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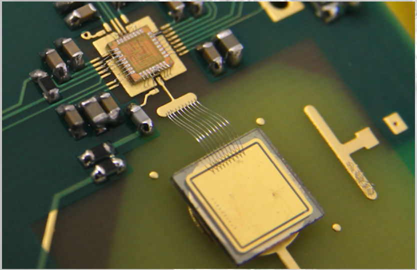

High Rate Tests of CVD Diamond Pad Detectors

RD42 Meeting

Michael Reichmann

10th May 2019

Table of Contents

Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers $\rightarrow$ highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- $\rightarrow$ **R&D towards more radiation tolerant detector designs and/or materials**

Diamond as Detector Material

- innermost tracking layers → highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- → **R&D towards more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- advantageous properties
- **after** $1 \cdot 10^{16}\,\mathrm{n/cm^2}$ **the mean drift path in diamond larger than in silicon**

Diamond as Detector Material

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- $\rightarrow$ **R&D towards more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- advantageous properties
- **after $1 \cdot 10^{16}\,\mathrm{n/cm^2}$ the mean drift path in diamond larger than in silicon**

Work at ETH:

- investigate signals and radiation tolerance in various detector designs:
  - Pad Detectors $\rightarrow$ whole diamond as single cell readout
  - Pixel Detectors $\rightarrow$ diamond sensor on pixel readout chip
  - 3D Pixel Detectors $\rightarrow$ 3D diamond detector on pixel readout chip

Diamond as Detector Material

- innermost tracking layers → highest radiation damage $\mathcal{O}\left(\mathrm{GHz/cm^2}\right)$
- → **R&D towards more radiation tolerant detector designs and/or materials**

Diamond as Detector Material:

- advantageous properties
- **after $1 \cdot 10^{16}\,\mathrm{n/cm^2}$ the mean drift path in diamond larger than in silicon**

Work at ETH:

- investigate signals and radiation tolerance in various detector designs:
  - **Pad Detectors** → this talk
  - Pixel Detectors
  - 3D Pixel Detectors

Section 2

Website

Website

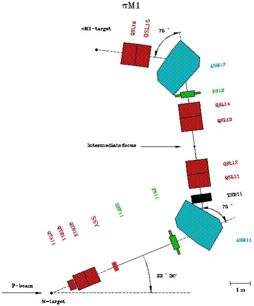
- finished analysis of all the pad data taken at PSI (Oct 2015 - Oct 2018)
- most of the following results on the website (https://diamond.ethz.ch/psi)

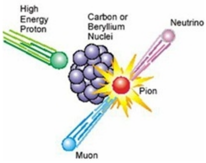
Section 3

Setup

Test Site

- High Intensity Proton Accelerator (HIPA) at PSI (Cyclotron) $\rightarrow$ beam line PiM1
- clean positive pion beam ($>90\,\%\ \pi^+$) with momentum of 260 MeV/c
- **tunable particle fluxes from $\mathcal{O}\left(1\,\mathrm{kHz/cm^2}\right)$ to $\mathcal{O}\left(10\,\mathrm{MHz/cm^2}\right)$** with collimators
- **significant multiple scattering $\rightarrow$ worsens resolution**





Final Setup

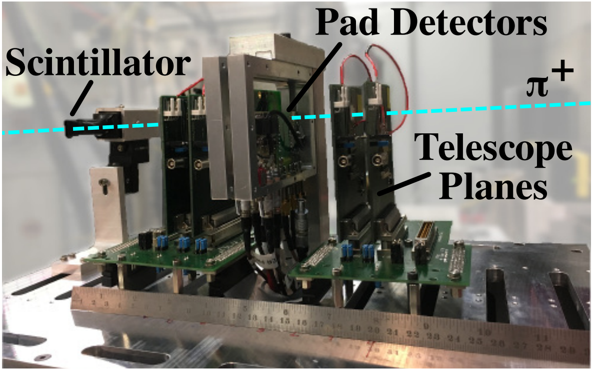


Figure: Modular Beam Telescope

- 4 tracking planes → trigger (fast-OR) with adjustable area (max 8 mm × 7.8 mm)
- diamond pad detectors in between tracking planes
- fast scintillator → precise trigger timing of $\mathcal{O}\,(1\,\mathrm{ns})$

Setup Development

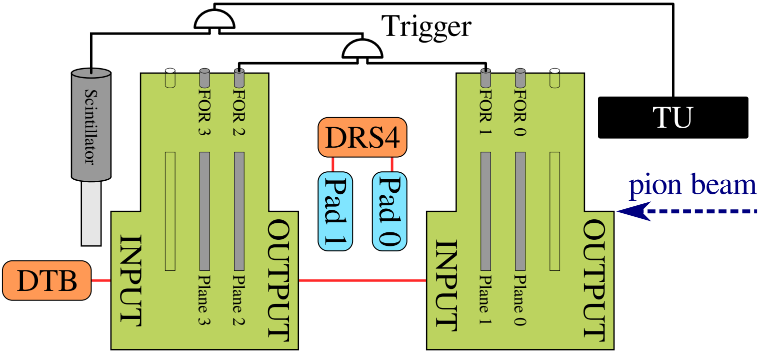


Figure: Current Setup (Aug16 - Oct18)

- scintillator → precise trigger timing of $\mathcal{O}(1\,\mathrm{ns})$
- Trigger Unit (TU) → strongly simplifying setup
- global trigger → (Plane 1 AND Plane 2) AND Scintillator

Section 4

Measurements

Tested Detectors

Name	Nick	Producer	Type	T [μm]	Irr_{max}	Comments
S129	S129	e6	scCVD	528	0	reference
IIa-3	IIa-3	IIa	scCVD	?	$5 \cdot 10^{13}$	
SiD1	SiD1	PSI	Si-Diode	300	0	calibration
SiD2	SiD2	IJS	Si-Diode	100	0	calibration
2A87-e	2A87-e	II-VI	pCVD	?	$5 \cdot 10^{13}$	
II6-78	poly-A	II-VI	pCVD	?	0	
II6-79	poly-B	II-VI	pCVD	?	0	fixed surface
II6-81	poly-D	II-VI	pCVD	?	$1 \cdot 10^{14}$	
II6-94	94	II-VI	pCVD	?	0	also as pixel
II6-95	95	II-VI	pCVD	?	$5 \cdot 10^{14}$	also as pixel
II6-96	96	II-VI	pCVD	?	0	
II6-97	97	II-VI	pCVD	510	$3.5 \cdot 10^{15}$	irradiation studies
II6-B2	B2	II-VI	pCVD	455	$8 \cdot 10^{15}$	irradiation studies
II6-E5	E5	II-VI	pCVD	520	0	bcm prime test
II6-H0	H0	II-VI	pCVD	515	0	bcm prime test
II6-H8	H8	II-VI	pCVD	505	0	bcm prime test

Table: Pad Detector Information.

2015 - 2016

Diamond	May15	Aug15	Oct15	Aug16	Oct16
S129	✓(0)	✓(0)	✓(0)	✓(0)	✓(0)
IIa-3	✗	✗	✓($5 \cdot 10^{13}$)	✗	✗
SiD1	✗	✗	✗	✓(0)	✓(0)
SiD2	✗	✗	✗	✗	✓(0)
2A87-e	✗	✗	✓($5 \cdot 10^{13}$)	✗	✗
II6-78	✓(0)	✗	✗	✗	✗
II6-79	✓(0)	✓(0)	✗	✗	✗
II6-81	✓($1 \cdot 10^{14}$)	✗	✓($1 \cdot 10^{14}$)	✗	✗
II6-94	✓(0)	✗	✗	✓(0)	✗
II6-95	✓(0)	✗	✗	✓($5 \cdot 10^{14}$)	✗
II6-96	✓(0)	✗	✗	✗	✗
II6-97	✗	✓(0)	✓(0)	✓($5 \cdot 10^{14}$)	✓($1.5 \cdot 10^{15}$)
II6-B2	✗	✓(0)	✓($5 \cdot 10^{14}$)	✓($1 \cdot 10^{15}$)	✓($2 \cdot 10^{15}$)
II6-E5	✗	✗	✗	✗	✗
II6-H0	✗	✗	✗	✗	✗
II6-H8	✗	✗	✗	✗	✗

Table: Pad Detector Timeline. Irradiation in n/cm^2 in parenthesis.

2017 - 2018

Diamond	May17	Jul17	Aug17	Aug18	Oct18
S129	✓(0)	✓(0)	✓(0)	✓(0)	✗
IIa-3	✗	✗	✗	✗	✗
SiD1	✗	✗	✗	✗	✗
SiD2	✓(0)	✓(0)	✓(0)	✓(0)	✗
2A87-e	✗	✗	✗	✗	✗
II6-78	✗	✗	✗	✗	✗
II6-79	✗	✓(0)	✗	✗	✗
II6-81	✗	✗	✗	✗	✗
II6-94	✗	✗	✗	✗	✗
II6-95	✗	✗	✗	✗	✗
II6-96	✗	✗	✗	✗	✗
II6-97	✗	✓($1.5 \cdot 10^{15}$)	✓($3.5 \cdot 10^{15}$)	✗	✗
II6-B2	✗	✓($2 \cdot 10^{15}$)	✓($4 \cdot 10^{15}$)	✓($8 \cdot 10^{15}$)	✗
II6-E5	✗	✓*(0)	✗	✗	✗
II6-H0	✓*(0)	✓*(0)	✗	✗	✗
II6-H8	✗	✗	✗	✓(0)	✓*(0)

Table: Pad Detector Timeline. Irradiation in n/cm^2 in parenthesis. * - BCMPrime devices.

Scan Types

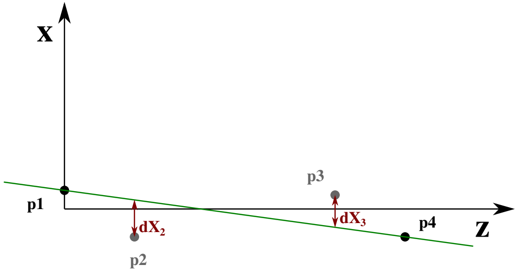
Diamond	Rate Scan	Voltage Scan	Random Scan
S129	✓	✓	✗
IIa-3	✓	✗	✗
SiD1	✓	✓	✗
SiD2	✓	✓	✗
2A87-e	✓	✗	✗
II6-78	✓	✗	✗
II6-79	✓	✗	✗
II6-81	✓	✓	✗
II6-94	✓	✓	✓
II6-95	✓	✓	✓
II6-96	✓	✗	✗
II6-97	✓	✗	✓
II6-B2	✓	✓	✓
II6-E5	✓	✗	✗
II6-H0	✓	✗	✗
II6-H8	✓	✗	✗

Table: Pad Detector Scan Types.

Section 5

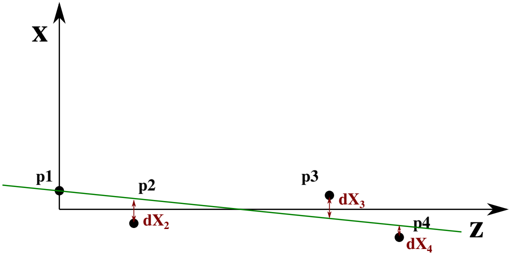
Analysis

Alignment



- assume the same error for all planes: $\frac{2.5}{\sqrt{12}} \cdot$ pixel dimension
- set errors of p1 to 0 (anchor $\rightarrow$ remains untouched)
- first coarse **pre-alignment** by connecting the outer planes with a straight line
  - move inner planes by mean of the residual distribution

Alignment

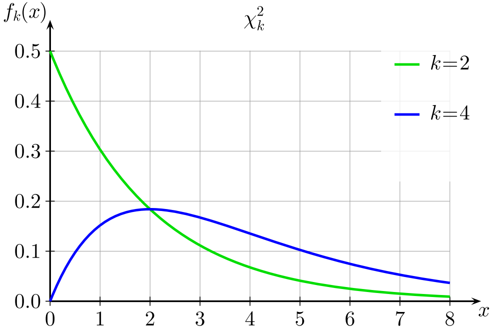


- assume the same error for all planes: $\frac{2.5}{\sqrt{12}} \cdot$ pixel dimension
- set errors of p1 to 0 (anchor $\rightarrow$ remains untouched)
- first coarse **pre-alignment** by connecting the outer planes with a straight line
  - move inner planes by mean of the residual distribution
- then **fine alignment** by fitting a straight line through all planes
  - keep p1 fixed and iteratively translate and rotate the other planes according to residuals

Theoretical Distribution

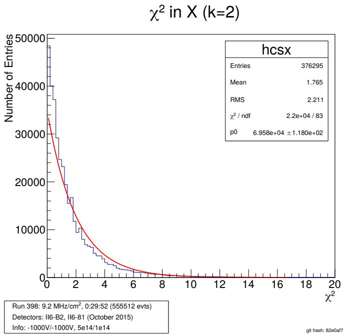
Chi-squared distribution:

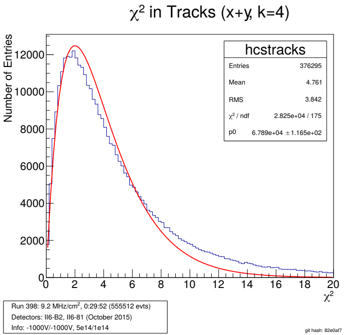
$$\frac{1}{2^{k/2}\Gamma\left(k/2\right)}x^{k/2-1}e^{-x/2}$$



- k = degrees of freedom
- special case of Gamma-Distribution
- theoretical distribution of the χ^2 from the track fits fully known

Distribution after Alignment





- fit function: [0]*TMath::GammaDist(x, $k/2$, 0, $\theta = 2$)
- k - number degrees of freedom = NPlanes - 2
- does not fit very well $\rightarrow$ incorrect errors of the individual points (planes)

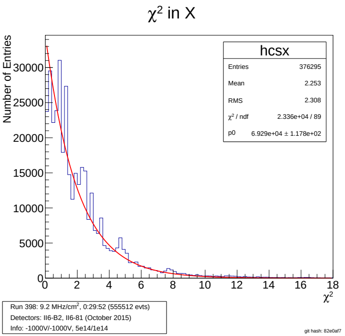
Determination of the Errors

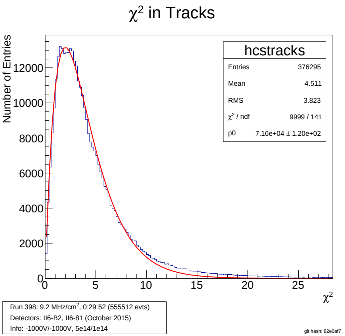
1. General Scaling:

- leave width of the distribution as free parameter in fit (indicator the errors)
- adjust all errors by same factor until width converges to theoretical value of 1

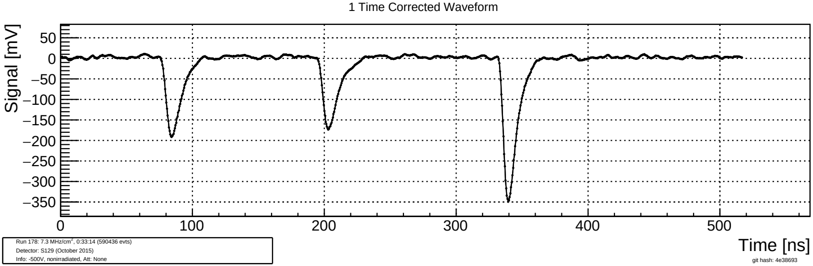
2. Individual Scaling:

- set one plane under test (not included in fit)
- iteratively adjust errors of the other planes

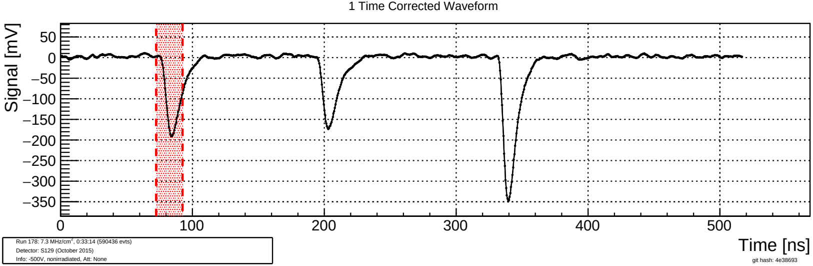




Region and Range

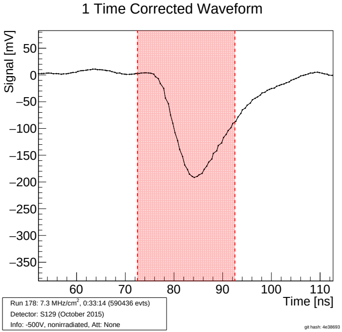


Region and Range



- define signal region: one bunch wide (20 ns) around the triggered signal

Region and Range



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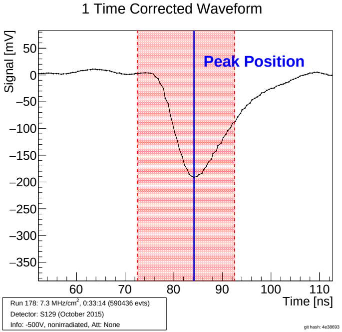
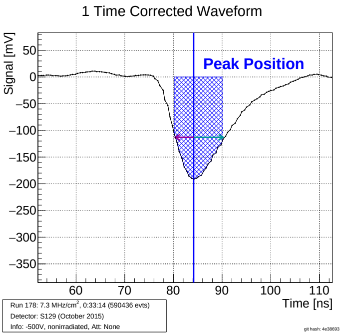


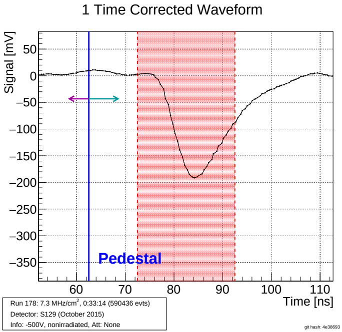
- define signal region: one bunch wide (20 ns) around the triggered signal
- find the peak within the signal region by max value

Region and Range



- define signal region: one bunch wide (20 ns) around the triggered signal
- find the peak within the signal region by max value
- signal: integrate asymmetrically around the peak (optimisation by SNR)

Region and Range



- define signal region: one bunch wide (20 ns) around the triggered signal
- find the peak within the signal region by max value
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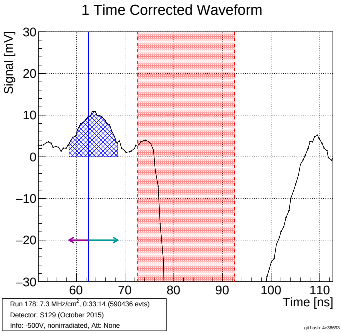
- pedestal: same integration window in centre of pre-trigger bunch

Region and Range



- define signal region: one bunch wide (20 ns) around the triggered signal
- find the peak within the signal region by max value
- signal: integrate asymmetrically around the peak (optimisation by SNR)
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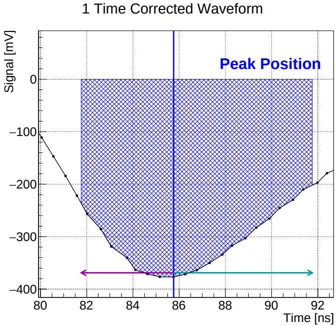
Integration



- integration performed on time corrected waveform
- single bin integral: (w) times the mean of the two values: $w \cdot (v1 + v2)/2$
- sum up the single integrals + interpolated edges to get the exact integration width
- normalise by the width of the integral

Section 6

Analysis

Cuts

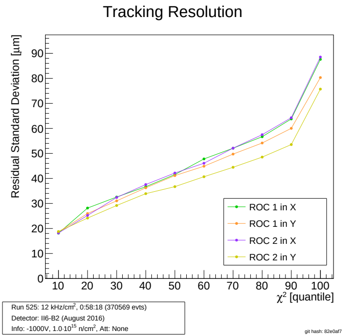
Cut	Excluded Events
saturated	saturated waveforms
pulser	pulser (reference) events
event range	first minute of the run due to various beam conditions
beam interruptions	during rate changes of the beam due to beam interruption
pedestal sigma	baseline offsets, strange waveforms
timing	wrong timing of the peak of triggered signal
bucket	flat waveforms due to wrong trigger
aligned	Waveforms and Telescope are not aligned (event-wise)
tracks	not all telescope planes have exactly one cluster
chi2 (x/y)	badly fit tracks ($>$50 % quantile)
track slope (x/y)	large angles of the tracks ($>$2 deg)
fiducial	not in selected (fiducial) area of the DUT

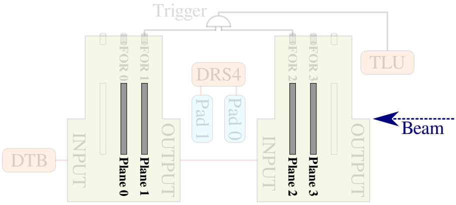
Table: Analysis cut flow.

Section 7

Results

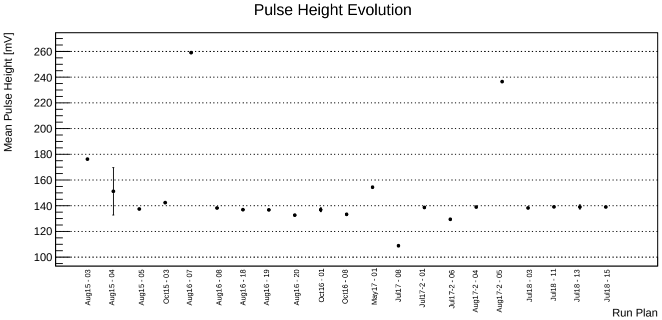
Tracking Resolution





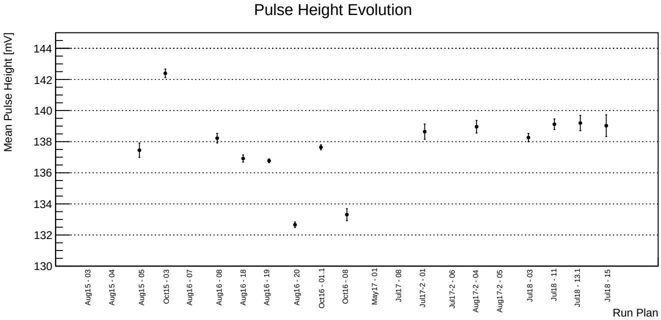
- ROC = Plane
- resolution = width of the residual distribution at the plane under test
- can achieve ∼20 µm resolution at very low χ^2
- resolution at the front slightly better than in the back
  - less multiple scattering

S129



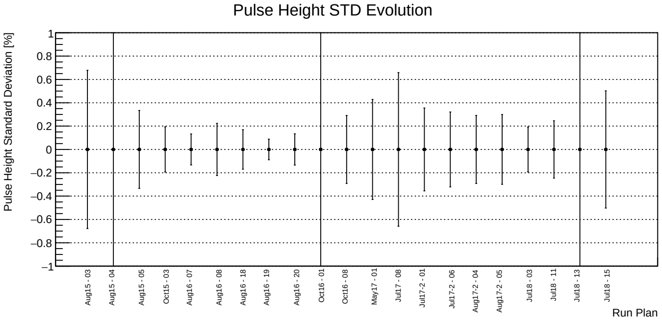
- every point the mean of a whole rate scan
- very high points have no attenuator
- first two points have a change in amplifier

S129



- every point the mean of a whole rate scan
- very high points have no attenuator
- first two points have a change in amplifier
- most points very stable over time but some fluctuate (maybe DRS4 issue)

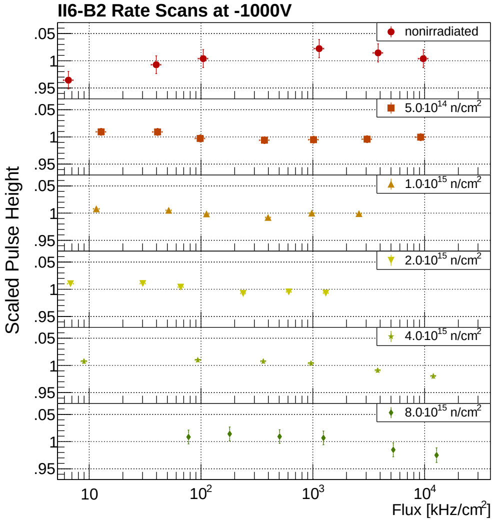
S129



- every point the mean of a whole rate scan
- very high points have no attenuator
- first two points have a change in amplifier
- most points very stable over time but some fluctuate (maybe DRS4 issue)
- standard deviation in general below 0.5 %

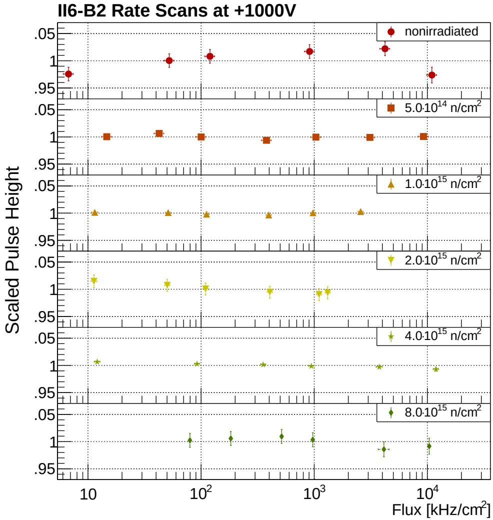
B2 Rate Scans

- after irradiation pulse height is very stable
- maximum irradiation: $8 \cdot 10^{15}\ \mathrm{n/cm^2}$
- little drop for high rates at high irradiations
- $\rightarrow$ due to decreasing signals one cut is working less efficient

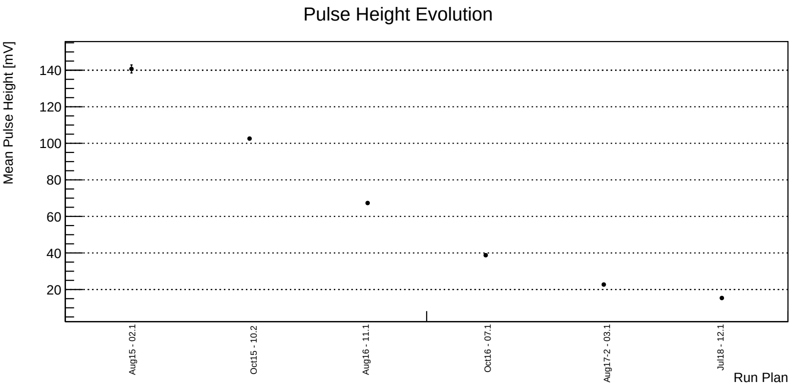


B2 Rate Scans

- after irradiation pulse height is very stable
- maximum irradiation: $8 \cdot 10^{15}\ \mathrm{n/cm^2}$
- little drop for high rates at high irradiations
- $\rightarrow$ due to decreasing signals one cut is working less efficient
- positive and negative bias agree very well



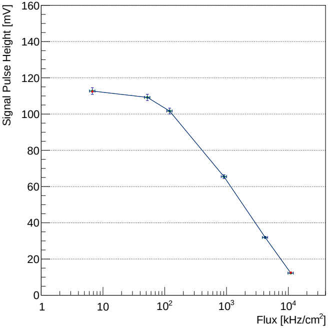
B2 Pulse Height Evolution



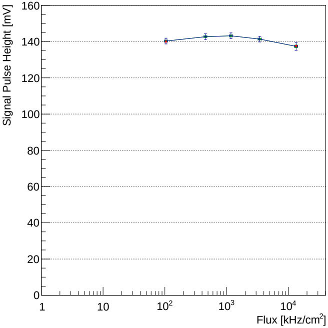
$$0 \;\rightarrow\; 5 \cdot 10^{14} \;\rightarrow\; 1 \cdot 10^{15} \;\rightarrow\; 2 \cdot 10^{15} \rightarrow 4 \cdot 10^{15} \rightarrow 8 \cdot 10^{15}\,\mathrm{n/cm^2}$$

- absolute pulse height decreases exponentially
- SNR at highest irradiation only $2/1 \rightarrow$ prevents next step with this amplifier $\rightarrow$ use new OSU amp?

Fix Rate Dependence



(a) First measurement



(b) After reprocessing

- less than 20 % of the tested diamonds show rate dependence >10 %
- very large rate dependence at the first measurement (>90 %)
- after reprocessing and surface cleaning with RIE very stable behaviour (∼2 %)
- feasible to "fix" bad diamonds

Section 8

Conclusion

Conclusion

- all the data we took with the digital ETH Telescope at PSI was analysed
  - needs to be fully checked
- most important results are available on the website
- improved and sped up alignment procedure
- iteratively adjust errors of the individual planes to fix χ^2-distribution
- improved integration procedure of the waveforms
- scCVD diamond is stable over the year
  - mean pulse height of the rate scans stays constant
  - standard deviation of the rate scans in general $<0.5\,\%$
- irradiated pCVD diamond does not show dependence on rate to $\mathcal{O}\,(2\,\%)$ up to $20\,\mathrm{MHz/cm^2}$
- possible to fix diamonds that show rate dependence due to surface issues

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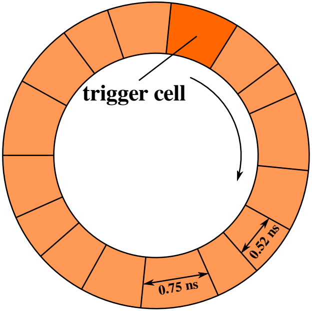
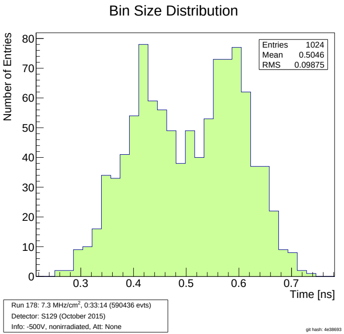
Section 9

Backup

Ringbuffer



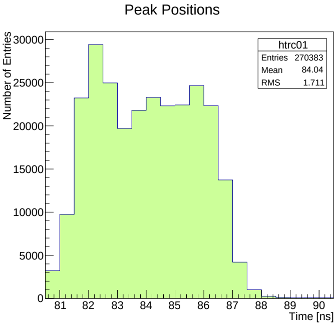
(a) Ringbuffer



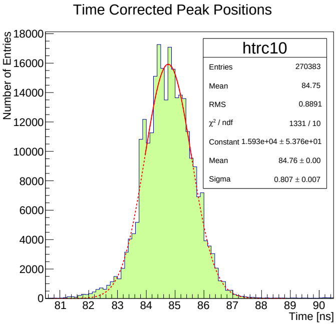
(b) Length of memory cells.

- analogue signals of the diamonds constantly digitised and saved in ringbuffer
- overwrite old data once again at first cell
- once triggered data is saved starting from the current cell $\rightarrow$ trigger cell
- measure the length the of memory cells of the DRS4 (before every beam test)
- record trigger cell for every event

Peak Position



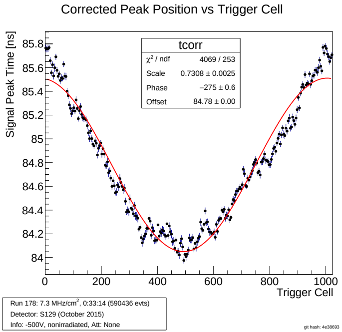
(a) no correction



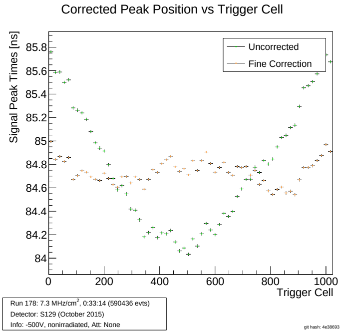
(b) with correction

- timing of the signals should be fixed and determined by the scintillator
- non-corrected peak time distribution resembles cell size distribution
- correcting for the different cell sizes $\rightarrow$ strong improvement in timing

Fine Correction



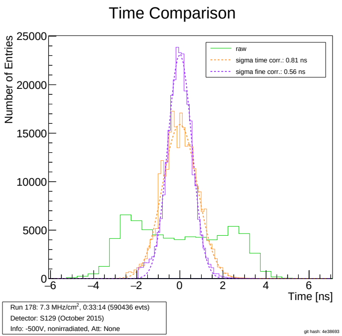
(a) Dependence on trigger cell.



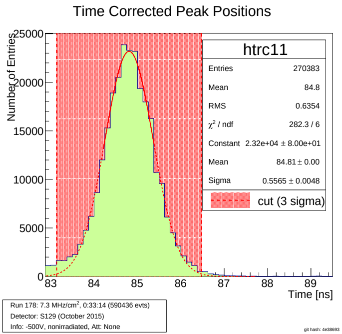
(b) fine correction

- after drs4 time correction $\rightarrow$ still timing depends periodically on the trigger cell (why?)
- fit with periodic function with known period

Timing Correction + Cut

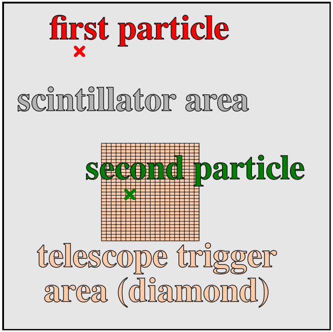


(a) All corrections

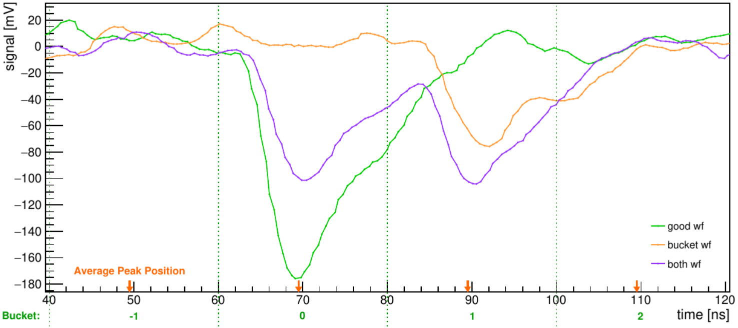


(b) Timing cut

- achieve $\sim$500 ps timing resolution
- exclude signals outside $3\,\sigma$) of this distribution
  - wrong timing means something went wrong in the data-taking or the waveform is bad

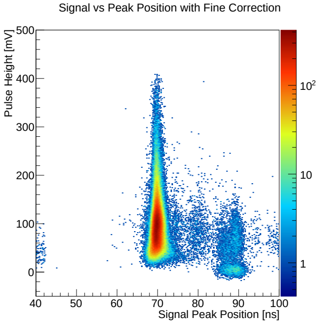


- bunch spacing of PSI (19.7 ns) small than clock cycle of fast-OR (25 ns)
- scintillator area $\sim$10 times larger than active trigger area
- within one clock cycle of 25 ns:
  - one particle only hits the scintillator
  - second particle hits the telescope and the diamond
- $\rightarrow$ no signal in signal region!



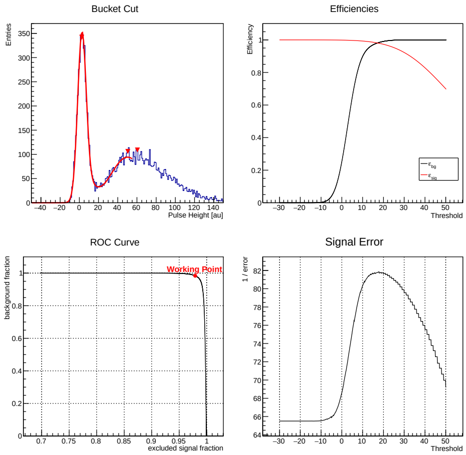
- bunch spacing of PSI (19.7 ns) small than clock cycle of fast-OR (25 ns)
- scintillator area ∼10 times larger than active trigger area
- within one clock cycle of 25 ns:
  - **one particle only hits the scintillator**
  - **second particle hits the telescope and the diamond**
- → no signal in signal region!

Bucket Pedestal



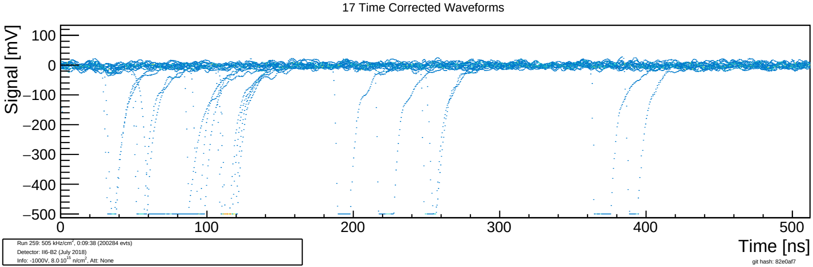
- flat lines only when the highest peak is in the bunch after the trigger

Bucket Cut



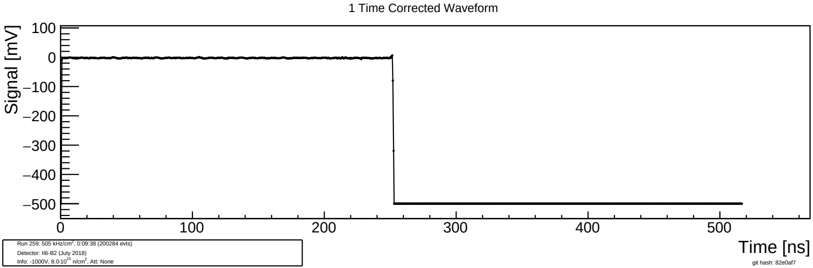
- fit signal distribution when signal in the bunch after the trigger is higher
- signal and background well separated
- shift threshold and minimise the error on the signal

Saturated



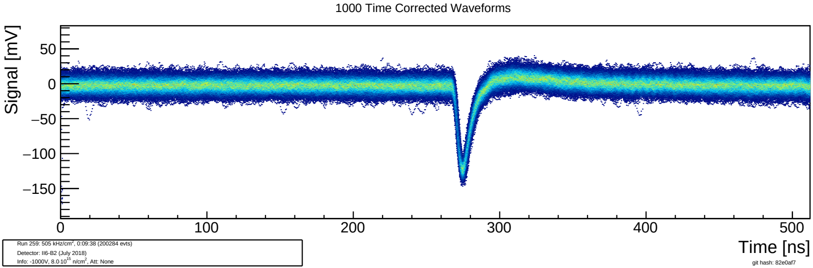
- DRS4 signal range: [-500, +500] mV
- exclude saturated waveforms → full pulse height information lost
- main source should be protons
- 17/200000 events in example above

Pulser



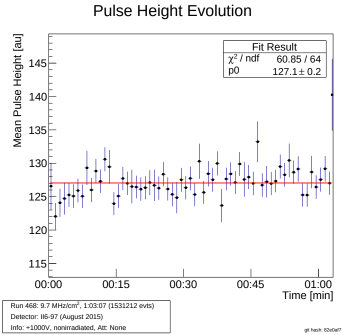
- use pulser as a reference signal
- tag pulser events by extra channel of the DRS4

Pulser



- use pulser as a reference signal
- tag pulser events by extra channel of the DRS4
- exclude these event since they don't have a diamond signal
- use for pulser analysis to compare to diamond signal

Event Range

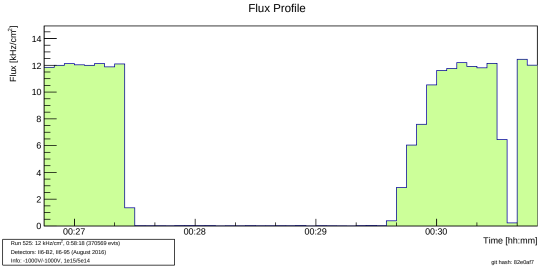


- until October 2015 $\rightarrow$ beam shutter opened after run was started
  - unstable conditions
  - exclude first five minutes of the run
- past October 2015 exclude first minute as safety margin
  - sometimes small adjustments made (e.g. collimator changed too late)

Beam Interruption

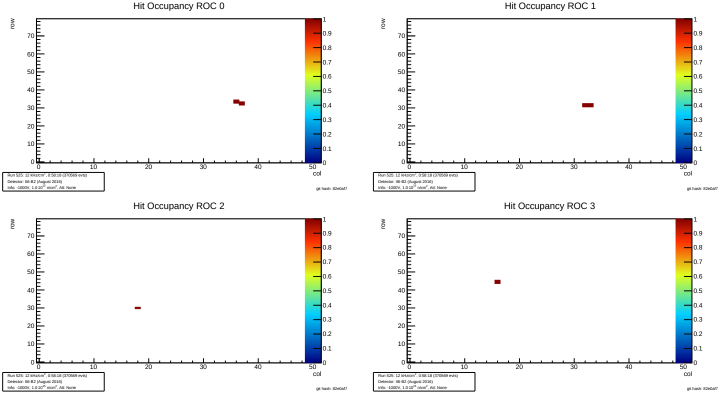
- usually short beam interruption every 5 min at PSI + other interruption

Beam Interruption



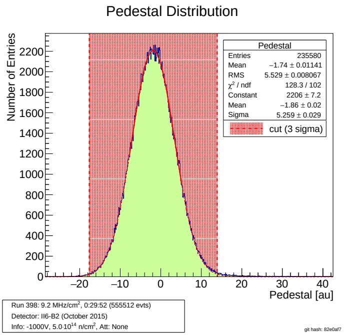
- usually short beam interruption every 5 min at PSI + other interruption
- particle rate slowly ramps up after interruption
- exclude events when rate drops less than 40 % + 5 s before
- until rate is larger than 40 % + 20 s after this
- let pulse height adjust after beam interruption (safety margin)

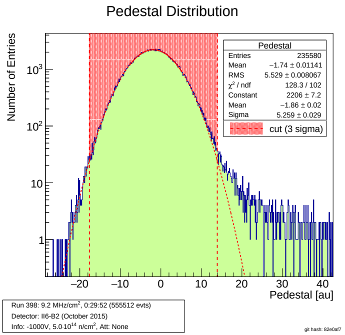
Tracks



- only use events with exactly one track
- require one and only one cluster per plane

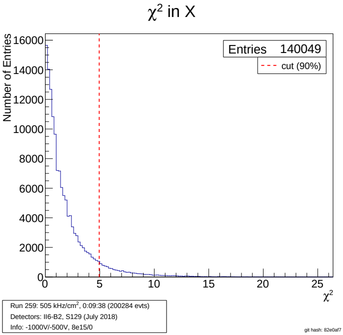
Pedestal Sigma

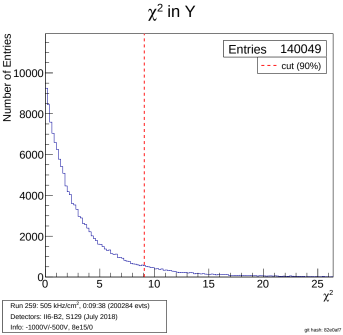




- exclude pedestals outside the 3 sigma region
- baseline shifts
- bad waveforms

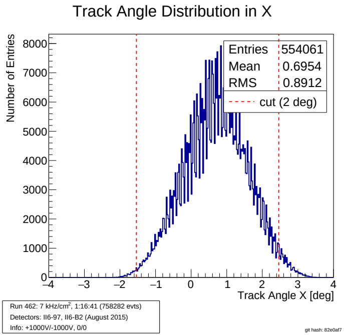
χ^2

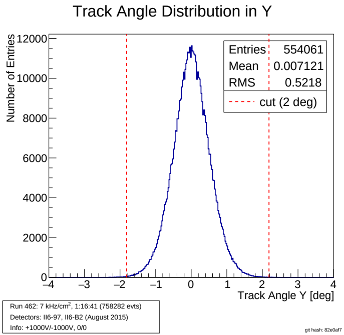




- exclude the bad tracks

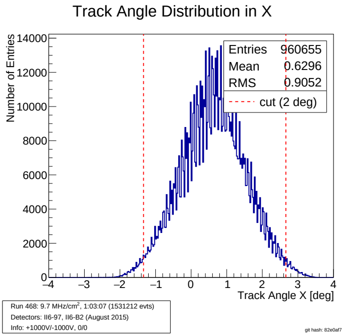
Tracking Angle

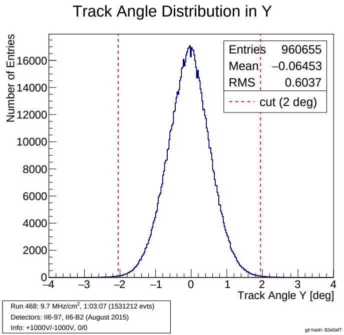




- only accept tracks with small angles

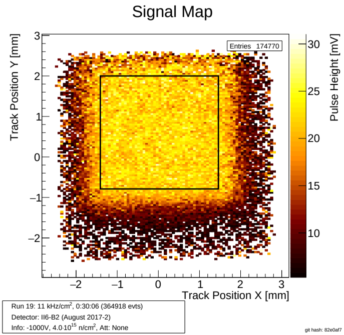
Tracking Angle

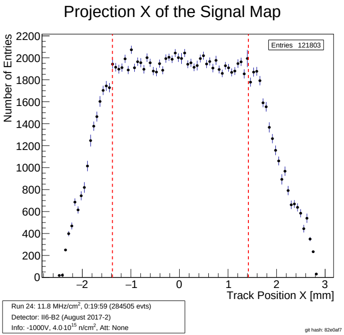




- only accept tracks with small angles
- angle only very slightly changes with rate

Fiducial Cut





- select area of the diamond
- find first and last bin when signal drops lower than 93 % of the maximum value
- interpolate with the adjacent bins when threshold is exactly hit
- adjust manually if it fails or still pedestal left