

## Beam Tests Investigating Diamond as Detector Material

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# Table of contents I

## 1 Motivation

## 2 Diamond Detectors and Materials

- Detector designs
- Diamond as detector material
- Artificial diamond types

## 3 Rate Studies at PSI

- General information
- Setup
- Analysis and Results

## 4 3D Detectors at CERN

- Working Principle
- Beam Tests at CERN

## 5 Conclusion

## 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  $250 \text{ fb}^{-1}$  of integrated luminosity
  - ▶ High-Luminosity LHC: replace detector every 12 month
- → **look for more radiation hard detector designs and/or materials**

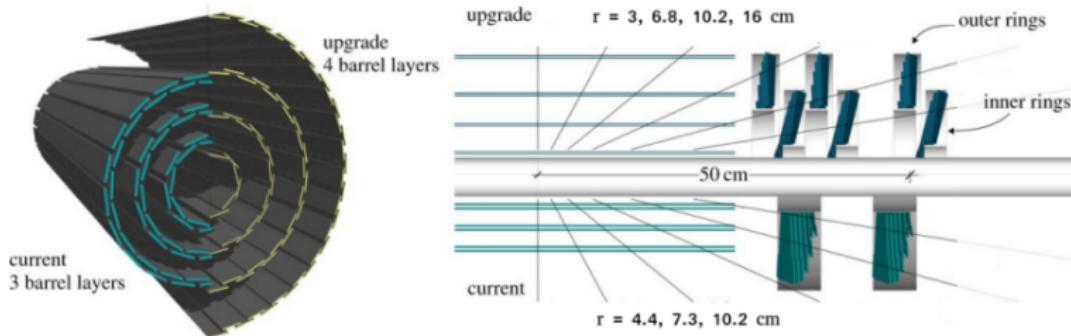


Figure: CMS Barrel Pixel Detector upgrade with end caps



## Section 2

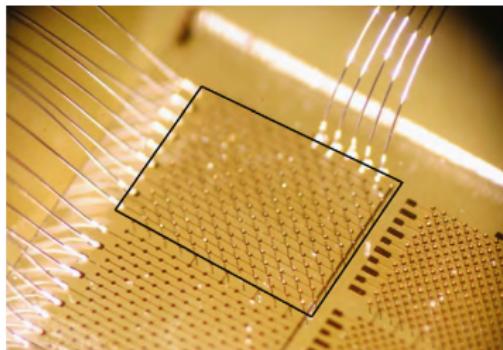
### Diamond Detectors and Materials



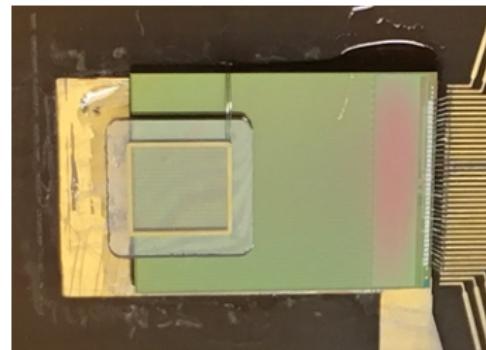
## Detector designs

## 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

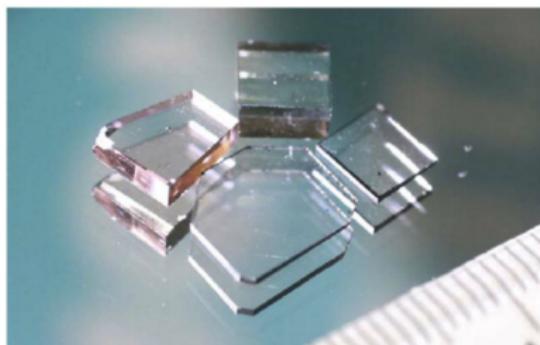
- 7 – 10 times smaller charge loss due to radiation damage than in silicon
- signals (electrons created by a charged particle) half the size of silicon
- → diamond becoming superior than silicon at a certain irradiation
- other advantageous properties:
  - ▶ isolating material → negligible leakage current → 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



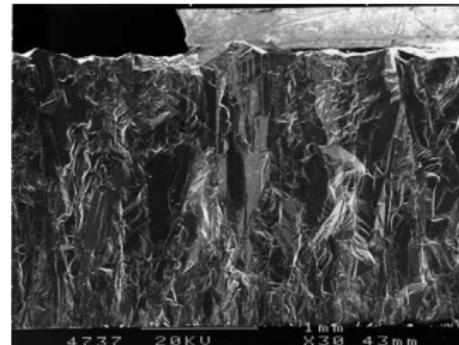
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## Artificial diamond types

- diamonds in use artificially grown in chemical vapor deposition (CVD) process
- investigation of two different diamond types:



(a) single crystal CVD



(b) poly crystal CVD

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

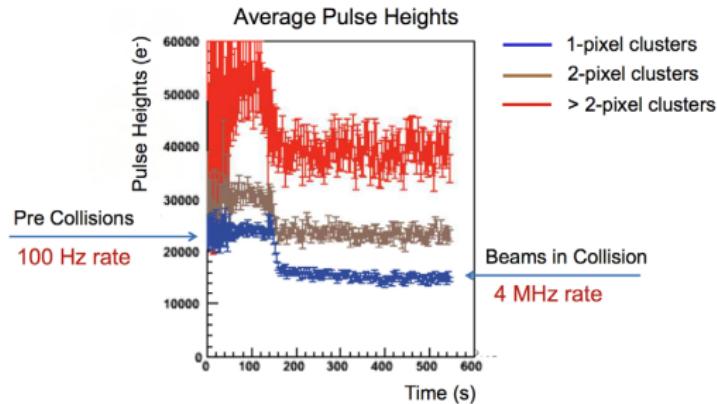
- grown on Si substrate with diamond powder
- large wafers (5 cm to 6 cm  $\varnothing$ )
- non-uniformities and grains



## 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



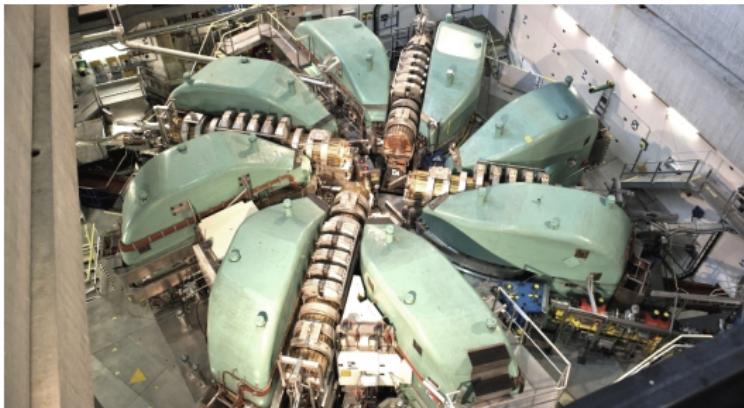
## Section 3

### Rate Studies at PSI

## General information

## Beam line at Paul Scherrer Institute (PSI)

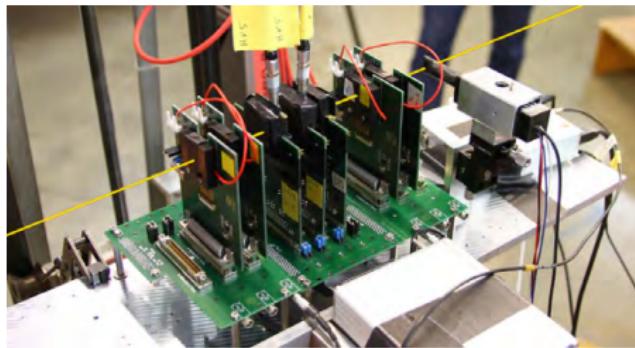
- High Intensity Proton Accelerator (HIPA) at PSI (Cyclotron)
- 590 MeV proton beam with beam current up to 2.4 mA
  - ▶  $\sim 1.4 \text{ MW} \rightarrow$  most powerful proton accelerator in the world
- using beam line  $\pi M1$  with 260 MeV positive pions ( $\pi^+$ )
- tunable particle fluxes from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



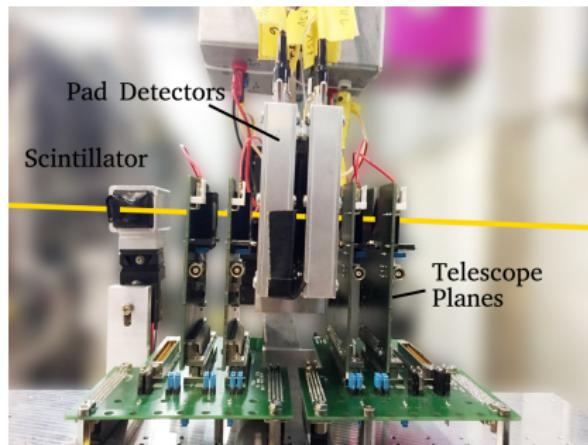
General information

## 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  $1 \times 10^{16}$  neq/cm<sup>2</sup>)



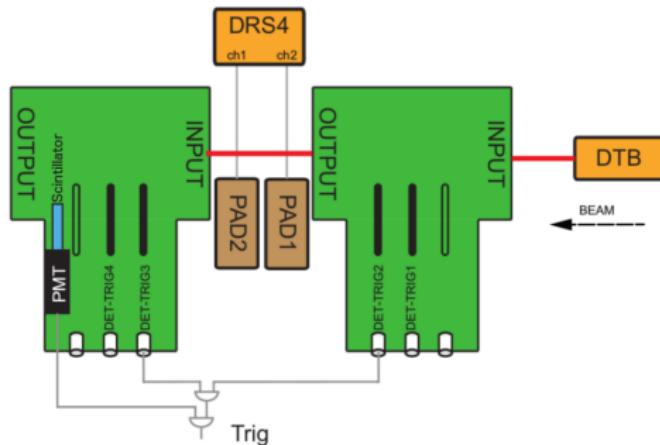
## Setup



- 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

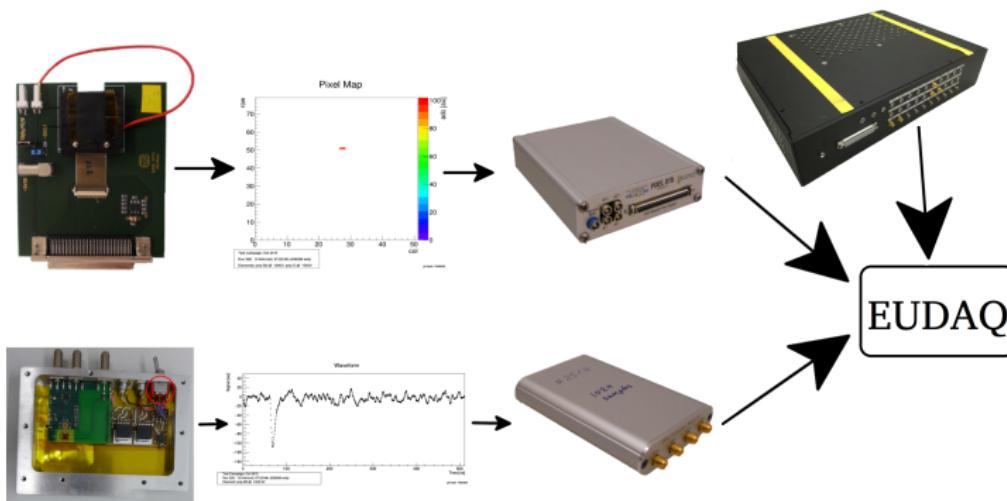


- using PSI DRS4 Evaluation Board as digitizer for the pad waveforms
- using Digital Test Board (DTB) and pXar software for the telescope readout
- global trigger as coincidence of fastOR self trigger and scintillator signal
- EUDAQ as DAQ framework



## Setup

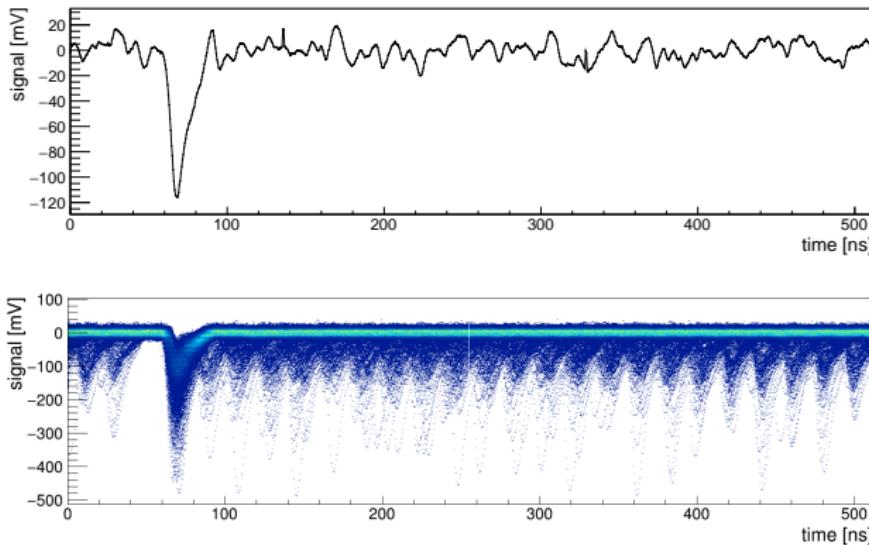
## DAQ



- 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

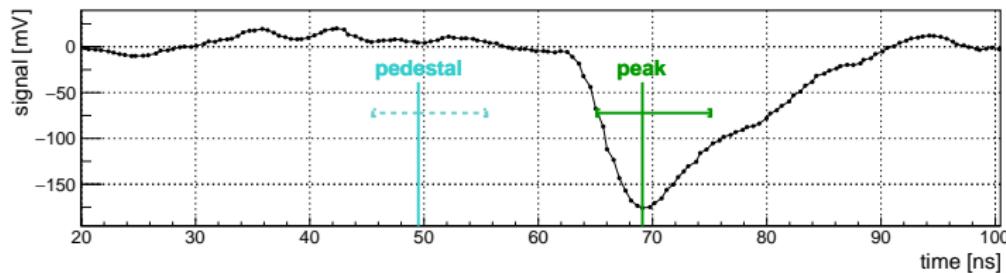
## Waveforms



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

## Analysis and Results

## Pulse Height Calculation

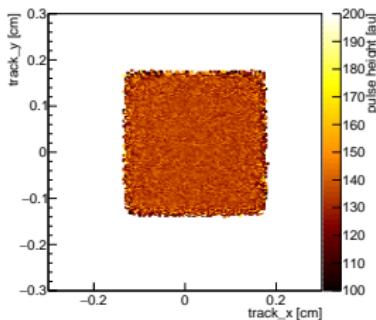
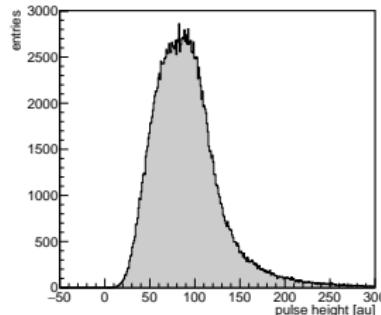
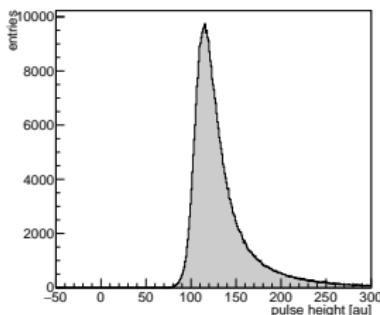


- finding the peak in the signal region
- integrating the signal in time fixed asymmetric integral around peak
- same integration for pedestal (base line → noise)
- optimising the integral width by highest SNR (Integral / Pedestal Sigma)
- subtracting the pedestal from the signal integral on event-wise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

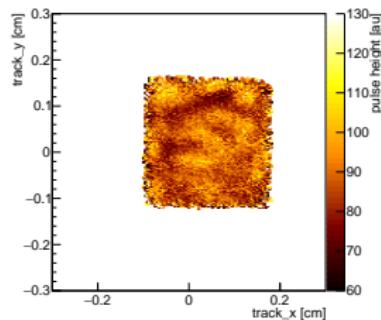


## Analysis and Results

## Pulse Height Distribution and Signal Maps



(a) single crystal



(b) poly crystal



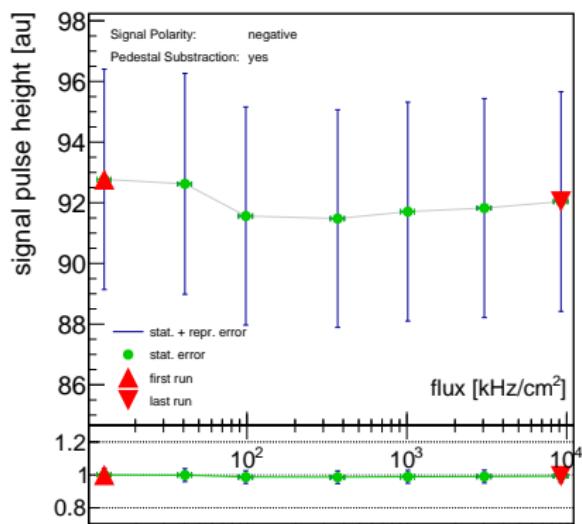
## Analysis and Results

## 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  $1 \times 10^{16}$  neq/cm<sup>2</sup>
- large systematic errors due to reproducibility

### To do:

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



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## Section 4

### 3D Detectors at CERN

## Working Principle

## Working Principle

- 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 (i.a. graphitic material)

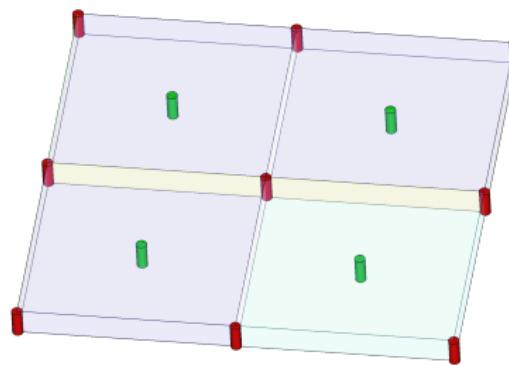


Figure: array of four 3D cells, bias electrodes in red, readout electrodes in green



## Beam Tests at CERN

## Beam Tests at CERN

- using more than 20 years old fixed telescope at SPS at CERN
- 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
- scCVD diamonds not suitable due to dependence on particle flux after irradiation
- pCVD diamonds show no rate dependence up to fluxes of  $10 \text{ MHz}/\text{cm}^2$  and irradiations up to  $1 \times 10^{16} \text{ neq}/\text{cm}^2$
- successfully proven the working principle of a 3D diamond detector
- testing the very first 3D-Pixel detector

### Ultimate Goal:

- build fully working pixel detector