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ULTIMATE: a High Resolution CMOS Pixel Sensor for the STAR Vertex Detector Upgrade

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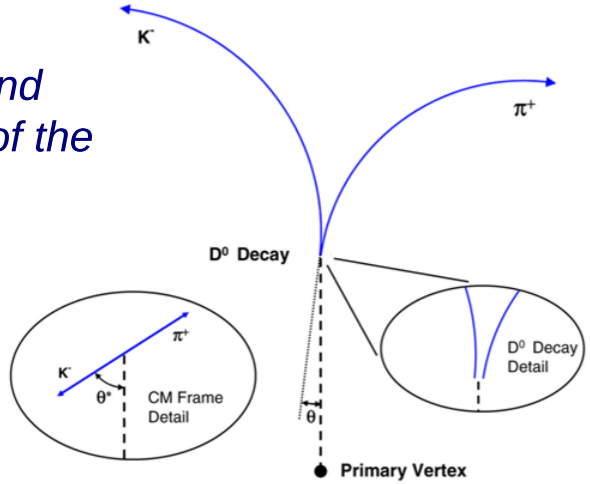
on behalf of the IPHC (Strasbourg) CMOS Sensors group

Outline

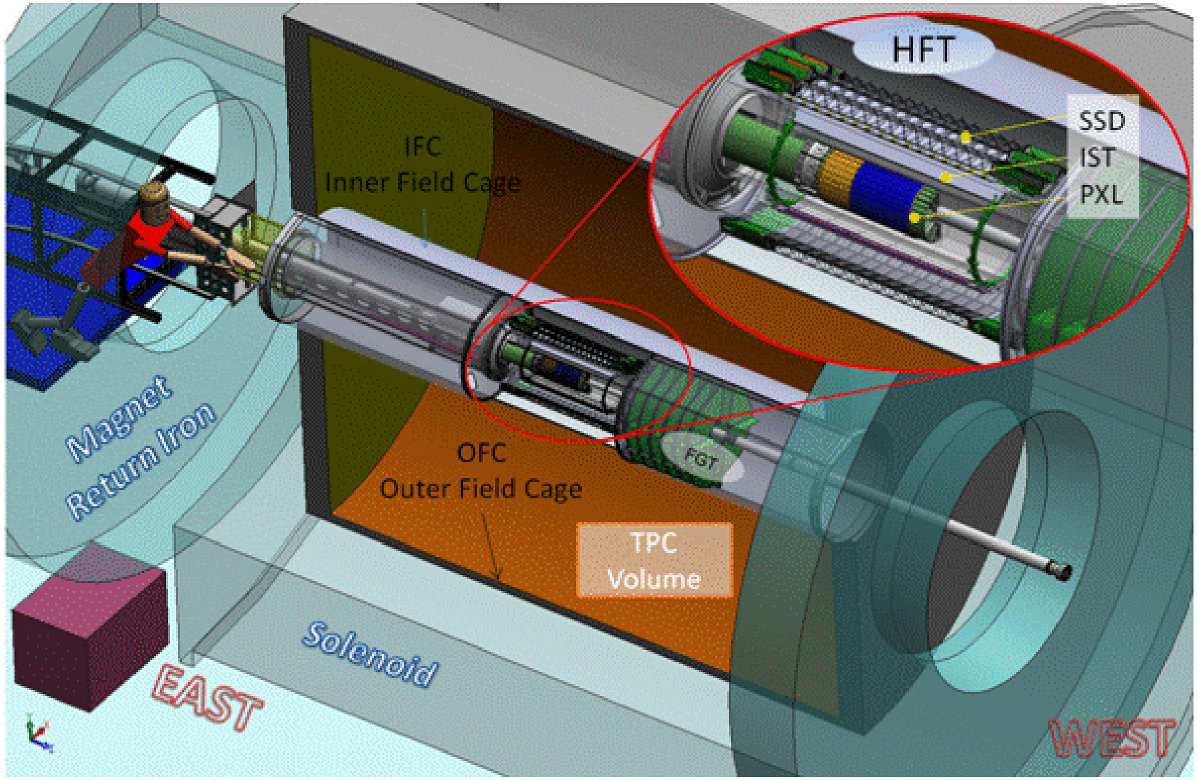
- ***STAR HFT Upgrade: PIXEL detector***
  - *MAPS (Monolithic Active Pixel Sensors) requirements*
- ***Recent MIMOSA26 test results***
  - *Comparison between standard and high resistivity EPI layers*
- ***ULTIMATE design & optimisation***
- ***Summary + Future plans***

STAR Heavy Flavor Tracker (HFT) Upgrade

- *Physics Goals:*
  - *Identification of mid rapidity Charm and Beauty mesons and baryons through direct reconstruction and measurement of the displaced vertex with excellent pointing resolution*



courtesy of M. Szelezniak / Vertex-2010



TPC – Time Projection Chamber (main detector in STAR)

HFT – Heavy Flavor Tracker

- **SSD – Silicon Strip Detector**
- **IST – Inner Silicon Tracker**
- **PXL – Pixel Detector (PIXEL)**

Goal: Increasing pointing resolution from the outside in

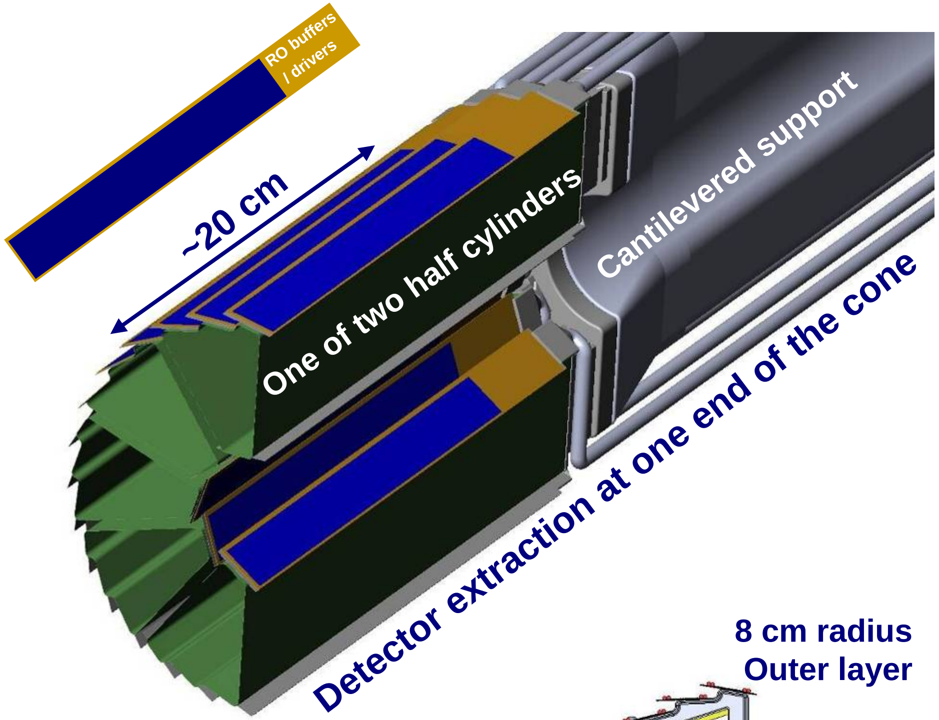
TPC → ~1 mm → **SSD** → ~300 µm → **IST** → ~250 µm → **PXL** → <30 µm → **vertex**

STAR PIXEL Detector

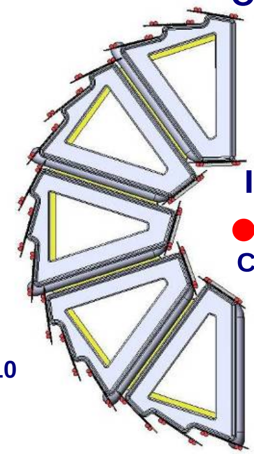
Sensors Requirements

- Multiple scattering minimisation:
  - *Sensors thinned to 50 um, mounted on a flex kapton/aluminum cable*
  - ➔ X/X_0 = 0.37% per layer
- Sufficient resolution to resolve the secondary decay vertices from the primary vertex
  - *< 10 um*
- Luminosity = 8 x 10^{27} / cm² / s at RHIC_II
  - *~200-300 (600) hits / sensor (~4 cm²) in the integration time window*
  - *Shot integration time ~< 200 µs*
- Low mass in the sensitive area of the detector ➔ airflow based system cooling
  - *Work at ambient (~ 35 °C) temperature*
  - *Power consumption ~ 100 mW / cm²*
- Sensors positioned close (2.5 - 8 cm radii) to the interaction region
  - *~ 150 kRad / year*
  - *few 10^{12} N_{eq} / cm² / year*

Total: 40 ladders
Ladder = 10 MAPS sensors (~2x2 cm² each)



End view

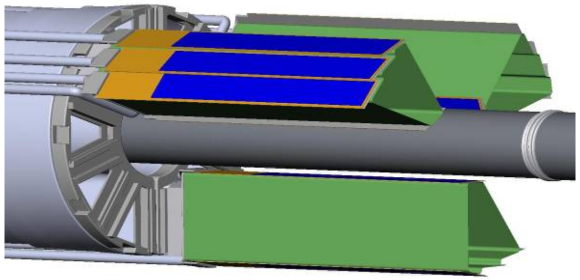


courtesy of M. Szelezniak / Vertex-2010

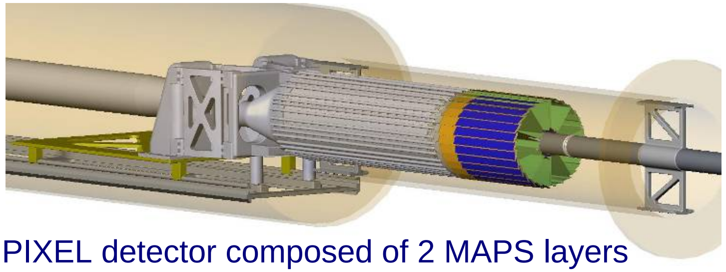
STAR PIXEL Detector

- **3 steps evolution:**
  - 2007: A MimoSTAR-2 sensors based telescope has been constructed and performed measurements of the detector environment at STAR
    MimoSTAR-2: sensor with analogue output
  - 2012: The engineering prototype detector with limited coverage (1/3 of the complete detector surface), equipped with PHASE-1 sensors will be installed
    PHASE-1: sensor with binary output without zero suppression
  - 2013: The pixel detector composed with 2 layers of ULTIMATE sensors will be installed
    ULTIMATE: sensor with binary output and with zero suppression logic

3 plans telescope with MImoSATR-2 sensors

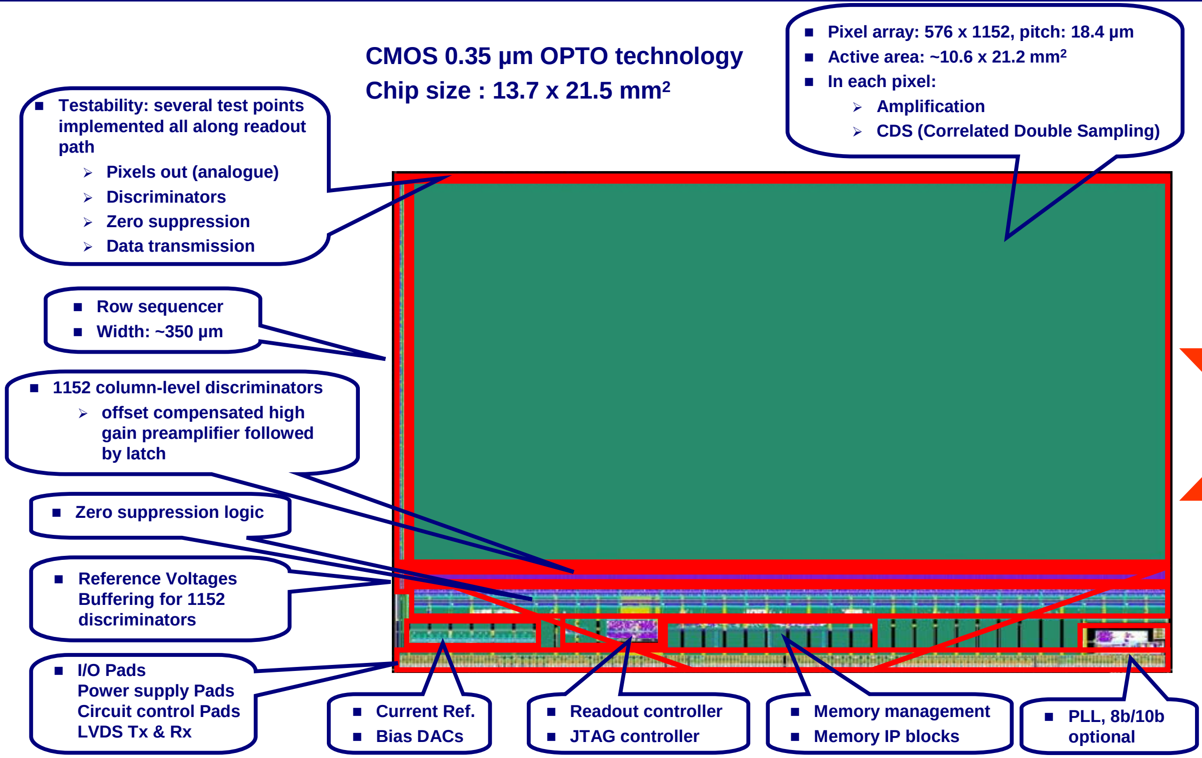


Prototype detector composed of 3 sectors with PHASE-1 sensors



PIXEL detector composed of 2 MAPS layers

MIMOSA26: Sensor for EUDET Beam Telescope



Collaboration with IRFU/Saclay

Main characteristics of MIMOSA26 sensor equipping EUDET BT:

- Column // architecture with in-pixel Amp & CDS and end-of-col. discrimination, followed by Ø
- Active area: 21.2×10.6 mm² ,1152 x 576 pixels, pitch: 18.4 µm ➔ $\sigma_{sp.}$ <~ 4 µm
- Read out time <~ 100 µs (10^4 frames/s) ➔ suited to >10^6 particles/cm²/s
- Yield ~90% (75% fully functional sensors thinned to 120 µm + 15% (showing one bad row or column)
- Thinning yield to 50 µm ~90%

MIMOSA26 with high resistivity EPI layer (1)

- *Charge collection efficiency for the seed pixel, and for 2x2 and 3x3 pixel clusters*

EPI layer	Standard (~10 Ω.cm) 14 µm			High resistivity (~400 Ω.cm)			
	Seed	2x2	3x3	EPI thickness	seed	2x2	3x3
CCE (^{55}Fe source)	~21%	~ 54 %	~ 71 %	10 µm	~ 36 %	~ 85 %	~ 95 %
				15 µm	~ 31 %	~ 78 %	~ 91 %
				20 µm	~ 22 %	~ 57 %	~ 76 %

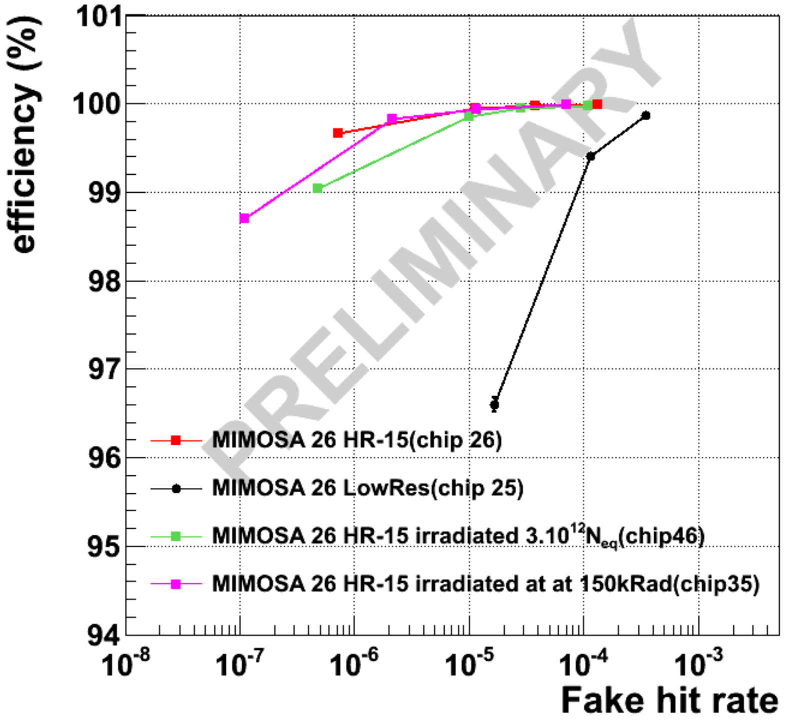
- *Signal to noise ratio for the seed pixel before irradiation and after exposure to a fluence of 6 x 10^{12} n_{eq} / cm^2*

EPI layer	Standard (~10 Ω.cm) 14 µm		High resistivity (~400 Ω.cm)		
	Before irradiation	After 6x10^{12} n_{eq}/cm^2	EPI thick	Before irradiation	After 6x10^{12} n_{eq}/cm^2
S/N at seed pixel (^{106}Ru source)	~ 20 (230 e^-/11.6 e^-)	10.7	10 µm	~ 35	22
			15 µm	~ 41	28
			20 µm	~ 36	--------

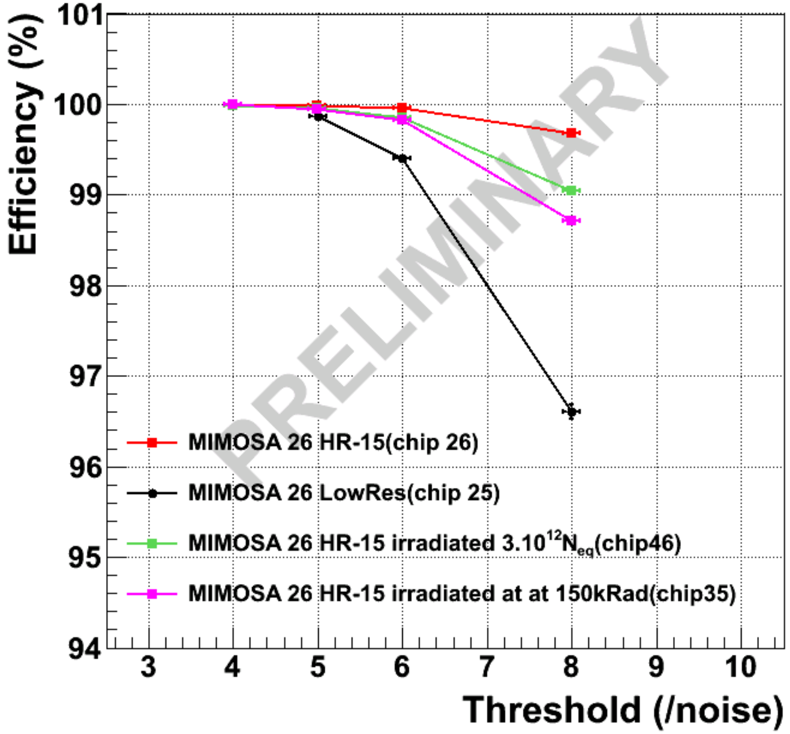
MIMOSA26 with high resistivity EPI layer (2)

- ***Beam test at CERN SPS (120 GeV pions)***
  - *Test conditions:*
    - *50 MHz to emulate the longer integration time in ULTIMATE*
    - *35 °C temperature!*

Efficiency vs Fake hit rate

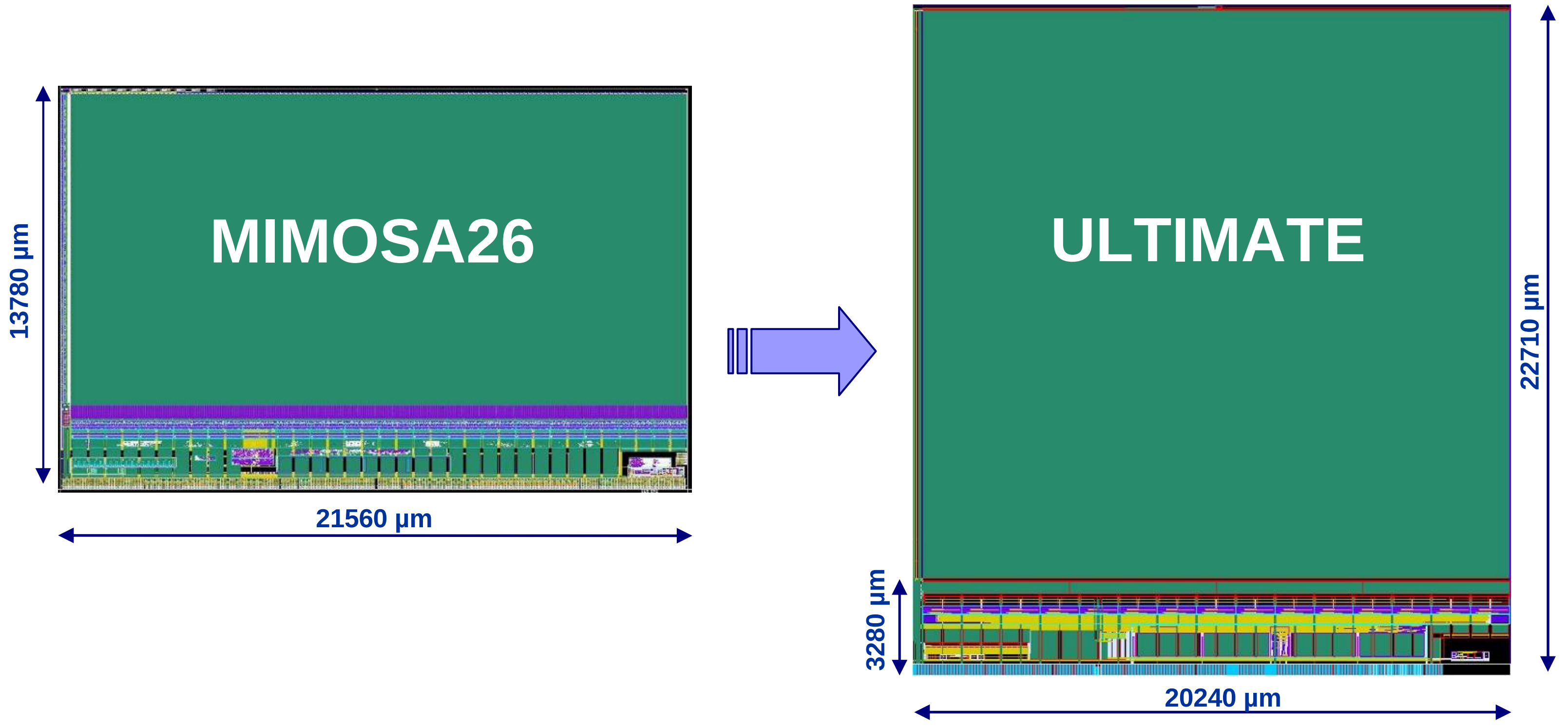


Efficiency vs Threshold



resolution < 5um

ULTIMATE: Extension of MIMOSA26



- 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

➔ **Optimisation**

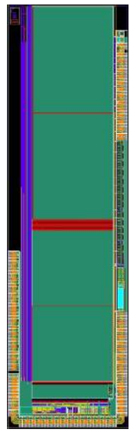
ULTIMATE Design & Optimisation (1)

- ***Reduction of power dissipation:***
  - *Power supply voltage reduced from 3.3 to 3 V*
  - *Optimisation of pixel pitch v.s. non ionising radiation tolerance*
    - *Larger pitch: 18.4 µm ➔ 20.7 µm*
      - *Shorter integration time: 185.6 µs*

    ➔ Validated by a small prototype
  - *Optimisation of power consumption of some blocks*

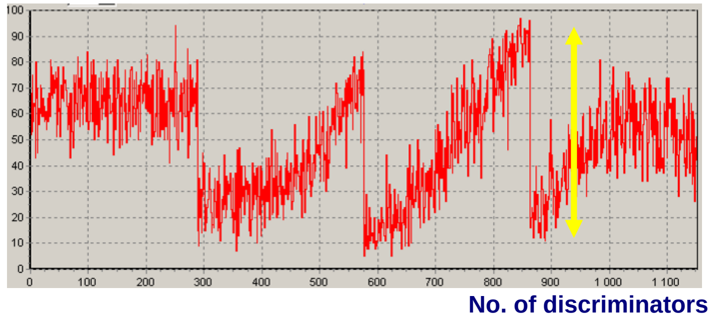
➔ Estimated power consumption ~130 mW/cm²

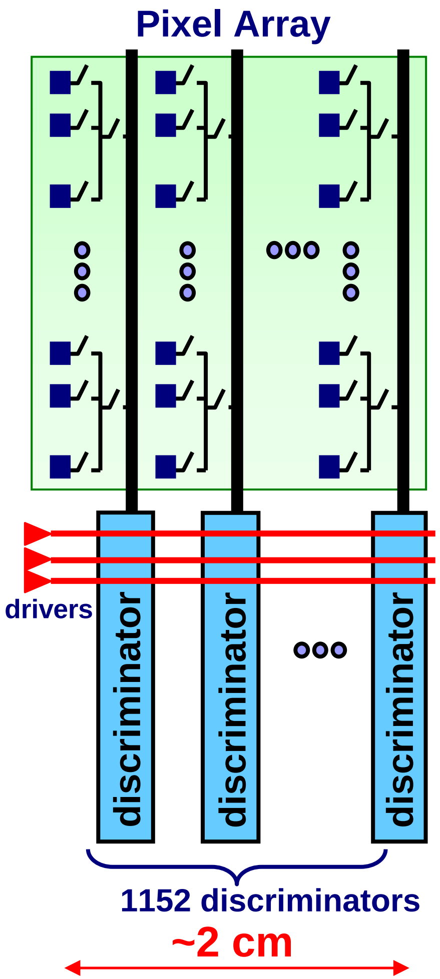
- ***Pixel improvement: charge collection, radiation tolerance***
  - *High resistivity EPI substrate & radiation tolerance design*
    - *Lab test with ^{55}Fe at 35 °C and integration time imposed by the STAR requirements shows:*
      - *Conversion gain is improved by a factor of two*
      - *ENC >~ 10 e^- before irradiation*
      - *ENC >~ 13 e^- after irradiation with 150 kRad*
      - *ENC >~ 16 e^- after irradiation with 3×10^{12} Neq/cm²*
      - *SNR up to 30 after irradiation*
        SNR ~30 for standard resistivity EPI before irradiation
    - *Beam test measurements are in progress*
      - *Preliminary results show further performance improvements*

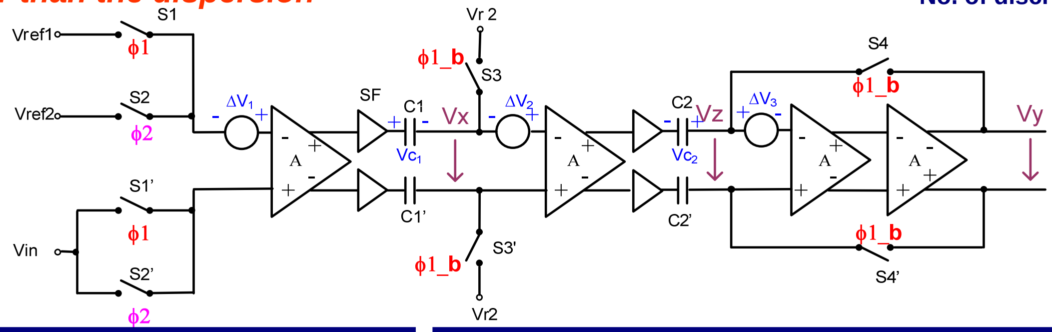


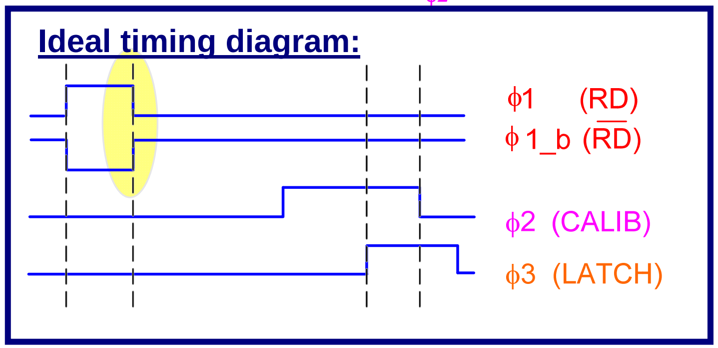
ULTIMATE Design & Optimisation (2)

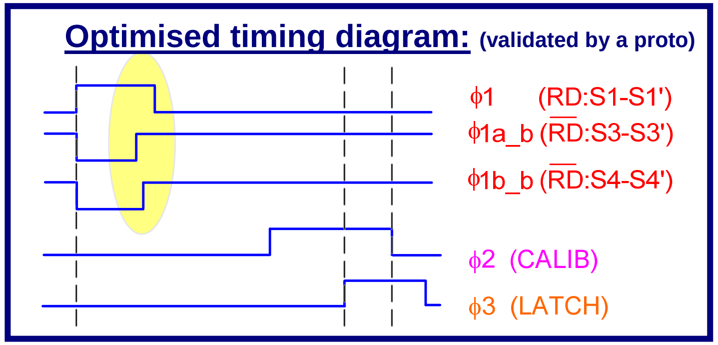
- ***Discriminator timing diagram optimisation***
  - *Threshold non-uniformity reduction*
    - ***Mimosa26: Threshold dispersion of 1152 discriminators (divided in 4 groups)***
    - ***It doesn't disturb chip operation if threshold is set to be higher than the dispersion***



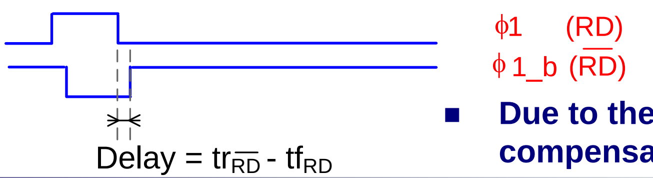








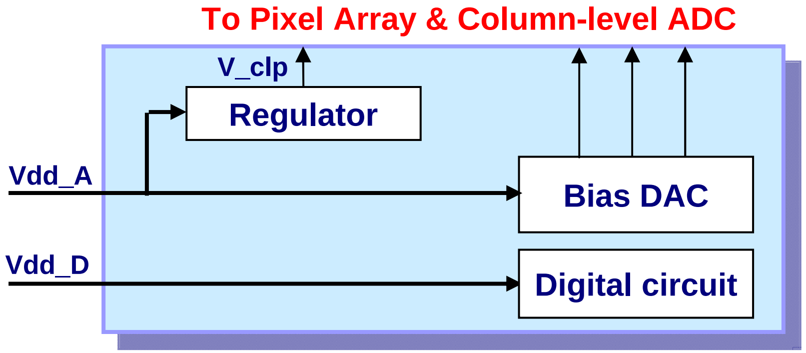
Obtained timing diagram due to long track:

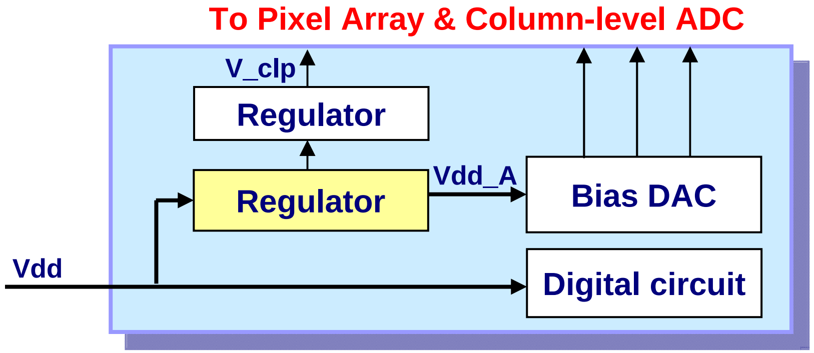


- **Due to the delay, ex. charge injections by S3, S4 cannot be compensated by the auto 0 phase**

ULTIMATE Design & Optimisation (3)

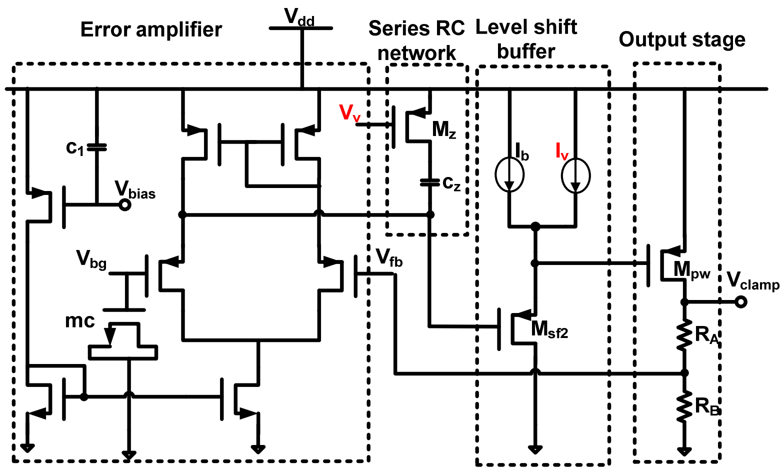
- ***On-chip voltage regulators***
  - *Interferences minimisation on critical nodes*
  - *Common power supply for A & D*

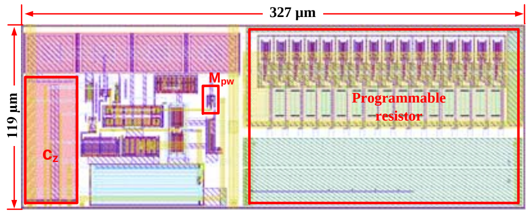




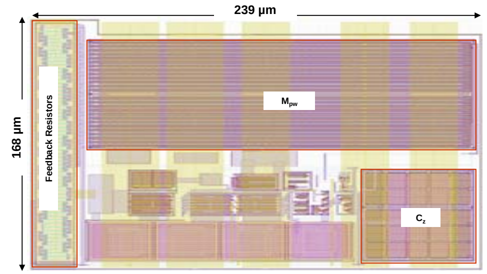
See Jia Wang's poster

  - *Regulator: Low Dropout (Vin = 3 - 3.3 V)*
    - *Characteristics: Dropout voltage: ~0.3 V, PRSS: ~40 dB, Noise: < 1 µV/sqrt(Hz) (freq at 10 KHz), Power consumption: <~ 1mW,*





For Pixels Clamping



For Analogue Power Supply

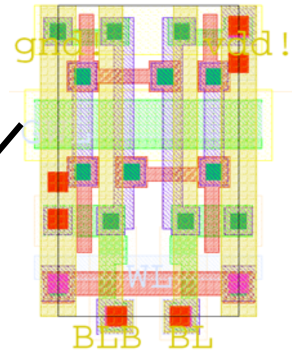
ULTIMATE Design & Optimisation (4)

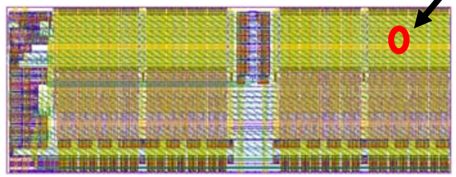
- ***Zero Suppression circuit (SuZe) adapted to STAR condition***
  - *Higher hit density ➔ larger memories*
  - *2 memories of 2048x32 bits*
  - *2 LVDS data out at 160 MHz*

- ***Latch up free memory may be integrated in future chip***
  - Prototype: SRAM memory module
    - Size: 256 x 8 bits
    - Area: 1000 x 375 µm²
    - **Self-timing for radiation tolerance**
    - Write Access Cycle: 4.3 ns
    - Read Access Cycle: 4.4 ns
    - Power consumption: 0.15 mA/MHz

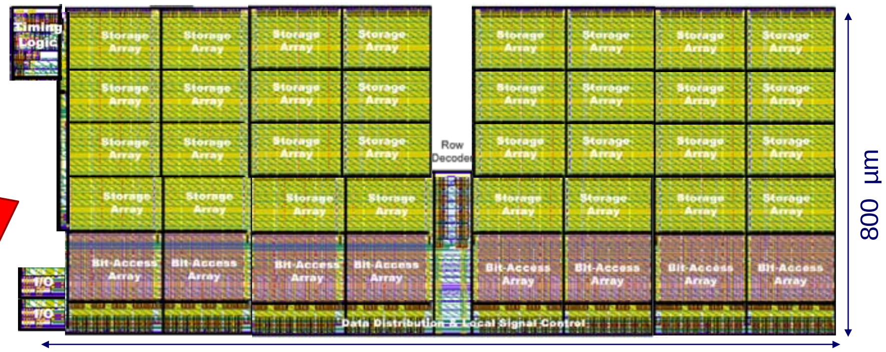
Compatible with IP block

Memory cell





  - A larger memory can be built by reorganizing the designed module [1]



[1] **K. Kloukinas, G. Magazzu, A. Marchioro,** "A Configurable Radiation Tolerant Dual-Ported Static RAM macro, designed in a 0.25 µm CMOS technology for applications in the LHC Environment ", 8th Workshop on Electronics for LHC Experiments, 2002

Summary + Future plans

- ***MAPS with high-resistivity epitaxial layer show excellent detection performances:***
  - *Detection efficiency >99.8% (at 10^{-5} fake hit rate)*
  - *Improvement of radiation tolerance, non ionising radiation tolerance increased by $O(10^2)$*

- ***PIXEL detector for the STAR experiment based on ULTIMATE sensors will fulfil the STAR HFT requirement***
  - *ULTIMATE sensor is planned to be delivered to LBL in Q1 2011*
  - *400 sensors per detector*

- ***Engineering prototype detector equipped with PHASE-1 sensors covering 1/3 of the complete detector surface, will be installed in 2012 (physics in 2013)***

- ***Nominal detector installation is scheduled 2013 (physics in 2014)***

Milestone: CMOS Sensors for the STAR PXL detector

- *LBNL-IPHC collaboration on vertex detector upgrade of STAR experiment (RHIC)*
  - *PXL: 2 layers equipped with 10/ in + 30/ out ladders, each made of 10 sensors designed by IPHC*
  - *CMOS pixel sensors ➔ breaking edge technology: granular, thin, swift, low power*
- *November 2009: technological choice of PXL discussed in CD-1 review*
  - *formally approved in Spring 2010 ➔ 1st vertex detector ever operated with CMOS sensors*
- *2009/2010 activities on 2 generations of sensors :*
  - *PHASE-1 (physics in 2013): validated & integrated on ladders at LBNL*
  - *ULTIMATE (physics in 2014): 4 times faster, more radiation tolerant, etc.*
    - *design under way in a new fabrication technology*
    - *main innovative features w.r.t. PHASE-1 validated on prototype tested at CERN-SPS*
- *Next steps :*
  - *submission of ULTIMATE sensor in December 2010 tests in Spring 2011*
  - *contribution to ladder testing*
  - *contribution to STAR central software development for tracking in PXL*