PLUME

Ultra-light double-sided ladders for a LC vertex detector

Outline:

- Motivation for ultra-light vertex detector
- PLUME collaboration: status and results

Ingrid-Maria Gregor, DESY
for the PLUME Collaboration
LC Forum
DESY, October 2013

ILC Vertex Detector

- 1 Giga channels of 20×20 µm pixels in 5 layers with fast readout
  - excellent IP resolution **(5 µm)² + (10 µm /p)²**
  - Low material budget 0.1% X_0 per layer
    - Air cooling
  - Radiation tolerance 300krad, $10^{11} n_{eq}/cm^2$
  - Peak power < 0.1 – 2 W/cm²

- Sophisticated algorithms using vertexing
  - Vertex mass
  - Vertex charge
  - Vertex dipole
- Flavour tagging
  - Excellent performance for b- and c-tagging

ILD vertex detector layout:

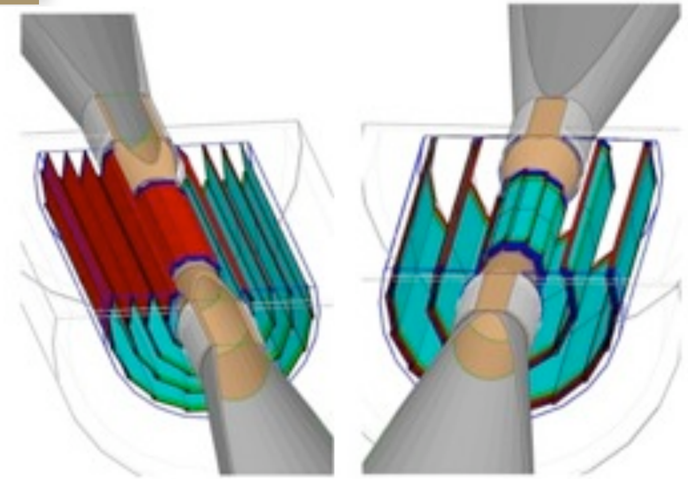


Figure of merit for the VXD:
Impact Parameter Resolution

$$\sigma_{r\phi} \approx \sigma_{rz} \approx a \oplus b/(p \sin^{3/2}\vartheta)$$

Accelerator	a (µm)	b (µm)
LEP	25	70
SLD	8	33
Tevatron	10	40
LHC	12	70
RHIC-II	12	19
ILC	**<5**	**<10**

(Marc Winter)

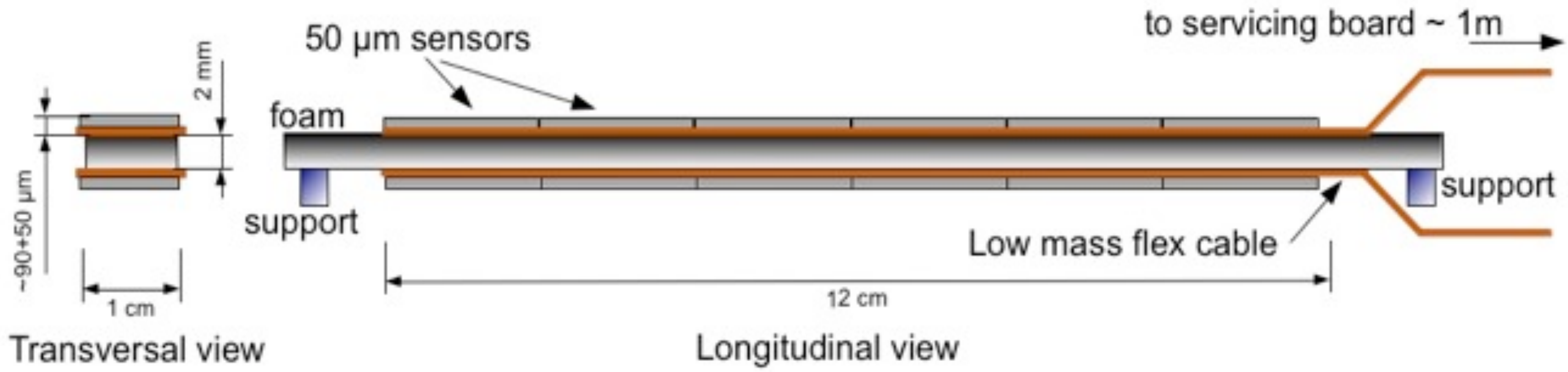
The PLUME collaboration

- ILC-oriented
  - Double-sided ladders
  - Air cooled
  - Power pulsed @ T=200ms
  - 125 mm long
  - Material budget goal ~ 0.35 % X0

PLUME = Pixelated Ladder with Ultra-Low Material Embedding

- Double-sided ladders benefits
  - Redundancy
  - Alignment: faster and/or more robust
  - Track finding boosted by mini-vectors

The “classical” sandwich



The PLUME collaboration

University of BRISTOL

- Mechanical design
  stiffener, supports
- Stability measurements
- Modules mounting on ladders

DESY

- Ladder mock-up & thermal measurement
- Power pulsing tests
- New: test beam analysis

IPHC Institut Pluridisciplinaire Hubert Curien Strasbourg

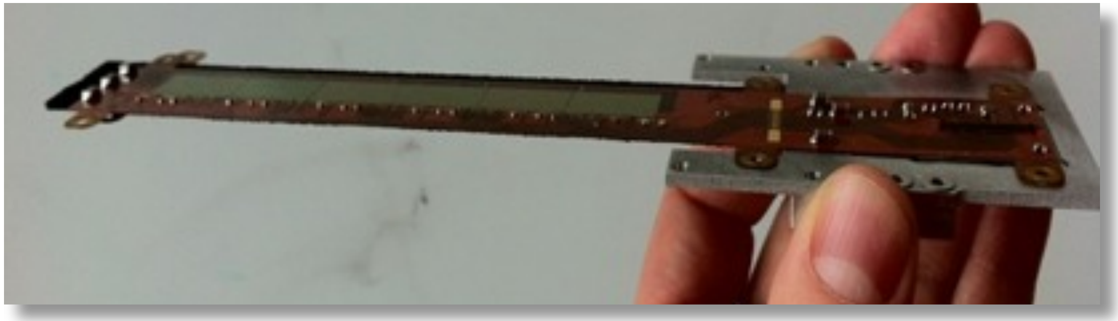
- Sensors mounting on modules
- Electrical tests
- Readout & DAQ
- Cooling system
- Test beam infrastructure & analysis

- Synergy with
  - IKF – Frankfurt, CBM group
  - LBNL – Berkeley, STAR-HFT group
  - CERN - ALICE@LHC

PLUME-1 design

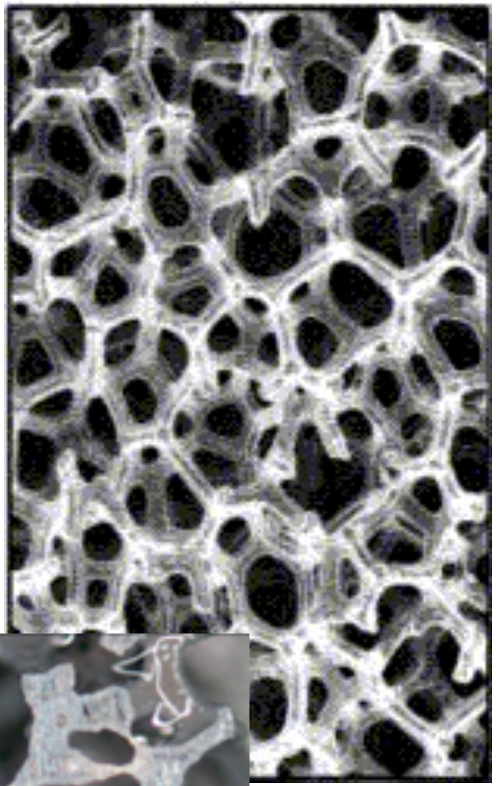
- **Goals**
  - Electrical functionality with 6 MIMOSA 26
  - Address the full fabrication, assembly & test chains

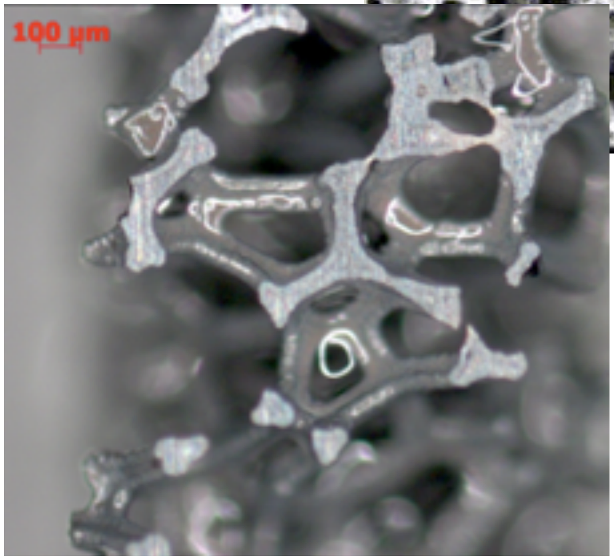
- **Key features**
  - 6x MIMOSA 26 thinned down to 50 µm
  - Low mass cable = 140 µm thick with 2x20 µm copper
  - Spacer = SiC foam at 8% density
  - 1 ladder = 8M pixels, 10g, 0.6 % X_0 (cross section)



SiC Spacer

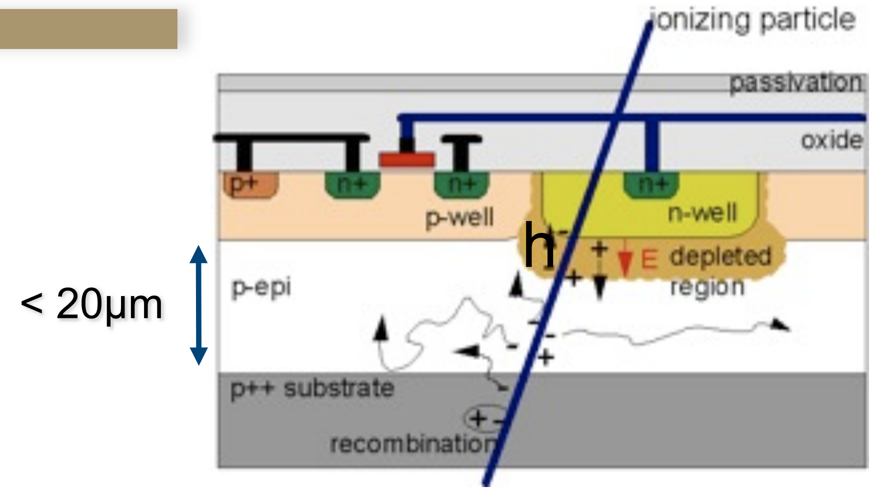
- Used as support in PLUME ladders
  - Follow-up work on LCFI (Bristol U.)
- Lightweight elements in silicon carbide (SiC) foam
  - Commercially available
  - Can be machined
- Properties:
  - Open-cell foam
  - Macroscopically uniform
  - 4 to 8 % fill factor (2-3% possible)
  - low thermal and electrical conductivity (50W/m/K)





Choice of Pixel Sensor: MAPS

- PLUME R&D transferable to all monolithic sensor approaches
- Our choice: MIMOSA
- IPHC Strasbourg working on this since >15 years -> Mimosa (Minimum Ionizing Particle MOS Active Pixel Sensor)



- Active area underneath the electronics (epi-layer <20μm thick) providing ~100% fill-factor
- Charge generated by ionization in the epitaxial layer thermally diffuse toward low potential n-well region
- Standard, cost-effective CMOS process, no post-processing

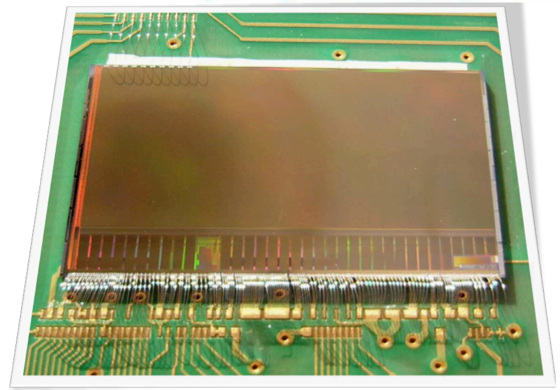
Features of the MIMOSA – detectors:

- Single point resolution 1 μm – 4 μm
- Pixel – pitch 10-40 μm
- Thinning achieved 50 - 120μm
- S/N for MIPs >40 (high resistivity substrate)
- Detection efficiency > 99%
- Radiation hardness: 1MRad ; 2 x 10^{13} n_{eq}/cm^2
- Produced in various commercial CMOS-processes

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

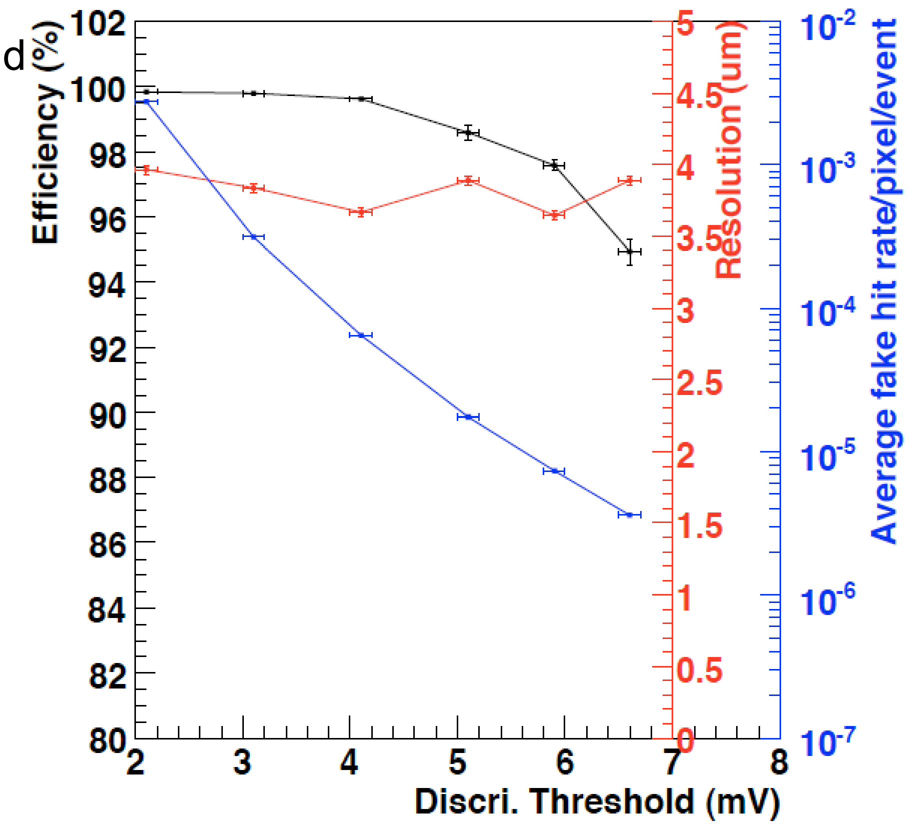
Mimosa26

- Mimosa-26 well known chips
  - used for EUDET style telescopes since 2009
- Active surface : 1152 columns of 576 pixels
- 21.2 x 10.6 mm^2
- Pixel pitch : **18.4 µm** -> 663k pixels
- Integration time ~110 µs -> 10^4 frames / second



Test Results

- Chip operating with >99.5 % detection efficiency over the whole sensitive area
- Fake hit rate of better than 10^{-4}
- Optimal discri. threshold ~5–6 x Noise value
- spacial resolution ~3.5 ± 0.2 µm (preliminary)



Plot: IPHC

MIMOSA26: 1st MAPS with Integrated Ø

- Pixel array: 576 x 1152, pitch: 18.4 µm
- Active area: ~10.6 x 21.2 mm²
- In each pixel:
  - Amplification
  - CDS (Correlated Double Sampling)

CMOS 0.35 µm OPTO technology

Chip size : 13.7 x 21.5 mm²

- Testability: several test points implemented all along readout path
  - Pixels out (analogue)
  - Discriminators
  - Zero suppression
  - Data transmission

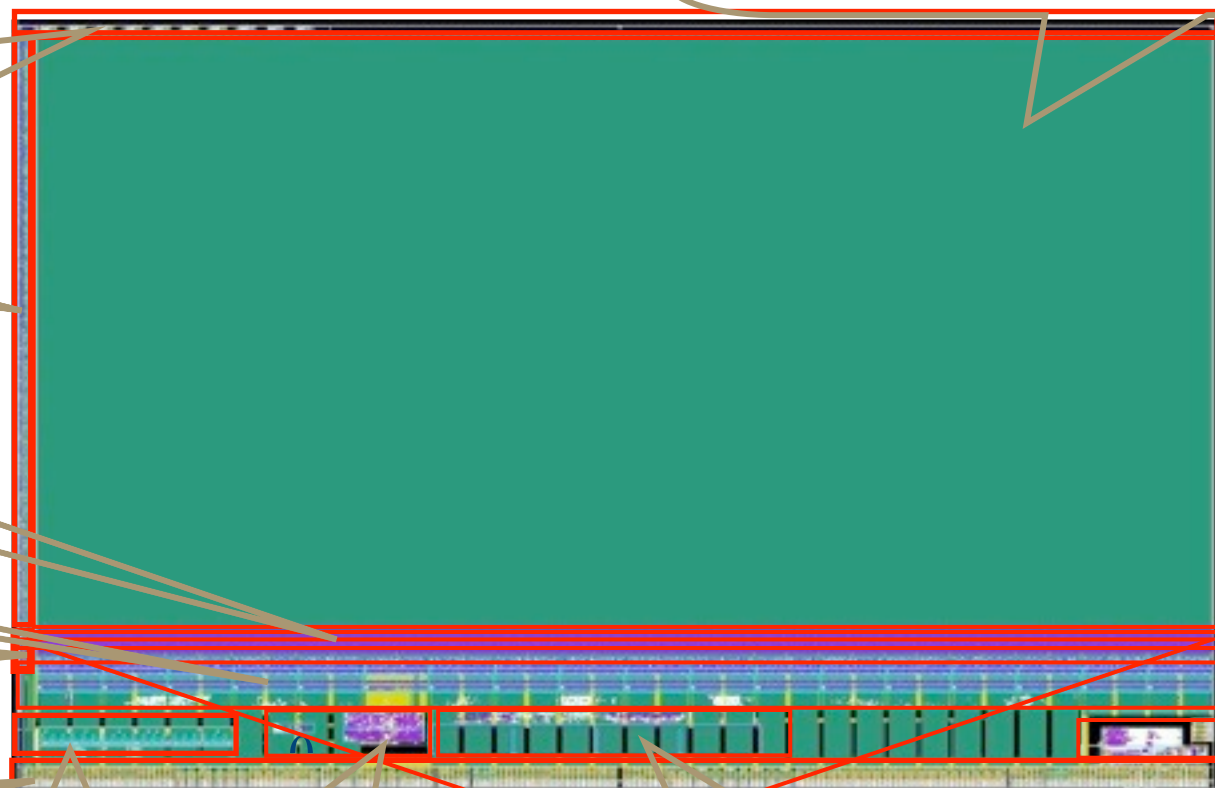
- Row sequencer
- Width: ~350 µm

- 1152 column-level discriminators
  - offset compensated high gain preamplifier followed by latch

- Zero suppression logic

- Reference Voltages Buffering for 1152 discriminators

- I/O Pads
  Power supply Pads
  Circuit control Pads
  LVDS Tx & Rx



- Current Ref.
- Bias DACs

- Readout controller
- JTAG controller

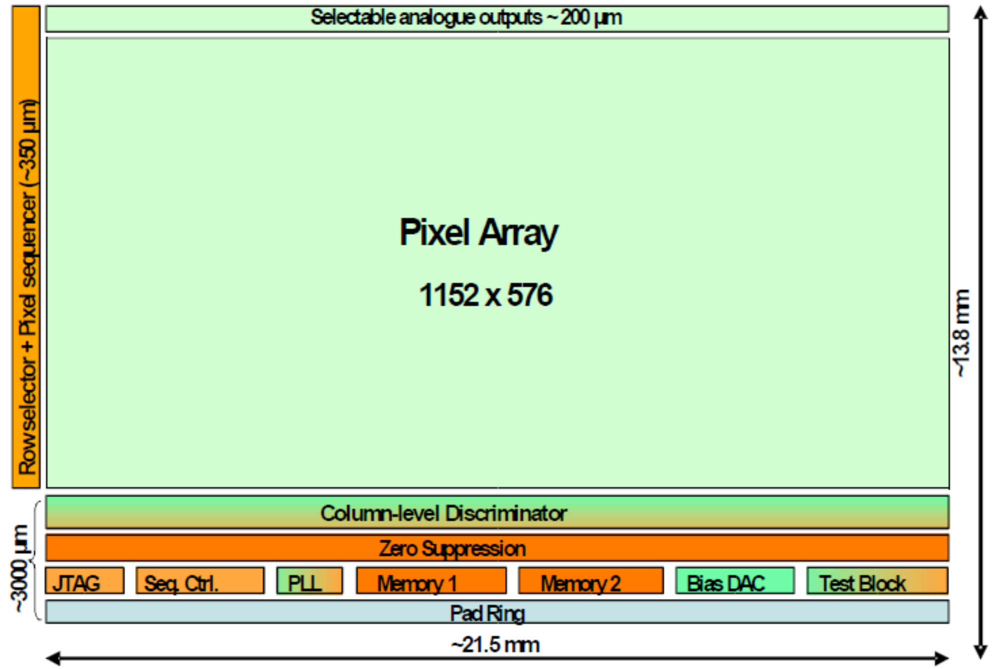
- Memory management
- Memory IP blocks

- PLL, 8b/10b optional

See Ref. C. Hu et al., TWEPP-09

Rolling Shutter

- A row is selected via a sequencer
- the signal is
  - amplified in each pixel by a pre-amplification stage
  - decoupled from the column driver by a double sampling circuit based on a clamping capacitor.

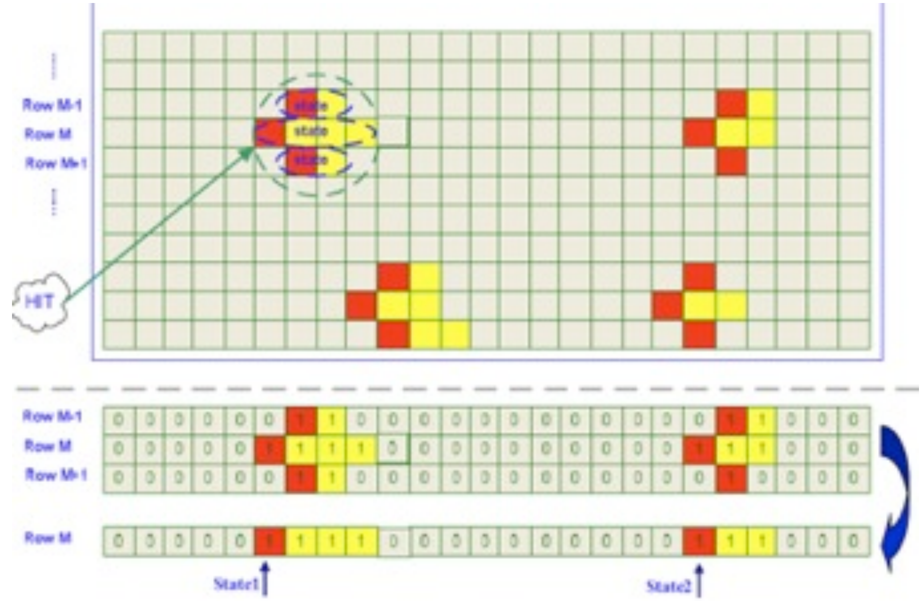


- 1152 signals of the selected row are transmitted to the bottom of the pixel array
- Column-level, offset compensated discriminators -> analogue-to-digital conversion.
- Outputs are connected to a zero-suppression circuitry, organized in a pipeline mode, which scans the sparse data of the current row.

Zero-Suppression

Two steps

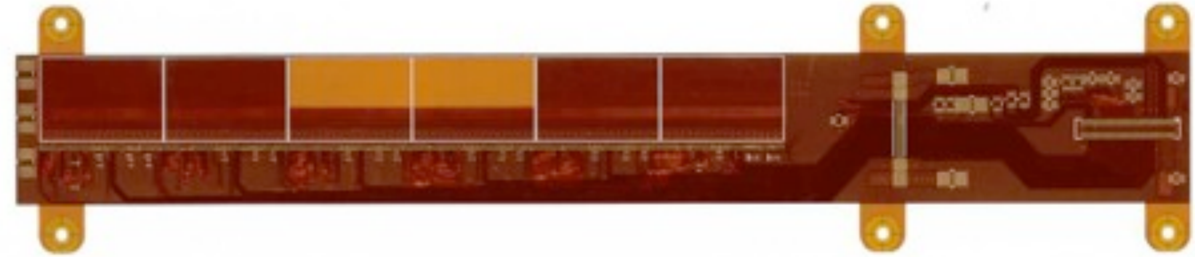
- Row closest to the discriminator outputs is split into 18 blocks of 64 columns.
- Inside each block:
  - the circuitry scans the 64 columns, skipping non-hit pixels and identifying contiguous pixels having their signals above the threshold.
  - Considers up to 6 strings per block, each string being composed of up to 4 hit pixels.



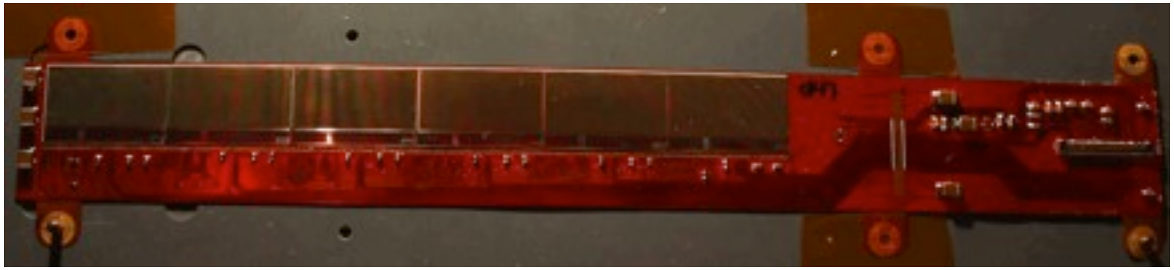
- The outputs of the 18 blocks are combined in up to 9 strings, strings overlapping two neighboring blocks being merged in a single one.

PLUME-1 DESIGN

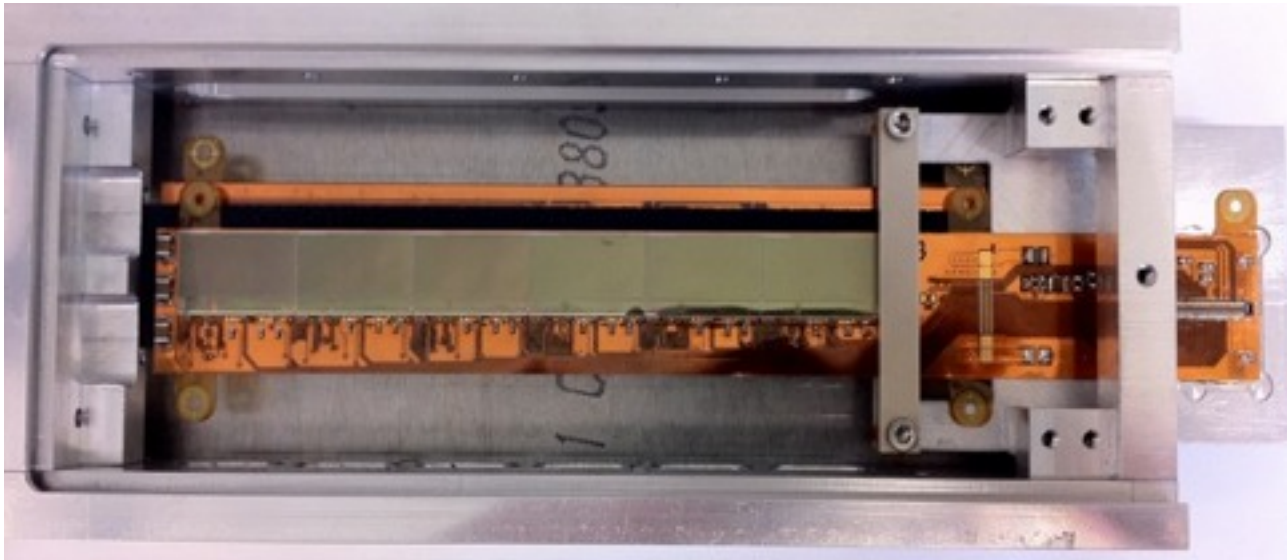
bare low mass cable



module with 6 sensors



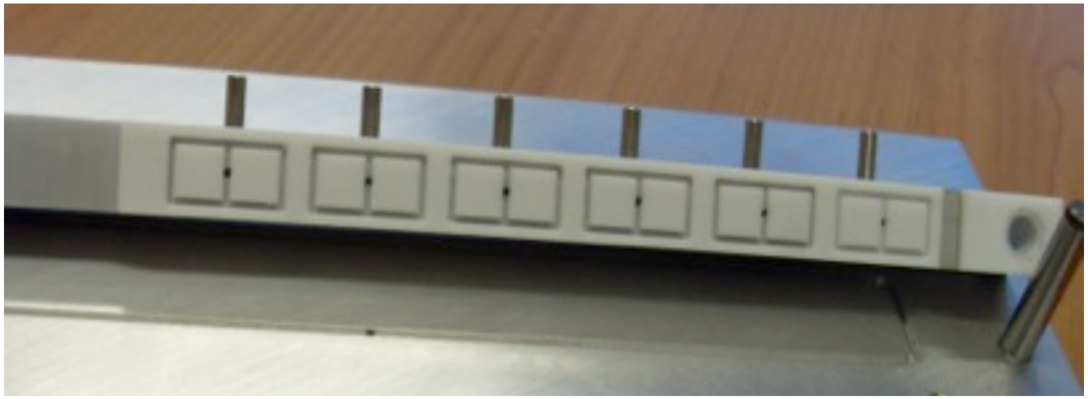
complete ladder
(2 modules)



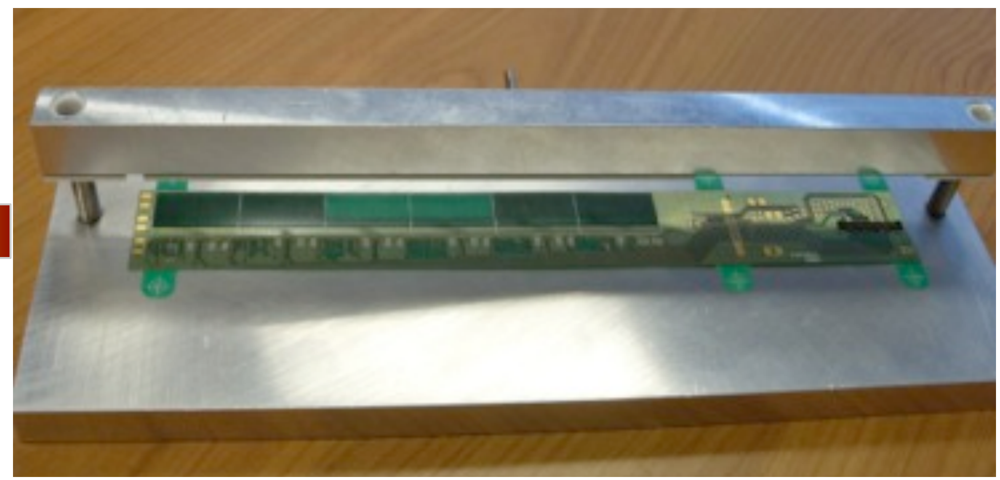
PLUME-1 module assembly

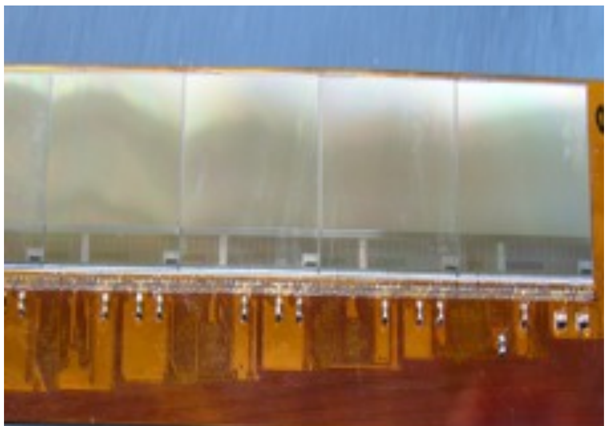
MIMOSA 26
50 µm thick

x6, manual positioning,
vacuum fixed



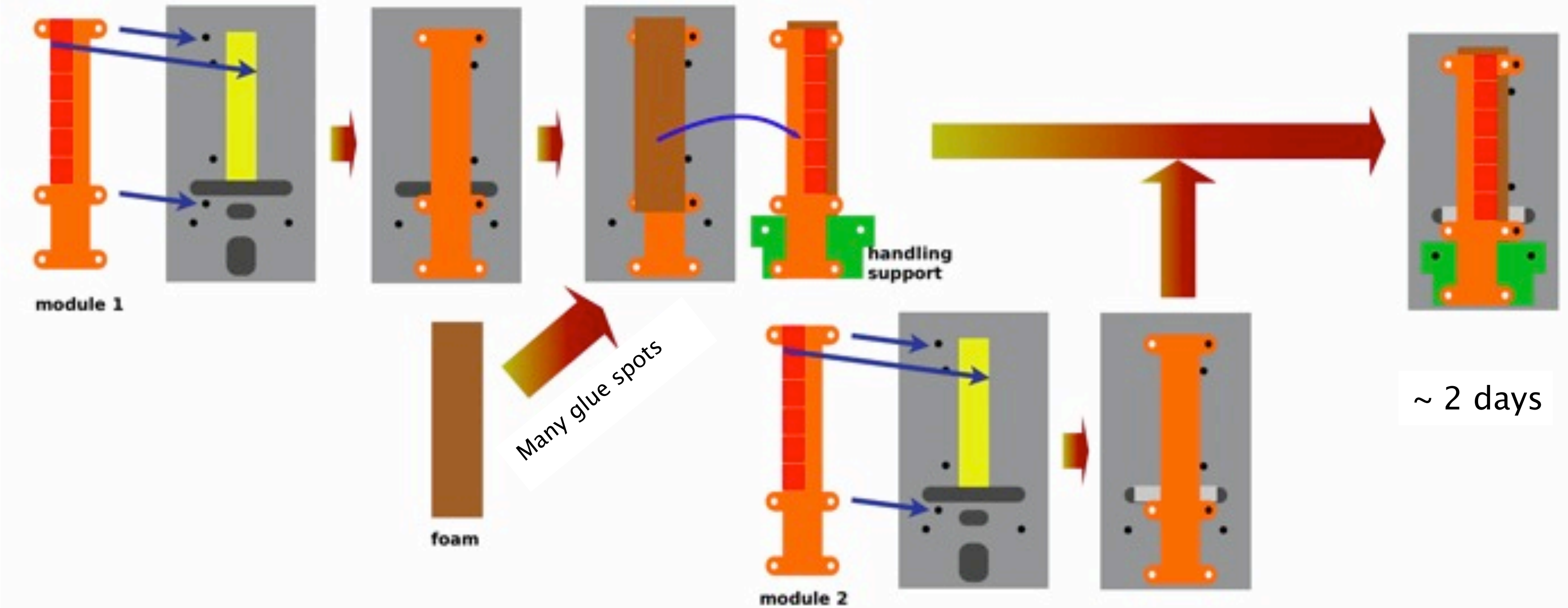
Controlled glue dispensing
small pressure while curing
Then wire bonding





~20 µm space bw sensors

PLUME-1 ladder assembly

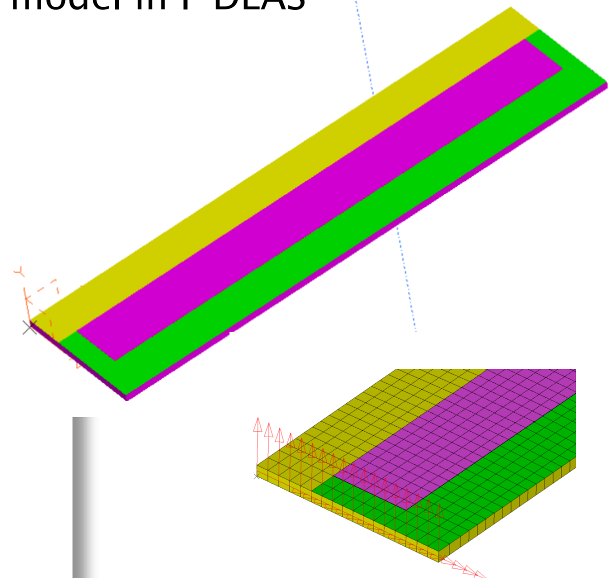


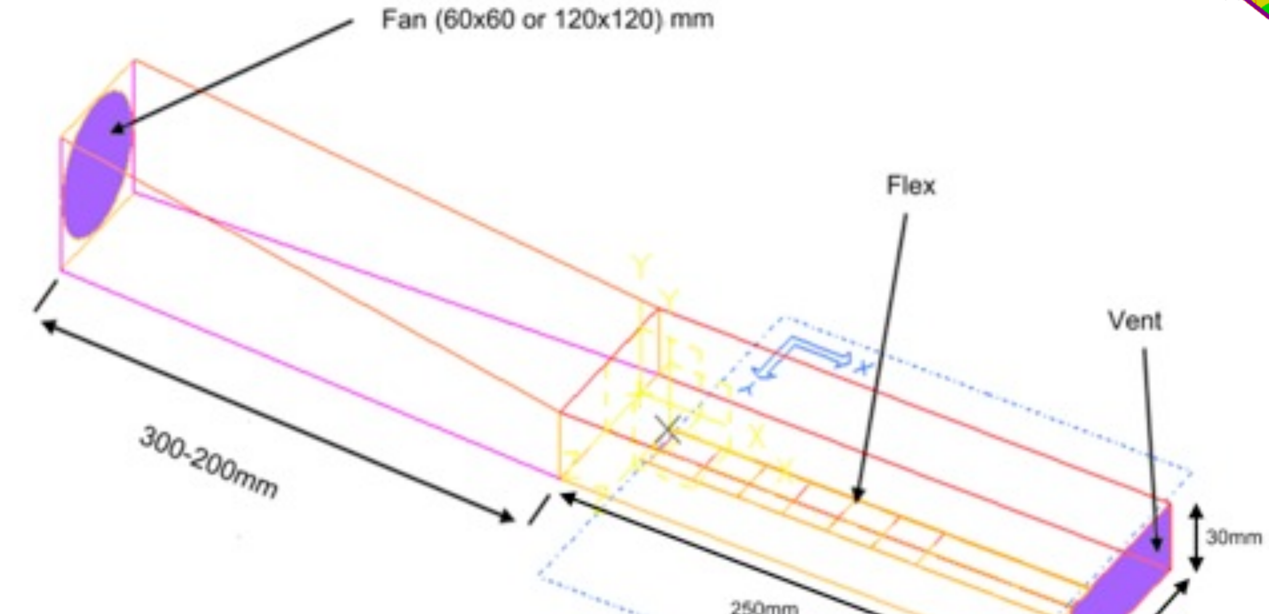
- Modules
- ~30 low mass cables produced (all copper)
- 5 equipped with 6 MIMOSA26
  - ➔ All electrically functional
  - ➔ 3 with 1 or 2 non-functional sensors

- **Ladders**: 3 assembled
  - ➔ 1 with dummy sensors
  - ➔ 1 electrically functional
  - ➔ 1 complete stave

PLUME-1 simulations

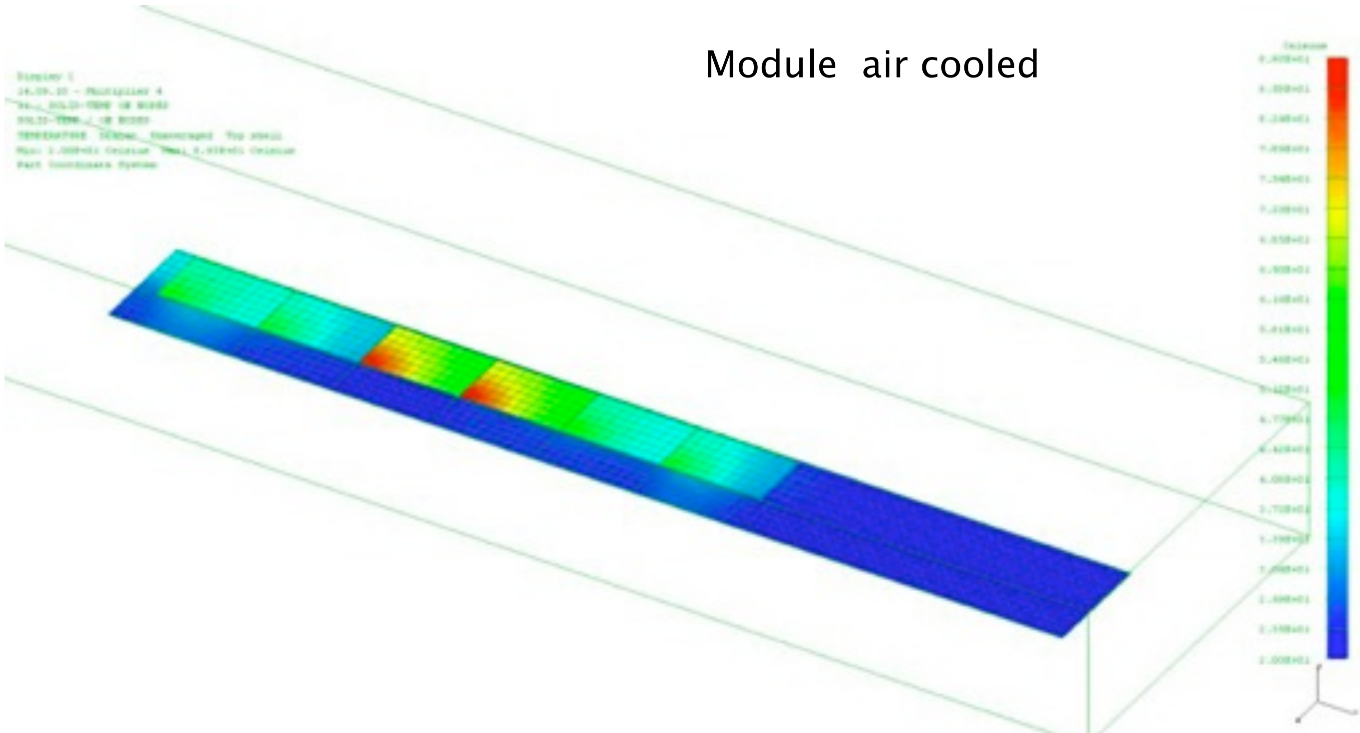
Ladder model in I-DEAS





Module in the air cooling box

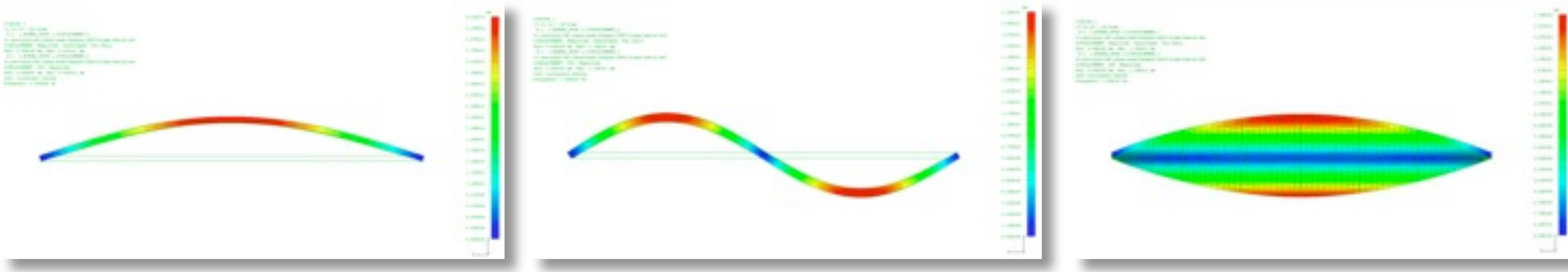
PLUME-1 SIMULATIONS



→ importance of heat conductivity among sensors for efficient cooling by air

PLUME-1 SIMULATIONS

Ladder supported at both ends



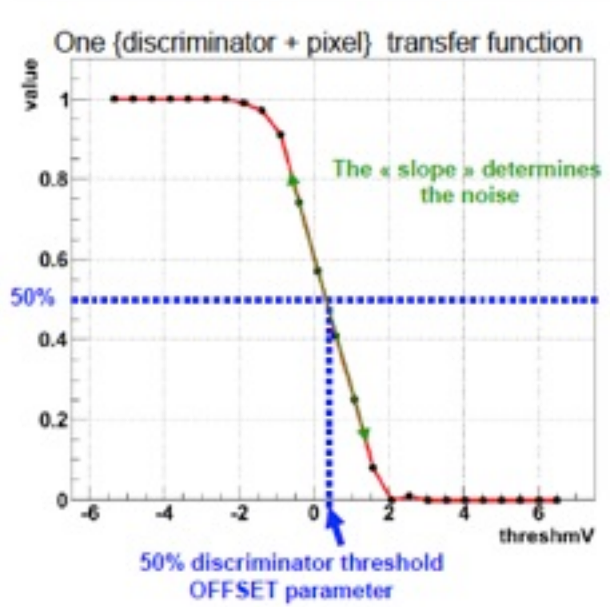
2C - Mode		SiC foam 8% in Hz	SiC foam 4% in Hz	RVC in Hz
One sensor/ Two sensors/ Three sensors	1	255	265	235
	2	990	981	453
	3	1281	1117	674

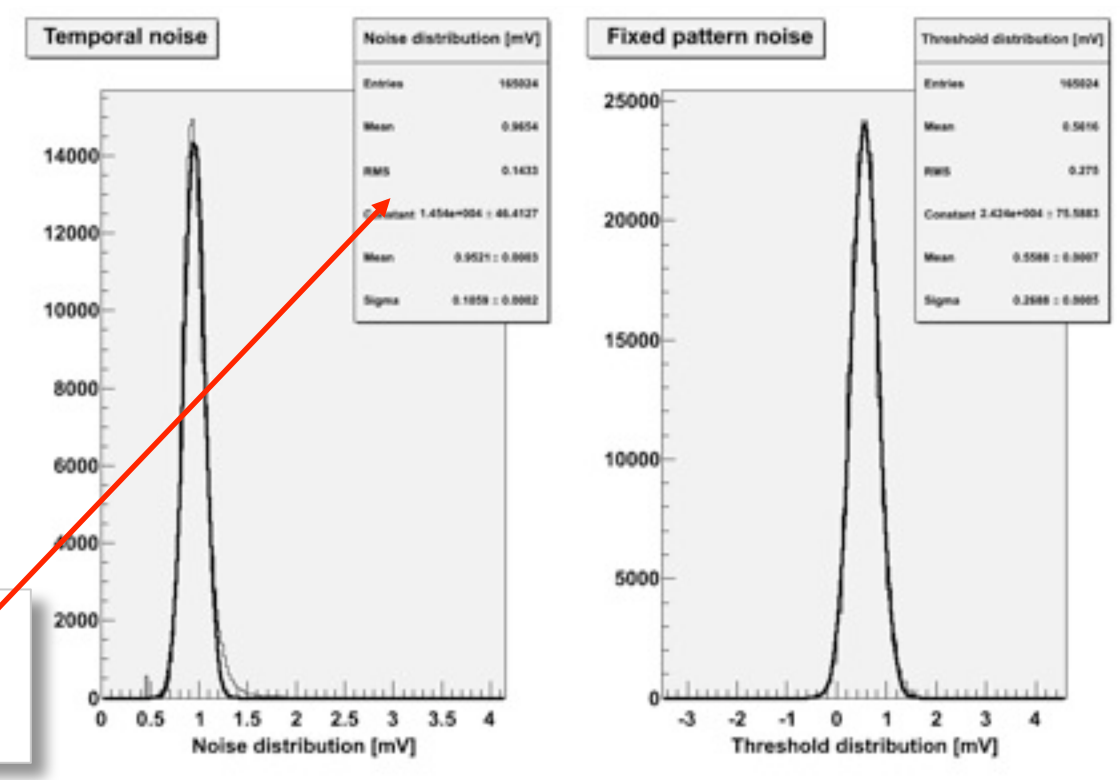
→ importance of sandwich effect for stiffness

PLUME-1 Electrical Tests

Scan of the discriminator thresholds with all 6 sensors switched on (5 tuned for 1% occupancy)

Current consumption/sensor ~230 mA
@ low threshold

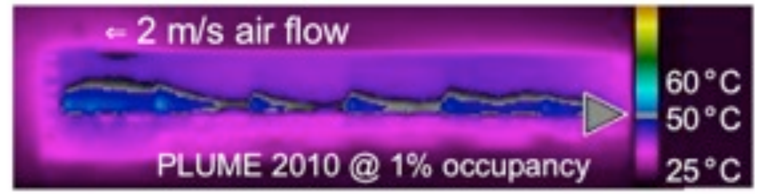




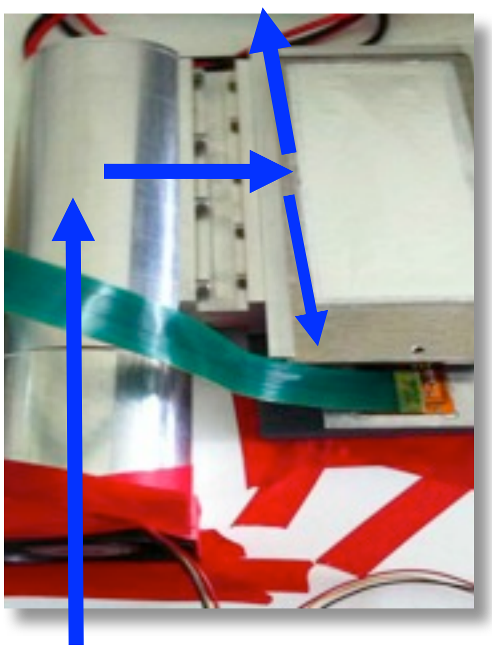
Temporal noise at mV level
as expected from single sensor
measurements

PLUME-1 thermal tests

IR camera thermal measurement on a single module

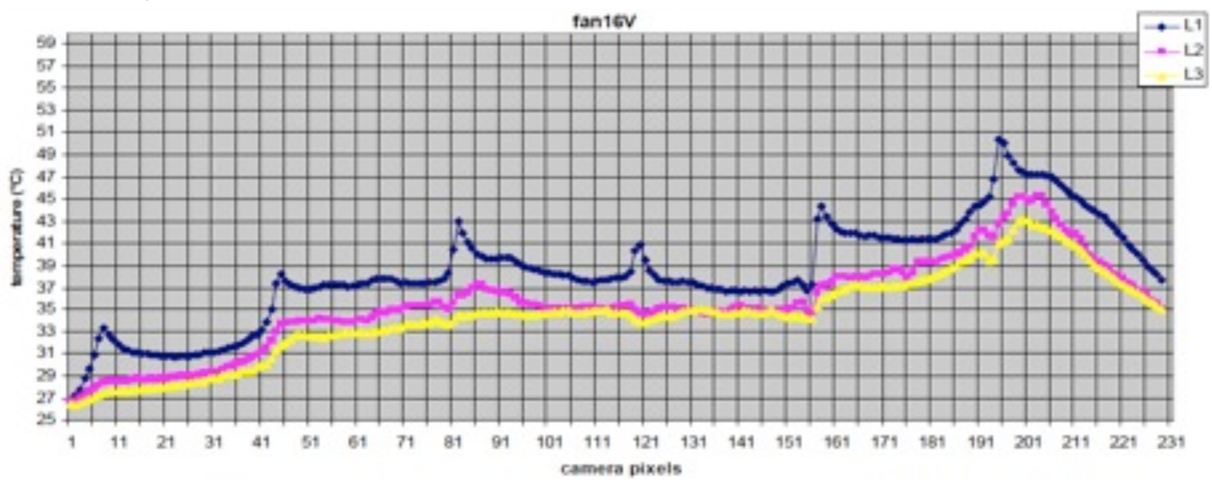


MIMOSA 26 internal (diode) temp. measurement on ladder
only 1 over the 2 modules switched on



ambient air

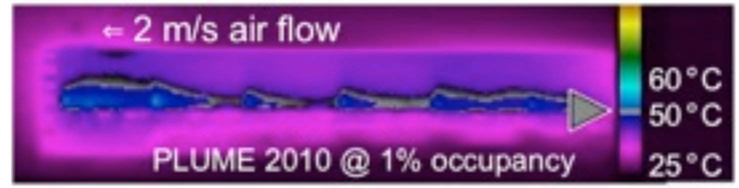
Low air flow



High air flow
+1.5 m/s

PLUME-1 thermal tests

IR camera thermal measurement on a single module



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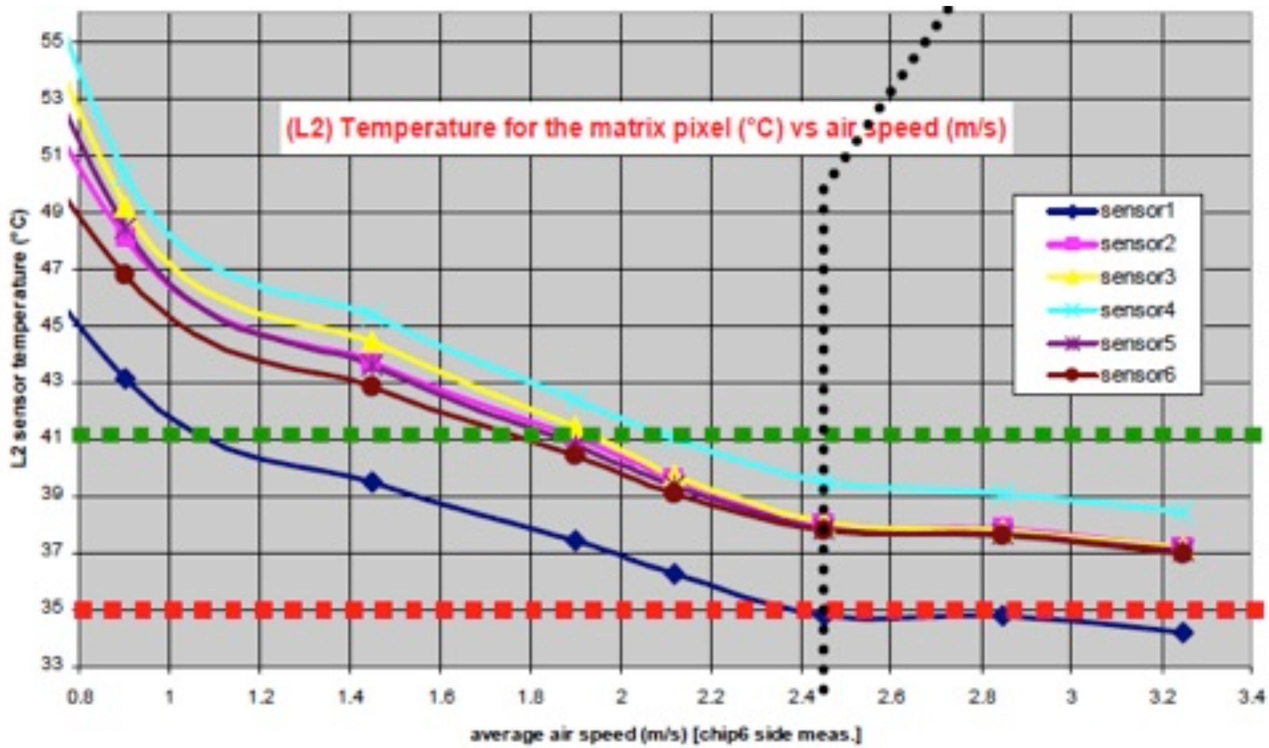
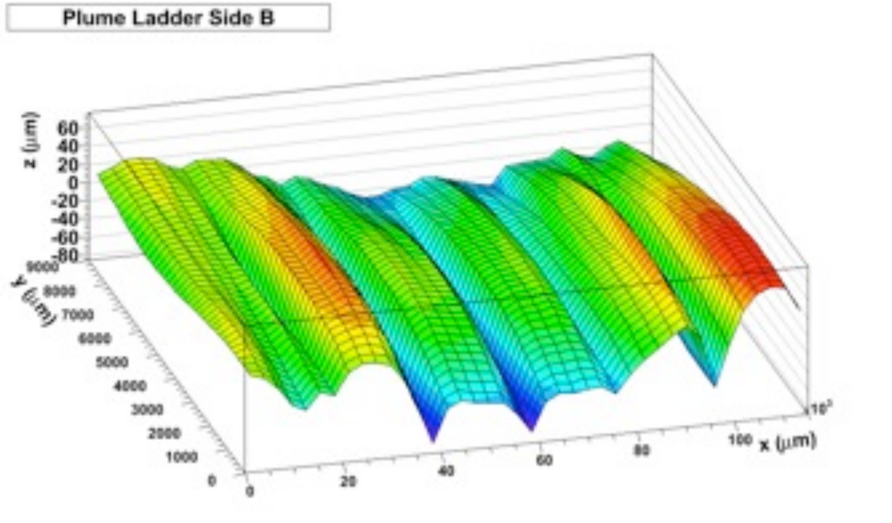


PLUME-1 mechanical tests

Surface survey of ladder with dummy sensors

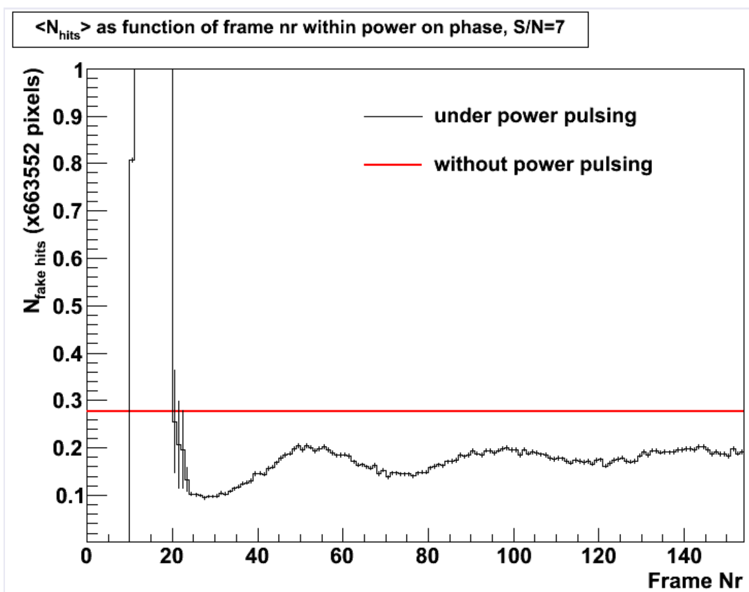


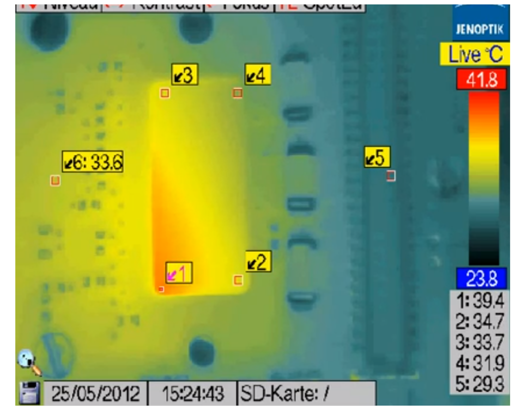
With the help of Ryan Page & setup from RAL

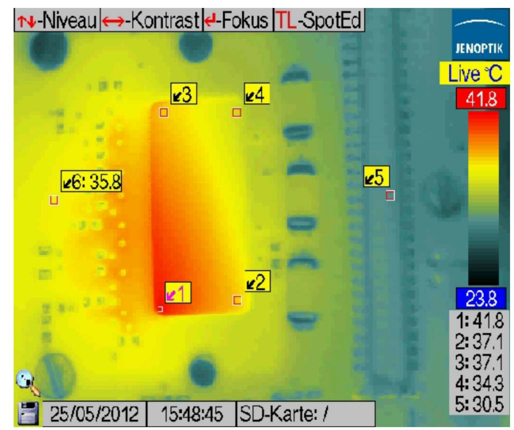
Power Pulsing

- Mimosa not designed for power pulsing, nevertheless power pulsing studies are possible.
- Nominal value of 3.3V is reduced to 1.8V:
  - to maintain M26 programming; reprogramming would take too much time
  - to allow continuous clock and control signals (synchronisation).

- Reasonable good performance of sensor when power pulsed
- Fake hit rate with and without power pulsing shows reasonable operation about 5ms after turn on.

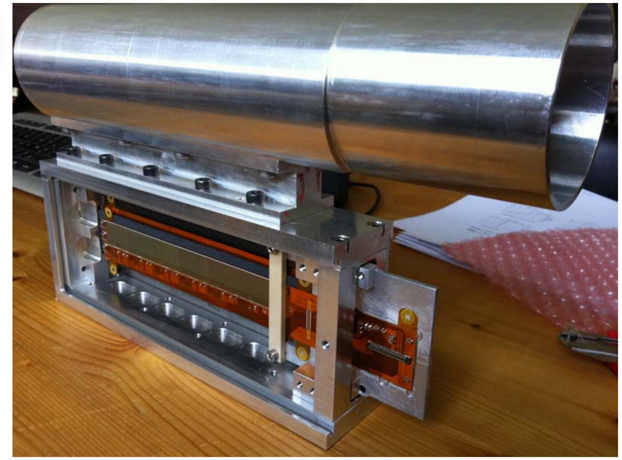




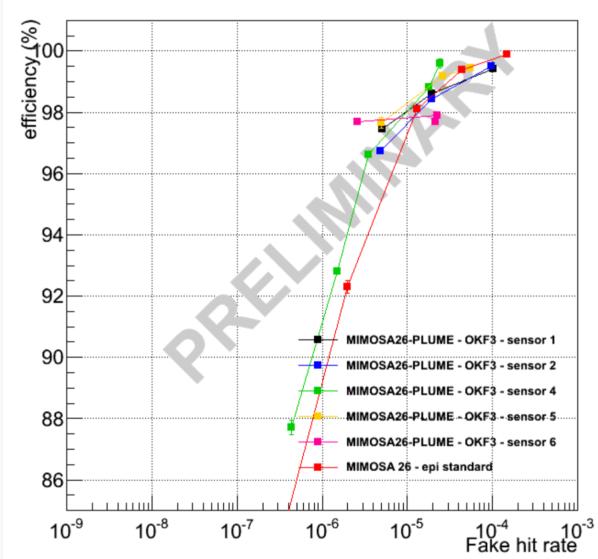


Test Beam Results

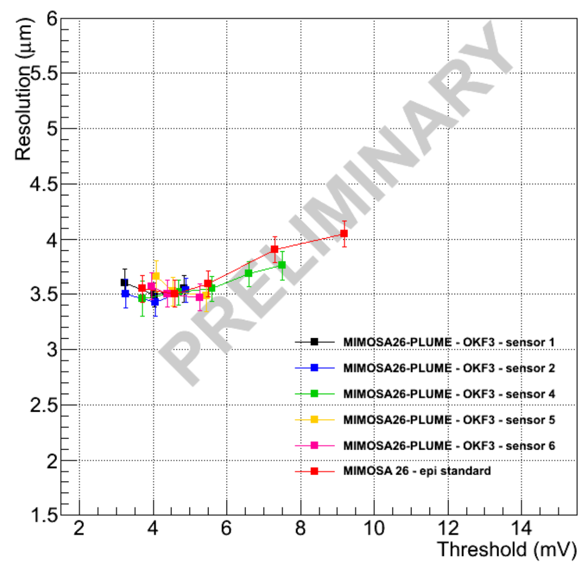
- Test beam November 2011 at CERN SPS (H6)
- PLUME Ladder 01 : OKF3 + OKF6
  12 Mimosa 26 epi standart sensors. (6 per side)
- thinned down to 50 µm.
  All sensors at same threshold.
- Data : only from 2 sensors per side.
- 2 mm SiC foam between sides.
  Double-sided 50 µm kapton PCB. (Cu, 20µm/side)
  0,6% X0 material budget.



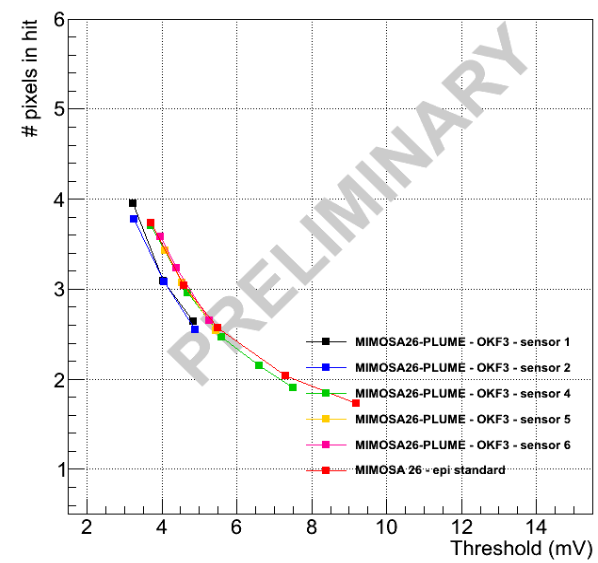
Efficiency vs Fake hit rate



Resolution vs Threshold

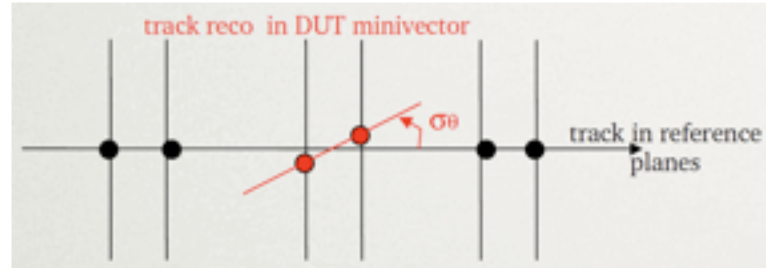


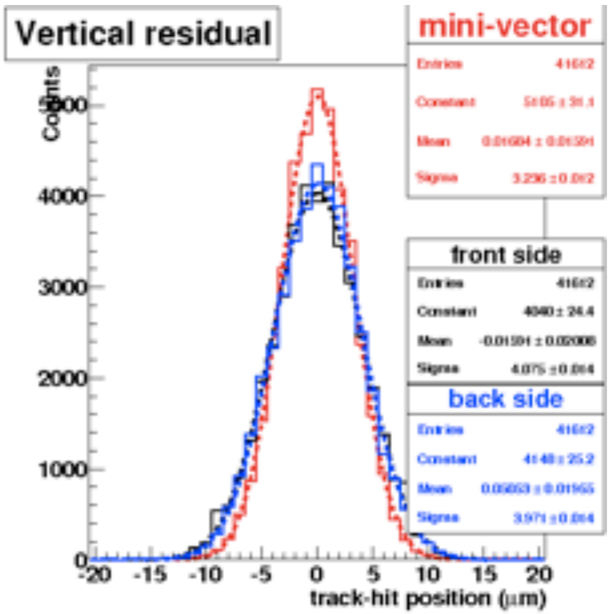
Pixel multiplicity vs Threshold

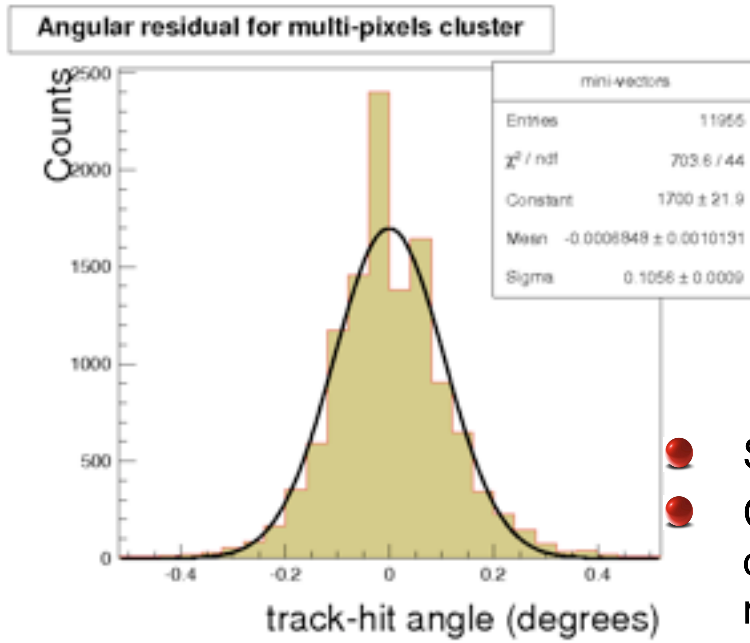


Mini Vectors

- Mini-vectors between the two side of the ladder :
  → To improve spatial resolution.
  → To estimate angular resolution.
- Hit selection to make the mini vector = hits with the minimum track-hit distance.



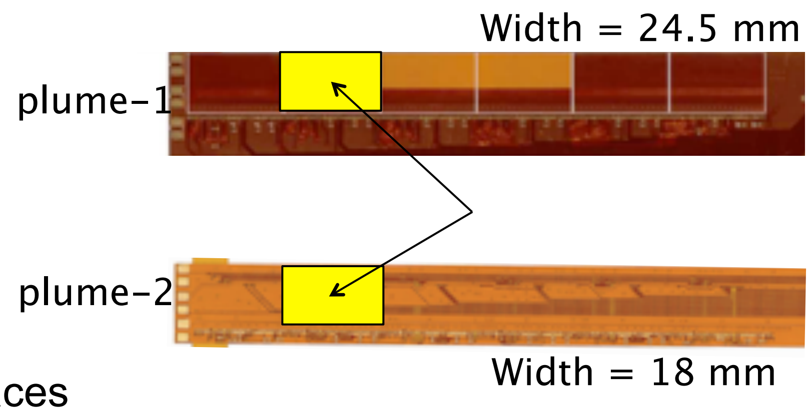




- Spatial resolution improved.
- Correlation between observation and theoretical result =>mechanical stability of the ladder.

PLUME-2 DESIGN

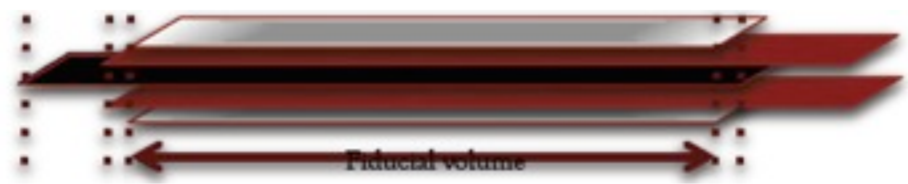
- Why is the 2010 design so thick
  - cable width ~ 2 x sensor width
  - metal ~ copper
  - SiC foam (spacer) density ~ 8%



- **Improvements**
  - low mass cable narrower and aluminum traces
    → first samples fabricated January 2012
    → sensor mounting ongoing…
  - spacer (SiC foam) decreased to 4% density (FEA simulation predicts no change in stiffness)
  - New board for power pulsing studies
  - Automatic placement machine available for fast and reliable assembly

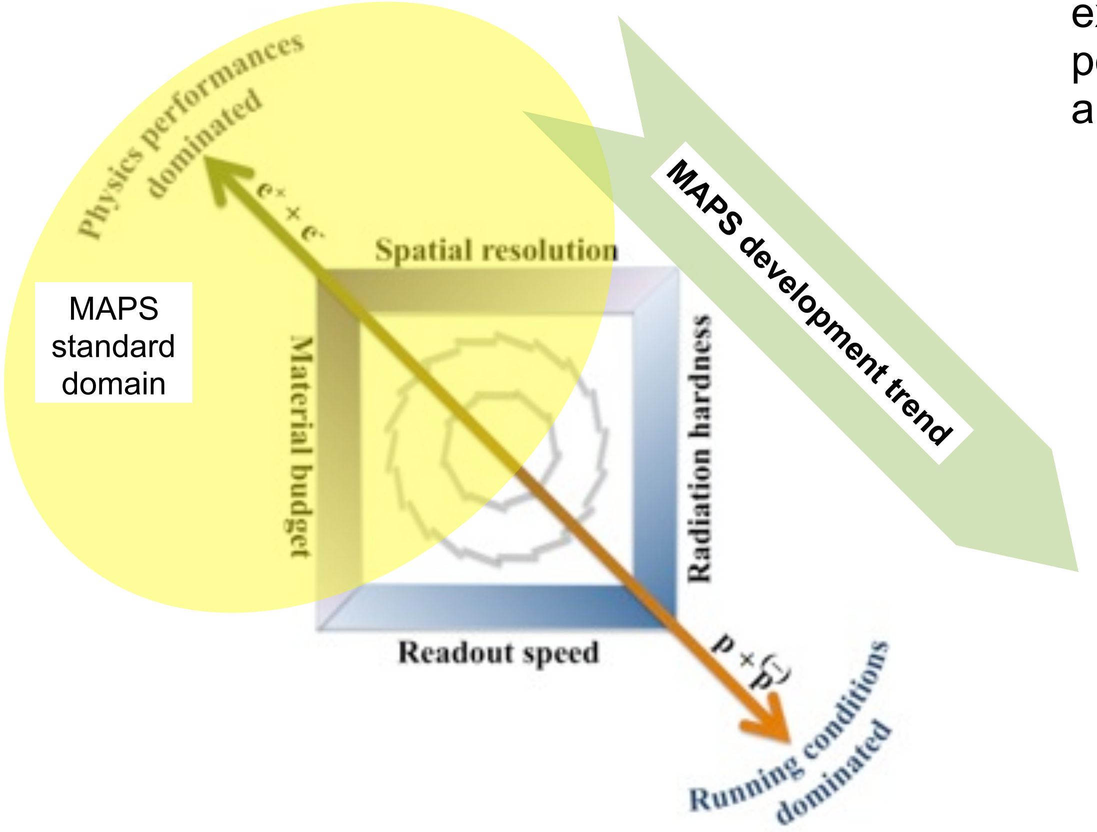
PLUME-2 design

- Expected material budget
  - transverse cross-section
    - ➔ 0.344 % X0 = 2x0.053(sensors) + 2x0.058(flex) + 0.092(SiC4%) + 0.030(SMD)
  - average (weighted / 10 mm wide MIMOSA 26 sensitive layer)
    - ➔ 0.502 % X0 = 2x0.069 (sensor) + 2x0.098 (flex) + 0.138 (SiC4%) + 0.030 (SMD)



- **Schedule**
  - First ladder (single side) in hands
  - Mirror aluminum flex expected at the end of the month
  - assembly setup being prepared
  - PLUME-2 beginning of next year -> test beam !
  - Small production to to follow

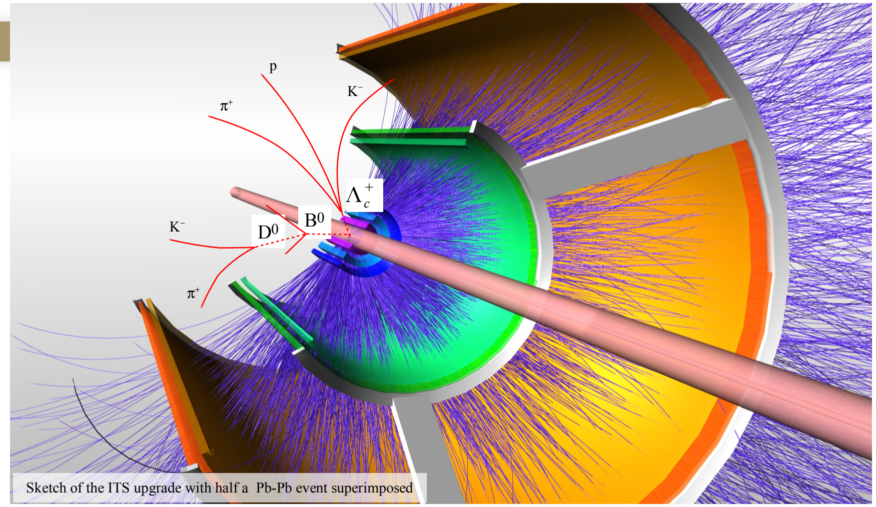
VXD Parameter Space



- “New” development: LHC experiments are investigating possibility to use CMOS/monolithic approaches for upgrades

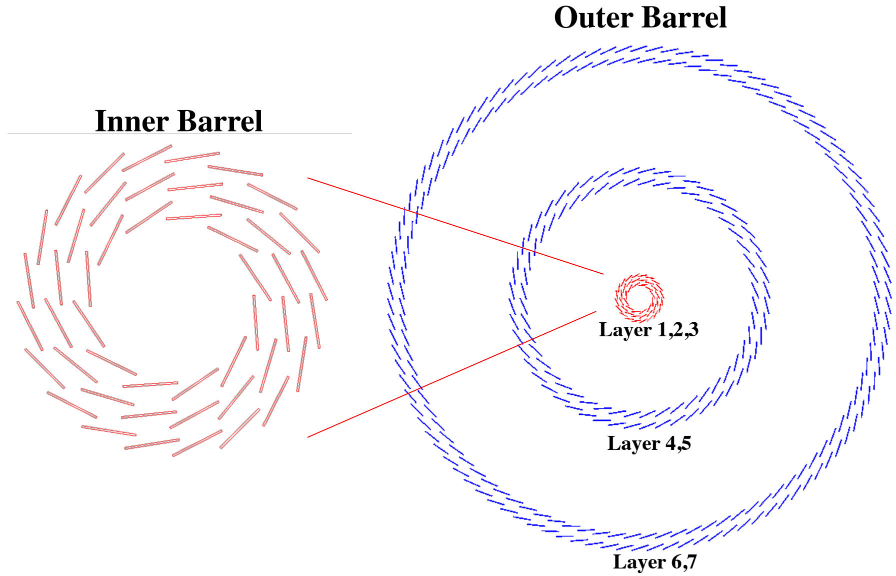
ALICE Tracker Upgrade

- After LHC Upgrade ~2018 Pb−Pb collisions at 50 kHz expected
- Opens the door for a unique physics program in 10 nb^{-1} regime
- Requires significant upgrade of the inner tracking system (ITS) and time projection chamber (TPC).



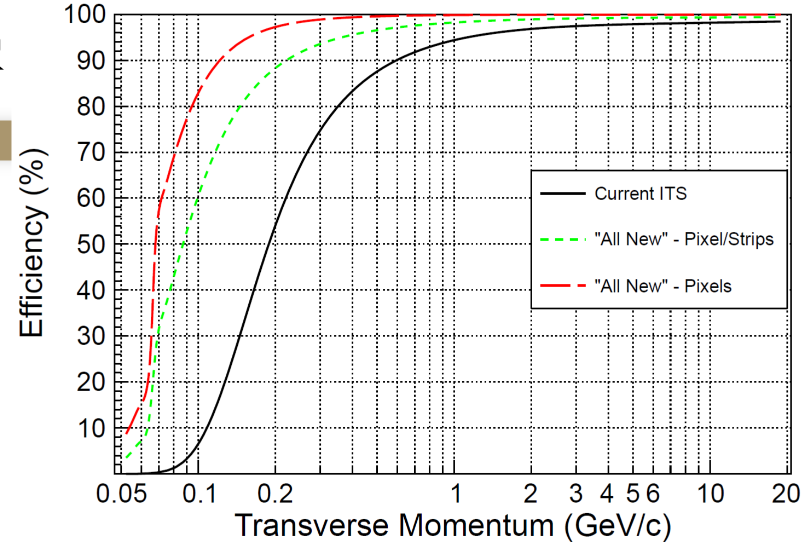
- New high-resolution, low material Inner Tracking System (ITS)
  - Measurements closer to interaction point
  - Reduce material budget: 0.003 X0/layer
  - Increase granularity
  - Increase η coverage

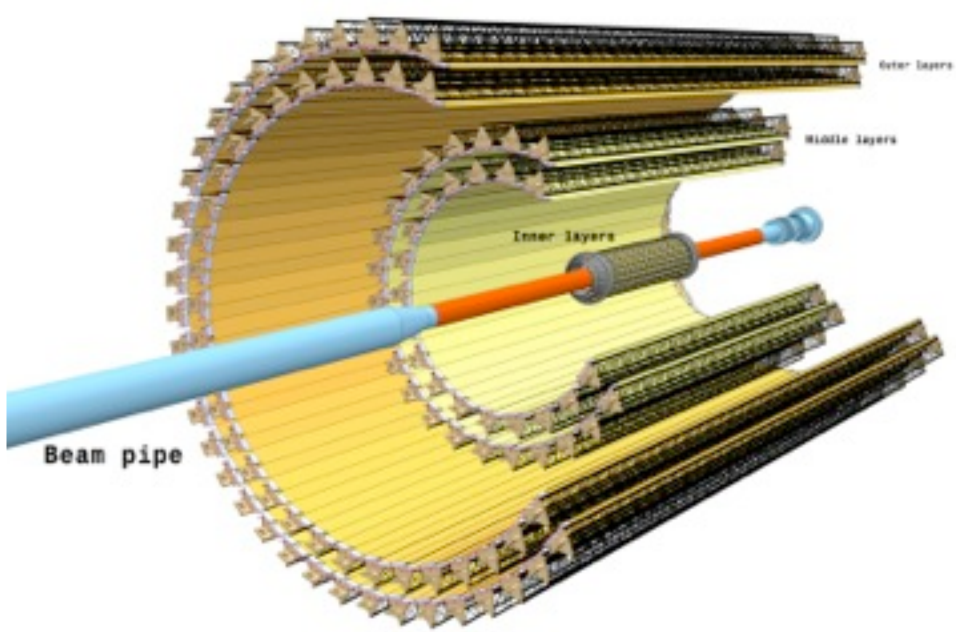
Schematic Layout



ALICE Pixel Detector

- Different options for the layout were studied
- Baseline design
  - 7 layers of monolithic pixel detectors
  - Improved standalone tracking efficiency and pt resolution
- Under investigation: Enable charge amplitude measurement in outer layers for dE/dx measurement -> PID



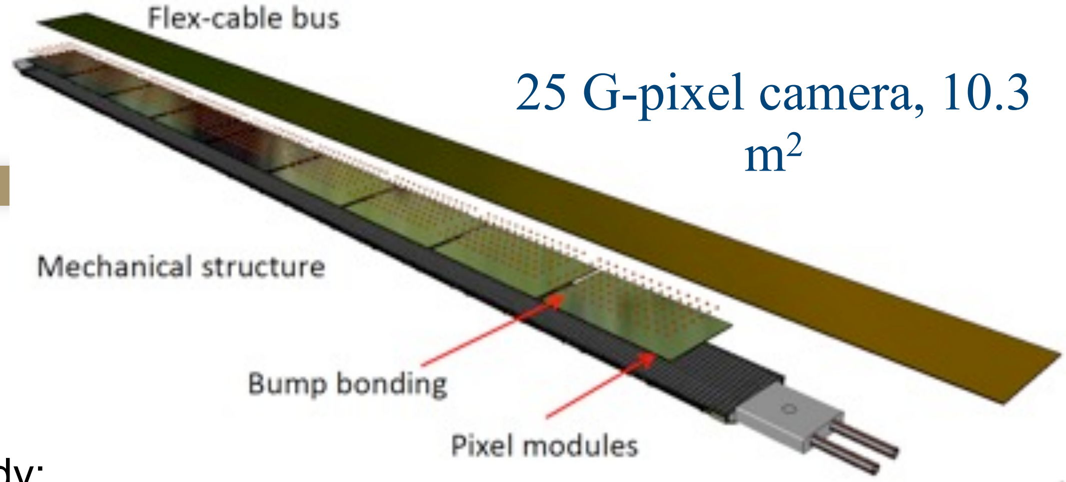


Option A: 7 pixel layers
Resolutions: $\sigma_{r\varphi}$ = 4 µm, σ_z = 4 µm for all layers
Material budget: X/X_0 = 0.3% for all layers

Option B: 3 layers of pixels + 4 layers of strips
Resolutions: $\sigma_{r\varphi}$ = 4 µm, σ_z = 4 µm for pixels

$\sigma_{r\varphi}$ = 20 µm, σ_z = 830 µm for strips
Material budget: X/X_0 = 0.3% for pixels
X/X_0 = 0.83% for strips

ALICE Pixel R&D

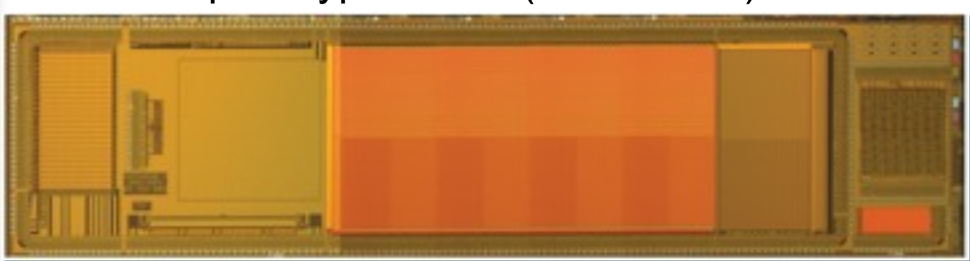


25 G-pixel camera, 10.3 m^2

- Sensor baseline decision: Monolithic pixels for all 7 layers
- Chosen technology is the Tower Jazz Technology
- Three different architectures under study:
  - **MISTRAL/ASTRAL (IPHC-IRFU) based on MIMOSA**
  - CHERWELL2 (RAL) based on FORTIS and TPAC
  - ALPIDE (CERN-INFN-CCNU)

- Modules/stave:
  - carbon fibre structure
  - cooling
  - sensors
  - polimide printed circuit board

MISTRAL prototype circuit (Mimosa 34)



ALPIDE (CERN-INFN-CCNU)

MISTRAL/ASTRAL

- Moved to a 0.18 µm imaging CMOS process (Tower/Jazz SC):
  - Deep P-well (quadruple well techno.) ⇛ in-pixel discriminators
  - 6 metal layers (instead of 4) ⇛ in-pixel discriminators, avoids insensitive zones
  - Epitaxial layer : high-resistivity (> 1 kΩ · cm), ”18 µm thick”
  - Stiching ⇛ multi-chip slabs
    ⇛ process very well suited to the VXD specifications

- MISTRAL ≡ MIMOSA FOR THE INNER SILICON TRACKER OF ALICE
  - Col. // pixel array with in-pixel ampli + pedestral subtraction (cDS)
  - Each of 128 columns ended with discriminator + 8 columns without discri.
  - Pixel array sub-divided in sub-arrays featuring different pixel designs (22×22/33 µm2)
  - 2 options submission in Decembre’12 :
  - single end of column discriminator ≡ translation of MIMOSA-22AHR (0.35 techno.)
  - simultaneous 2-row encoding & 2 discriminators/column ⇛ twice faster

- AROM-1 (Accelerated Read-Out Mimosa) ⇛ ASTRAL (2nd step)
- in-pixel discri. & simultaneous 4-row encoding

  ⇛ 8 times faster than MIMOSA-22THR

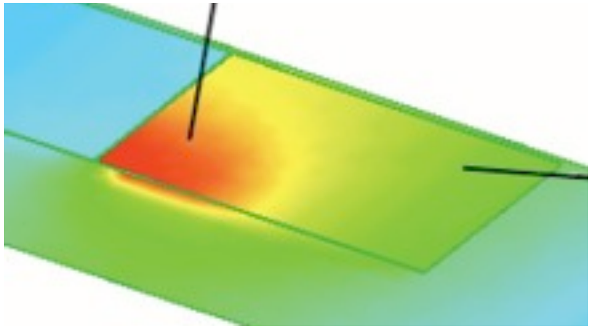
Summary

- PLUME
  - A first (functionally) successful design of PLUME-1 fully validated
  - New design PLUME-2 to reach material budget of (cross sect.) O(0.035) % X_0
  - Simulation effort to validate models to predict new designs performances
  - “infrastructures” in place for further designs and/or other sensors
- Applications:
  - PLUME beam tests will be an important milestones for the ILD (to be compared with DEPFET-based Belle II-VXD & STAR-PXL)
  - 6 to 8 ladders (12 x MIMOSA 26 each) will run during long beam periods in the framework of the FP7-AIDA project
    - ➔ Complementary experience wrt STAR-PXL
    - ➔ ALICE ITS foresees a fully monolithic 7 layer vertex detector

PLUME Ongoing Work and Plans

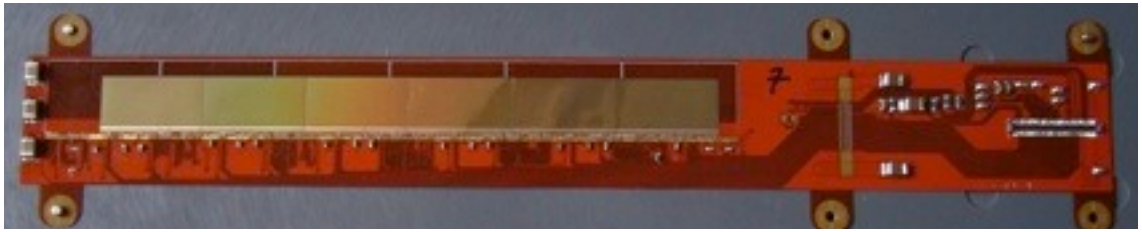
Ongoing Work

- Measurements with PCB ladder (3 sensors connected).
- Preparation and tests of flex kapton ladder with 6 thin sensors.
- Mechanical studies of carbide support and flex prototype.
- Thermal simulations and measurements of heat transfer (with air cooling).
- Power pulsing tests with source and laser.
- Investigation of alternative flex vendors.
- Material optimization of flex design.



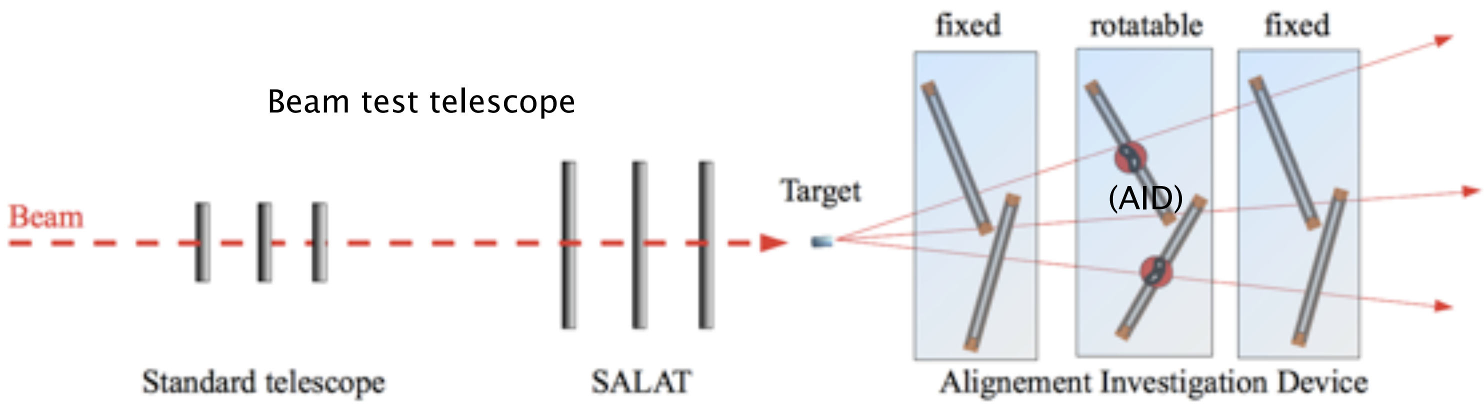
Plans

- Realistic ILC VD ladder prototype by 2012
  - ILC Detailed Baseline Design (DBD) due in 2012
- Steps:
  - 2x6 MIMOSA-26, 0.65% X_0
  - 2x6 MIMOSA-26, 0.4% X_0
  - 2x6 optimized MIMOSA's, 0.3% X_0
- Use PLUME ladders within FP7 AIDA project



ILC Vertex Detector in EU-FP7 AIDA

Collaboration :
PLUME collaboration + Geneva University + Warsaw University + ...



On-beam test infrastructure:

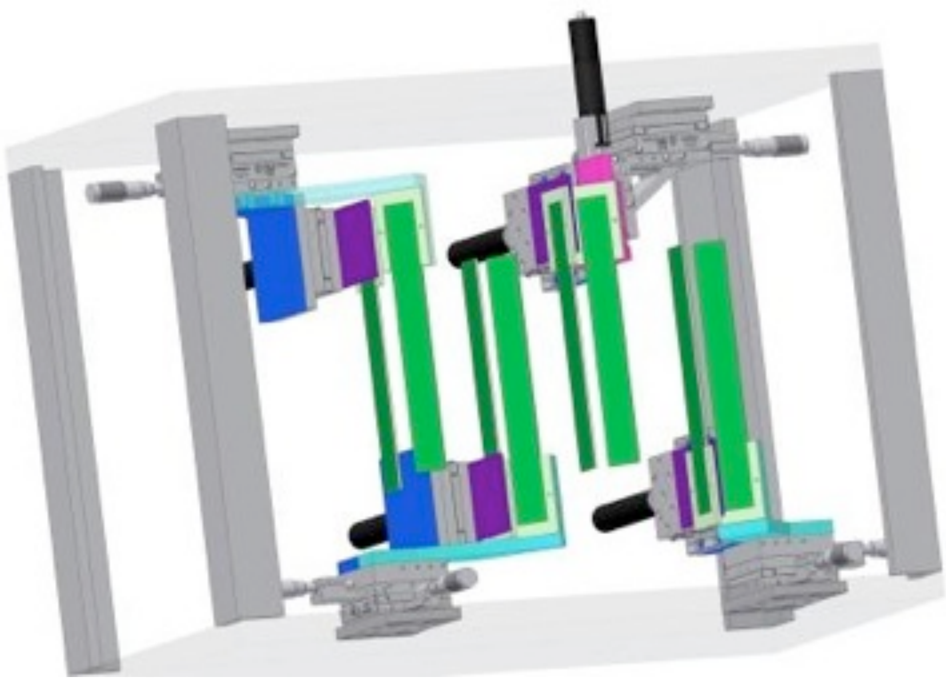
- Very thin removable target
- Large Area beam Telescope (LAT) : EUDET-like Beam Telescope
- Alignment Investigation Device (AID): ladder box

Off-beam test infrastructure:

- Thermo-mechanical studies, including effects of air-flow cooling
- Power cycling effect in strong magnetic field: Lorentz forces on ultra-light PLUME ladders

AID Layout

- Aim: alignment studies for PLUME or any other VD ladders
- Four stations with precise adjustable stages
  - Two overlapping ladders in each station
  - Middle station with three additional degrees of freedom
- Conceptual drawings:

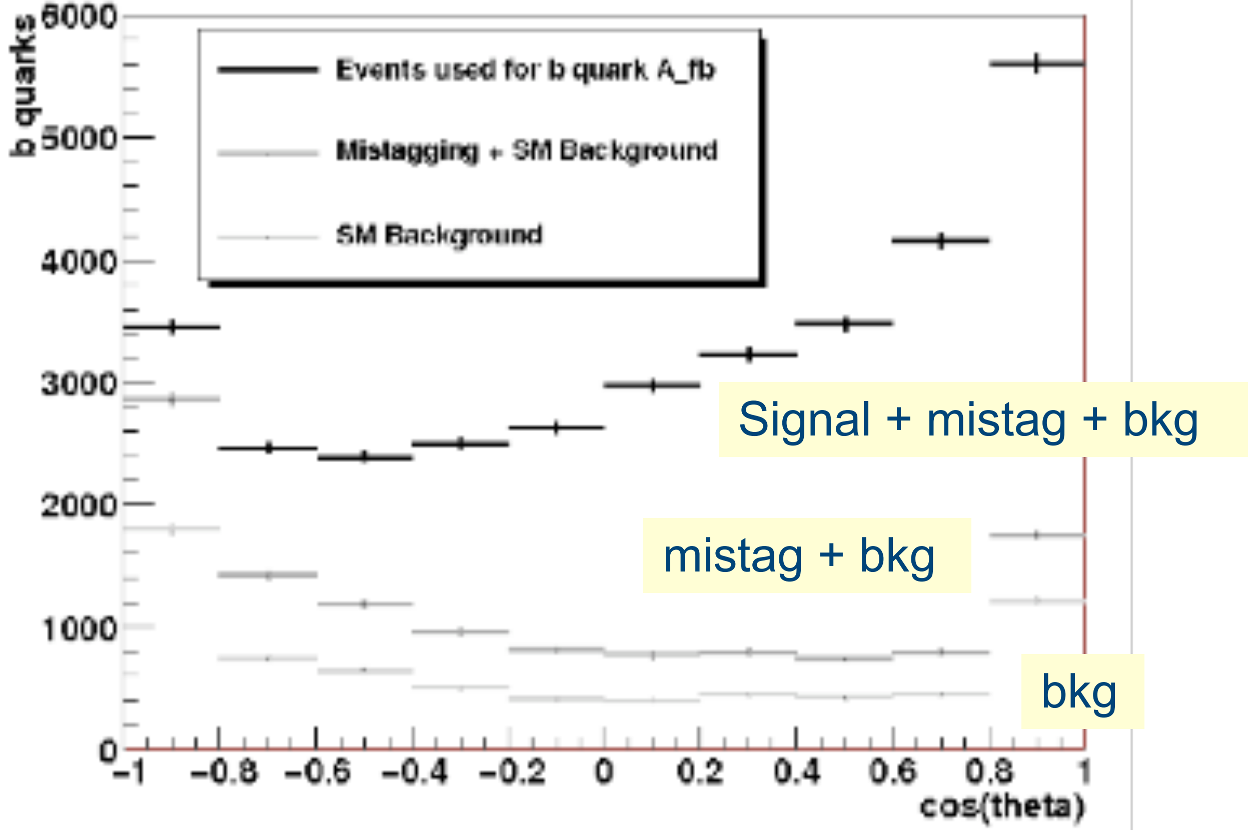


Example: Top Asymmetry

- Process: tt →WbWb → bbqqqq : two b-quarks in final state
- Deviations from SM predictions in asymmetry is excellent probe of new physics
  - One of benchmarking channels for ILC LOI

Note:

- Large asymmetry in forward region
- Large mistag rate in forward region



Top quark anomalous couplings at the International Linear Collider, E.Devetak and A.Nomerotski, submitted to PRD