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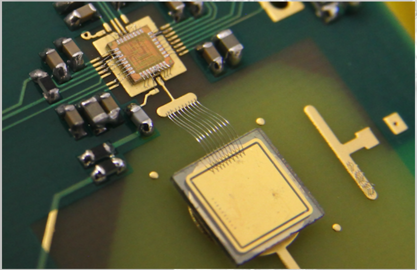

High Rate Tests of CVD Diamond Pad Detectors

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**

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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)

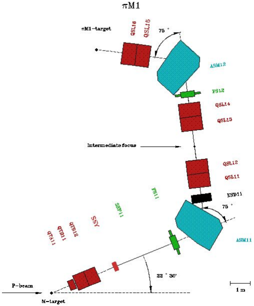
Section 3

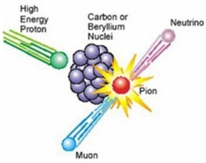
Setup


SCHWEISSWERK BÜLACH AG

Test Site

- High Intensity Proton Accelerator (HIPA) at PSI (Cyclotron) $\rightarrow$ beam line PiM1
- clean positive pion beam ($>90\,\%$ π^+) with momentum of $260\,\mathrm{MeV/c}$
- **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

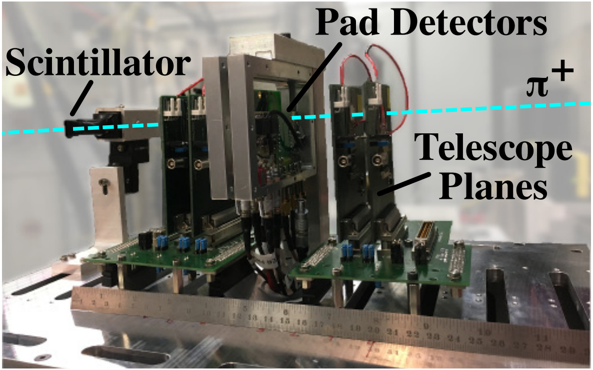


Figure: Modular Beam Telescope

- 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 $\mathcal{O}(1\,\text{ns})$

Setup Development

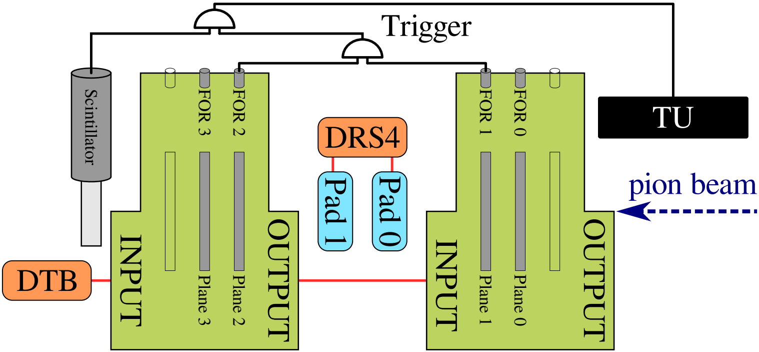


Figure: Current Setup (Aug16 - Oct18)

- 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

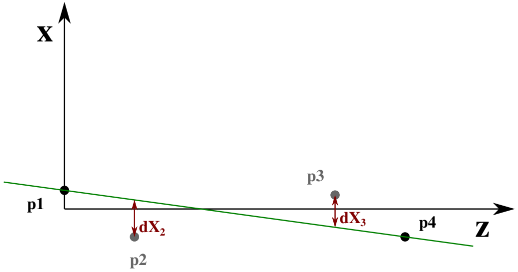
Diamond	Rate Scan	Voltage Scan	Random Scan
S129	✓	✓	✗
IIa-3	✓	✗	✗
SiD1	✓	✓	✗
SiD2	✓	✓	✗
2A87-e	✓	✗	✗
II6-78	✓	✗	✗
II6-79	✓	✗	✗
II6-81	✓	✓	✗
II6-94	✓	✓	✓
II6-95	✓	✓	✓
II6-96	✓	✗	✗
II6-97	✓	✗	✓
II6-B2	✓	✓	✓
II6-E5	✓	✗	✗
II6-H0	✓	✗	✗
II6-H8	✓	✗	✗

Table: Pad Detector Scan Types.

Section 5

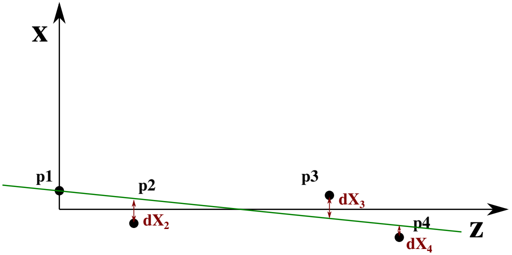
Analysis

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

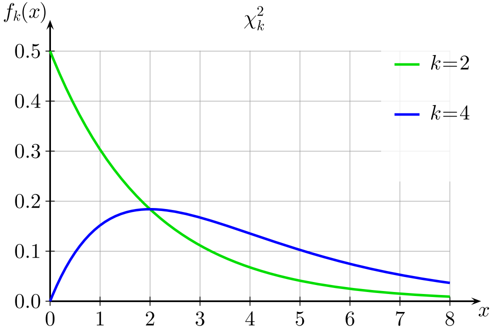


- assume the same error for all planes: $\frac{2.5}{\sqrt{12}} \cdot$ pixel dimension
- set errors of p1 to 0 (anchor $\rightarrow$ remains untouched)
- first coarse **pre-alignment** by connecting the outer planes with a straight line
  - move inner planes by mean of the residual distribution
- then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

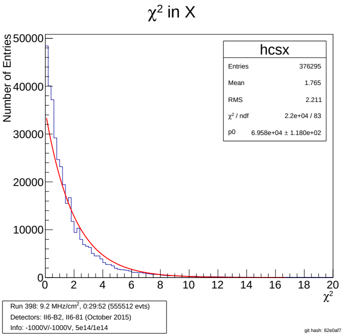
Chi-squared distribution:

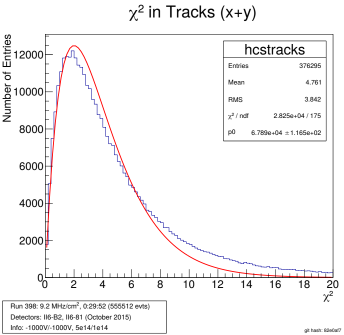
$$\frac{1}{2^{k/2}\Gamma\left(k/2\right)}x^{k/2-1}e^{-x/2}$$



- 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)

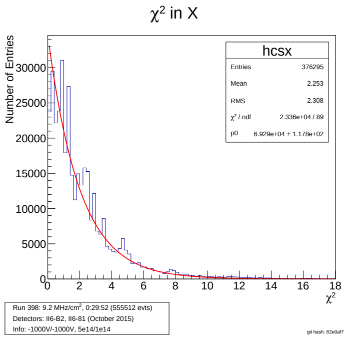
Determination of the Errors

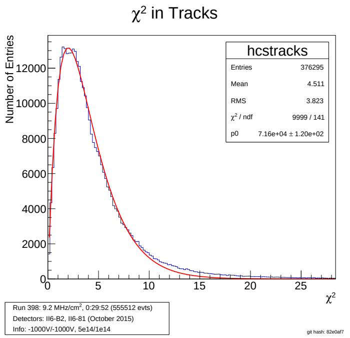
1. General Scaling:

- 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

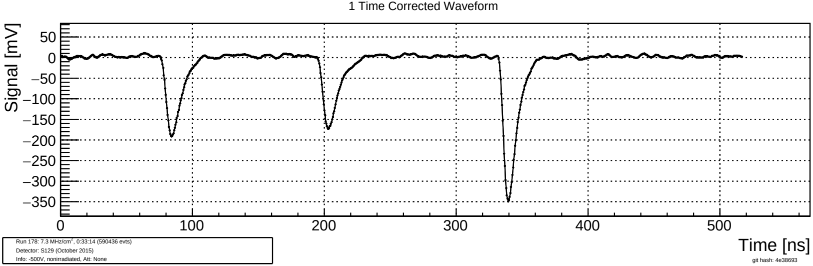
2. Individual Scaling:

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

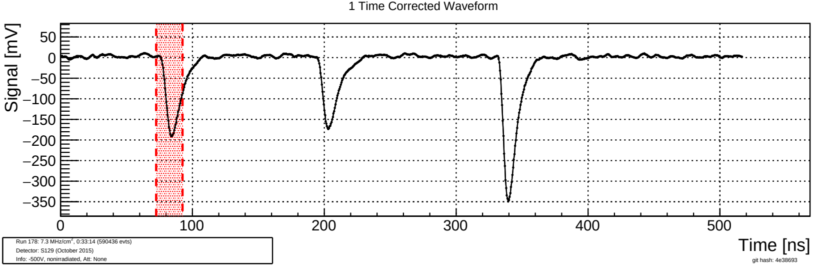




Region and Range

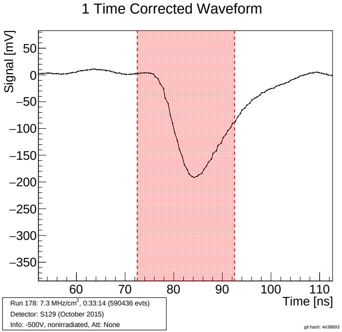


Region and Range



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

Region and Range



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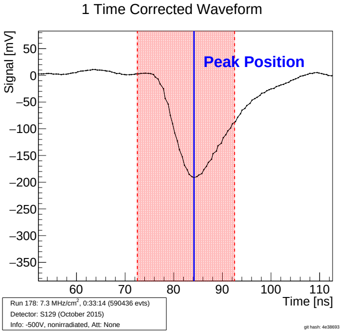
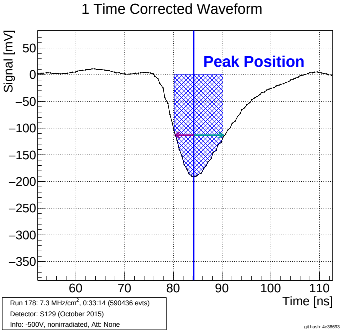


- define signal region: one bunch wide (20 ns) around the triggered signal
- find the peak within the signal region by max value

Region and Range



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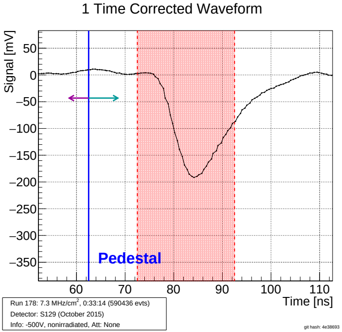
- signal: integrate asymmetrically around the peak (optimisation by SNR)

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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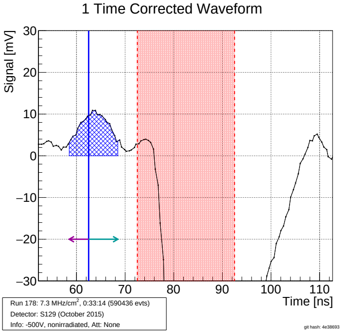
- pedestal: same integration window in centre of pre-trigger bunch

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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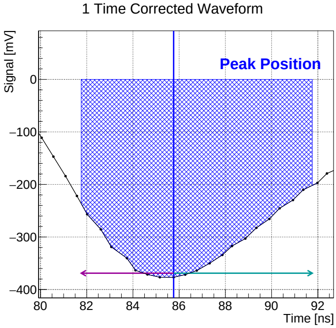
Integration

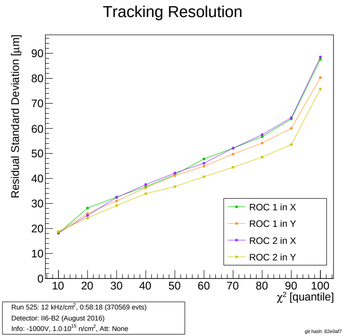


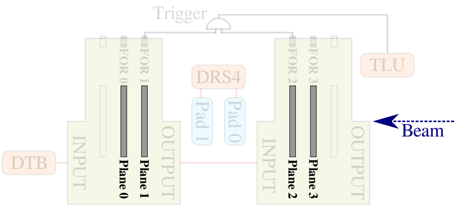
- integration performed on time corrected waveform
- single bin integral: (w) times the mean of the two values: $w \cdot (v1 + v2)/2$
- sum up the single integrals + interpolated edges to get the exact integration width
- normalise by the width of the integral

Section 6

Results

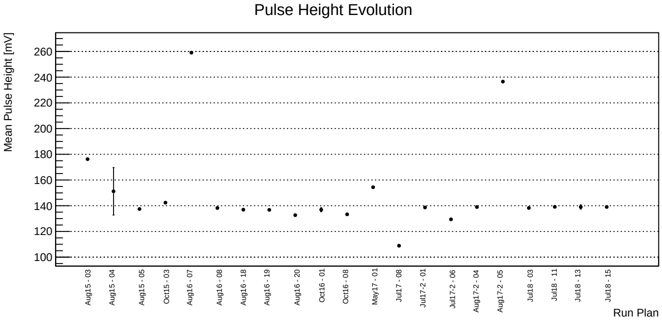
Tracking Resolution





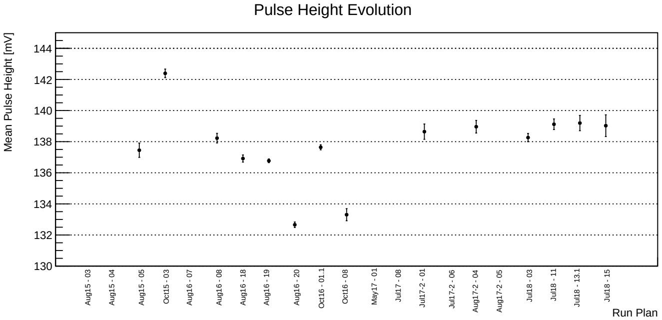
- ROC = Plane
- resolution = width of the residual distribution at the plane under test
- can achieve ~20 μm resolution at very low χ^2
- resolution at the front slightly better than in the back
  - less multiple scattering

S129



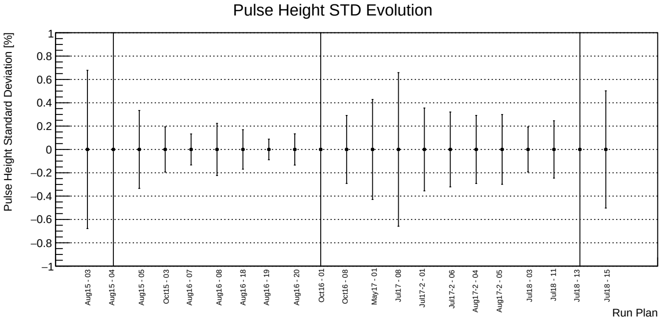
- every point the mean of a whole rate scan
- very high points have no attenuator
- first two points have a change in amplifier

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)

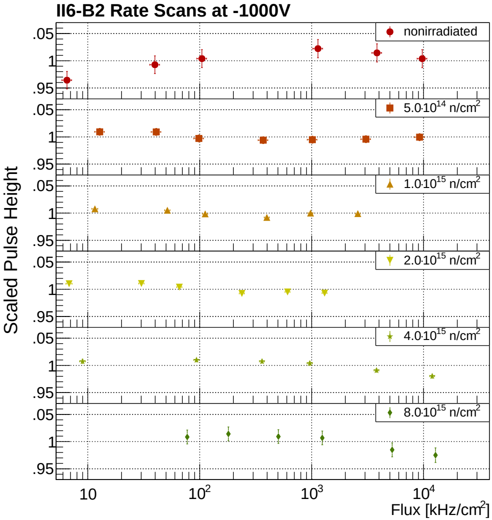
S129



- 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 %

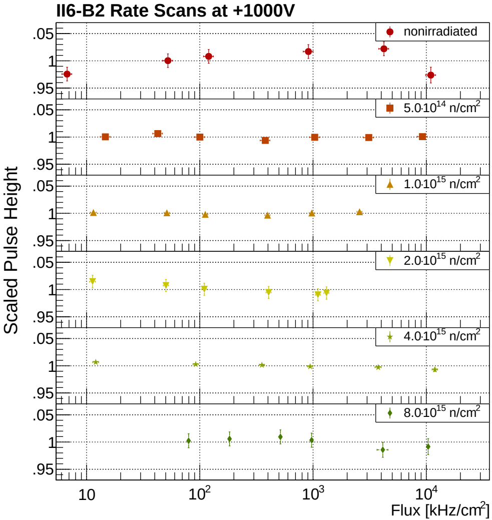
B2 Rate Scans

- 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

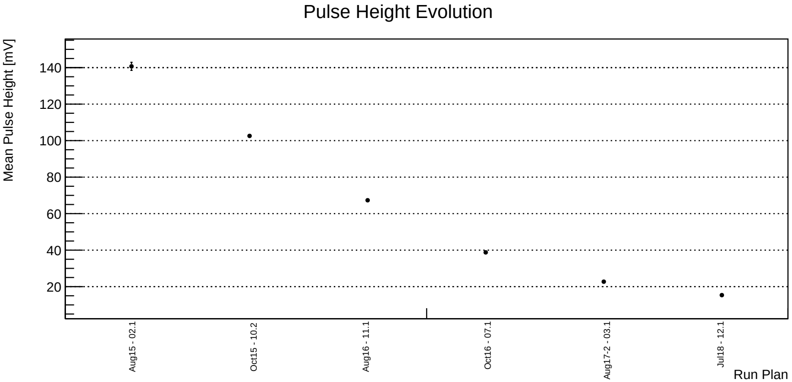


B2 Rate Scans

- 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



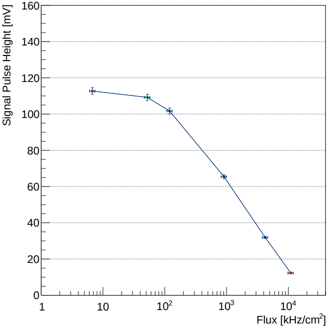
B2 Pulse Height Evolution



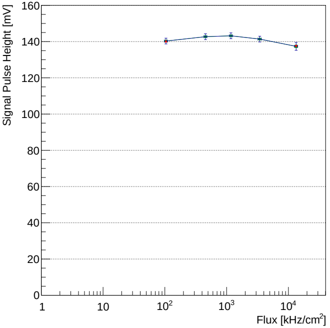
$$0 \;\rightarrow\; 5\cdot10^{14} \;\rightarrow\; 1\cdot10^{15} \;\rightarrow\; 2\cdot10^{15} \rightarrow 4\cdot10^{15} \rightarrow 8\cdot10^{15}\,\mathrm{n/cm^2}$$

- 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 7

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 $<0.5\,\%$
- 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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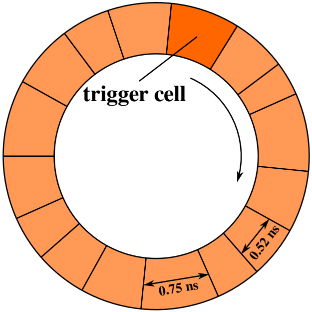
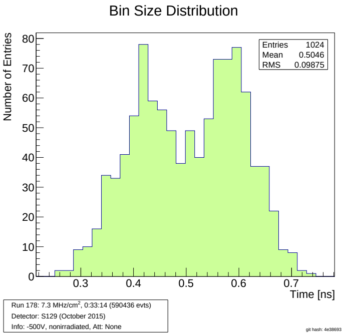
Section 8

Backup



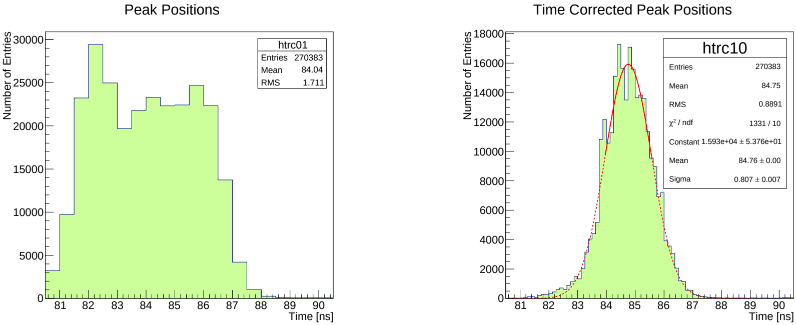
(a) Ringbuffer



(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

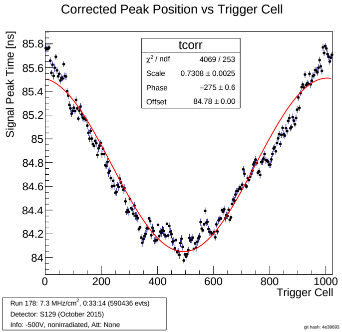


(a) no correction

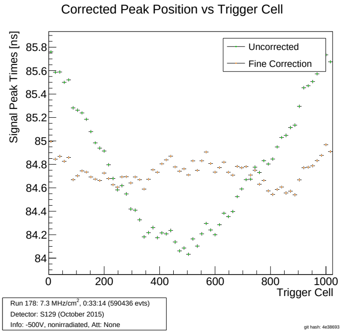
(b) with correction

- 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



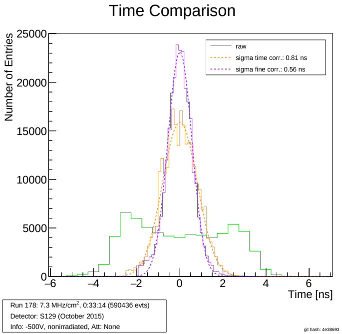
(a) Dependence on trigger cell.



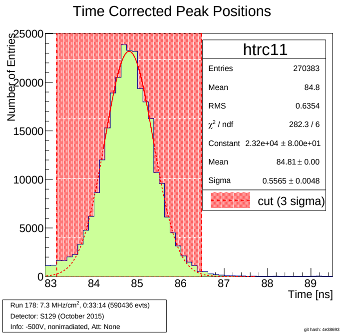
(b) fine correction

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

Timing Correction + Cut

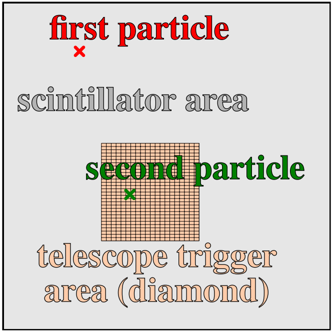


(a) All corrections



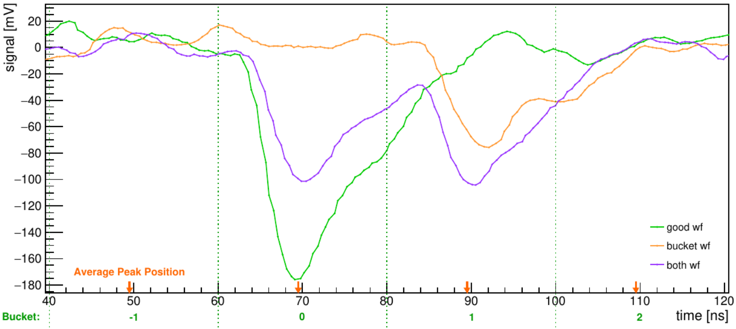
(b) Timing cut

- 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



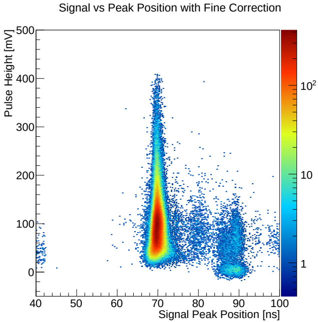
- bunch spacing of PSI (19.7 ns) small than clock cycle of fast-OR (25 ns)
- scintillator area $\sim$10 times larger than active trigger area
- within one clock cycle of 25 ns:
  - one particle only hits the scintillator
  - second particle hits the telescope and the diamond
- $\rightarrow$ no signal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

Origin



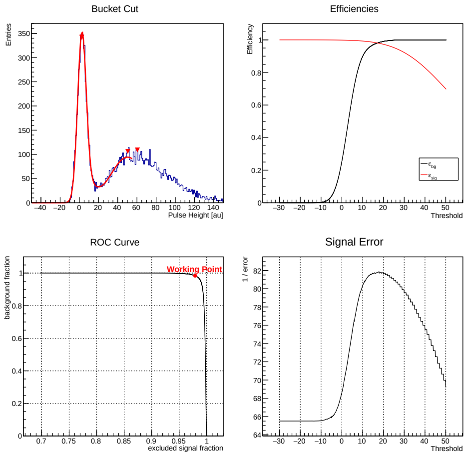
- bunch spacing of PSI (19.7 ns) small than clock cycle of fast-OR (25 ns)
- scintillator area ∼10 times larger than active trigger area
- within one clock cycle of 25 ns:
  - **one particle only hits the scintillator**
  - **second particle hits the telescope and the diamond**
- → no signal in signal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

Bucket Pedestal



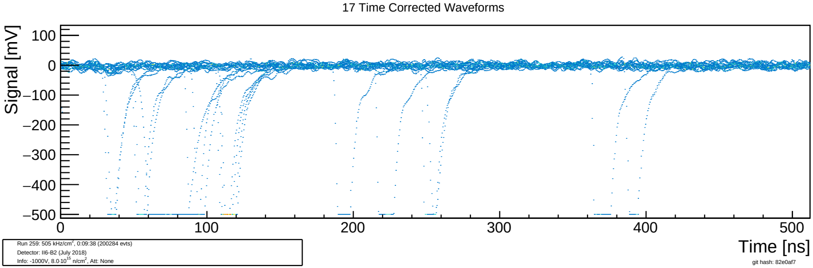
- flat lines only when the highest peak is in the bunch after the trigger

Bucket Cut



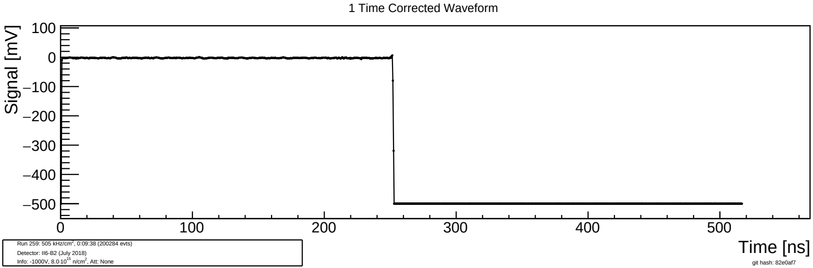
- fit signal distribution when signal in the bunch after the trigger is higher
- signal and background well separated
- shift threshold and minimise the error on the signal

Saturated



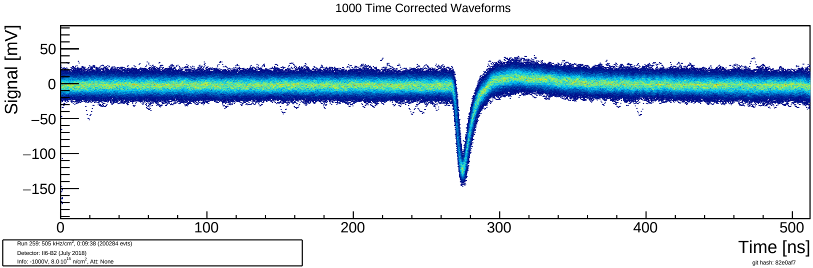
- DRS4 signal range: [-500, +500] mV
- exclude saturated waveforms → full pulse height information lost
- main source should be protons
- 17/200000 events in example above

Pulser



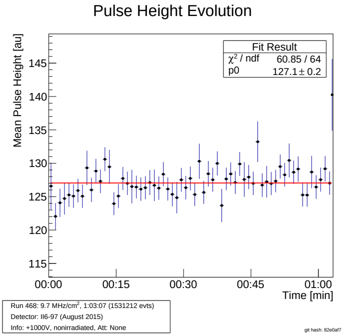
- use pulser as a reference signal
- tag pulser events by extra channel of the DRS4

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

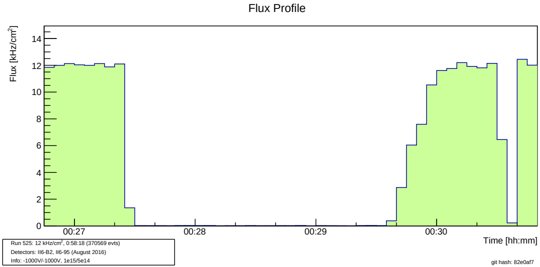


- until October 2015 $\rightarrow$ beam shutter opened after run was started
  - unstable conditions
  - exclude first five minutes of the run
- past October 2015 exclude first minute as safety margin
  - sometimes small adjustments made (e.g. collimator changed too late)

Beam Interruption

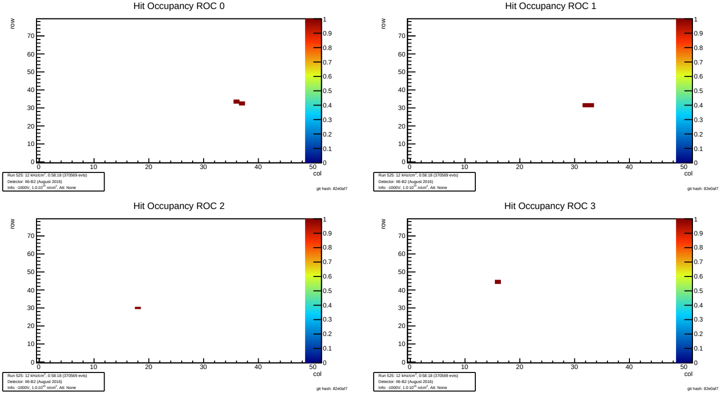
- usually short beam interruption every 5 min at PSI + other interruption

Beam Interruption



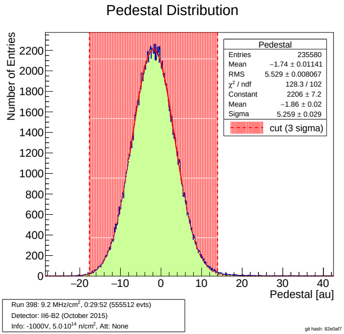
- usually short beam interruption every 5 min at PSI + other interruption
- particle rate slowly ramps up after interruption
- exclude events when rate drops less than 40 % + 5 s before
- until rate is larger than 40 % + 20 s after this
- let pulse height adjust after beam interruption (safety margin)

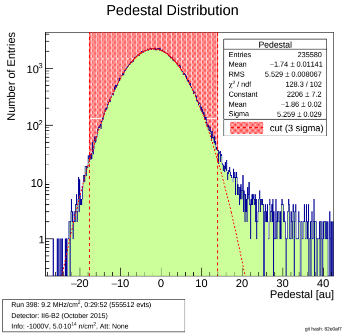
Tracks



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

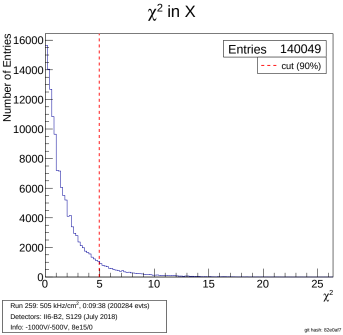
Pedestal Sigma

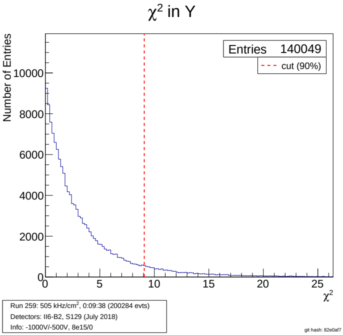




- exclude pedestals outside the 3 sigma region
- baseline shifts
- bad waveforms

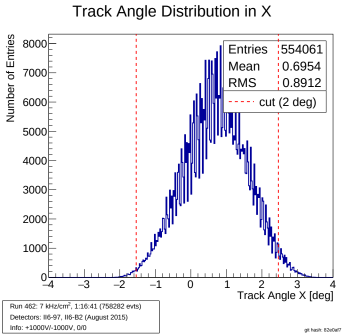
χ^2

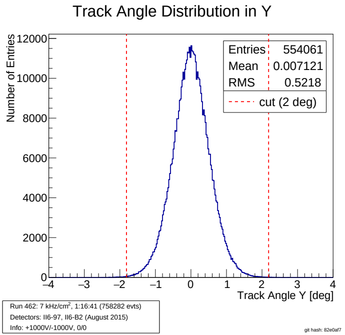




- exclude the bad tracks

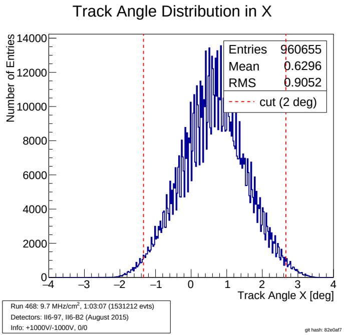
Tracking Angle

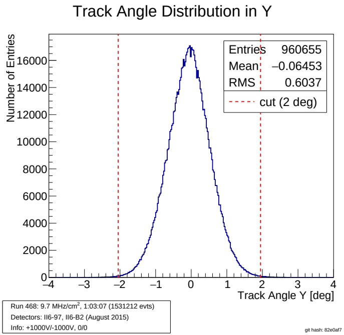




- only accept tracks with small angles

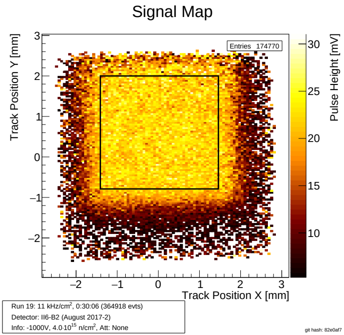
Tracking Angle

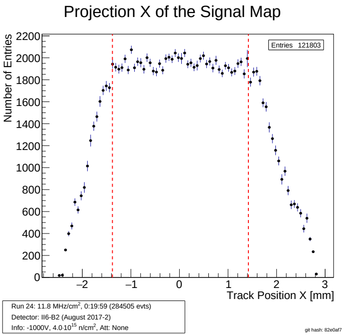




- only accept tracks with small angles
- angle only very slightly changes with rate

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