IMPROVING SPATIAL RESOLUTION OF RADIATION-TOLERANT PIXEL SENSORS

—A CONCEPT

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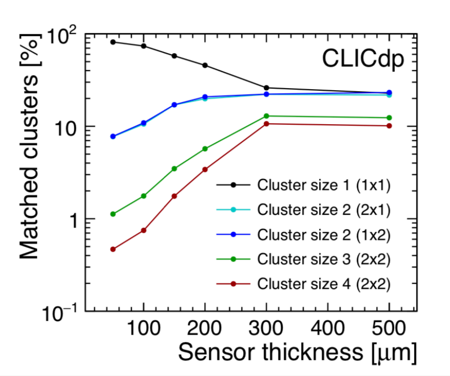
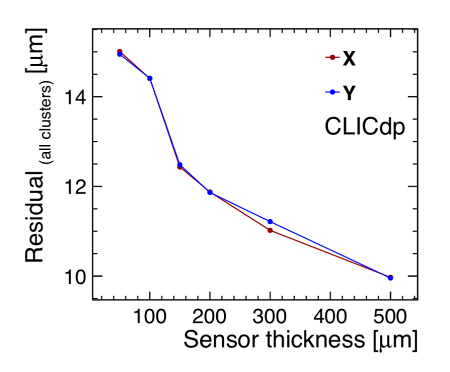
MOTIVATION

- Small charge cloud width per incident particle —> less charge sharing
  - For instance: thin detectors
  - ➡ Cluster size is dominated by 1-pixel clusters
  - ➡ Spatial resolution is limited by the size of pixels
- ➡ "Easy" solution: reduce the pixel size, BUT:
  - limited by the size of bonding bump (for hybrid detectors)
  - requires much denser R/O electronics (for monolithic and hybrid detectors)

- After irradiation:
  - charge-carrier trapping
  - smaller depletion depth
  - higher bias voltage, etc.
  - ➡ further limit the cluster size

$50\mu m \times 50\mu m$

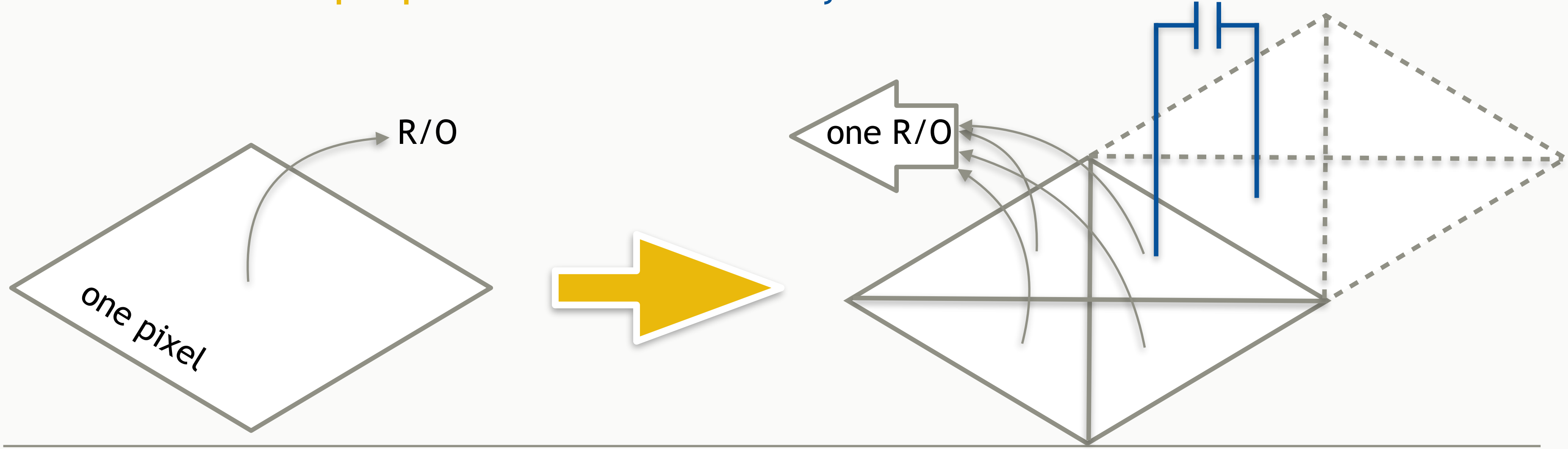




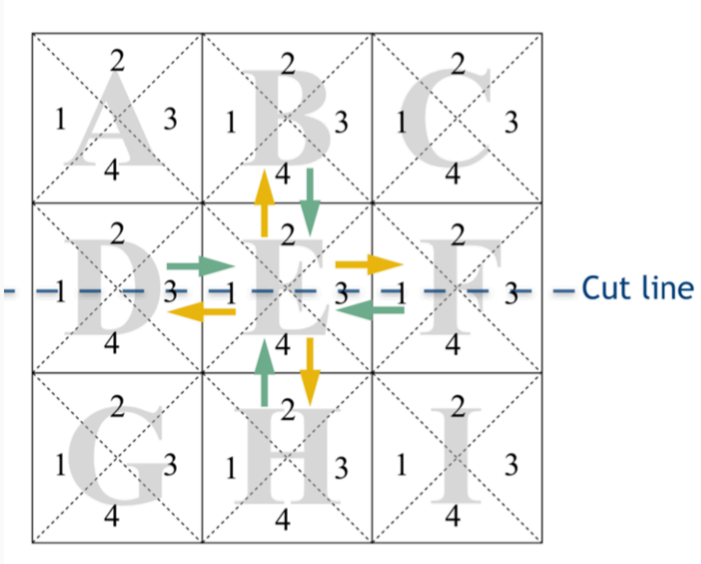
Test-beam results from CLIC (CLICdp-Note-2016-001)

SOLUTION: CROSS-TALK + SUB-PIXEL CODING

- Segment electrode implants: **create sub-pixels** & add spatial information **(sub-pixel coding)**
- AC-couple nearest sub-pixels in the neighboring pixel: add directional **cross-talk** to enhance **charge sharing**
- **One R/O channel per pixel**: maintain the density of R/O electronics

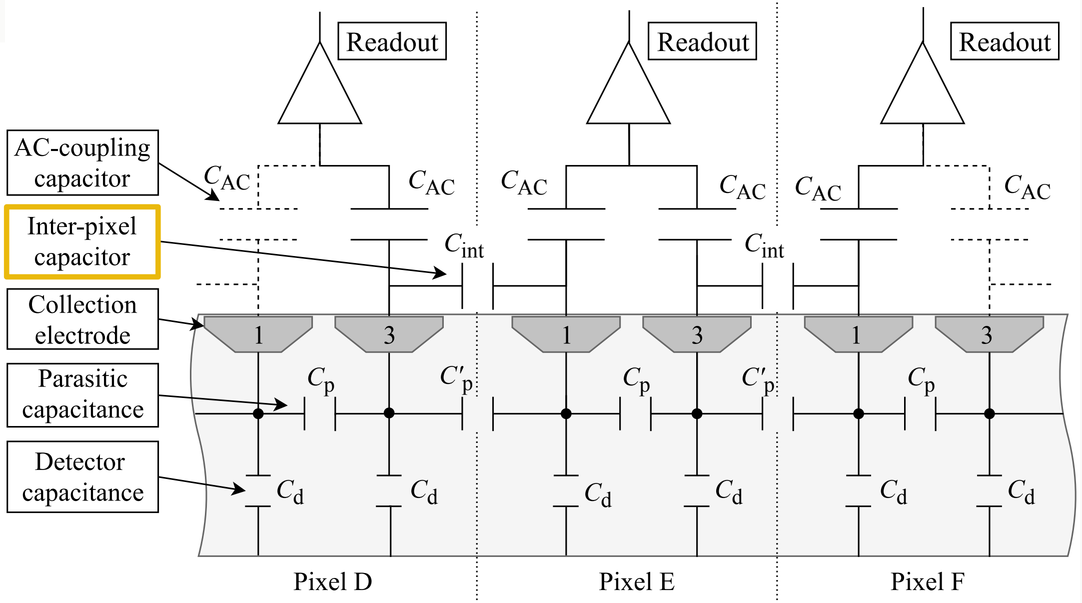


COUPLING SCHEME AND SIMULATION



Pixel matrix layout

- Charge is shared through coupling
- Hit information is encoded in the resulting charge array



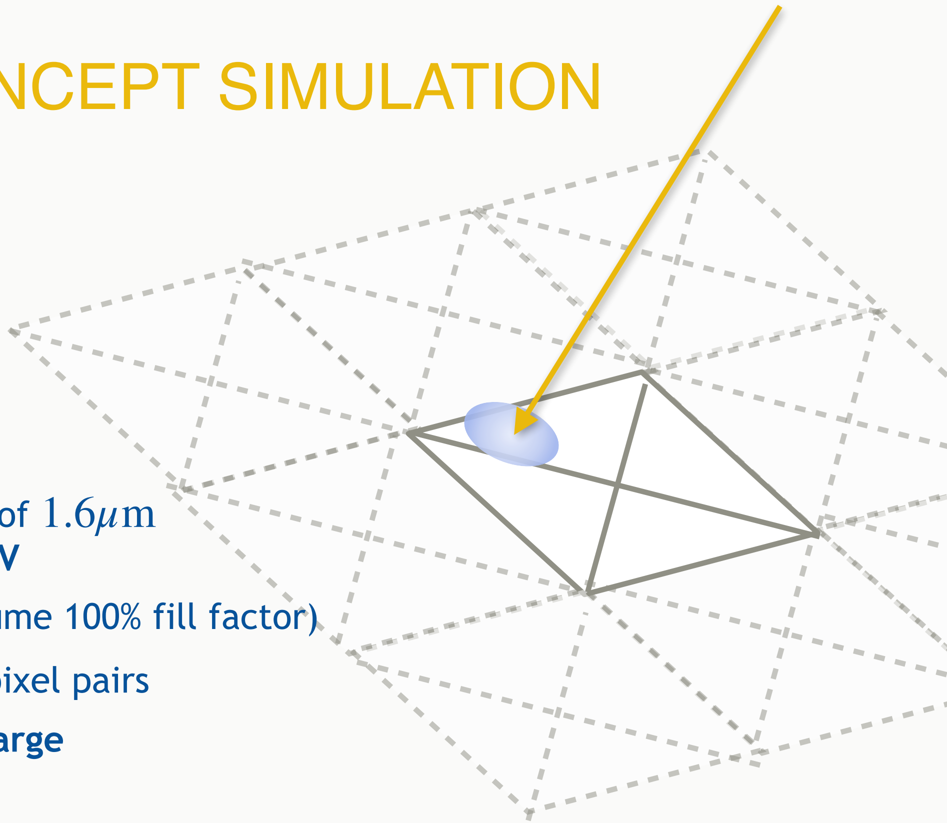
Schematic equivalent circuit along the “Cut line”

- CMOS technology allows special sensor features*
- 150 nm LFoundry passive sensors with AC-coupling shows high efficiency*
- Good performance after irradiation*

* D-L. Pohl, T. Hemperek et al (2017) http://dx.doi.org/10.1088/1748-0221/12/06/P06020

PROOF-OF-CONCEPT SIMULATION

- Particle track **perpendicular** to the detector plane
- Pixel geometry: $50\mu\mathrm{m} \times 50\mu\mathrm{m} \times 100\mu\mathrm{m}$
- Injection throughout the matrix with $0.1\mu\mathrm{m}$ step
- Charge cloud density of electrons:
    - 2D projection (**Gaussian**) on detector plane
    - Width: **average extension** from thermal diffusion of $1.6\mu\mathrm{m}$ for **full depletion voltage=51V & bias voltage=80V**
- **Charge collection: integrate over sub-pixel area** (assume 100% fill factor)
- **Charge sharing fraction** k**:** applied to all coupled sub-pixel pairs
- **Threshold per pixel: 10% and 20% total deposited charge**
- **Charge resolution: 10% total deposited charge**
- Hit reconstruction: “template-based algorithm” *



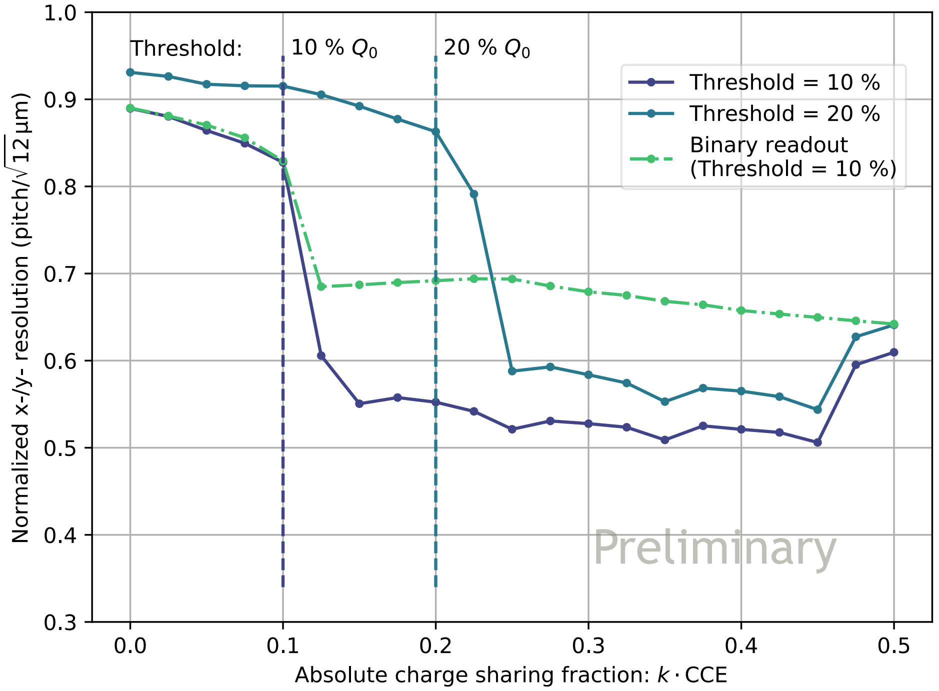
➡ Calculate resolution

* Similar to: CMS-NOTE-2007-033

RESULTS: RESOLUTION

- Shared charge from 0% to 50% of **total deposited charge**
- Without charge sharing:
  - Threshold dependent large resolution
  - Values closer to $50/\sqrt{12} \approx 14.4\mu m$
- Increase charge sharing fraction k:
  - Residual drops at threshold
  - **Improved by about 40%**
  - At about 50% charge sharing, ambiguity arises
  - Binary readout has less improvement due to lacking of charge information

➡ Better resolution when shared charge is higher than threshold

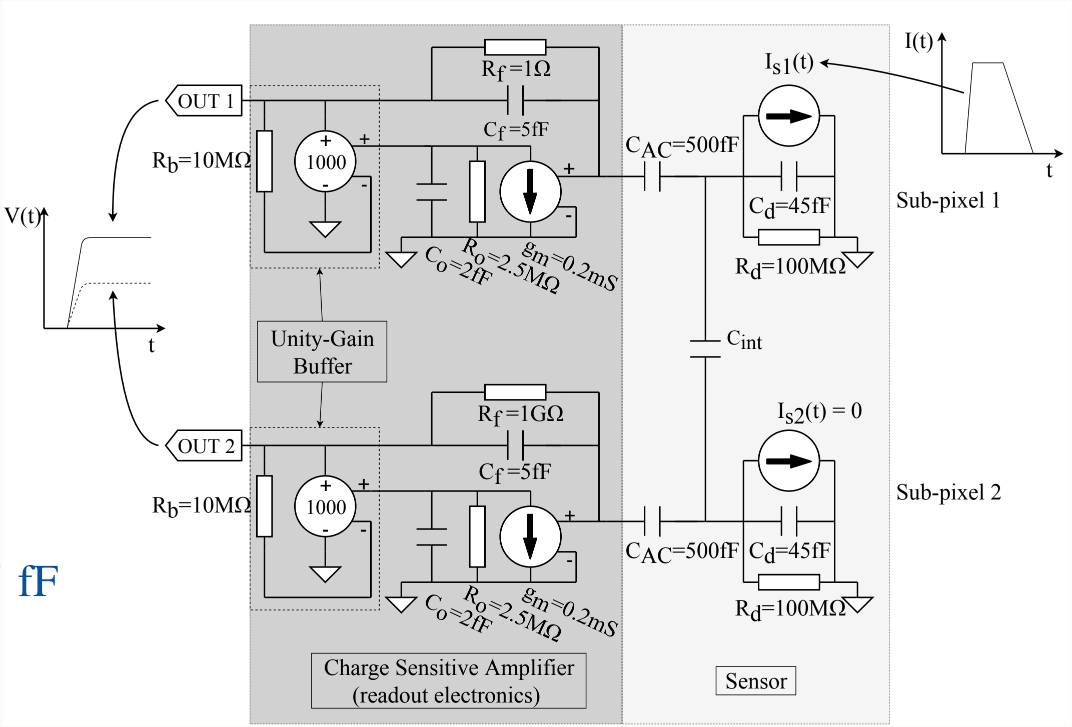


AN EXAMPLE OF IMPLEMENTATION

- SPICE simulation of 2 sub-pixels
- AC-coupled sensor and R/O
- Sensor:
  - $C_{\mathrm{d}} = 45\mathrm{fF}$
  - $C_{\mathrm{AC}} = 500\mathrm{fF}$
  - **Neglect parasitic capacitances**
- R/O (a linearised CSA model):
  - Open-loop gain $Aol = 500$
  - Effective capacitance $C_{\mathrm{CSA}} \approx 2.5\mathrm{pF}$

➡ $C_{\mathrm{CSA+AC}} = 1/(1/C_{\mathrm{CSA}} + 1/C_{\mathrm{AC}}) \approx 417\ \mathrm{fF}$

- Inject pulse current on sub-pixel 1 sweep inter pixel capacitance C_{int}, readout both



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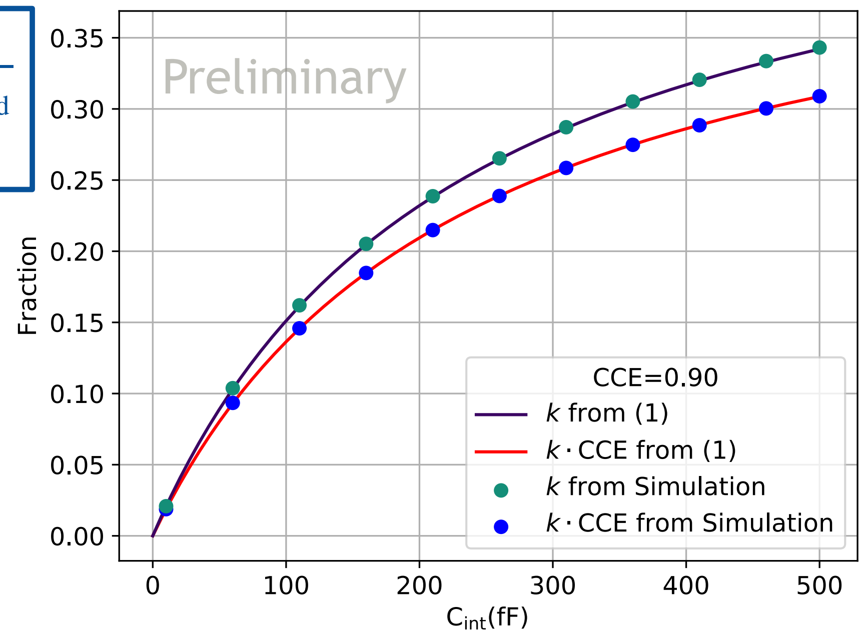
CHARGE SHARING & CAPACITANCE

- Charge seen by the coupled CSA (calculation):

(1) $$Q_{\mathrm{CSA,2}} = Q_{\mathrm{deposited}} \cdot \underbrace{\frac{C_{\mathrm{int}}}{C_{\mathrm{CSA+AC}} + C_{\mathrm{d}} + 2C_{\mathrm{int}}}}_{\text{Charge sharing fraction } k} \underbrace{\frac{C_{\mathrm{CSA+AC}}}{C_{\mathrm{CSA+AC}} + C_{\mathrm{d}}}}_{\text{CCE}}$$

- For $C_{\mathrm{CSA+AC}} \approx C_{\mathrm{int,max}}$ (usual case): k is restricted to approximately 1/3 (already sufficient)
- For $C_{\mathrm{CSA+AC}} < C_{\mathrm{int,max}}$: k can reach 50% of the **total collected charge**. **BUT** the **CCE drops** with decreasing $C_{\mathrm{CSA+AC}}$, otherwise C_{int} will be too large
  - ➡ Leads to a trade-off between **charge sharing strength**, **collection ability**, and **capacitors' size**.



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FEASIBILITY AND CHALLENGE

- Based on the demonstrated implementation strategy
- Capacitors:
  - Typical CMOS process allows: $2\ \mathrm{fF}/\mu\mathrm{m}^2$ or higher
  - For $C_{\mathrm{AC}} = 500\mathrm{fF} \quad C_{\mathrm{int}} \leq 500\mathrm{fF}$, capacitors occupies $\leq 60\ \%$ pixel area
- Noise in CSA:
  - **increases** with **CSA input capacitance**
  - Inter-pixel capacitance **increases** the input capacitance of CSA

➡ C_{int} should be possibly small—> balance between charge sharing & SNR

SUMMARY AND CONCLUSION

- Improving spatial resolution via applying position dependent directional cross-talks is proven
  - An improvement of about 40% can be achieved, when shared charge is above threshold

- A possible implementation strategy is discussed
  - A charge sharing fraction of about 30% can be obtained with realizable inter-pixel capacitors in CMOS processes
  - Some limitations are reflected by balancing charge sharing fraction, charge collection ability, SNR and frequency response of the system

  ➡There should be many ways to implement
  Requires detailed studies and careful chip/sensor design for implementations

Thank you

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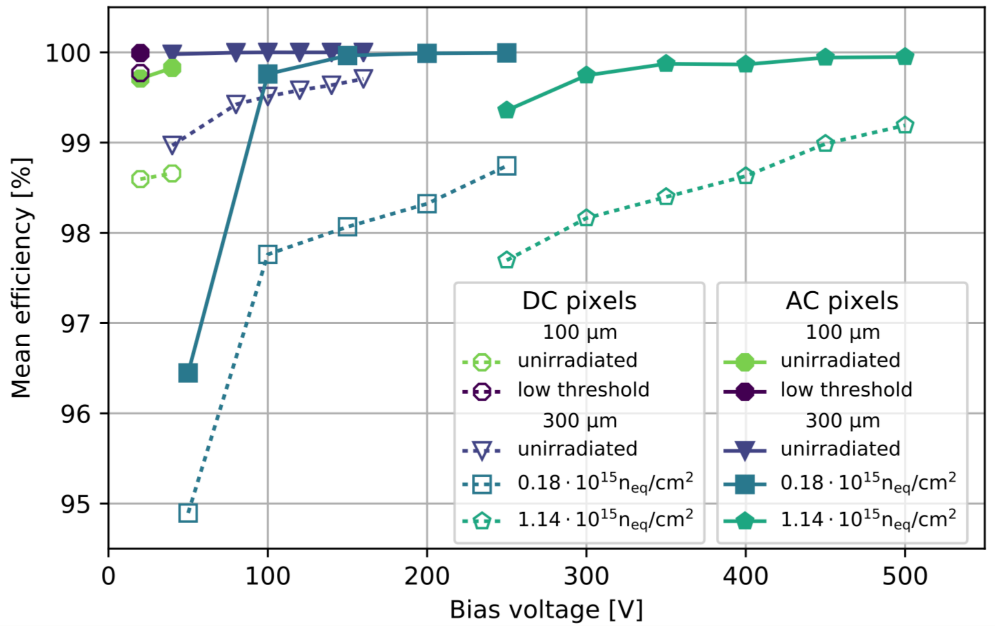
BACK UP

RADIATION TOLERANT CMOS SENSORS

- CMOS technology allows special sensor features
- 150nm LFoundry passive CMOS sensors:
  - High detection efficiency and noise performance
  - Equally well as standard pixel sensors

Detection efficiency of LFoundry passive CMOS sensors

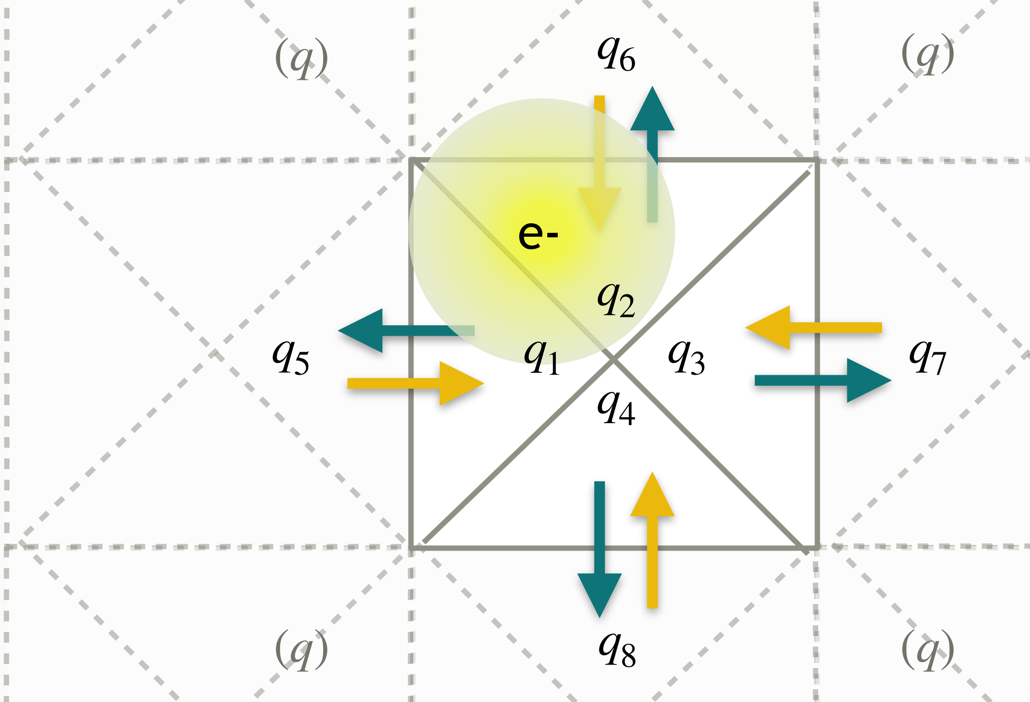


D-L. Pohl, T. Hemperek et al (2017) http://dx.doi.org/10.1088/1748-0221/12/06/P06020

CHARGE SHARING

- Initial charge array:
  $\vec{q} = (q_1, q_2, \cdots q_8, \cdots)$
- Forward coupling:
- Backward coupling:

- A **fraction** k of charge at **each sub-pixel** is attributed to the coupled one (neglecting all parasitic capacitances)

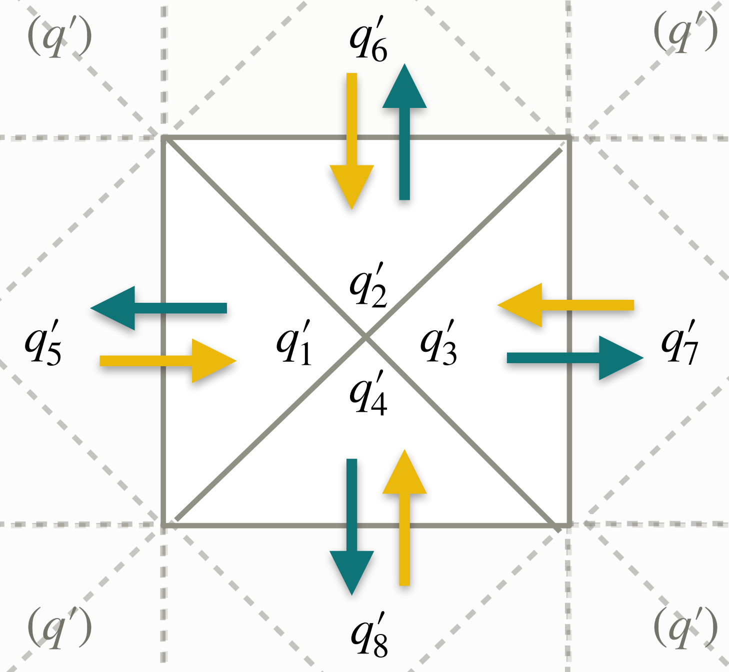


CHARGE SHARING

- Initial charge array:
  $\overrightarrow{q} = (q_1, q_2, \cdots q_8, \cdots)$
- Forward coupling:
- Backward coupling:

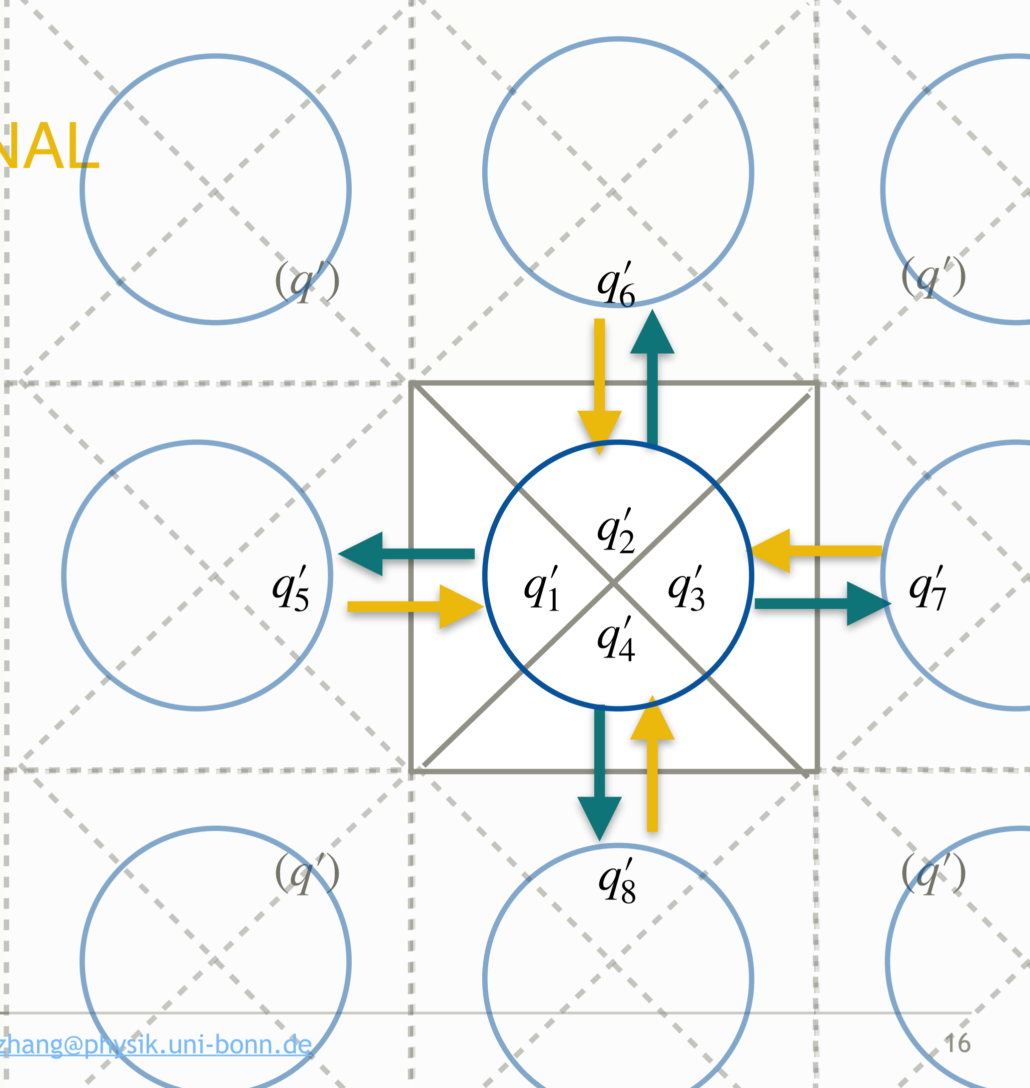
- A **fraction** k of charge at **each sub-pixel** is attributed to the coupled one (neglecting all parasitic capacitances)

- Resulting charge array:
  $\overrightarrow{q'} = (q'_1, q'_2, \cdots q'_8, \cdots)$



READOUT SIGNAL

- Charge collected per pixel Q: sum over 4 sub-pixels
- For a 9 pixel matrix: acquire a charge array with 9 elements $\overrightarrow{Q} = (Q_1, \cdots, Q_9)$
- This will be further processed



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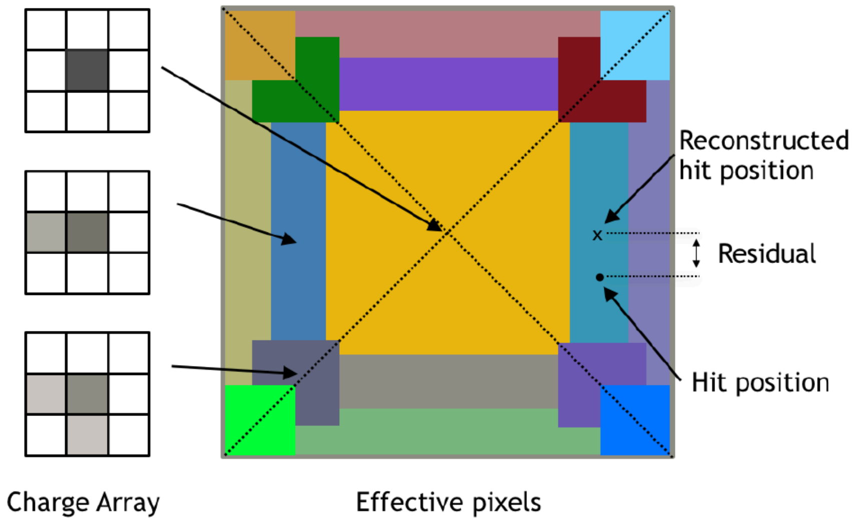
ESTIMATE SPATIAL RESOLUTION

- Template-based algorithm:
  (similar to CMSSW of CMS collaboration)

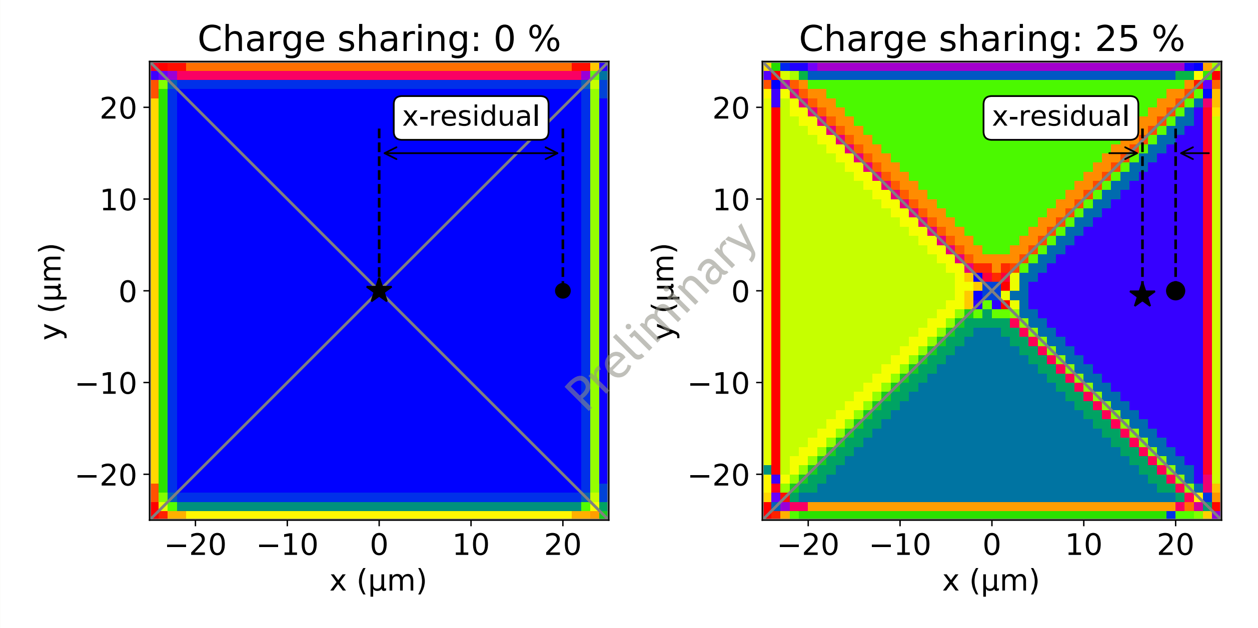
➡ "Effective pixels"

  - Each effective pixel represents a unique charge array (signature)
  - Reconstructed hits at the centre of gravity of effective pixel
  - Calculate residuals & average with the weight (eff. pixel area / pixel area)



CHARGE SHARING FRACTION VS. RESIDUAL

Threshold: 10%



no cross-talk

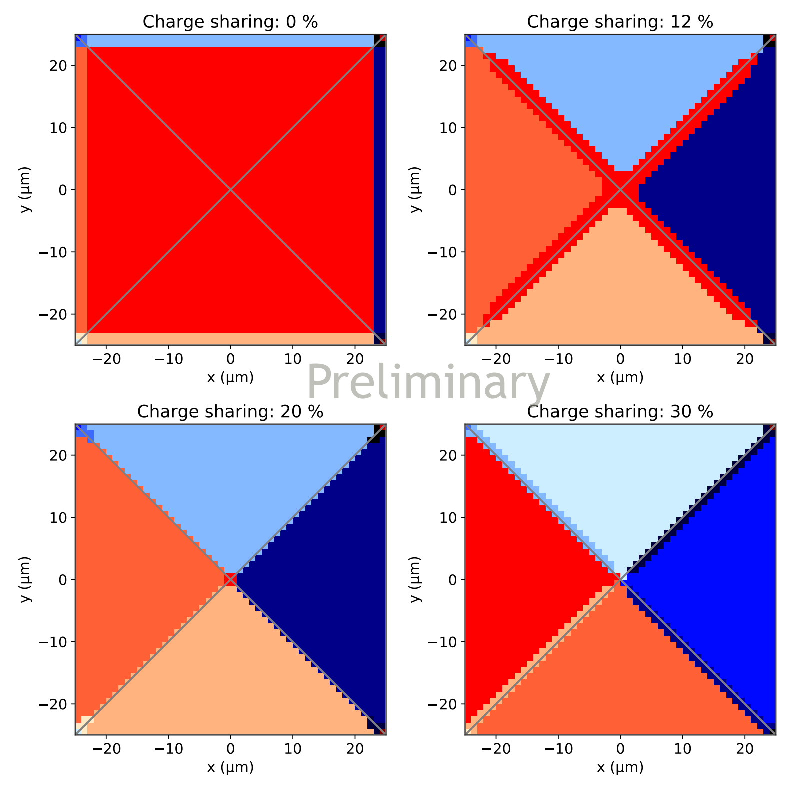
with cross-talk

★: Reconstructed position

• : Hit position

cross-talk subdivides effective pixels, thus reduces the residual

CHARGE SHARING FRACTION VS. CLUSTER SIZE



Binary readout
Threshold: 10%