Recent testbeam results of 50 µm pitch 3D sensors at high incidence angle for HL-LHC

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HL-LHC experiments pixels

- Higher fluence
  - From ϕ_{eq}~$5x10^{15}$ n_{eq}/cm^2 (IBL) to ϕ_{eq}~$2x10^{16}$ n_{eq}/cm^2 for inner layers

    → Radiation hard technology: **3D**/planar/diamond/...
- Higher pile-up/rate
  - Better position resolution is needed

    → Smaller pitch pixels: **50x50 μm²** / 25x100 μm² pixels

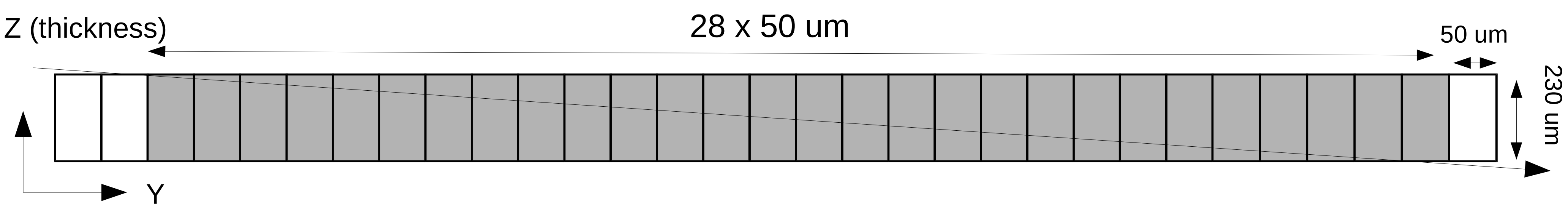
    → Lower capacitance ~ Lower noise

    → Lower threshold (~500 e in RD53 chip)
- Thickness
  - Thinner (~100 μm) sensor to reduce occupancy at high-η?
  - "**Thick**" (~200 μm) sensors to allow in-sensor tracking

In **bold** are the considered technologies/geometries in this talk, not preferences

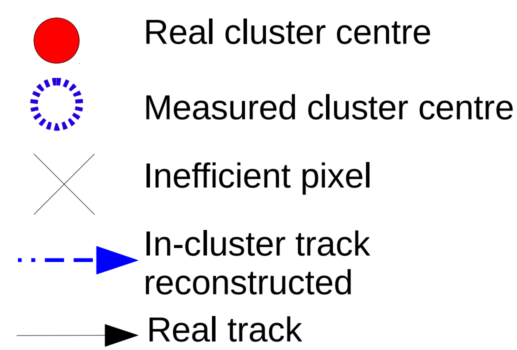
“50 µm pitch” pixels in high angle

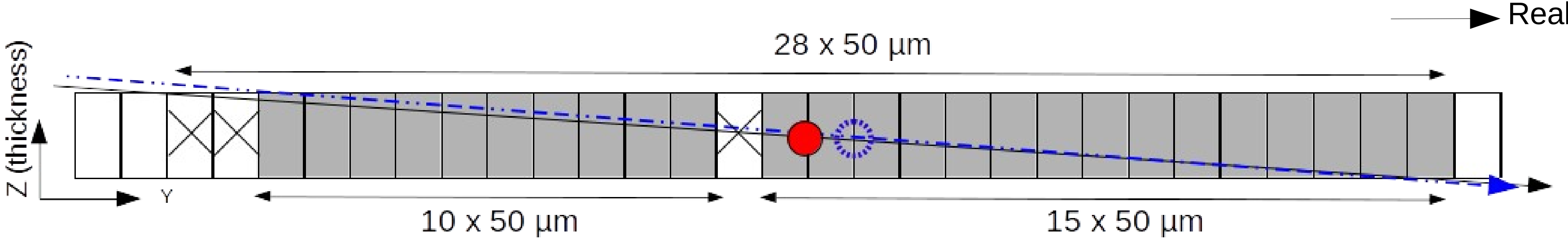
- High angle with 50 µm pitch pixels
  - Long mip path
    - → Large total deposited charge
    - → High “cluster” efficiency (i.e. have a cluster of any length for each track)
  - But 50x50 μm^2 pitch pixels implies low charge per pixel at high angle
    - → ~ 3.3 ke for 50 µm pitch
  - Study the “pixel” efficiency under such conditions (i.e. a pixel along the track path fired)



Possible problems for 50 µm pixels at high incidence angle

- Cluster splitting:
  - Pixel inefficiency ↔ “holes” inside a cluster
    → Can lead to cluster splitting
- Z position resolution in 1 point-per-plane reconstruction
  - If a pixel in an edge of the cluster is not fired due to inefficiency
    → Cluster centre biased by pitch/2
- Z position resolution in in-cluster-tracking reconstruction
  - Bias if any edge pixel of the cluster is not fired due to inefficiency





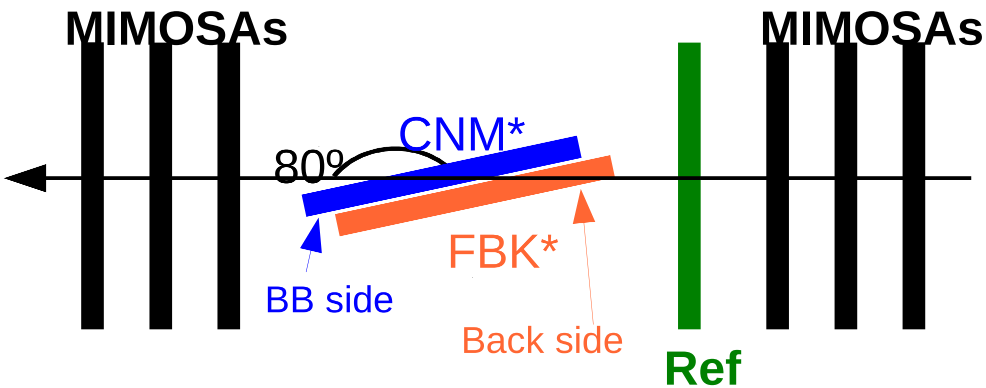
Need to study 50 µm pitch pixels at high incidence angle

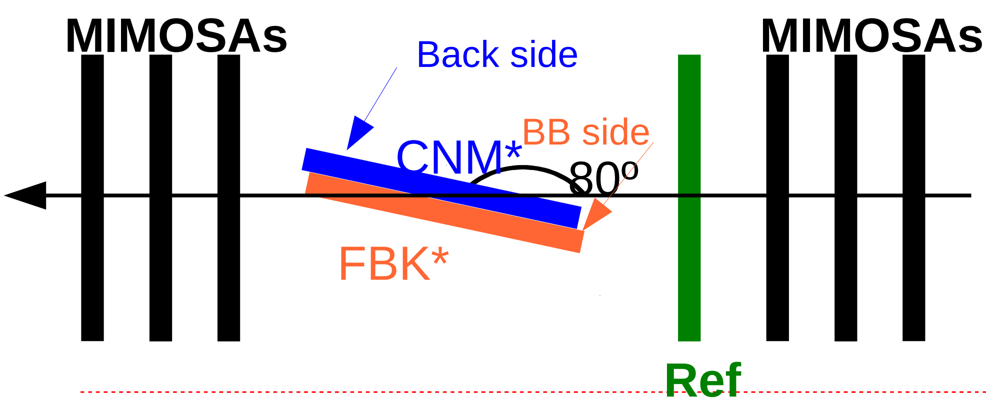
Testbeam set-up

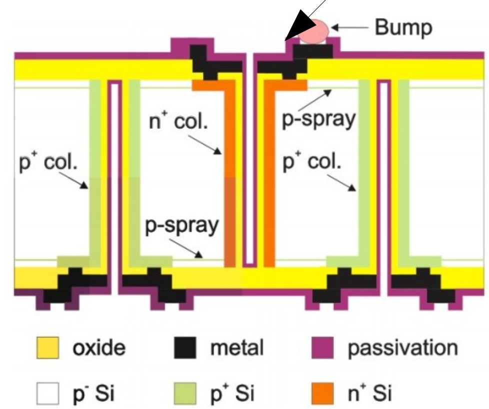
No 50x50 µm² pitch pixel 3Dsensors avilable for testbeam studies
→Use FEI4 3D sensors (50x250 µm² pixels) at high incidence angle along the short pixel direction

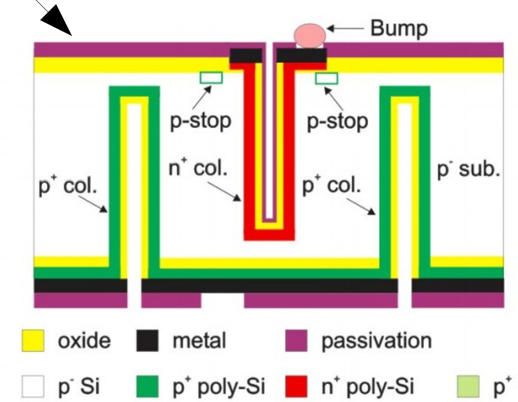
November 2014 CERN testbeam and March 2015 DESY testbeam

- 80 º (|η|~2.4) → clusters of ~27 pixels
- Shoot from Bump-bond side and Back side
- IBL FBK and CNM 3D sensors

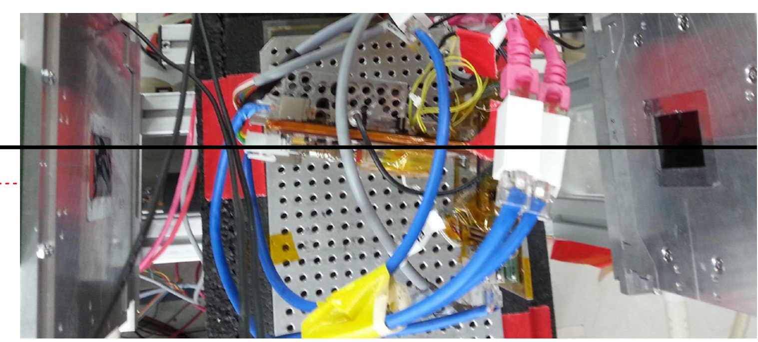








All tunings:
→ Threshold: 1000e
→ ToT: 6ToT at 3ke
Non-irradiated and Irradiated devices



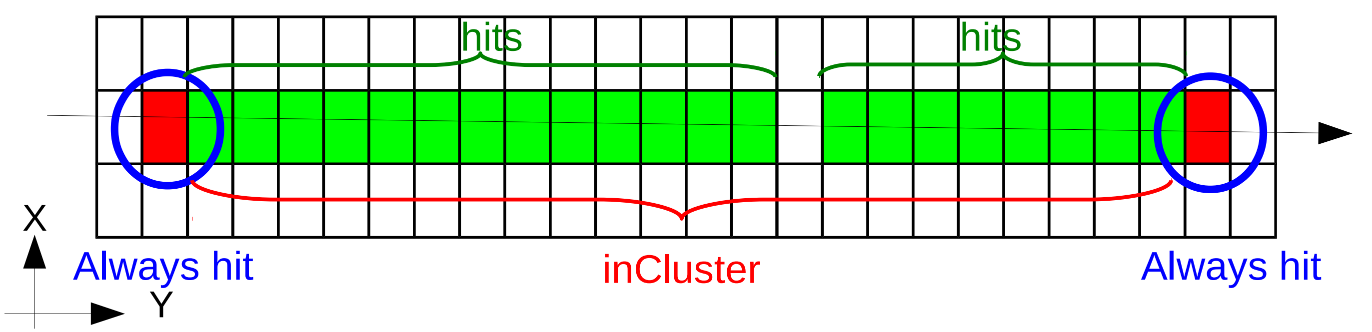
Efficiency calculation

- Analysis:
  - Based on hit information
- Efficiency per cluster
  - At 80º incidence, cluster efficiency should be ~100%
    - Cluster inefficiency goes (naïvely) as $(1-\varepsilon_{pixel})^{N_{cl}}$
- Look at per pixel efficiency instead
  - Use long clusters as “tracks”

    → Take long cluster's ends and count pixel hits between them

$$\varepsilon_{pixel}(i,j)=\frac{\#hits(i,j)}{\#inCluster(i,j)}$$

  - Fix Cluster Size X = 1 to avoid inefficiencies from charge sharing
  - Don't count first and last pixels in cluster



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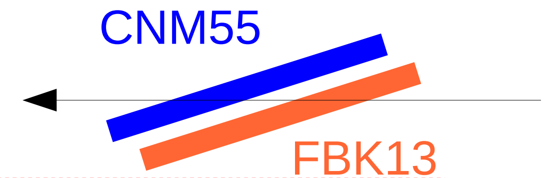
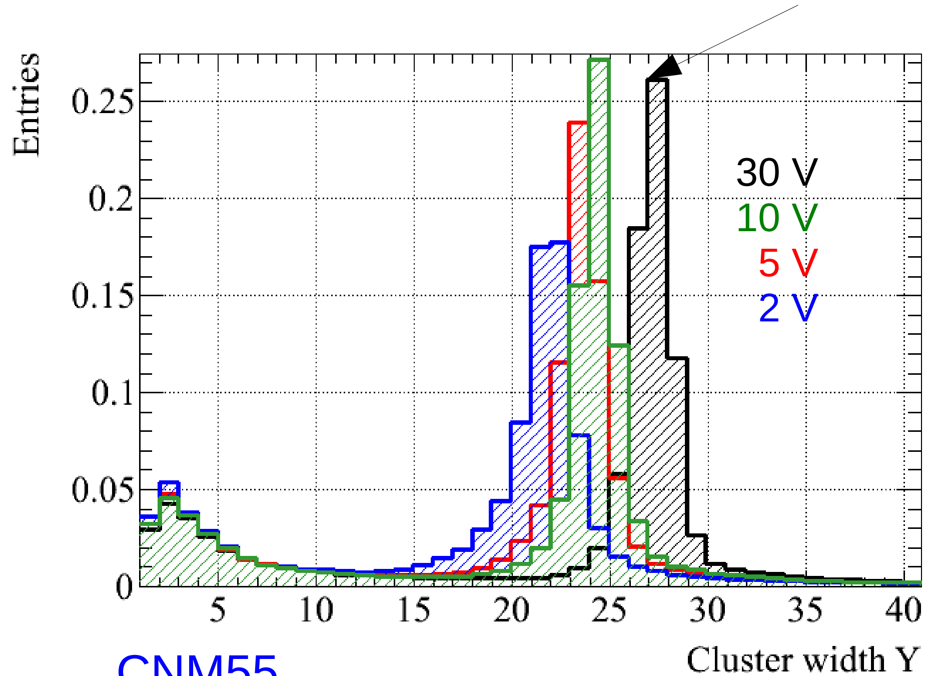
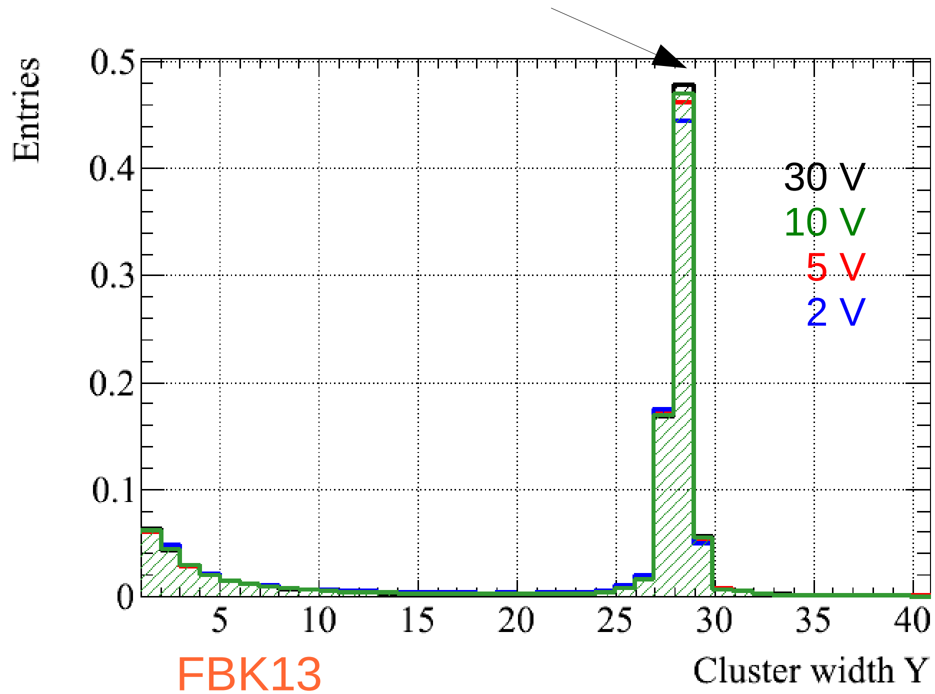
Non irradiated sensors

Cluster Size



Expected Cluster size due to geometry at 80º along 50 µm pixels in a 230 µm thick sensor ~27 (sensitive to misalignment)



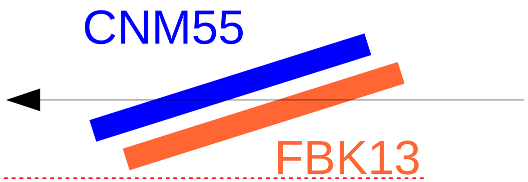


CNM55
→ Thr: 1000 e
→ 6ToT @ 3ke

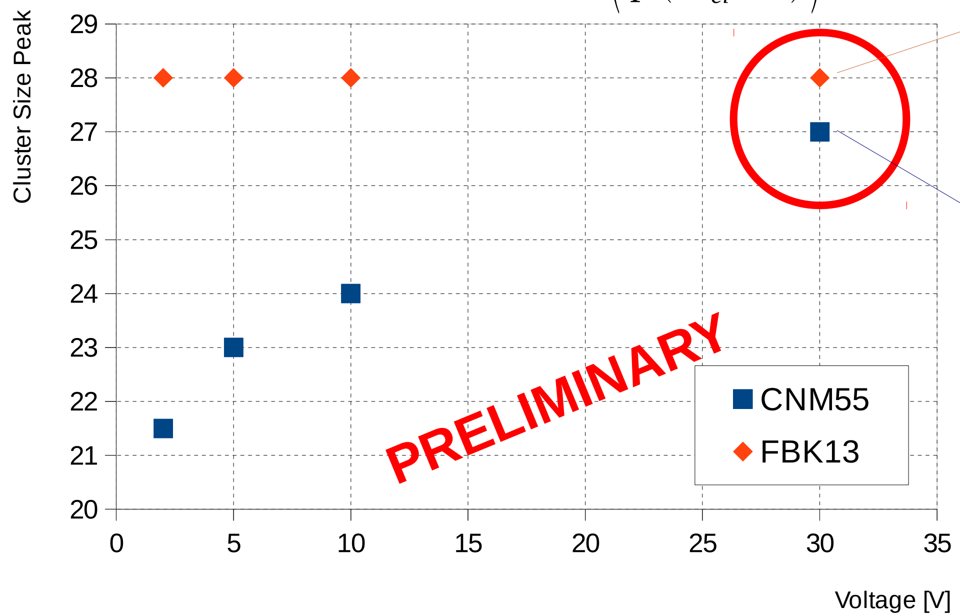
FBK13
→ Thr: 1000 e
→ 6ToT @ 3ke

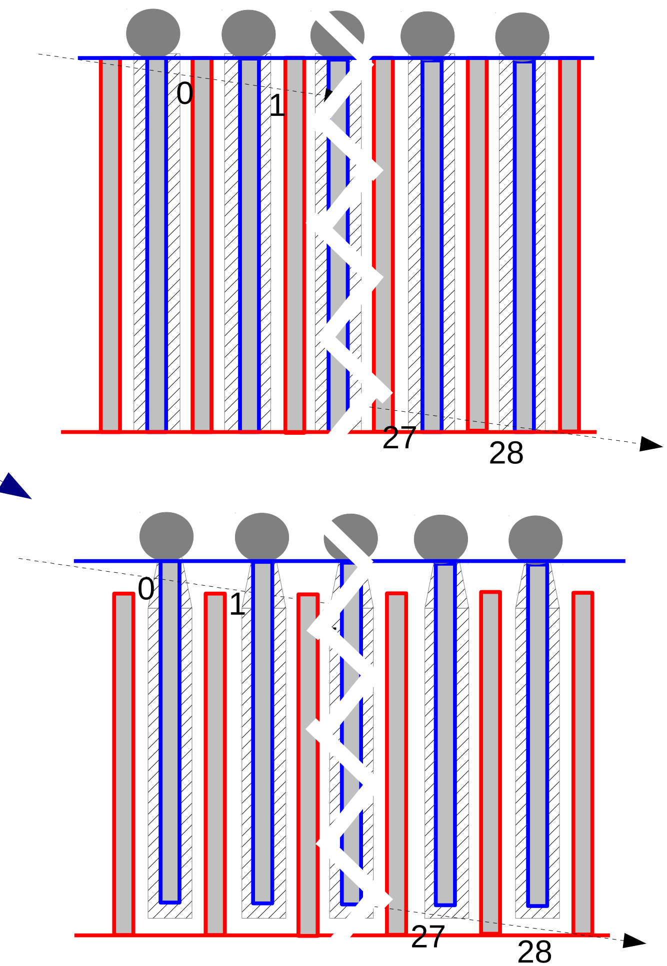
CNM sensor's cluster size shifted to lower values at lower voltages even though the set-up didn't move between measuremets
→ Not caused by misalignment!

Cluster Size Peak



$$\varphi = \frac{\pi}{2} - \arctan\left(\frac{w}{p(N_{cl}-1)}\right)$$ ~80º





- Even under depleted, the FBK sensor will have all the thickness sensitive
- CNM, due to the non-passing-through columns there will be regions along the sensor's thickness non-depleted (insensitive)

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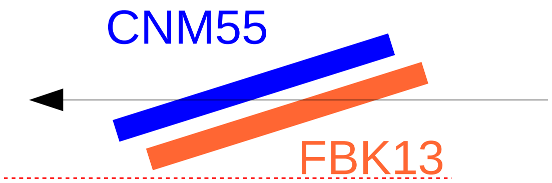
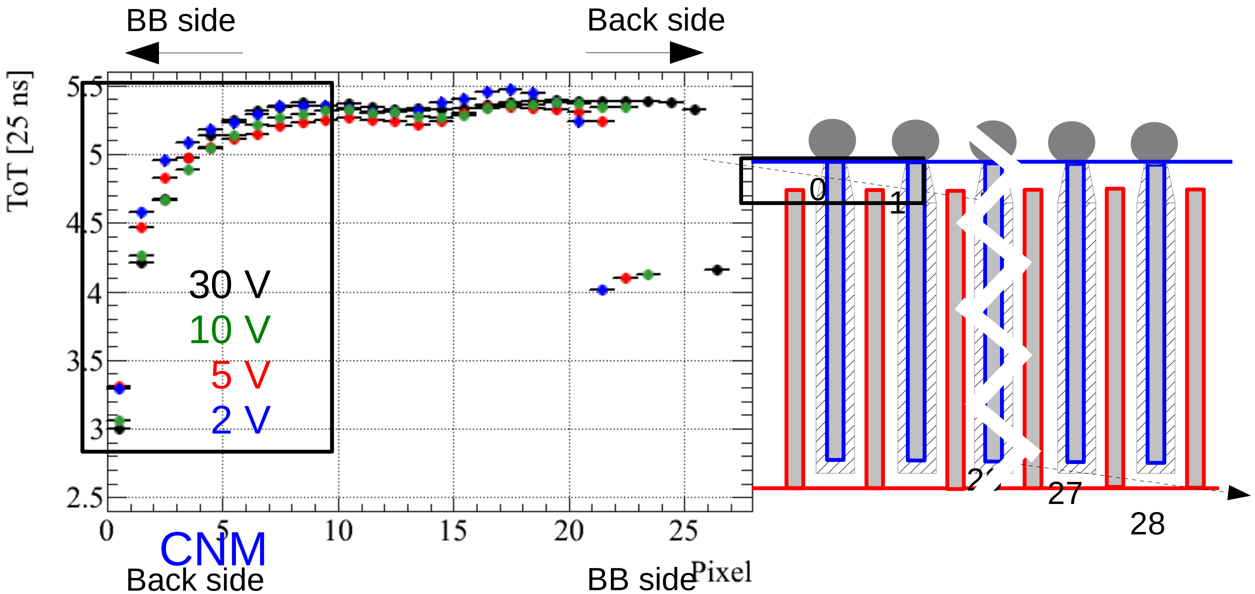
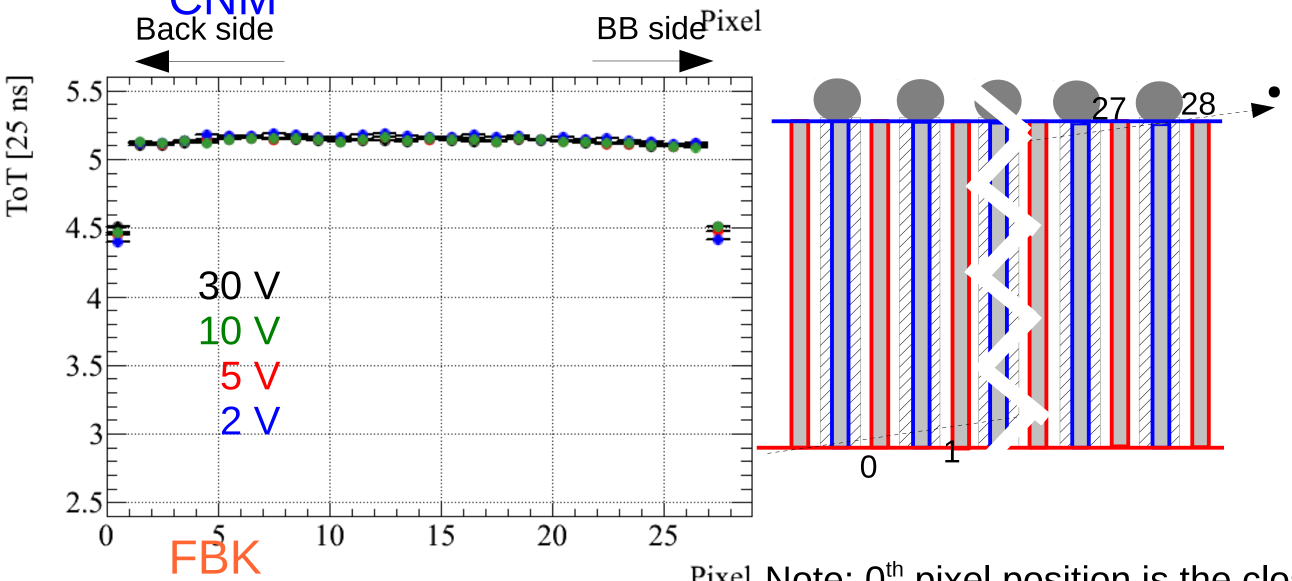
Avg ToT per pixel





- Lower charge collected in first pixels of the cluster shooting from the BB side

  → Low charge collection around BB side (non-passing through ohmic columns)



- Uniform E field (passing through columns)

  → Uniform charge collection along cluster

Note: 0^{th} pixel position is the closest pixel **hit** to the (0,0) pixel inside the cluster

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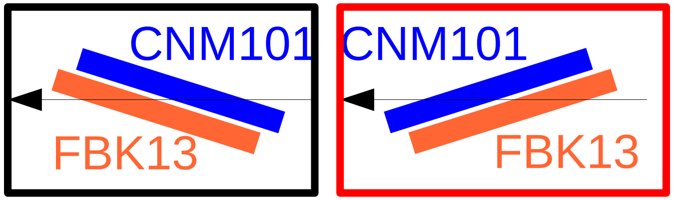
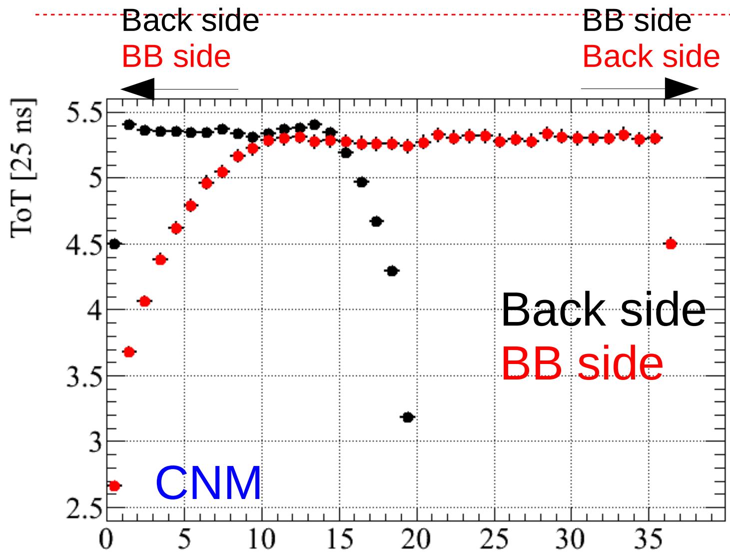
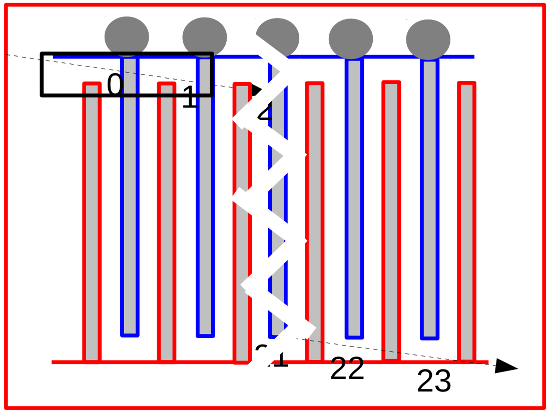
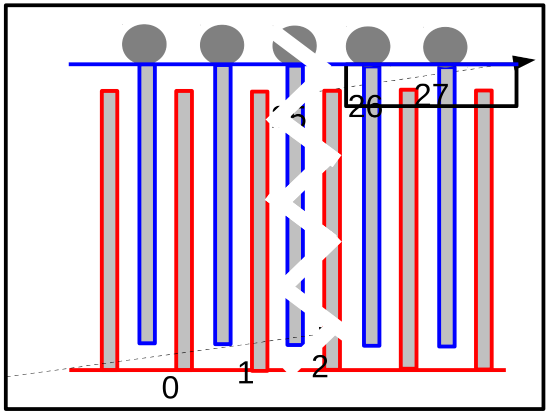
Avg ToT per pixel



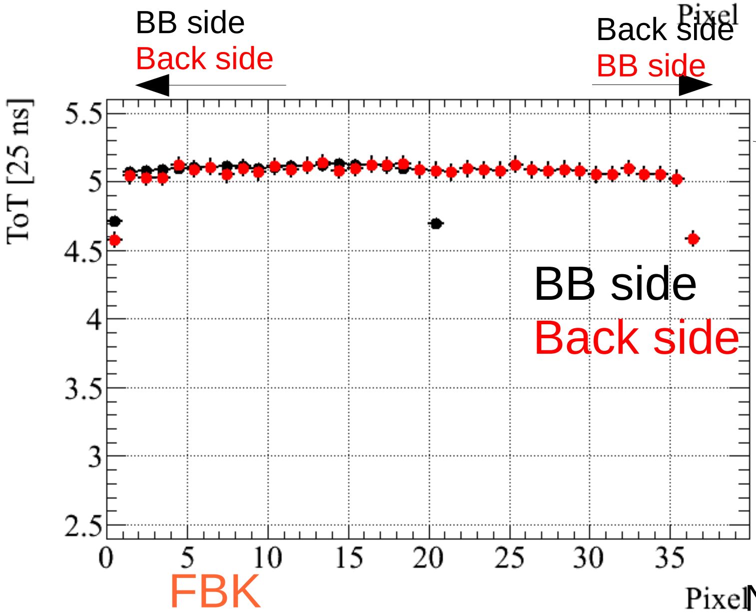


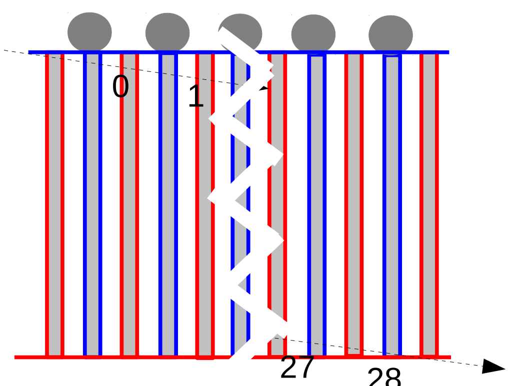


BB side



Back side





BB side

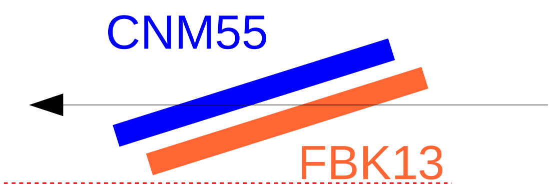
- Shooting from different sides mirrors the distribution in CNM sample

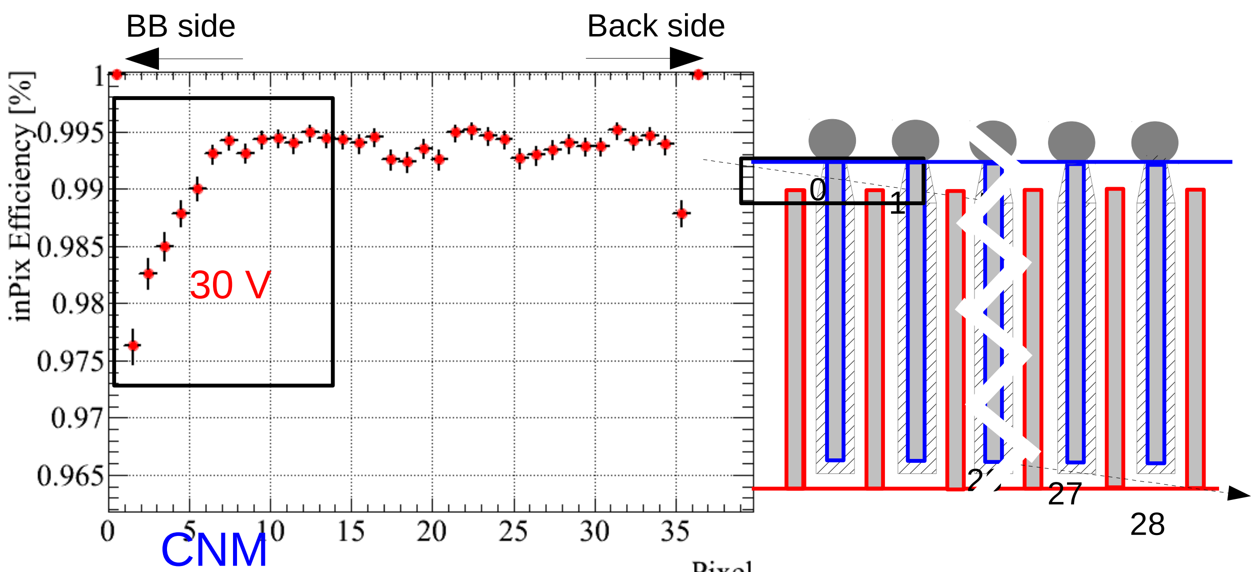
  → Turn-on curve comes from the low charge collection in the BB side

- Difference in cluster size due to ~3º misalignment

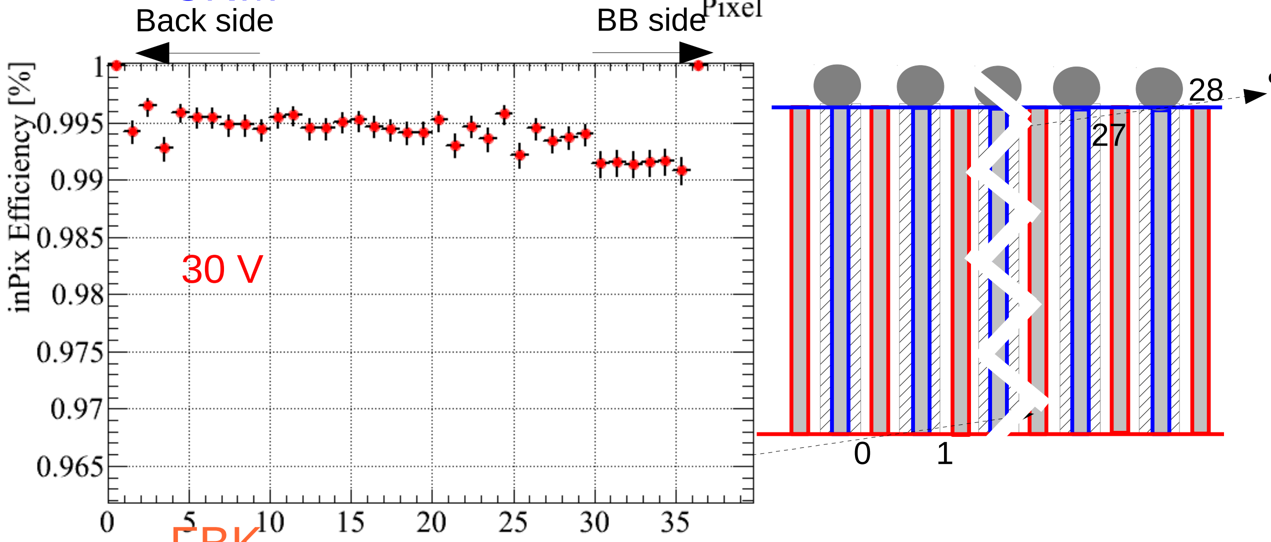
Note: 0th pixel position is the closest pixel **hit** to the (0,0) pixel inside the cluster

Efficiency per pixel vs cluster position





- Lower efficiency correlated with lower charge collection area in the area near the bump-bonds
- Asymmetric efficiency
  - One-sided inefficiencies



- Uniform efficiency

Pixel Note: 0th pixel position is the closest pixel **hit** to the (0,0) pixel inside the cluster

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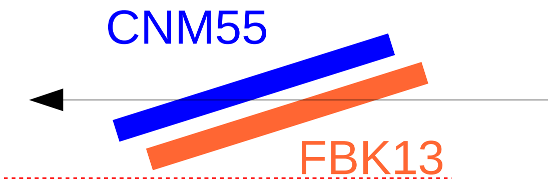
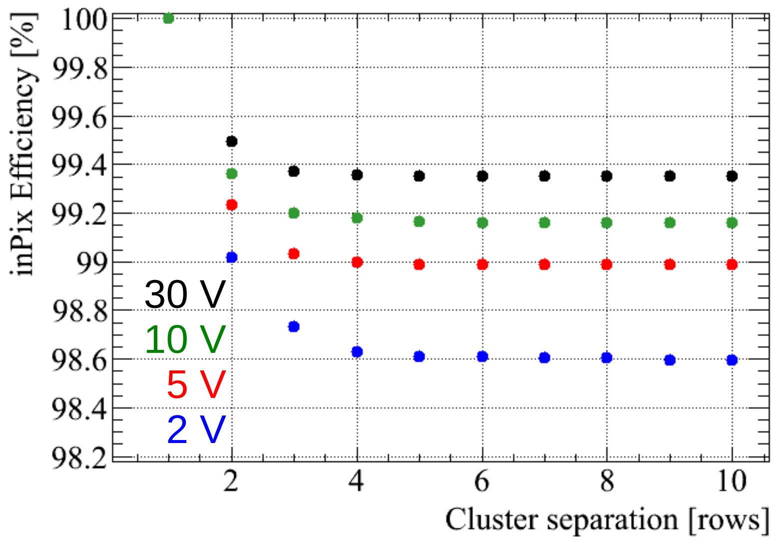
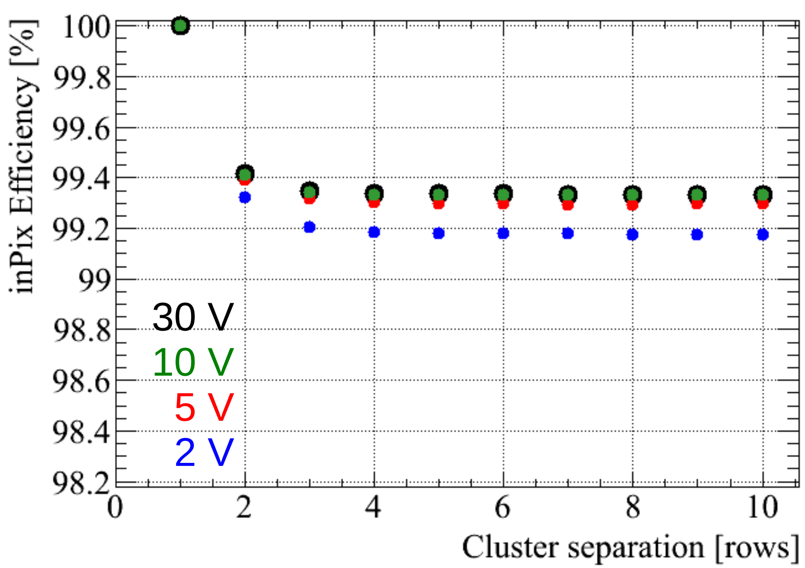
Per Pixel Efficiency

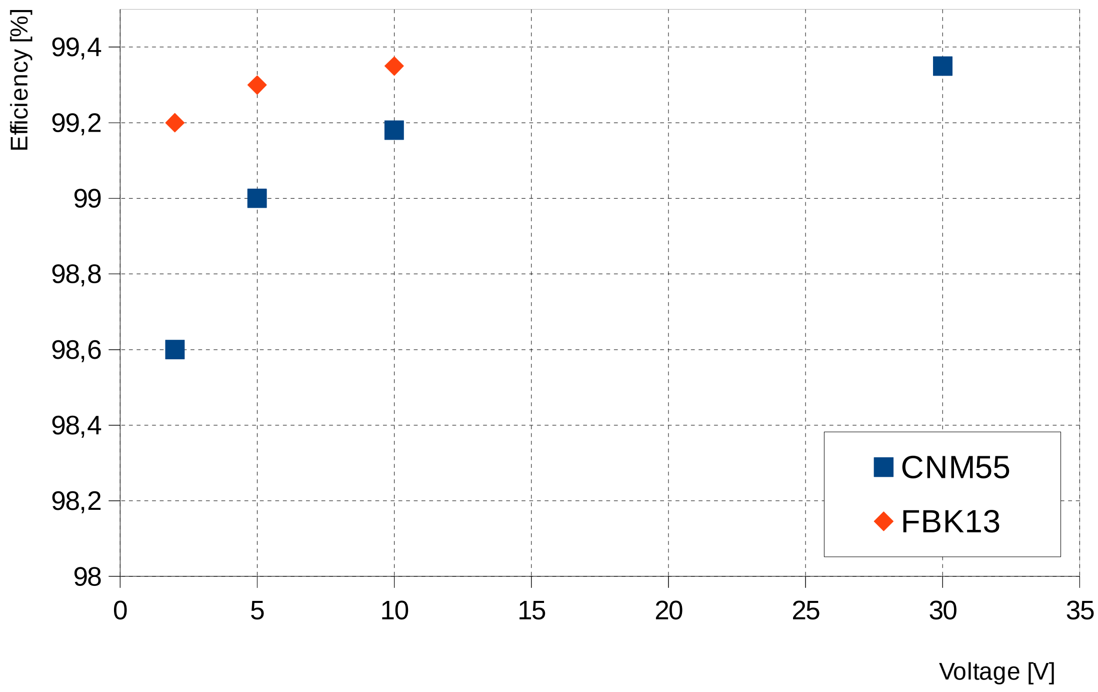






- "Cluster separation":
  How many consecutive holes (-1) do we allow inside a cluster
- In Pixel Efficiency using clusters sizes $ClSize_{peak}$±1 in the plateau

  → Avoid noise and bias to large efficiencies
- **Unirradiated sensors are >99.3%/pixel efficient**



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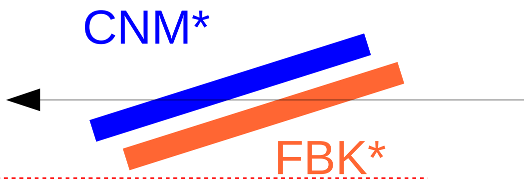
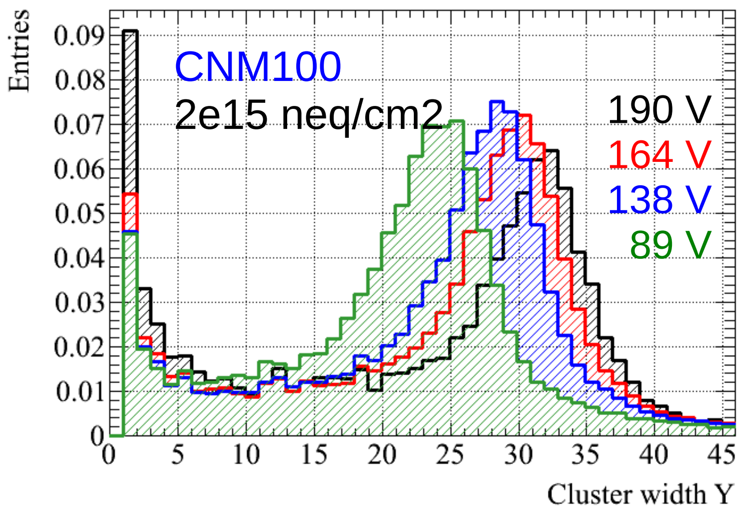
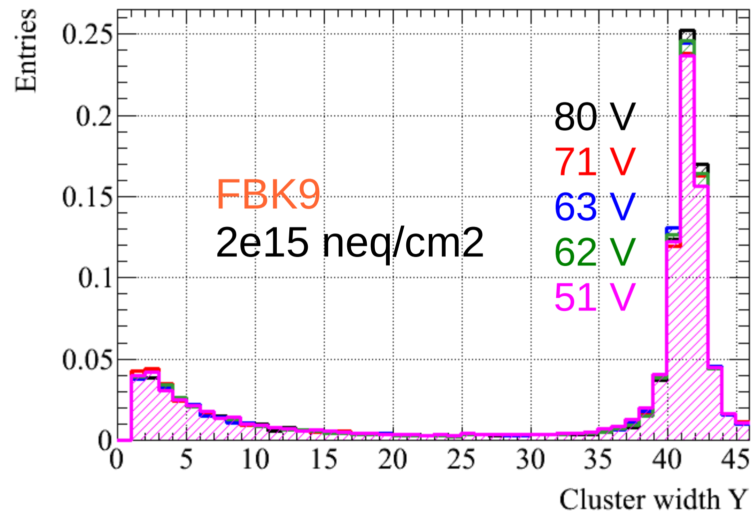
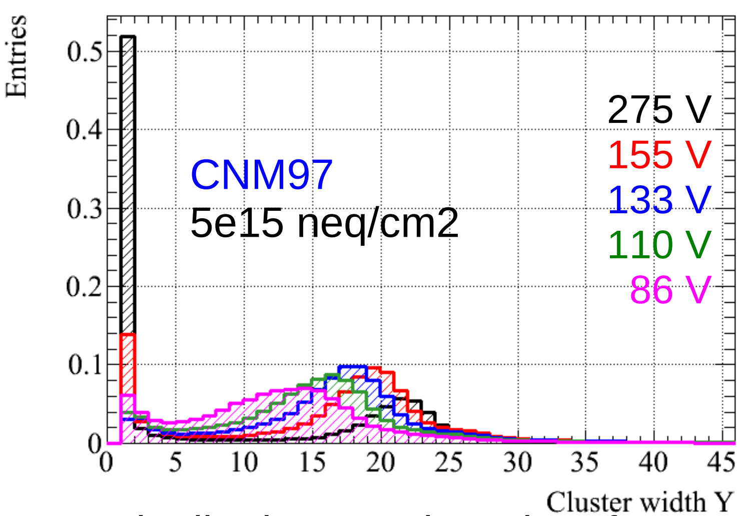
Irradiated sensors

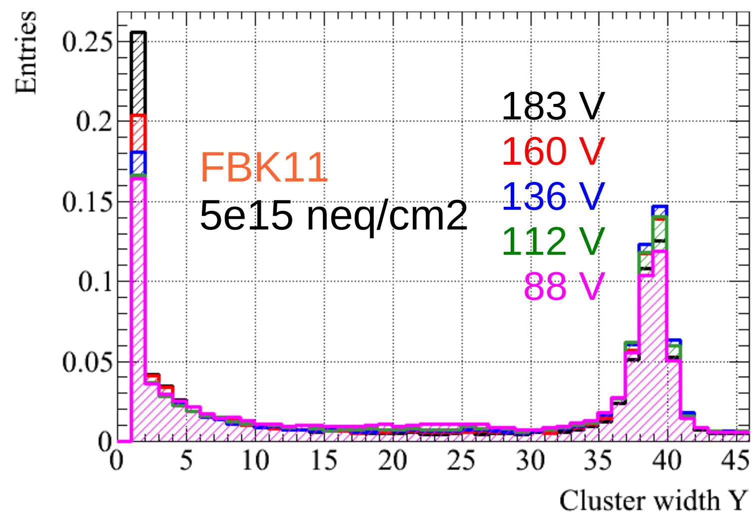
Cluster Size









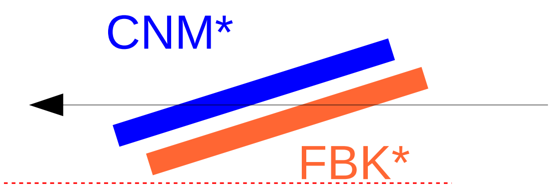


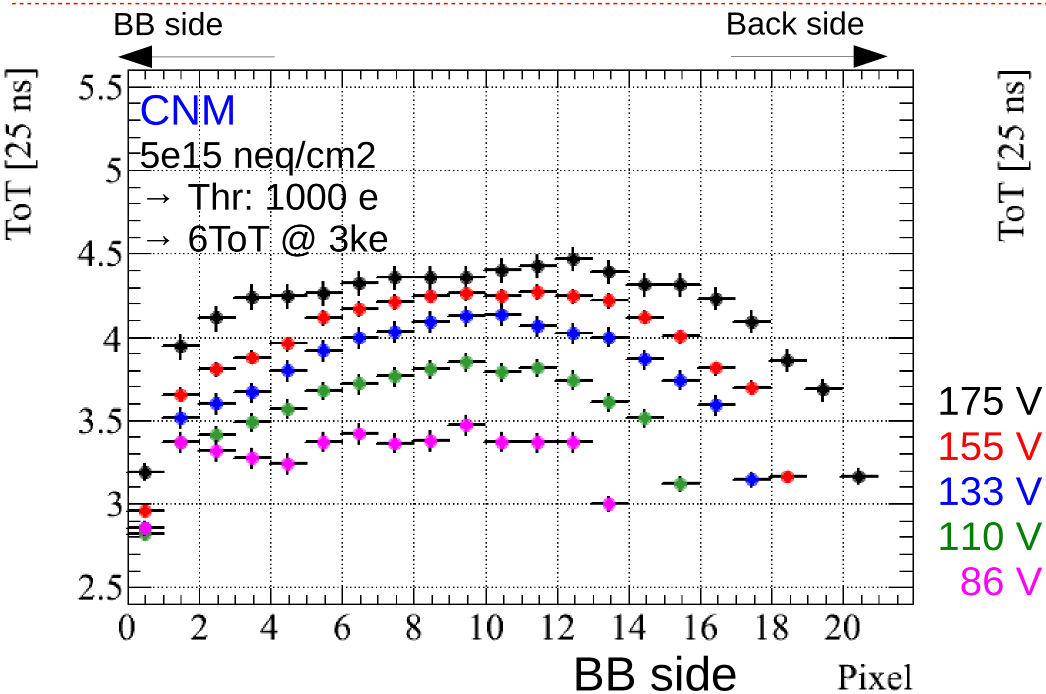
- Low threshold (1ke)

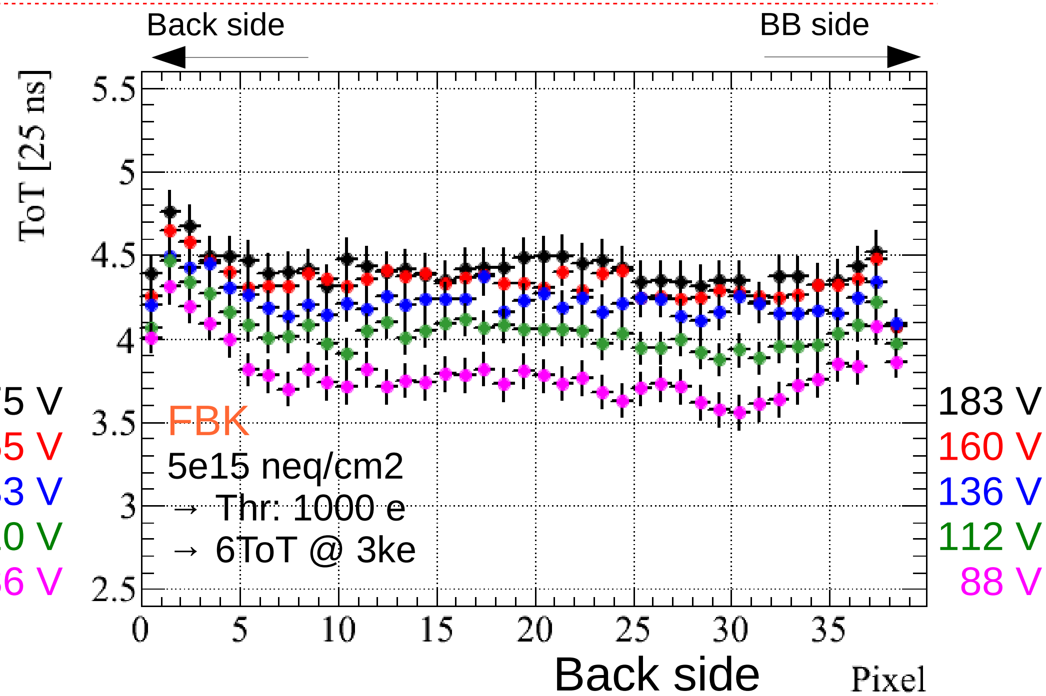
→ Very noisy devices (at 5e15)

- Distribution gets broader after irradiation → cluster end-pixels ineff.?
- For FBK is not so significant

Avg ToT per pixel







- Charge collection decreased after irradiation (as expected)
- CNM sensor has low charge collection at **both** ends of the clusters (as opposed to non-irrad)
  - Compatible with non-passing-through columns
- FBK sensor has relatively uniform charge collection along the clusters

Note: 0th pixel position is the closest pixel **hit** to the (0,0) pixel inside the cluster

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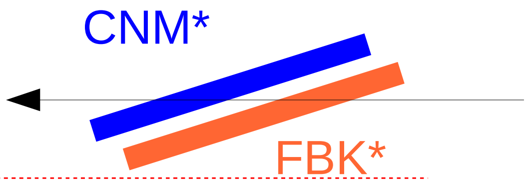
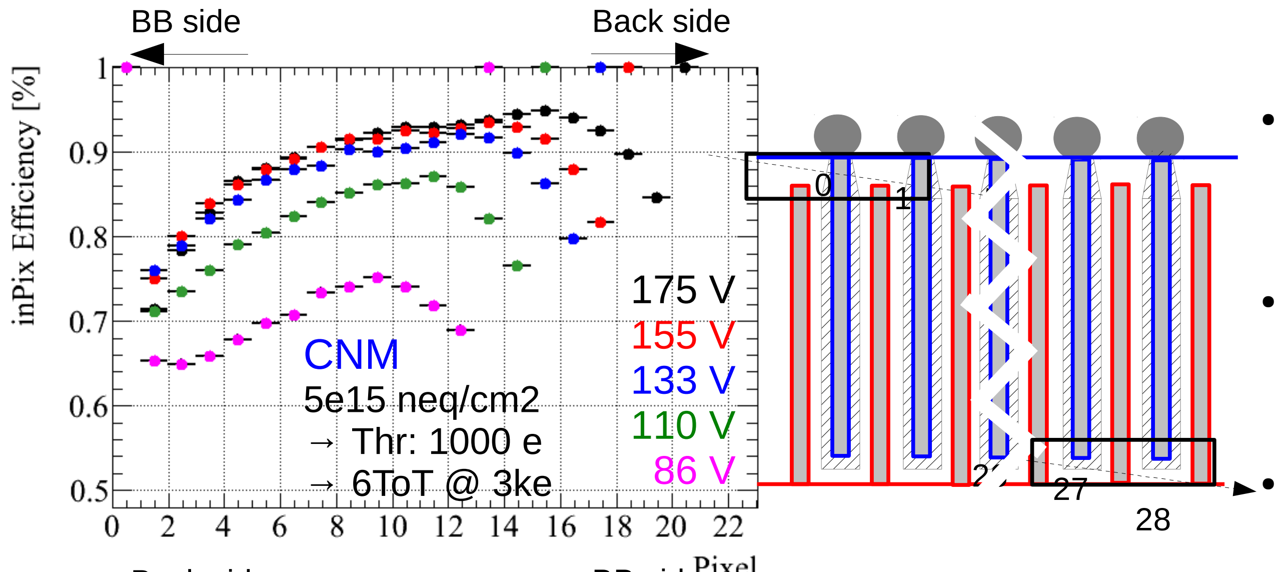
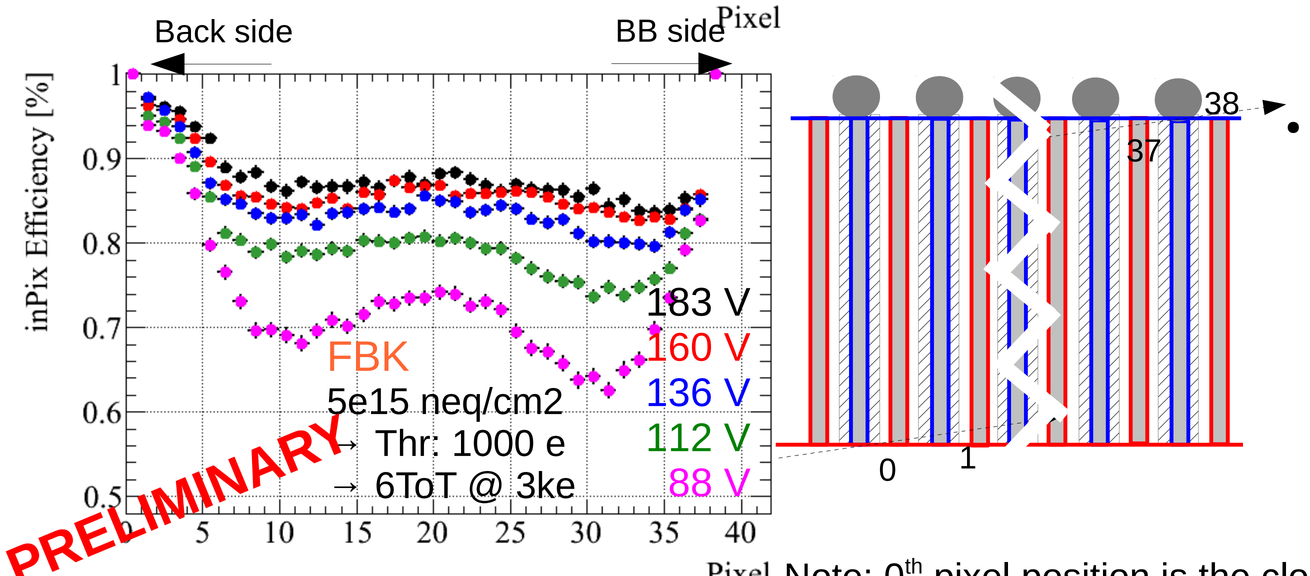
Efficiency per pixel vs cluster position



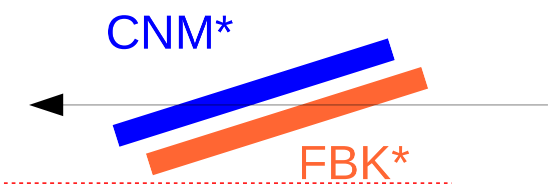


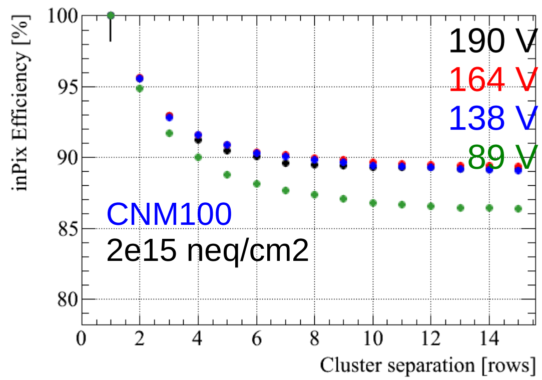


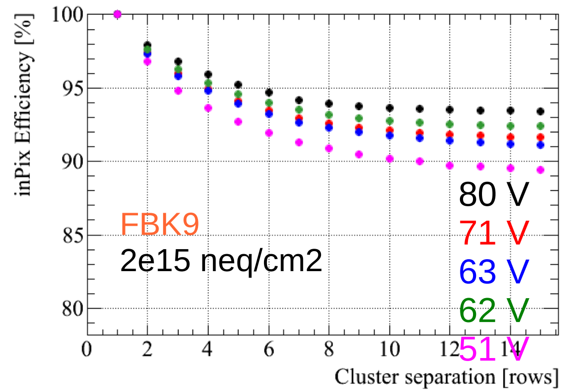
- Lower efficiency correlated with lower charge collection area in the area near the bump-bonds
- At such fluences, the area around the end of the n-column also has reduced efficiency
- Asymmetric efficiency
  - One-sided inefficiencies
- FBK behaviour still under investigation

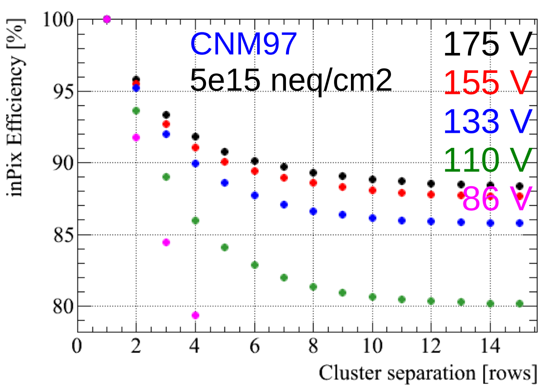
Note: 0^{th} pixel position is the closest pixel **hit** to the (0,0) pixel inside the cluster

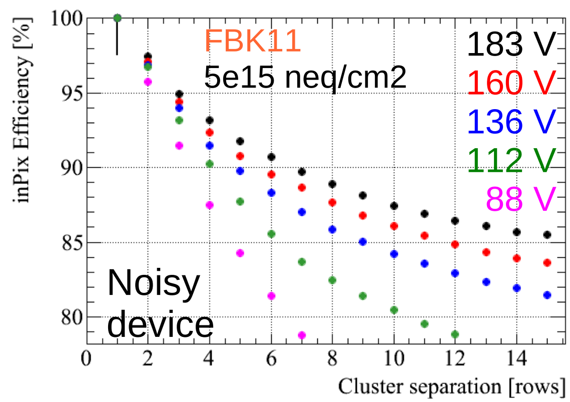
Per pixel efficiency







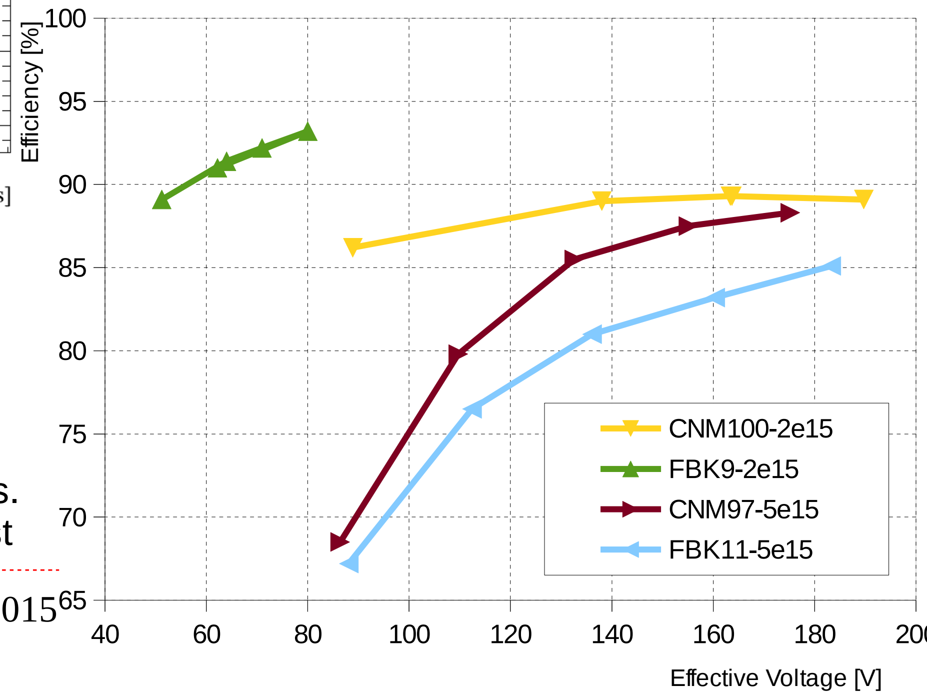




- "Cluster separation": How many consecutive holes (-1) do we allow inside a cluster
- In Pixel Efficiency using clusters sizes $ClSize_{peak}\pm1$ in the plateau

→ Avoid noise and bias to large efficiencies

- **Good efficiency per pixel for a non optimized structure**



Note: Efficiencies are the plateau values.
If plateau is not reached, take the lowest

Conclusions

- High angle and high segmentation → low charge collection per pixel (~3.3ke for 50 µm pitch)
- However, with a non optimized 3D structure at high angle it was possible to reach:

*No charge sharing was considered

  - Good efficiency was observed

    → Small probability of cluster splitting

  - Lower noise (lower capacitance due to smaller pixels) and threshold (RD53) would improve these efficiencies
- Studied charge collection for 50 µm pitch pixels at high angles:
  - Non passing-through column devices show a lower charge collection around the BB side

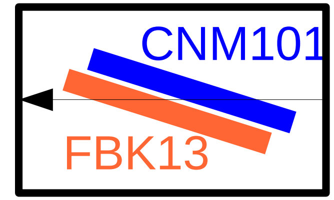
    → Can lead to (one-sided) cluster end-pixel inefficiencies

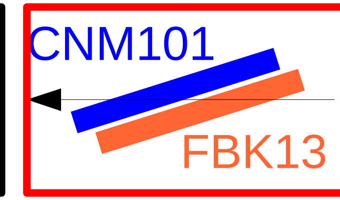
  - Clusters in non passing-through column devices get smaller for lower voltages and size distribution is broader

    → Also a sign of end-pixel inefficiencies
- Outlook:
  - Further studies and (edge-) TCT measurements
  - Looking forward for real 50 x 50 µm sensors

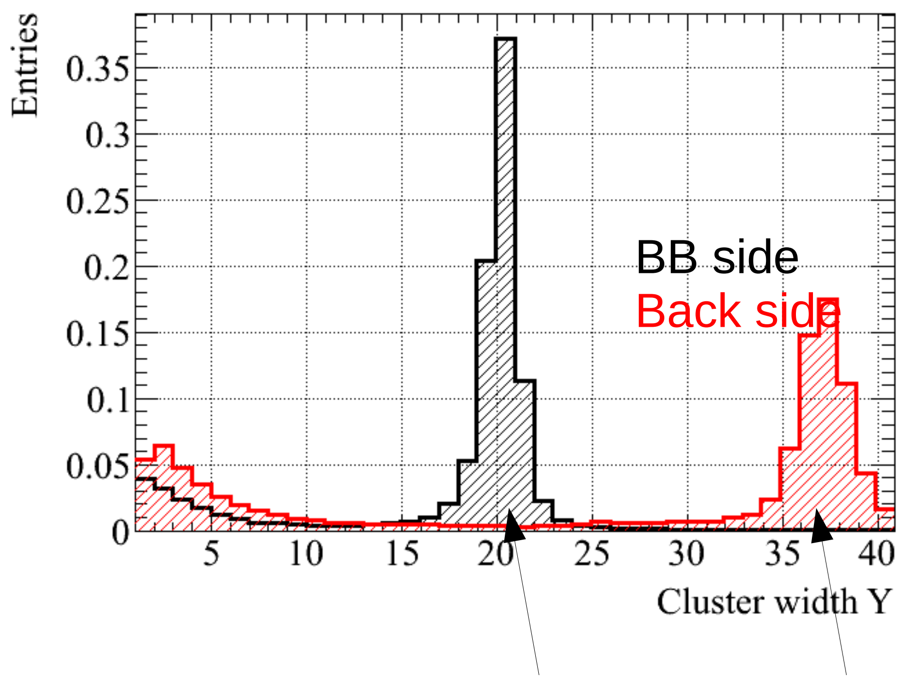
Back-up slides

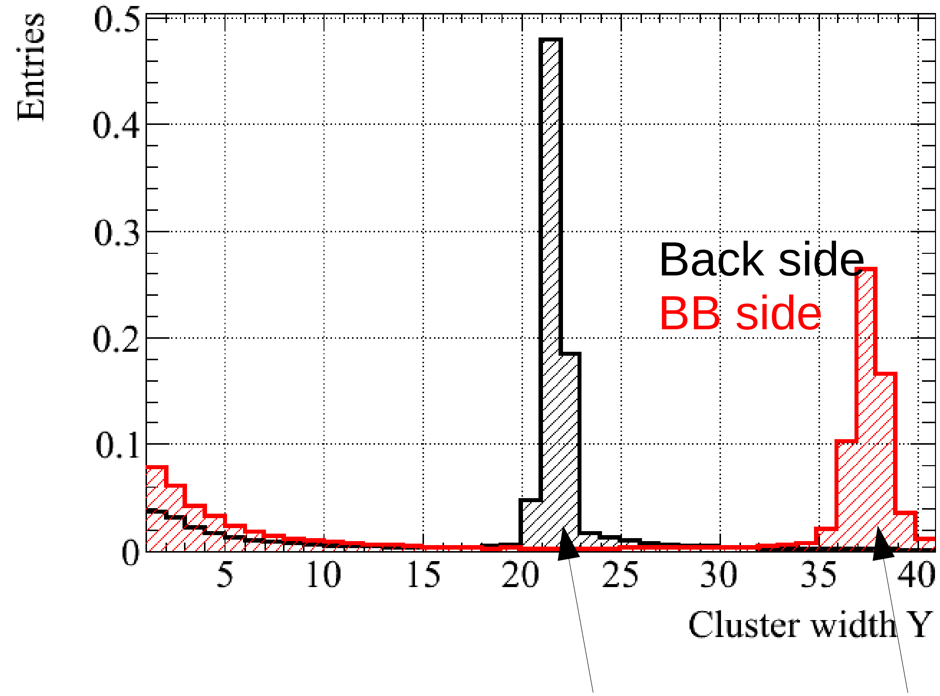
Cluster Size (B/F, Unirrad)





- Cluster Separation 3:
  - A maximum of 2 unfired pixels between 2 hits to form a cluster





CNM101
→ Thr: 1000 e
→ 6ToT @ 3ke
→ 30 V

φ ~ 76.4 φ ~ 82.7

$$\varphi = \frac{\pi}{2} - \arctan\left(\frac{w}{p\left(N_{cl}-1\right)}\right)$$

FBK13
→ Thr: 1000 e
→ 6ToT @ 3ke
→ 30 V

φ ~ 77.0 φ ~ 82.7

$$\varphi = \frac{\pi}{2} - \arctan\left(\frac{w}{p\left(N_{cl}-1\right)}\right)$$

~3º missalignment

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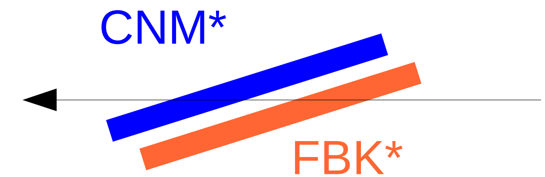
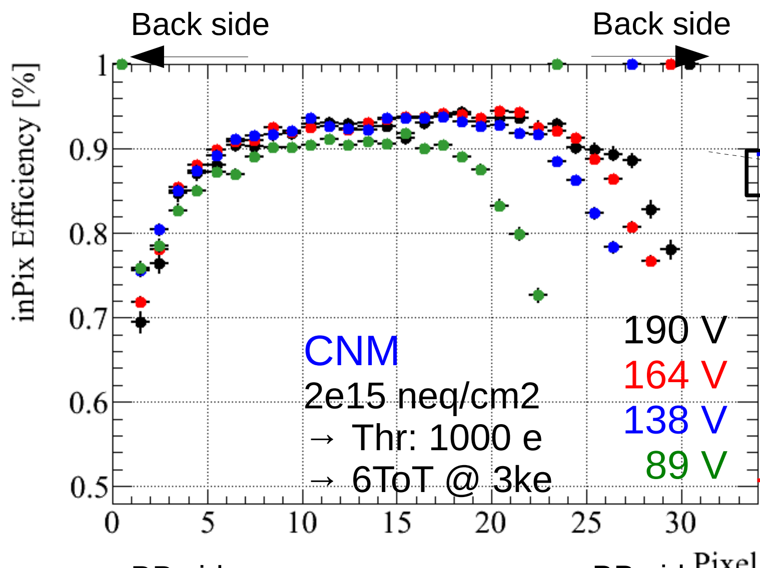
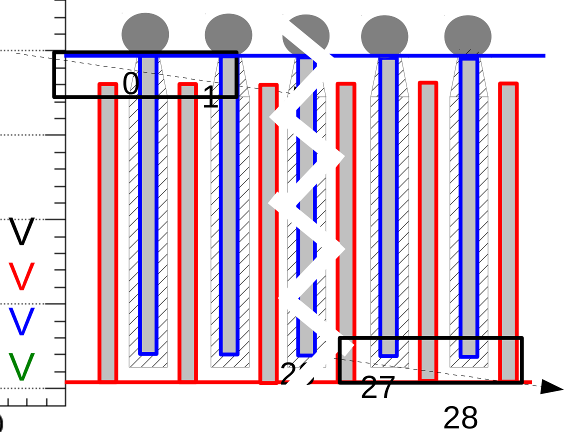
Efficiency per pixel vs cluster position







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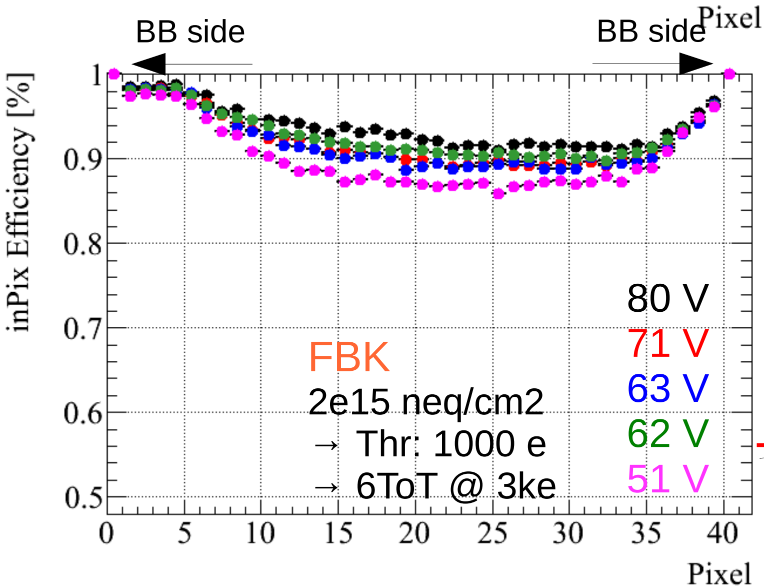
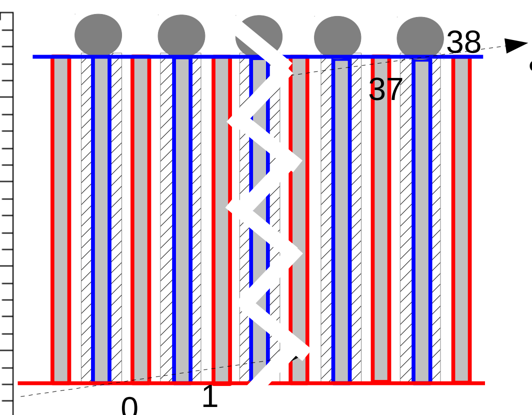
- At such fluences, the area around the end of the n-column also has reduced efficiency
- Asymmetric efficiency
  - One-sided inefficiencies





- After irradiation, a relatively uniform response is kept in fulling passing-trough columns structures

Note: 0th pixel position is the closest pixel **hit** to the (0,0) pixel inside the cluster