Towards the Final Telescope Sensor

Progress Report

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on behalf of IPHC and IRFU/Saclay

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OUTLINE

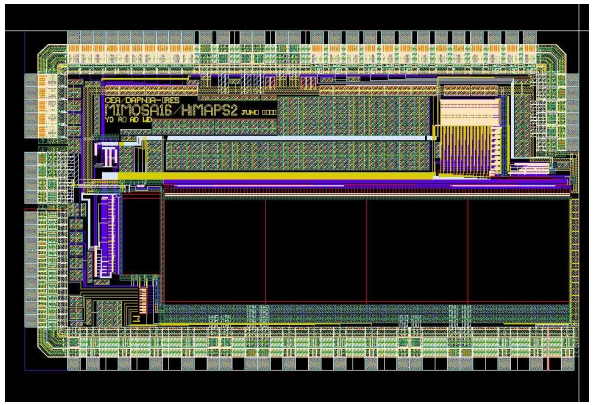
- **Strategy of the chip development (reminder)**
- **Col. *II* sensor prototyping :** *Objectives of IDC/MIMOSA-22 prototyping – Lab & beam test results*
- **The question of radiation tolerance**
- **Status of MIMOSA-22bis :** *Differences with IDC/MIMOSA-22 – Preliminary test results*
- **Final chip : status of design and plans**
- **Summary - Outlook**

- **Specific goals of IDC/MIMOSA-22 :**
  - *validate the fast read-out architecture developed in MIMOSA-16 (next slide) at* **Real Scale**
  - *extract an optimal pixel design (sensing diode and signal prcoessing μcircuits)*
  - *improve the chip testability (JTAG, analog outputs, pads, ...)*

- **Objective beyond IDC/MIMOSA-22 :**
  - *once validated, the IDC/MIMOSA-22 architecture will be merged with SDC-2/SUZE-01*
    - ⇛ *Final Sensor (TC/MIMOSA-26), to be sent for fabrication in Autumn*

Performances of a Small Prototype with Digitised Output

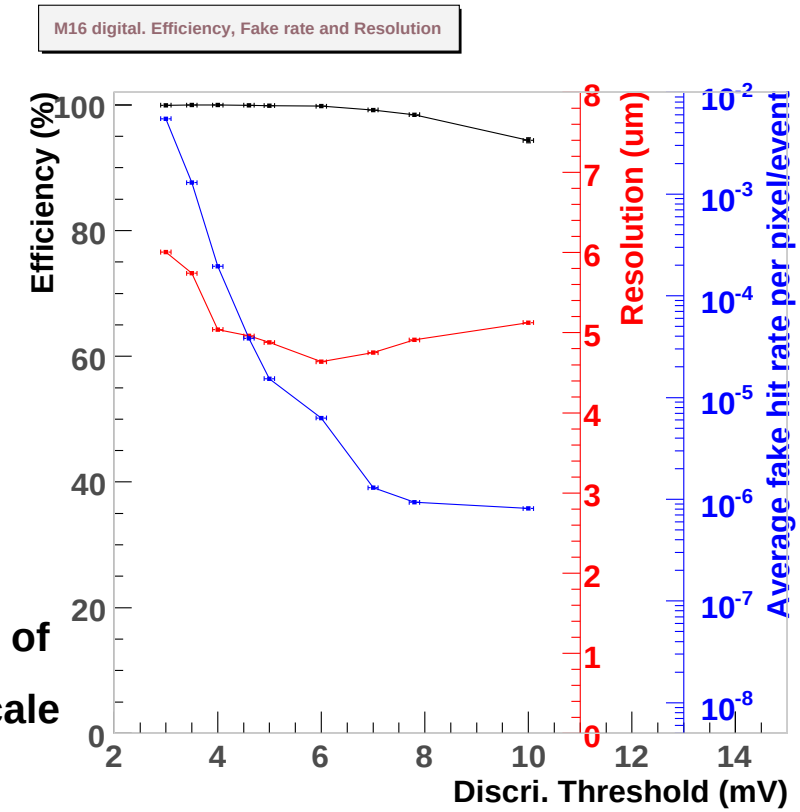
- *MIMOSA-16 :* ◇ *fabricated in 2006 (coll. with IRFU/Saclay)*
  - ◇ *32 col. of 128 pixels (25 μm pitch, integrated CDS)*
  - ◇ *24 col. ended with an integrated discriminator*
  - ◇ *4 different pixels (i.e. 4 sub-arrays)*



- *Tests at CERN-SPS ($\sim$ 180 GeV π^-) in Summer 2007*

  $\longmapsto$ *results of one sub-array (S4)*

Discri. threshold	*Detection eff.*	*Fake rate*	*Resolution*
4 m V	*99.96 $\pm$ 0.03 (stat) %*	*$\sim 2{\cdot}10^{-4}$*	*$\sim$ 4.8 – 5.0 μm*
6 m V	*99.88 $\pm$ 0.05 (stat) %*	*$<10^{-5}$*	*$\sim$ 4.6 μm*



▷▷▷ **Architectures of pixel (integrated CDS) and of full chain made of ”columns ended with integrated discri. ” validated at small scale**

Main Characteristics of the IDC/MIMOSA-22 Sensor

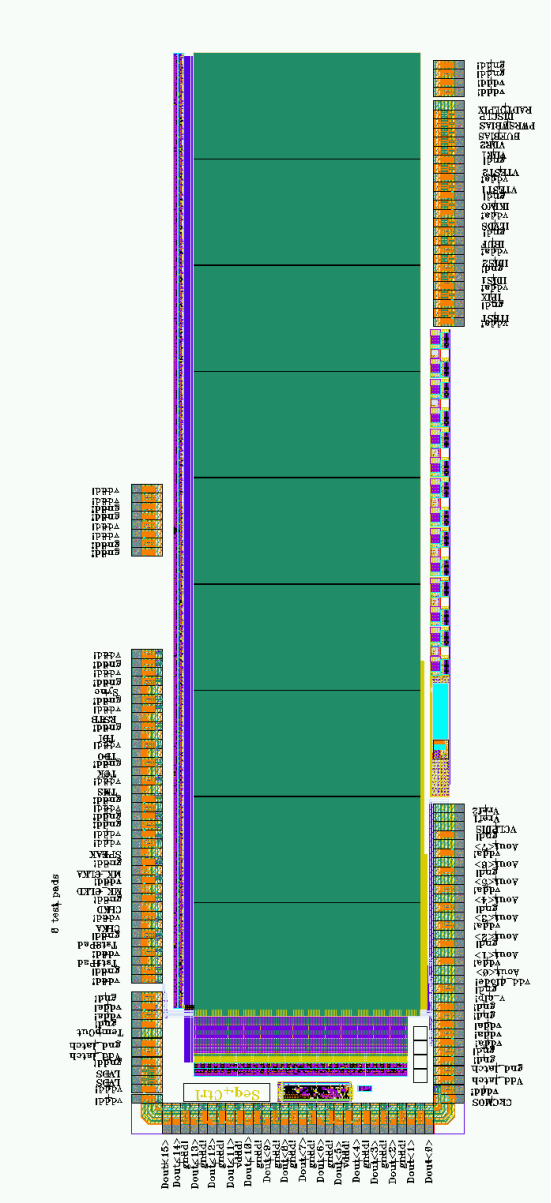
♣ **Extension of MIMOSA-16 ⟼ larger surface, smaller pitch, optimised pixel, JTAG, more testability**

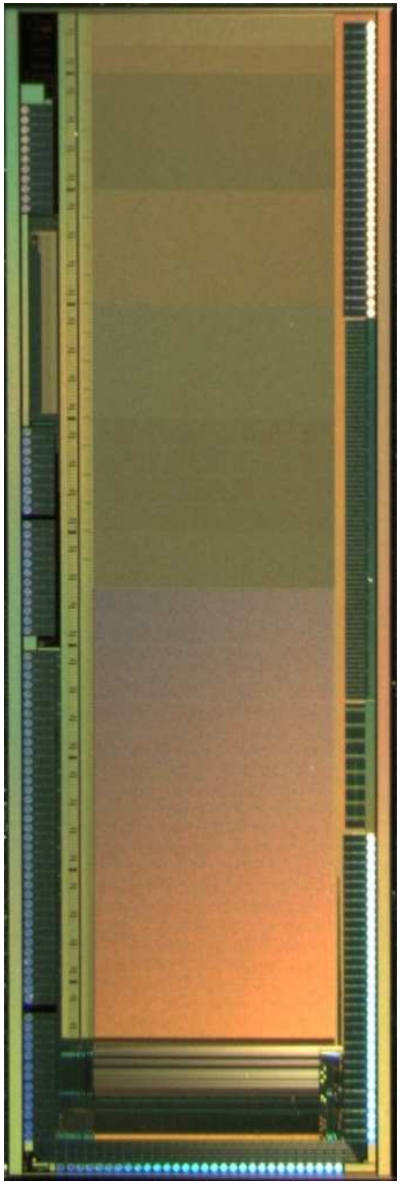
Pixel characteristics (*optimal charge coll. diode size ?*) :

- ⁕ **pitch : 18.4** μm (compromise resolution/pixel layout)
- ⁕ diode surface : $\sim$ 10 – 20 μm^2 to optimise charge coll. & gain
- ⁕ **128 columns ended with discriminator**
- ⁕ **576 pixels per column (≡ final column length)**
- ⁕ 8 columns with analog output for test purposes
- ⁕ 9 sub-matrices of 64 rows :

  17 pixel designs w/o ionising rad. tol. diode

  ⟹ **active digital area $\sim$ 25 mm^2** (128 x 576 pixels)
- ⁕ **read-out time $\sim$ 100** μs **($\sim 10^4$ frames/s)**





Testability :

- ⁕ JTAG + bias DAC ⟼ **programmable chip steering**
- ⁕ 2 additionnal DC voltages to emulate pixel's output

  for independent discriminator performance assessment
- ⁕ output frequency $\leq$ 40 MHz

- **Topics investigated :**
  - ⁂ *optimum between CCE (⇛ large diode) and capacitive noise (⇛ small diode)*
  - ⁂ *effective and robust pre-amplification scheme*
  - ⁂ *low noise (ionising) radiation tolerant design*
  - ⁂ *temperature dependence of performances*
  - ⁂ *performance uniformity over full active surface*
  - ⁂ *comparison with MIMOSA-16 performances (24 columns of 128 pixels)*

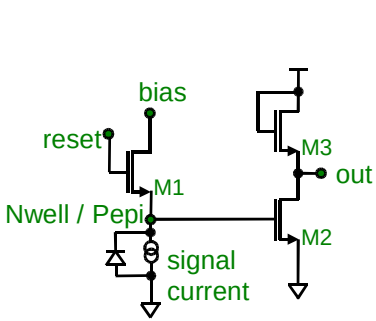
- **5 pixel designs implemented, combining 2 reset & 2 ampli. variants (w/o rad. tol. diode, diff. diode sizes):**
  - ⁂ *reset diode with (standard) common source amplifier : w/o improved gain*
  - ⁂ *self-biased feedback diode with common source amplifier with improved gain*
  - ⁂ *feedback reset diode with common source amplifier : w/o improved gain*

- **Status :**
  - ⁂ *back from foundry since Feb.'08*
  - ▷ *lab tests of analog and digital (discri.) outputs with ^{55}Fe source completed*
  - ▷ *first beam tests (CERN-SPS / August '08) analysed*

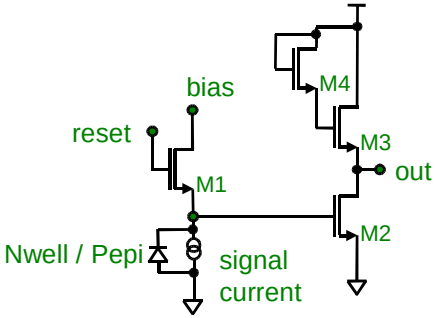
IDC/MIMOSA-22 Lab Test Results

Various pixel designs (rad. tol. and standard) :

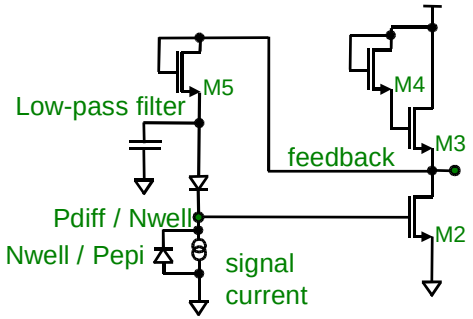
- *reset diode (improved gain)*
- *self-biased diode with feedback (improved gain)*



(S13)



(S10)



(S6)

Main results obtained with exposure to ^{55}Fe source ($t_{r.o.}$ = 92.5 μs) :

- *Noise :*
  - *Temporal (pixel) Noise $\sim$ 0.5 – 0.7 mV (10 $<$ N $<$ 14 e^- ENC)*
  - *FPN $\sim$ 0.25 mV*
  - *N (rad. tol. pixels) $\sim$ N (standard pixels) + 1 e^- ENC*
- *Cluster CCE :*
  - *3x3 pixels : 70 – 80 %*
  - *5x5 pixels : 80 – 90 %*
- *modest T dependence between $\sim 10^\circ$C and 35°C : $\lesssim$ 10 % noise variation*
- *5 different chips characterised : identical performances within $\pm$ 5 %*

IDC/M22 Lab Tests : Analog Output Results

	S6		S7		S8		S9		S10	
	mV	e-	mV	e-	mV	e-	mV	e-	mV	e-
TN	0.612	11.5	0.601	10.7	0.615	11.3	0.595	10.0	0.639	11.6
FPN	0.250	4.7	0.263	4.6	0.254	4.4	0.273	4.6	0.222	4.0

	S12		S13		S15		S16		S17	
	mV	e-	mV	e-	mV	e-	mV	e-	mV	e-
TN	0.636	11.2	0.692	13.4	0.682	12.8	0.536	12.4	0.527	11.4
FPN	0.225	4.0	0.269	5.2	0.277	5.2	0.218	5.1	0.217	4.7

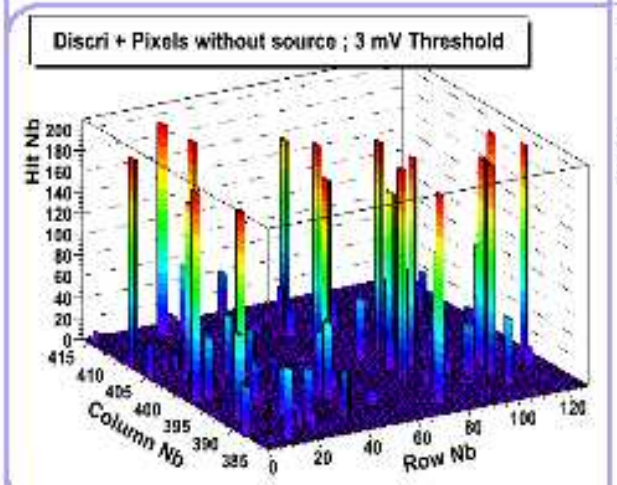
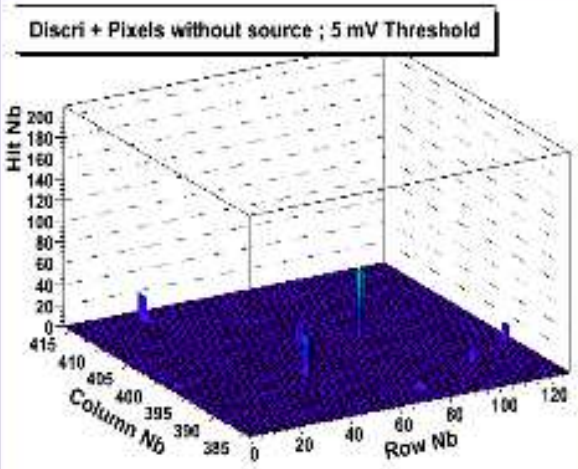
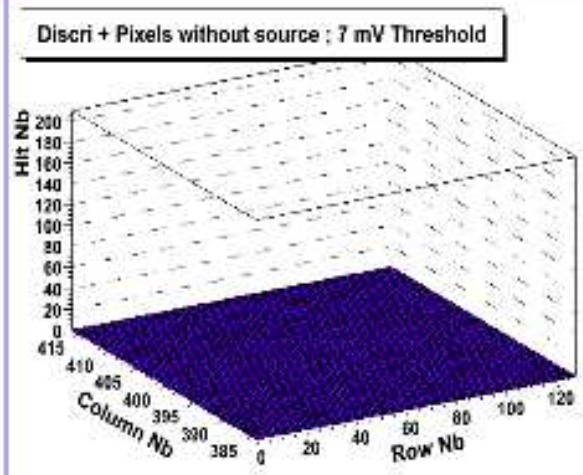
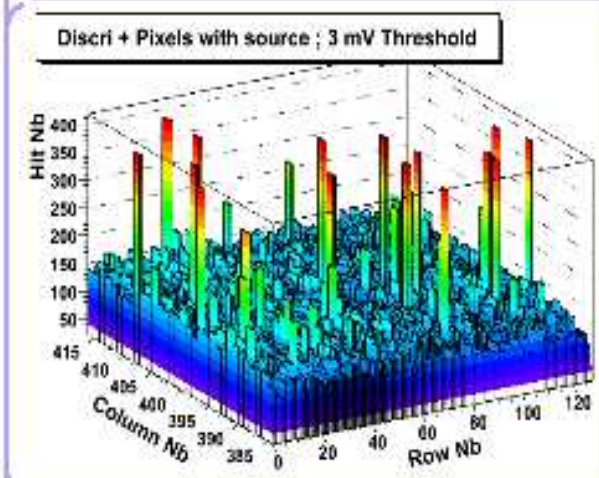
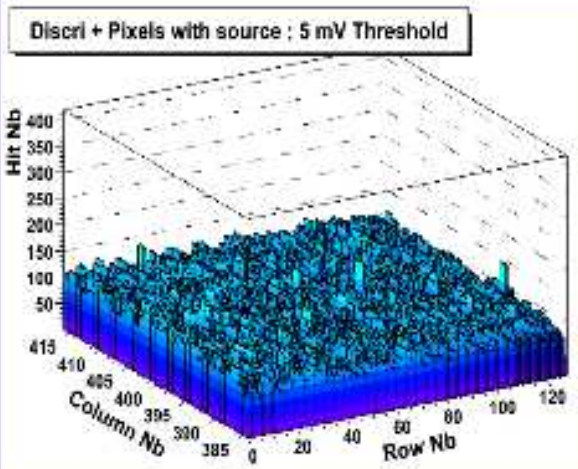
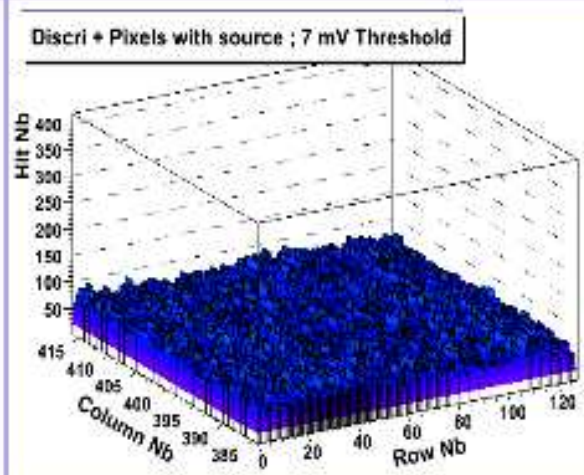
- Pixel Noise ~ 0.6mV
- FPN ~ 0.25 mV

⇒ Similar results than smaller prototype MIMOSA16 ones

- RadTol pixels (S6, S10, S13) Noise slightly higher than for standard pixels

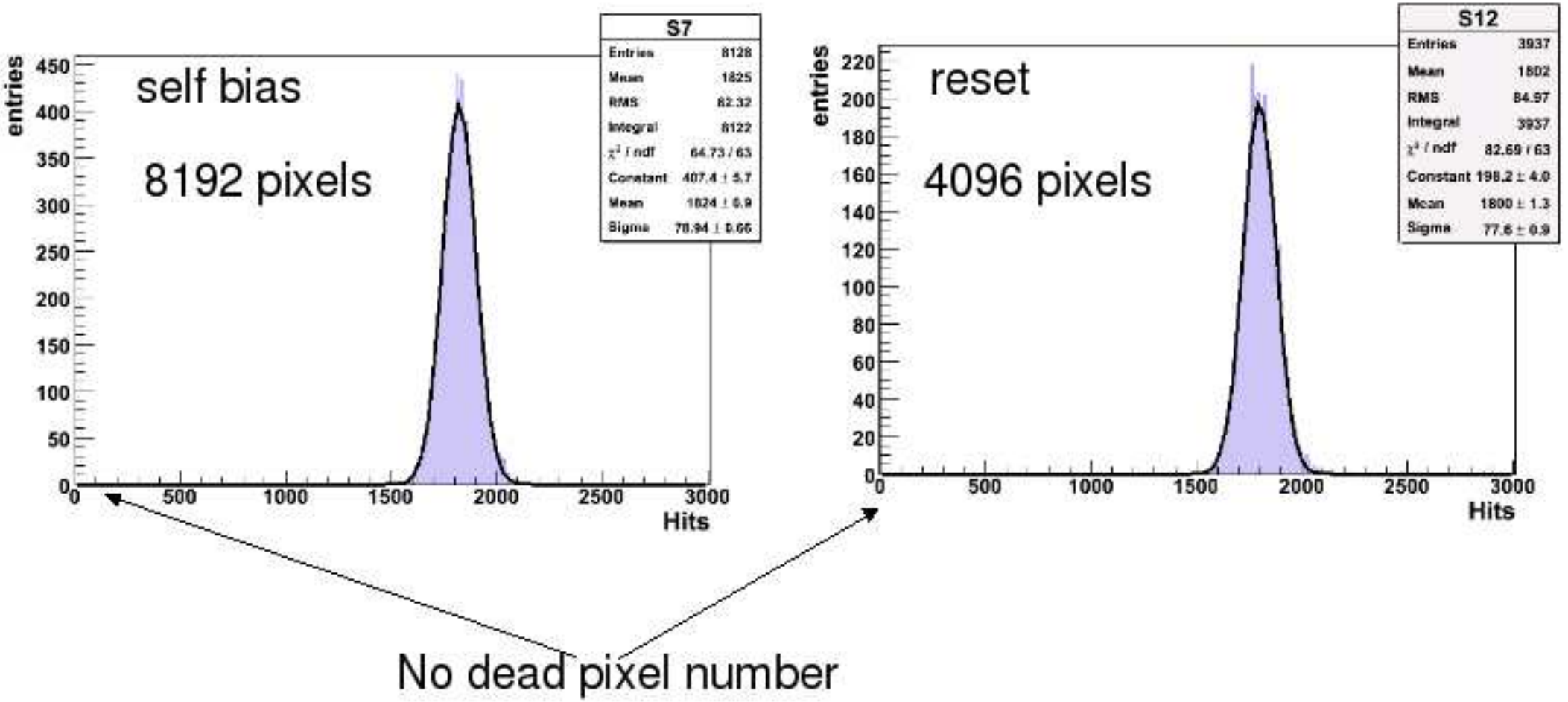
IDC/M22 Lab Tests : Digital Output Results (1/2)

S12 response for 3, 5 and 7 mV threshold without and with ^{55}Fe source

3 mV threshold	5 mV threshold	7 mV threshold	
			Without source
			With source
100.000 events	100.000 events	100.000 events	

IDC/M22 Lab Tests : Digital Output Results (2/2)

5 mV threshold with ^{55}Fe source



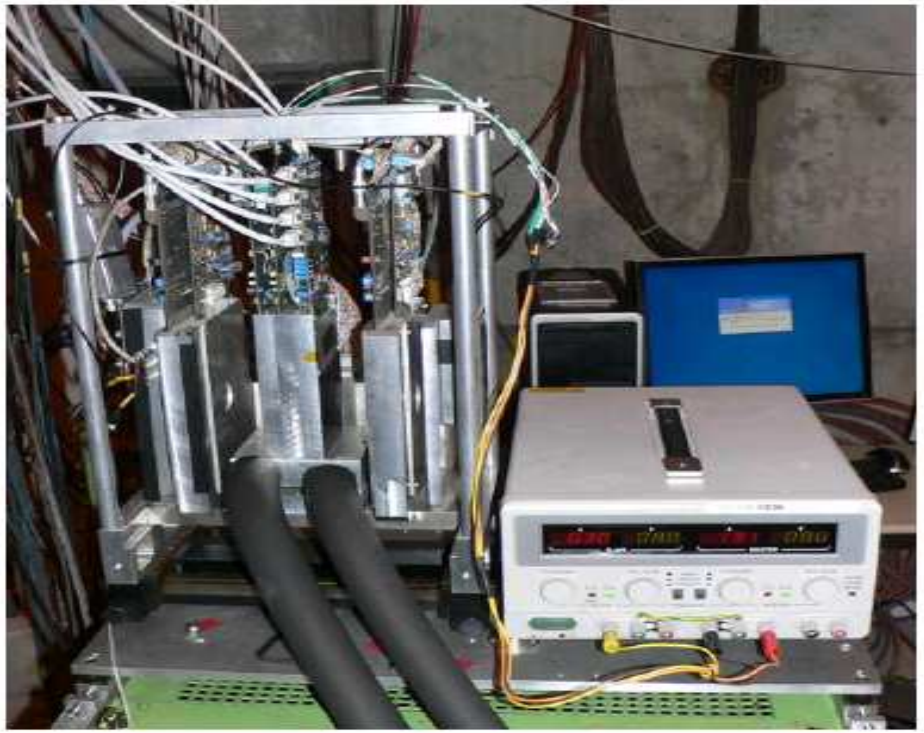
Good uniformity of discriminator response, within 4%

IDC/M-22(bis) Beam Tests : Data Taking Conditions

- **4 weeks of beam time at CERN-SPS :**
  - ▷ ∼ *2 weeks in August with MIMOSA-22 (EUDET period)*
  - ▷ ∼ *2 weeks in Sept.-Oct. with MIMOSA-22bis (SiLC period)*

- **T4-H6 beam line : ∼ 120 GeV π^- beam** ▷▷▷▷

- **Chips mounted at center of Si-strip telescope**
  (4 pairs of orthogonal strips) ▷▷▷▷

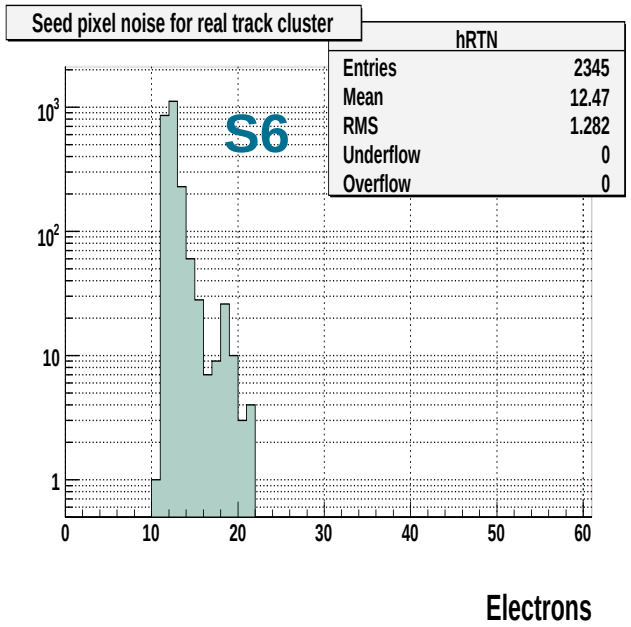


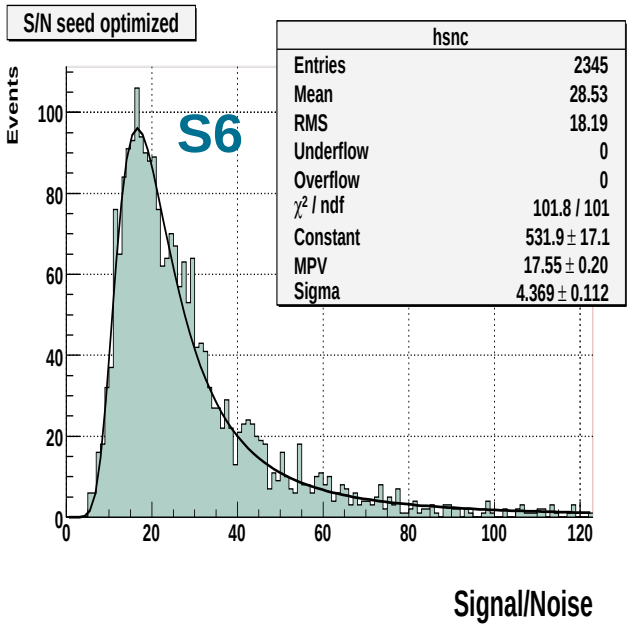
- **6 chips tested at various discri. threshold values:**
  - ▷ *2 MIMOSA-22 : 0 & 150 kRad*
  - ▷ *4 MIMOSA-22bis : 0, 150 & 300 kRad, $6{\cdot}10^{12}$ n_{eq}/cm^2*

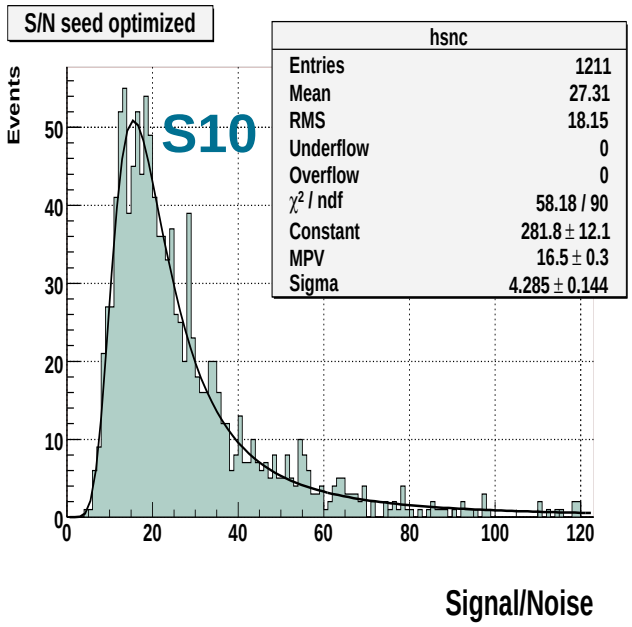
- **> 1 million tracks reconstructed in the sensors**

IDC/M-22 Beam Tests : Analog Output Performances

Noise and S/N (seed pixel) distributions delivered by the 8 columns without discriminator







Detection performances (det. eff. , N and S/N for hits where the seed pixel exhibits S/N $>$ 4) :

Sub-array	*S6*	*S7*	*S8*	*S9*	*S10*	*S12*	*S13*
Det. eff.	*99.93 % ± 0.05 %*	*99.95 % ± 0.04 %*	*100.00 % +0/-0.30 %*	*100.00 % +0/-0.14 %*	*99.87 % ± 0.09 %*	*100.00 % +0/-0.08 %*	*100.00 % +0/-0.07 %*
N (e^- ENC)	*12.5 ± 0.1*	*11.6 ± 0.1*	*12.3 ± 0.1*	*10.6 ± 0.1*	*13.6 ± 0.1*	*12.1 ± 0.1*	*14.0 ± 0.1*
S/N (seed, MPV)	*17.6 ± 0.2*	*18.5 ± 0.2*	*20.9 ± 1.1*	*19.5 ± 0.5*	*16.5 ± 0.3*	*18.2 ± 0.3*	*16.0 ± 0.3*

✳ *very satisfactory performances (det. eff. $\sim$ 99.9 % and single pt resolution $\lesssim$ 1.5 μm)*

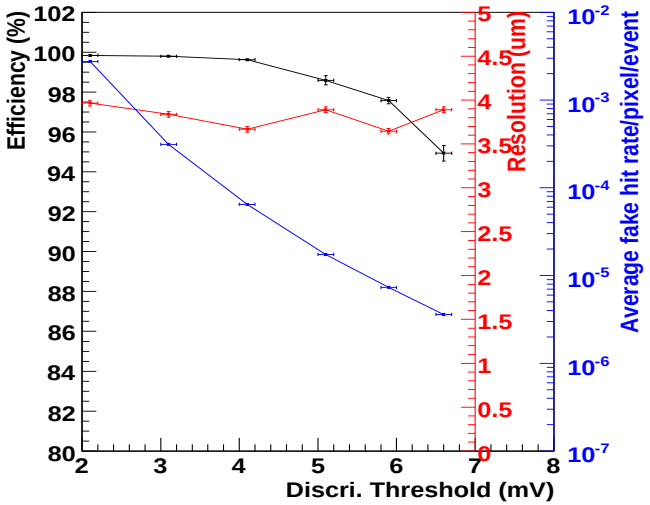
⇒ **pixel architecture (diode size, rad. tol. diode design, amplification scheme) validated**

IDC/M-22 Beam Tests : Digital Output Performances

Det. efficiency, fake hit rate & single pt resolution for S6, S7, S12, S13 vs discri. threshold :

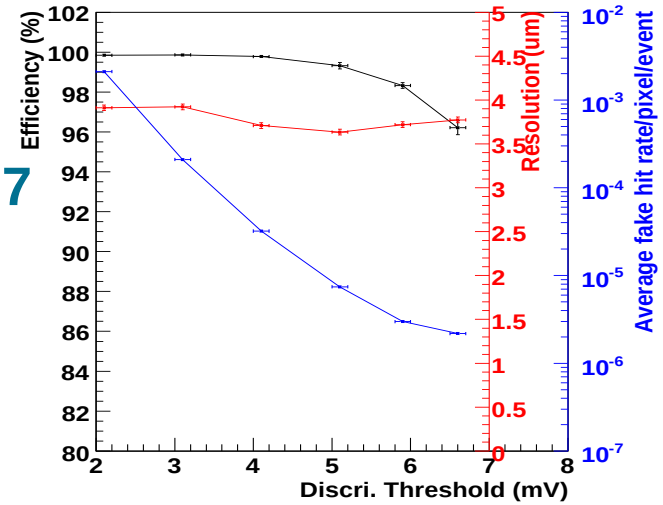
M22 digital S6. Efficiency, Fake rate and Resolution

S6



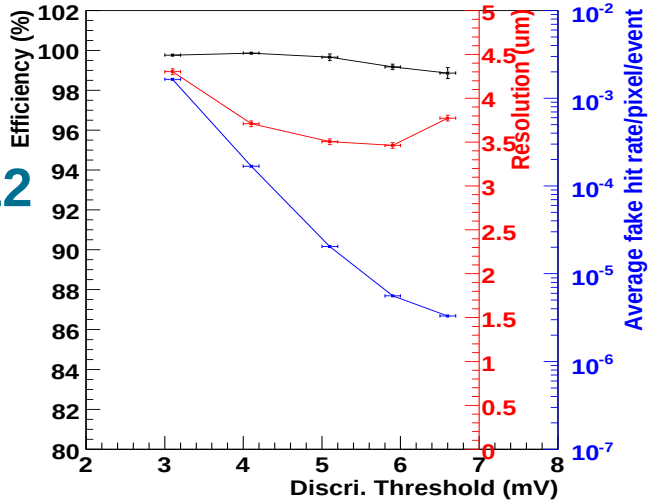
M22 digital S7. Efficiency, Fake rate and Resolution

S7



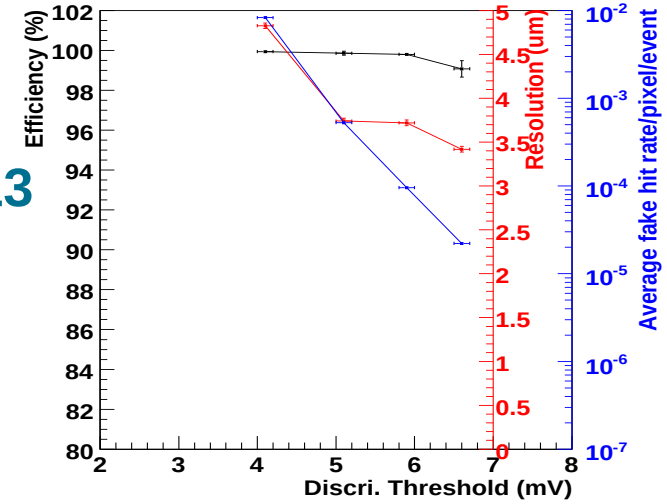
M22 digital S12. Efficiency, Fake rate and Resolution

S12



M22 digital S13. Efficiency, Fake rate and Resolution

S13

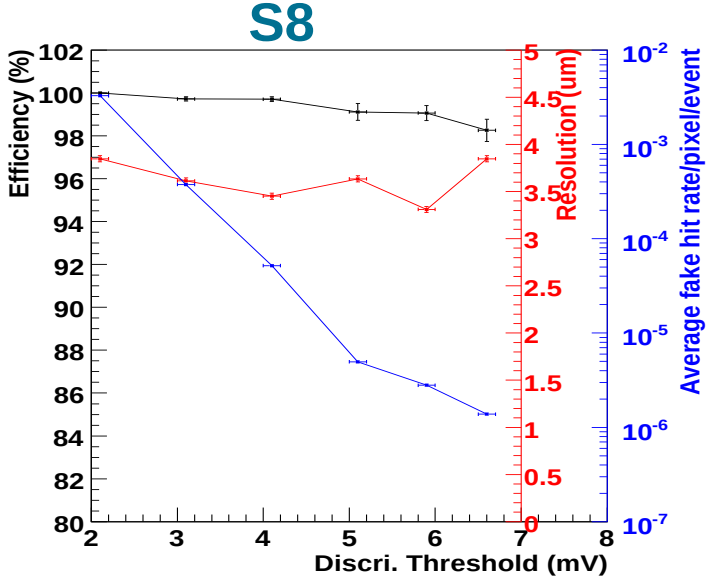


▷ ▷ ▷ **Detection efficiency $\gtrsim$ 99.8 % for all (rad. tol. and standard) pixel architectures !!!**

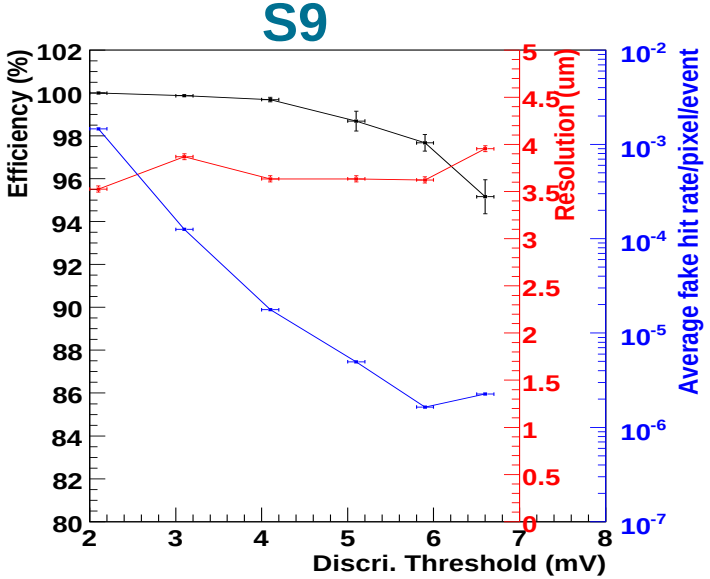
IDC/M-22 Beam Tests : Digital Output Performances

Detection efficiency, fake hit rate & single pt resolution for S8, S9, S10 vs discri. threshold :

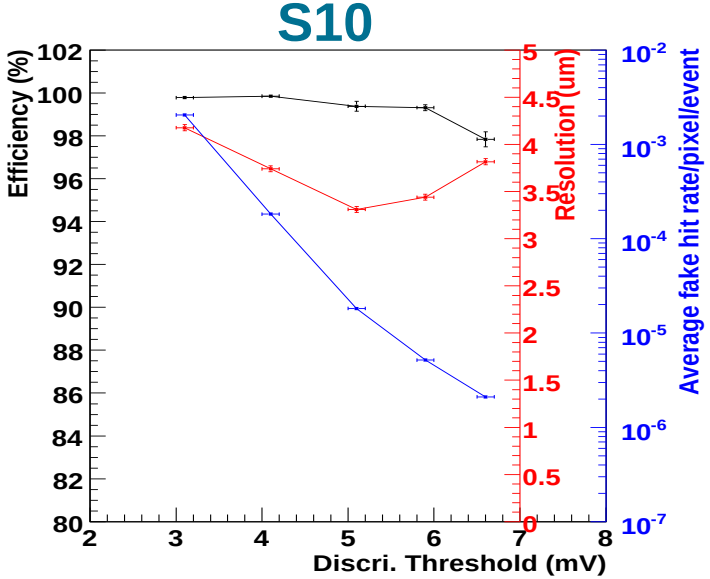
M22 digital S8. Efficiency, Fake rate and Resolution



M22 digital S9. Efficiency, Fake rate and Resolution



M22 digital S10. Efficiency, Fake rate and Resolution



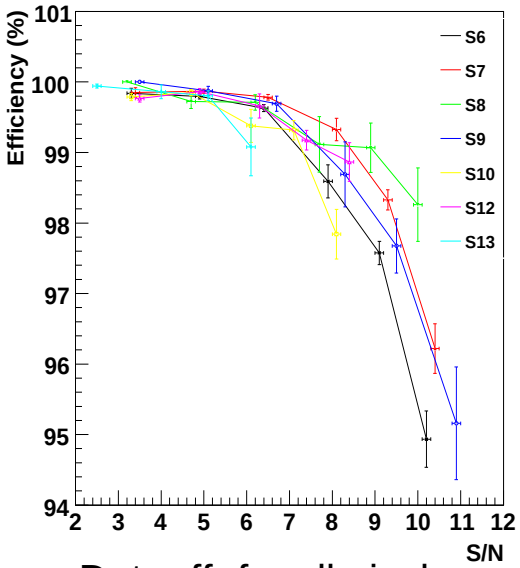
Main results:

- *rather marginal performance differences between the 7 sub-arrays (e.g. rad. tol. vs standard)*
- *det. eff. of analog output $\sim$ 99.9 % for all sub-arrays $\Rightarrow$ pixel architecture validated*
- *det. eff. of digital output $\gtrsim$ 99.8 % for all 7 sub-arrays (agrees with MIMOSA-16)*
- *fake hit rate seems larger than for MIMOSA-16 but acceptable : O(10^{-4} – 10^{-5})*
- *single point resolution $\gtrsim$ 3.5 μm (as expected)*
- *no performance non-uniformity observed over the chip surface $\Rightarrow$ real scale check validated*

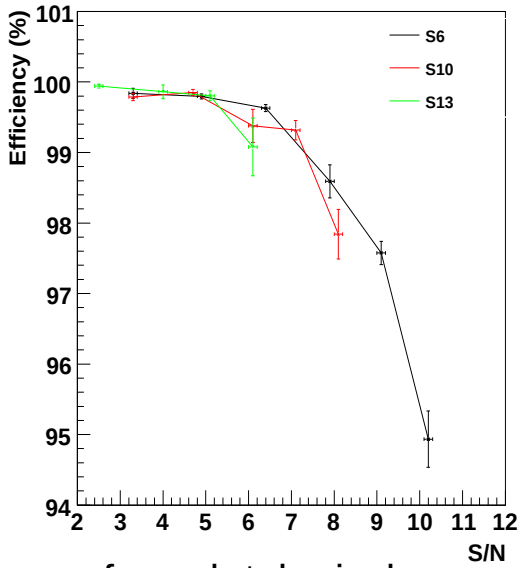
IDC/M-22 Beam Tests : Pixel Performance Comparison

Comparison of det. efficiency & fake hit rate vs S/N for all sub-arrays (prelim.) :

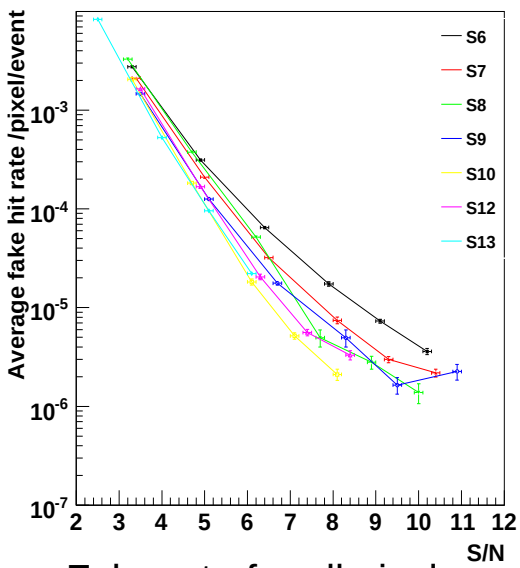
M22 digital	M22 digital	M22 digital	M22 digital



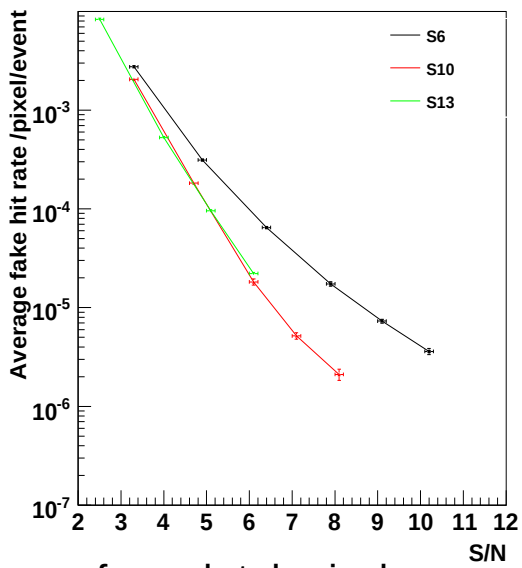
Det. eff. for all pixels



for rad. tol. pixels



Fake rate for all pixels



for rad. tol. pixels

▷ **Observed performance differences (& analysis maturity) don't allow deciding for a given pixel archi.**

⇛ **Wait for :**

- ※ *more sensors tested*
- ※ *more beam tests*
- ※ *MIMOSA-22bis performances*
- ※ *radiation tolerance studies*

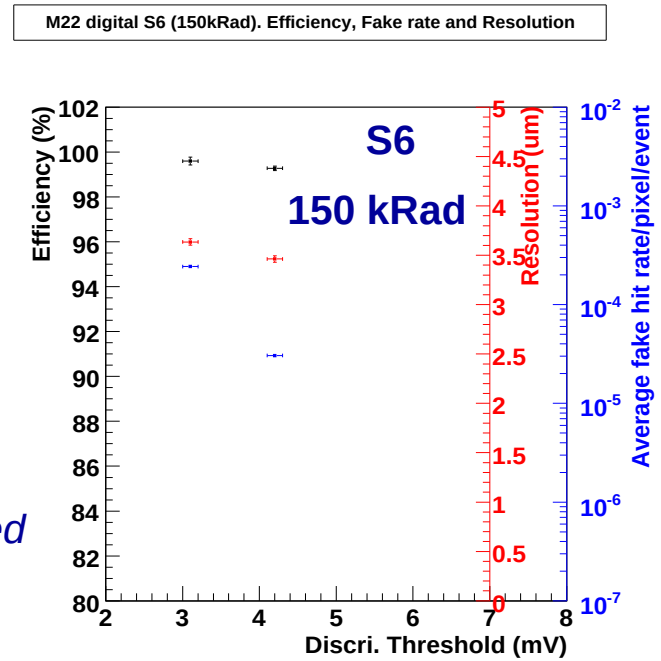
The Question of Radiation Tolerance

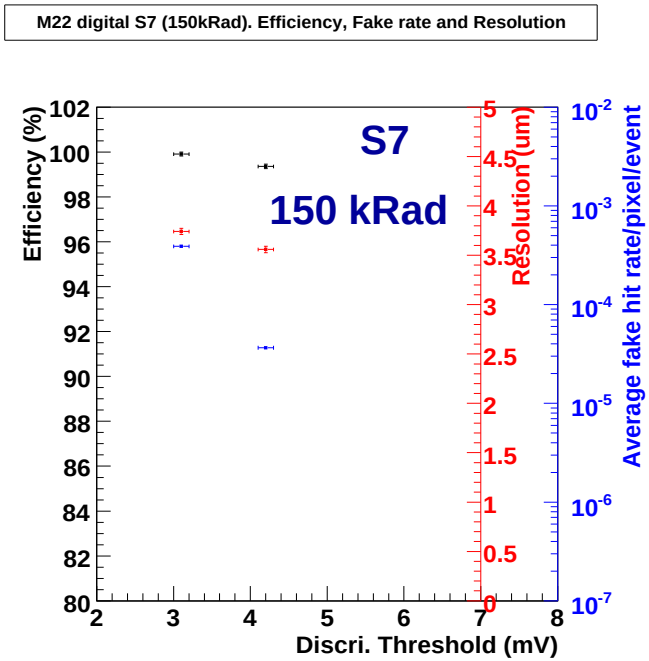
Why may radiation tolerance be a concern ?

- *max. annual doses at DESY $\lesssim 10^{11}$ e^- (few GeV)/yr $\Rightarrow$ $\lesssim$ 3.5 kRad & 10^{10} n_{eq}/cm^2*
- *max. annual doses at CERN $\lesssim$ several 10^{12} π^- (10^2 GeV)/yr $\Rightarrow$ $\lesssim$ O(10^2) kRad & O(10^{12}) n_{eq}/cm^2*

Assessing radiation tolerance (10 keV X-Rays):

- *Noise of IDC/M-22 (S6) at 20°C :*
  - *$\sim$ 12.5 e^- ENC before irradiation*
  - *$\sim$ 16 e^- ENC after 150 kRad* $\longmapsto$
  - *$\sim$ 18 e^- ENC after 300 kRad*





- *New design (MIMOSA-22bis) fabricated*
  - ▷ *tests in Sept.–Oct. (lab, SPS)*

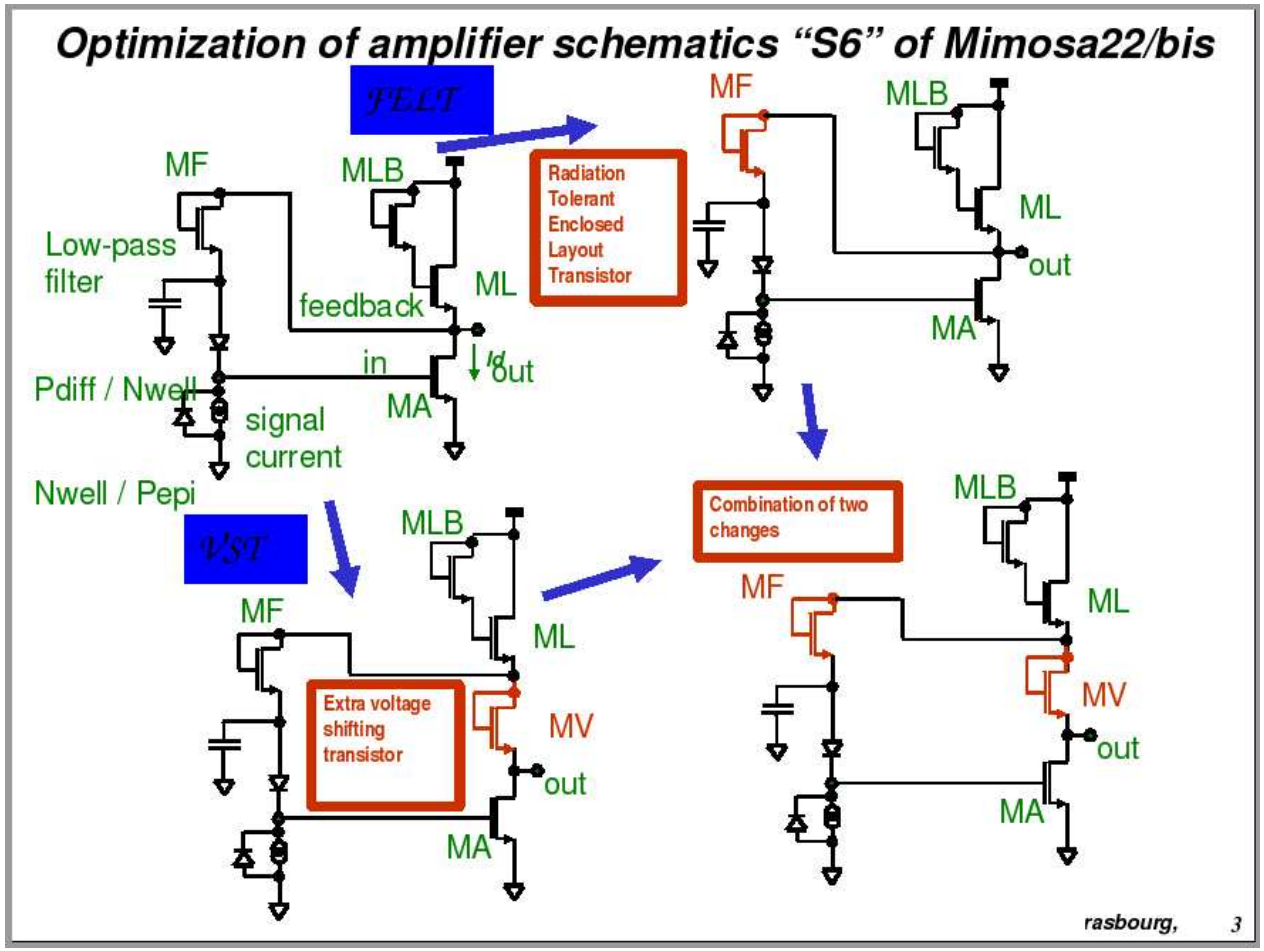
- *MIMOSA-22 non-ionising radiation tolerance assessment under way with fluences of 3 & 6·10^{12} n_{eq}/cm^2*

- *Latch-up tests of SDC-2/SUZE-01 foreseen in Octobre*

MIMOSA-22bis : Design Motivations

Main objectives of the MIMOSA-22bis prototype :

- *check robustness of pixel operation against steering parameter values (e.g. T dimensions)*
- *optimise combination of parameters driving S/N value (e.g. coll. diode dimensions)*
- *optimise design against ionising radiation damage (e.g. enclosed T)*

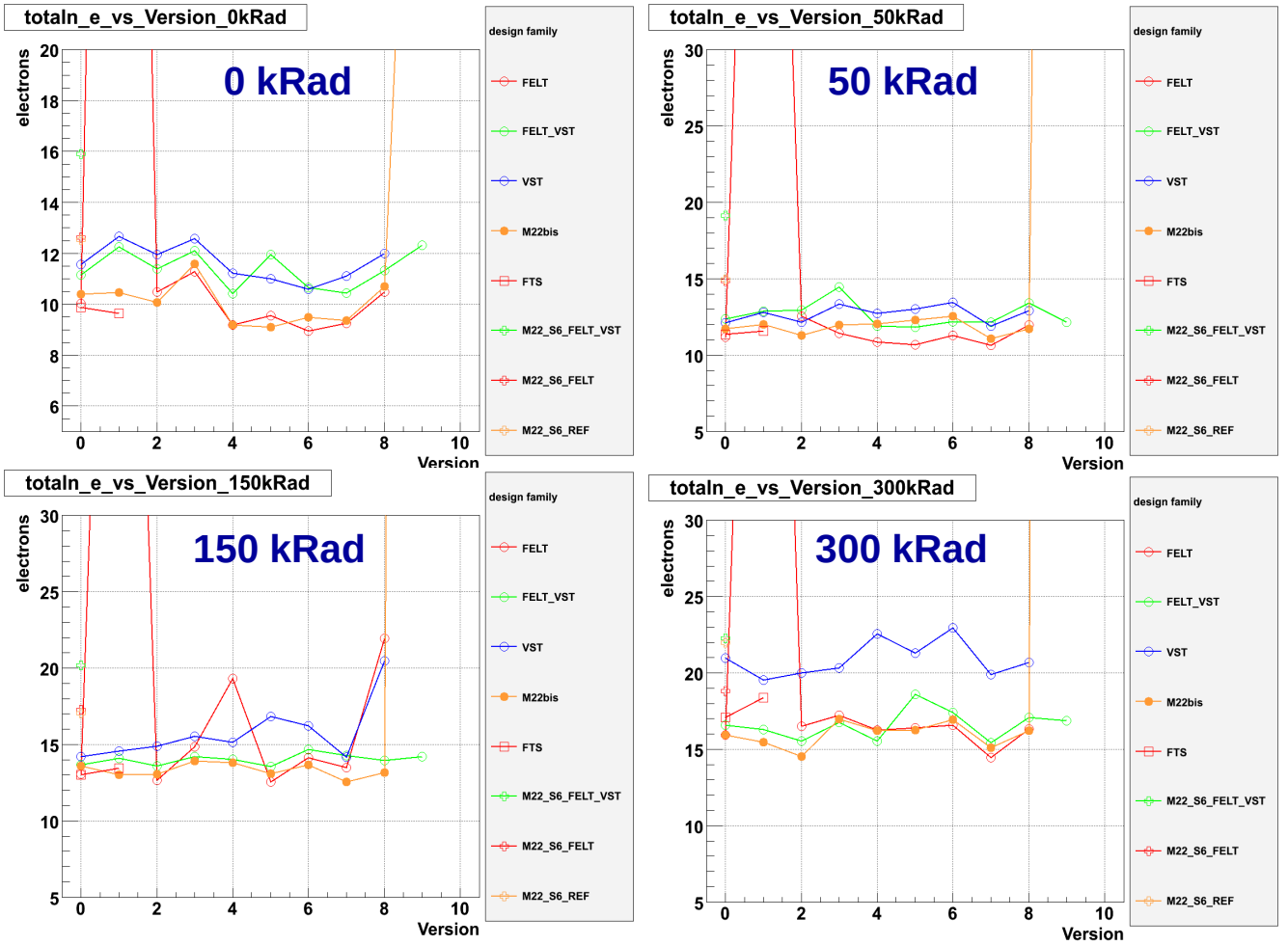


MIMOSA-22bis : Lab Test results

Lab test results :

▷ *ex. of S6 (M22) variants at 20°C*

- ⁂ *before irradiation* $\gtrsim$ *9.5 e⁻ ENC*
- ⁂ *after 50 kRad* $\gtrsim$ *11 e⁻ ENC*
- ⁂ *after 150 kRad* $\gtrsim$ *13 e⁻ ENC*
- ⁂ *after 300 kRad* $\gtrsim$ *15 e⁻ ENC*



▷▷▷ **Excellent stability of circuit behaviour against parameter variations**

▷▷▷ **Excellent noise performance**

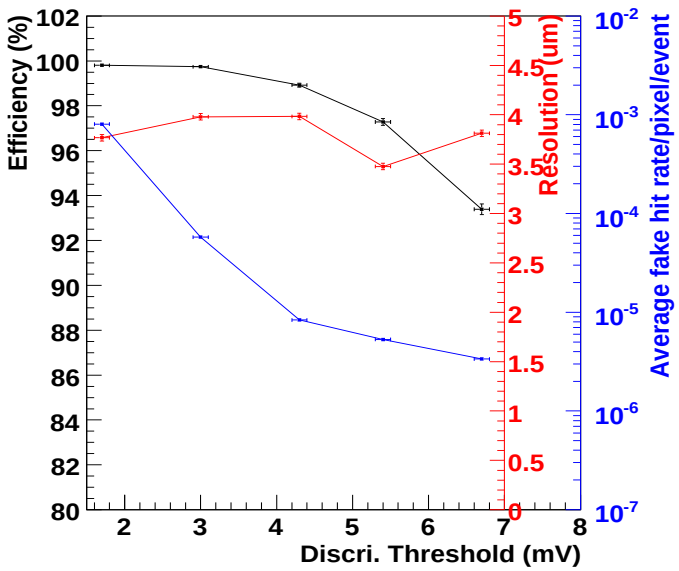
(... watch CCE ...)

MIMOSA-22bis : Preliminary Beam Test results

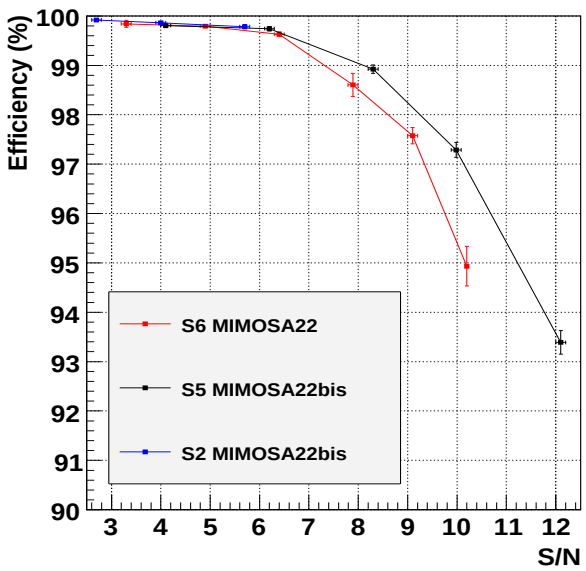
- **Data collected at CERN-SPS (T4–H6) during SiLC period (Sept. 24 – Oct. 6):**
  - *1 non-irradiated chip tested at 20°C*
  - *1 chip irradiated with 150 kRad tested at 20°C and 35°C*
  - *1 chip irradiated with 300 kRad tested at 20°C*
  - *1 chip irradiated with $6 \cdot 10^{12}$ n_{eq}/cm^2 at 20°C*

- **Beam test results (*ex. of S6 (M22) variants*) :**

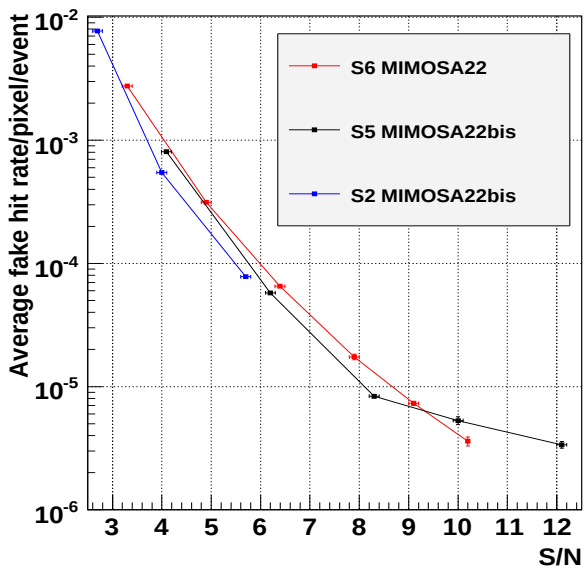
M22bis digital S5. Efficiency, Fake rate and Resolution



S6 M22, S5 M22bis & S2 M22bis digital Efficiency



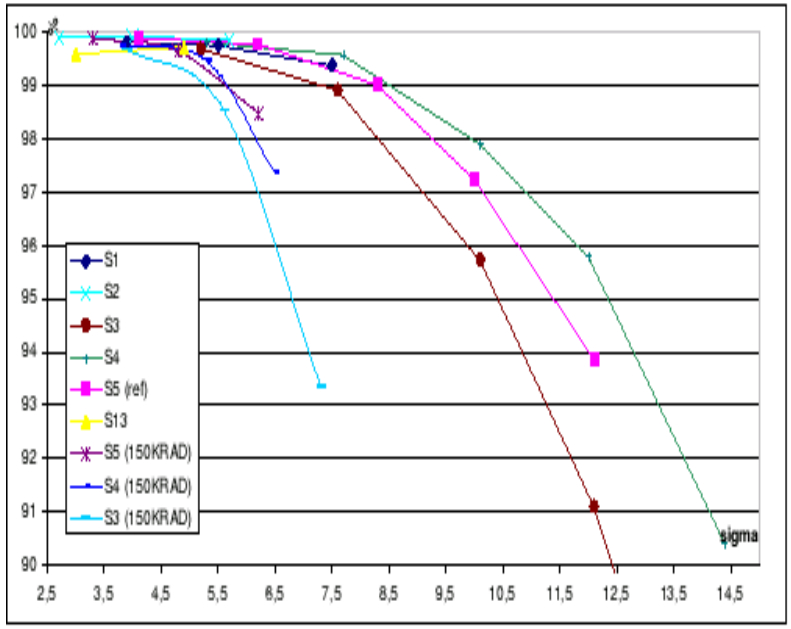
M22bis digital fake hit rate



▷▷▷ **Performances of reference sub-array in MIMOSA-22 (S6) and -22bis (S5) are identical**

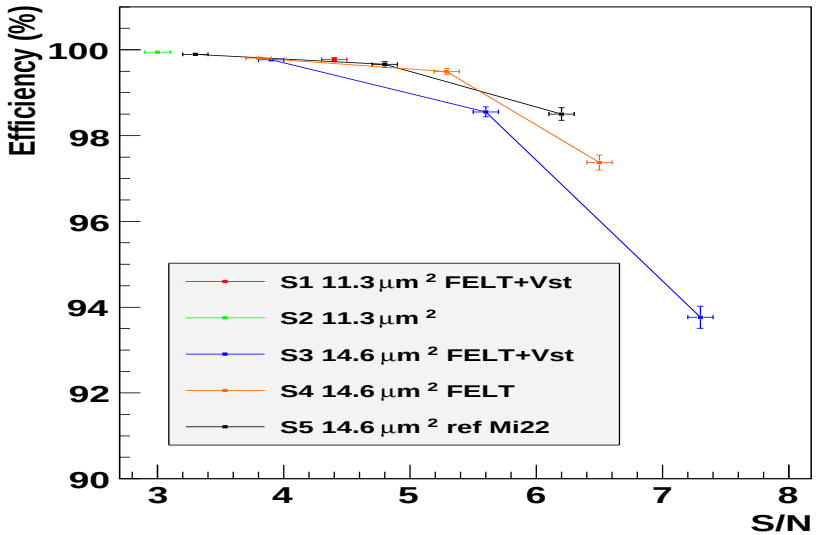
MIMOSA-22bis : Beam Test Results on Radiation Tolerance

- **Beam test results with chips irradiated with 150 kRad :**

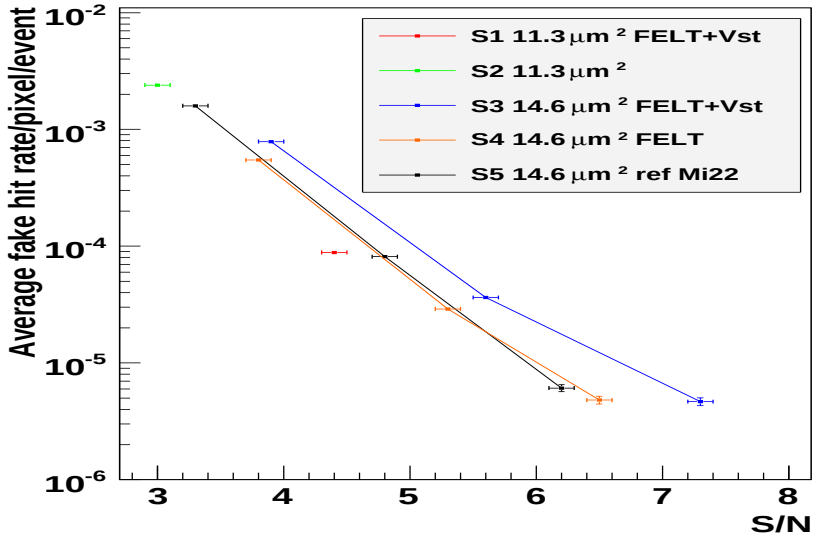


Det. eff. vs SNR before and after irradiation (150 kRad)

M22bis digital Efficiency after 150kRad



M22bis digital fake hit rate



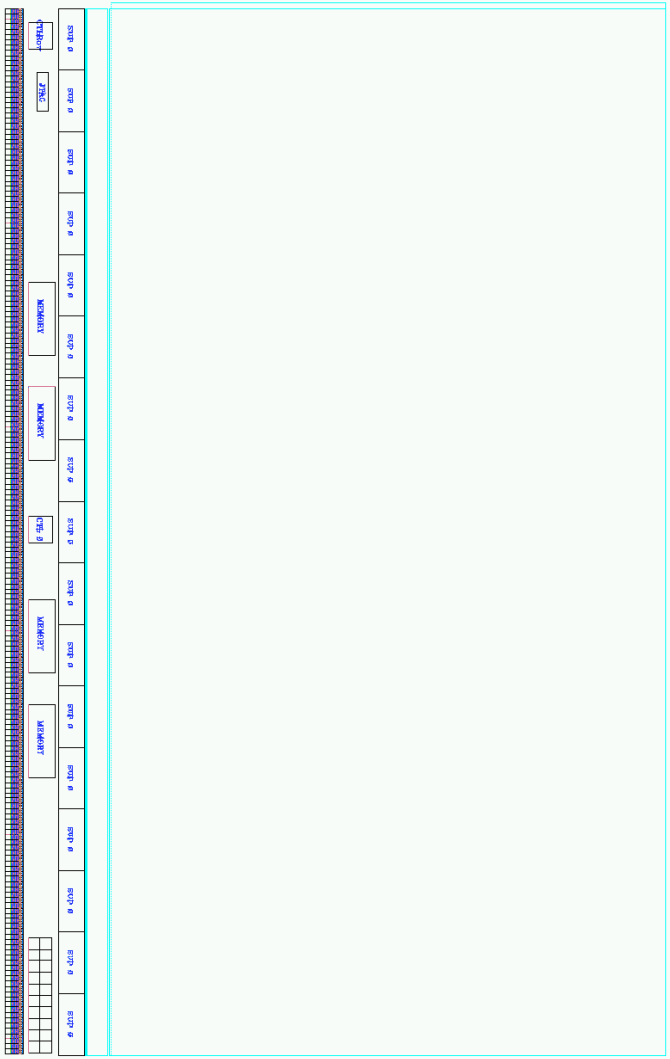
▷▷▷ Pixel & column parallel architecture with integrated discriminators

Fully Validated !!!

Main Parameters of the Final Sensor : TC/MIMOSA-26

Autumn 2008 : fabrication of MIMOSA-26 = Final Sensor (TC)

- **IDC/M-22 (binary outputs) complemented with $\emptyset$ (SDC-2/SUZE-01)**
- best performing (rad. tol.) pixel architecture of IDC/M-22(bis)
  - $\hookrightarrow$ wait for Octobre beam test final results
- **Active surface : 1152 columns of 576 pixels (21.2 x 10.6 mm^2)**
  - $\hookrightarrow$ **extension of IDC & SDC-2 from 128 col. to 9 x 128 col.**
- **Pixel pitch : 18.4 μm $\rightarrowtail \sim$ 0.7 million pixels**
  - $\hookrightarrow \sigma_{sp} \gtrsim$ **3.5 μm $\Rightarrow$ pointing resolution $\sim$ 2 μm on DUT surface**
- **Integration time $\sim$ 110 μs $\rightarrowtail \sim 10^4$ frames / second**
- $\emptyset$ based on 18 groups of 64 columns and assuming $\leq$ 9 "clusters" per row
- Chip dimensions : $\sim$ 21 x 12 mm^2
- Data throughput: 1 output at $\geq$ 80 Mbits/s or 2 outputs at $\geq$ 40 Mbits/s
- Engineering run : 2 (+ $\leq$ 4) wafers of $\gtrsim$ 30 chips expected (if yield $\sim$ 50 %)



- **Design under way $\Rightarrow$ planned submission date $\geq$ mid-November '08**

- **Col. *//* architecture with discri. outputs validated for m.i.p. detection on real scale (*128 col. of final length*) :**
  - *read-out frequency $\sim 10^4$ frames/s* ✓
  - *pixel noise $\sim$ 10–13 e^- ENC* $\Rightarrow$ *S/N $\sim$ 17–22 (MPV)* ✓
  - *$\epsilon_{det} > 99.5$ % with fake rate $\sim$ O(10^{-4} - 10^{-5}), similar to MIMOSA-16* ✓
  - *$\sigma_{sp} \gtrsim 3.5\ \mu m$* $\Rightarrow$ *resolution on impact position on DUT surface $\lesssim 2\ \mu m$* ✓
- **$\emptyset$ μ-circuit with output buffers validated for 128 col. at read-out frequency $>$ nominal value** ✓
- **Radiation tolerance :**
  - *achieved ionising radiation tolerance of pixel array sufficient for use of BT at CERN, FermiLab, ...* ✓
    (but source of noise increase still being investigated)
  - *non-ionising radiation tolerance may still be a concern once integrated particle flux $\gtrsim$ O(10^{12}) $\pi^{\pm}/cm^2$*
  - *latch-up tests of output memories in preparation (to be done in Octobre)*

$\Rightarrow$ **TC $\equiv$ final sensor (combining col. *//* architecture with $\emptyset$ μ-circuit) :**

- *design under way (crucial issues : extension from 128 to 1152 col. of IDC combined with SDC-2)*
- *in absence of unexpected pb, submission will occur $\gtrsim$ mid-Novembre '08*

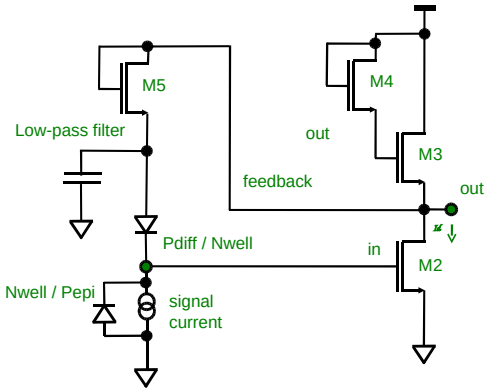
$\hookrightarrow$ **TC sensor tests expected to start in January 2009**

IDC/MIMOSA-22 Lab Tests : Analog Output Results (1/2)

Best performing pixels (rad. tol. design) :

- *self-biased feedback diode (improved gain)*

Amplifier schematics (3): improved common source + continuously biased from feedback (self-biased)



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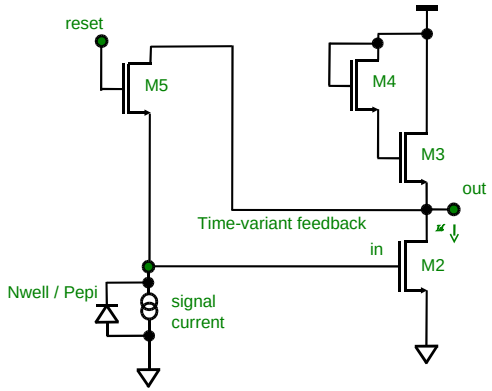
A. Dorokhov, IPHC, Strasbourg, France

- *reset diode (improved gain)*

Amplifier schematics (4): improved common source + reset from feedback (time-variant feedback)



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Main results obtained with exposure to ^{55}Fe source :

- *Chip-4 ; $F_{r.o.}$ = 100 MHz ($t_{r.o.}$ = 92.5 μs) ; $T \simeq 15\,^{\circ}C$ (coolant) / $20\,^{\circ}C$ (chip) ;*

Pixel	diode	Noise (ENC)	CCE (4 pix)	CCE (9 pix)	CEE (25 pix)	comment
S6	14.6 μm^2	12.4 e^-	57 %	73 %	84 %	rad.tol. – self-bias – high gain
S7	14.6 μm^2	11.4 e^-	58 %	75 %	85 %	stand. – self-bias – high gain
S8	19.4 μm^2	12.8 e^-	65 %	82 %	90 %	stand. – self-bias – high gain
S9	11.6 μm^2	10.5 e^-	54 %	72 %	83 %	stand. – self-bias – high gain
S10	15.2 μm^2	13.3 e^-	60 %	77 %	86 %	rad.tol. – feedback reset – high gain
S12	15.2 μm^2	11.8 e^-	58 %	75 %	84 %	stand. – feedback reset – high gain

Dispersion between chips (rad. tol. pixels, with high gain) :

Pixel	*chip*	*Noise (ENC)*	*CCE (4 pix)*	*CCE (9 pix)*	*CEE (25 pix)*
S6	*4*	*12.4 e^-*	*57 %*	*73 %*	*84 %*
	3	*12.7 e^-*	*59 %*	*76 %*	*86 %*
	1	*12.6 e^-*	*58 %*	*74 %*	*85 %*
S10	*4*	*13.3 e^-*	*60 %*	*77 %*	*86 %*
	3	*12.8 e^-*	*58 %*	*75 %*	*85 %*
	1	*13.5 e^-*	*59 %*	*76 %*	*86 %*

Sensitivity to operating temperature (rad. tol. pixels, with high gain) :

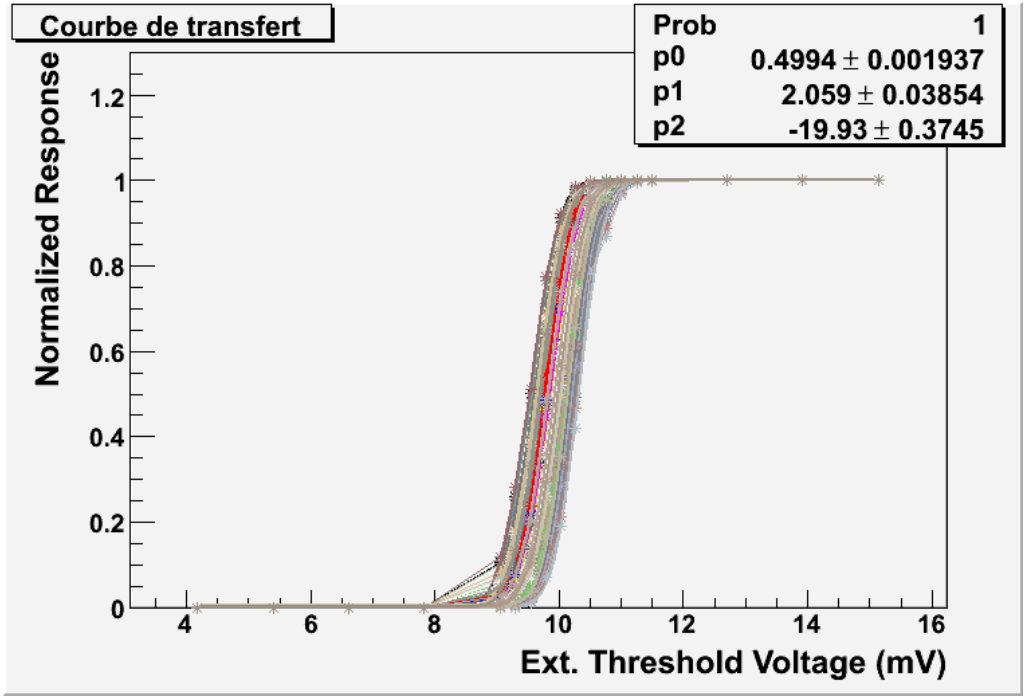
Pixel	*T ($^\circ$C)*	*Noise (ENC)*	*CCE (4 pix)*	*CCE (9 pix)*	*CEE (25 pix)*
S6	*0 / 10*	*12.5 e^-*	*58 %*	*75 %*	*85 %*
	10 / 15	*12.6 e^-*	*58 %*	*74%*	*85%*
	30 / 35	*13.0 e^-*	*59 %*	*76 %*	*80 %*
S10	*0 / 10*	*12.8 e^-*	*59 %*	*77 %*	*84 %*
	10 / 15	*13.5 e^-*	*59 %*	*76 %*	*86 %*
	30 / 35	*14.2 e^-*	*60 %*	*76 %*	*86 %*

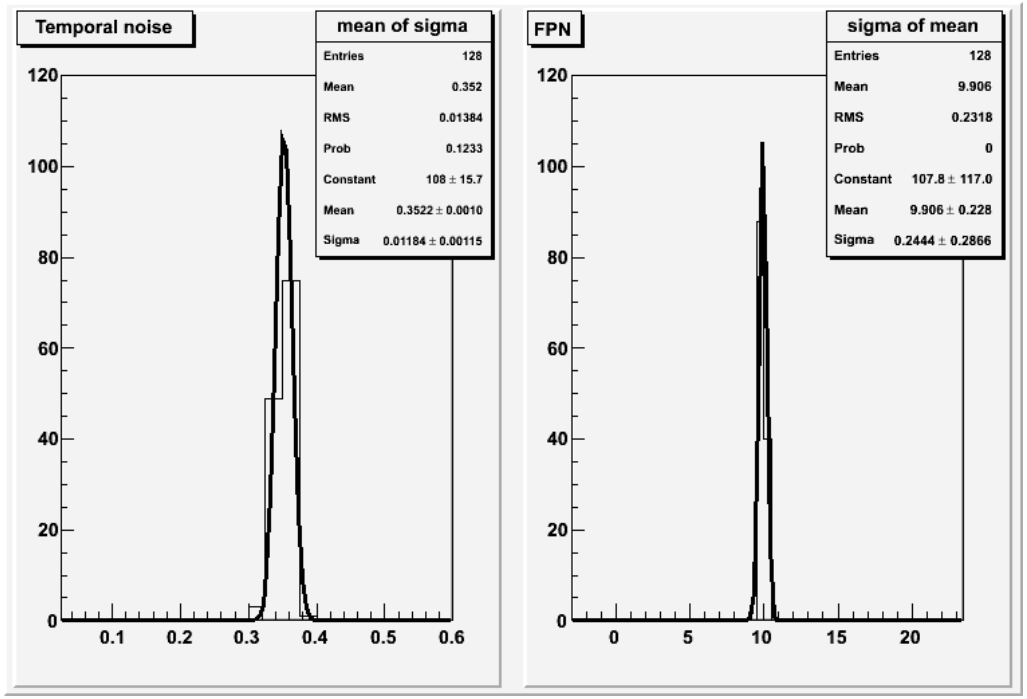
Conclusions :

- *Pixel array operationnal at nominal frequency and room temperature*
- *Rad. tol. pixel exhibits rather moderate noise (12.5–13.5 e^- ENC), $\sim$ +1 e^- ENC w.r.t. standard diode*
- *Self-bias pixel seems slightly less noisy than reset pixel $\longmapsto$ assess ionising rad. tol. before chosing*

MIMOSA-22 Lab Tests : Digital Output Results (1/2)

- **Uniform voltage (-10 mV $\longmapsto$ 0 V) injected in discri. $\longmapsto$ transfer functions of all 128 discriminators** :





- **Noise performances for F_{clock} = 100 MHz, T $\sim$ 15 / 20°C**

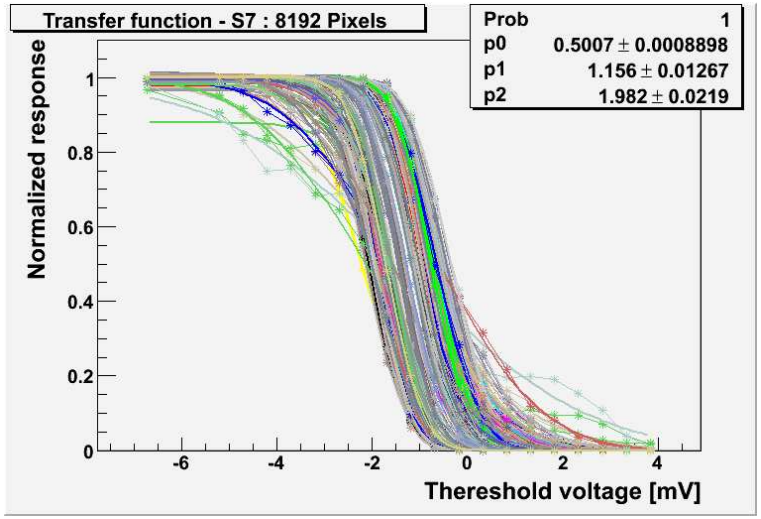
  - *Temporal noise $\simeq$ 0.35 mV*
  - *Fixed Pattern Noise $\simeq$ 0.25 mV*

  $\Rightarrow$ **Very satisfactory performances**

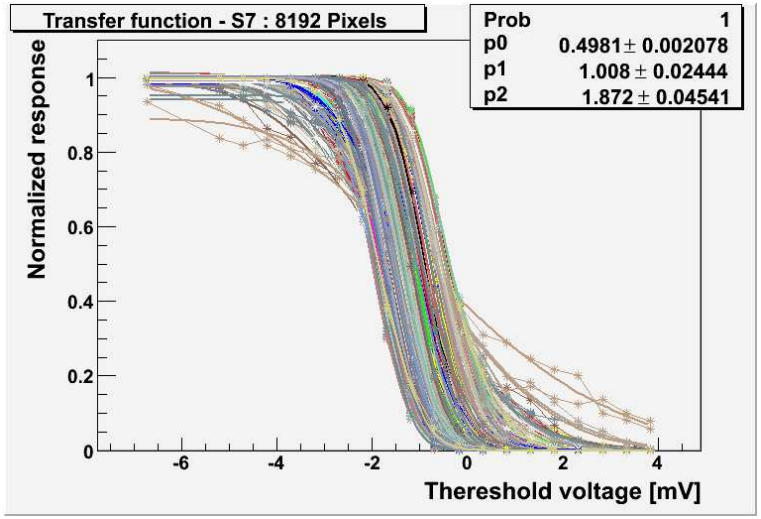
IDC/MIMOSA-22 Lab Tests : Digital Output Results (2/2)

Threshold scan of pixel noise from S6 & S7 *(self-biased feedback with high gain)* :

※ *rad. tol. diode (S6)*



※ *standard diode (S7)*



Noise derived from scan of S6 (CFC $\simeq$ 50 $\mu V/e^-$)

※ *Running conditions : 100 MHz, T $\sim 25^\circ C$*

※ *Pixel noise $\simeq$ 0.6 mV*

※ *Fixed Pattern Noise $\simeq$ 0.3 mV ($\equiv$ MIMOSA-16)*

$\Rightarrow$ **Performances satisfy requirements**