CMOS Pixel Sensors designed for the STAR-PXL

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- coll. with IRFU-Saclay -

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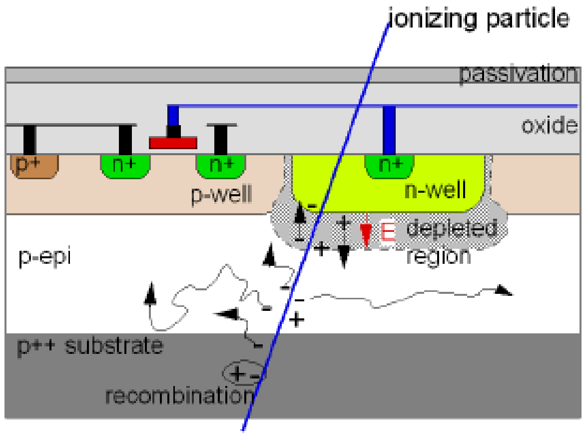
- *Summary*

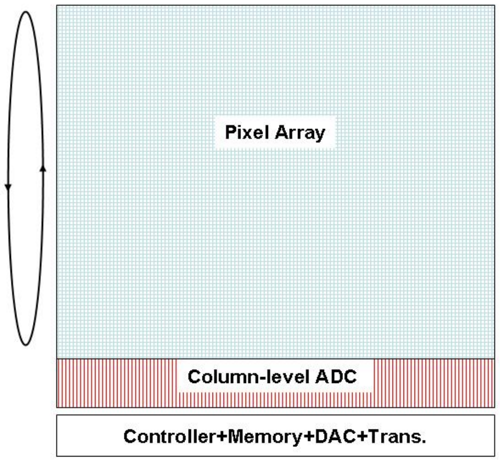
CMOS Pixel Sensors: State of the Art

- **Prominent features of CMOS pixel sensors:**
  - ✳ high granularity ⇛ excellent (micronic) spatial resolution
  - ✳ very thin (signal generated in 10-20 μm thin epitaxial layer)
  - ✳ signal processing μ-circuits integrated on sensor substrate
    - ⇛ impact on downstream electronics (⇛ cost)



- **Organisation of MIMOSA sensors:**
  - ✳ manufactured in 0.35 μm OPTO process
  - ✳ signal sensing and analog processing in pixel array
  - ✳ mixed and digital circuitry integrated in chip periphery
  - ✳ read-out in rolling shutter mode

    (pixels grouped in columns read out in //)
    - ⇛ impact on power consumption



Granularity versus Speed

- **Impact of high granularity:**
  - ⋇ large number of pixels $\Rrightarrow$ handicap for read-out speed of the full pixel array
  - ⋇ **but:** slow down of detector read-out frequency compensated by accuracy
    - $\hookrightarrow$ single point resolution and material budget :
      - ⊸ improved neighbouring hit separation on each detector layer
      - ⊸ improved track extrapolation accuracy during track reconstruction from layer to layer
      - ⊸ effect enhanced by small material budget
      - ⊸ strategy option: connect CMOS pixels sensors to 2-layer fast&thick detector
  - ⋇ **global effect :** improved track reconstruction capability in high density conditions
    - $\Rrightarrow$ data rate handling capability not really downgraded (but track rec. SW needs to be adapted)

- **Illustration with CMOS pixels (20$\times$20 μm^2) :**
  - ⋇ $>$ 60 times smaller than ATLAS pixels (50$\times$425 μm^2)
  - ⋇ $\gtrsim$ O(10-100) times more accurate track extrapolation for hit search

$\Rrightarrow$ $\sim$ **3 ordres of magnitude improvement in hit rate handling capability**

- $\hookrightarrow$ single CMOS pixel layer in a tracker does not provide all added value of granular & thin sensors
- $\hookrightarrow$ large particle rate does not necessarily imply priority to r.o. speed

CMOS Pixel Sensors: General Remarks

- **Intrinsic limitations of technology :**
  - ⋇ very thin sensitive volume $\Rrightarrow$ impact on signal magnitude
  - ⋇ standard process sensitive volume almost undepleted $\Rrightarrow$ impact on radiation tolerance & speed
  - ⋇ commercial fabrication (parametres) $\Rrightarrow$ not optimised for charged particle detection
    $\Rrightarrow$ impact on sensing performances and radiation tolerance

- **Limitations of the fabrication process retained for ULTIMATE:**
  - ⋇ only 4 ML $\Rrightarrow$ rolling shutter sequencer in 350 μm wide side band
  - ⋇ feature size $\Rrightarrow$ restricted nb of transistors in the pixel
  - ⋇ oxide thickness (from feature size) $\Rrightarrow$ weakens the tolerance to ionising radiation
  - ⋇ double-well technology $\Rrightarrow$ restricted circuitry inside pixel

- **Limitations due to the STAR environment :**
  - ⋇ limited cooling $\Rrightarrow$ power consumption is a concern (consequences on SNR, alignment)
  - ⋇ limited cooling $\Rrightarrow$ reduced noise performance, in particular after irradiation (though not critical)

CMOS Pixel Sensors: State of the Art

- **Main characteristics of MIMOSA sensor equipping EUDET BT:**

  ⋇ 0.35 μm process with high-resistivity epitaxial layer
  (coll. with IRFU/Saclay)

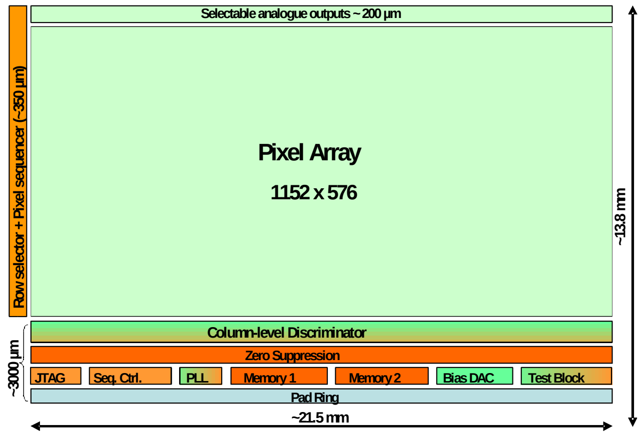
  ⋇ column // architecture with in-pixel amplification (CDS)
  and end-of-column discrimination, followed by $\emptyset$

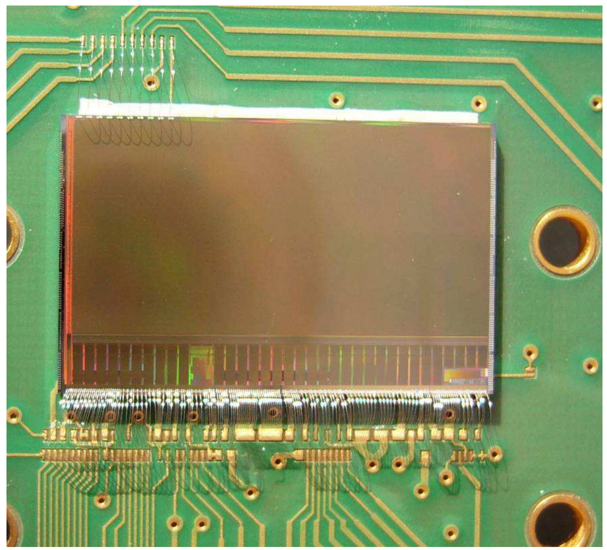
  ⋇ active area: 1152 columns of 576 pixels (21.2$\times$10.6 mm^2)

  ⋇ pitch: 18.4 $\mu m \rightarrowtail \sim$ 0.7 million pixels
  charge sharing $\Rrightarrow$ $\sigma_{sp} \lesssim$ 4 μm

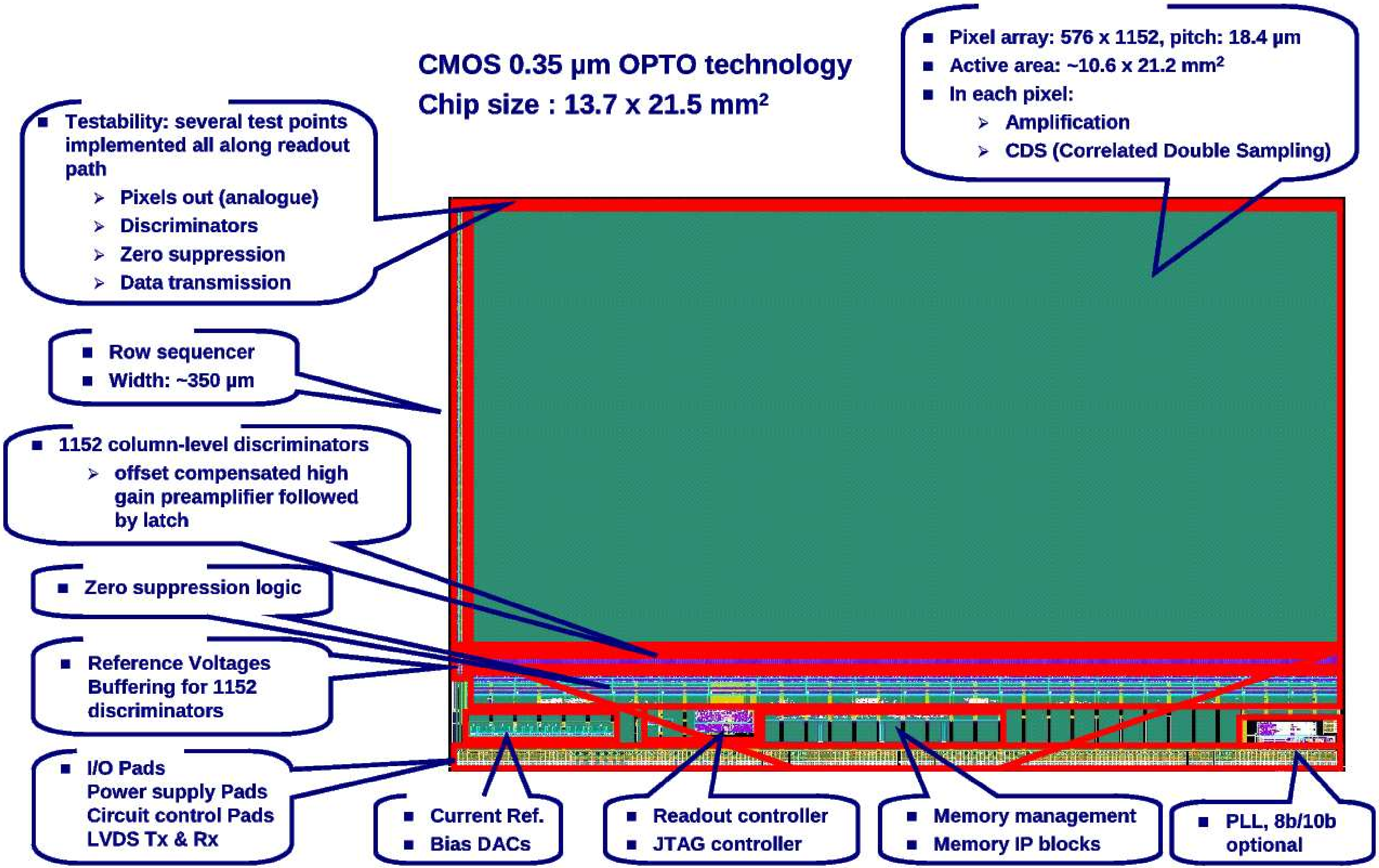
  ⋇ t$_{r.o.} \lesssim$ 100 μs ($\sim$10^4 frames/s)
  $\Rrightarrow$ suited to $>$10^6 part./cm^2/s

  ⋇ $\sim$ 250 mW/cm^2 power consumption (fct of N$_{col}$)



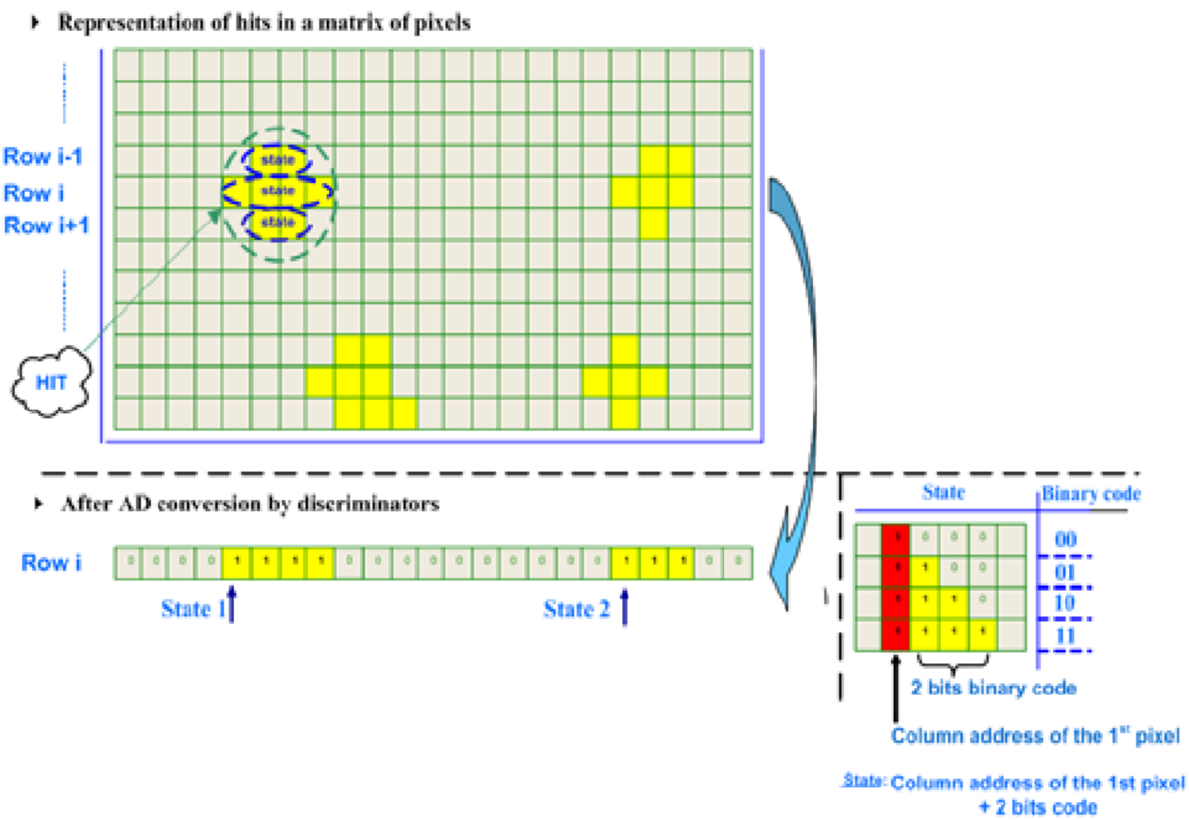


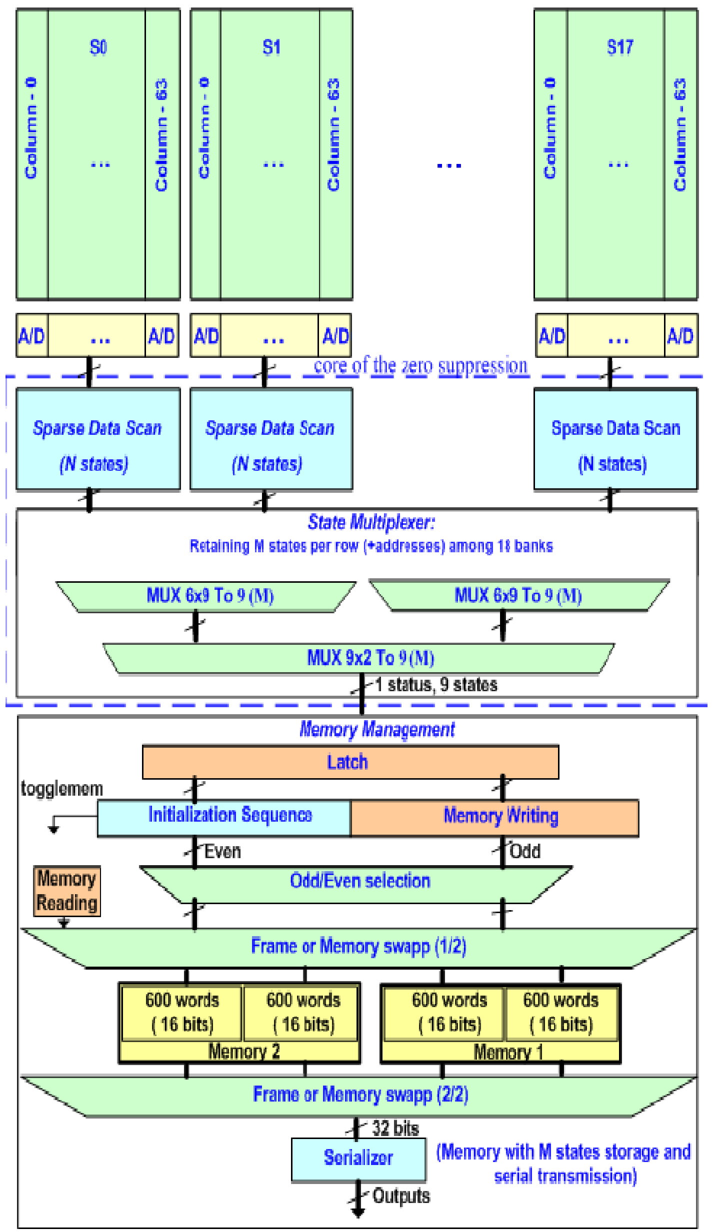
MIMOSA-26: Functionality Implementation



courtesy of Ch. Hu-Guo / TWEPP-2010

MIMOSA-26 Zero-Suppression Logic



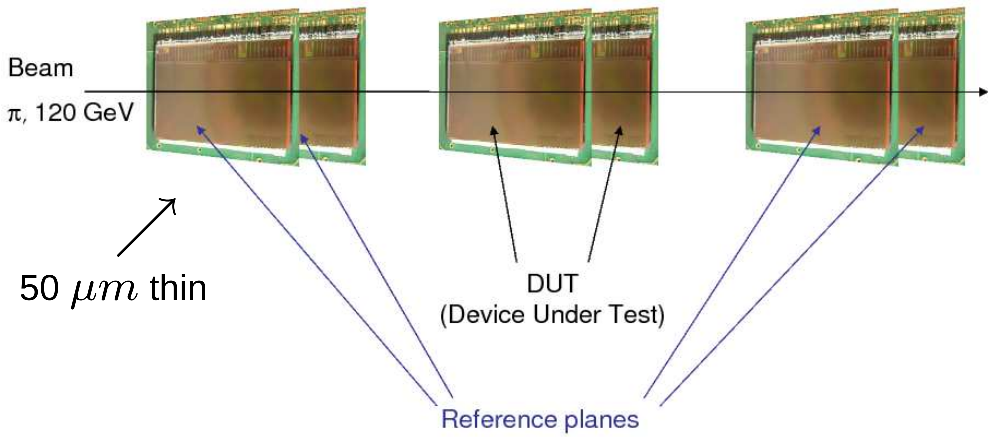


- Encoding limited to raws
  - ⇛ no raw to raw correlation for clustering
- Same logic implemented in Ultimate

High-Resistivity CMOS Pixel Sensors

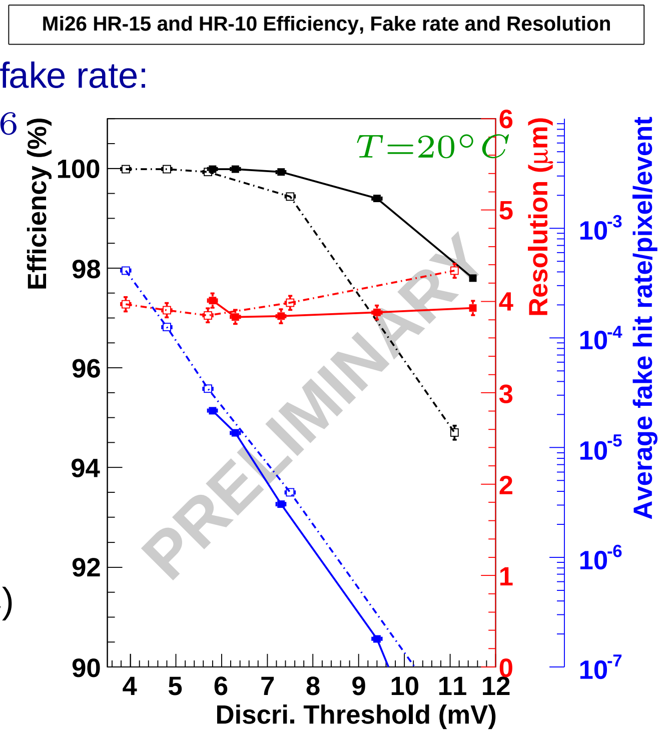
- **M.i.p. detection with LOW & HIGH resistivity CMOS sensors combined in a Beam Telescope (BT)**
  - ⋇ 4 EUDET ref. sensors & 2 sensors under test
  - ⋇ June 2010 at CERN-SPS ($\sim$ 120 GeV pions)
  - ⋇ sensor variants : standard epitaxy (14 μm thick)

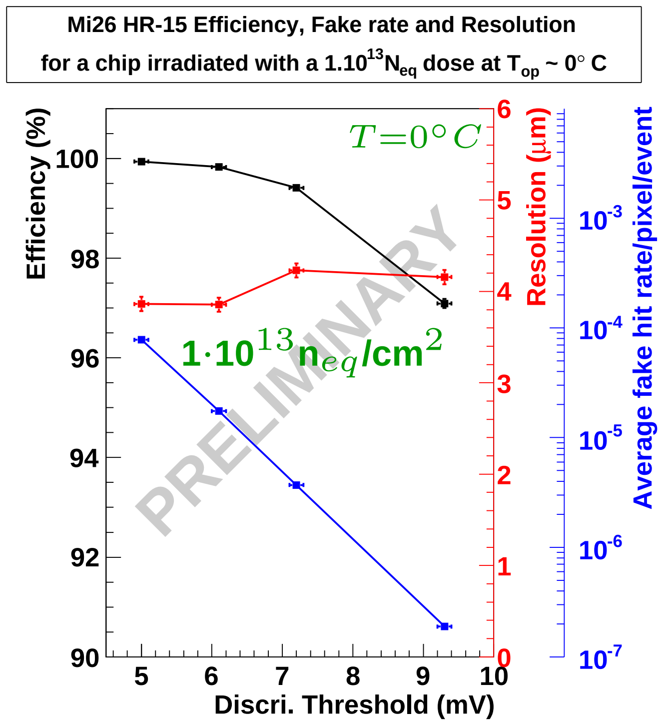
    & high-resistivity epitaxy (10 & 15 μm thick)



- **Main Results:**
  - ⋇ det. eff. $\sim$ 100 % (SNR $\sim$ 40) for very low fake rate:
    - ▷ plateau until fake rate of few 10^{-6}
  - ⋇ single point resolution $\lesssim 4\ \mu m$
  - ⋇ det. eff. still $\sim$ 100 % after exposure

    to fluence of $1{\cdot}10^{13} n_{eq}/cm^2$





$\Rrightarrow$ **Excellent detection performances**

with high-resistivity epitaxial layer

despite moderate resistivity (400 $\Omega \cdot cm$)

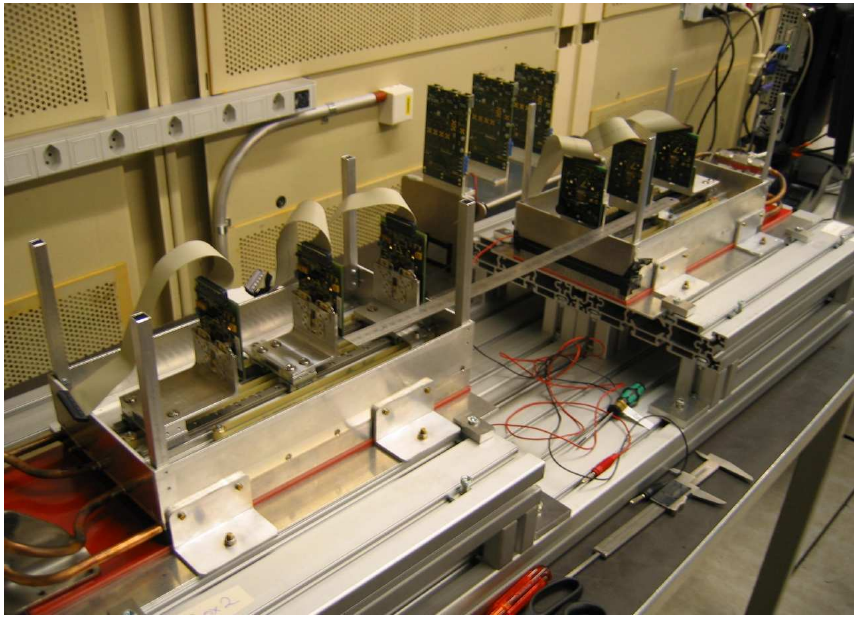
and poor depletion voltage ($<$ 1 V)

$\Rrightarrow$ **Tolerance to $\gtrsim$ O(10^{14})n_{eq}/cm^2 seems within reach (study under way)**

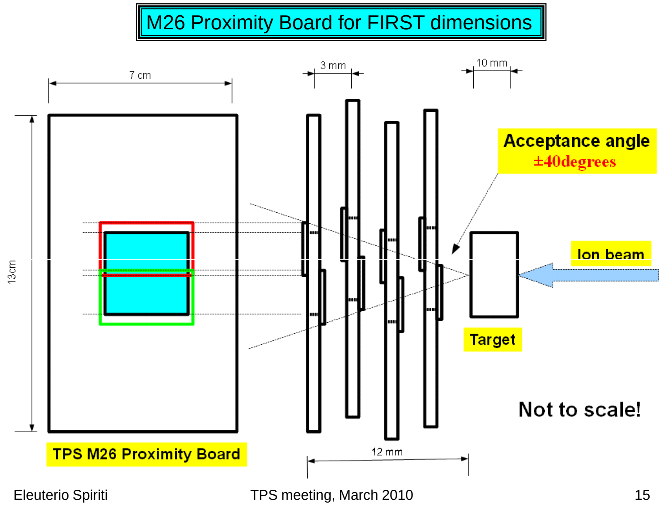
Direct Applications of MIMOSA-26

- Beam telescope of the FP6 project EUDET
  - ⋇ 2 arms of 3 planes (plus 1-2 high resolution planes)
  - ⋇ MIMOSA-26 thinned to 50 μm
  - ⋇ $\sigma_{extrapol.} \sim$ 1-2 μm EVEN with e^- (3 GeV, DESY)
  - ⋇ frame read-out frequency O(10^4) Hz
  - ⋇ running since '07 (demonstrator: analog outputs)

    at CERN-SPS & DESY (numerous users)

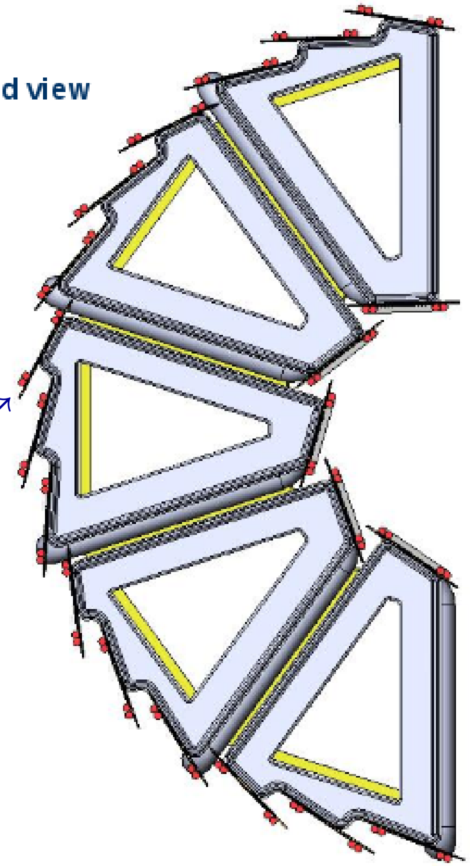


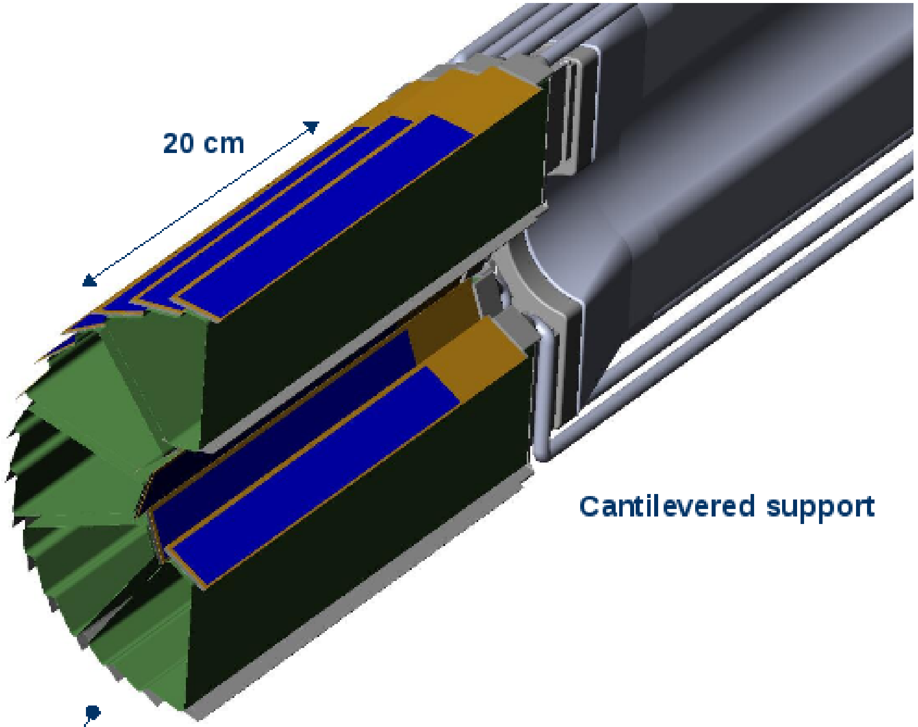
- **Spin-offs :**
  - ⋇ **Several BT copies :** foreseen for detector R&D
  - ⋇ **BT** for channelling studies, mass spectroscopy, etc.
  - ⋇ **CBM (FAIR) : MVD demonstrator (2-sided layers) for CBM-MVD** (HP-2 project)
  - ⋇ **FIRST (GSI) :** VD for hadrontherapy $d\sigma/d\Omega$ measurements ▷▷▷



Application of CMOS sensors to the STAR-PXL

The detector ladders are 50 µm thinned silicon, on a flex kapton/aluminum cable.

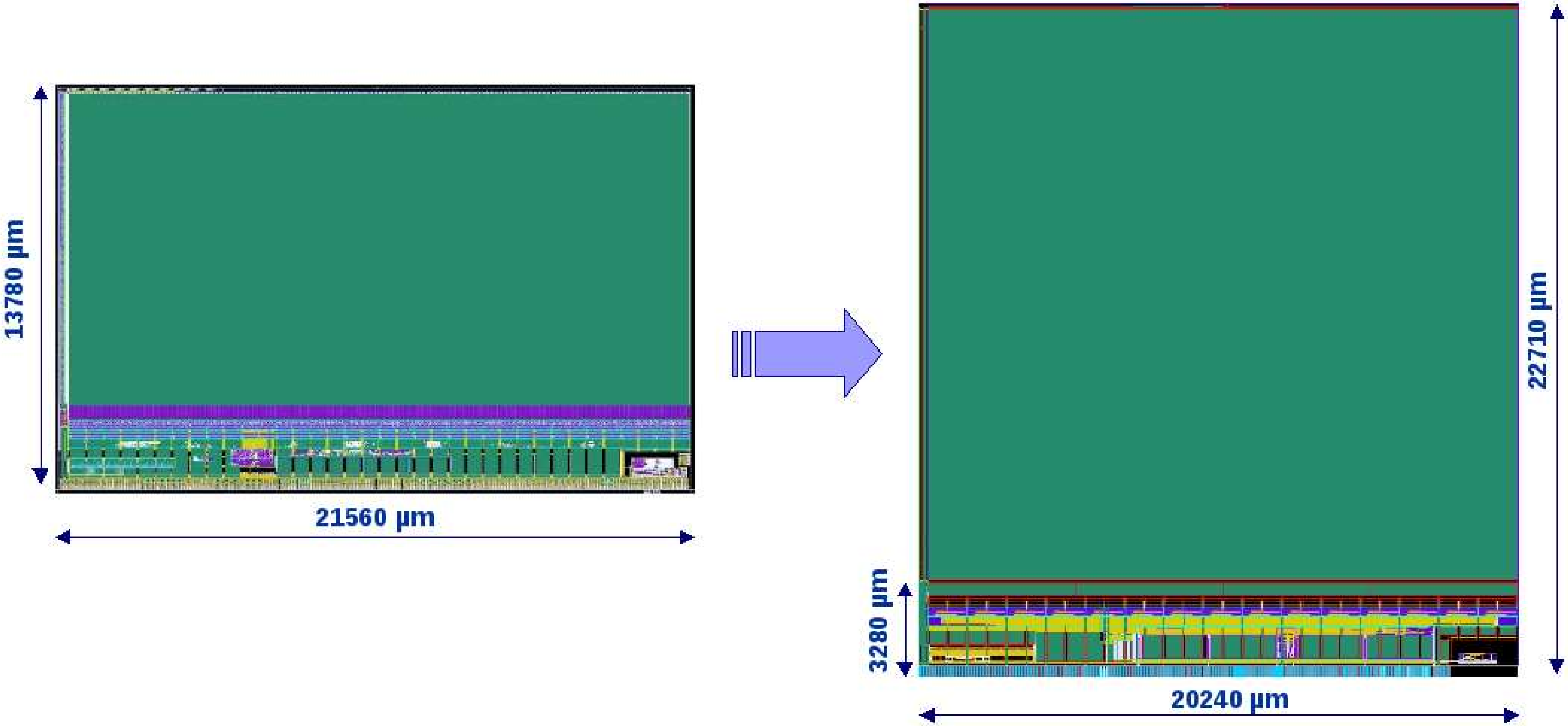




courtesy of Michal Szelezniak / Vertex-2010

▷▷▷ **1st vertex detector equipped with CMOS pixel sensors** ⟶ **1st data taking in 2013**

From MIMOSA-26 to ULTIMATE



- Half reticle 1152 x 567 pixel matrix
- Temperature ~20 °C
- Light power consumption constrains
- Space resolution ~4 µm
- No constrains on radiation tolerance

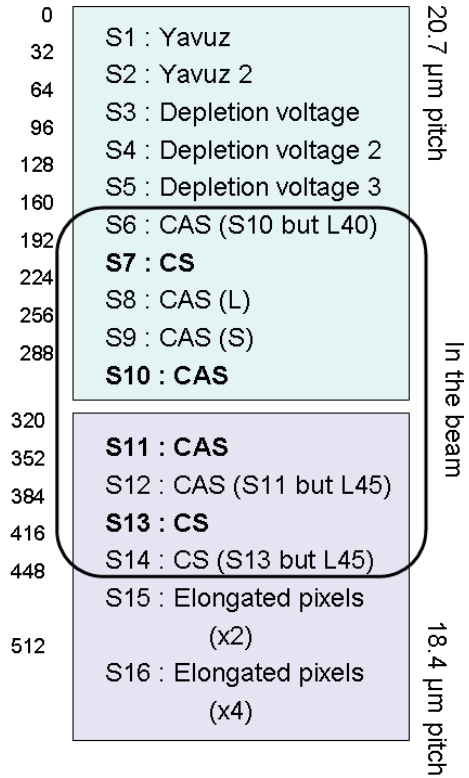
- Full reticle 960 x 928 pixel matrix
  - Longer integration time ~200 µs
- Temperature 30-35 °C
- Power consumption ~100 mW/cm²
- Space resolution < 10 µm
- 150 kRad / yr & few 10^{12} Neq /cm² /yr

courtesy of Ch. Hu-Guo / TWEPP-2010

➔ Optimisation

MIMOSA-22AHR: Motivations, Properties, Tests Performed

- **Motivations :**
  - ⋇ validate larger pitch design ⇛ power dissipation
  - ⋇ try enhancing in-pixel amplification ⇛ sensitivity to discri. offset
  - ⋇ enhance radiation tolerance at 30°C
  - ⋇ explore and validate new epitaxial layers (AMS home made vs provider)

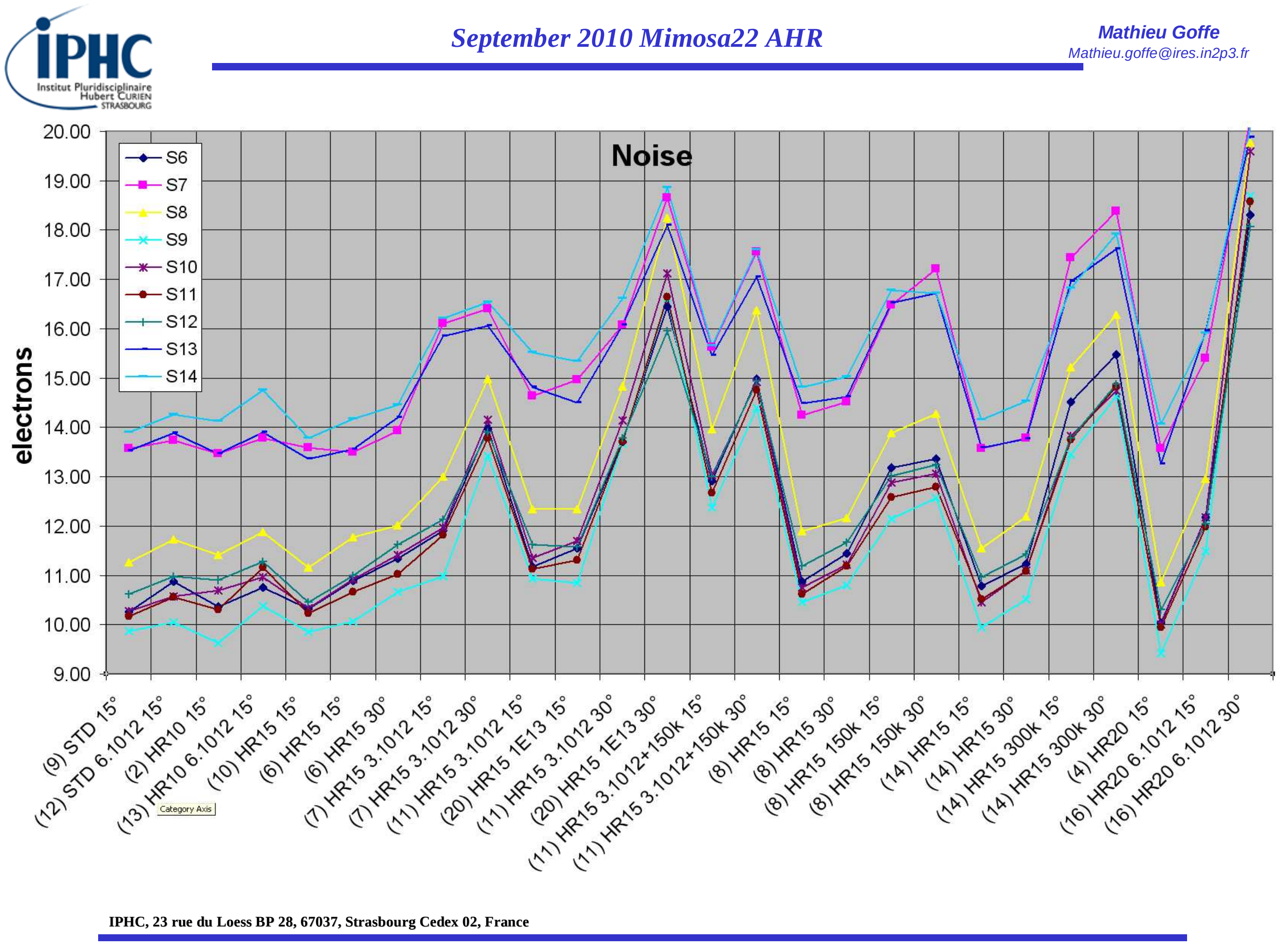


- **Main components:**
  - ⋇ pitch: 20.7 μm (UTIMATE) and 18.4 μm (MIMOSA-26)
  - ⋇ in-pixel amplification: Common Source & Cascode
  - ⋇ various features against ionising radiation damage: ETL, wide T gate
  - ⋇ features against non-ionising radiation damage: diode size, depletion potential

- **Fabrication:**
  - ⋇ part of an AMS-0.35 μm engineering run submitted in May 2010 ⟶ back in July
  - ⋇ various epitaxial layers: standard (M-22 & M-26), HR-10 (M-26), HR-15 (AMS), HR-20 (AMS)

- **Tests performed** (mainly at 3.3 V)**:**
  - ⋇ extensive lab tests: CCE (^{55}Fe), noise (fake rate)
  - ⋇ HR-15 and HR-10 tested at CERN-SPS (August & Sept. 2010)
  - ⋇ irradiation tolerance tests: 150 kRad, $3{\cdot}10^{12} n_{eq}/cm^2$ and combined
  - ⋇ temperature dependence: 20°C and 30°C
  - ⋇ "STAR running conditions": 150 kRad $\oplus$ $3{\cdot}10^{12} n_{eq}/cm^2$ $\oplus$ 30°C $\oplus$ 75 MHz (should have been 50 MHz)

MIMOSA-22AHR: Noise Performance

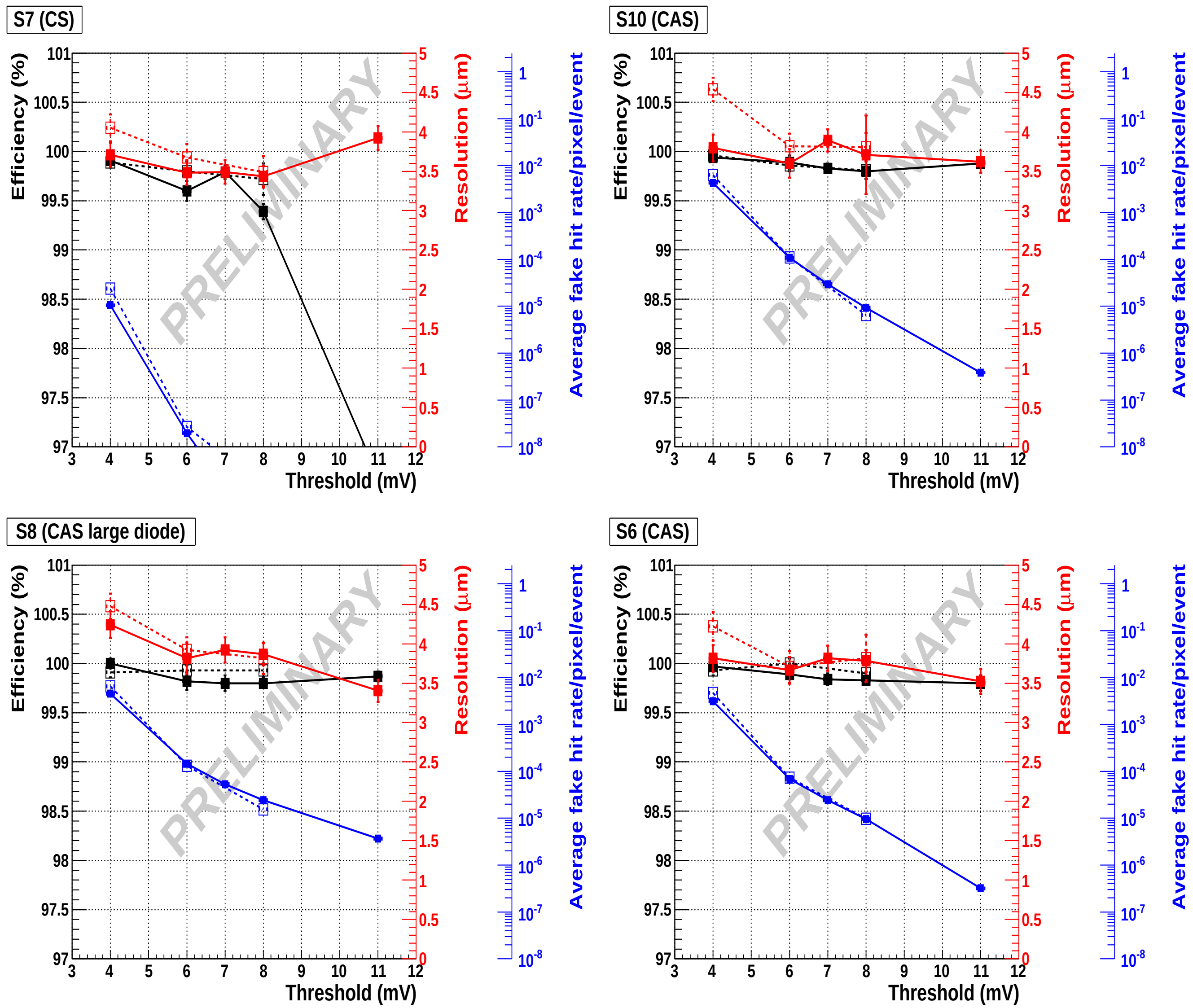


MIMOSA-22AHR: Performances before Irradiation

- **Tests performed at CERN-SPS:**
  - ⋇ sensor mounted on beam telescope (4 pairs of Si-strip detectors)
  - ⋇ vary discriminator threshold (JTAG), temperature, clock frequency
  - ⋇ measure detection efficiency, fake hit rate, single point resolution

- **Results for 20.7 μm pitch pixels ▷ mV-SNR equivalence at 30°C**

Threshold ▷	**4 mV**	**6 mV**	**8 mV**
S7	*4.1*	*6.4*	*8.7*
S10	*2.5*	*4.2*	*5.9*
S6	*2.7*	*4.4*	*6.1*
S8	*2.5*	*4.2*	*5.9*



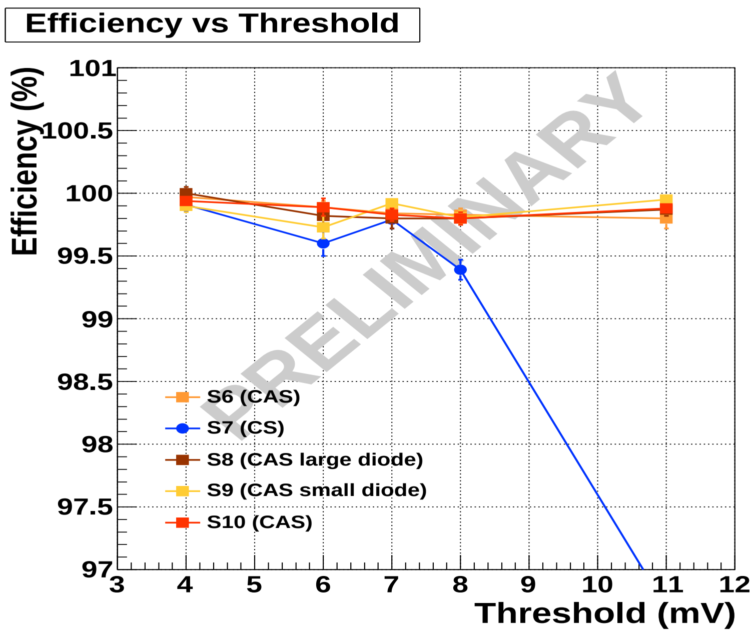
- **Typical noise performance :** 12-14 e$^-$ ENC

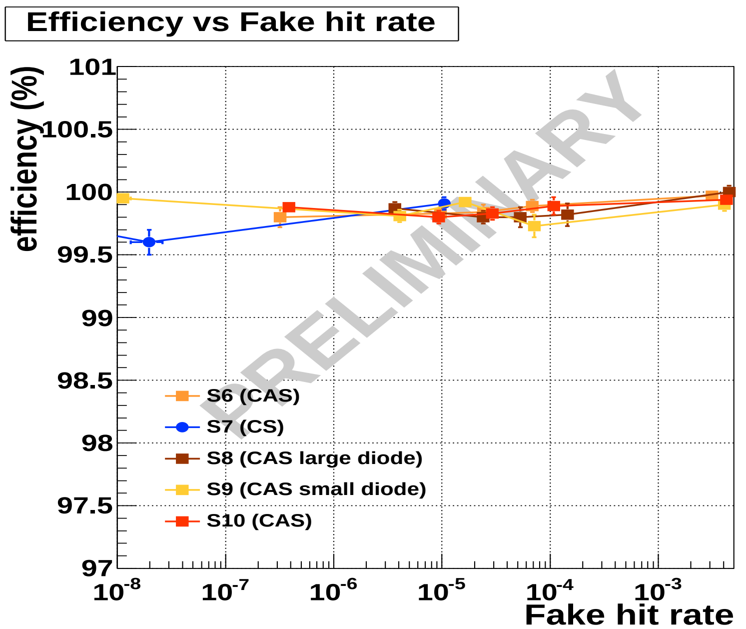
MIMOSA-22AHR: Performances before Irradiation

- **Efficiency vs fake hit rate:**
  - ⋇ define threshold values allowing high detection efficiency and low fake rate
  - $\Rightarrow$ keep fake rate $\lesssim 10^{-4}$

- **Results for 20.7 μm pitch pixels** ▷ **mV-SNR equivalence at 30°C**

Threshold ▷	4 mV	6 mV	8 mV
S7	*4.1*	*6.4*	*8.7*
S10	*2.5*	*4.2*	*5.9*
S6	*2.7*	*4.4*	*6.1*
S8	*2.5*	*4.2*	*5.9*



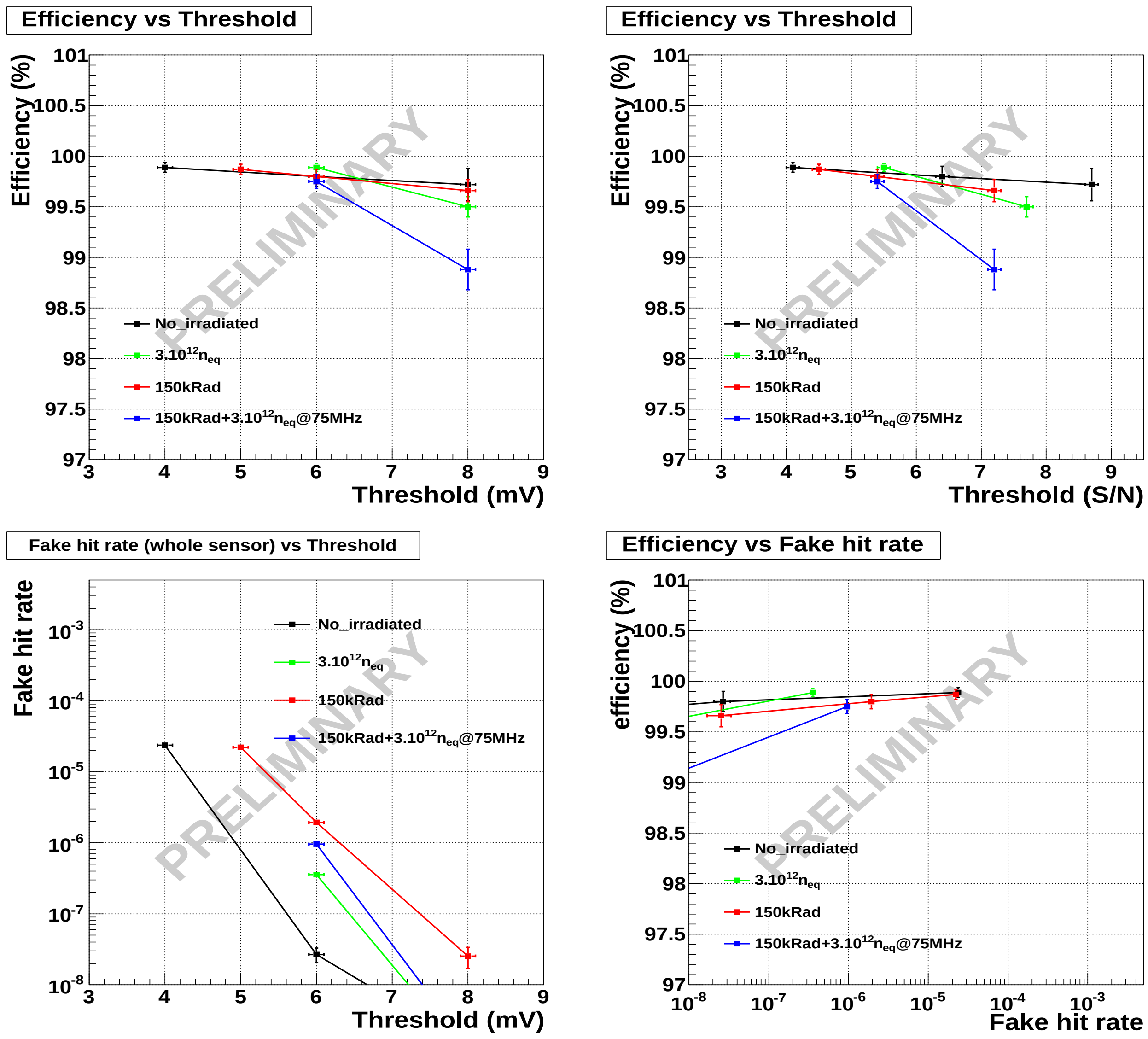


MIMOSA-22AHR S7 Pixel : Summary

- **Summary of results obtained with S7 (CS) :**
  - ⋇ evolution of detection efficiency
  - ⋇ evolution of fake hit rate
    - ⟶ look for viable working point

- **Results for 20.7 μm pitch pixels ▷**
  mV-SNR equivalence at 30°C

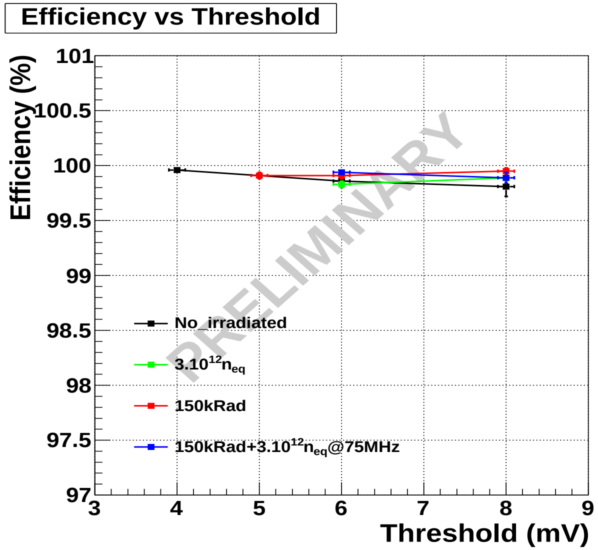
Threshold (mV) ▷	4	5	6	8
before irrad.	*4.1*		*6.4*	*8.7*
$3{\cdot}10^{12}$ n_{eq}/cm^2			*5.5*	*7.7*
150 kRad		*4.5*	*5.4*	*7.2*
combined (75 MHz)			*5.2*	*6.9*

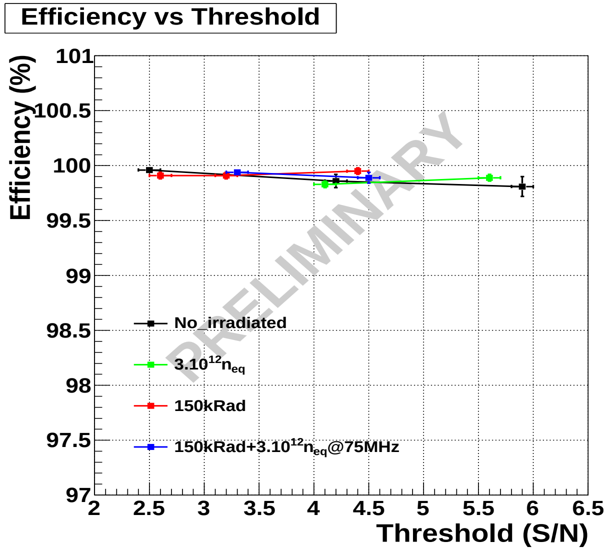


⇛ **No problem to find a threshold where the detection efficiency is > 99.5 % while the fake hit rate remains negligible**

MIMOSA-22AHR S10 Pixel : Summary

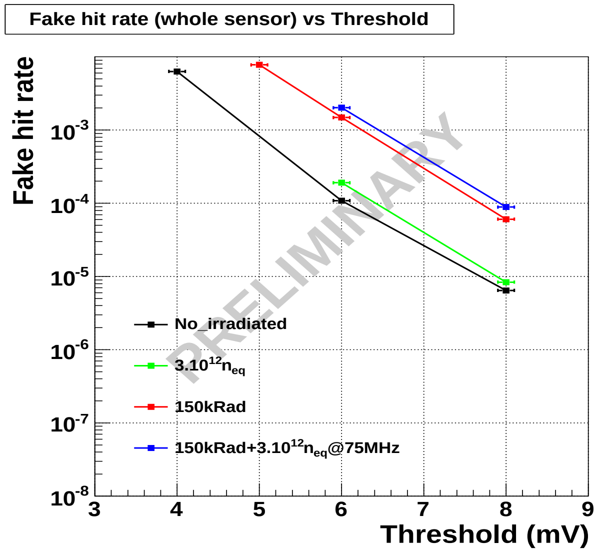
- **Summary of results obtained with S10 (CAS) :**
  - ⋇ evolution of detection efficiency
  - ⋇ evolution of fake hit rate
    - ↪ look for viable working point

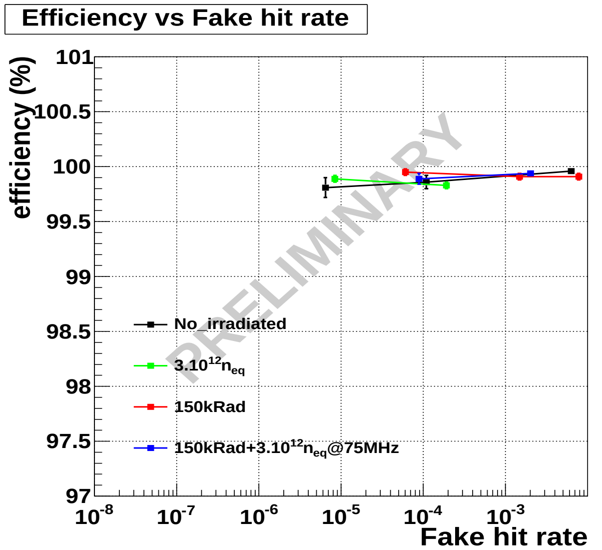




- **Results for 20.7 μm pitch pixels** ▷
  mV-SNR equivalence at 30°C

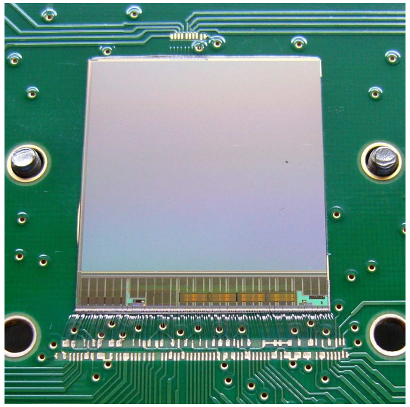
Threshold (mV) ▷	**4**	**5**	**6**	**8**
before irrad.	*2.5*		*4.2*	*5.9*
$3{\cdot}10^{12}$ n_{eq}/cm^2			*4.1*	*5.6*
150 kRad		*2.6*	*3.2*	*4.4*
combined (75 MHz)			*3.2*	*4.3*



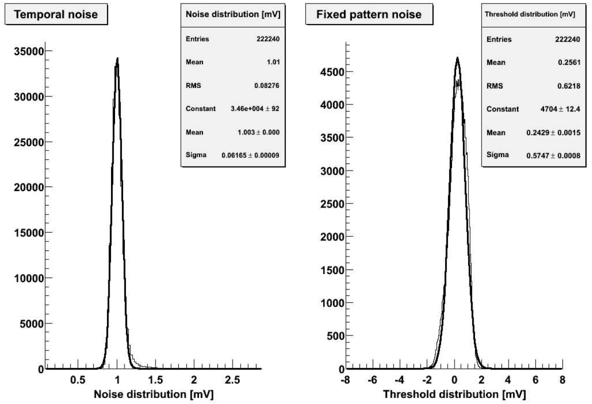


⇛ **No problem to find a threshold where the detection efficiency is $>$ 99.5 % while the fake hit rate remains negligible**

STAR-PXL Detector : MIMOSA-28



- **Main characteristics of ULTIMATE:**
  - ⋇ 0.35 μm process with high-resistivity epitaxial layer
  - ⋇ column // architecture with in-pixel cDS & amplification
  - ⋇ end-of-column discrimination and binary charge encoding, followed by $\emptyset$
  - ⋇ active area: 960 columns of 928 pixels (19.9$\times$19.2 mm^2)
  - ⋇ pitch: 20.7 μm $\rightarrowtail$ $\sim$ 0.9 million pixels
    - $\hookrightarrow$ charge sharing $\Rrightarrow$ $\sigma_{sp} \sim$ 3.5 μm expected
  - ⋇ $t_{r.o.} \lesssim$ 200 μs ($\sim$ 5$\times$10^3 frames/s)
    - $\Rrightarrow$ suited to $>$10^6 part./cm^2/s
  - ⋇ 2 outputs at 160 MHz
  - ⋇ $\lesssim$ 150 mW/cm^2 power consumption

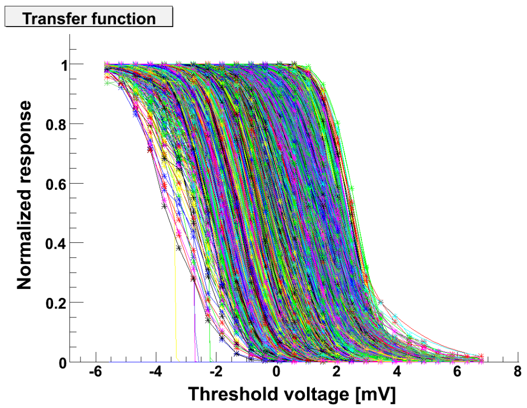


▷▷▷ **Chip back from foundry $\Rrightarrow$ lab tests under way since early April :**

- ⋇ N $\lesssim$ 15 e$^-$ ENC at 30-35°C (as MIMOSA-22AHR)
- ⋇ CCE (^{55}Fe) similar to MIMOSA-22AHR

—o **m.i.p. detection assessment at CERN-SPS in June-July '11**

—o radiation tolerance assessment through Spring and Summer



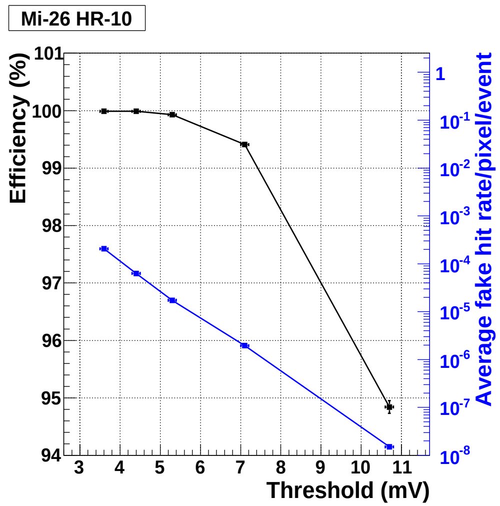
Expected M.I.P. Detection Performances of MIMOSA-28

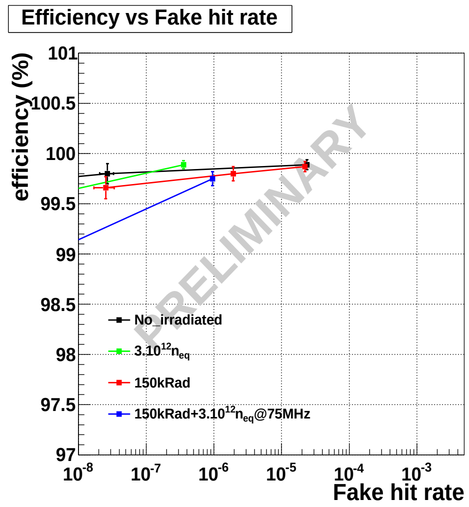
- **Expected m.i.p. detection performances** determined with MIMOSA-26 and with medium size MIMOSA-22AHR prototype of ULTIMATE/M28 at SPS with $\sim$ 100 GeV π^- (Summer '10)

- **Detection efficiency vs fake hit rate :**

  sensor works with high detection efficiency and

  marginal contamination by noise fluctuations (fake hits)

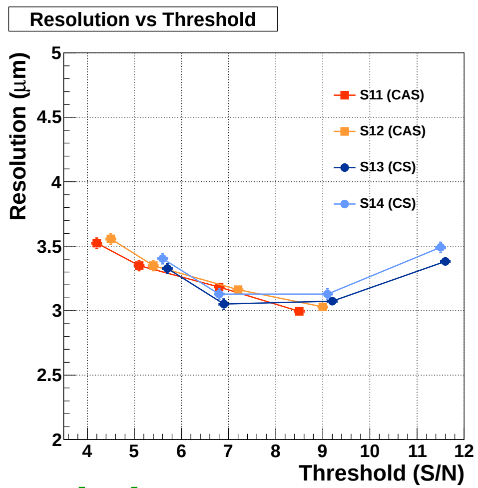




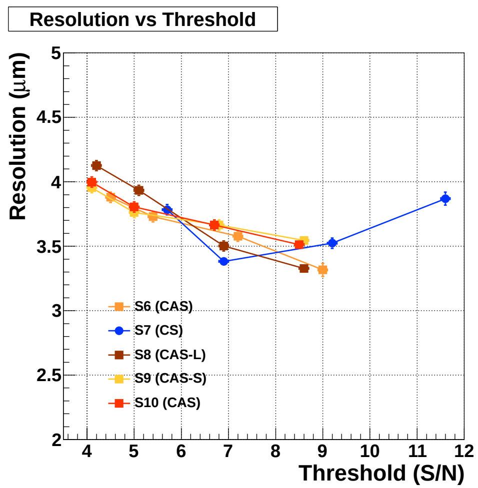
- **Single point resolution :**

  ※ 18.4 μm pitch (MIMOSA-26) $\rightarrowtail$ $\sigma_{sp} \sim 3\ \mu m$

  ※ 20.7 μm pitch (ULTIMATE) $\rightarrowtail$ $\sigma_{sp} \sim 3.5\ \mu m$



Pitch : 18.4 μm



20.7 μm

SUMMARY

- **The translation from MIMOSA-26 to ULTIMATE/Mimo-28 completed**

  ↪ in time for data taking in FY 2014

- **Sensors were fabricated and are being tested :**

  ⋇ lab tests before irradiation show expected behaviour

  ⋇ irradiation tests under way: 150 kRad and 3·10^{12}n$_{eq}$/cm^2

  ⋇ mip detection performance assessment: beam tests at CERN-SPS in June/July

- **Pending question :** should the digital circuitry be made latch-up free ?

- **ULTIMATE acts as an important forerunner for several sensors of upcoming vertex detectors**