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Bundesministerium für Bildung und Forschung

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Precision determination of the tracking resolution of beam telescopes

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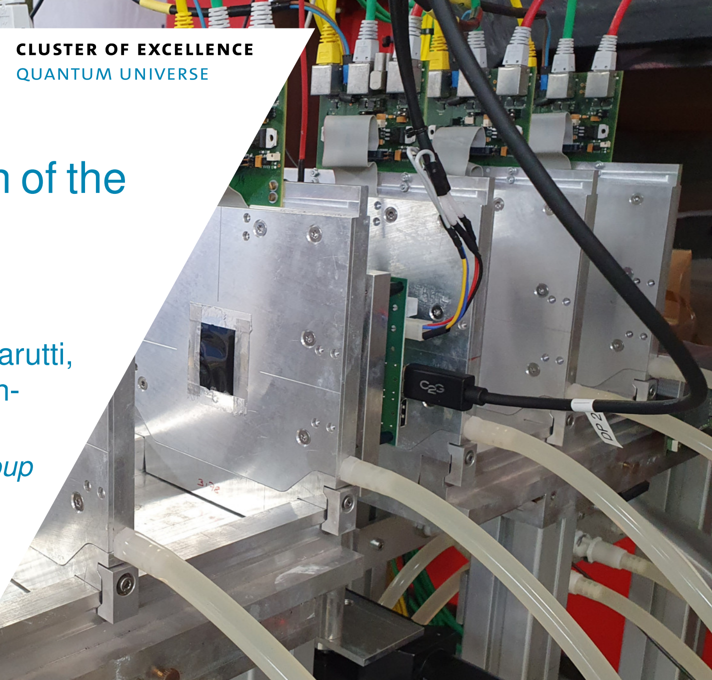
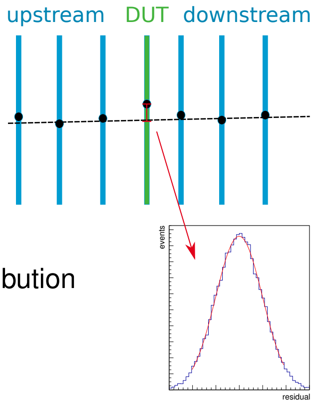
– on behalf of the CMS Tracker Group



43rd RD50 Workshop
CERN, Dec 1, 2023

Motivation



To determine the position resolution of segmented silicon detectors experimentally: beam tests

Position resolution of detectors from residuals:
beam track minus position in DUT (*device under test*)

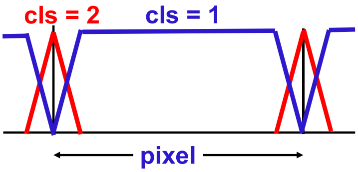
DUT resolution by unfolding “beam resolution“ from residual distribution

Typically $\sigma^2_{\mathrm{DUT}} = \sigma^2_{\mathrm{meas}} - \sigma^2_{\mathrm{beam}}$

Precise knowledge of beam position on DUT essential

Available methods

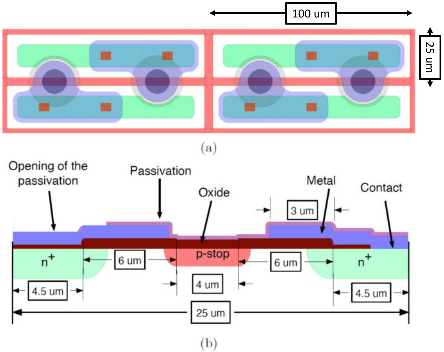
- Simulations and parametrised resolution
- Two beam telescopes (upstream and downstream), extract beam resolution from $\frac{1}{2}\sigma(\mathrm{up} - \mathrm{down})$
- Cluster size 1 events:
  box distribution of residuals for
  $\rightarrow$ from smearing of edges: σ_{beam}
- Cluster size 2 events *at normal incidence*:
  residual distribution have sub-micrometer resolution
  Reason: diffusion only few µm
  $\rightarrow$ small region of charge sharing results in cluster-size 2



Simulation setup

1×10^5 events simulated with PIXELAV [CMS-NOTE-2002-027]:

- 150 µm thick silicon sensor
- Sensor: 25 µm × 100 µm pixels
- 40 GeV/c pions with normal incidence
- Tracks uniformly distributed over one pixel
- Total simulated charge Q,
  Landau distributed with MPV 11.1 k e
  and mean 14.1 k e



Simulation: Event selection, Eta

Select events with:

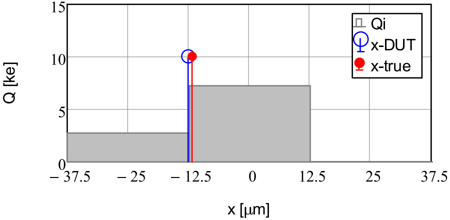
- Projected cluster size 2
- Minimum charge Q_i: 1200 electrons

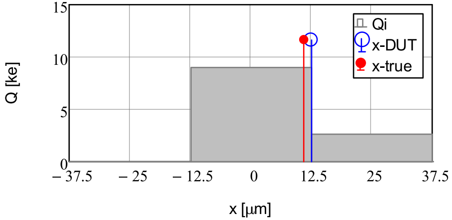
Define charge asymmetry

$$\eta_x = \frac{Qx_2 - Qx_1}{Qx_1 + Qx_2}$$

where Qx_1 is the charge in the pixel with the lower, and Qx_2 the one with the higher x-value

Assign boundary of pixels to position x_{DUT}





Charge asymmetry distributions

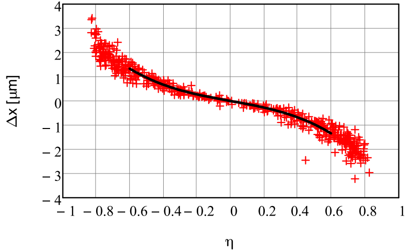
Distribution $\Delta x = x_{\mathrm{DUT}} - x_{true}$ versus η_x

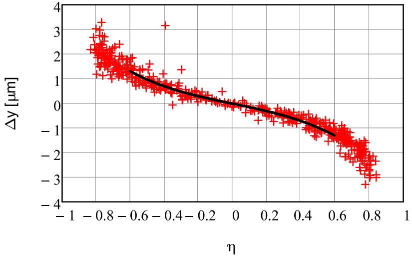
S-shape:
Boundary between the pixels is assigned to x_{DUT}, x_{true} moves towards pixel centre with increasing $|\eta|$

Regression of third-order polynomials
for $-0.6 < \eta < +0.6$
$\rightarrow$ can be used to correct x_{DUT} and y_{DUT}.

Note:

- Same distributions for x- and y-directions
- For small $|\eta_x|$: Δx much smaller 1 µm





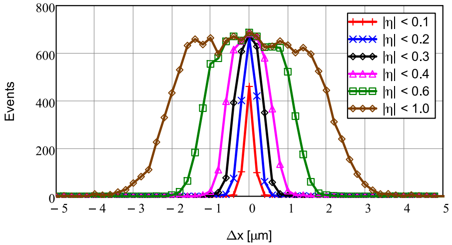
S-shape correction

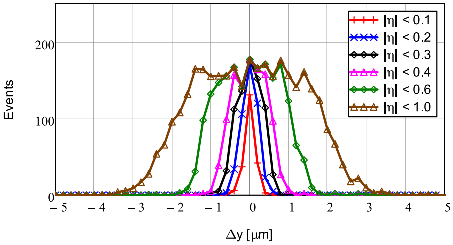
Correction for the mean of $\Delta(\eta)$:

Corrected DUT position:

$x_{\text{DUT, corr}} = x_{\text{DUT}} - \langle \Delta x(\eta_x) \rangle$,
where $\langle \Delta x(\eta_x) \rangle$ is the mean of $\Delta x(\eta_x)$

Third-order polynomials in η cut range:
Parametrisation for $\langle \Delta(\eta) \rangle$





S-shape correction

Correction for the mean of $\Delta(\eta)$:

Corrected DUT position:

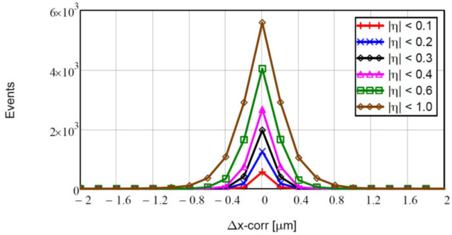
$x_{\mathrm{DUT,corr}} = x_{\mathrm{DUT}} - \langle \Delta x(\eta_x) \rangle$,

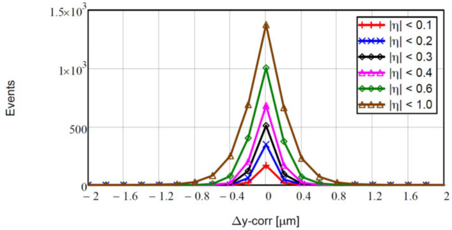
where $\langle \Delta x(\eta_x) \rangle$ is the mean of $\Delta x(\eta_x)$

Third-order polynomials in η cut range:

Parametrisation for $\langle \Delta(\eta) \rangle$

$\rightarrow$ Obtain corrected distributions



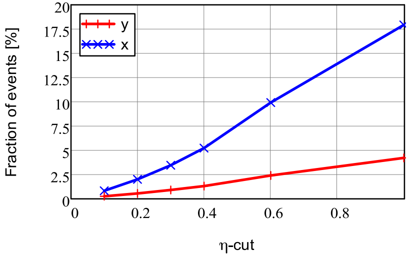


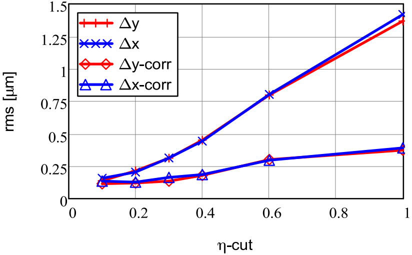
Eta cut

Apply different cuts on charge asymmetry $|\eta|$

Observations:

- Fraction of events increases ≈ linearly
- Ratio of events between *x*- to *y*-direction agrees with the inverse of the pixel pitches
- *rms* values of residual distributions for *x* and *y* agree





Noise studies

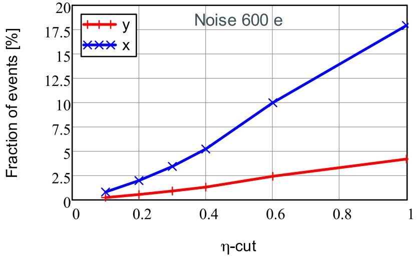
Effects of noise investigated:

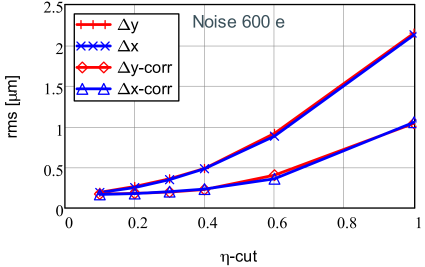
Simulate electronics noise from 300 e to 600 e.

Observations:

- Fraction of cluster-size 2 events increases slightly
- *rms* of the residual distributions increased
- Still typically less than 1 µmm

→ No relevant influence on the position accuracy of pixel-size 2 clusters





Cross-talk

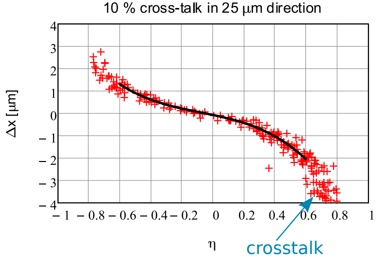
Simulated sensor:
Significant cross-talk expected in *x* direction
(significantly less in the *y* direction)

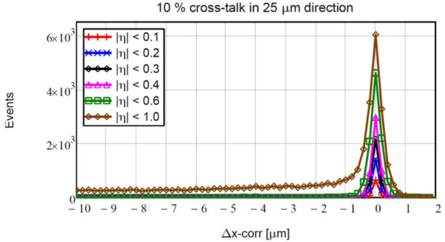
Cross-talk of 10 % in *x* direction implemented
(multiply charge values of individual pixels with cross-talk matrix A_x),
no cross-talk in *y* direction considered

Otherwise same analysis as before

Apply cut $|\eta_x| < 0.6$:

$\rightarrow$ Narrow distributions like no cross-talk scenario





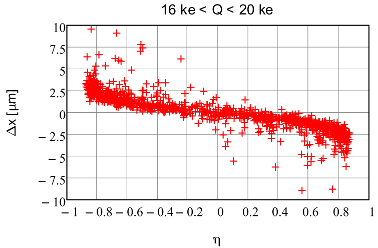
Delta electrons

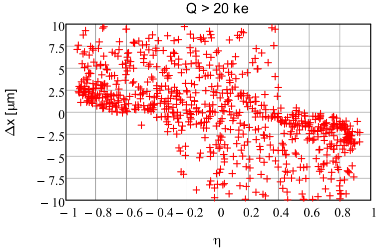
Study influence of energetic δ-electrons on the position resolution of cluster-size 2 events:

- Events with cluster charges $16\,\text{ke} < Q < 20\,\text{ke}$:
  Fraction of events “outside the band“ higher,
  rms of residual distributions increase: factor ≈ 1.7
- Events with $Q > 20\,\text{ke}$:
  Most events are outside,
  position resolution severely degraded

Remove the effects of δ-electrons:

$\rightarrow$ Cut to remove charges larger ≈ 1.5 times the MPV





Finite angles

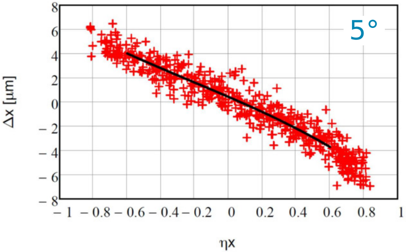
Sensitivity of the method to small deviations from normal incidence of the beam:

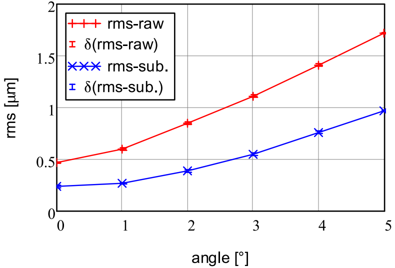
Simulated incident angle in 25 µm direction, varied between 0 ° and 5 ° in 1 °-steps

Observed changes of Δx distribution:

1. fraction $x\text{-}cls = 2$ events increases,
2. value of the slope $|\,\mathrm{d}\Delta x / \mathrm{d}\eta_x\,|$ increases,
3. width of the Δx band increases.

For angles below a few degrees:
Position resolutions of 1 µm can be achieved





Simulation: Conclusions

Method:

- Cluster-size 2 events are selected
- Charge asymmetry of the two signals is calculated
- Events in a given charge-asymmetry interval are selected
- Pixel (or strip) boundary of the two readout elements of the cluster is taken as reconstructed position

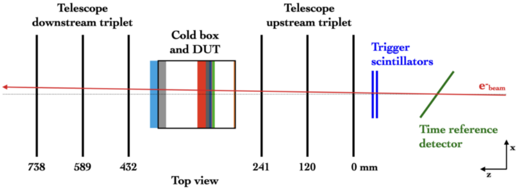
$\rightarrow$ Position resolutions of 1 µm and less are achieved.

$\rightarrow$ Cross-talk, electronics noise, δ-electrons and angular deviations of a few degrees can be handled.

Application to data: Setup

Testbeam setup:

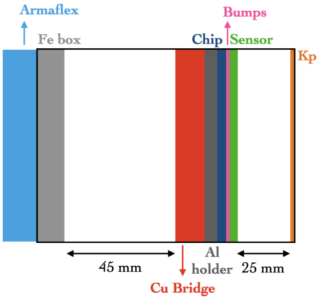
- DESY-II Test Beam Facility
- 5.2 GeV - 5.6 GeV electrons
- Two beam telescopes, one upstream and one downstream,
  each 3 planes of Mimosa26 Monolithic Active Pixel Sensors (MAPS)
  pitch of 18.4 µm × 18.4 µm, single-plane position resolution 3.2 µm
- Time reference to select track in coincidence with the DUT:
  CMS Phase-1 pixel detector
  (pixel size of 150 µm × 100 µm,
  analogue readout at a frequency of 40 MHz)



Application to data: Setup (2)

Device under test:

- Sensor: CMS Phase-2 prototype pixel sensors
  (with 25 µm × 100 µm pixels)
  - a) non-irradiated sensor
  - b) sensor irradiated by 23 MeV protons to 1 MeV neutron equivalent fluence $\Phi_n = 2 \times 10^{16}\,\mathrm{cm}^{-2}$
- Readout: RD53A chip,
  4-bit Time-over-Threshold (ToT) charge-digitisation
  above adjustable threshold (between 1250 e and 1450 e)
- Irradiated sensor: operated in cooling box
  $\rightarrow$ significant extra material downstream of the DUT



Experimental conditions

Data-taking and sensor parameters:

Sensor No.	Φ_n [10^{15}/cm^3]	V_b [V]	T [°C]	I_{dark} [µA]	*Noise* [e]	*Thr* [e]
612	0	120	$\approx +20$	3.0	$\approx$ 70	$\approx$ 1250
613	20	800	≈ -26	355	$\approx$ 110	$\approx$ 1450

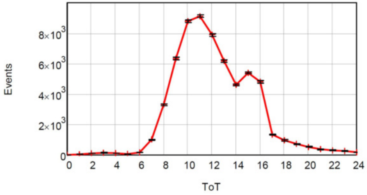
Calculated beam-tracking resolutions σ at the DUT [doi:10.5281/zenodo.48795]:

Sensor No.	E_e [GeV]	z_{DUT} [mm]	σ_{up} [µm]	σ_{down} [µm]
612	5.2	284	5.1	7.0
613	5.6	331	9.0	–

Given the extra material from the cooling box, only upstream telescope used for irradiated sensor

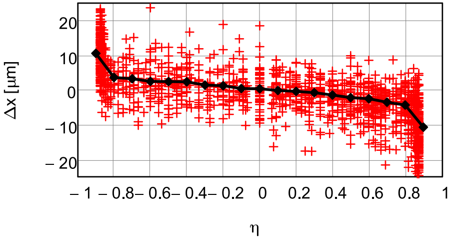
Charge assymetry distribution

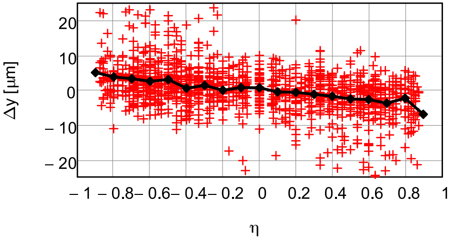
Charge spectrum in ToT (non-irradiated):



Coarse binning $\rightarrow$ visible quantisation in η

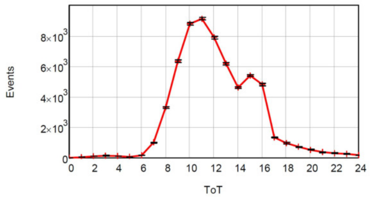
- $\Delta x = x_{\mathrm{DUT}} - x_{beam}$ versus η_x
- Δy versus η_y
- Non-irradiated sensor in both directions





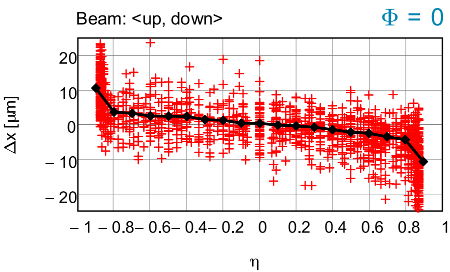
Charge assymetry distribution

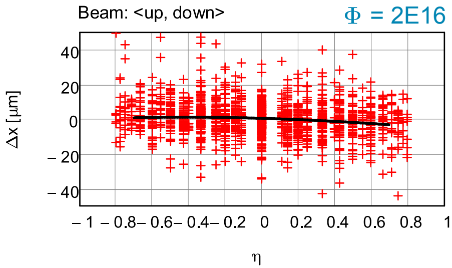
Charge spectrum in ToT (non-irradiated):



Coarse binning $\rightarrow$ visible quantisation in η

- $\Delta x = x_{\mathrm{DUT}} - x_{beam}$ versus η_x
- Δy versus η_y
- Non-irradiated sensor in both directions
- 2E16 irradiated sensor

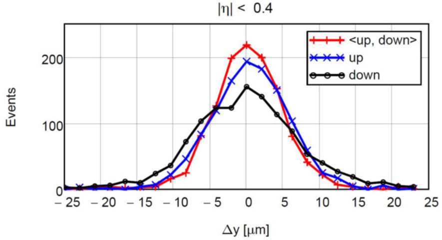




Comparison

Comparison of beam-track resolutions for the non-irradiated DUT:

- Calculated values
- Measured values are for $|\eta| < 0.4$



	σ_{up} μm	σ_{down} [μm]	$\sigma_{0.5\,(up+down)}$ [μm]	$\sigma^{beam}_{0.5\,(up-down)}$ [μm]
calculated	5.14 ± 0.06	7.01 ± 0.07	4.30 ± 0.05	–
measured in x	5.2 ± 0.1	7.0 ± 0.2	4.6 ± 0.1	4.4 ± 0.04
measured in y	5.0 ± 0.2	6.6 ± 0.3	4.3 ± 0.2	4.4 ± 0.12

$\rightarrow$ Agreement demonstrates validity of the method

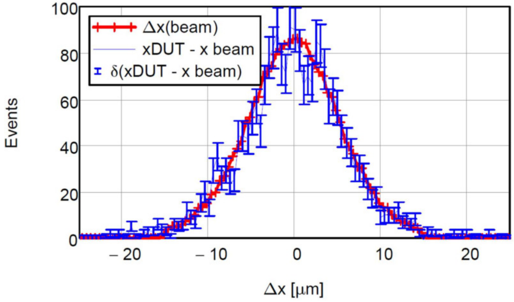
Angle studies

Non-irradiated sensor with shallow incidence:
76.7° incidence in 100 µm direction,
Normal incidence in 25 µm direction

Compare

- Distribution of $\Delta x = x_{\mathrm{DUT}} - x_{beam}$ for $|\eta_x| < 0.4$
- To distribution of $(x_{up} - x_{down})/2$

$(x_{up} - x_{down})/2$ distribution normalised to the Δx distribution



Distributions agree:

→ Proposed method also works for beams with normal incidence in one view only

Summary ...

Goal: precise knowledge of track resolution at the DUT

Proposed method: tracks with normal incidence close to pixel boundaries
$\rightarrow$ cluster-size 2 events

Simulation results: with delta-electron charge cut
$\rightarrow$ position resolution below 0.5 µm is found for $|\eta| \leq 0.4$

Cross-talk between pixels, electronics noise, deviations from normal incidence up to 5°
$\rightarrow$ can be controlled with cuts on η and on the total cluster charge

Application to data: Agreement between the two methods using

a) difference of positions reconstructed by two beam telescopes extrapolated to DUT
b) difference of mean position reconstructed by telescopes with respect to position reconstructed by the DUT using cluster-size 2 events

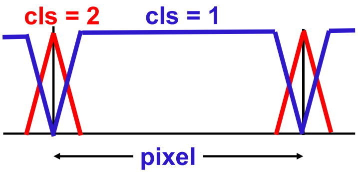
... & Conclusions

Cluster-size-2 method easy to implement, and offers multiple benefits:

- Allows determining separately the pointing resolutions of the upstream, the downstream and the combined beam telescope at the DUT
- Applicable also for data with normal incidence in only one view
  $\rightarrow$ Pos resolution for view with normal incidence not affected by angle in the other
- If tracking resolution of beam telescopes is same in both views, (normally the case)
  $\rightarrow$ possible to determine track resolutions for every data set of angular scans

Backup slides

Comparison



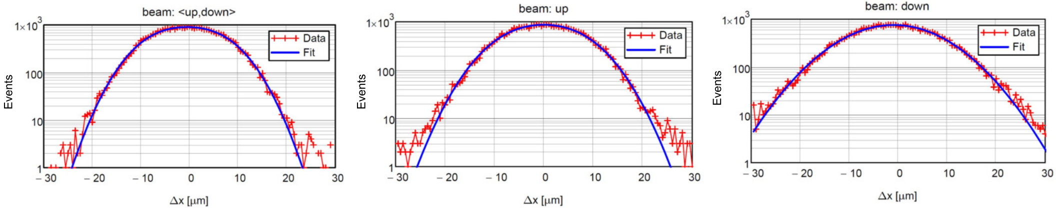
Comparison of the cluster-size 1 and 2 methods

The *cls* $=$ 2 **events**:
- Occupy a narrow region around the pixel boundaries
- After convolution with the beam resolution: directly measure beam-resolution function

The *cls* $=$ 1 **events**:
- Occupy the remaining regions
- Are reconstructed in the centre of the pixels $\rightarrow$ box-type distribution
- After convolution with the beam-position resolution: distribution can be described by the difference of two error functions corresponding to the beam resolution

Cluster-size 1 plots in x-direction

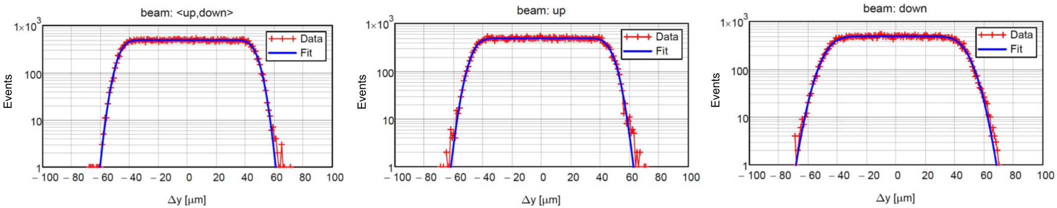
Distributions for upstream and downstream beam telescopes and their average:



The expected flat top is absent.

Cluster-size 1 plots in y-direction

Distributions for upstream and downstream beam telescopes and their average:



The expected flat top is observed.

Cluster-size 1 fit

Fit to the residual distribution with

$$f(x) = \frac{A}{2} \cdot \left(\mathrm{erf}\left(\frac{x - x_0 + w_x/2}{\sqrt{2}\sigma_x} \right) - \mathrm{erf}\left(\frac{x - x_0 - w_x/2}{\sqrt{2}\sigma_x} \right) \right)$$

The free parameters of the fits are:

- the normalisation, A
- the mean position of the box distribution, x_0
- the full width of the box distribution, w_x, and
- σ_x the *rms* of the convolution by the beam-position resolution, assumed to be Gaussian

Cluster-size 1 fit results

Beam	y_0 [µm]	w_y [µm]	σ_y [µm]
$\langle \text{up}, \text{down} \rangle$	-0.25 ± 0.10	94.5 ± 0.2	4.68 ± 0.15
up	-0.37 ± 0.12	94.6 ± 0.3	4.65 ± 0.1
down	-0.04 ± 0.16	94.6 ± 0.3	7.33 ± 0.24

Beam	x_0 [µm]	w_x [µm]	σ_x [µm]
$\langle \text{up}, \text{down} \rangle$	0.47 ± 0.04	17.3 ± 0.3	4.88 ± 0.12
up	0.02 ± 0.05	17.1 ± 0.5	5.52 ± 0.18
down	–	–	–