CMOS Pixel Sensors for the CBM Micro-Vertex Detector

M.Winter / IPHC, 18 May 2017

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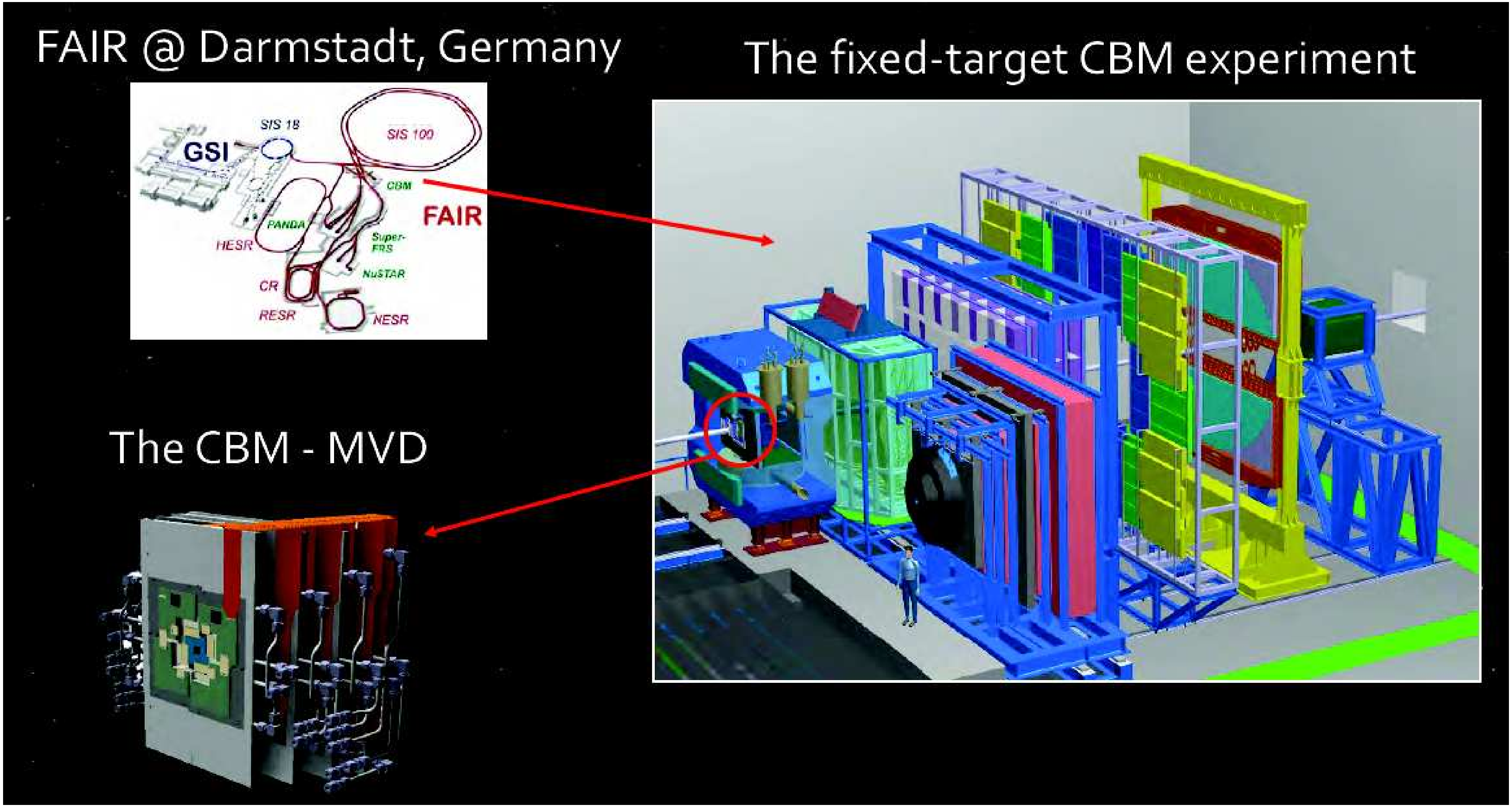
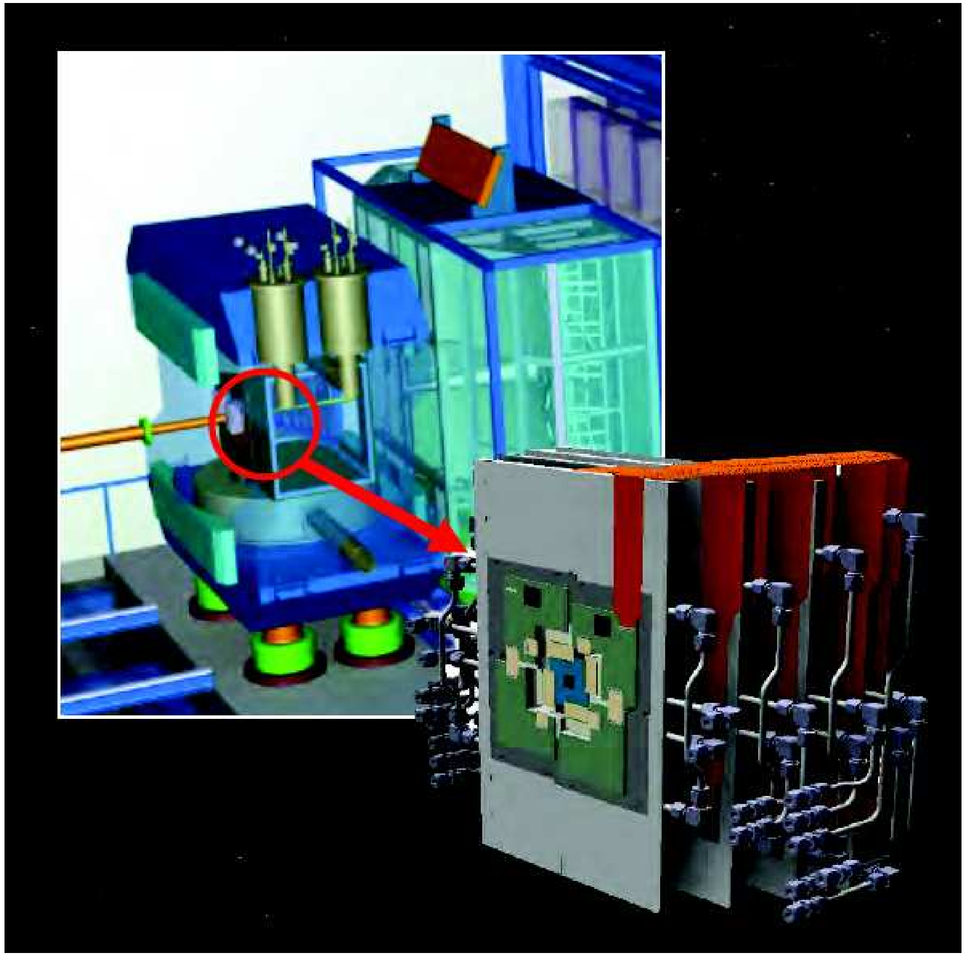
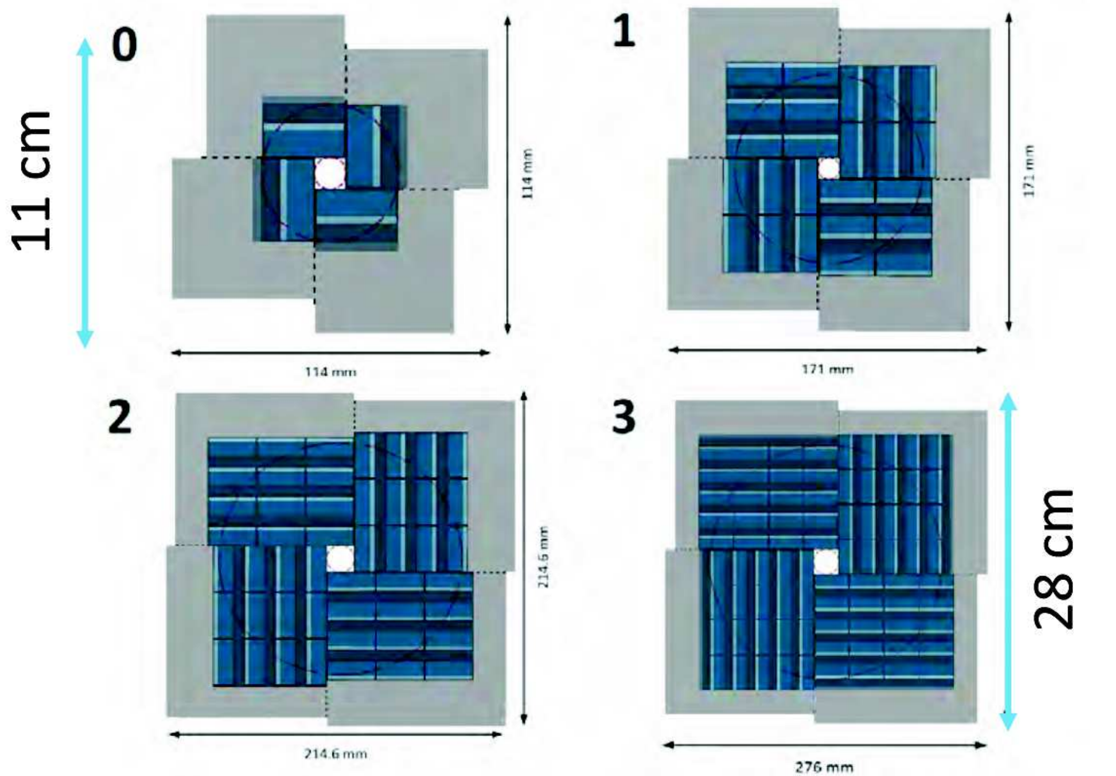
The CBM Micro-Vertex Detector

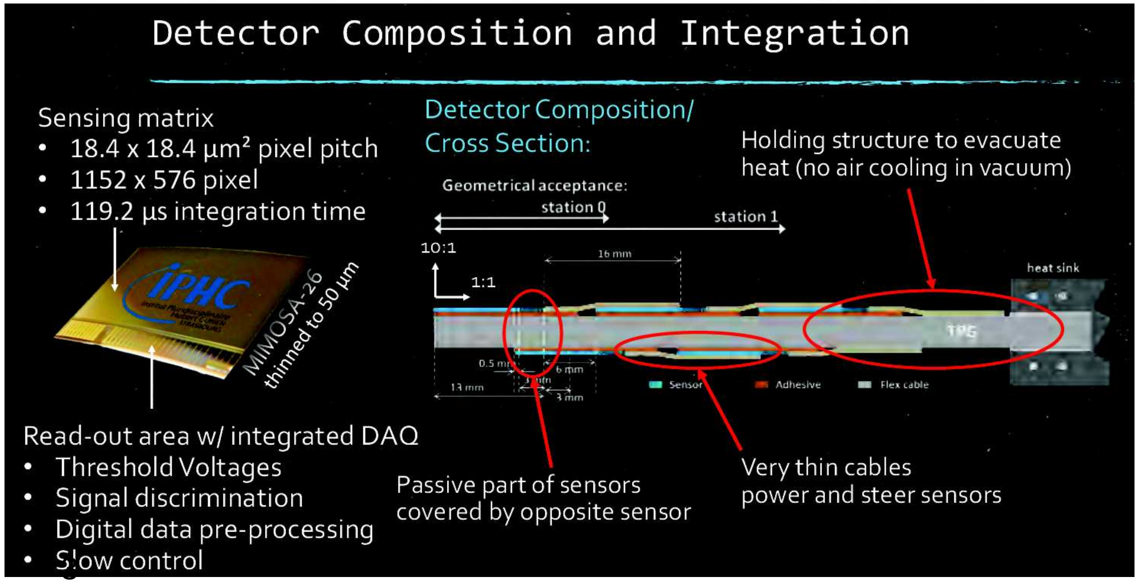


- **4 double-sided stations located at 5, 10, 15, 20 cm behind the target**

The CBM Micro-Vertex Detector





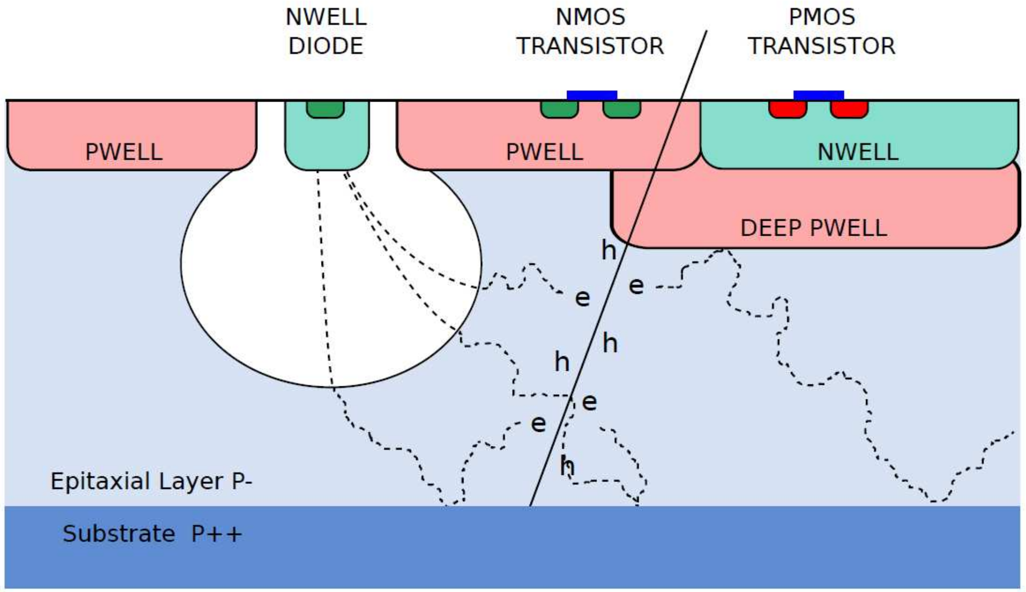


- **MVD based on 50 μm thin CMOS sensors**
  - single point resolution: 5 μm x 5 μm
  - time resolution: 5 μs
  - power consumption $\lesssim$ 200–350 mW/cm^2
  - radiation tol. (-20°C): 3 MRad, $3\cdot10^{13}$ n_{eq}/cm^2

CMOS Pixel Sensors (CPS): Main Features

- **CPS fabricated via industrial processes used for ASIC production**
  - Thin sensitive volume (e.g. 20 - 40 μm)
  - Full signal processing micro-circuitry integrated on chip (low noise !)

    $\Rightarrow$ Very modest material budget: $\sim$ 0.05 % X_0



- **CPS provide O(μm) spatial resolution**
  - Small pixels: typically 20-30 μm x 20-30 μm
  - Charge sharing between neighbouring pixels

    $\Rightarrow$ binary charge encoding often sufficient

- **Read-out speed & radiation tolerance**
  - Usually the main R&D drivers
  - In conflict with small pixels, low power, thin sensitive volume, etc.

- **CPS used successfuly in STAR-RHIC/BNL (2014-16), presently produced for ALICE-ITS&MFT (30,000 sensors)**

CPS Design Required for the MVD: MIMOSIS Sensor

- **MIMOSIS derived from ALPIDE pixel array read-out architecture (ITS, MFT)**

- **Required radiation tolerance significantly higher than ALPIDE**

  ($\gtrsim$ 10 times higher locally)

- **Required data throughtput $\sim$ 10 times higher than ALPIDE**

  (hit density actually up to $\sim 10^2$ times higher locally)

	ITS (IB)	CBM (1^{st} station)
Radiation Load TID	~270 krad	3 Mrad @ -20°C, 1 Mrad @ +30°C
Radiation Load NIEL	~$1{,}7\times10^{12}$ 1MeV n_{eq}/cm^2	3×10^{13} n_{eq}/cm^2 @-20°C, 1×10^{13} n_{eq}/cm^2 @+30°C
Peak hit rate	~$1{,}25\times10^6/cm^2/s$ → $1{,}25\times10^4/mm^2/s$	$7\times10^5/mm^2/s$ (x 56 times than ITS)
Trigger	yes	no
Heavy Ion Effect		

- **Fully revisited digital circuitry (data sparsification & transfer logic)**

IPHC Team developing the MIMOSIS Sensor

- **Development started in 2003 ....**

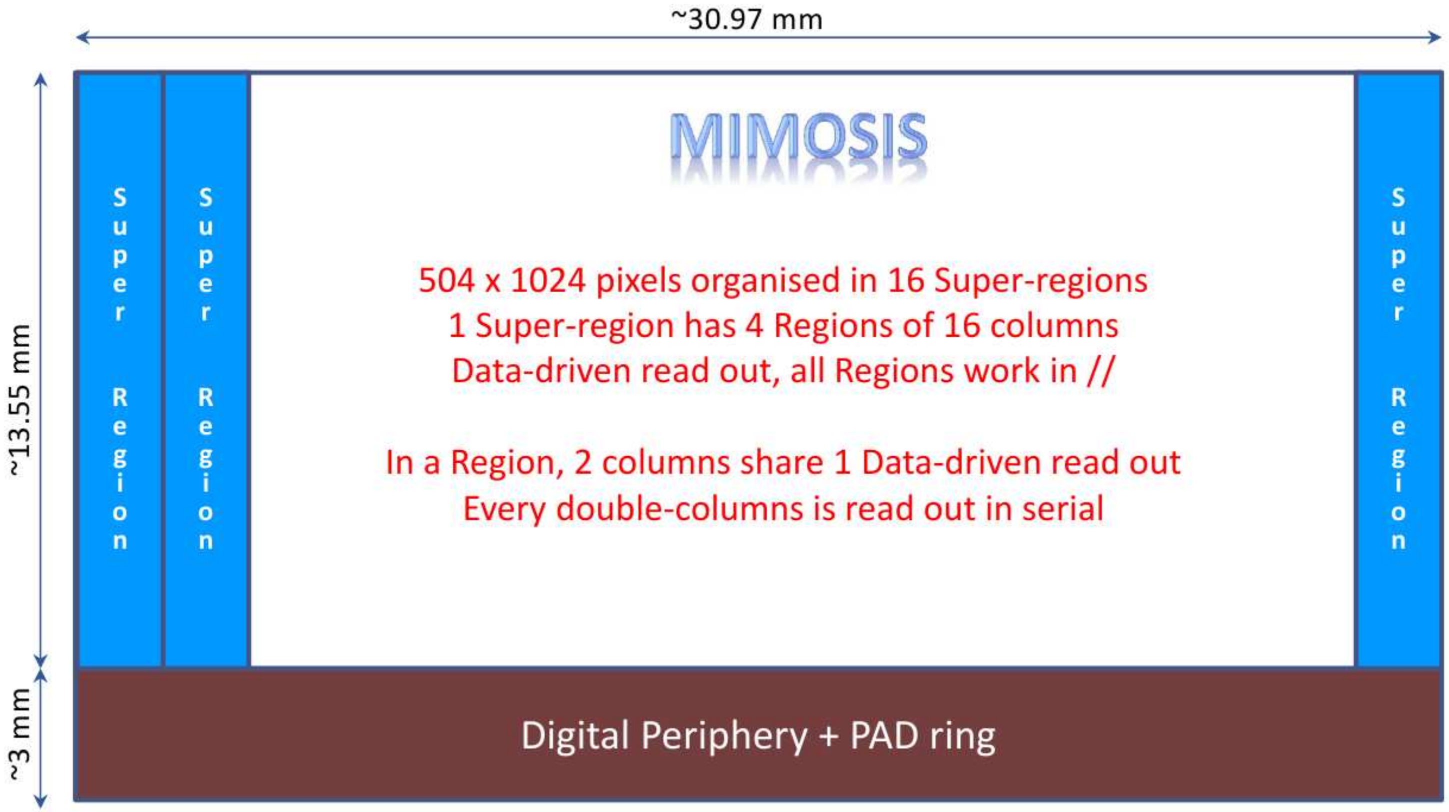
  $\hookrightarrow$ R&D went through numerous different intermediate applications

- **IPHC-PICSEL team members involved presently:**
  - physicist: M.Winter
  - μ-circuit designers: A.Dorokhov, G.Dozière, A.Himmi, Ch.Hu-Guo, F.Morel,
    H.Pham, I.Valin, Y.Zhao
  - electronics engineers: G.Claus, M.Goffe

- **Responsibility: realisation of the MVD sensor MIMOSIS**
  - sensor design
  - foundry runs of consecutive prototypes
  - electronics/functionnal tests of prototypes
  - prototypes' detection performance assessment (in collaboration with IKF-Frankfurt)

MIMOSIS Overview

- **Pixel dimensions**
  26.88 μm x 30.24 μm
- **In-pixel discrimination**
- **Binary charge encoding**
- **Data driven read-out**



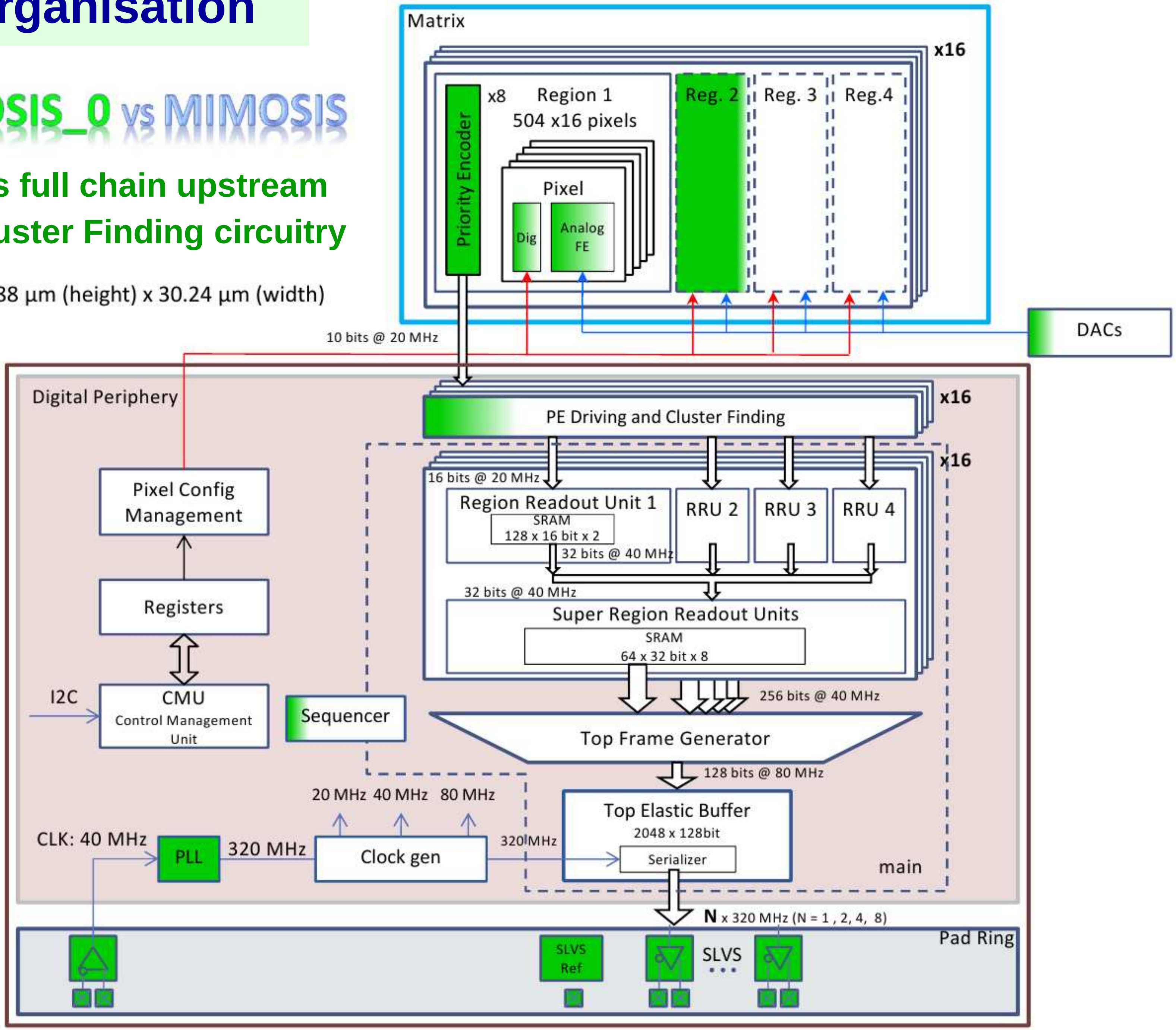
- **MIMOSIS development plan:**
  - MIMOSIS-0: portion of pixel array with 2 diff. pixel designs $\rightarrowtail$ submitted in May/'17
  - MIMOSIS-1: 1st prototype of complete sensor, to be submitted in $\gtrsim$ Q2/'18
  - MIMOSIS-2: 2nd prototype of complete sensor, to be submitted in $\gtrsim$ Q2/'19
  - MIMOSIS-3: final sensor pre-production, to be submitted early in 2020

Overall Sensor Organisation

1. MIMOSIS_0 vs MIMOSIS

Includes full chain upstream from Cluster Finding circuitry

Pixel dimension: 26.88 µm (height) x 30.24 µm (width)



SUMMARY

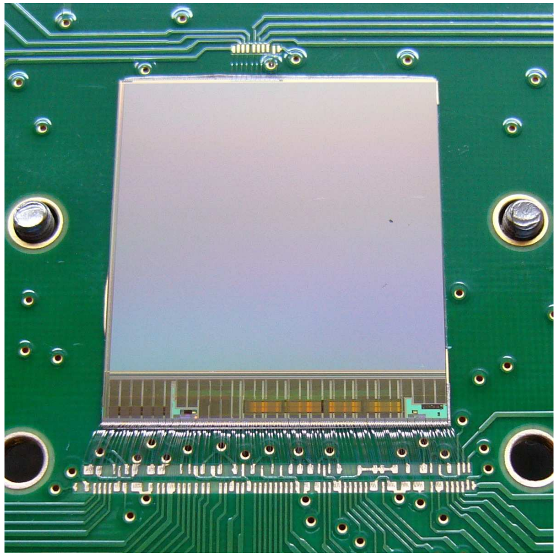
- **CBM-MVD:**
  - requires very high precision in challenging running conditions
  - will be equipped with CPS designed and developed at PHC-Strasbourg
  - based on $>$ 10 years of fruitful partnership between IPHC and IKF(+GSI)
- **Technological aspects:**
  - well defined CPS development plan until 2020
  - challenging devopment: no table ready solution available
  - will become the state-of-the-art (CPS, whole detector)
- **Partnership extension :**
  - CPS detection performance and radiation tolerance assessment
  - contribution to system integration studies and preparation for assembly
  - N.B.: acquired expertise addresses a very promising instrumentation domain
  - numerous spin-offs

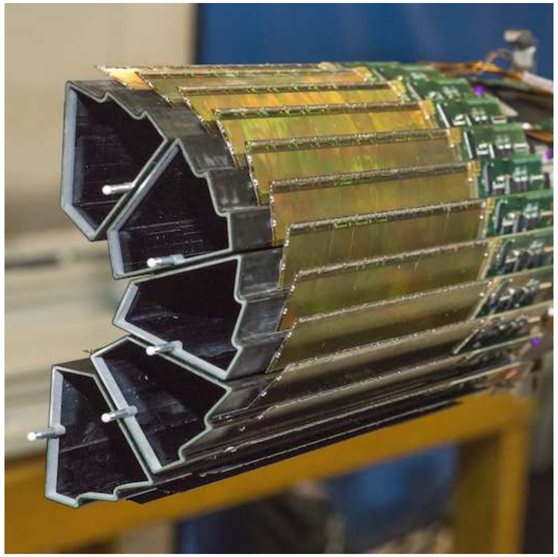
Achievement: MIMOSA-28 & STAR-PXL Detector (+ spin-offs)

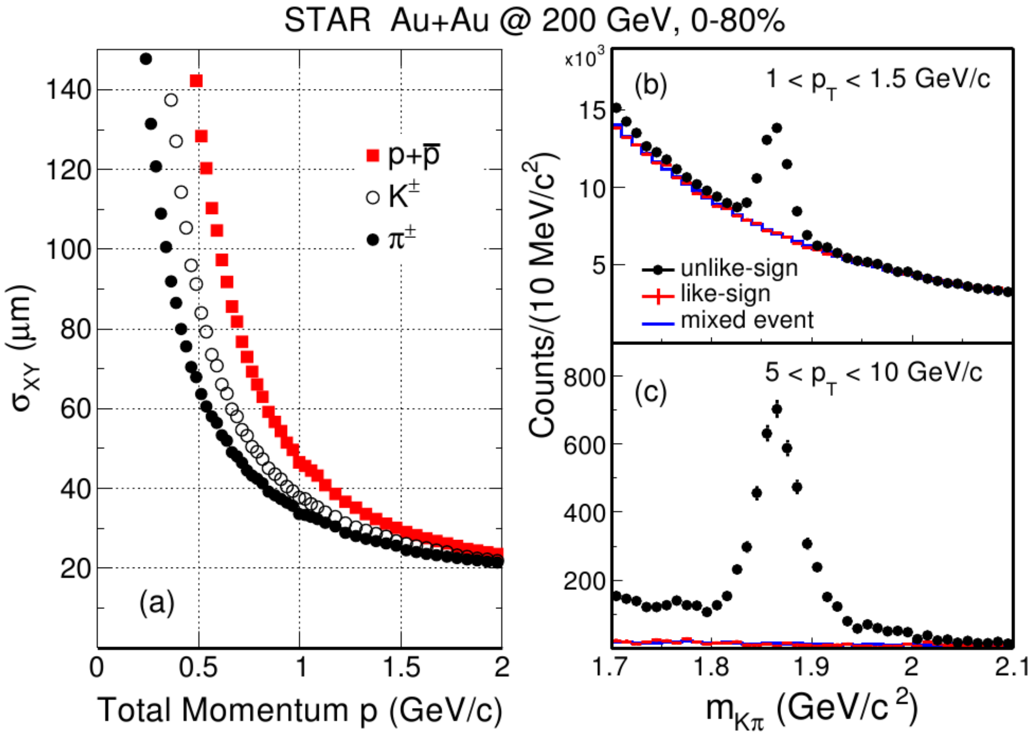
- **MIMOSA-28: 1st CPS equipping a subatomic phys. experiment (STAR at RHIC/BNL)**

  $\sigma_{R\Phi,Z} \simeq$ **3.7** μm; **thickness** $\simeq$ **50** μm; **970,ooo pixels over 2x2 cm^2**; $>$ **10^6 part./cm^2/s**

3 date taking campaigns (2014–16) $\Rightarrow$ **state-of-the-art of the technology**



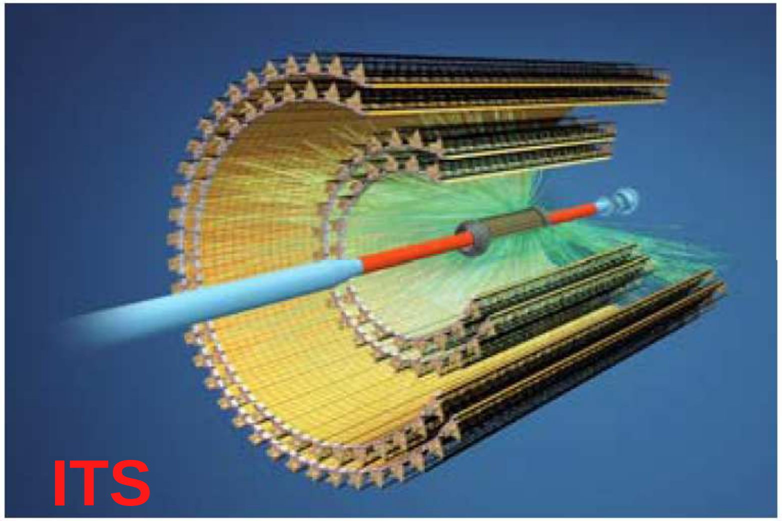


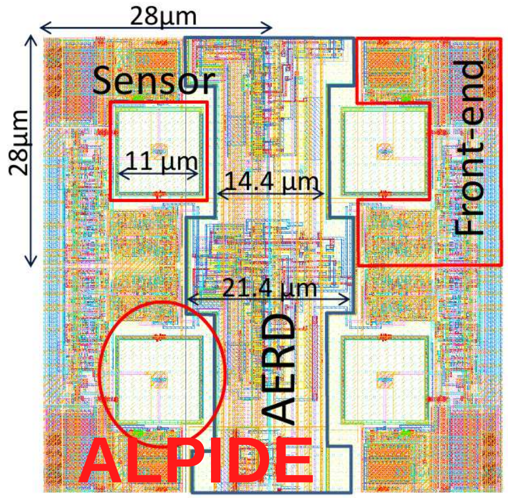


- MIMOSA-28 equips numerous devices, e.g.:
  - AIDA BT: 4 millions of pixels per plane (4x4 cm^2, $<$ 0.1% X_0)
  - BT part of LNF permanent infrastructure (450 MeV e^-)
  - telescope for hadrontherapy (GSI), etc.
  - demonstrator for inner tracker upgrade of BES-3 expt. at BEPC/IHEP

Achievement: 2 sensors for ALICE-ITS (LHC)

- **Objective: 1st pixellated inner tracker ($>$ 10 m^2 sensitive area, 25,ooo CPS)**
- **More demanding requirements than for STAR-PXL (MIMOSA-28)**
  - $\Rightarrow$ **evolution toward more advanced technology: TowerJazz 0.18μm**
- **2 approaches:**
  - MISTRAL: extension of MIMOSA-28 (STAR-PXL) – validated & robust
  - ALPIDE: extrapolation from hybrid pixels – higher perfo. but less robust & understood



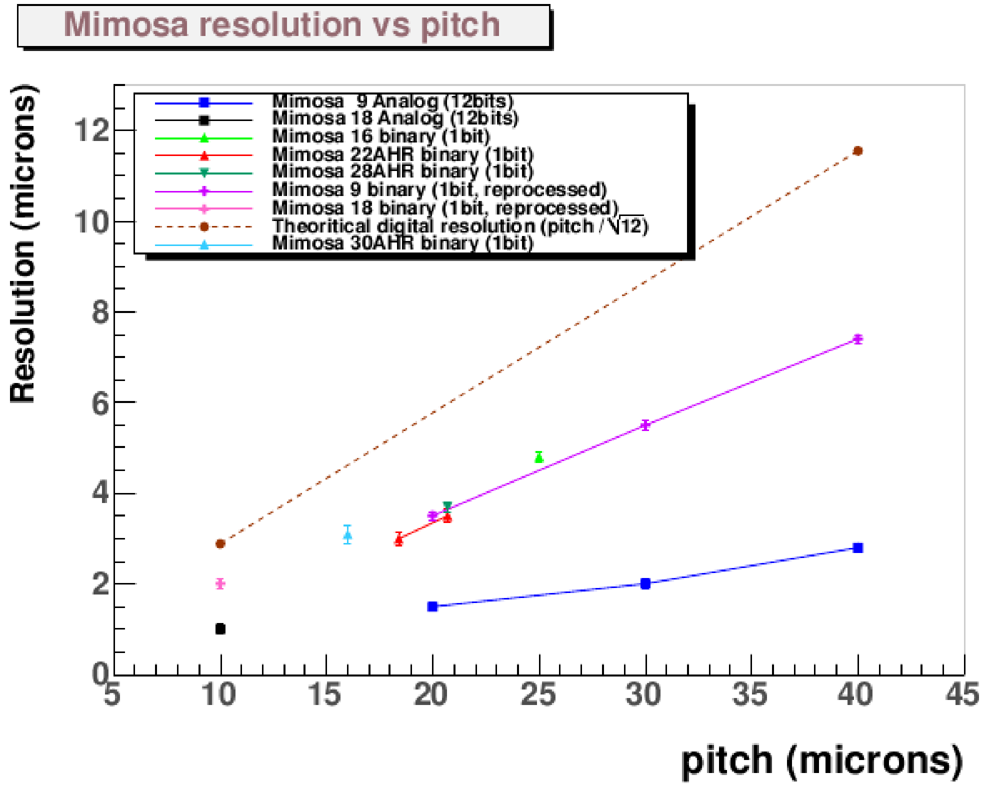


	σ_{sp}	t$_{r.o.}$	Dose	Fluency	T$_{op}$	Power	Active area
STAR-PXL	$<$ 4 μm	$<$ 200 μs	150 kRad	3·10^{12} n$_{eq}$/cm^2	30-35°C	160 mW/cm^2	0.15 m^2
ITS-in	$\lesssim$ 5 μm	$\lesssim$ **30** μs	**2.7 MRad**	**1.7·10^{13} n$_{eq}$/cm^2**	30°C	$<$ 300 mW/cm^2	0.17 m^2
ITS-out	$\lesssim$ 10 μm	$\lesssim$ **30** μs	15 kRad	4·10^{11} n$_{eq}$/cm^2	30°C	$<$ **100 mW/cm^2**	$\sim$ **10 m^2**

Measured Spatial Resolution

- Several parametres govern the spatial resolution :
  - pixel pitch
  - epitaxial layer thickness and resistivity
  - sensing node geometry & electrical properties
  - signal encoding resolution

  $\Rrightarrow$ σ_{sp} fct of pitch $\oplus$ SNR $\oplus$ charge sharing $\oplus$ ADCu, ...



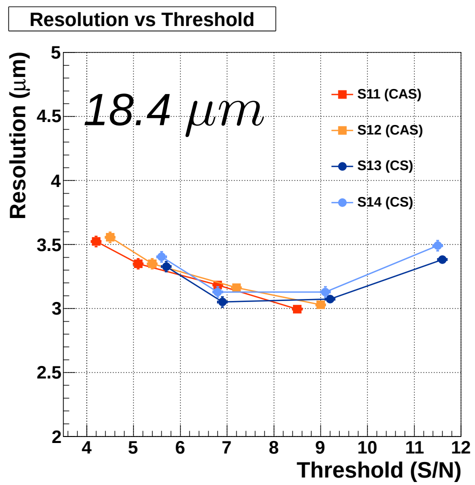
- Impact of **pixel pitch** (analog output) :

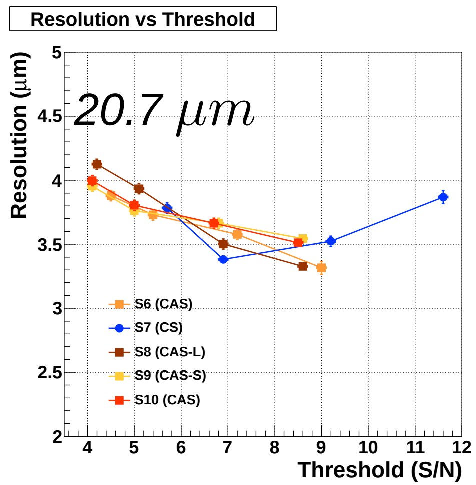
$\boldsymbol{\sigma_{sp} \sim 1\ \mu m}$ (10 μm pitch) $\rightarrowtail$ $\boldsymbol{\lesssim 3\ \mu m}$ (40 μm pitch)

- Impact of **charge encoding resolution** :

▷ ex. of 20 μm pitch $\Rrightarrow$ σ_{sp}^{digi} = pitch/$\sqrt{12} \sim$ 5.7 μm

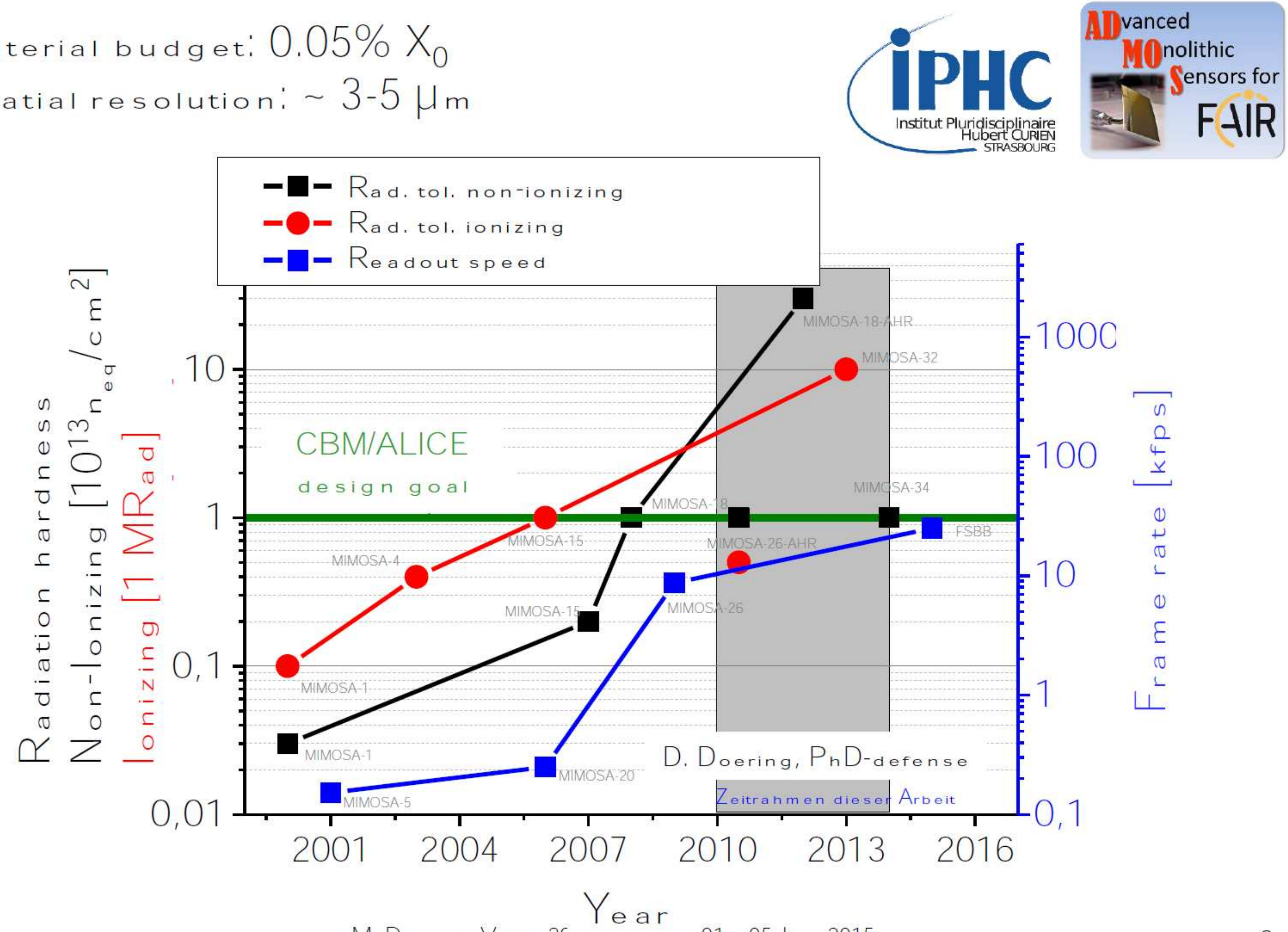
Nb of bits	12	3-4	1
Data	*measured*	*reprocessed*	*measured*
σ_{sp}	$\lesssim 1.5\mu m$	$\lesssim 2\mu m$	$\lesssim 3.5\mu m$





Radiation Tolerance

Material budget: 0.05% X_0
Spatial resolution: ~ 3-5 μm



Speed vs Pixel Dimensions

- **Pixel dimensions govern the spatial resolution at the expense of read-out speed**
  $\Rrightarrow$ **Trade-off to be found specific to each application**

Pixel pitch	$< 10\ \mu m$	$\gtrsim 15\ \mu m$	$> 20\ \mu m$	$\gtrsim 25\ \mu m$	$\lesssim 50\ \mu m$
Nb(T)	2–3	15	$\gtrsim 50$	$\gtrsim 200$	HV: few 10^2
σ_{sp} **[μm]**	$\lesssim$ 1x1	$<$ 3x3	$<$ 5x5	$\lesssim$ 5x5	$\gtrsim$ 10x10
Δt **[μs]**	10^3	$\lesssim$ 30/200	$\gtrsim$ 10-15	< 10	10^{-2}
Pre-Amp+Filter	Out	In-Pix	In-Pix	In-Pix	In-Pix
Discrimination	Out	Out	In-Pix	In-Pix	In-Pix
Sparsification	Out	Out	Out	In-Pix	In-Pix
Ex.(chip)	Mimosa-18	ULTIMATE/MISTRAL	ASTRAL	ALPIDE	HV-CMOS
Depleted	No	No	No	Yes	YES
CMOS Process	AMS-0.35	AMS-0.35/Tower-0.18	Tower-0.18	Tower-0.18	AMS-0.35/0.18
Ex.(appli.)	Beam Tele.	STAR-PXL/ALICE-ITS	ALICE-ITS	ALICE-ITS	LHC ?