

High Rate Tests of CVD Diamond Pad Detectors

RD42 Meeting

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10th May 2019

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Section 1

Motivation

Diamond as Detector Material

- innermost tracking layers \rightarrow highest radiation damage \mathcal{O} (GHz/cm²)
- \rightarrow **R&D towards more radiation tolerant detector designs and/or materials**

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Diamond as Detector Material:

- advantageous properties
- **after $1 \cdot 10^{16}$ n/cm² the mean drift path in diamond larger than in silicon**

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Diamond as Detector Material:

- advantageous properties
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Work at ETH:

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

Diamond as Detector Material

- innermost tracking layers \rightarrow highest radiation damage \mathcal{O} (GHz/cm²)
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Diamond as Detector Material:

- advantageous properties
- **after $1 \cdot 10^{16}$ n/cm² the mean drift path in diamond larger than in silicon**

Work at ETH:

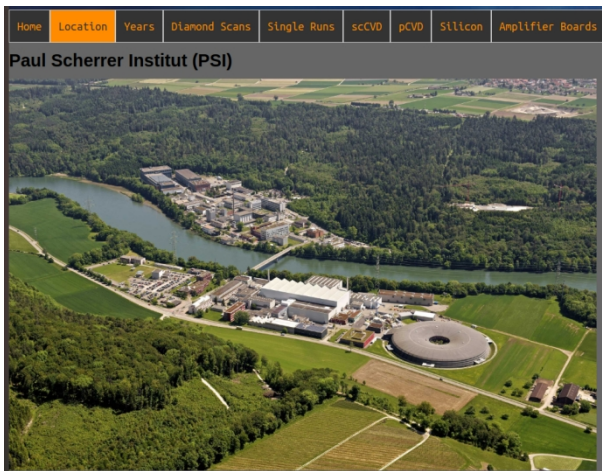
- investigate signals and radiation tolerance in various detector designs:
 - ▶ **Pad Detectors** \rightarrow this talk
 - ▶ Pixel Detectors
 - ▶ 3D Pixel Detectors

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) (<https://diamond.ethz.ch/psi>)



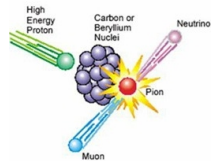
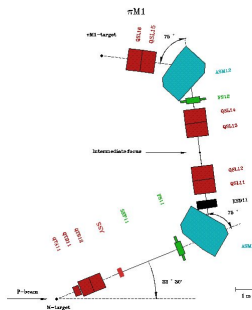
Section 3

Setup



Test Site

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



Final Setup

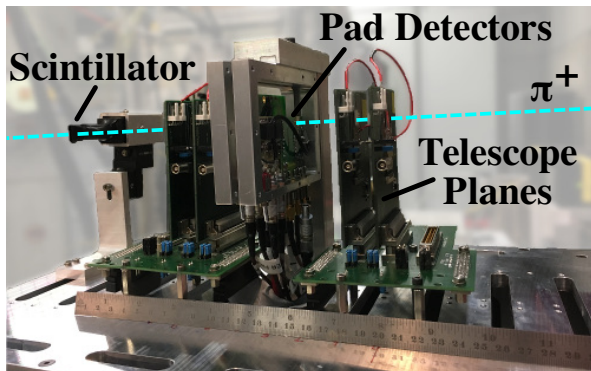


Figure: Modular Beam Telescope

- 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

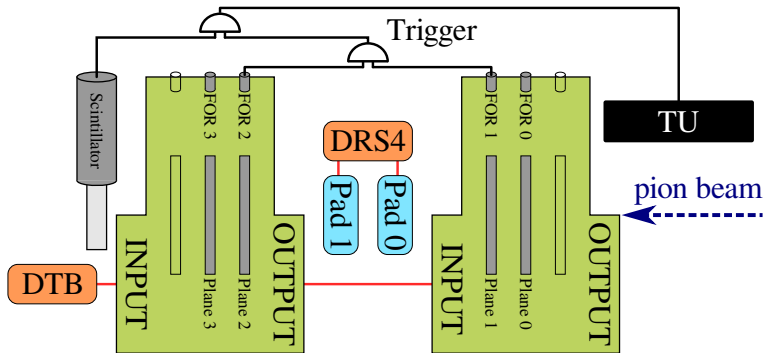


Figure: Current Setup (Aug16 - Oct18)

- scintillator \rightarrow precise trigger timing of $\mathcal{O}(1 \text{ ns})$
- Trigger Unit (TU) \rightarrow strongly simplifying setup
- global trigger \rightarrow (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

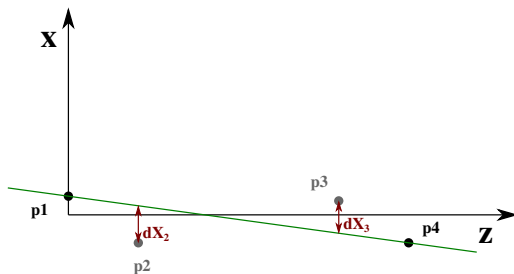
Diamond	Rate Scan	Voltage Scan	Random Scan
S129	✓	✓	✗
IIa-3	✓	✗	✗
SiD1	✓	✓	✗
SiD2	✓	✓	✗
2A87-e	✓	✗	✗
II6-78	✓	✗	✗
II6-79	✓	✗	✗
II6-81	✓	✓	✗
II6-94	✓	✓	✓
II6-95	✓	✓	✓
II6-96	✓	✗	✗
II6-97	✓	✗	✓
II6-B2	✓	✓	✓
II6-E5	✓	✗	✗
II6-H0	✓	✗	✗
II6-H8	✓	✗	✗

Table: Pad Detector Scan Types.

Section 5

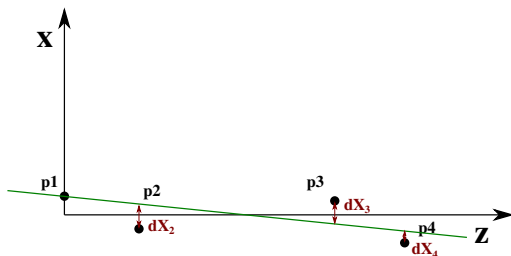
Analysis

Alignment



- assume the same error for all planes: $\frac{2.5}{\sqrt{12}} \cdot \text{pixel dimension}$
- 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

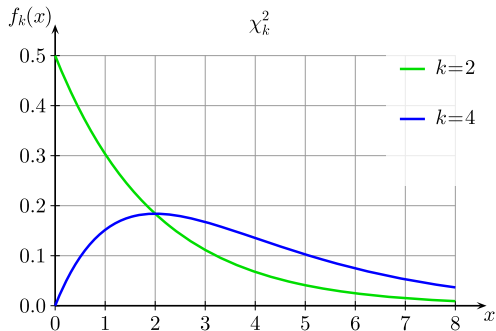


- assume the same error for all planes: $\frac{2.5}{\sqrt{12}} \cdot \text{pixel dimension}$
- set errors of p1 to 0 (anchor \rightarrow remains untouched)
- first coarse **pre-alignment** by connecting the outer planes with a straight line
 - ▶ move inner planes by mean of the residual distribution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

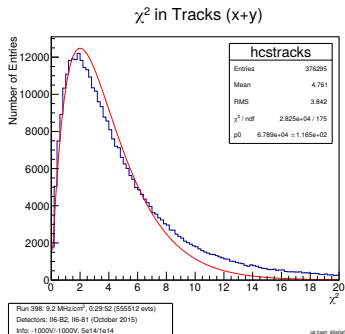
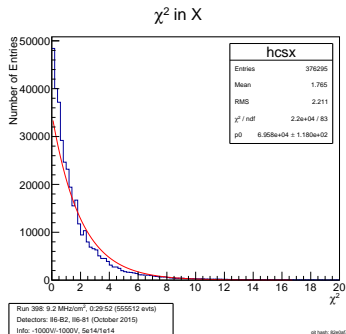
Chi-squared distribution:

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



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

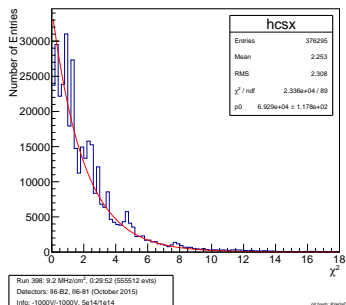
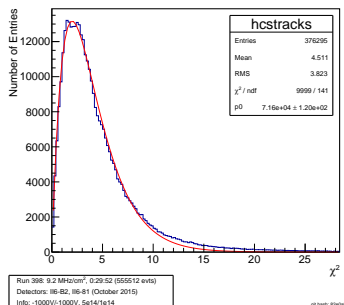
Determination of the Errors

1. General Scaling:

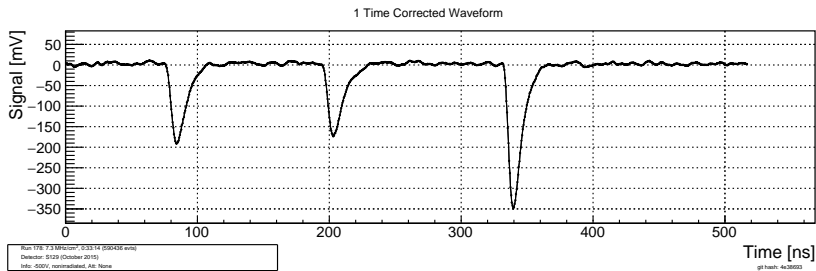
- leave width of the distribution as free parameter in fit (indicator the errors)
- adjust all errors by same factor until width converges to theoretical value of 1

2. Individual Scaling:

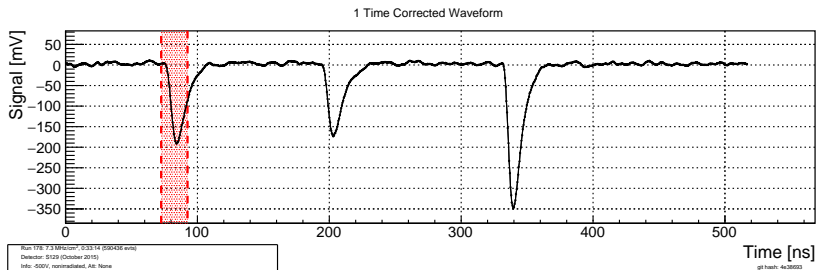
- set one plane under test (not included in fit)
- iteratively adjust errors of the other planes

 χ^2 in X

 χ^2 in Tracks


Region and Range

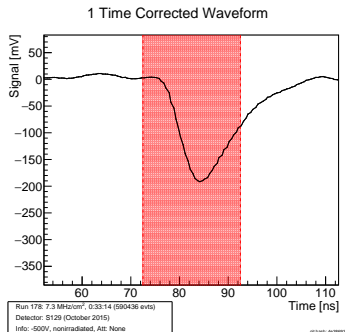


Region and Range



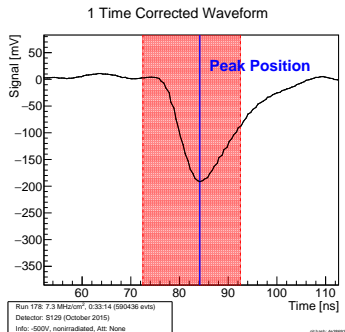
- define signal region: one bunch wide (20 ns) around the triggered signal

Region and Range



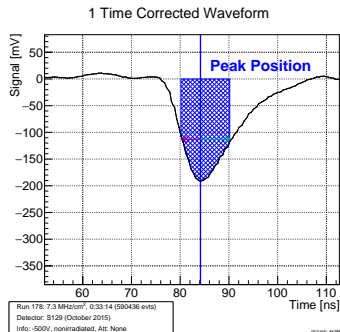
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Region and Range



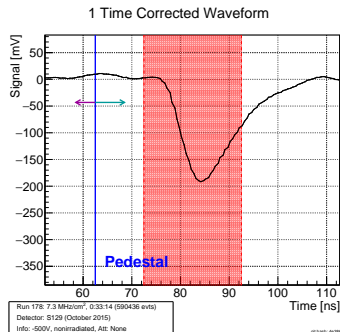
- define signal region: one bunch wide (20 ns) around the triggered signal
- find the peak within the signal region by max value

Region and Range



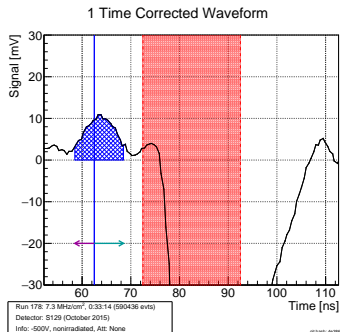
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- signal: integrate asymmetrically around the peak (optimisation by SNR)

Region and Range



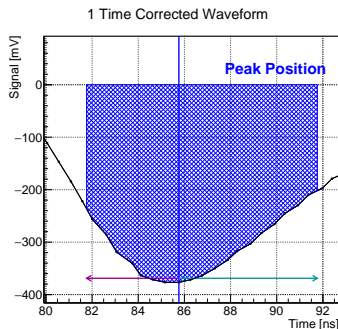
- define signal region: one bunch wide (20 ns) around the triggered signal
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- pedestal: same integration window in centre of pre-trigger bunch

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



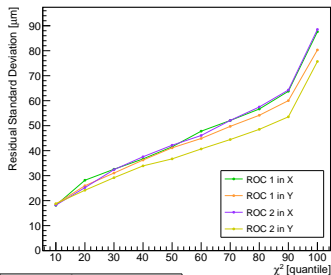
- integration performed on time corrected waveform
- single bin integral: (w) times the mean of the two values: $w \cdot (v1 + v2)/2$
- sum up the single integrals + interpolated edges to get the exact integration width
- normalise by the width of the integral

Section 6

Results

Tracking Resolution

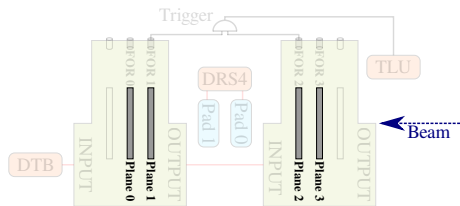
Tracking Resolution

Run 525: 12 kHz/cm², 0.58-1.8 (370569 evts)

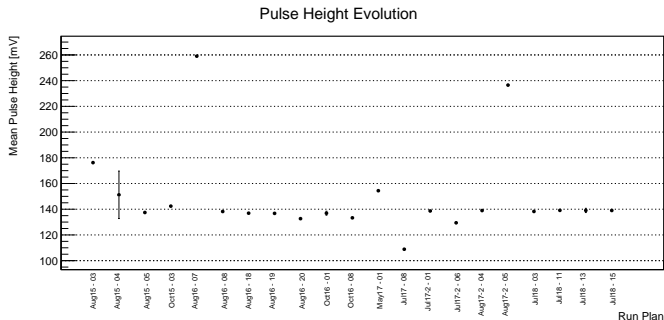
Detector: I16-B2 (August 2016)

Info: -1000V, 1.0 $\cdot 10^{10}$ n/cm², Alt: None

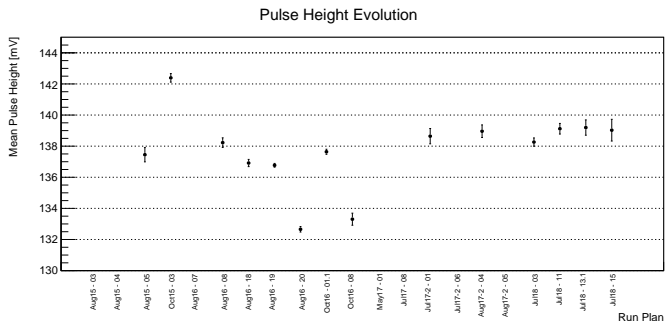
git hash: 82a6a77



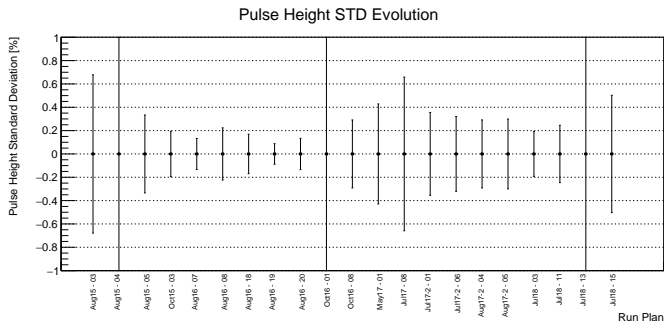
- ROC = Plane
- resolution = width of the residual distribution at the plane under test
- can achieve $\sim 20 \mu\text{m}$ resolution at very low χ^2
- resolution at the front slightly better than in the back
 - less multiple scattering



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



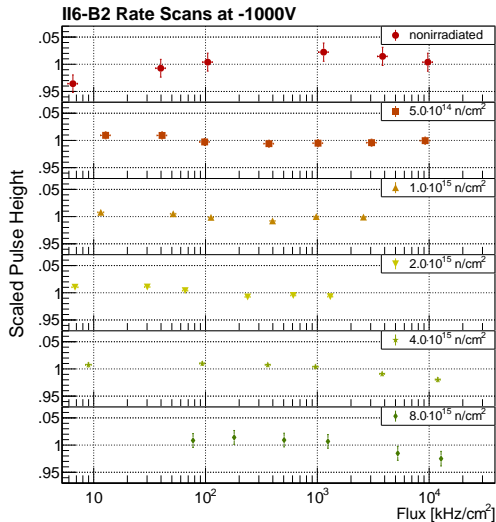
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- most points very stable over time but some fluctuate (maybe DRS4 issue)



- 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 %

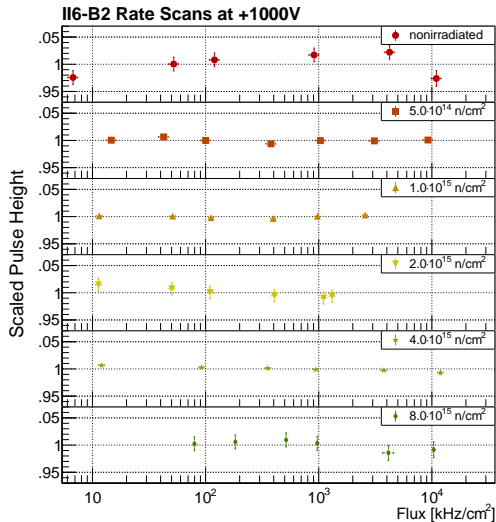
B2 Rate Scans

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

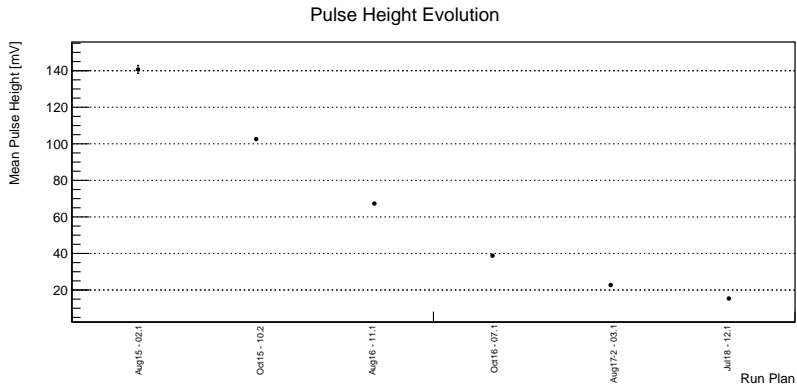


B2 Rate Scans

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



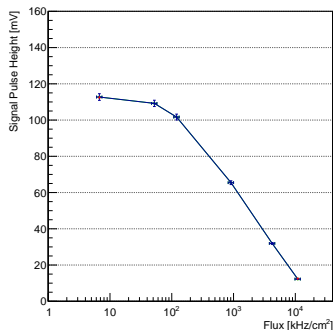
B2 Pulse Height Evolution



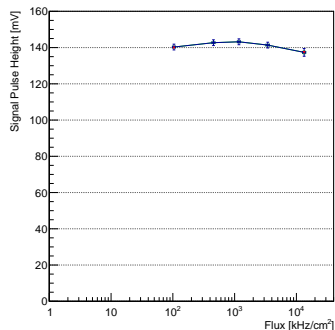
$$0 \rightarrow 5 \cdot 10^{14} \rightarrow 1 \cdot 10^{15} \rightarrow 2 \cdot 10^{15} \rightarrow 4 \cdot 10^{15} \rightarrow 8 \cdot 10^{15} \text{ n/cm}^2$$

- 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 ($\sim 2\%$)
- feasible to “fix” bad diamonds

Section 7

Conclusion

Conclusion

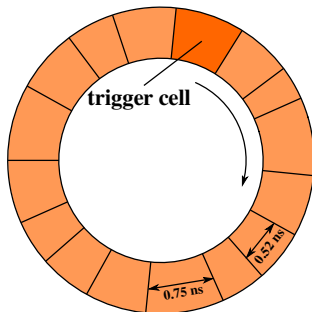
- all the data we took with the digital ETH Telescope at PSI was analysed
 - ▶ needs to be fully checked
- most important results are available on the website
- improved and sped up alignment procedure
- iteratively adjust errors of the individual planes to fix χ^2 -distribution
- improved integration 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 MHz/cm^2
- possible to fix diamonds that show rate dependence due to surface issues

DEL FIN

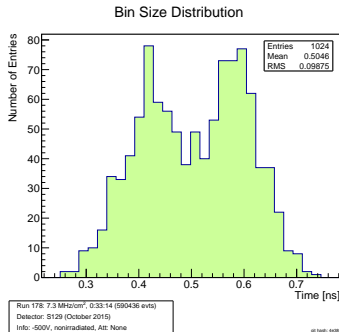


Section 8

Backup



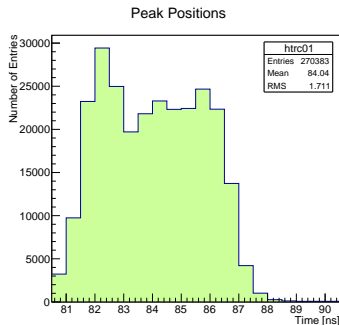
(a) Ringbuffer



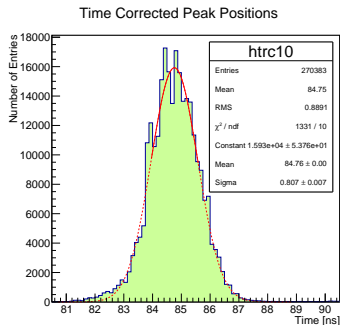
(b) Length of memory cells.

- 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 → trigger cell
- measure the length the of memory cells of the DRS4 (before every beam test)
- record trigger cell for every event

Peak Position



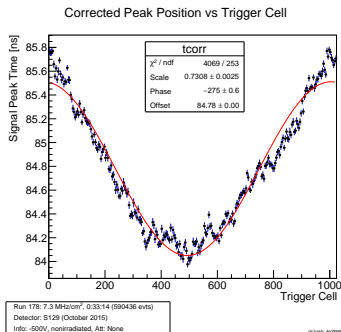
(a) no correction



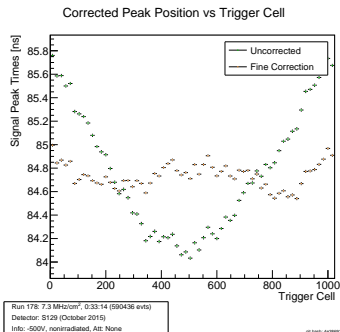
(b) with correction

- 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 → strong improvement in timing

Fine Correction



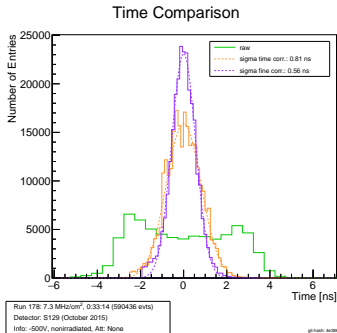
(a) Dependence on trigger cell.



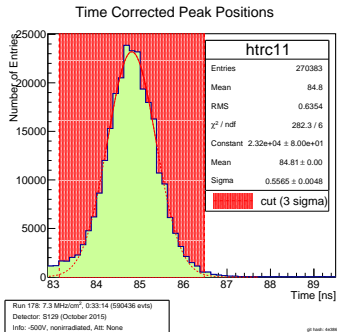
(b) fine correction

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

Timing Correction + Cut

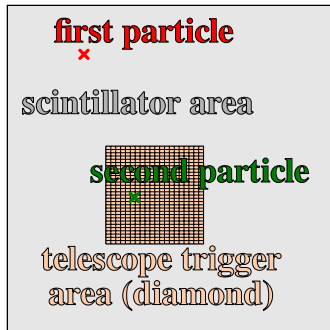


(a) All corrections



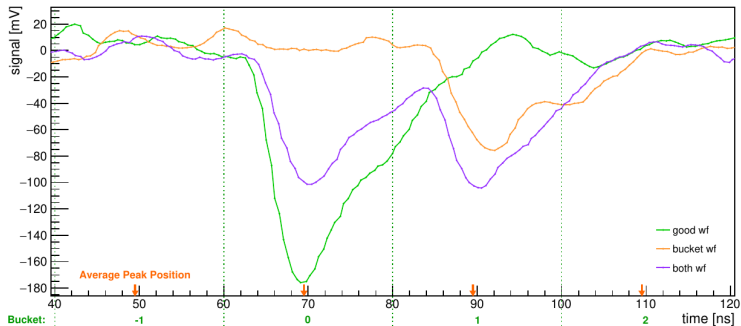
(b) Timing cut

- achieve ~ 500 ps timing resolution
- exclude signals outside 3σ of this distribution
 - wrong timing means something went wrong in the data-taking or the waveform is bad



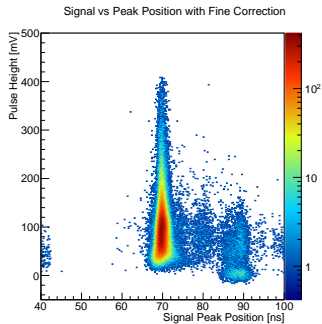
- bunch spacing of PSI (19.7 ns) small than clock cycle of fast-OR (25 ns)
- scintillator area ~ 10 times larger than active trigger area
- within one clock cycle of 25 ns:
 - ▶ **one particle only hits the scintillator**
 - ▶ **second particle hits the telescope and the diamond**
- \rightarrow no signal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

Origin



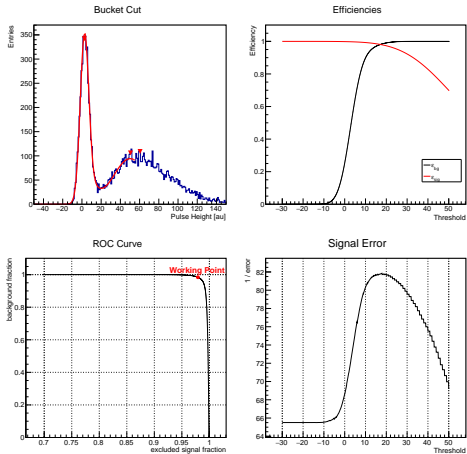
- bunch spacing of PSI (19.7 ns) small than clock cycle of fast-OR (25 ns)
- scintillator area ~ 10 times larger than active trigger area
- within one clock cycle of 25 ns:
 - ▶ one particle only hits the scintillator
 - ▶ second particle hits the telescope and the diamond
- \rightarrow no signal in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

Bucket Pedestal



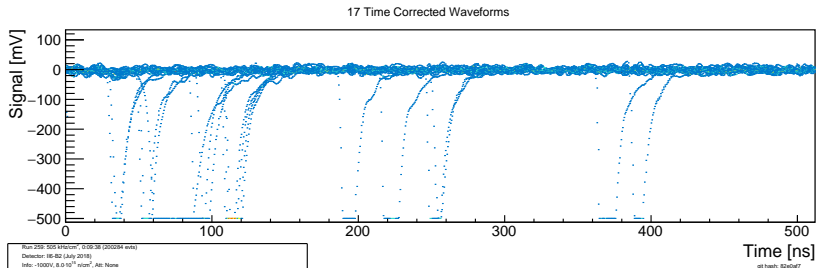
- flat lines only when the highest peak is in the bunch after the trigger

Bucket Cut



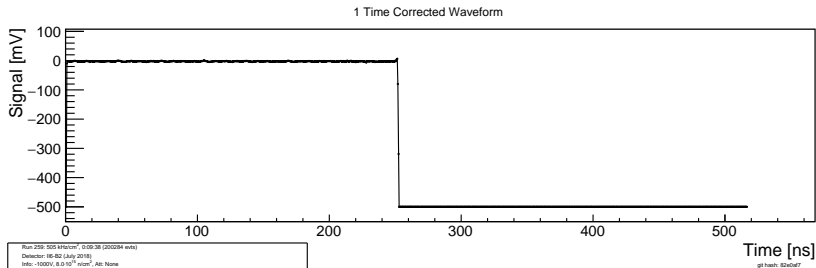
- fit signal distribution when signal in the bunch after the trigger is higher
- signal and background well separated
- shift threshold and minimise the error on the signal

Saturated



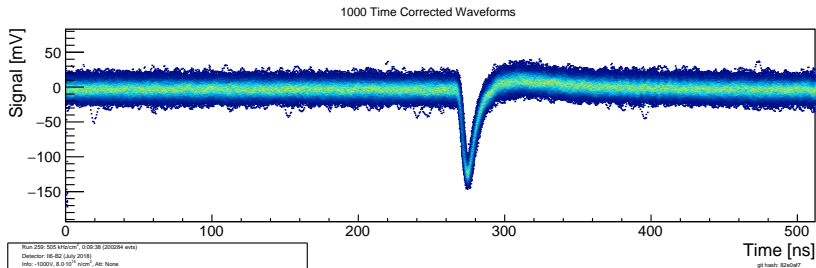
- DRS4 signal range: [-500, +500] mV
- exclude saturated waveforms → full pulse height information lost
- main source should be protons
- 17/200000 events in example above

Pulser

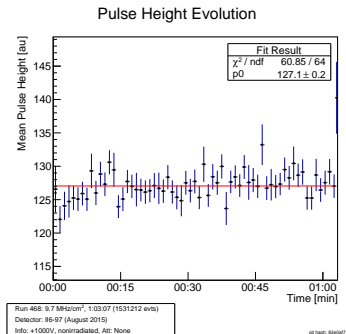


- use pulser as a reference signal
- tag pulser events by extra channel of the DRS4

Pulser

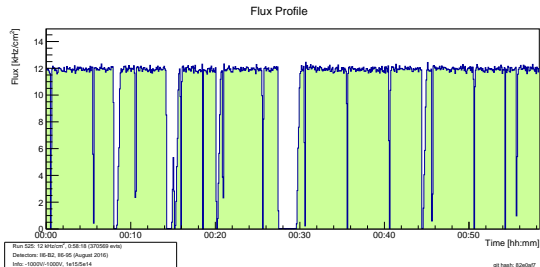


- use pulser as a reference signal
- tag pulser events by extra channel of the DRS4
- exclude these event since they don't have a diamond signal
- use for pulser analysis to compare to diamond signal



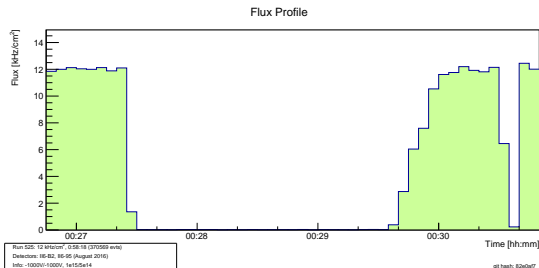
- until October 2015 → beam shutter opened after run was started
 - ▶ unstable conditions
 - ▶ exclude first five minutes of the run
- past October 2015 exclude first minute as safety margin
 - ▶ sometimes small adjustments made (e.g. collimator changed too late)

Beam Interruption



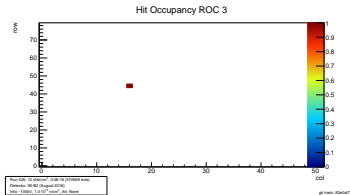
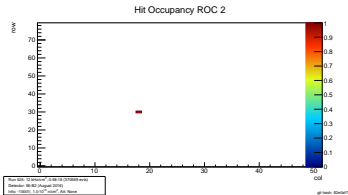
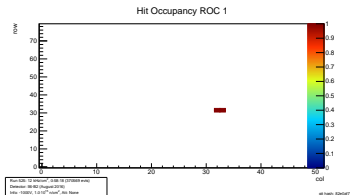
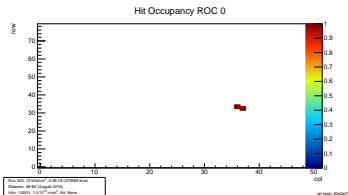
- usually short beam interruption every 5 min at PSI + other interruption

Beam Interruption



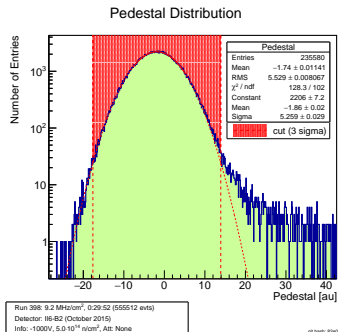
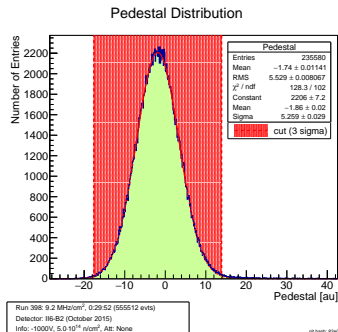
- usually short beam interruption every 5 min at PSI + other interruption
- particle rate slowly ramps up after interruption
- exclude events when rate drops less than 40 % + 5 s before
- until rate is larger than 40 % + 20 s after this
- let pulse height adjust after beam interruption (safety margin)

Tracks

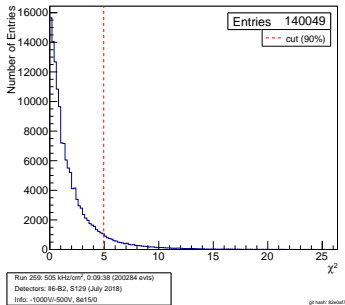
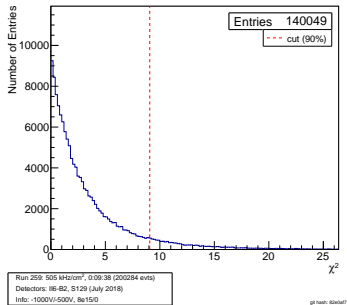


- only use events with exactly one track
- require one and only one cluster per plane

Pedestal Sigma



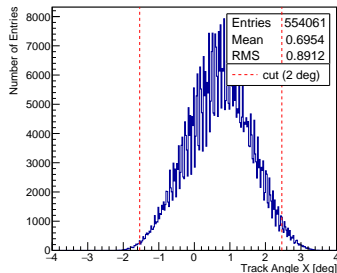
- exclude pedestals outside the 3 sigma region
- baseline shifts
- bad waveforms

χ^2 in X χ^2 in Y

- exclude the bad tracks

Tracking Angle

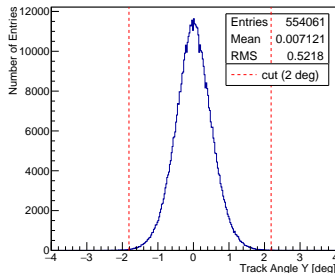
Track Angle Distribution in X



Run 462: 7 kHz/cm², 1:16:41 (758282 evts)
Detectors: I16-97, I16-B2 (August 2015)
Info: +1000V/-1000V, 0/0

g0 hash: 82ebaf7

Track Angle Distribution in Y



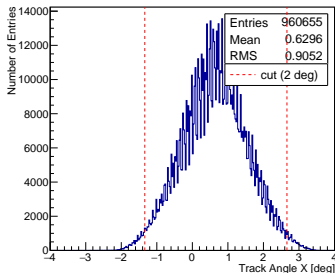
Run 462: 7 kHz/cm², 1:16:41 (758282 evts)
Detectors: I16-97, I16-B2 (August 2015)
Info: +1000V/-1000V, 0/0

g0 hash: 82ebaf7

- only accept tracks with small angles

Tracking Angle

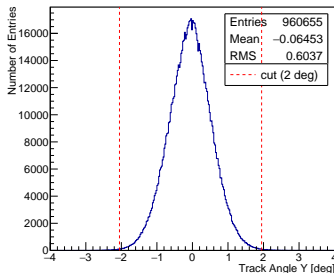
Track Angle Distribution in X



Run 468: 9.7 MHz/cm², 1:03:07 (1531212 evts)
Detectors: I16-B2 (August 2015)
Info: +1000V/-1000V, 0/0

git hash: 82e6a77

Track Angle Distribution in Y

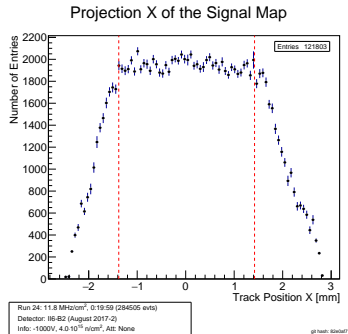
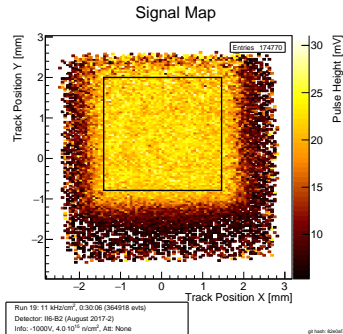


Run 468: 9.7 MHz/cm², 1:03:07 (1531212 evts)
Detectors: I16-B2 (August 2015)
Info: +1000V/-1000V, 0/0

git hash: 82e6a77

- 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