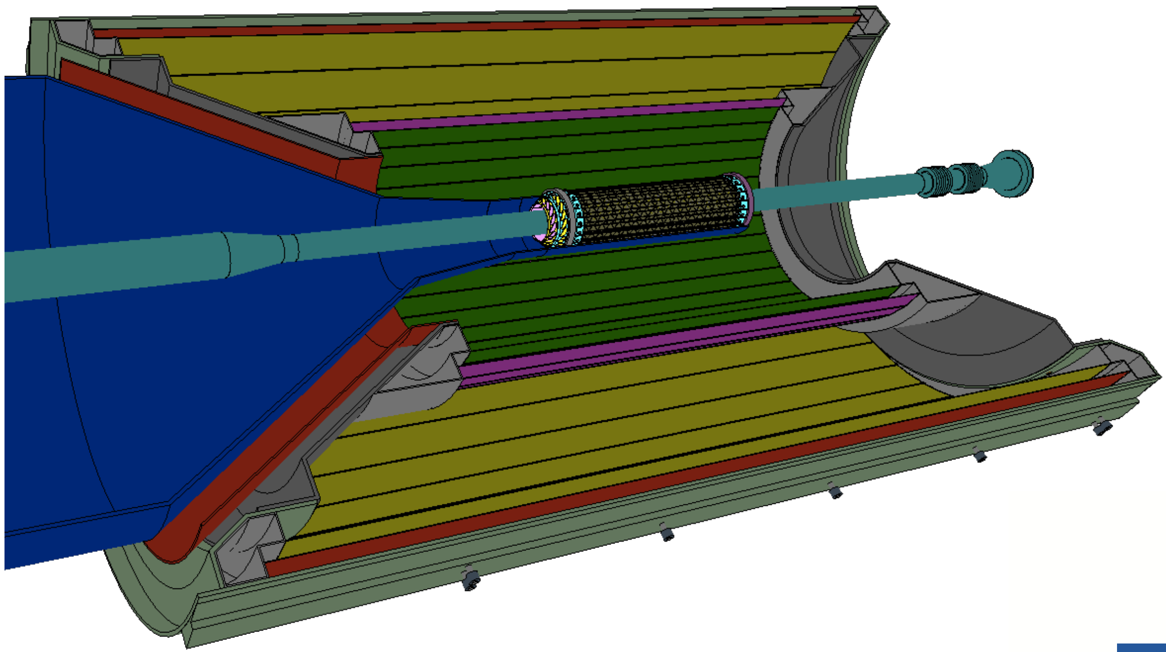
A Large Ion Collider Experiment

The ALICE Inner Tracker Upgrade



Petra Riedler/CERN
on behalf of the ALICE ITS upgrade collaboration

Joint Instrumentation Seminar of the Particle Physics and Photon Science communities at DESY, Hamburg University and XFEL, October 12, 2012

Outlook

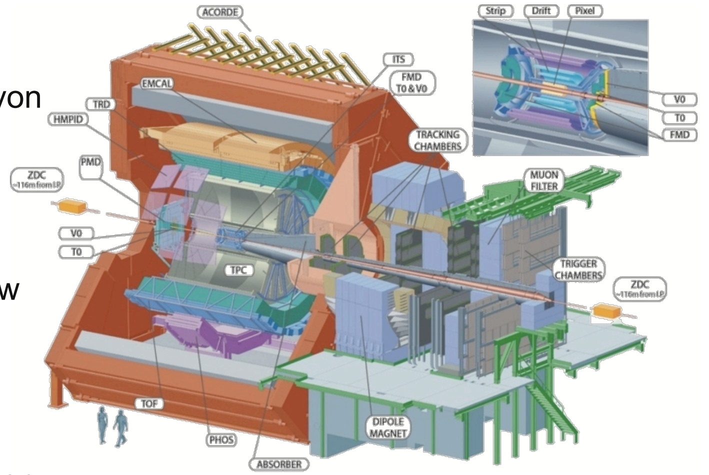
- **The ALICE upgrade strategy**
- **The upgrade of the ALICE Inner Tracker**
  - Present system
  - Upgrade plans: motivation, design goals, requirements
- **R&D activities – status and outlook**
  - Pixel technologies: monolithic – hybrid
  - System layout considerations
  - Interconnection and bus studies
- **Summary**

The ALICE upgrade

ALICE – dedicated heavy ion experiment to study strongly interacting matter at extreme energy densities

The upgrade targets physics topics uniquely accessible to ALICE:

- **Measurement of heavy-flavour transport parameters:**
  - diffusion coefficient – azimuthal anisotropy and R_{AA}
  - in-medium thermalization and hadronization – meson-baryon mass dependence of energy loss – R_{AA}
  - study of QGP properties via transport coefficients (η/s, q)
- **J/ψ , ψ', and χ_c states down to zero p_t in wide rapidity range**
  - yields and transverse momentum spectra – R_{AA}, elliptic flow
  - density dependence – central vs. forward production
  - statistical hadronization vs. dissociation/recombination
- **Measurement of low-mass and low-p_t dileptons**
  - chiral symmetry restoration – vector-meson spectral function
    - (disappearance of vacuum condensate and generation of hadron masses)
  - QGP thermal radiation – low-mass dilepton continuum
  - space-time evolution of the QGP – radial and elliptic flow of emitted radiation



The ALICE upgrade

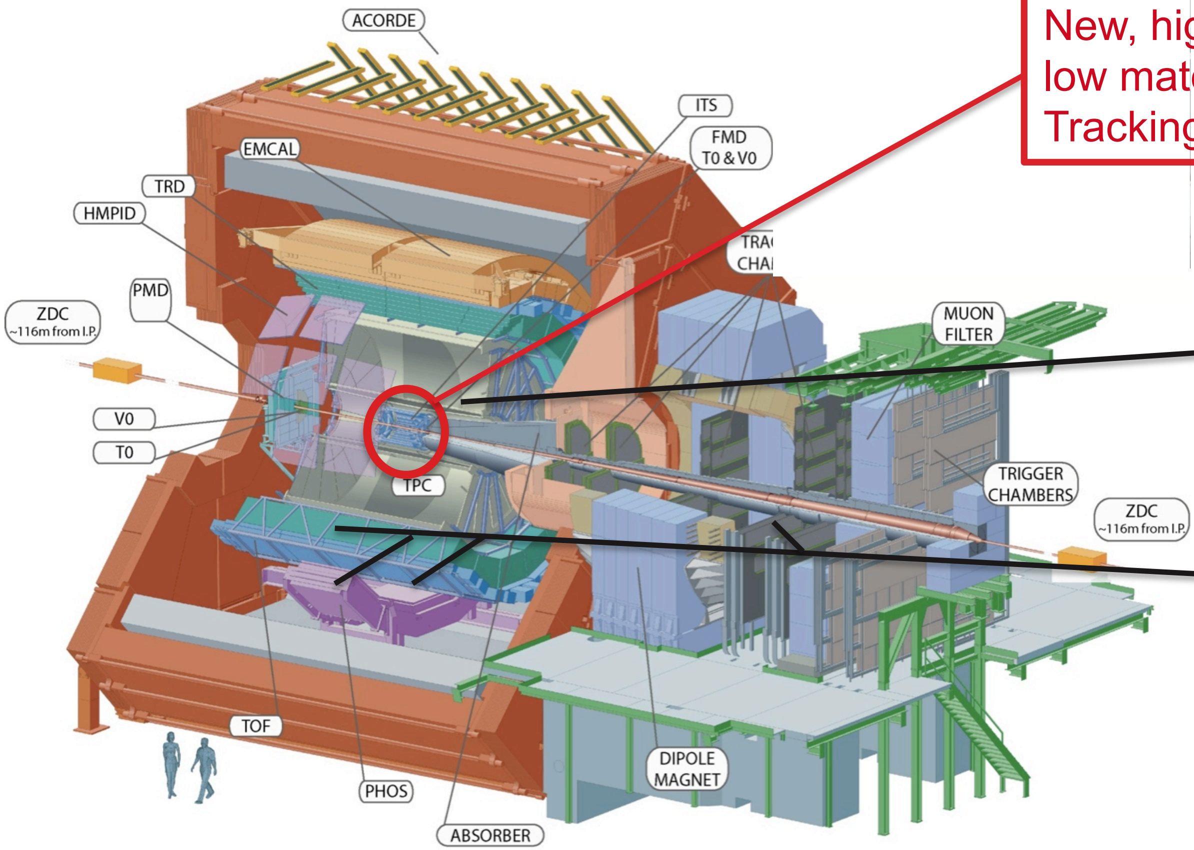
High precision measurements of rare probes at low p_T after the long shutdown at 2018/19, which cannot be selected with a trigger, require a large sample of events recorded on tape and **improvement on vertexing and tracking capabilities.**

Pb-Pb recorded luminosity	≥ 10 nb^{-1}	8 x 10^{10} events
pp (@5.5 Tev) recorded luminosity	≥ 6 pb^{-1}	1.4 x 10^{11} events

→ Upgrade ALICE readout and online systems

→ **Improve vertexing and tracking** → **Inner Tracker Upgrade**

The ALICE upgrade



New, high-resolution and low material Inner Tracking System (ITS)

TPC upgrade: replace MPWCs with GEMs and new piplelined readout

Upgrade of readout electronics (TRD, TOF, PHOS, MUON)

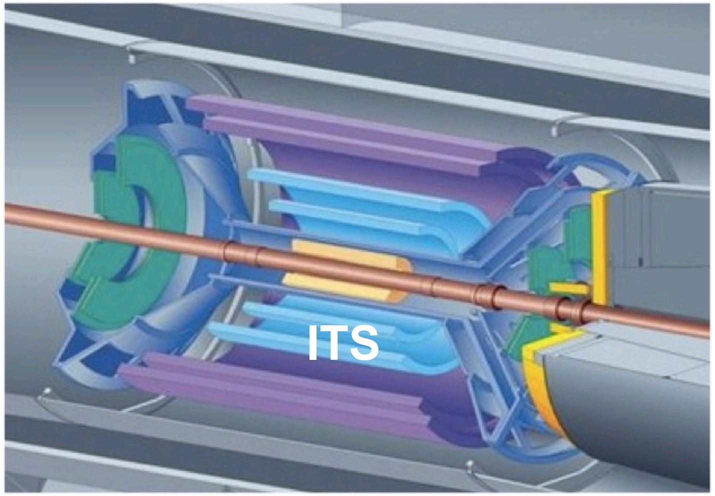
Upgrade of the forward trigger detectors

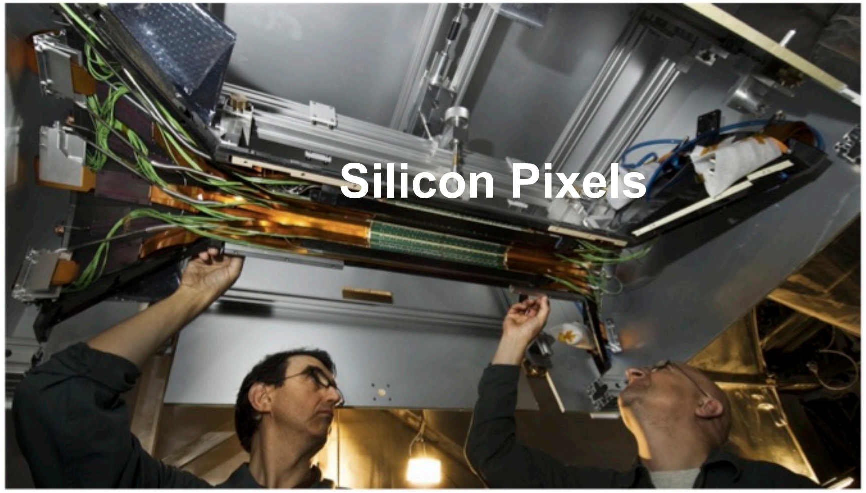
Upgrade of online systems and of offline reconstruction and analysis framework and code

The upgrade of the ALICE Inner Tracker

The present ITS

- 6 layers of silicon detectors (pixels, drift, strips)
- PID (drift and strips)
- Pixel multiplicity trigger
- Low material budget: 1.14 % X_0 per pixel layer, 7.2 % X_0 for ITS
- L_0 at 3.9 cm from IP

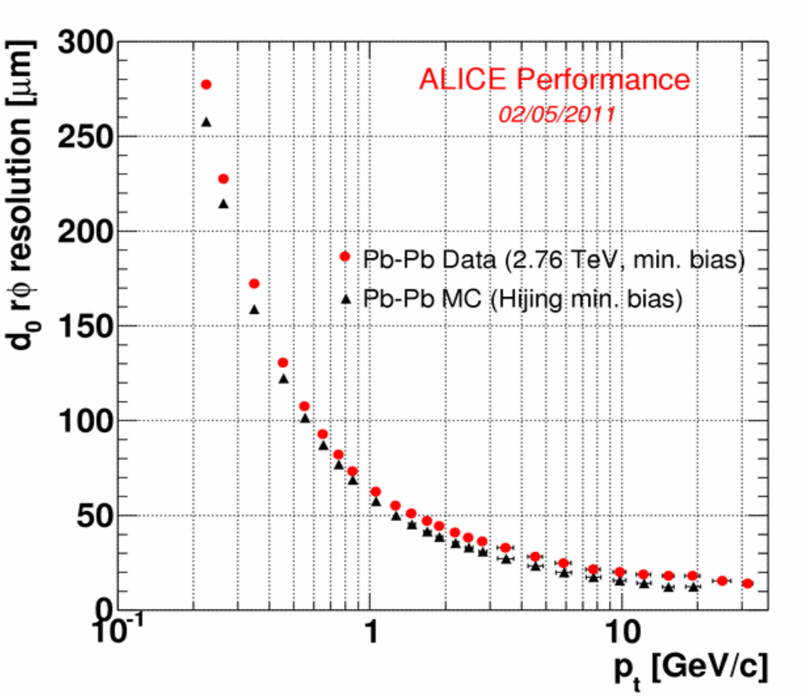




The upgrade of the ALICE Inner Tracker

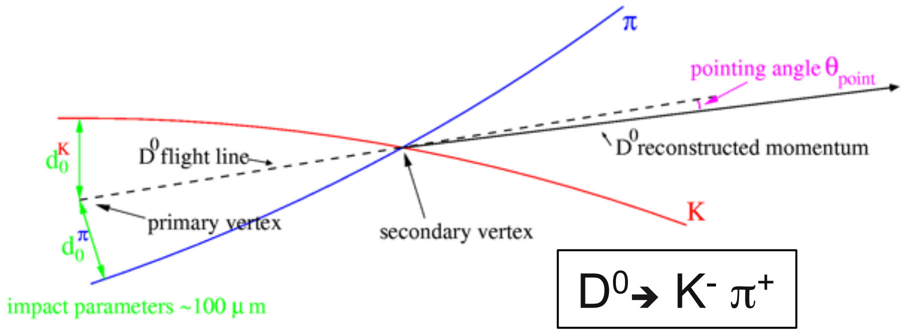
The present ITS

Impact parameter resolution



Limitations:

- Charmed mesons difficult for $p_T \rightarrow 0$ (background is too large)
- resolution not sufficient for charmed baryons, Λ_c ($c\tau \sim 60 \mu m$) impossible in Pb-Pb collisions , at the limit in pp (only high p_T)
- Λ_b impossible in Pb-Pb collisions (insufficient statistics and resolution)
- indirect B measurement via electrons, B/D separation difficult, especially at low p_t (e PID + vertexing)



The upgrade of the ALICE Inner Tracker

Design goals

Improve impact parameter resolution by a factor of ~3 (r-phi)

- Get closer to IP
- Reduce material budget
- Reduce pixel size

High standalone tracking efficiency and p_t resolution

- Increase granularity
- Increase radial extension

Fast readout

- Readout of Pb-Pb interactions at 50 kHz

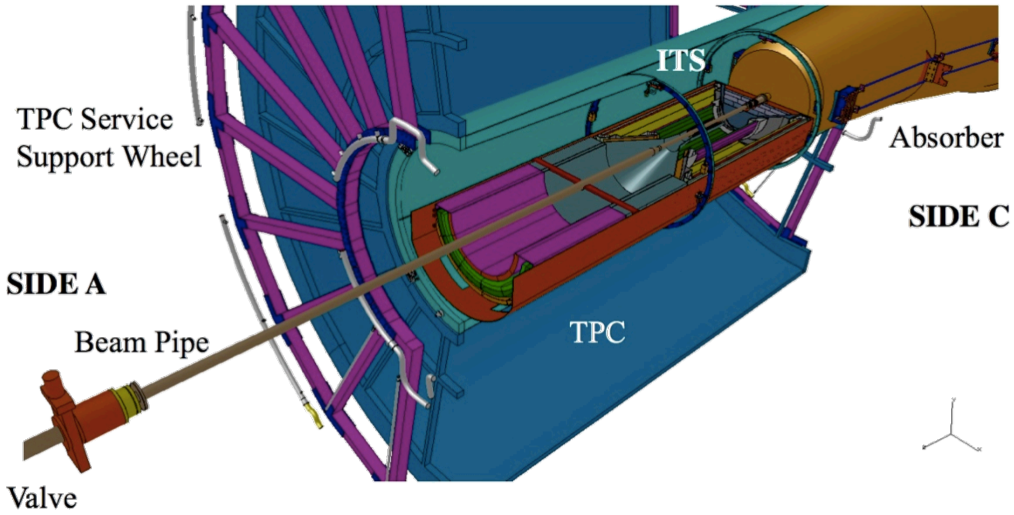
Fast insertion/removal for yearly maintenance

- Possibility to replace non functioning detector modules during yearly winter shutdown

The upgrade of the ALICE Inner Tracker

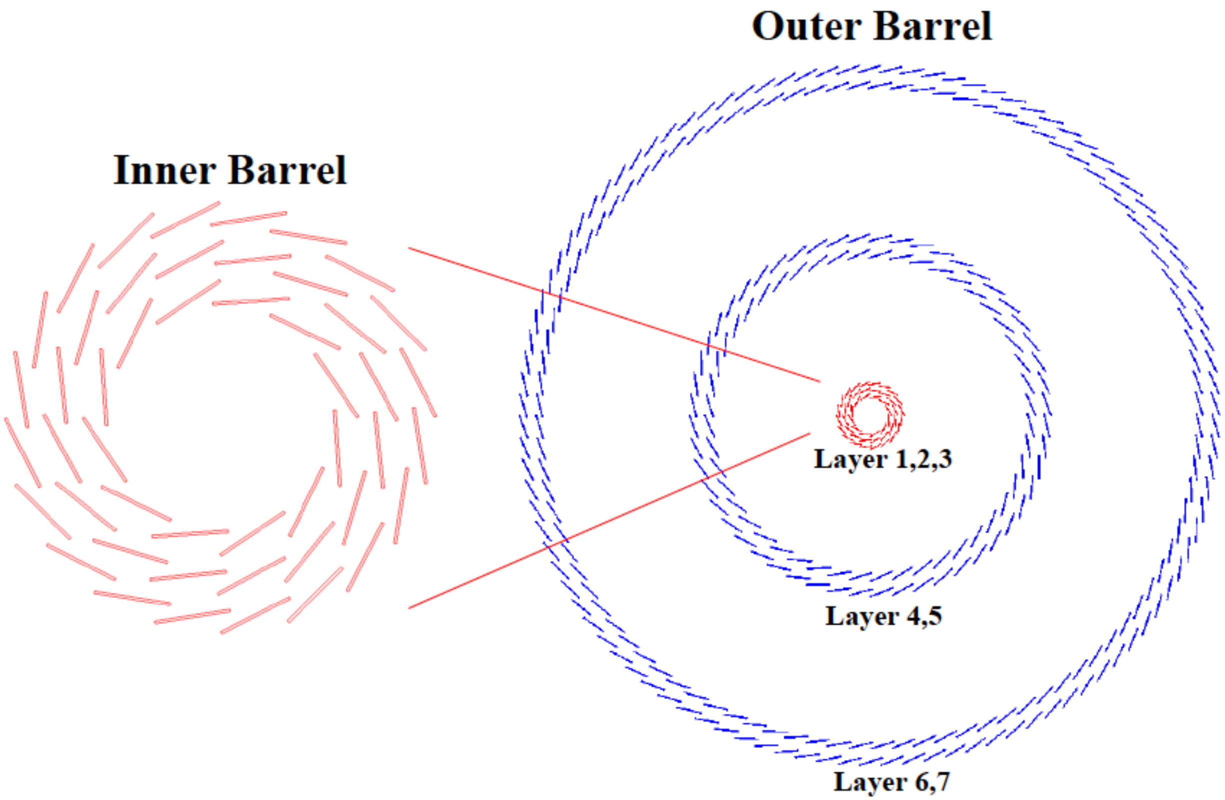
Tracker geometry - 1

- Beampipe outer radius: r=17.2 mm
  - presently 29.8 mm
- First layer at 22 mm
  - presently 39 mm
- Radial coverage up to 430 mm
- 7 layers
  - presently 6
- $|\eta|<1.22$ over 90% of the luminous region
  - presently 0.9



The upgrade of the ALICE Inner Tracker

Tracker geometry - 2



Layer	Radius [cm]	+/- z
1	2.2	11.2
2	2.8	12.1
3	3.6	13.4
4	20	39.0
5	22	41.8
6	41	71.2
7	43	74.3

The upgrade of the ALICE Inner Tracker

Requirements

Targets for Inner Layers (1, 2, 3)

- Pixel size ($r\phi$ x z): 20 x 20 μm²
  (max: 30 x 50 μm²)
- Readout time: <30 μs
- Chip size: 15 mm x 30 mm (target)
- Material budget per layer: 0.3 % X_0
- Radiation: 700 krad/ 10^{13} n_{eq}
- Hit density: <150 cm^{-2} in layer 1
- Power Density: 0.3 W/cm²
  (max: 0.5 W/cm²)

→ Pixels

Targets for Outer Layers (4, 5, 6, 7)

- Cell size ($r\phi$ x z): max: 70 μm x 2 cm
- Readout time: <30 μs
- Material budget per layer: 0.3 % X_0
  (max: 0.8% X_0)
- Radiation: 10 krad/ $3 \cdot 10^{11}$ n_{eq}
- Hit density: 1 cm^{-2} in layer 4
- Power Density: 0.3 W/cm²
  (max: 0.5 W/cm²)

→ Pixels or Strips

The upgrade of the ALICE Inner Tracker

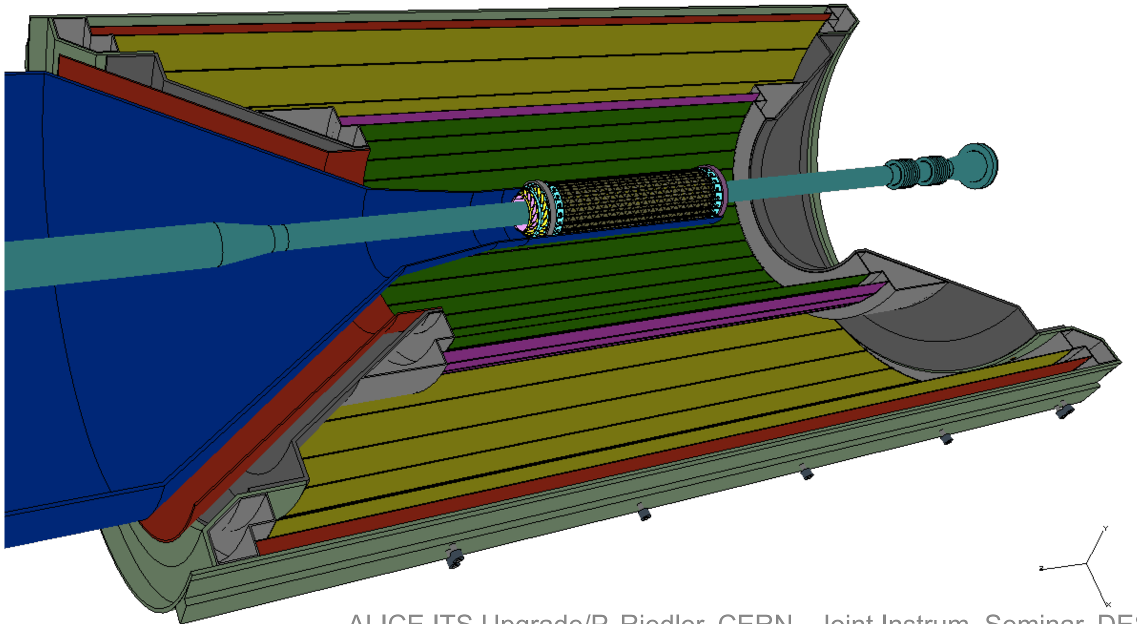
2 layout options

A. 7 layers of pixel detectors

- better standalone tracking efficiency and p_t resolution

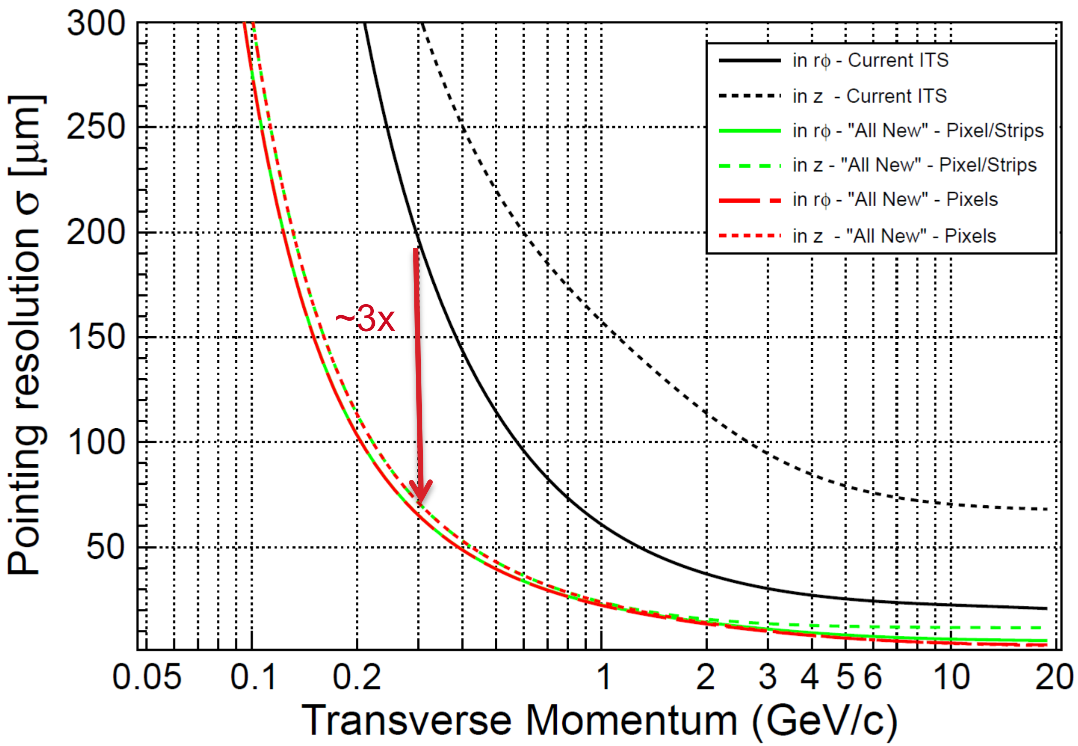
B. 3 inner layers of pixel detectors and 4 outer layers of strip detectors

- worse standalone tracking efficiency and momentum resolution
- PID



The upgrade of the ALICE Inner Tracker

Performance - 1



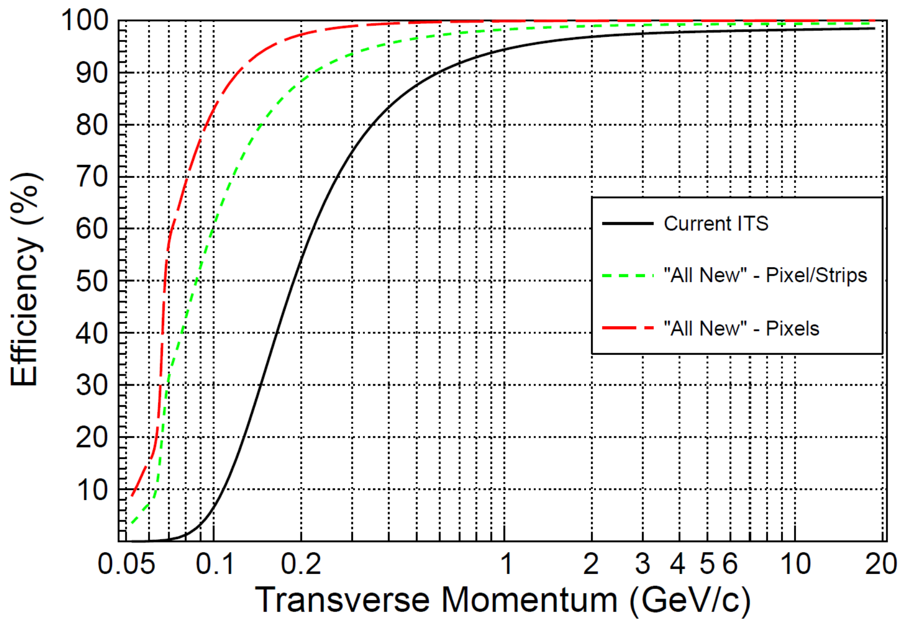
Layout A (7 pixel layers)	
$\sigma_{r\phi}$ = 4 μm	σ_z=4 μm
X/X_0	0.3 %

Layout B (3 pixel + 4 strip layers)	
$\sigma_{r\phi}$ = 4 μm (pixel), 20 μm (strips)	σ_z=4 μm (pixel), 830 μm (strips)
X/X_0	0.3% (pixel), 0.8 % (strips

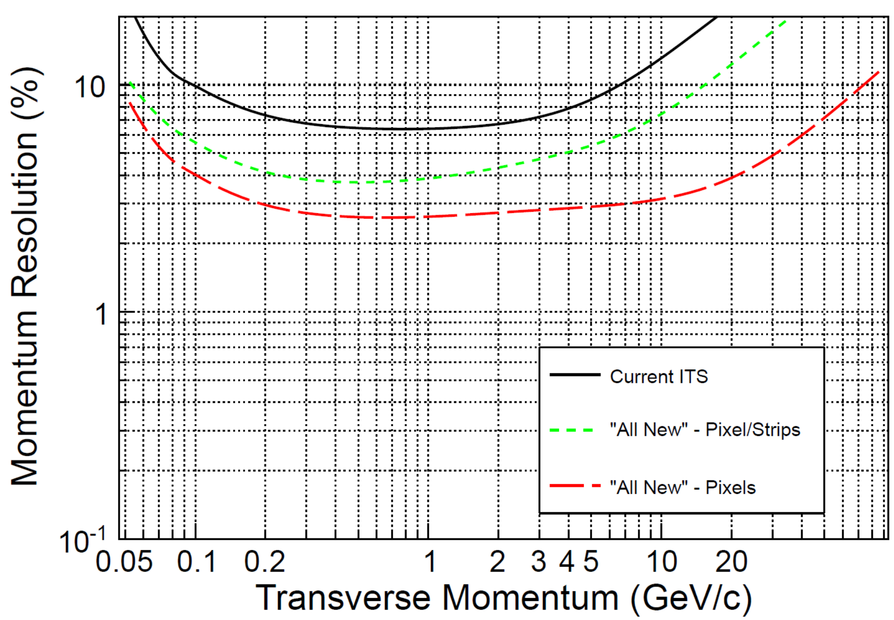
The upgrade of the ALICE Inner Tracker

Performance - 1

Tracking efficiency



Momentum resolution



Layout A (7 pixel layers)

Layout B (3 pixel + 4 strip layers)

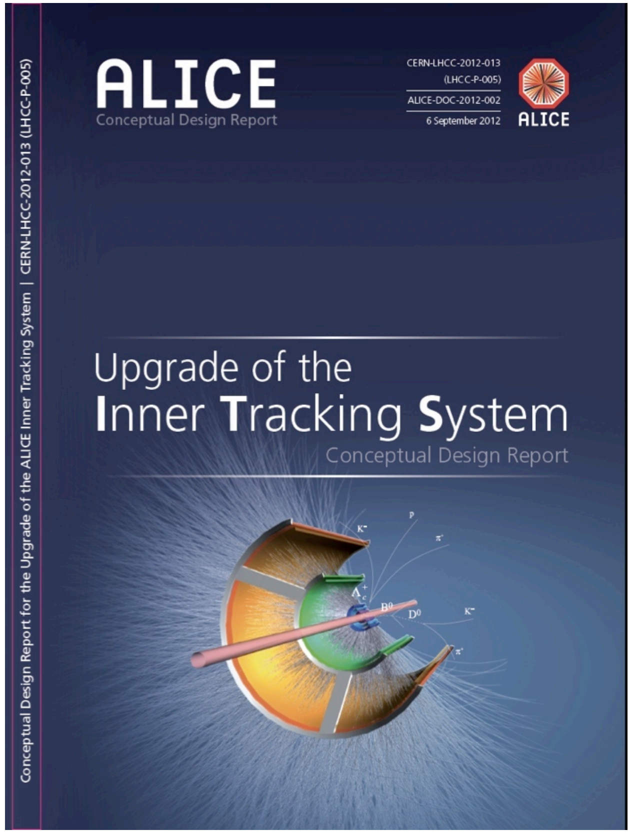
The upgrade of the ALICE Inner Tracker

Conceptual Design Report

Presents physics case, detector performance studies and R&D on detector technologies, mechanics and cooling aspects.

Version CDR1 presented to LHCC in September 2012 (available on CDS).

http://cdsweb.cern.ch/record/1475244/files/LHCC-P-005.pdf



R & D activities

Focus is set on several key points, mainly related to pixels. The layout of the strips layers follows closely the present strip detector installed in ALICE.

R&D activities related to detector technology, mechanics and cooling in 2012 presented in the following slides:

- Silicon strip detector design
- Irradiation tests of 0.18 μm CMOS technology
- Development and test of prototype pixel matrices
- Thin hybrid pixel detectors
- Thinning tests to 50 μm
- Evaluation of interconnection techniques
- First studies of module concepts
- Mechanical concept and cooling studies

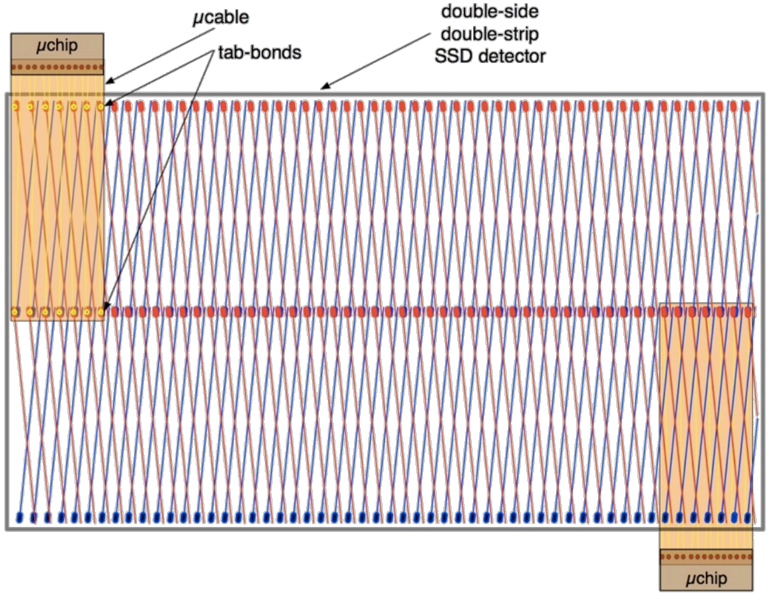
Silicon Strip R&D

Sensor design based on current ALICE SSD

- Standard 300 μm double-sided micro-strip sensors
- 768 strip/side, 35 mrad stereo angle

Reduced strip length down to 20 mm

- Half cell-size: 95 μm x 20 mm
  - Higher granularity
  - Better ghost hit rejection
- Doubled channel density
  - Challenging interconnection layout
  - Power consumption



New ASIC design:

- 0.18 μm technology (rad. hard)
- Low power and fast ADC (10 bits)
- Preserve 20 MIP range and 0.1 MIP resolution

Pixel technologies

2 basic concepts

Hybrid pixels

- Separate optimization of sensor and circuitry, complex in-pixel signal processing
- State-of-the-art detectors but are limited to inner layers due to their cost
- Charge collected by drift, high resistivity wafers (4-6 kΩcm)
- Proven radiation resistance to ALICE levels

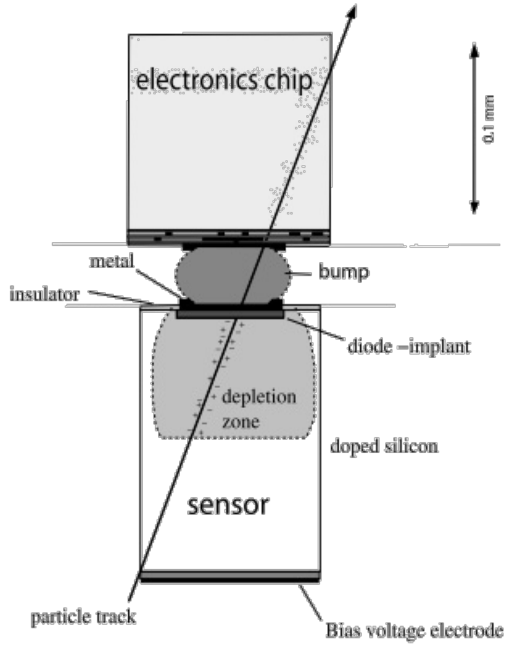


Figure - Rossi, L., Fischer, P., Rohe, T. & Wermes, N. (2006). Berlin: Springer.

Monolithic pixels

- Sensing layer (~1kOhmcm) is integrated into the CMOS chip
- Have shown significant progress in recent years and will soon be installed in STAR (HFT)
- Charge collected by drift and diffusion
- Thickness of the sensing layer typically 10-20 μm
- Radiation resistance needs to be proven

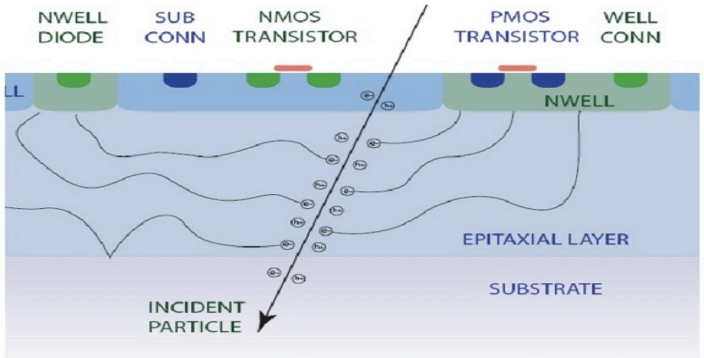


Figure Stanitzki, M. (2010). Nucl. Instr. and Meth. A doi:10.1016/j.nima.2010.11.166

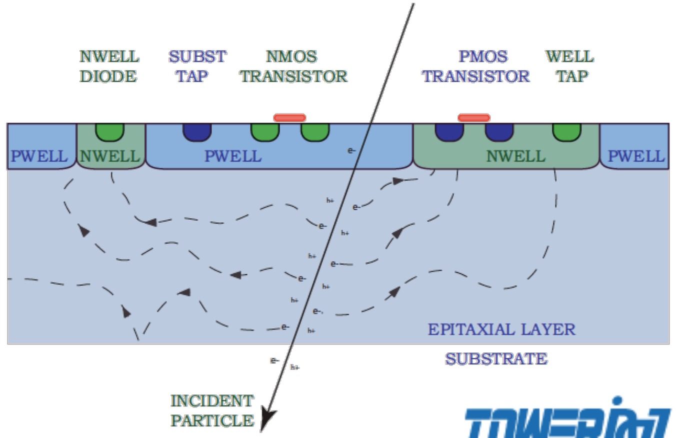
Monolithic pixel R&D for the ALICE ITS

New specialty CMOS technologies available for monolithic pixel detectors.

Development of monolithic detectors using Tower/Jazz 0.18 µm CMOS technology:

- Improved TID resistance due to smaller technology node
- Available with high resistivity (1-5k Ω•cm) epitaxial layer up to 18 µm (substantial depletion at 1-2V)
- Special quadruple-well available to shield PMOS transistors (allows in-pixel truly CMOS circuitry)

CMOS



CMOS with deep p-well

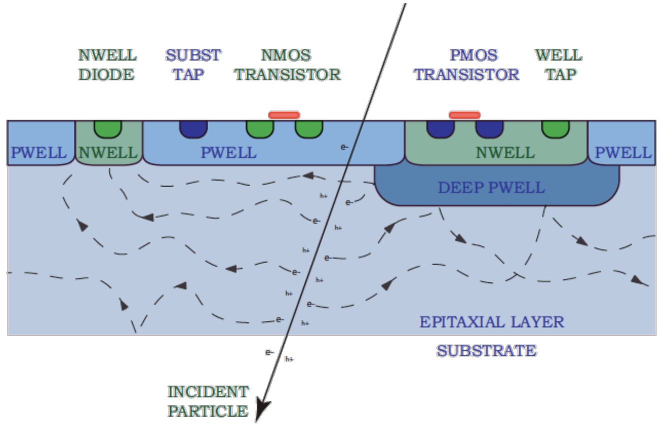


Figure Stanitzki, M. (2010). Nucl. Instr. and Meth. A doi:10.1016/j.nima.2010.11.166

Monolithic pixel R&D for the ALICE ITS

Radiation hardness tests of structures in 0.18 µm

1. Test of basic structures (transistors, shift registers etc.)
   - Study threshold shift, leakage current, SEU, ..
2. Test of prototype matrices
   - Study of charge collection performance, noise, …

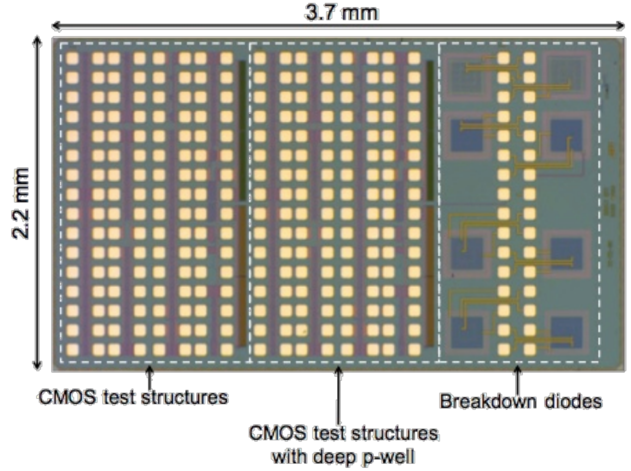
Transistors, capacitors, diodes,…

Prototype matrices

Monolithic pixel R&D for the ALICE ITS

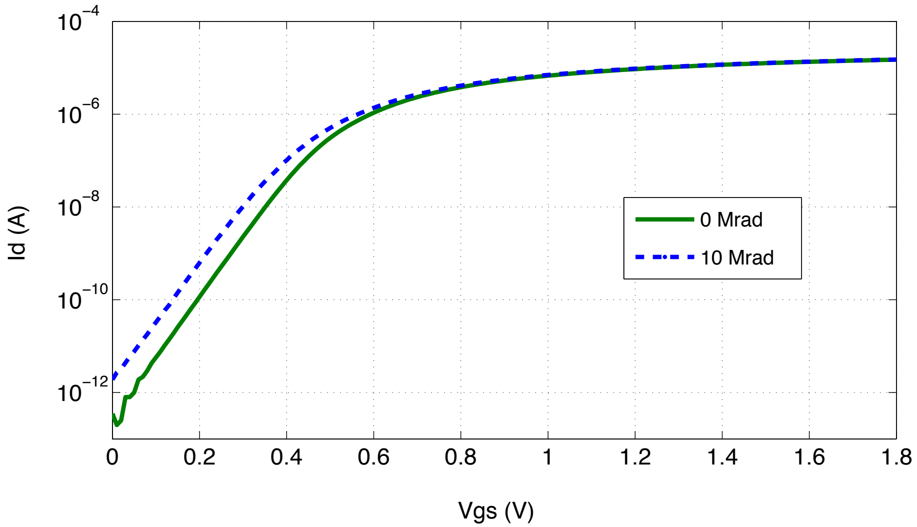
Transistor structures in 0.18 μm

- Designed in 2012 containing single NMOS and PMOS transistors (w/wo deep-p-well) and breakdown structures (CERN).
- First structures irradiated at the X-ray system at CERN in summer 2012 up to 10 Mrad.
- Following standardized irradiation procedure with annealing of 24 hours and 1 week.
- During irradiation worst case bias scenario (V_g = 1.8 V, V_s = 0 V, V_d = 0 V, V_{sub} = 0 V)

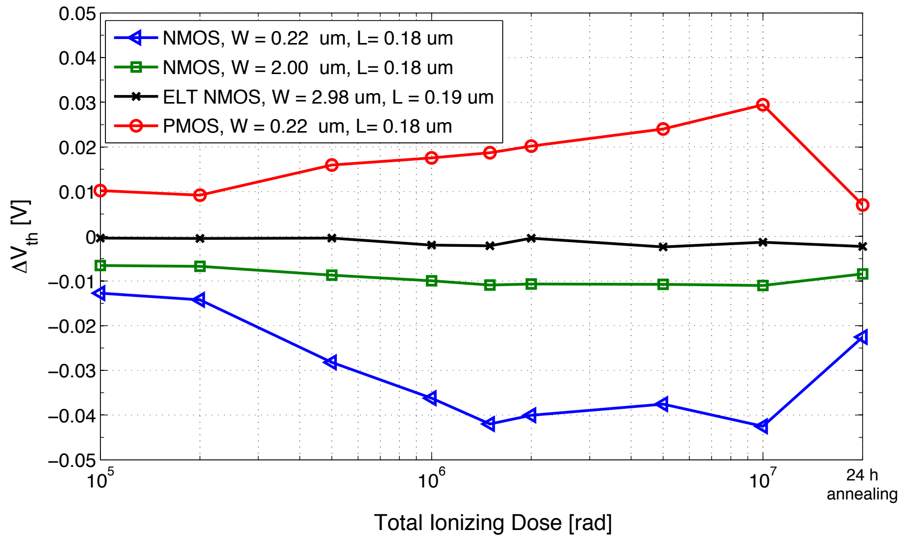


Monolithic pixel R&D for the ALICE ITS

Transistor structures in 0.18 µm – first results



Drain current as function of the gate voltage
Minimum size NMOS



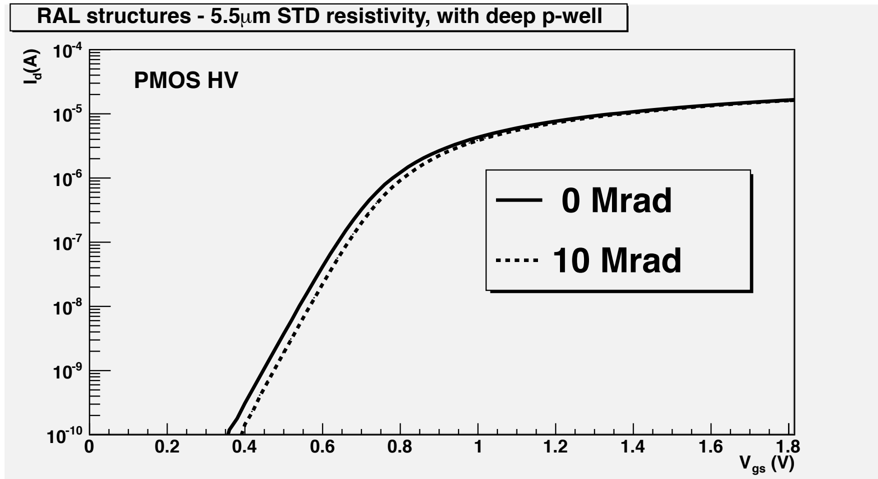
Threshold shift as function of TID

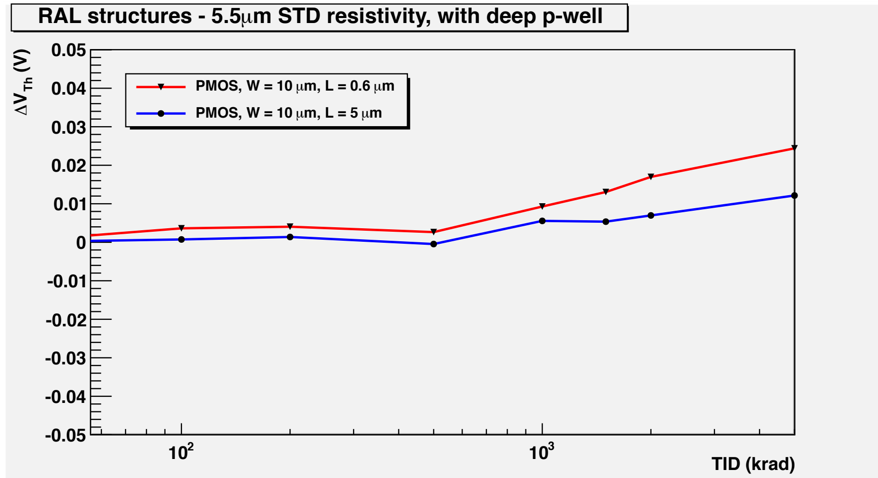
Monolithic pixel R&D for the ALICE ITS

Transistor structures in 0.18 µm

• Test structures designed by RAL with single transistors, capacitors and insulations structures were available for tests.

• First results from X-ray irradiation tests carried out with test system developed at CERN.





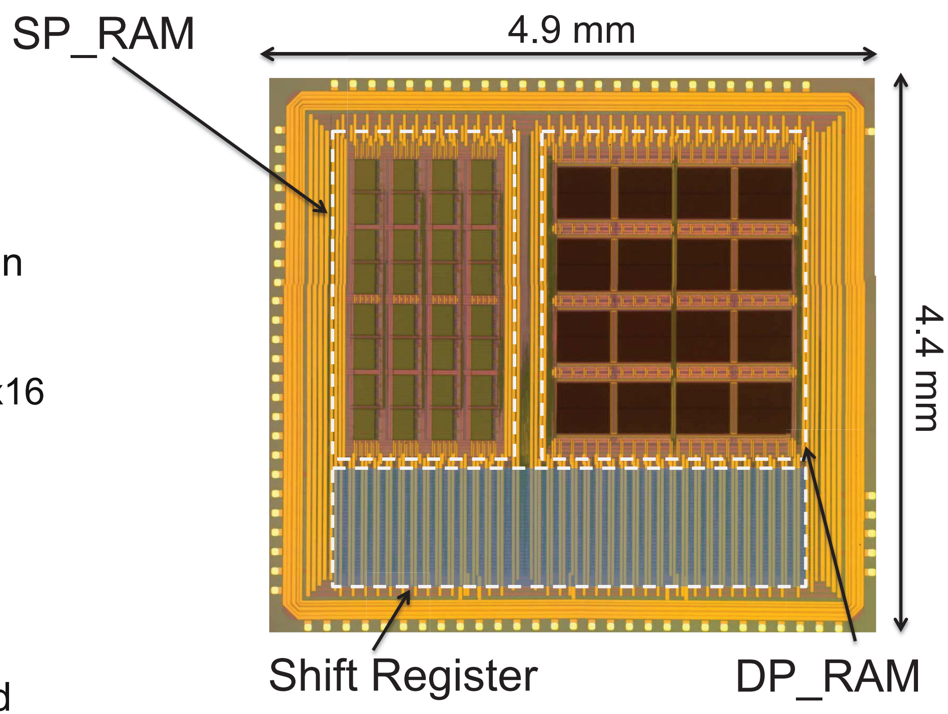
Monolithic pixel R&D for the ALICE ITS

SEU chip

- Dedicated structure designed to study the Single Event Upset (SEU) sensitivity of the 0.18µm CMOS technology (CERN, CCNU).

- **Contains 3 modules** which share a common clock (10 MHz) and I/Os:
  - 16 single port RAM memories of 1024x16 bits
  - 8 dual port RAM memories of 2048x16 bits
  - 16 bit 2048 stages shift register

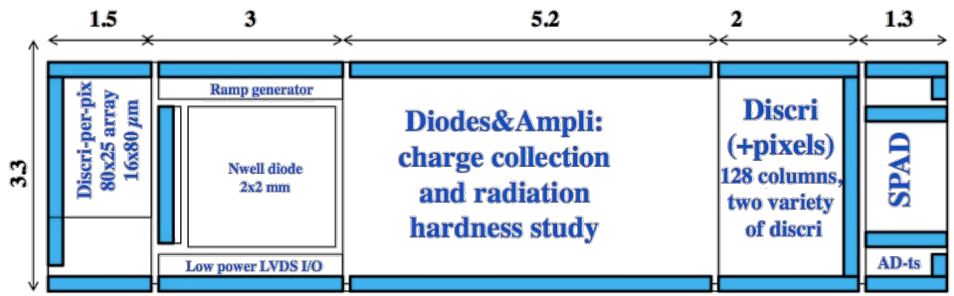
- The test system is currently being completed and first tests are planned for the end of October

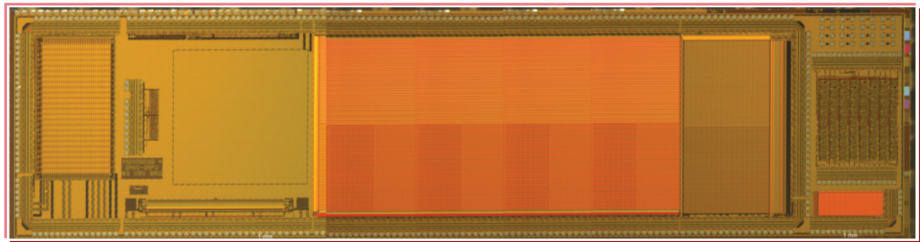


Monolithic pixel R&D for the ALICE ITS

MIMOSA32

- Designed by IPHC Strasbourg
- Digital and analog blocks (2T and 3T structures with various diodes)
- Test with Fe^{55} source
- Irradiation tests (X-ray, neutron)
- Beam-tests Jun, Jul and Aug 2012 at CERN

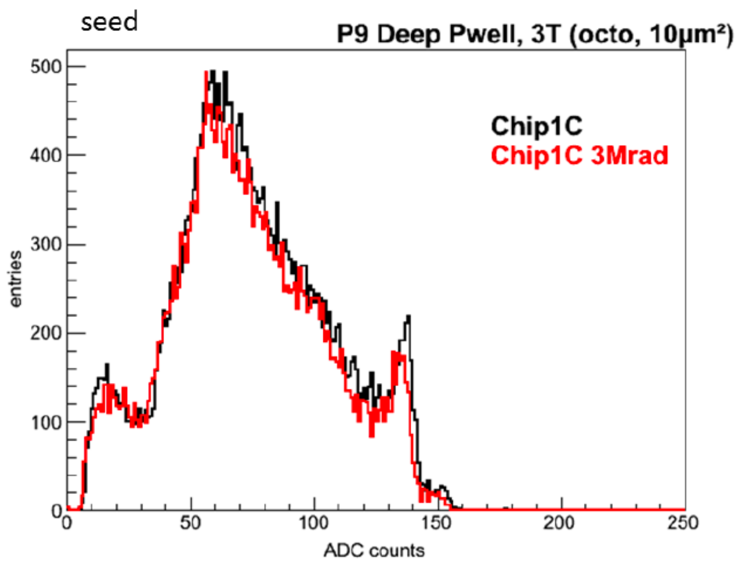


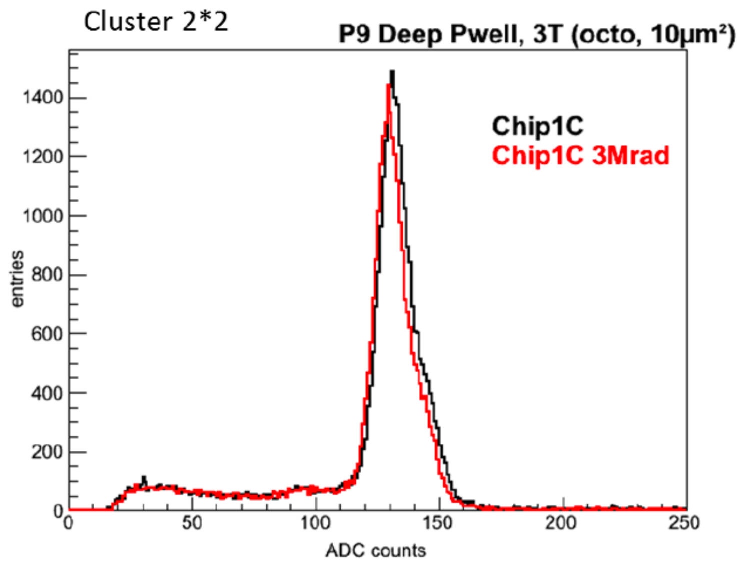


Monolithic pixel R&D for the ALICE ITS

MIMOSA32

Measurement with Fe^{55} source before and after X-ray irradiation





Charge collected in seed pixel
Collects typically 40-50%

Cluster signal of cluster size 2x2

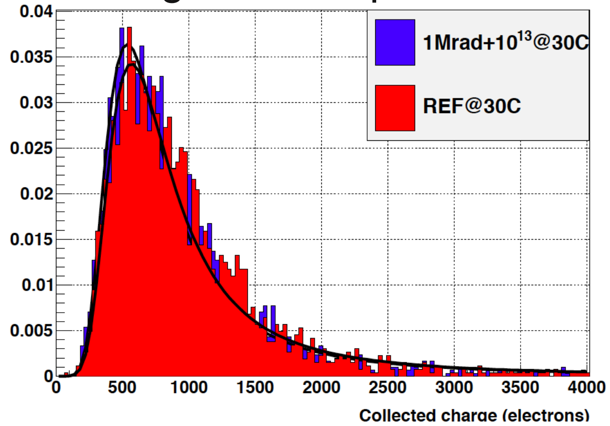
Pixel noise 15-20 electrons at RT (20°C)

Monolithic pixel R&D for the ALICE ITS

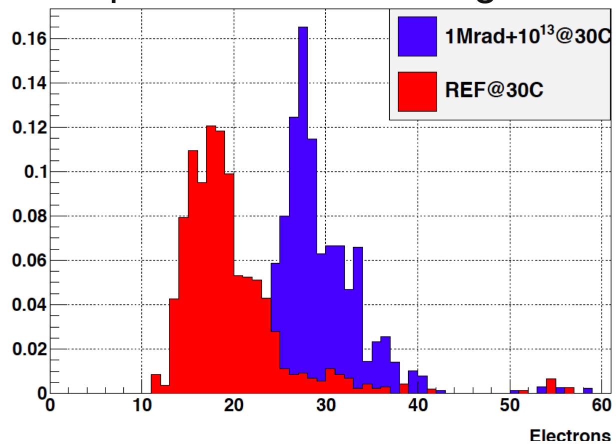
MIMOSA32

Measurements at SPS test beam with 60-120 GeV particles

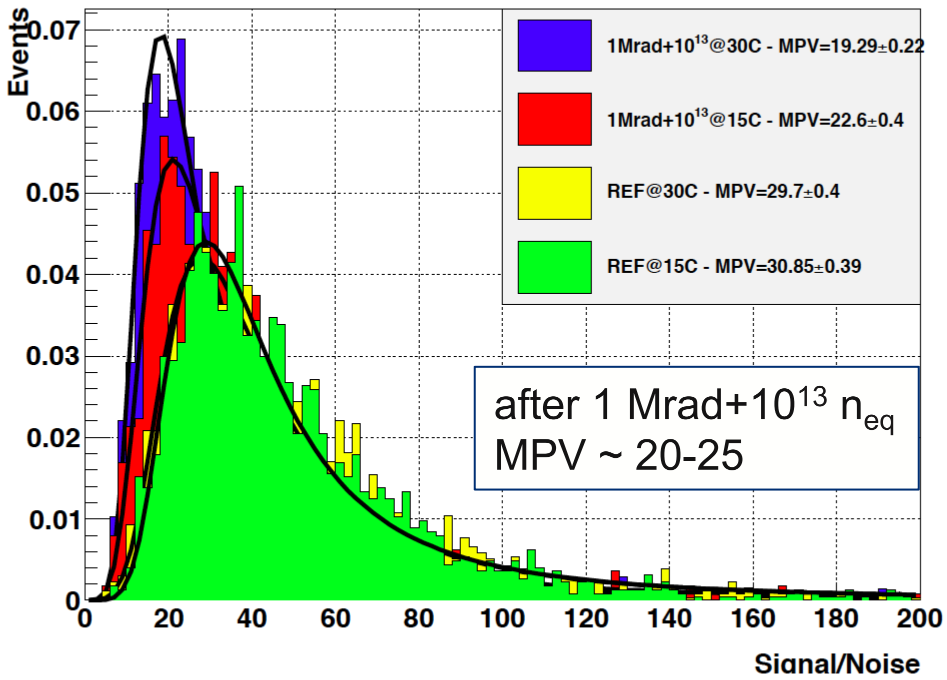
Charge in seed pixel



Equivalent noise charge



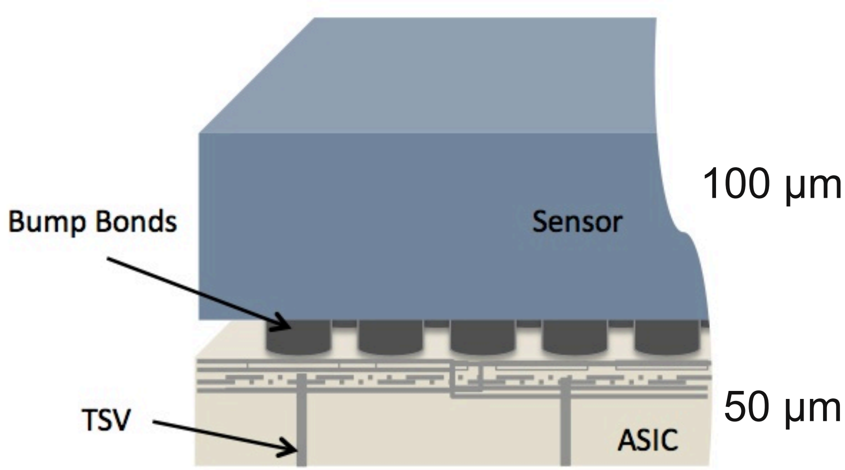
Signal to Noise Ratio



Detection eff. ~99.8%

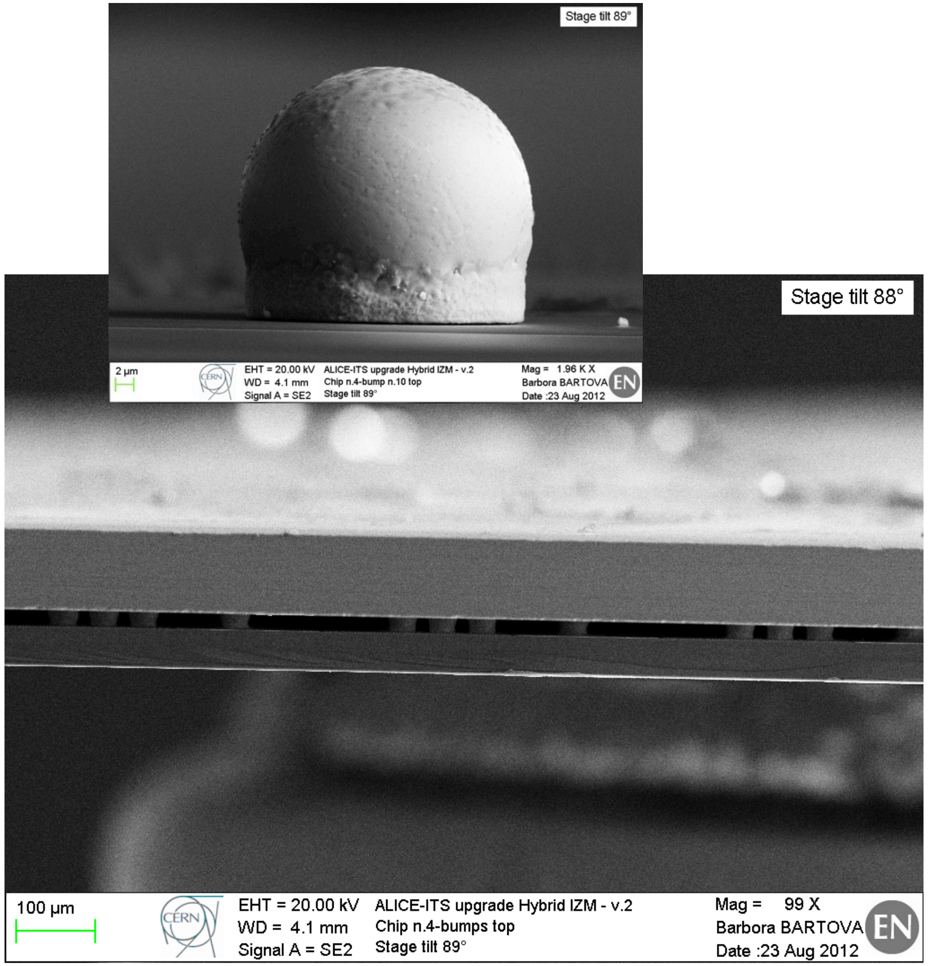
Hybrid pixel R&D for the ALICE ITS

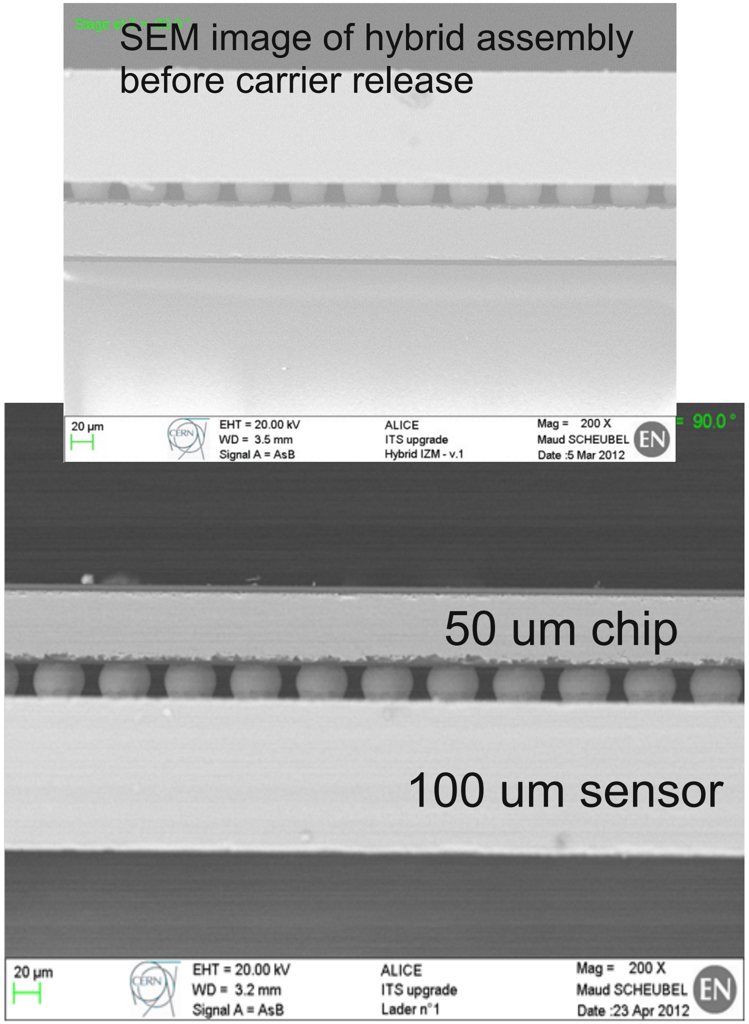
- **Development with IZM Berlin to produce hybrid pixel detector with 50 µm chip and 100 µm sensor**
  - Tests with dummy components using ALICE SPD layout
  - Ladders (5 chips + 1 sensor) and singles with final thicknesses bonded and delivered
- **Participate in TSV studies with Medipix**
- **Study of edgeless sensors:**
  - Using epitaxial and standard FZ wafers (FBK and VTT)



Hybrid pixel R&D for the ALICE ITS

Thin dummy assemblies - IZM



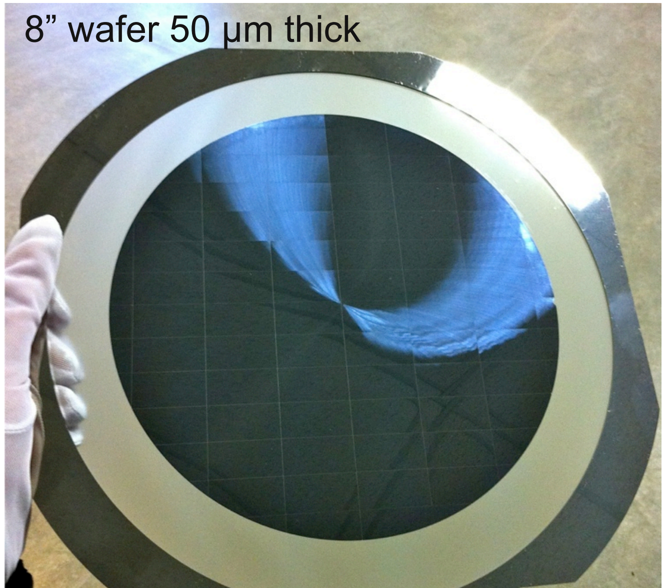


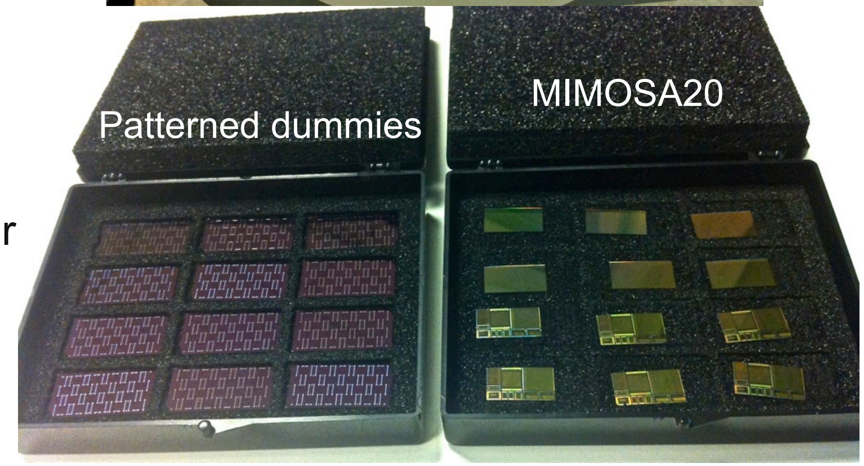
Thinning tests

CMOS wafers

Work with commercial supplier to **thin wafers to 50 µm** assuming chip size of 15 mm x 30 mm

1. Thinning and dicing of blank 200 mm wafers (13) - completed
2. Thinning and dicing of patterned 200 mm wafers (pads for interconnection tests) – 5 wafers completed
3. Thinning and dicing of one MIMOSA20 wafer (die size 10 mm x 20 mm) – completed





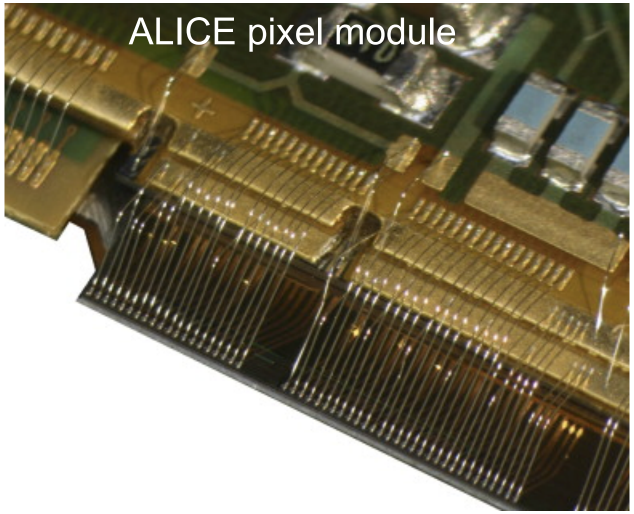
Interconnection studies

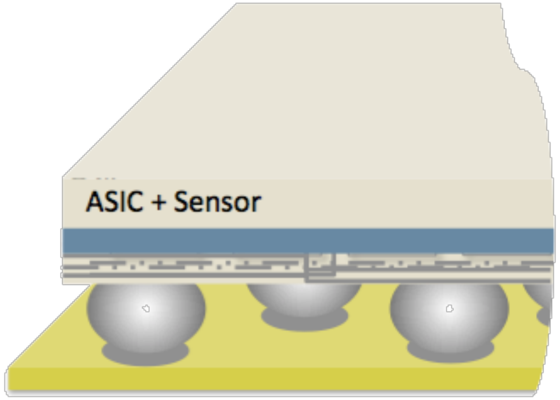
Techniques

- Wedge wire bonding is the state of the art technique to connect silicon chips/sensors to a cable or printed circuit board.

- This implies a dedicated region on the ASIC for the wire bonding pads and end of column circuitry. This area is not sensitive to passing particles and adds to the dead area.

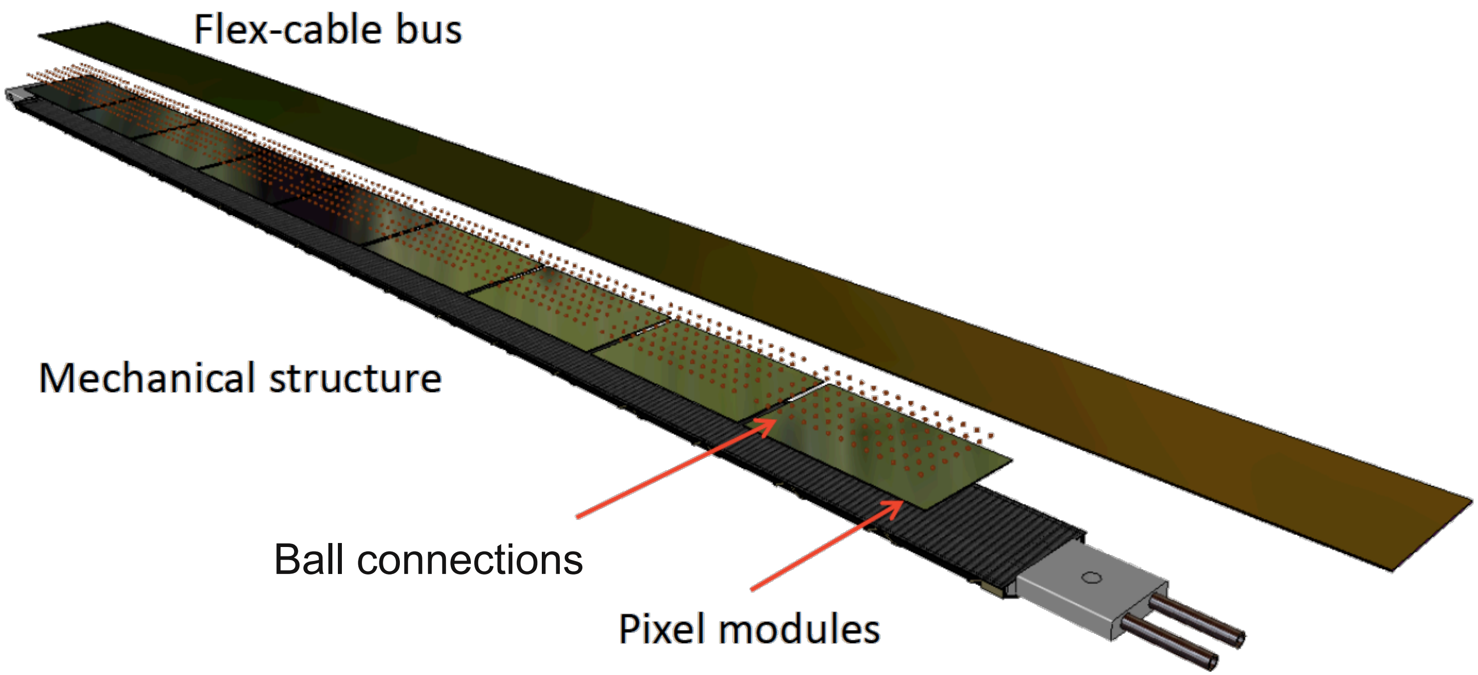
- **Wire bonding is one option for interconnection, but alternatives are under investigation** which allow a compact module design and a reduction of the insensitive area.





Interconnection studies and module concepts

Module concept



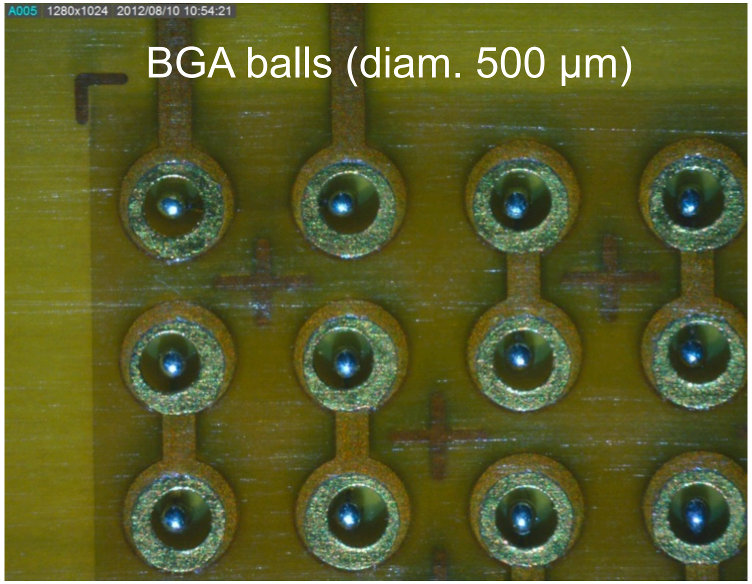
Study ongoing to build highly compact modules by connecting each chip (15 mm x 30 mm) via ball type connections to a flex cable (~50 connections/chip).

Power and electrical connections off-detector are provided at the end of the module.

Interconnection studies

Evaluation of different techniques

Several alternative interconnections techniques are under investigation using specially produced test chips and kapton flex cables.



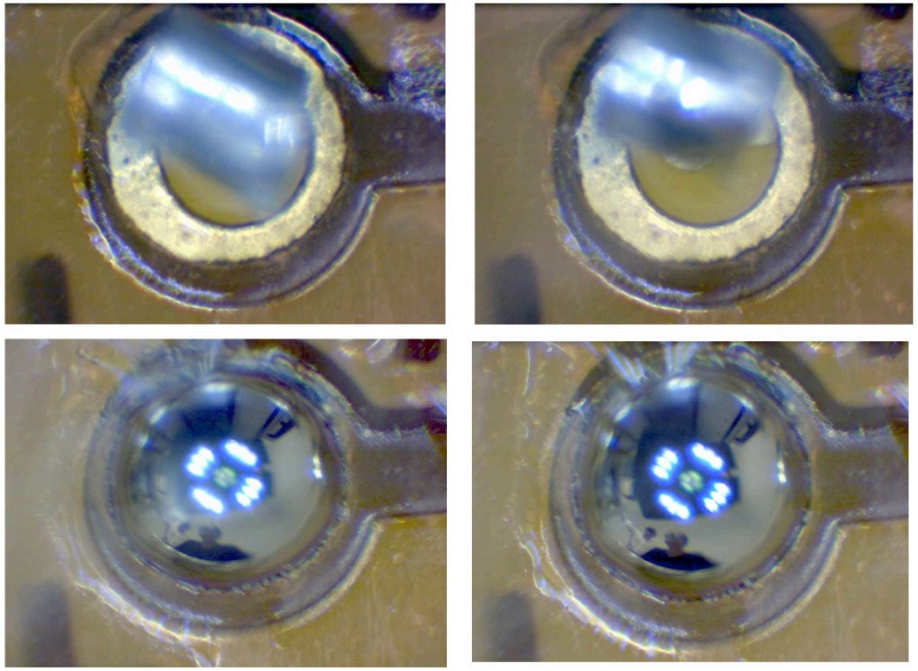
1. BGA ball connections (includes reflow in furnace)
2. Solder ball connections using laser soldering
3. Au-stud bonding (includes curing step at moderate temperature)
4. Ultra-thin chip packaging

Interconnection studies

Laser soldering

- Local heating of solder balls using a laser
- Advantage: stress only induced locally during few hundred ms
- First trials with kapton chips and cables successfully completed
- **Next step:** solder tests with silicon test chips connected to a kapton flex cable

1 2

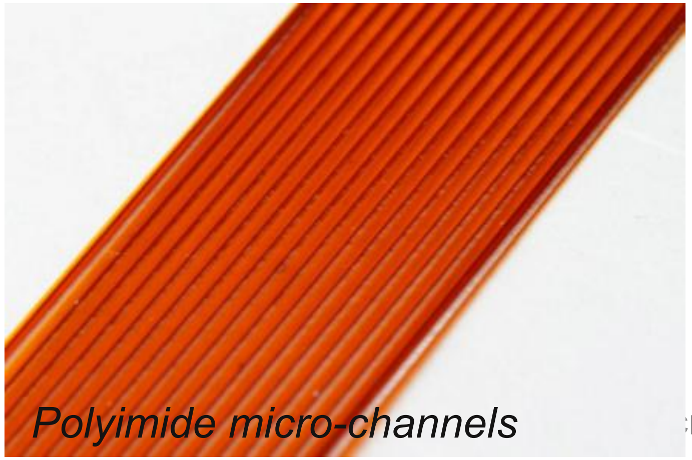


3 4

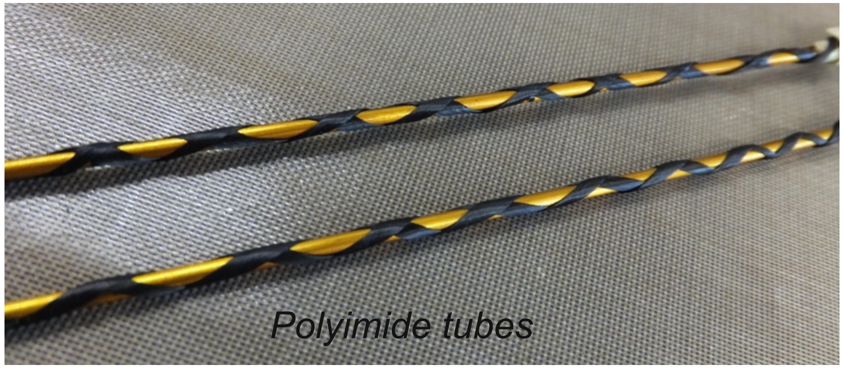
Cooling studies

2 concepts – Layers 1,2,3

Cold plate



Cooling pipes



Prototype modules built
Evaluation and simulation work ongoing

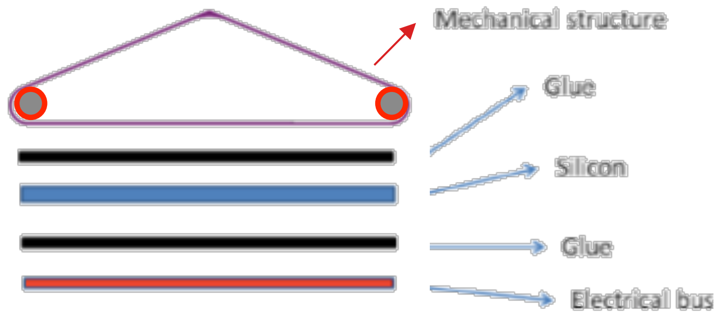
<u>Example:</u> polyimide tubes shown in the following slides

Mechanical structure

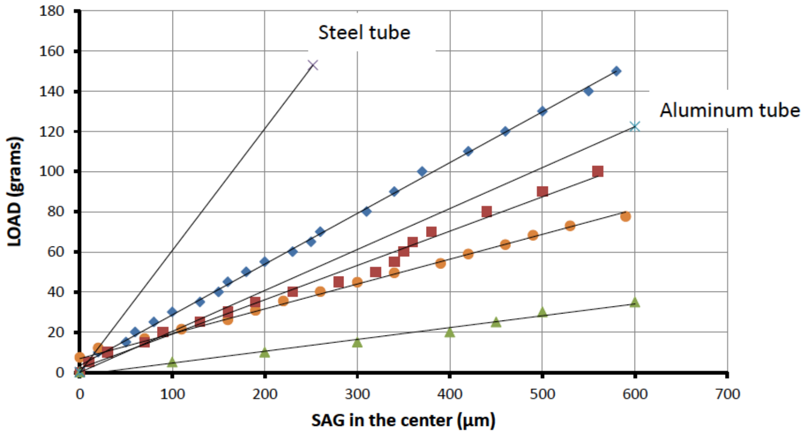
Prototype modules

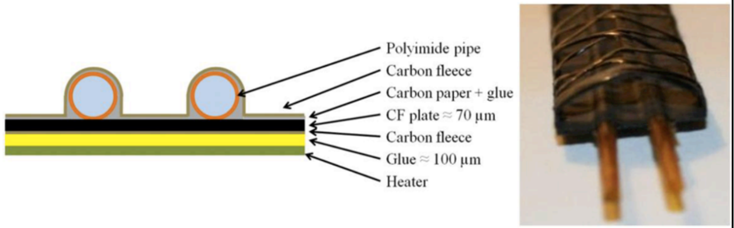
Module prototype equipped with dummy components (27 cm long, inner layers)

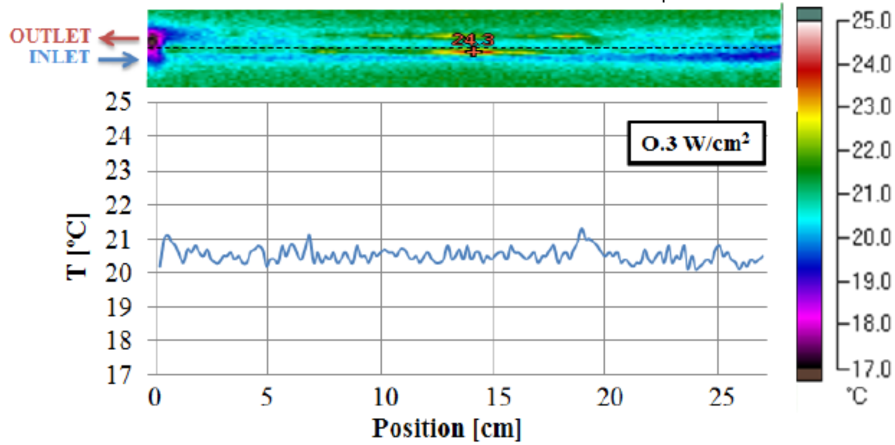
Material	Surface (%)	Tickness (μm)	X_0 (cm)	X/X_0 (%)	Contribution to the total X/X_0 (%)
CFRP filament	100	70	25	0.035	12.6
Polyimide Tubes	19	70	28.6	0.005	1.8
Water	19	1450	36.1	0.06	22.8
Glue (CFRP - silicon)	50	100	44.4	0.01	4.4
Silicon	100	50	9.36	0.054	20.7
Glue (silicon - bus)	100	100	44.4	0.022	8.7
Electrical bus	100	-	-	0.075	29.0
Total				≈ 0.26	

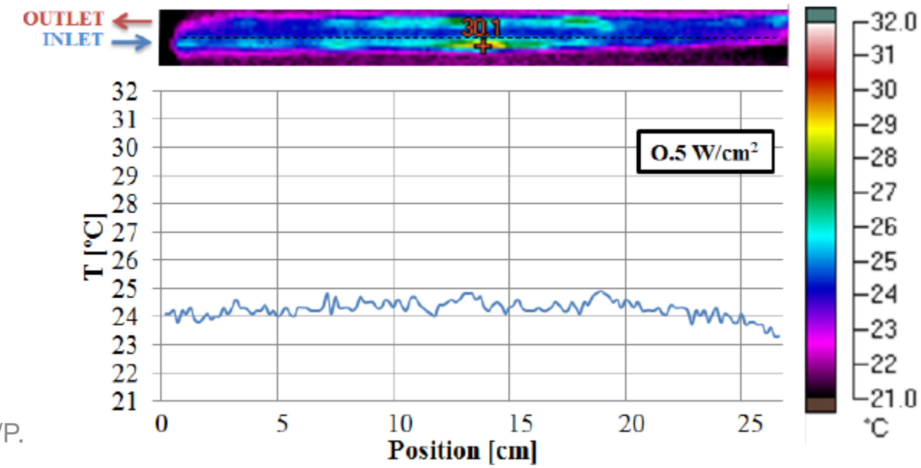


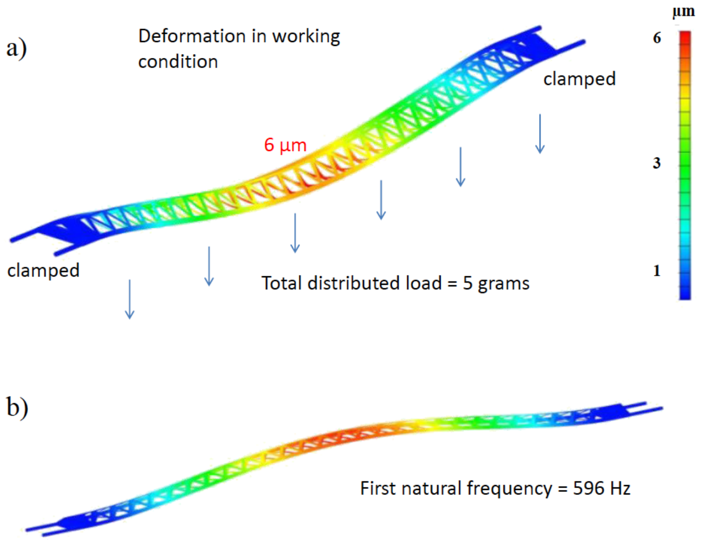
Structural and thermal tests











Prototype of inner half-barrel

Timeline

2012–2014	R&D
2012	evaluation of technologies & prototypes
2013	selection of technologies, eng. Design, TDR
2014	final design and validation
2015-18	Construction and Installation
2015-16	production, construction and test of detector modules
2017	assembly and pre-commissioning
2018	installation in the cavern

Summary

The ALICE Silicon Tracker Upgrade will allow to address new physics topics like:

- Quark mass dependence of in-medium energy loss
- Thermalization of heavy quarks in the medium

New Tracker composed of 7 silicon layers characterized by:

- Impact parameter resolution improved by factor 3x
- First detecting layer @22 mm from the beam line
- Material budget x/X_0 ~ 0.3 % in the first layers
- High tracking efficiency down to low p_t (> 95% for p_t > 200 MeV/c)
- Fast access for maintenance

Detector technology evaluation ongoing - to be installed during LS2

Backup slides

The ALICE upgrade strategy

Upgrade the ALICE readout and online system:

- read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6x10^{27}$ $cm^{-1}s^{-1}$), with a minimum bias trigger
- Perform online data reduction based on reconstruction of clusters and tracks (tracking used only to filter out clusters not associated to reconstructed tracks)

Requirements

Focus of ALICE upgrade on physics probes requiring high statistics: sample 10 nb^{-1}

Online System Requirements
Sample full 50kHz Pb-Pb interaction rate
(current limit at ~500Hz, factor 100 increase)

⇨ ~1.1 TByte/s detector readout

However:

- storage bandwidth limited to ~20 GByte/s
- many physics probes have low S/B:
  classical trigger/event filter approach not efficient

Strategy

Data reduction by (partial) online reconstruction and compression

Store only reconstruction results, discard raw data
- Demonstrated with TPC clustering since Pb-Pb 2011
- Optimized data structures for lossless compression
- Algorithms designed to allow for offline reconstruction passes with improved calibrations

⇨ Implies much tighter coupling between online and offline reconstruction software

Why triggering does not work? The open charm case

Estimated signal statistics and trigger rate for minimum-bias Pb-Pb collisions

Hadronic Interaction rate of 50 kHz

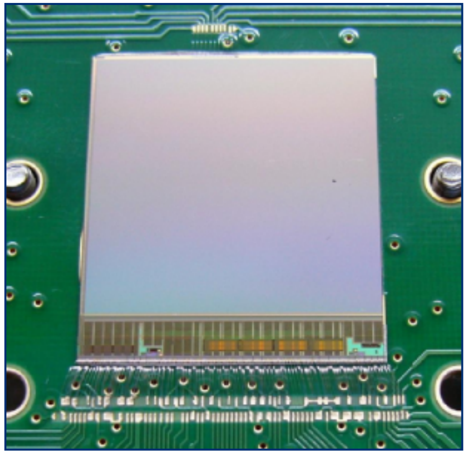
Particle	Eff	S/ev	S/B	B'/ev	trigger rate (Hz)	S/nb^{-1}
D^0	0.02	$1.6 \cdot 10^{-3}$	0.03	0.21	$11 \cdot 10^3$	$1.3 \cdot 10^7$
D_s^+	0.01	$4.6 \cdot 10^{-4}$	*0.01*	0.18	$9 \cdot 10^3$	$3.7 \cdot 10^6$
Λ_c	0.01	$1.4 \cdot 10^{-4}$	$5 \cdot 10^{-5}$	11	$5 \cdot 10^4$	$1.1 \cdot 10^6$
Λ_c ($p_t > 2$ GeV/c)	0.01	$0.8 \cdot 10^{-4}$	0.001	0.33	$1.6 \cdot 10^4$	$0.6 \cdot 10^6$
$B \to D^0(\to K^-\pi^+)$	0.02	$0.8 \cdot 10^{-4}$	0.03	$11 \cdot 10^{-3}$	$5 \cdot 10^2$	$0.6 \cdot 10^6$
$B \to J/\psi(\to e^+e^-)$	0.1	$1.3 \cdot 10^{-5}$	*0.01*	$5 \cdot 10^{-3}$	$3 \cdot 10^2$	$1 \cdot 10^5$
$B^+ \to J/\psi K^+$	*0.01*	$0.5 \cdot 10^{-7}$	*0.01*	$2 \cdot 10^{-5}$	1	$4 \cdot 10^2$
$B^+ \to \overline{D}^0\pi^+$	*0.01*	$1.9 \cdot 10^{-7}$	*0.01*	$8 \cdot 10^{-5}$	4	$1.5 \cdot 10^3$
$B_s^0 \to J/\psi\phi$	*0.01*	$1.1 \cdot 10^{-8}$	*0.01*	$4.4 \cdot 10^{-6}$	$2 \cdot 10^{-1}$	$9 \cdot 10^1$
$\Lambda_b(\to \Lambda_c + e^-)$	*0.01*	$0.7 \cdot 10^{-6}$	*0.01*	$2.8 \cdot 10^{-4}$	14	$5 \cdot 10^3$
$\Lambda_b(\to \Lambda_c + h^-)$	*0.01*	$0.7 \cdot 10^{-5}$	*0.01*	$2.8 \cdot 10^{-3}$	$1.4 \cdot 10^2$	$5 \cdot 10^4$

B' is the background in the broad invariant mass range (±12σ)

Triggering on D^0, D_s and Λ_c (p_T>2 Gev/c) ➡ ~ 36 kHz

Monolithic Pixels (IPHC)

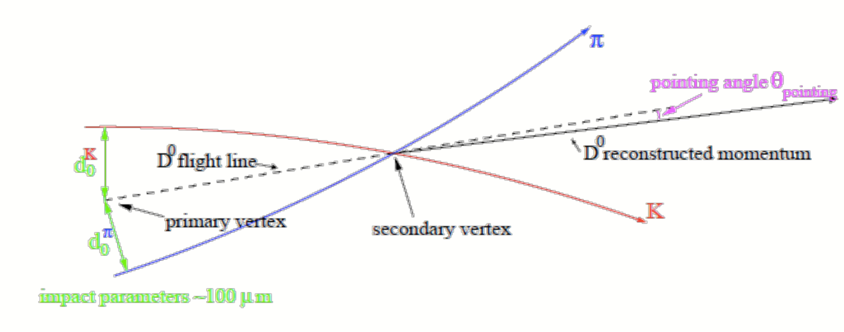
- CMOS sensors with rolling-shutter readout architecture
- MIMOSA series for STAR
  - Continuous charge collection (mostly by diffusion) inside the pixel
    - Charge collection time ~200 ns
  - Pixel matrix read periodically row by row: column parallel readout with end of column discriminators
    - Integration time ≡ readout period ~100 μs
    - Low power consumption: only one row is powered time: (150-250 mW/cm²)
  - Pixel size 20 μm
  - Total material budget x ~ 0.3% X_0
  - 0.35 μm technology node

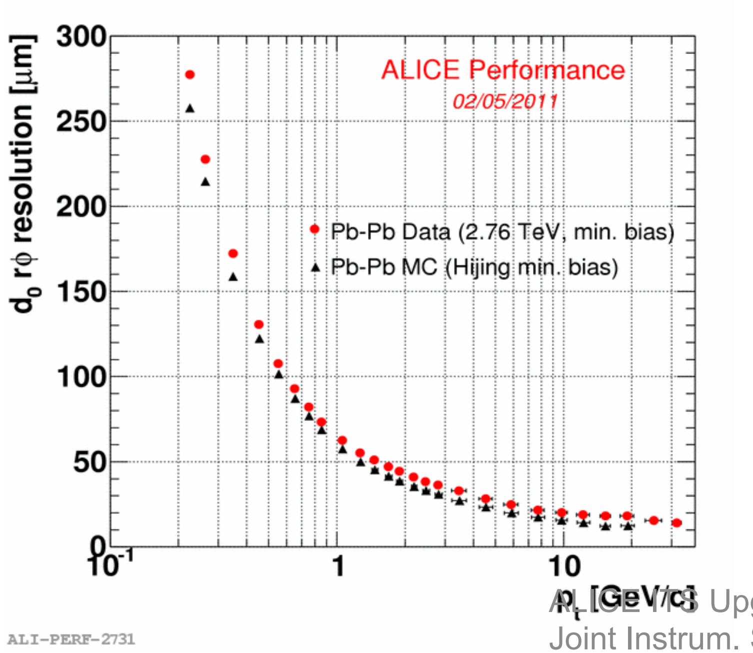


ULTIMATE sensor for STAR HFT

ALICE ITS (current) performance

1. **The Identification of secondary vertices** relies on the impact parameter **d_0** (in rφ and z)





2. **The PID performance** **(from SDD & SSD)**

- PID combined with stand-alone tracking allows to identify charged particles below 100 MeV/c
- p-K (3σ) separation up to 1 GeV/c
- π-K (3σ) separation up to 600 MeV/c
- dE/dx resolution of about 10-15%