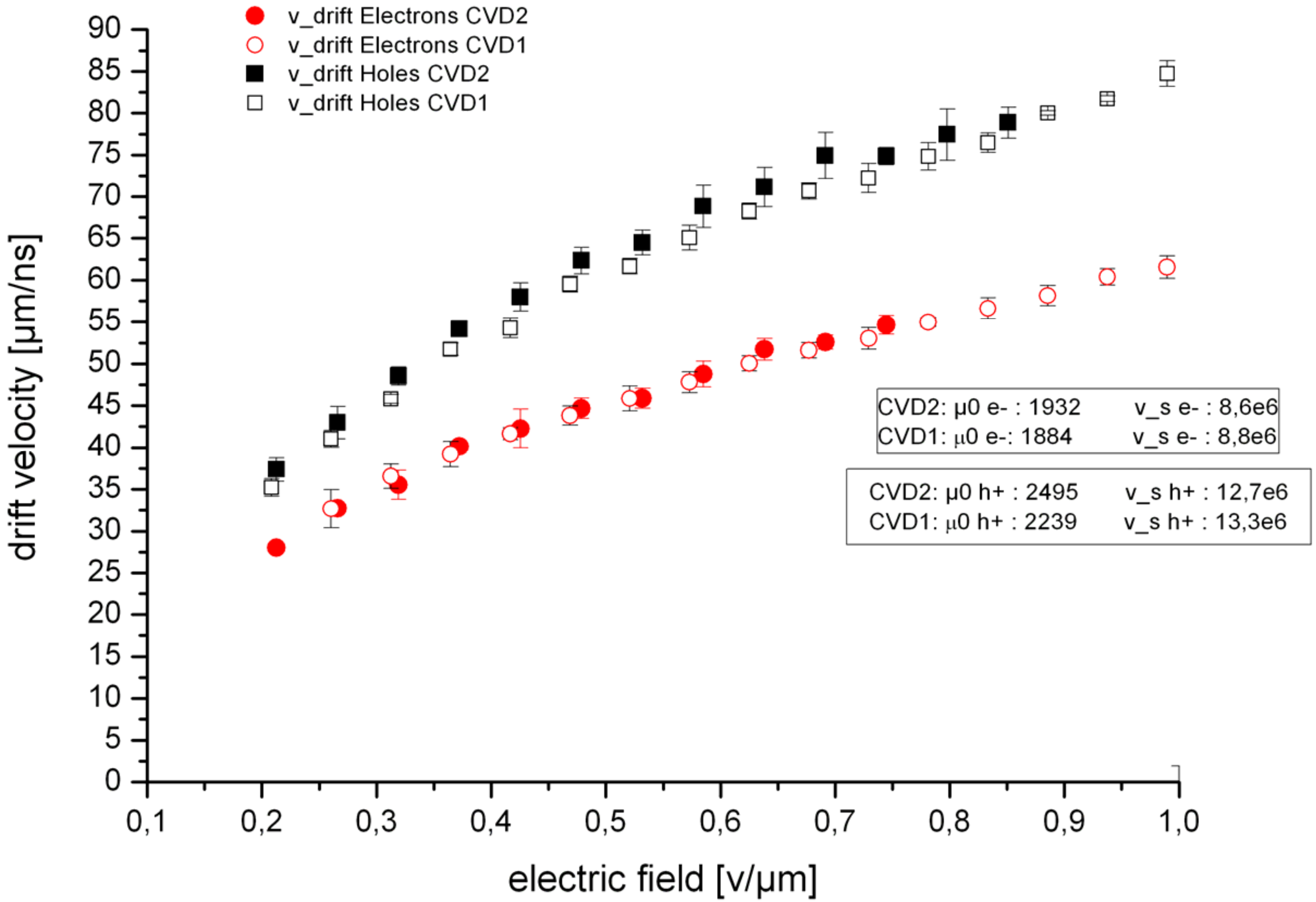
- Extract low field mobility μ_0 and saturation velocity v_s

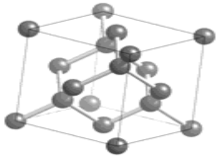
$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_s}}$$

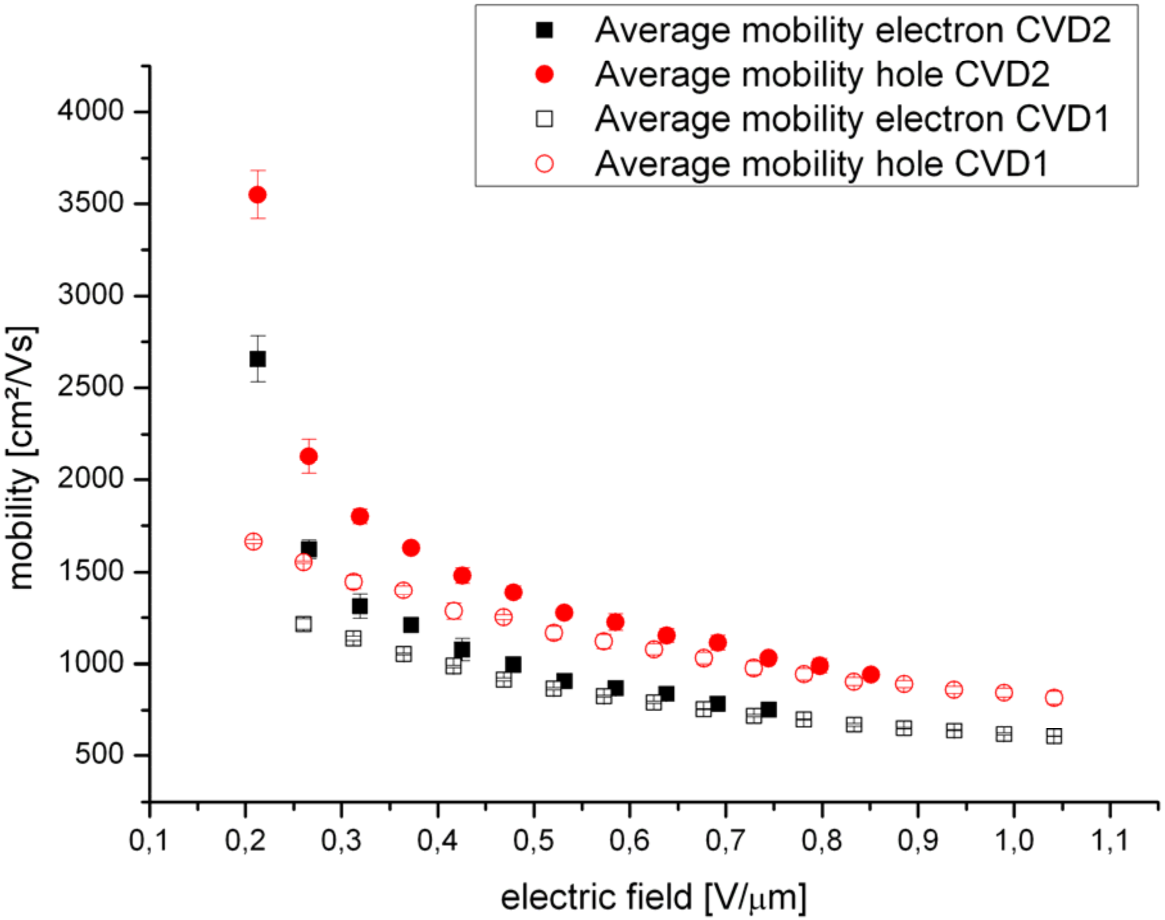
μ_0 for the 2 first samples:

  – Electrons: 1714 cm2/Vs and 1884 cm2/Vs
  – Holes: 2064 cm2/Vs and 2239 cm^2/Vs

- Saturation velocity:
  – Electrons: 0.96 10^7 cm/s and .88 x 10^7cm/s
  – Holes: 1.41 10^7 cm/s and 1.33 x 10^7 cm/s


v_drift Electrons CVD2
v_drift Electrons CVD1
v_drift Holes CVD2
v_drift Holes CVD1
CVD2: μ0 e- : 1932 v_s e- : 8,6e6
CVD1: μ0 e-: 1884 v_s e- : 8,8e6
CVD2: μ0 h+ : 2495 v_s h+ : 12,7e6
CVD1: μ0 h+ : 2239 v_s h+ : 13,3e6
drift velocity [μm/ns]
electric field [v/μm]

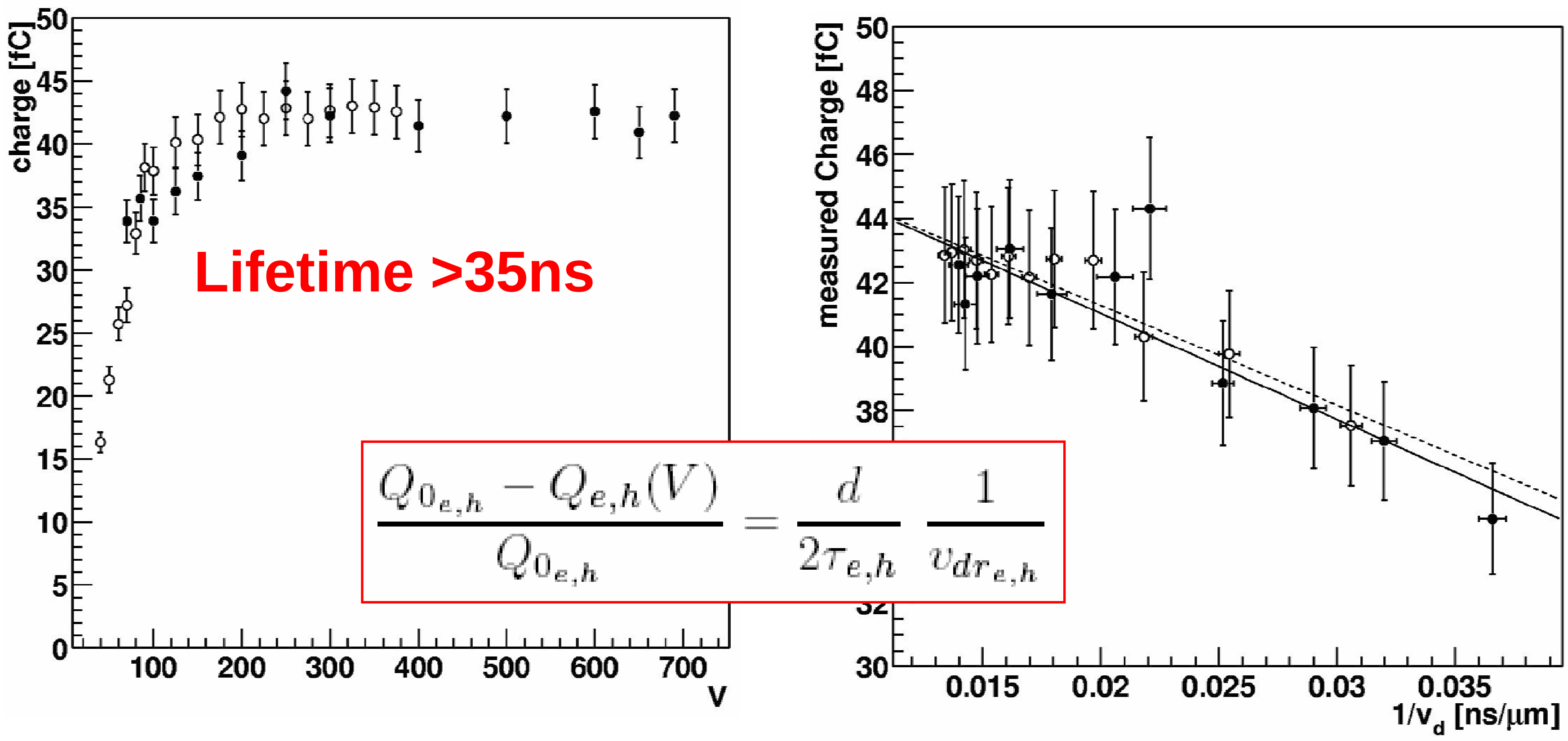




Average mobility electron CVD2
Average mobility hole CVD2
Average mobility electron CVD1
Average mobility hole CVD1
mobility [cm²/Vs]
4000
3500
3000
2500
2000
1500
1000
500
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
1,1
electric field [V/µm]

Preliminary carrier lifetime measurements

- Extract carrier lifetimes from measurement of total charge

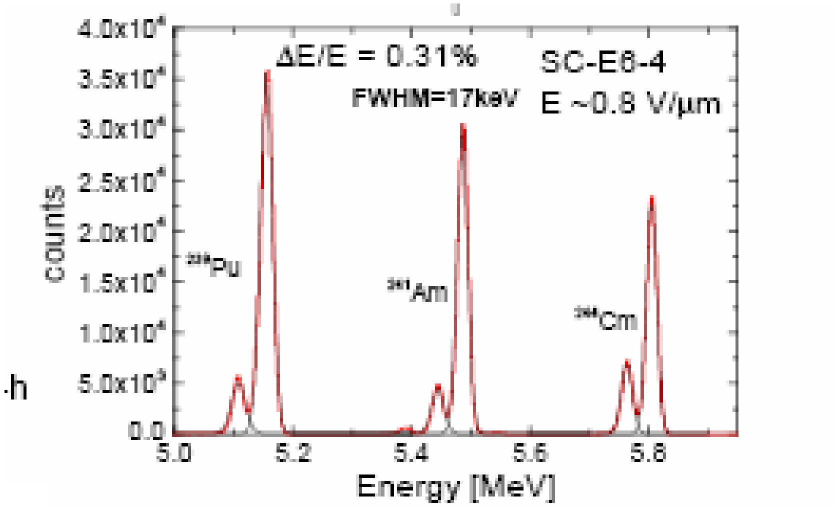


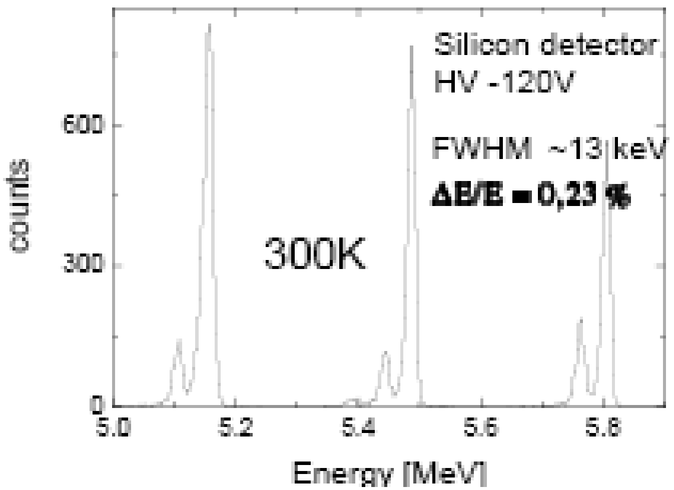
$$\frac{Q_{0_{e,h}} - Q_{e,h}(V)}{Q_{0_{e,h}}} = \frac{d}{2\tau_{e,h}} \frac{1}{v_{dr_{e,h}}}$$

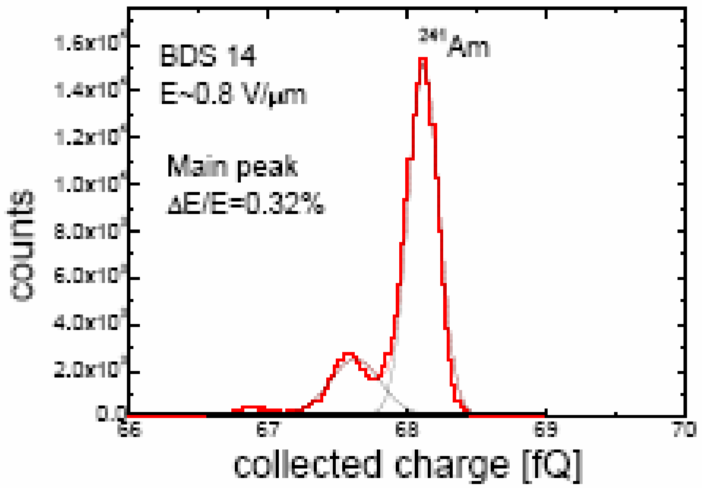
Charge trapping doesn't seem to limit signal lifetime -> full charge collection (for typical operation voltages and thickness)

More GSI Measurements on Spectroscopy

Energy resolution measured with sc CVD diamonds is close to what is achieved with silicon.



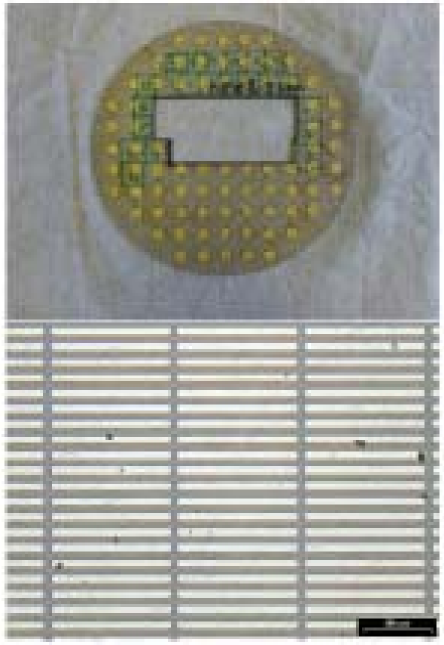


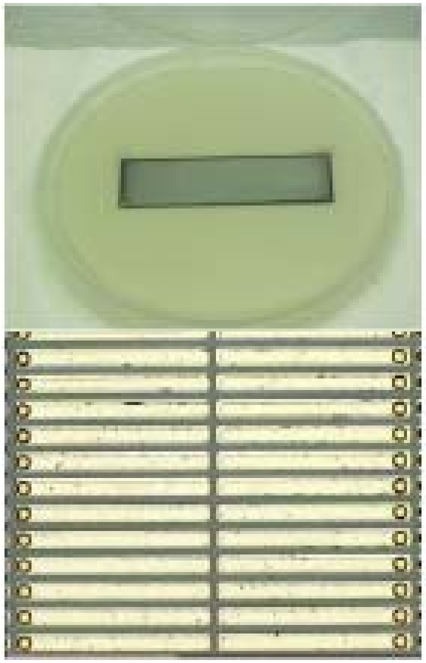


A full ATLAS Pixel Module with pCVD Diamond

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

A complete ATLAS pixel module has been assembled over the last two years

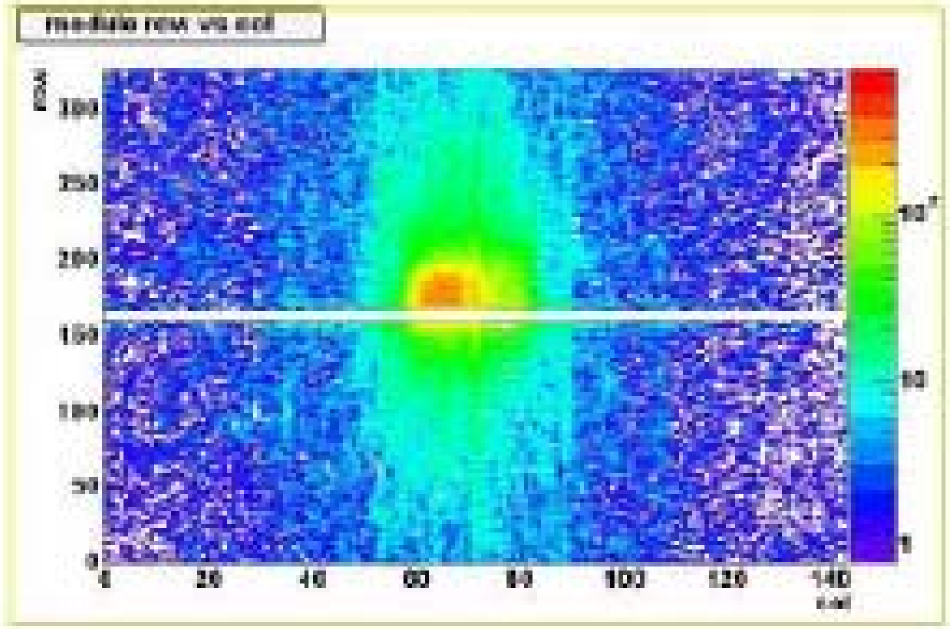




Module equipped with 16 fully radhard IBM readout chips

Several assembly steps

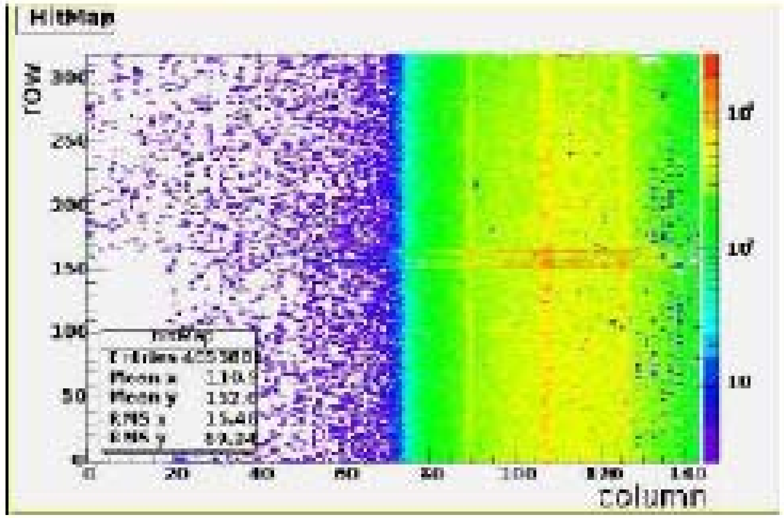
Very short test in the high energy ATLAS test beam at CERN



Beam profile

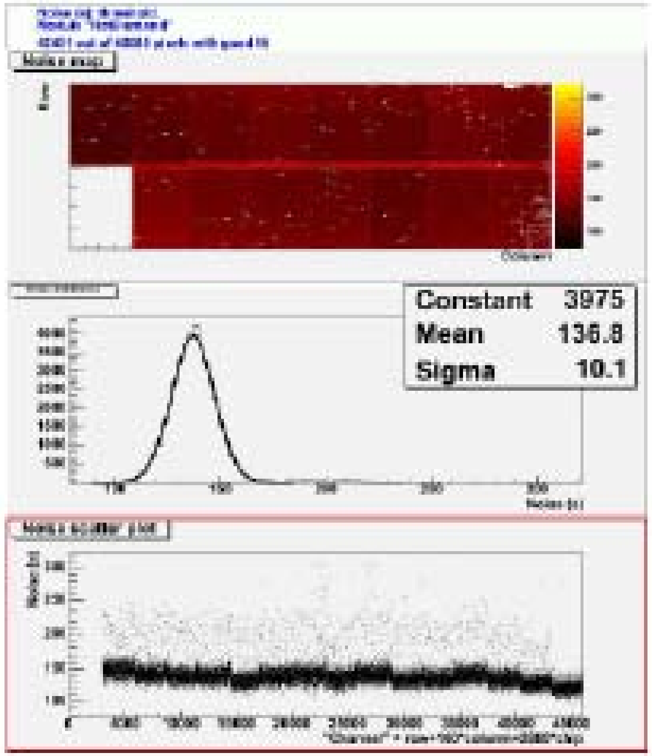
All channels are working

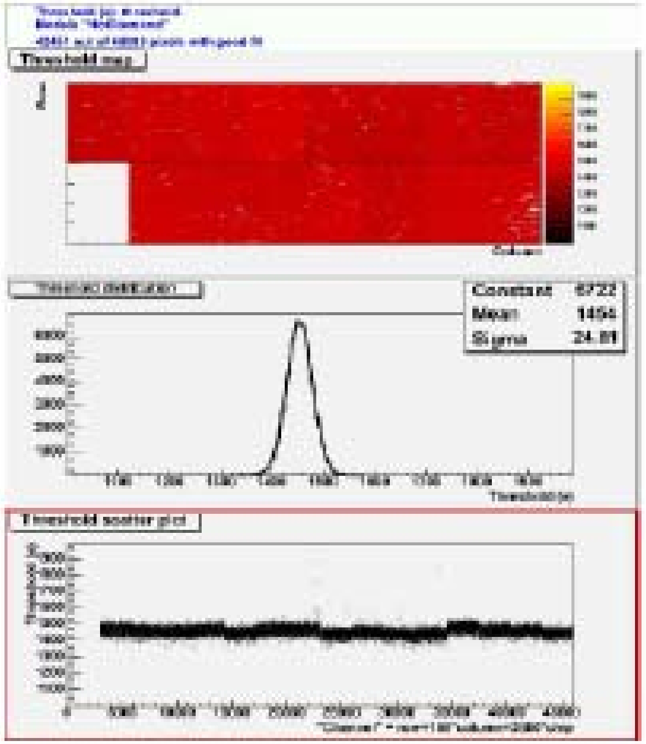
The ATLAS Pixel Module in a DESY Test Beam



Hit map is good The edge is the trigger scintillator

Noise and Threshold Plots

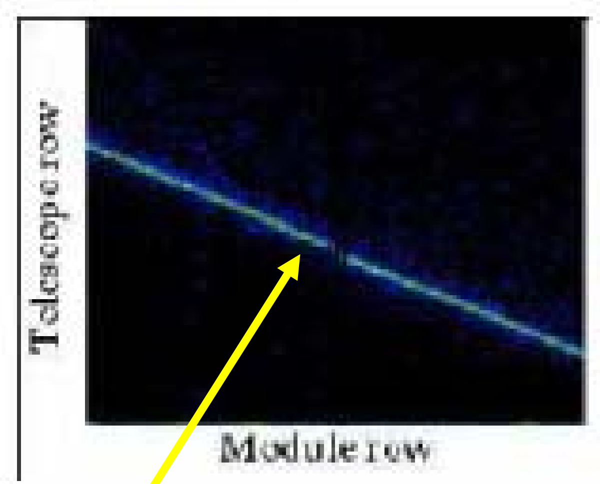




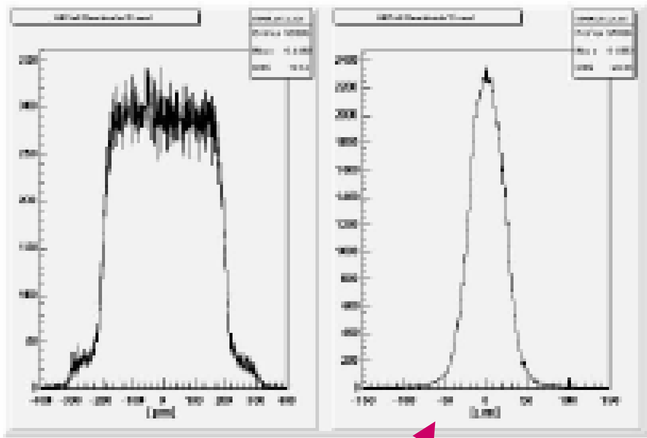
Results: Noise ~ 137 e- ENC Mean Threshold : 1450 e-

Threshold Spread ~ 25 e-

Correlation with Beam Telescope and Spatial Resolution



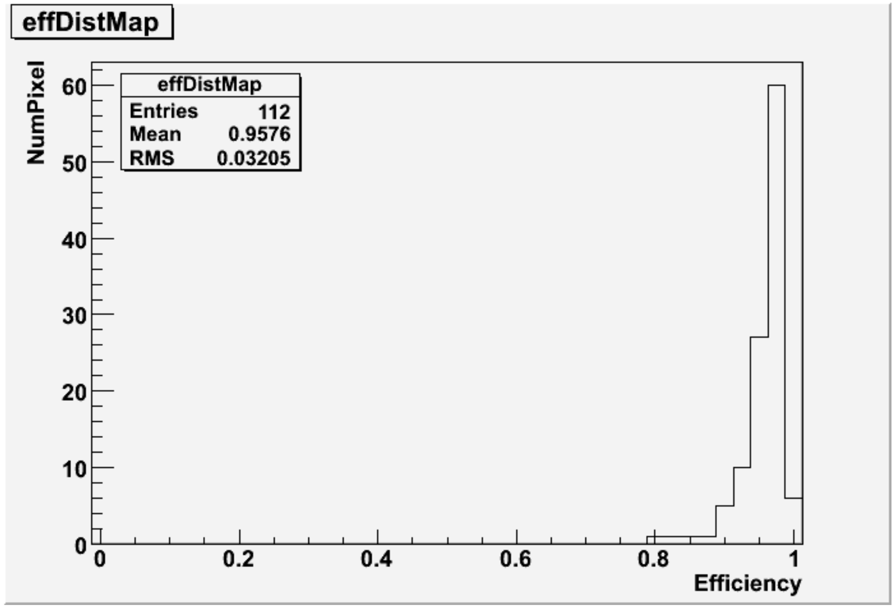
Correlation of hits in beam telescope and pixel module

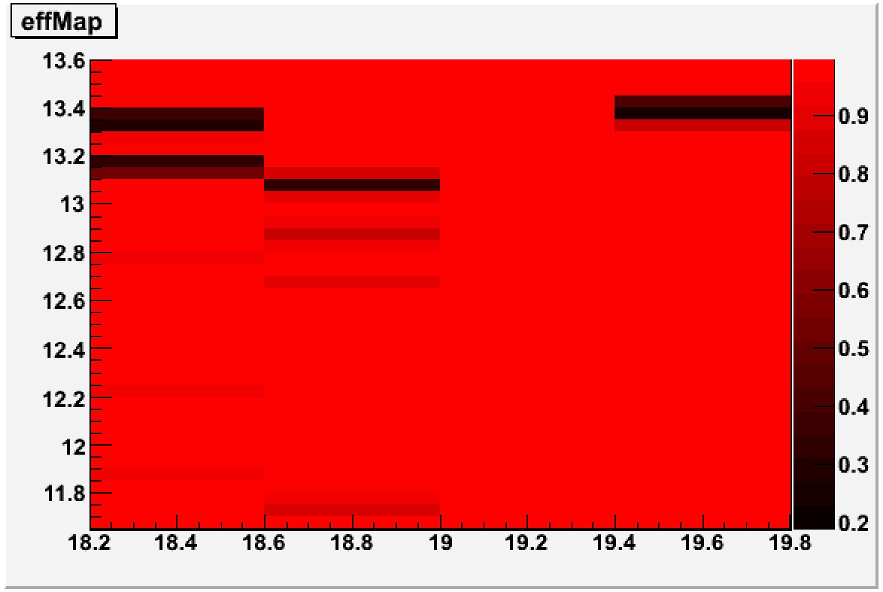


Residual is ~17 µm, includes multiple scattering (low energy electrons)

Efficiency is reasonably high

Above 97%





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

- Single particle counting
  - Detect min. ionizing particles
  - Benefits from fast diamond signal
  - Allows more sophisticated logic coincidences, timing measurements
- Requires fast electronics (GHz range) with very low noise
- Examples
  - Atlas Beam conditions monitor

The ATLAS Beam Conditioning Monitor (BCM)

Principle and Main Goals

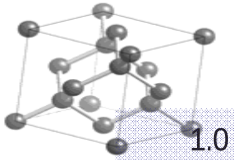
- Instantaneous measurement of beam conditions
  - interaction rate
  - background condition
  - warning/alarm/abort signals
- Measurement every BX
- Distinguish between interaction events and other events

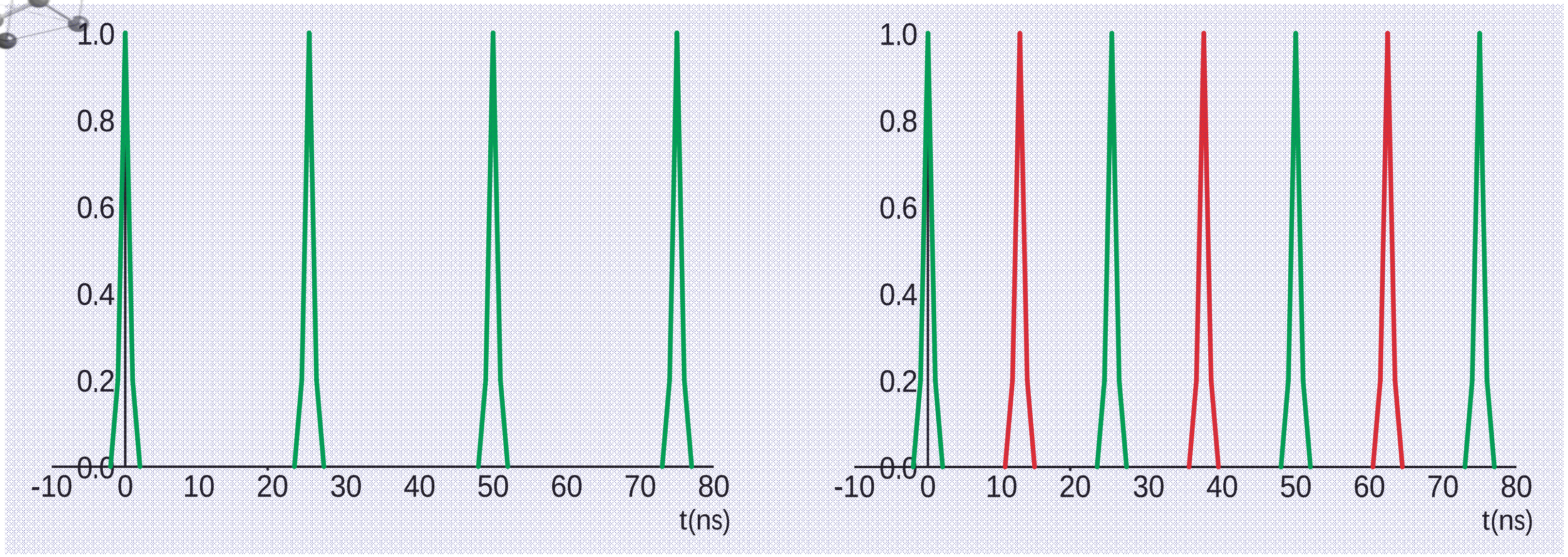
Set-Up in ATLAS Detector

▌ ▌ 2 detector stations, symmetric in z, $2z_0$ apart

··········▸ TAS (collimator) event: $\Delta t=2z_0/c$

◂·········▸ Interaction event: Δt = 0, 25, … ns



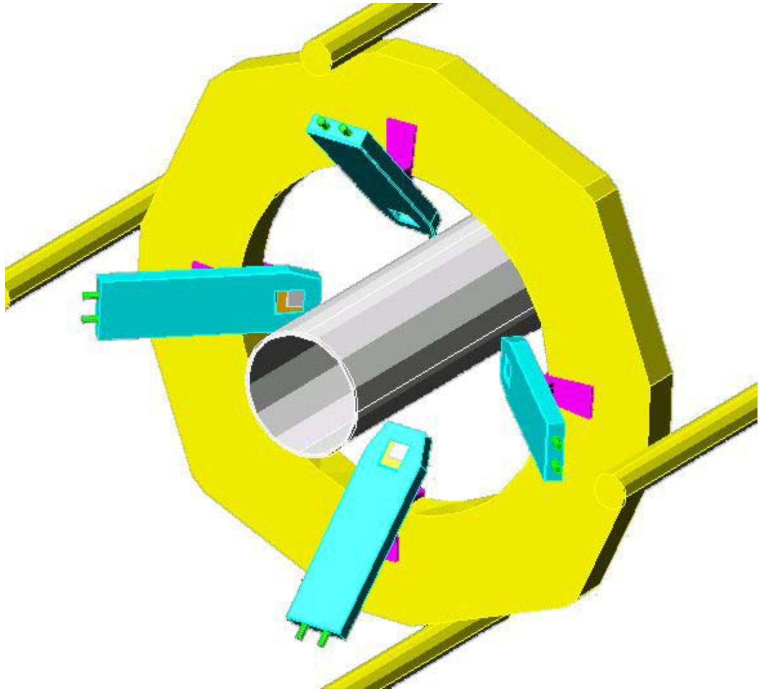


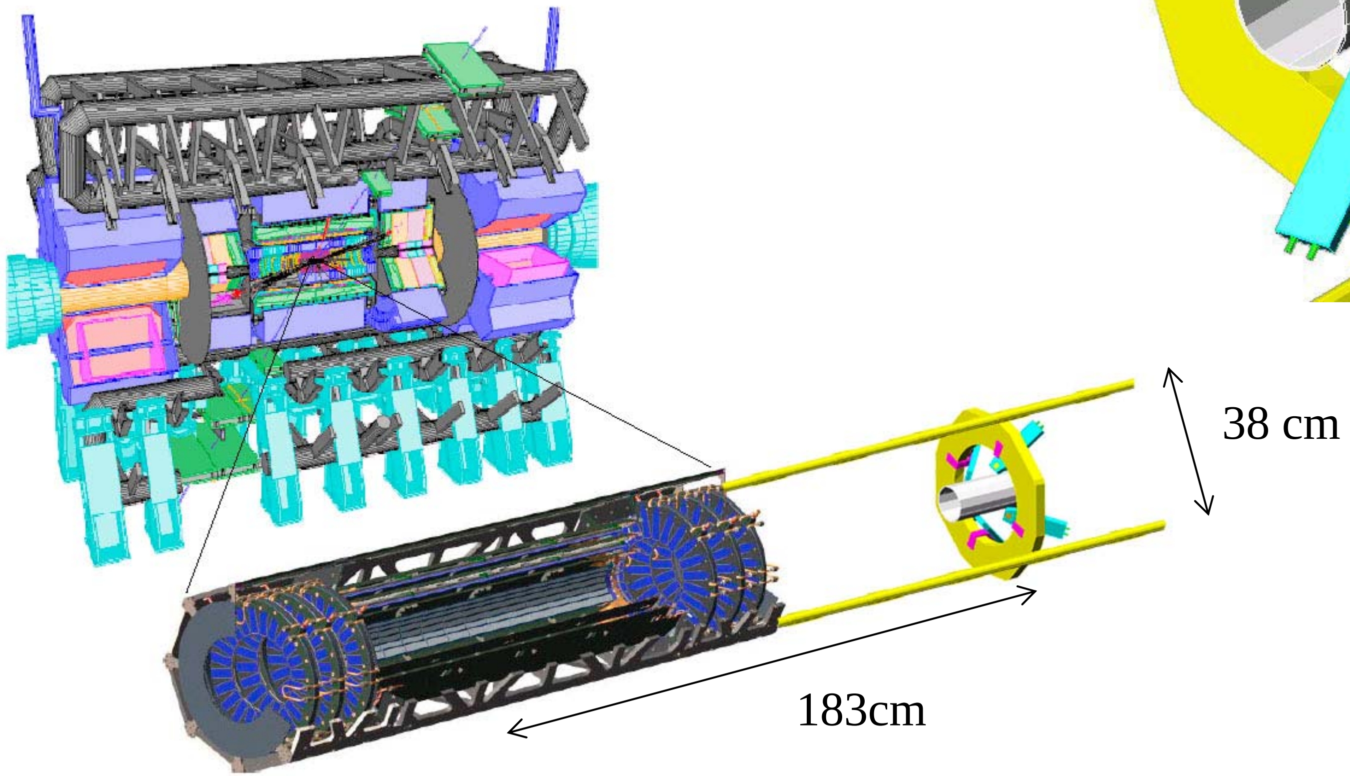
Baseline requirements: beam abort operation

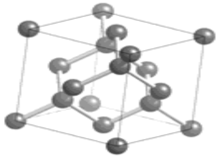
- one 7 TeV proton on TAS gives ~ 1 MIP/cm^2 inside PST
- Installation at Δt = 12.5 ns -› Δz = 3.75 m
- ➢ Rise-time < 1 ns
- ➢ Pulse-width < 3 ns
- ➢ Base-line restoration < 10 ns

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





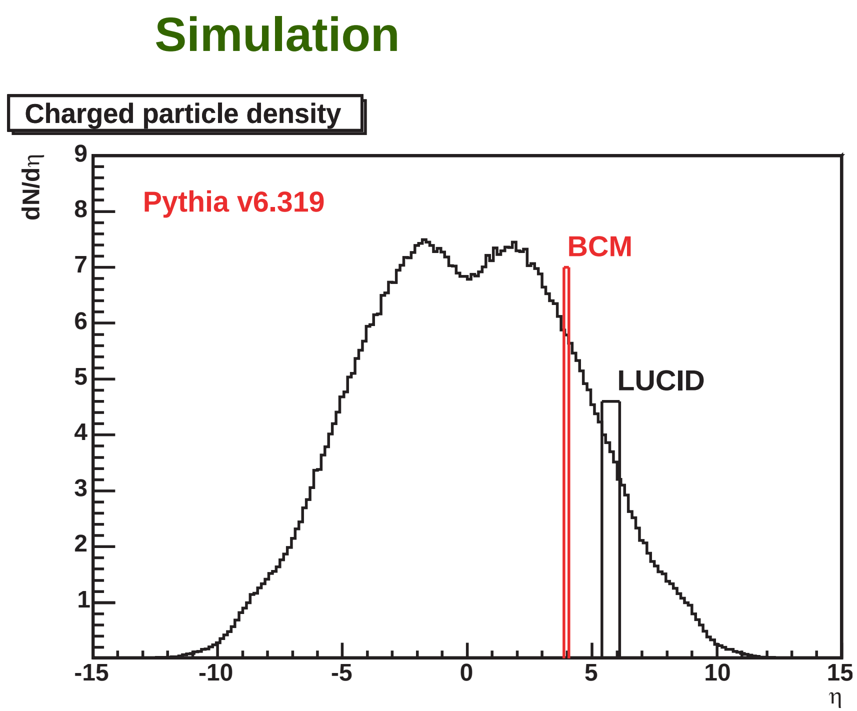


Requirements for luminosity determination

- additional to ATLAS main luminosity monitor LUCID

Single MIP sensitivity

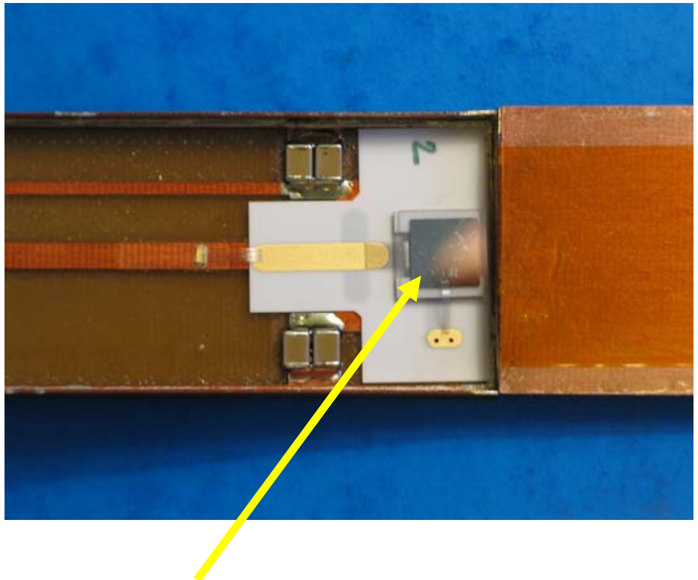
- Poisson with average of < 1 MIP per diamond detector
- S/N for MIP's ~10:1 before irradiation
- 4 detectors per station (coincidence)



Poly-CVD Diamonds as Sensors

- Radiation hard
  - Shown to withstand > 10^{15} p/cm^2
- Fast and short signal
  - High charge carrier velocity
  - Narrow pulses partially due to short charge lifetime
- Operates with a high drift field
  - Carrier velocity close to saturation velocity
- Very Low leakage current after irradiation
  - Does not require detector cooling

ATLASBCM Module

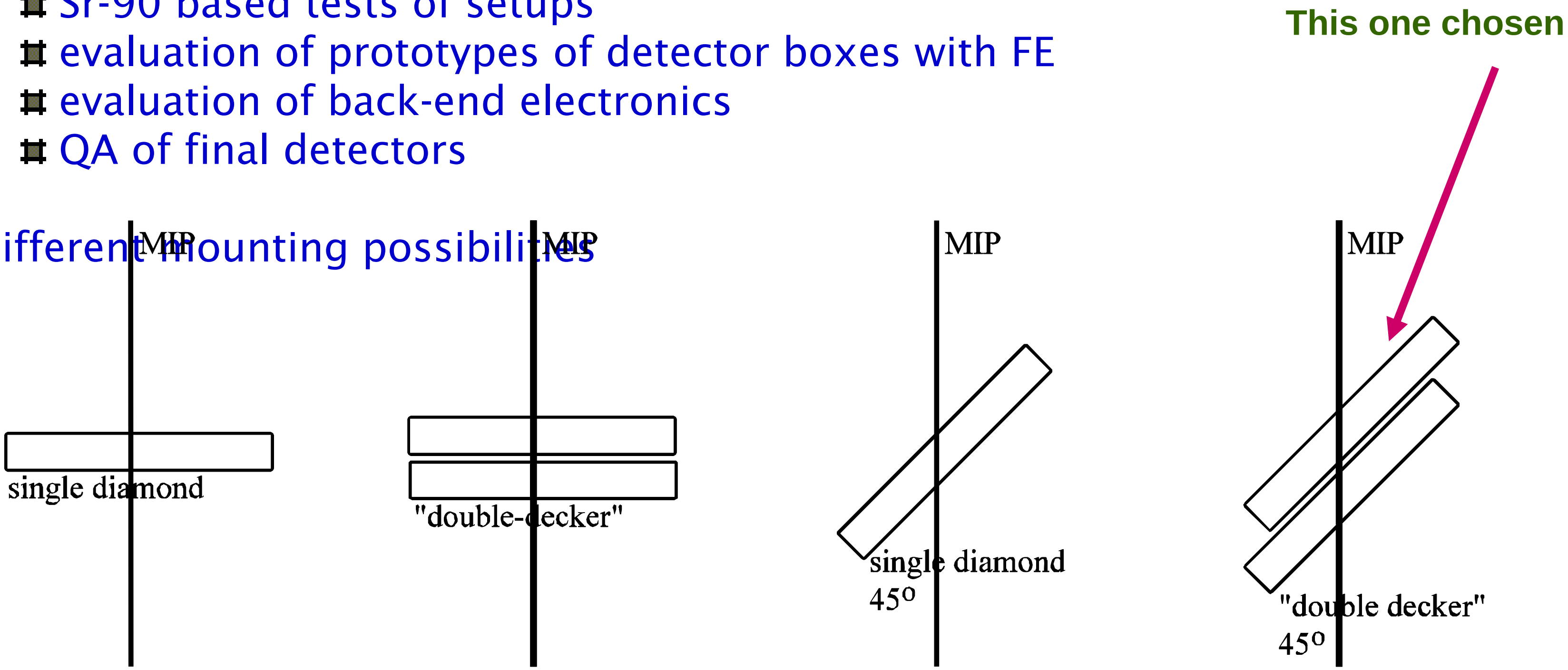


Many tests already done:

- beam-test measurements
  - evaluation of prototypes of detectors and FE electronics
  - Boston beam-test: May 2004
  - SPS CERN beam-test: November 2004
  - KEK test beam

- bench-tests
  - Sr-90 based tests of setups
  - evaluation of prototypes of detector boxes with FE
  - evaluation of back-end electronics
  - QA of final detectors

- different mounting possibilities

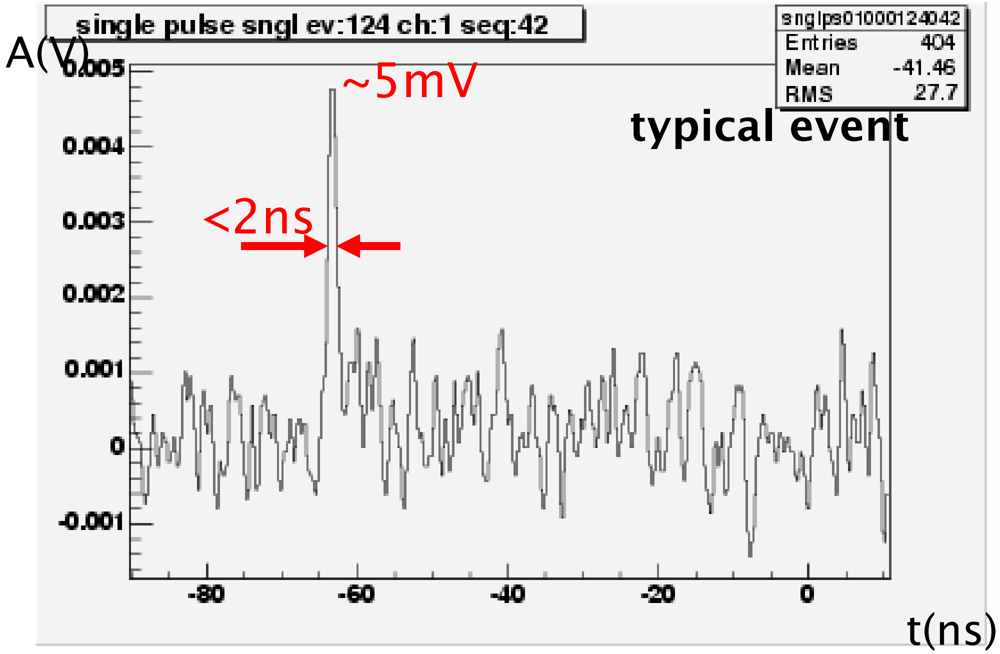


- irradiations of components

Some Results

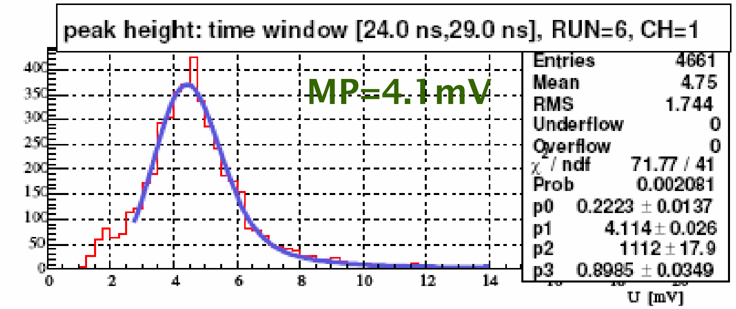
- **SPS H8 pion beam - MIP's**

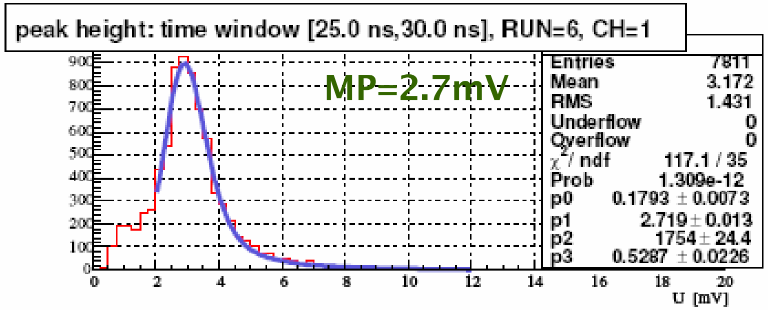
- **Diamond detectors**
  - 2 double-deckers:
    - CDS154+CDS155, w=360 μm
    - CDS159+CDS160, w=515 μm
  - HV Bias ~2 V/μm
  - Placed at 0° and 45°
- **2 scintillators for triggering**
- **LeCroy 1 GHz scope**



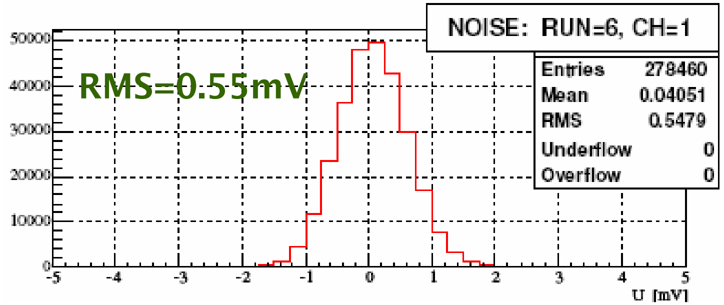
Limiting bandwidth on scope to 200 MHz **improves** S/N

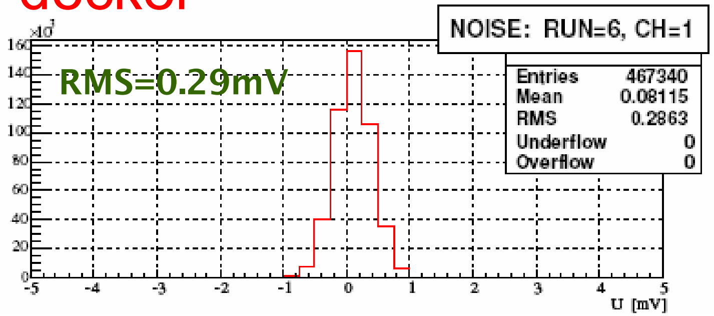
No bandwidth limit | **200 MHz bandwidth limit**



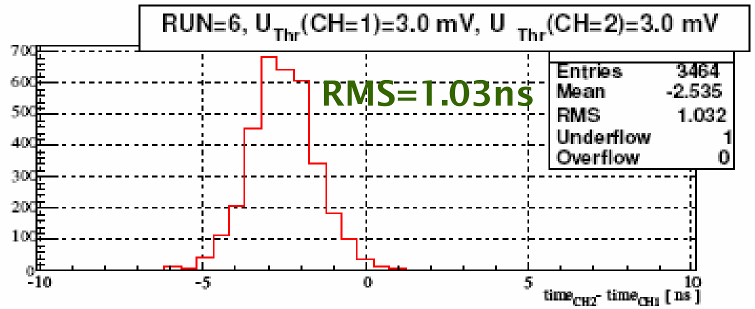


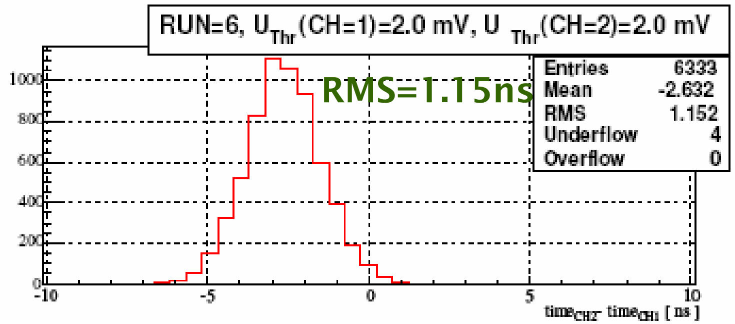
45° double-decker





SNR(MP) ~ 7.5:1 | **SNR(MP) ~ 9.2:1**



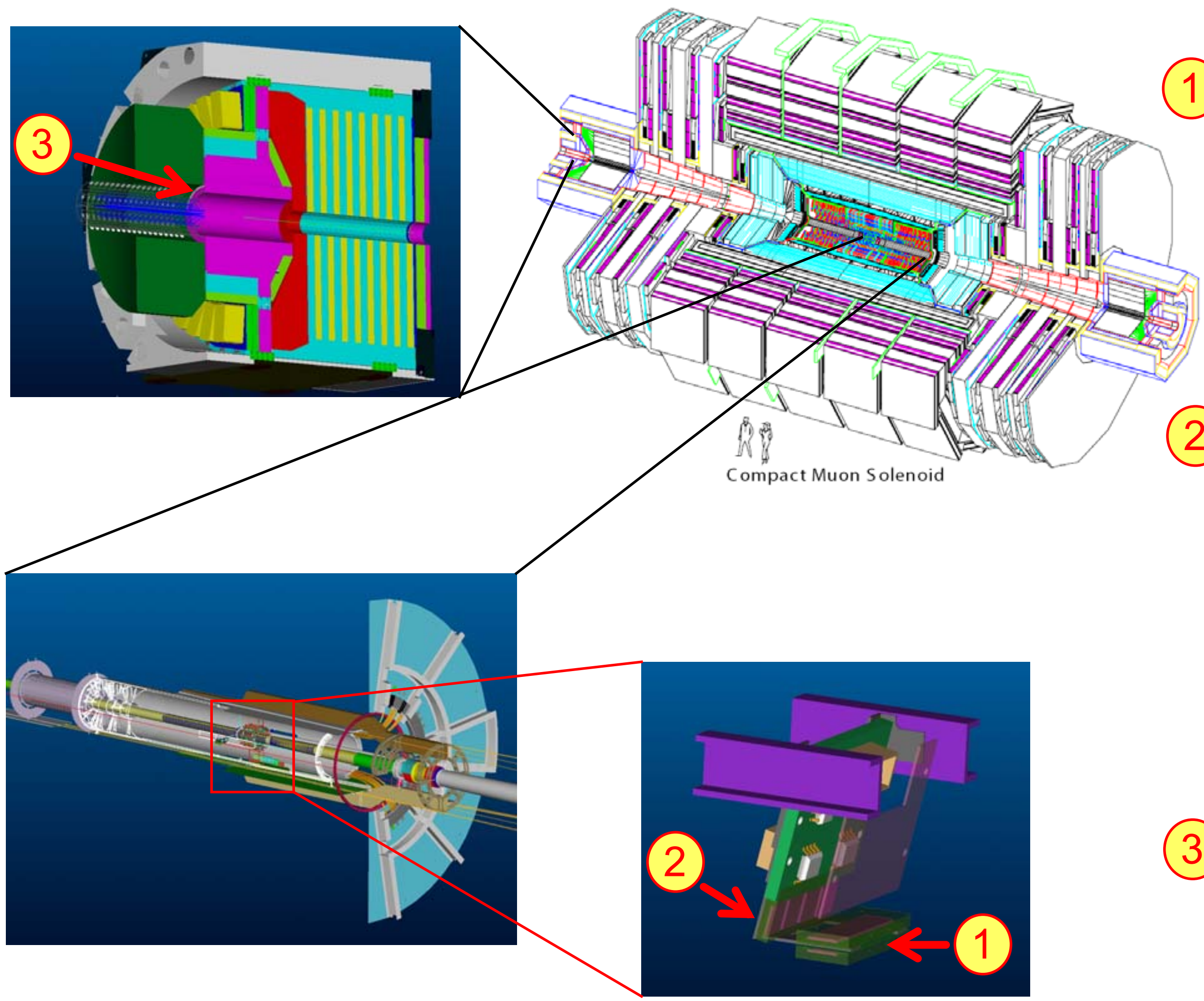


10 % worse timing

Diamonds in CMS: Overview

- CMS Milestones
  - May 2005:
    - CMS Endorses Beam Conditions Monitor (BCM) program
      - The BCM is an independent real time safety system to monitor beam conditions within the experimental volume.
      - Endorsement included approval of synthetic diamond as sensor choice
  - Oct 2005:
    - Successful Procurement Readiness Review:
      - Authorization for procurement of diamond
  - April 2006: Commissioning of BCM prototype units inside CDF
    - Use Tevatron environment to understand proton beam environment to optimize integration times and pre-commission the diamond response/alarm thresholds
  - April 2007: BCM Installation into CMS
- CMS_BCM Objectives for 2006
  - CMS BCM is looking to continue its development of poly and single crystal diamond for BCM applications in the LHC
    - Application to existing rad hard 0.25um front end electronics
    - Radiation and material properties studies, as still some features
    - Studies of irradiated sensor behaviour in strong magnetic field
  - Application of single crystal diamond to pixelized structures
    - development of a pixel telescope as a relative luminosity monitor

CMS Beam Conditions Monitor



CMS BCM Units

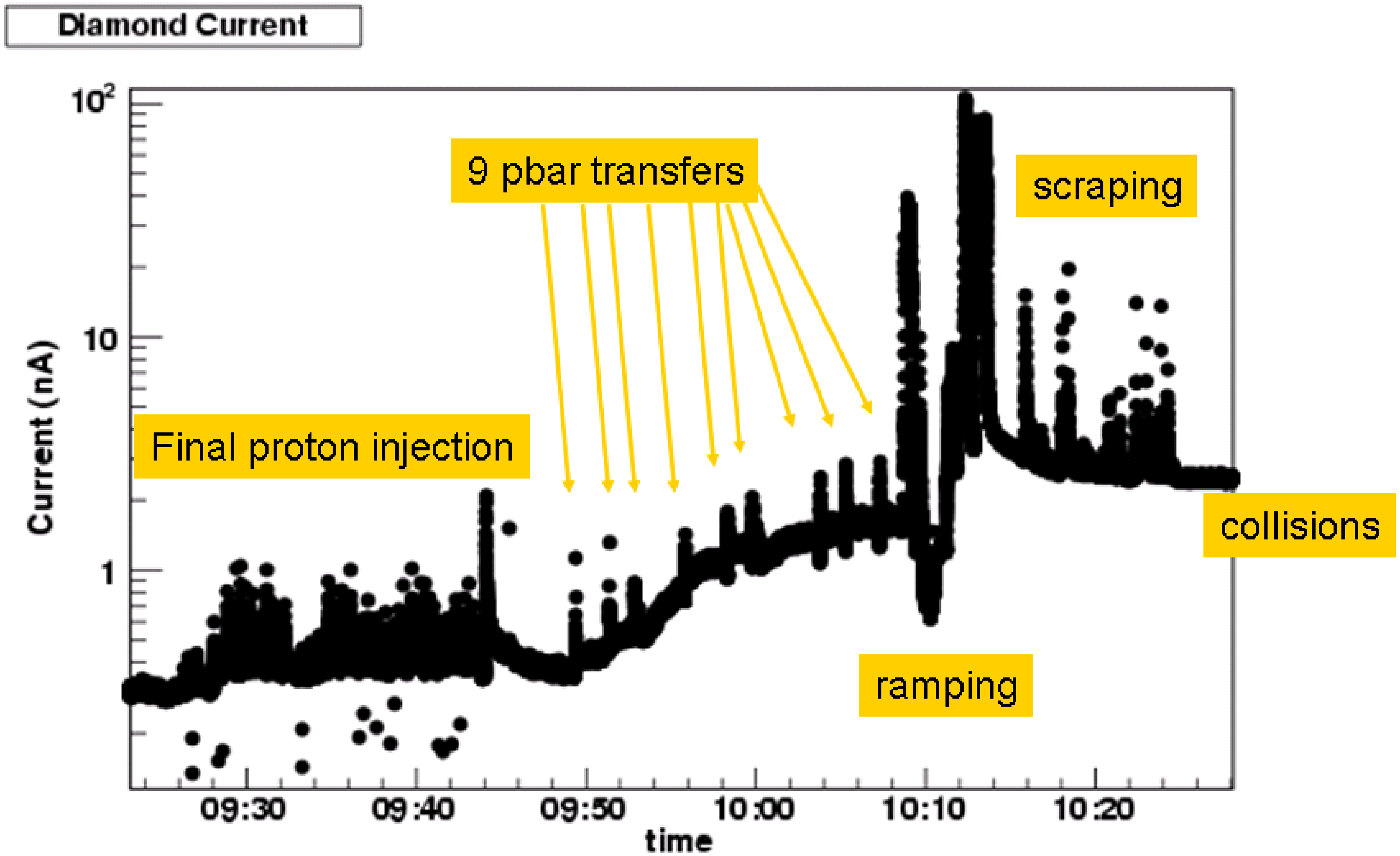
① **Leakage current monitor**
Location: z=±1.9m, r=4.5cm
4 stations in θ
Sensor: 1cm^2 PCVD Diamond
Readout: 10kHz

② **Fast BCM unit**
Location: z=±1.9m, r=4.3cm
4 stations in θ
Sensor: Single Crystal Diamond
Electronics: Analog+ optical
Readout: bunch by bunch

③ **Leakage current monitor**
Location: z=± 14.4m, r=29cm
8 stations in θ
Sensor: 1cm^2 PCVD Diamond
Readout: 10kHz
Sensors shielded from IP

2 Sensor Locations, 2 Monitoring Timescales

A CVD Diamond installed in CDF Experiment running since one year



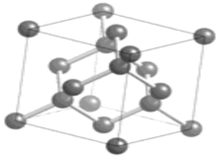
SUMMARY

pCVD diamond

- Collection distance now around 300 μm (as grown); reproducible material can be obtained on production reactor.
- Leakage current on good samples very low; still to improve understanding of contacts.
- Radiation hardness studies up to fluence of 1.8 x 10^{16} p/cm^2

scCVD diamond

- Many more samples available; material properties more stable
- Full charge collection on many samples
- Studies of material properties continued
  - Most samples now without space charge



- Mobilities and saturation velocities measured with good precision on many samples (μ_{0hole} = 2200 cm²/Vs and $\mu_{0electron}$ = 1800 cm²/Vs)
- Carrier lifetime is not limiting charge collection
- Good spectroscopy has been demonstrated

Applications

- **ATLAS Pixel Module**
  - Further beam tests in DESY: good performance
  - Efficiency > 97%
  - Spatial resolution in short direction <~ 22 μm
- **ATLAS BCM**
  - Performance of pCVD detectors work according to requirements
  - Installation should be completed in first half of 2006