Highly Pixelated Transparent Devices for Future Vertex Detectors

Marc Winter (IPHC-Strasbourg)

(on behalf of the MIMOSA, PLUME, Hadron Physics 2 & AIDA collaborations)

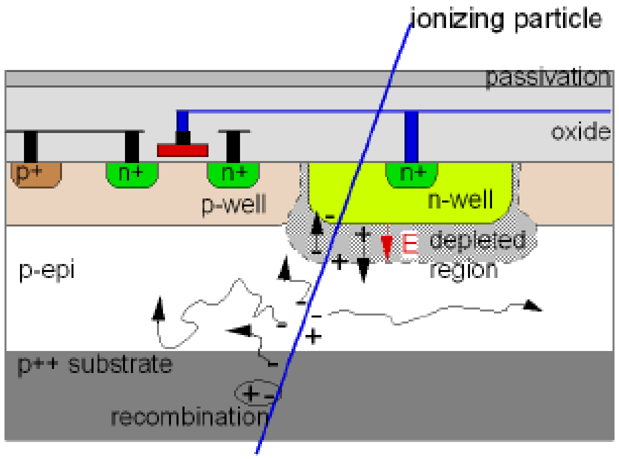
▷ **more information on IPHC Web site: http://www.iphc.cnrs.fr/-CMOS-ILC-.html**

CONTENTS

- **CMOS pixel sensors developed by IPHC** (& IRFU) **:** Main Features
- **Achieved performances & and Applications**
- **Plans for the coming 3-4 years**
- **Summary**

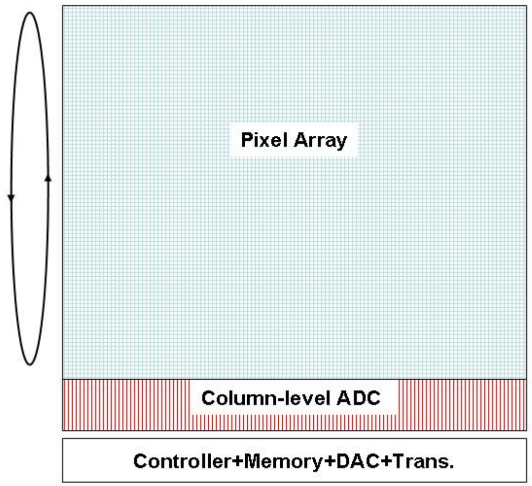
CMOS Pixel Sensors: State of the Art

- **Prominent features of CMOS pixel sensors:**
  - ⋇ high granularity $\Rrightarrow$ excellent (micronic) spatial resolution
  - ⋇ very thin (signal generated in 10-20 μm thin epitaxial layer)
  - ⋇ signal processing μ-circuits integrated on sensor substrate



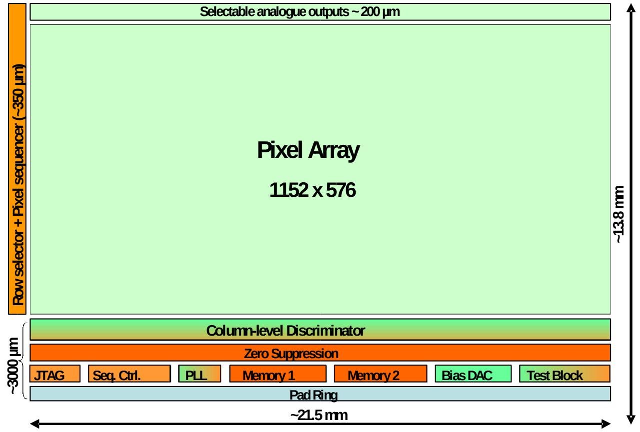
- **Sensor organisation:**
  - ⋇ signal sensing and analog processing in pixel array
  - ⋇ mixed and digital circuitry integrated in chip periphery
  - ⋇ read-out in rolling shutter mode

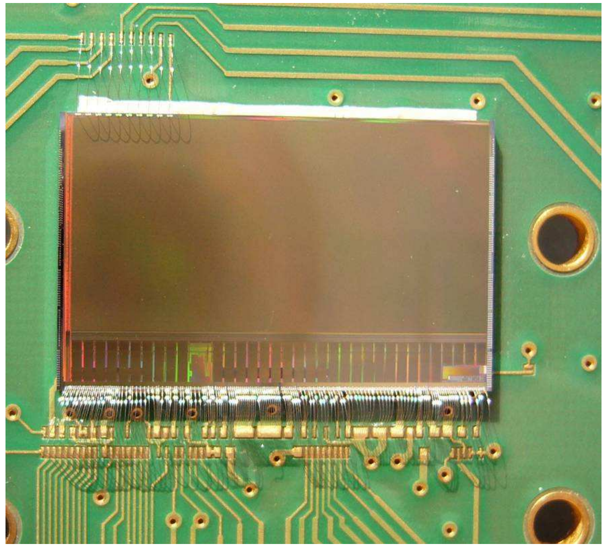
    (pixels grouped in columns read out in //)



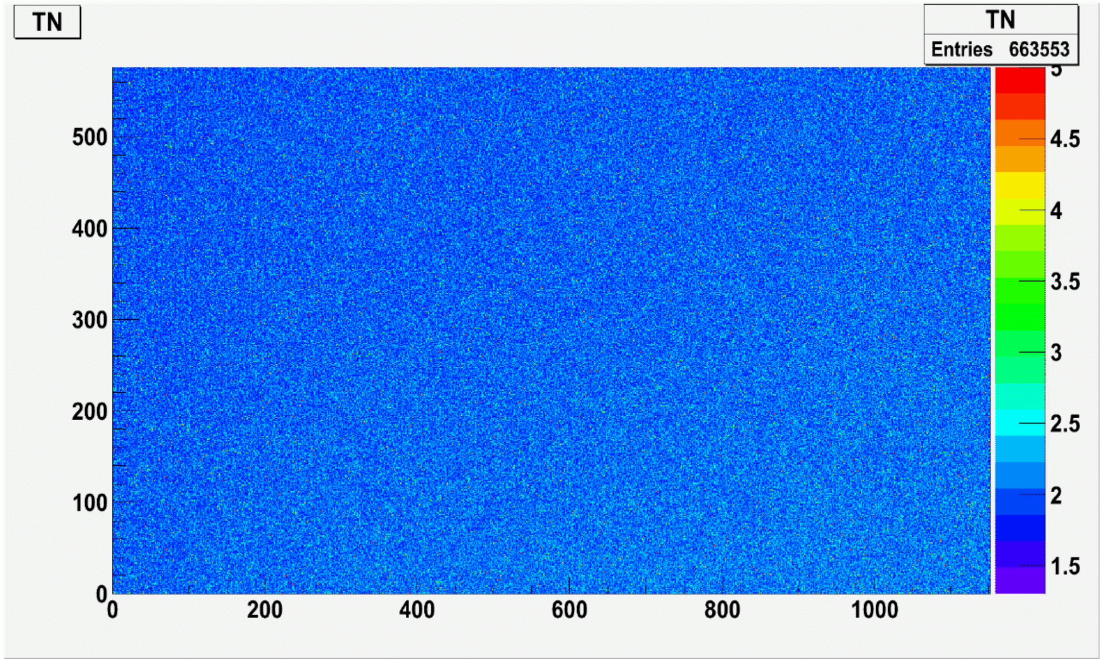
CMOS Pixel Sensors: State of the Art

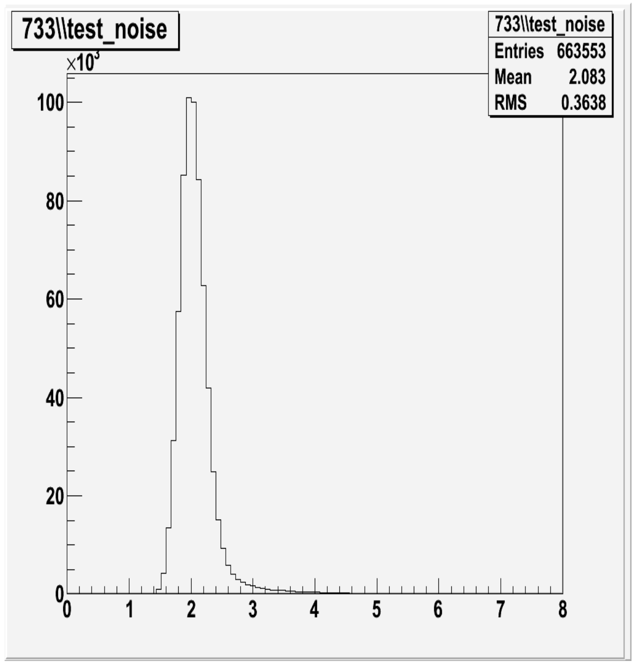
- **Main characteristics of MIMOSA sensor equipping EUDET BT:**
  - ⋇ 0.35 μm process with high-resistivity epitaxial layer (coll. with IRFU/Saclay)
  - ⋇ column // architecture with in-pixel amplification (CDS) and end-of-column discrimination, followed by $\emptyset$
  - ⋇ active area: 1152 columns of 576 pixels (21.2$\times$10.6 mm^2)
  - ⋇ pitch: 18.4 $\mu m \rightarrowtail \sim$ 0.7 million pixels
    charge sharing $\Rrightarrow$ $\sigma_{sp} \lesssim$ 4 μm
  - ⋇ $t_{r.o.} \lesssim$ 100 μs ($\sim$$10^4$ frames/s)
    $\Rrightarrow$ suited to $>$$10^6$ part./cm^2/s
  - ⋇ $\sim$ 250 mW/cm^2 power consumption (fct of N_{col})





MIMOSA-26 Lab Tests: Noise Performance





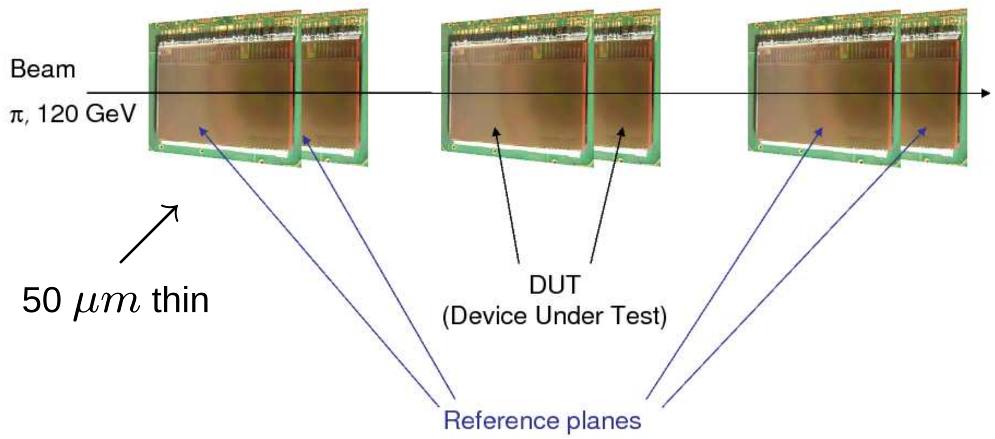
- **Noise uniformity tested on > 60 sensors (analogue output)**

- **Main conclusions:**
  - ⋇ no dead pixel over > 50 arrays of 665,000 pixels !
  - ⋇ N $\lesssim$ 14 e^-ENC
  - ⋇ marginal noise dispersion between chips

High-Resistivity CMOS Pixel Sensors

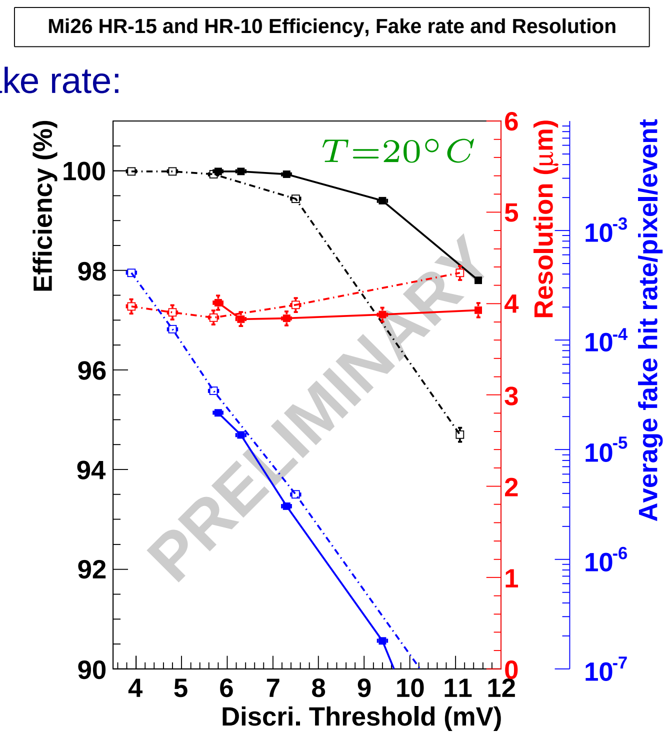
- **M.i.p. detection with LOW & HIGH resistivity CMOS sensors combined in a Beam Telescope (BT)**
  - ⋇ 4 EUDET ref. sensors & 2 sensors under test
  - ⋇ June 2010 at CERN-SPS ($\sim$ 120 GeV pions)
  - ⋇ sensor variants : standard epitaxy (14 μm thick)

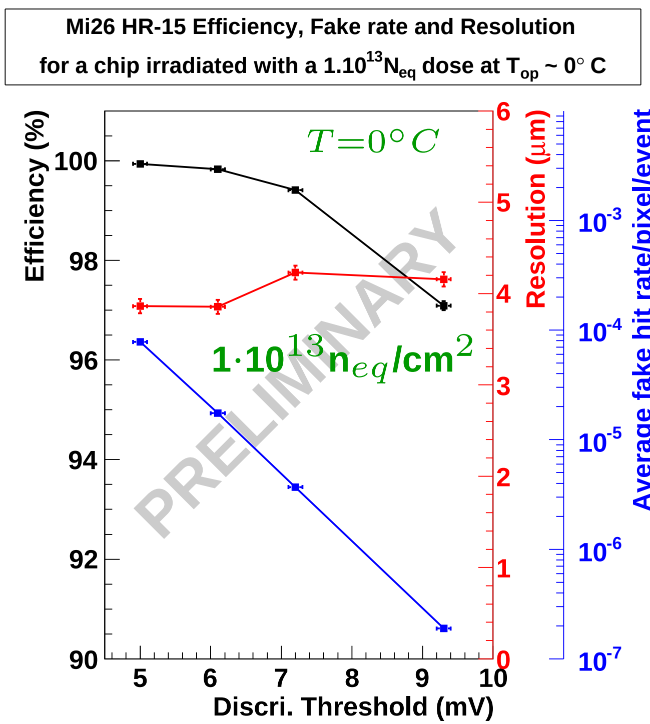
    & high-resistivity epitaxy (10 & 15 μm thick)



- **Main Results:**
  - ⋇ det. eff. $\sim$ 100 % (SNR $\sim$ 40) for very low fake rate:
    - ▷ plateau until fake rate of few 10^{-6}
  - ⋇ single point resolution $\lesssim 4\ \mu m$
  - ⋇ det. eff. still $\sim$ 100 % after exposure

    to fluence of $1{\cdot}10^{13} n_{eq}/cm^2$





$\Rightarrow$ **Excellent detection performances**

with high-resistivity epitaxial layer

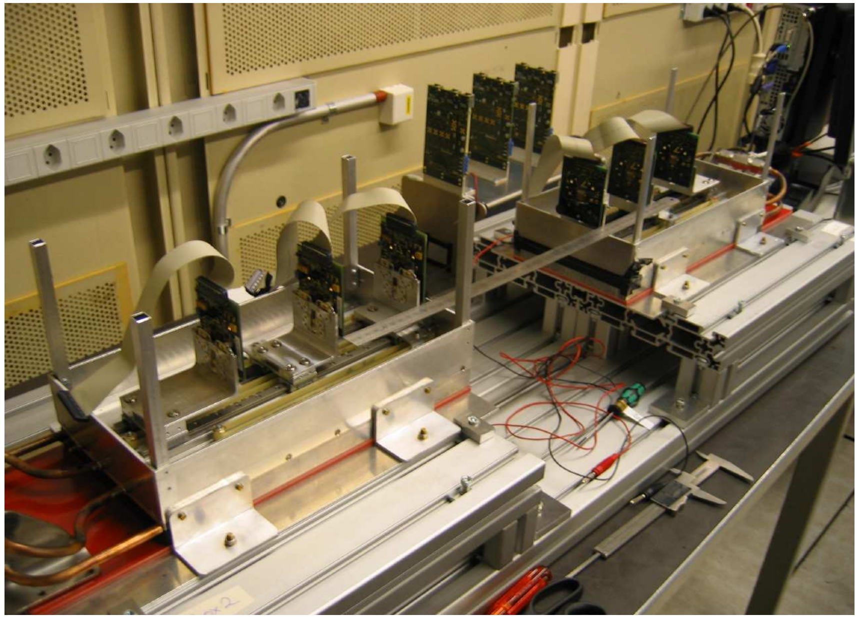
despite moderate resistivity (400 $\Omega \cdot cm$)

and poor depletion voltage ($<$ 1 V)

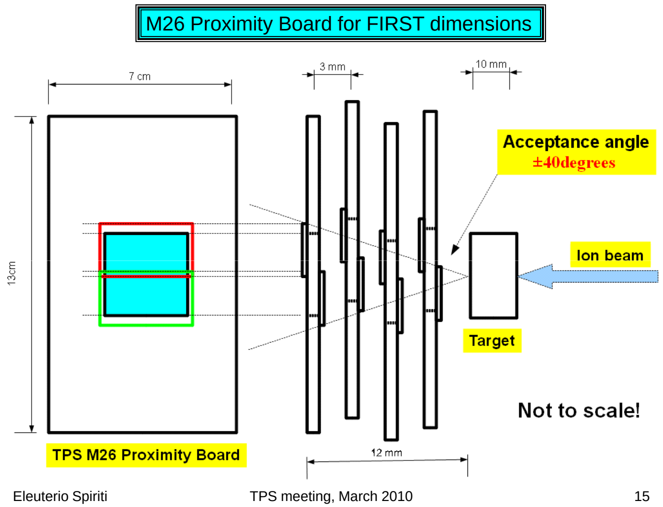
$\Rightarrow$ **Tolerance to $\gtrsim$ O(10^{14}) n_{eq}/cm^2 seems within reach (study under way)**

Direct Applications of MIMOSA-26

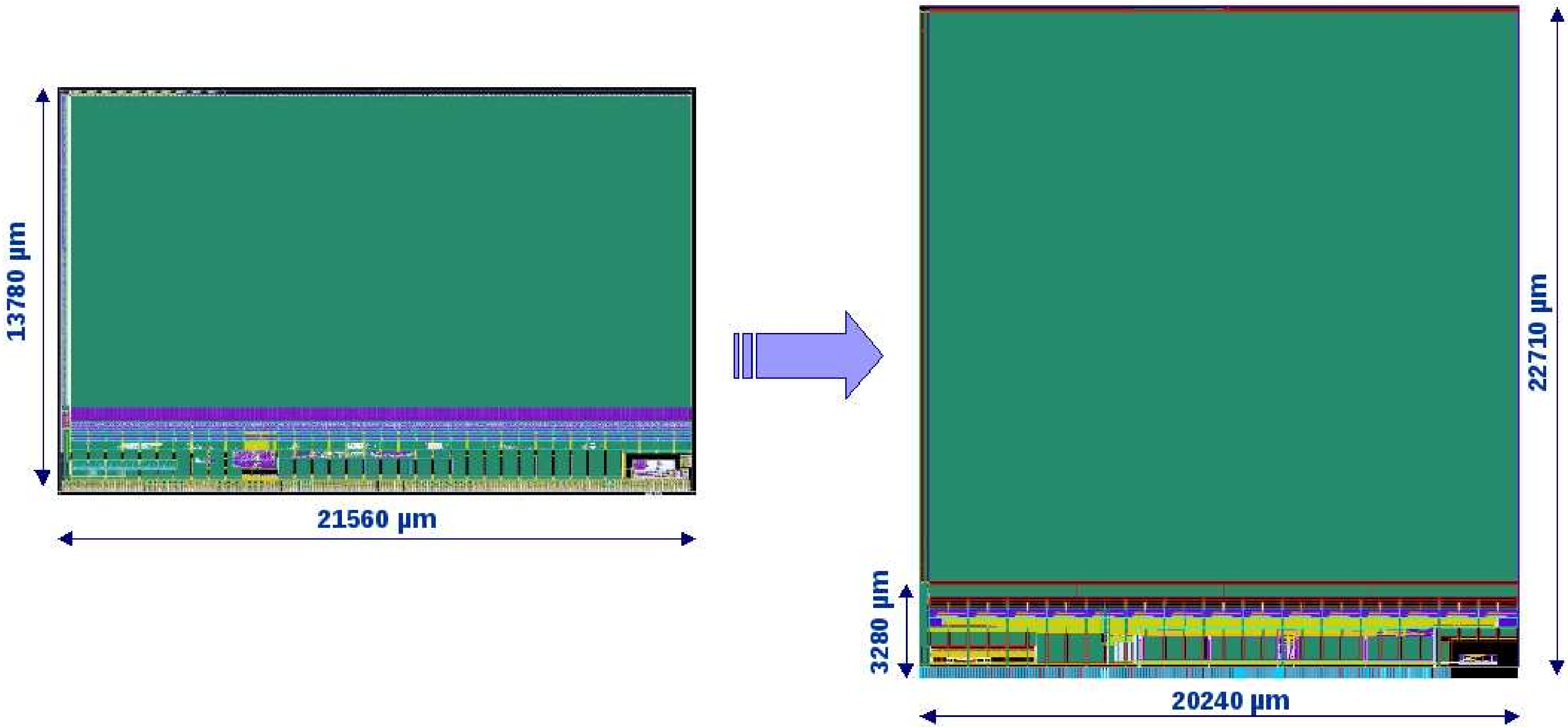
- **Beam telescope of the FP6 project EUDET**
  - 2 arms of 3 planes (plus 1-2 high resolution planes)
  - M-26 thinned to 50 μm
  - $\sigma_{extrapol.} \sim$ 1-2 μm EVEN with e^- (3 GeV, DESY)
  - frame read-out frequency O(10^4) Hz
  - running since '07 (demonstrator: analog outputs) at CERN-SPS & DESY (numerous users)



- **Spin-offs :**
  - **Several BT copies :** foreseen for detector R&D
  - BT for channelling studies, mass spectroscopy, etc.
  - **CBM (FAIR) :** MVD demonstrator (2-sided layers) for CBM-MVD (HP-2 project)
  - **FIRST (GSI) :** VD for hadrontherapy σ measurements ▷▷▷



From MIMOSA-26 to ULTIMATE



- Half reticle 1152 x 567 pixel matrix
- Temperature ~20 °C
- Light power consumption constrains
- Space resolution ~4 µm
- No constrains on radiation tolerance

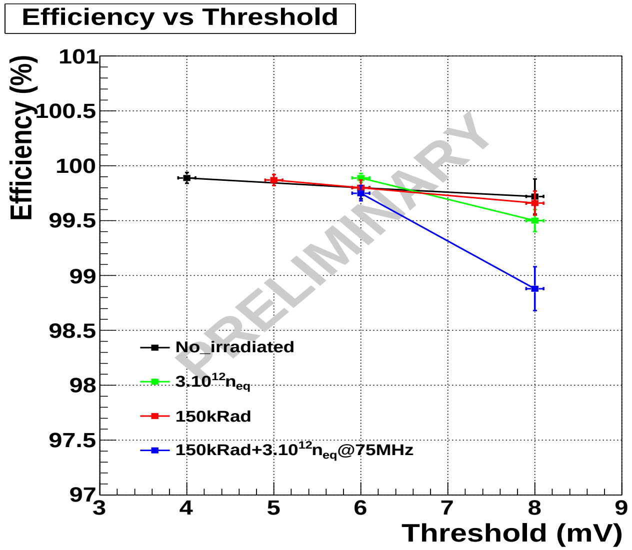
- Full reticle 960 x 928 pixel matrix
  - Longer integration time ~200 µs
- Temperature 30-35 °C
- Power consumption ~100 mW/cm^2
- Space resolution < 10 µm
- 150 kRad / yr & few 10^{12} Neq $/cm^2$ /yr

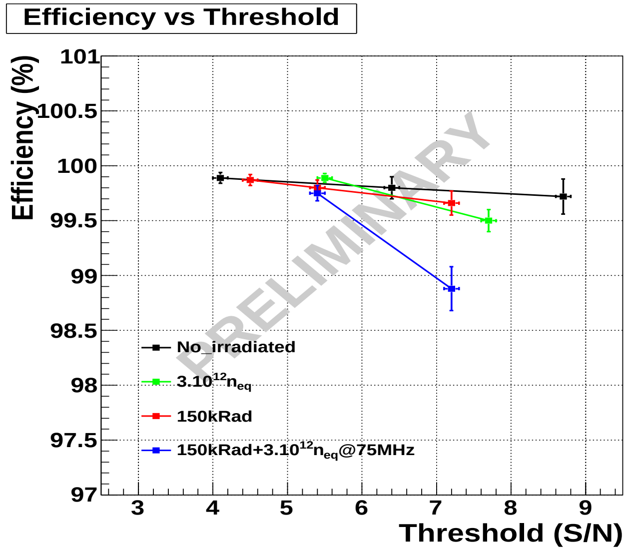
➔ **Optimisation**

courtesy of Ch. Hu-Guo / TWEPP-2010

Ultimate Pixel Performances

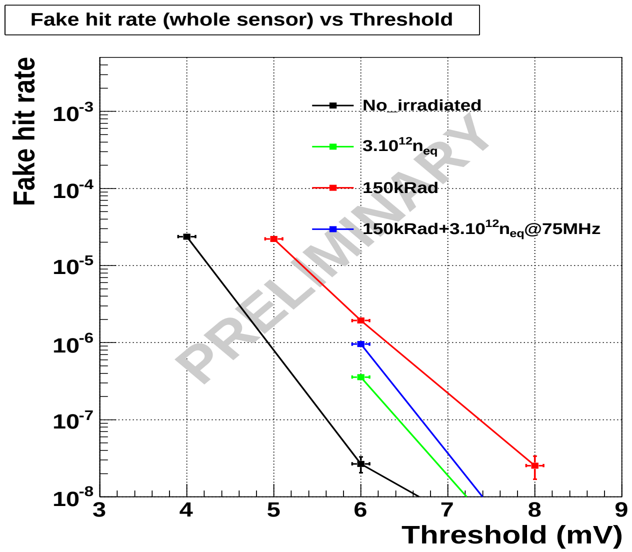
- **Summary of results obtained with S7 (CS) :**
  - ⋇ detection efficiency vs discri. threshold
  - ⋇ fake hit rate vs discri. threshold
    - ↪ look for viable working point (fake $< 10^{-4}$)

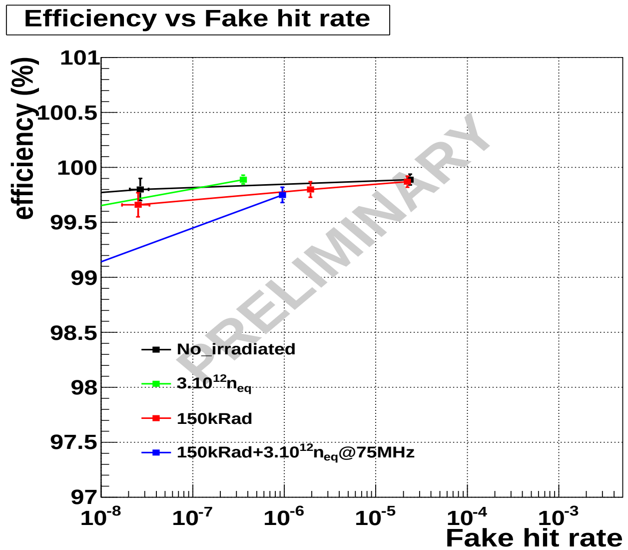




- **Results for 20.7 μm pitch pixels ▷ mV-SNR equivalence at 30°C**

Threshold (mV) ▷	4	5	6	8
before irrad.	*4.1*		*6.4*	*8.7*
$3{\cdot}10^{12}$ n_{eq}/cm^2			*5.5*	*7.7*
150 kRad		*4.5*	*5.4*	*7.2*
combined (75 MHz)			*5.2*	*6.9*

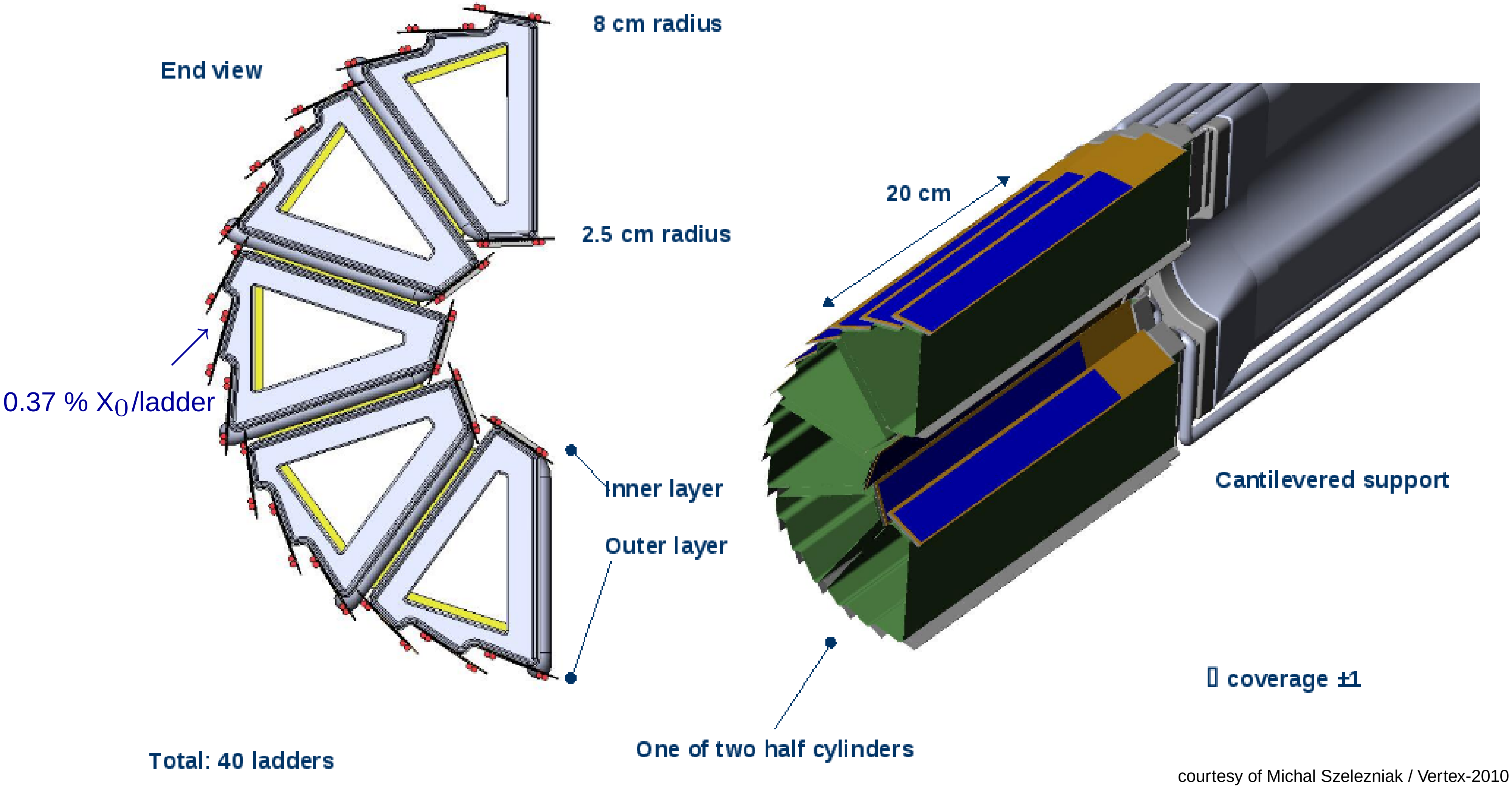




⇛ **No problem to find a threshold where the detection efficiency is $>$ 99.5 % while the fake hit rate remains marginal**

Application of CMOS sensors to the STAR-PXL

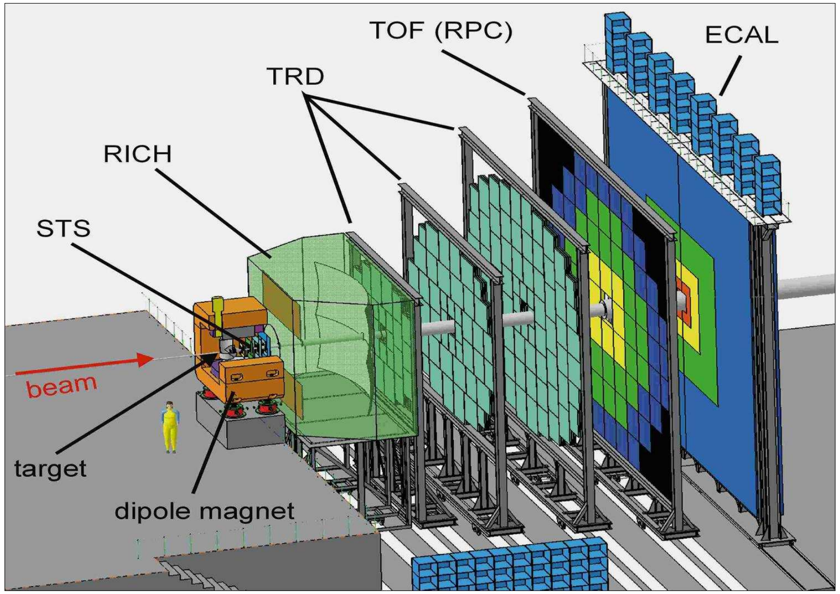
The detector ladders are 50 µm thinned silicon, on a flex kapton/aluminum cable.



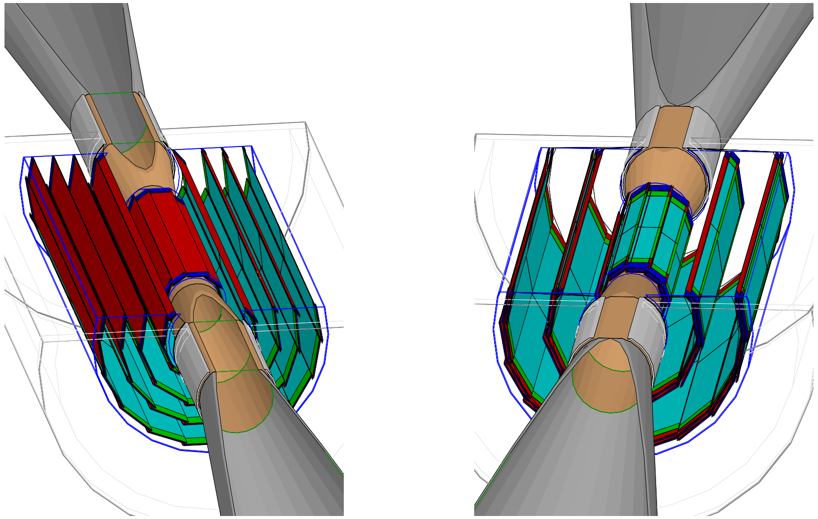
▷▷▷ **1st vertex detector equipped with CMOS pixel sensors ⟶ 1st data taking in 2012/13**

Next Extensions of MIMOSA-26

- **Vertex Detector of the CBM expt / FAIR**
  - ⋇ 2 double-sided stations operated in vacuum
  - ⋇ 0.3–0.5 % X_0 per station
  - ⋇ $\lesssim$ 5 μm single pt resolution
  - ⋇ $\lesssim$ 10 μs r.o. time
  - ⋇ several MRad & $> 10^{13}$ $n_{eq}/cm^2/s$ (T $< 0^\circ$C)
  - ⋇ data taking $\gtrsim$ 2016 (SIS-100) ... 2020 (SIS-300)



- **ILD Vertex Detector** (option) **:**
  - ⋇ geometry : 3 double-sided or 5 single-sided layers
  - ⋇ $\sim$ 0.2 % X_0 total material budget per layer
  - ⋇ $\sigma_{sp} \lesssim 3\ \mu m$
  - ⋇ r.o. time $\lesssim$ 25–100 μs (500 GeV)

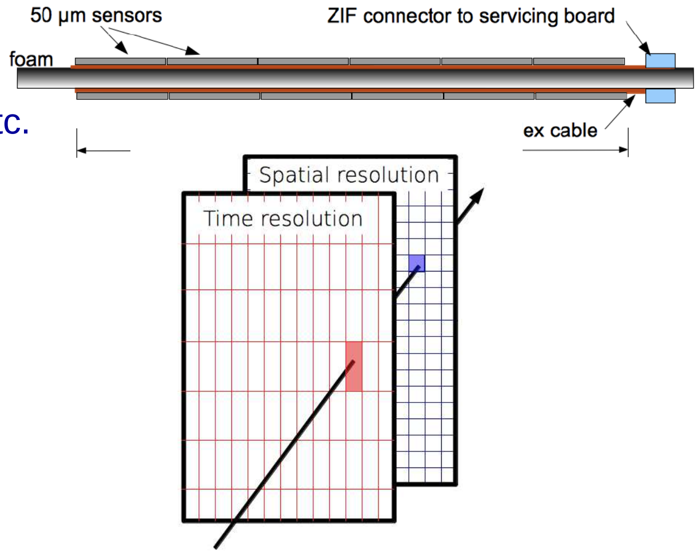


- **Other applications under consideration :**

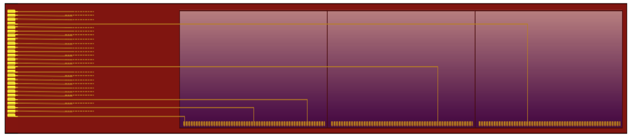
  ITS/ALICE upgrade, FOCAL/ALICE, VD/EIC, VD/CLIC, (HL-)LHC upgrades, etc.

Sensor Integration in Ultra Light Devices

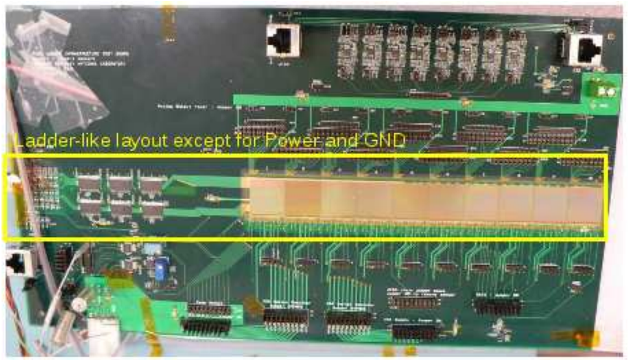
- **Double-sided ladders with time stamping :**
  - ✳ manyfold bonus expected from 2-sided ladders:
    compactness, alignment, pointing accuracy (shallow angle), redundancy, etc.
  - ✳ studied by PLUME coll. (Oxford, Bristol, DESY, IPHC) & AIDA (EU)
    $\hookrightarrow$ **P**ixelated **L**adder using **U**ltra-light **M**aterial **E**mbedding
  - ✳ square pixels for single point resolution on beam side
  - ✳ elongated pixels for 4-5 times shorter r.o. time on other side
  - ✳ correlate hits generated by traversing particles
  - ✳ expected total material budget $\sim$ 0.2 - 0.3 % X_0



- **Unsupported & flexible (?) ladders (Hadron Physics 2 / FP-7)**
  - ✳ 30 μm thin CMOS sensors mounted on thin cable
    and embedded in thin polyimide $\rightarrowtail$ suited to beam pipe ?
  - ✳ expected total material budget $\lesssim$ 0.15 % X_0

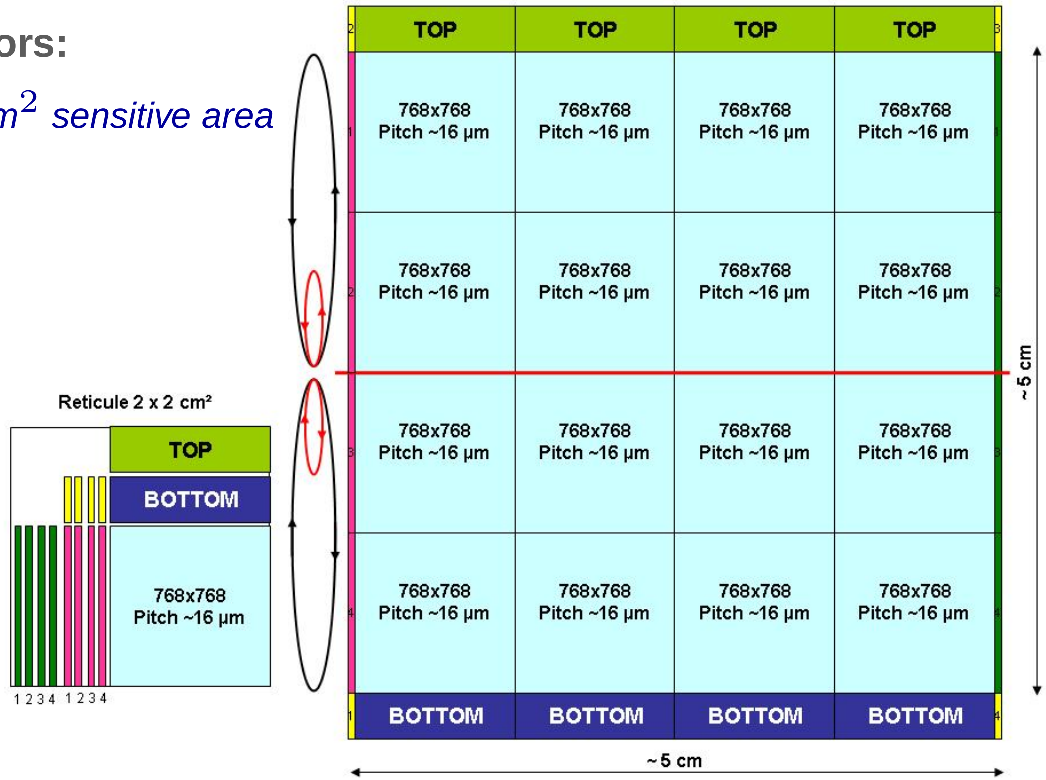


- **STAR-PXL ladder:**
  - ✳ total material budget $\sim$ 0.37 % X_0
    $\Rightarrow$ would be $\sim$ 0.3 % X_0 with less stiffener (vibrations)



Investigating Large Area Sensors

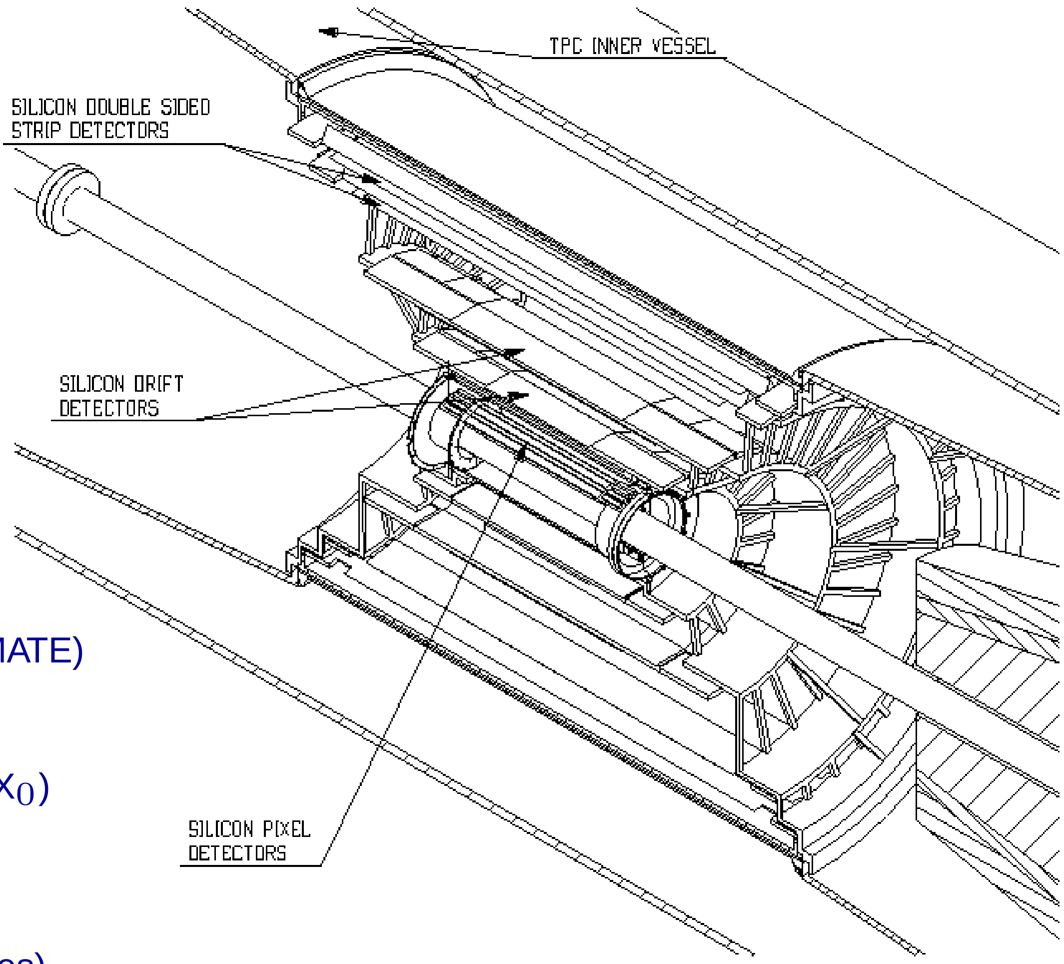
- **Prototype multireticule sensor for "large" area detectors:**
  - *2304/3072$\times$2304/3072 pixels (22/16 μm pitch) $\Rrightarrow$ 5$\times$5 cm^2 sensitive area*
  - *requires combining several reticules*
    - $\Rrightarrow$ *stitching process* $\Rrightarrow$ *establish proof of principle*
  - *2-sided read-out of 1152/1536 rows in 200-300 μs*
    - $\Rrightarrow$ *Large Area Telescope for AIDA project (EU-FP7 approved recently)*
  - *windowing of $\lesssim$ 1$\times$5 cm^2 (collim. beam)*
    - $\Rrightarrow$ $\lesssim$ *50–60 μs r.o. time*
  - *50-100 μm pitch variants under consideration*
    - $\Rrightarrow$ *trackers & FW disks (e.g. VD for EIC)*



- **Submission expected in 2013/14:**
  - 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
  - 6 sensors will compose a beam telescope at CERN (AIDA project deliverable)
    - ▷ few ns time stamping resolution associated to each hit by TLU (scintillator)

Upgrade of ALICE-ITS

- **ITS upgrade :**
  - ⋇ envionned for ”2016” LHC long shutdown
  - ⋇ exploits spece left by replacement of beam pipe
    with small radius (19 mm) section
  - ⋇ consists (at least) in introducing L0
    $\equiv$ additionnal layer at $\lesssim$ 25 mm radius
    (potentially : replace part of the ITS)
  - ⋇ 2 pixel otions considered :
    - ◇ Hybrid pixel sensors with reduced material budget
    - ◇ CMOS pixel sensors derived from STAR-PXL (ULTIMATE)
  - ⋇ main characteristics of CMOS option :
    - ◇ double-sided ladder derived from PLUME ($<$ 0.5 % X_0)
    - ◇ $\lesssim$ 50 μs read-out time
    - ◇ $\sim$ 4 μs spatial resolution
    - ◇ $>$ 1 MRad & $10^{13} n_{eq}/cm^2$ at T = 30°C (target values)
      $\hookrightarrow$ move to 0.18 μm technology



▷▷▷ **Technical Proposal due for 2011**

SUMMARY

- **CMOS sensor technology is mature for high performance vertexing :**
  - ⋇ well suited for specifications governed granularity, material budget, power consumption, ... (large surfaces ?), ...
  - ⋇ excellent performance record with beam telescopes (e.g. EUDET project)
  - ⋇ 1st vertex detector experience will be gained with STAR-PXL, starting data taking in $\gtrsim$ 2 years

- **Next steps :**
  - ⋇ CBM-MVD : 2013/14 sensor with 40-50 μs r.o. time and several MRad $\oplus$ 10^{13} n_{eq}/cm^2
    - ↪ could also be an option for the upgrade of ALICE-ITS
  - ⋇ Large sensors : 2013/14 ▷ 5×5 cm^2 sensors for forward disks (e.g. EIC vertex detector)
    - ↪ will also equip large area telescope of EU-AIDA project
  - ⋇ Faster 2D sensors (with in-pixel FEE) : $\geq$ 2015 ▷ 1-2 μs read-out time

- **Full potential of technology far from being exploited :**
  - ⋇ important 1st step (2011) : move to 0.18 μm feature size
  - ⋇ far future ($>$ 5 years) : multi-tier (3D) sensors using vertical integration