Test beam results from 3D and epitaxial sensors flip-chip bonded to the ALICE pixel front-end chip

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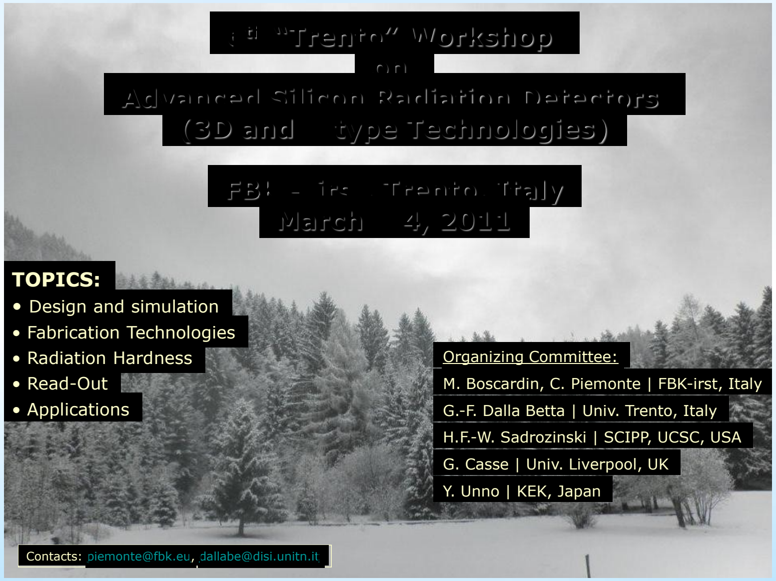

“Trento” Workshop
on
Advanced Silicon Radiation Detectors
(3D and type Technologies)

FBK – irst, Trento, Italy
March 4, 2011

TOPICS:
- Design and simulation
- Fabrication Technologies
- Radiation Hardness
- Read-Out
- Applications

Organizing Committee:
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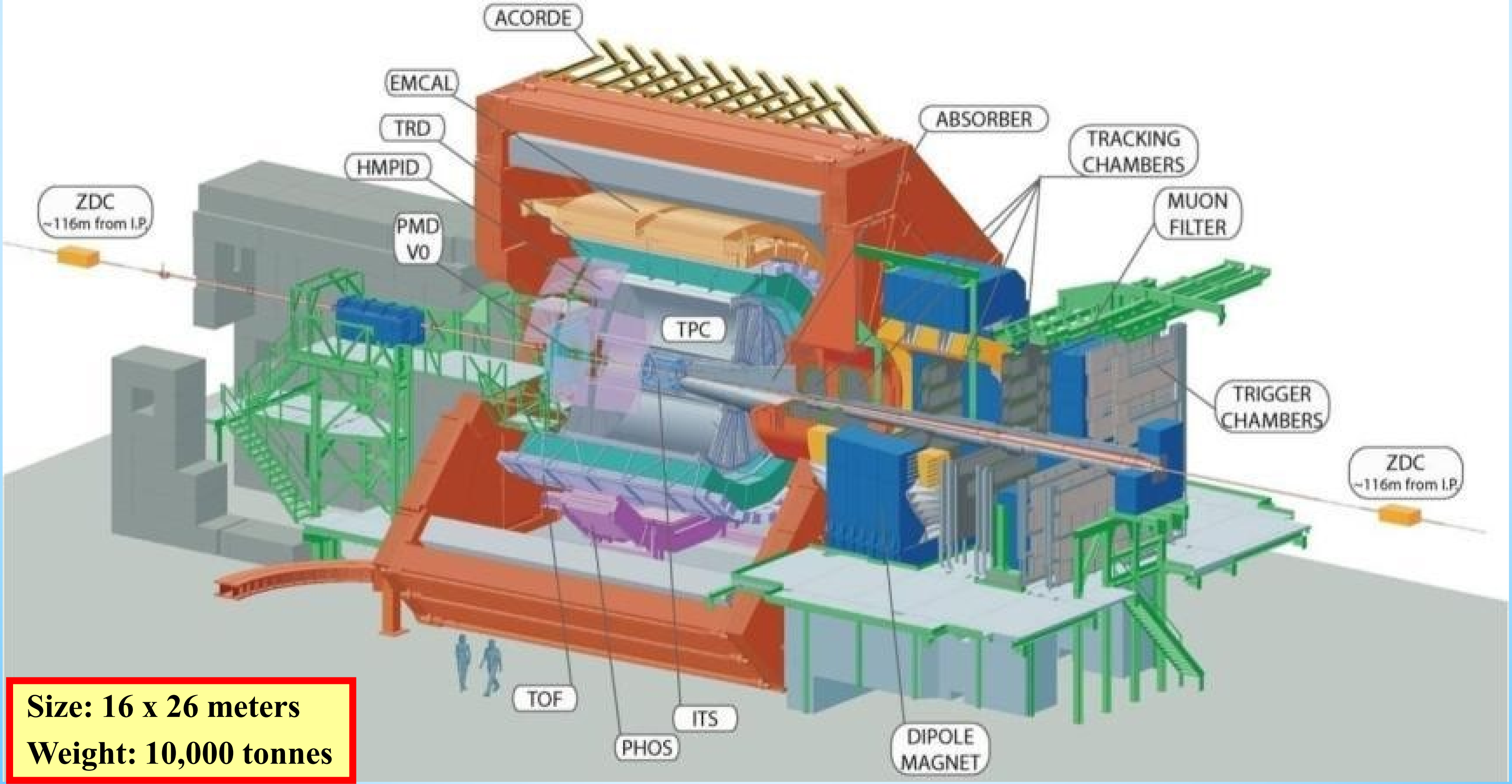
Outline

- The ALICE Inner Tracking System
- Hybrid Pixels for the ITS upgrade: 3D and Epitaxial sensors
- Beam test setup
- Preliminary results
- Summary and conclusions

The ALICE experiment

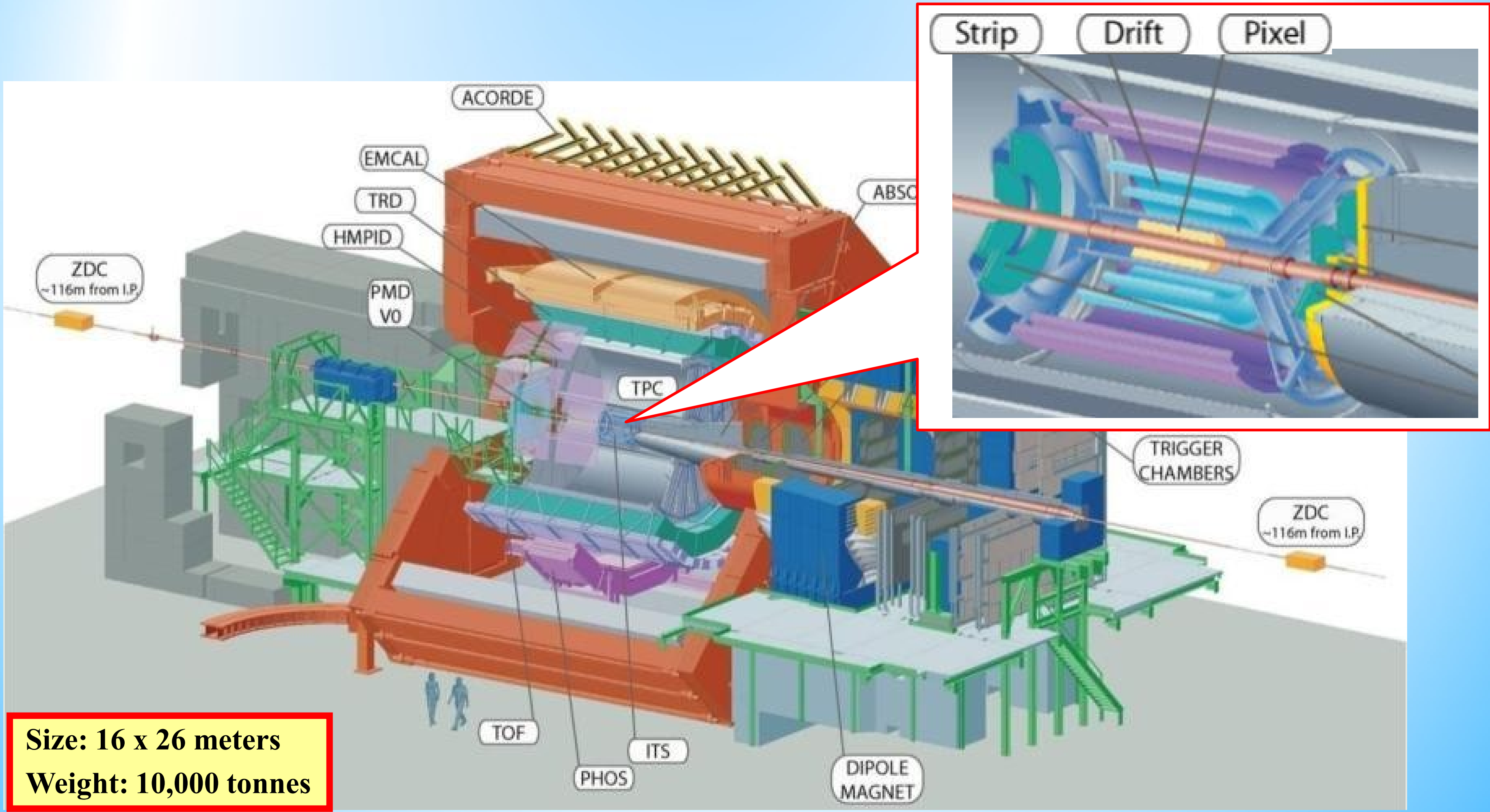
- **Ultra-relativistic nucleus-nucleus collisions**
  - study behavior of strongly interacting matter under extreme conditions of compression and heat
- **Proton-Proton collisions**
  - reference data for heavy-ion program
  - unique physics (momentum cutoff <100MeV/c, excellent PID, efficient minimum bias trigger)



Size: 16 x 26 meters
Weight: 10,000 tonnes

The ALICE Inner Tracking System

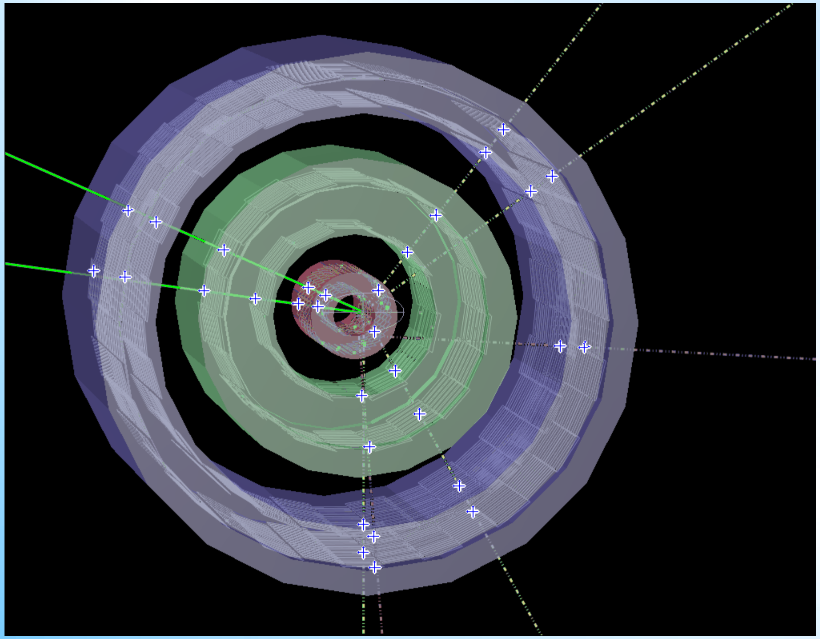
- **6-layer barrel**
- **3 different silicon detector technologies,** 2 layers each (inner → outer):
  - **Pixels (SPD), Drift (SDD), double-side Strips (SSD)**

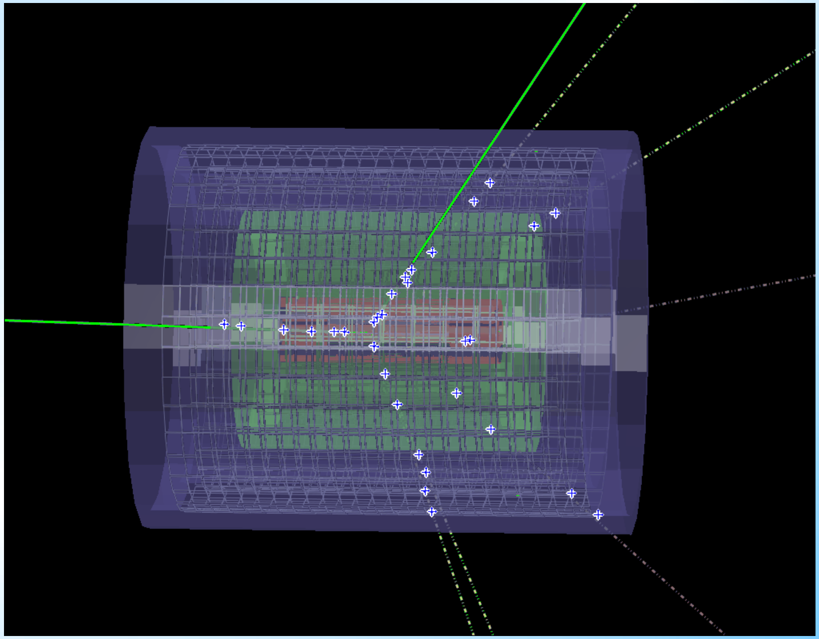


Size: 16 x 26 meters
Weight: 10,000 tonnes

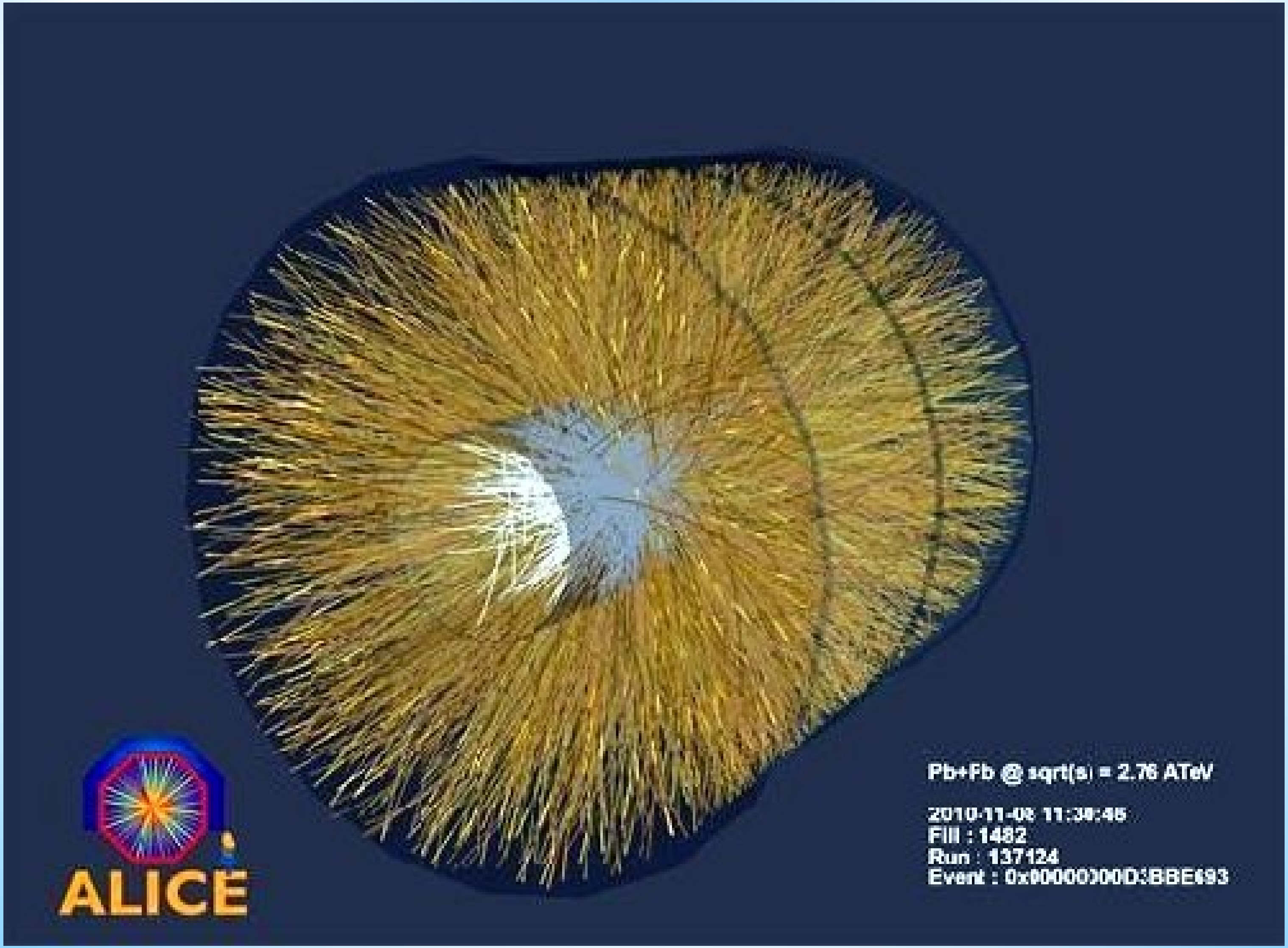
The ALICE Inner Tracking System

Layer	Det.	Radius (cm)	Length (cm)	Surface (m^2)	Chan.	Spatial precision (µm)		Cell (µm^2)	Max occupancy central PbPb (%)	Power dissipation (W)	
						rϕ	z			barrel	end-cap
1	**SPD**	3.9	28.2	0.21	9.8M	12	100	50x425	2.1	1.35k	30
2		7.6	28.2						0.6		
3	**SDD**	15.0	44.4	1.31	133K	35	25	202x294	2.5	1.06k	1.75k
4		23.9	59.4						1.0		
5	**SSD**	38.0	86.2	5.0	2.6M	20	830	95x40000	4.0	850	1.15k
6		43.0	97.8						3.3		





Pb-Pb event


ALICE
Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ITS Upgrade

- Aims to extend
  - the physics capabilities for the identification of short-lived particles containing heavy quarks through reconstruction and identification of the displaced vertex at mid-rapidity
  - the acceptance to larger rapidity

- Goals:
  - Improve impact parameter resolution, pointing resolution ≈50 μm up to very low p_T
    - Get closer to the Interaction Point: ≤25mm innermost radius (at present 39mm)
      - reduce beam pipe radius (at present 29mm)
    - Reduce material budget, especially innermost layers (at present ≈1.1% X_0 per layer)
      - reduce mass of silicon, power and signals bus, cooling, mechanics
      - monolithic pixels
    - Reduce pixel size, mainly for medium/high p_T (at present 50μm x 425μm)

  - Improve standalone tracking and PID capabilities

  - Improve readout and trigger capabilities

Pixel R&D

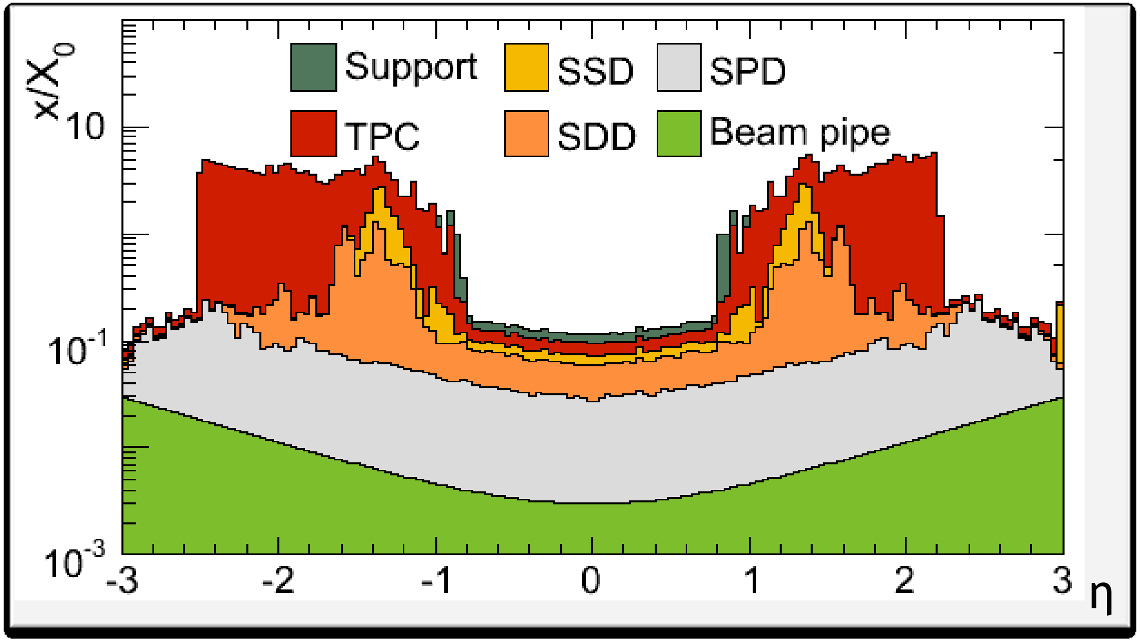
- In particular, for the innermost layers two main options are being considered:

- Monolithic pixel detectors
  - MIMOSA or future developments like LePix
  - Lower material budget and larger area (low cost)
  - Radiation tolerance and readout speed to be evaluated

- Hybrid pixel detectors
  - “state-of-the-art” of pixel detectors at LHC
  - R&D on low cost bump-bonding and low material budget
    - Reduce the thickness of the silicon substrates (sensor and ASIC)
    - Reduce the need for overlaps between modules (new sensor technologies: active edge, 3D)

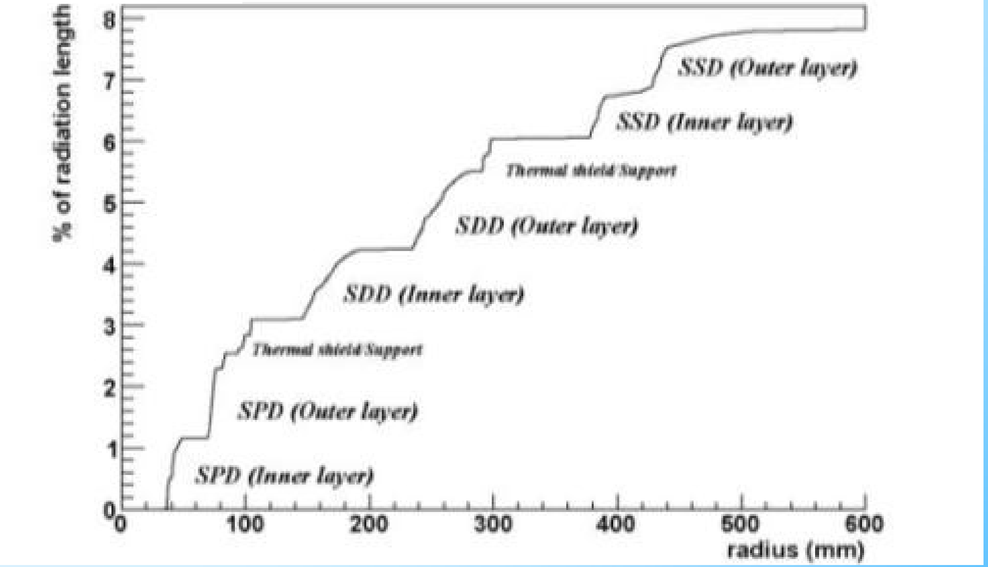
- Charge collection speed is not an issues and only a moderate radiation tolerance is needed

ALICE ITS Material Budget



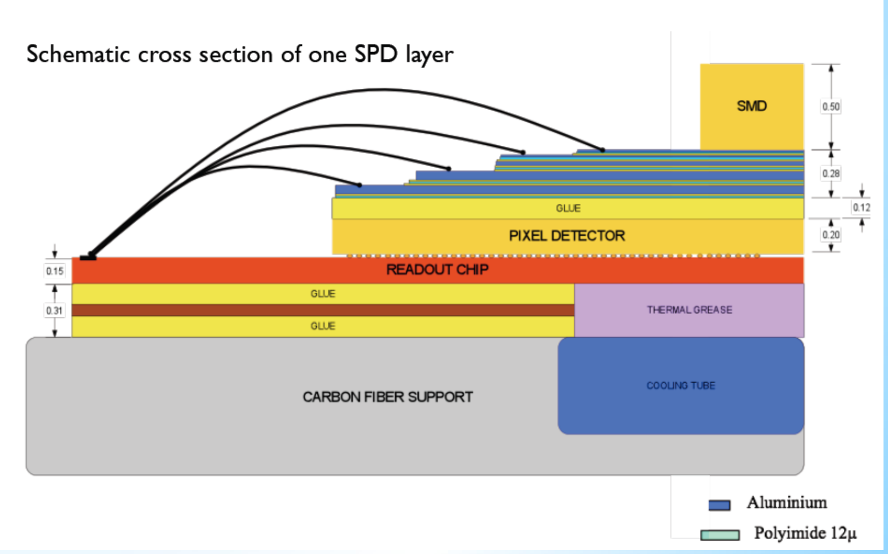
- About 1.1% X_0 per Pixel layer in the central region

- Integral of material thickness traversed by a perpendicular track originating at the primary vertex versus radius



ALICE Pixel Material Budget

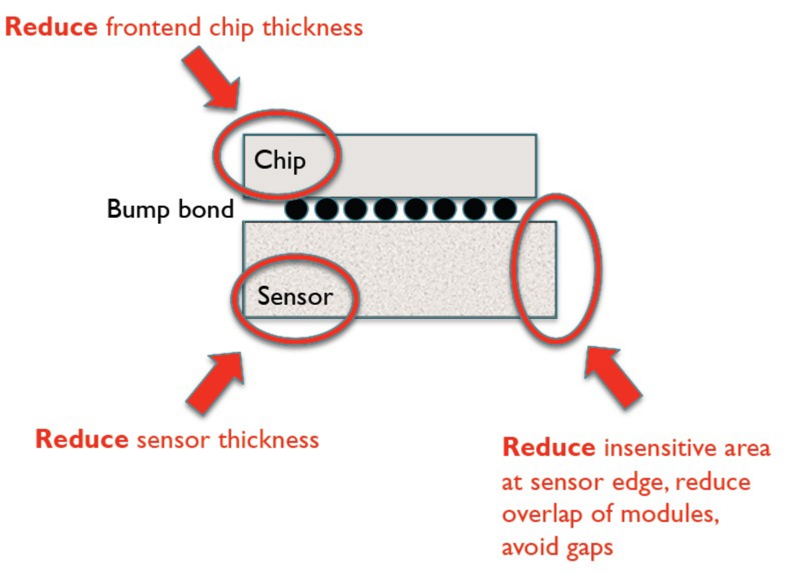
- Contributions to one current Pixel layer
  - Carbon fiber support: 200 µm
  - Cooling tube (Phynox): 40 µm wall thickness
  - Grounding foil (Al-Kapton): 75 µm
  - Pixel chip (Silicon): 150 µm ➡ 0.16% X_0
  - Bump bonds (Pb-Sn): diameter ~15-20 µm
  - Silicon sensor: 200 µm ➡ 0.22% X_0
  - Pixel bus (Al+Kapton): 280 µm ➡ 0.48% X_0
  - SMD components
  - Glue (Eccobond 45) and thermal grease


Schematic cross section of one SPD layer

Two main contributors: silicon and interconnect structure (bus)

Material Budget R&D

- How can the material budget be reduced?
  - Reduce silicon chip thickness
  - Reduce silicon sensor thickness
  - Thin monolithic structures
  - Reduce bus contribution (reduce power)
  - Reduce edge regions on sensor
  - Review also other components (but average contribution 0.01-0.02%)



Reduce frontend chip thickness

Reduce sensor thickness

Reduce insensitive area at sensor edge, reduce overlap of modules, avoid gaps

- What can be a reasonable target
  - Hybrid pixels:
    - silicon: 0.16% X_0 (at present 0.38%)
    - bus: 0.24% X_0 (at present 0.48%)
    - others: ?? (at present 0.24%)
  - Monolithic: 0.3÷0.4% X_0 (e.g. STAR)

Silicon Thickness: Status and R&D

	Si sensor [μm]	X_0 [%]	ASIC [μm]	X_0 [%]	X_0 total [%]
ALICE SPD	200	0.22	150	0.16	0.38
R&D intermediate	180, 150	0.19, 0.16	80	0.09	0.28, 0.25
R&D target	100	0.11	50	0.05	0.16

Reminder:

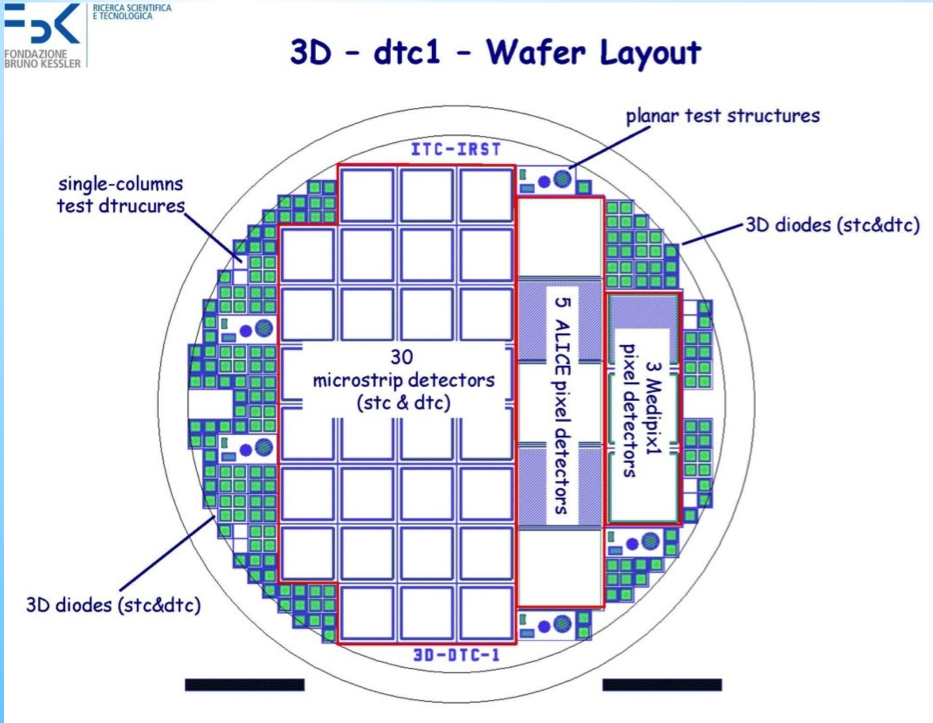
- Currently 1.14% X_0 per layer
- 2 main contributors: silicon (0.38%) and bus (~0.48%)

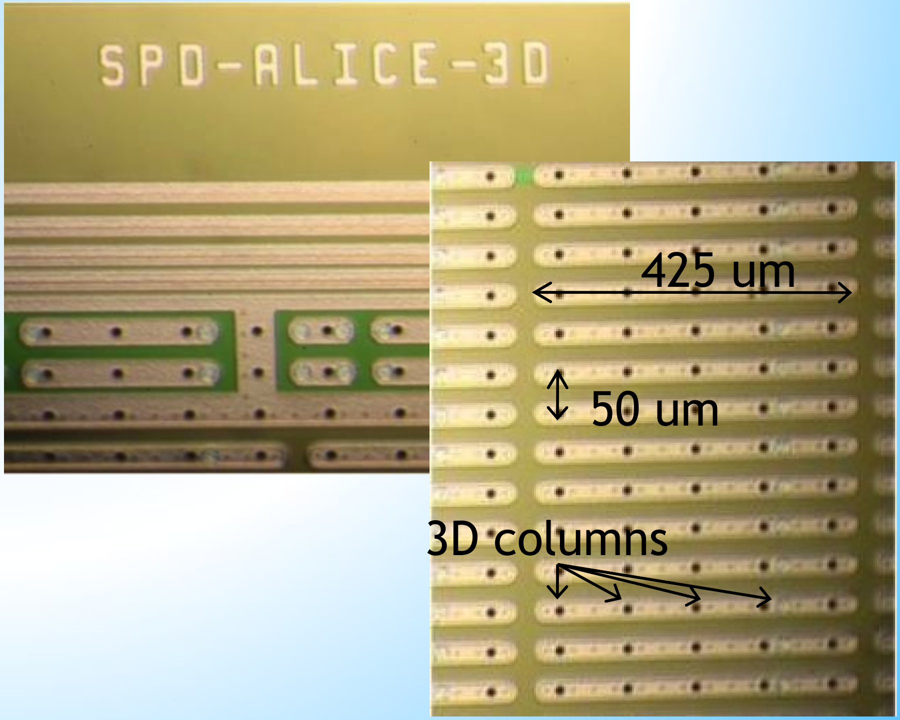
ALICE 3D-Pixel

- **ALICE 3D-Pixel sensor**

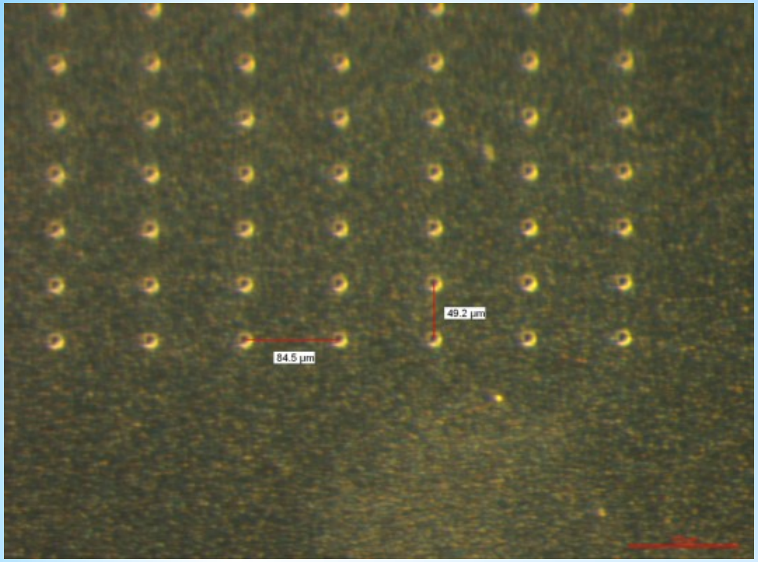
IEEE TRANSACTIONS ON NUCl. SC., VOL. 55, NO. 5 (2008) 2775

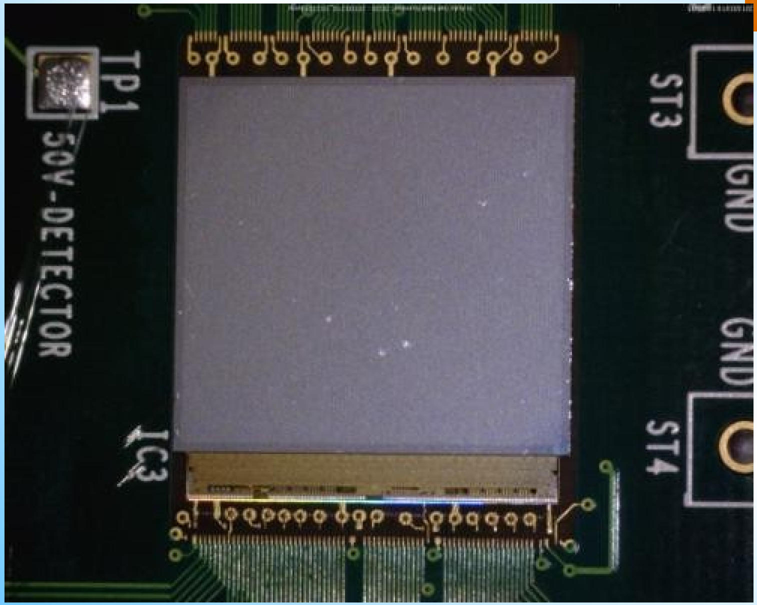
  - FBK multi-project wafer
    - n-type, Float Zone, crystal orientation <100>, nominal resistivity > 6 kΩ cm
    - Substrate thickness 300µm, Column depth 180µm
    - Double-sided Double-Type Column (DDTC)
  - Bump-bonded at VTT to ALICE pixel front-end chip

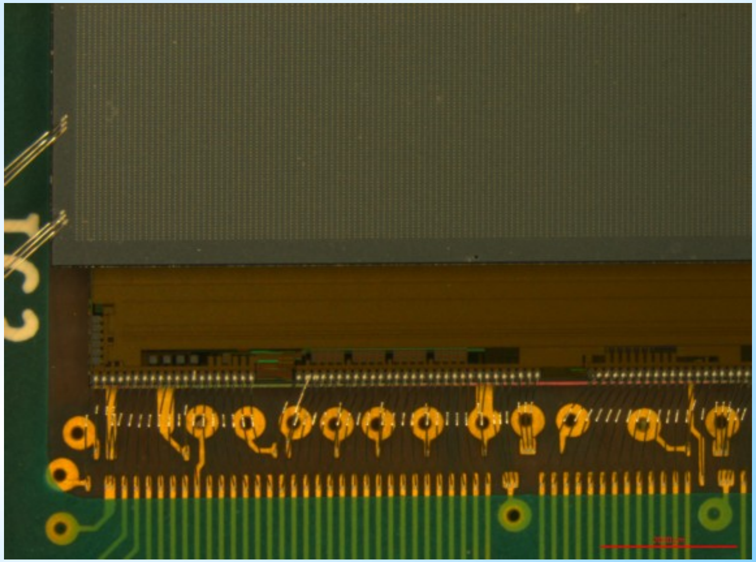




ALICE 3D-Pixel







Thinner Sensor Wafers

- Procurement and Processing of thin (≈100μm) blank wafers is challenging
  - Processing and Handling during bump-bonding
- Alternative:

  Epitaxial Wafers which can be thinned during the bumping process

  - Epitaxial wafers provide a mean to use very thin sensor wafers (carrier wafer "included for free")
- First tests to use epitaxial sensors with a pixel chip done by PANDA (Daniela Calvo et al.) [*see NIM A 595(2008)*]
  - Using existing ALICE SPD chips and sensor layout
  - Process epi wafers with 50 -100 um epi layer at FBK, native thickness 525 um
  - Bump bond and back grind them at VTT 100 -150 um
  - All wafers broke in the thinning step, but few singles could be recovered

Epitaxial Sensor Wafers

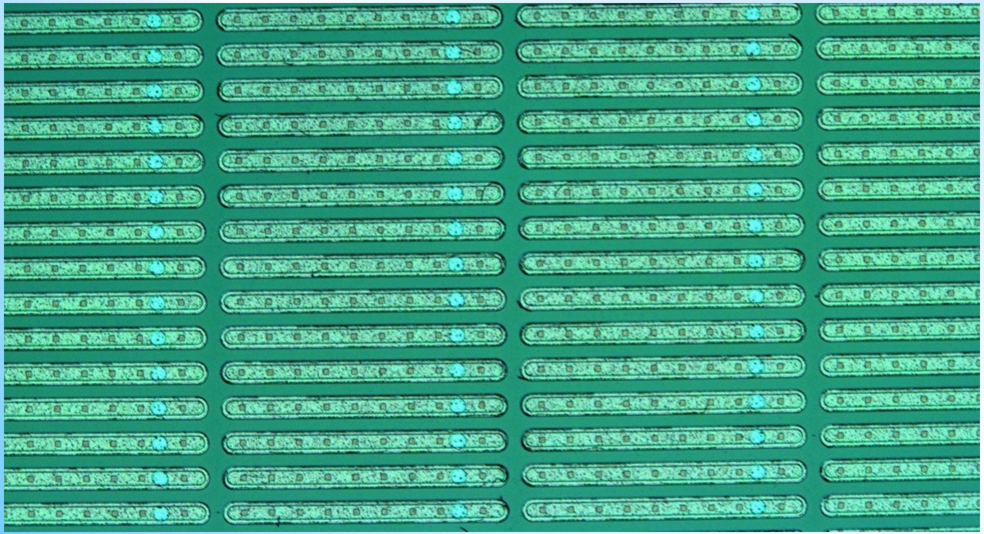
- **ALICE Epi-Pixel sensor**
  - Goal: achieve a sensor thickness of 100 µm (~ 0.11% X_0)
  - Test the sensors with the current ALICE pixel chip (optimized for 200µm sensor)
    - Purchase of 16 epi wafers from ITME (Poland): epi layer thickness 100µm and 120µm
  - First set of wafers processed at FBK
  - 3 wafers processed at VTT
    - Substrate 525µm, n/Sb, res 0.008-0.02 Ωcm, <111>
    - Epi layer 95-105µm, n/P, res 2000±100 Ωcm
    - 2 wafers went successfully through all process steps, including thinning and back side patterning, no breakage!

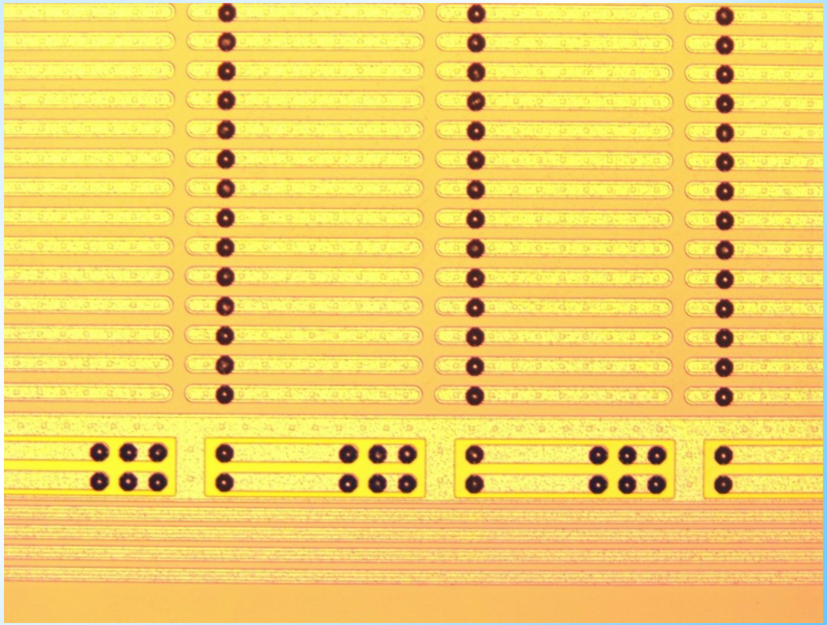
ALICE Epi-Pixel

- **ALICE Epi-Pixel sensor**
  - 5 singles flip-chip bonded to the current ALICE pixel front-end chip
  - Overall sensor thickness: 105-115 μm (epi layer + ≈10 μm)
  - 2 assemblies mounted on test-cards:

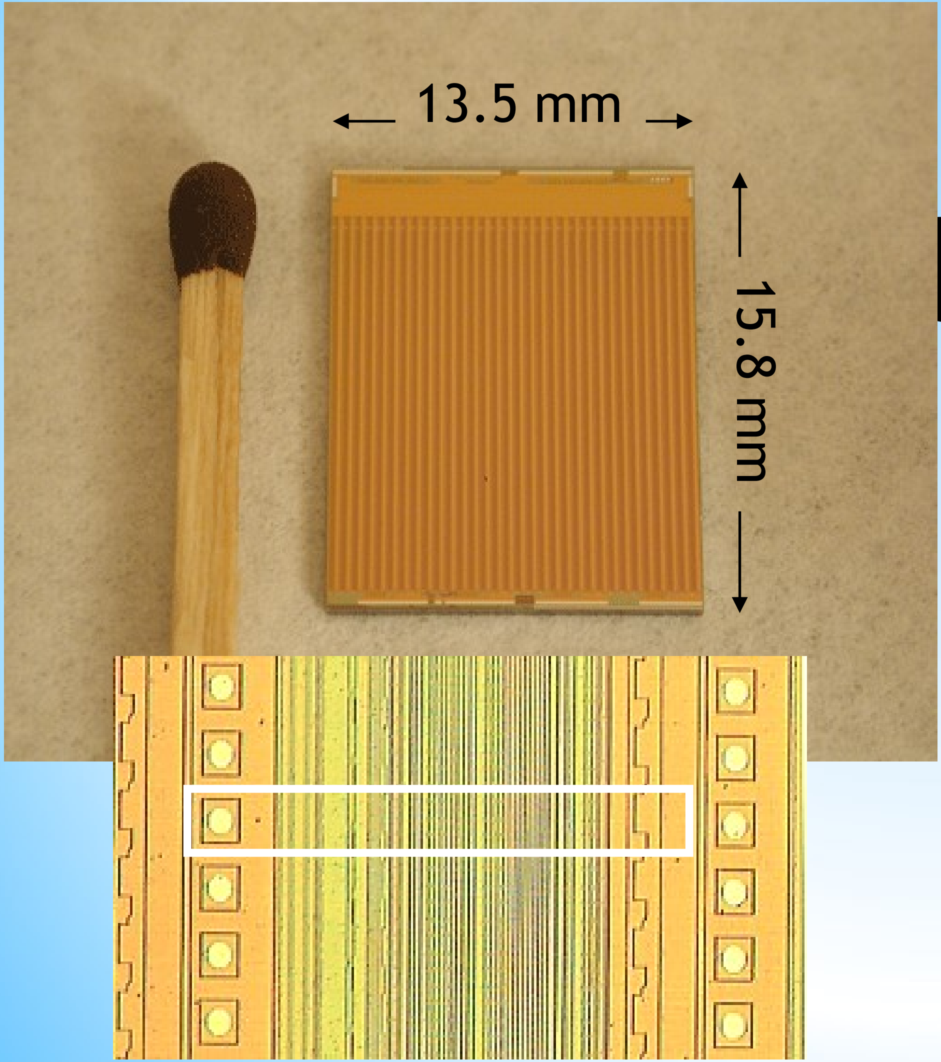
    - Preliminary electrical tests in lab showed good results

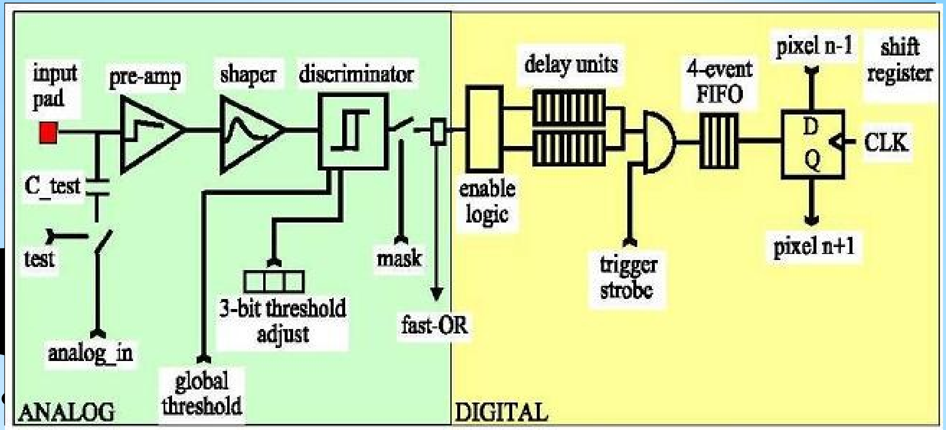
      ~30 nA at 20V at RT, min. threshold ~ 1500 el., ~30 missing pixels





ALICE Pixel front end chip





process (6 metal layers, 8” wafers)

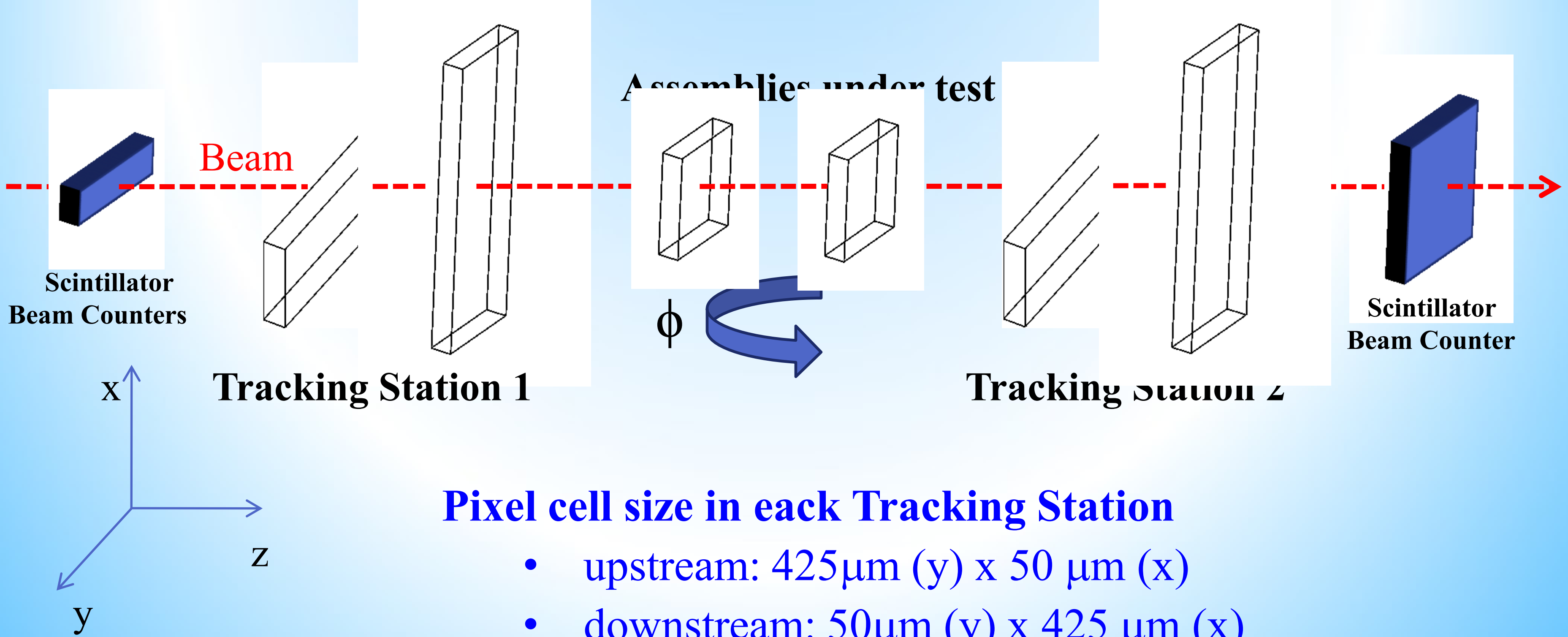
- Radiation tolerant design (enclosed gates, guard rings)
- 8192 pixel cells
- JTAG
- FastOR trigger signal
- 50 µm (rf) x 425 µm (z) pixel cell
- ~100 µW/channel
- ~1000 e^- mean threshold (~200 e^- RMS)
- ~110 e^- mean noise

Beam Test

- Assemblies to be tested:
  - 2 ALICE 3D-Pixel
  - 2 ALICE Epi-Pixel
- Beam
  - From 8/11/2010 to 15/11/2010
    - *Bad coincidence with the start-up of the first LHC heavy ion run!*
  - SPS Beam line H4
  - Positive beam (pions, protons), 350 GeV/c, up to 10^4 particles/spill
  - Duty cicle 49s, Flat top ≈ 9s, Trigger rate ≈3KHz
- Tracking Telescope
  - 4 ALICE Pixel modules arranged in two stations
- Trigger
  - FastOr logic used for selecting events (1 hit per tracking plane)
  - Scintillators for beam monitoring (never used for data taking)

Beam Test

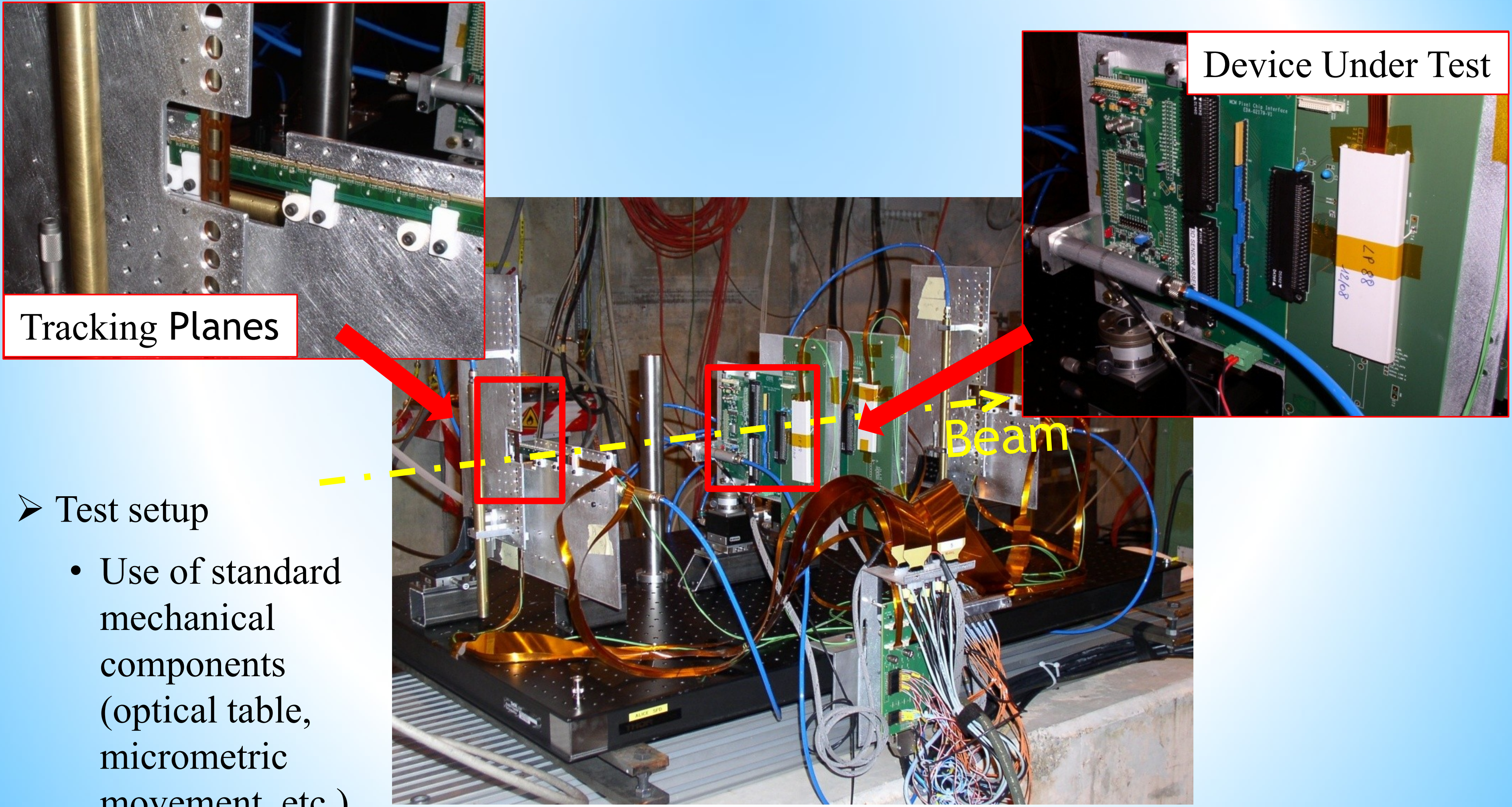
- Tracking telescope:
  - 2 stations, each made of 2 ALICE Pixel modules arranged in cross geometry
    - pixel cell dimensions 50 x 425 μm^2
  - Estimated tracking precision ≈10µm both in x and y directions
- Micrometric position adjustment:
  - x-y movements for the tracking planes and x-y-ϕ for the assemblies under test



Pixel cell size in eack Tracking Station

- upstream: 425µm (y) x 50 µm (x)
- downstream: 50µm (y) x 425 µm (x)

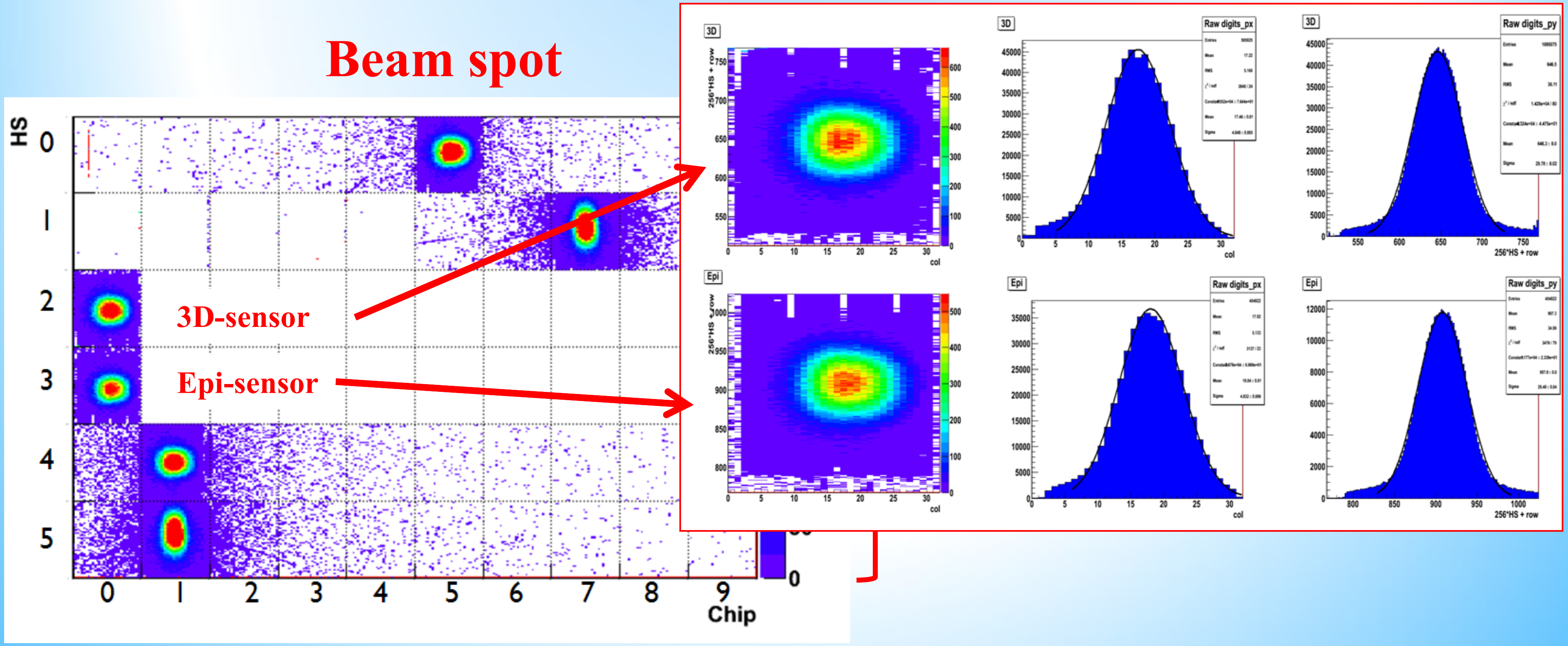
Beam Test Set-up



- Test setup
  - Use of standard mechanical components (optical table, micrometric movement, etc.)
  - Maximum compatibility with the ALICE DAQ, Trigger, DCS and on-line

Beam Test Measurements

Beam spot

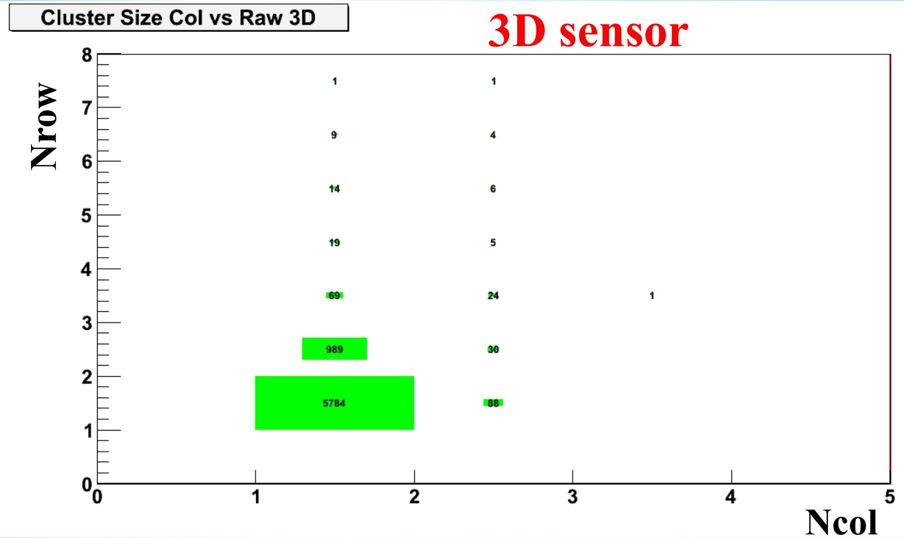


Cluster Size

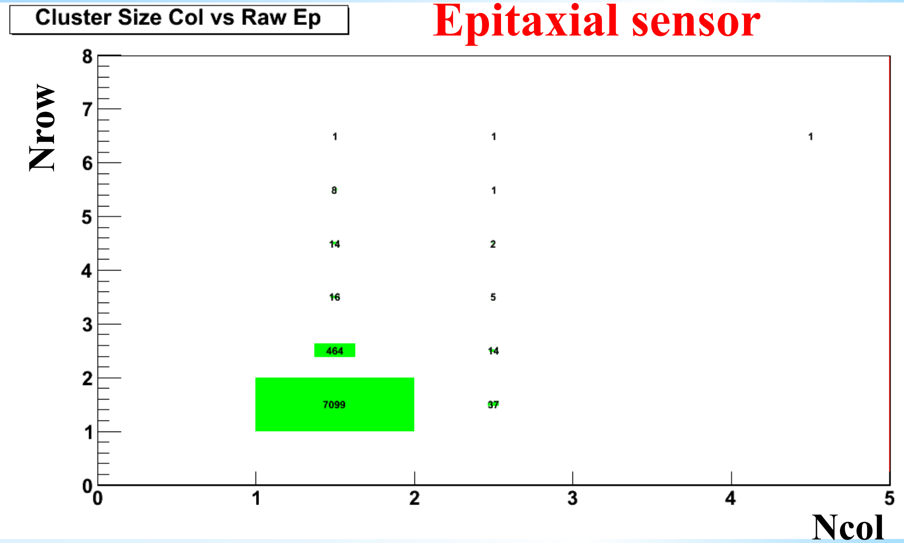
Pixel cell dimensions:

N_{col} (50 µm)

N_{col} (425 µm)



Depletion Voltage = 16V
Threshold = 180 Dac
Track impact angle = 0°



Depletion Voltage = 18V
Threshold = 200 Dac
Track impact angle = 0°

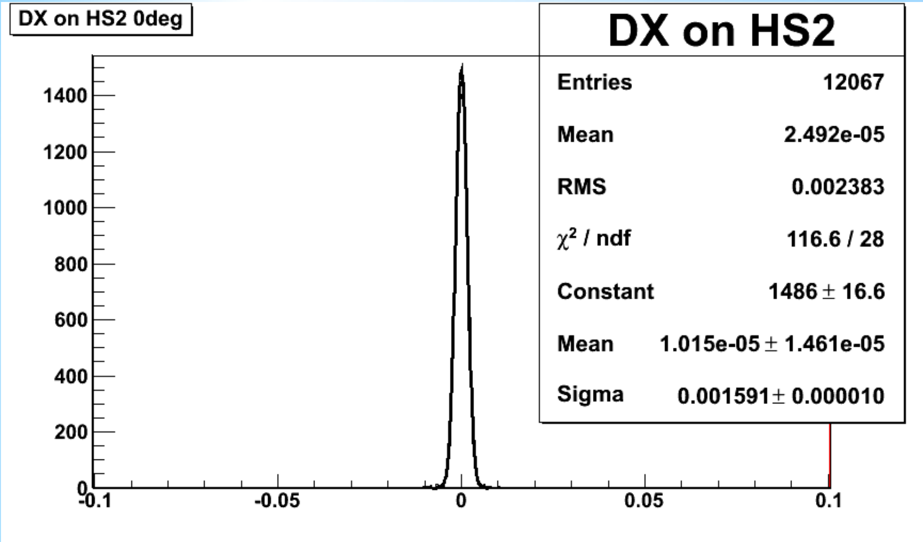
- **Almost all single and double clusters (≈ 97%)**
  - 3D → ≈82% cluster1 & ≈15% cluster2
  - Epitaxial → ≈92% cluster1 & ≈6% cluster2

Alignment

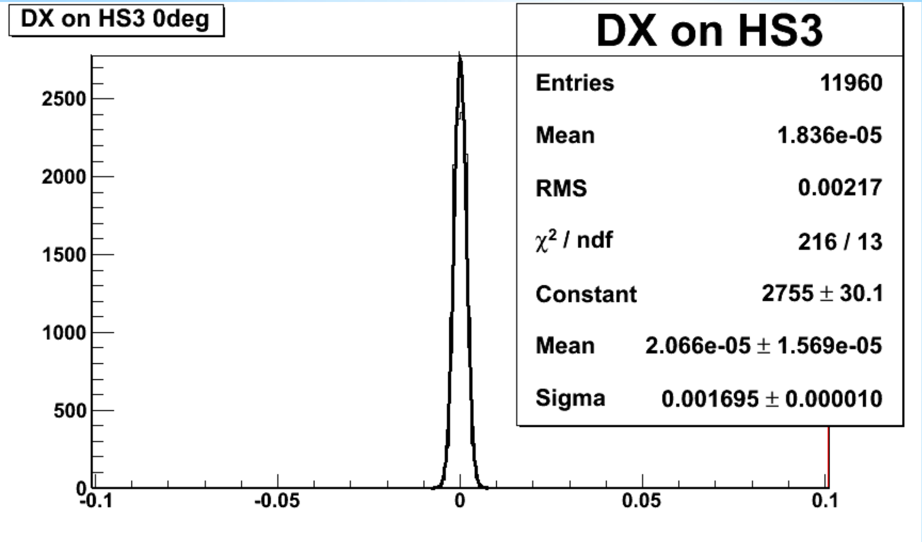
- **Track Selection**
  - Mask noisy pixels
  - Select a clean event sample: i.e. events with one hit in each tracking plane
- **Tracking Telescope alignment**
  - Fitting straight tracks excluding the detectors under test
    - 4 space points per track
    - Distance between planes within a tracking station ≈ 1cm
    - Tracks with small angles (less than 1°)
    - Multiple scattering negligible
      - 350 GeV tracks
      - low material budget (<1% X_0 per plane)
- **Final alignment**
  - Re-fitting tracks including the detector under test
    - Use 5 points for the track fitting excluding one plane at a time
    - Iterative procedure for all planes

3D and Epi Residuals

3D sensor



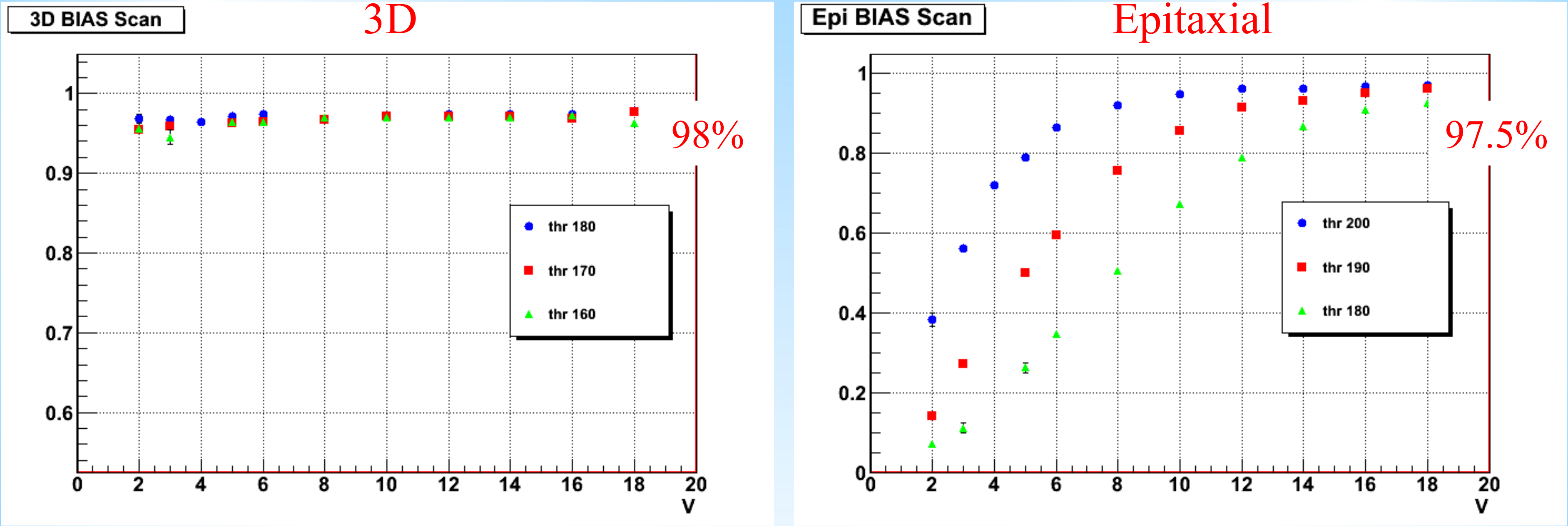
Epi sensor



0° Tracks, 16 V Bias
Minimum Threshold: 3D → 180 DAC (≈4300 el), Epi → 200 DAC (≈3000 el)

Efficiency vs V_{bias}

0° tracks



3D

98%

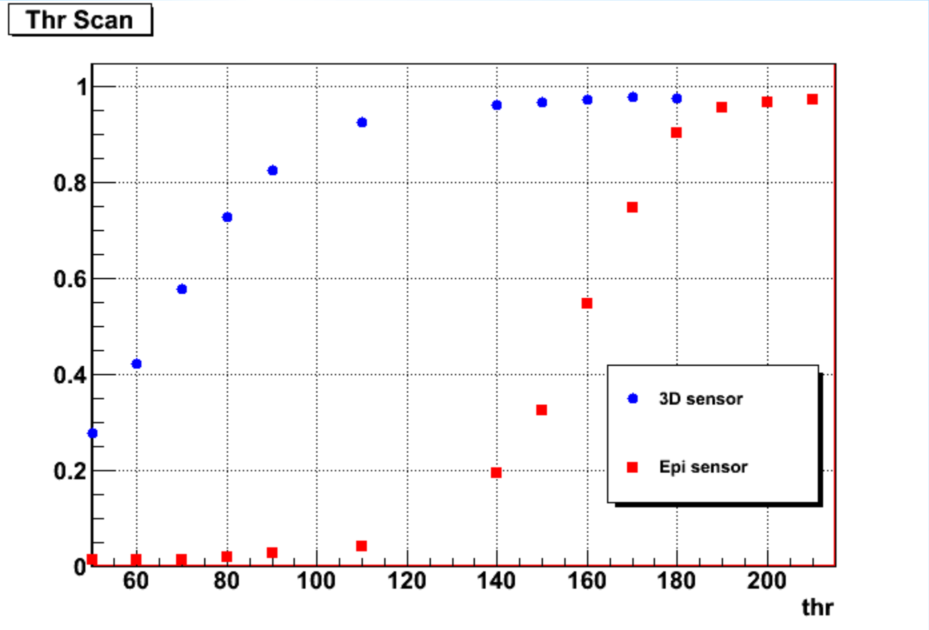
Epitaxial

97.5%

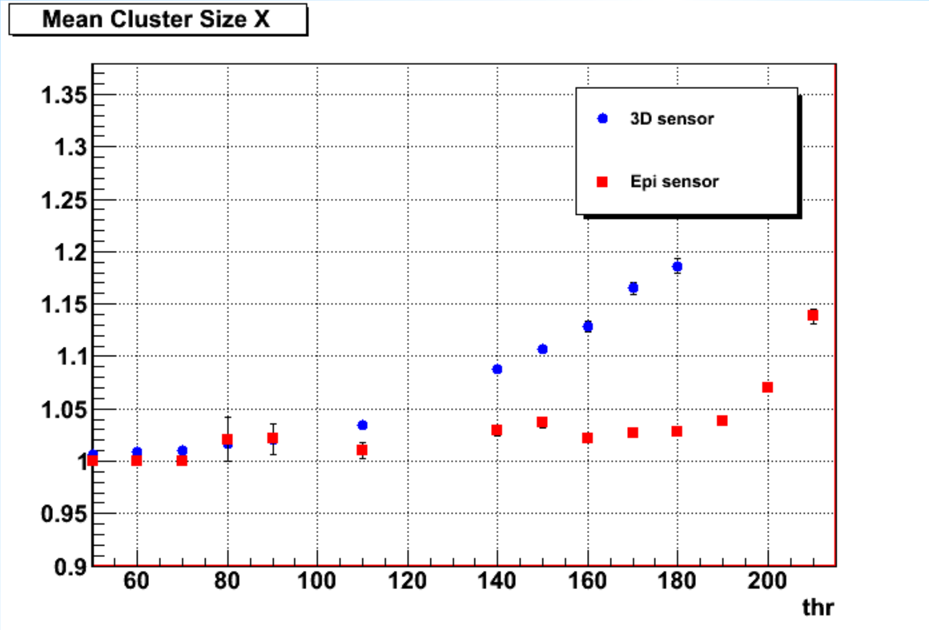
Detection Efficiency vs Depletion Voltage

Efficiency and Mean Cluster Size vs Thr

0° tracks – 16 V depletion voltage



Detection Efficiency vs Threshold



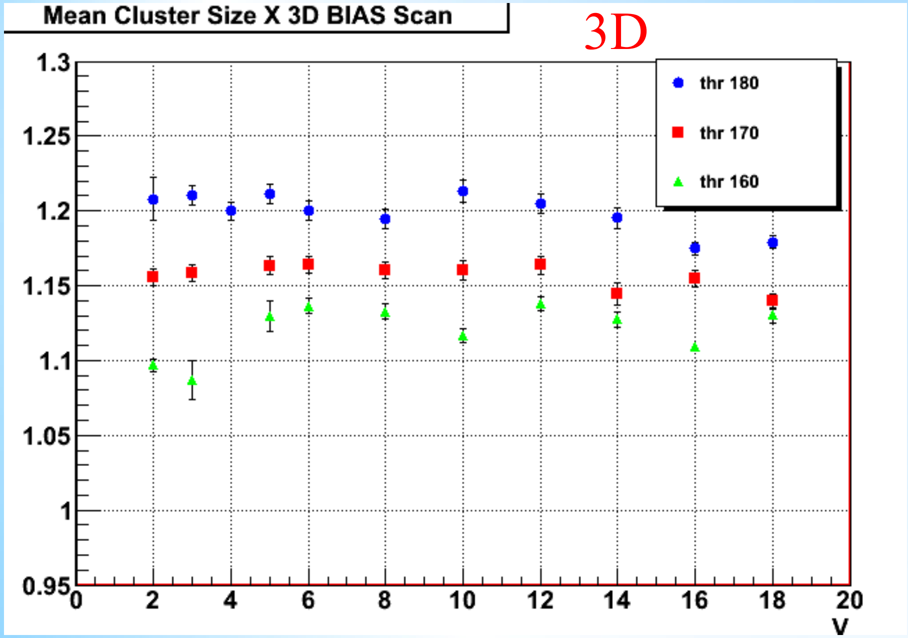
Mean Cluster Size along short pixel dimension (50 µm) vs Threshold

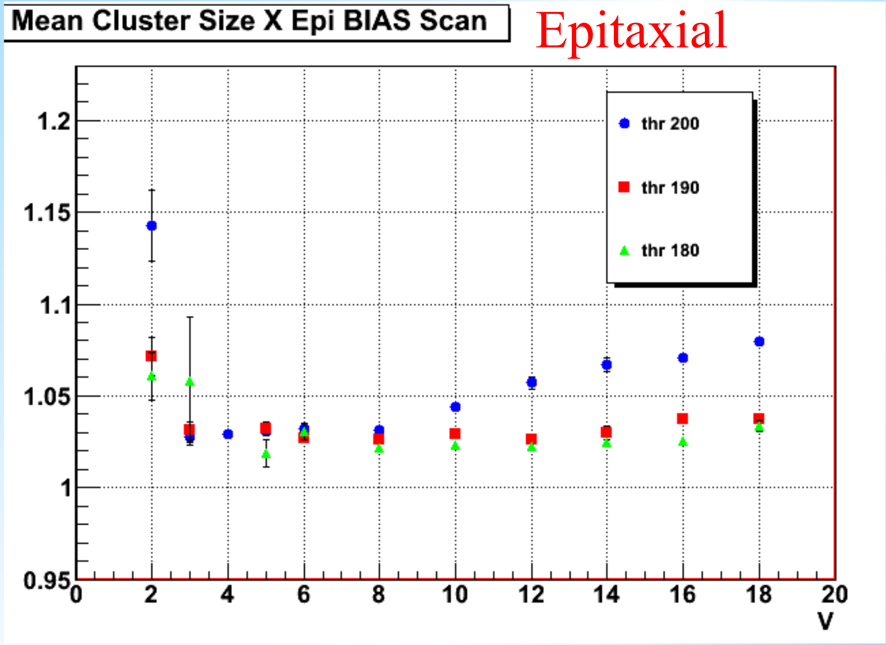
Thr (DAC)	Thr (el.)
200	3000
190	3600
180	4200
170	4800

- ❖ increasing DAC values correspond to decreasing effective threshold

Mean Cluster Size vs V_{bias} and Thr

0° tracks

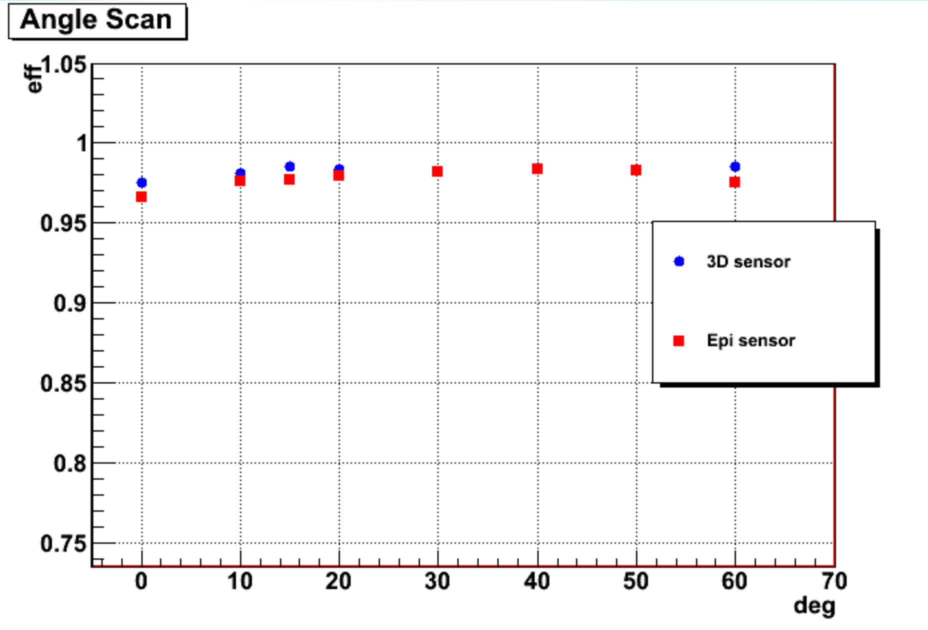




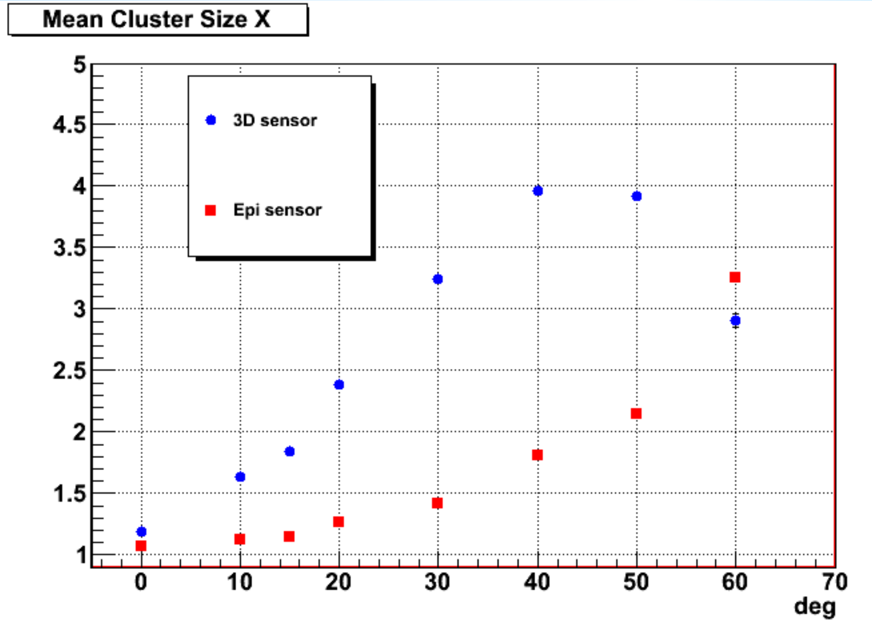
Mean Cluster Size along short pixel dimension (50 μm) vs Depletion Voltage

Efficiency and Mean Cluster Size vs Angle

16V Depletion Voltage
Threshold: 180 for 3D and 200 for Epi



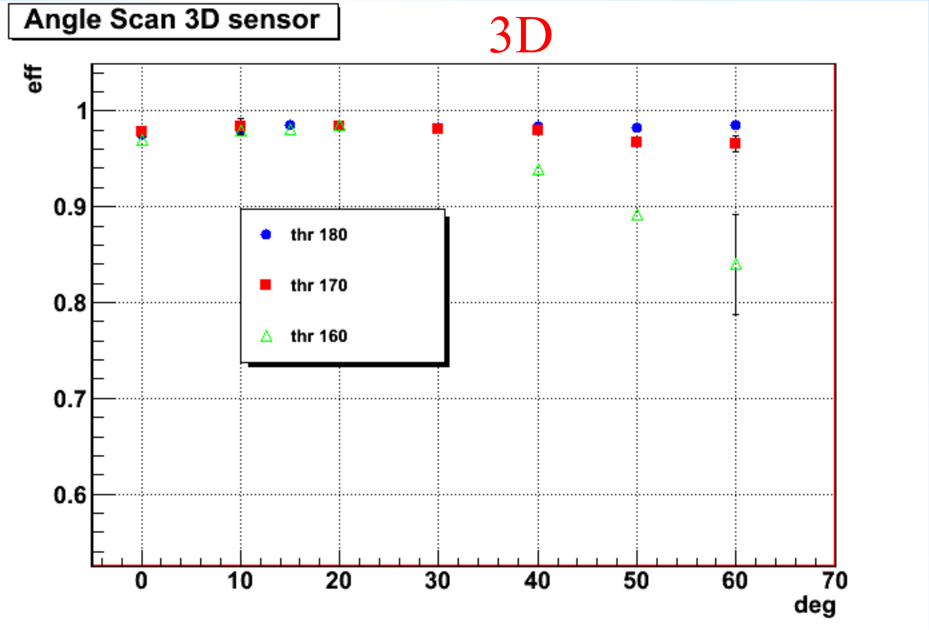
Detection Efficiency vs Track Impact Angle

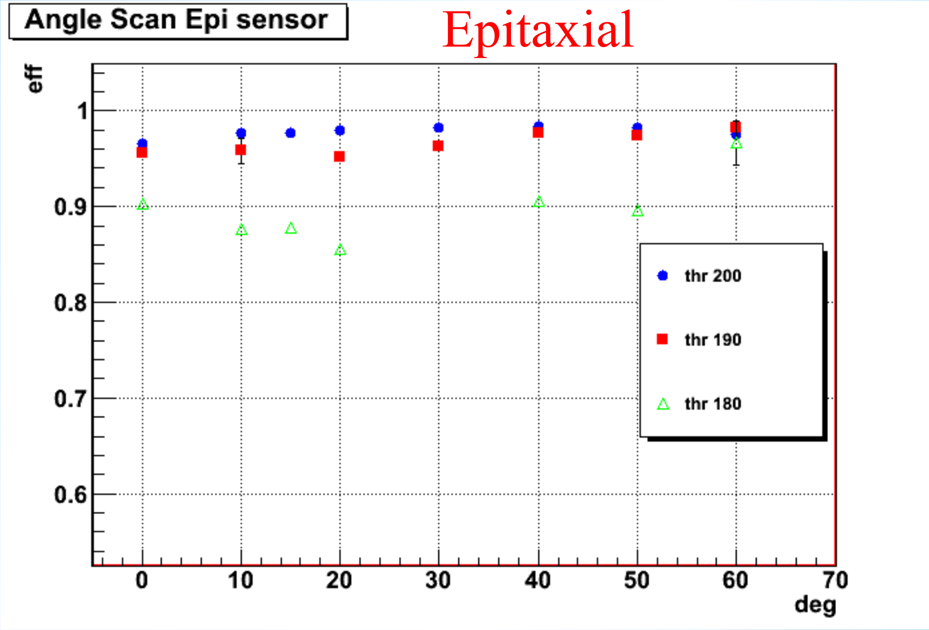


Mean Cluster Size along short pixel dimension (50 µm) vs Track Impact Angle

Efficiency vs Angle

16 V depletion voltage

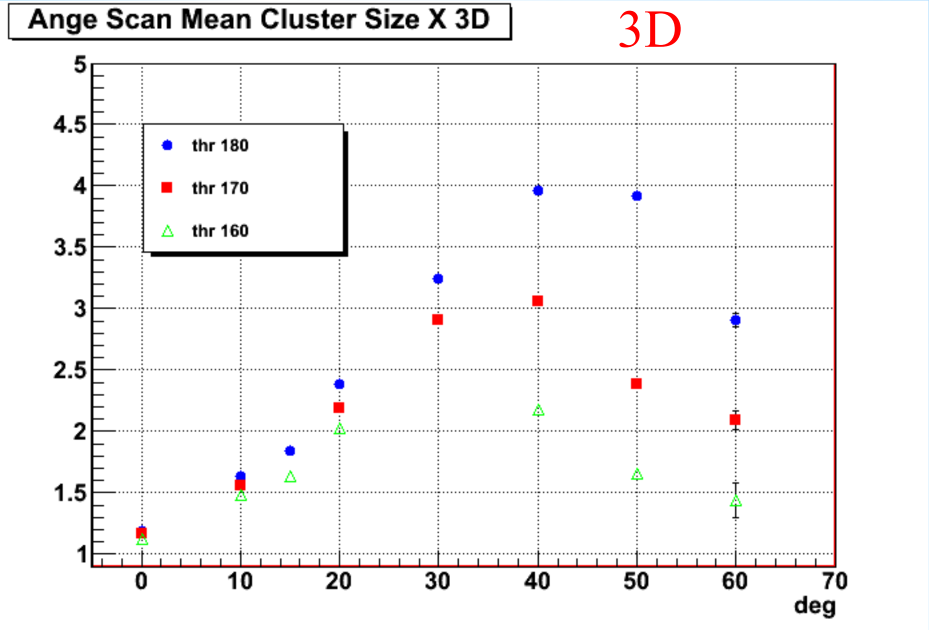


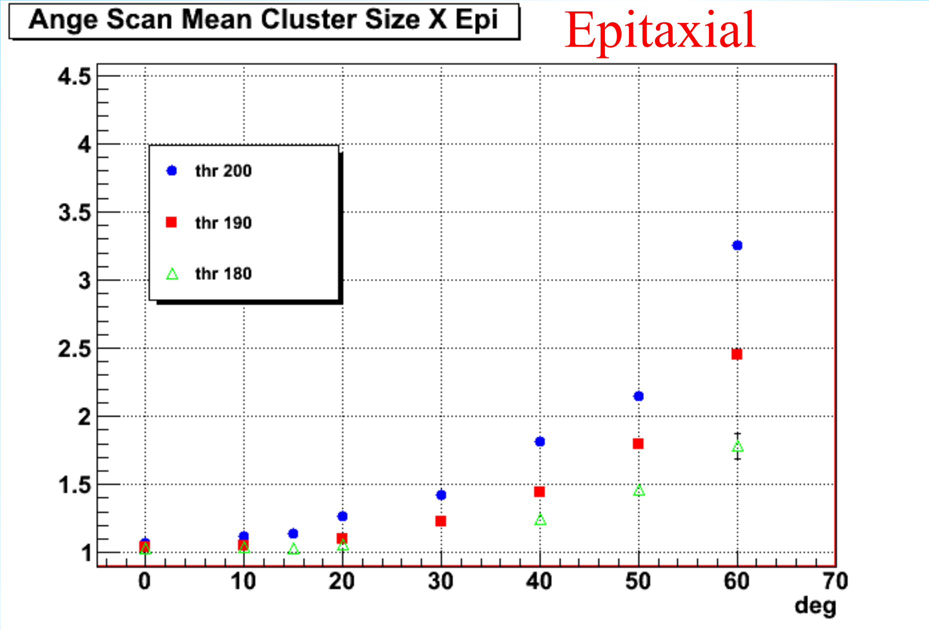


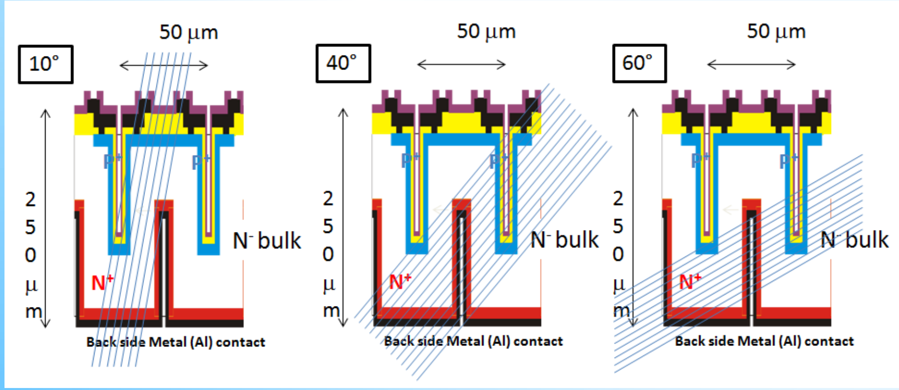
Detection Efficiency vs Track impact angle

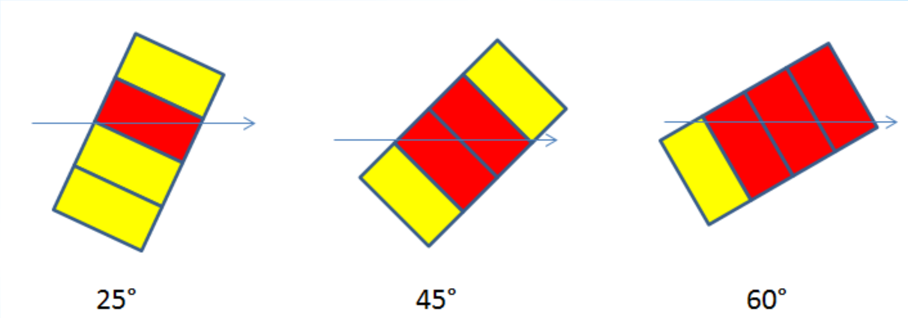
Mean Cluster Size vs Angle and Thr

Mean Cluster Size vs Track Impact Angle – 16 V Depletion Voltage









Summary and Conclusions

- 3D Double-sided Double-Type Column and Epitaxial sensors have been bump-bonded to the current ALICE pixel front-end chip and tested in a beam at the SPS

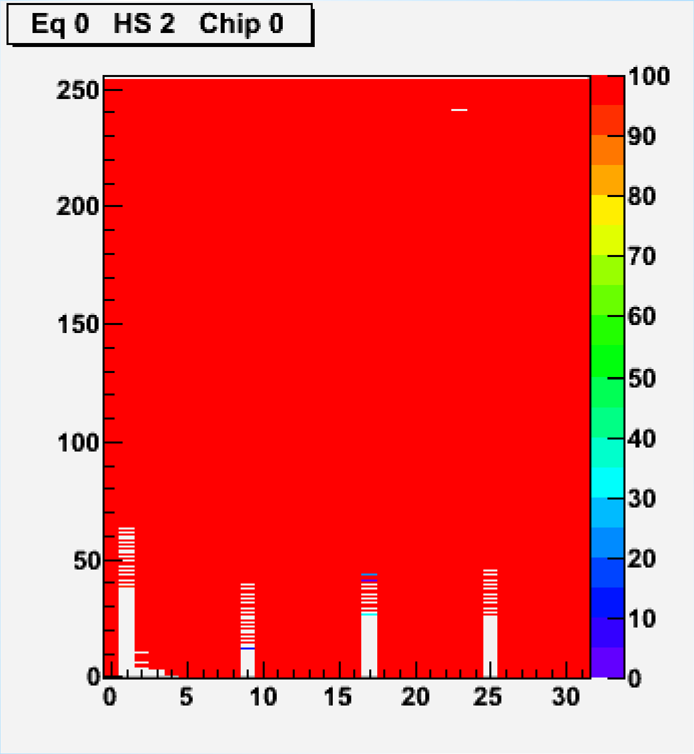
- Preliminary results are very promising and in particular the epitaxial thin sensor is very attractive for very light hybrid pixel detectors

- Outlook:
  - ALICE Epi-Pixel sensor with active edge
  - Upgrade the beam test facility with a finer pitch tracking telescope

Back-up slides

Uniformity matrix scan

Assembly 01 (3D)



Assembly 02 (EPI 100um)