

Beam Tests Investigating Diamond as Detector Material

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Section 1

Motivation

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Motivation

- diamond as possible future material for the tracking detectors of the LHC
- innermost layers → highest radiation damage
- current detector designed to withstand 250 fb^{-1} of integrated luminosity
 - ▶ High-Luminosity LHC: replace detector every 12 month
- → **look for more radiation hard detector designs and/or materials**

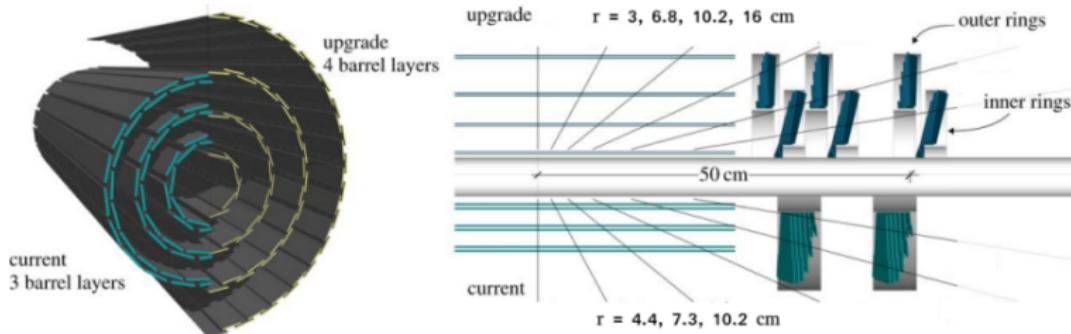


Figure: CMS Barrel Pixel Detector upgrade with end caps



Section 2

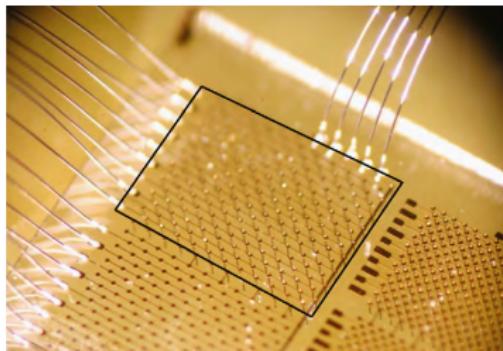
Diamond Detectors and Materials



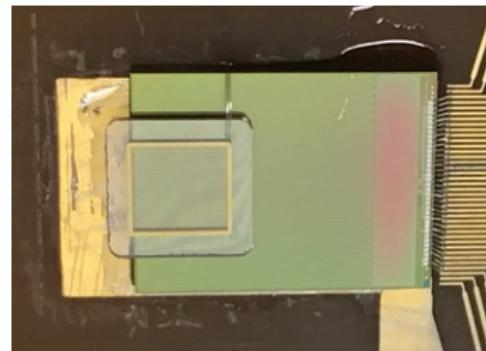
Detector designs

Detector designs

- Investigation of two different detector designs
 - ▶ **planar diamonds**
 - ★ exchange of material
 - ▶ **3D diamonds**
 - ★ new type of detector



(a) prototype



(b) on CMS-Pixel chip

Figure: 3D diamond detectors



Diamond as detector material

Diamond as detector material

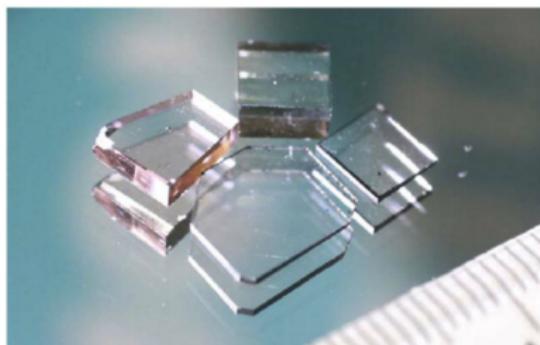
- 7 – 10 times smaller charge loss due to radiation damage than in silicon
- signals (electrons created by a charged particle) half the size of silicon
- → diamond becomes superior than silicon at a certain irradiation
- other advantageous properties:
 - ▶ isolating material → negligible leakage current → power saving
 - ▶ high thermal conductivity → heat spreader for electronics
 - ▶ large band gap → no cooling required
 - ▶ high charge carrier mobility → fast signals
 - ▶ working principle like a solid state ionisation chamber → no pn-junction required
- disadvantages:
 - ▶ high price
 - ▶ some not fully understood behaviours



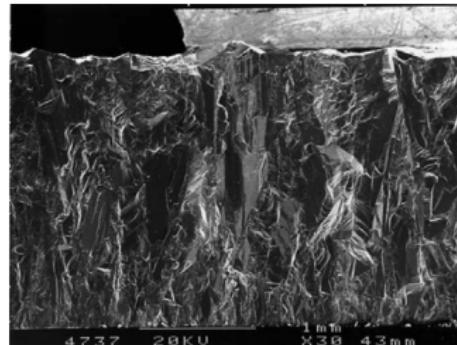
Artificial diamond types

Artificial diamond types

- used diamonds artificially grown with a chemical vapor deposition (CVD) process
- investigation of two different diamond types:



(a) single-crystalline CVD



(b) poly-crystalline CVD

- grown on existing diamond crystal
- only small sizes ($\sim 0.25 \text{ cm}^2$)
- larger signals than pCVD (5 : 3)

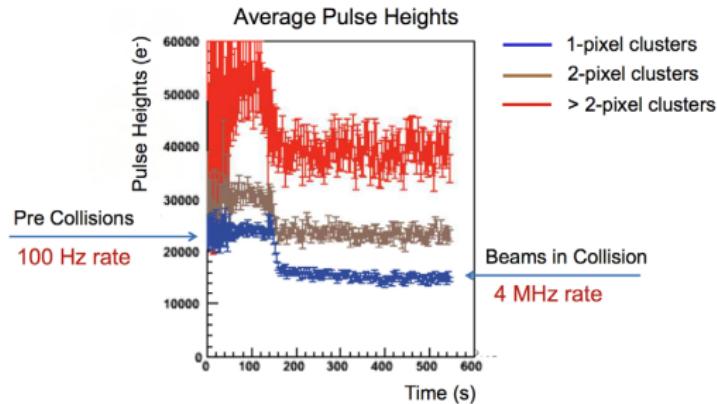
- grown on Si substrate with diamond powder
- large wafers (5 cm to 6 cm \varnothing)
- non-uniformities and grains



Artificial diamond types

Diamonds in CMS

- scCVD diamond pixel detector used in Pixel Luminosity Telescope (PLT)
 - ▶ goal: stand-alone luminosity monitor for CMS
- observation of a signal dependence on incident particle rate:



Consequences:

- investigation of the rate effect in scCVD diamonds
- using pCVD diamond and prove that they show no rate dependence



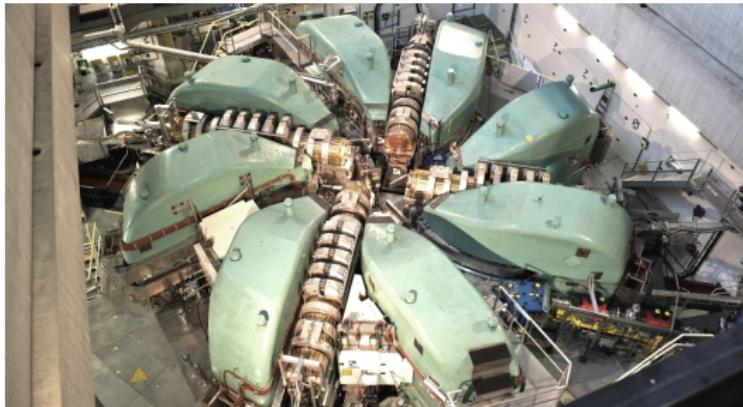
Section 3

Rate Studies at PSI

General information

Beam line at Paul Scherrer Institute (PSI)

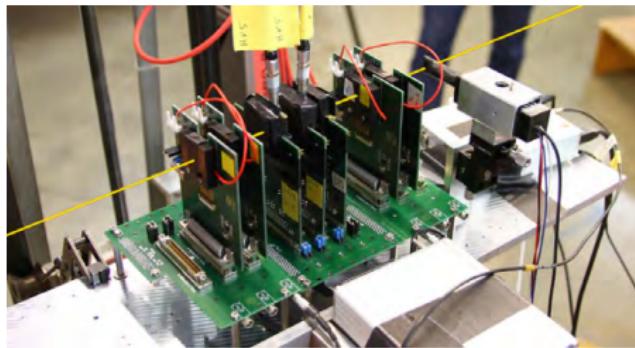
- High Intensity Proton Accelerator (HIPA) at PSI (Cyclotron)
- 590 MeV proton beam with beam current up to 2.4 mA
 - ▶ $\sim 1.4 \text{ MW} \rightarrow$ most powerful proton accelerator in the world
- using beam line $\pi M1$ with 260 MeV positive pions (π^+)
- tunable particle fluxes from 2 kHz/cm^2 to 10 MHz/cm^2



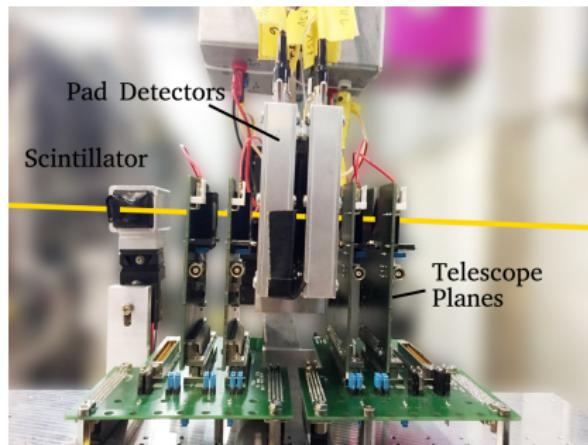
General information

Measurements

- performing several beam tests starting in 2013
- using a modular self-built beam telescope with two possible setups:
 - ▶ pad setup (testing whole diamonds as single pad detector)
 - ▶ pixel setup (testing diamond sensors implanted on CMS-Pixel Chips)
- investigating several materials and devices
 - ▶ scCVD pad detectors (reproduce rate effect)
 - ▶ pCVD pad and pixel detectors
 - ▶ very first 3D pixel detector
- studying non-irradiated and irradiated devices (up to 1×10^{16} neq/cm²)



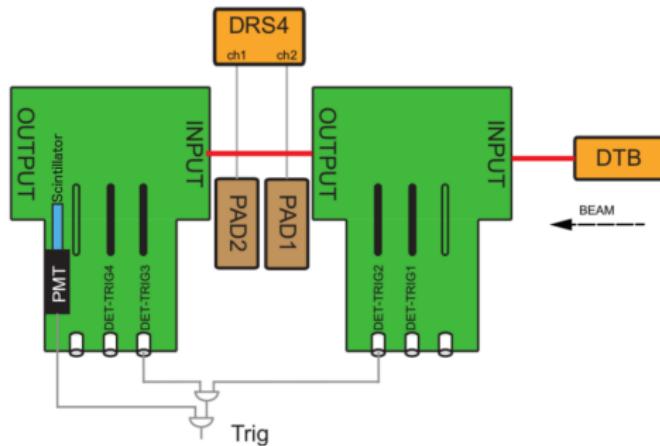
Setup



- 4 tracking planes with analogue CMS pixel chips
- 2 diamond pad detectors
- scintillator for precise trigger timing: sigma of 1.3(1) ns
- resolution: $\sim 80 \mu\text{m} \times 50 \mu\text{m}$



Schematics

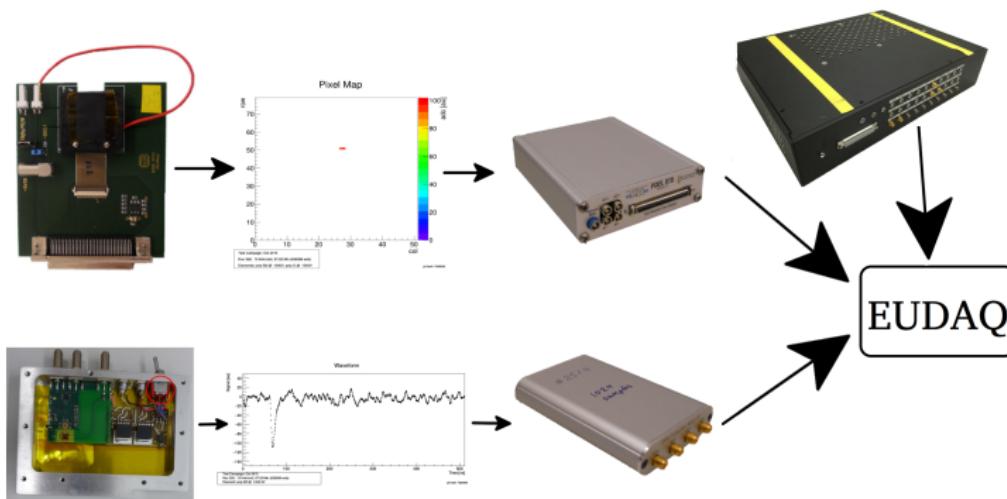


- using PSI DRS4 Evaluation Board as digitizer for the pad waveforms
- using Digital Test Board (DTB) and pXar software for the telescope readout
- global trigger as coincidence of fastOR self trigger and scintillator signal
- EUDAQ as DAQ framework



Setup

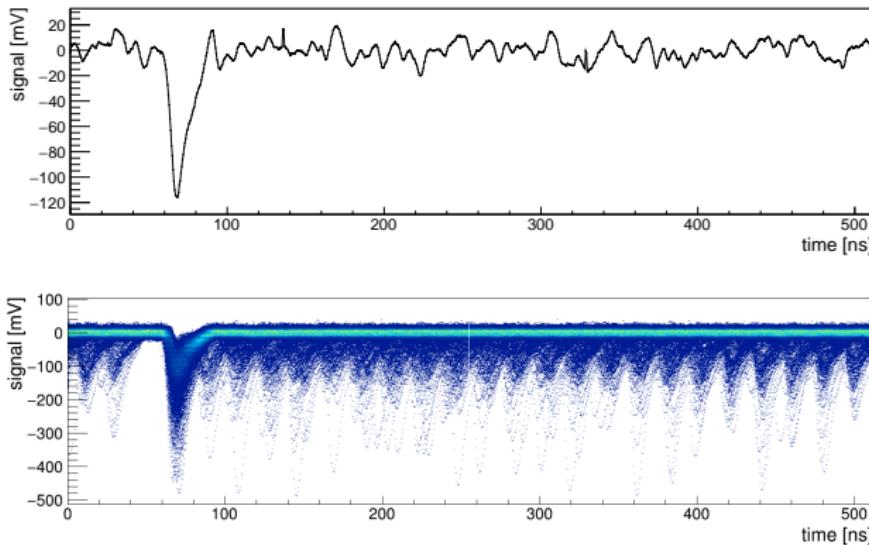
DAQ



- custom-built trigger unit to process the single triggers and provide global one for all devices
- saving event based data stream as binary file using EUDAQ

Analysis and Results

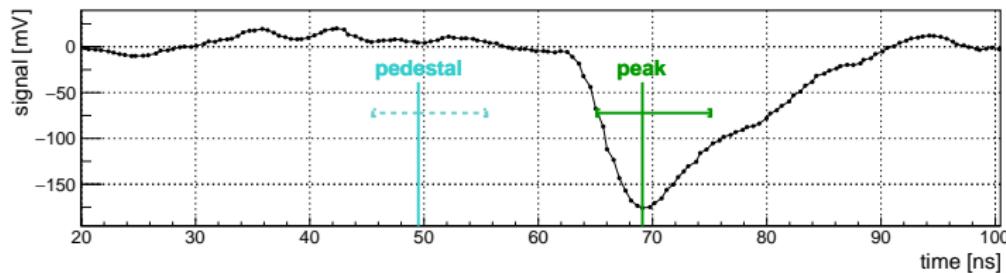
Waveforms



- most frequent peak (~ 70 ns): triggered signal
- other peaks originate from other buckets (\rightarrow resolve beam structure of ≈ 19.7 ns)
- system does not allow signals in pre-signal bucket due to fastOR trigger deadtime

Analysis and Results

Pulse Height Calculation

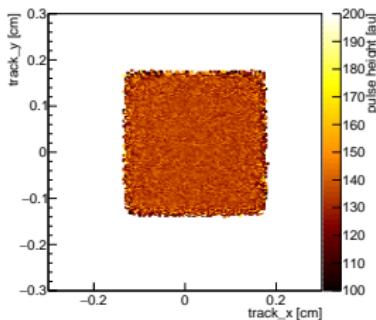
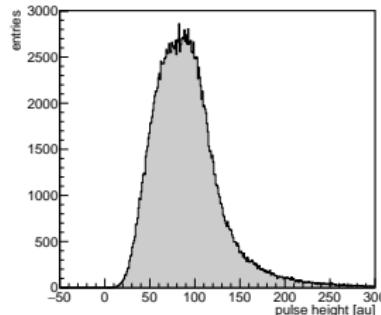
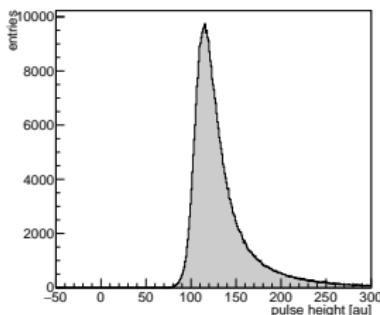


- finding the peak in the signal region
- integrating the signal in time fixed asymmetric integral around peak
- same integration for pedestal (base line → noise)
- optimising the integral width by highest SNR (Integral / Pedestal Sigma)
- subtracting the pedestal from the signal integral on event-wise basis

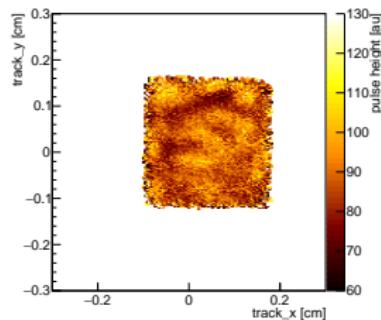


Analysis and Results

Pulse Height Distribution and Signal Maps



(a) single-crystalline



(b) poly-crystalline

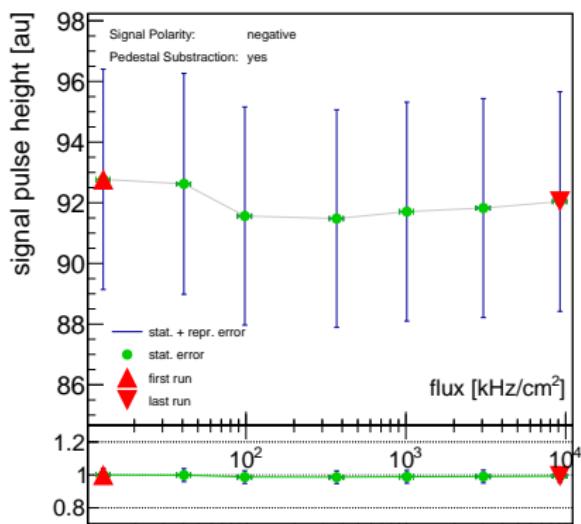
Analysis and Results

Signal vs. Particle Flux

- after all analysis steps: look for rate dependence of pCVD diamonds
- found diamond pad detectors that show no or very little dependence on rate
- no dependence up to 1×10^{16} neq/cm²
- large systematic errors due to reproducibility

To do:

- test higher irradiated samples
- improve reproducibility
- prove the same for pixel detectors



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Section 4

3D Detectors at CERN

Working Principle of a 3D Detector

Working Principle of a 3D Detector

- insert electrodes perpendicular to the plane
 - ▶ reduce drift distance
 - ▶ increase collected charge in detectors with limited mean free path
- one readout electrode surrounded by four bias electrodes
- in diamond electrodes formed with a pulsed laser
 - ▶ transition of diamond to conducting material (graphitic material i.a.)

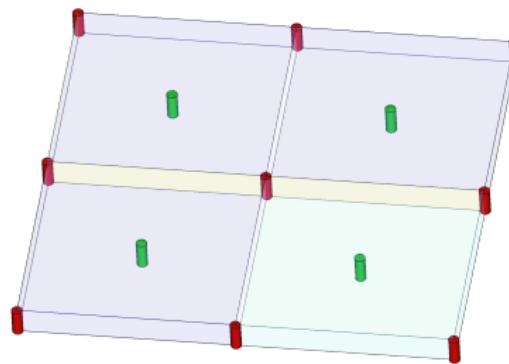


Figure: array of four 3D cells, bias electrodes in red, readout electrodes in green



Beam Tests at CERN

Beam Tests at CERN

- using more than 20 years old fixed telescope at SPS at CERN (high spatial resolution)
- testing multiple 3D strip detectors
- basic working principle has been proven
- full charge collection not yet reached in pCVD
- improve fabrication technique

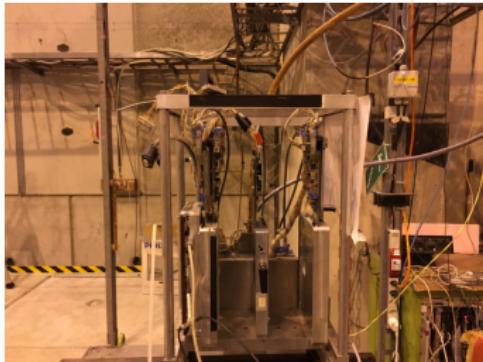


Figure: Strasbourg Telescope

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Section 5

Conclusion



Conclusion

- High Luminosity LHC requires a new detector technology due to the highly increased radiation damage
- diamond detector designs viable option due to its radiation tolerance, among other advantages
- scCVD diamonds not suitable due to signal dependence on particle flux after irradiation
- pCVD diamonds show no rate dependence up to fluxes of 10 MHz/cm^2 and irradiations up to $1 \times 10^{16} \text{ neq/cm}^2$
- successfully proven the working principle of a 3D diamond detector
- tested the very first 3D-Pixel detector

Ultimate Goal:

- build fully working pixel detector