Detector Characterisation: Irradiation and Test Beam

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German Academic Exchange Service

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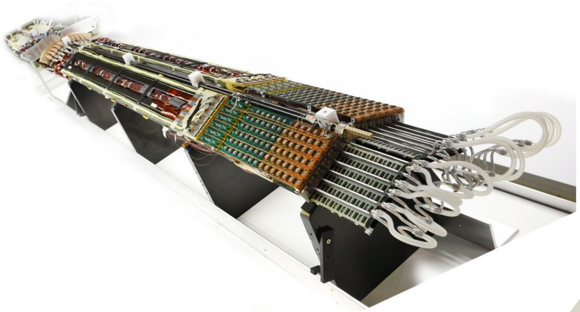
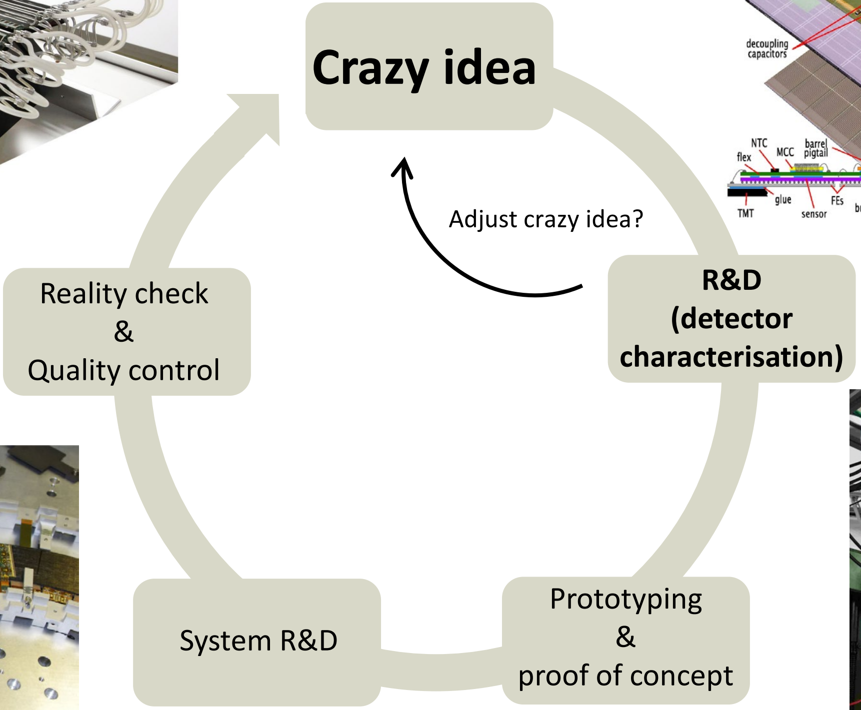
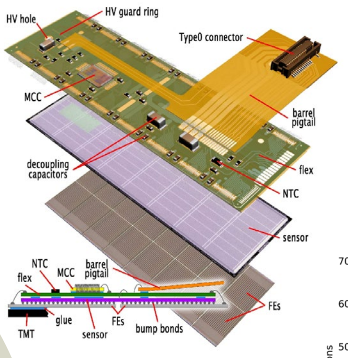
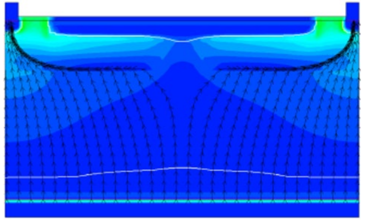
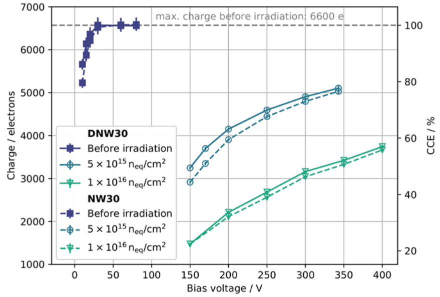
WHY IS DETECTOR CHARACTERISATION IMPORTANT?

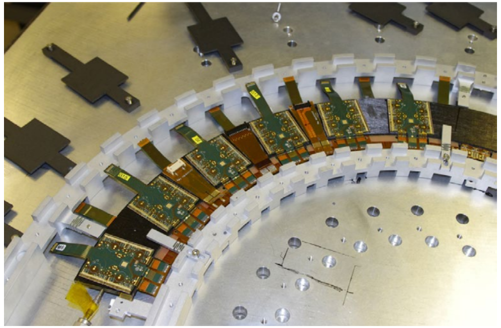


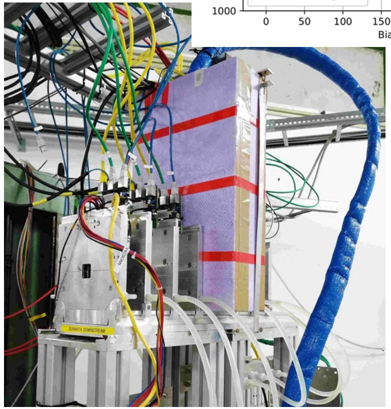










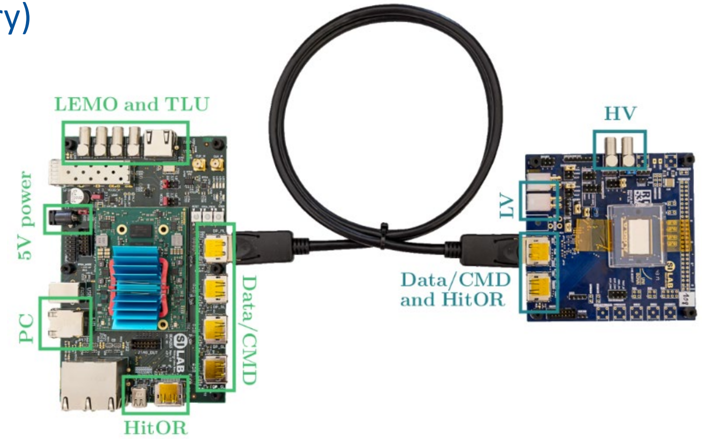


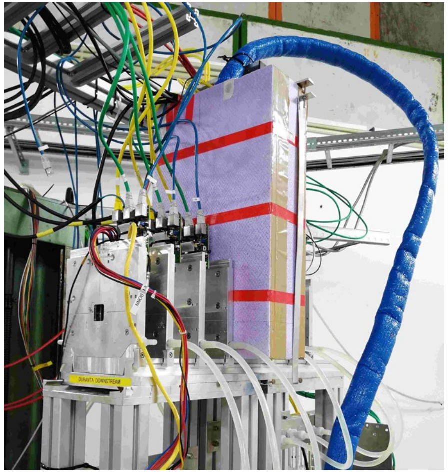
LAB TESTING AND TEST BEAM

Typically, new device is characterised in lab and in test beam (complementary)

Lab characterisation (‚simple‘ table-top setup in lab):

- Current vs. voltage characteristic (IV-curve)
- Optimisation of device settings/configuration (power, threshold, speed, noise, …)
- Calibration of detector with radioactive sources or x-ray tube (photons with well known energy)



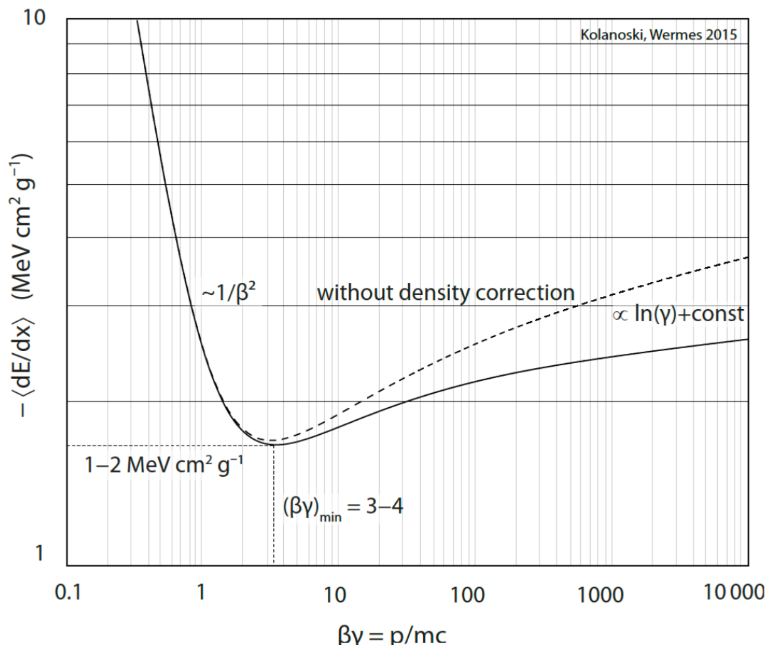


Test beam (‚complex‘ setup at external facility):

- Spatial and time resolution of detector
- Detailed studies of efficiency and charge collection (within pixels)
- System integration tests (readout of several detectors in parallel or testing of larger subsystems)

BASICS: INTERACTION OF PARTICLES WITH MATTER

- Restrict here to **charged** particles
- (Mean) energy loss of charged particles in matter described by Bethe-Bloch
- Broad minimum at $\beta\gamma = 3$ -> „minimum ionising particles“ (MIP)
- In practice, all particles $\beta\gamma > 3$ are considered as MIPs
- MIPs are what we use for test beam measurements!
  - …. a few GeV electrons
  - …. 120 GeV hadrons



BASICS: INTERACTION OF PARTICLES WITH MATTER

- Bethe-Bloch describes the **mean** energy loss, but actually thats not a good estimator to quantify energy loss!
- Energy loss fluctuates -> Landau distribution
  - **Number fluctuations** -> number of collisions varies
  - **Energy-transfer fluctuations**
- Most-probable value (MPV) is more stable wrt. to fluctuations
- In silicon, MPV is ~75 e/h per um (depends on thickness!)

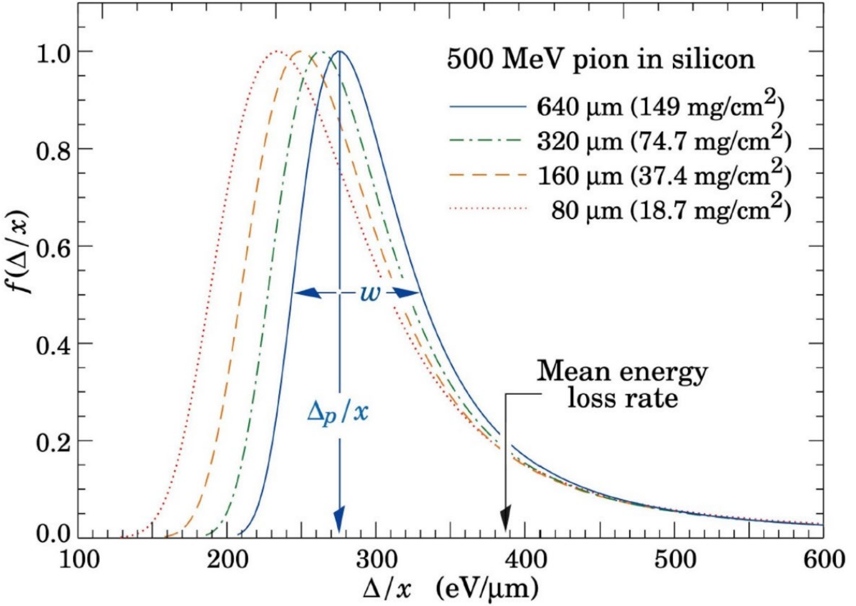
$$\Delta_p = \xi \left[\ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right]$$

$$\xi = (K/2) \langle Z/A \rangle z^2 (x/\beta^2)$$

[PDG (2022), 34.2.9]

$w_i = 3.65\,\mathrm{eV}$ (in Silicon)

[PDG (2022), 34.2.9]



IRRADIATION

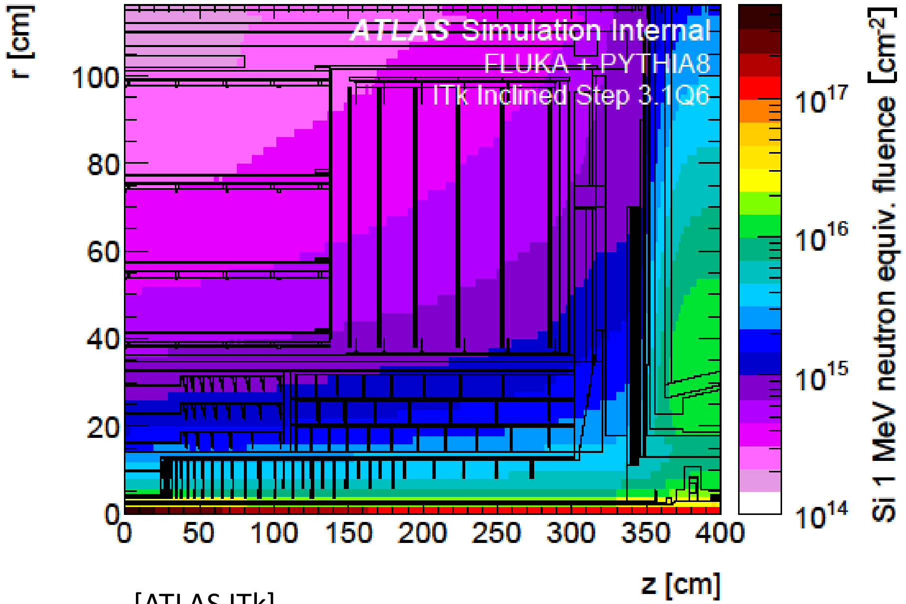
We will only talk about **bulk damage**

IRRADIATION

- Reminder: **1 MeV neutron-equivalent fluence**: Φ_{eq} $[n_{eq}/cm^2]$
  → Amount of radiation damage caused by 1 MeV neutrons with fluence Φ_{eq}
- Why is this important?

Fluences in HEP experiments can reach up to $10^{16} n_{eq}/cm^2$ after life time of detectors

We need to make sure that performance of detector is still fulfilling the requirements!



[ATLAS ITk]

IRRADIATION FACILITIES: HOW?

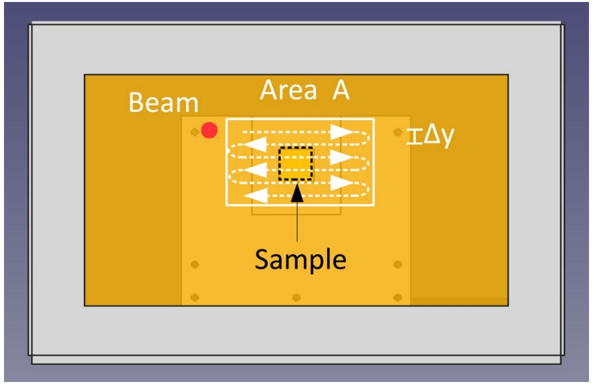
- Irradiation facility provides particle beam (e.g. protons)
- Install device under test in beam and shoot particles onto it

$$\phi_p = \frac{I_p \cdot t}{e \cdot A} \qquad \kappa = \frac{\phi_{neq}}{\phi}$$

Hardness factor scales fluence to neutron-equivalent fluence (NIEL scaling)

- By measuring the beam current we can then estimate how much „damage“ we create in the detector material
- Typically, a homogenous irradiation over the detector is wanted

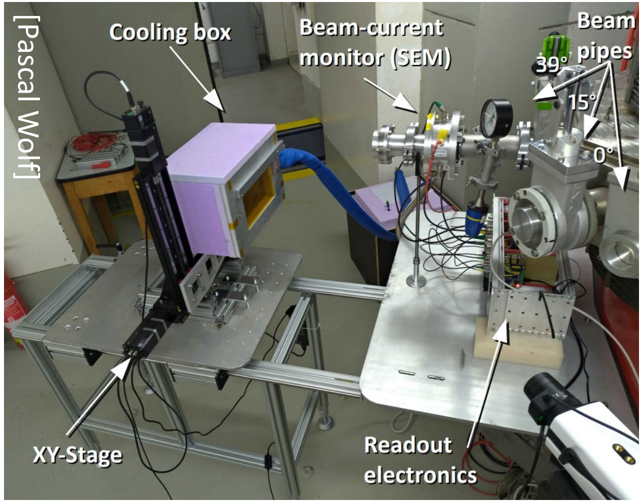
-> Move the device in beam („scanning“)

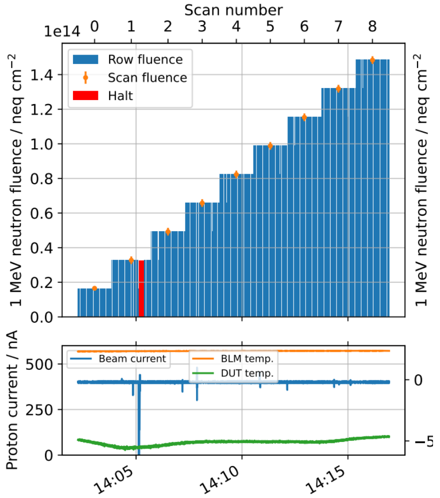


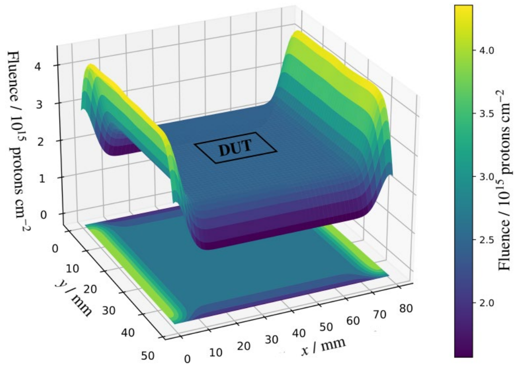
[Pascal Wolf]

IRRADIATION SITES: SOME EXAMPLES

- A very nice irradiation facility is Bonn at the Isochronous Cylotron at HISKP
  - Provides protons, deuterons, alphas… up to ^{12}C
  - 7 MeV – 14 MeV per nucleon
- Mostly proton beam is used for irradiation:
  - A few nA to 1 uA beam current
  - Gaussian beam profile (up to 2 cm FWHM)
  - Flux (1 uA) = $6 \times 10^{12}\ s^{-1}cm^{-2}$
- Live monitoring: precise knowledge of fluence and feedback
- Homogeneous application of fluence
- 5×10^{15} within 60 min (for a 2 cm² sample)







[Pascal Wolf]

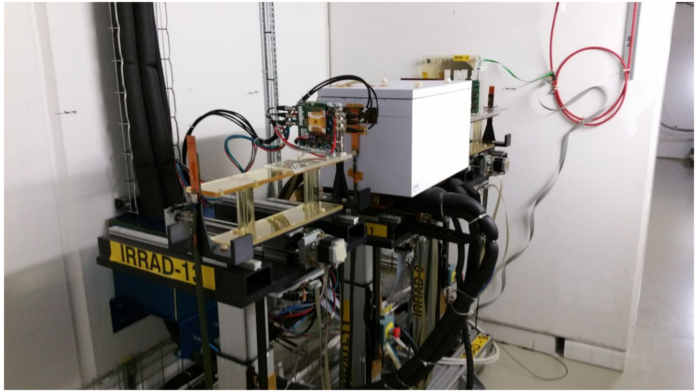
IRRADIATION SITES: SOME EXAMPLES

Of course there are many other facilities…

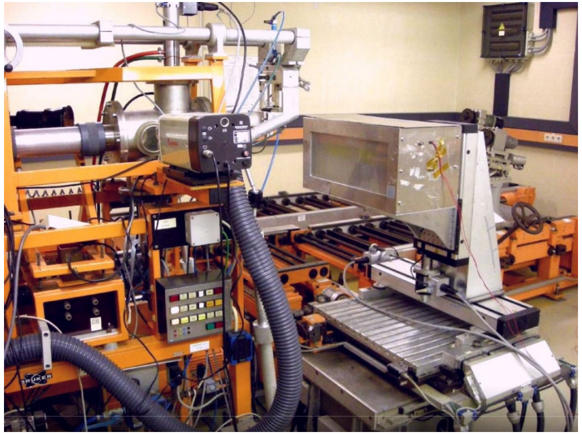
A nice summary of the irradiation sites

27 MeV protons at MC40 Cyclotron in Birmingham…

23 GeV protons at IRRAD proton facility at CERN (PS)…



24 MeV protons at KIT irradiation facility in Karlsruhe…



RADIATION DAMAGE: BULK DAMAGE

Leakage current

- Operation temperature
- Electronic noise
- DC current

Trapping

- Smaller charge signal

Doping concentration

- Bias voltage
- Drift field change

1 MeV neutron-equivalent fluence: Φ_{eq} [n_{eq}/cm^2]

→ Amount of radiation damage caused by 1 MeV neutrons with fluence Φ_{eq}

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$$I_{\text{leak}} = \alpha V \phi_{eq}$$

→ leakage current scales with fluence

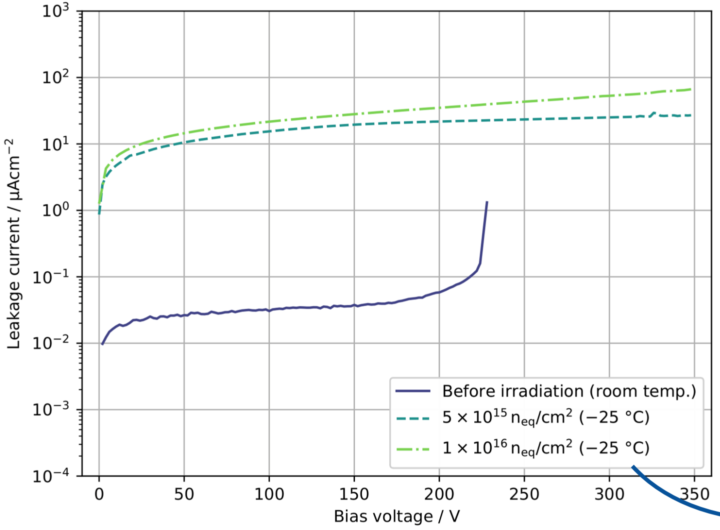
→ drastic increase in leakage current

$$I_{\text{leak}} \sim T^2 \exp\left(-E_a/2k_B T\right)$$

→ cool detectors!

$$\text{ENC}_{\text{shot}} \sim \sqrt{I}$$

→ Increased electronic noise



Use a climate chamber

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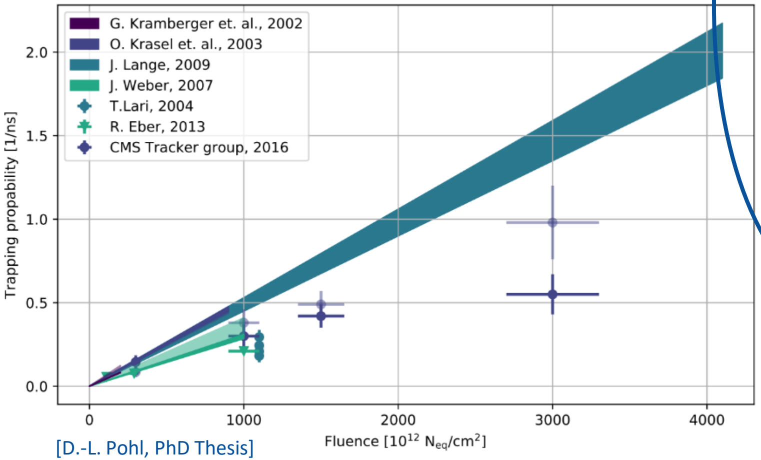

[D.-L. Pohl, PhD Thesis]

Effective trapping: „sum over all traps with emmission times larger than integration time of R/0"

$$\frac{1}{\tau_{\mathrm{eff,e/h}}} = \frac{1}{\tau_0} + \beta_{e/h}\phi_{eq}$$

→ Trapping probability scales with fluence

$$Q(t) = Q_0 \exp\left(-\frac{t}{\tau_{\mathrm{eff,e/h}}}\right)$$

→ Fast charge collection

RADIATION DAMAGE: BULK DAMAGE

Leakage current
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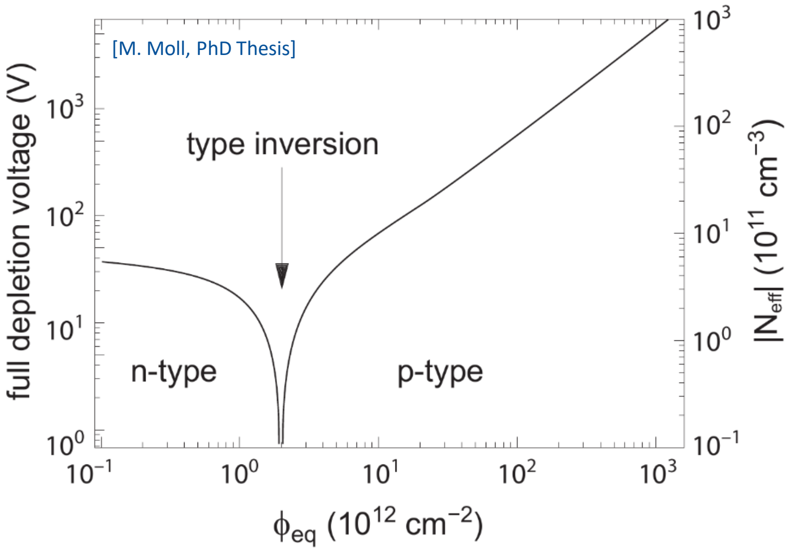

$$\Delta N_C = N_{C,0}\left(1 - \mathrm{e}^{-c\phi_{eq}}\right) + g_C\phi_{eq}$$

→ For $\Phi_{eq} > 10^{13}$ n_{eq}/cm^2: effective doping concentration scales with fluence

$$d \sim \sqrt{\frac{V_{\mathrm{bias}}}{N_{\mathrm{eff}}}}$$

→ Larger bias voltage required to sufficiently deplete the detector

RADIATION DAMAGE: BULK DAMAGE

Leakage current

- Operation temperature
- Electronic noise
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Trapping

- Smaller charge signal

Doping concentration

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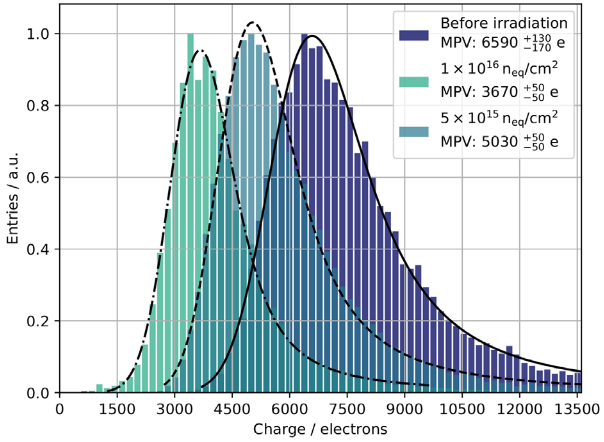

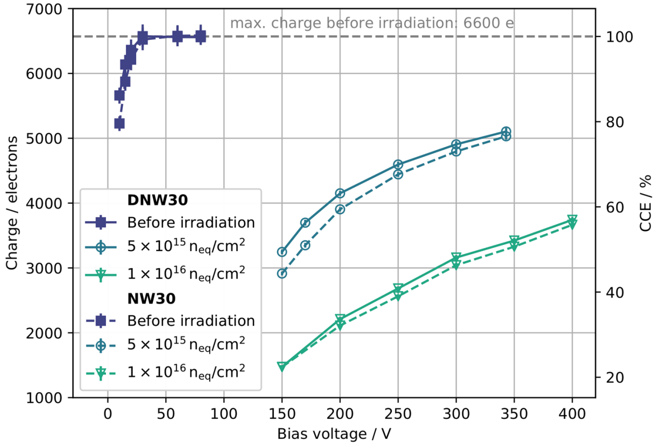

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TEST BEAMS

TEST BEAMS

- Goal: Measure reponse of detector under test (DUT) to particle beam (MIPS)
- Interested in measuring …

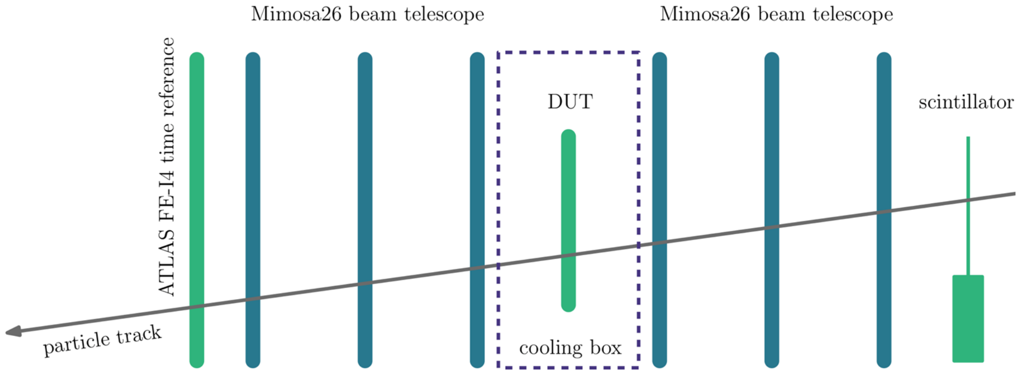
  … Hit detection efficiency

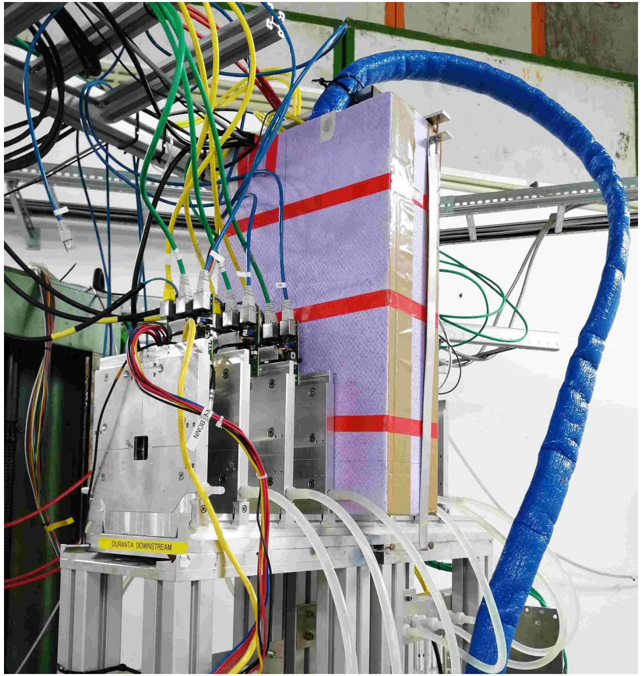
  … Temporal resolution

  … Spatial resolution

  … Charge collection properties

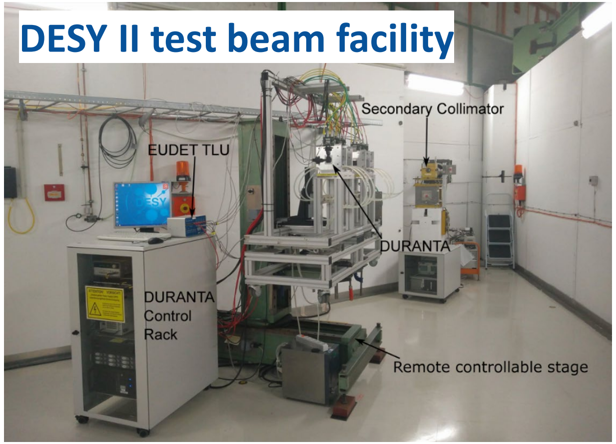
  all versus detector parameters (detection threshold, bias voltage, …)





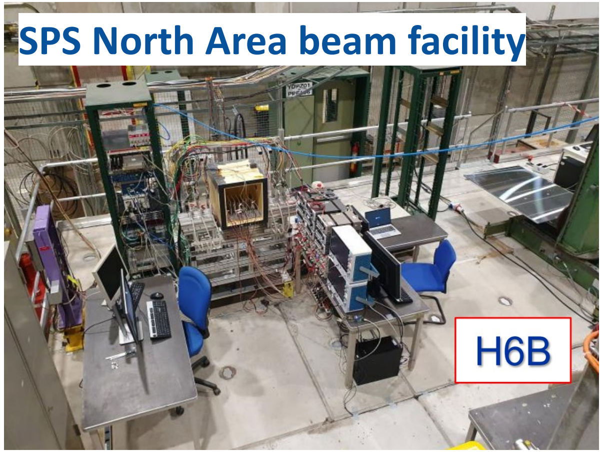
TEST BEAM FACILITIES

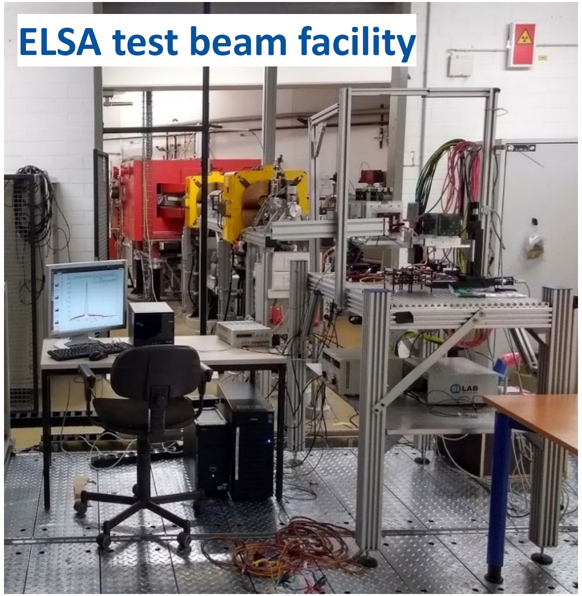
Many test beam facilities available…



SPS North Area beam facility

- converted beam from SPS
- several beam lines with high energetic protons (400 GeV)
- beam has spill structure from SPS
- 5 – 10 sec. spill length (1 spill every 14 – 60 sec)





DESY II test beam facility

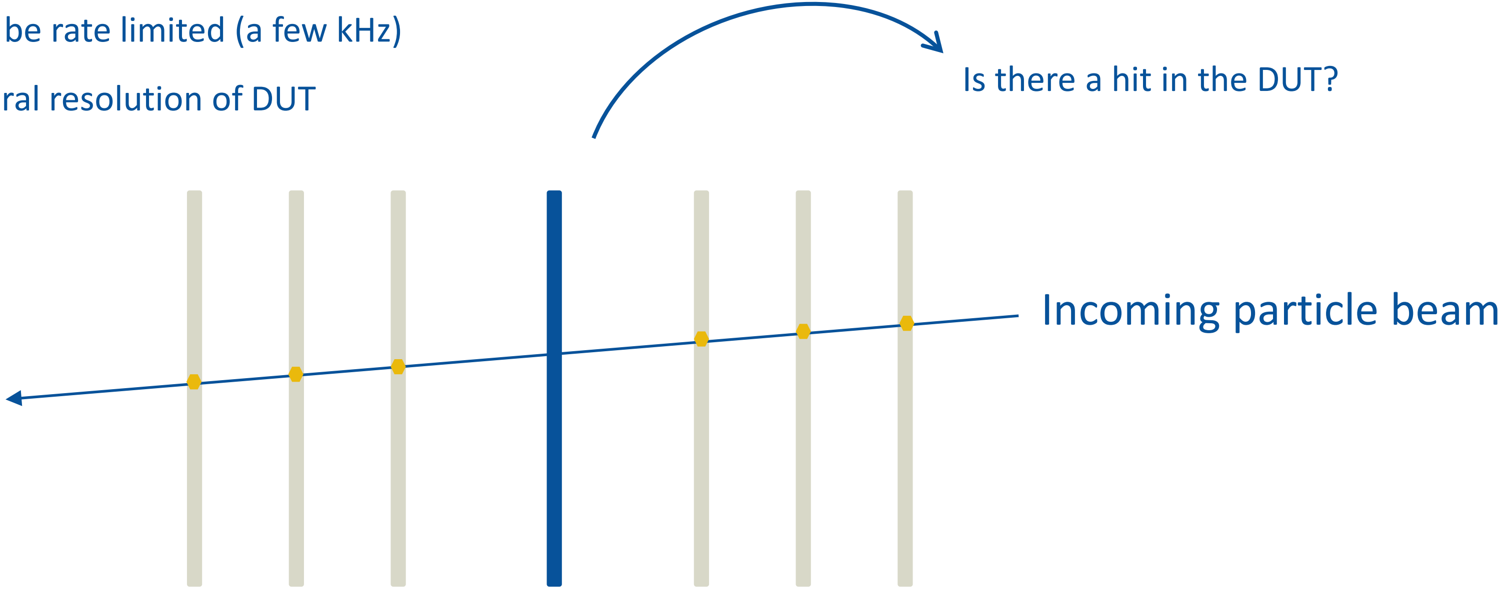
- bremstrahlungs converted electron beam
- several beam lines with 1 – 5 GeV electron beam
- a few kHz beam rate

ELSA test beam facility

- primary electron beam
- single extraction line provides 3 GeV electron beam
- user-adjustable beam rate ranging from 1 Hz – 625 MHz
- Spill duty cycle (80 %)

BEAM TELESCOPE

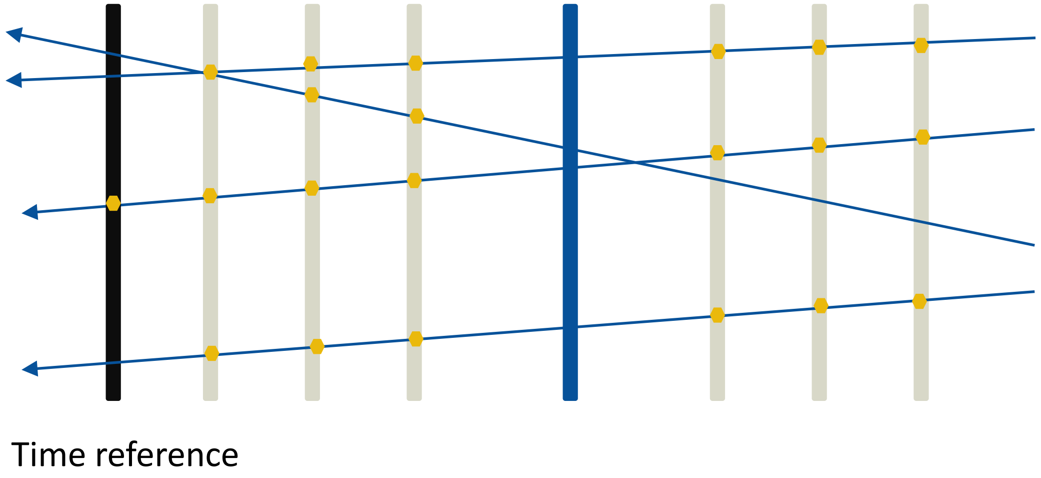
- Aim of beam telescope is to track incoming particle beam and extrapolate trajectory on DUT
- Several pixel detectors with excellent spatial resolution (a few um)
- Optional: good timestamping capabilites (ns - us)
  - Do not want to be rate limited (a few kHz)
  - Study of temporal resolution of DUT



BEAM TELESCOPE: TIME REFERENCE

- Typical time resolution of (current) beam telescope not sufficient (a few hundred us)
- Several tracks are „integrated“ -> track ambiguity (track multiplicity)
- Use high precision timing layer to disentangle track multiplicity

Snapshot of one event



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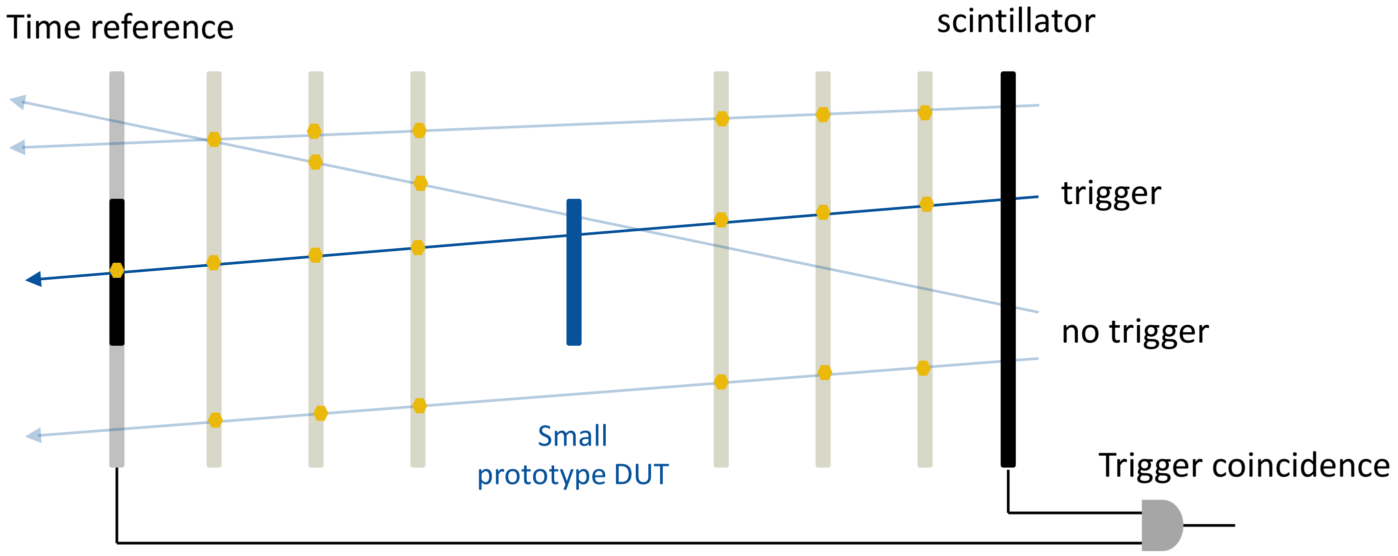
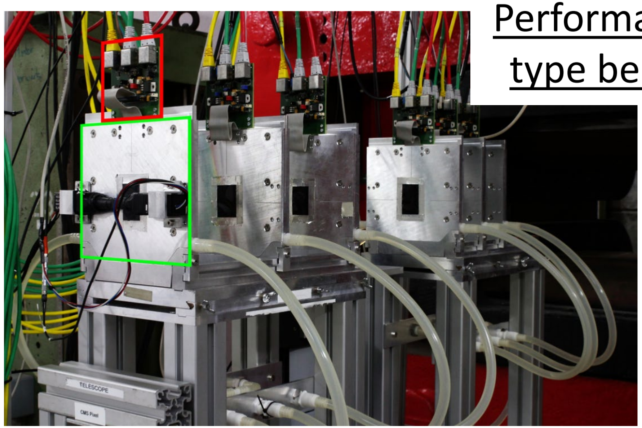
- We can also use this additional layer as **„region of interest“** (ROI)



EXAMPLE OF A BEAM TELESCOPE

- EUDET-type beam telescope available since years
- Highly used tool for device characterisation in test beams
  - Several copies of the telescope at various places Bonn, CERN, SLAC, DESY, …
- Consisting of 6 high resolution MIMOSA26 sensors (MAPS)
- Great track resolution of a few um and very little material budget …
- Charge collection mainly due to diffusion (20 um epi-layer)
- … but slow (rolling shutter readout)



More about Performance of EUDET type beam telescope

	Mimosa 26
Chip sensitive size	21.2 mm × 10.6 mm
Chip thickness	50 µm to 70 µm
Pixel pitch	18.4 mm × 18.4 µm
Pixel matrix	1152 × 576
Detection efficiency	>99 %
Fake-hit rate	$\sim 10^{-4}$ pixel^{-1}event^{-1}
Typical frame readout time	115.2 µs

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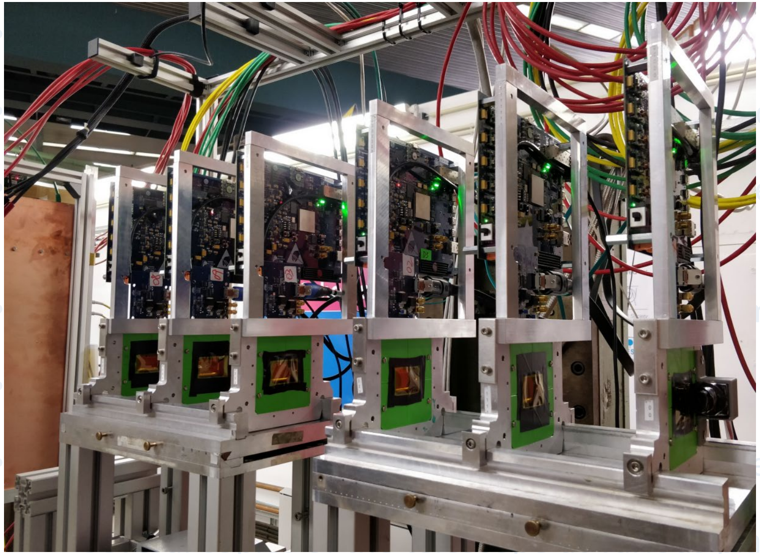
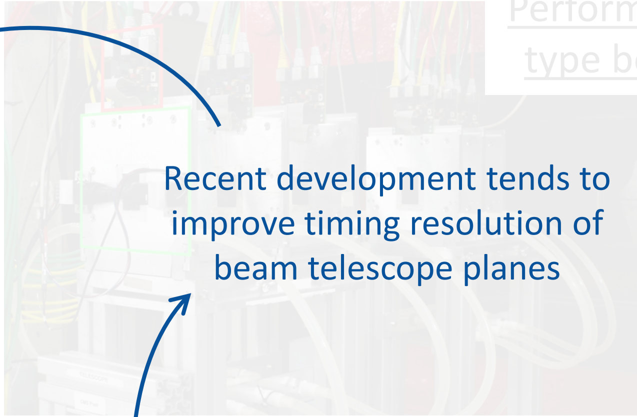


Bonn, CERN, SLAC, DESY, …

More about beam telescope built from ALPIDE chips

More about Performance of EUDET type beam telescope



Recent development tends to improve timing resolution of beam telescope planes

	Mimosa 26	ALPIDE
Chip sensitive size	21.2 mm × 10.6 mm	13.8 mm × 29.9 mm
Chip thickness	50 µm to 70 µm	50 µm to 100 µm
Pixel pitch	18.4 mm × 18.4 µm	26.88 mm × 29.24 µm
Pixel matrix	1152 × 576	512 × 1024
Detection efficiency	>99 %	>99 %
Fake-hit rate	$\sim10^{-4}$ pixel^{-1}event^{-1}	$<10^{-6}$ pixel^{-1}event^{-1}
Typical frame readout time	115.2 µs	10 µs

TRACK RECONSTRUCTION

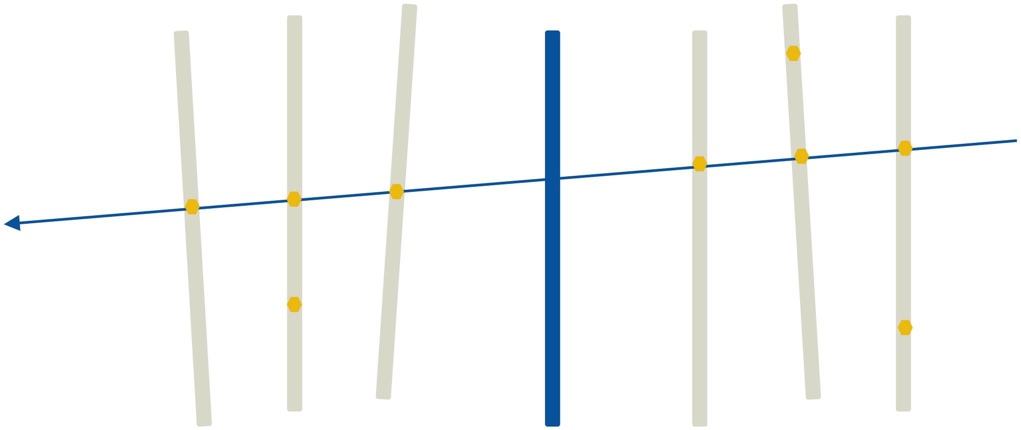
TRACK RECONSTRUCTION OVERVIEW

... from hits to reconstructed tracks...

Corryvreckan

BTA

Beam telescope analysis



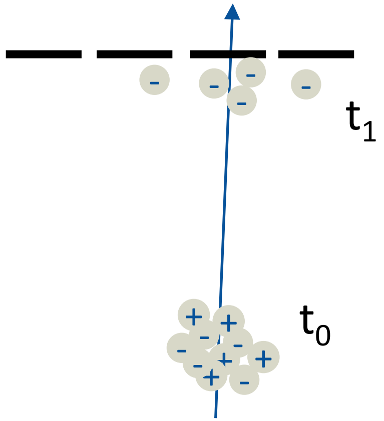
Noisy pixel masking → Clustering → Alignment → Track finding → Track fitting → Data selection → Result analysis

CLUSTERING

- Cluster: Accumulation of (neighboring) pixel hits from the same particle („charge sharing“)

  … due to lateral **charge carrier diffusion** $\sigma(t) = \sqrt{2Dt}$ ~ few um!

  … large track angles (particle crosses several pixels)



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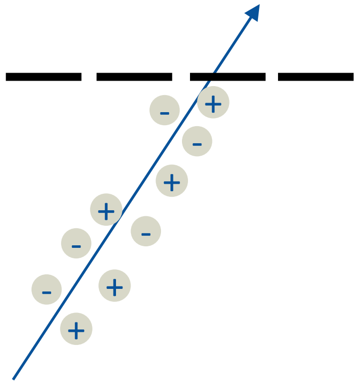

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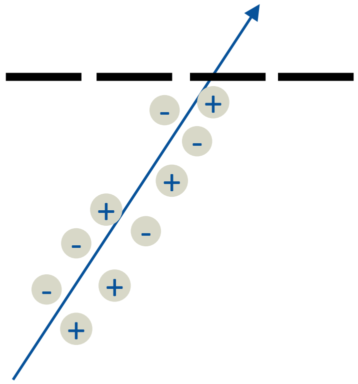
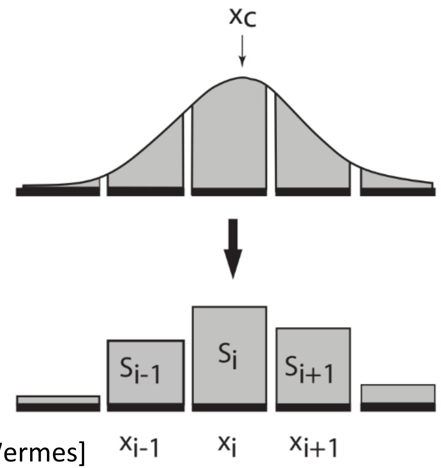


- For track reconstruction we need to combine these hits into single (x,y) -> **clustering**
- Typically, use „centre-of-gravity“ method (if charge information available)

$$x_{rec} = \frac{\sum S_i \, x_i}{\sum S_i}$$

- Position resolution can improve with „centre-of-gravity“ method

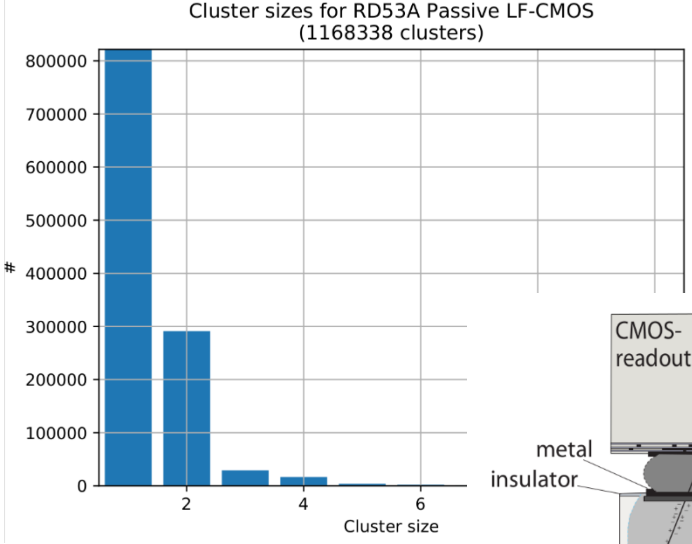
$$\sigma_x = a/\sqrt{12}$$ (Binary hit resolution)

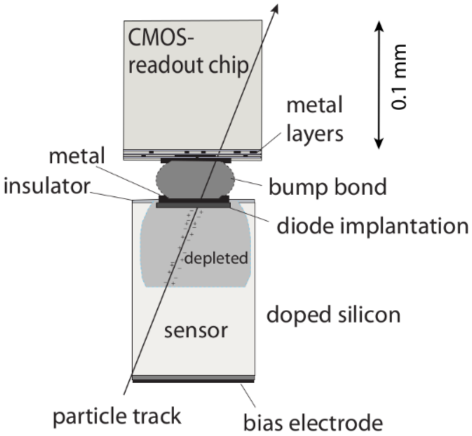


[N. Wermes]

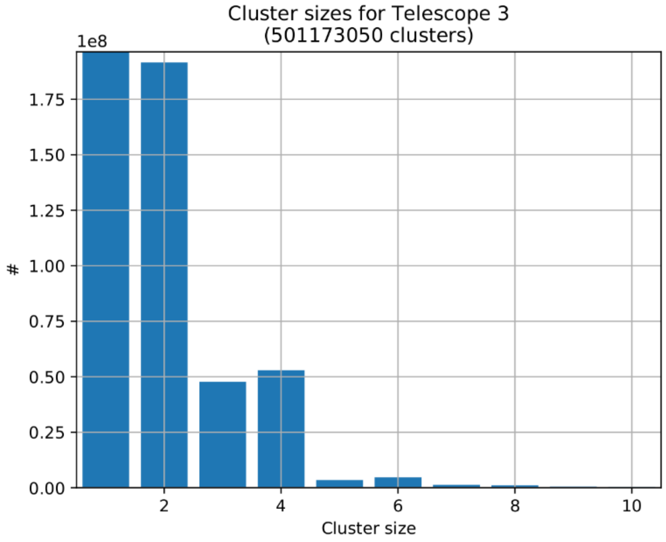
CLUSTER SIZE DISTRIBUTIONS

… some real examples

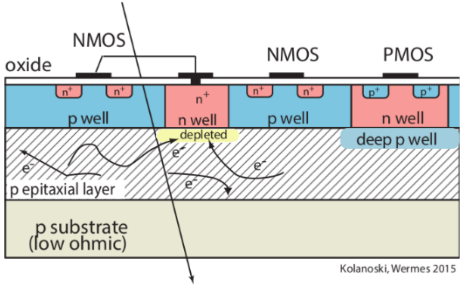




Largely depleted „hybrid“ pixel dectors
-> mostly drift



Very small depleted volume in MAPS
-> Mainly diffusion (charge sharing)



TRACKING

- Goal of tracking: Get optimal (least χ^2) estimate of track parameters using the hit information
- Simplest case is straight line:

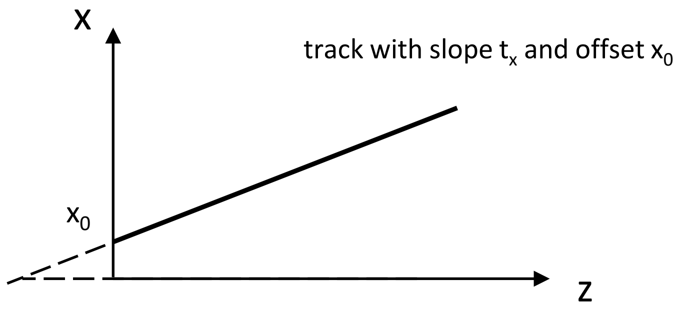
$$x = t_x z + x_0$$
$$y = t_y z + y_0$$

$$S = \sum_{i=1}^{N} \frac{(\xi_i^{\text{meas}} - \xi_i^{fit}(\theta))^2}{\sigma_i^2}$$

(Assuming diagonal covariance matrix)

- At least two points required to determine track parameters

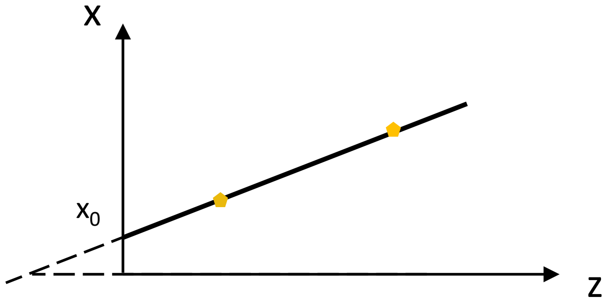
$$p_k = \begin{pmatrix} x \\ y \\ t_x \\ t_y \end{pmatrix}$$



DIRECTION UNCERTAINTY: POSITION RESOLUTION

- If we have only two measuements, we can derive the direction uncertainty analytically

$$b = \frac{x_2 - x_1}{z_2 - z_1} = \frac{x_2 - x_1}{D}$$



- Each position measurement has intrinsic detector resolution
- Direction uncertainty then becomes:

$$\sigma_b = \sqrt{\sigma_{x_1}^2 / D^2 + \sigma_{x_2}^2 / D^2} = \frac{\sqrt{2}\sigma_{\text{meas}}}{D}$$

- For N layers:

$$\sigma_b = \frac{\sigma_{\text{meas}}}{D} \sqrt{\frac{12(N-1)}{N(N+1)}}$$

This is why we would like to have several planes with good intrinsic position resolution

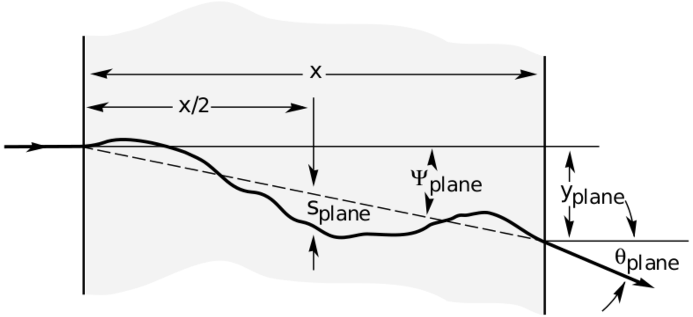
In reality, we have to consider multiple scattering!

TRACKING: MULTIPLE SCATTERING

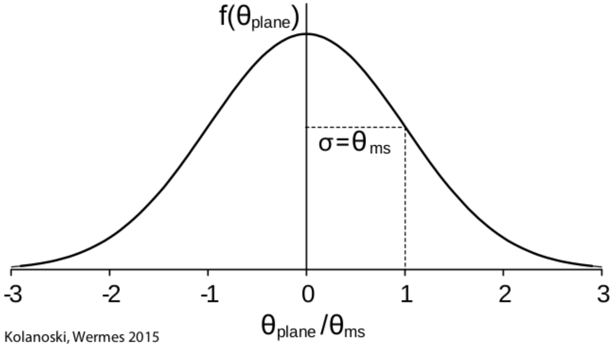
- Multiple Coulomb scattering: scattering of particles in the Coulomb field of nuclei (Rutherford cross section)
- Typically we can neglect „offset“ y_{plane}
- RMS-value of scattering angle can be approximated by

$$\theta_{ms} = \frac{13.6\,\mathrm{MeV/c}}{p\beta} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln \frac{x}{X_0}\right) .$$

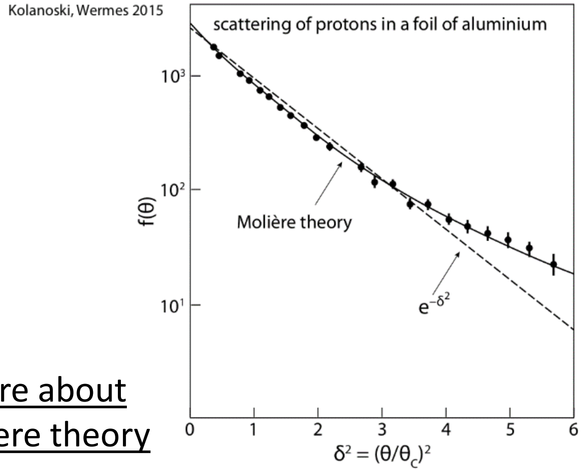
[Lynch and Dahl]



„material budget“

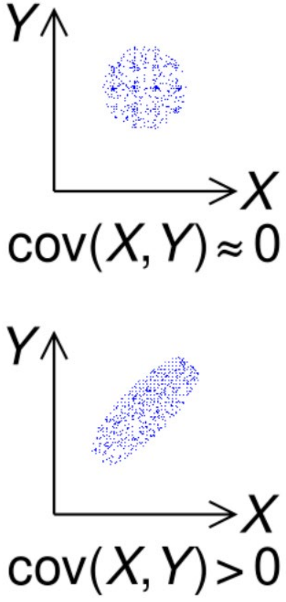


Multiple scattering limits spatial resolution -> want high energetic particle beam

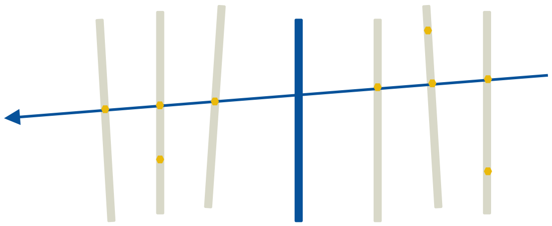


More about Moliere theory

TRACKING: MULTIPLE SCATTERING



- How to include multiple Coulomb scattering tracking? **-> covariance matrix**
- **Covariance: „How much two random variables vary together“**
- **Covariance matrix allows to describe correlation between scattering angles and track parameters**
- Global fit method („all at once“):
  - Requires inversion of n x n covariance matrix (n: number of measured coordinates)
  - Computationally expensive! (~n^3)
- Local method (recursive track fitting, „step by step“):
  - Assume scatterings only at several detector planes
  - Propagate track state iteratively from detector to detector
  - Kalman Filter is one option



KALMAN FILTER

- Advantages of Kalman Filter:
  - Simultaneous track finding and track fitting
  - No inversion of large matrices needed
- What do we need?
  - State vector describing the track (track parameters)
  - Measurements (hits in our detector)
  - Measurement transformation (from track parameters to measurements)
  - Transportation matrix (from plane k -> k +1)
  - Measurement noise (detector resolution)
  - **Process noise (includes multiple scattering)**

More about Kalman Filter: "A new approach to linear filtering and prediction problems" (1960)

KALMAN FILTER: TRACK MODEL

- Track model:

Model how track parameters at a given detector plane k-1 depend on the track parameters on plane k

$$x_k = F_{k|k-1} x_{k-1} + w_k$$

Process noise (multiple scattering)

$$V_\theta = \begin{pmatrix} \theta_{\mathrm{ms}}^2 & 0 \\ 0 & \theta_{\mathrm{ms}}^2 \end{pmatrix}$$

Covariance matrix of scattering angles

$$Q_k = \frac{\partial g_{\mathrm{ms}}(\theta_1, \theta_2)}{\partial p_k} = G_k V_\theta G_k^\top$$

Change of track parameter with respect to scattering angles

- Measurement model

$$m_k = H_k x_k + \epsilon_k$$

Measurement noise (position resolution)

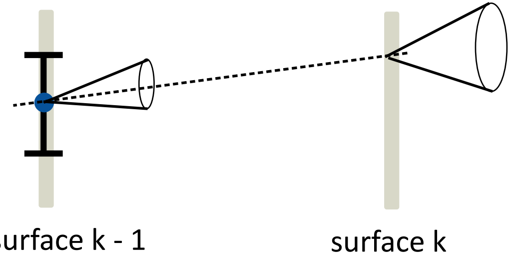
$$V_k = \begin{pmatrix} \sigma_{\mathrm{int},x}^2 & 0 \\ 0 & \sigma_{\mathrm{int},y}^2 \end{pmatrix}$$

<u>More about covariance matrices for Kalman Filter track fitting</u>

KALMAN FILTER: TRACK FITTING

- Start with defining some initial state and initial covariance matrix (uncertainty)
- Then propagate track state through detector planes

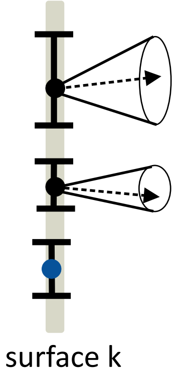
1) Prediction step



$$x_k = F_{k|k-1} x_{k-1}$$

$$C_{k|k-1} = F_{k|k-1} C_{k-1|k-1} F_{k|k-1}^{\mathrm{T}} + Q_{k-1}$$

2) Filter/Update step:



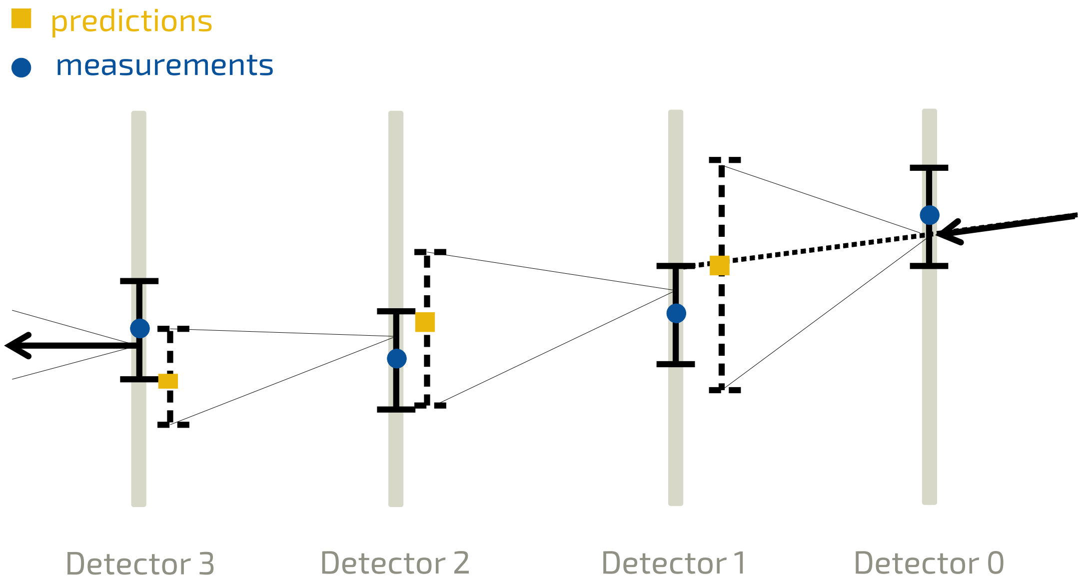
$$x_{k|k} = x_{k|k-1} + K_k (m_k - H_k x_{k|k-1})$$

$$C_{k|k} = (1 - K_k H_k) C_{k|k-1}$$

Update step shrinks covariance matrix since more information is added!

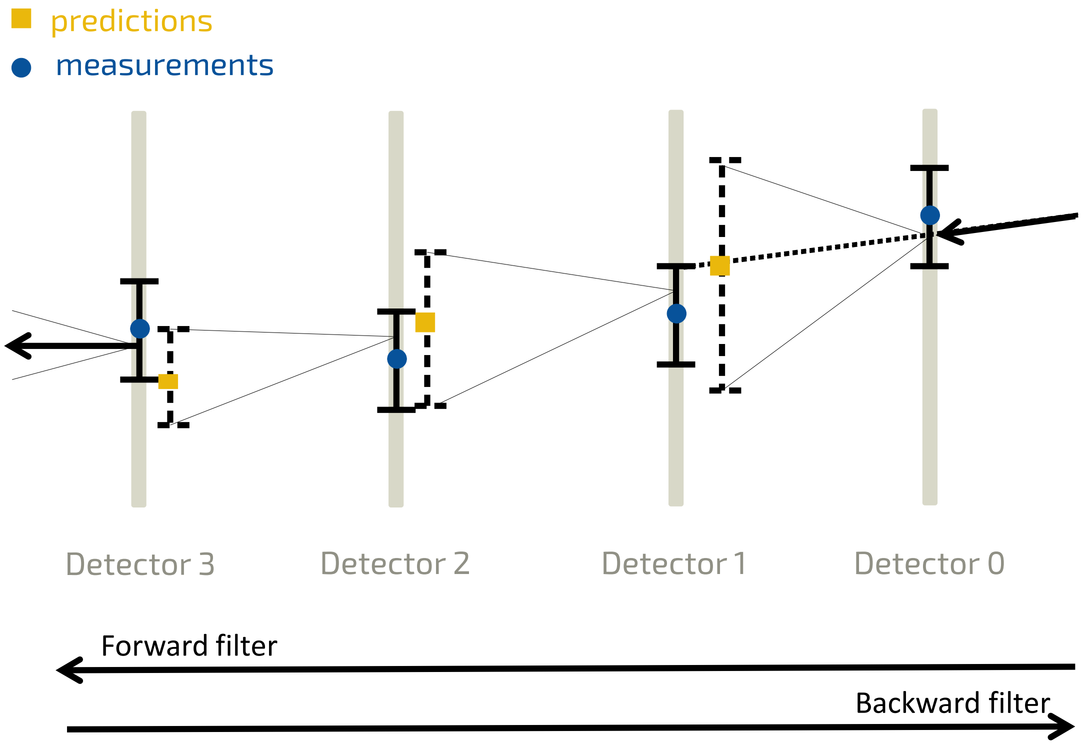
TRACKING: KALMAN FILTER

The more information we add, the smaller the error on the track state is!



TRACKING: KALMAN FILTER

The more information we add, the smaller the error on the track state is!



Smoothing: combine forward and backward filter (to include information before and after scattering)

RESIDUALS

$$S = \sum_{i=1}^{N} \frac{(\xi_i^{\text{meas}} - \xi_i^{fit}(\theta))^2}{\sigma_i^2}$$

- How can we „judge“ a track fit? -> **residuals**

$$\Delta r_x = x_{\text{hit}} - x_{\text{track}}$$

- **Unbiased and biased residuals**

This is what we have minimised

$$\sigma_{\text{res}} = \sqrt{\sigma^2_{\text{meas}} + \sigma^2_{\text{track}}}$$

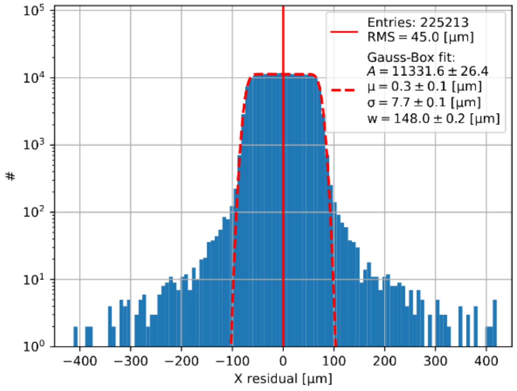
Unbiased: Hit in DUT is **not included** in track fit

$$\sigma_{\text{res}} = \sqrt{\sigma^2_{\text{meas}} - \sigma^2_{\text{track}}}$$

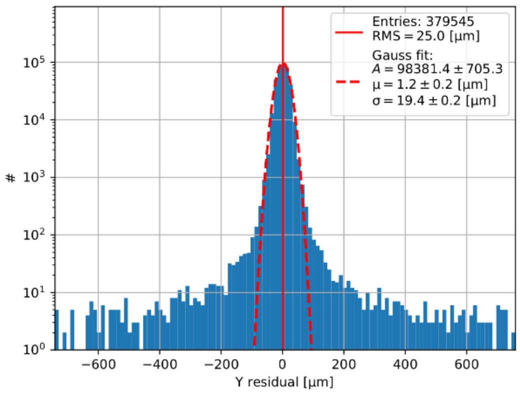
Biased: Hit in DUT is **included** in track fit

Resolution is dominated by pixel pitch
Box distribution with RMS = 45 um
(~150/√12)

150 um pixel pitch



50 um pixel pitch

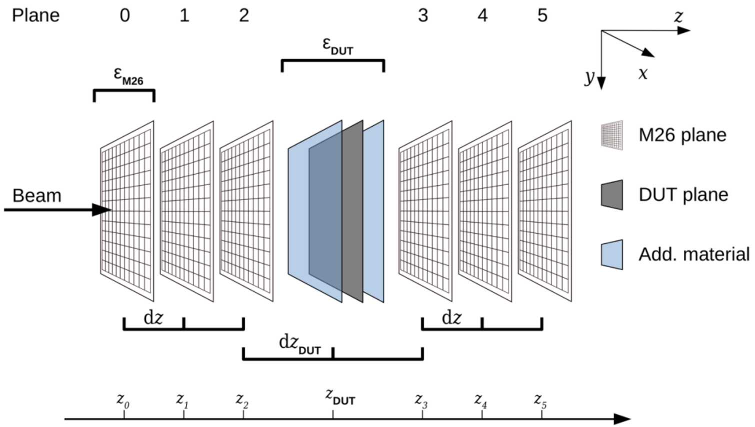


Resolution is dominated by multiple scattering
Gaussian distribution with σ = 19 um
(~50/√12)

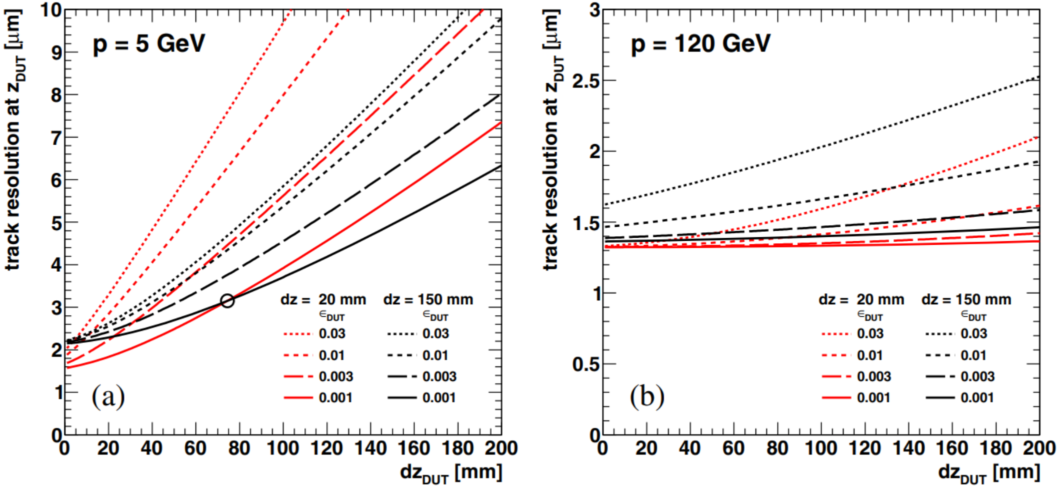
TELESCOPE CONFIGURATION

[H. Jansen et al.]

- Goal: Optimise track resolution at DUT depending on „size“ of DUT
- Telescope spacing: dz
- DUT spacing: dz_{DUT}
- Material budget (of DUT): ϵ_{DUT}



[H. Jansen et al.]



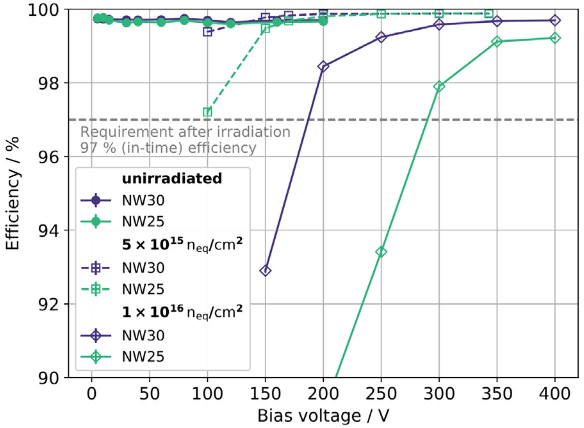
DETECTOR CHARACTERISATION
-
RESULTS

EFFICIENCY AND CHARGE COLLECTION

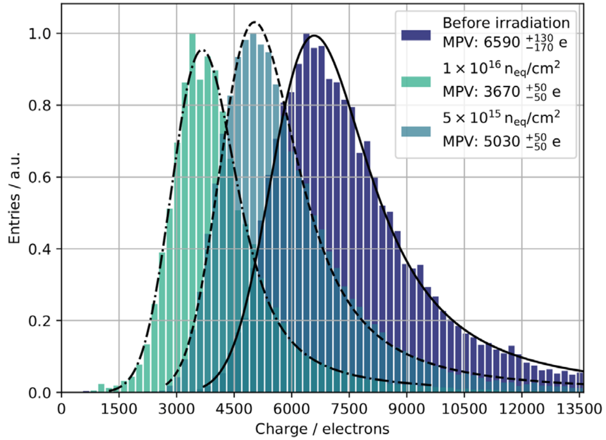
- Measure efficiency and charge collection as a function of bias voltage …

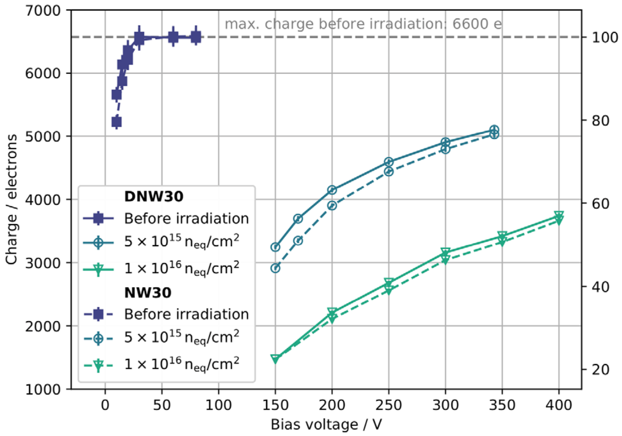
  … for different detection threshold settings

  … different levels of irradiation



Typical requirement for silicon tracking detectors
99 % efficiency before irradiation
97 % effciency after irradiation





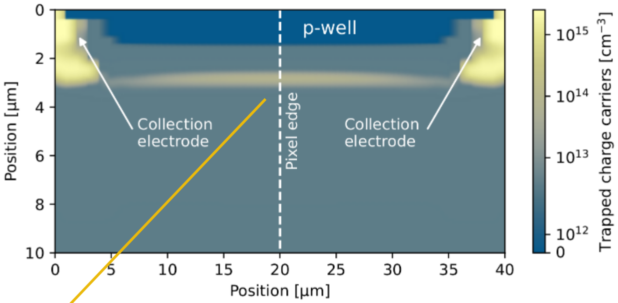
Hit detection efficiency
(noise occupancy is important!)

$$\epsilon = \frac{N^{\mathrm{DUT}}_{\mathrm{tracks}}}{N^{\mathrm{total}}_{\mathrm{tracks}}}$$

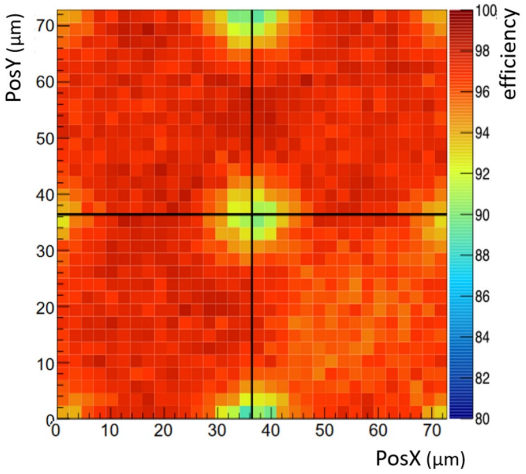
IN-PIXEL STUDIES

- Map all data into pixel unit cell to see „what happens inside the pixel“ -> **in-pixel plots**
- **Gives useful insights into charge collection processes in sensor**

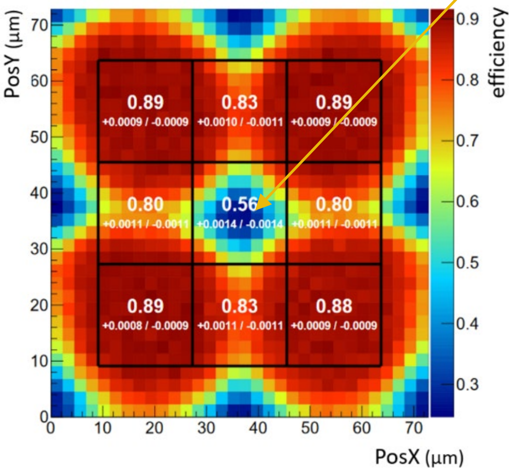
[Christian Bespin, PhD thesis]



Before irradiation



After irradiation

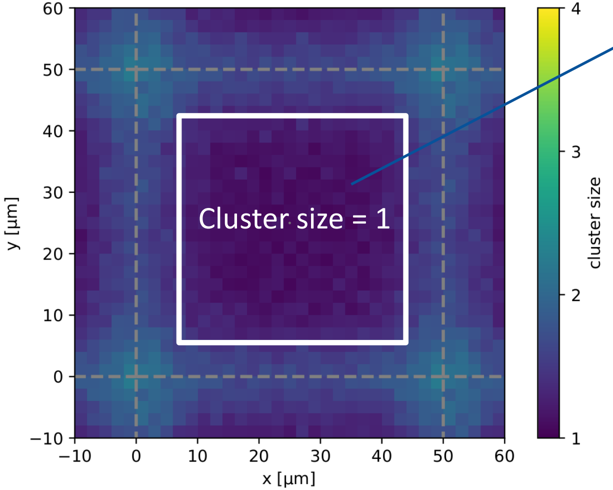


Low E-fields in inter-pixel region causing efficiency drop

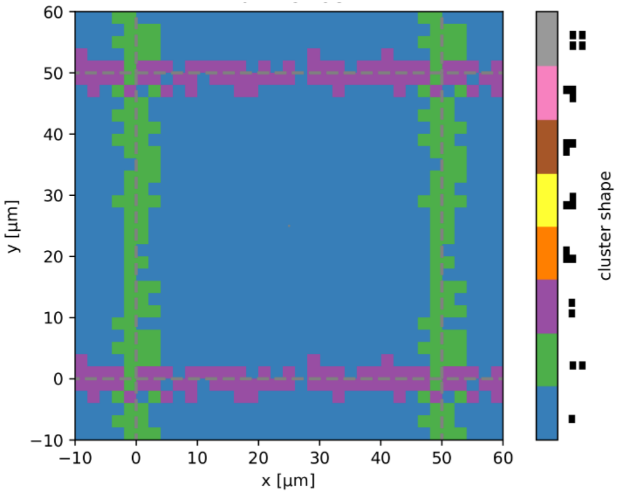
More about the Characterisation of the MALTA CMOS sensor

… we can also map cluster size into one pixel …

The larger the diffusion is, the smaller this „cluster size 1 area“ is



Average **cluster size** inside pixel (50 x 50 um²)



Dominant **cluster shape** inside pixel (50 x 50 um²)

SPATIAL RESOLUTION

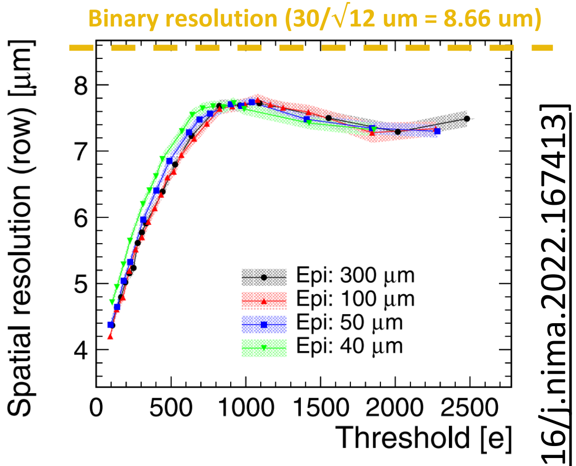
- Spatial resolution depends on…

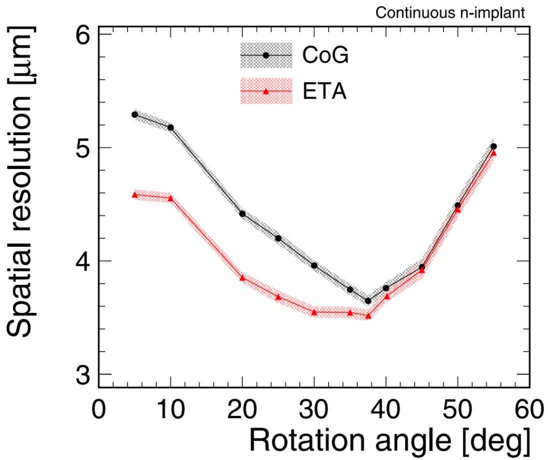
  …. threshold setting -> charge sharing!

  …. rotation angle -> charge sharing!

$$\sigma_{\mathrm{res}} = \sqrt{\sigma_{\mathrm{meas}}^2 + \sigma_{\mathrm{track}}^2}$$

Spatial resolution of detector





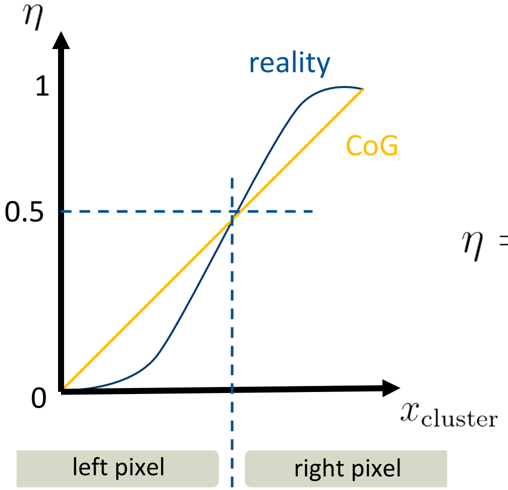
[https://doi.org/10.1016/j.nima.2022.167413]

SPATIAL RESOLUTION

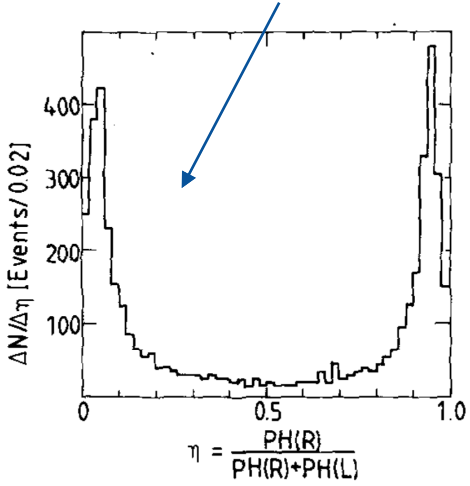
- Spatial resolution depends on…
  - …. threshold setting -> charge sharing!
  - …. rotation angle -> charge sharing!
  - **… cluster reconstruction algorithm**
- Centre-of-gravity method not suitable if $\frac{\text{pitch}}{\sigma_{\text{diff}}}$ is large

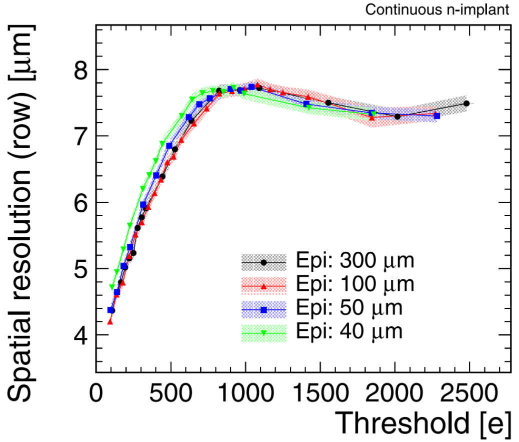
More in: Turchetta et al., A335 (1993) 44-58

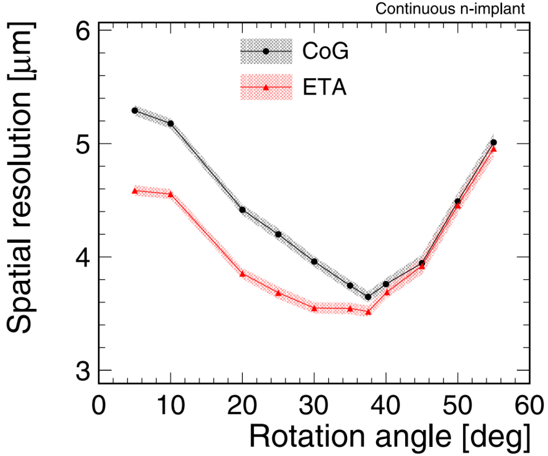
η distribution is not flat -> non linear charge division!



$$\eta = \frac{Q_1}{Q_1 + Q_2}$$



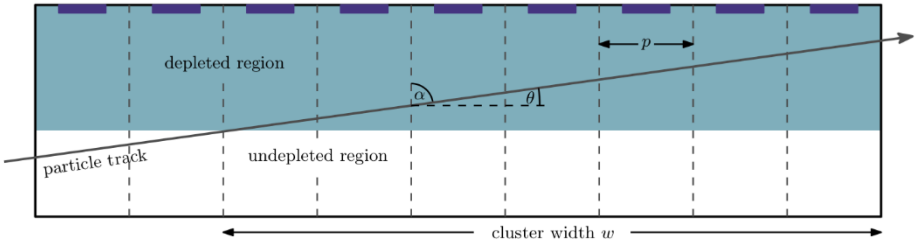


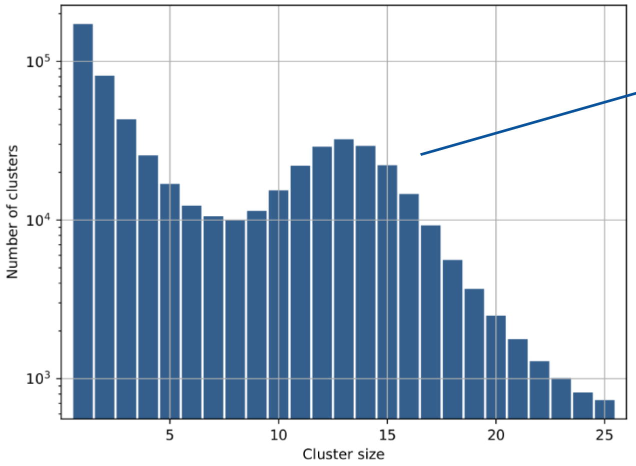


[https://doi.org/10.1016/j.nima.2022.167413]

GRAZING ANGLE TECHNIQUE

One can even study **depletion depth** using so-called „angular scans" („grazing angle" technique)

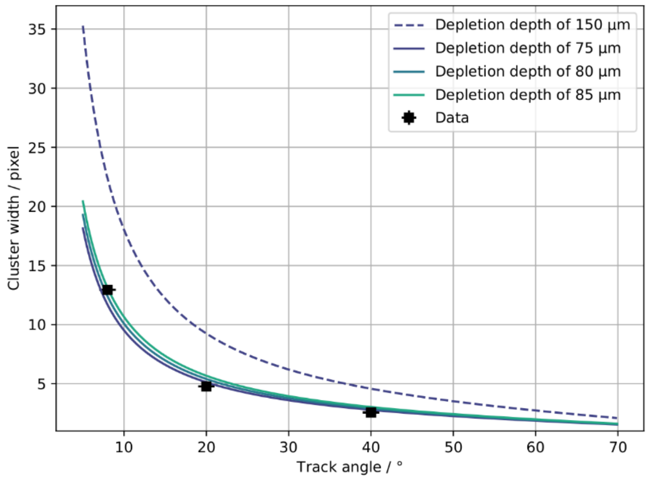




Cluster size enhancement due to large track angle

depletion depth

$$w\,[\text{pixel}] = \frac{d}{p \cdot \tan\theta} + 1$$

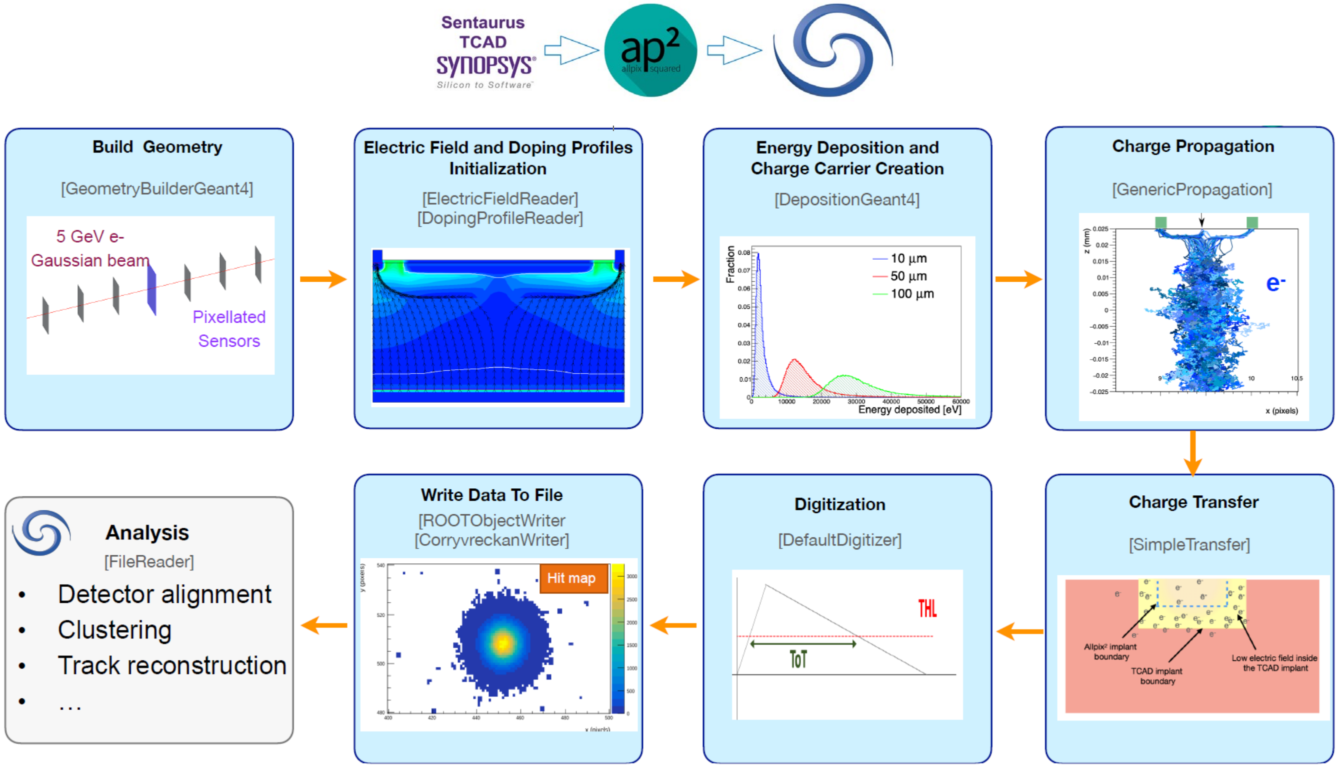


A QUICK WORD ABOUT SIMULATIONS

- Beam time can be …
  - … Costly
  - … Rare to get
  - … Tideous (a lot of night shifts + complex setup)
- Sometimes it is easier to use a simulation instead of measuring everything (you can have a lot of design variants!)
- Many nice tools available like
  - GEANT4
  - Allpix^2
  - TCAD
  - ….

[GEANT4] [TCAD] [Allpix^2]

A COMPLETE SIMULATION OF DEVICE IN TEST BEAM



[Taken from Sara Ruiz]

More about simulating doping profiles

More about Monte Carlo simulating a beam telescope

TAKE HOME MESSAGE

- Device characterisation consists of
  - Lab testing + test beam
  - Irradiation
  - (Simulation)

  … to understand the detector and do design adjustments if needed
- A beam telescope setup in combination with a high energetic particle beam is a very powerful tool to characterise the detector
  - Particle reconstruction is key
  - We can study spatial resolution, charge collection, efficiency, … of our detectors
- Simulation can help us to characterise detector if many design variants need to be studied

LITERATURE

- N. Wermes and H. Kolanoski, **„Particle Detectors: Fundamentals and Applications"**
- R. Frühwirth et al., **„Data Analysis Techniques for High-Energy Physics"**

- Many papers, links, … on slides ;)

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