Results from test-beam measurements of monolithic pixel detectors in SOI technology

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on behalf of the CLICdp collaboration

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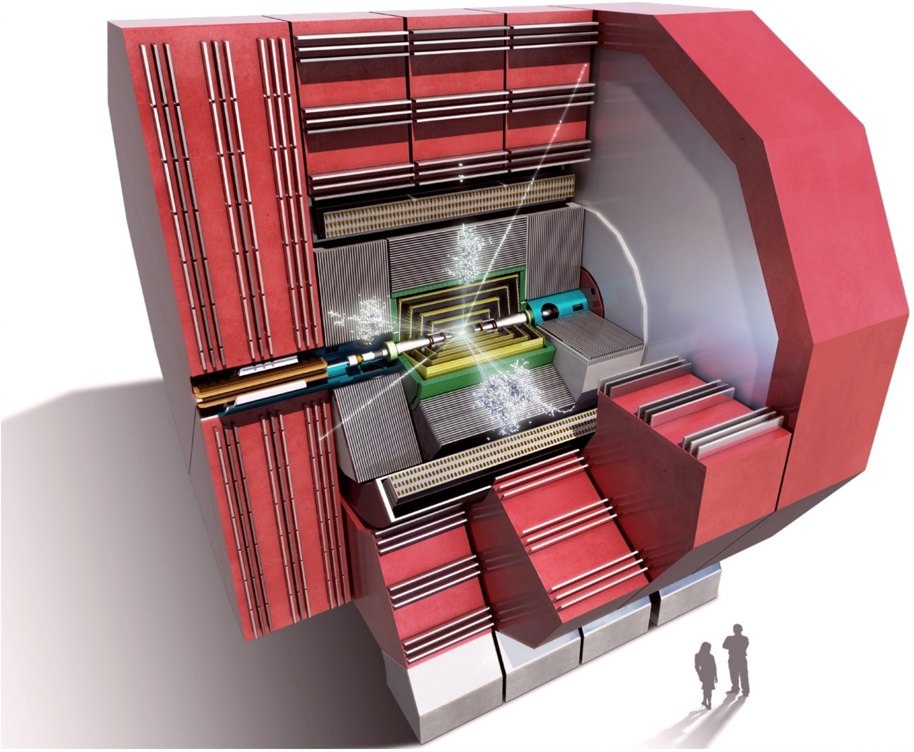
Outline

- **Introduction**
  - Motivation, SOI technology
- **SOI pixel detector prototype**
  - Architecture and performance
- **Testbeam measurement results**
  - Setup
  - Data preparation
  - Efficiency
  - Spatial resolution
- **New SOI prototype detector for CLICdp**
- **Summary**

Introduction - Motivation

CLIC – Compact Linear Collider

Linear e^+e^- Collider with sqrt(s) up to 3 TeV



CLIC accelerator:

- electron-positron collider
- tunnel length: 11.4 m - 50.1 m
- center-of-mass: 360 GeV - 3 TeV
- train length: 156 ns
- BX: 312 with 0.5 ns repetition
- train repetition: 50 Hz
- two drive-beam acceleration
- "Higgs factory", top quark
- physics, BSM, SUSY

Requirements for CLIC vertex detector:

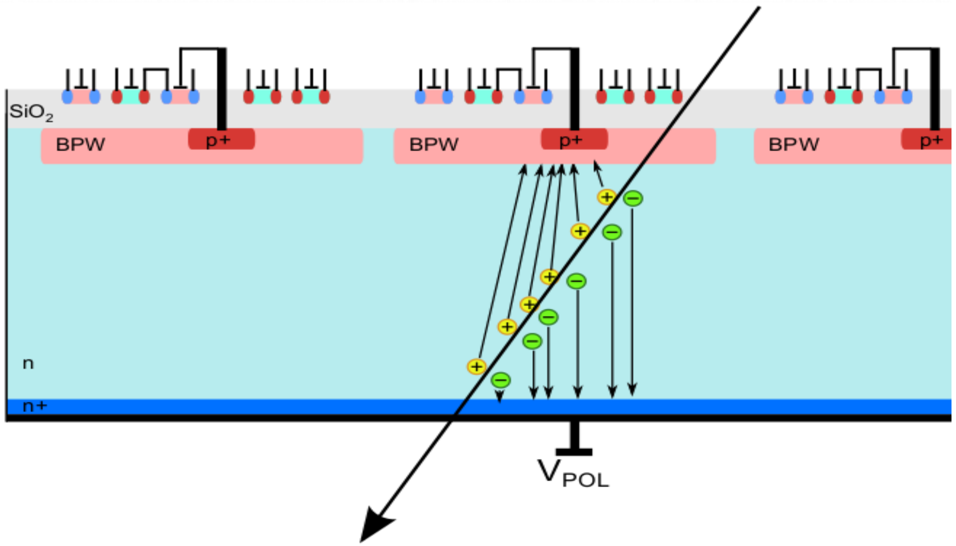
- Single point resolution ~3um
- Silicon detector thickness 50-100um
- Time resolution ~10ns

Prototype SOI detector structures shown in this talk were designed as generic R&D, not yet for CLIC specifications

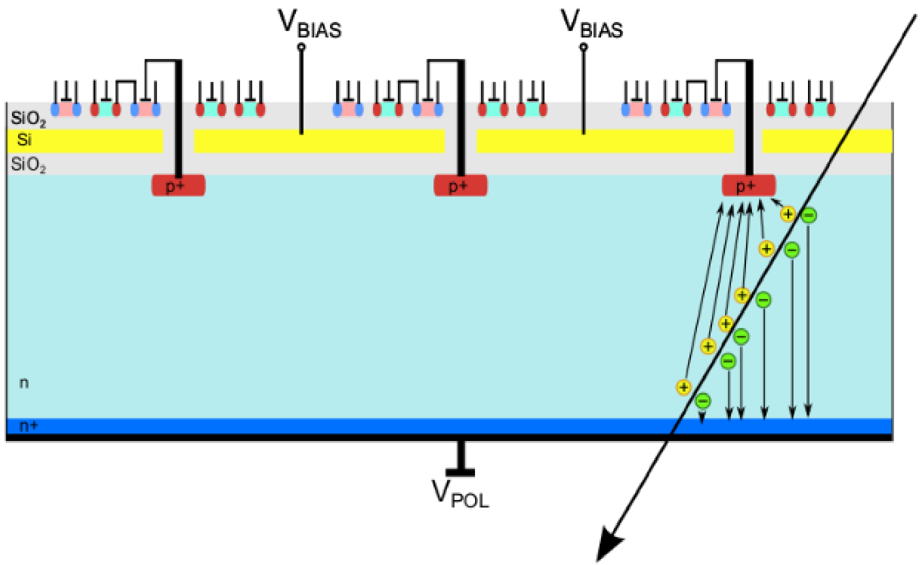
Introduction – SOI CMOS process

Main advantages of monolithic detector in SOI Lapis technology for imaging/tracking :

- Separate thin 200nm SOI CMOS and thick sensor bulk
- Full CMOS process available
- Sensor can be fully depleted and thinned down to ~50um
- High resistivity (up to >10 kΩcm) n-type and p-type bulk
- Double SOI version available (better shielding, helpful for radiation hardness)



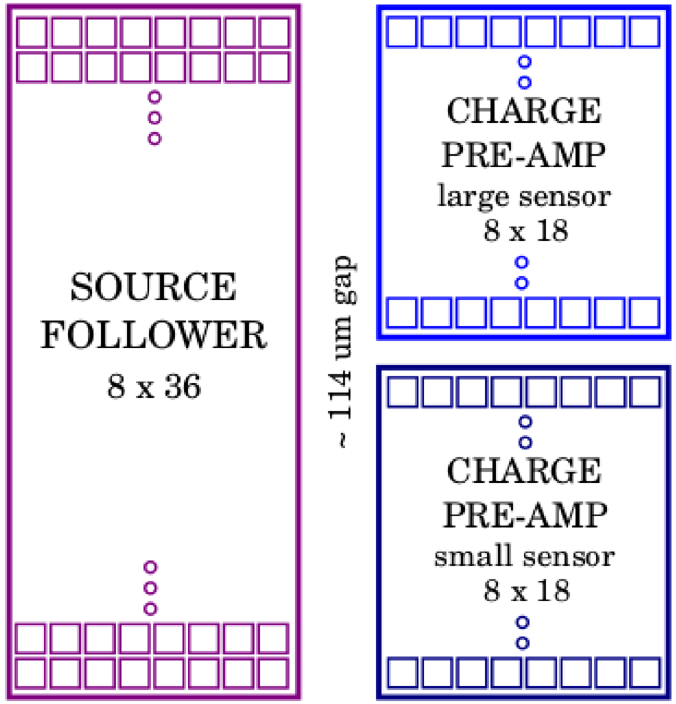
SOI structure

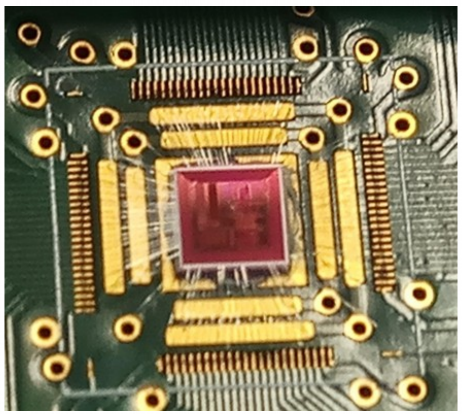


Double SOI structure

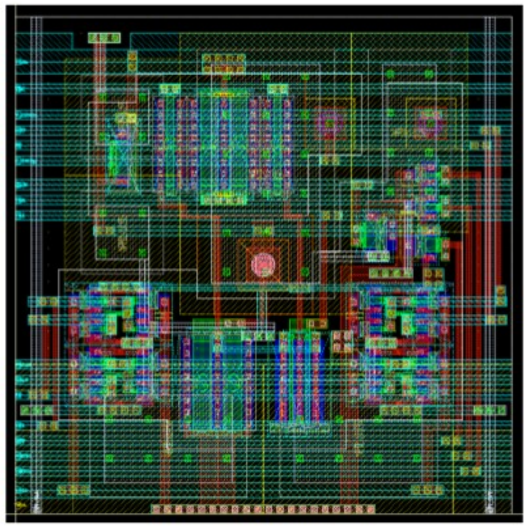
Chip overview

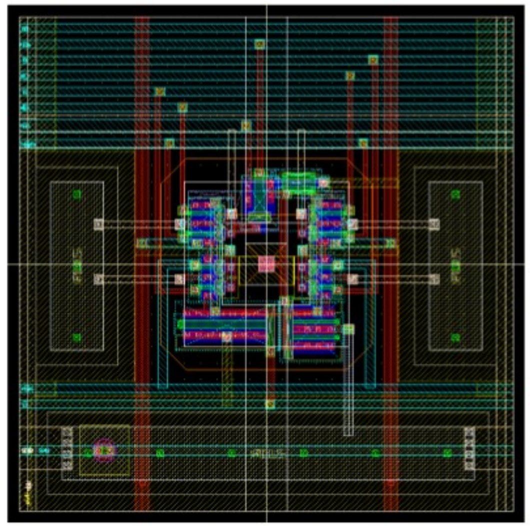
- Two pixel types:
  - source follower front-end (**SF**)
  - charge-preamplifier front-end with two sensing diode sizes (**CPAsmall**,**CPAlarge**)
- In total 16 x 36 pixel in matrix
- 30 um x 30 um pixel size
- Rolling shutter readout
- Two wafer types:
  - **FZ-n** 500 um thickness
  - **DSOI-p** 300 um thickness





CHARGE PRE-AMPLIFIER





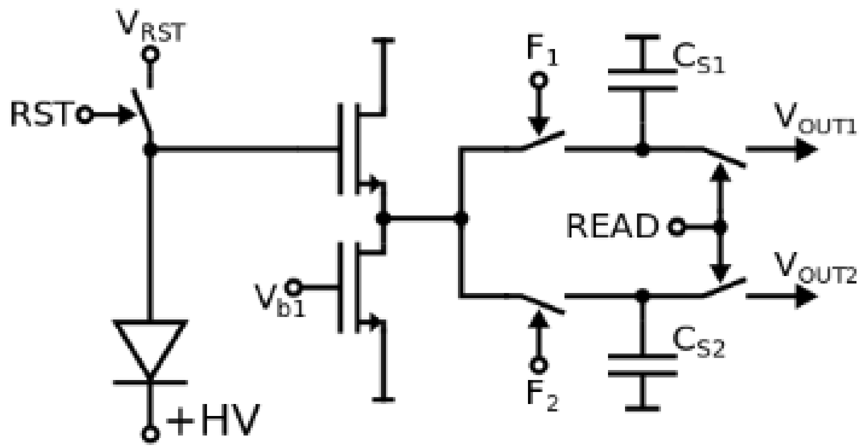
SOURCE FOLLOWER

Pixel archirecture

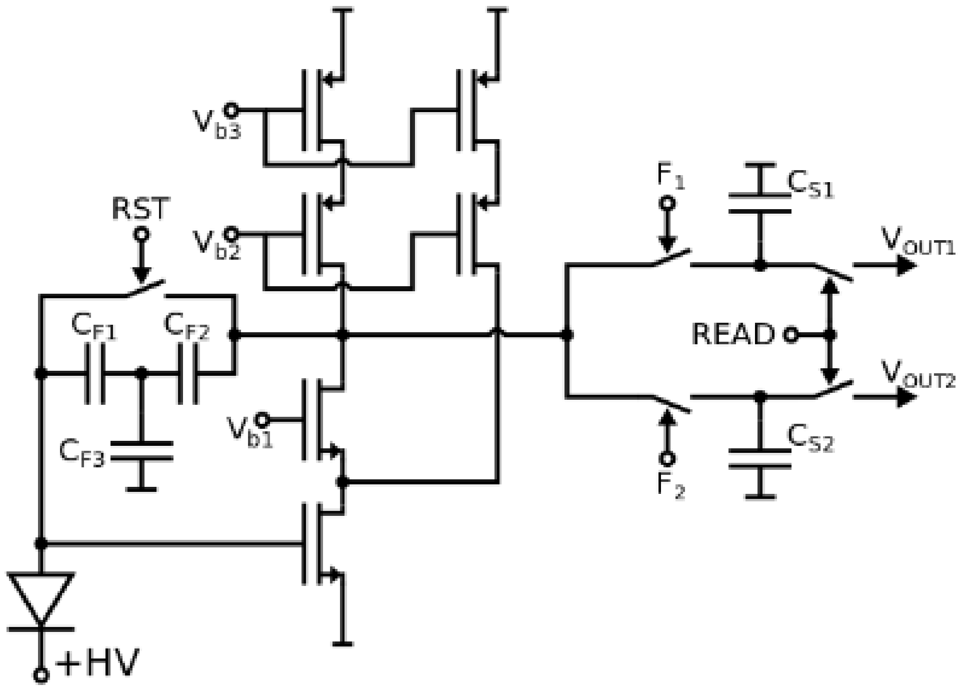
SOURCE FOLLOWER front-end:
- source follower input stage
- Correlated Double Sampling (CDS)
- 16x16 um sensor implant, 30x30 um pixel size
- dedicated for FZ-n wafer
- sensitive for detector capacitance:
- simple archirecture benefits in reducing sources of electronic noise

CHARGE PREAMPLIFIER front-end:
- telescopic amplifier with additional current source in input stage,
- "T-shape" capacitor feedback structure to decrease capacitance(~6 fF) / increase gain
- CDS
- sensor implant 5x5um, 29x29um, pixel size 30x30um

SOURCE FOLLOWERS

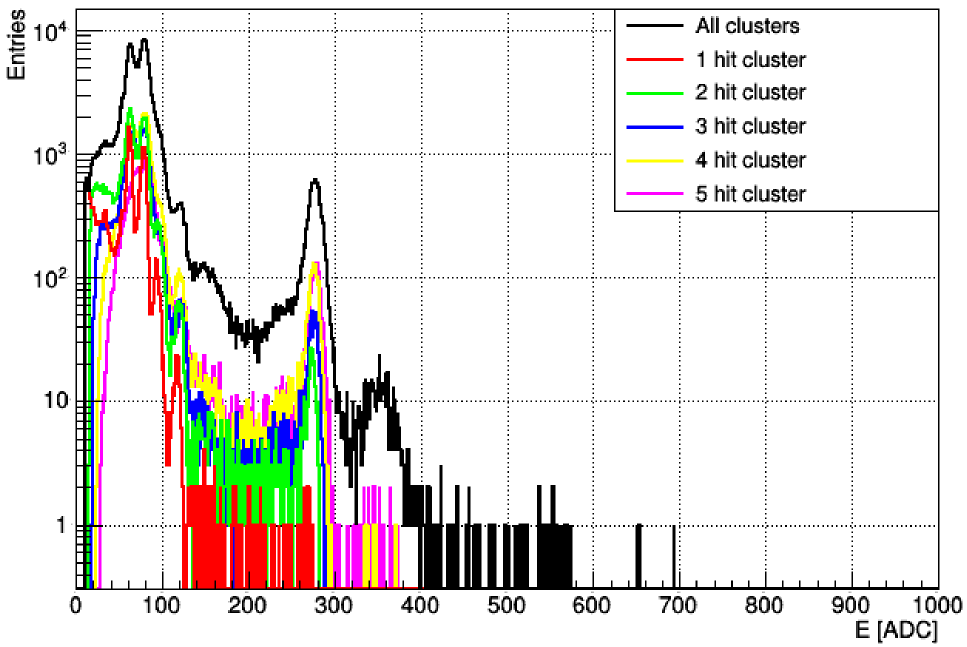


CHARGE PRE-AMP

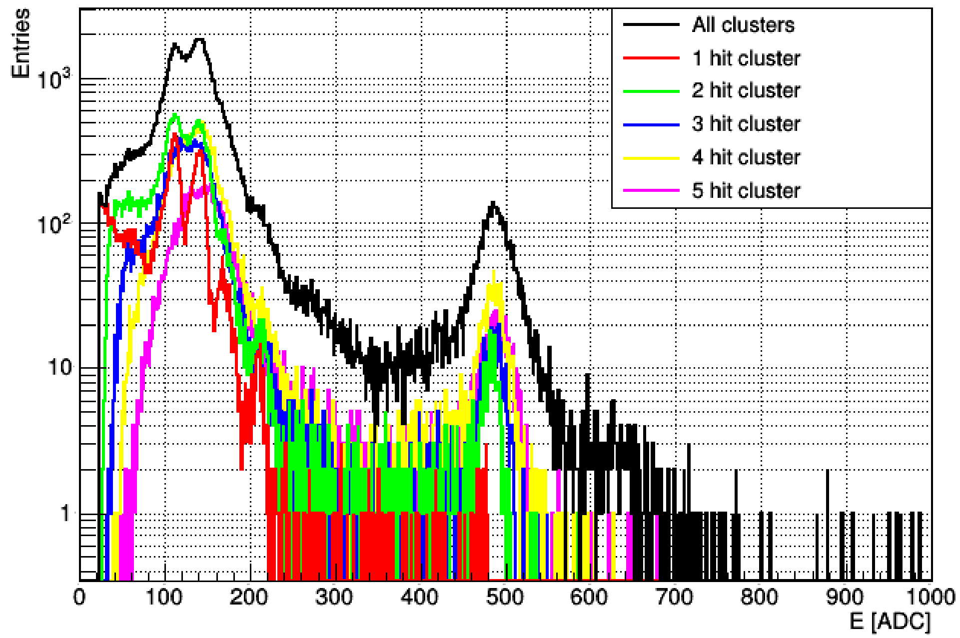


LAB test: Noise performance

SOURCE FOLLOWER (SF)



CHARGE PRE-AMP (CPAlarge)



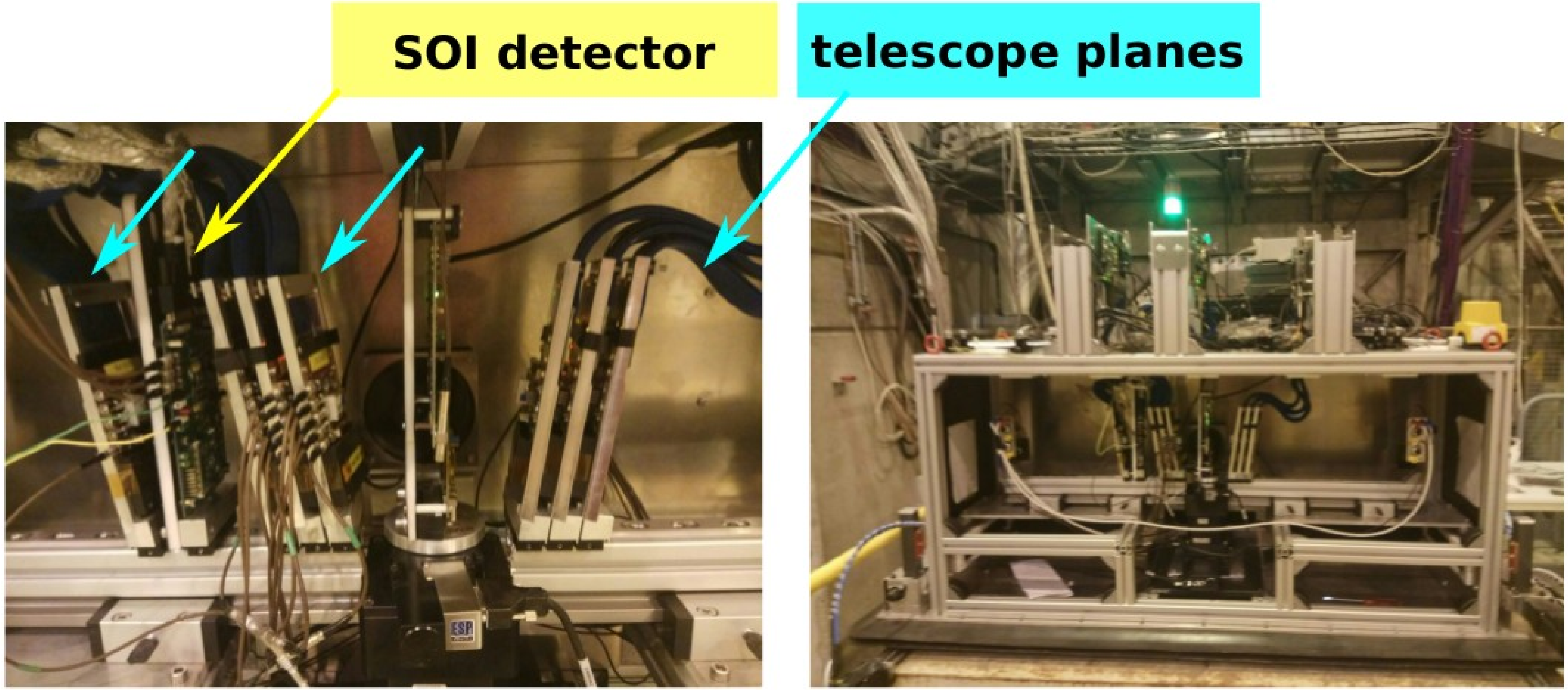
	DSOI-p	FZ-n
CPAlarge	128 e-	131e-
CPAsmall	98 e-	148 e-
Source follower	321 e-	113 e-

- measurements with Am-241 source
- gain and noise calculated from Am,Np,Cu X-ray lines

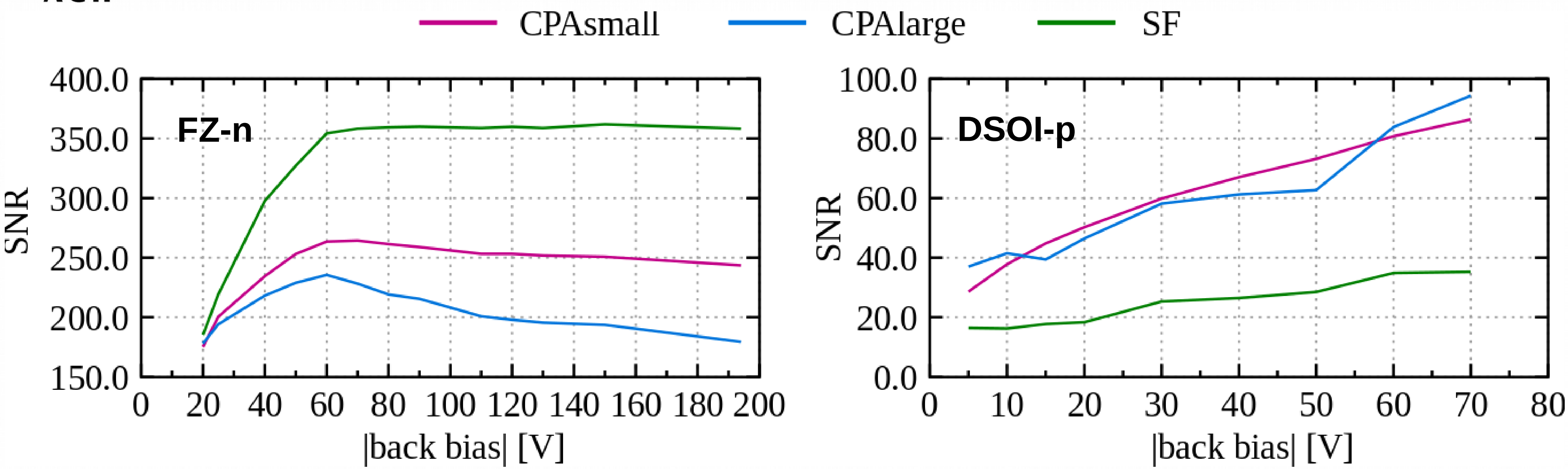
Testbeam setup

DAQ setup:
- Main readout PCB + mezzanine board with prototype SOI chips
- FPGA – PC → Ethernet
- DAQ Software – ROOT 6

Testbeam:
- SPS H6 beam line at CERN with Timepix-3 based CLICdp telescope
- CLICdp test-beam with 120 GeV pion beam



Signal to noise ratio



FZ-n:

- Fully depleted around 70V (corresponding resistivity ~12.3 kOhm cm)
- Best SNR for source followers (**SF**): above 350 for full depletion
- Good performance also for CPA matrices (**CPAsmall**, **CPAlarge**) with good SNR (~250, ~200)
- Even at very low back bias voltages the SNR is high

DSOI-p:

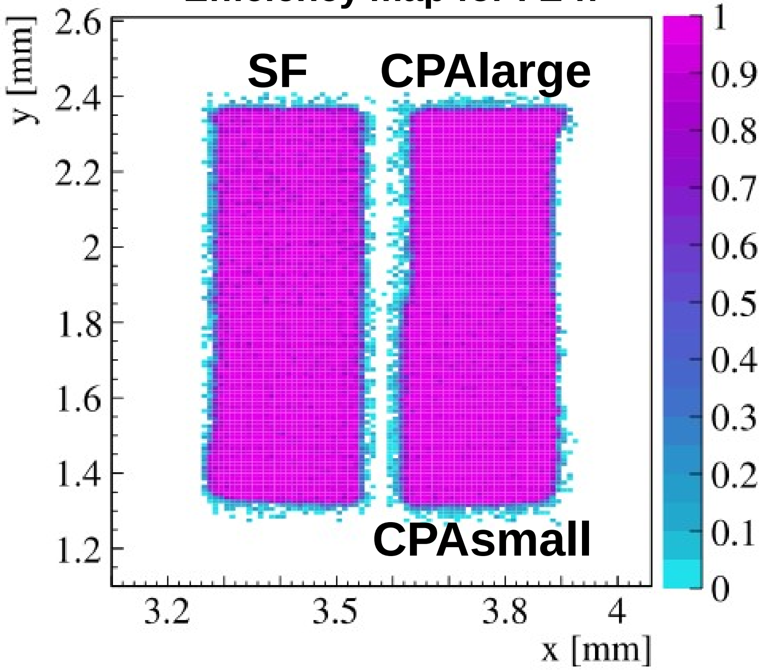
- Not fully depleted, bias only up to ~70V (leackage of unknown source prevented higher bias)
- SNR in the range 20-100
- Charge preamplifier performance better than source follower (due to detector capacitance)

Detector efficiency

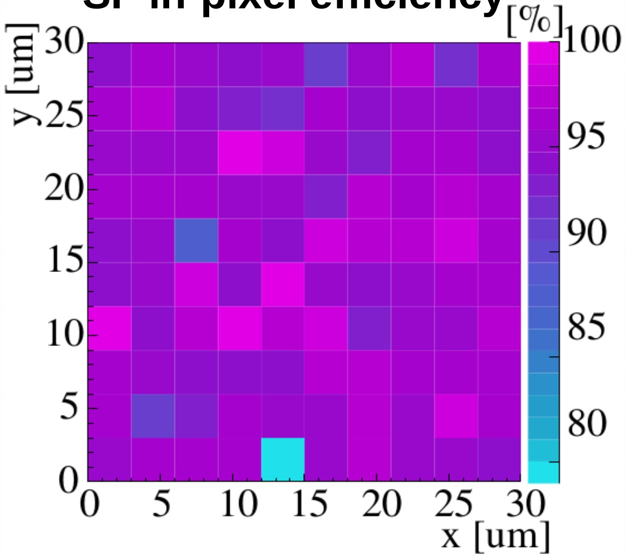
Efficiency = SOI events / all telescope tracks

- For FZ-n at full depletion
  - Source followers →97.98% (average)
  - Charge preamplifiers → 96.80% (average)
  - Within pixel efficiency looks uniform
  - Unefficiency is caused most probably by the dead time in the rolling shutter readout (reset phase)
- Similar results are obtained for DSOI-p matrix at high enough sensor bias voltage

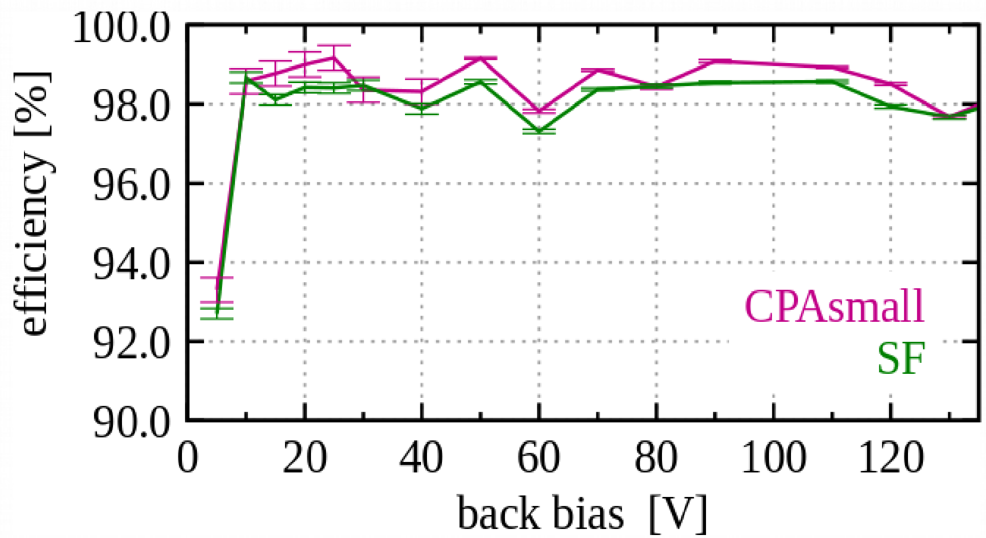
Efficiency map for FZ-n



SF in-pixel efficiency



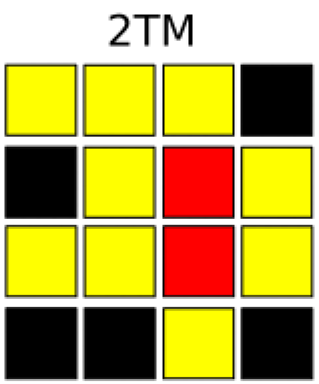
FZ-n
130V

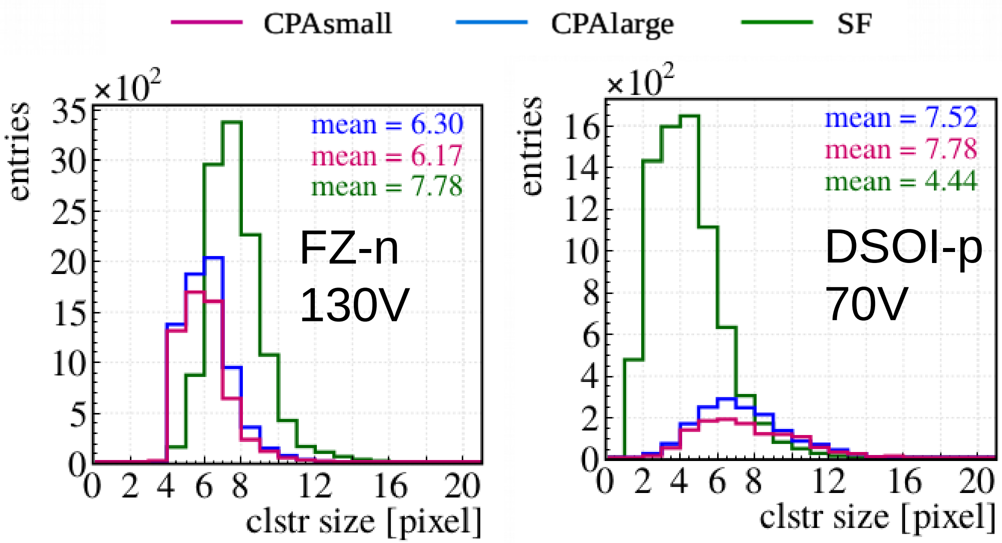


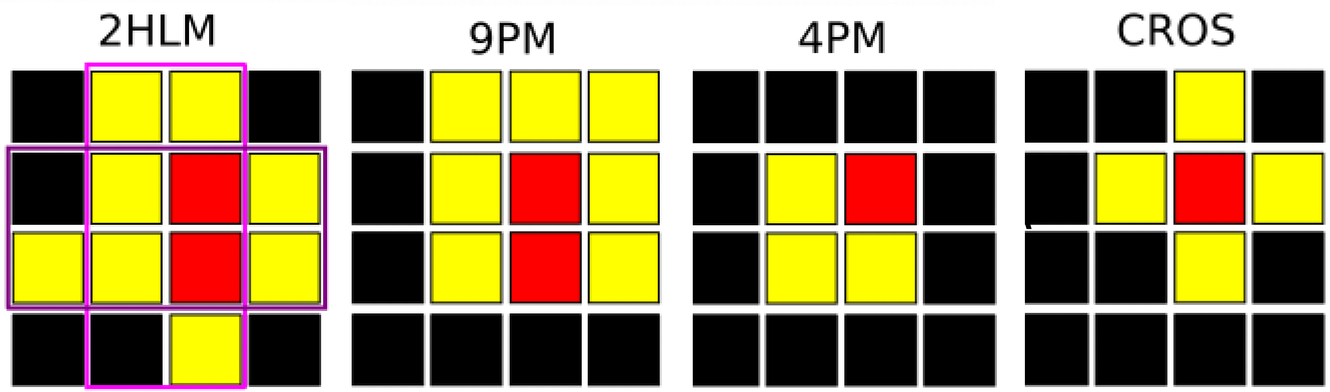
Cluster reconstruction

To check the sensitivity of spatial resolution to main cluster parameters like size, shape or SNR, analyses are done with several methods to find cluster. Two thresholds are used: high threshold – th_{seed} (red) and lower one – th_{neigh} (yellow). Different values of these theresholds are tried.

- 2TM - 2 thresholds method
- 2HLM - 2 highest lines (rows) method
- 9PM - 9 pixel method (only th_{seed})
- 4PM - 4 pixel method (only th_{seed})
- CROS - cross method (only th_{seed})

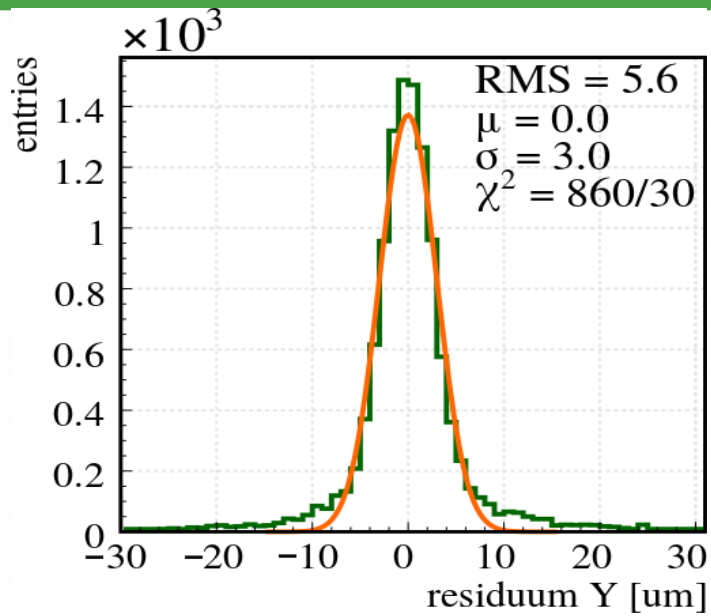




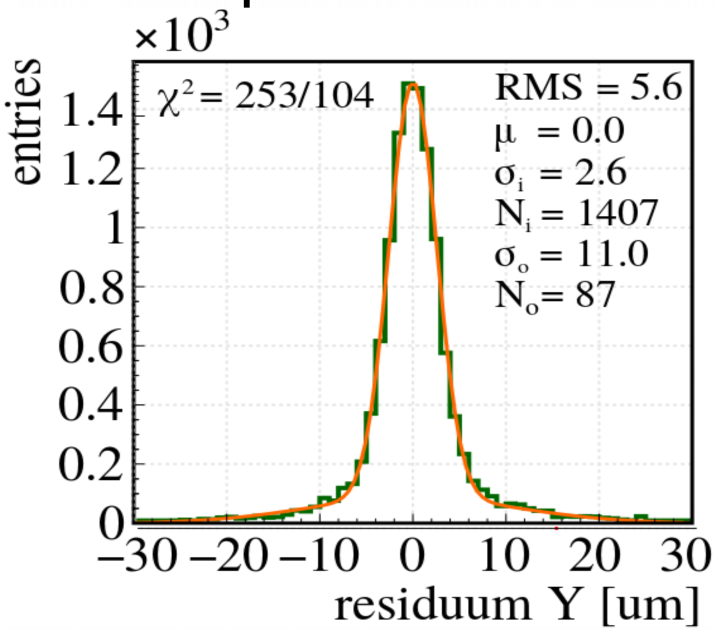


Spatial resolution

- Spatial resolution is calculated fitting gauss curve to the residuum distribution (difference between telescope and SOI position)
- Calculated raw SOI detector resolution is corrected for the telescope resolution (2um)
- Since the residuum distribution contains non-gaussian tail different fitting approaches may be used
- Examplary plots for SF matrix of FZ-n wafer at 130V bias are shown here for:
  - Single gauss fit to 95.5% of statistics
  - Fit of Sum of 2 gausses to the whole statistics
- For the above example, after telescope correction, one gets
  - 2.2um for single gauss
  - 1.7um for „inner" gauss sigma in 2-gauss fit
  - 5.2um taking RMS without fitting
- **In this work we show the results of single gauss fitting to 95.5% of the statistics, as was proposed by CLICdp collaboration**
- Analyses are ongoing, fitting procedure can still be modified...



After telescope correction σ=2.23um



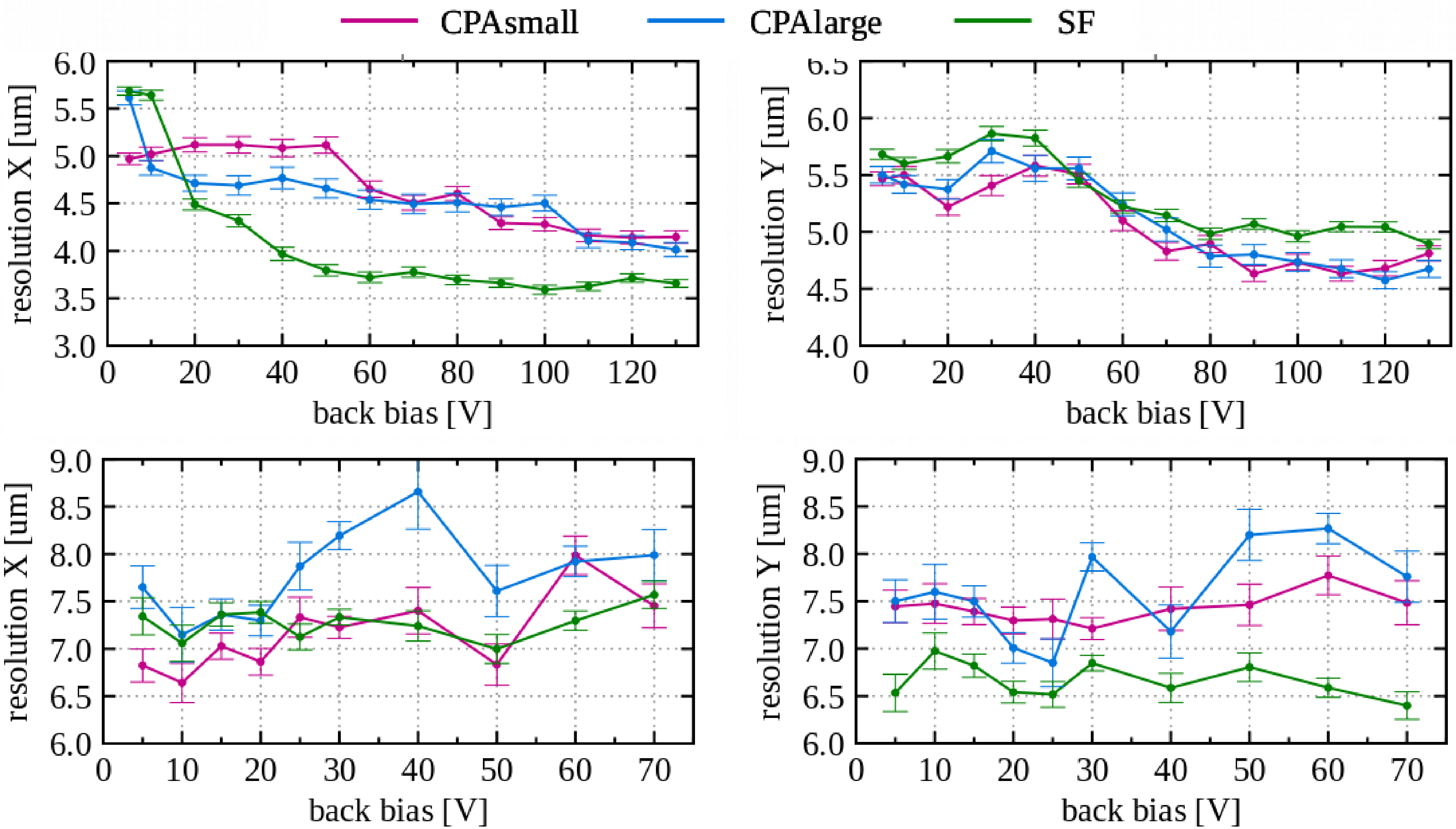
Corrected „inner" σ=1.67um

Spatial resolution - COG

First analyses of spatial resolution were done with Center Of Gravity (COG) method

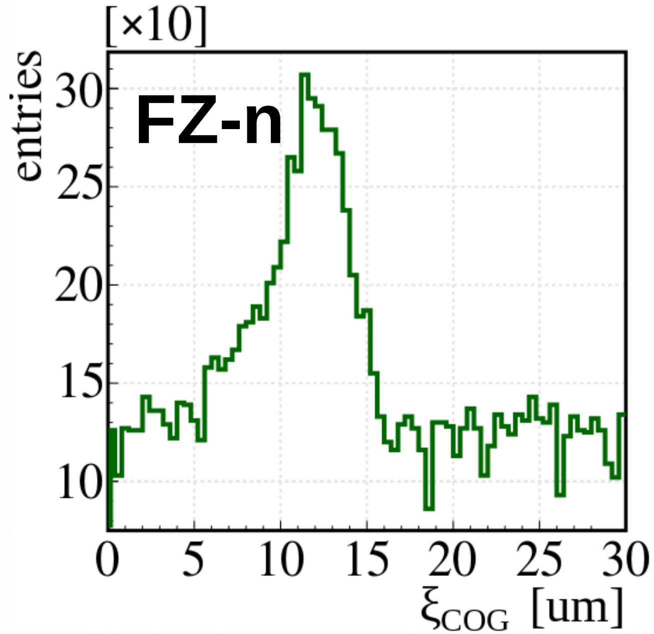
FZ-n
130V
CROS

DSOI-p
70V
CROS

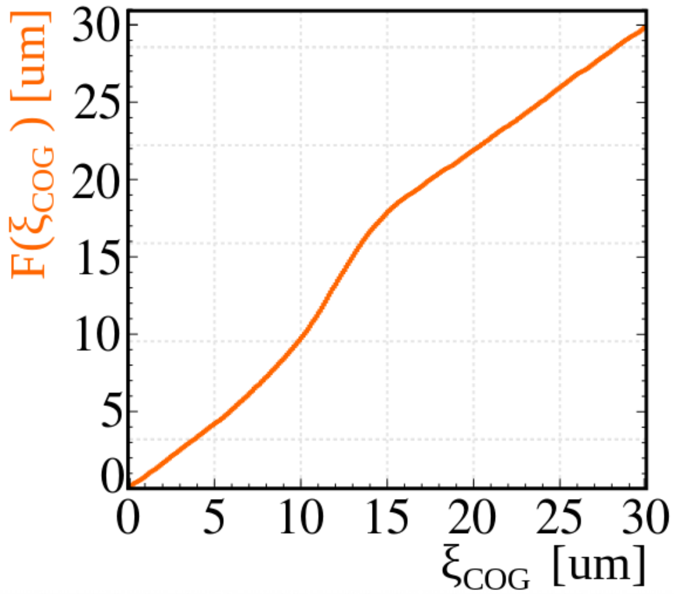


For FZ-n wafer ~3.5um, ~4.5um are obtained for „X”, „Y” direction at full depletion
For DSOI-p spatial resolution is worse than 6.5um in both directions

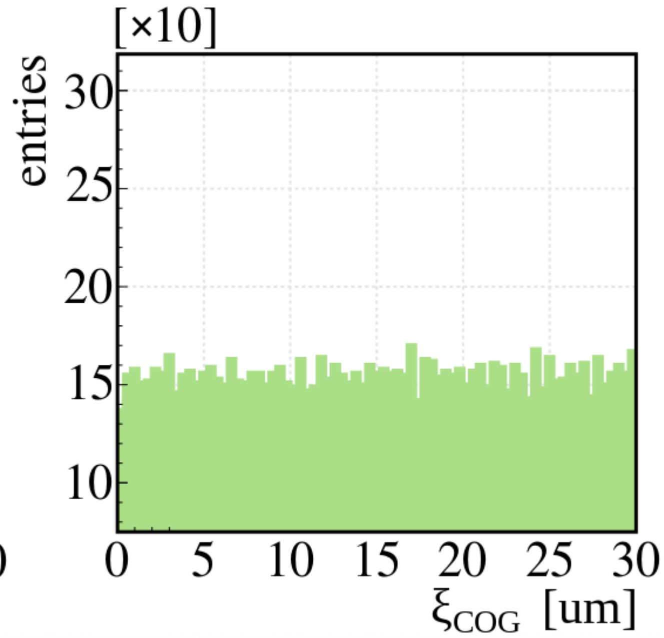
Distribution of COG hit x-position projected on pixel pitch



Cumulative function of distribution on left



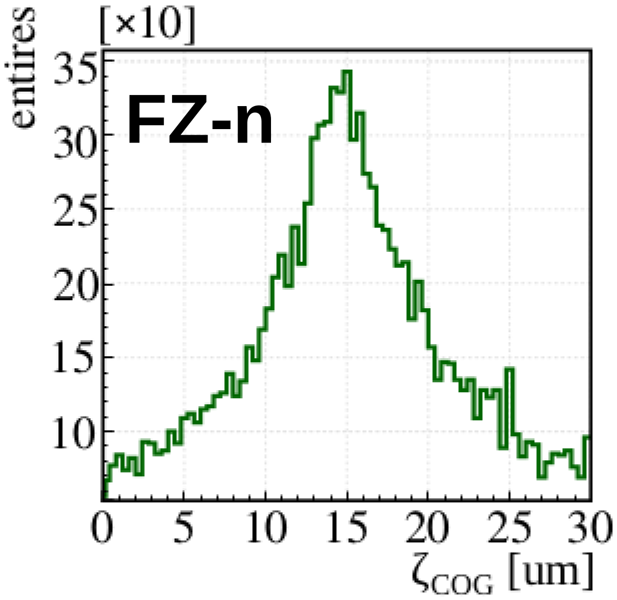
Distribution of ETA-corrected hit x-position projected on pixel pitch



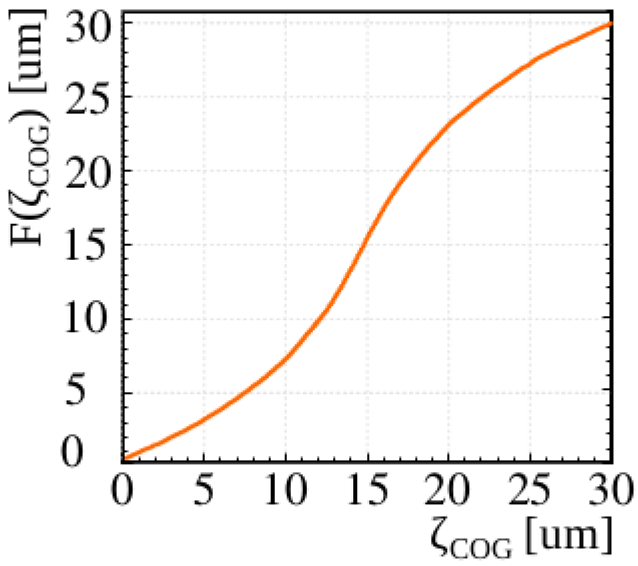
- Due to diffusion in sensor the charge sharing between neighbouring pixels is not linear
- Eta correction of hit position is proposed, projecting the COG hit position onto pixel pitch and assuming that the distribution of the projected hit position ξ_{COG} should be uniform
- After the correction, using eta cumulative function (middle plot), the initial projected hit position histogram (left plot) becomes uniform (right plot)
- Typically, one would expect the initial hit position histogram (left plot) to be symmetrical in respect to the center of pixel (15um). This is not the case for „X” direction
- Most probable explanation, confirmed by the inspection of detector layout, is the existence of parasitic crosstalk to „left” neighbour

Multi-pixel eta correction for „Y”

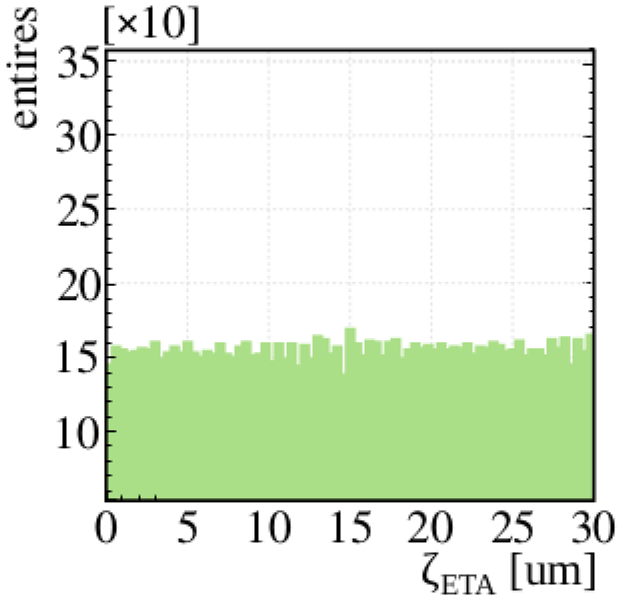
Distribution of COG hit y-position projected on pixel pitch



Cumulative function of distribution on left



Distribution of ETA-corrected hit y-position projected on pixel pitch



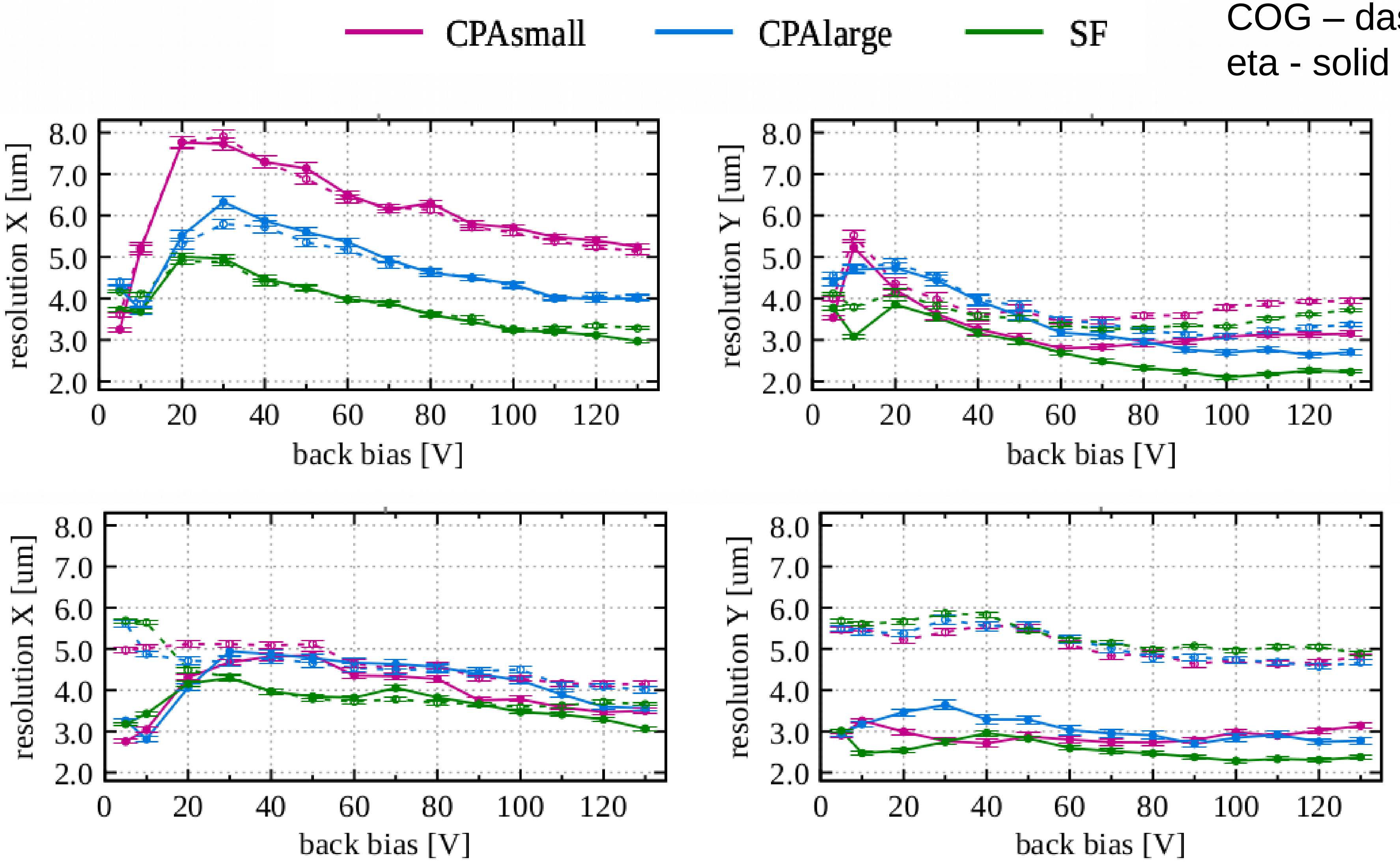
- Eta correction in „Y” direction is done in exactly the same was as in „X” direction
  - Using cumulative function (middle plot) a uniform distribution of the projected hit position ξ_{COG} (right plot) is obtained from the initial distribution of the projected hit position ξ_{COG} (left plot)
- In „Y” direction the initial distribution of the projected hit position ξ_{COG} is symmetrical about the pixel center, as one would expect from the symmetrical layout of the pixel

Spatial resolution - eta vs COG

COG – dashed
eta - solid

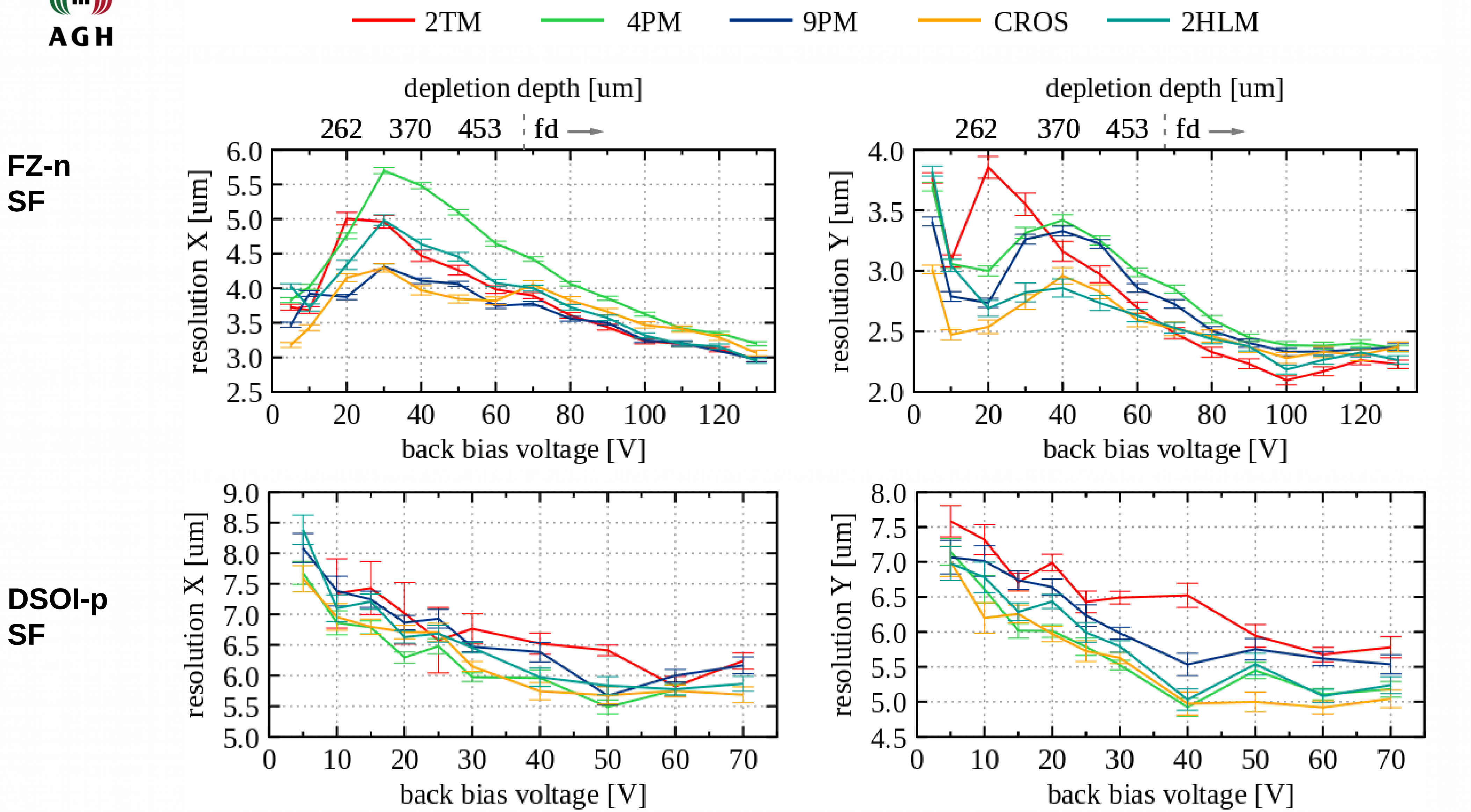
FZ-n
130V
2TM

FZ-n
130V
CROS



- For „Y” results with eta are definitely better, for „X” they are not, probably due to crosstalk effect.
- SF matrix (highest SNR) gives the best resolution.

Spatial resolution – clustering methods



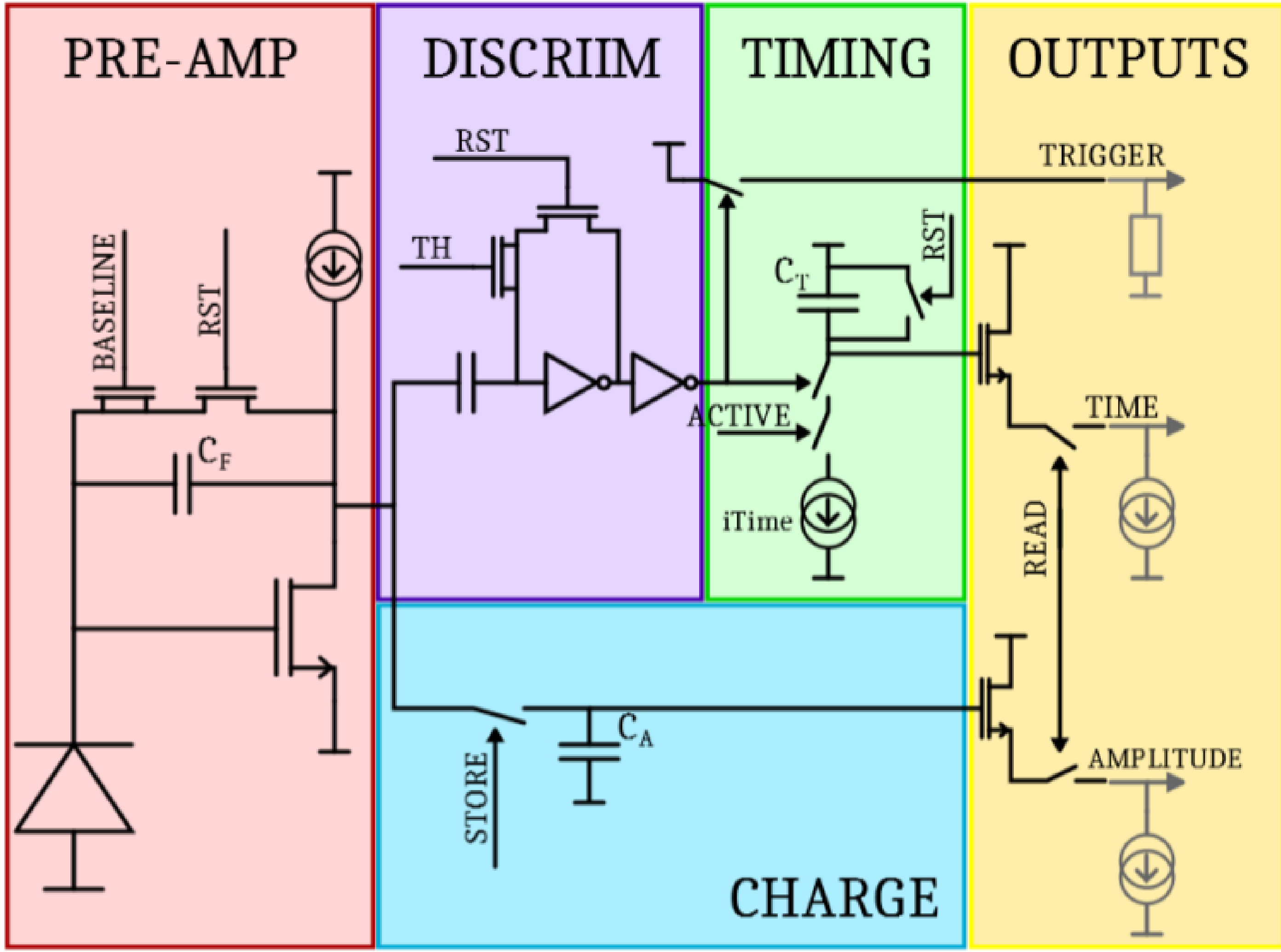
Trends similar for all methods, absolute values may differ significantly, the best resolution not always obtained by the same method, although CROS is a good candidate. Needs more studies...

CLIPS detector for CLIC

CLIPS
CLIc Pixel SoI

Main features

- targeting CLIC vertex detector resolutions specifications (time: 10ns, spatial: 3um)
- 3 matrices, each 64x64
- 20x20 um^2 pixel pitch
- Anaougue information about time and amplitude stored in capacitors on each pixel → no need for fast clock distribution
- snapshot readout between bunch trains
- analogue multiplexing to external ADC
- external readout control possible



Prototype of CLIPS chip already designed and fabricated. Test setup needs to be developed...

Summary

- Prototype SOI monolithic pixel structures have been developed and studied in lab measurements and on beam line
- Good efficiency >97% has been measured
- Measurements show that for 30x30 um^2 pixel detector the spatial resolution of 2-2.5 um can be achieved
- More analyses still needed for better understanding of clustering methods, etc...
- New, CLICdp dedicated, prototype pixel detector – CLIPS has been developed and fabricated

Thank You for Attention

Back-up

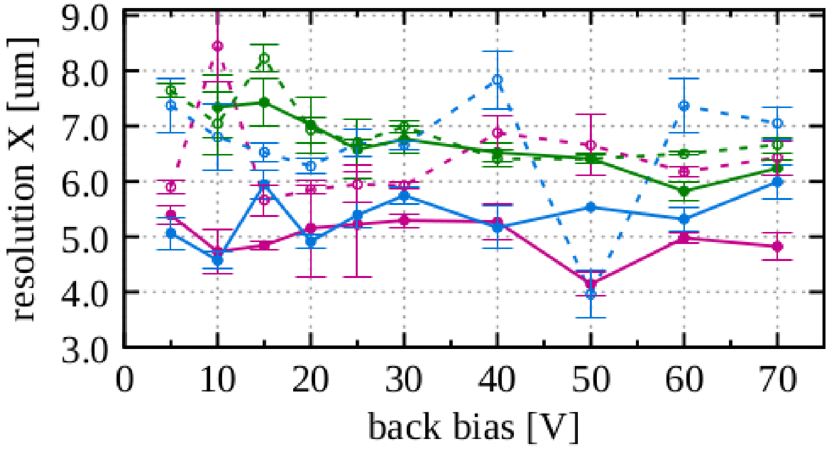
....

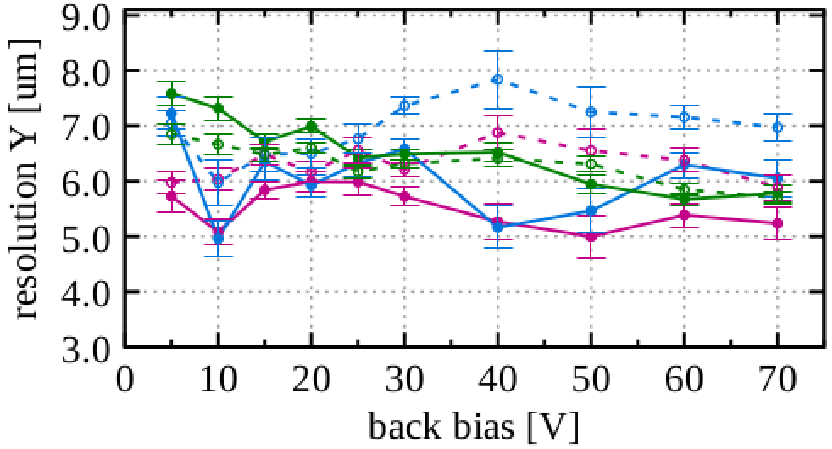
Spatial resolution eta vs COG

CPAsmall CPAlarge SF

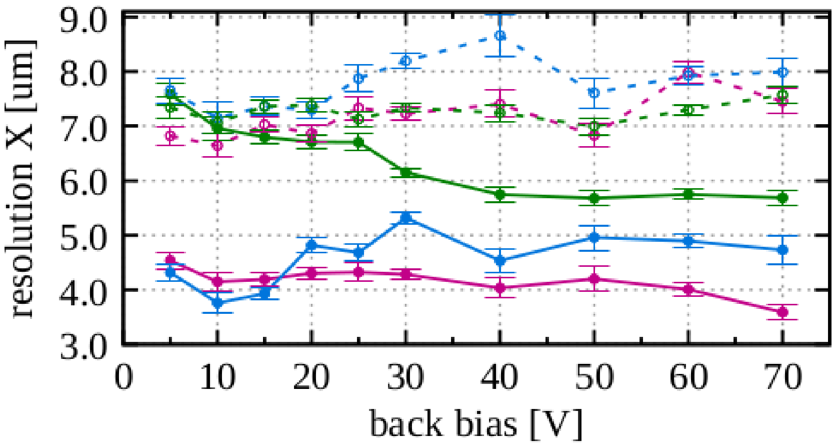
COG – dashed
eta - solid

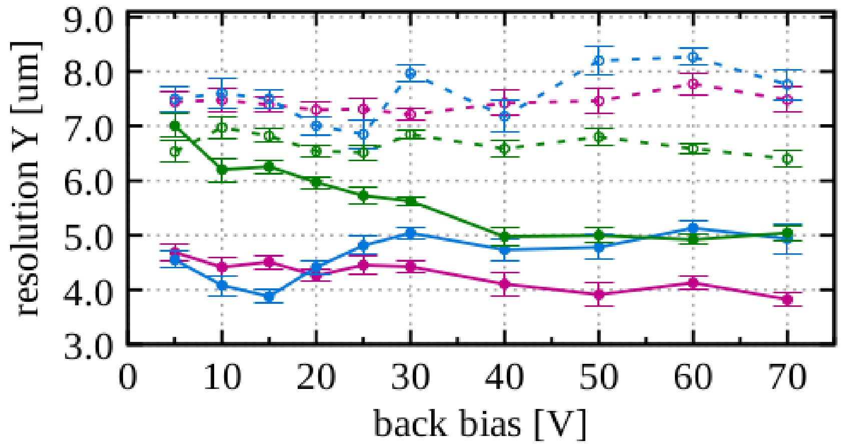
DSOI-p
70V
2TM





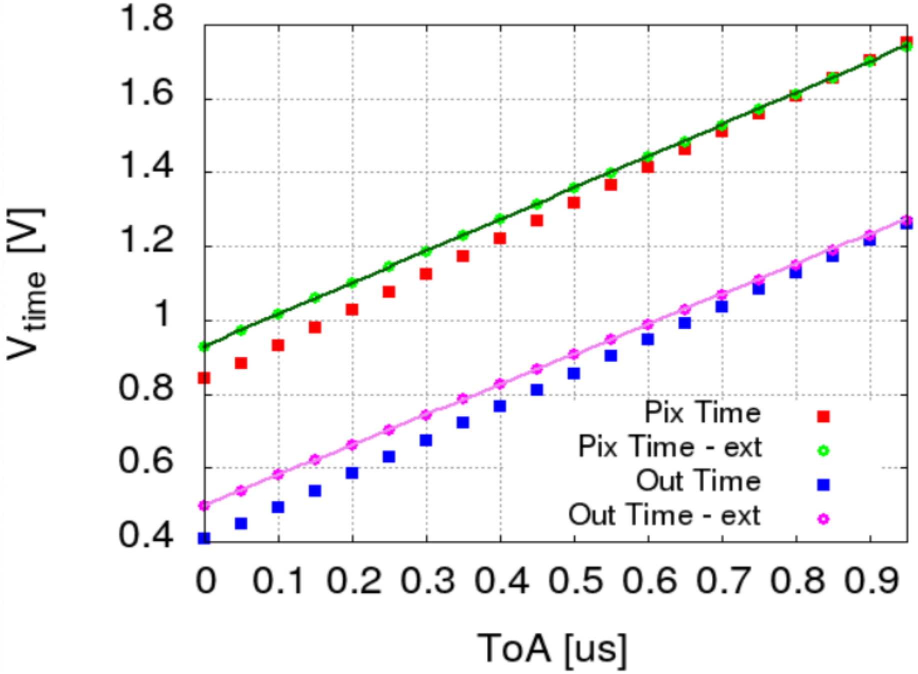
DSOI-p
70V
CROS

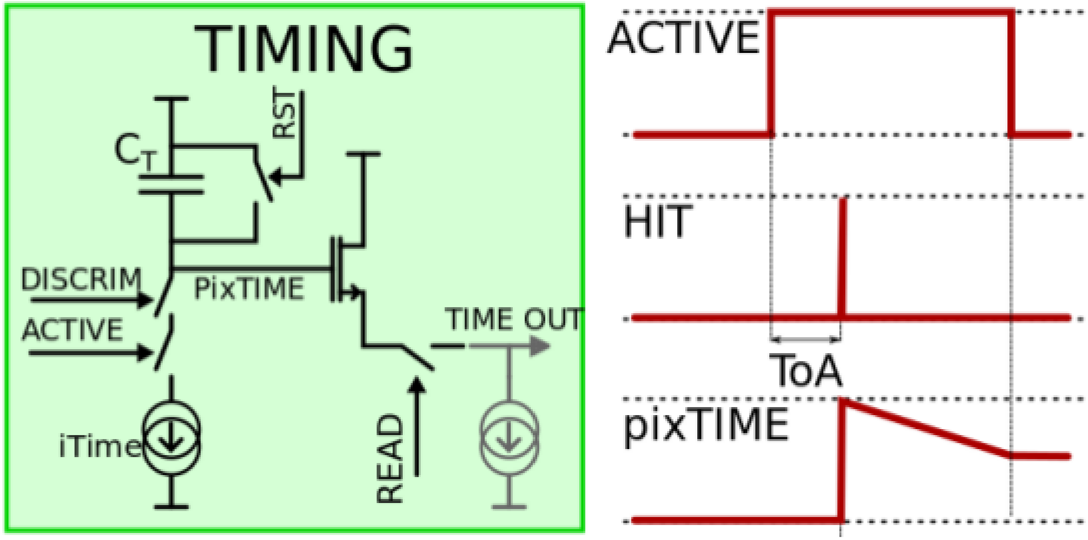


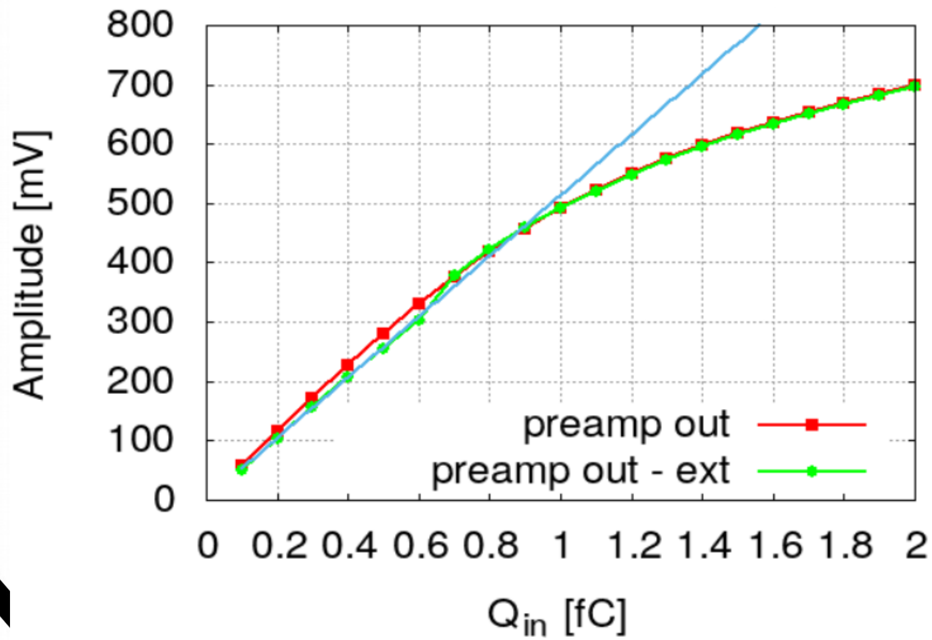


- For „Y” eta definitely better.

CLIPS



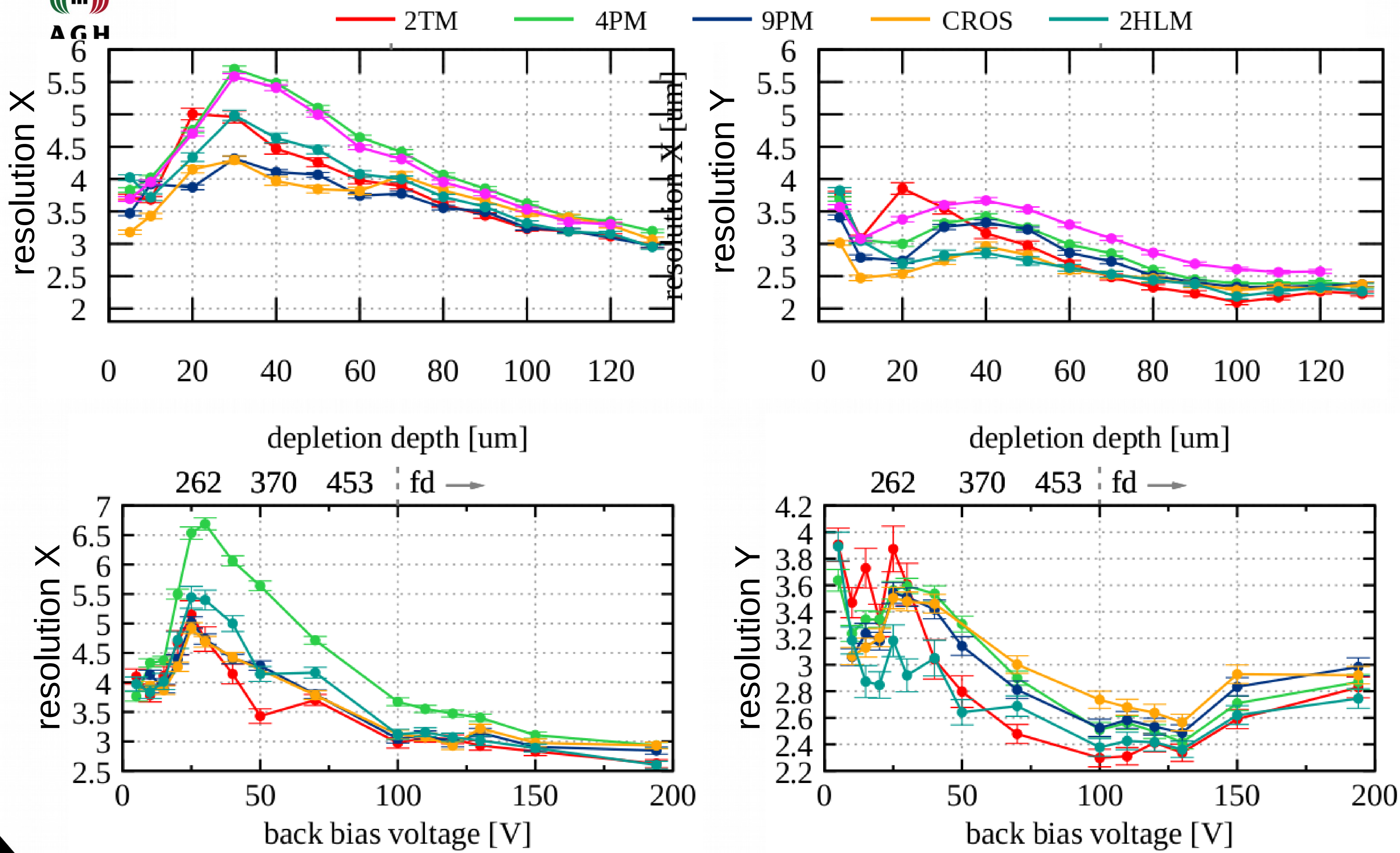




- Active time is adjustable (from 100 ns – 300 us)
- Timing resolution depends on active time
- Simulations done for 1 us active width
- Nonlinearities below 0.5% (below 5 ns)

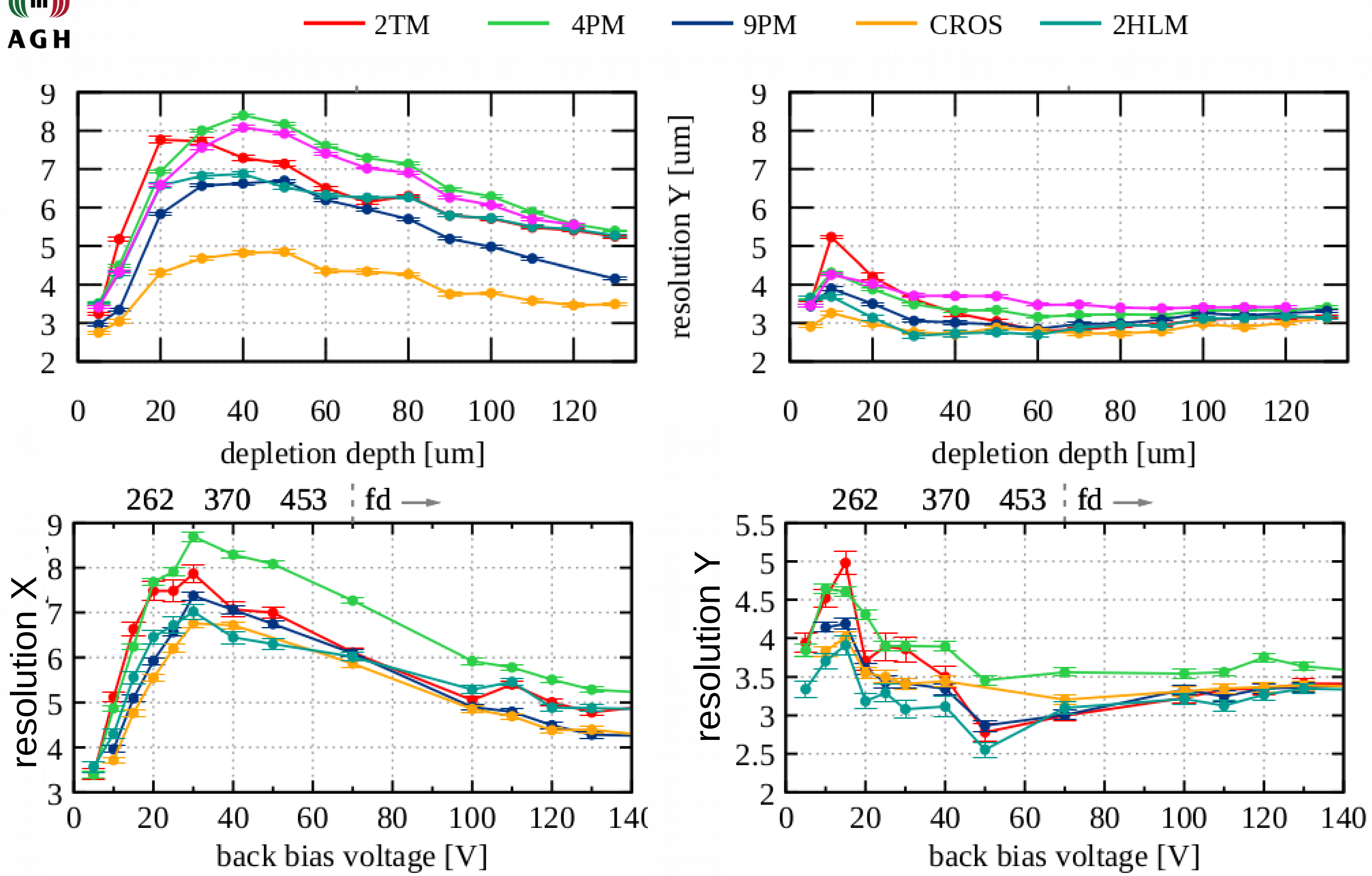
- After sensor thinning to 100 um expect signal for MIP is around 1fC
- Linear dynamic range up to ~1fC
- Above 1fC signal starts to saturate

Spatial resolution FZ-n prot1vs 3 SF



AGH

Spatial resolution FZ-n prot1vs 3 CPAsma



Spatial resolution FZ-n prot1vs 3 CPAlarg