

## Beam Tests Investigating Diamond as Detector Material

Michael Reichmann



## Table of contents I

1 Motivation

2 Diamond Detectors and Materials

3 Rate Studies at PSI

4 3D Detectors at CERN

5 Conclusion



## Section 1

### Motivation



## Motivation

### Diamond as 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**

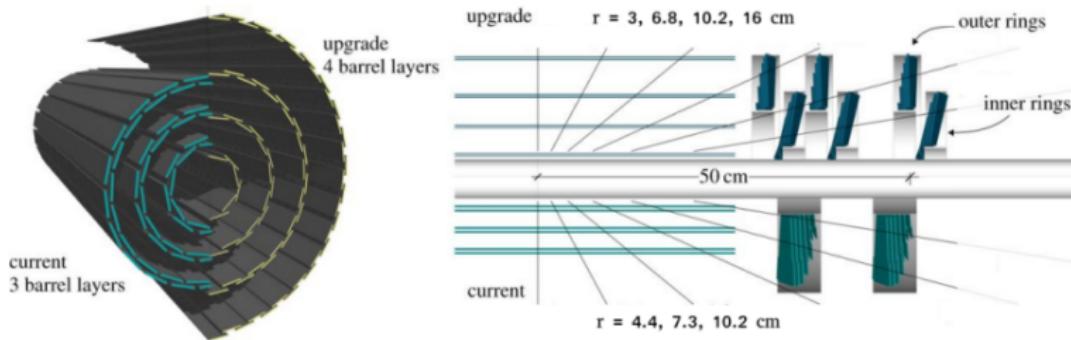


Figure: CMS Barrel Pixel Detector upgrade with end caps



## Section 2

### Diamond Detectors and Materials



Diamond as detector material

## Diamond as detector material

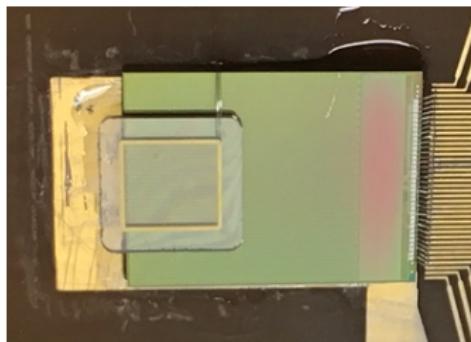
- 7 – 10 times smaller charge loss due to radiation damage than in silicon
- signals (electrons created by a charged particle) half the size of silicon
- → diamond becomes superior than silicon at a certain irradiation
- other advantageous properties:
  - ▶ isolating material (large band gap)
    - negligible leakage current → power saving
    - no cooling required
  - ▶ high thermal conductivity → heat spreader for electronics
  - ▶ 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



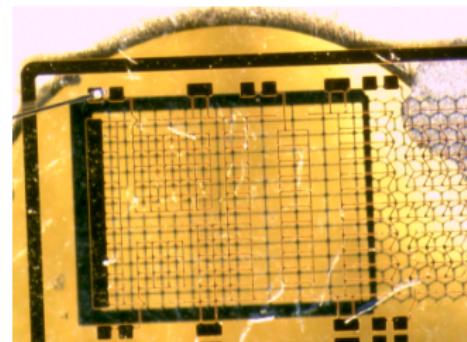
## Detector Concepts

## Detector Concepts

- investigation of two different detector concepts
  - ▶ planar diamonds
    - ★ exchange of material
  - ▶ 3D diamonds
    - ★ new type of detector



(a) on CMS-Pixel chip



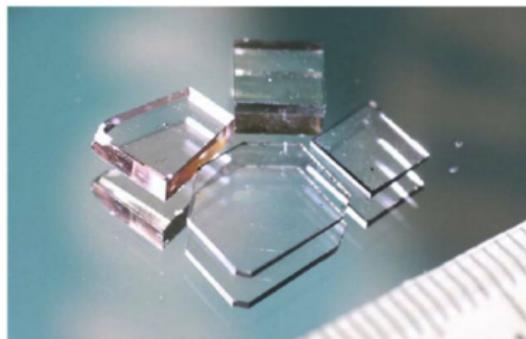
(b) multi pattern

Figure: 3D diamond detectors

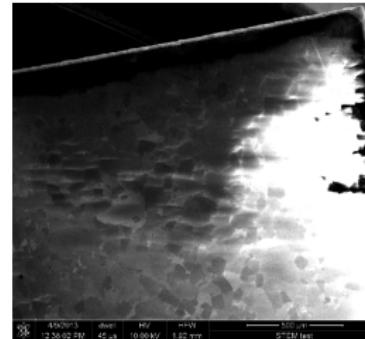


## Artificial diamond types

- 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)

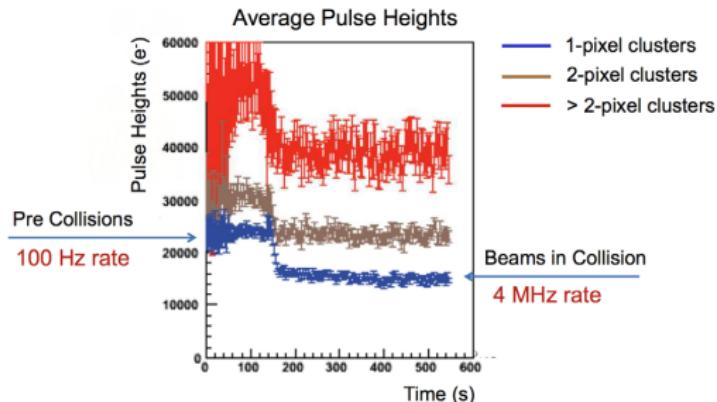
- grown on Si substrate with diamond powder
- large wafers (5" to 6"  $\varnothing$ )
- non-uniformities and grains



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 (Edge-TCT)
- using pCVD diamond and prove that they show no rate dependence



## Section 3

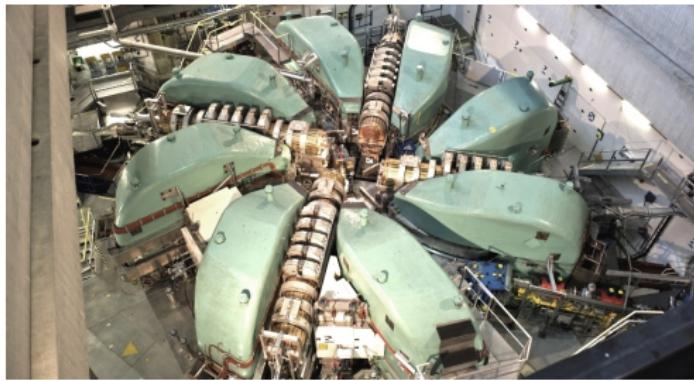
### Rate Studies at PSI



## General information

## Proton Accelerator 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 ( $1.5 \times 10^{16}$  protons/s)
  - ▶ ~1.4 MW → most powerful proton accelerator in the world
- only two comparable accelerators
  - ▶ TRIUMF in Vancouver (~0.25 MW)
  - ▶ LAMPF in Los Alamos (~0.8 MW)



○  
○  
○○

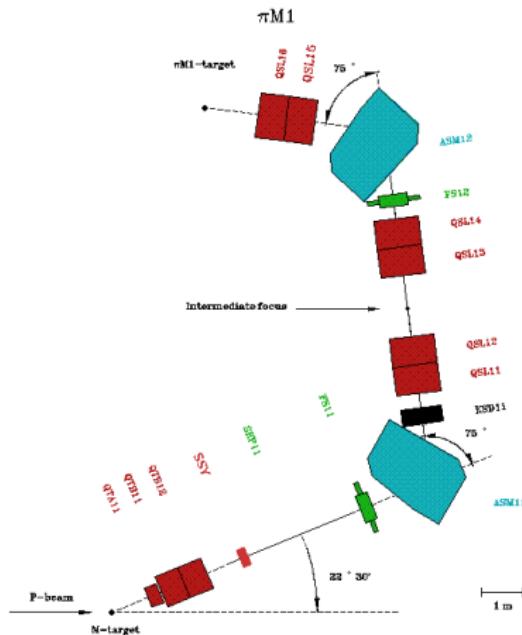
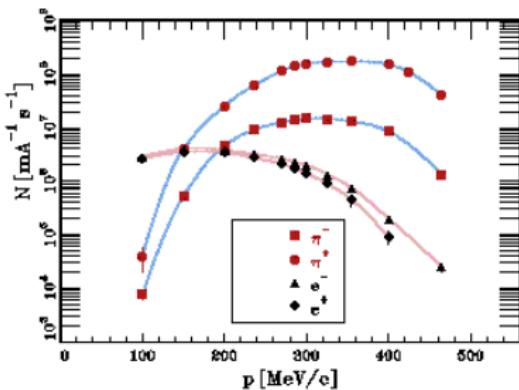
○○○  
○○○○○  
○○○○○○○  
○○○○○○○○

○  
○  
○  
○

## General information

## Beam line at Paul Scherrer Institute (PSI)

- using beam line  $\pi M1$  with 260 MeV/c positive pions ( $\pi^+$ )
- tunable particle fluxes from 2 kHz/cm<sup>2</sup> to 10 MHz/cm<sup>2</sup>

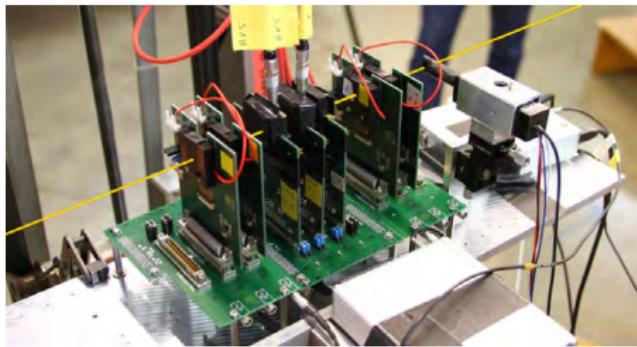




## General information

## Measurements

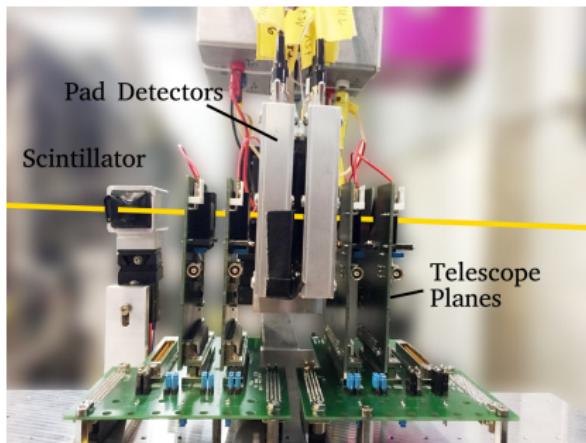
- performing several beam tests starting in 2013
- using a modular self-built beam telescope with two possible setups:
  - ▶ pad setup (testing whole diamonds as single pad detector)
  - ▶ pixel setup (testing diamond sensors implanted on CMS-Pixel Chips)
- investigating several materials and devices
  - ▶ scCVD pad detectors (reproduce rate effect)
  - ▶ pCVD pad and pixel detectors
  - ▶ very first 3D pixel detector
- studying non-irradiated and irradiated devices (up to  $2 \times 10^{15}$  neq/cm<sup>2</sup>)





## Setup

# Setup

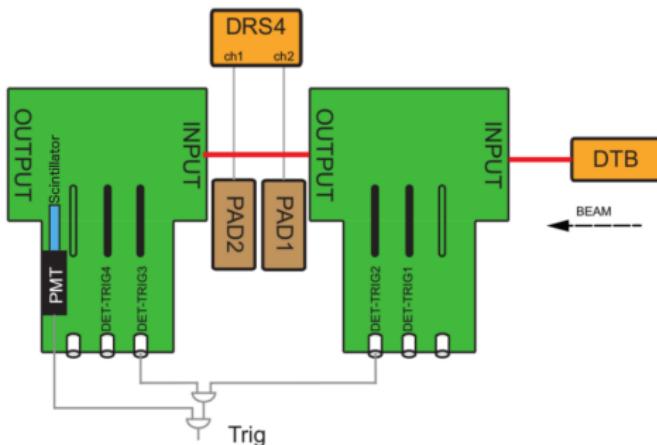


- 4 tracking planes with analogue CMS pixel chips → provide scalable trigger
- 2 diamond pad detectors
- scintillator for precise trigger timing: sigma of 1.3(1) ns
- resolution:  $\sim 80 \mu\text{m} \times 50 \mu\text{m}$



## Setup

## Schematics

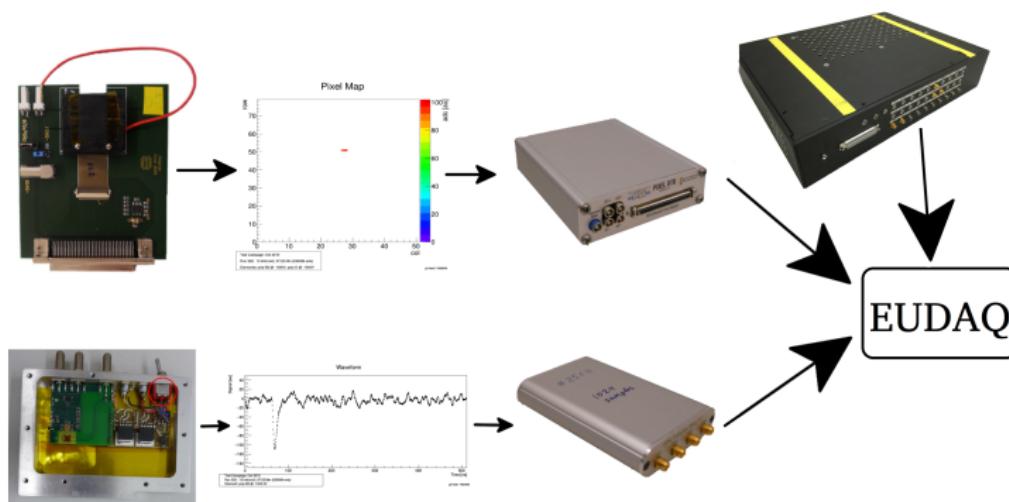


- using PSI DRS4 Evaluation Board as digitizer for the pad waveforms
- using Digital Test Board (DTB) and pXar software for the telescope readout
- global trigger as coincidence of fastOR self trigger and scintillator signal
- EUDAQ as DAQ framework



## Setup

## DAQ



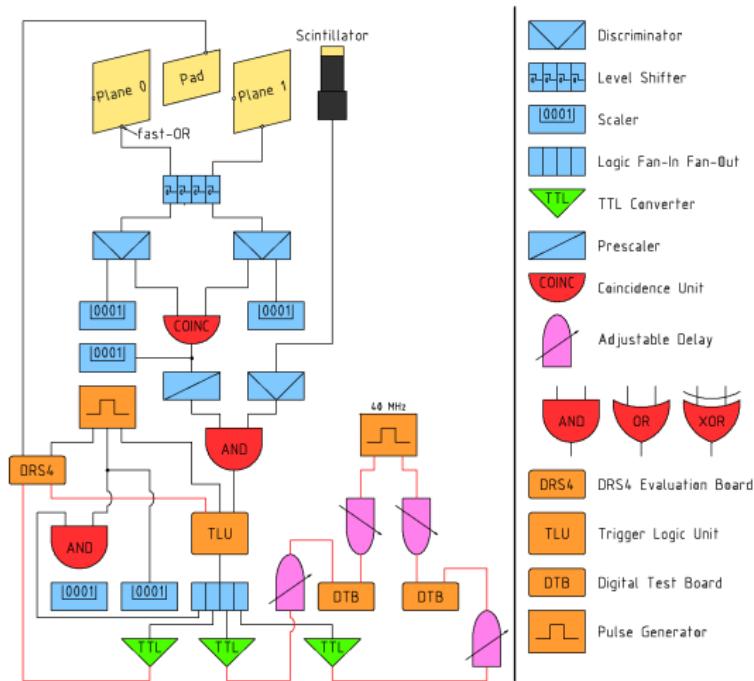
- trigger unit to provide global trigger for all devices
- saving event based data stream as binary file using EUDAQ



## Setup

## Trigger Logic

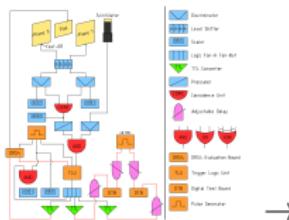
- complicated trigger logic
- long setup time
- error prone
- varying cable length





## Setup

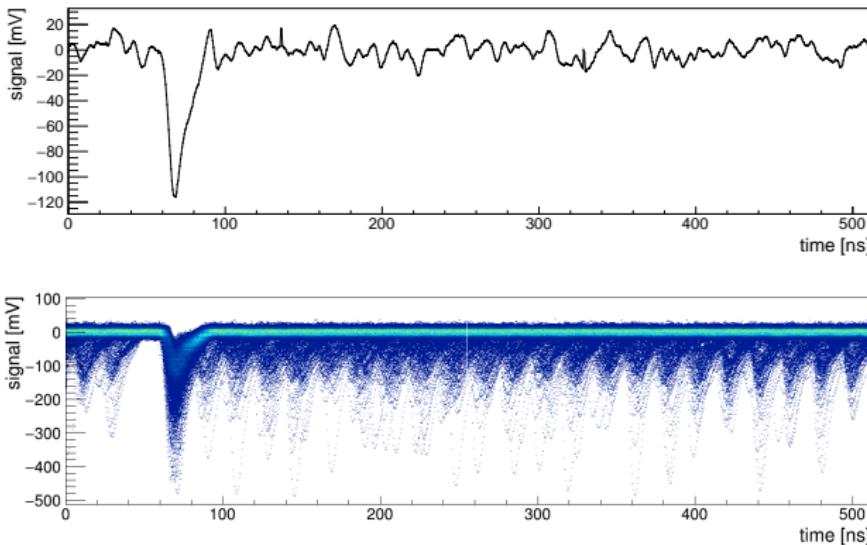
# Trigger unit (TU)



- handles (almost) all trigger logic of the setup with FPGA system
- provides scalers (counter) for the input triggers, pad signals and beam current
- sends calibration pulses as reference signal
- pre-scalers to guarantee stable pulser rates
- coincidence and handshake logic

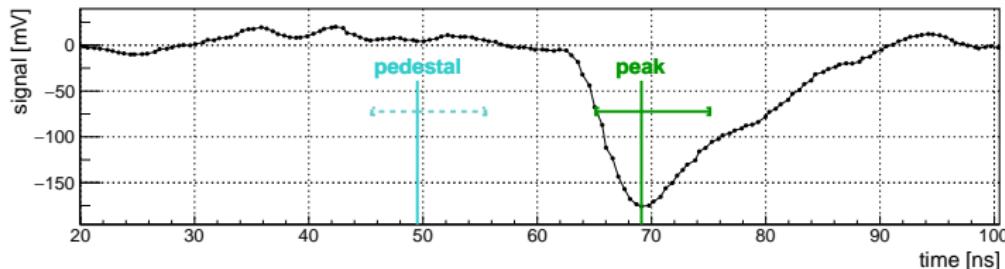
## Analysis

## Waveforms



- most frequented 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

## Pulse Height Calculation



- finding the peak in the signal region
- integrating the signal in time fixed asymmetric integral around peak
- time averaging
- same procedure 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

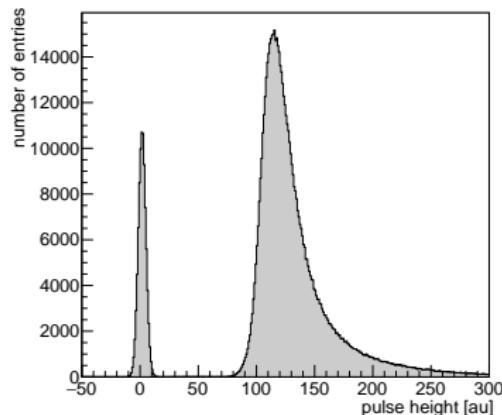
○  
○  
○○

○○○  
○○○○○  
○○●○○○○○○  
○○○○○○○○○

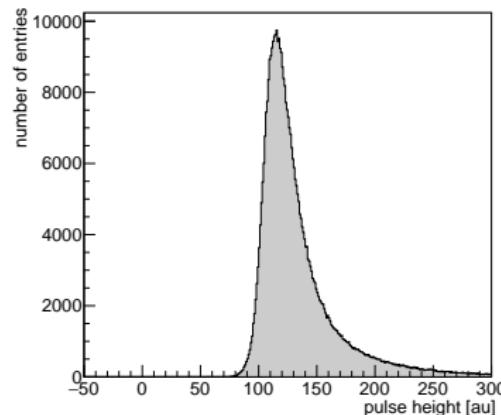
○  
○  
○  
○

## Analysis

## Event based cuts



(a) no cuts



(b) all cuts

- many undesirable events in the full data (no signal, pulser, multiple hits, ...)
- apply cuts to select only signal events (diamond hit by a single pion)



## Analysis

## Cuts (1)

saturated:

- saturated waveforms
- most likely protons

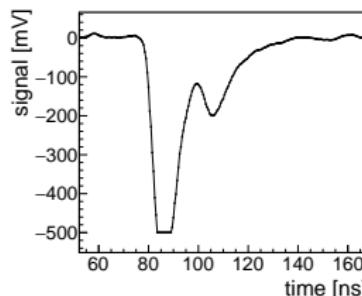


Figure: saturated waveform

pulser:

- reference events with different timing
- no signal in signal region

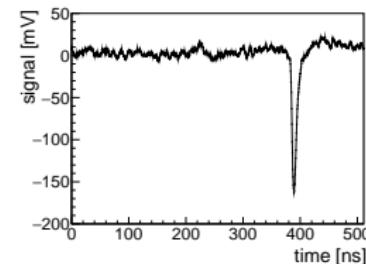


Figure: pulser waveform

tracks:

- only take events with exactly one cluster in each tracking plane



## Analysis

## Cuts (2)

timing:

- signal peak timing follows Gaussian distribution
- discard events with wrong timing (more than  $3\sigma$ )
  - ▶ overlay from waveforms of different buckets
  - ▶ other particles (electrons, muons)

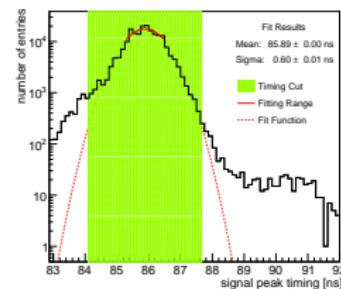


Figure: signal peak timing

bucket:

- two particles in consecutive buckets
- first one hits the scintillator but not the diamond
- wrong trigger timing (20 ns)
- no signal in signal region

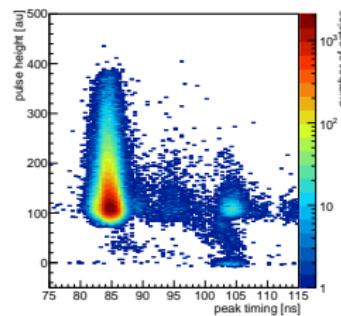


Figure: bucket pedestal

○  
○  
○○

○○○  
○○○○○  
○○○○●○○○  
○○○○○○○○

○  
○  
○  
○

## Analysis

## Cuts (3)

fiducial:

- only select uniform physical center area of the diamond
- exclude edges and guard ring

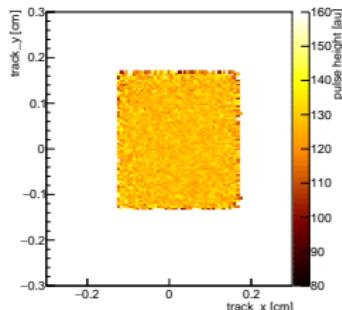


Figure: signal map

other:

- $\chi^2$  in  $x$  and  $y$  of the track fit
- track angle in  $x$  and  $y$
- event range
- beam interruptions
- pedestal sigma

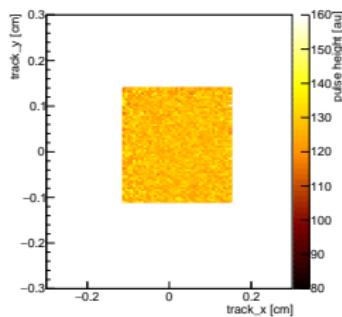
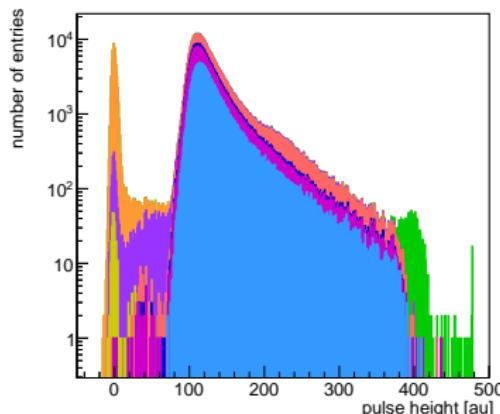
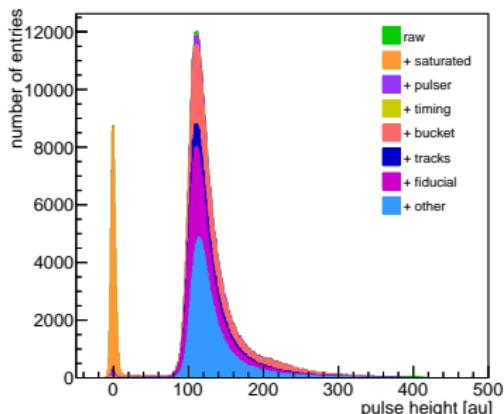


Figure: with fiducial cut

## Analysis

Taken out:

- saturated events
- pedestal events (no signal)
- multiple hits ( $\sim 2$  times the signal)
- low signal events (guard ring, edge hits)

○  
○  
○○

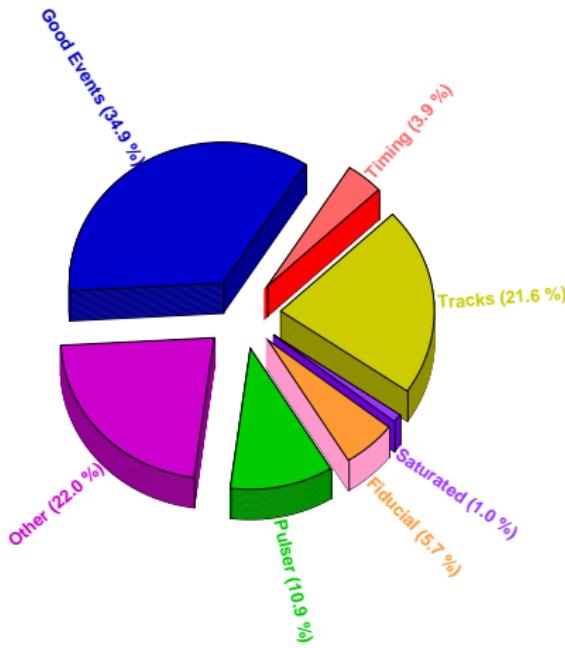
○○○  
○○○○○  
○○○○○○●○  
○○○○○○○○

○  
○  
○  
○

## Analysis

## Cut Contributions

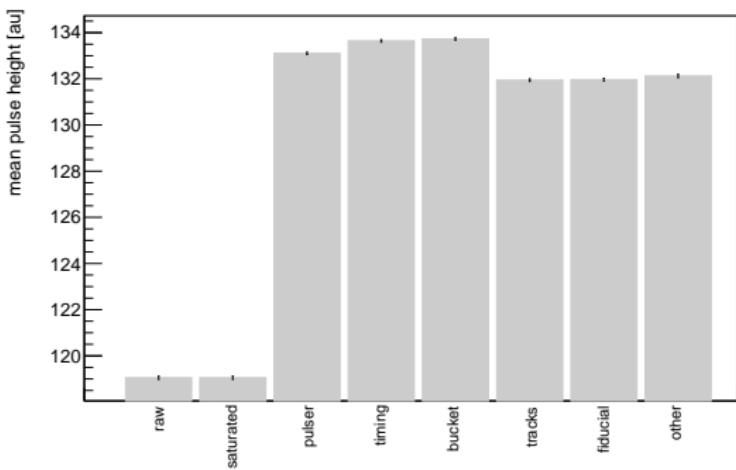
- stable pulser rate around 10 % to 20 %
- many events with incomplete or multiple tracks
- 30 % to 40 % good events after cuts



## Analysis

## Cut Influence on the Mean Pulse Height

- very few saturated events
- pulser takes out pedestal events
- tracks discard multiple hits





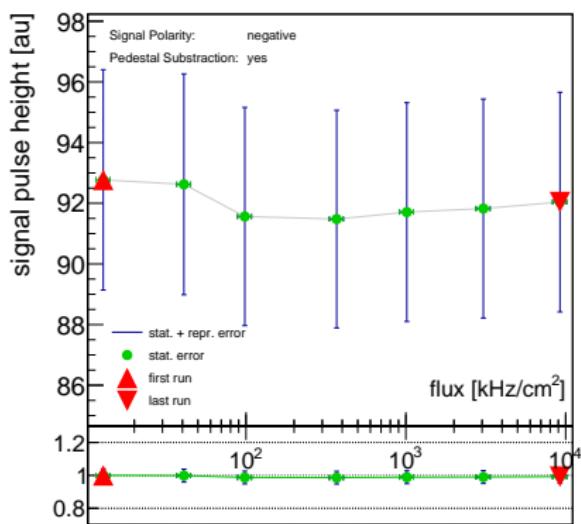
## Results

## 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  $2 \times 10^{15}$  neq/cm<sup>2</sup>
- large systematic errors due to reproducibility

To do:

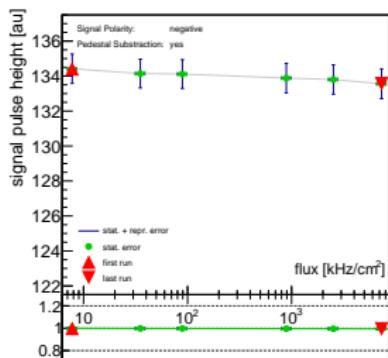
- test higher irradiated samples
- improve reproducibility
- check the same for pixel detectors



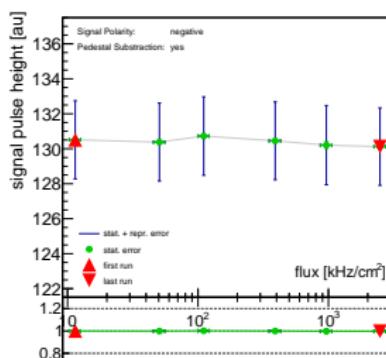
## Results

## Non-Irradiated Single Crystalline Diamond

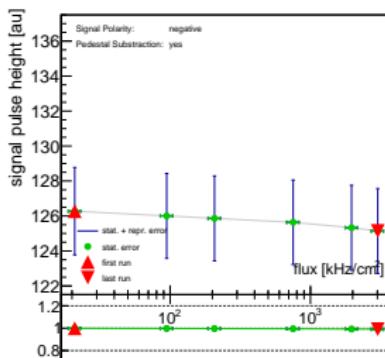
October 2015



August 2016



October 2016

noise  $\sigma \approx 2.6$  aunoise  $\sigma \approx 2.6$  aunoise  $\sigma \approx 2.6$  au

- measurements taken under the same conditions
- noise stays the same
- pulse height very stable



## Results

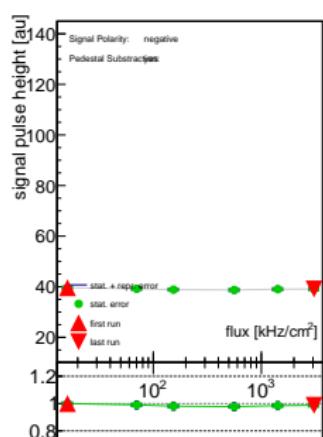
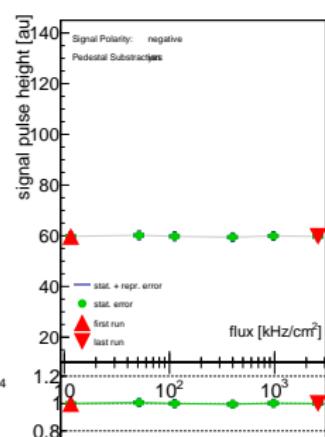
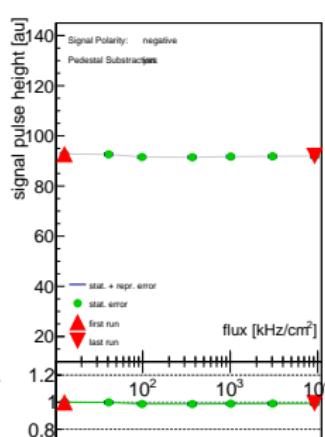
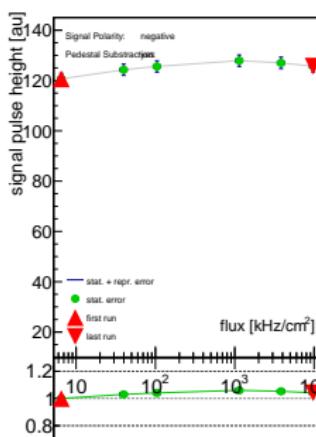
## Poly crystalline diamond

August 2016 -  
unirradiated

October  
2015 -  $5 \cdot 10^{14} \text{ n/cm}^2$

August  
2016 -  $1 \cdot 10^{15} \text{ n/cm}^2$

October  
2016 -  $2 \cdot 10^{15} \text{ n/cm}^2$



noise  $\sigma \approx 4.9 \text{ au}$

- pulse height very stable after irradiation
- noise stays the same

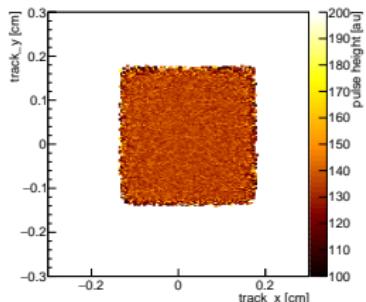
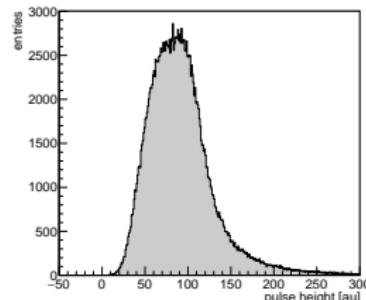
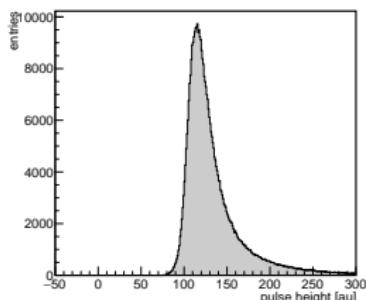
○  
○  
○○

○○○  
○○○○○  
○○○○○○○○○○  
○○○●○○○○○

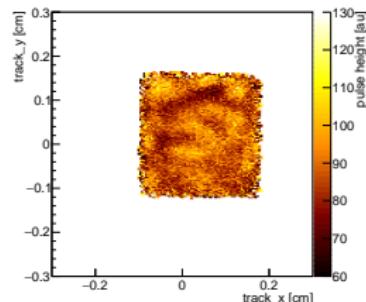
○  
○  
○  
○

## Results

## Pulse Height Distribution and Signal Maps



(a) single-crystalline



(b) poly-crystalline

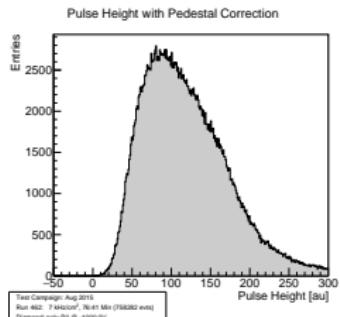
○  
○  
○○

○○○  
○○○○○  
○○○○○○○○○  
○○○●○○○○

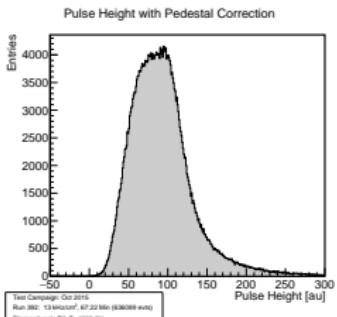
○  
○  
○  
○

## Results

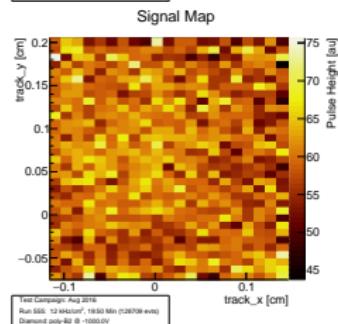
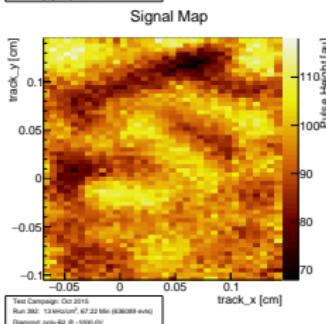
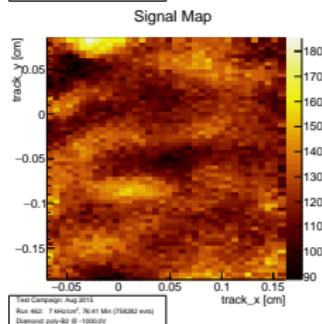
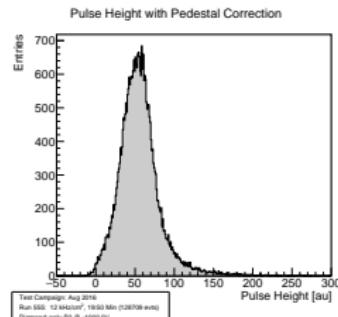
August 2016 -  
unirradiated



October 2015 -  
 $5 \cdot 10^{14} \text{ n/cm}^2$



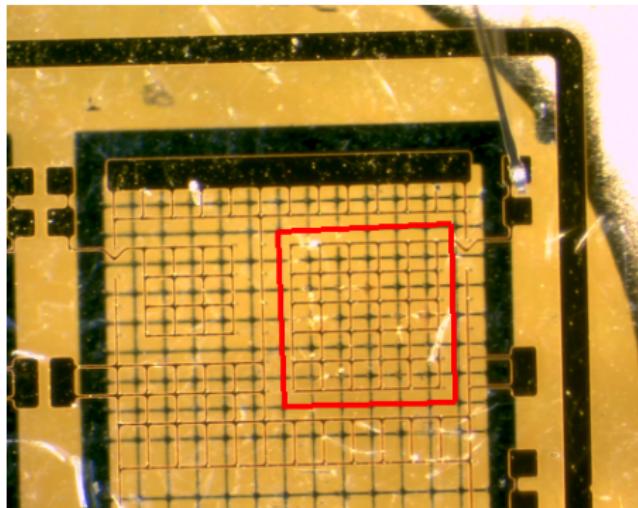
August 2016 -  
 $1 \cdot 10^{15} \text{ n/cm}^2$



## Results

## 3D Multi Pad

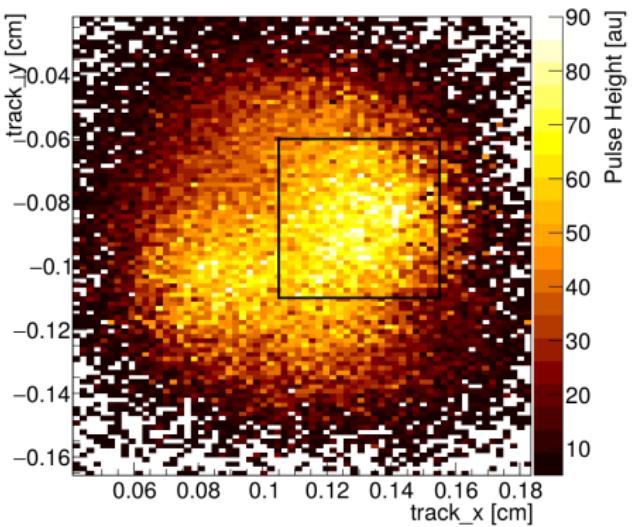
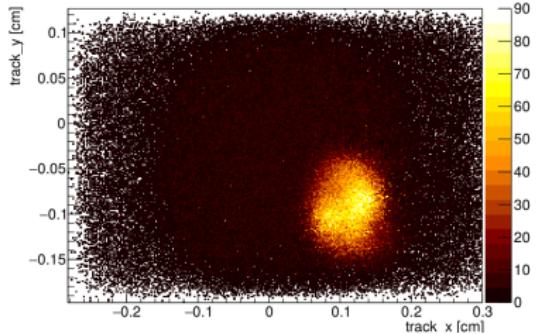
- 500 µm thick poly-crystalline diamond sensor
- 25 3D cells ganged together into a single readout (quasi-pad)





## Results

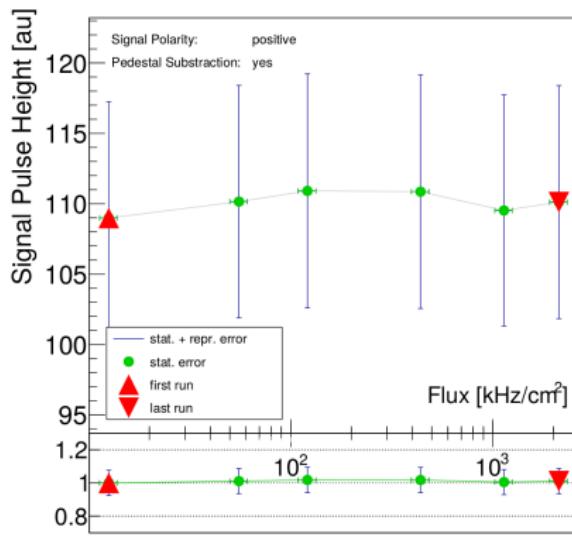
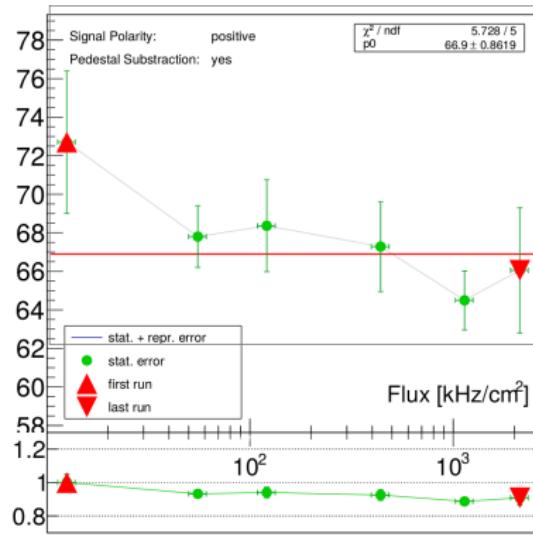
## 3D Multi Pad - Signal Maps





## Results

## 3D Multi Pad - Pulse Height

(a) 100  $\mu\text{m}$  silicon diode(b) 500  $\mu\text{m}$  poly-crystalline diamond

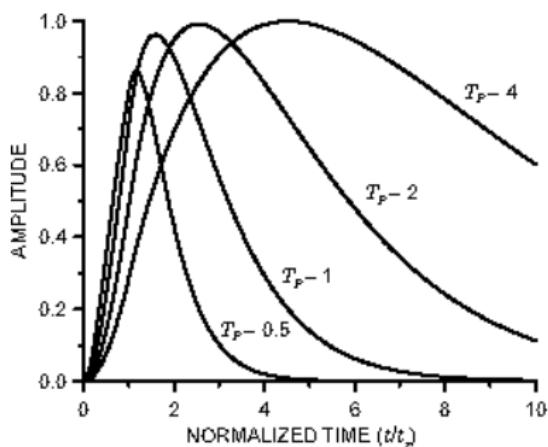
○  
○  
○○

○○○  
○○○○○  
○○○○○○○○○○  
○○○○○○○○●

○  
○  
○  
○

## Results

## Reasons for Low Pulse Height





## Section 4

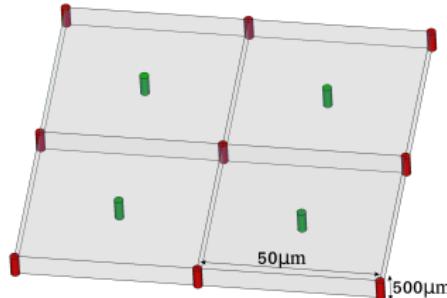
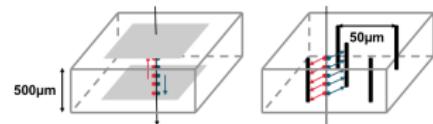
### 3D Detectors at CERN



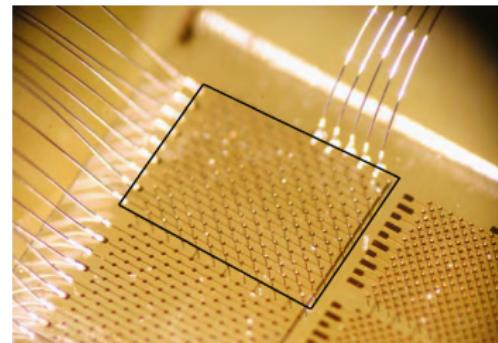
## Working Principle of a 3D Detector

## 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



(a) array of four 3D cells, bias electrodes in red, readout electrodes in green

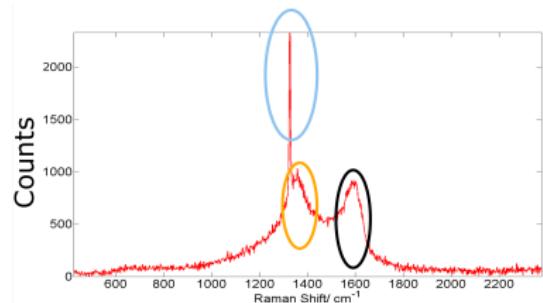
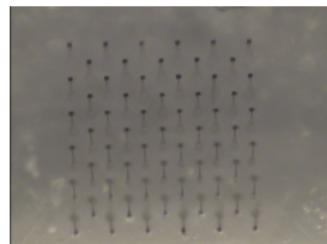


(b) 3D diamond detector

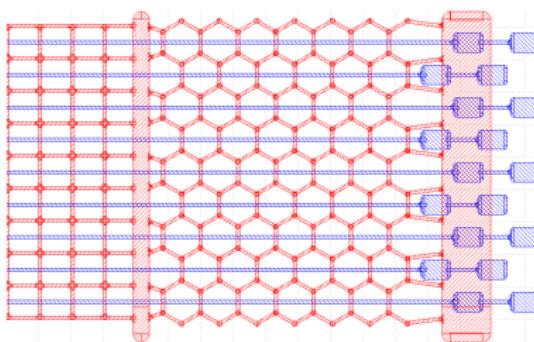


## 3D Diamond Detector

- electrodes formed with a pulsed femto second laser
  - ▶ transition of diamond to conducting material (graphitic material i.a.)
- tested different geometries (4 or 6 bias columns)



(a) blue: Diamond peak. Orange and black: Graphitic material



(b) square and hexagonal bias patterns (red) and readout channels (blue).



## 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 with 120GeV protons
- basic working principle has been proven



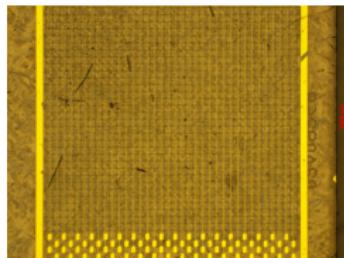
Figure: Strasbourg Telescope



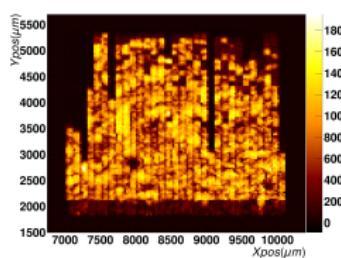
## Analysis

## 3D Full detector

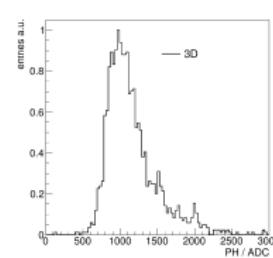
- more than 2000 laser fabricated columns (1152 square cells)
- columns yield >90 %
- >85 % charge collection for a corresponding thickness



(a) photograph of the metalization pattern in the 3D Full detector



(b) signal map of the 3D Full detector. Broken channels (c) signal distribution of good regions due to fabrication mishandling





## Section 5

### Conclusion

o

o

oo

ooo

oooo

oooooooooooo

oooooooooooo

o

o

o

o

## 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
- pCVD diamonds show no rate dependence up to fluxes of  $10 \text{ MHz/cm}^2$  and irradiations up to  $2 \times 10^{15} \text{ neq/cm}^2$
- plan to publish results soon
- successfully proven the working principle of a 3D diamond detector
- tested the very first 3D-Pixel detector

### Ultimate Goal:

- build fully working pixel detector