From the STAR CMOS Pixel Sensors to an eRHIC Sensor : A Path guided by Synergies

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- *Basic features of CMOS sensors*
  - ⋇ attractiveness
  - ⋇ limitations ⇛ R&D
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  - ⋇ sensor architecture
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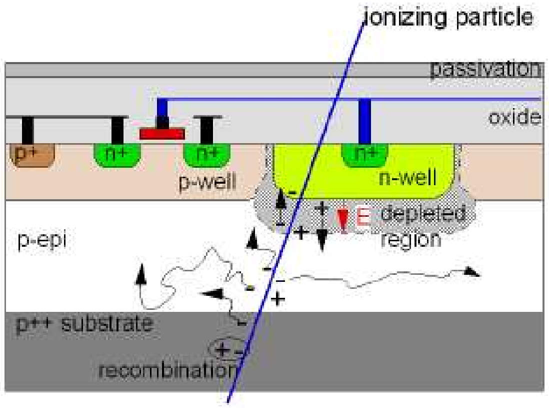
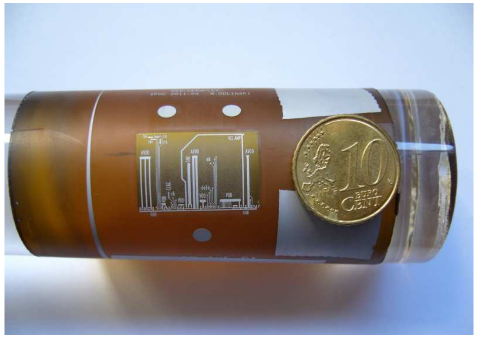
- *Projection in the coming 4 years*
  - ⋇ ALICE, AIDA, CBM
  - ⋇ spin-offs : eRHIC, BES-3, ...
- *Summary*

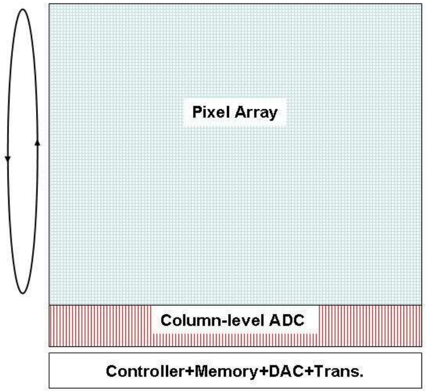
Attractive Aspects of CMOS Pixel Sensors

- **Thin :**
  - ⋇ $\lesssim$ 20 μm thick sensitive volume
  - ⋇ $\sim$ 10 μm thick integrated circuitry
  - ⋇ 50 μm thinning of large CPS has good yield (in CA-USA !)
  - ⋇ stitching (& redistribution layer) alleviates material budget for steering & read-out
  - ⋇ CPS may be flexible enough to equip curved surfaces (beam pipes ...) ▷ ▷ ▷





- **Granular :**
  - ⋇ 20 μm pitch $\Rrightarrow$ 3.5 - 1.5 μm with 1 - 4 bit charge encoding
- **Low power (**despite high granularity**) :**
  - ⋇ use rolling-shutter read-out $\Rrightarrow$ full sensitive area dissipates $\simeq$ 1 row ▷▷▷



- **Room temperature operation (**despite signal smallness**)**
- **Low cost :**
  - ⋇ STAR-PXL (1500 cm^2) $\Rrightarrow$ 400 sensors for $\sim$ 150 keuros (0.35μm process)

Where are the Most Limiting Factors ?

- **Radiation tolerance :** (see talk by M. Deveaux)
  - ⋇ Non-Ionising : depends on pitch, T, epitaxy resistivity
    - $\Rrightarrow$ at present in the range 10^{12}–10^{13}n$_{eq}$/cm^2 at T$_{room}$
  - ⋇ Ionising : presumably mainly limited by feature size, less by T and integration time
    - $\Rrightarrow$ at present $<$ 1 MRad at T$_{room}$ (due to in-pixel circuitry)

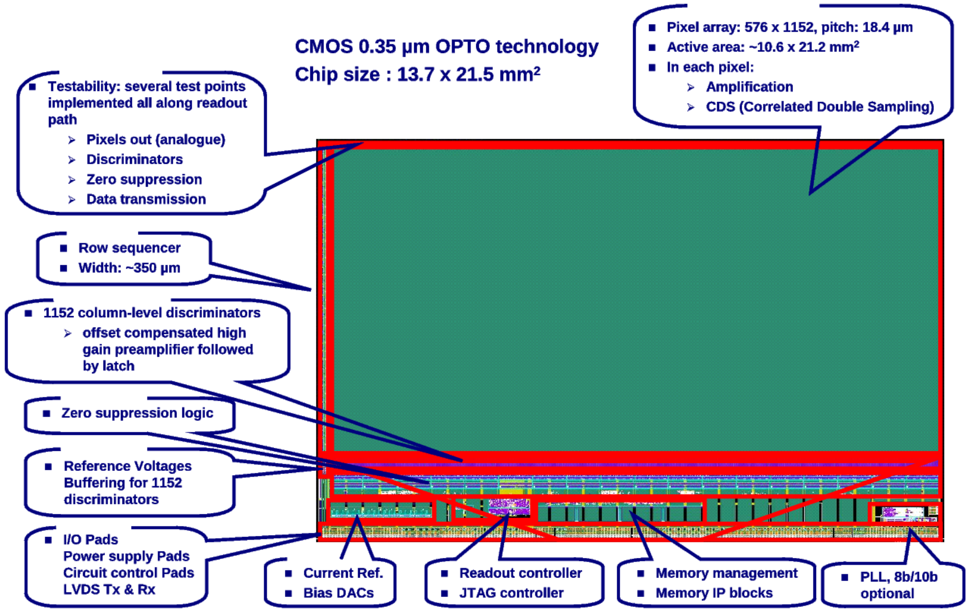
- **Read-out speed :**
  - ⋇ consequence of pixel size (granularity) and rolling shutter (power saving) read-out
  - ⋇ could be as high as for Hybrid pixels, at the expense of power consumption and granularity

▷▷▷ **Major goals of present R&D :**

- ⋇ improve the radiation tolerance to several 10^{13}n$_{eq}$/cm^2 and several MRad at T$_{room}$
- ⋇ achieve an integration time close to 10 μs
- ⋇ accompanied by ultra-light system integration

Overview of Sensor Organisation

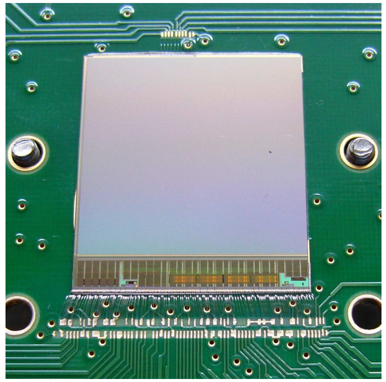
- **Sensor organisation :**
  - ⋇ functionnalities inside each pixel :
    - ⊸ charge sensing
    - ⊸ conversion of charge in electrical signal (voltage)
    - ⊸ average noise (pedestal) subtraction (cDS)
  - ⋇ functionnalities at periphery of pixel array :
    - ⊸ signal discrimination at end of each column
    - ⊸ discriminator output encoding and sparsification
    - ⊸ data transmission logic $\rightarrowtail$ outside world
    - ⊸ sequencers, JTAG, DAC, ...

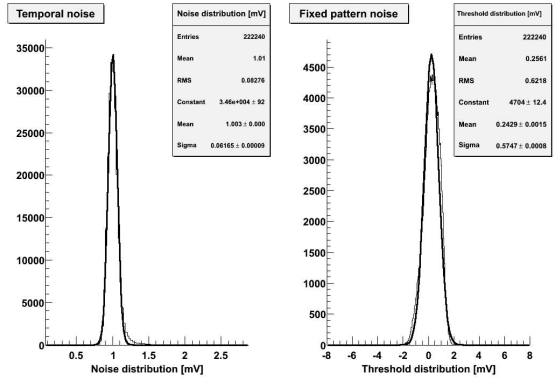


- **State-of-the art sensor : MIMOSA-26**
  - ⋇ Orginally developped for the EUDET (EU-FP6) BT
  - ⋇ Numerous spin-offs (besides EUDET-BT copies) $\Rrightarrow$ expertise expands
    - ⊸ CBM-MVD demonstrator : 16 sensors (see talk of T. Tischler)
    - ⊸ Hadrontherapy : FIRST expt (8 sensors)
    - ⊸ Proton imaging and dosimetry (ocontherapy) : $\sim$ 10 sensors
    - ⊸ NA63 expt (positron prod. in crystal) : 8 sensors
    - ⊸ PLUME double-sided ladder : 12 sensors (see talk of J. Baudot)
    - ⊸ AIDA (EU-FP7) alignment device : $\geq$ 6 PLUME ladders $\equiv$ 72 sensors

STAR-PXL Detector : MIMOSA-28/ULTIMATE

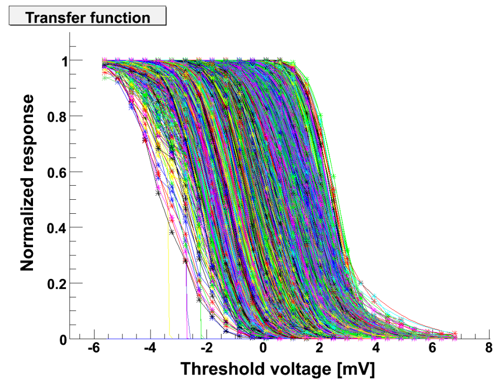
- **Main characteristics of ULTIMATE ($\equiv$ MIMOSA-28):**
  - ⋇ 0.35 μm process with high-resistivity epitaxial layer
  - ⋇ column // architecture with in-pixel cDS & amplification
  - ⋇ end-of-column discrimination and binary charge encoding, followed by $\emptyset$
  - ⋇ active area: 960 columns of 928 pixels (19.9$\times$19.2 mm^2)
  - ⋇ pitch: 20.7 μm $\rightarrowtail$ $\sim$ 0.9 million pixels
    - $\hookrightarrow$ charge sharing $\Rrightarrow$ $\sigma_{sp} \gtrsim$ 3.5 μm expected (M22-AHR beam tests)
  - ⋇ $t_{r.o.} \lesssim$ 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





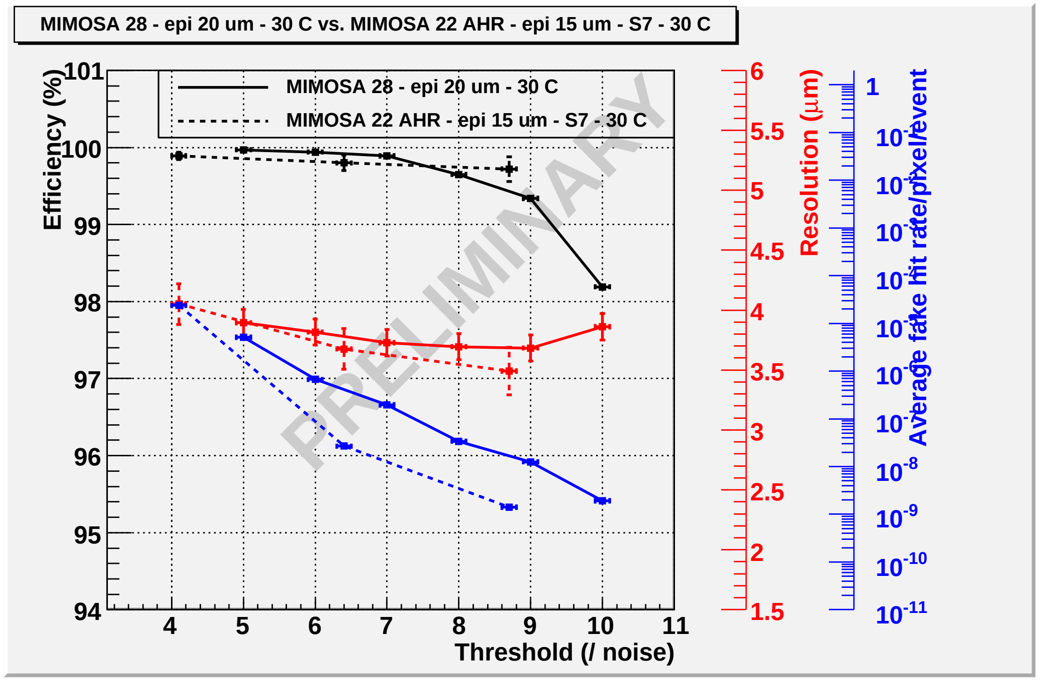
▷▷▷ **Tests under way since early April :** not yet completed

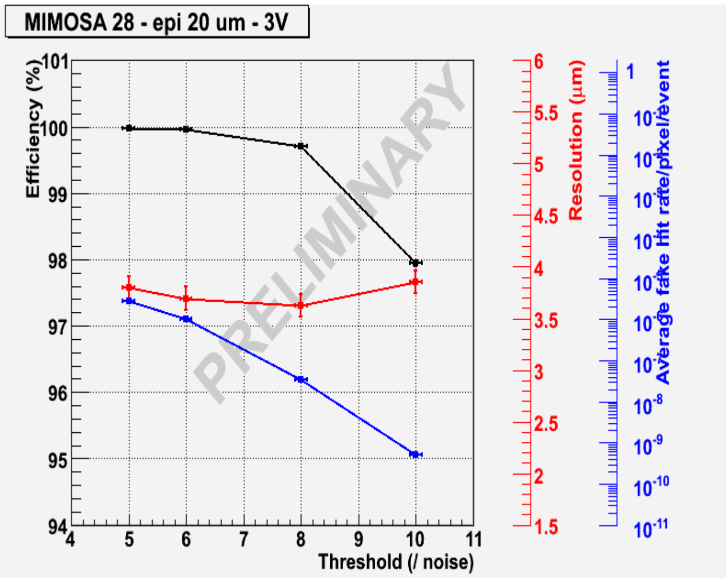
- ⋇ N $\lesssim$ 15 e$^-$ ENC at 30-35°C (as MIMOSA-22AHR)
- ⋇ CCE (^{55}Fe) similar to MIMOSA-22AHR
- ⊸ Ionising rad. tolerance validated (150 kRad at 30°C)
- ⊸ NI rad. tolerance validation (3$\cdot$10^{12}n$_{eq}$/cm^2 at 30°C) scheduled in Autumn 2011

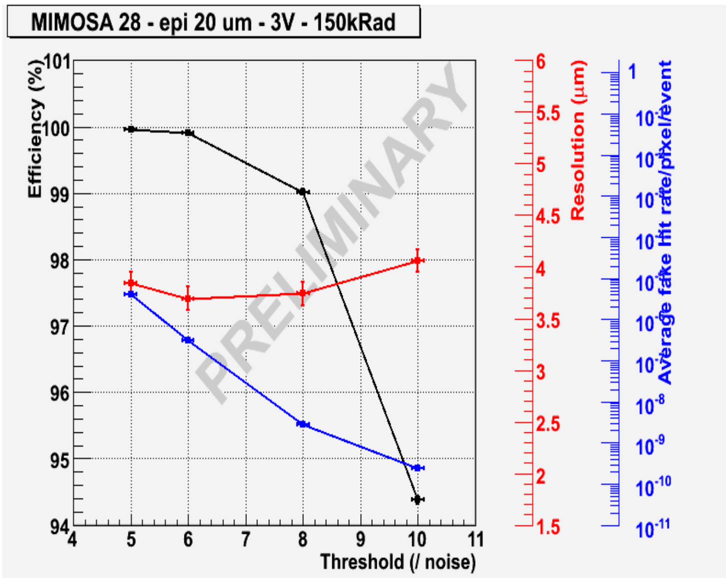


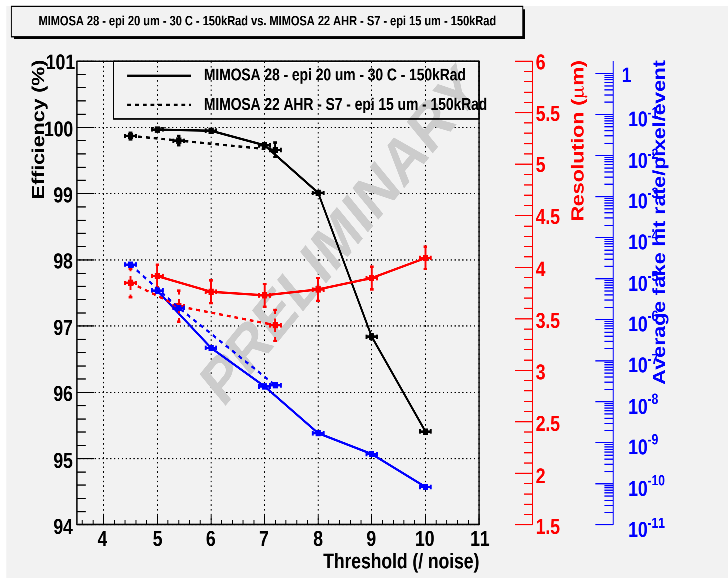
Observed M.I.P. Detection Performances of ULTIMATE

- **Beam tests at CERN-SPS with O(10^2) GeV "π^- beam" :**
  - ⁜ 1 week of data taking : June 27 - July 4
  - ⁜ BT made of 6 ULTIMATE sensors (20 μm thick epi):
    - ⊸ 2 pairs ($\equiv$ arms) of reference sensors
    - ⊸ separated by 1 pair of DUTs
  - ⁜ test variables (preliminary results) :
    - ⊸ operating temperature : 20 & 30°C
    - ⊸ ionising radiation dose : 0 & 150 kRad
    - ⊸ steering voltage : 3.3 & 3.0 V





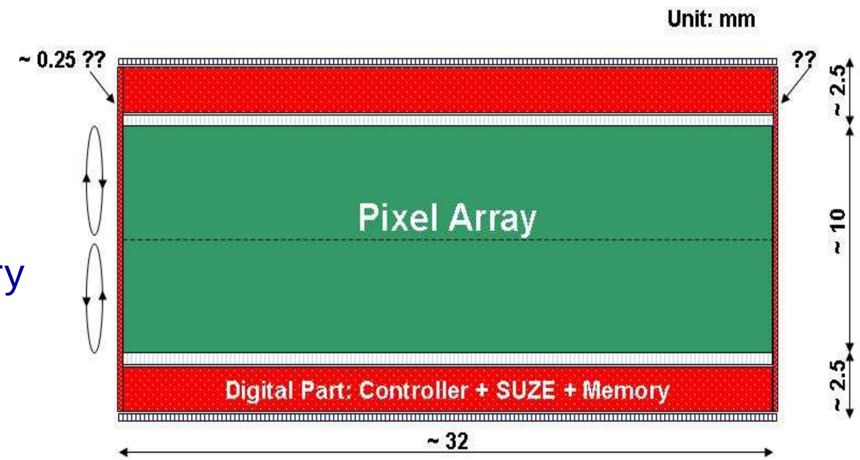




From ULTIMATE to MISTRAL

- **MISTRAL** $\equiv$ **MI**MOSA **S**ensor for the inner **TR**acker of **AL**ICE $\triangleright$ ALICE-ITS upgrade pixel option

- **Derived from ULTIMATE (STAR - PXL) :**



  - ⋇ in-pixel pre-amp + cDS
  - ⋇ column parallel read-out ($\equiv$ rolling shutter)
  - ⋇ each column ended with discri. $\triangleright$ binary charge encoding
  - ⋇ zero-suppression & output buffers integrated at chip periphery
  - ⋇ JTAG programmable
  - ⋇ thinned to 50 μm

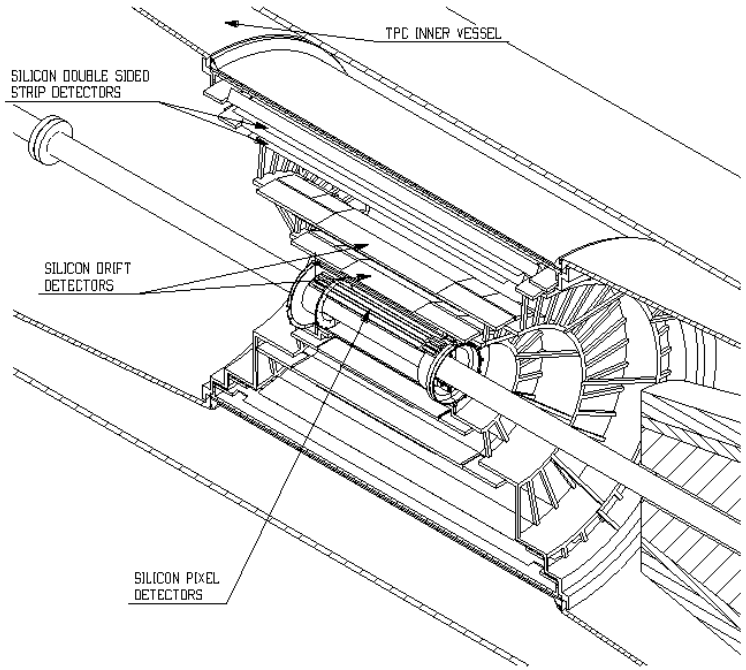
- **Differences w.r.t. ULTIMATE :**
  - ⋇ 0.18 μm triple-well HR-epi techno. (instead of 0.35 μm double-well hR-epi)
  - ⋇ $\sim$ 1$\times$3 cm^2 large sensitive area (instead of 2$\times$2 cm^2)
  - ⋇ possibly : use of L0 (and L1 ?) trigger decision(s) to squeeze data flow and power
  - ⋇ possibly double-sided read-out (instead of single-sided) : depends on NI radiation tolerance
  - ⋇ 1 or 2 output pairs at $\gtrsim$ 200 MHz (instead of 1 output pair at 160 MHz)
  - ⋇ two $\lesssim$ 200 μm wide raw sequencers (instead of one 350 μm wide sequencer)
    - $\triangleright$ potentially : raw sequencers moved to bottom (requires $\sim$ 6 ML $\Rrightarrow$ depends on design duration)

MISTRAL : Main Specifications

- **Detection related characteristics :**

Pixel dimensions	$\sigma_{R\phi,z}$	read-out	$\mathbf{t}_{integ}$	P_{diss}
option 1: 20 $\times$ 20 μm^2	*3.5–4 μm*	*2-sided*	*40–50 μs*	$\lesssim$ *250(400) mW/cm^2*
option 2: 20 $\times$ 40 μm^2	*5–6 μm*	*2-sided*	*20–25 μs*	$\lesssim$ *250(400) mW/cm^2*
		1-sided	*40–50 μs*	$\lesssim$ *150(200) mW/cm^2*
STAR : 20.7 $\times$ 20.7 μm^2	$\sim$ *3.5 μm*	*1-sided*	$<$ *200 μs*	$\lesssim$ *150(200) mW/cm^2*

- **Radiation tolerance at +30°C :**
  - ⋇ ionising radiation $\gtrsim$ 2 MRad
  - ⋇ non-ionising radiation $\gtrsim$ 2$\times$10^{13}n_{eq}/cm^2

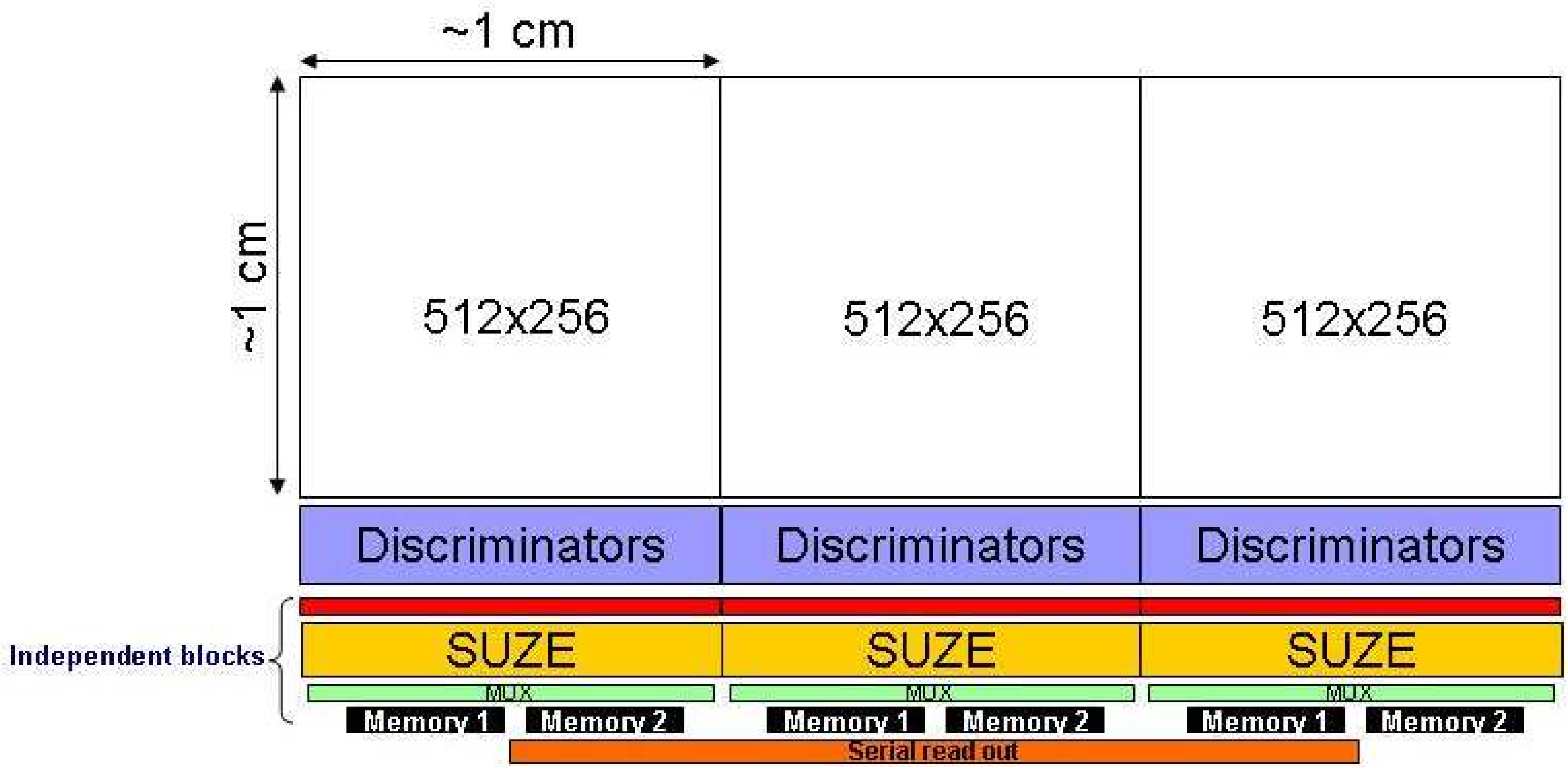


- **Surface to cover :**
  - ⋇ seemingly at least 3 inner layers (L0, L1, L2) :
    - ▷ at least 3000 – 4000 cm^2
  - ⋇ perhaps 2 sensor geometries (?) :
    - ▷ 1$\times$3 cm^2 (L0) and 2$\times$3 cm^2 (L1-2) $\Rrightarrow$ $\sim$ 200 + 500 sensors

MISTRAL : Multi Purpose Architecture

- **Modular design :**

▷ overcome design complexity (frequency, read-out time, layout) over 3 cm sensor extension



- **Other advantages :**

  ⋇ basic blocks can be reused for other applications : CBM, AIDA, eRHIC, ...

  ⋇ easy for prototype evaluation (⇛ incorporate all pads needed for tests in basic block)

MISTRAL : Moving to 0.18 μm CMOS Technology

- **Evolve towards feature size $<<$ 0.35 μm :**
  - ⋇ **μcircuits :** smaller transistors, more Metal Layers, ... ⋇ **sensing :** quadruple well, depleted sensitive volume, ...
- **Benefits :**
  - ⋇ faster read-out $\Rrightarrow$ improved time resolution
  - ⋇ higher μcircuit density $\Rrightarrow$ higher data reduction capability
  - ⋇ thinner gates, depletion $\Rrightarrow$ improved radiation tolerance (in particular ionising radiation)
- **Image Sensor process of Tower/Jazz Semi-Conductor :**
  - ⋇ systematic contact established with founder (ticketting) $\Rrightarrow$ design under way
  - ⋇ attractive features of technology (and founder):
    - ⊸ optimised sensing systems available and tunable (?) $\Rrightarrow$ enhanced SNR
    - ⊸ high-resistivity epitaxy (1 - 5 $k\Omega \cdot cm$) $\Rrightarrow$ enhanced SNR
    - ⊸ 6 ML, deep P-well, etc.
    - ⊸ stitching $\Rrightarrow$ multireticule surface sensor
    - ⊸ $\geq$ 8 Multi-Project-Wafer runs per year $\rightarrowtail$ Shuttle Nr 62 on 24.10.11
- **Synergies :**
  - ⋇ CBM - MVD, AIDA-SALAT, eRHIC VD, BES-3 inner tracker, other ALICE sub-systems, ILD-VTX, ...
  - ⋇ SuperB vertex detector: in-pixel μs time-stamping architecture fits in 50×50 μm^2 pixel

MISTRAL : Chip Submission Plans

- **Chip submission flow :**

  ⋇ Q4/2011 : MIMOSA-32 ▷ prototype for technology exploration

  ⋇ Q2/2012 :

  —○ MIMOSA-22THR ▷ prototype with 128 columns (of 128-256/512 pixels) ended with discriminators

  —○ SUZE-02 ▷ prototype with latch-up free zero-suppression μcircuit and output buffers (trigger ?)

  ⋇ Q2/2013 : FSBB ▷ Full Scale (1 cm^2) Basic Block combining MIMOSA-22THR & SUZE-02 designs

  ⋇ Q2/2014 : MISTRAL ▷ final sensor $\equiv$ optimised FSBB design, repeated to cover 3–6 cm^2

- **Still pending :**

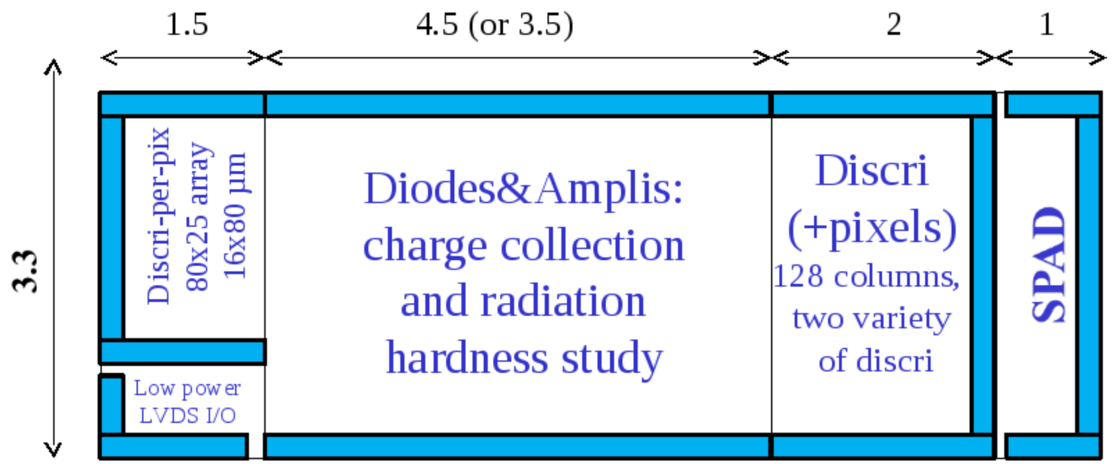
  ⋇ building blocks vs radiation tolerance : do we need ELT, latch-up free design, etc. ?????

  ⋇ optimisation of data transfer μcircuitry ???

  ⋇ integration of trigger information for sensor output filtering ????

MIMOSA-32 : Prototyping a 0.18 μm Process

- **0.18 μm imaging technology options used :**
  - ⋇ Epitaxial layer $\sim$ 14 μm thick with High-Resistivity (1-5 $k\Omega \cdot cm$)
  - ⋇ Quadruple well : deep P-type layer embedding N-well hosting P-MOS transistors
  - ⋇ MIM capacitor
  - ⋇ start with 4 Metal Layers (6 ML run in 2012)
  - ⋇ CIS (very low noise) sensing system

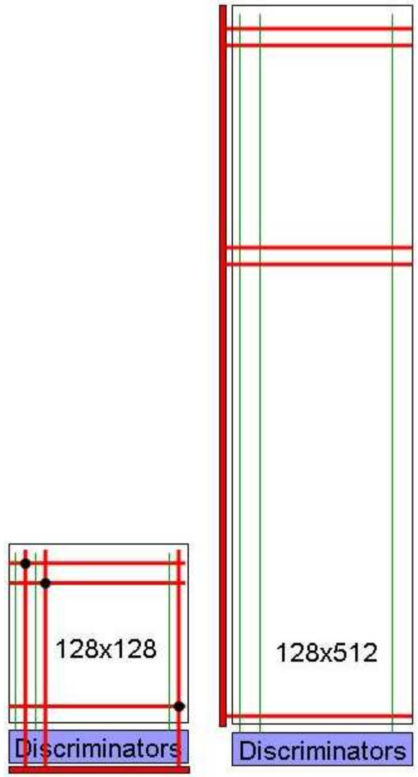


- **Prototype sub-divided in several blocks :** ▷ ▷
  - ⋇ Sensing elements and in-pixel amplifiers :
    - ⟶ pixel dimensions : 20×20, 40, 80 μm^2
    - ⟶ 3 different types of sensing elements : diodes of $\sim$ 10–100 μm^2
    - ⟶ N-MOS and P-MOS transistor based amplifiers
  - ⋇ Discriminators :
    - ⟶ Col. // pixel array ended with 1 discriminator/col. (2 variants)
    - ⟶ Pixel array with in-pixel discriminator (16×80 μm^2 pixels)
  - ⋇ Total surface $\lesssim$ 30 mm^2

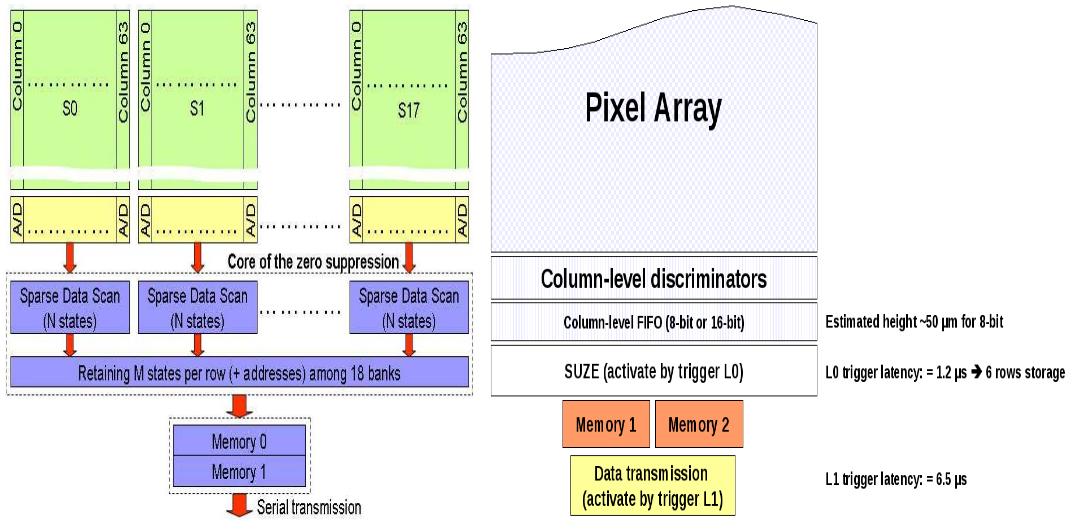
- **Submission :** Octobre 24th, 2011

MISTRAL : Architecture Prototyping

- **MIMOSA-22THR :**
  - ⋇ Col. // pixel array with in-pixel ampli + pedestral subtraction (cDS)
  - ⋇ Each of 128 columns ended with discriminator + 8 columns without discri.
  - ⋇ Pixel array sub-divided in sub-arrays featuring different pixel designs
  - ⋇ 2 options for row sequencer :
    - ⊸ parallel to columns $\Rrightarrow$ dead zone inbetween neighbouring chips
    - ⊸ together with signal processing circuitry $\Rrightarrow$ avoids the dead zone



- **SUZE-02 :**
  - ⋇ $\emptyset$ μ-circuits & output buffers ($\equiv$ SUZE-01)
  - ⋇ add trigger L0 info after discriminators for data filtering $\Rrightarrow$ flow & power reduction ?
  - ⋇ add trigger L1 (?) downstream of output buffers for further filtering ?

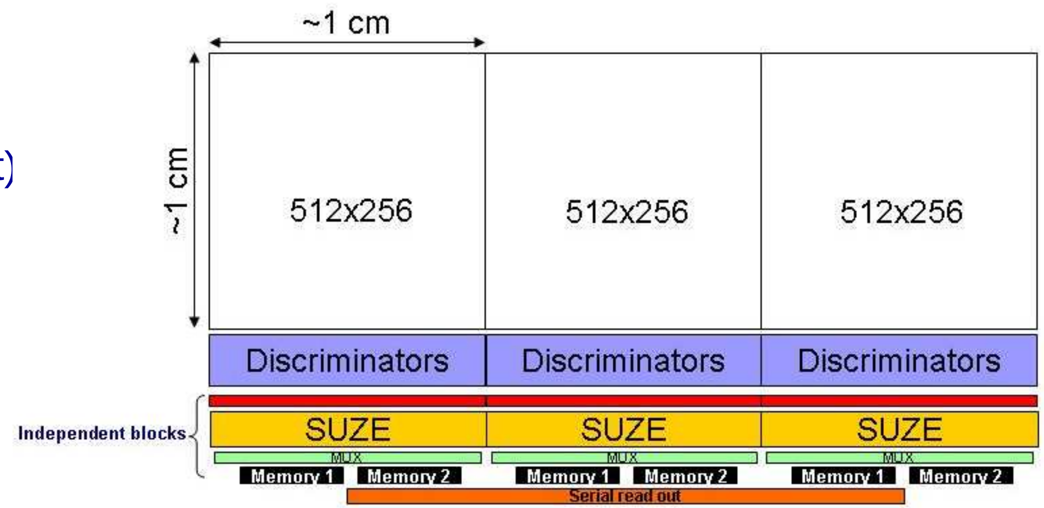


- **Submission** $\leq$ Spring 2012
  - $\hookrightarrow$ determine sensor adequacy w.r.t. rad. tol. spec.

MISTRAL : Final Steps

- **FSBB (Full Scale Basic Block) :**
  - ⋇ Composition :
    - ⊸ Pixel array with final pixel design ($\sim$ 1 cm^2)
    - ⊸ Final r.o. circuitry ($\varnothing$, filtering, data transmission, ...)
    - ⊸ All read-out circuitry split in elementary blocks according to stitching design rules
  - ⋇ Submission : Spring 2013

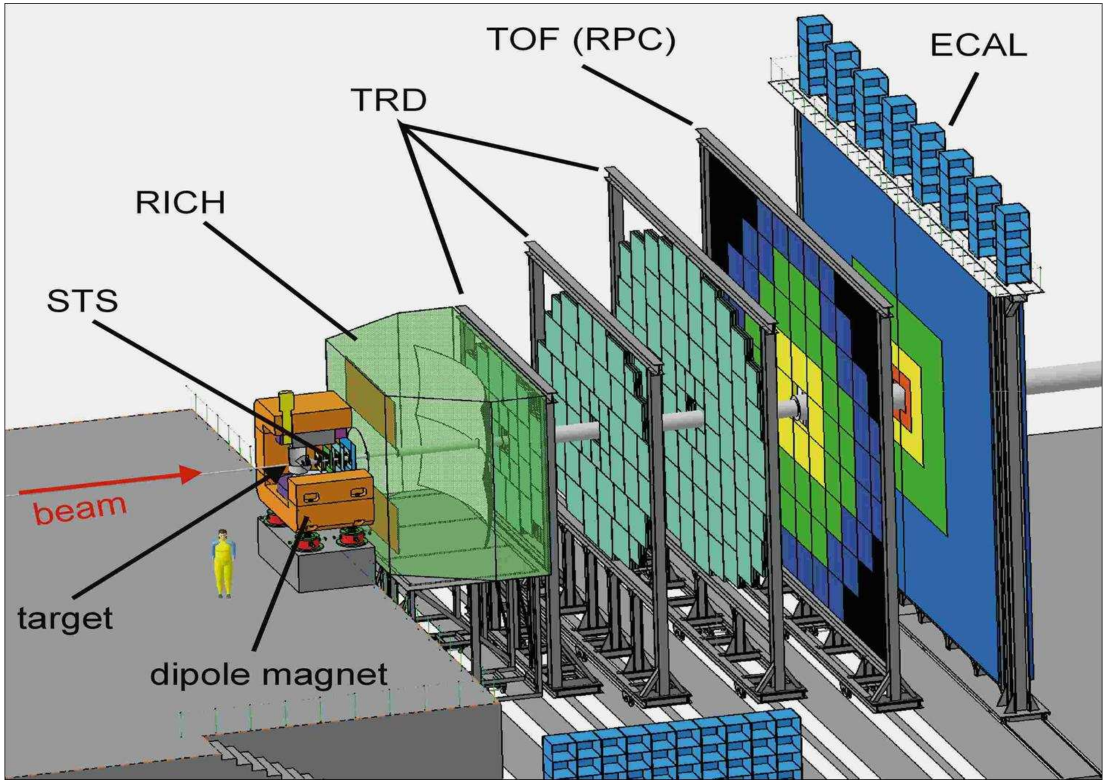
- **MISTRAL :**
  - ⋇ Composition :
    - ⊸ 3 full-size adjacent FSBB (1-sided read-out) or 6 half FSBB (2-sided read-out)
    - ⊸ Complemented with serial r.o. circuitry
  - ⋇ Submission : Spring 2014



- **Start MIMAIDA & MIMOSIS designs :**
  - ↪ submission in 2015

Next Step : CBM-MVD

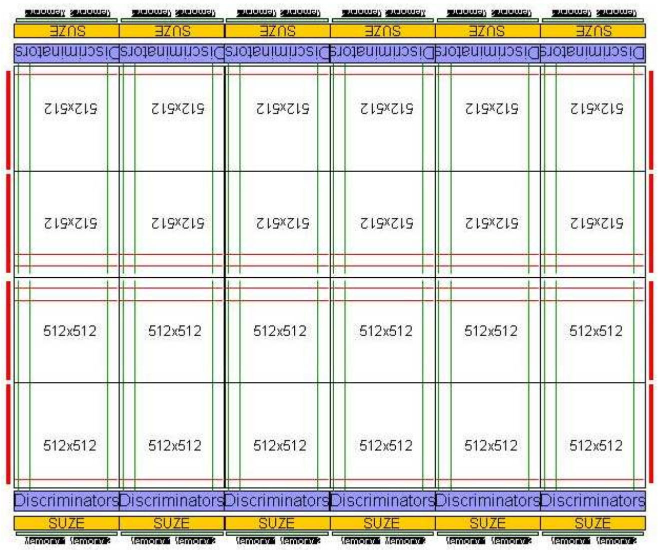
- **Cold Baryonic Matter (CBM) experiment at FAIR:**
  - ⋇ Micro-Vertex Detector (MVD) made of 3 (2 ?) stations located behind fixed target
  - ⋇ double-sided stations equipped with CMOS pixel sensors
  - ⋇ **operation at negative temperature in vacuum**
  - ⋇ each station accounts for $\lesssim$ 0.5 % X_0
  - ⋇ sensor architecture very close to MISTRAL
    - ⟶ shorter col. ($\sim$ 150 pixels) ▷ r.o. speed



- **Most demanding requirements :**
  - ⋇ ultimately ($\sim$ 2020): 3D sensors
    $\lesssim$ 10 μs, $>$ $10^{14} n_{eq}/cm^2$, $\gtrsim$ 30 MRad
  - ⋇ intermediate steps: 2D sensors
    $\lesssim$ 30-40 μs, $>$ $10^{13} n_{eq}/cm^2$, $\gtrsim$ 3 MRad
  - ⋇ 1st sensor for SIS-100 (data taking $\gtrsim$ 2017-18)
    ▷ MIMOSIS-1

Investigating Large Area Sensors

- **Prototype multireticule sensor for "large" area detectors :**
  - ⋇ *2048$\times$3072 pixels ($\sim$ 20 μm pitch)*
    - $\Rrightarrow$ *4$\times$6 cm^2 sensitive area, 3.5 μm spatial resolution*
  - ⋇ *requires combining several reticules*
    - $\Rrightarrow$ *stitching process* $\Rrightarrow$ *establish proof of principle*
  - ⋇ *2-sided read-out of 1024 rows in $\sim$ 200 μs*
    - $\Rrightarrow$ *3 planes of Large Area Telescope for AIDA project (EU-FP7)*
  - ⋇ *windowing of $\lesssim$ 1$\times$6 cm^2 (collimated beam)*
    - $\Rrightarrow$ *$\sim$ 50 μs r.o. time*
  - ⋇ *50-100 μm pitch variants under consideration*
    - $\Rrightarrow$ *trackers & FW disks (e.g. VD for eRHIC)*



- **Submission scheduled for 2015 :**
  - ⋇ bonus: avoid paving "large" areas with reticule size sensors
    - $\Rrightarrow$ dead zones, material, connectics/complexity
  - ⋇ synergy with tracker layers and forward disk projects on collider & fixed target experiments
  - ⋇ 3 sensors will compose a beam telescope at CERN (AIDA project deliverable) : SALAT
    - ▷ few ns time stamping resolution associated to each hit by TLU (scintillator)

Besides/Beyond MISTRAL

- **Motivations :**
  - ⋇ baseline improvements (e.g. CCE, SNR)
  - ⋇ extended running conditions or physics goals (e.g. read-out speed)

- **Baseline improvements $\equiv$ keep baseline architecture :**
  - ⋇ use of technology features improving charge collection or noise performance
  - ⋇ full use of $\geq$ 6 ML (e.g. row sequencer at bottom)
  - ⋇ etc.

- **Extended running conditions $\Rrightarrow$ modify baseline architecture :**
  - ⋇ 2 different architectures ;
    - ⊸ parallel rolling shutter (PRS) architecture
    - ⊸ high-density in-pixel (HDIP) functionnalities
  - ⋇ **Each option explores a different optimisation of speed $\star$ resolution $\star$ power :**
    - ⊸ PRS $\Rrightarrow$ slower but more precise and dissipating less power
    - ⊸ HDIP $\Rrightarrow$ faster and more selective but less precise and dissipating more power

SUMMARY

- **Sensor development for STAR-PXL nearly completed**

  $\Rrightarrow$ **precious know-how from sensor integration in the HFT** (e.g. see talks at this workshop)

- **Translation 0.35 $\mu m \rightarrowtail$ 0.18 μm CMOS under way :**

  $\triangleright$ MIMOSA-32 to be submitted for fabrication on 24.10.2011

  $\triangleright$ design flexible enough to be adaptable to various applications

- **First full scale sensor in 0.18 μm technology ready for detector expected in 2014 :**

  ⋇ MISTRAL for ALICE-ITS upgrade (if chosen)

  ⋇ based on FSBB to be fabricated in 2013, cornerstone for several other applications

- **Next steps : 2015-2016**

  ⋇ AIDA SALAT : extension of FSBB to 4$\times$6 cm^2 using stitching $\Rrightarrow$ validation for eRHIC (LDRD)

  ⋇ CBM-MVD : variant of MISTRAL with shorter columns ($\equiv$ integration time)
  operated in vacuum at T$<$ 0°C

- **Numerous spin-offs foreseen $\Rrightarrow$ opportunities of combined efforts**