CMOS pixel sensors for high precision vertex detectors

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- Physics motivations.
- CMOS principle of operation and performances.
- MIMOSA-26 and its applications.
- System integration.
- Developments.
- Summary and conclusions.

The International Linear Collider

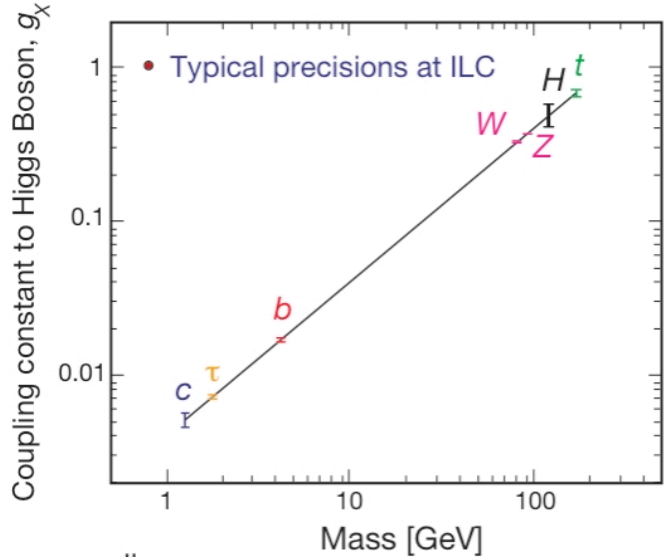
Goals

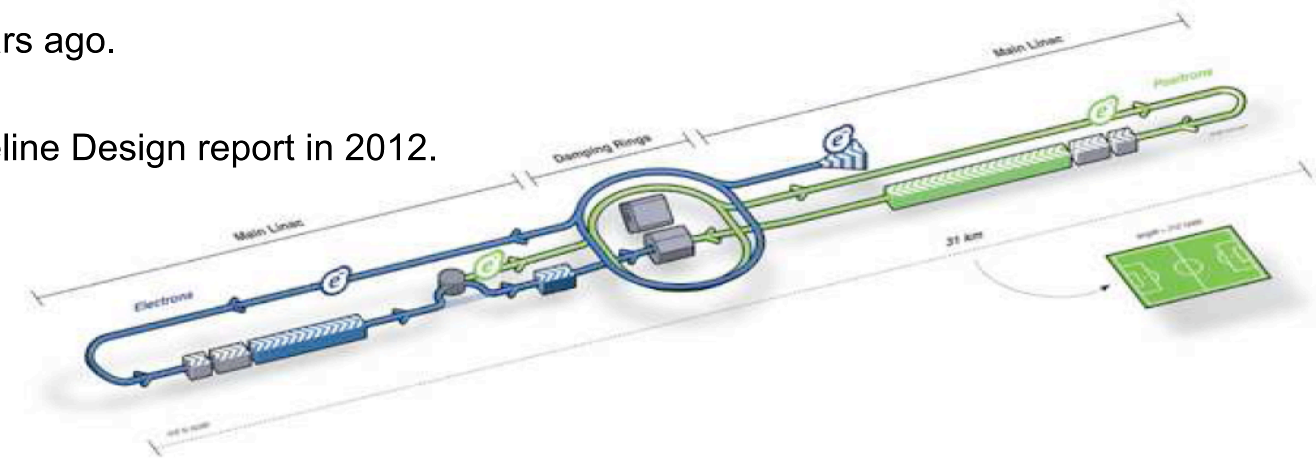
- Higgs physics: quantum numbers, couplings, rare decays.
- New particles production.
- Extended sensitivity via loop effects.

$e^+ e^-$ collider

- Clean initial and final state.
- (Relatively) low background.

- Center of mass energy up to ~ 1 TeV.
- Superconducting RF technology.
- ~ 31 km long.
- L = 2 x 10^{34} cm^{-2} s^{-1}.
- R&D started more than 10 years ago.
- Physics after 2020.
- Next milestone: Detector Baseline Design report in 2012.





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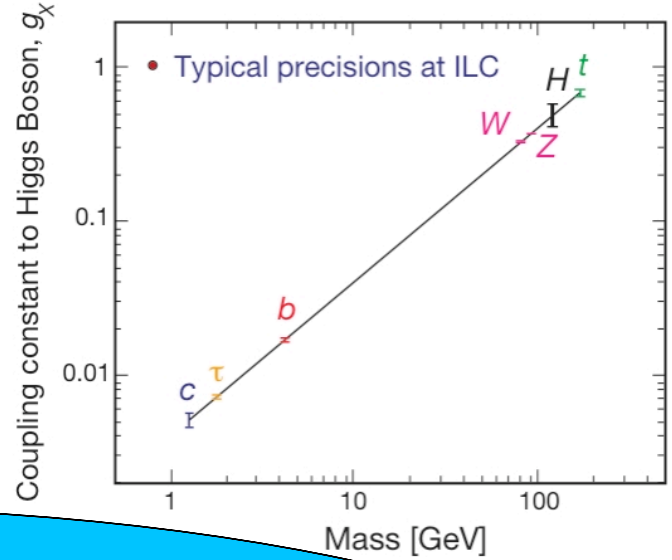

$e^+ e^-$ linear collider

- Clean initial and final state.
- (Relatively) low background.

- Center of mass energ
- Supercon
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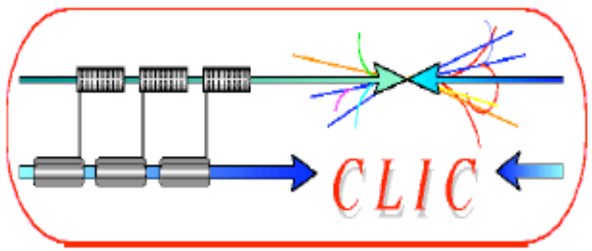
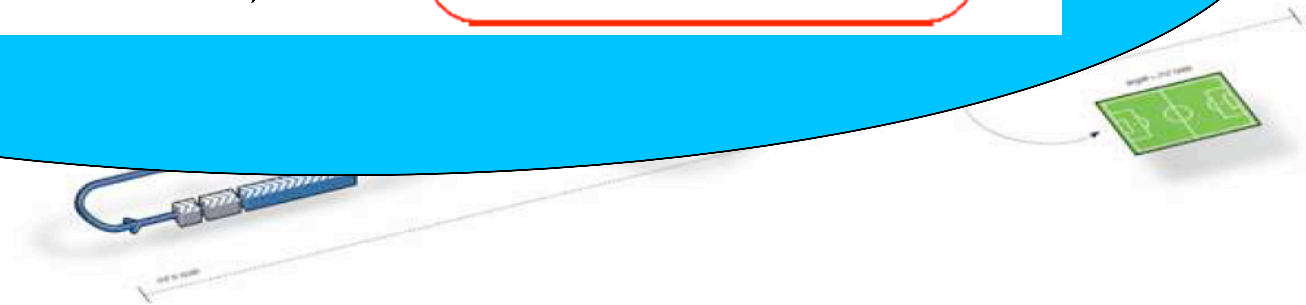
Compact LInear Collider (CLIC)

- New acceleration technique.
- Up to 3 TeV.
- Lot of R&D (machine and detector).



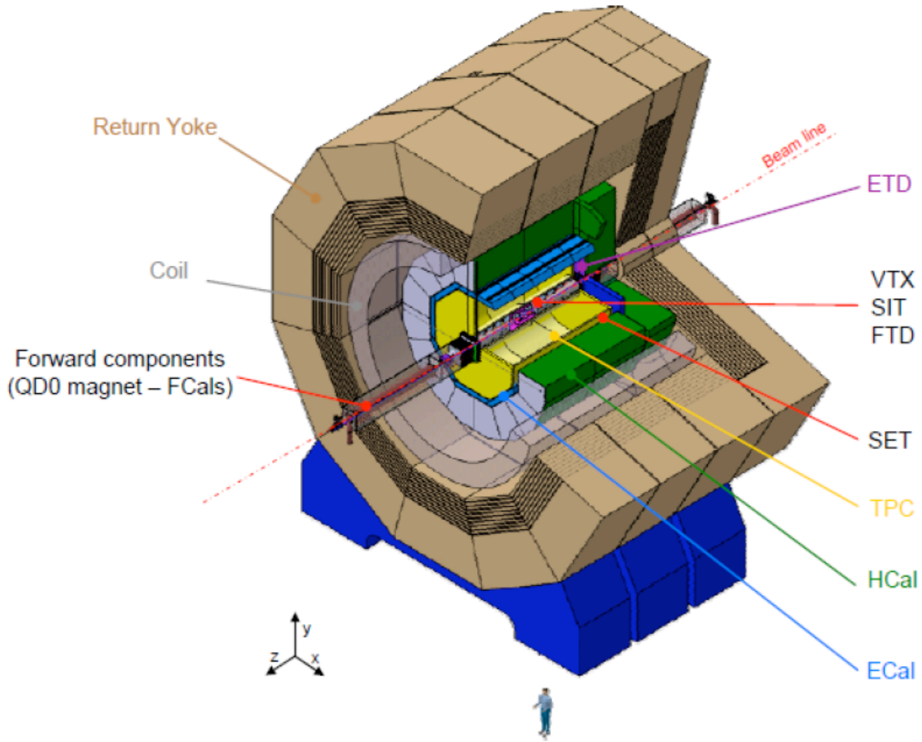


The ILD concept

Detector issues

- Particle flow
  - Granular calorimeter
  - “Light” tracker

- Excellent tracking and vertexing.
  - σ_{IP} = 5μm $\oplus$ 10μm GeV /psin$^{3/2}\theta$
  - $\delta p/p = 5 \times 10^{-5}$.



Particle flow in a nutshell:

- reconstruction of single particles in a jet;
- charged particle with tracker;
- photons with ECAL;
- neutrons with HCAL.

The ILD concept

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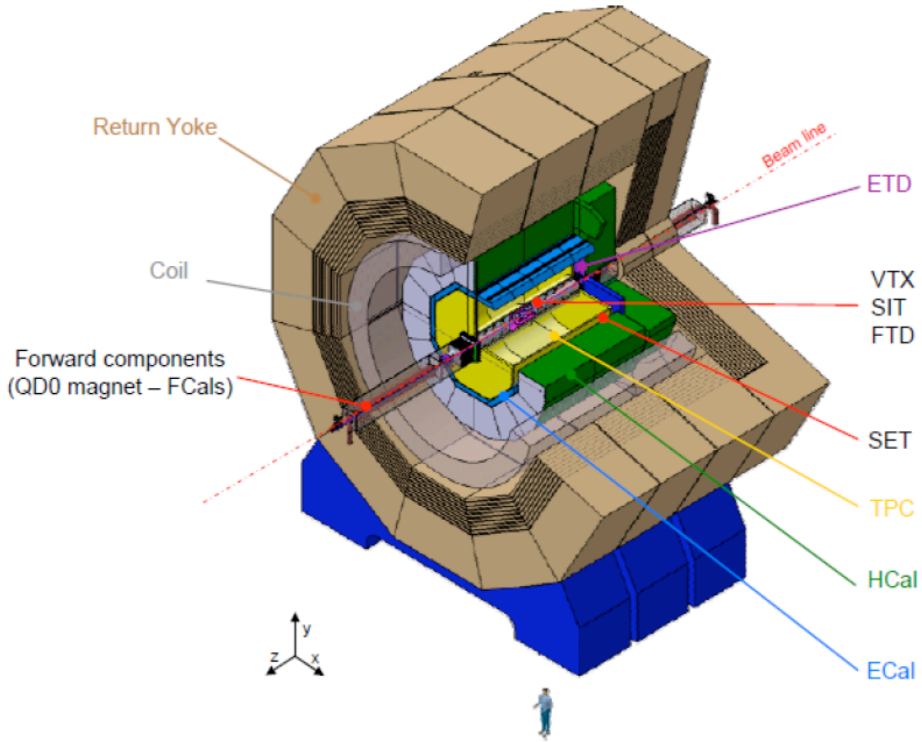

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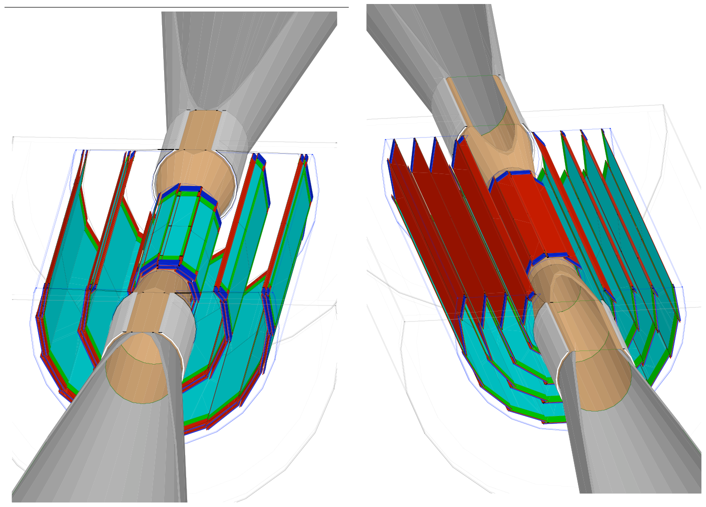
- reconstruction of single particles in a jet;
- charged particle with tracker;
- photons with ECAL;
- neutrons with HCAL.

SiD detector concept:
Si tracking system

A vertex detector for the ILD - 1

Two alternative geometries

- 5 single-sided layers.
- 3 double-sided layers.



Sensor requirements

- Single point resolution ~ 3μm.
- Material budget 0.16/0.11% X_0/layer.
- Integration time 25 – 100 μs.
- 16/15 mm inner radius.
- Radiation tolerance ~0.3MRad, few $10^{11} n_{eq}/cm^2$.
- $O(10^3)$ hit pixels/cm^2/10 μs on the inner layer.
- Averaged power dissipated << 100 W.

A vertex detector for the ILD - 2

Accelerator	*a (μm)*	*b (μm GeV)*
LEP	25	70
SLD	8	33
LHC	12	70
RHIC-II	13	19
ILC	< 5	< 10

$$\sigma_{IP} = a \oplus b/p\sin^{3/2}\theta$$

a depends on the intrinsic resolution and inner radius

b depends on material budget

Fast, highly granular, light detector !

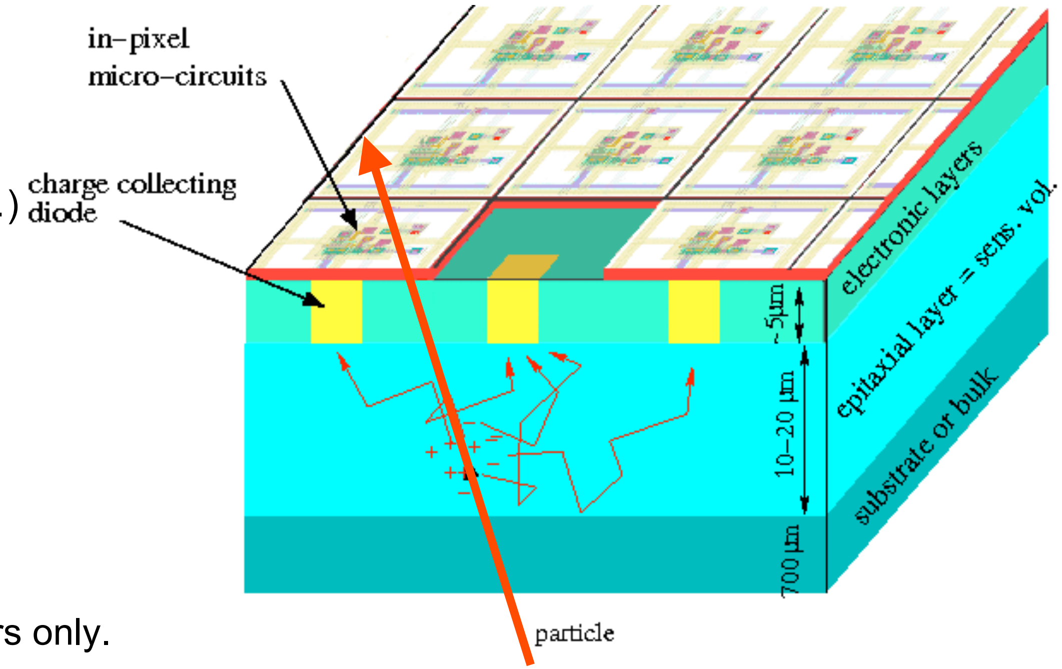
CMOS sensor principle

Signal collection

- Charges generated in epitaxial layer → ~1000 e^- for MIP.
- Charge carriers propagate thermally.
- In-pixel charge to signal conversion.

Advantages

- High granularity (< 10 μm pitch).
- Thickness (<50μm).
- Integrated signal processing.
- Standard process (cost, prototyping, …)

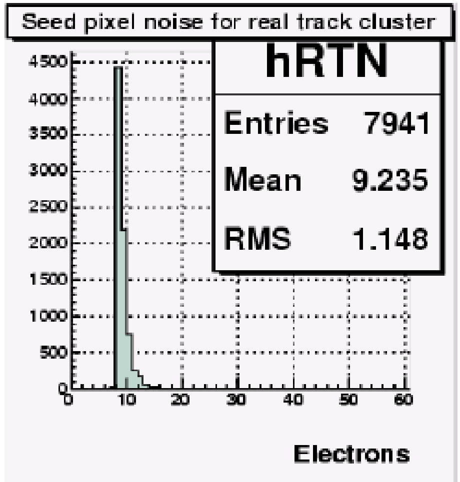


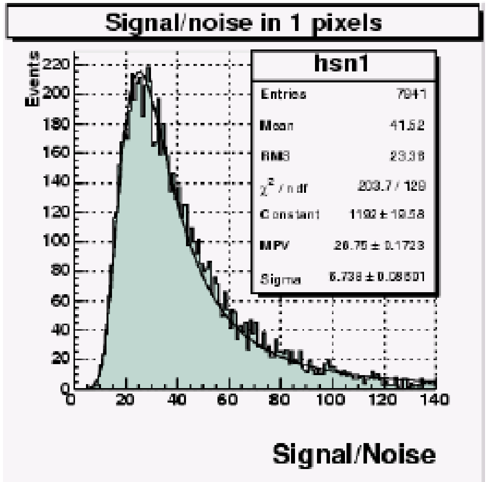
Issues

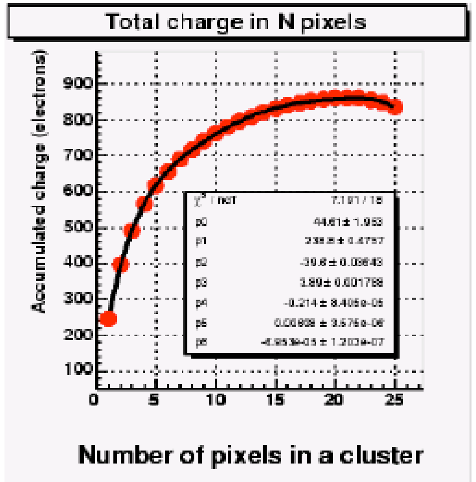
- Undepleted volume limitations .
  - radiation tolerance.
  - intrinsic speed.
- Small signal O(100e^-)/pixel.
- In-pixel μ-circuits with NMOS transistors only.

Basic performances

- More than 30 different sensors designed, fabricated and tested (lab & beam).
- Extensive use of 0.35μm CMOS technology.
- Room temperature operation.
- Noise ~10-15e^-.
- S/N ~ 15-30.
- Detection efficiency ~100% @ fake hit rate O(10^{-4} -10^{-5}).
- Radiation tol. > 1MRad and $10^{13} n_{eq}/cm^2$ with 10μm pitch ($2x10^{12} n_{eq}/cm^2$ with 20μm pitch).
- Spatial resolution 1-5 μm (pitch and charge-encoding dependent).
- Macroscopic sensors (Ex. MIMOSA-5: 1.7 x 1.7 mm^2, 10^6 pixels).
- Used in beam telescopes and VTX demonstrators (EUDET, TAPI, STAR, CBM).





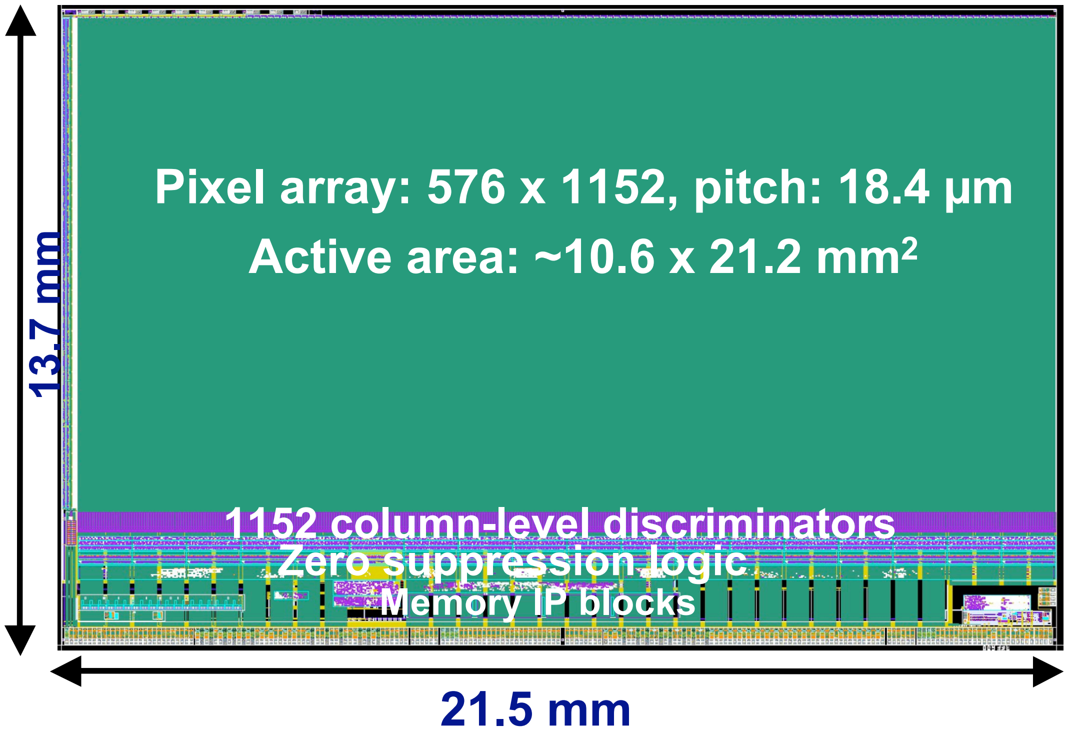


Mimosa-26

Fast full scale sensors: ~10kFrame/s

column parallel architecture + integrated zero-suppression

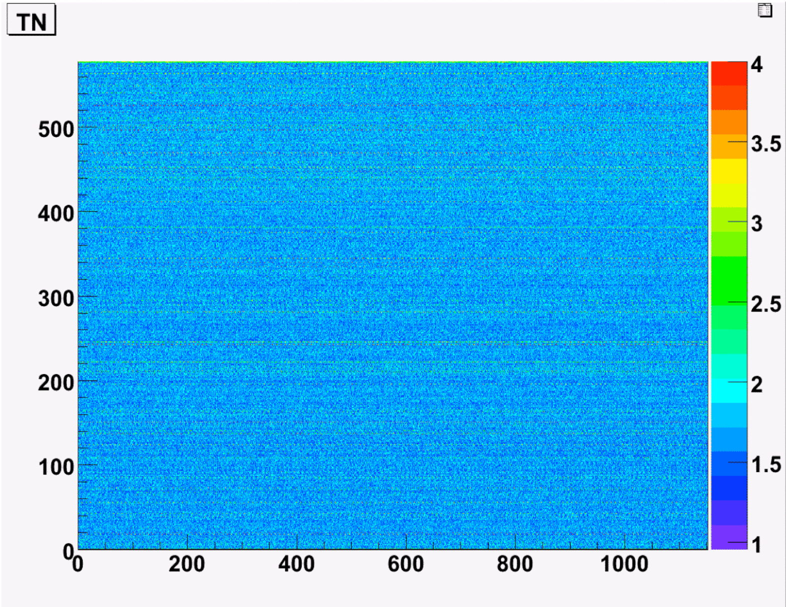
(prototyping with MIMOSA-22 for binary output + SUZE-01 for ∅)



- Active area ~2 cm^2.
- 0.35 µm technology.
- Binary output (3.5 - 4 µm spatial resolution).
- In-pixel CDS + preamp.
- Column level discrimination.
- Power dissipated ~280 mW/cm^2 (rolling shutter).
- Integration time ~100µs.

6 wafers x 77 sensors produced: fabrication yield ~90%

Laboratory tests



Analogue response for 8 different sensors:

• All pixels are alive.
• Noise is uniform across the sensitive area (~2cm^2).
• Operated from 80 MHz (nominal) down to 20 MHz.
• Noise and CCE (from ^{55}Fe source) as expected (like MIMOSA-22).

Digital response for 21 different sensors:

• All discriminators are operational at nominal speed.
• Discriminator noise like MIMOSA-22.

Analogue + digital response:

• Total noise 0.7 mV (~12-13 e^- ENC) like MIMOSA-22.

Zero-suppression works as expected.

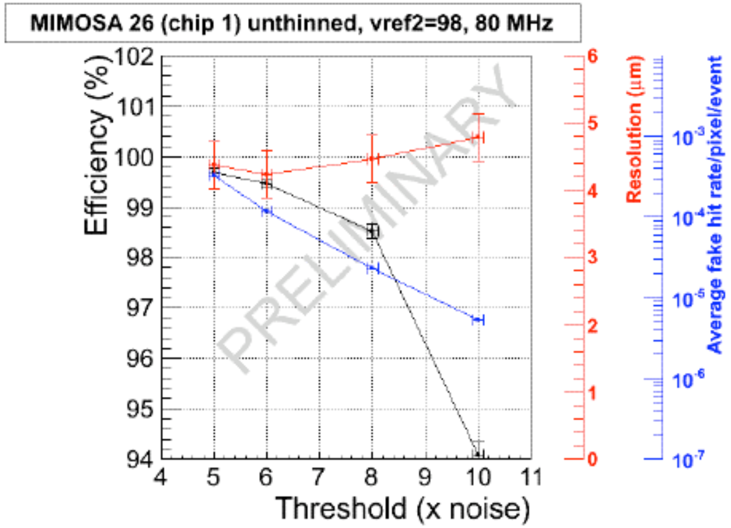
Full chain:

• Fake hit rate O(10^{-4}) @ 6N discri. threshold.
• Performances unchanged for 20° < T < 40°

Array of 660,000 pixels coupled to 1152 discriminators works ~ as expected

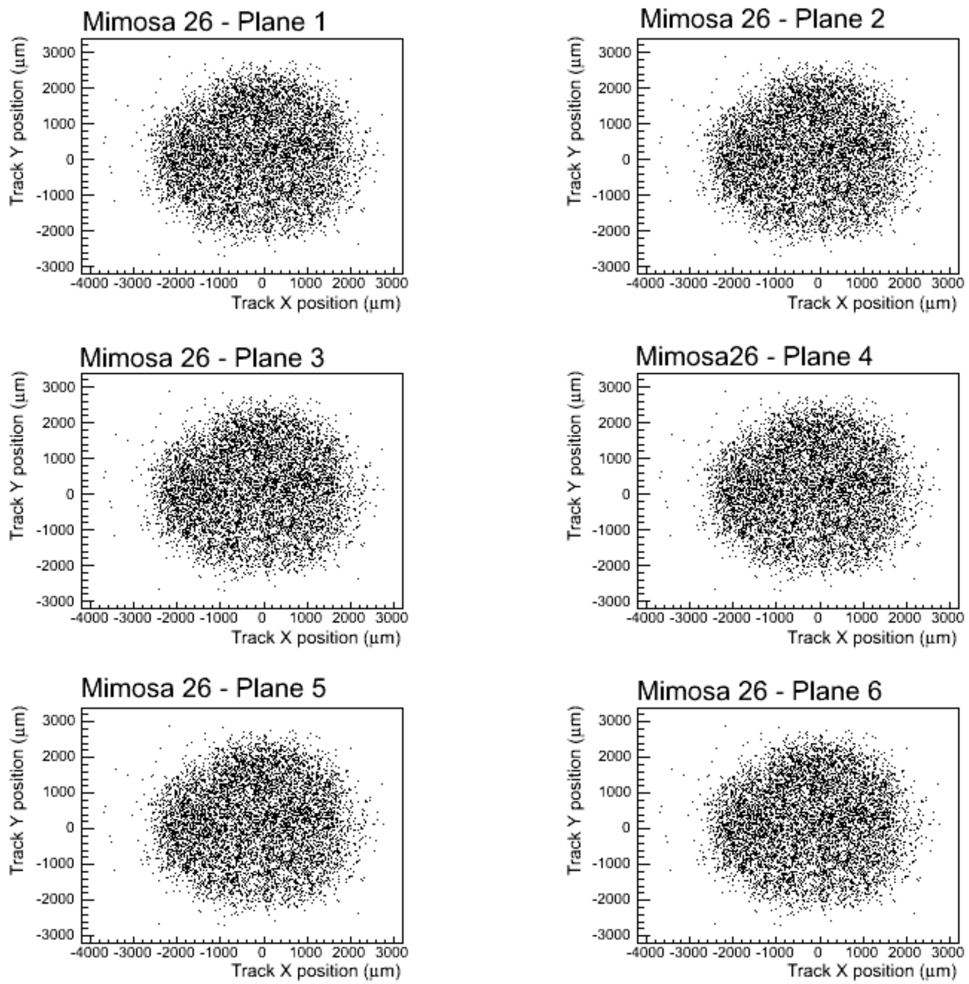
Preliminary beam test results

- TAPI = IPHC-Strasbourg BT for MIMOSA development.
- Test @ CERN-SPS (120 GeV π^- beam).
- 6 MIMOSA-26 sensors running simultaneously at nominal speed (80 MHz).
- 3 x 10^6 triggers.



ε = 99.5 ± 0.1 (stat.) ± 0.3 (prel.) %

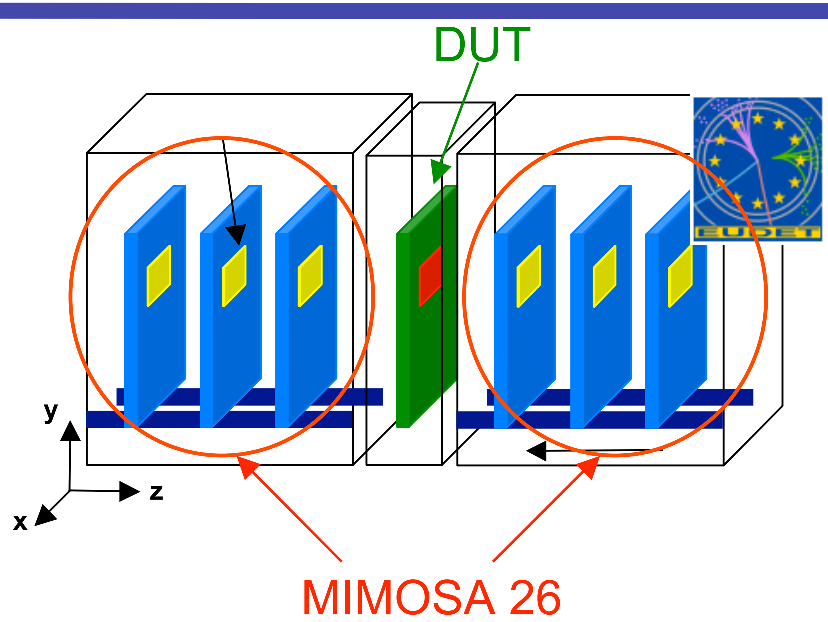
@ fake hit rate O(10^{-4})

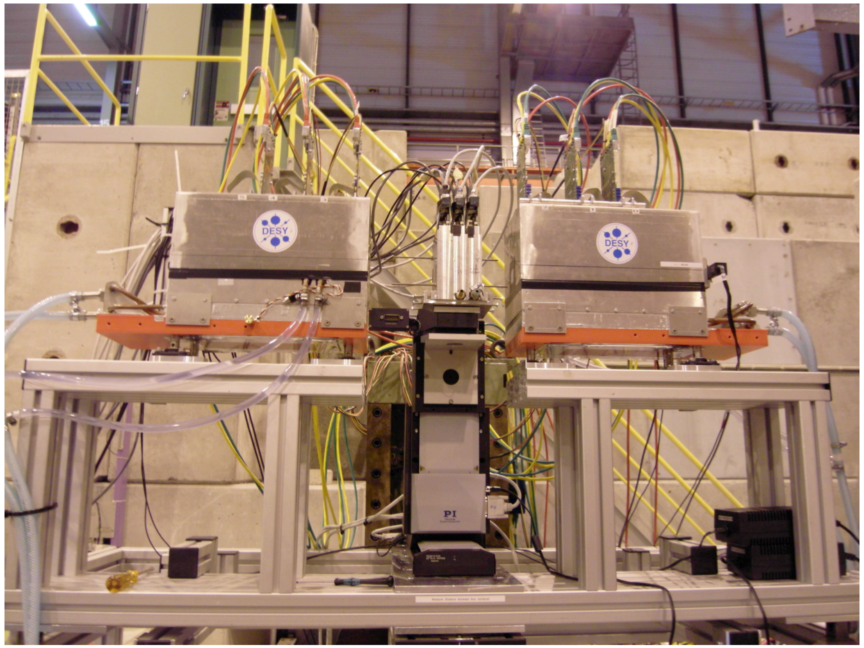


EUDET beam telescope

Reference planes of EUDET Beam Telescope

- Supported by EU FP6.
- Infrastructure to support the ILC detector R&D.
- Specifications:
  - Extrapolated resolution <2 μm.
  - Sensor area ~2 cm^2.
  - Read-out speed ~ 10 kframe/s.
  - Up to 10^6 hits/s/cm^2.



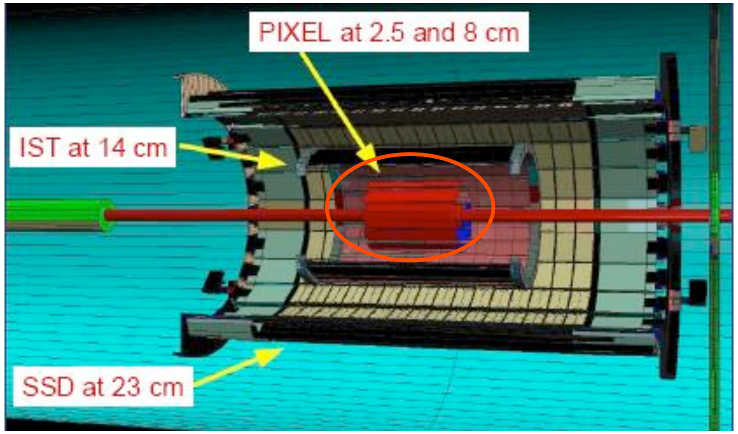


Commissioning @ CERN-SPS last year:

- BT completely equipped with MIMOSA-26.
- Largely used by ILC and non-ILC groups.

www.eudet.org

Mimosa-26 evolutions: STAR HFT



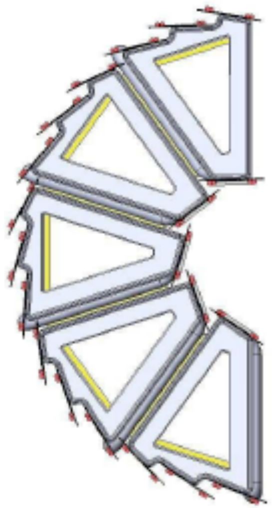
STAR @ RHIC Heavy Flavour Tracker

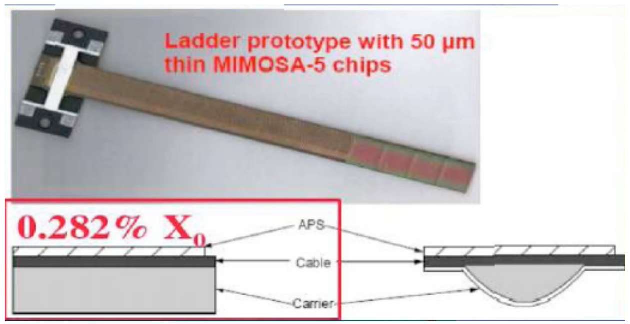
PHASE-1:

- no ∅
- 640 x 640 pixels (30 μm pitch);
- 640 μs integration time.
- 50 μm thin.
- 1/4 of the detector.

ULTIMATE:

- MIMOSA-26 like.
- 1152 x 1024 pixels (18.4 μm pitch);
- 200 μs integration time.
- 50 μm thin.
- Improved radiation tolerance.
- First data in 2012

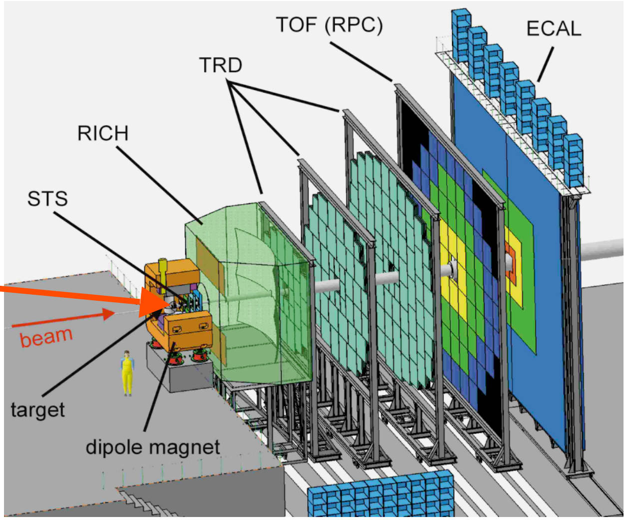




Mimosa-26 evolutions: CBM MVD

CBM @ FAIR Micro Vertex Detector

- Double sided readout.
- 0.18 μm (40→20μs integration time).
- Improved radiation tolerance.
- Prototyping until 2012.

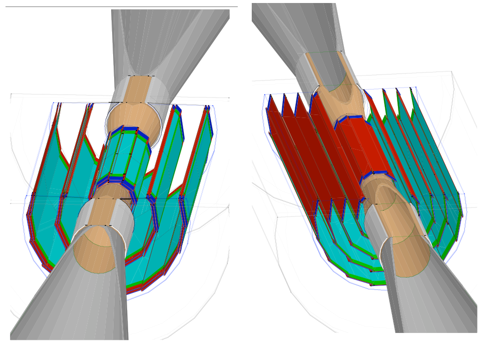


Interest expressed by the ALICE collaboration for the upgrade in view of sLHC

The ILD applications

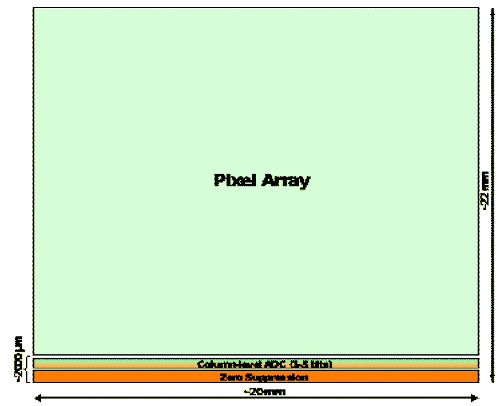
Physics requirements

- single point resolution ~ 3μm.
- integration time 25 – 100 μs.
- O(10^3) hit pixels/cm^2/10 μs on the inner layer.
- …



From 0.35 μm to (<)0.18 μm feature size:

- improved clock frequency, more metal layers, more compact peripheral circuitry, …

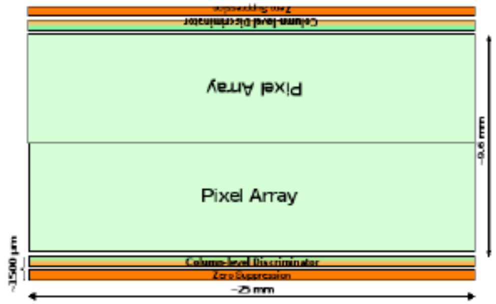


Extension for the outer VTX layers:

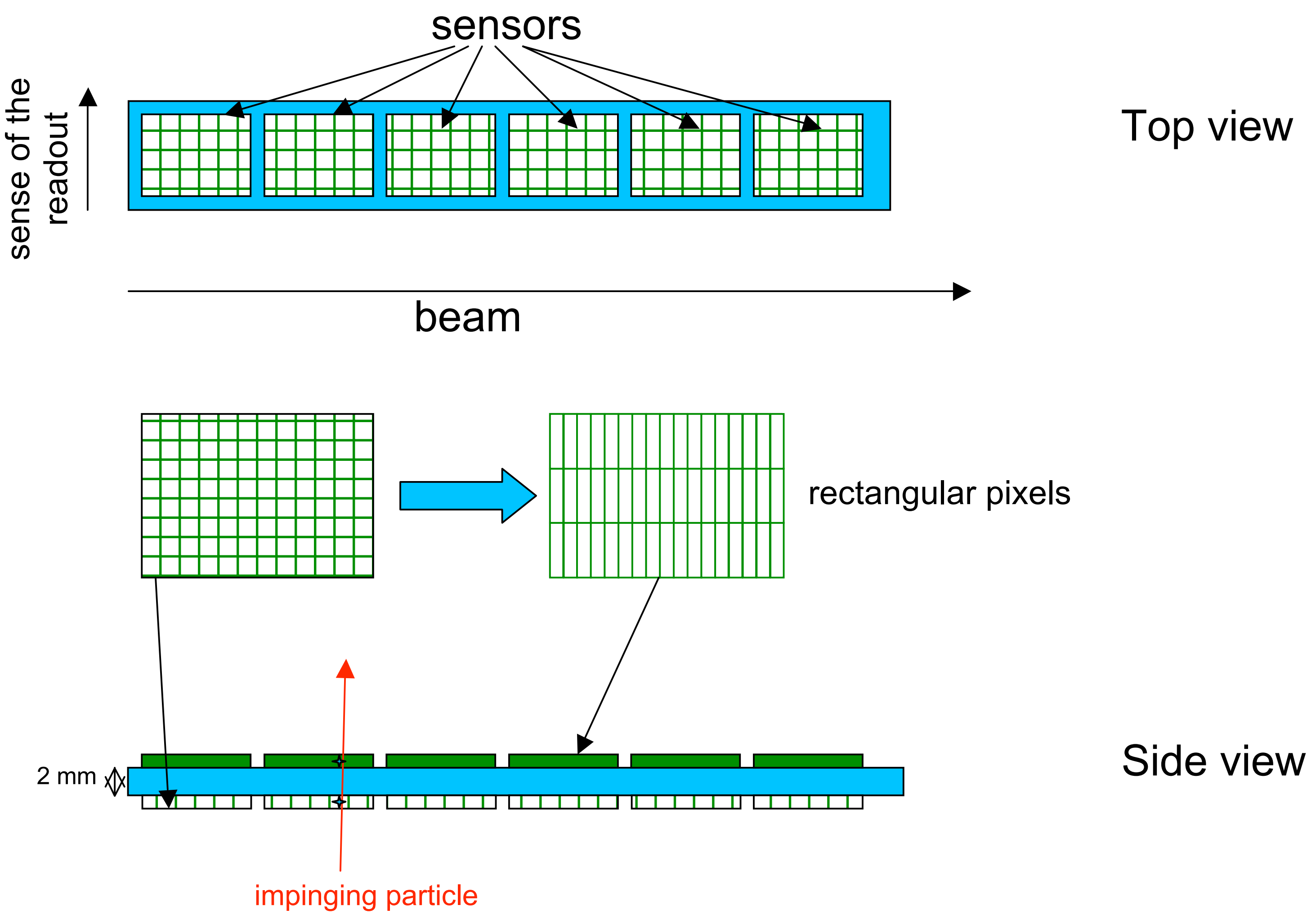
- σ ~ 3 μm: 4 bits ADC and a ~ 35 μm pitch (r.o. ~100 μs).

For the inner layers:

- ~ 15 μm pitch → binary readout.
- Double-sided r.o. → r.o. ~ 50 μs.
- Smaller feature size → 35 – 40 μs.
- Double sided ladders → << 35 μs.



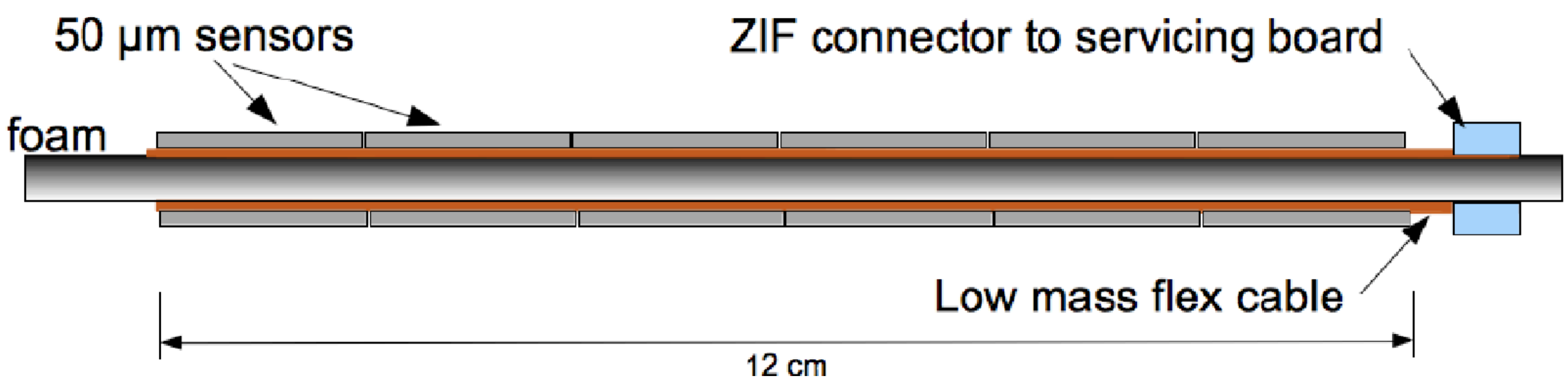
Improve time resolution with double sided structure



From 15μm to 60μm pitch → from 40μs to 10μs readout time

System integration: the PLUME project

- **P**ixel **L**adder with **U**ltra-low **M**aterial **E**mbedding.
- Bristol - DESY - Oxford - Strasbourg (synergy with CBM-MVD).
- Double sided ladder equipped with 2x6 MIMOSA-26 (ILC DBD 2012).
- 0.2 - 0.3 % X_0.
- Explore feasibility, performances and added value of double-sided ladders.
- Allows for improved time resolution (outer layer with longer and fewer pixels).



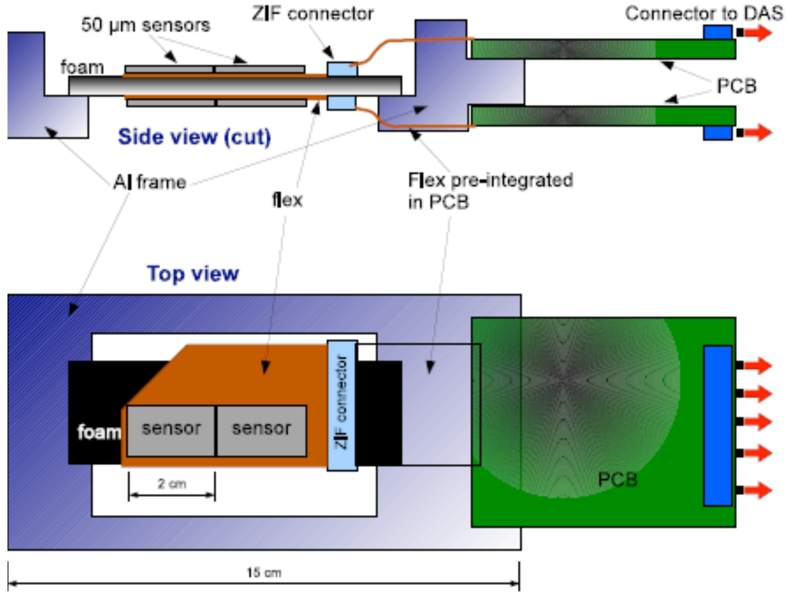
System integration: the PLUME project

2009

• 2 pairs of MIMOSA-20 sensors (4 x 1 cm^2, 50μm thin) mounted on flex cable + SiC support.

• Total material budget ~0.5% X_0 .

• Beam test at CERN-SPS in November.



2009 - 2012

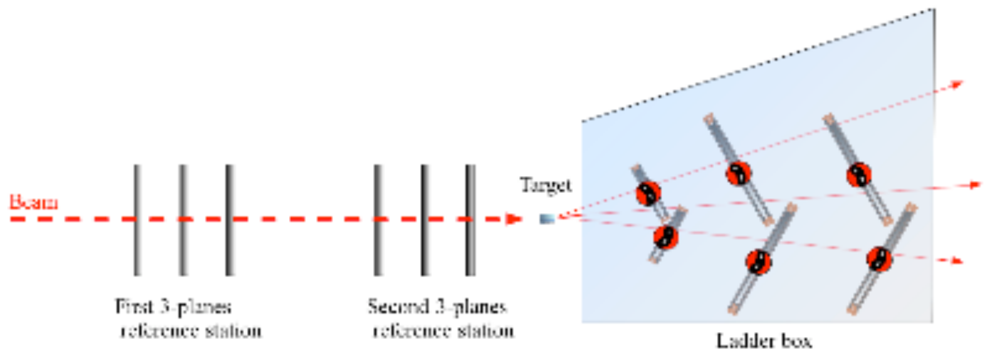
• 2 x 6 MIMOSA-26 sensors (12.5 x 1 cm^2, 50μm thin) mounted on flex cable + SiC support.

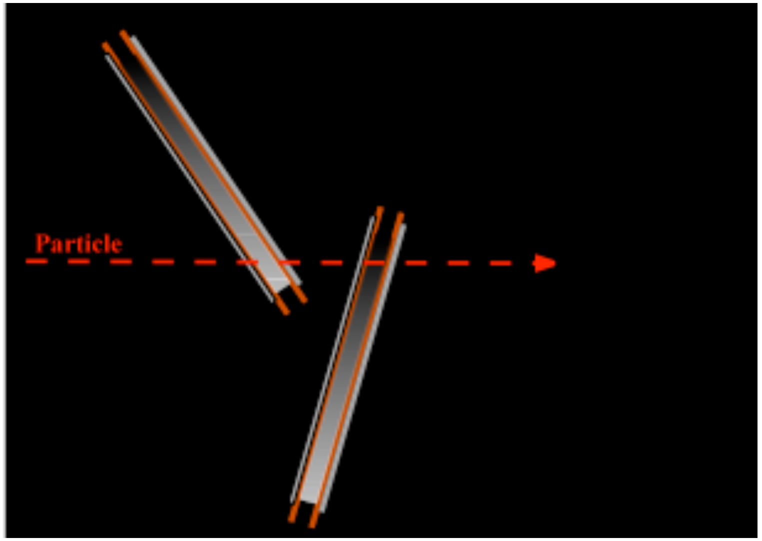
• Total material budget ~ 0.2% X_0 .

VXD infrastructure proposed for AIDA

On-beam test infrastructures:

- Large area telescope.
- Alignment Investigation Device (AID).
- Thin removable target.





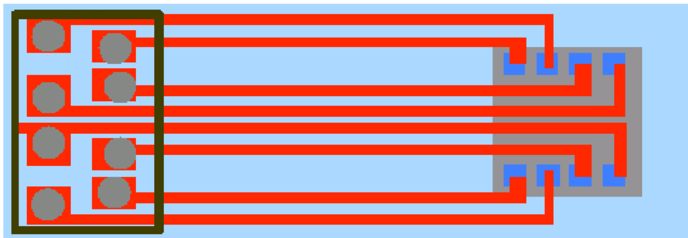
Off-beam test infrastructures:

- Thermo-mechanical studies (i.e. air flow cooling).
- Power cycling effects in strong magnetic field.

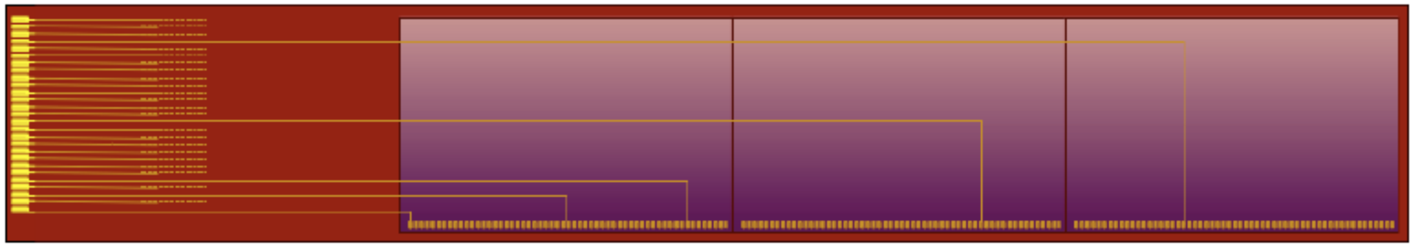
System integration: SERWIETE

- **SE**nsor **R**ow **W**rapped **I**n **E**xtra-**T**hin **E**nvelope (HP 2 Project).
- Frankfurt – Darmstadt – Strasbourg.
- Sensors wrapped in thin polymerised film.
- <0.15% X_0 expected for sensor (35 μm thin) ⊕ flex ⊕ film (no mechanical support).
- May match cylindrical surfaces (beam pipe?).
- Proof of principle in 2012.
- First prototype by Spring (analog output, ~4ms)
- Second prototype by 2011 (digital output, ~110μs)

Proto 1 ▷ Spring 2010



Proto 2 ▷ Summer 2011



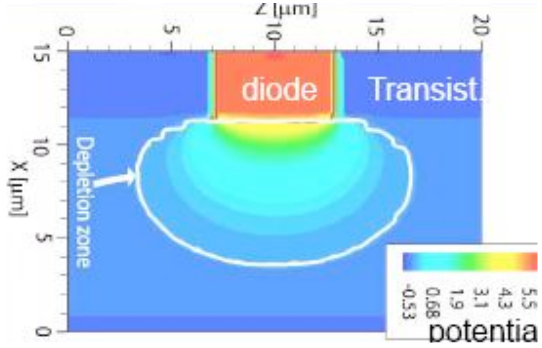
Further developments: high resistivity epi layer

High resistivity epitaxial layer(O(10^3) Ω·cm) ⇒ depleted sensitive volume!

⇒ Faster charge collection

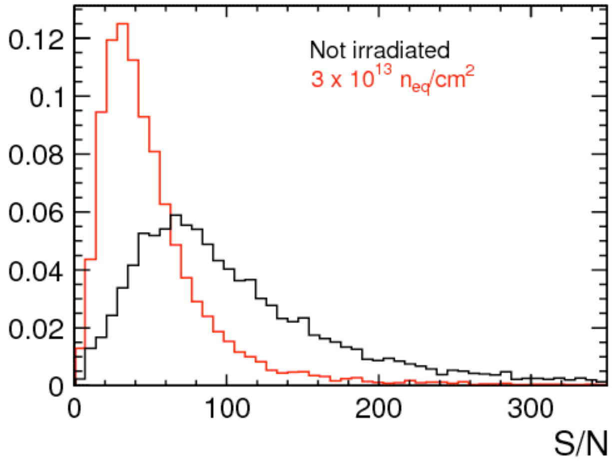
⇒ Shorter path length (improved tolerance to non-ionising radiation)

⇒ Larger CCE (larger pitch possible without affecting the detection efficiency)

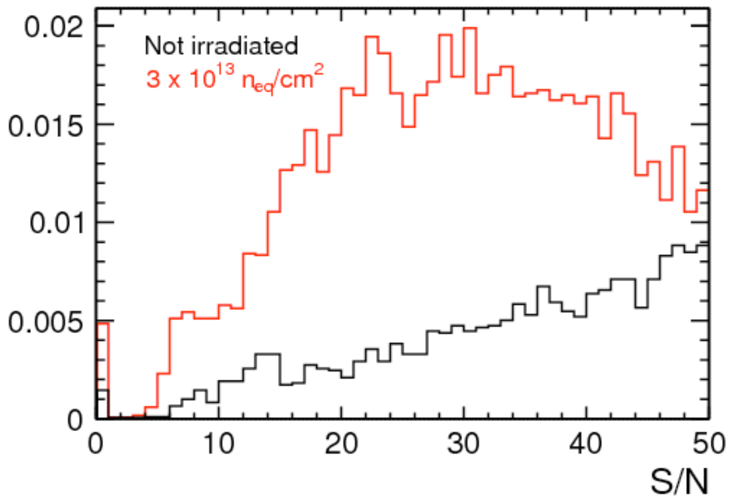


Exploratory sensor: MIMOSA-25 (0.6 μm technology)

- Fabricated in 2008 and tested at CERN-SPS before and after irradiation.
- Cluster size ~ 2×2 pixels (3×3 for low resistivity epi-layer).
- S/N ~ 60 for seed (20-25 for low resistivity epi-layer - ~ 30 @ $3 \cdot 10^{13} n_{eq}/cm^2$).
- ε = 99.9% (99.5% @ $3 \cdot 10^{13} n_{eq}/cm^2$).
- Improved tolerance to non-ionizing radiation (1-2 OoM).



ZOOM

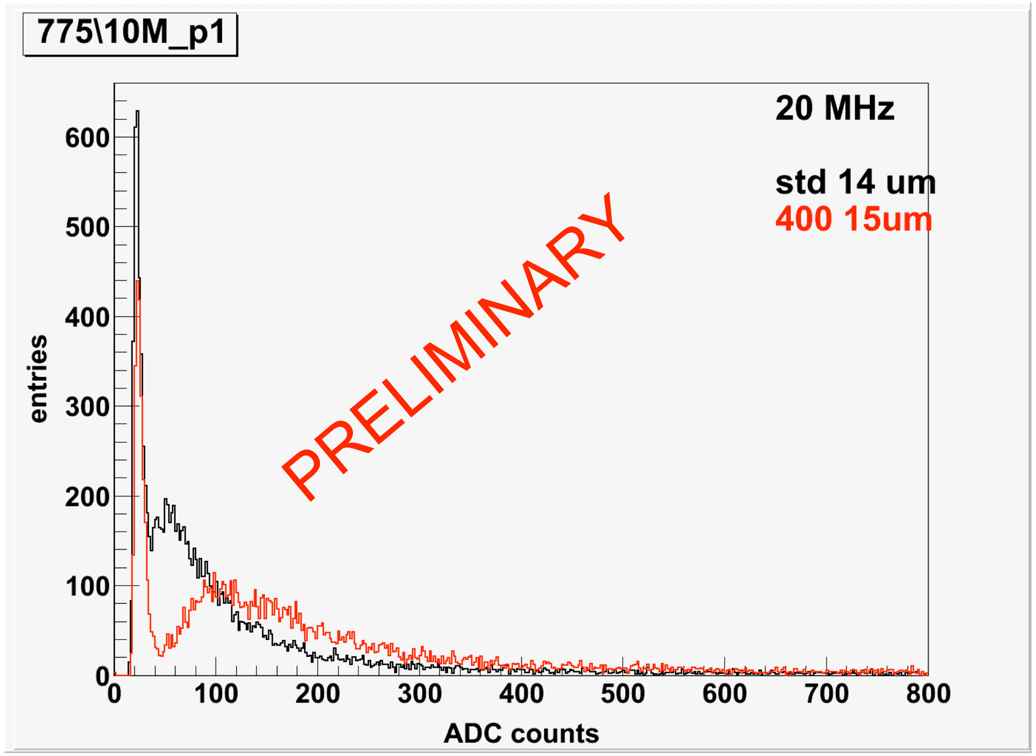


MIMOSA-26 with high resistivity epi layer

NEW!

MIMOSA-26 high res.(400 Ω·cm) 0.35 μm presently under test (for STAR-HFT)

Preliminary lab test with Ru source (Analog test mode)

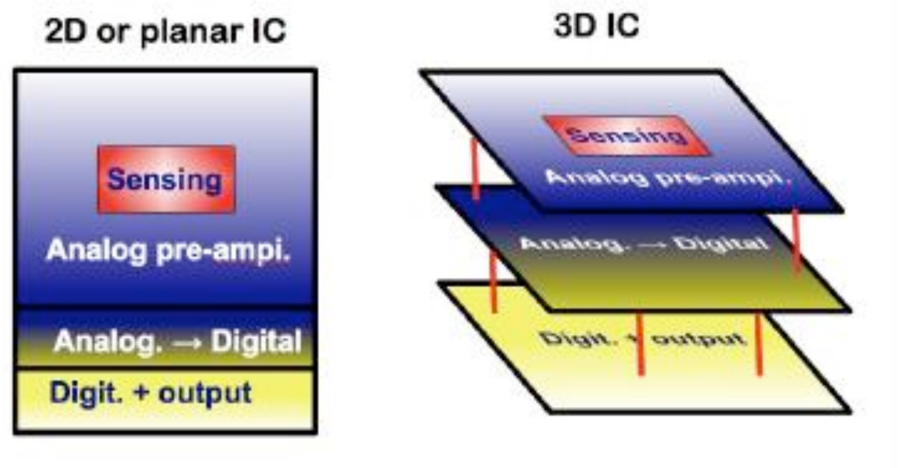


Also: VDSM technology under study in coll. with CERN for sLHC (LePIX) (<< 1 μs)

Further developments: 3D IT

Benefits:
- Increase integrated processing.
- 100% sensitive area.
- Select best process per layer task.

To be assessed:
- Material budget?
- Power dissipation?



Example
- Tier1: charge collection.
- Tier2: analog signal processing.
- Tier3: digital signal processing.
- Tier4: data transfer.

FNAL + IN2P3 + INFN + … consortium (3DIC)

First chips (2-Tier 130nm technology) being fabricated

3D IT first try

2 Tiers sensor for delayed readout:

- ILC delayed readout.
- ro + discri+ time stamp + memory in each pixel.
- 12 μm pitch (reduce # hits/pixel/ro)

2 Tiers sensor to minimize power consumption:

- IPHC-IRFU
- Rolling-shutter in submatrices

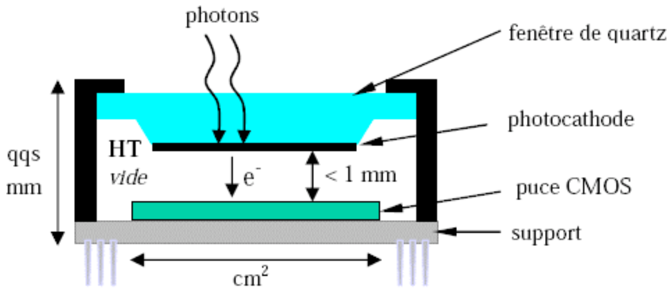
3 Tiers sensor:

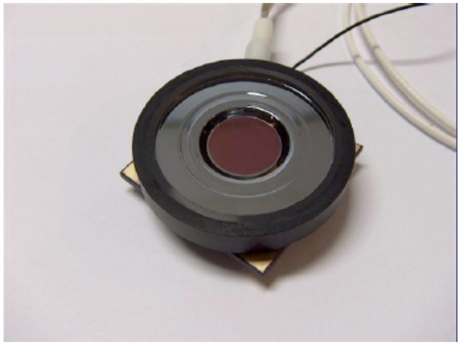
- IPHC-INFN Padova/Bergamo
- 2 Tiers signal processing + 1 Tier detection (High res.)
- ~ 1 μs readout

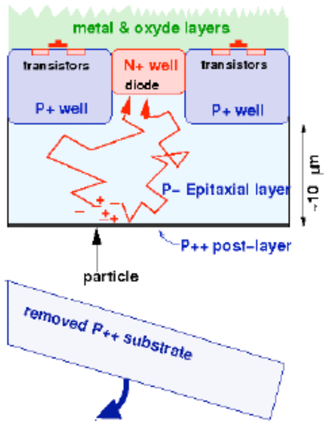
Other (non HEP) applications

ebCMOS:

- IPHC-IPNL-PHOTONIS.
- Single (visible) photon detection.
- Fluorescence microscopes.

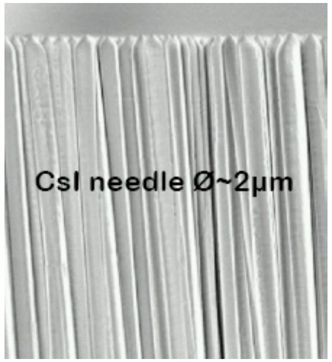






X-rays :

- Direct illumination below 10 keV
- Converter above 10keV (Columnar CsI crystals from Hammamatsu)



Other applications :

- Dosimetry, surgery camera, hadron therapy…

Summary and future perspectives

Current CMOS sensors

- Mature technology for real scale applications.
- High resolution, very low material budget.

First full scale sensor with high read-out speed: MIMOSA-26.

- Binary output + integrated zero-suppression.
- Tested in laboratory and on beam.
- EUDET-BT, STAR-HFT, ALICE, CBM-MVD, ILD-VTX (option).

System integration studies started: PLUME, SERWIETE, …. ➔ Material budget O(0.1 % X_0)

New perspectives

Depleted sensitive volume:

- Technology prototyped with MIMOSA-25.
- MIMOSA-26 high res. under test.
- Expectations: fast charge collection and non ionizing radiation tolerance > $10^{14} n_{eq}/cm^2$.

3D integration technique:

- 3 CAIRN prototypes being produced (low power, few μs r.o., delayed readout with timestamp).
- Heterogeneous chip (depleted sensitive volume).

More information on

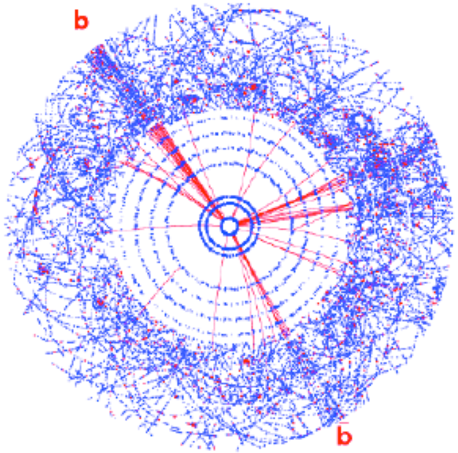
http://www.iphc.cnrs.fr/-CMOS-ILC-.html

Backup slides

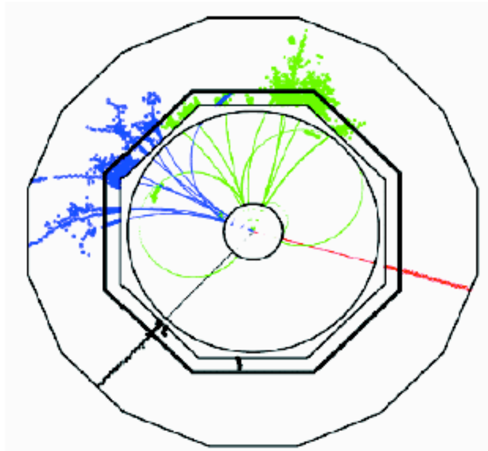
Calorimeter R&D for HEP detectors

The largest scale HEP detectors at (s)LHC and the future LC

The LHC $pp \rightarrow H + X$



The ILC $e^+e^- \rightarrow HZ$

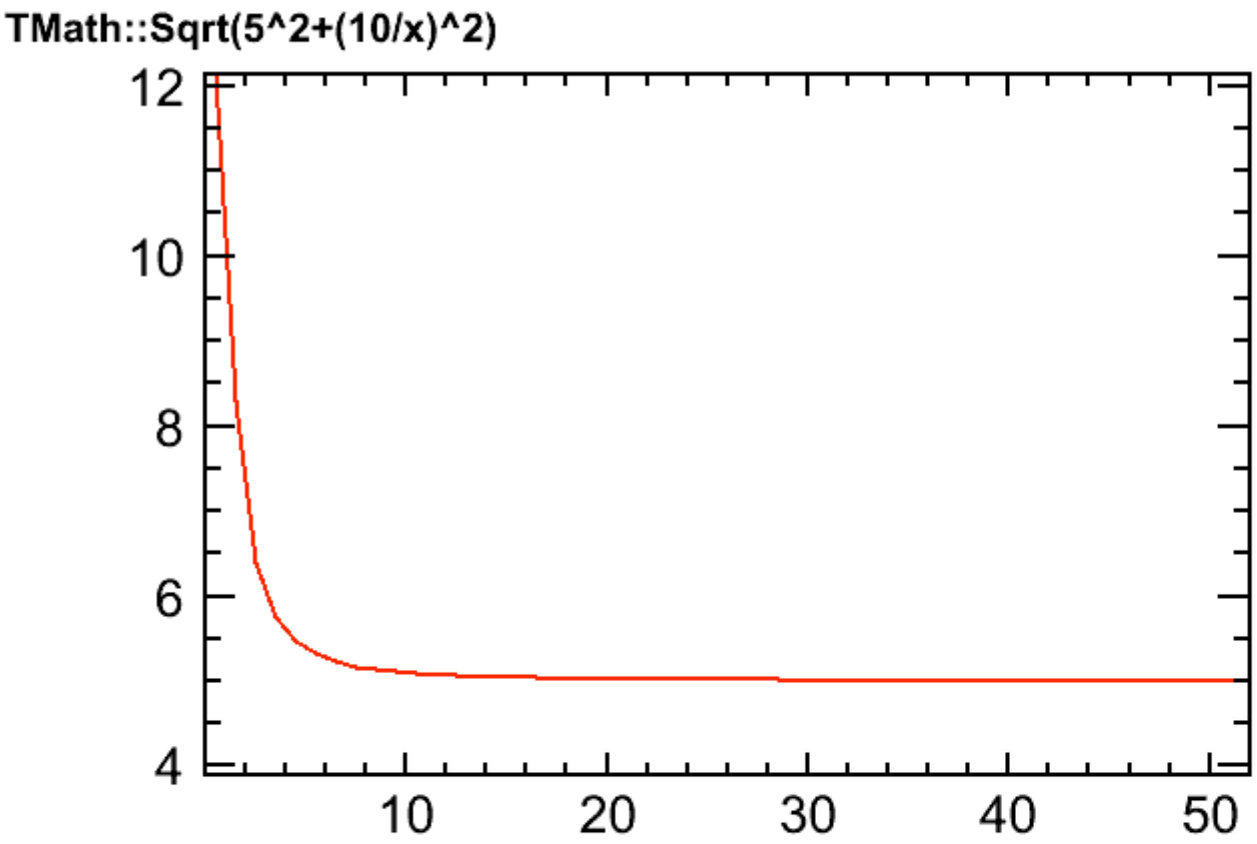


★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see** $H \rightarrow b\bar{b}$ **and** $Z \rightarrow \mu^+\mu^-$ **and nothing else…**

High precision LC physics demands a high precision detector:

- high precision vertex (flavor tagging) and tracking (Higgs from di-lepton recoil mass)
- precision calorimetry (heavy bosons reconstruction from di-jet decay)

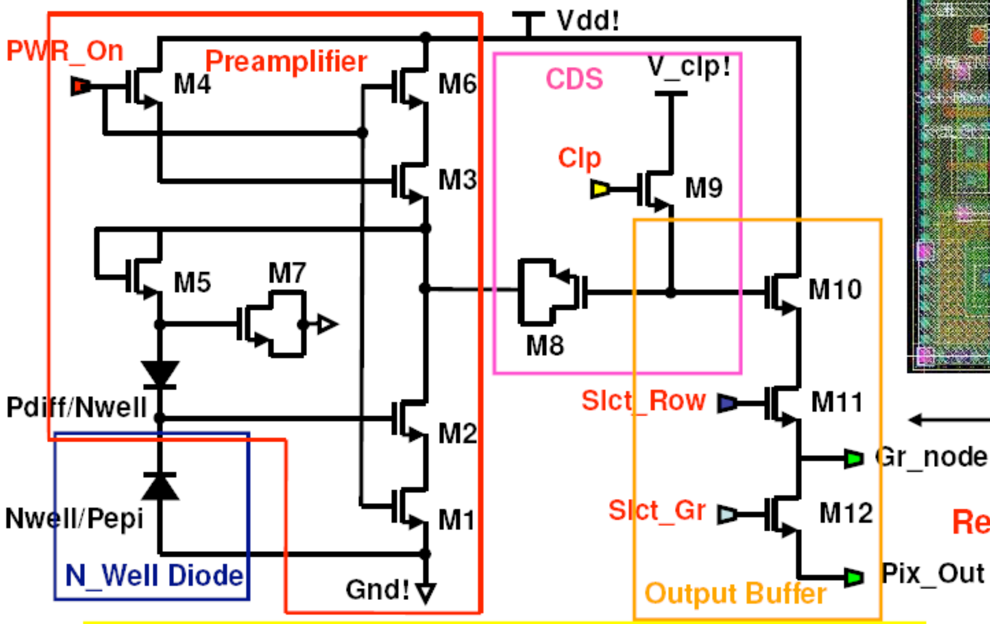
➔ significant improvements in the calo. system, in particular in the HCAL

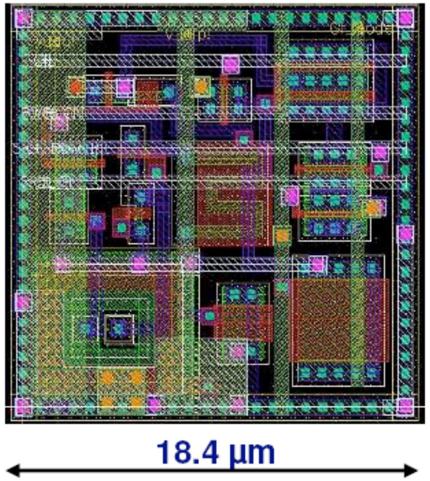


TMath::Sqrt(5^2+(10/x)^2)
12
10
8
6
4
10
20
30
40
50

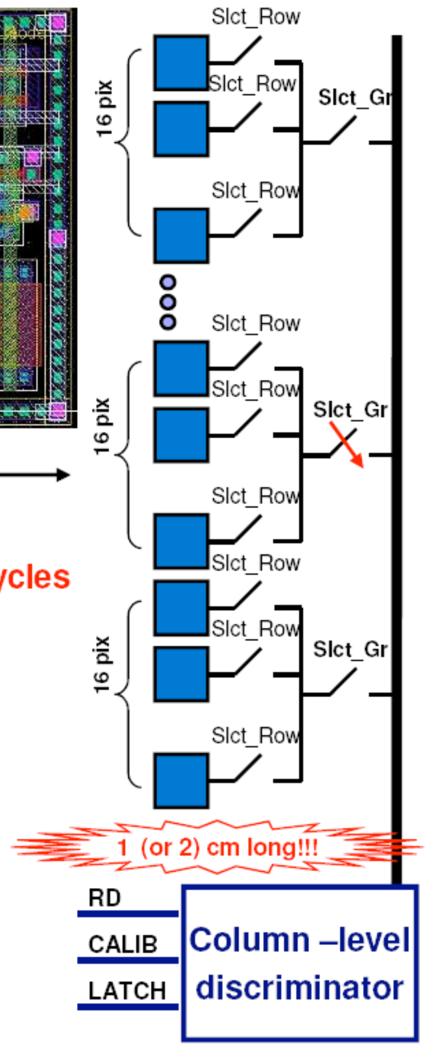
Readout Chain: Pixel

See Ref. A. Dorokhov et al., TWEPP-07 CERN-2007-007 proceeding pp. 423-427





Readout = 16 CK cycles



ONLY NMOS transistors can be used, since any additional N-well used to host PMOS transistors would compete for charge collection with the sensing N-well diode

- *4 digital control signals per row: PWR_On, Slct_Row, Slct_Gr, Clp*
  - *Slct_Row (16CK), PWR_On (2x16CK), Slct_Gr (16x16CK): power activate signals*
  - *Clp: signal for CDS (3CK)*
- *Power consumption: ~200 µW/pixel*