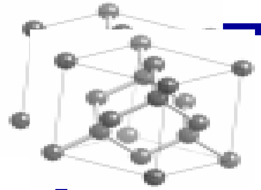

RD42 STATUS REPORT

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

presented by

P. Weilhammer
CERN/Ohio State University/University of PERUGIA

For the RD42 COLLABORATION

RD42 COLLABORATION

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Outline

- Motivation

- A Short Course on Synthetic Diamond

- Summary of RD42 Results: Old and New

- First R&D to use diamonds as beam monitors
    - In HEP
        - Beam steering
        - Beam abort
    - For Hadron Therapy: beam positioning

- Summary

Main Motivation for R&D on CVD Diamond Material

- At LHC and SLHC radiation levels for inner tracking layers are predicted to be extremelyhigh

- CVD Diamond material has promise to be exceptionally radiation hard

- Good material candidate for development of tracking detectors surviving significantly higher radiation doses than warm (“cool”) silicon.

- Tracking information as close as possible to the interaction point is most valuable, especially for vertex finding:
    - Diamond pixel detector
    - Beam monitoring and abort

A Short Course on Synthetic CVD Diamond

Some Material Properties of Diamond

	Diamond	Silicon
Band Gap [eV]	5.47	1.12
Resistivity [Ωcm]	$>10^{11}$	2.3×10^{5}
Ionisation Energy [eV]	13	3.6
Ionisation Density MIP [eh/mm]	36	89
Break-down Field [V/cm]	10^{7}	3×10^{5}
μ_e [cm^2/Vs]	1800	1450
M_h [cm^2/Vs]	1200	480
Density [g/cm^3]	3.52	2.33
ε	5.7	11.9
Radiation Length	12.2	9.4
Average charge created/100μm	3600	8900
Charge lifetime (un-irradiated)	Short	Infinite
Leakage current(~ T = 300Deg)	extr. Low	low. But with dose ↗

Important Properties for Tracking:

GOOD

Both electron and hole velocities are high

At E = 1 V/μm ➔ Diamond= 1.7 x 10^7 cm/sec

➔ Silicon = ~ 8 x 10^6 cm/sec

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

Diamond has 1.3 times less radiation length compared with Si

“Good” CVD Diamond is an insulator with Resistivity greater than 10^{14} Ωcm.

Leakage current: I_{leak} <~ 100pA/cm^2 for a 500μm thick sample.

➔ Low load capacitances are limiting electronic noise

BAD

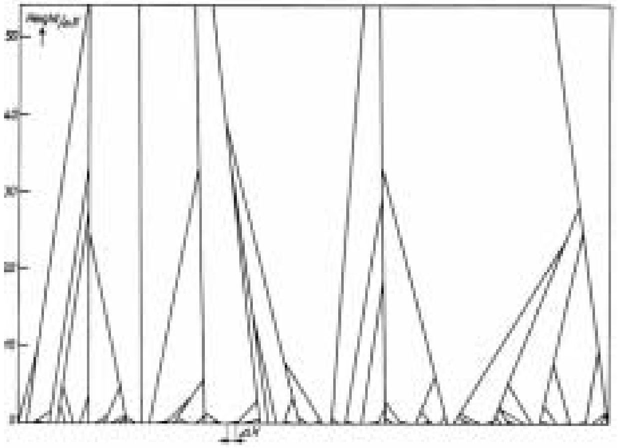
The **generated charge** in diamond is **3600** electron- hole pairs per 100 μm compared with **10600** electron hole pairs in Si.

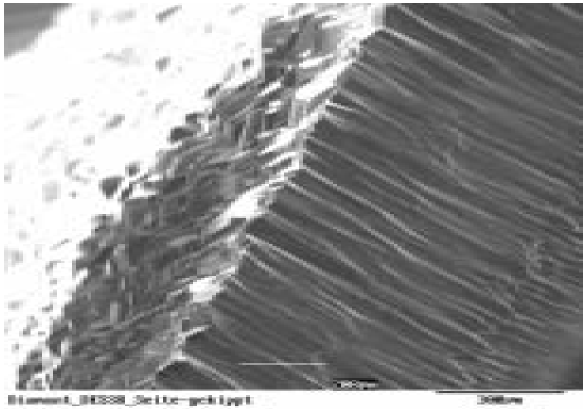
Slightly more favorable when one compares **generated charge per .3% of radiation length**:

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

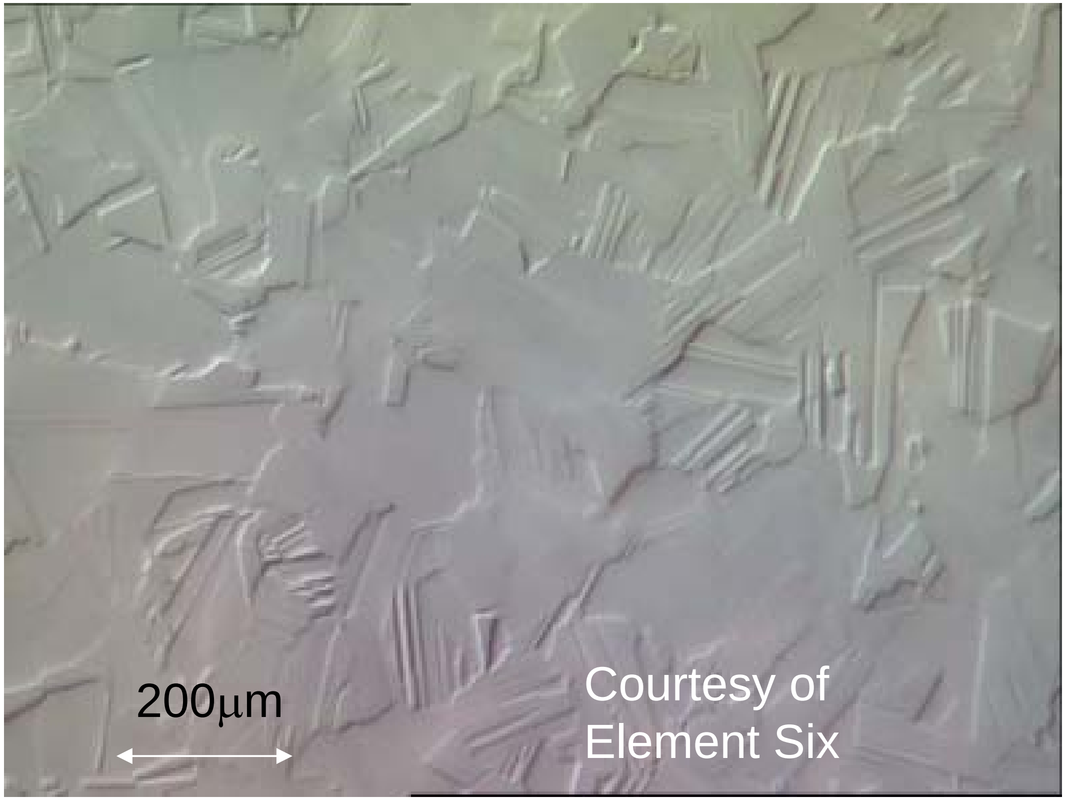
Lifetime of both holes and electrons is smaller than the transit time at 1V/μm (in un-irradiated silicon lifetime is 10's of ms)

- Diamond material
  - Synthetic diamond
  - Chemical Vapour Deposition
  - Polycrystalline films



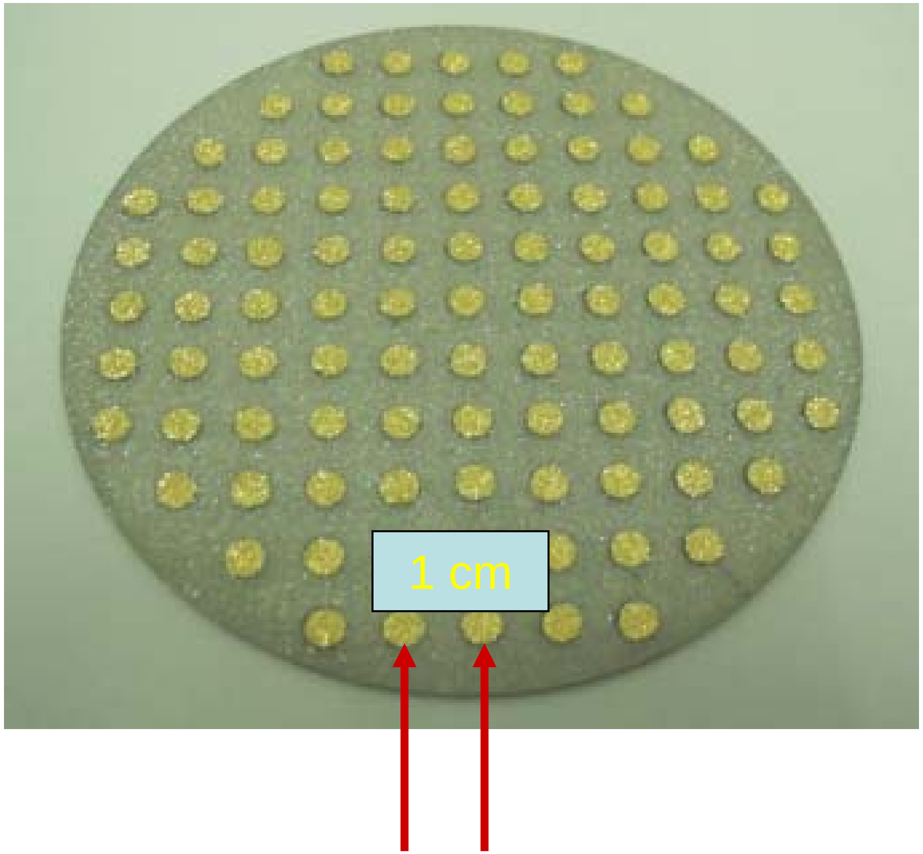


Growth Side of a recent polycrystalline CVD diamond



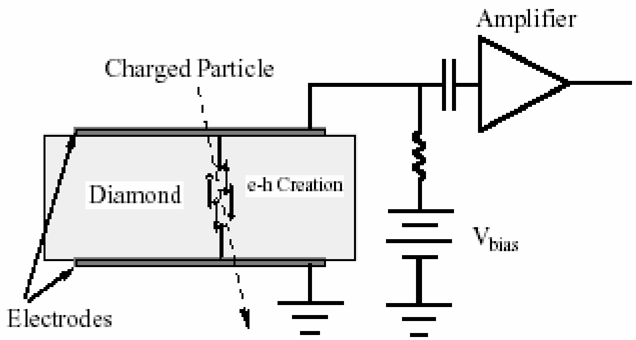
"DeBeer Industrial Diamonds" has become "Element6"

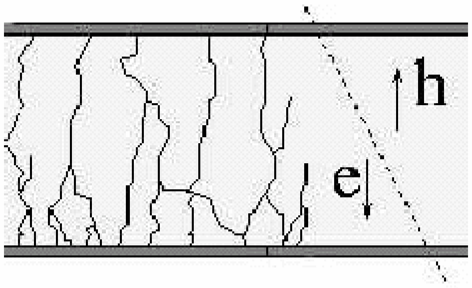
- Large Wafer Production (5”) possible



Signal Formation and Collection Distance

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

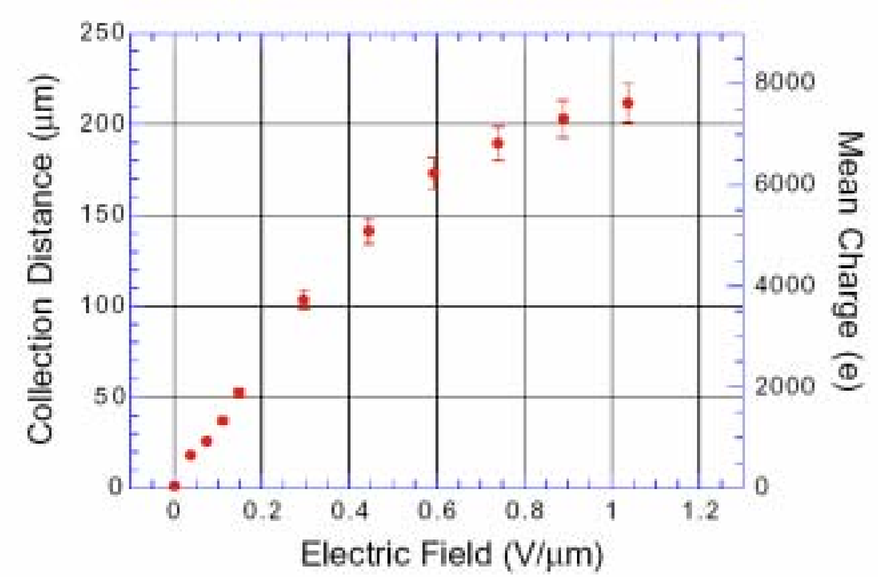
Signal versus applied Field:

Saturation above 1 V/μm.

Shape governed by μ(E) dependence.

Metallization typically
is a carbide former plus over-metal like
Cr/Au
Ti/Au
Ti/Pt/Au
Ti/W

New much better process used recently:
Non carbide former
Results are very regular

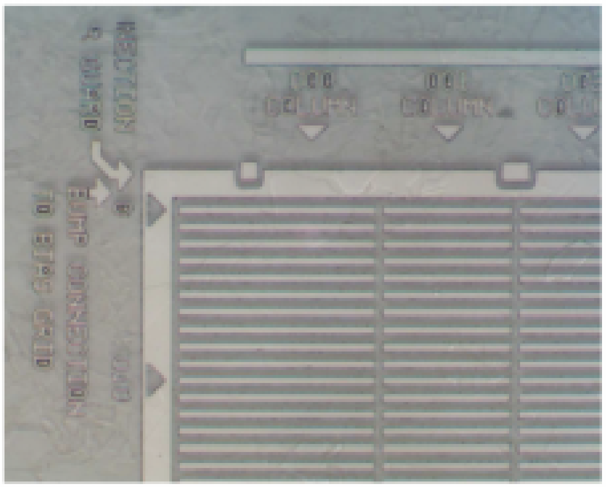


Types of DETECTORS RD42 IS WORKING WITH

- Dot detectors
  - Characterization
- Strip detectors
  - Tracking
  - Slow VA2 for beam test and fast SCTA LHC electronics
  - Irradiated and non-irradiated
- Pixel detectors
  - Tracking
  - CMS and Atlas patterns / electronics

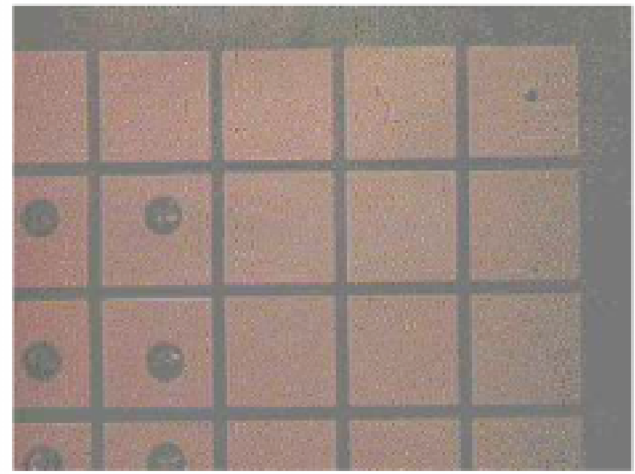
Diamond Pixel Detectors

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)



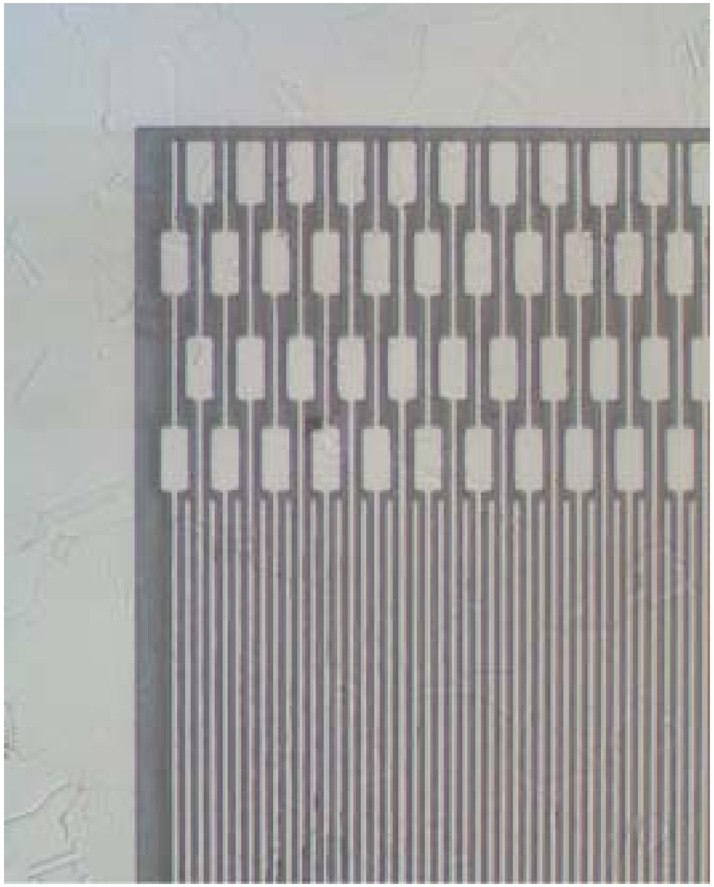
- CMS pixel pitch $125\mu m \times 125\mu m$
- Metalization: Ti/W
- Indium bumping at UC Davis

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

New radiation hard chips produced this year.

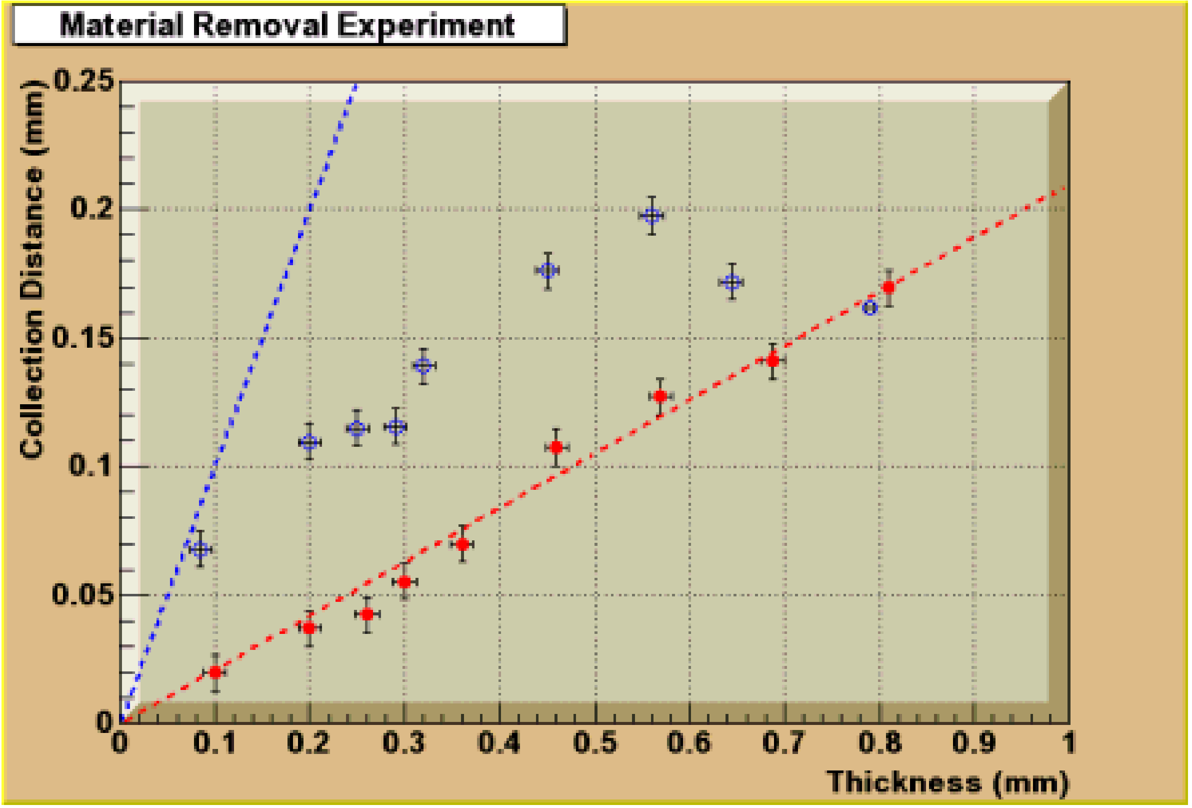
Next Step:
Biased intermediate strips to benefit from charge sharing.
Should improve resolution.

Data have been taken recently.
Analysis still to be done



Overview of RD42 Results: Old and New

Thinning Experiment

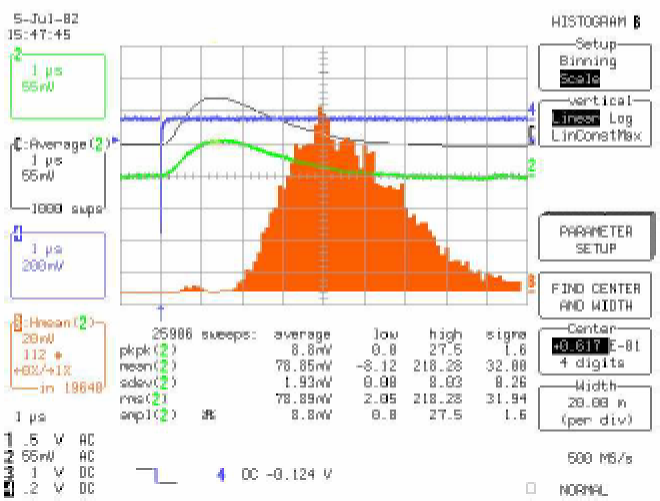


Gain knowledge on CCD properties during growth

A diamond sample from one of the recent productions

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

Latest Diamonds Measured with a ^{90}Sr Source:

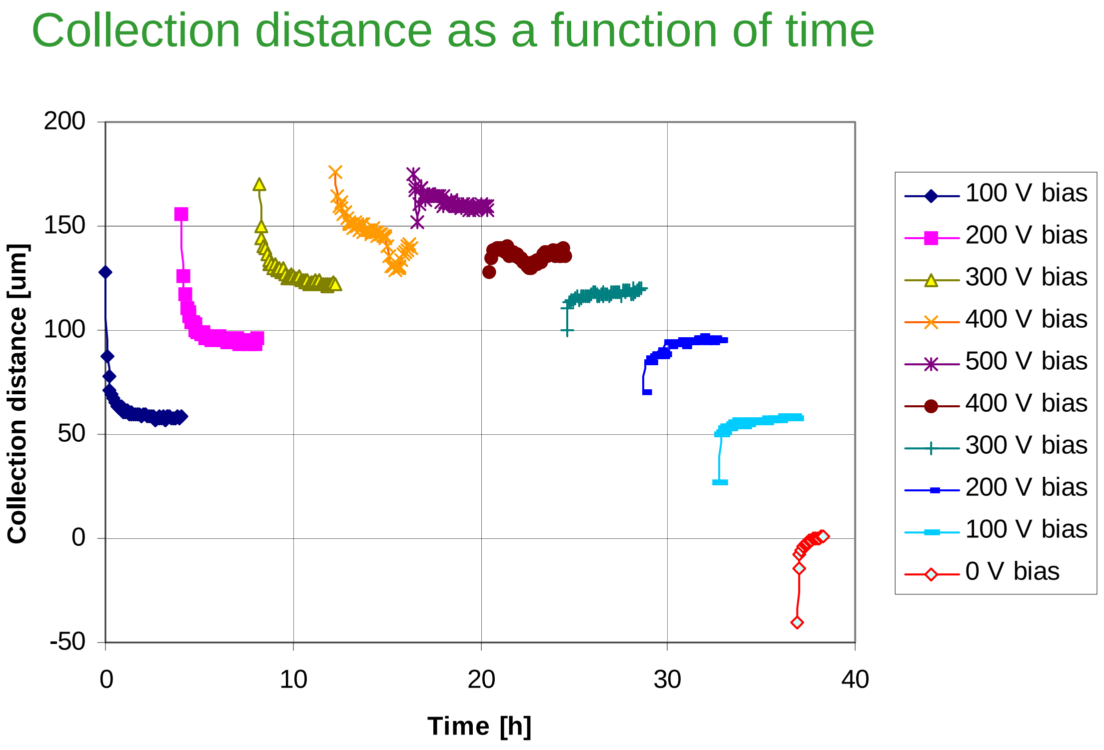


- System Gain $= 124\ e/\mathrm{mV}$
- $Q_{MP} = 62\mathrm{mV} = 7600e$
- Mean Charge $= 79\mathrm{mV} = 9800e$

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

The Research program worked!

At CERN the diamond characterization station has been rebuilt. Full automatic readout of wave forms . Wave form analysis



Radiation Hardness

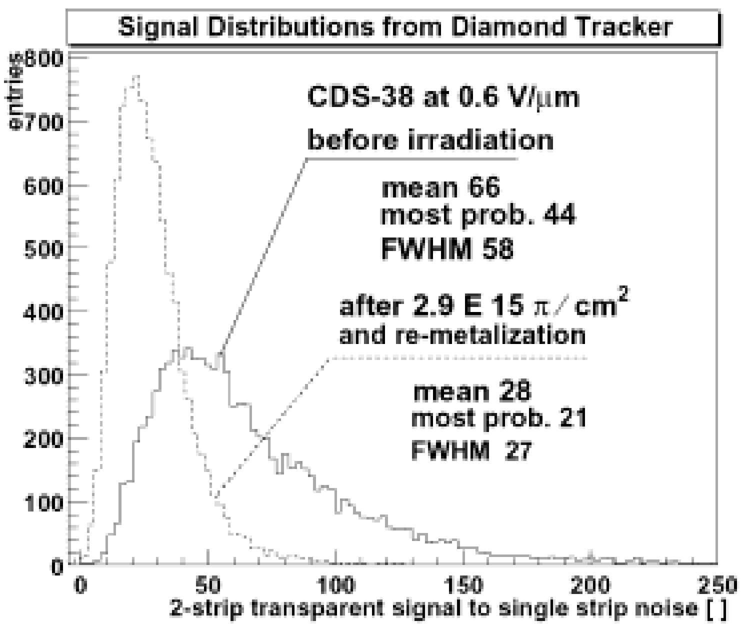
- Studied with Protons, Neutrons and Pions on pCVD Strip Detectors
- Fluences of 2-3 10^{15} particles/cm^2
- Generally decrease of leakage current with dose observed.
- Resolution of Strip detectors gets better with fluence.
- 300 MeV Pions damage more than 27 GeV protons.

  ➔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

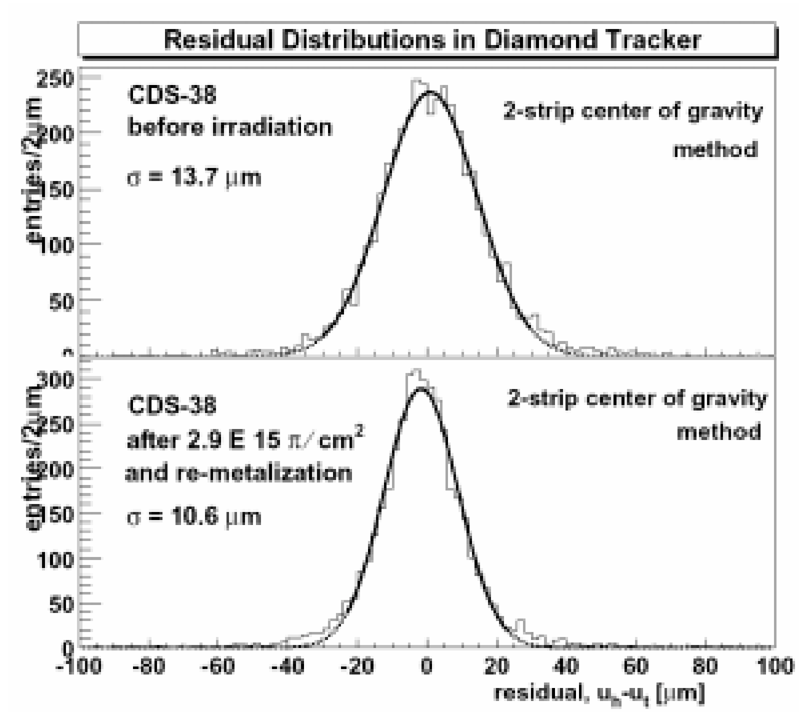
- No loss seen for EM radiation up to 10MGy.
  (Behnke et al., Nucl.Instrum.Meth. A489 (2002) 230-240.)

Pion Irradiation Results

Landau Distribution before and after irradiation



Spatial Resolution

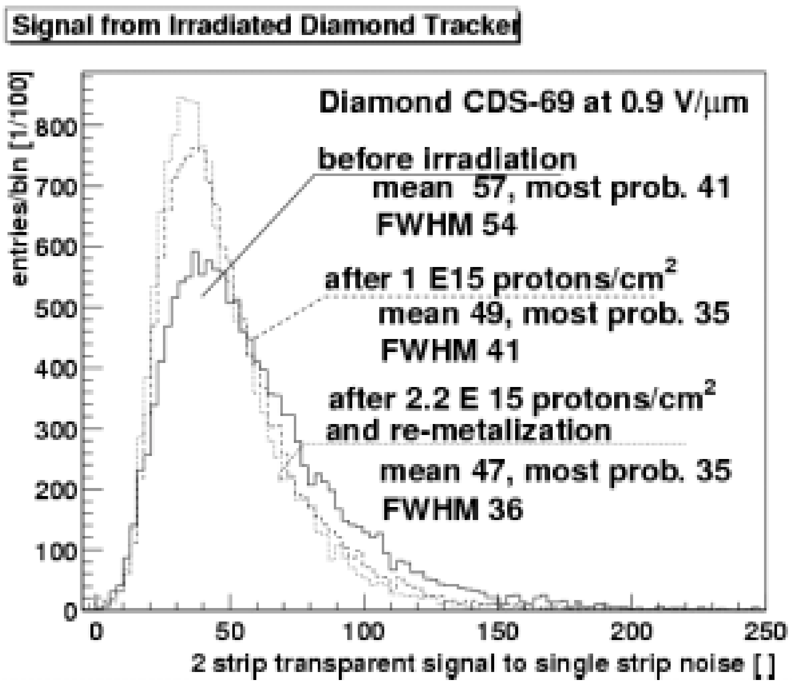


52% loss of S/N at 2.9 1015 p/cm2

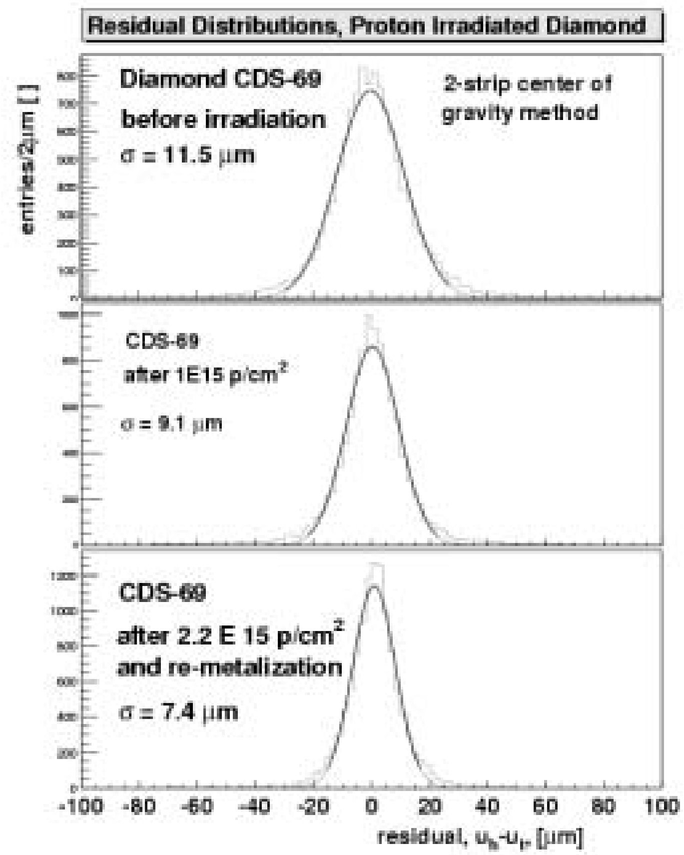
23% improvement in resolution

Proton Irradiation Results

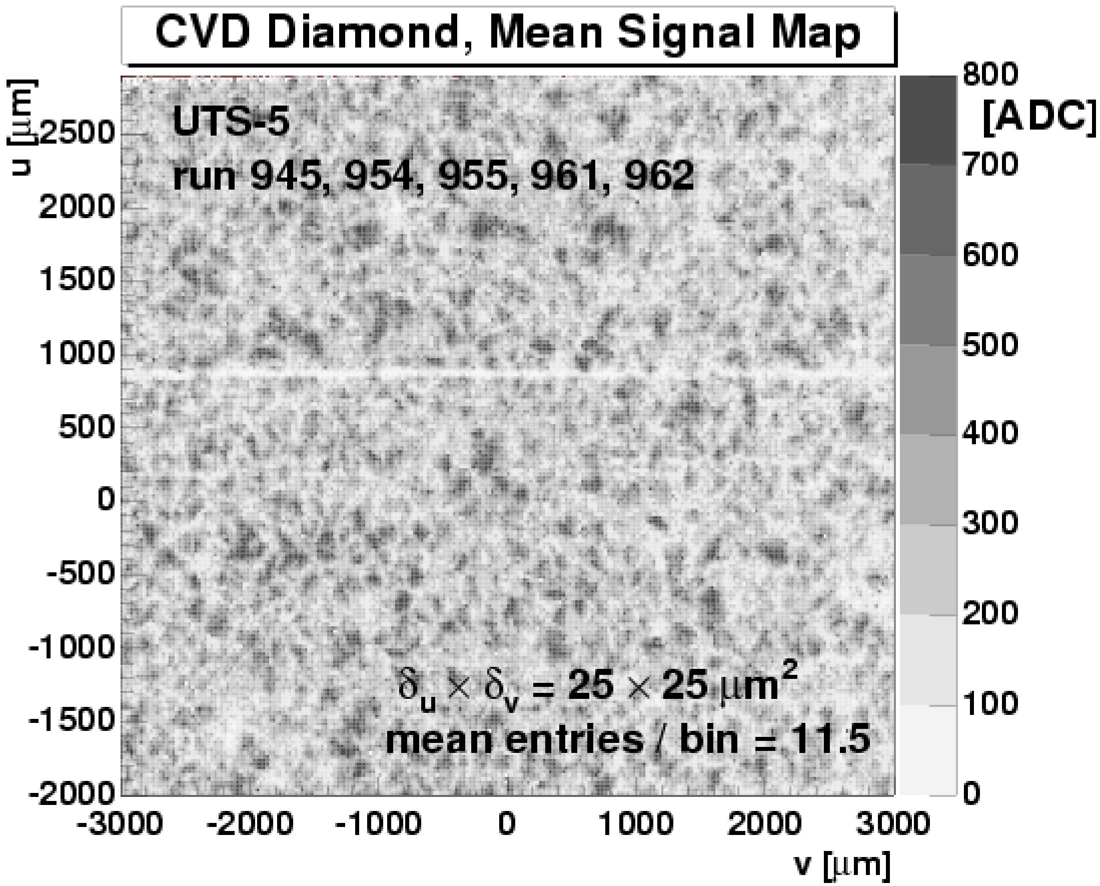
Landau Distribution before and after irradiation



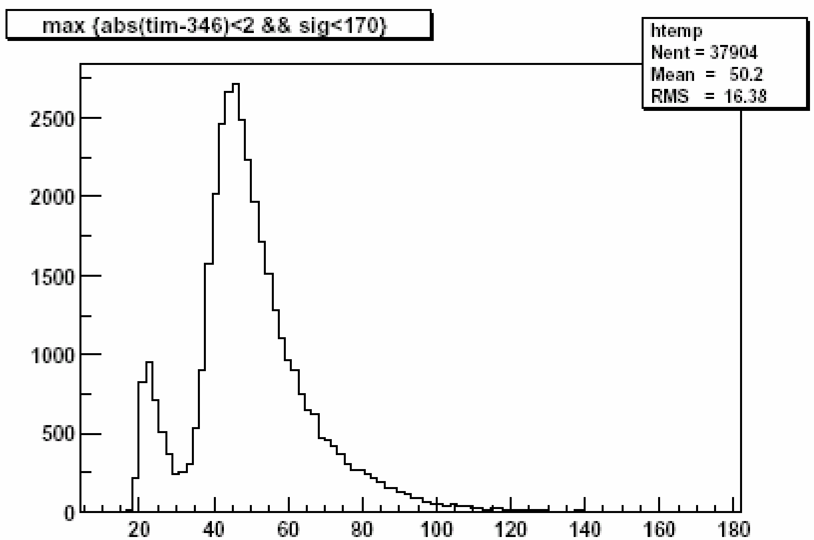
Spatial Resolution



Uniformity in Charge Collection of CVD Diamonds



Radiation Hard Diamond Tracking Modules:

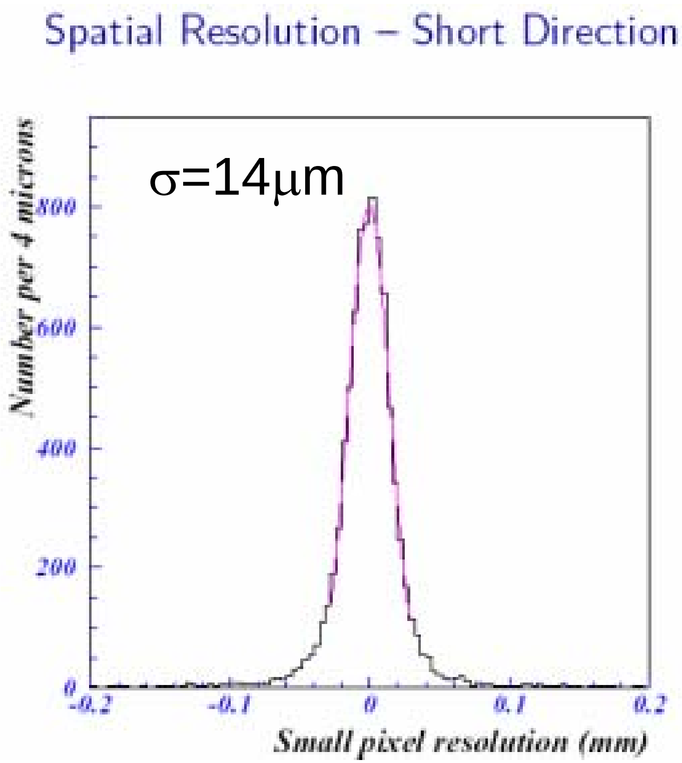


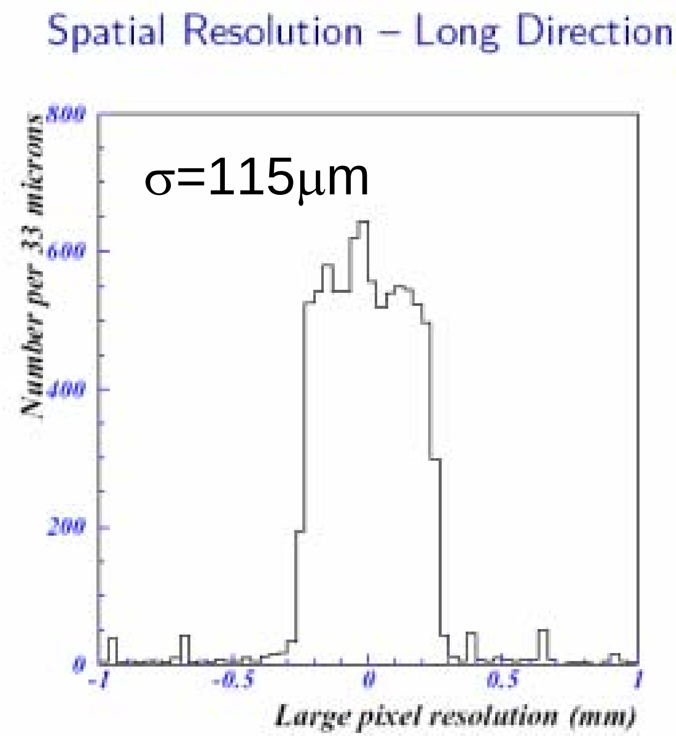
Landau distribution measured with source with LHC-type radiation hard front-end electronics: the SCTA chip.

Beam test performed this autumn but not yet analysed

- 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
- Efficiency will be measured in test beams at 40 MHz clock rate

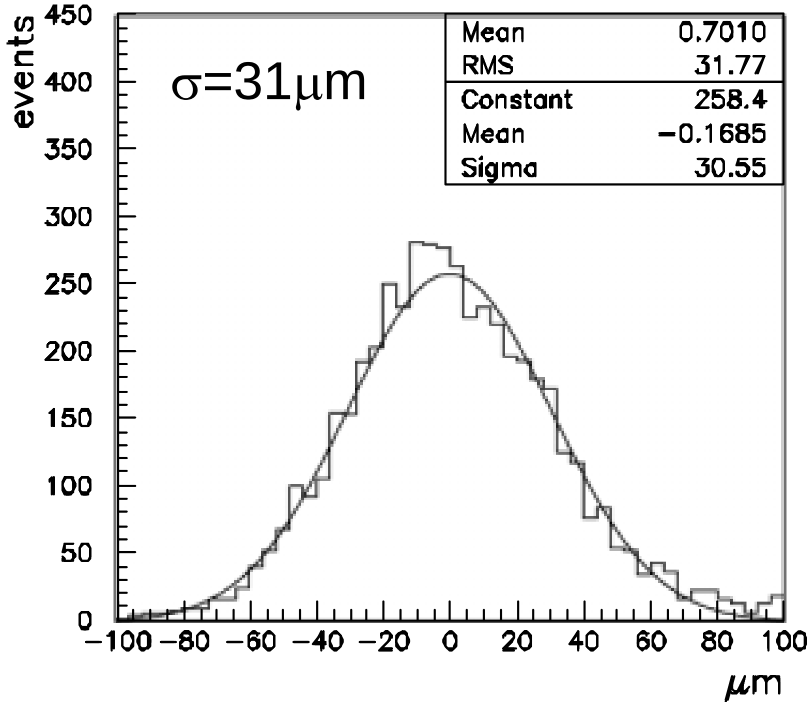
Results from Atlas Diamond Pixel Detectors

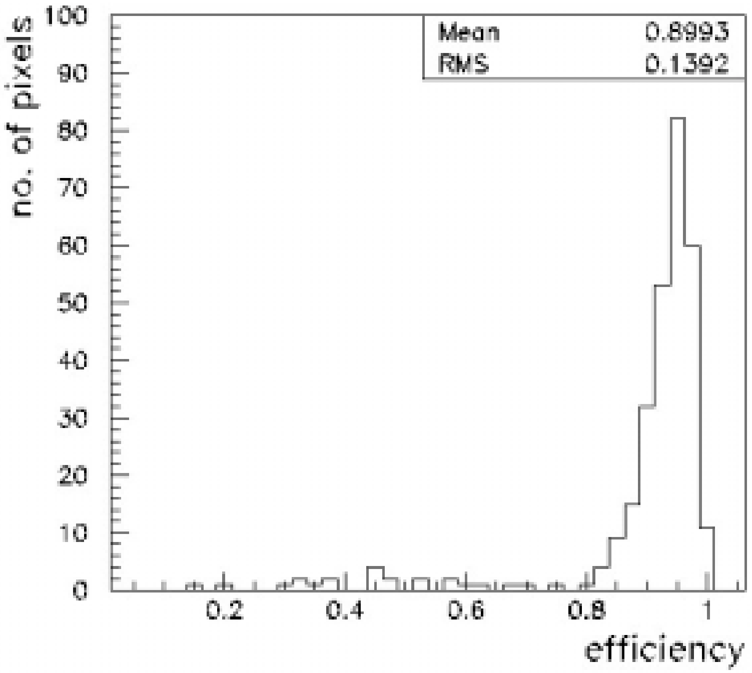




- Efficiency = 80%
- Resolution = digital

Results from CMS Diamond Pixel Detectors





- Efficiency = 90%
- Resolution = digital

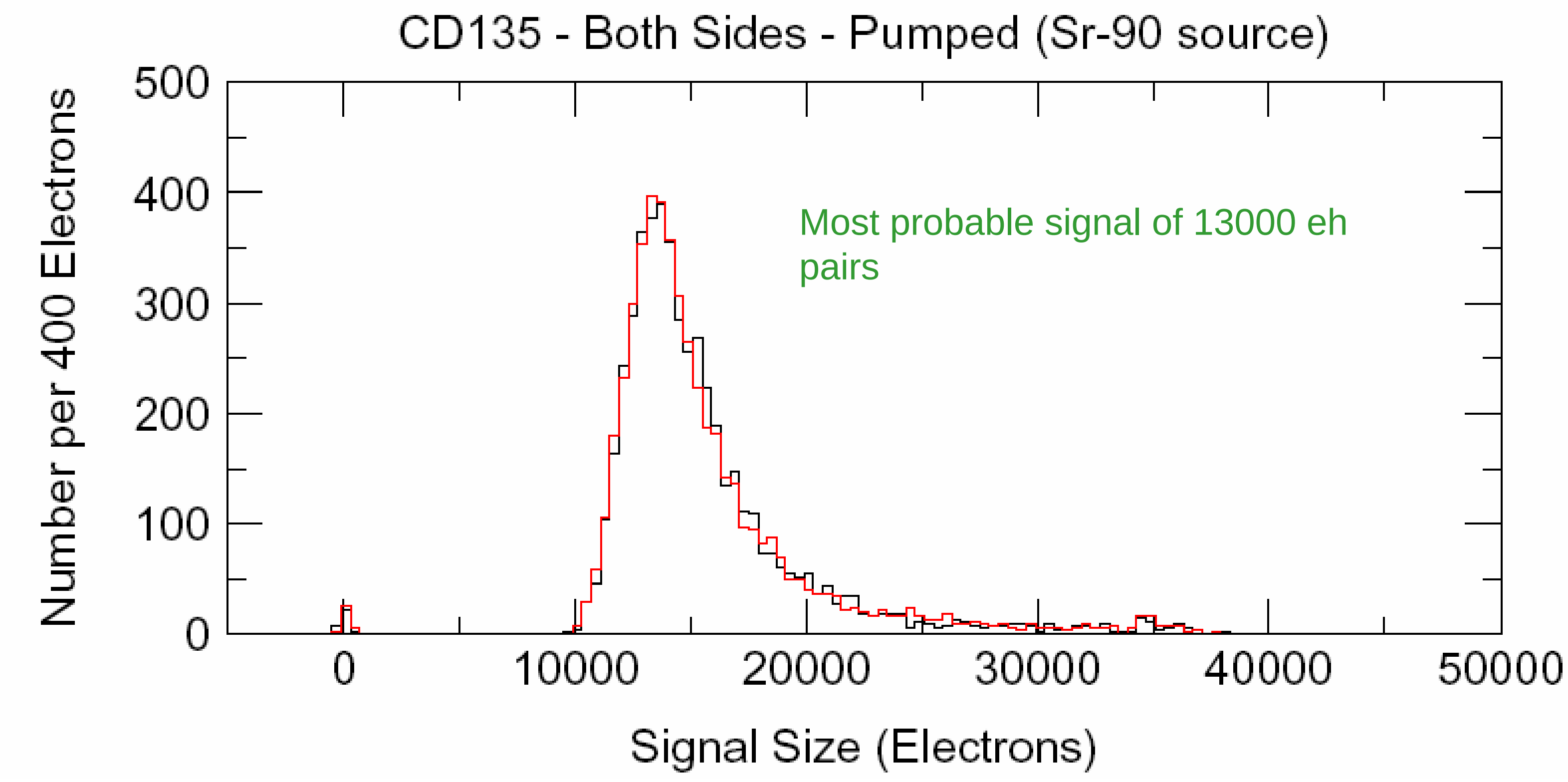
Weaknesses of polycrystalline CVD diamond:

- Many grain boundaries -> defects
- Non-uniformity of collection properties

Mono-crystalline CVD diamond could be a solution:

- No grain boundaries -> less defects
- Uniform collection properties
- First samples available

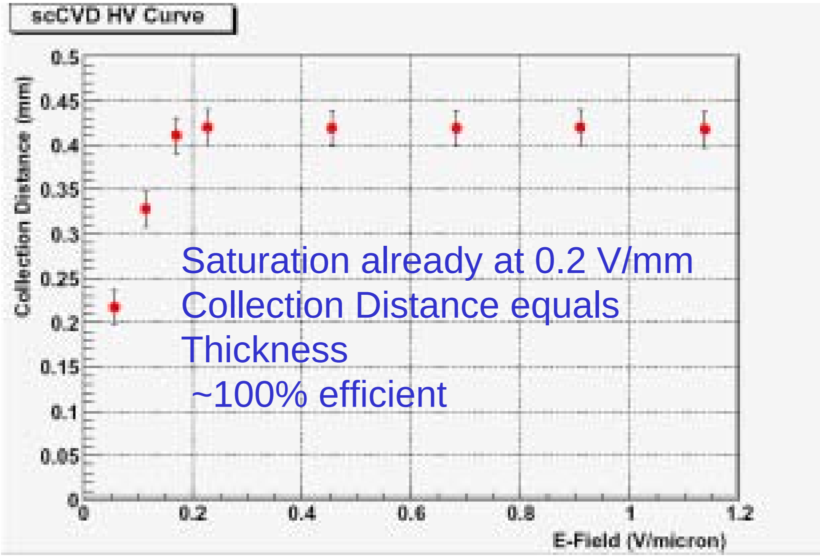
NEW!! Single Crystal CVD Diamond



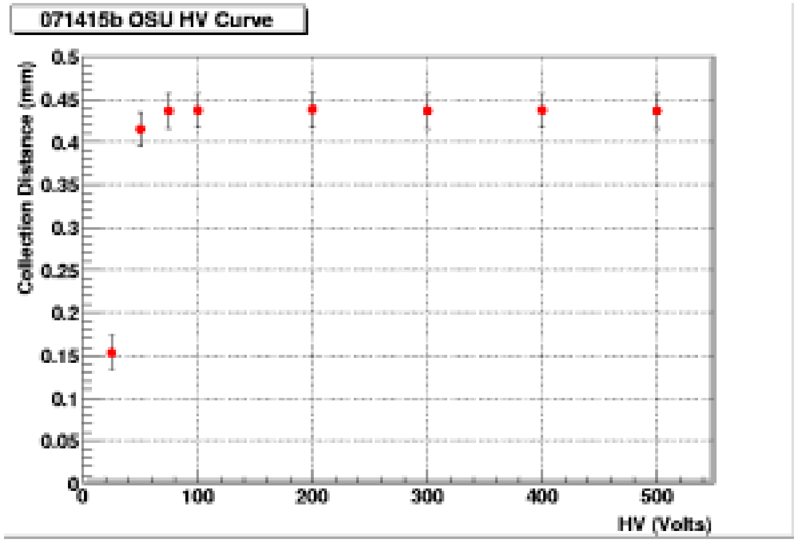
[Isberg *et al.*, Science 297 (2002) 1670]

•Mono-crystalline CVD

Collection Distance as Function of El. Field for 2 Samples



Diamond Sample CD135



Diamond Sample CD71415b

Applications in HEP and other Fields

- Vertex Pixel Detectors with CVD Diamond are a realistic option for LHC detector upgrades.

- For Beam monitoring CVD Diamond is an option for the LHC experiments. Under study.

- BaBar and BELLE employ already CVD Diamond in their beam monitoring system.

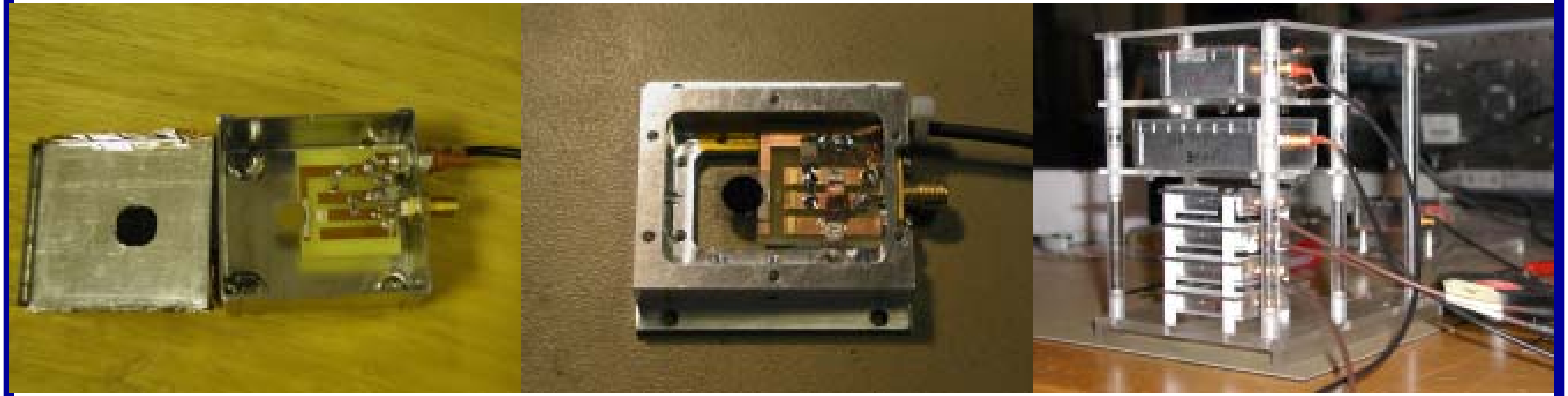
Initial R&D to use diamonds as beam monitors

Beam loss and conditions monitor for CMS and Atlas

- CMS and Atlas investigate diamond as a sensor for a beam loss and conditions measurements close to the beam pipe.
- Same type of device considered by CMS & Atlas inside their tracker
  - CMS: ~ $z=\pm1.8$m and $r=4$cm
  - Atlas: ~ $z=\pm3.5$m close to beam pipe
- Act as part of a radiation monitoring system for equipment safety and radiation level/beam monitoring
- A beam conditions monitor can in particular address the following issues:
  - Allow to protect equipment during instabilities / accidents
  - Providing feedback to the machine thereby helping them to routinely provide optimum conditions
  - Monitor the instantaneous dose during operation
- Advantages of diamond for this application
  - Radiation hard, low leakage currents at room temperature, fast signal response
- The goal is to detect signs of beam losses and monitor beam conditions

Test of response to beam loss: T7 PS testbeam

Beam intensity: 8×10^{11}protons per spill
Fluence: 4×10^{10} protons/cm^2/spill at the centre of the beam spot - 1×10^{8} protons/cm^2/spill in the halo
Train of 40ns-wide bunch extracted from PS with 260ns gap.
Use RD42 diamond samples for first CMS and Atlas tests:

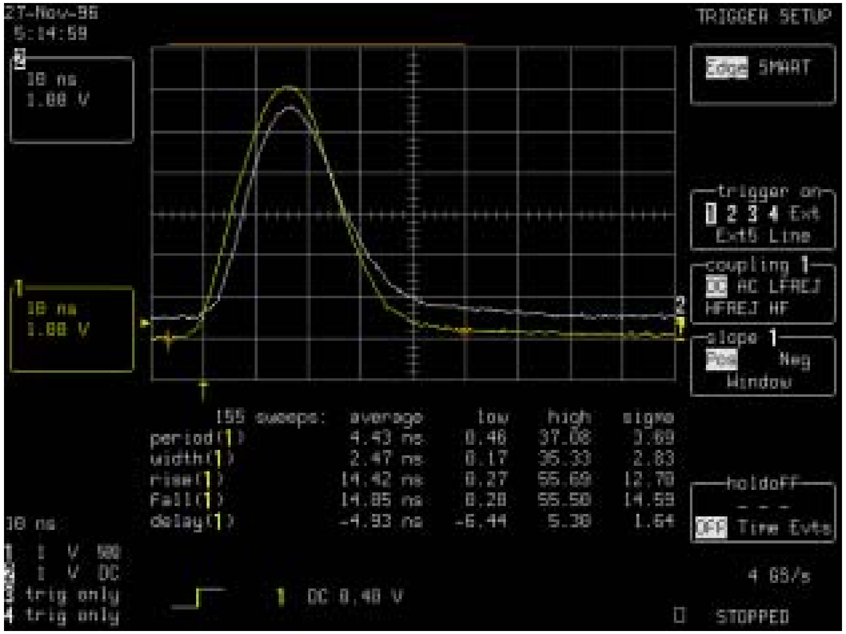


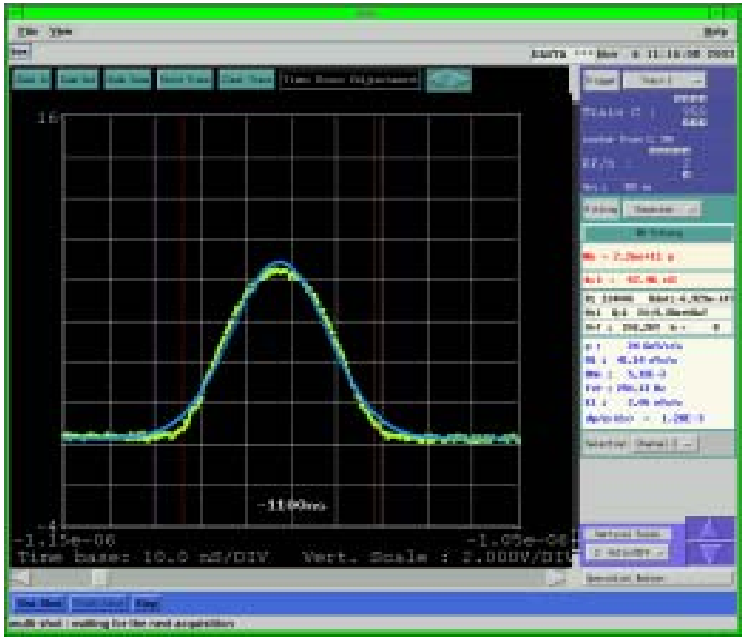
⌘Read out through 16m long RG58 cable connected directly to diamond (no electronics close to beam).

Diamond signal response to high intensity bunch

Single pulses from diamond
Bias on Diamond = +1 V/um
Readout of signal:
16m of cable
no electronics
20dB attenuation on signal
cable (factor 10)

Signal maintained over the duration of the spill
Almost identical diamond response to PS beam monitor response (pulse length 40ns)





High-speed single-particle beam monitor

Use high-speed single-particle COUNTER

- Beam conditions monitor to track instantaneous rate for CMS and Atlas (under study)
- Beam monitor for Hadron-Therapy in proton accelerators (use as beam diagnostic tool and monitoring of beam intensity and time structure in MedAustron)

Based on diamond : It benefits from fast signal response due to high drift velocity combined with short charge live time of poly-crystaline CVD diamond and radiation hardness

Principle: Benefit from fast signal by reading out the direct ionization CURRENT signal (no integration) using a 2GHz bandwidth current amplifier

First test results of this high-speed beam monitor

Test in a high intensity proton accelerator at IUCF, Indiana, US
Test with a beam typically used for proton-therapy:

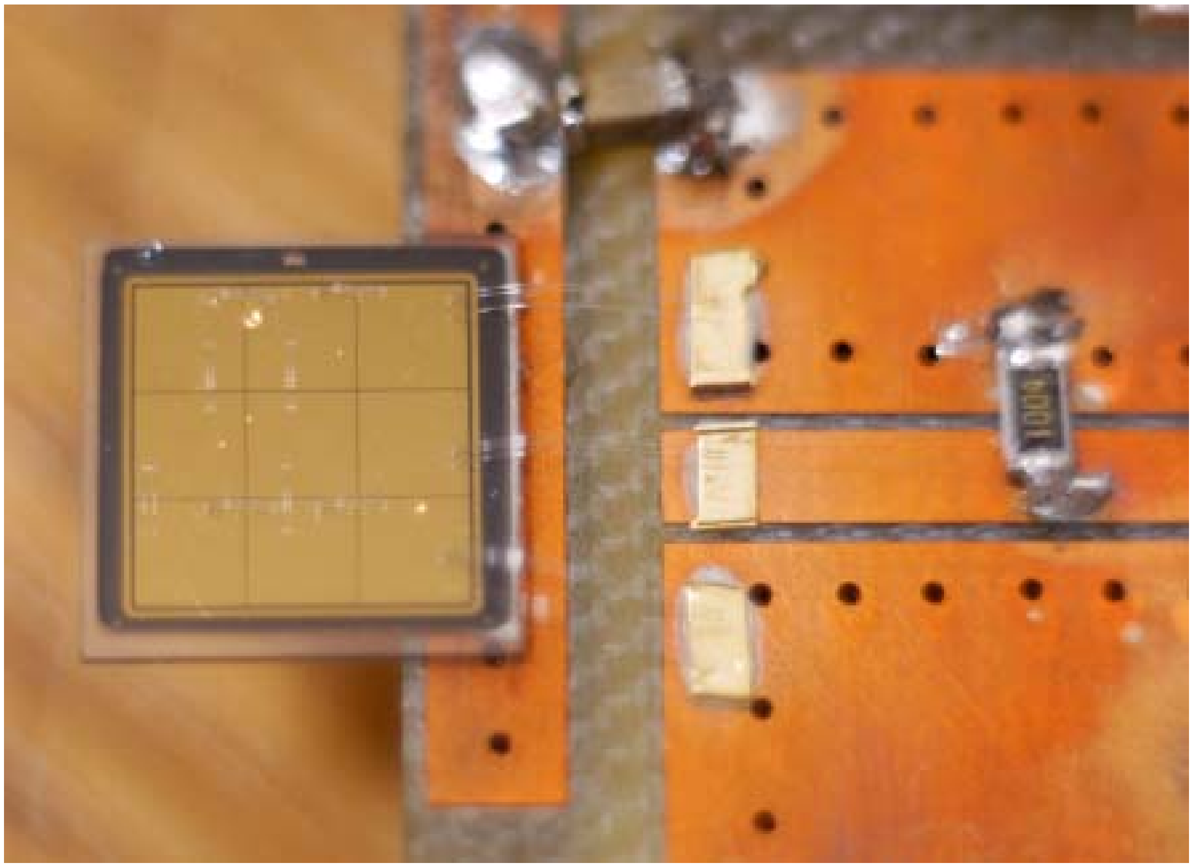
- Proton kinetic energy 55-200MeV
- Beam measured by recording SINGLE particles
- Single particle ionization signal = 2.3 to 6.3 x MIP

Used 2 RD42 polycrystaline diamonds with ccd=190mm (after pumping)

- One diamond with Pad size 7.5x7.5mm2
- One diamond with 3x3 padarray with pad size 2.5x2.5mm2

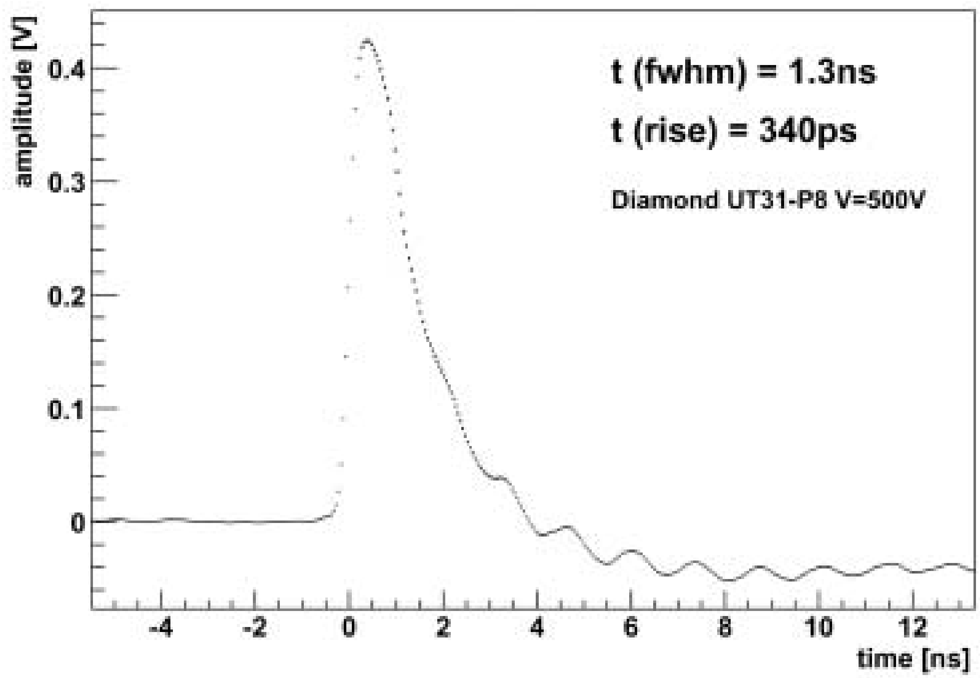
Diamonds are readout using 3 stages of a 2GHz bandwidth current amplifier (amplification approximately 1500 total) , amplifier HFK-2GHz (FOTEC, Austria)
Amplifier analog output readout via 15m cable to scope or signal processing electronics for rate monitoring

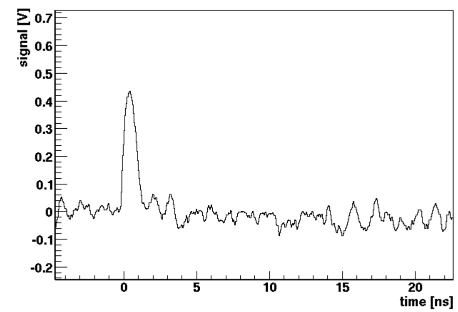
Diamond assembly used during high-speed monitor test



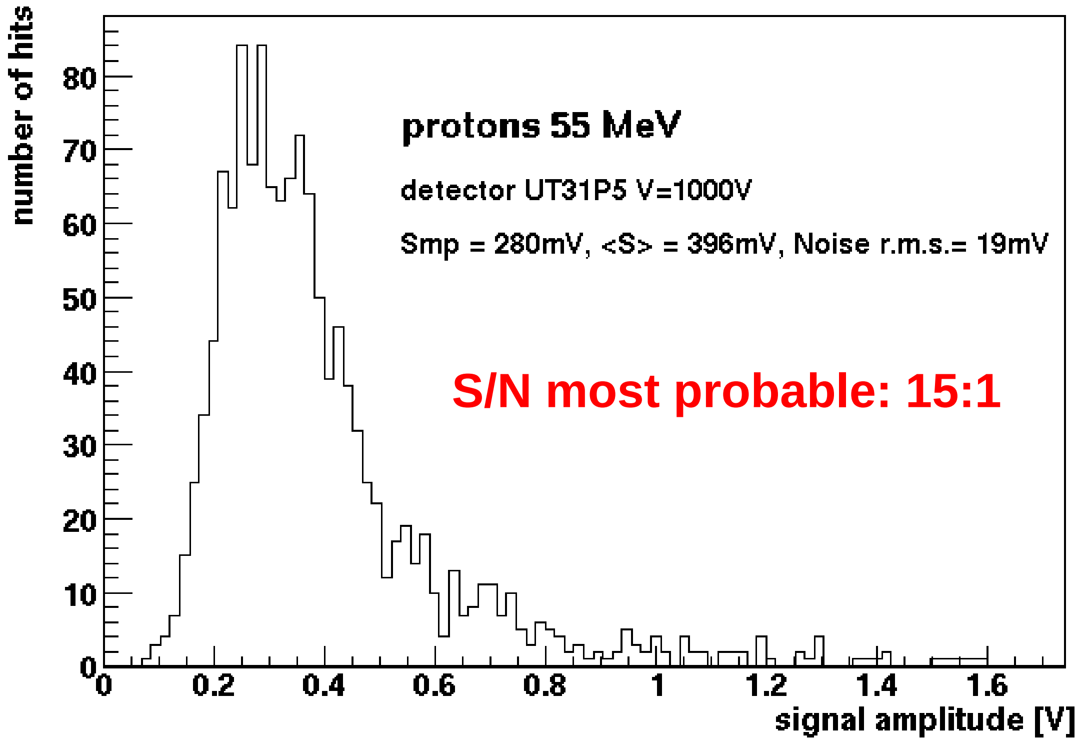
The analog pulse from a single particle:

Beam momentum 330MeV/c , recorded single pulses in LeCroy Wavemaster digital scope (5GHz analog bandwidth, 20Gs/s





Peak current distribution



BaBar beam monitor

So far Si PIN diodes have been used.

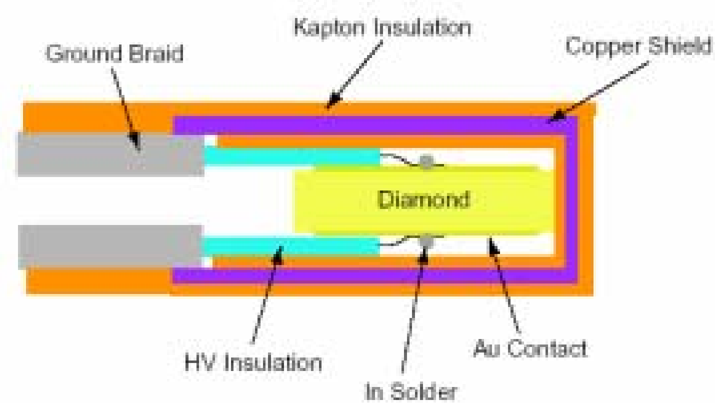
Ubias = 50V, Ileak increases with 1nA/krad

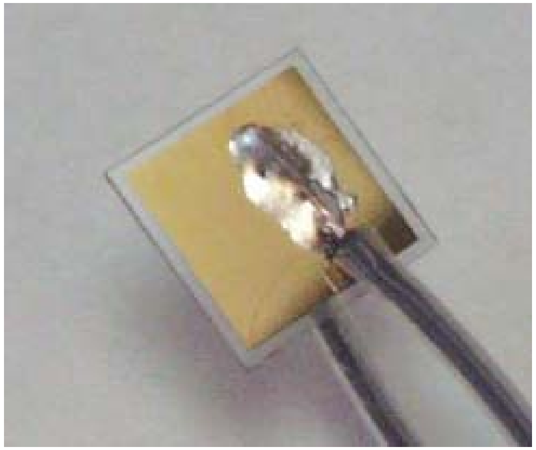
After 100fb-1, noise 50mA, signal 10nA

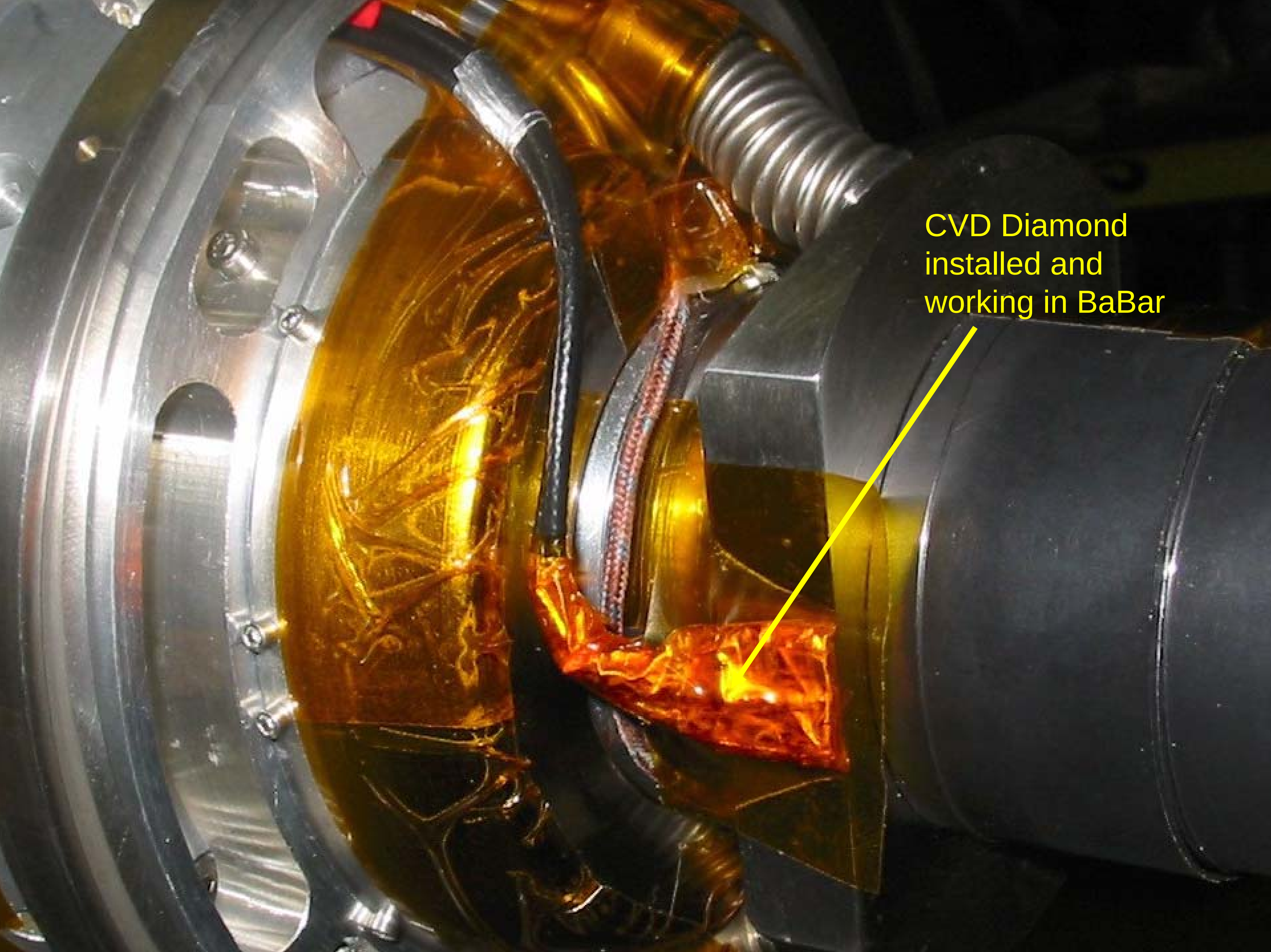
Since 4 month CVD diamond beam monitor prototype installed

Package must fulfill space constraints

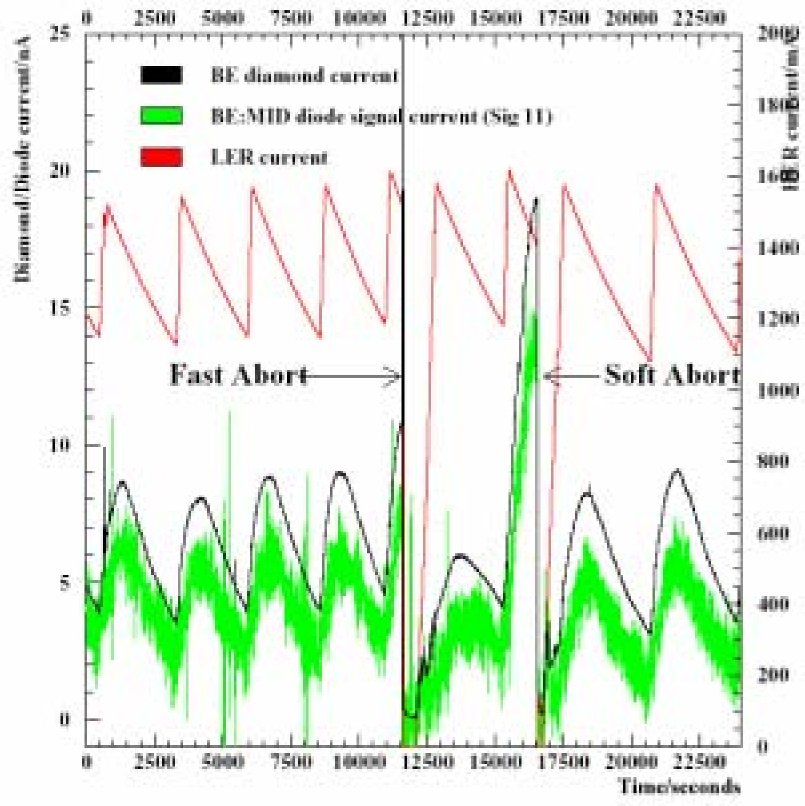
Robustness






CVD Diamond
installed and
working in BaBar

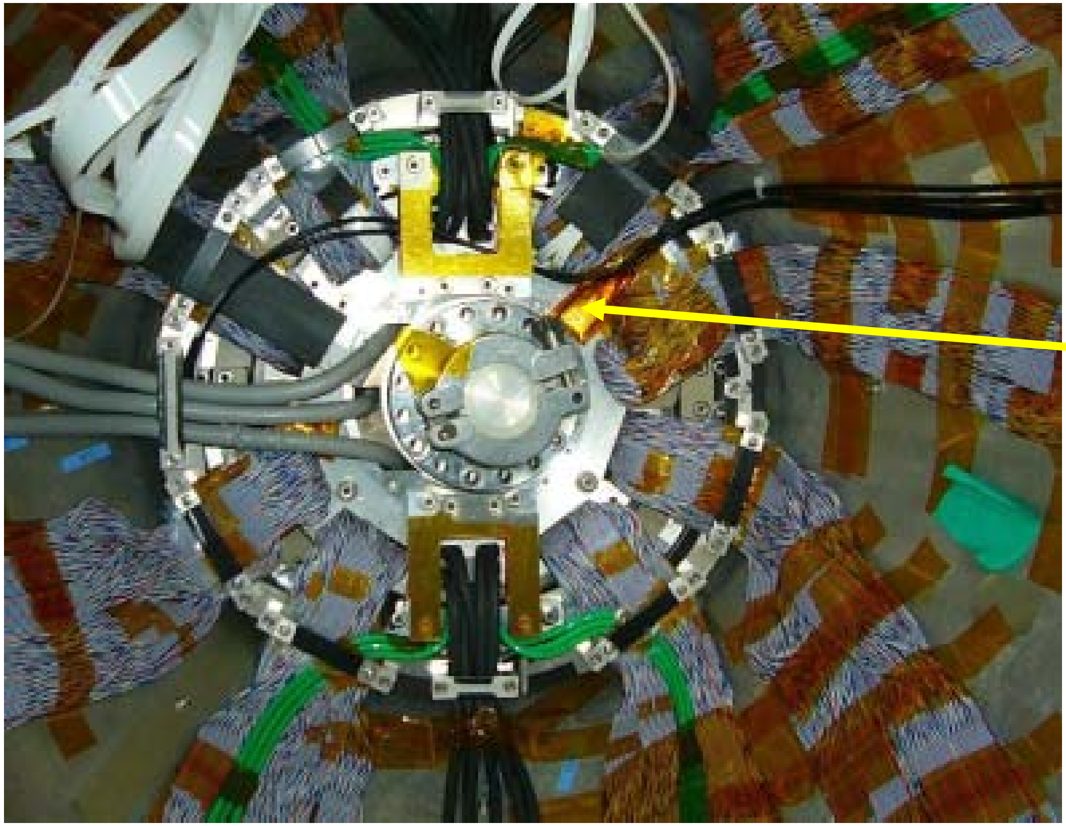
BaBar beam monitor



Promising results!

- Stable operation
- Follows closely diode signal

BELLE Diamond Beam Monitor



CVD diamond is installed and working

Summary

•Further progress with polycrystalline CVD diamond samples has been achieved: Collection Distance increased to 225 μm – 250μm for some samples

•Thinning experiment successfully terminated: understanding of CCD properties in growth process

•Work is ongoing to produce 6 x 2 cm^2 pixel module with latest rad hard ATLAS pixel chip (in coll. With IZM Berlin and Bonn)

•2 fully automated diamond characterization stations have been brought into operation at CERN

•Data taken in test beam with rad-hard SCTA128 ATLAS analog chip with full LHC architecture

•New single crystal CVD diamond successfully developed by Element6, has been tested: close to full charge collection

Summary continued

- Applications of CVD diamond extended into beam monitoring/ beam abort systems for
  - LHC experiments
  - e^+e^- B-factories: monitors installed and running
- Tests underway to do very fast (Gigahertz bandwidth) single particle counting for hadron therapy facilities and maybe for LHC beam monitoring

Proposed Research Program for 2004

The overall goal for the year 2004 and beyond is to continue in developing and stabalise the process for the best electronic grade polycrystalline CVD diamond material in collaboration with Element6. In particular:

- Further improve and characterize material with a CCD of 250μm and above
- Perform more irradiations with this quality material
- More material studies: defects, mobilities, lifetime of carriers, etc..
- Build and test tracking detectors, in particular real size pixel modules with finalised ATLAS/CMS fully radiation hard .25 μm front-end chips.
- Exploit new ohmic contact technology

Proposed Research Program for 2004, continued

- Development with Element6 and characterization of single crystal CVD diamond material. A research contract with Element6 is starting still in 2003.
- Irradiation studies with sc-diamond
- Continue development of systems for beam monitoring around LHC and B-factories
- Similar work for hadron therapy installations

Request to CERN

•Further extension of the RD42 project as a recognized CERN R&D

•Four 4-day test beam periods in 2004; two could be parasitic

•Maintain the present 20 m^2 of laboratory space in building 15 for test set-up, two characterization stations, detector preparation and some electronics development

•Maintain the present minimal office space for full time visitors and visiting members of the RD42 collaboration