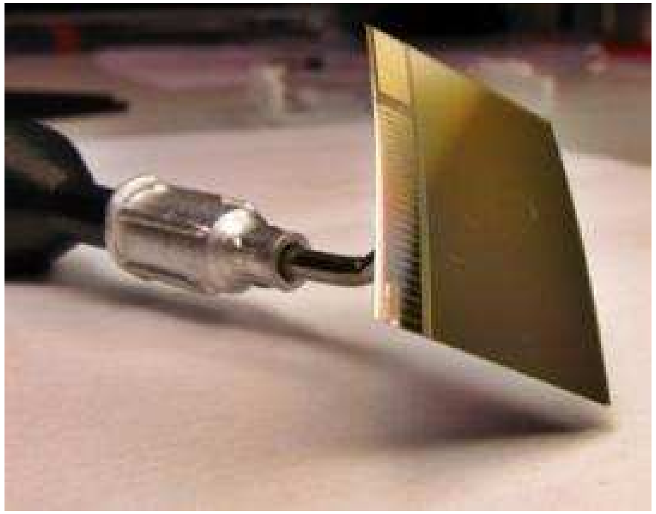
Detection Performances of MIMOSIS-1

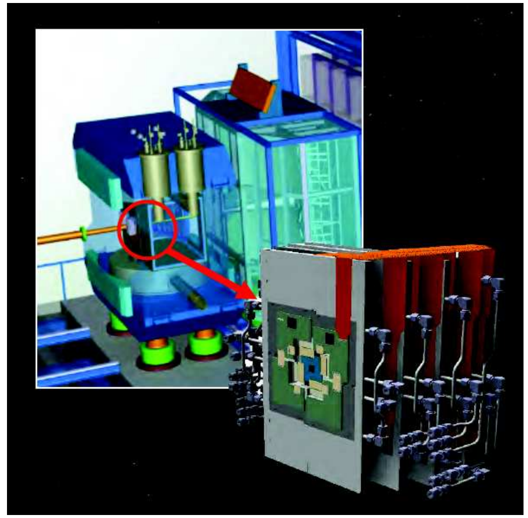
M.Winter / IJCLab, 2 Septembre 2022

on behalf of the CBM-MVD teams of IPHC/CNRS, IKF & GSI

- **CONTENTS:**
  - MIMOSIS: a multipurpose CMOS Pixel Sensor
  - The case of the CBM-MVD $\equiv$ driving force
  - Description of MIMOSIS-1 (novel aspects):
    - sensitive volume & in-pixel circuitry
    - digital signal compression circuitry
  - MIMOSIS-1 test results:
    - noise performance: pixel level, pixel-to-pixel
    - M.I.P. detection efficiency & Spatial resolution
    - Impact of radiation load
  - Summary & Outlook



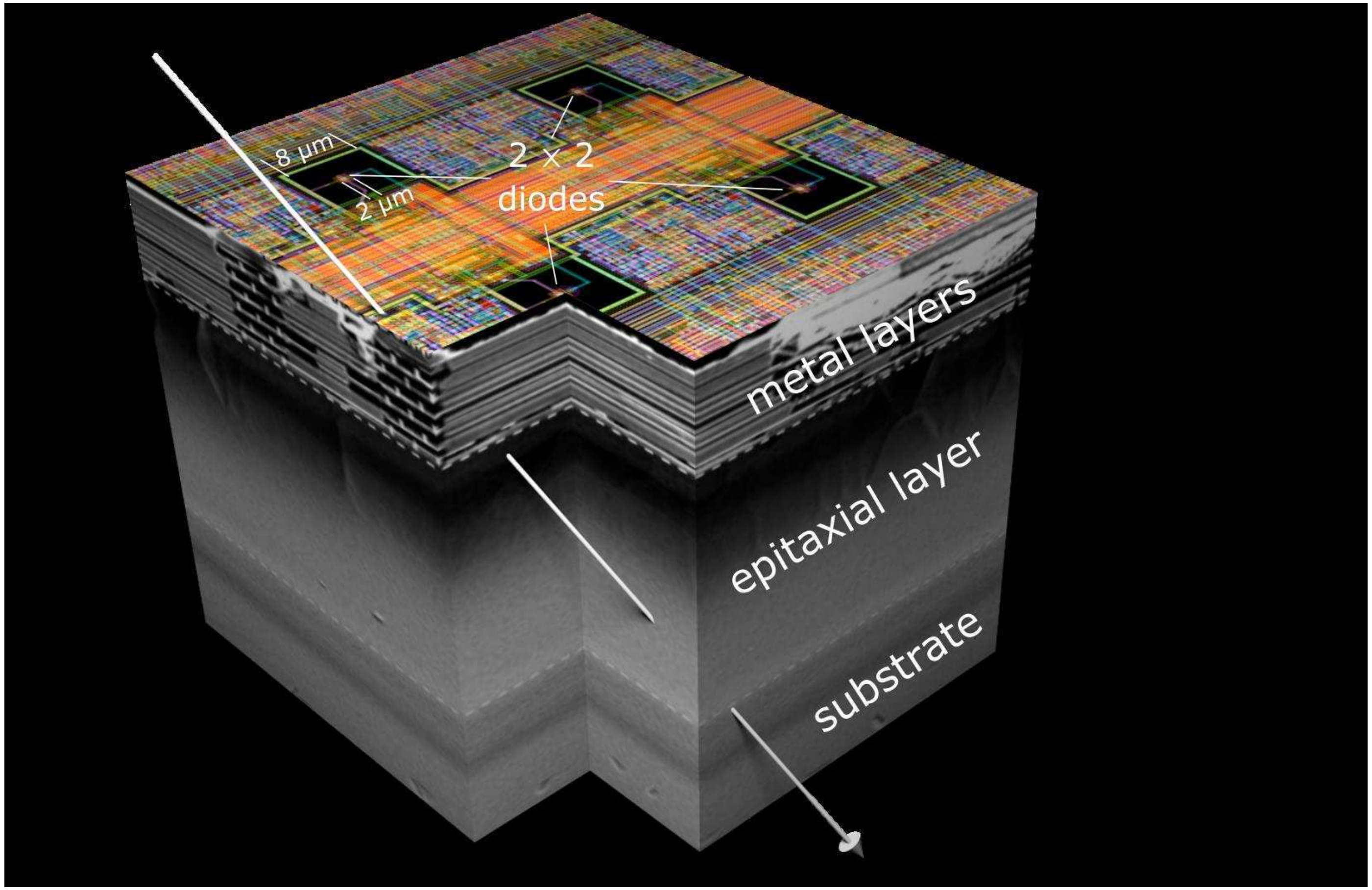
MIMOSIS-1 thinned to 60 μm



CBM-MVD

- More on the CBM-MVD: M.Deveaux et al. (CBM coll.), *The Micro-Vertex Detector of the CBM Experiment at FAIR*, preprint GSI-2022-00549
- More on MIMOSIS: F. Morel at TIPP-21, R. Bugiel at TWEPP-21, A. Dorokhov at VCI-22, J.B. Arnoldi-Meadows & H. Darwish at IWORID-22
- More on CREMLINplus applications: WP-7 of H2020-EU, Grant agreement ID: 871072, DOI 10.3030/871072
- More on Higgs-factory applications: M. Winter et al., *Status and Perspectives of ...*, PoS(Vertex2019)045, DOI: 10.22323/1.373.0045

CMOS Pixel Sensor $\equiv$ DETECTOR with INTEGRATED FRONT-END CIRCUITRY



Cross-section of ALPIDE sensor (Courtesy of M. Mager et al.)

- **Detector $\oplus$ Readout $\oplus$ Steering $\oplus$ Slow control μcircuits in same die**
- **R&D addresses SIMULTANEOUSLY Sensing Element $\oplus$ Read-Out μcircuitry**

- **Thin sensitive volume ($\pm$ 30 μm) $\Rrightarrow$** small signal charge/pixel ($\sim 10^{2-3}$ e$^-$)

  $\Rrightarrow$ very low noise μcircuits ($<$ 30 e$^-$ENC)

MIMOSIS for VARIOUS UPCOMING TRACKING DEVICES

- **MIMOSIS:** 5 μm ; 5 μs ; 100 MHz/cm^2 ; $<$ 100 mW/cm^2 ; 10^{14}n$_{eq}$/cm^2 ; 5 MRad ; ...
  - **SHORT Term:** Vertex Detector of the CBM Heavy Ion Expt / FAIR $\equiv$ Driving Force
  - **SPIN-OFF:** H2020-CremlinPlus $\Rrightarrow$ Beam Telescope, neutron detectors, tau-charm factory ?
  - **LONG TERM:** Vertex Detector & Trackers for a Higgs-Top Factory

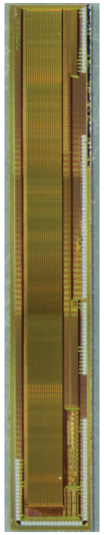
- **CBM-MVD vs Higgs-Top FACTORY EXPTS:** SIMILAR REQUIREMENTS with DIFFERENT OPTIMISATIONS
  - **CBM-MVD :** radiation tolerance requires dedicated design effort
  - **Higgs-Top Factory :** spatial resolution & read-out speed require dedicated design effort

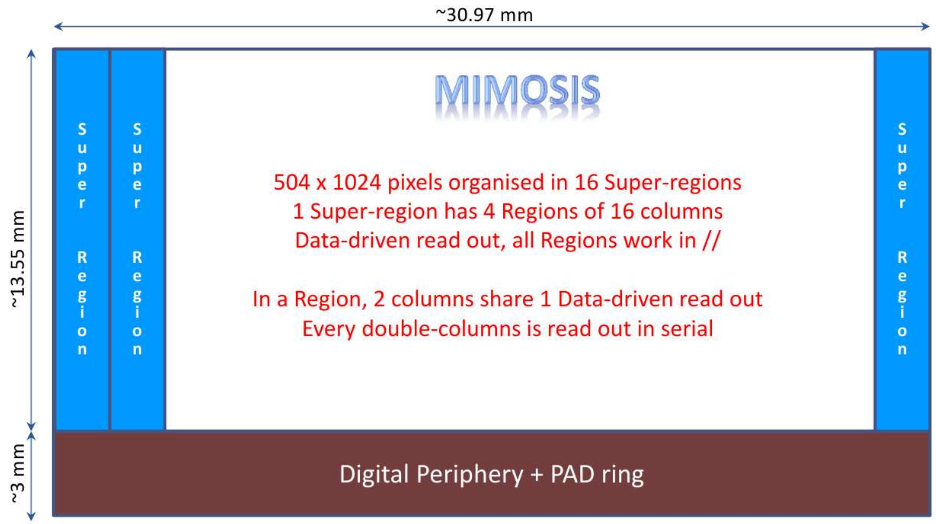
- **DESIGN PARAMETRES CONCERNED BY THE OPTIMISATIONS:**
  - **Epitaxial Layer Characteristics :** doping profile, thickness
  - **In-Pixel Circuitry:**: strength of drift field in the epitaxial layer

MIMOSIS Prominent Parametres

- **MIMOSIS pixel array derived from ALPIDE:**
  - TJsc 180 nm imager process with high-res ($\gtrsim$ 25 μm thick) epitaxy
  - **modified epitaxy profile to enhance depletion against NI radiation ($\sim$ 10 times higher than ALPIDE)**
  - 1024 col. of 504 pixels with asynchronous r.o. (ALPIDE)
    in-pixel discri. with binary charge encoding
    with DC-coupling (a la ALPIDE) & **AC-coupling (new)**
  - pixel: 27x30 $\mu m^2 \Rrightarrow \sigma_{sp} \gtrsim 5\ \mu m$
  - **affordable hit density $\simeq$ 50 x ALPIDE (new digital circuitry)**
  - $\Delta t \sim 5\ \mu s$ **= twice faster than ALPIDE**
  - power density $\gtrsim$ 50 mW/cm^2 (vs hit density)
- Step-1 (2018): MIMOSIS-0 proto. (32 col. of 504 pixels)
  - validated in-pixel circuitry variants ($\sim$ 200 T/pixel)
  - allowed exploring the limit of time resolution
- Step-2 (2020): MIMOSIS-1 full size prototype
  - fabricated in 2020 $\Rrightarrow$ fonctionnality tests
  - **2021-22: noise & detection performance ($\gtrsim$ 5 beam tests)**

Physics parameter	Requirements
Spatial resolution	~ 5 um
Time resolution	~ 5 us
Material budget	0.05% X_0
Power consumption	< 100 – 200 mW/cm^2
Operation temperature	- 40 °C to 30 °C
Temp gradient on sensor	< 5K
Radiation tol* (non-ion)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation tol* (ionizing)	~ 5 MRad
Data flow (peak hit rate)	@ 7 x 10^5 / (mm^{2}s) > 2 Gbit/s



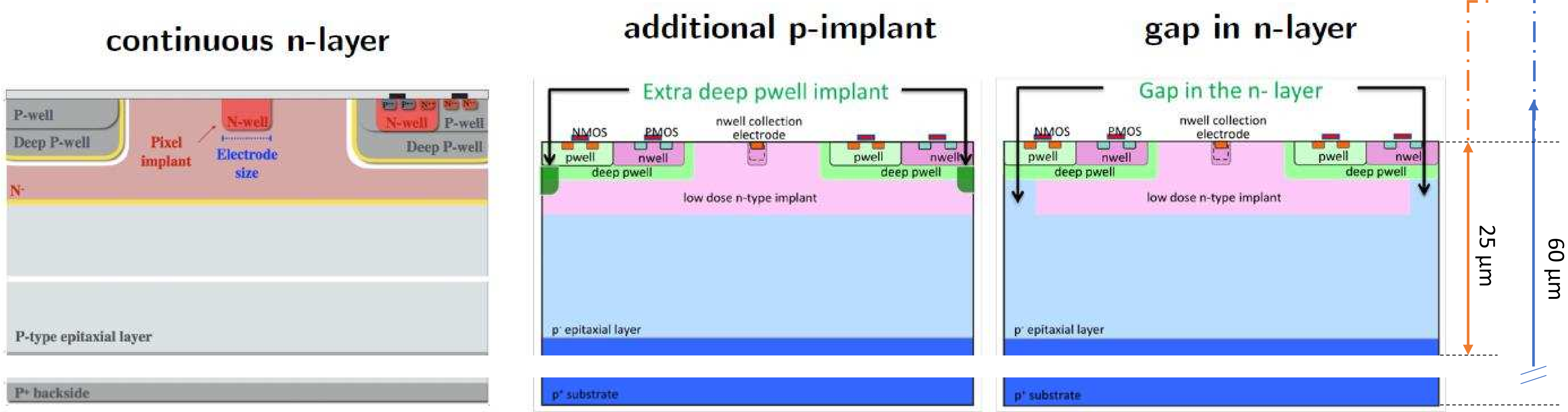


MIMOSIS-1: EXPLORATION OF EPITAXY VARIANTS

MIMOSIS-1 – TECHNOLOGY

- Tower/Jazz 180 nm CIS technology
- Various epi:
  - standard process
  - modified (continuous n-layer, additional p-implant, gap in n-layer)
    - → to increase lateral depletion field
    - → anticipated radiation tolerance improvement

Parameter	Value
Sensor thickness	60 µm
Epi layer thickness	~ 25 µm
Epi layer resistivity	> 1 kΩcm



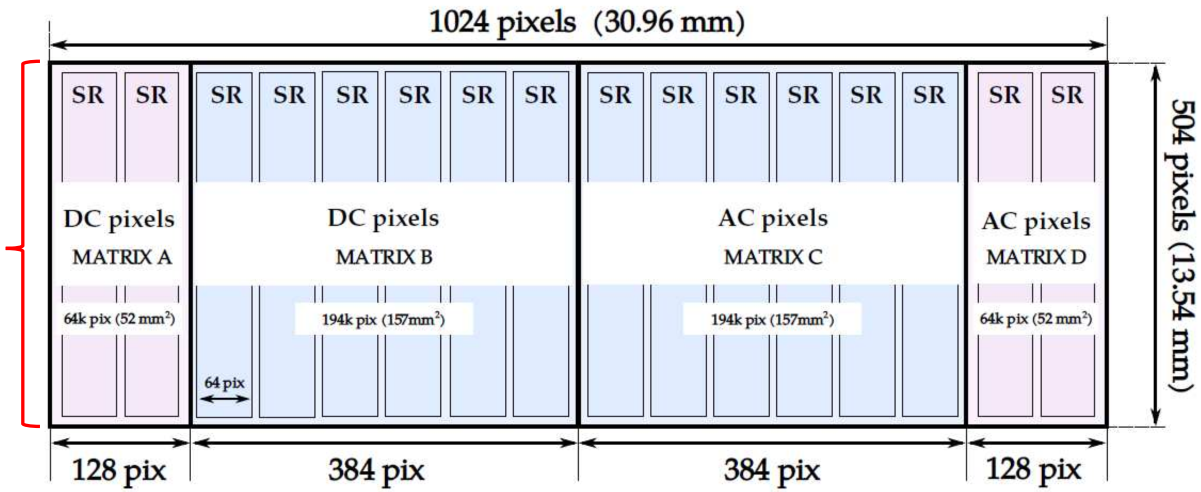
W. Snoeys, "FASTPIX: sub-nanosecond radiation tolerant CMOS pixel sensors", ATTRACT

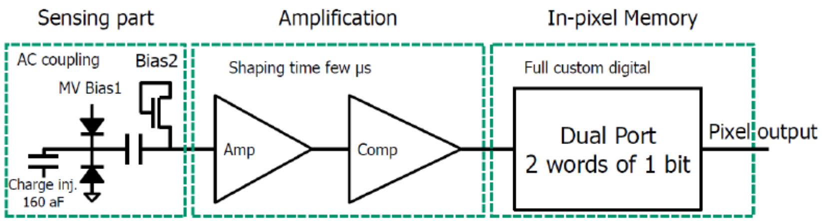
from R. Bugiel - TWEPP-21

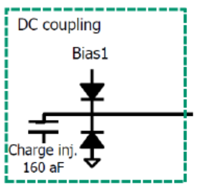
MIMOSIS-1: EXPLORATION OF IN-PIXEL CIRCUITRY VARIANTS

MIMOSIS-1 – SENSOR OVERVIEW

MIMOSIS-1 fabrication reticules







More details on MIMOSIS-1 design
→ F. Morel, "The MIMOSIS pixel sensor ", TIPP 2021

- 4 submatrices
  - A, D → optimization of CE18 for radiation hardness
  - B, C → similar to MIMOSIS-0
- Pixel size: 26.88 µm x 30.25 µm
- Pixel types:
  - → DC pixels: ALPIDE-derived
  - → **AC pixels: top bias up to > 20V**
- Possibility of pulse injection and pixel masking
- Matrix active area: ≈ **4.2 cm²**
- Power consumption: **40 – 70 mW/cm²** → depending on hit rate

from R. Bugiel - TWEPP-21

MIMOSIS-1: NOISE PERFORMANCE

GENERAL PERFORMANCE – LABORATORY CHARACTERIZATION

Laboratory characterization

- characterization by pulse injection
- complex phase space of MIMOSIS1 (tuning parameters needed)
    - estimation of thresholds, Fixed Pattern Noise (FPN) and Thermal Noise (TN)
    - all measurements at 15°C

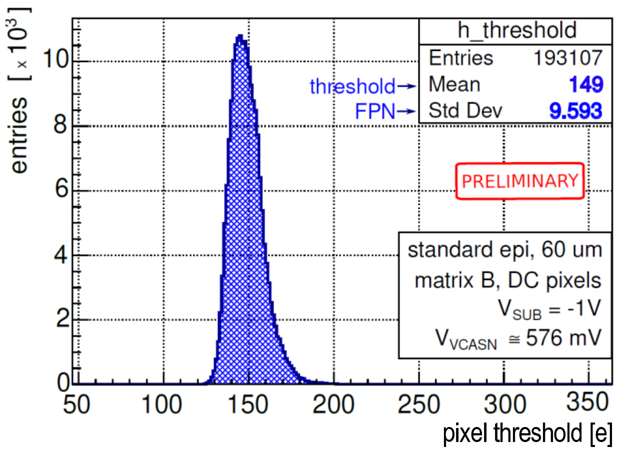
- Ex: performance of matrix B @ 150e threshold (before irradiation):
    - TN: ~3.5 e ENC
    - FPN: ~10 e ENC

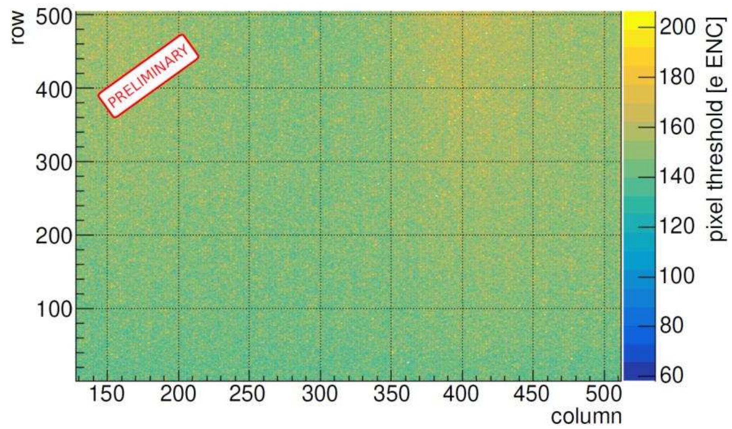
Preliminary conversion factor from 1 mV →1 e- (within +/- 25%)

Summary performance before irradiation:

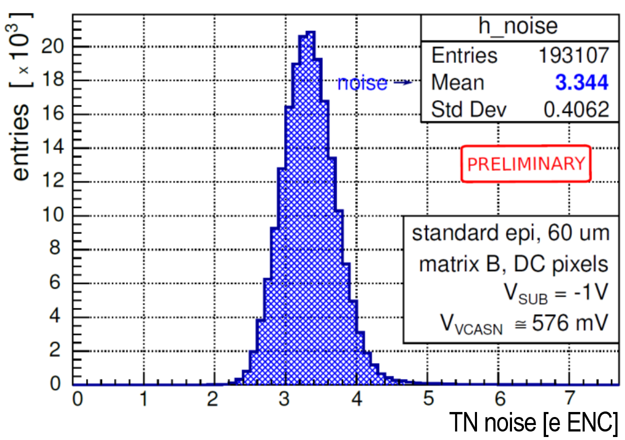
- Similar, satisfactory performance of all matrices
- **TN: 3-5 e ENC**
- **FPN: 7-10 e ENC** in the operation range
- **AC pixels slightly lower FPN than DC**

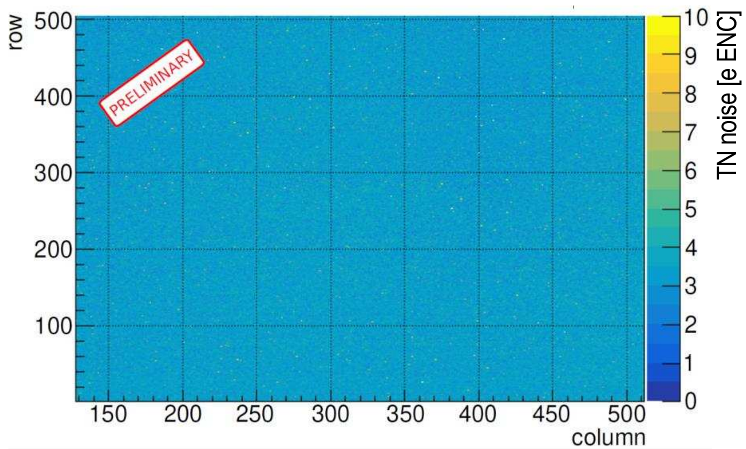
DC PIXELS (mat B) – PIXEL THRESHOLD





DC PIXELS (mat B) – THERMAL NOISE

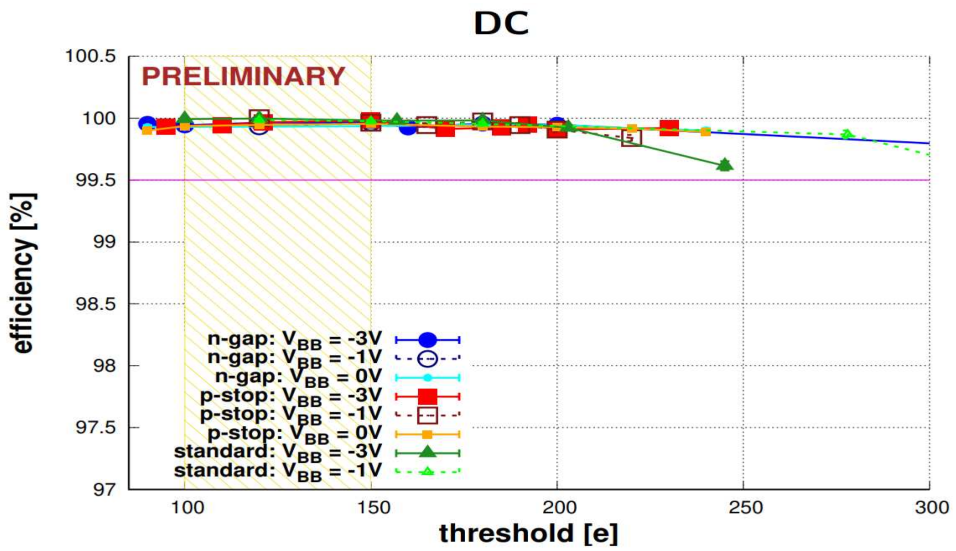


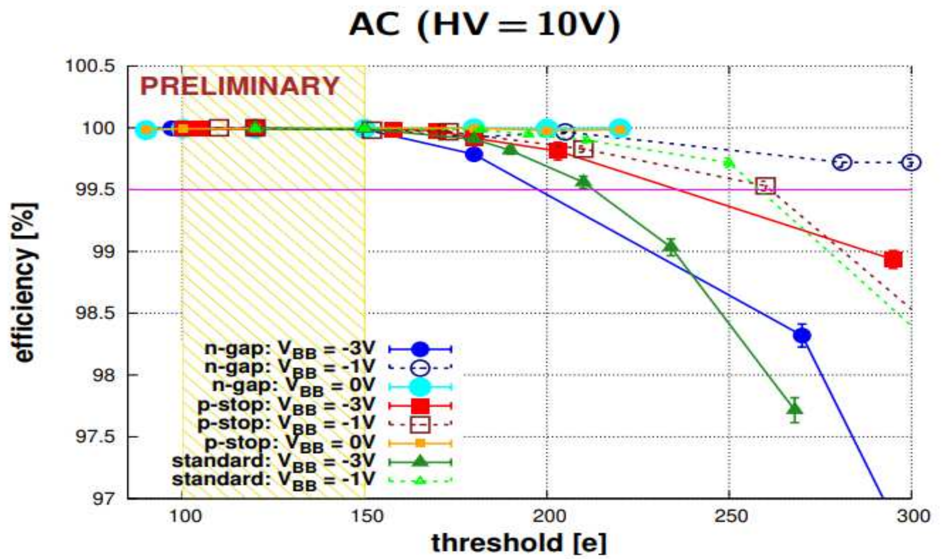


from R. Bugiel - TWEPP-21

MIMOSIS-1: M.I.P. DETECTION EFFICIENCY

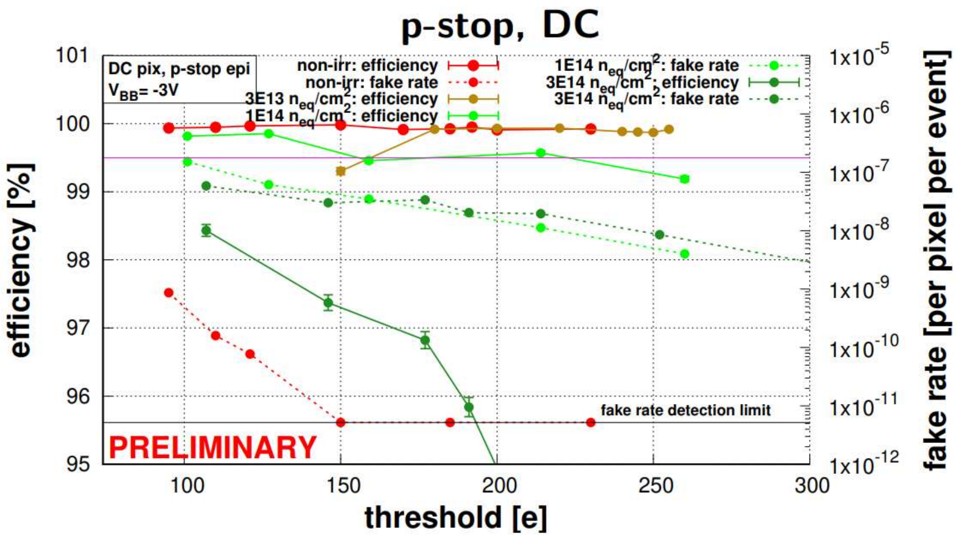
- DESY (3-6 GeV $e^{\pm}$) & CERN-SPS ($O(10^2)$ pions):
  - tests of 3 epitaxy variants: standard, n-gap, p-stop
  - various back-bias values considered: -3 V, -1 V, 0 V
  - studies performed w.r.t. in-pixel discriminator threshold
  - **results are still preliminary**
- DC-coupled pixels:
  - $\epsilon_{det} \gtrsim$ 99.5 % up to $>$ 250 e^-
  - no significant EPI profile or V_{BB} dependence
- AC-coupled pixels: top-bias of + 10 V
  - $\epsilon_{det} \gtrsim$ 99.5 % up to $>$ 250 e^-
  - efficiency seems V_{BB} dependent $\Rrightarrow$ origin ?
- COMMENTS:
  - Det. effi. $\simeq$ 100 % over large range of threshold values
    $\hookrightarrow$ in particular for EPI & in-pixel μcircuit variants
  - Role of back-bias voltage for AC-pixels requires better understanding

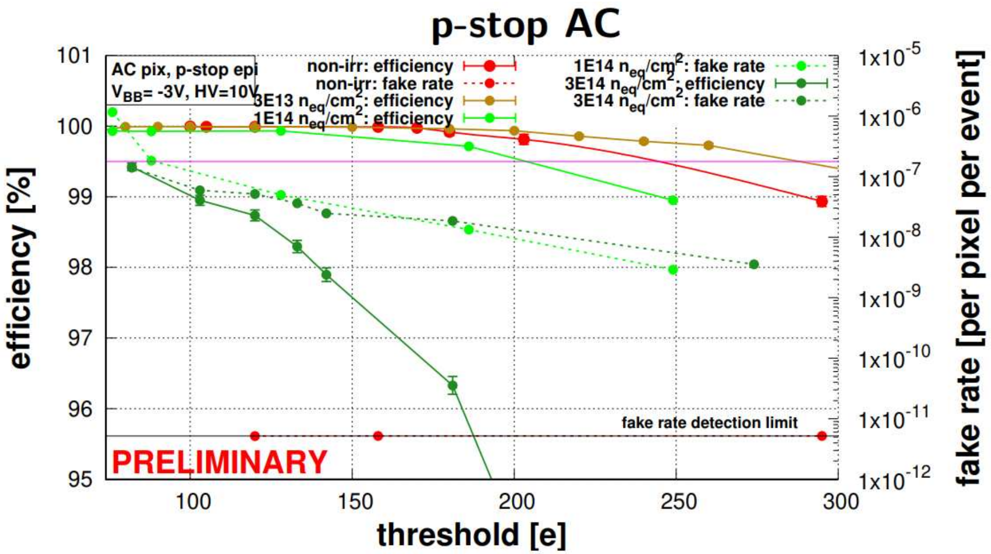




MIMOSIS-1: IMPACT of NIEL on DETECTION EFFICIENCY

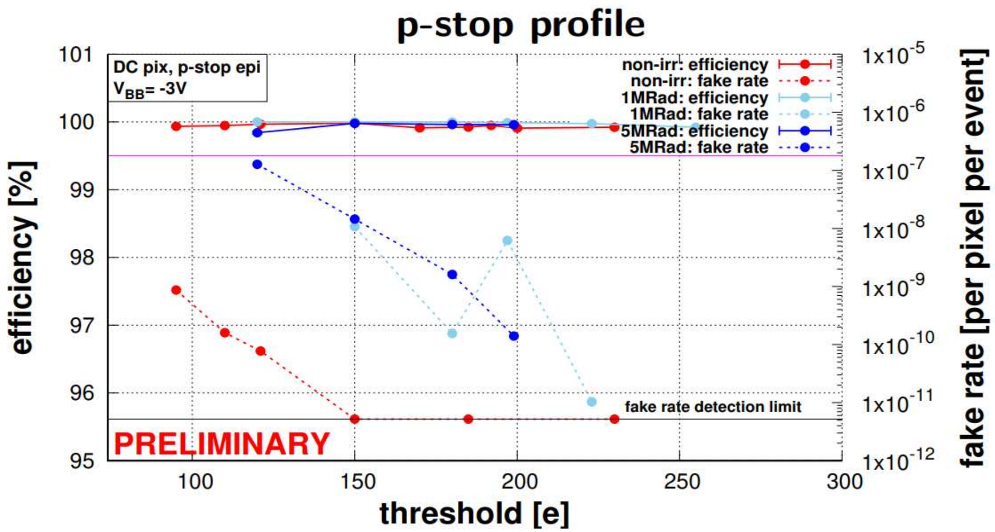
- Sensors exposed to neutron source:
  - 3 fluence values: 0.3 / 1 / 3·10^{14}n$_{eq}$/cm^2
  - example of p-stop epitaxy variant
- DC-coupled pixels: V$_{BB}$ = -3 V
  - $\lesssim$ 1·10^{14}n$_{eq}$/cm^2: ϵ_{det} $\gtrsim$ 99% up to $\gtrsim$ 250 e$^-$
  - 3·10^{14}n$_{eq}$/cm^2: ϵ_{det} $\lesssim$ 98% above 120 e$^-$
- AC-coupled pixels: top-bias of + 10 V
  - $\lesssim$ 1·10^{14}n$_{eq}$/cm^2: ϵ_{det} $\gtrsim$ 99% up to $\gtrsim$ 250 e$^-$
  - 3·10^{14}n$_{eq}$/cm^2: ϵ_{det} $\gtrsim$ 98% up to 140 e$^-$
- COMMENTS:
  - Det. effi. $\gtrsim$ 99% over large range of threshold values for anticipated annual fluence (1·10^{14}n$_{eq}$/cm^2)
  - 3 X annual fluence still affordable (best with AC pixel)
  - Added value of AC-pixels significant but relatively modest
  - Fake rate still modest $\Rrightarrow$ threshold values $\lesssim$ 150 e$^-$ OK

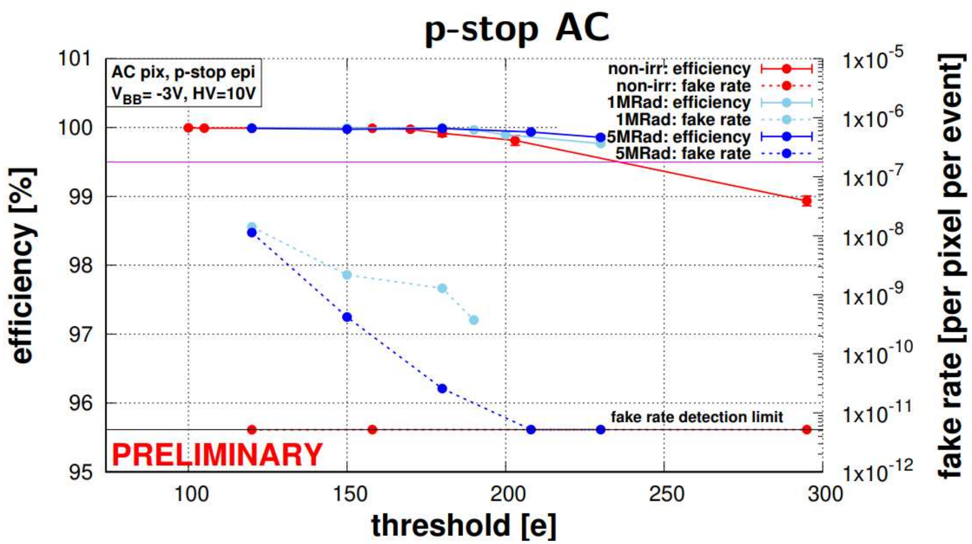




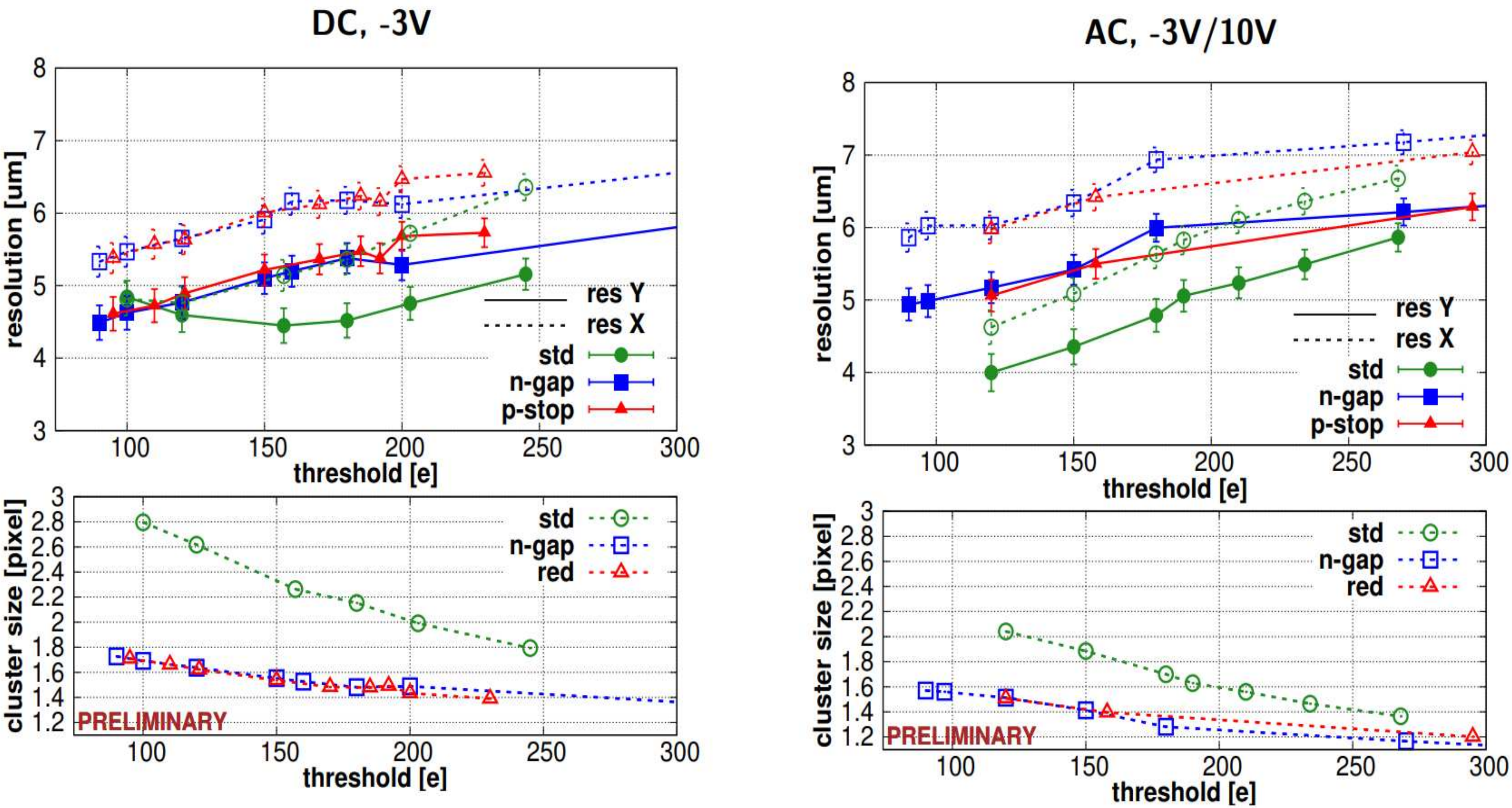
MIMOSIS-1: IMPACT of TID on DETECTION EFFICIENCY

- Sensors exposed to XRay sources:
  - ⋇ 2 TID doses: 1 & 5 MRad
  - ⋇ example of p-stop epitaxy variant
- DC-coupled pixels: V_{BB} = -3 V
  - ⋇ $\epsilon_{det} \gtrsim$ 99.5% up to well beyond 250 e^-
  - ⋇ fake rate increase without impact on lowest operationnal threshold values ($\sim$ 100 e^-)
- AC-coupled pixels: top-bias of + 10 V
  - ⋇ $\epsilon_{det} \gtrsim$ 99.5% up to well beyond 250 e^-
  - ⋇ V_{BB} dependence seems "compensated" by TID (under study)
- COMMENTS:
  - ⋇ Det. effi. not significantly affected by anticipated TID/yr
  - ⋇ Behaviour of AC-pixels requires more understanding
  - ⋇ Fake rate still modest $\Rrightarrow$ threshold values $\sim$ 100 e^- OK





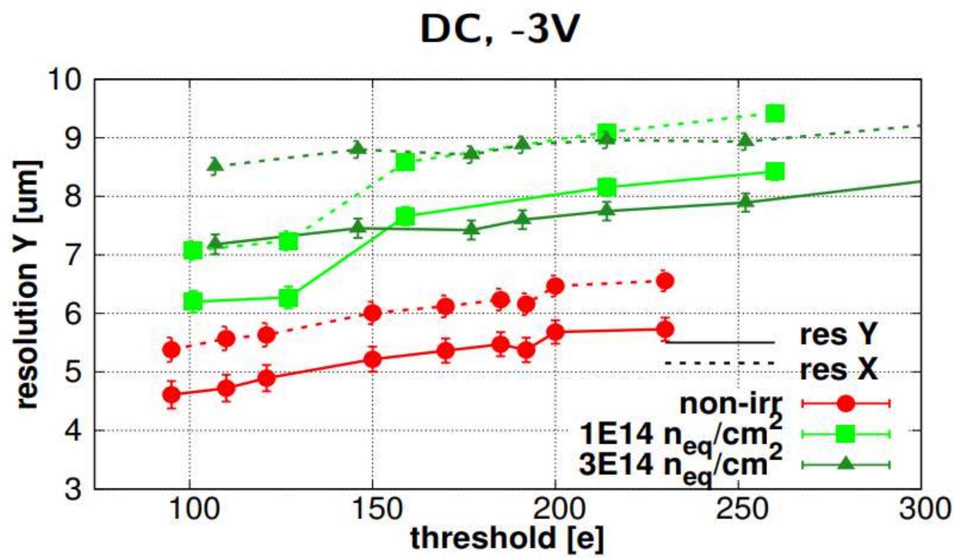
MIMOSIS-1: SPATIAL RESOLUTION and CLUSTER SIZE

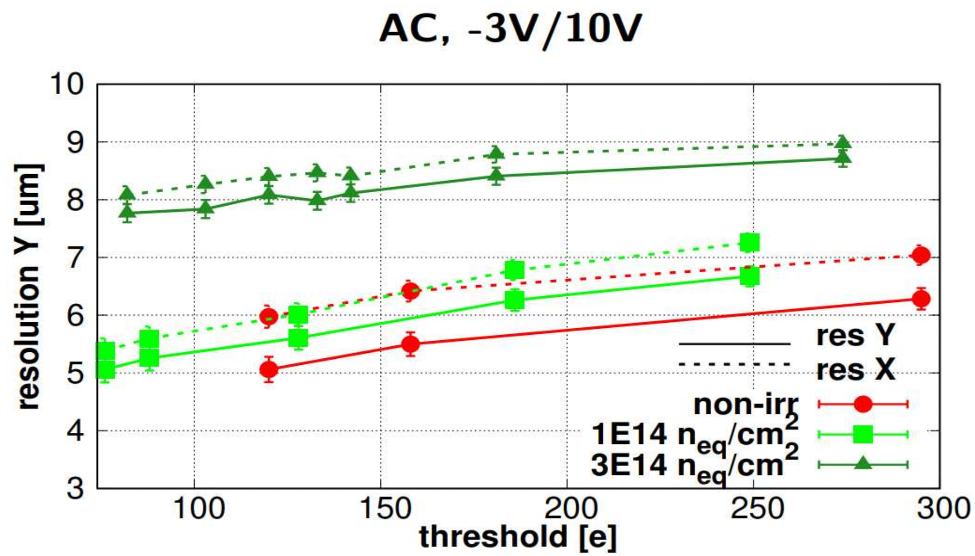


- Objective of $\sim 5\ \mu m$ proven to be reachable
- Standard EPI provides about 1 μm better resolution ; AC-pixels $\gtrsim 0.5\ \mu m$ worst then DC-pixels
- Certain low threshold measurements still under investigation

MIMOSIS-1: IMPACT of N.I. LOAD on SPATIAL RESOLUTION

- Example of p-stop epitaxy:
  - 2 fluence values considered: 1 & 3·10^{14}n$_{eq}$/cm^2
  - resolutions along both pixel dimensions (27 & 30 μm)
- DC-coupled pixels:
  - 1·10^{14}n$_{eq}$/cm^2: loss of $\lesssim$ 1 μm
  - 3·10^{14}n$_{eq}$/cm^2: loss of $\lesssim$ 3 μm
- AC-coupled pixels: top-bias of + 10 V
  - 1·10^{14}n$_{eq}$/cm^2: loss of $\lesssim$ 0.5 μm
  - 3·10^{14}n$_{eq}$/cm^2: loss of $\lesssim$ 2.5 μm





- COMMENTS :
  - Difference between DC & AC-pixel performance modest
  - Up to anticipated yearly N.I. load, the resolution remains close enough to 5 μm for threshold values $\lesssim$ 150 e$^-$
  - Spatial resolution significantly degrades after 3 times yearly N.I. load

SUMMARY - OUTLOOK

- MIMOSIS-1 $\equiv$ 0.5 MPix full size prototype for CBM-MVD / FAIR:
  - ⋇ 5 μm ; 5 μs ; $> 10^{14}$ n_{eq}/cm^2 ; 5 MRad, etc. **validated**
  - ⋇ Added value of AC-coupling & EPI variants $\pm$ **assessed**
  - ⋇ Still some observations requiring further studies (N.B.: results based on single chips):
    e.g.: M.I.P. detection with modified epitaxy, spatial resolution at low threshold, etc.
  - ⋇ Standard epitaxy indicates that $\sim$ 4 μm resolution may be achievable
    in absence of sizeable radiation loads (topic addressed within next step)

- NEXT MAJOR STEP: MIMOSIS-2 $\equiv$ complete full size prototype for CBM-MVD
  - ⋇ Engineering Run launched in August $\Rrightarrow$ possibly back from foundry in Q4/'22 (tbc)
  - ⋇ New epitaxy thicknesses explored: 30 and 50 μm
    $\Rrightarrow$ possibly improving detection performances, e.g. resolution, efficiency after NIEL (?)
  - ⋇ Engineering Run includes a $\lesssim$ 500 ns variant of medium size (32 x 504 pixels) prototype
    addressing tracking devices adapted to future e^+e^- colliders (modest radiation load)
    $\Rrightarrow$ investigate whether 50 μm thick epitaxy allows for $\lesssim$ 4 μm resolution

- BEYOND MIMOSIS-2: Final MVD sensor MIMOSIS-3 fabrication anticipated in 2023-24