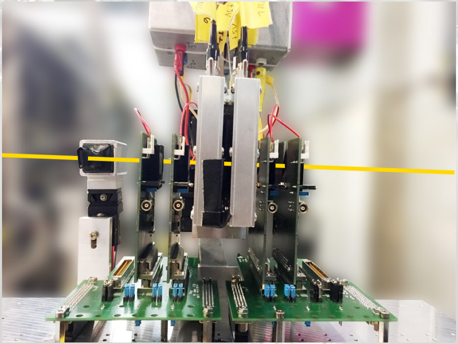

Beam Tests Investigating Diamond as Detector Material

Michael Reichmann

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Section 1

Motivation

Motivation

Diamond as future material for the tracking detectors of the LHC:

- innermost layers $\rightarrow$ highest radiation damage
- current detector designed to withstand $250\,\text{fb}^{-1}$ of integrated luminosity
  - High-Luminosity LHC: replace detector every 12 month
- $\rightarrow$ **look for more radiation hard detector designs and/or materials**

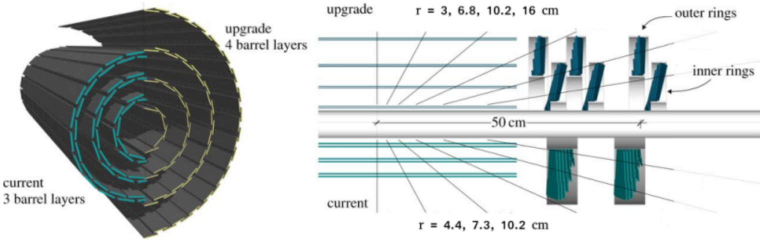


Figure: CMS Barrel Pixel Detector upgrade with end caps

Section 2

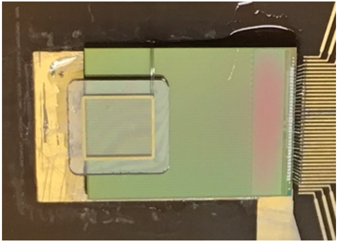
Diamond Detectors and Materials

Diamond as detector material

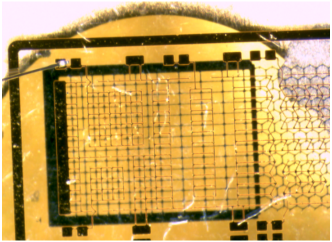
- $7 - 10$ times smaller charge loss due to radiation damage than in silicon
- signals (electrons created by a charged particle) half the size of silicon
- $\rightarrow$ diamond becomes superior than silicon at a certain irradiation
- other advantageous properties:
  - isolating material (large band gap)
    - $\rightarrow$ negligible leakage current $\rightarrow$ power saving
    - $\rightarrow$ no cooling required
  - high thermal conductivity $\rightarrow$ heat spreader for electronics
  - high charge carrier mobility $\rightarrow$ fast signals
  - working principle like a solid state ionisation chamber $\rightarrow$ 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

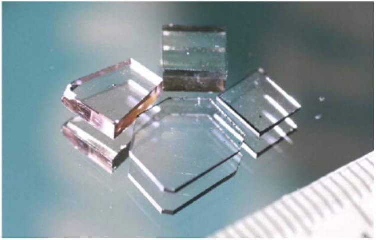


(b) multi pattern

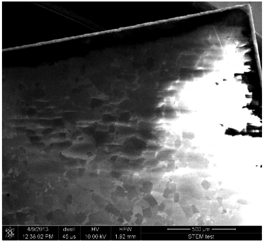
Figure: 3D diamond detectors

Artificial diamond types

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



(a) single-crystalline CVD



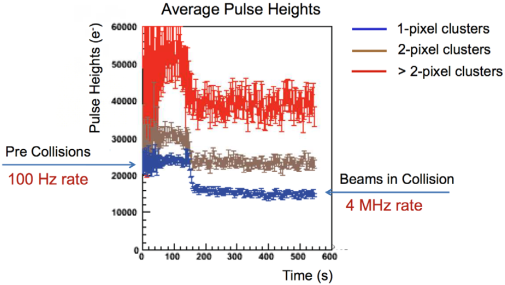
(b) poly-crystalline CVD

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

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

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:

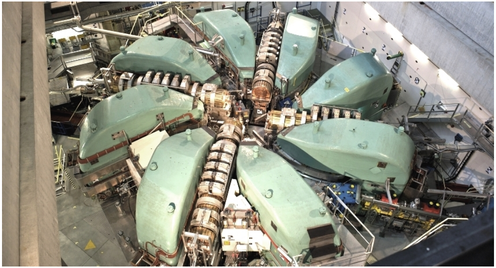
- investigation of the rate effect in scCVD diamonds (Edge-TCT)
- using pCVD diamond and prove that they show no rate dependence

Section 3

Rate Studies at PSI

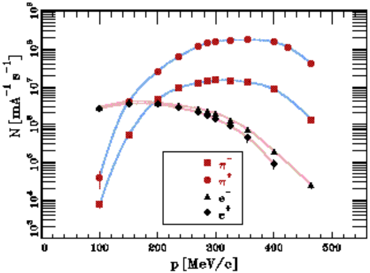
Proton Accelerator at Paul Scherrer Institute (PSI)

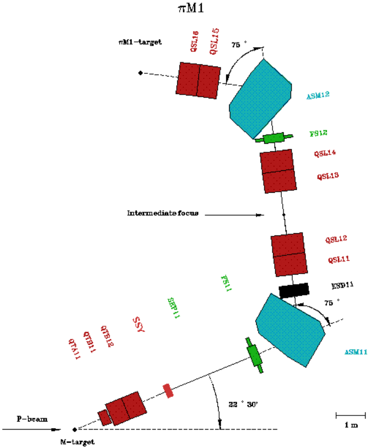
- High Intensity Proton Accelerator (HIPA) at PSI (Cyclotron)
- 590 MeV proton beam with beam current up to 2.4 mA (1.5×10^{16} protons/s)
  - $\sim$1.4 MW $\rightarrow$ most powerful proton accelerator in the world
- only two comparable accelerators
  - TRIUMF in Vancouver ($\sim$0.25 MW)
  - LAMPF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



Beam line at Paul Scherrer Institute (PSI)

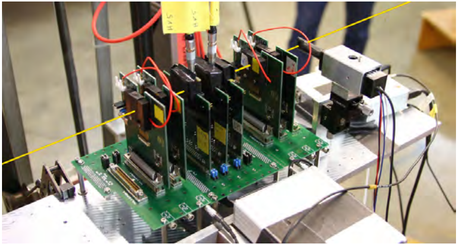
- using beam line πM1 with 260 MeV/c positive pions (π^+)
- tunable particle fluxes from 2 kHz/cm^2 to 10 MHz/cm^2



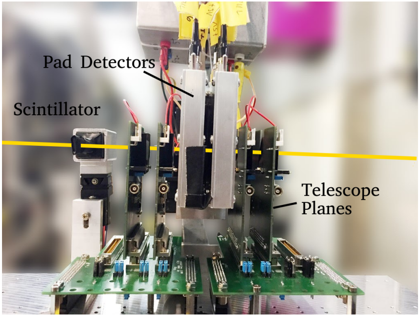


Measurements

- 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 2×10^{15} neq/cm^2)

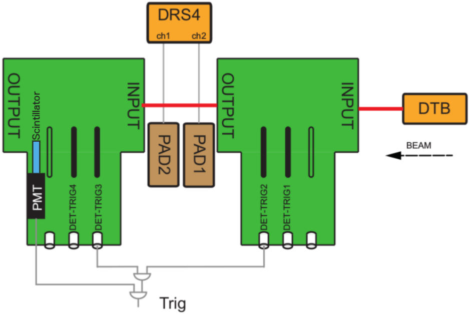


Setup



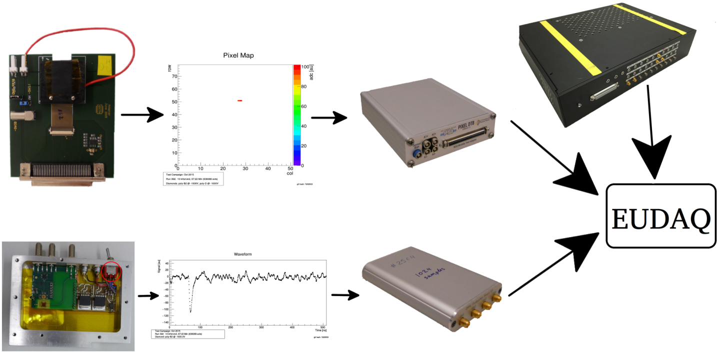
- 4 tracking planes with analogue CMS pixel chips → provide scalable trigger
- 2 diamond pad detectors
- scintillator for precise trigger timing: sigma of 1.3(1) ns
- resolution: ∼80 µm × 50 µm

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

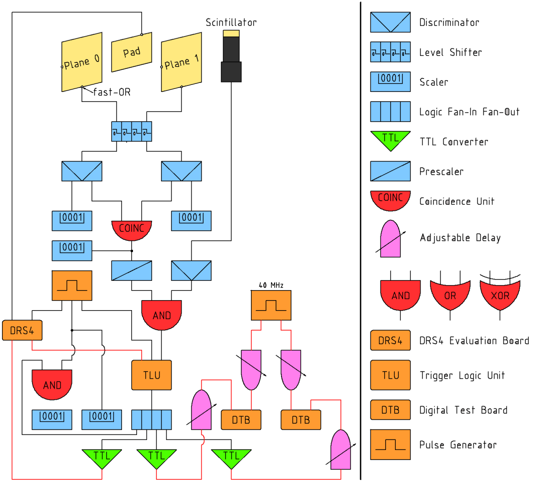
DAQ



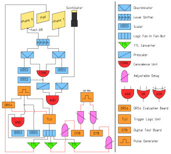
- trigger unit to provide global trigger for all devices
- saving event based data stream as binary file using EUDAQ

Trigger Logic

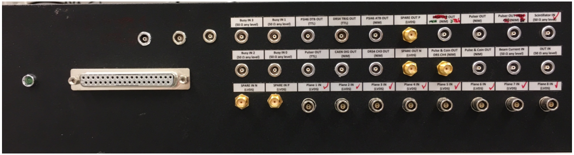
- complicated trigger logic
- long setup time
- error prone
- varying cable length



Trigger unit (TU)

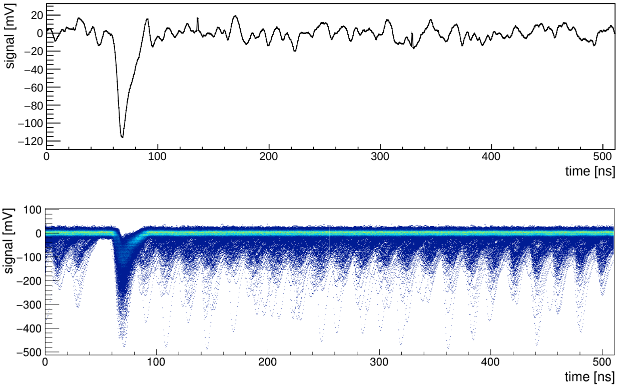


→



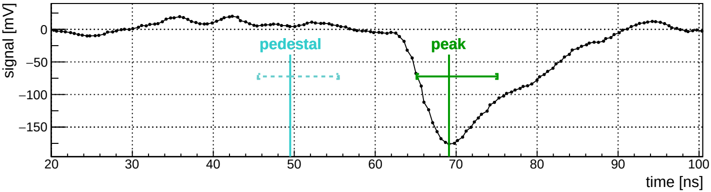
- handles (almost) all trigger logic of the setup with FPGA system
- provides scalers (counter) for the input triggers, pad signals and beam current
- sends calibration pulses as reference signal
- pre-scalers to guarantee stable pulser rates
- coincidence and handshake logic

Waveforms



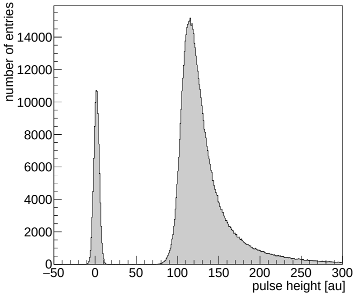
- most frequented peak (∼70 ns): triggered signal
- other peaks originate from other buckets (→ resolve beam structure of ≈19.7 ns)
- system does not allow signals in pre-signal bucket due to fastOR trigger deadtime

Pulse Height Calculation



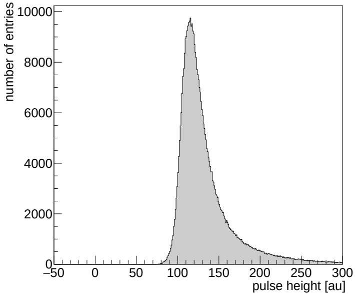
- finding the peak in the signal region
- integrating the signal in time fixed asymmetric integral around peak
- time averaging
- same procedure for pedestal (base line → noise)
- optimising the integral width by highest SNR (Integral / Pedestal Sigma)
- subtracting the pedestal from the signal integral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

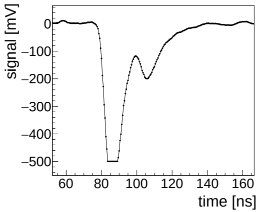


Figure: saturated waveform

pulser:

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

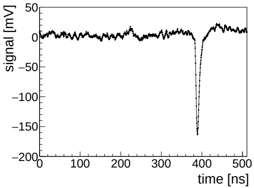


Figure: pulser waveform

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 σ)
  - overlay from waveforms of different buckets
  - other particles (electrons, muons)

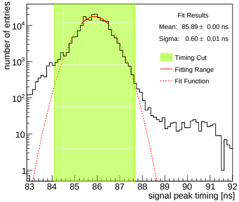


Figure: signal peak timing

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

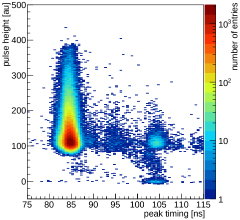


Figure: bucket pedestal

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

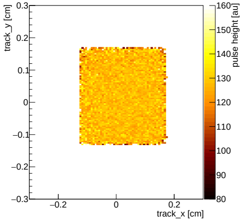


Figure: signal map

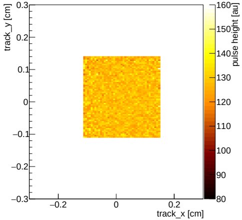
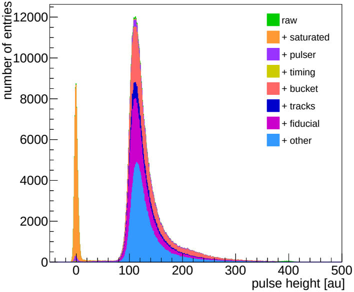
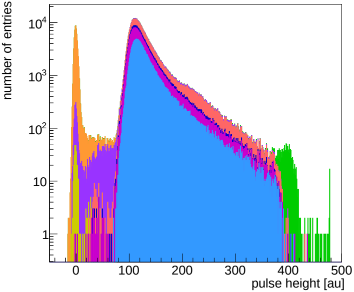


Figure: with fiducial cut



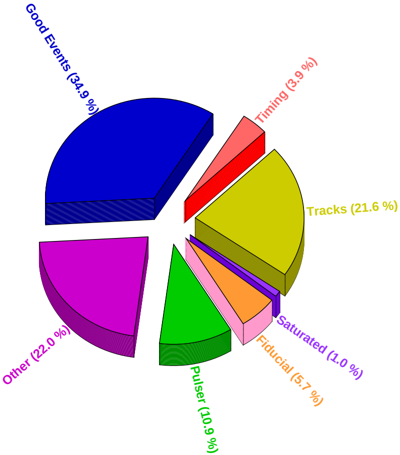


Taken out:

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

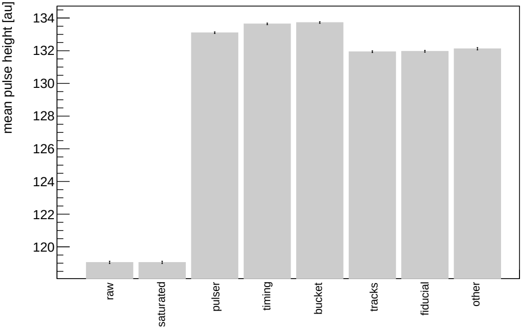
Cut Contributions

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



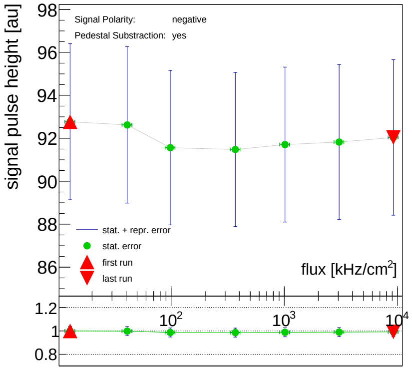
Cut Influence on the Mean Pulse Height

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



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 2×10^{15} neq/cm^2
- large systematic errors due to reproducibility

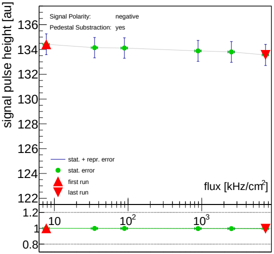


To do:

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

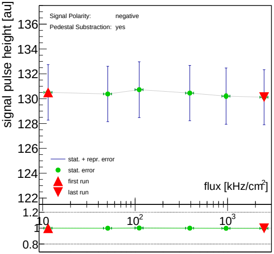
Non-Irradiated Single Crystalline Diamond

October 2015



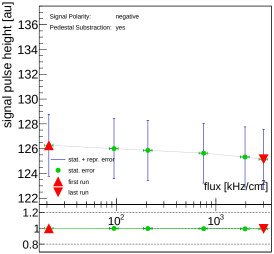
noise $\sigma \approx 2.6\,\mathrm{au}$

August 2016



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

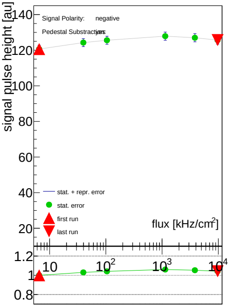
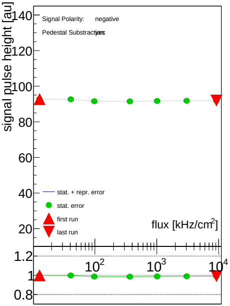
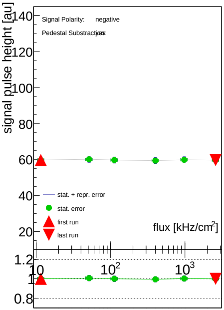
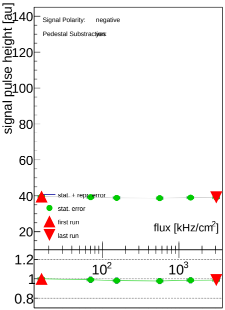
October 2016



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

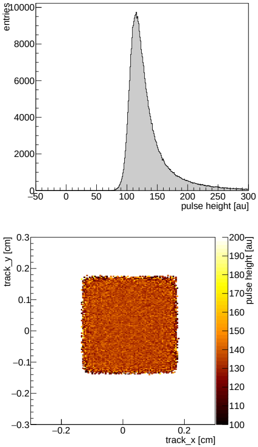
- measurements taken under the same conditions
- noise stays the same
- pulse height very stable

Poly crystalline diamond

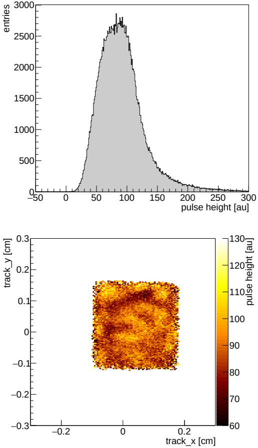
August 2016 - unirradiated	October 2015 - $5 \cdot 10^{14}$ n/cm^2	August 2016 - $1 \cdot 10^{15}$ n/cm^2	October 2016 - $2 \cdot 10^{15}$ n/cm^2
			
noise $\sigma \approx 4.9$ au	noise $\sigma \approx 4.9$ au	noise $\sigma \approx 4.9$ au	noise $\sigma \approx 4.9$ au

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

Pulse Height Distribution and Signal Maps

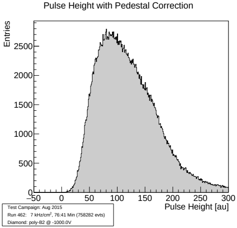


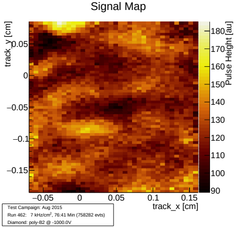
(a) single-crystalline



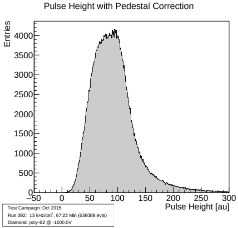
(b) poly-crystalline

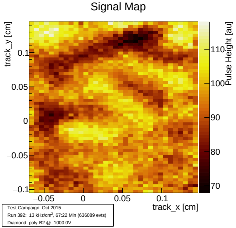
August 2016 - unirradiated



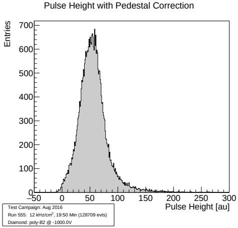


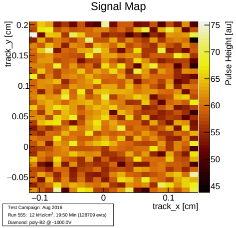
October 2015 - $5 \cdot 10^{14}$ n/cm^2





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



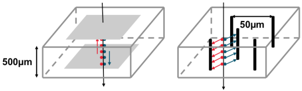


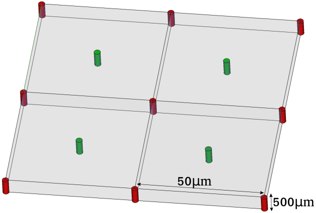
Section 4

3D Detectors at CERN

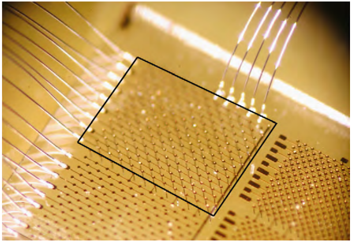
Working Principle of a 3D Detector

- 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





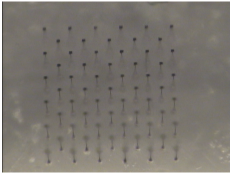
(a) array of four 3D cells, bias electrodes in red, readout electrodes in green

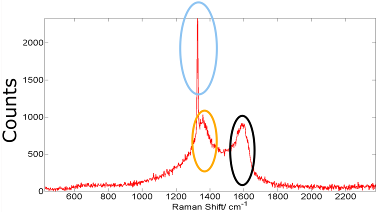


(b) 3D diamond detector

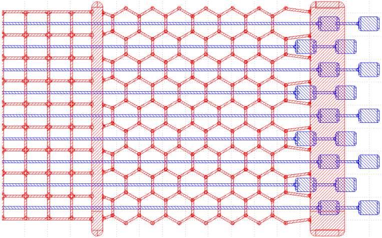
3D Diamond Detector

- electrodes formed with a pulsed femto second laser
  - 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 ∼3 µm)
- testing multiple 3D strip detectors with 120 GeV protons
- basic working principle has been proven

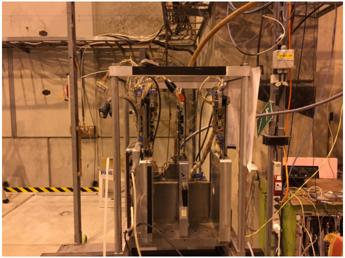
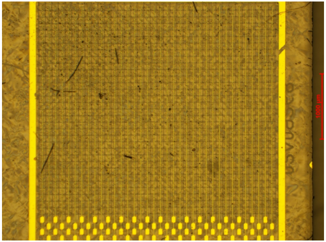


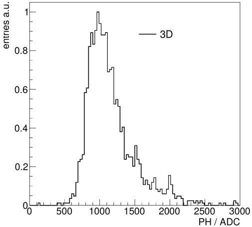
Figure: Strasbourg Telescope

3D Full detector

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



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



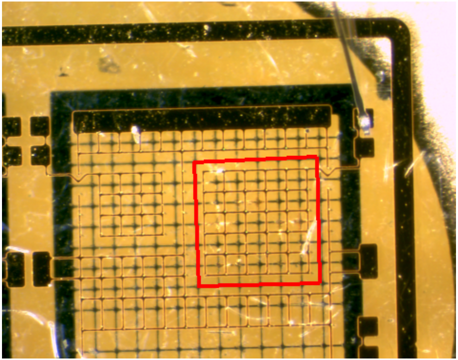
(b) signal distribution of good regions

Section 5

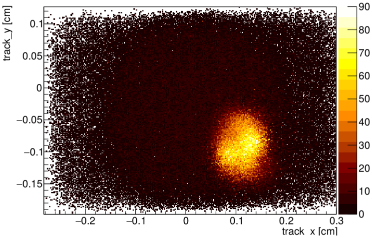
3D Rate Results

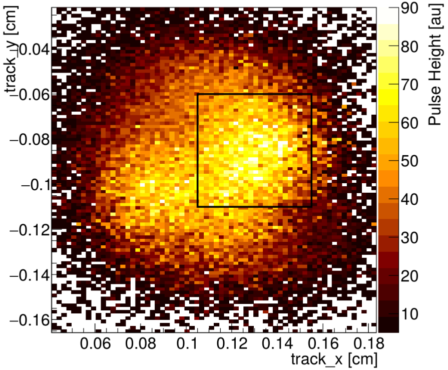
3D Multi Pad

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

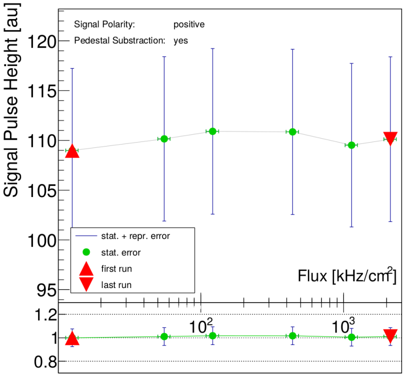


3D Multi Pad - Signal Maps

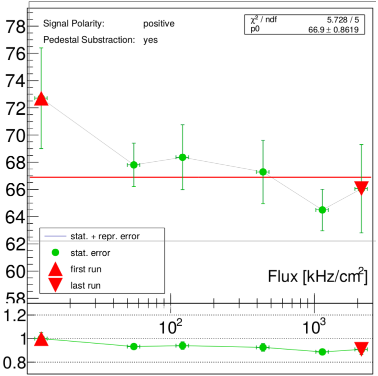




3D Multi Pad - Pulse Height



(a) 100 µm silicon diode



(b) 500 µm poly-crystalline diamond

- pulse height in diamond three times less than expected!
  - under investigation

Section 6

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
- pCVD diamonds show no rate dependence up to fluxes of $10\,\mathrm{MHz/cm^2}$ and irradiations up to $2 \times 10^{15}\,\mathrm{neq/cm^2}$
- 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 module

Section 7

Backup

Ballistic Deficit