The MIMOSIS pixel sensor for the CBM Micro-Vertex Detector and beyond

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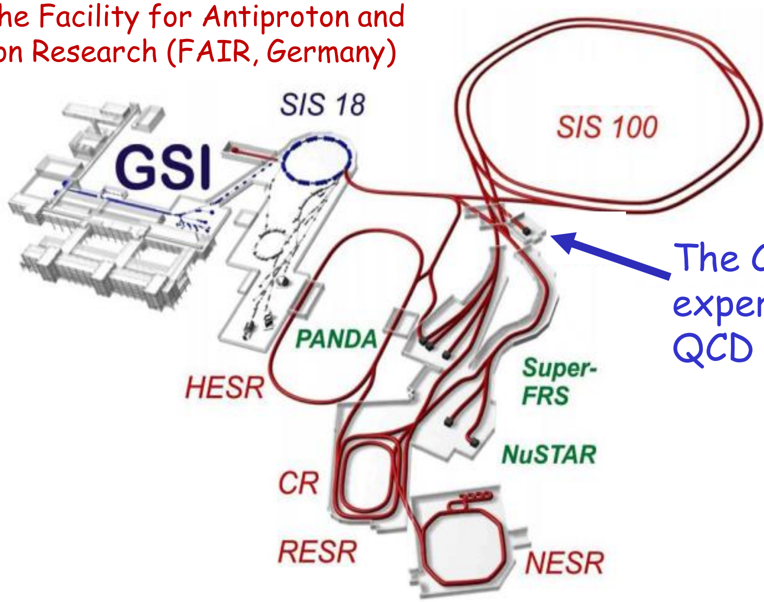
- CBM experiment and MVD
- Requirements for MVD and it's sensor (MIMOSIS)
- Description of MIMOSIS sensor and technology options
- Results of test of full scale prototype (MIMOSIS-1) and small prototypes (CE_18-x)
    - ✓ Charge collection efficiency, gain, timing parameters
    - ✓ Detection efficiency, fake hit rate
    - ✓ Resolution, cluster size
- Conclusions, future plans

The Compressed Baryonic Matter experiment @ FAIR

The Facility for Antiproton and Ion Research (FAIR, Germany)

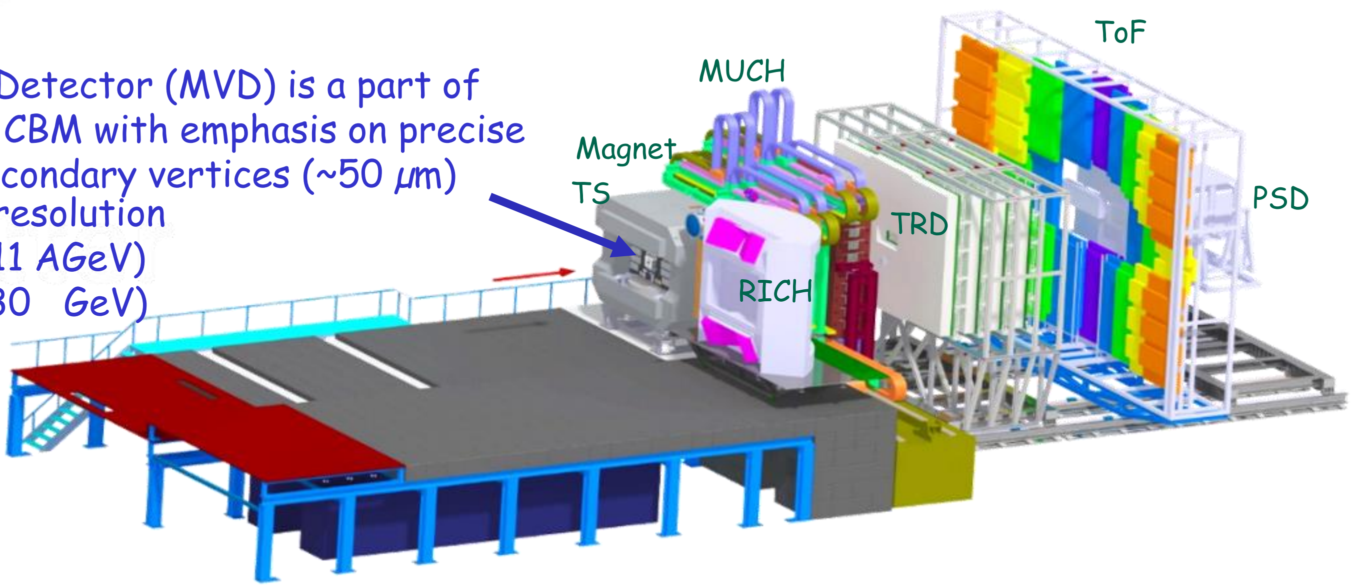


The Compressed Baryonic Matter (CBM) fixed target experiment will explore the properties of high-density QCD matter

The CBM detector is designed to measure the collective behavior of hadrons, together with rare diagnostic probes such as multi-strange hyperons, charmed particles and lepton pairs with unprecedented precision and statistics.

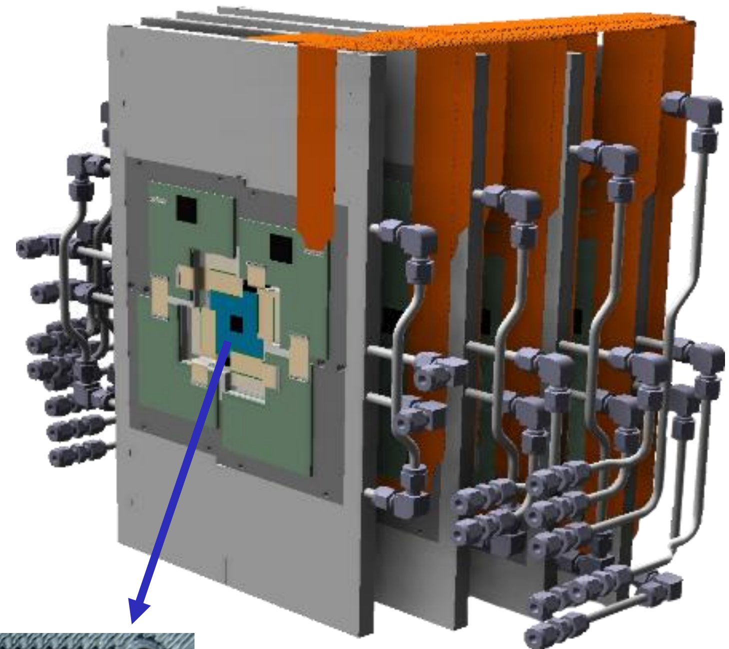
The Micro-Vertex Detector (MVD) is a part of tracking system of CBM with emphasis on precise identification of secondary vertices (~50 μm)

- ~ 5μm spatial resolution
- 10^5 Au+Au/s (11 AGeV)
- 10^7 p+Au/s (30 GeV)



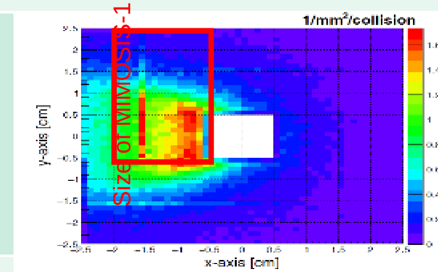
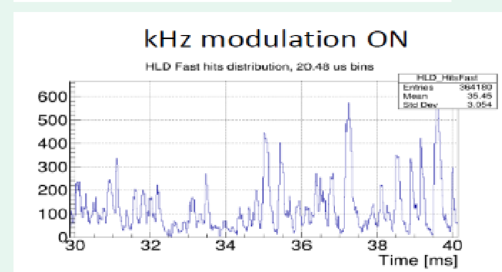
Micro Vertex Detector

- 4 planar detector stations at 5, 10, 15 & 20 cm downstream the target
- Will be equipped with ~300 CMOS sensors (MAPS)



MIMOSIS-1 chip – full scale prototype of one CMOS sensor
✓Matrix dimension: 1024 columns. X 504 rows
✓Pixel dimension: 26.88 μm (height) x 30.24 μm (width)
✓Fabricated with Tower Semiconductor, 180 nm technology

MIMOSIS: requirements for the sensor

	Target requirement	comments/complications
Spatial resolution	~5 µm	
Radiation length	~ 0.3 % X_0 (first station) ~ 0.5 % X_0 (other stations)	thickness ~50 µm
Power dissipation	< 200 mW/cm²	operates at vacuum - cooling
Operation temperature	- 40°C to +30°C	temperature gradient 5 K
Heavy Ion tolerance	10 Hz/mm²	
Rate (average/peak)	150/700 kHz/mm²	Fake hit rate < 10^{-5} pix / 5 µs
Time resolution	~5 µs	
Radiation hardness	~ $7\text{x}10^{13}$ n_{eq}/cm² ~ 5 Mrad	radiation gradient 100% over one sensor area
Occupancy gradients in space		 (MVD TDR)
Beam intensity fluctuations in time		 (HADES, GSI)

MIMOSIS: considerations for the sensor design

- The existing sensor (ALPIDE for ALICE experiment, CERN) can provide the required time and spatial resolution, so the pixel front end circuit can be inherited from that sensor

- The requirements (and hence the design goal) for ALPIDE chip where factors of less demanding in terms of hit rate (1/50) and radiation tolerance (1/10), so the digital readout circuitry has to be re-designed

- CMB DAQ will run continuously (without trigger), which makes it a challenge to handle with continuous data flow (ALPIDE was not designed for that mode of operation)

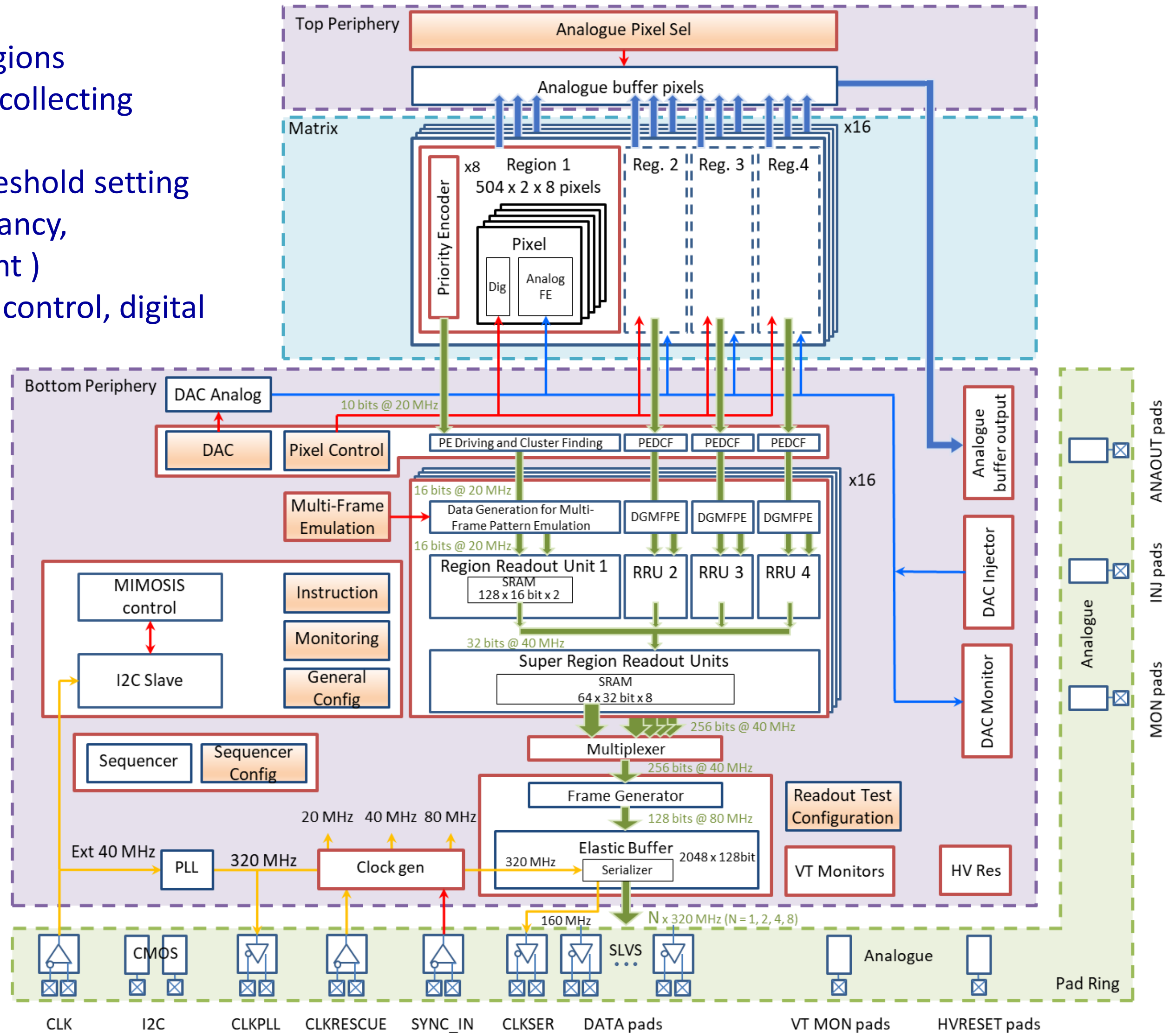
✓ In 2018, MIMOSIS-0 chip was designed and tested in order to demonstrate the concept (FE + readout)

✓ In 2020, full scale and size chip, MIMOSIS-1 is designed with several pixel variants/technology options, tests and validation are in progress, -> validation / improvements for final prototype MIMOSIS-2

✓ MIMOSIS-2 design is ongoing, submission in 2022

MIMOSIS (MIMOSIS-1) chip diagram

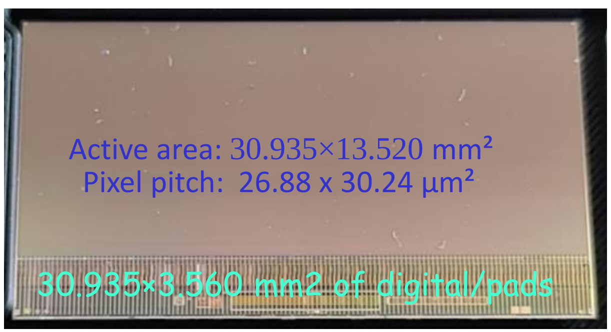
- Top Periphery: one line of pixels with buffered output – test performances of FE
- Pixel array: 504 x 1024 pixels in 64 regions
  - 2 AC and 2 DC coupled charge collecting diode pixel flavors
  - 4 regions with independent threshold setting (compensate un-uniform occupancy, irradiation, temperature gradient)
- Bottom periphery: Biasing DACs, slow control, digital readout, PLL



F. Morel, TIPP 2021

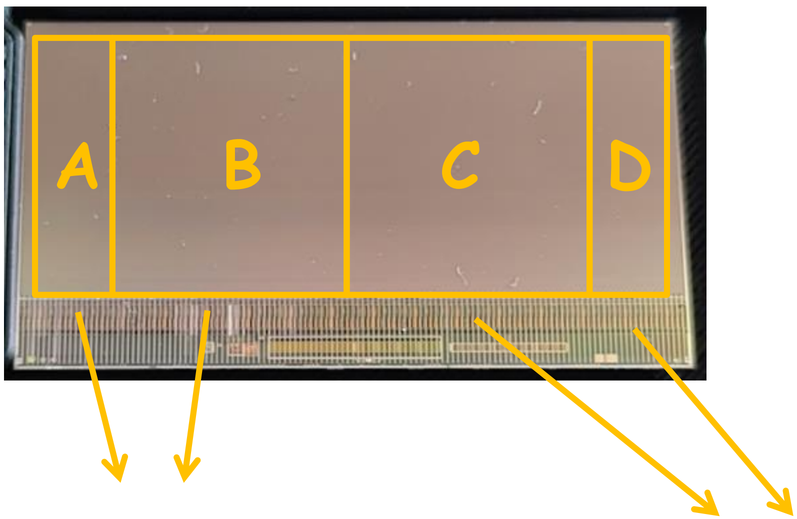
MIMOSIS-1 (in 2020): full scale prototype

Chip dimension: 31.150 × 17.250 mm²
Thickness 50 µm

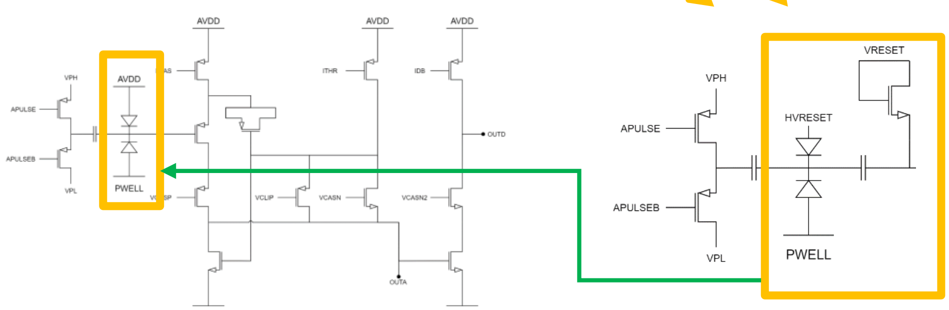


MIMOSIS-1: sensor and front end

There are four pixel versions in MIMOSIS-1 chip:
- B and C is baseline designs
- A and D with some transistors modifications (increased L) for optimisation of mismatch dispersion and radiation tolerance



In analogue part, one difference from ALPIDE is the introduction of AC coupled sensing node.
The motivations are:
- increase radiation tolerance
- flexible control on depletion ("Study of the depletion depth in a front side biased CMOS pixel sensors", *J. Heymes et al 2019 JINST 14 P01018*)
- depletion without back substrate bias and/or process modification

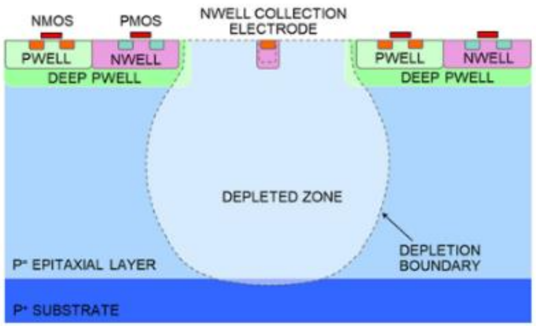


- Larger parasitic capacitance…

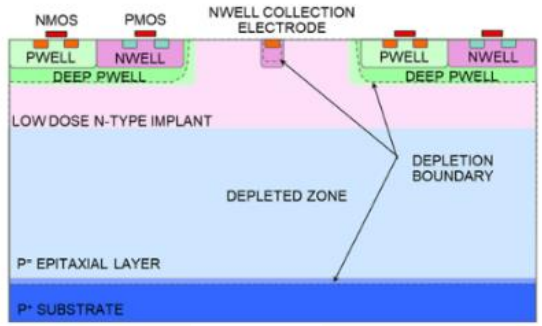
A and B: DC coupled FE , amplifier/discriminator for pixel is inherited from ALPIDE FE (*D. Kim et al 2016 JINST* ***11*** *C02042*)

C and D: change sensing element to AC coupling, same FE amplifier

MIMOSIS-1: technology options

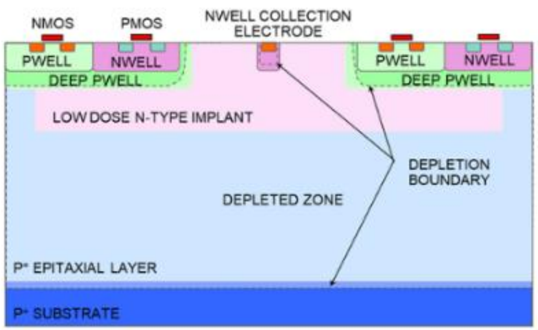


Split1

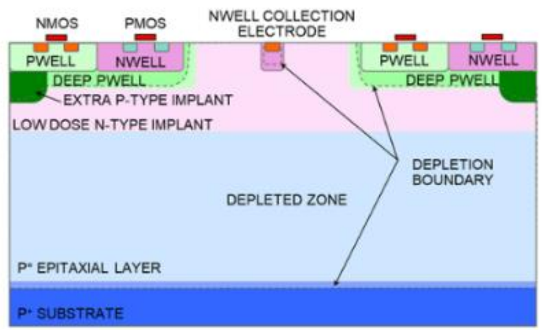


Split2

MIMOSIS-1 fabricated in 0.18 µm technology with several technology options (splits 1 to 6) in a view to optimize the performances for CBM-MVD and explore beyond…

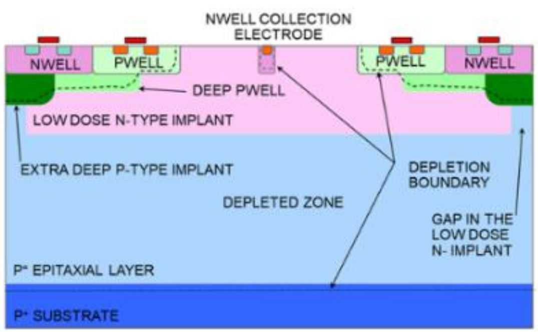


Split3



Split4

"FASTPIX: sub-nanosecond radiation tolerant CMOS pixel sensors", W. Snoeys et al, ATTRACT 2020



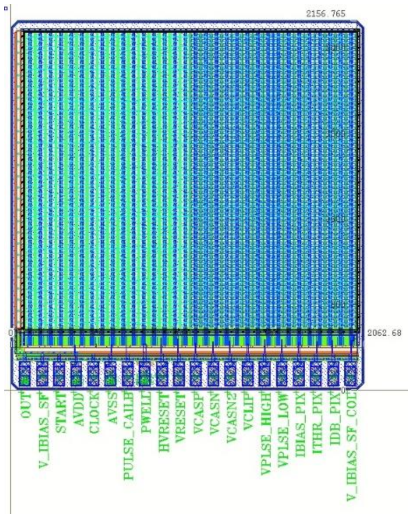
Split5 and Split6 (doping modification)

The results will be presented for split1, split3, split4 and split5

Small scale FE prototypes CE_18_xx

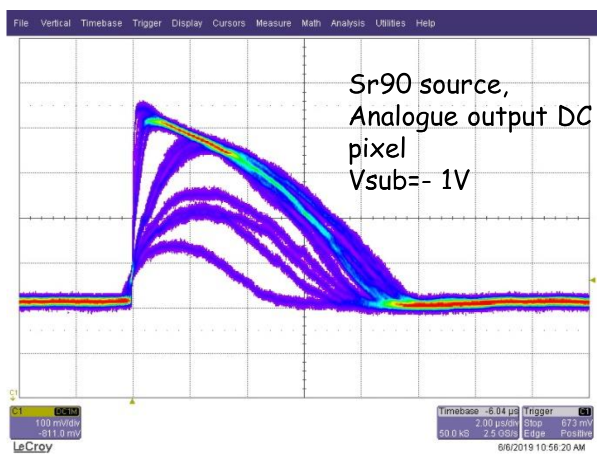
Motivation: test only FE/sensing node circuit in a simple way:

- due to system complexity, not all FE options or splits can be designed/tested in large scale prototype
- sensing node (and FE) calibration with ^{55}Fe radioactive source -> parasitic C/injection verification/tuning
- rolling shutter architecture: possibility to measure charge sharing (analogue amplitudes) -> technology options
- make biasing conditions phase space scan -> find optimal operating conditions for large scale chip FE
- measurement of amplifier gain/noise and discriminator performances

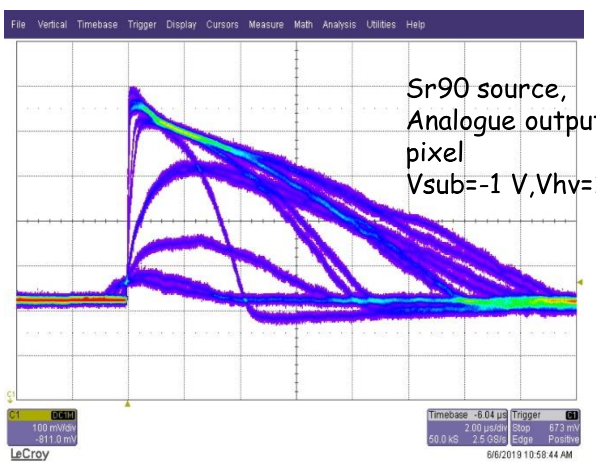


CE_18_xx chip:

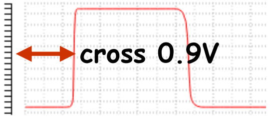
- 2 mm x 2 mm
- 64 x 64 = 4096 pixels
- multiplexed analogue output – charge sharing
- biases externally set – more freedom w.r.t. large scale chip



Sr90 source,
Analogue output DC pixel
Vsub=- 1V

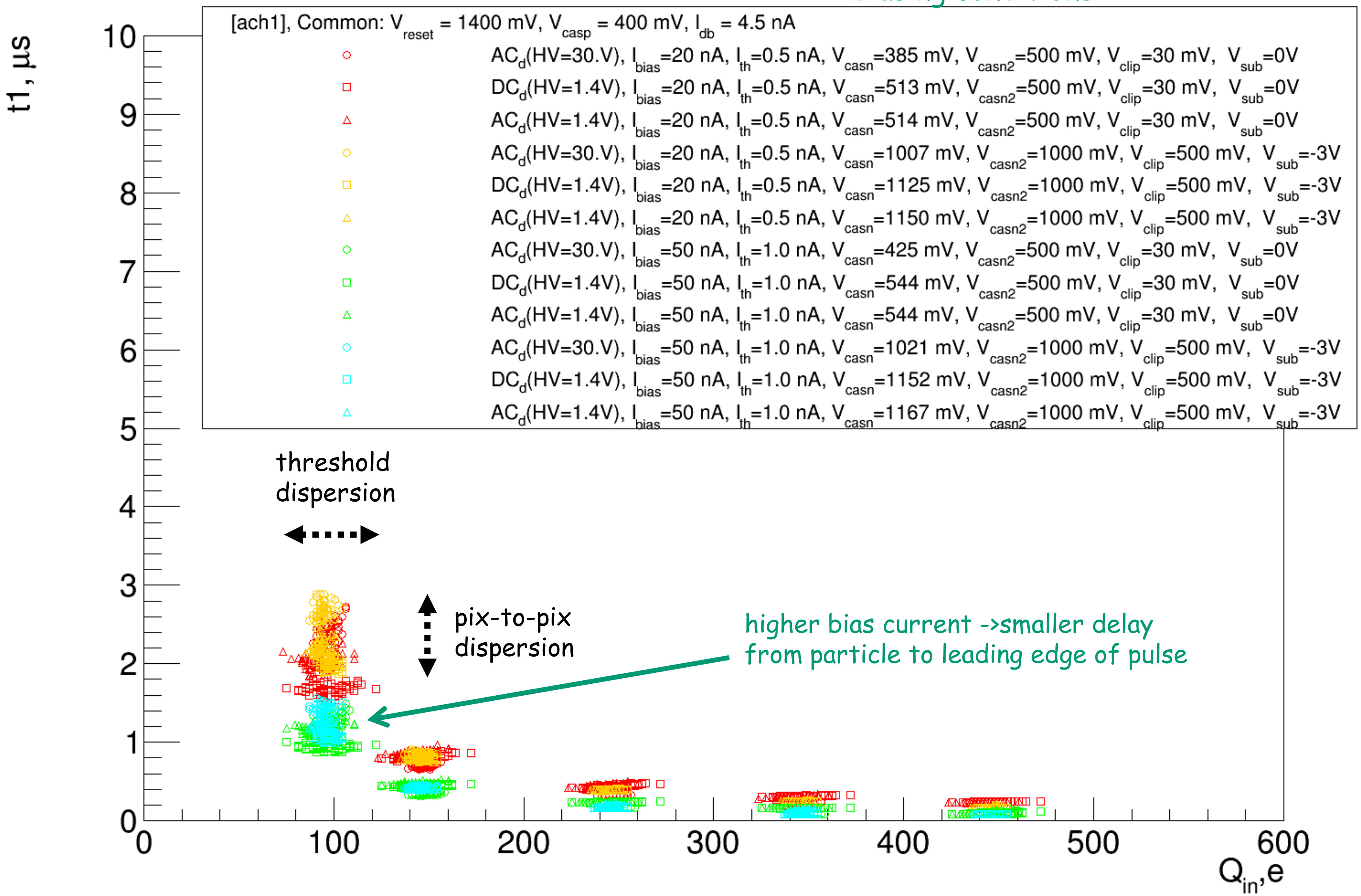


Sr90 source,
Analogue output AC pixel
Vsub=-1 V,Vhv=10 V

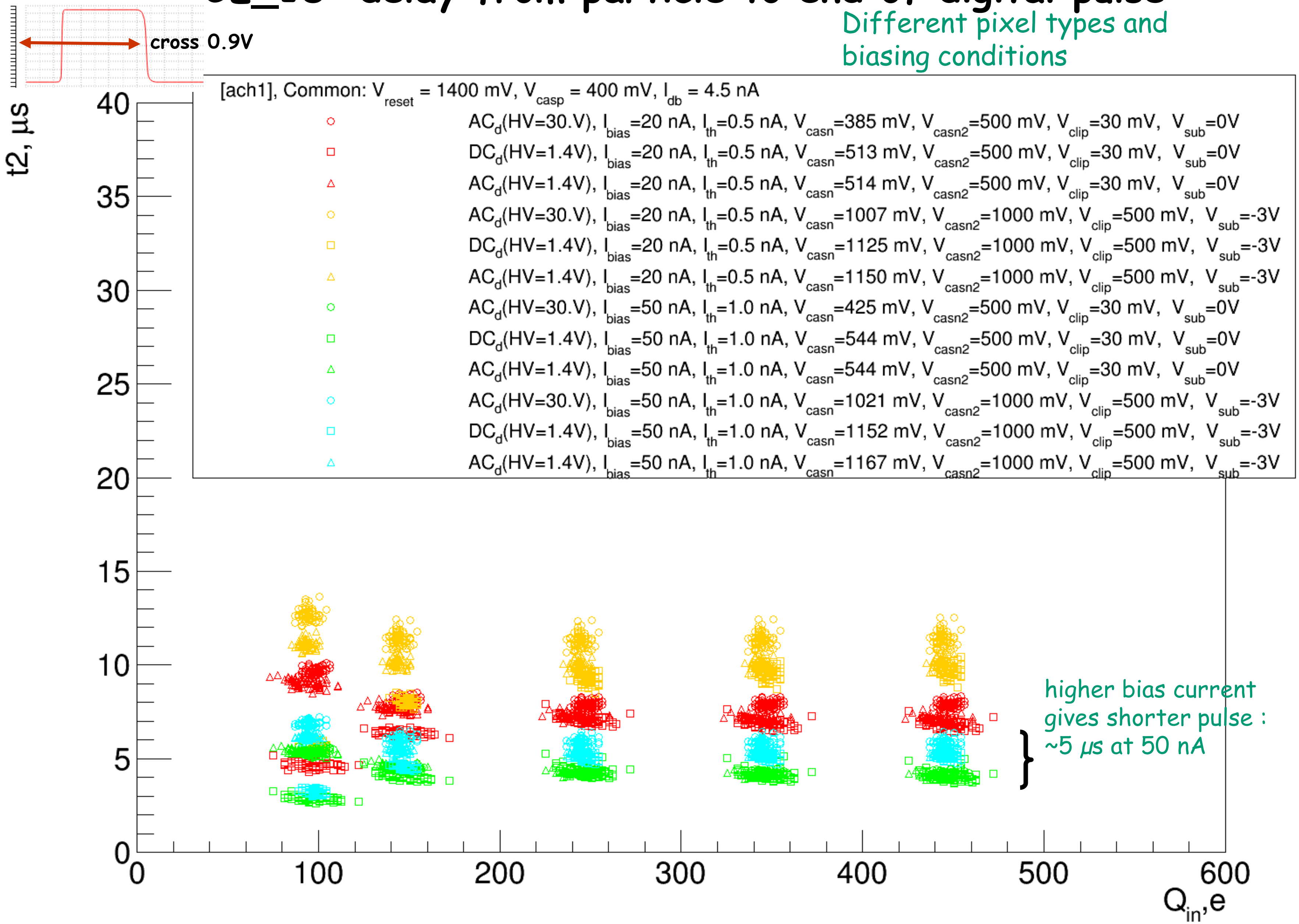


CE_18: delay from particle to digital signal

Different pixel types and biasing conditions



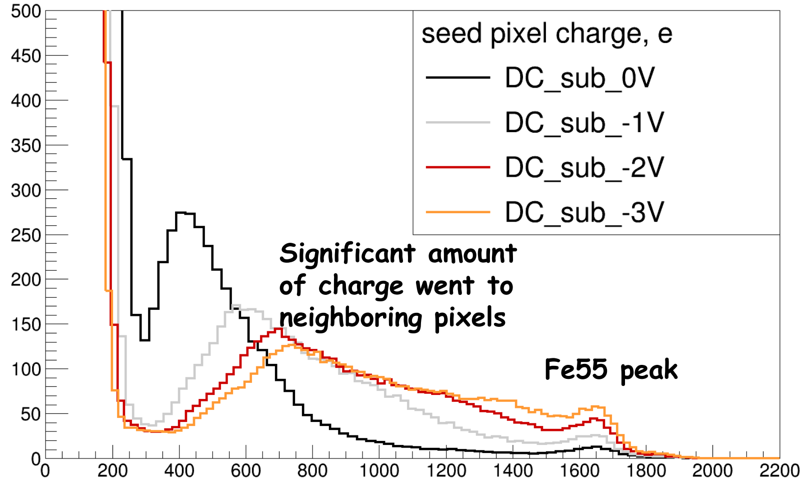
CE_18: delay from particle to end of digital pulse



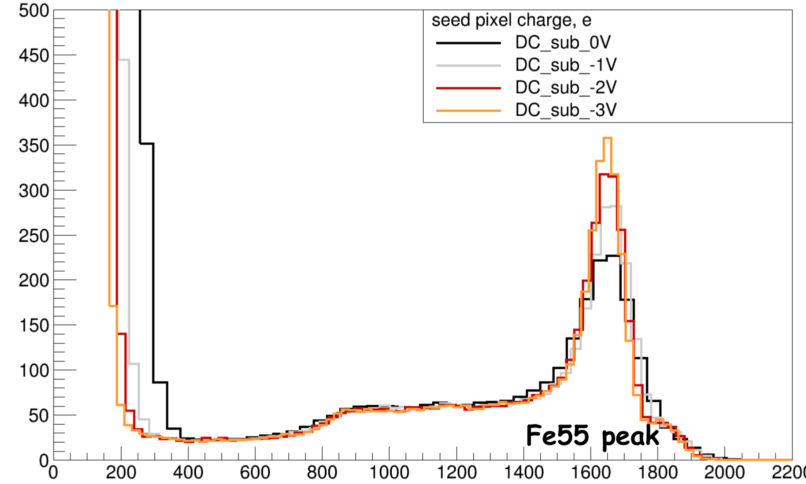
CE_18: charge collection assessment for technology splits

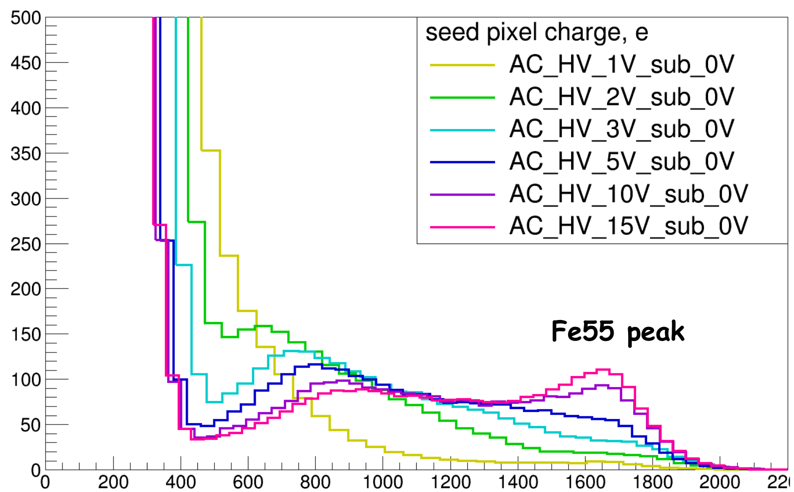
^{55}Fe source response spectrum, (e), seed pixel

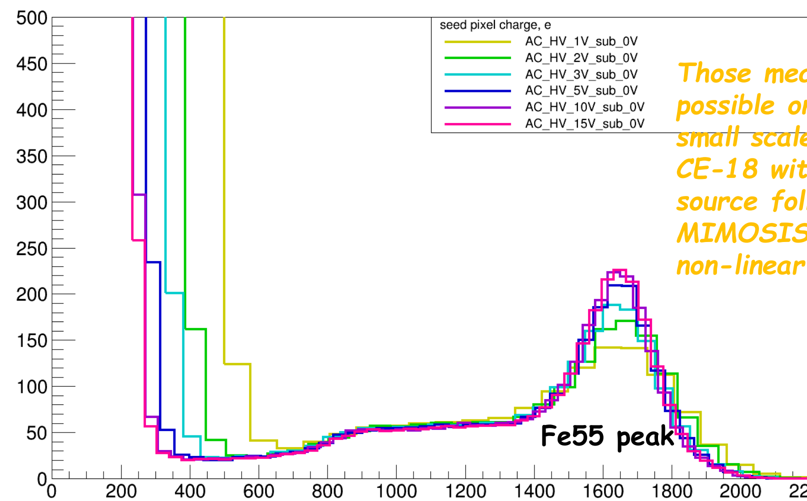
Split1



Split5



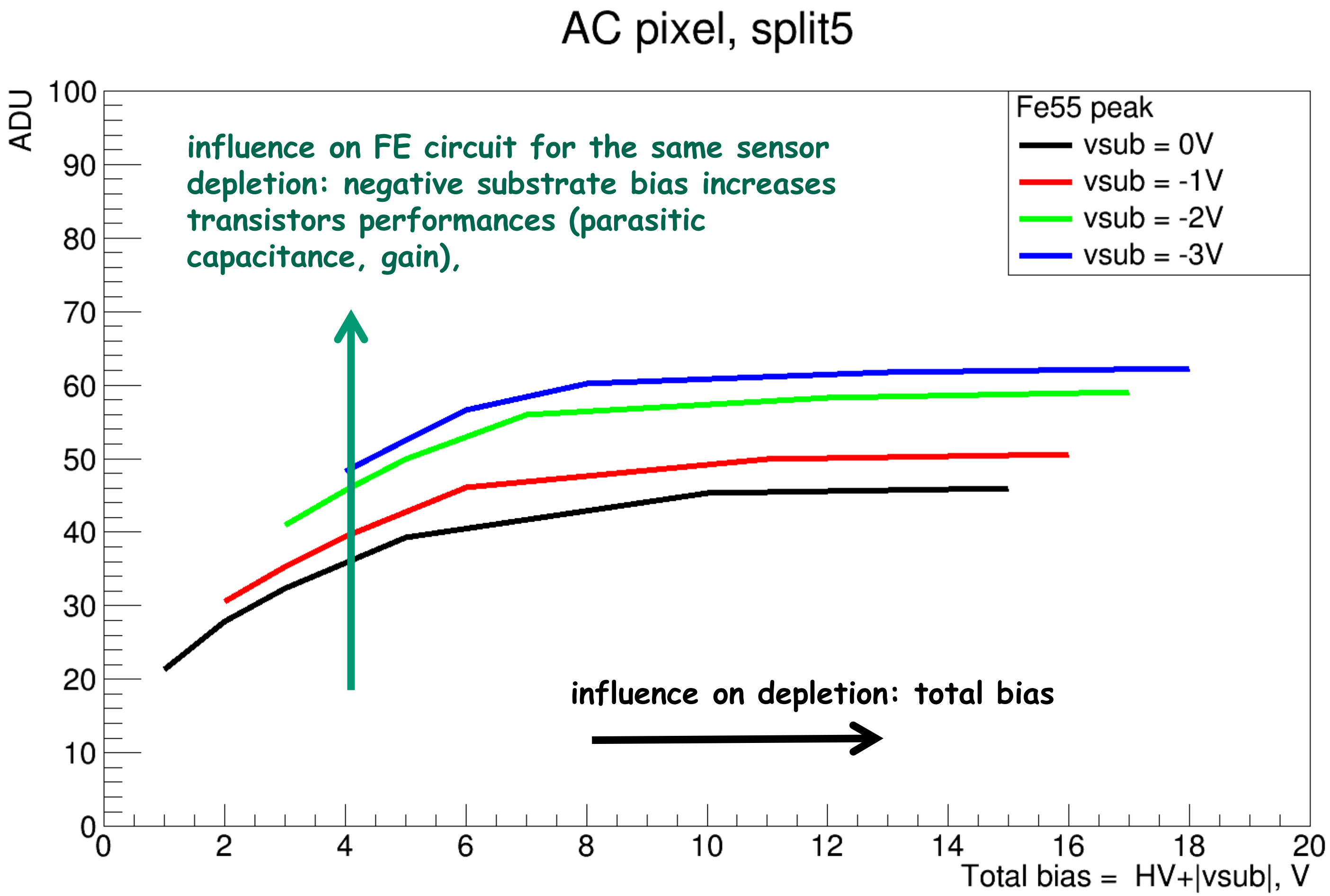


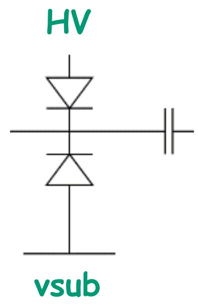


Those measurements possible only with small scale prototype CE-18 with simple source follower, while MIMOSIS-1 FE is non-linear

Split5 w.r.t Split1: almost no charge sharing at moderate voltages – everything is collected in seed pixel, full depletion?

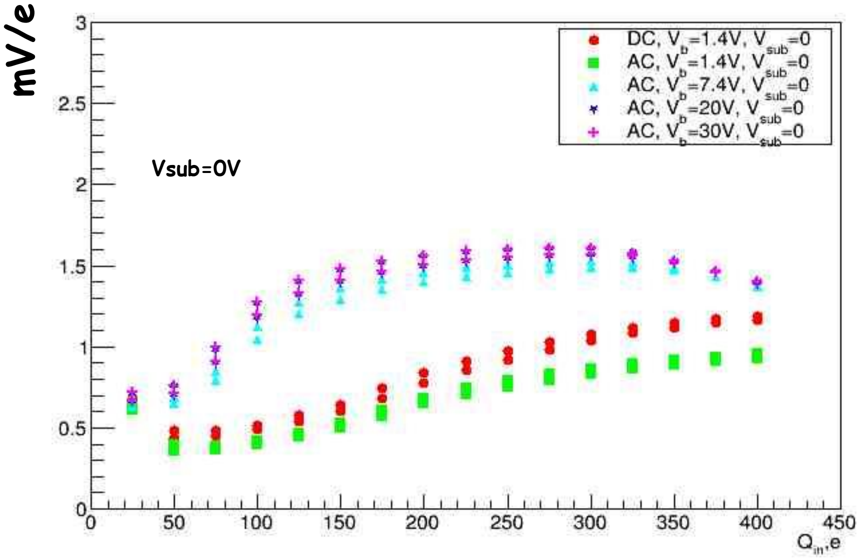
CE_18, AC pixel: disentangle effects: depletion voltage and substrate bias





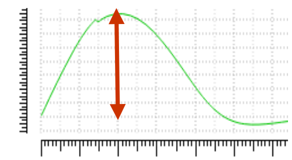
- Depletion: total bias = HV + |vsub| -> lower detector capacitance
- FE circuit: vsub -> better transistors parameters and lower detector capacitance

CE_18: HV value estimation for AC pixel with FE from MIMOSIS-1

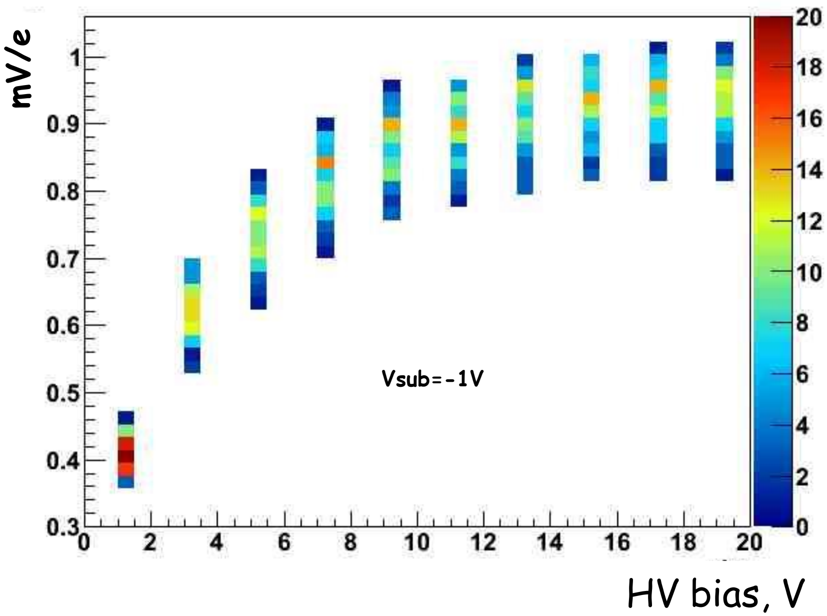


1. From HV = 1.4 V to 7.4 V AC pixel increases gain by factor of ~2 and becomes better than DC pixel
2. Going for 20 will increase ~10 % only
3. No difference between 20 V and 30 V

gain = peak/Qin, mV/e



AC pixels gain: Qin=150e



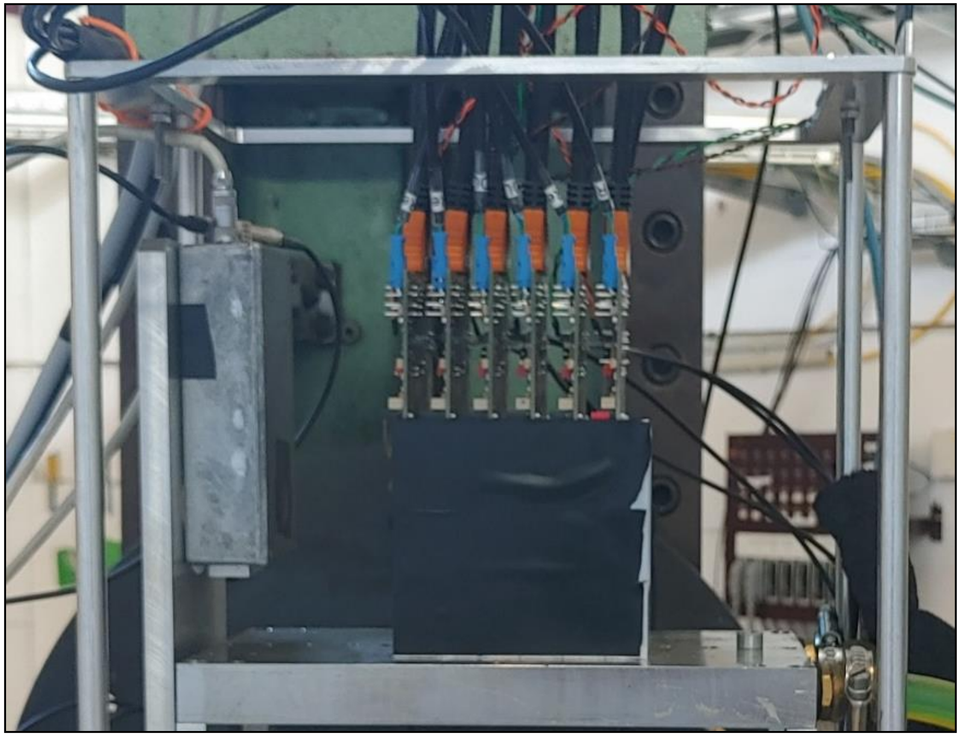
After ~10 V gain reaches plateau

Conclusion for HV: ~10 V seems to be reasonable value for AC pixels

MIMOSIS-1: beam test

The setup:

- ✓At DESY, beam energy 3 GeV, 5 GeV
- ✓6 detector planes at 15 mm distance: split 1, V_{sub} = - 3 V, Vhv=10 V
- ✓track precision: ~2.5 μm on DUT, 2 DUT in the middle
- ✓temperature stabilized (coolant T = 15°C)



What is tested / settings:

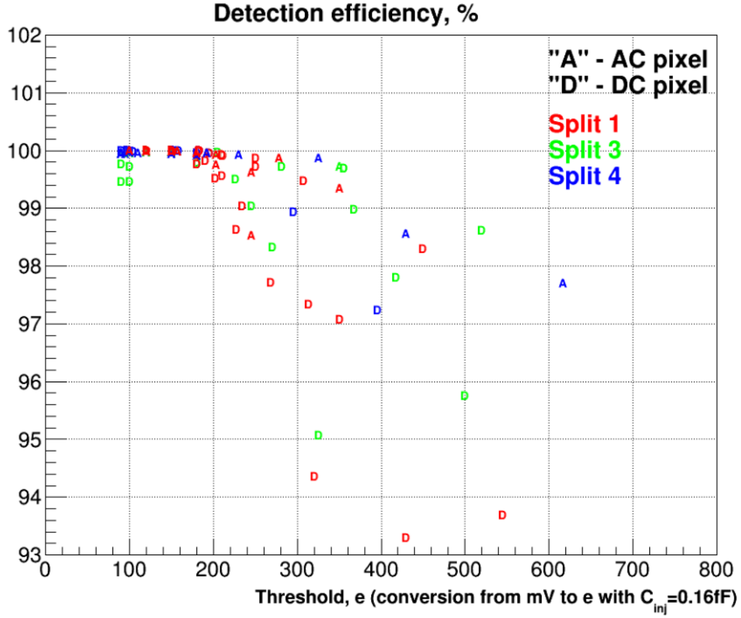
- ✓Different splits (Spli1, Split3, Split4)
- ✓Different pixel types AC (matrix C,D) and DC (matrix A, B)
- ✓Operating threshold range 100 – 200 e
- ✓Back bias: -1 .. -3 V
- ✓HV for AC pixels: 10 V

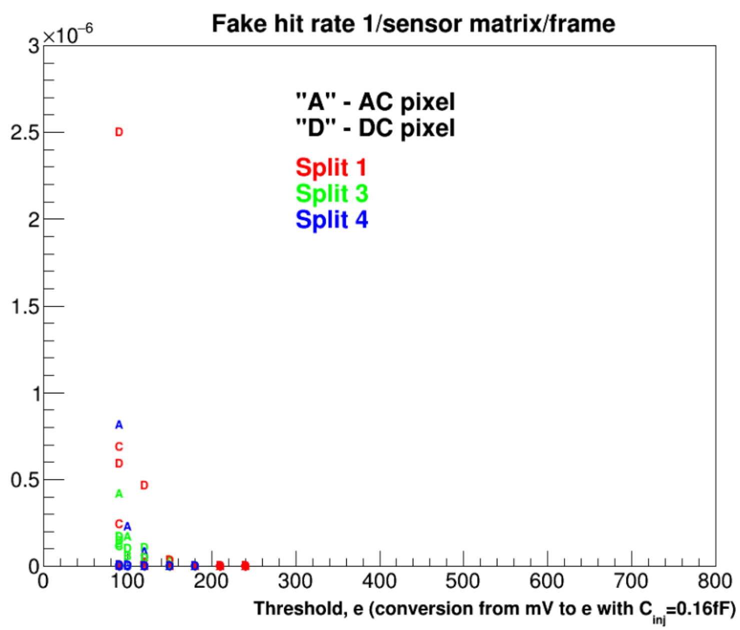
Outcome / results:

- ✓Detection efficiency
- ✓Fake hit rate
- ✓Cluster size
- ✓Resolution

Laboratory tests and preliminary test beam results were presented by R. Bugiel at TWEPP 2021

MIMOSIS-1: beam test results

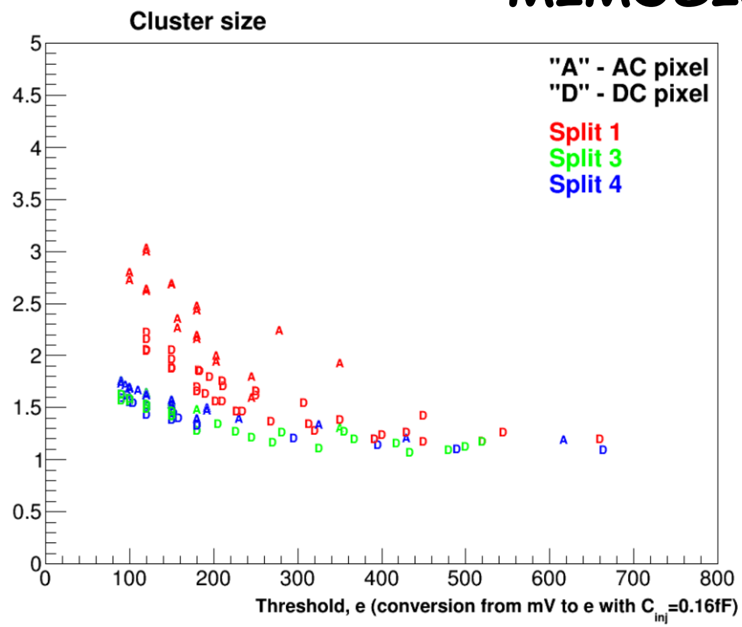




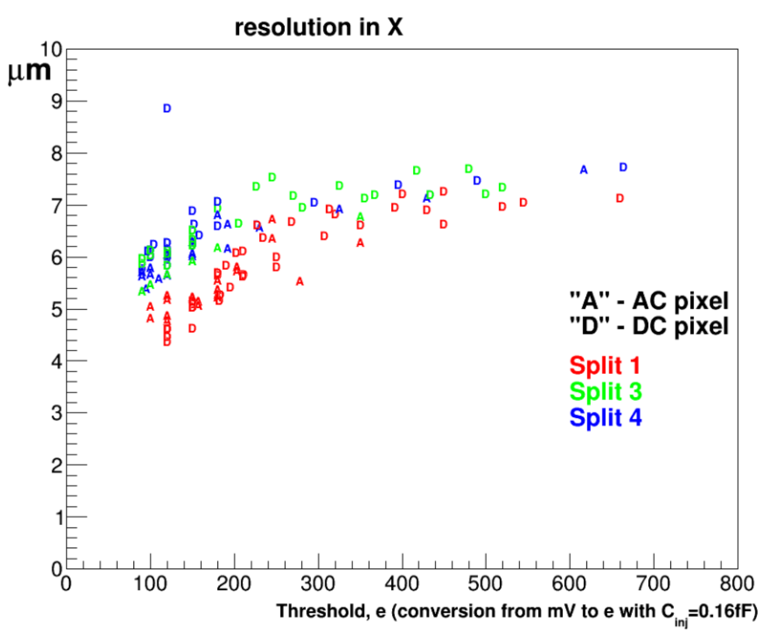
- ✓ All combination of split and pixel type perform similarly and match the MVD requirements for fake hit rate (<10^{-5}) even at 100 e threshold
- ✓ Detection efficiency > 99 % achieved at threshold < 220 e

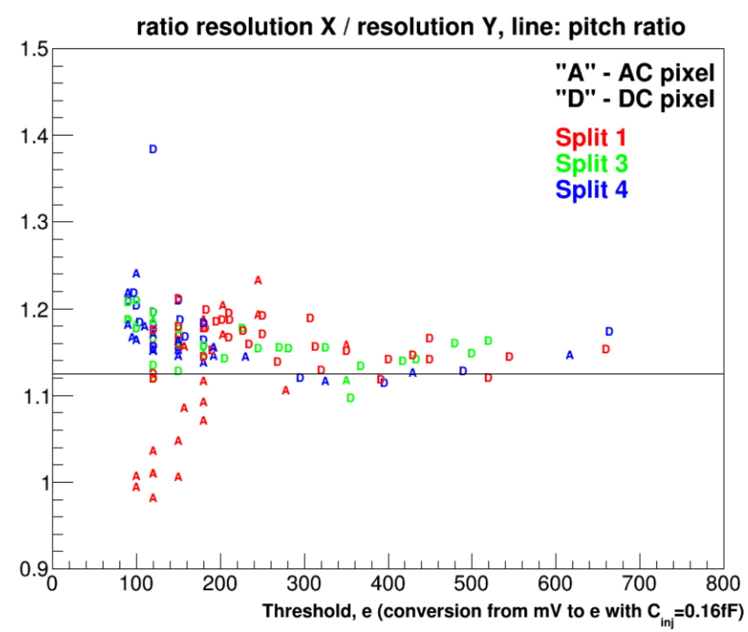
A. Dorokhov, IPHC, Strasbourg, France

MIMOSIS-1: beam test results



- ✓ Split 1 has better resolution than split 3 and split 4
- ✓ Better resolution related to increased cluster size due to larger charge sharing
- ✓ Ratio of resolution X/Y corresponds to pitch ratio





Conclusions and future plans

✓ MIMOSIS: dedicated CMOS pixel sensor for the CBM Micro-Vertex Detector

✓ Full-scale prototype of the sensor, MIMOSIS-1, extensively tested at lab and in beam, preliminary results for non-irradiated sensors:

- Fake hit rate < 10^{-5}
- Detection efficiency > 99 % at <220 e
- Resolution ~5 μm
- AC pixels show similar to DC pixels performances
- Possible advantages of AC pixels:
    - ➢ tune charge collection efficiency within same technology/split
    - ➢ more freedom to improve pixels in another technologies
    - ➢ applications beyond CBM, Cremlin+, future e+e- colliders

✓ Towards final prototype MIMOSIS-2:

- Results for non-irradiated sensors satisfy the requirements
- Irradiation and validation of MIMOSIS-1 is ongoing
- Continue tests of CE_18 and MIMOSIS-1 in order to find weak points for improvement of the final prototype

Thank you for your attention !