

Development of a Pixellised Ultra-Light Double-Sided Ladder for the ALICE Vertex Detector Upgrade

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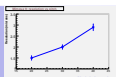
on behalf of the CMOS-ILC and ALICE teams of IPHC/Strasbourg

in contact with IRFU/Saclay

▷ more information on IPHC Web site: <http://www.iphc.cnrs.fr/-CMOS-ILC-.html>

Contents

- Major outcome of 11 years of CMOS pixel sensor R&D at IPHC:
 - ▷ Achieved performances
 - ▷ Applications under way
 - ▷ Plans → 2012/13
- Proposal for the ALICE vertex detector upgrade:
 - ▷ Objectives
 - ▷ Deliverables
 - ▷ Context
- Summary



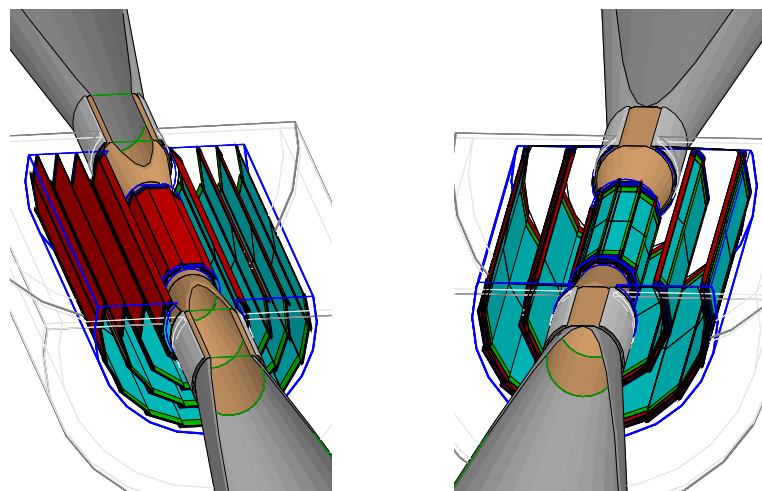
- Sensor requirements defined w.r.t. ILD VTX geometries

- ✳ 2 alternative geometries :

- ◇ 5 single-sided layers

- ◇ 3 double-sided layers (mini-vectors)

- ✳ pixel array read-out perpendicular to beam lines



- Prominent specifications :

- ✳ read-out time target values (continuous read-out version) :

SL1/SL2 /SL3 /SL4 /SL5

DL1 / DL2 / DL3

- ◇ single-sided : 25 / 50 / 100 / 100 / 100 μs

- ◇ double-sided : 25–25 / 100–100 / 100–100 μs

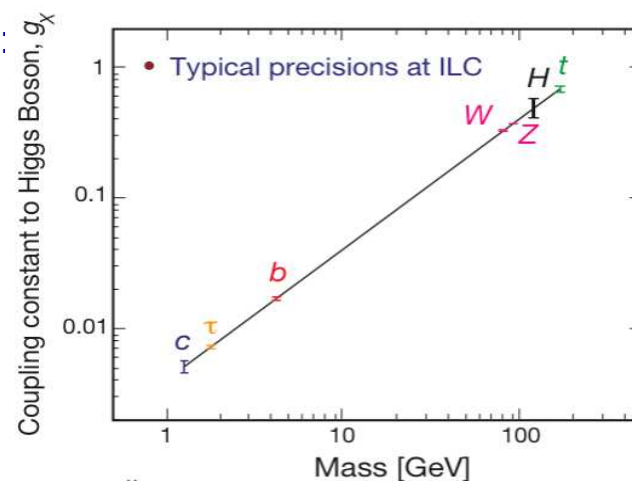
- ✳ $\sigma_{sp} < 3 \mu m$ (partly with binary outputs) \Rightarrow resolution on vertex position $\sim O(10) \mu m$

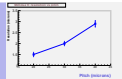
- ✳ ladder material budget in sensitive area ($\lesssim 50 \mu m$ thin sensors) :

- ◇ single-sided : $< 0.2 \% X_0$

- ◇ double-sided : $\sim 0.2 \% X_0$

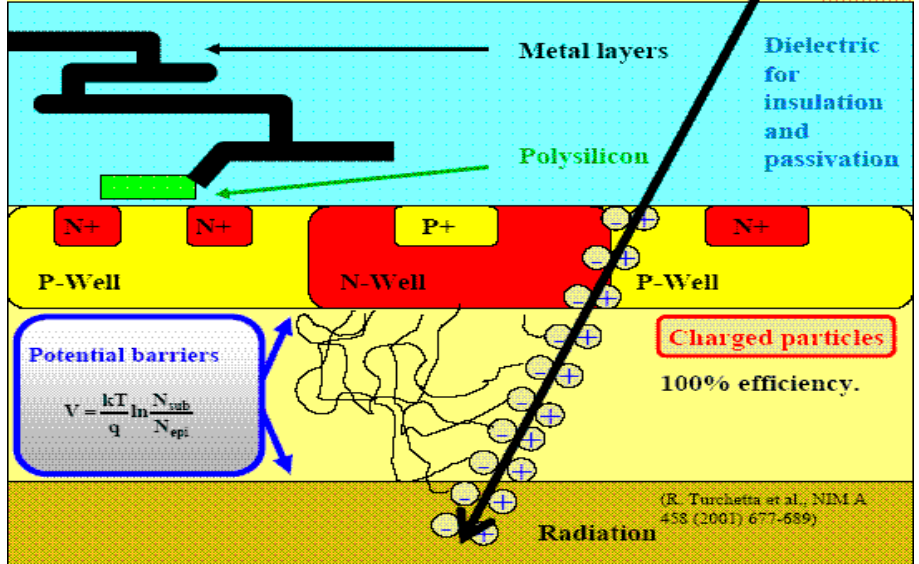
- ✳ $P_{diss} \lesssim 0.1-2 W/cm^2$





Main Features and Advantages of CMOS Sensors

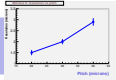
- P-type low-resistivity Si hosting n-type "charge collectors"
 - signal created in epitaxial layer (low doping):
 $Q \sim 80 \text{ e-h} / \mu\text{m} \mapsto \text{signal} \lesssim 1000 \text{ e}^-$
 - charge sensing through n-well/p-epi junction
 - excess carriers propagate (thermally) to diode with help of reflection on boundaries with p-well and substrate (high doping)



- Prominent advantages of CMOS sensors:
 - ◇ granularity: pixels of $\lesssim 10 \times 10 \mu\text{m}^2 \Rightarrow$ high spatial resolution
 - ◇ low mat. budget: sensitive volume $\sim 10 - 15 \mu\text{m} \Rightarrow$ total thickness $\lesssim 50 \mu\text{m}$
 - ◇ signal processing μ circuits integrated in the sensors \Rightarrow compacity, high data throughput, flexibility, etc.
 - ◇ other attractive aspects: cost, multi-project run frequency, T_{room} operation, etc.

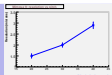
▷ ▷ ▷ Attractive balance between granularity, mat. budget, rad. tolerance, r.o. speed & power dissipation

- Limitations:
 - ✗ Very thin sensitive volume \mapsto impact on signal magnitude (mV !) \Rightarrow vey low noise FEE
 - ✗ Sensitive volume almost undepleted \Rightarrow impact on radiation tolerance & speed
 - ✗ Commercial fab. \Rightarrow fab. param. (doping profile, etc.) not optimal for charged part. detection
 - ✗ etc.

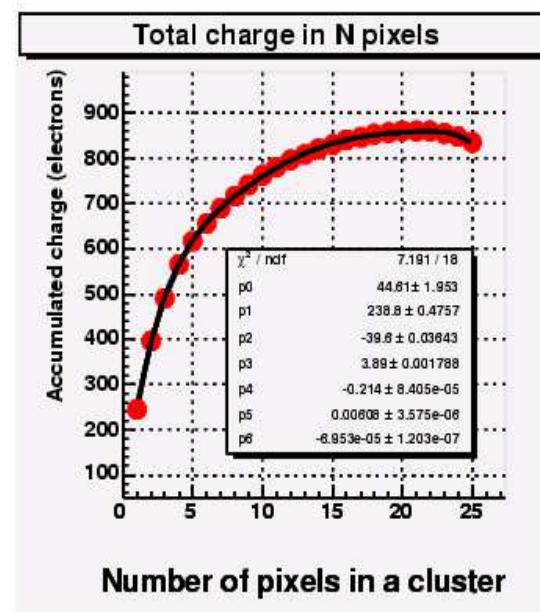
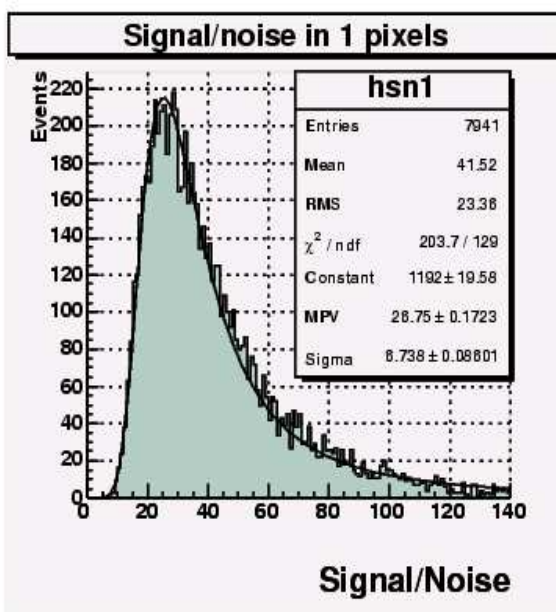
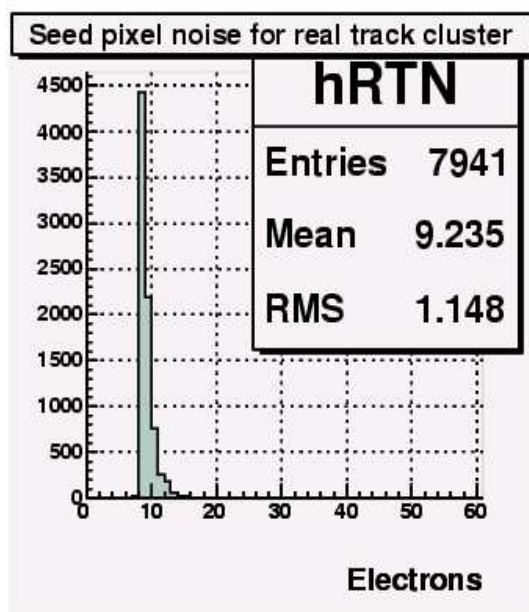


Achieved Performances

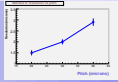
with Analog Output Sensors



- ~ 30 different prototypes designed at IPHC (some with IRFU/Saclay)
- ~ 100 chips tested on H.E. beams since 2001 at CERN & DESY, mounted on Si-strip or pixel telescope
 - \Rightarrow **well established performances (analog output):**
 - * Example of well performing technology: AMS $0.35 \mu\text{m}$ OPTO $\rightarrow \sim 14$ & $20 \mu\text{m}$ epitaxy thickness
 - * $N \sim 10 e^- \text{ ENC} \mapsto S/N \gtrsim 20 - 30$ (MPV) at room Temperature



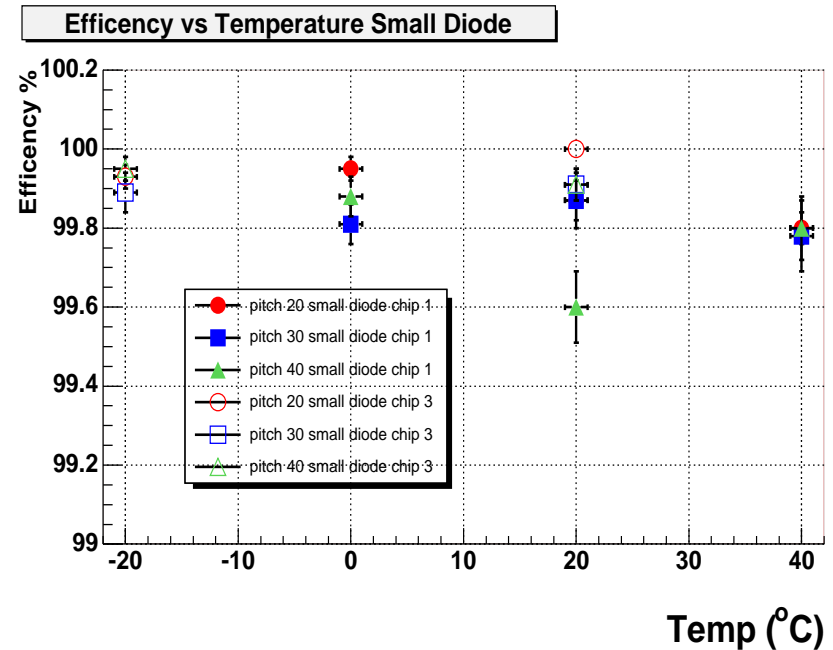
- * Macroscopic sensors : MIMOSA-5 ($\sim 1.7 \times 1.7 \text{ cm}^2$; 1 Mpix) ; MIMOSA-20 ($1 \times 2 \text{ cm}^2$; 200 kpix) ; MIMOSA-17 ($0.76 \times 0.76 \text{ cm}^2$; 65 kpix) ; MIMOSA-18 ($0.55 \times 0.55 \text{ cm}^2$; 256 kpix)



Detection Efficiency & Spatial Resolution

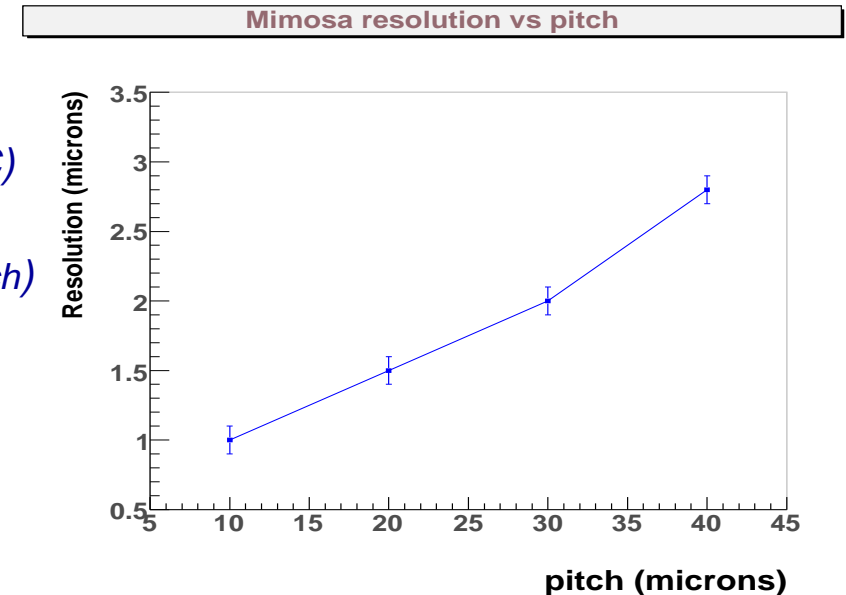
● Detection efficiency:

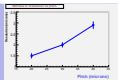
- * Ex: MIMOSA-9 data (20, 30 & 40 μm pitch)
- * $\epsilon_{det} \gtrsim 99.5\text{--}99.9\%$ repeatedly observed at room temperature (fake rate $\sim 10^{-5}$)
- * $T_{oper.} \gtrsim 40^\circ\text{C}$



● Single point resolution versus pixel pitch:

- * clusters reconstructed with eta-function, exploiting charge sharing between pixels (12-bit ADC)
- * $\sigma_{sp} \sim 1 \mu\text{m}$ (10 μm pitch) $\rightarrow \lesssim 3 \mu\text{m}$ (40 μm pitch)
- * 4-bit ADC simul. $\Rightarrow \sigma_{sp} \lesssim 2 \mu\text{m}$ (20 μm pitch)
- * measured binary output resolution (MIMOSA-16, -22):
 $\sigma_{sp} \gtrsim 3.5$ & $4.5 \mu\text{m}$ (18.4 & 25 μm pitch)





Radiation Tolerance: Condensed Summary

● Ionising radiation tolerance (chips irradiated with 10 keV X-Rays) :

✳ Pixels modified against hole accumulations (thick oxide) and leakage current increase (guard ring)

✳ MIMOSA-15 tested with $\sim 5 \text{ GeV } e^-$ at DESY after 10 kGy exposure : Preliminary results

- $T = -20^\circ\text{C}$, $t_{r.o.} \sim 180 \mu\text{s}$
- $t_{r.o.} \ll 1\text{ms}$ crucial at T_{room}

Integ. Dose	Noise	S/N (MPV)	Detection Efficiency
0	9.0 ± 1.1	27.8 ± 0.5	100 %
1 MRad	10.7 ± 0.9	19.5 ± 0.2	$99.96 \pm 0.04 \%$

● Non-ionising radiation tolerance (chips irradiated with O(1 MeV) neutrons):

✳ MIMOSA-15 (20 μm pitch) tested on DESY e^- beams : Preliminary results

- $T = -20^\circ\text{C}$, $t_{r.o.} \sim 700 \mu\text{s}$
- $5.8 \cdot 10^{12} \text{ n}_{eq}/\text{cm}^2$ values with **standard** & **soft** cuts

Fluence ($10^{12} \text{ n}_{eq}/\text{cm}^2$)	0	0.47	2.1	5.8 (5/2)	5.8 (4/2)
S/N (MPV)	27.8 ± 0.5	21.8 ± 0.5	14.7 ± 0.3	$8.7 \pm 2.$	$7.5 \pm 2.$
Det. Efficiency (%)	100.	99.9 ± 0.1	99.3 ± 0.2	$77. \pm 2$	$84. \pm 2.$

✳ MIMOSA-18 (10 μm pitch) tested at CERN-SPS (120 GeV π^- beam) : Preliminary results

- $T = -20^\circ\text{C}$, $t_{r.o.} \sim 3 \text{ ms}$

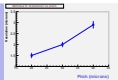
○ parasitic 1–2 kGy γ gas \Rightarrow N ↗

Fluence ($\text{ n}_{eq}/\text{cm}^2$)	0	$6 \cdot 10^{12}$	$1 \cdot 10^{13}$
$Q_{clust} (e^-)$	1026	680	560
S/N (MPV)	28.5 ± 0.2	20.4 ± 0.2	14.7 ± 0.2
Det. Efficiency (%)	99.93 ± 0.03	99.85 ± 0.05	99.5 ± 0.1

● Conclusion :

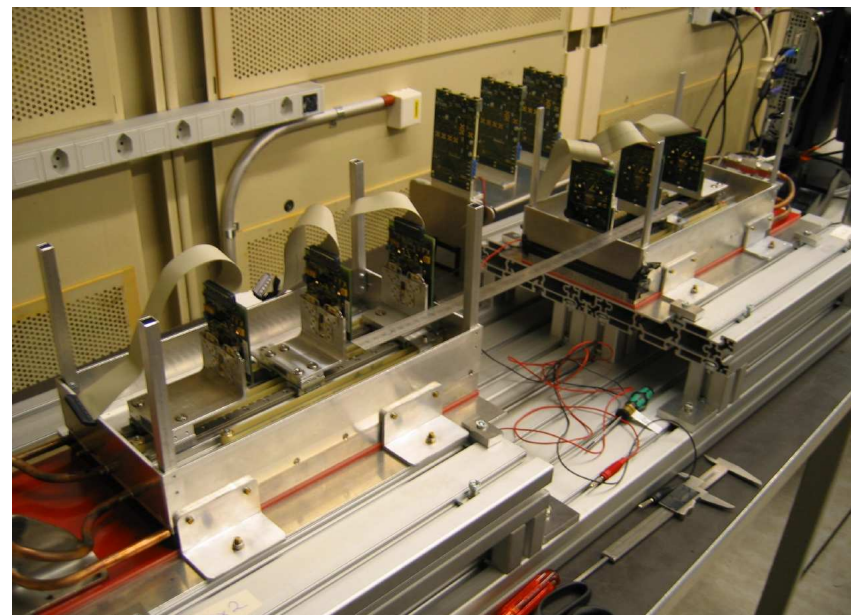
✳ observed ionising radiation tolerance: O(10 kGy)

✳ observed non-ionising rad. tol.: $> 1 \cdot 10^{13} \text{ n}_{eq}/\text{cm}^2$ (10 μm pitch) & $2 \cdot 10^{12} \text{ n}_{eq}/\text{cm}^2$ (20 μm pitch)



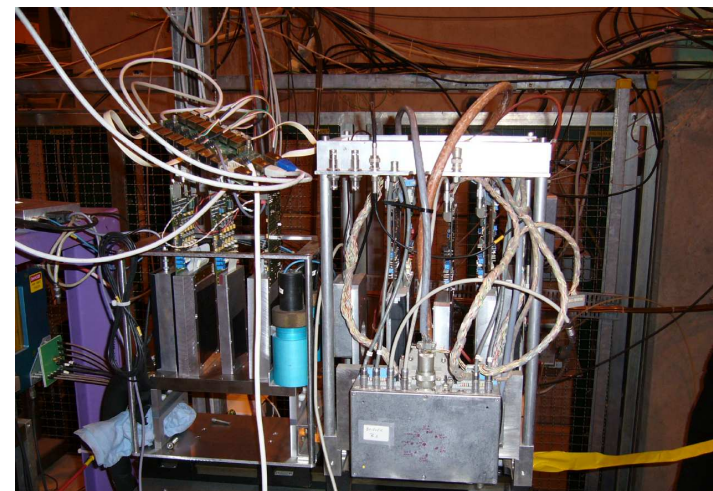
- Beam telescope of the FP6 project EUDET

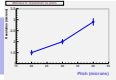
- * 2 arms of 3 planes (plus 1 high resolution plane)
- * $\sigma_{extrapol.} \lesssim 1 \mu m$ EVEN with e^- (3 GeV, DESY)
- * frame read-out frequency $O(10^2)$ Hz
- * running since '07 CERN-SPS & DESY (numerous users)
- * evolution towards 10^4 frames/s in 2009, using binary output sensors (see later)



- Several other applications :

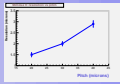
- * MIMOSA sensor R&D : Pixel telescope of Strasbourg (TAPI) \rightarrow
- * STAR (RHIC) : telescope (3 MIMOSA-14) inside apparatus (2007)
 \rightarrow background measurement, no pick-up !
- * CBM (FAIR) : MVD demonstrator (double-sided layers) to be used for high precision tracking in HADES (GSI) \sim 2010
- * Spin-offs : beta imaging, hybrid photo-detector, dosimetre, ...





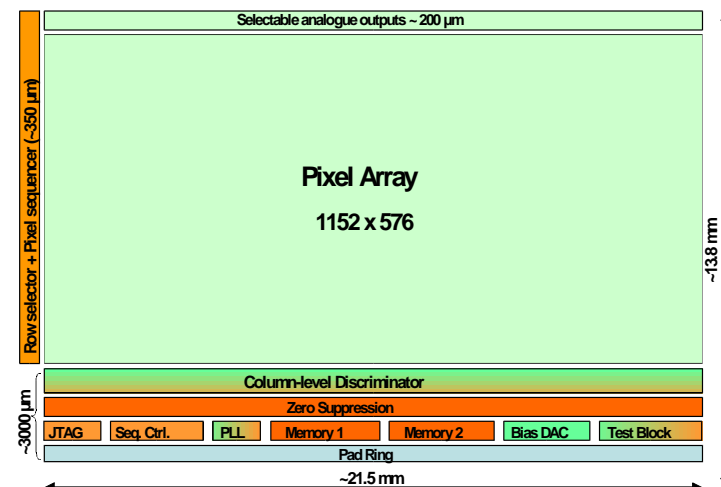
Improving the Read-Out Speed

with Digital Output Sensors



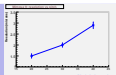
- TC \equiv 1st sensor with integrated zero-suppression

- * MIMOSA-22 (binary outputs) combined with \emptyset (SUZE-01)
- * Active area: 1152 columns of 576 pixels ($21.2 \times 10.6 \text{ mm}^2$)
- * Pitch: $18.4 \mu\text{m} \rightarrow \sim 0.7$ million pixels $\Rightarrow \sigma_{sp} \gtrsim 3.5 \mu\text{m}$
- * $T_{r.o.} \lesssim 110 \mu\text{s} \rightarrow \sim 10^4$ frames/s
 \Rightarrow suited to $> 10^6$ particles/cm²/s
- * \emptyset in 18 groups of 64 col. allowing ≤ 9 "pixel strings" / raw
- * Sensor full dimensions : $\sim 22 \times 14 \text{ mm}^2$
- * Data transmission: 1 output at $\geq 160 \text{ Mbits/s}$ or 2 outputs at $\geq 80 \text{ Mbits/s}$



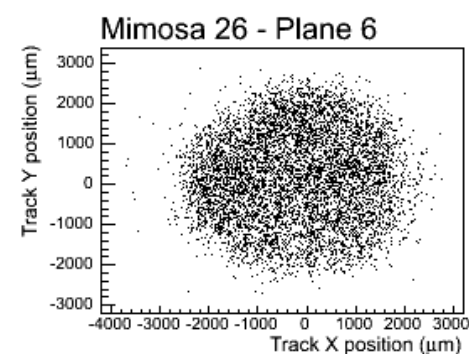
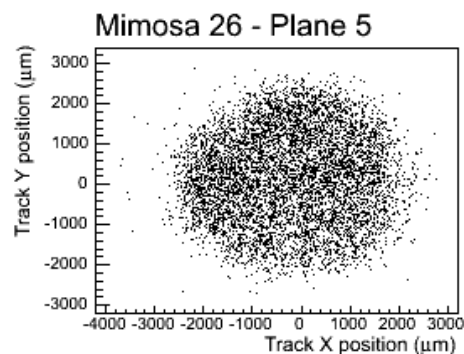
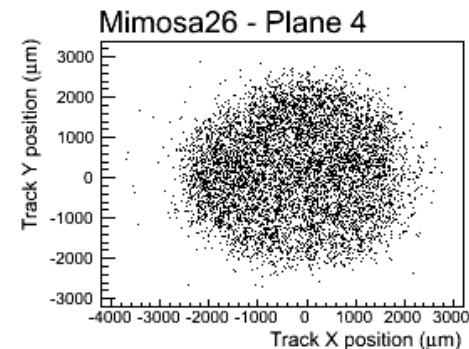
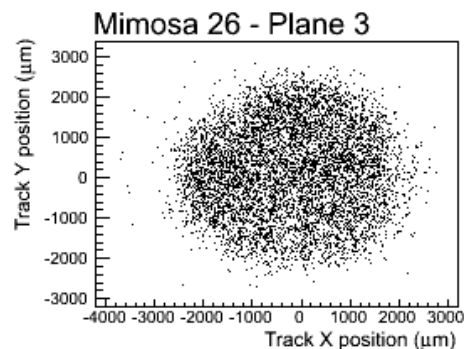
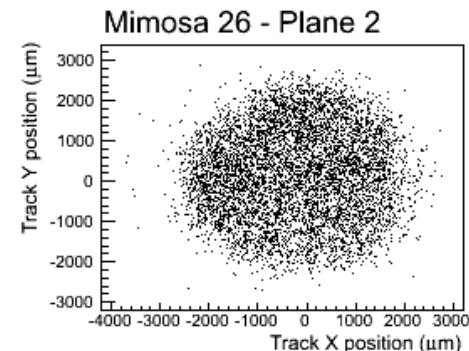
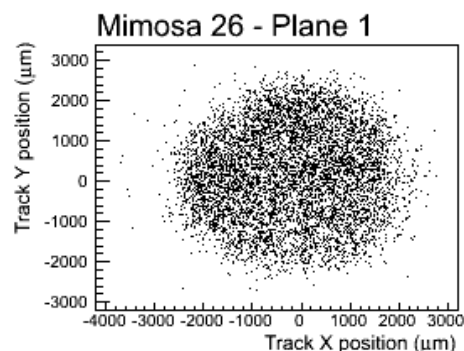
- Fabricated in $0.35 \mu\text{m}$ "Opto" technology:

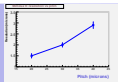
- * Equips the final version of EUDET Beam Telescope (EU-FP6 project)
- * Architecture is baseline for STAR, CBM and ILC vertex detectors
- * Sensor still being characterised \Rightarrow test results are **Preliminary**



- **6 sensors used:**
 - ✧ some thinned to $120 \mu m$
 - ✧ assembled in telescope configuration
 - ✧ for minimum ionising particle detection performance evaluation

- **CRN-SPS (T4-H6)**
 - ✧ $\gtrsim 120 \text{ GeV } \pi^-$ beam
 - ✧ 10 days of run in Sept. 2009
 - ✧ 3×10^6 triggers collected, out of which $\sim 80 \%$ events reconstructed





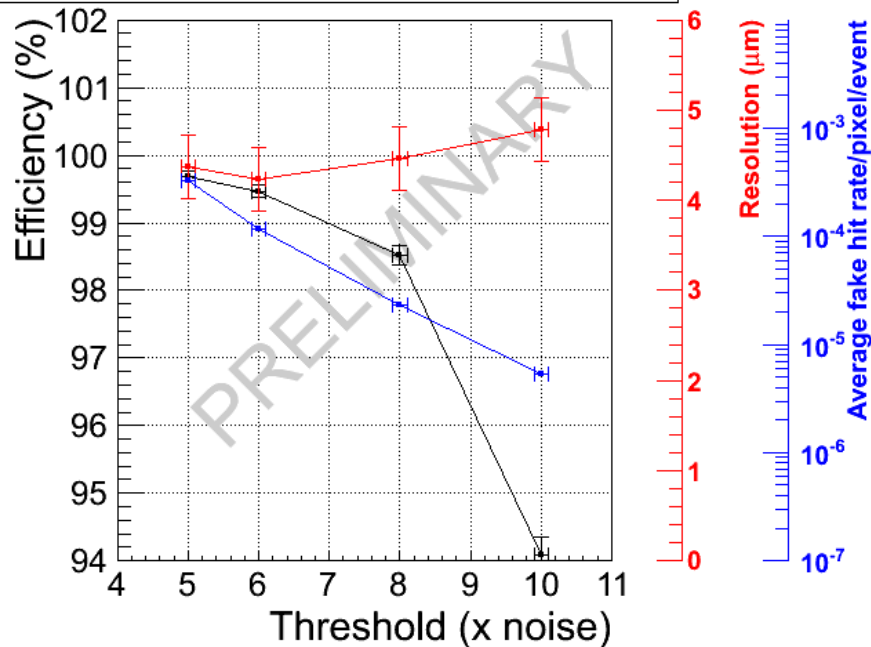
- TC sensors quite extensively characterised by now (quantitative results still preliminary):

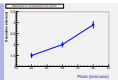
- * TC operating with $\gtrsim 99.5\%$ detection efficiency over the whole sensitive area, with a fake rate $\lesssim O(10^{-4})$
- * Optimal discrim. threshold $\sim 5\text{--}6 \times$ Noise value
- * $\sigma_{sp}^{TC} \lesssim 4.5 \pm 0.2 \mu m$ (preliminary)
 \hookrightarrow room for improvement towards $\sigma_{sp}^{TC} \lesssim 4 \mu m$

- Conclusion:

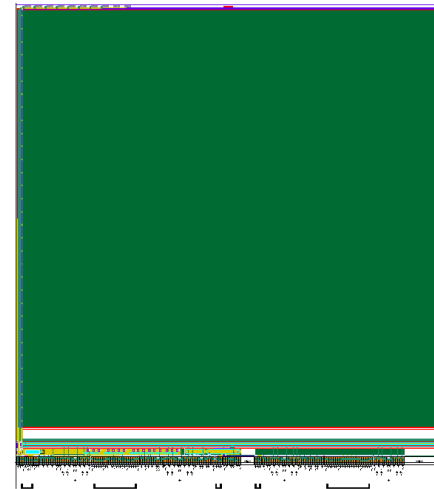
- * TC operational for the final EUDET BT ✓
- * TC architecture validated for devt of application specific sensors:
 - ▷ STAR-PIXEL, CBM-MVD, ILD-VTX, ...

MIMOSA 26 (chip 1) unthinned, vref2=98, 80 MHz



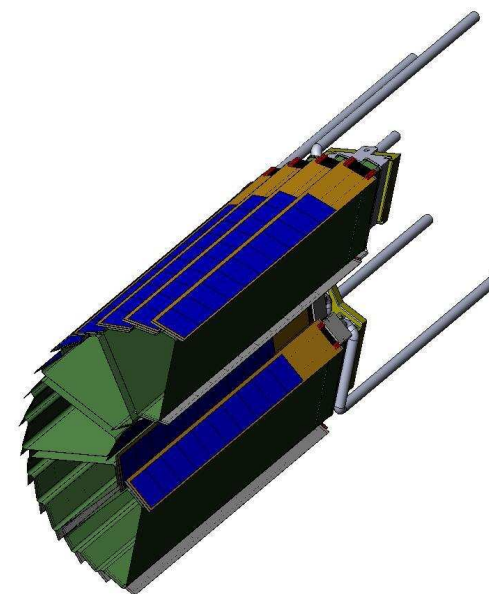


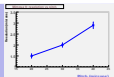
- **1st generation sensor for the HFT-PIXEL of STAR (PHASE-1):**
 - ✧ **full scale extension of MIMOSA-22 (no \emptyset)**
 - ✧ *640x640 pixels (30 μm pitch) \Rightarrow active surface: 19.2 x 19.2 mm²*
 - ✧ *integration time : 640 μs*
 - ✧ *designed and fabricated in 2008 \rightarrow currently under production test at LBNL*
 - ✧ *3 + 9 ladders to equip with 10 sensors thinned to 50 μm (1/4 of PIXEL)*
 - ✧ *1st physics data expected in 2011*



- **Final HFT-PIXEL sensor :**

- ✧ **MIMOSA-26 with active area $\times 1.8$**
& improved rad. tolerance
 - \hookrightarrow 1088 col. of 10^3 pixels (20 x 18.5 mm²)
- ✧ **Pitch : 18.4 μm \rightarrow \sim 1.1 million pixels**
- ✧ **Integration time \lesssim 200 μs**
- ✧ *Design in 2009 \rightarrow fab. Q1 (2010)*
 - \rightarrow *1st physics data expected in 2012/13*



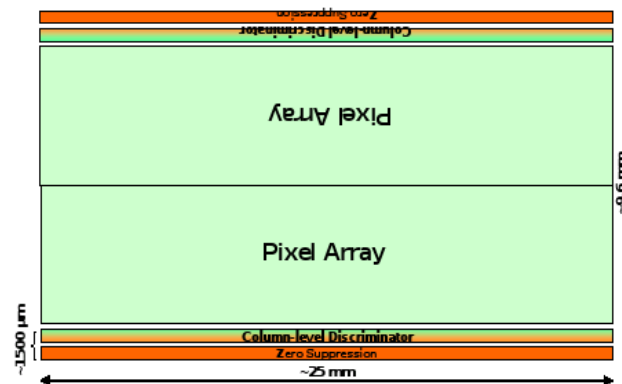


From TC to Faster Devices

- Move from $0.35 \mu m$ to feature size $\leq 0.18 \mu m$
 \Rightarrow improved clock frequency, more metal layers, more compact peripheral circuitry, etc.

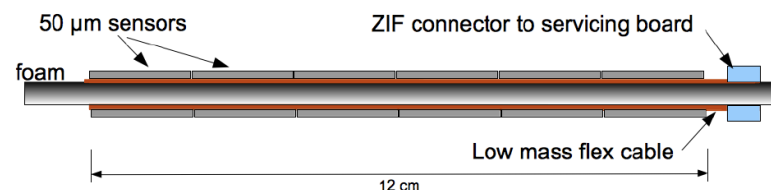
- ILD VTX inner layers ($t_{int} \sim 25 - 50 \mu s$):

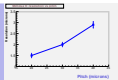
- * double-sided r.o. \Rightarrow twice shorter (= faster) columns
- * pitch $\lesssim 15 \mu m$
- * binary r.o. $\Rightarrow \sigma_{sp} \lesssim 3 \mu m$



- Implement elongated pixels on one side of double-ladder:

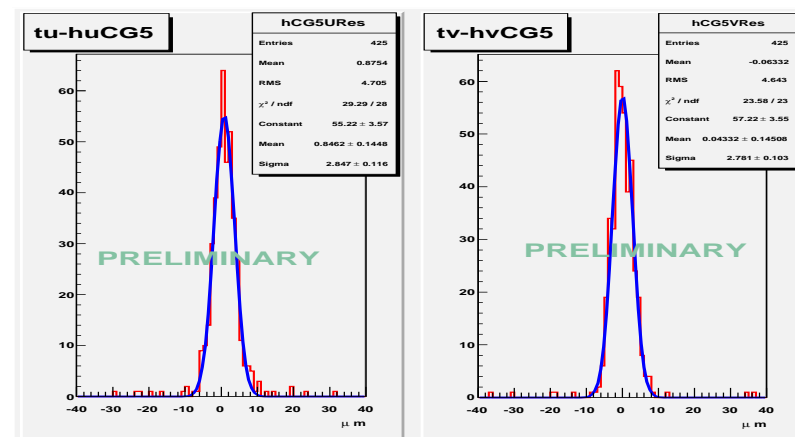
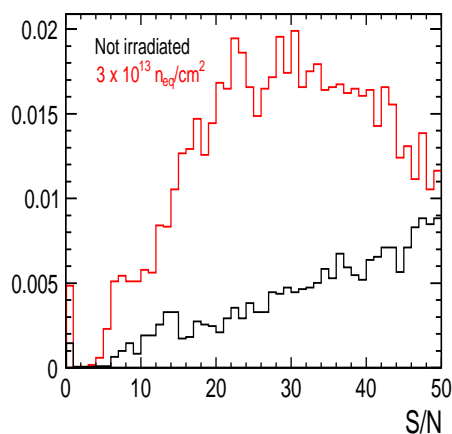
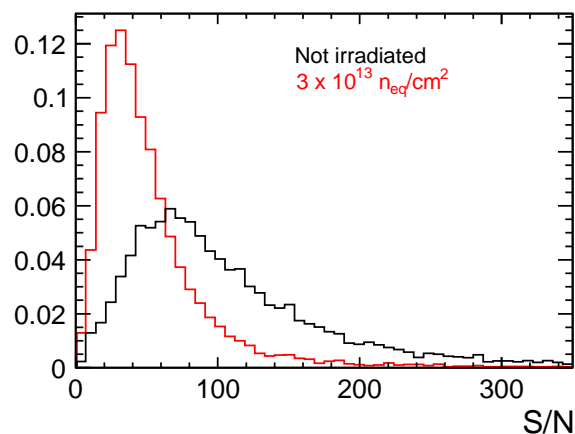
- * pixel pitch of $\sim 14 \times 50-80 \mu m$
- * reduced nb of pixels per column
 \Rightarrow shorter read-out (goal: factor 4-6)
- * depleted epitaxial layer
 \Rightarrow wider sensing diode spacing (next slide)
 $\hookrightarrow \lesssim 10 \mu s$ may be reachable





High Resistivity Sensitive Volume

- Advantages of depleted epitaxial layer:
 - * faster charge collection ($< 10 \text{ ns}$) \Rightarrow faster frame read-out frequency possible
 - * shorter minority charge carrier path length \Rightarrow improved tolerance to non-ionising radiation
- Exploration of $0.6 \mu\text{m}$ techno: $\sim 15 \mu\text{m}$ thick epitaxy ; $V_{dd} \leq 5 \text{ V}$; $\rho \sim O(10^3) \Omega \cdot \text{cm}$
 - * MIMOSA-25: fabricated in 2008 & tested at CERN-SPS before/after $O(1 \text{ MeV})$ neutron irradiation

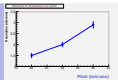


- Effect of $3 \cdot 10^{13} n_{eq}/\text{cm}^2$ at room temperature:

* SNR(MPV): $\sim 60 \searrow \sim 30 \triangleright \epsilon_{det}: 99.9\% \searrow 99.5\%$ at T_{room} with $20 \mu\text{m}$ pitch & $80 \mu\text{s}$ r.o. time
 \Rightarrow thin depleted epitaxy approach validated for $\gtrsim 10^{14} n_{eq}/\text{cm}^2 \triangleright 0.35 \mu\text{m}$ version available soon

$$(\sigma_{sp} \sim 2.5 \pm 0.2 \mu\text{m})$$

- Exploration of a new VDSM techno. with depleted substrate : project LePIX (see talk of W.Snoeys)
 - \triangleright aim for very short integration time

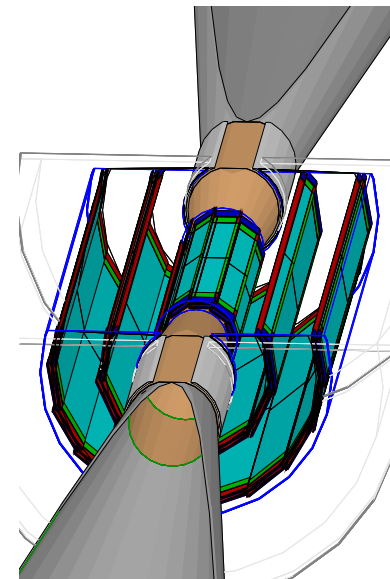


- **PLUME project**

≡ Pixelised Ladder using Ultra-light Material Embedding

- **Objectives :**

- * achieve a double-sided ladder prototype for an ILC vertex detector by 2012
- * evaluate benefits of 2-sided concept (mini-vectors) :
 σ_{sp} , alignment, shallow angle pointing, elongated vs square pixels

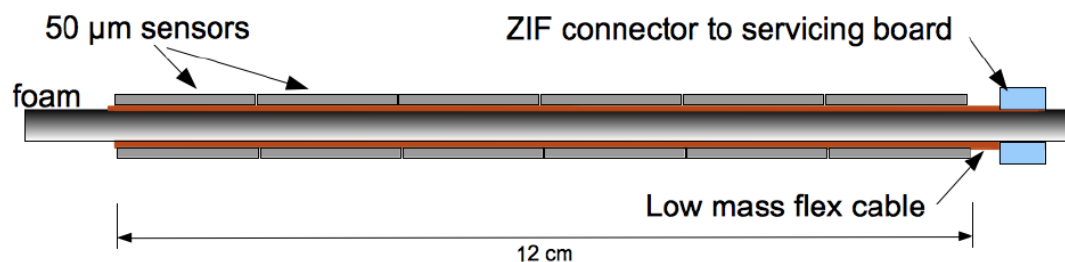


- **Collaboration:**

- * Bristol - DESY - Oxford - Strasbourg
- * Synergy with Vertex Detector of CBM/FAIR

- **Perspective:**

- * to be studied with infrastructure foreseen in FP-7 project AIDA (proposal in preparation)
- * interest for (s)LHC experiments ?





- **HP-2 project** ▷ **WP-26 (ULISI)** ≡ **SEnsor Row Wrapped In Extra-Thin film (SERWIET)**

- **Objectives :**

- ✧ achieve a sensor assembly mounted on flex and wrapped in polymerised film with $< 0.1 \% X_0$ in total
- ✧ evaluate possibility of mounting supportless ladder on cylindrical surface (serving as mechanical support)
- ✧ proof of principle expected in 2012

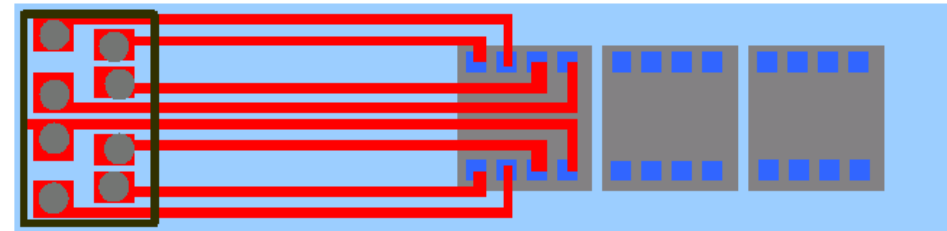
Proto 1 ▷ Spring 2010



- **Working programme:**

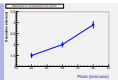
- ✧ prototype Nr. 1 (2010) made of 1 sensor :
MIMOSA-18 (analog output, $\lesssim 4$ ms)
- ✧ prototype Nr. 2 (2011) made of 3 sensors :
TC (digital output, $\lesssim 110 \mu s$)

Proto 2 ▷ Summer 2011



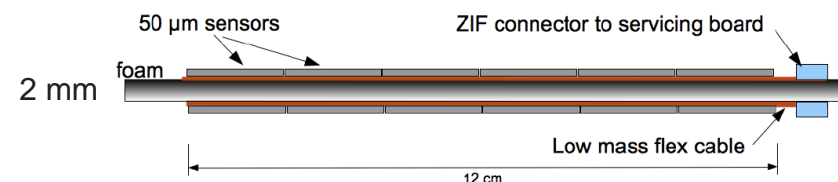
- **Context of development:**

- ✧ Collaboration with IKF-Frankfurt and GSI/Darmstadt (CBM coll.)
- ✧ **Synergy with Vertex Detector R&D for CBM, ILC, etc.**



■ Improve capability of displaced vertex reconstruction for charm tagging :

- Equip free space left by vacuum tube replacement with 1 or 2 double-sided high precision pixellised ladders (and envisage equipping beam pipe ???)

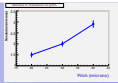


- Ambitionned performances:

- ✧ thin pixel sensors ($50 \mu m$) offering a single point resolution $< 5 \mu m$
- ✧ ladder with complete material budget $\sim 0.2-0.3 \% X_0$
- ✧ 2 contiguous impacts per particle detected \Rightarrow several benefits for detection performances:
 - ◇ resolution (impact param.)
 - ◇ track reconstruction
 - ◇ alignment (crucial !)

■ Context : R&D on-going at IPHC-Strasbourg

- Devt of thin, high resolution, CMOS pixel sensors for STAR & CBM (since 2000 & 2003)
 - \Rightarrow design of sensor architecture \sim mature (sensor operational on EUDET/FP-6 telescope)
- Devt of ultra-light ladders for CBM, ILC, etc. (since 2008) \rightarrow WP-26 (HP-2)
 - \Rightarrow several approaches investigated \rightarrow prototyping finalised \sim 2012/13
- First data collected with STAR-PIXEL (open charm) in 2012/13
 - \Rightarrow single-sided ladders: $\sigma_{sp} \lesssim 4 \mu m$, material budget $\sim 0.3 \% X_0$

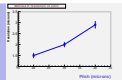


■ CMOS pixel sensors :

- Ambitionned performances (room T):
 - * $\sigma < 5 \mu m$ ✓
 - * thickness $\lesssim 50 \mu m$ ✓
 - * $t_{ro} \sim 10-20 \mu s$
 - * 1 MRad & $10^{14} n_{eq}/cm^2$
 - \Rightarrow on-going R&D on t_{ro} ($< 50 \mu s$) & rad. tolerance (> 300 kRad & $> 10^{13} n_{eq}/cm^2$)
- 3 sensor generations under development:
 - * 2D with undepleted sensitive volume $\rightarrow t_{ro} \sim 10-20 \mu s$ & 1 MRad (2011/12)
 - * 2D with depleted sensitive volume (elongated pixels) \rightarrow 1 MRad & $10^{14} n_{eq}/cm^2$ (2013)
 - * 3D with depleted sensitive volume $\rightarrow t_{ro} \lesssim 5 \mu s$ (2015)

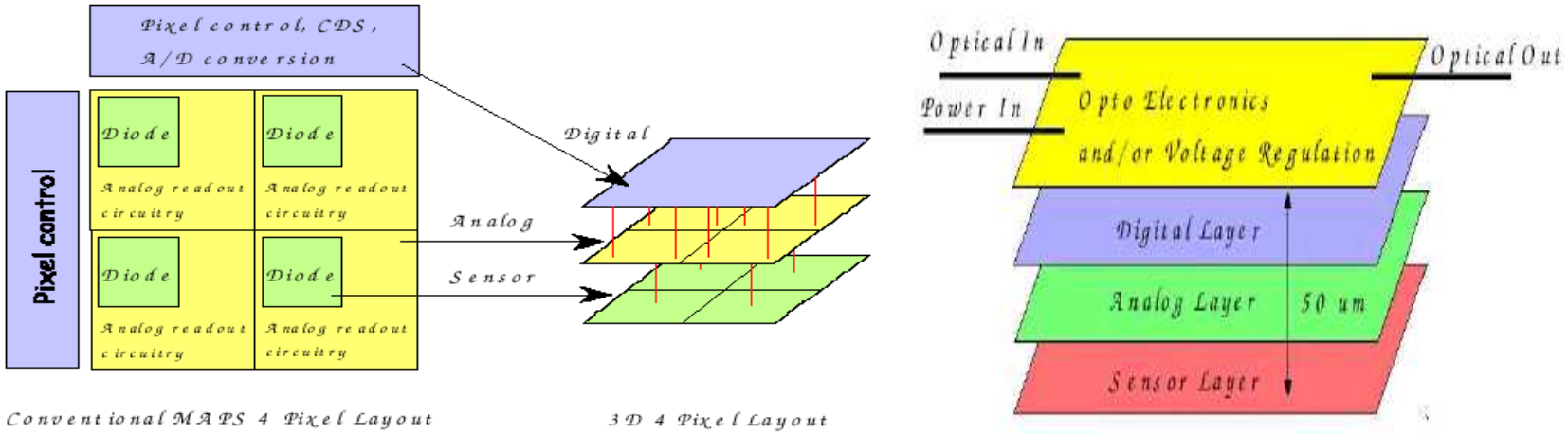
■ Ladder developed along 2 parallel approaches:

- Classical : sensors \oplus flex cable \oplus SiC foam \oplus flex cable \oplus sensors
 - $\Rightarrow \lesssim 0.3 \% X_0$ for the whole 2-sided ladder
- Innovating : sensors ($35 \mu m$) wrapped in polymerised film ($< 10 \mu m$)
 - $\Rightarrow \lesssim 0.1 \% X_0$ for 1 unsupported layer (sensors \oplus flex cable \oplus film)
 - \hookrightarrow adaptable to various mechanical supports \rightarrow beam pipe ?

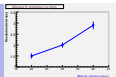


Using 3DIT to Improve CMOS Sensor Performances

- **3D Integration Techno.** allow integrating high density signal processing μ circuits inside small pixels by stacking ($\sim 10 \mu m$) thin tiers interconnected at pixel level
- **3DIT are expected to be particularly beneficial for CMOS sensors :**
 - ✧ combine different fab. processes \Rightarrow chose best one for each tier/functionnality
 - ✧ alleviate constraints on peripheral circuitry and on transistor type inside pixel, etc.
- **Split signal collection and processing fonctionnalities :**
 - ✧ *Tier-1: charge sensing*
 - ✧ *Tier-2: analog-mixed μ circuits*
 - ✧ *Tier-3: digital μ circuits*



- **First chips fabricated in 2009 within 3DIC Consortium (2-Tier 130 nm technology):**
 - ✧ 1 chip with sensitive area subdivided in "small" matrices running INDIVIDUALLY in fast rolling shutter mode \Rightarrow few μs r.o. time may be reached (?)
 - ✧ 1 chip aiming to combine 2-Tier read-out chip with sensing chip featuring DEPLETED epitaxial layer



- **Proposal: investigate possibility of translating ultra-light pixellised ladders developed for CBM & ILC to the specifications of the ALICE vertex detector upgrade, relying on 2 basic components:**
 - ✧ thin, depleted, CMOS pixel sensors (baseline 2D, potentially 3D)
 - ✧ ultra-light double-sided ladder complemented with potential pixelised beam pipe
- **CMOS pixel sensors developed for EUDET, STAR, CBM, ILC:**
 - ✧ offer necessary single point resolution and material budget for very high precision vertexing
 - ✧ have reached required maturity to be used in large (heavy ion) experiments (e.g. STAR-HFT)
 - ⇒ may be relevant for ALICE vertex detector upgrade > 2015: barrel & forward (CBM-MVD)
- **Ultra-light ladders developed for CBM & ILC:**
 - ✧ double-sided ladder with $\lesssim 0.3\% X_0$, expected to provide excellent pointing accuracy: impact parameter resolution even at shallow angle, track link with faster detectors, ...
 - ✧ supportless ladder expected to offer $< 0.1\% X_0$ \rightarrow explore possibility to equip beam pipe ?
- **Synergetic context to exploit:**
 - ✧ CMOS sensor development with IRFU/Saclay
 - ✧ ladder development within HP-2 (Frankfurt, GSI), PLUME collaboration (ILC teams)
 - ✧ perspective: AIDA FP-7 proposal (study of high precision vertex detector alignment issues)