Development of a Pixelated Ultra-Light Double-Sided Ladder for Future Vertex Detectors

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on behalf of the CMOS-ILC team of IPHC/Strasbourg

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

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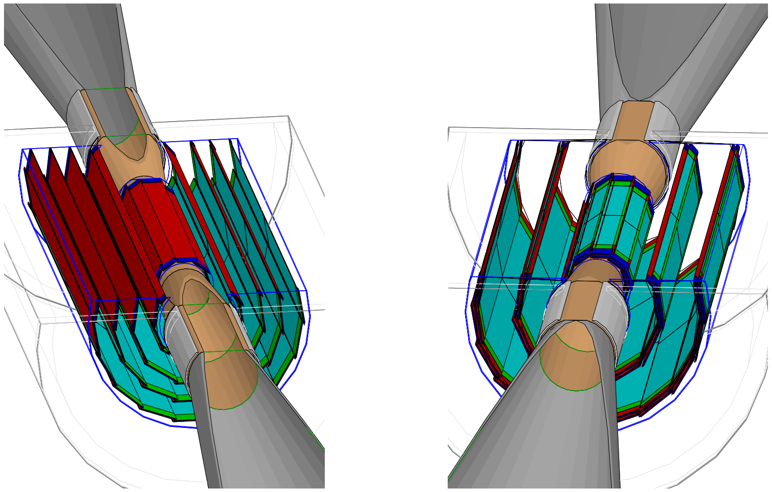
Context of R&D: ILC Vertex Detector

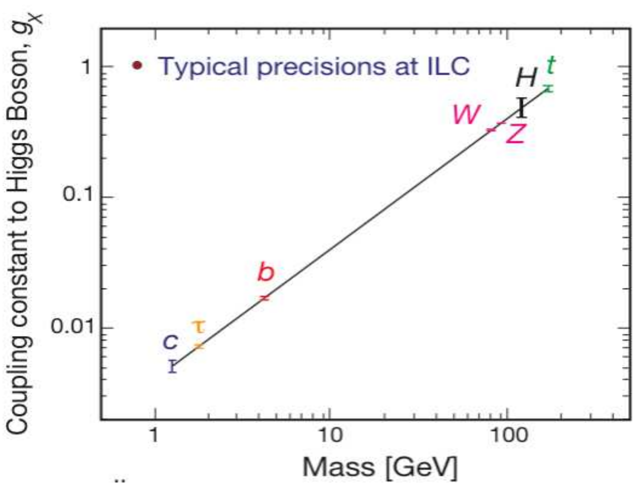


- **Sensor requirements defined w.r.t. ILD VTX geometries**
  - ⋇ 2 alternative geometries :
    - ◇ 5 single-sided layers
    - ◇ 3 double-sided layers (mini-vectors)
  - ⋇ pixel array read-out perpendicular to beam lines

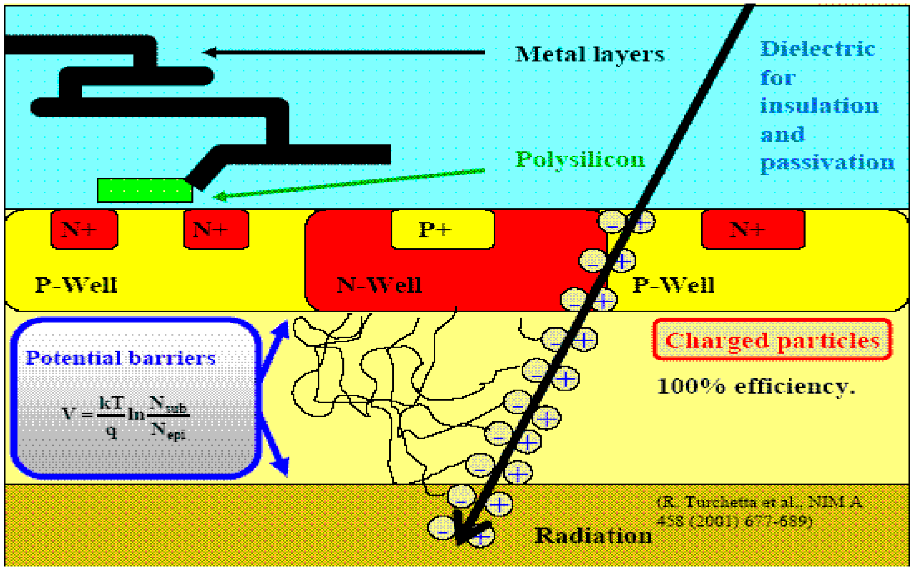
- **Prominent specifications :**
  - ⋇ read-out time target values (continuous read-out version) :

    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) $\Rrightarrow$ resolution on vertex position $\sim$ O(10) μm
  - ⋇ ladder material budget in sensitive area ($\lesssim$ 50 μm thin sensors) :
    - ◇ single-sided : < 0.2 % X_0
    - ◇ double-sided : ~ 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 e-h / $\mu m \mapsto$ signal $\lesssim$ 1000 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 $\lesssim 10 \times 10\ \mu m^2 \Rightarrow$ high spatial resolution**
  - ◇ **low mat. budget: sensitive volume $\sim$ 10 - 15 $\mu m \Rightarrow$ total thickness $\lesssim$ 50 μm**
  - ◇ **signal processing μcircuits 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 $\longrightarrow$ 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

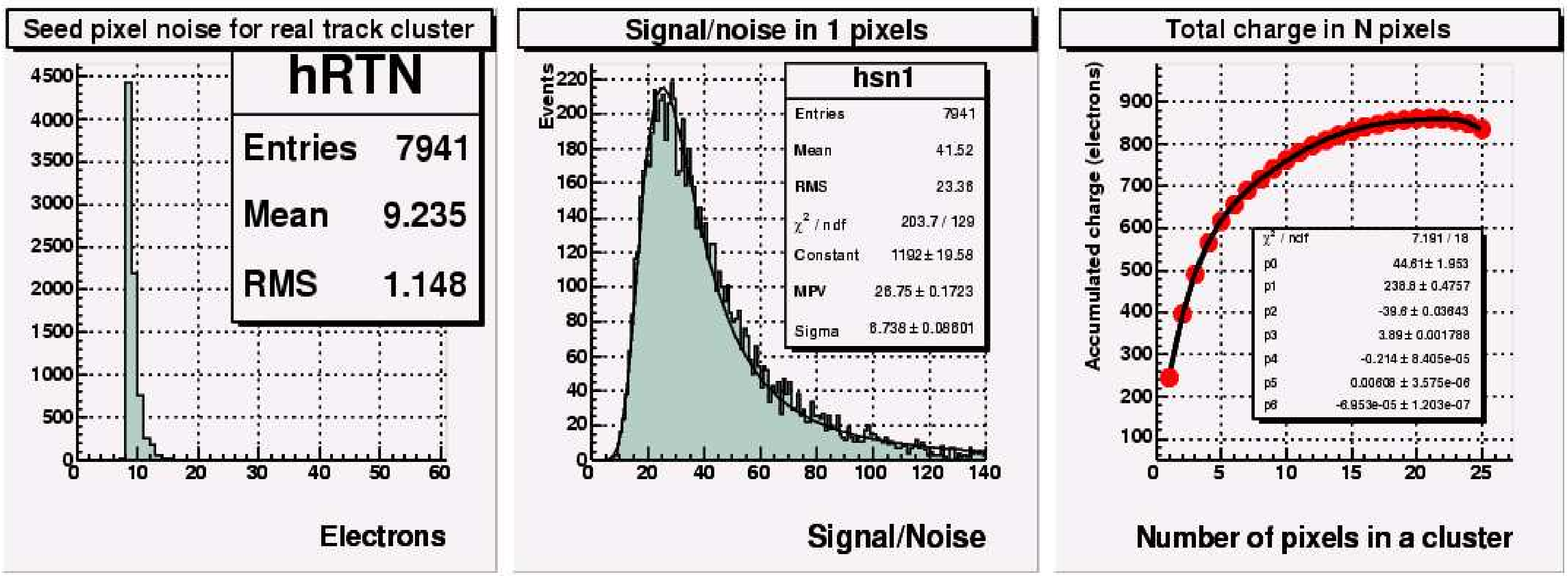
with Analog Output Sensors

- $\sim$ 30 different prototypes designed at IPHC (some with IRFU/Saclay)
- $\sim$ 100 chips tested on H.E. beams since 2001 at CERN & DESY, mounted on Si-strip or pixel telescope

  $\Rrightarrow$ **well established performances (analog output):**

※ Example of well performing technology: AMS 0.35 μm OPTO $\rightarrowtail$ $\sim$ 14 & 20 μm epitaxy thickness

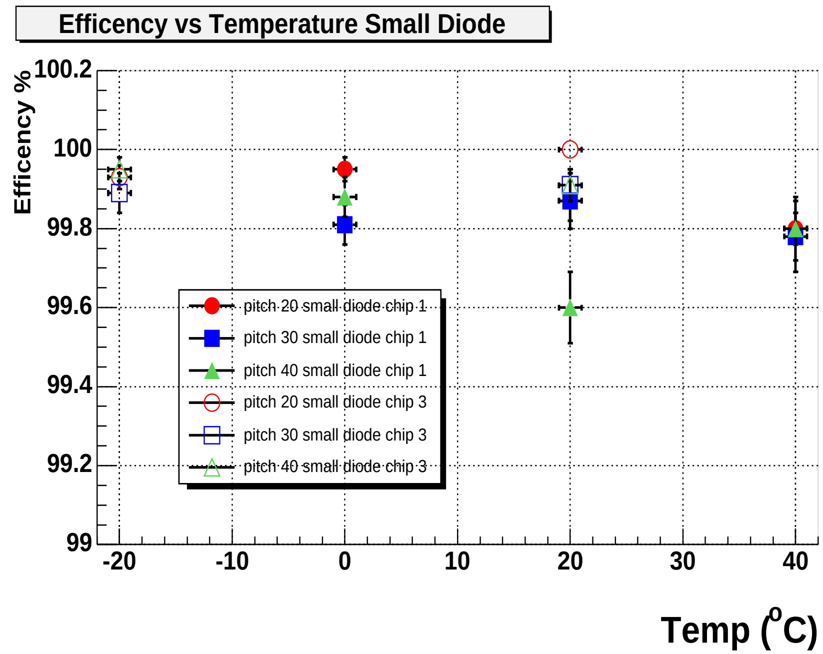
※ N $\sim$ 10 e^{-} ENC $\mapsto$ S/N $\gtrsim$ 20 – 30 (MPV) at room Temperature



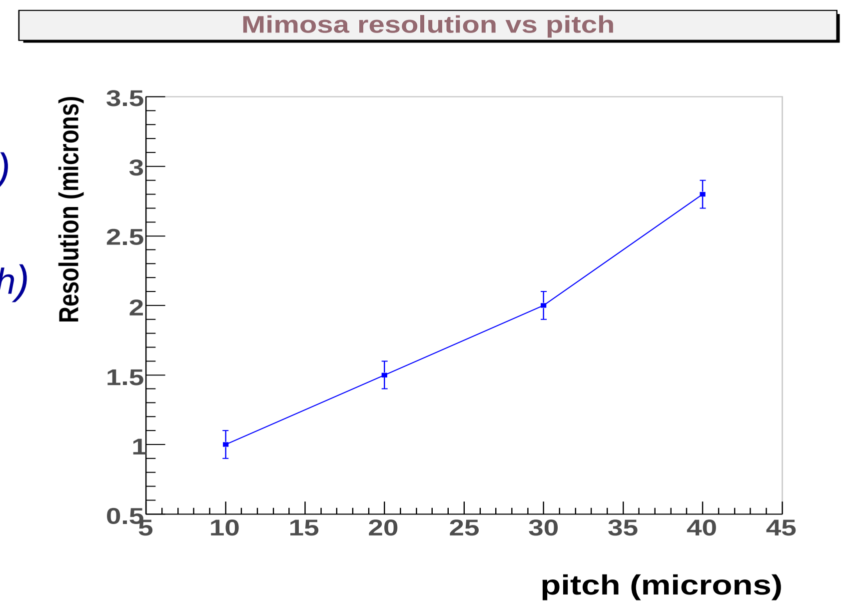
※ Macroscopic sensors : MIMOSA-5 ($\sim$ 1.7x1.7 cm^2; 1 Mpix) ; MIMOSA-20 (1x2 cm^2; 200 kpix) ;
MIMOSA-17 (0.76x0.76 cm^2; 65 kpix) ; MIMOSA-18 (0.55x0.55 cm^2; 256 kpix)

Detection Efficiency & Spatial Resolution

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



- **Single point resolution versus pixel pitch:**
  - ※ *clusters reconstructed with eta-function, exploiting charge sharing between pixels (12-bit ADC)*
  - ※ $\sigma_{\mathbf{sp}} \sim \mathbf{1}\ \mu\mathbf{m}$ *(10 μm pitch)* $\rightarrowtail \lesssim \mathbf{3}\ \mu\mathbf{m}$ *(40 μm pitch)*
  - ※ *4-bit ADC simul.* $\Rrightarrow \sigma_{\mathbf{sp}} \lesssim \mathbf{2}\ \mu\mathbf{m}$ *(20 μm pitch)*
  - ※ *measured binary output resolution (MIMOSA-16, -22):* $\sigma_{\mathbf{sp}} \gtrsim$ *3.5 & 4.5 μm (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 GeV e^- at DESY after 10 kGy exposure : Preliminary results**
    - T = - 20°C, $t_{r.o.}$ $\sim$ 180 μs
    - $t_{r.o.}$ $<<$ 1ms crucial at T_{room}

Integ. Dose	Noise	S/N (MPV)	Detection Efficiency
0	9.0 $\pm$ 1.1	27.8 $\pm$ 0.5	100 %
1 MRad	10.7 $\pm$ 0.9	19.5 $\pm$ 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°C, $t_{r.o.}$ $\sim$ 700μs
    - ○ 5.8·10^{12} n_{eq}/cm^2 values with standard & soft cuts

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

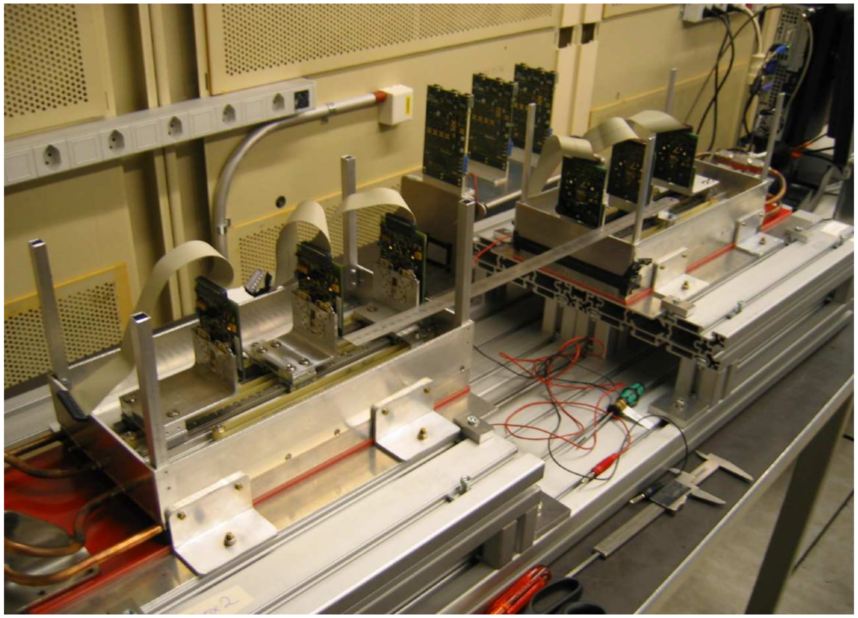
  - ⁂ **MIMOSA-18 (10 μm pitch) tested at CERN-SPS (120 GeV π^- beam) : Preliminary results**
    - T = - 20°C, $t_{r.o.}$ $\sim$ 3 ms
    - ○ parasitic 1–2 kGy γ gas $\Rrightarrow$ N $\nearrow$

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

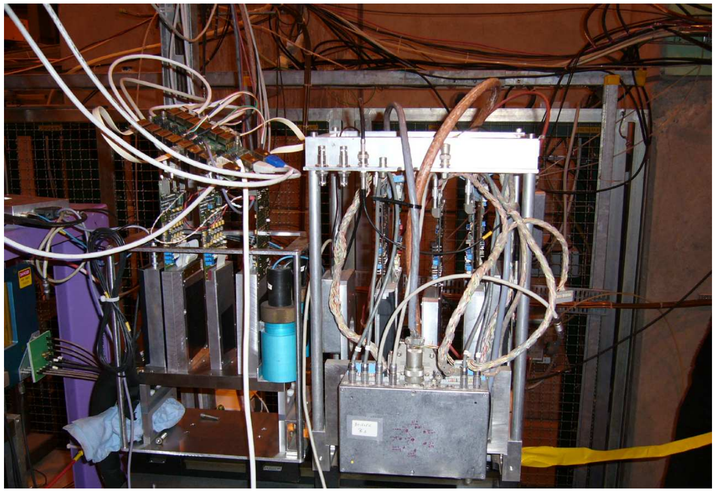
- **Conclusion :**
  - ⁂ observed ionising radiation tolerance: O(10 kGy)
  - ⁂ observed non-ionising rad. tol.: $>$ 1·10^{13} n_{eq}/cm^2 (10μm pitch) & 2·10^{12} n_{eq}/cm^2 (20μm pitch)

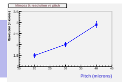
Applications of Sensors with Analog Output

- **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)* $\longrightarrow$
  - **STAR (RHIC) :** *telescope (3 MIMOSA-14) inside apparatus (2007)*
    $\longrightarrow$ *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:** β*-imaging, hybrid photo-detectors, dosimetry, ...*



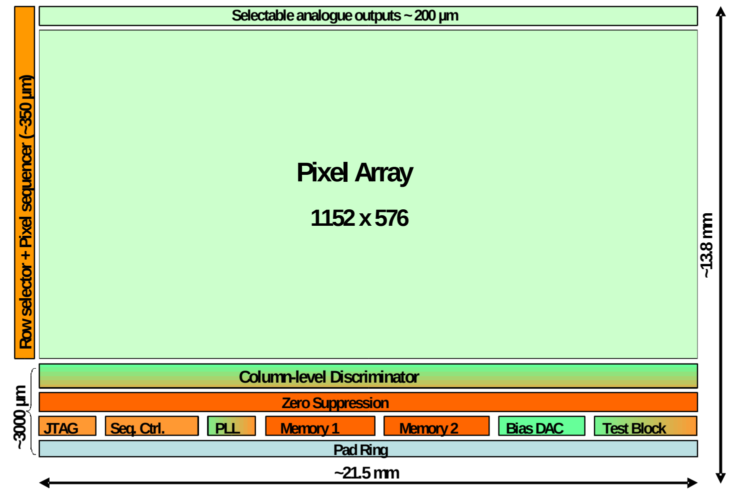


Improving the Read-Out Speed

with Digital Output Sensors

TC (MIMOSA-26) : Sensor with Integrated $\emptyset$

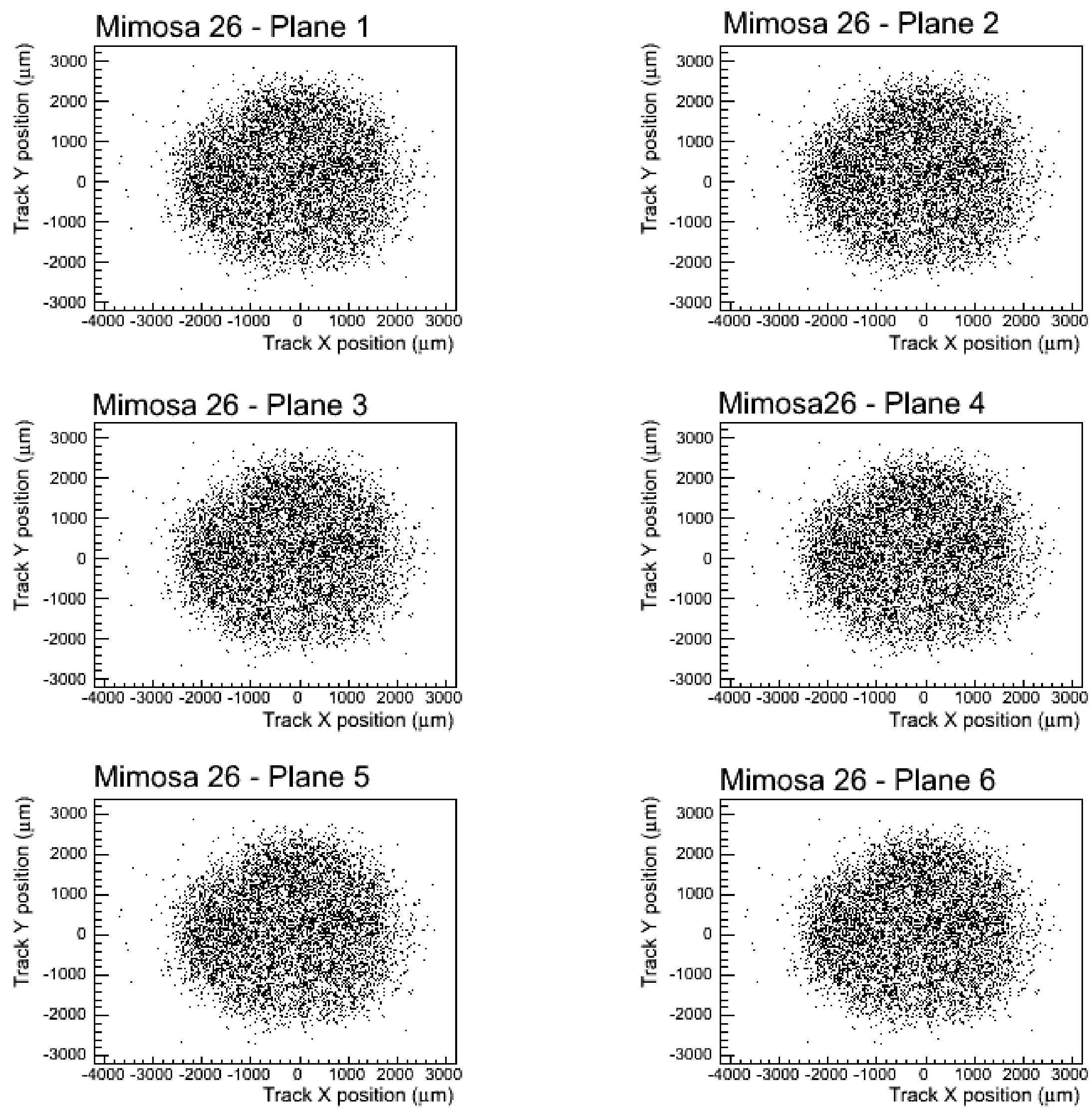
- **TC $\equiv$ 1st sensor with integrated zero-suppression**
  - **MIMOSA-22 (binary outputs) combined with $\emptyset$ (SUZE-01)**
  - **Active area: 1152 columns of 576 pixels (21.2$\times$10.6 mm^2)**
  - **Pitch: 18.4 μm $\rightarrowtail$ $\sim$ 0.7 million pixels $\Rrightarrow$ $\sigma_{sp} \gtrsim$ 3.5 μm**
  - **T$_{r.o.}$ $\lesssim$ 110 μs $\rightarrowtail$ $\sim$ 10^4 frames/s**
    $\Rrightarrow$ *suited to $>$ 10^6 particles/cm^2/s*
  - *$\emptyset$ in 18 groups of 64 col. allowing $\leq$ 9 "pixel strings" / raw*
  - *Sensor full dimensions : $\sim$ 22 x 14 mm^2*
  - *Data transmission: 1 output at $\geq$ 160 Mbits/s or 2 outputs at $\geq$ 80 Mbits/s*



- **Fabricated in 0.35 μm "Opto" technology:**
  - Equips the final version of EUDET Beam Telescope (EU-FP6 project)
  - Architecture is baseline for STAR, CBM and ILC vertex detectors (+ ALICE upgrade ?)
  - Sensor still being characterised $\Rrightarrow$ test results are **Preliminary**

TC Beam Tests: General Remarks

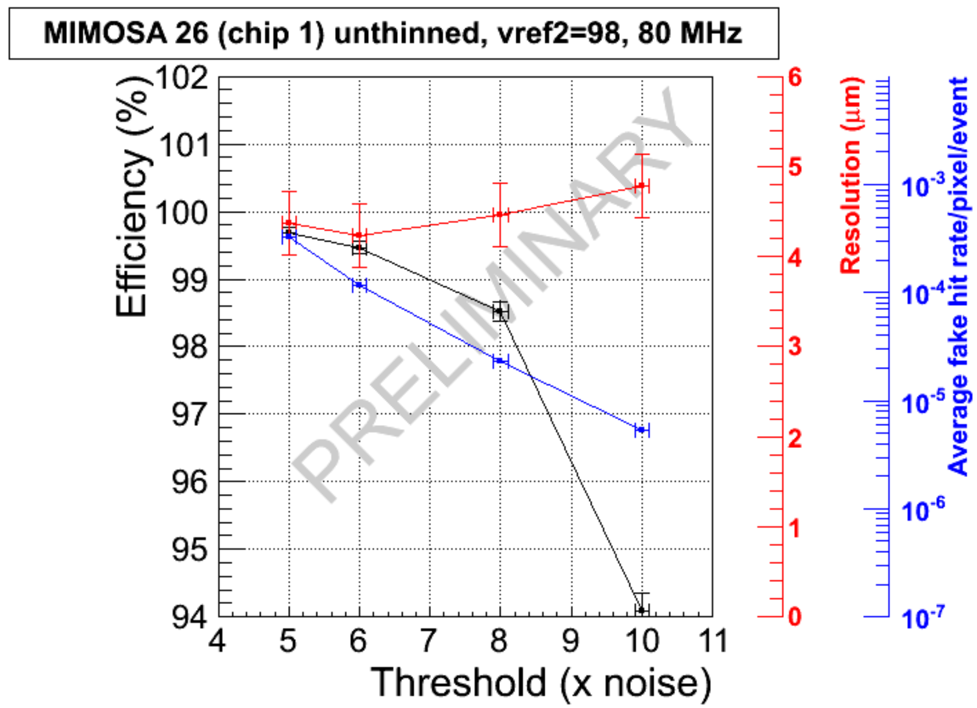
- **6 sensors used:**
  - ⋇ some thinned to 120 μm
  - ⋇ assembled in telescope configuration
  - ⋇ for minimum ionising particle detection performance evaluation



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

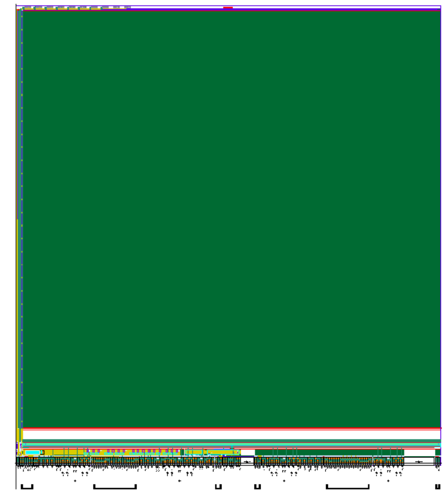
TC Beam Tests: Summary

- **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 discri. threshold $\sim$ 5–6 $\times$ Noise value
  - ⋇ $\sigma_{sp}^{TC} \lesssim 4.5 \pm 0.2\ \mu m$ (preliminary)
    $\hookrightarrow$ room for improvement towards $\sigma_{sp}^{TC} \lesssim 4\ \mu m$

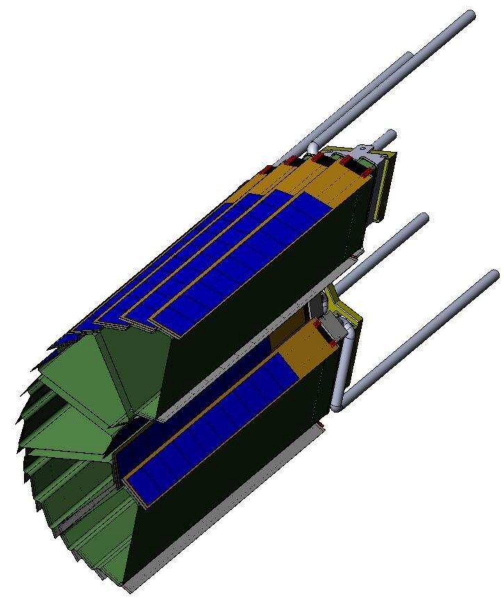


- **Conclusion:**
  - ⋇ TC operationnal for the final EUDET BT ✓
  - ⋇ TC architecture validated for devt of application specific sensors:
    - ▷ STAR-PIXEL, CBM-MVD, ILD-VTX, ... ALICE–ITS ?

- **1st generation sensor for the HFT-PIXEL of STAR (PHASE-1):**
  - **full scale extension of MIMOSA-22 (no $\emptyset$)**
  - *640x640 pixels (30 μm pitch) $\Rrightarrow$ active surface: 19.2 x 19.2 mm^2*
  - *integration time : 640 μs*
  - *designed and fabricated in 2008 $\rightarrowtail$ 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 2011/12*

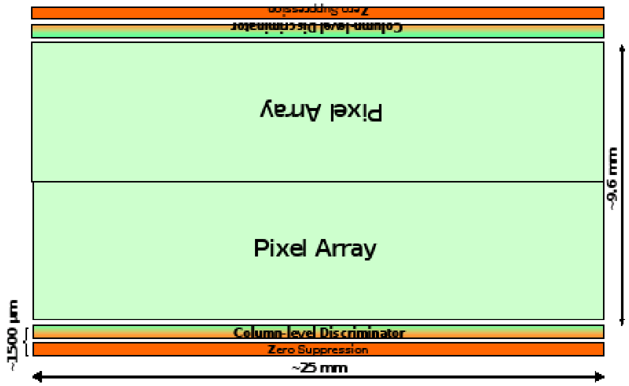


- **Final HFT-PIXEL sensor :**
  - **MIMOSA-26 with active area $\times$ 1.8**
    & improved rad. tolerance
    $\hookrightarrow$ *1088 col. of 10^3 pixels (20 x 18.5 mm^2)*
  - **Pitch : 18.4/20.7 μm $\rightarrowtail$ $\sim$ 1 million pixels**
  - **Integration time $\lesssim$ 200 μs**
  - *Design in 2009/10 $\rightarrowtail$ fab. Q4 (2010)*
    $\rightarrowtail$ *1st physics data expected in 2013/14*

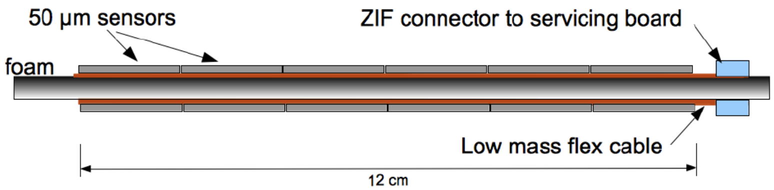


- Move from 0.35 μm to feature size $\leq$ 0.18 μm
  - $\Rrightarrow$ improved clock frequency, more metal layers, more compact peripheral circuitry, etc.

- ILD VTX inner layers ($t_{int} \sim$ 25 - 50 μs) :
  - ⋇ double-sided r.o. $\Rrightarrow$ twice shorter (= faster) columns
  - ⋇ pitch $\lesssim$ 15 μm
  - ⋇ binary r.o. $\Rrightarrow$ $\sigma_{sp} \lesssim$ 3 μm

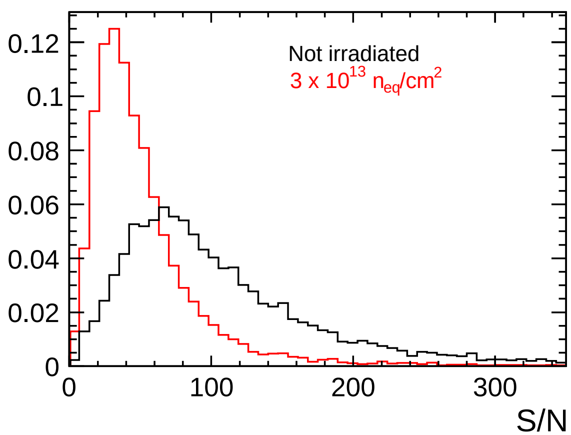


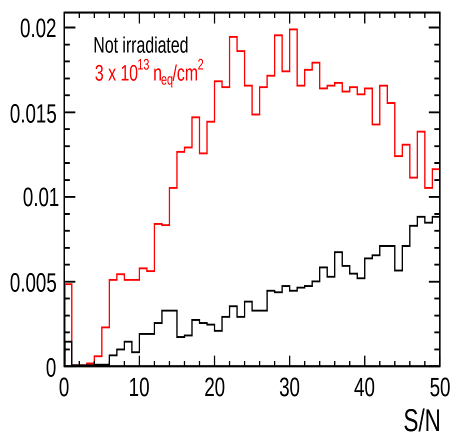
- Implement elongated pixels on one side of double-ladder:
  - ⋇ pixel pitch of $\sim$ 14$\times$50–80 μm
  - ⋇ reduced nb of pixels per column
    - $\Rrightarrow$ shorter read-out (goal: factor 4–6)
  - ⋇ depleted epitaxial layer
    - $\Rrightarrow$ wider sensing diode spacing (next slide)
    - $\hookrightarrow$ $\lesssim$ 10 μs may be reachable

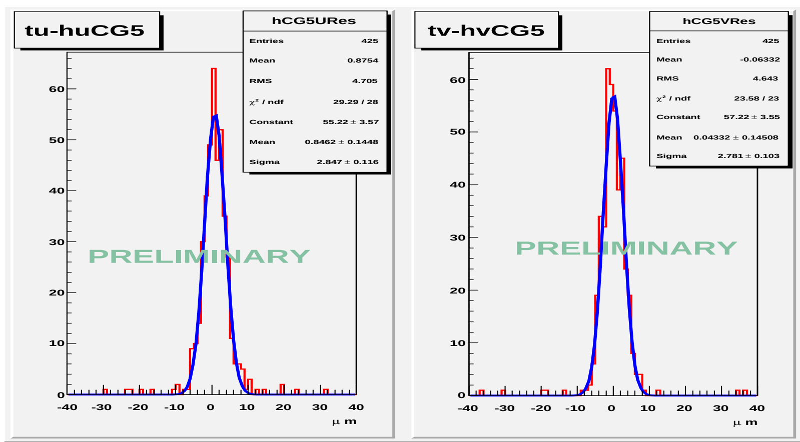


High Resistivity Sensitive Volume

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







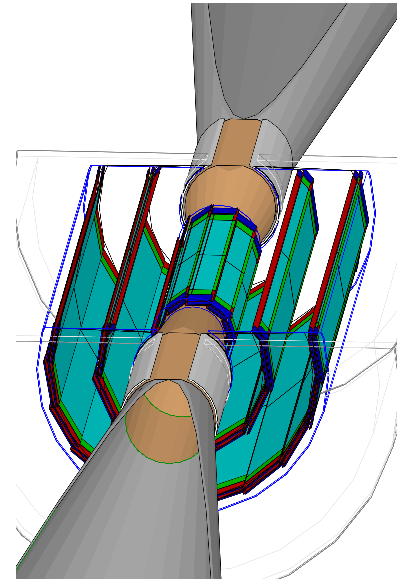
- **Effect of 3·10^{13}n$_{eq}$/cm^2 at room temperature:** ($\sigma_{sp} \sim$ 2.5 $\pm$ 0.2 μm)
  - ⋇ SNR(MPV): $\sim$ 60 $\searrow$ $\sim$ 30 $\triangleright$ ϵ_{det}: 99.9...% $\searrow$ 99.5% at T$_{room}$ with 20μm pitch & 80μs r.o. time
  - $\Rrightarrow$ thin depleted epitaxy approach validated for $\gtrsim$ 10^{14}n$_{eq}$/cm^2 $\triangleright$ 0.35 μm version available soon
- **Exploration of a new VDSM techno. with depleted substrate :** project LePIX (organised by CERN)

  $\triangleright$ aim for very short integration time

High Resistivity Sensitive Volume : Short & Mid-Term Plans

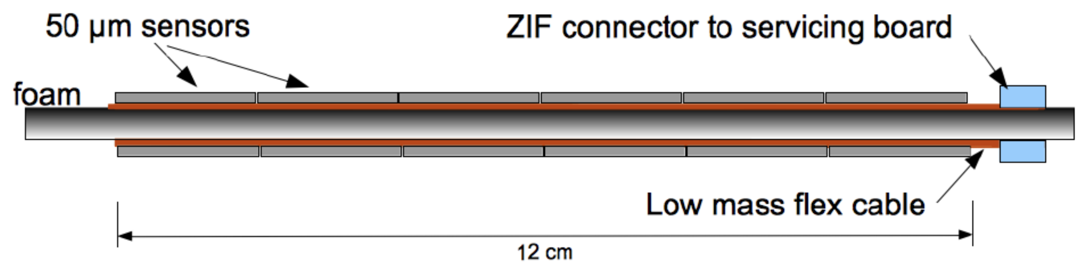
- **Explore newly available 0.35 μm High-Resistivity technology:**
  - *resistivities: 400 and 200 $\Omega \cdot cm$*
  - *epitaxial thickness: 10, 15, 20 μm*
  - *TC/MIMOSA-26 begin refabricated on various substrates*
  - *multi-project run in February for STAR:*
    - *larger pitch $\Rrightarrow$ reduced power dissipation and r.o. time*
    - *reduced steering voltage $\Rrightarrow$ reduced power dissipation*
    - *improved amplification gain $\Rrightarrow$ enhanced SNR*
    - *improved ionising radiation tolerance of in-pixel amplification circuitry*
- **Explore 0.35 μm techno. extrapolated from the former 0.6 μm techno.**
  - non-uniform resistivity (0.5 to 2 $k\Omega \cdot cm$) and only 3 metal layers
  - imaging device to be fabricated in Spring 2010
- **Explore VDSM techno. with high-resistivity substrate & deep depletion potential (HV)**
  - assess charge coll. properties, radiation tolerance, thinning (& post-processing) possibilities, etc.
  - envisage using this process for charge sensing in a 3D device (see later)

- **PLUME project**
  - **P**ixelated **L**adder using **U**ltra-light **M**aterial **E**mbedding



- **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

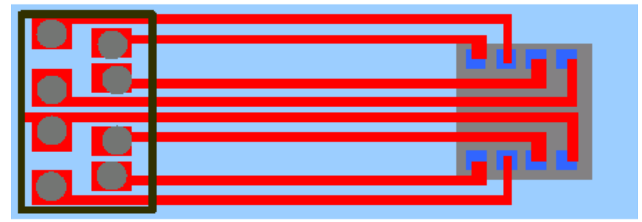


- **Perspective:**
  - to be studied with infrastructure foreseen in FP-7 project AIDA (proposal in preparation)
  - interest for EIC experiments ?

- **HP-2 project ▷ WP-26 (ULISI) ≡ SEnsor Row Wrapped In an Extra-Thin Envelope (SERWIETE)**

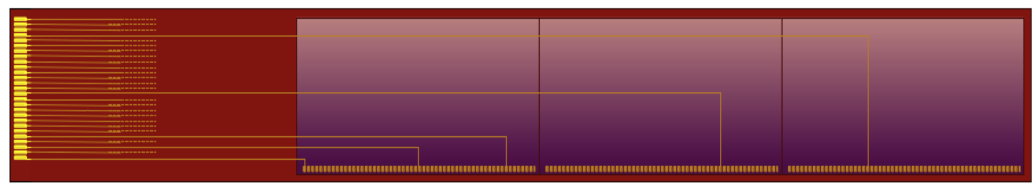
- **Objectives :**
  - ⋇ achieve a sensor assembly mounted on flex and wrapped in polymerised film with $\lesssim$ 0.15 % X_0 in total
  - ⋇ evaluate possibility of mounting supportless ladder on cylindrical surface (serving as mechanical support)
  - ⋇ proof of principle expected in 2012

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 μs)

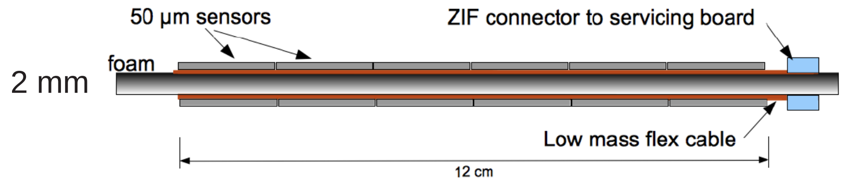
Proto 2 ▷ Summer 2011



- **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 :

- Foresee a detector made of 3 double layers (barrel & end-cap ?)
  (and envisage equipping beam pipe ???)



- Ambitionned performances:
  - ⋇ thin pixel sensors (50 μm) offering a single point resolution $\lesssim$ 5 μm ?
  - ⋇ ladder with complete material budget $\lesssim$ 0.3 % X_0
  - ⋇ 2 contiguous impacts per particle detected $\Rrightarrow$ several benefits for detection performances:
    - ◇ resolution (impact param.) ◇ track rec. ◇ alignment (crucial !) ◇ speed ?

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

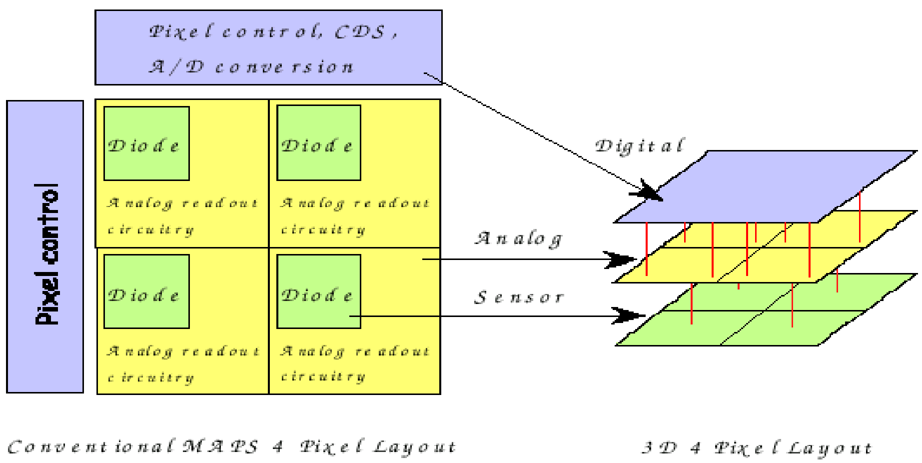
- Devt of thin, high resolution, CMOS pixel sensors for STAR & CBM (since 2000 & 2003)
  $\Rrightarrow$ design of sensor architecture $\sim$ mature (sensor operational on EUDET/FP-6 telescope)
- Devt of ultra-light ladders for CBM, ILC, etc. (since 2008) $\rightarrowtail$ WP-26 (HP-2)
  $\Rrightarrow$ several approaches investigated $\rightarrowtail$ prototyping finalised $\sim$ 2012/13
- First data collected with STAR-PIXEL (open charm) in 2012/13
  $\Rrightarrow$ single-sided ladders: $\sigma_{sp} \lesssim$ 5 μm, material budget $\sim$ 0.3–0.4 % X_0

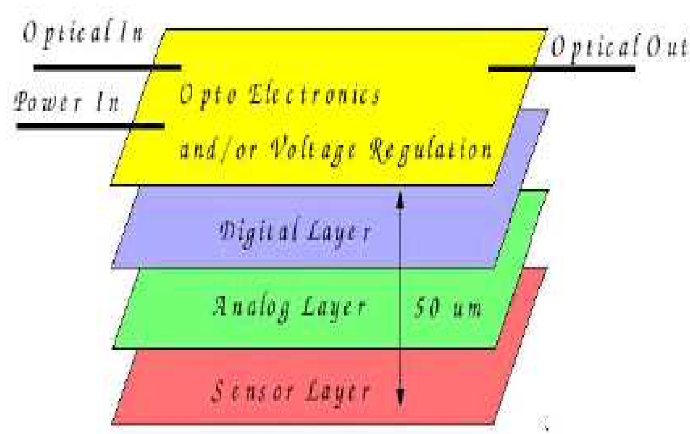
Using 3DIT to Improve CMOS Sensor Performances

- **3D Integration Techno.** allow integrating high density signal processing μcircuits inside small pixels by stacking ($\sim$ 10 μm) thin tiers interconnected at pixel level

- **3DIT are expected to be particularly beneficial for CMOS sensors :**
  - ⋇ combine different fab. processes $\Rrightarrow$ chose best one for each tier/functionnality
  - ⋇ alleviate constraints on peripheral circuitry and on transistor type inside pixel, etc.

- **Split signal collection and processing functionnalities :**
  - ⋇ *Tier-1: charge sensing* ⋇ *Tier-2: analog-mixed μcircuits* ⋇ *Tier-3: digital μcircuits*





- **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* $\Rrightarrow$ *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*

Contents of the Working Plan

CMOS pixel sensors :

- Ambitionned performances (room T):

  ⋇ $\sigma < 5\ \mu m$ ✓ ⋇ thickness $\lesssim$ 50 μm ✓ ⋇ $t_{ro} \sim$ 10-20 μs ⋇ 1 MRad & $10^{14} n_{eq}/cm^2$

  $\Rrightarrow$ 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 $\rightarrowtail$ $t_{ro} \sim$ 10-20 μs & 1 MRad (2011/12)

  ⋇ 2D with depleted sensitive volume (elongated pixels) $\rightarrowtail$ 1 MRad & $10^{14} n_{eq}/cm^2$ (2013)

  ⋇ 3D with depleted sensitive volume $\rightarrowtail$ $t_{ro} \lesssim$ 5 μs (2015)

Ladder developed along 2 parallel approaches:

- Classical : sensors $\oplus$ flex cable $\oplus$ SiC foam $\oplus$ flex cable $\oplus$ sensors

  $\Rrightarrow$ $\lesssim$ 0.3 % X_0 for the whole 2-sided ladder

- Innovating : sensors (35 μm) wrapped in polymerised film ($\lesssim$ 10 μm)

  $\Rrightarrow$ $\lesssim$ 0.15 % X_0 for 1 unsupported layer (sensors $\oplus$ flex cable $\oplus$ film)

  $\hookrightarrow$ adaptable to various mechanical supports $\rightarrowtail$ beam pipe ?

CONCLUSIONS – SUMMARY

- Proposal: **investigate possibility of translating ultra-light pixelated ladders developed for CBM & ILC to the specifications of an EIC vertex detector, relying on 2 basic components:**
  - ⋇ thin, depleted, CMOS pixel sensors (baseline 2D, potentially 3D)
  - ⋇ ultra-light double-sided ladder complemented with potential pixelated beam pipe
- **CMOS pixel sensors developed for EUDET, STAR, CBM, ILC, ALICE (?):**
  - ⋇ 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)
    - $\Rrightarrow$ may be relevant for an EIC vertex detector $>$ 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 $\lesssim$ 0.15 % X_0 $\rightarrowtail$ explore possibility to equip beam pipe ?
- **Synergetic context to exploit:**
  - ⋇ CMOS sensor development with Heavy Ion Community
  - ⋇ ladder development within HP-2 (Frankfurt, GSI), PLUME collaboration (ILC teams)
  - ⋇ perspective: AIDA FP-7 proposal (study of high precision vertex detector alignment issues)