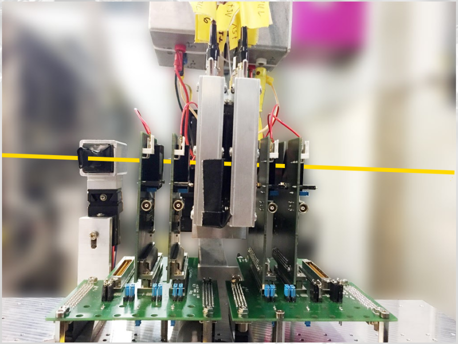

Beam Tests Investigating Diamond as Detector Material

Michael Reichmann

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

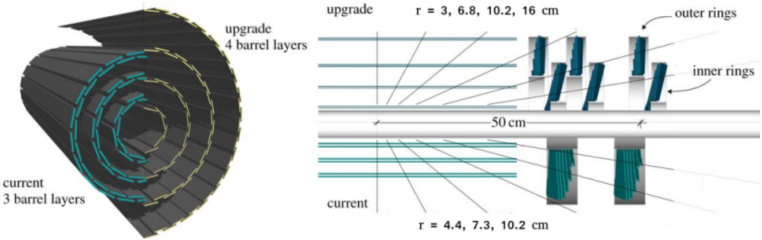


Figure: CMS Barrel Pixel Detector upgrade with end caps

Section 2

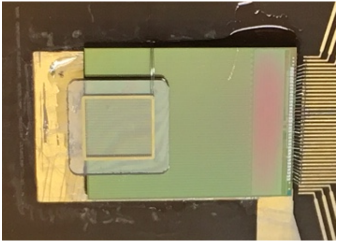
Diamond Detectors and Materials

Diamond as detector material

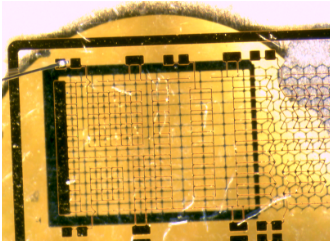
- 7 – 10 times smaller charge loss due to radiation damage than in silicon
- signals (electrons created by a charged particle) half the size of silicon
- → diamond becomes superior than silicon at a certain irradiation
- other advantageous properties:
  - isolating material → negligible leakage current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

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



(a) on CMS-Pixel chip

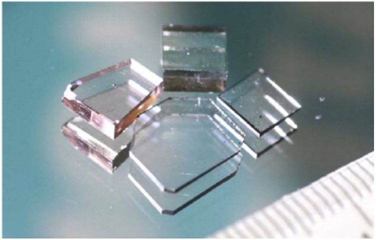


(b) multi pattern

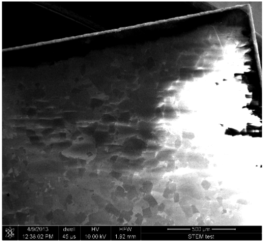
Figure: 3D diamond detectors

Artificial diamond types

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



(a) single-crystalline CVD



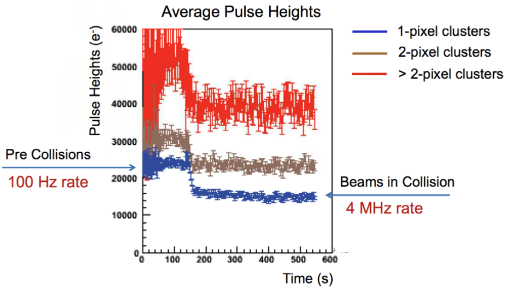
(b) poly-crystalline CVD

- grown on existing diamond crystal
- only small sizes (~0.25 cm^2)
- larger signals than pCVD (5 : 3)

- grown on Si substrate with diamond powder
- large wafers (5″ to 6″ ⌀)
- non-uniformities and grains

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:

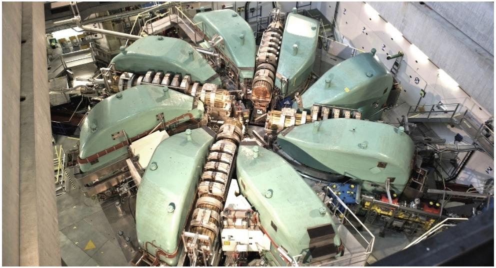
- investigation of the rate effect in scCVD diamonds (Edge-TCT)
- using pCVD diamond and prove that they show no rate dependence

Section 3

Rate Studies at PSI

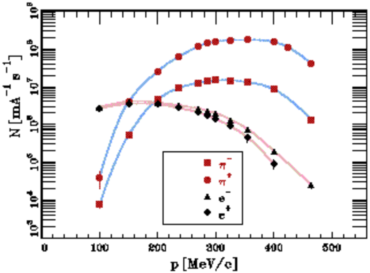
Proton Accelerator at Paul Scherrer Institute (PSI)

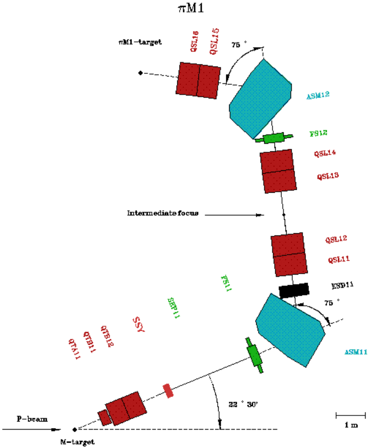
- High Intensity Proton Accelerator (HIPA) at PSI (Cyclotron)
- 590 MeV proton beam with beam current up to 2.4 mA (1.5×10^{16} protons/s)
  - $\sim$1.4 MW $\rightarrow$ most powerful proton accelerator in the world
- only two comparable accelerators
  - TRIUMF in Vancouver ($\sim$0.25 MW)
  - LAMPF in Los Alamos ($\sim$0.8 MW)



Beam line at Paul Scherrer Institute (PSI)

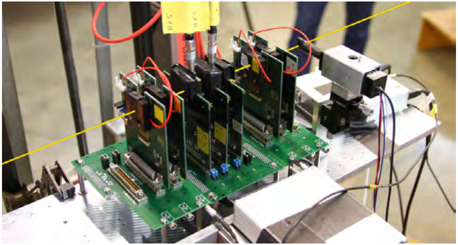
- using beam line πM1 with 260 MeV/c positive pions (π^+)
- tunable particle fluxes from 2 kHz/cm^2 to 10 MHz/cm^2



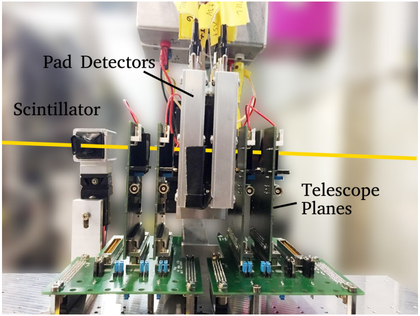


Measurements

- 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/cm^2)

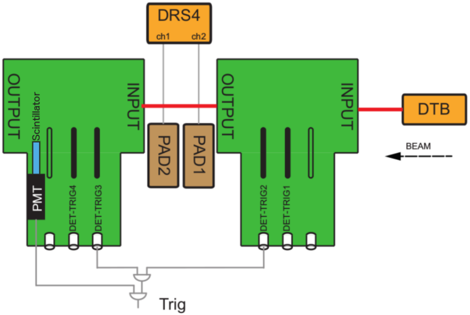


Setup



- 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: ∼80 μm × 50 μm

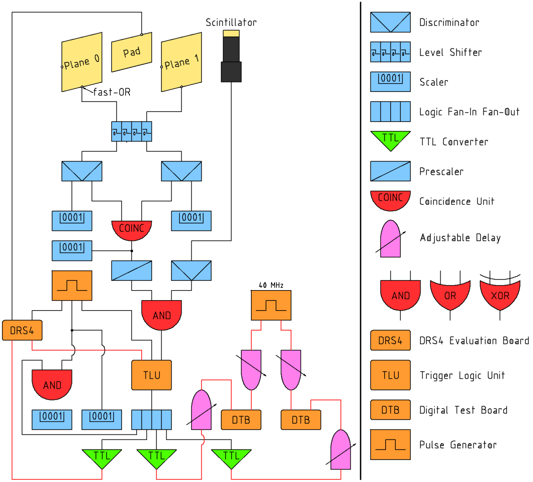
Schematics



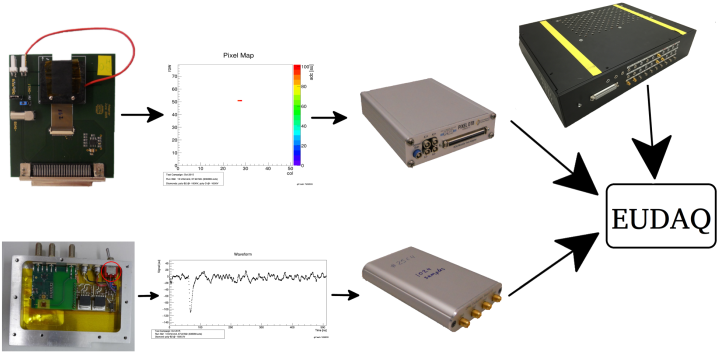
- using PSI DRS4 Evaluation Board as digitizer for the pad waveforms
- using Digital Test Board (DTB) and pXar software for the telescope readout
- global trigger as coincidence of fastOR self trigger and scintillator signal
- EUDAQ as DAQ framework

Trigger Logic

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

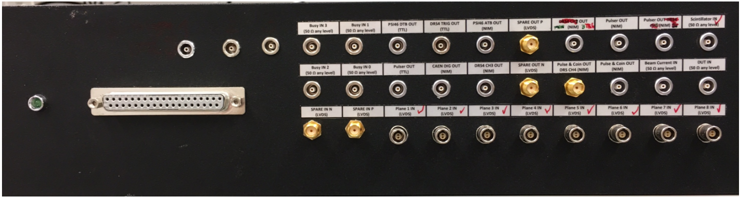


DAQ



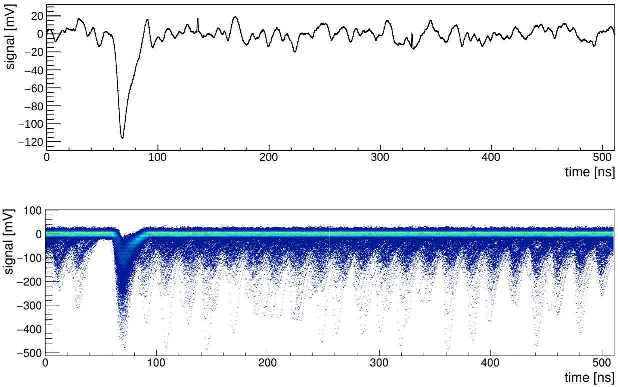
- trigger unit to provide global trigger for all devices
- saving event based data stream as binary file using EUDAQ

Trigger unit (TU)



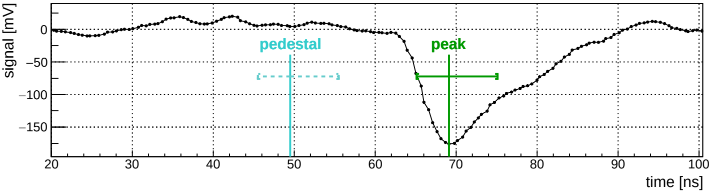
- handles (almost) all trigger logic of the setup with FPGA system
- provides scalers (counter) for the input triggers, pad signals and beam current
- sends calibration pulses as reference signal
- pre-scalers to guarantee stable pulser rates
- coincidence and handshake logic

Waveforms



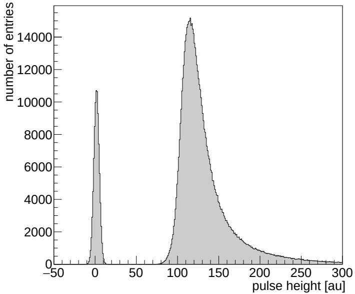
- most frequented peak (∼70 ns): triggered signal
- other peaks originate from other buckets (→ resolve beam structure of ≈19.7 ns)
- system does not allow signals in pre-signal bucket due to fastOR trigger deadtime

Pulse Height Calculation



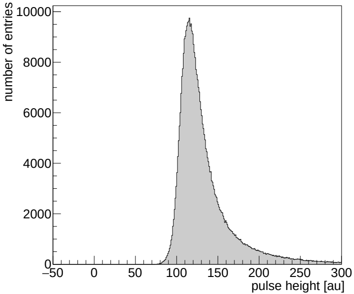
- finding the peak in the signal region
- integrating the signal in time fixed asymmetric integral around peak
- time averaging
- same procedure for pedestal (base line → noise)
- optimising the integral width by highest SNR (Integral / Pedestal Sigma)
- subtracting the pedestal from the signal integral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

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)

Cuts (1)

saturated:

- saturated waveforms
- most likely protons

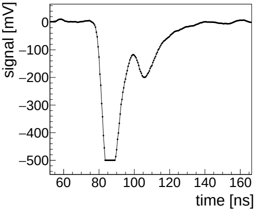


Figure: saturated waveform

pulser:

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

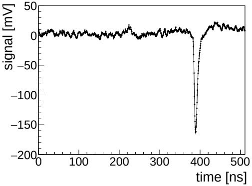


Figure: pulser waveform

tracks:

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

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)

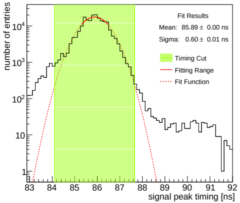


Figure: signal peak timing

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

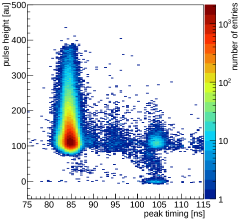


Figure: bucket pedestal

Cuts (3)

fiducial:

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

other:

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

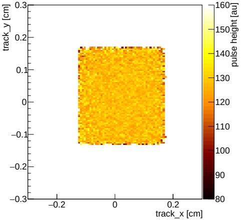


Figure: signal map

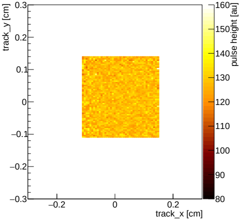
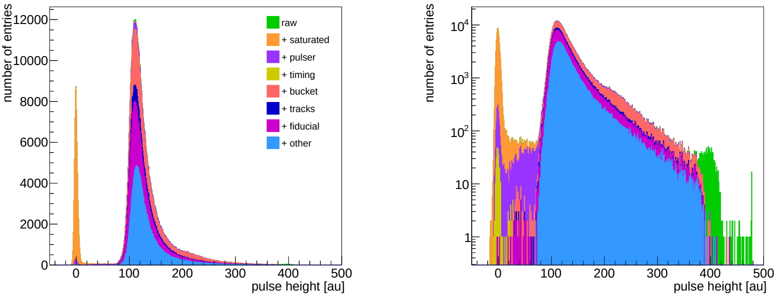


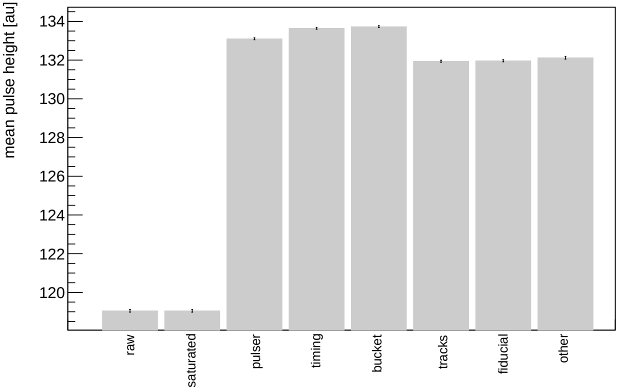
Figure: with fiducial cut



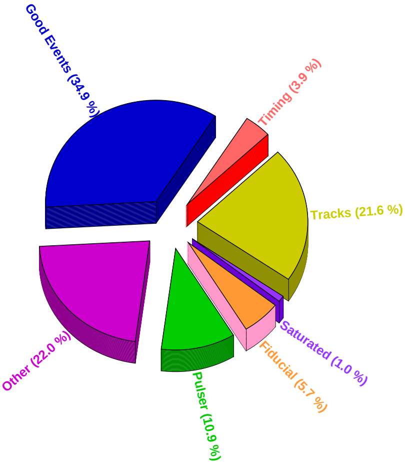
Taken out:

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

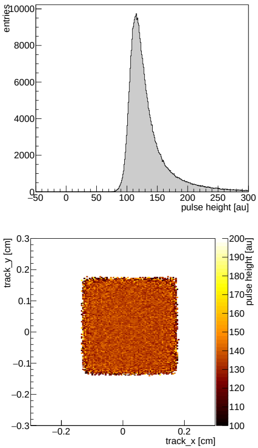
Cut Influence on the Mean Pulse Height



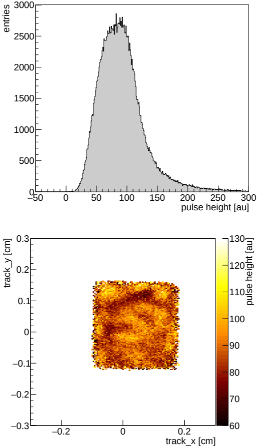
Cut Contributions



Pulse Height Distribution and Signal Maps



(a) single-crystalline



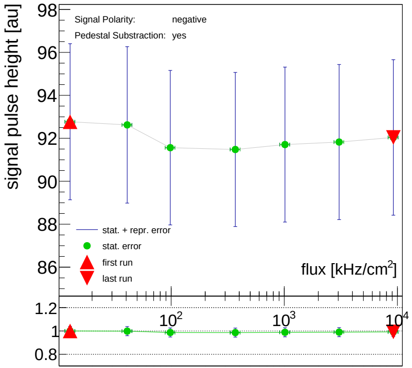
(b) poly-crystalline

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

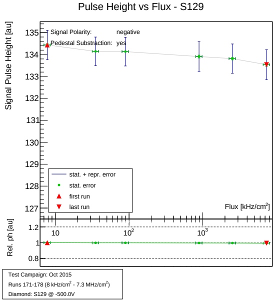
To do:

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



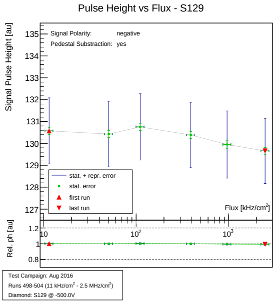
Single crystalline diamond

October 2015



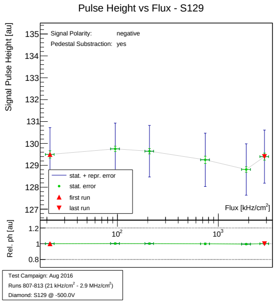
noise $\sigma \approx 2.6\,\mathrm{au}$

August 2016 - begin



noise $\sigma \approx 2.6\,\mathrm{au}$

August 2016 - end

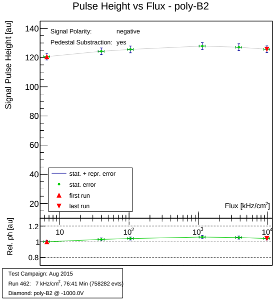


noise $\sigma \approx 2.6\,\mathrm{au}$

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

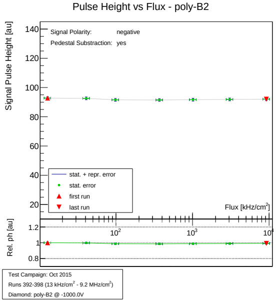
Poly crystalline diamond

August 2016 - unirradiated



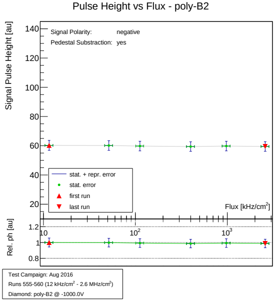
noise $\sigma \approx 4.9$ au

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



noise $\sigma \approx 4.9$ au

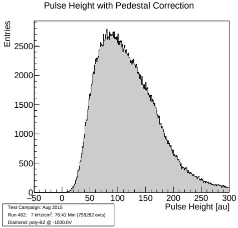
August 2016 - $1 \cdot 10^{15}$ n/cm^2

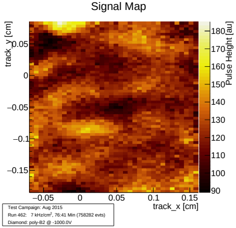


noise $\sigma \approx 4.9$ au

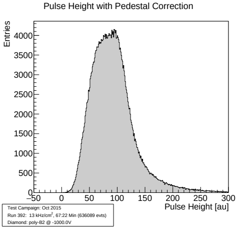
- pulse height very stable after irradiation
- noise stays the same

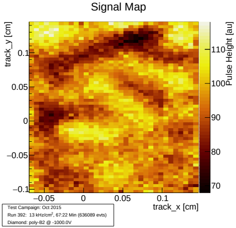
August 2016 - unirradiated



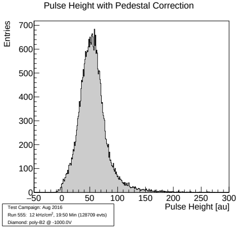


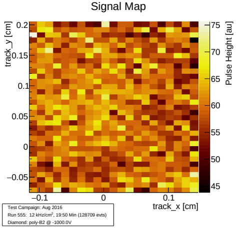
October 2015 - $5 \cdot 10^{14}\ \mathrm{n/cm^2}$





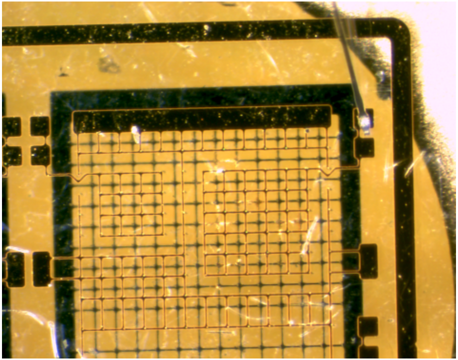
August 2016 - $1 \cdot 10^{15}\ \mathrm{n/cm^2}$



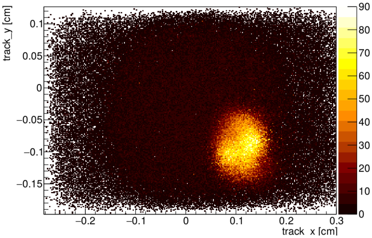


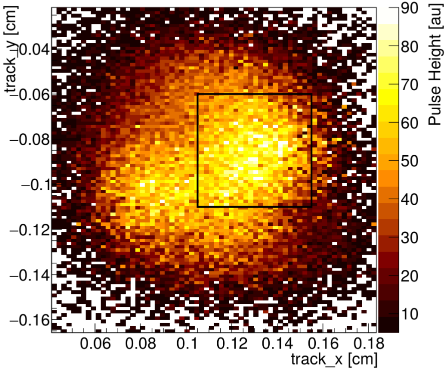
3D Multi Pad

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

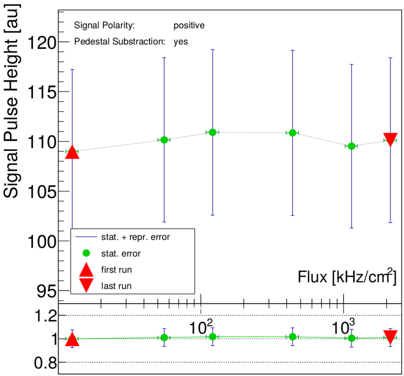


3D Multi Pad - Signal Maps

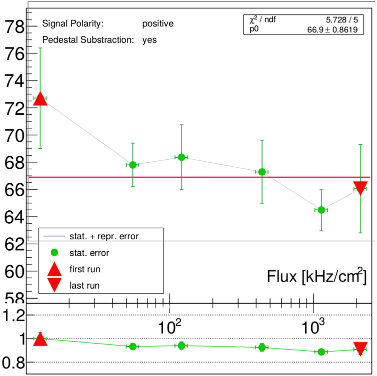




3D Multi Pad - Pulse Height

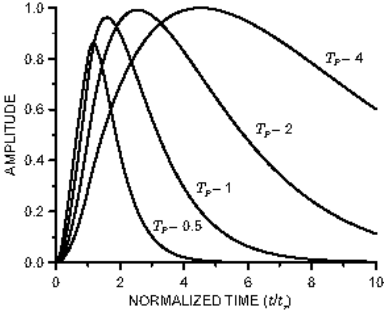


(a) 100 µm silicon diode



(b) 500 µm poly-crystalline diamond

Reasons for Low Pulse Height

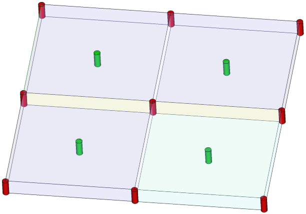


Section 4

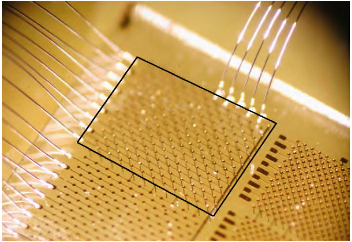
3D Detectors at CERN

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



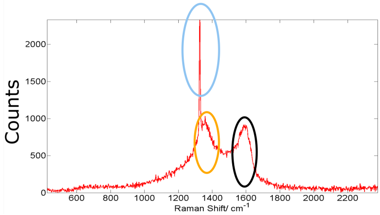
(a) array of four 3D cells, bias electrodes in red, readout electrodes in green



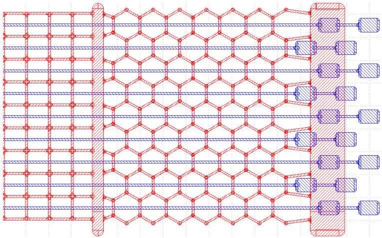
(b) 3D diamond detector

3D Diamond Detector

- electrodes formed with a pulsed femto second laser (100 fs pulse; 800 nm wavelength)
  - 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

- 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

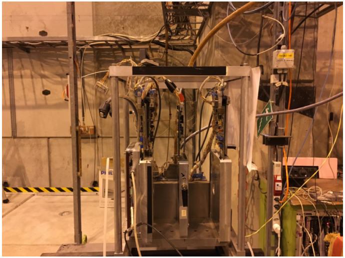
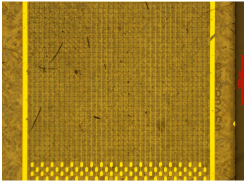


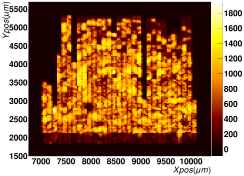
Figure: Strassbourg Telescope

3D Full detector

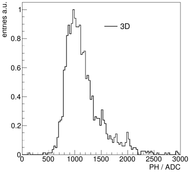
- more than 2000 laser fabricated columns (1152 square cells)
- columns yield $>90\,\%$
- $>85\,\%$ charge collection for a corresponding thickness



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



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



(c) signal distribution of good regions

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 $10\,\mathrm{MHz/cm^2}$ and irradiations up to $1 \times 10^{16}\,\mathrm{neq/cm^2}$
- successfully proven the working principle of a 3D diamond detector
- tested the very first 3D-Pixel detector

Ultimate Goal:

- build fully working pixel detector