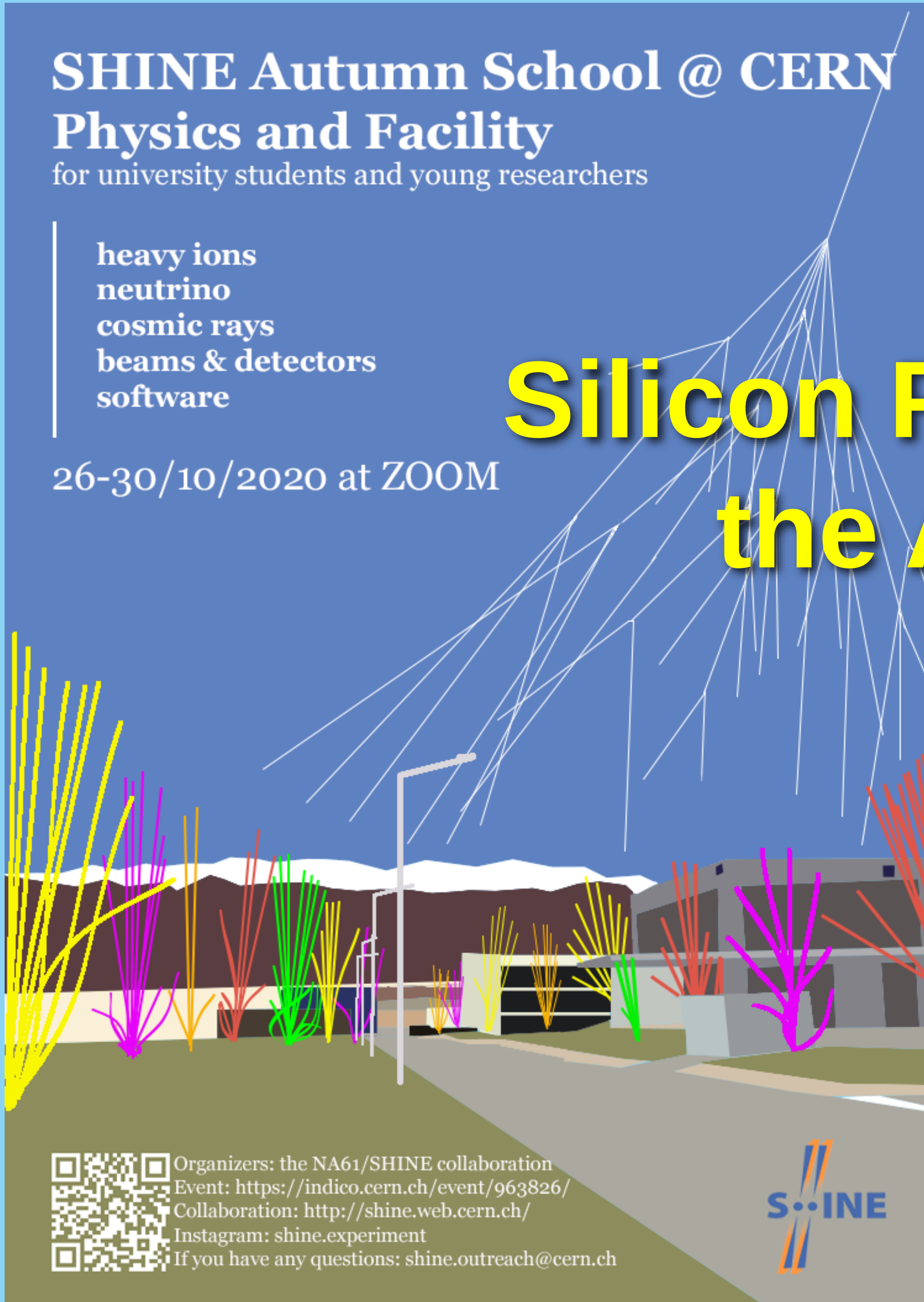


Silicon Pixel Detectors, the ALICE ITS2

P. Martinengo
CERN

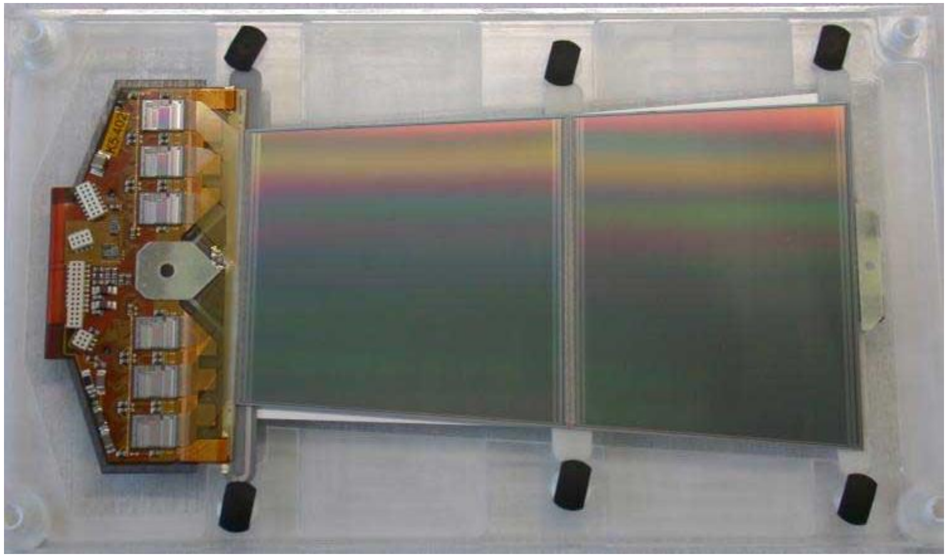
OUTLOOK

- General overview of Silicon Pixel Detector
- The ALICE case:
- Chip (ALPIDE)
- New Inner Tracking System (ITS2)

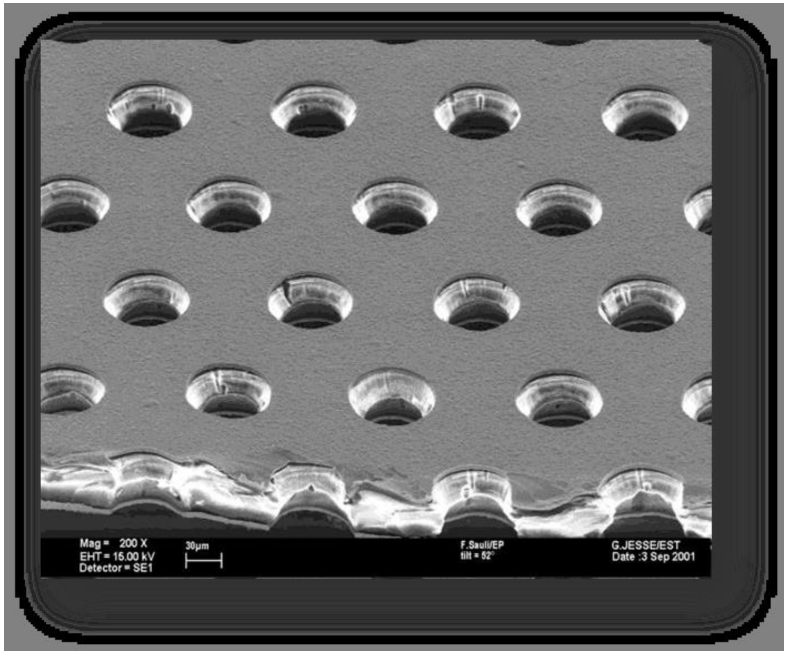
- Silicon Pixel Detectors are solid state detectors

- They are often (always ?) contrasted with Gaseous Detectors, Multi Wire Proportional Chamber (MWPC) in the past, today Micro Pattern Gaseous Detector (MPGD) like GEM

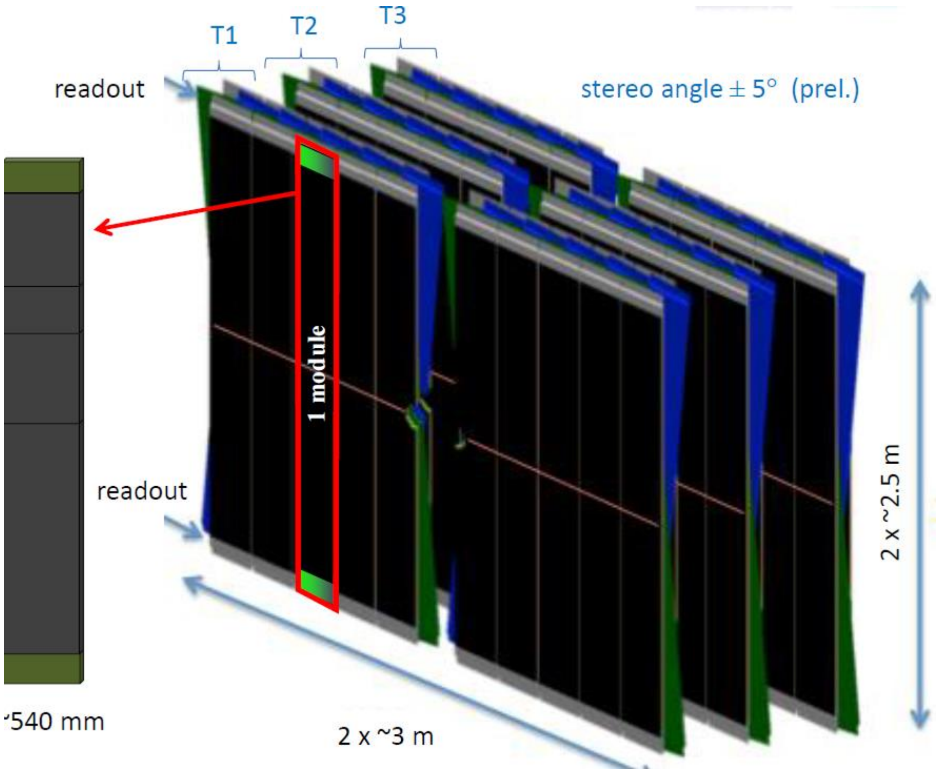
These are not the only options for a tracker !

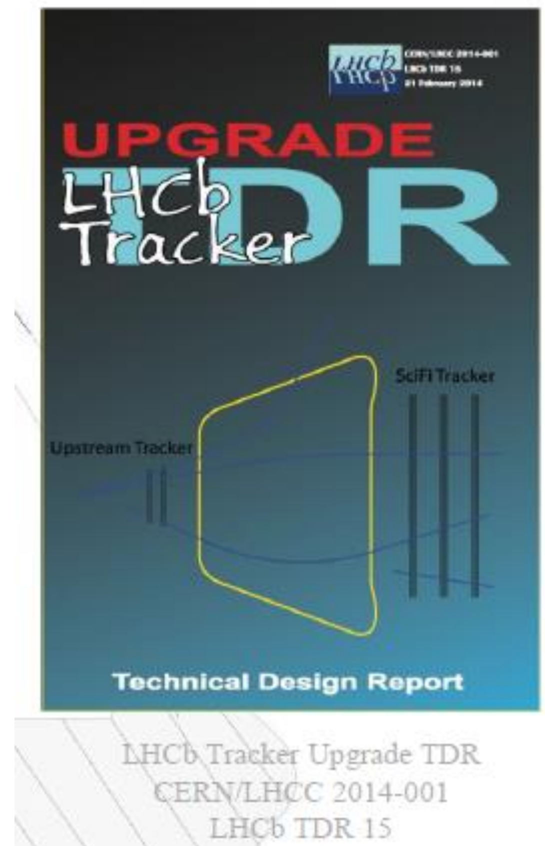


vs.



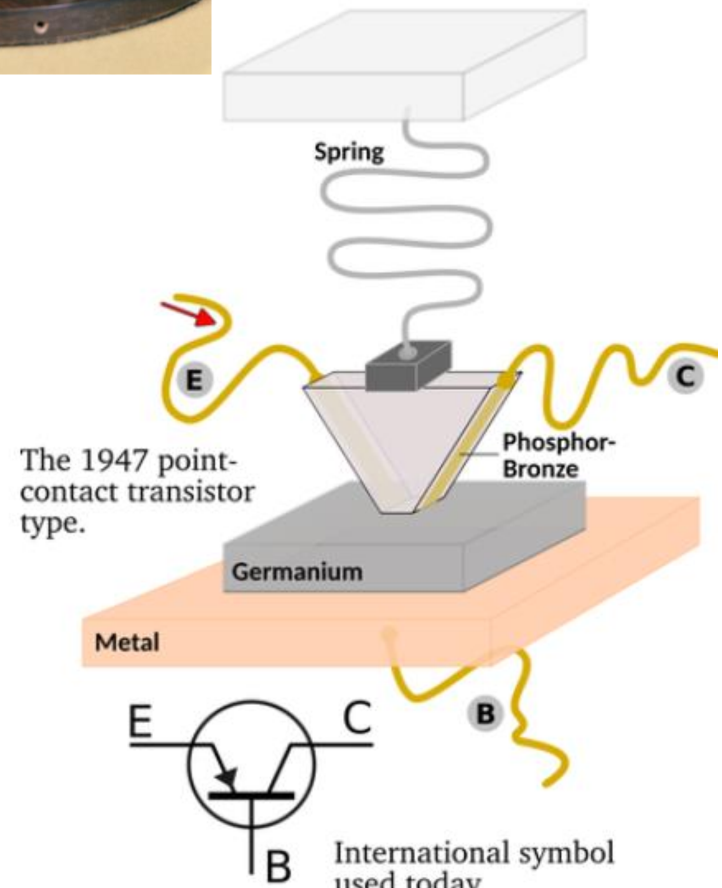
Scintillating fibers are also an option





https://twiki.cern.ch/twiki/pub/LHCb/UpgradeSciFiTracker/SciFi_TDR_20131220.pdf


Semiconductor physics
and
technology are very rich
and
very rapidly evolving
P. Martinengo, CERN



https://www.chiphistory.org/

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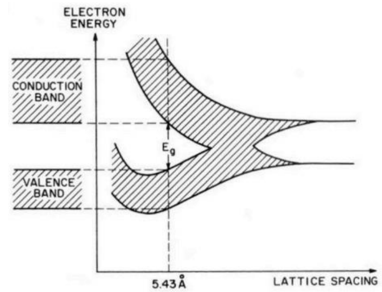
- Energy band structure



$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

- Electron density

$$n = N_C \cdot e^{(-(E_C - E_F)/kT)}$$

- Hole density

$$p = N_V \cdot e^{(-(E_F - E_V)/kT)}$$

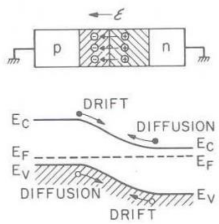
- Electron, hole drift velocity

$$v_e = -\mu_e E \qquad v_h = -\mu_h E$$

- Resistivity

$$\rho = \frac{1}{q(\mu_e n + \mu_h p)}$$

- PN-jonction



$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

and much more

© Kay Chernush

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Quite complete review
with a lot of information
and
references

Silicon Pixel Detectors

P. Riedler
CERN
CH-1211 Geneva 23

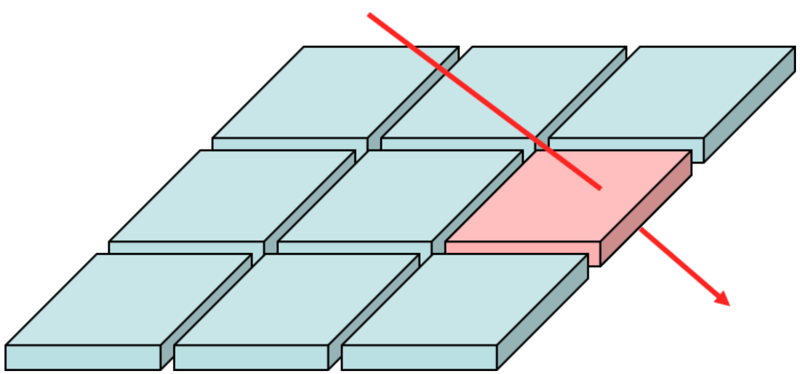
http://riedler.home.cern.ch/riedler/epfl2006/

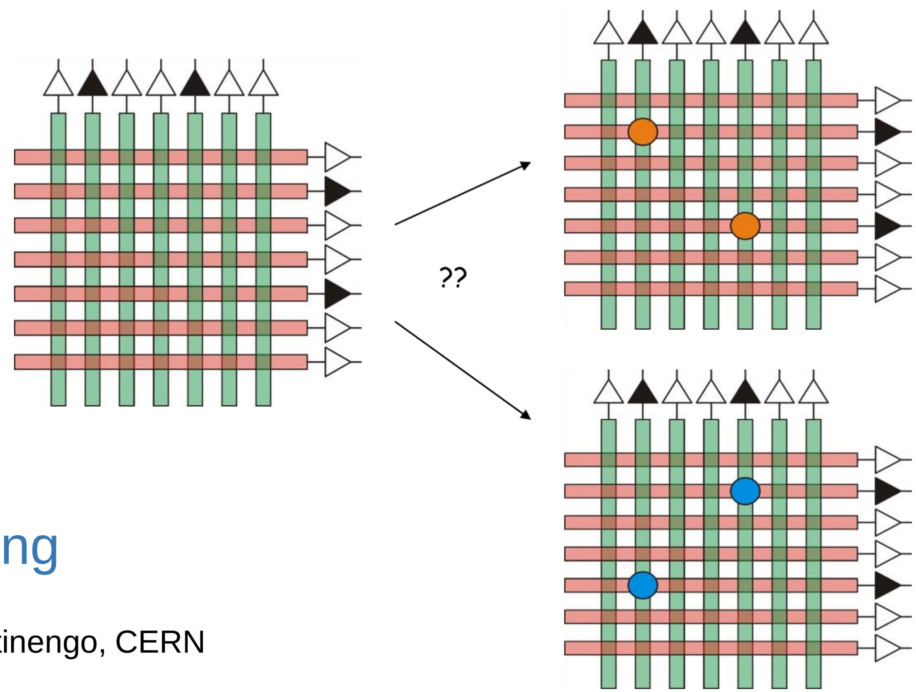
What are Silicon Pixel Detectors ?

- Solid state detectors, i.e. compact, thin (< 1 mm)
- made of silicon (so far)
- in which a passing charged particle or gamma ray produces a signal by ionization

(as in a gas but 3.6 eV to create an e-h pair, 30 eV in gases)

- The 2D-matrix allows to record images or complex multi-particle events.





On-detector circuitry & data processing

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Young technology (1990) but quite common nowadays

Tower Semiconductor CMOS Image Sensor Technolofgy Main Features

(TowerJazz)

Pixel Offering Mapping

Pixel Size [um]	Process Node	Market	Technology
15-300	180nm	Medical	RS
3.6-6		Cinema	RS
4-6		Broadcast	GS
3.6-20		Machine Vision	GS
>8um		Automotive	SPAD
>5um		3D, Gesture, AR/VR	TOF
3.8-5	110nm	DSLR	RS
2.75		Security	RS
2.8-10		Machine Vision	GS
3.2-6	65nm	DSLR, Cinema	RS
1.75-3.6		Security	RS
1.12-1.75		Consumer / Medical	RS
2.5-5		AR/VR, Machine Vision	GS

RS – Rolling Shutter **GS** – Global Shutter **SPAD** – Single Photon Avalanche Diode **TOF** – Time of Flight

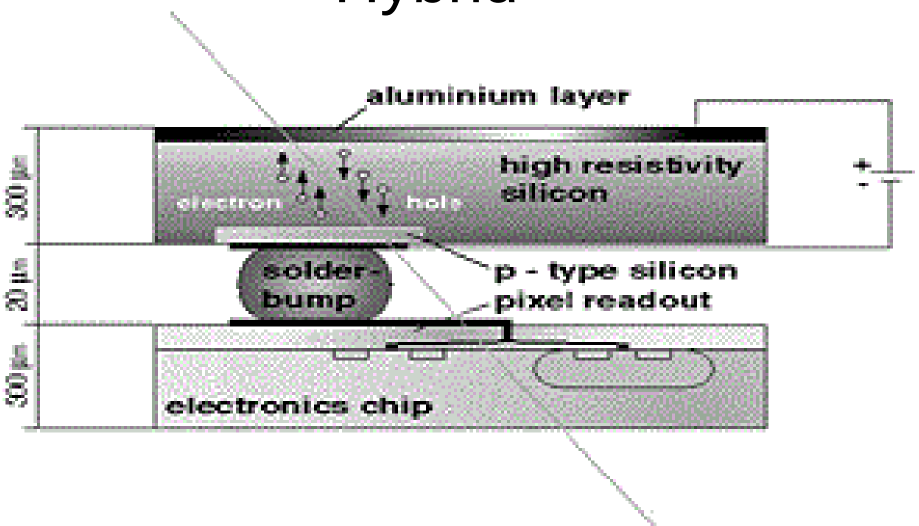
But:

- Main application is imaging, i.e. detection of photons
- High flux
- Poor time resolution

So we can’t simply browse the catalogue and place the order

Hybrid vs. Monolithic

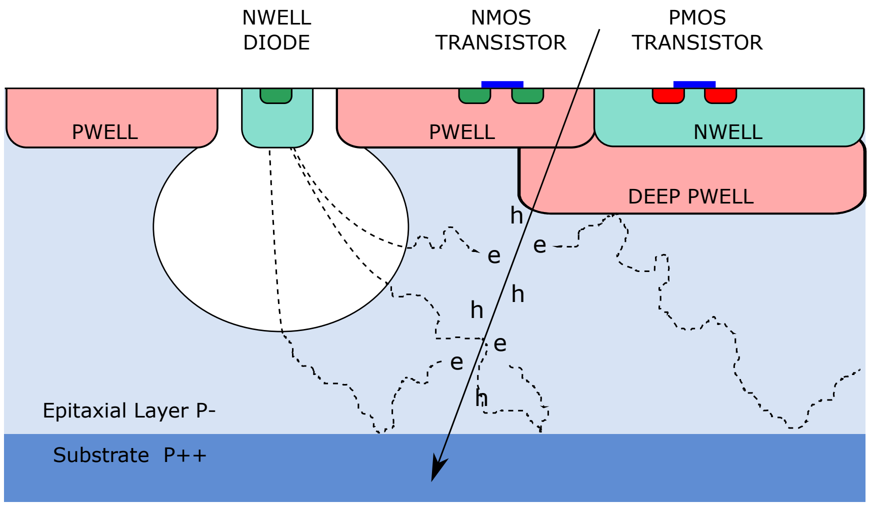
Hybrid



Two different chips, detector + electronics:

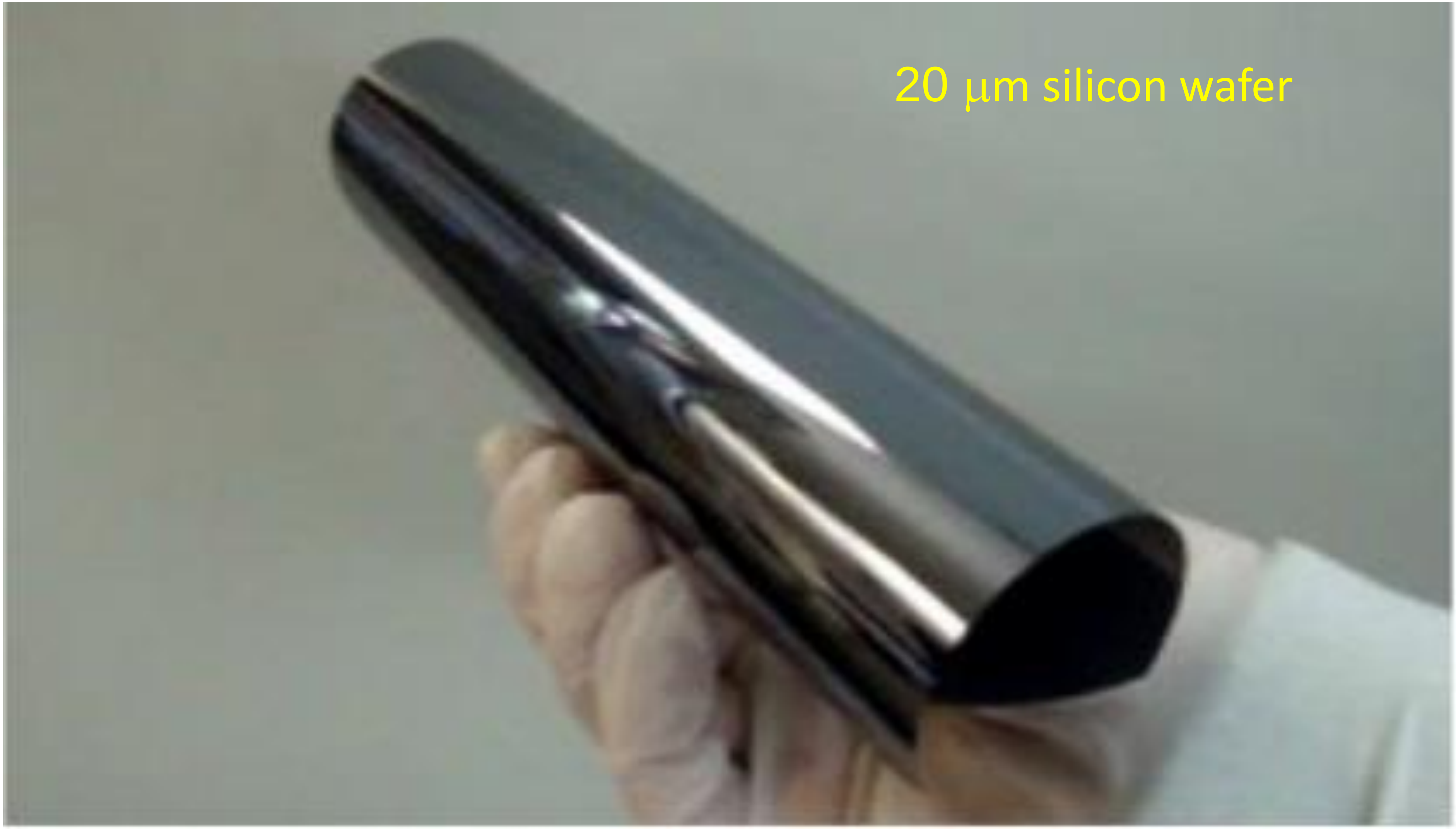
+ flexible (detector material can be different from Si), higher resistivity
- extra production step, yield
- thicker, more material
+ no constraints on electronics design (but bump)
+ no issue with back bias, full depletion possible (more robust w.r.t. radiation damage)
+ Mature technology, present in all LHC experiment

Monolithic

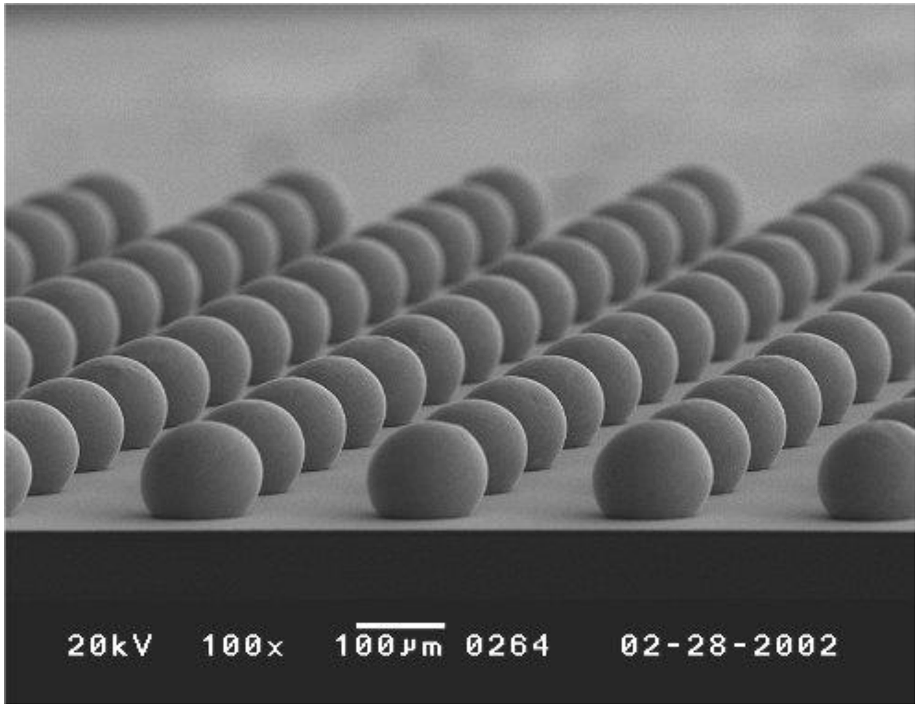


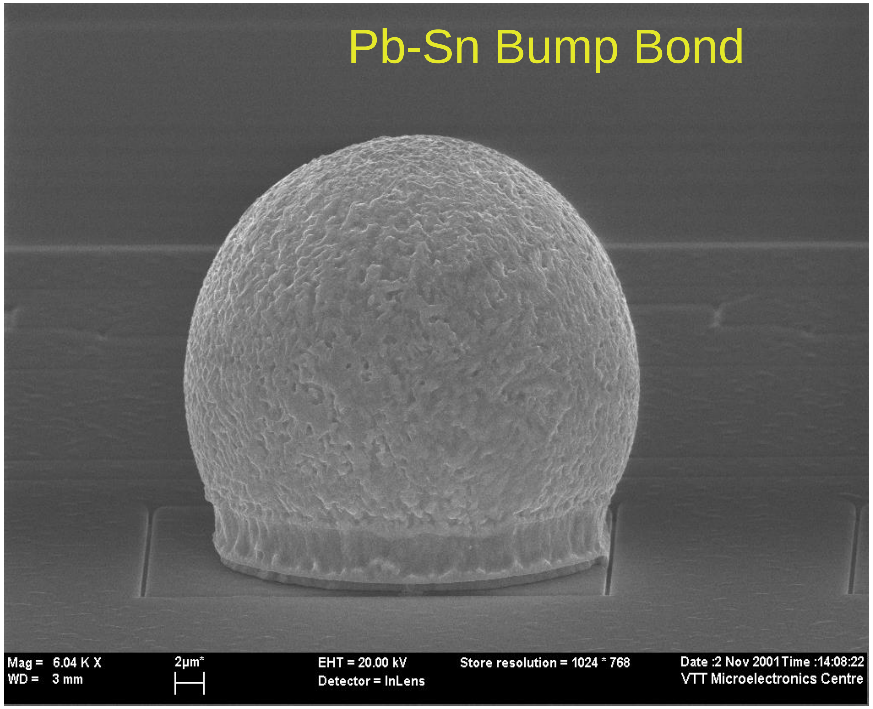
One chip, detector + electronics on the same substrate:

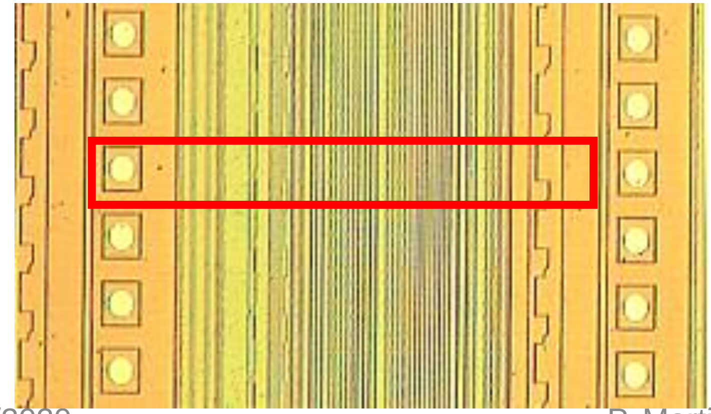
+ thinner, less material (down to 50 μm)
+ one production step
+ smaller readout chip (no bump)
+ issue with back bias, full depletion not (yet) possible (more sensitive to radiation damage)


20 μm silicon wafer

Pb-Sn solder bumps: ~25µm diameter





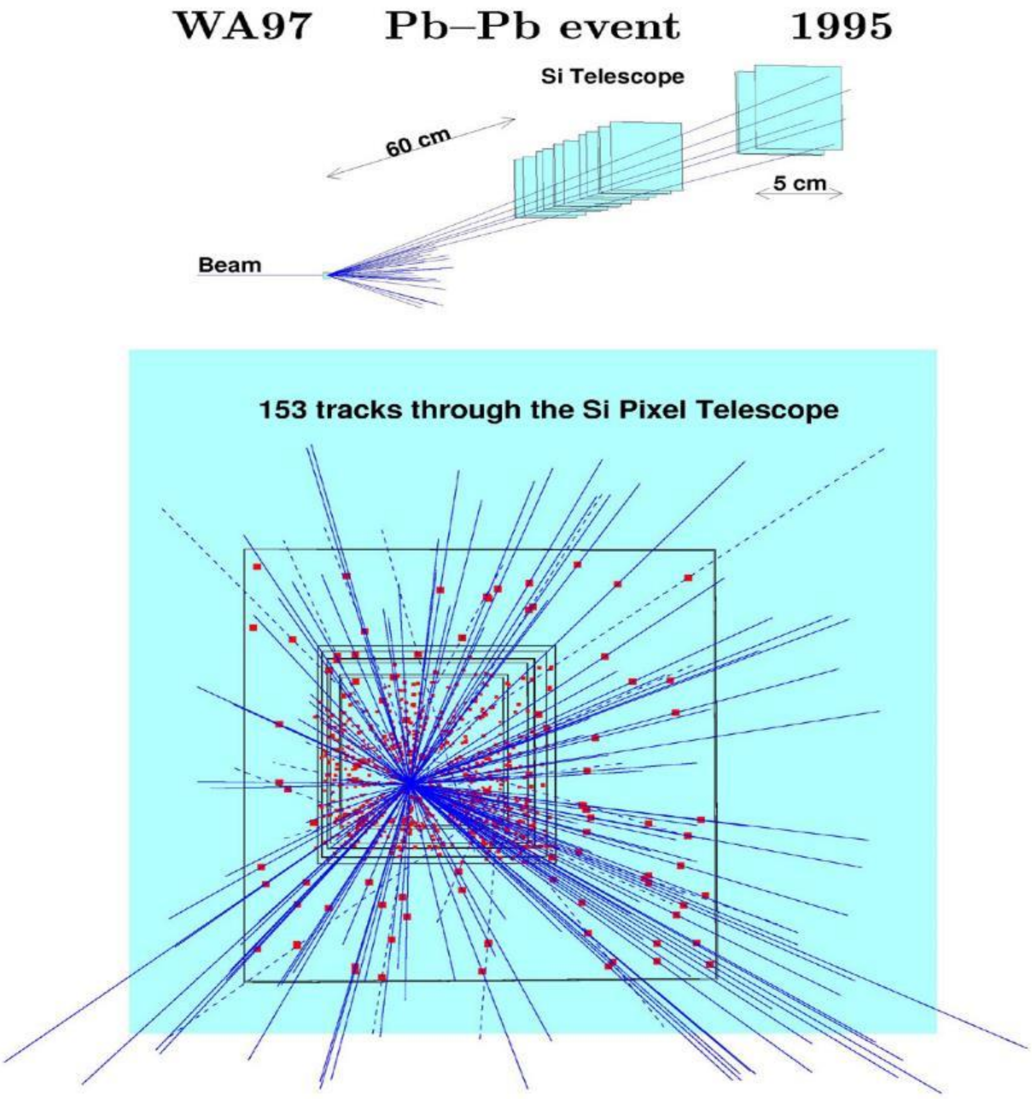


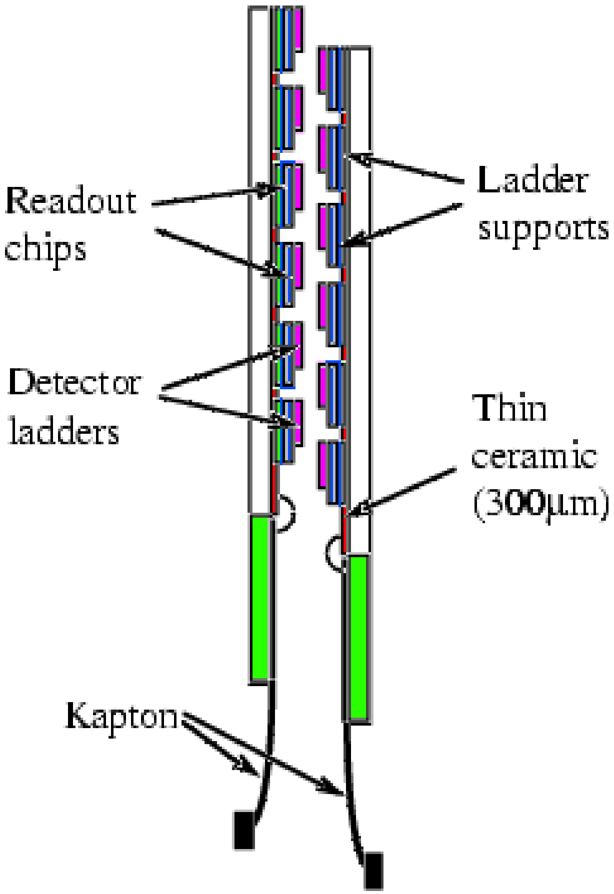
50 µm (rϕ) x 425 µm (z) pixel cell

(29 µm x 27 µm pixel pitch)

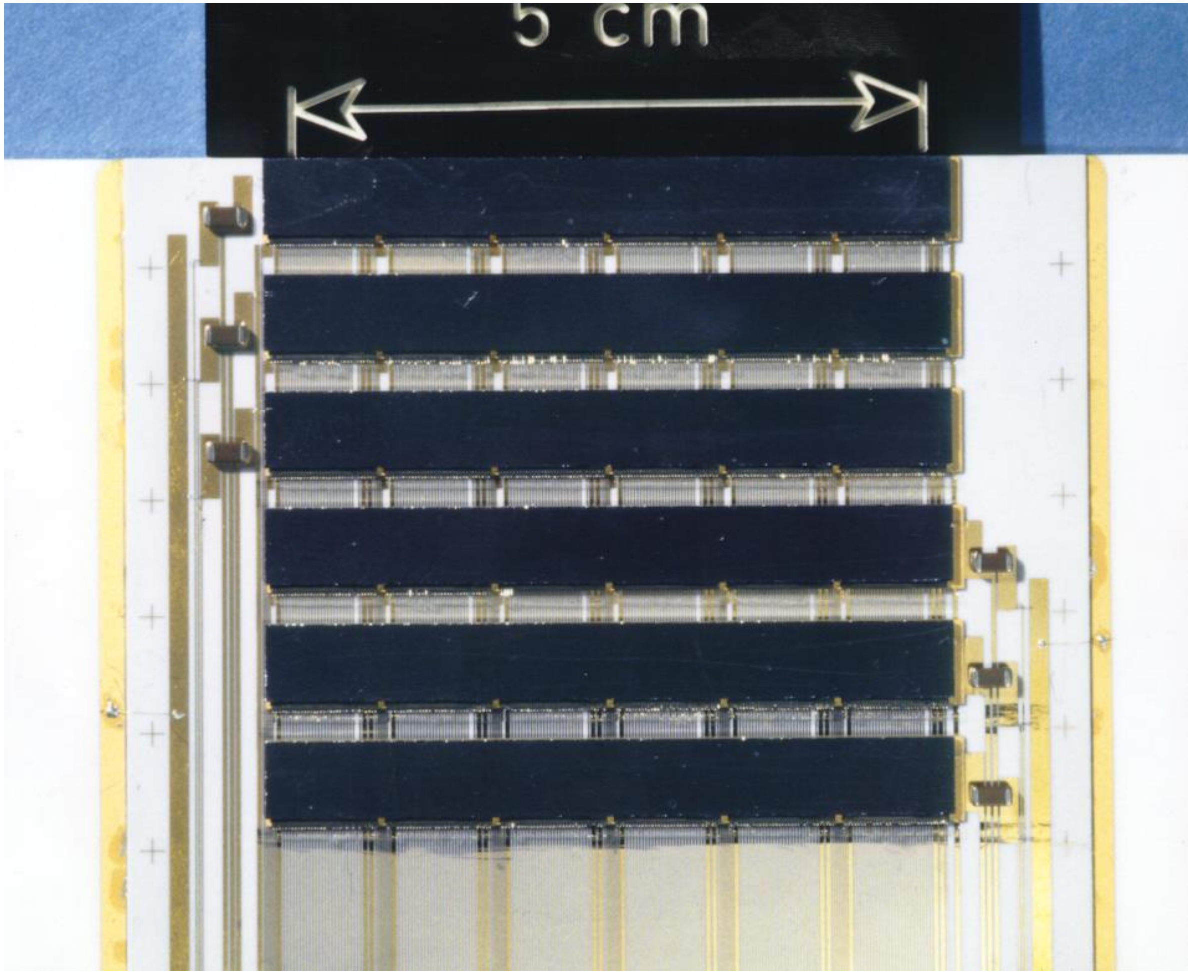
A bit of history

In 1995 the WA97 experiment operated the first pixel telescope in Pb-Pb collisions (fixed target mode)

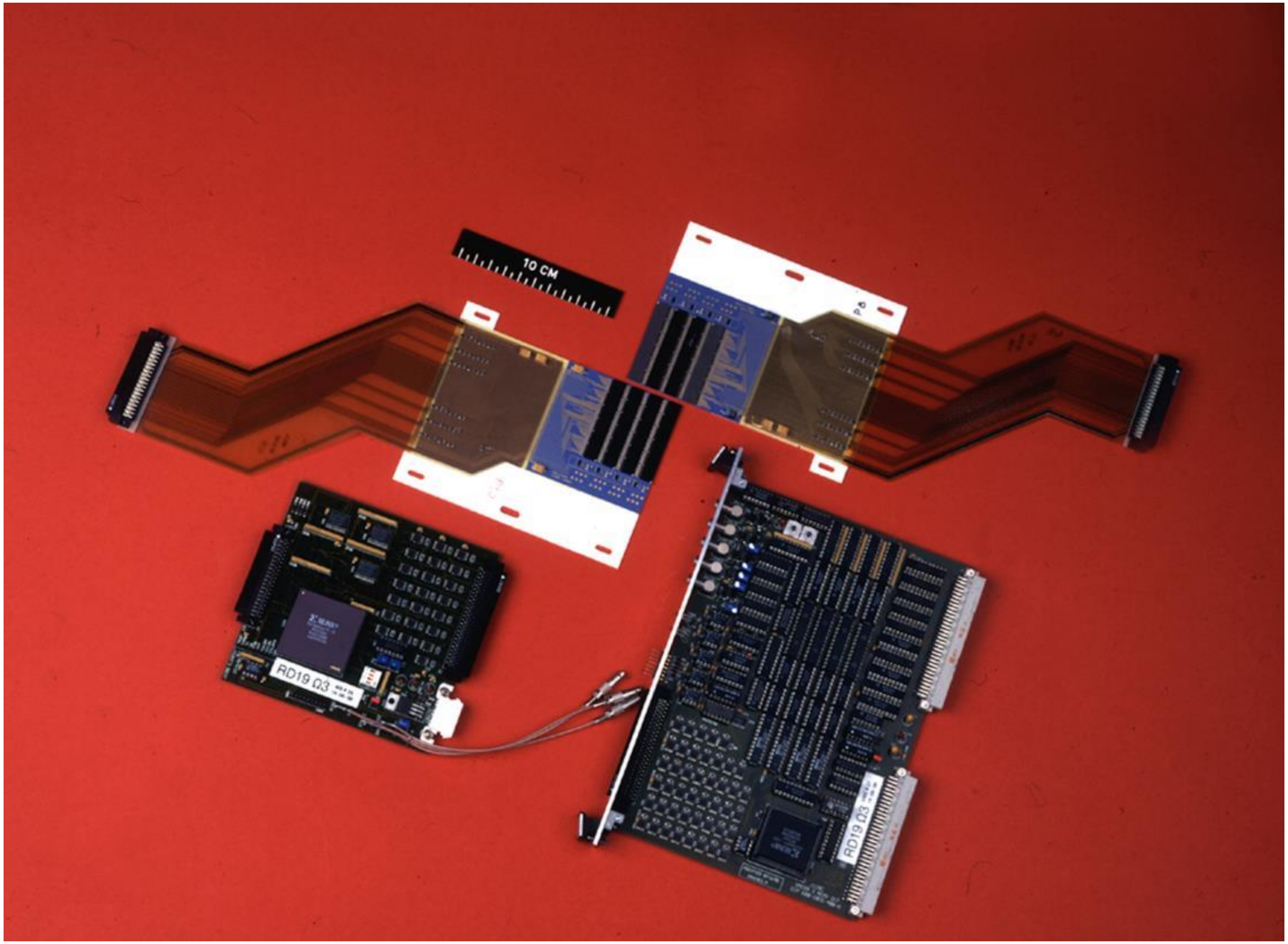




Readout chips
Detector ladders
Ladder supports
Thin ceramic (300µm)
Kapton



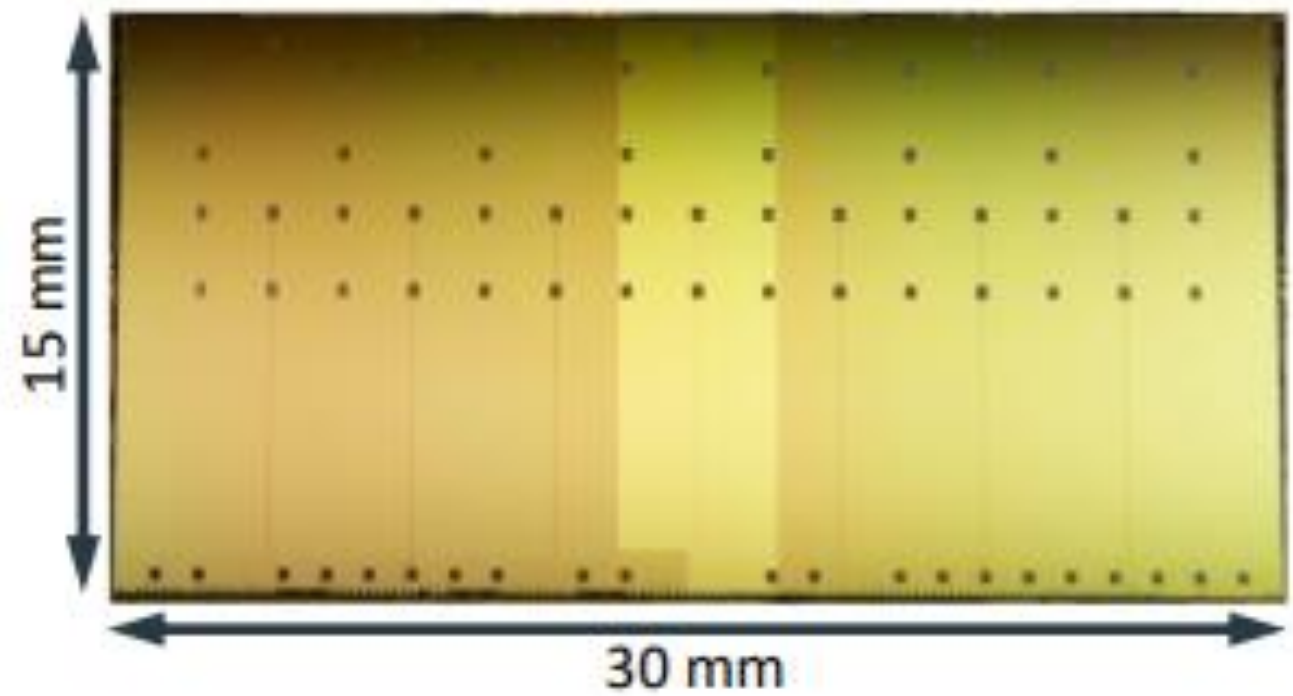
5 cm



The WA97 telescope consisted of 7 planes, 50 mm x 50 mm active area

0.5×10^{6} pixels in total

ITS2 is based on the ALPIDE chip (ALice PIxel DEtector) 30 mm x 15 mm, 0.5 x 10^6 pixels



ITS2 consists of 7 layers, more than 12 Gpixel

10 m^2 active Si area

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Nuclear Instruments and Methods in Physics Research A 465 (2001) 1–26

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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Semiconductor micropattern pixel detectors: a review of the beginnings

Erik H.M. Heijne

CERN, EP Division, CH 1211 Geneva 23, Switzerland

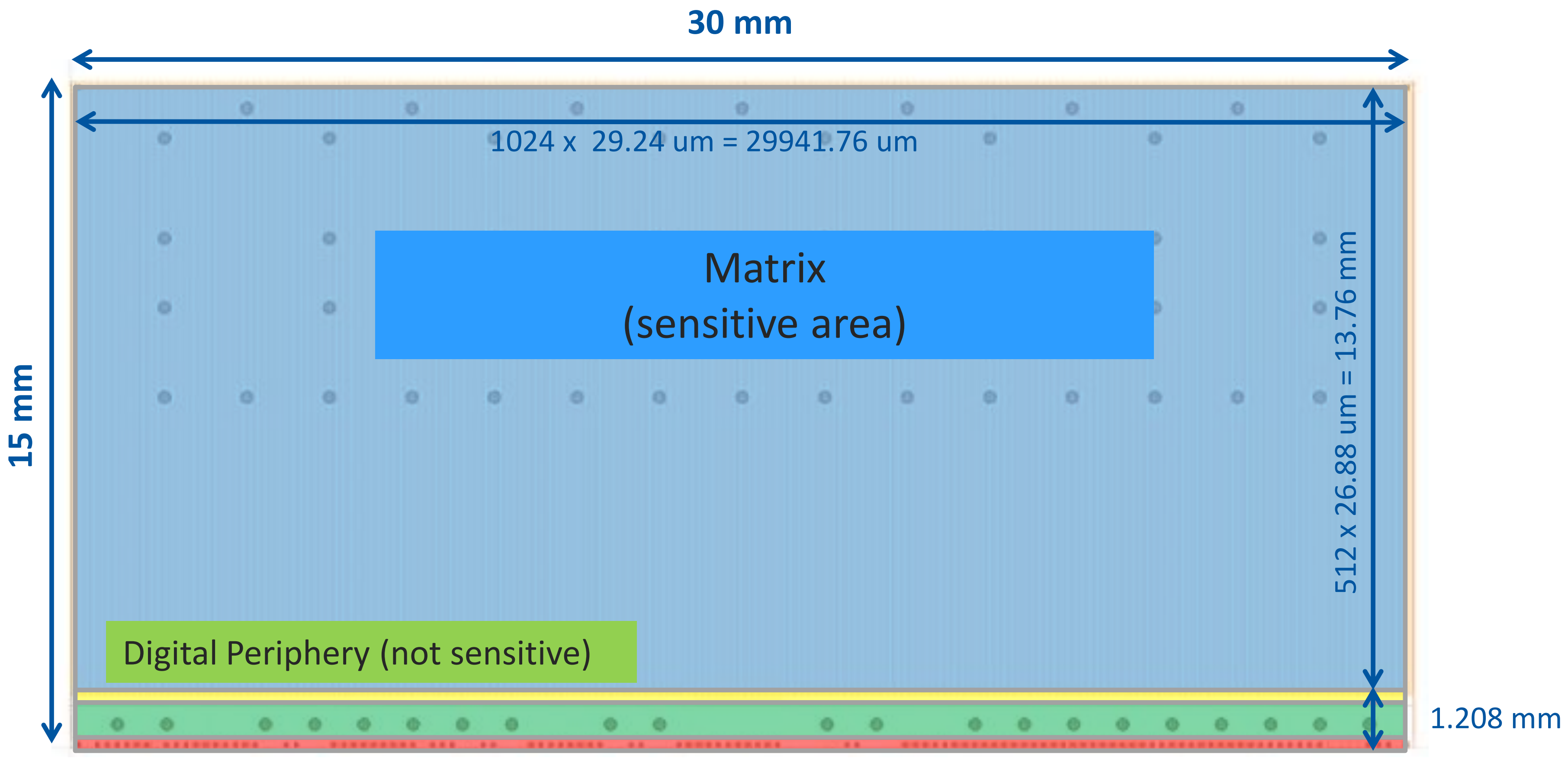
Abstract

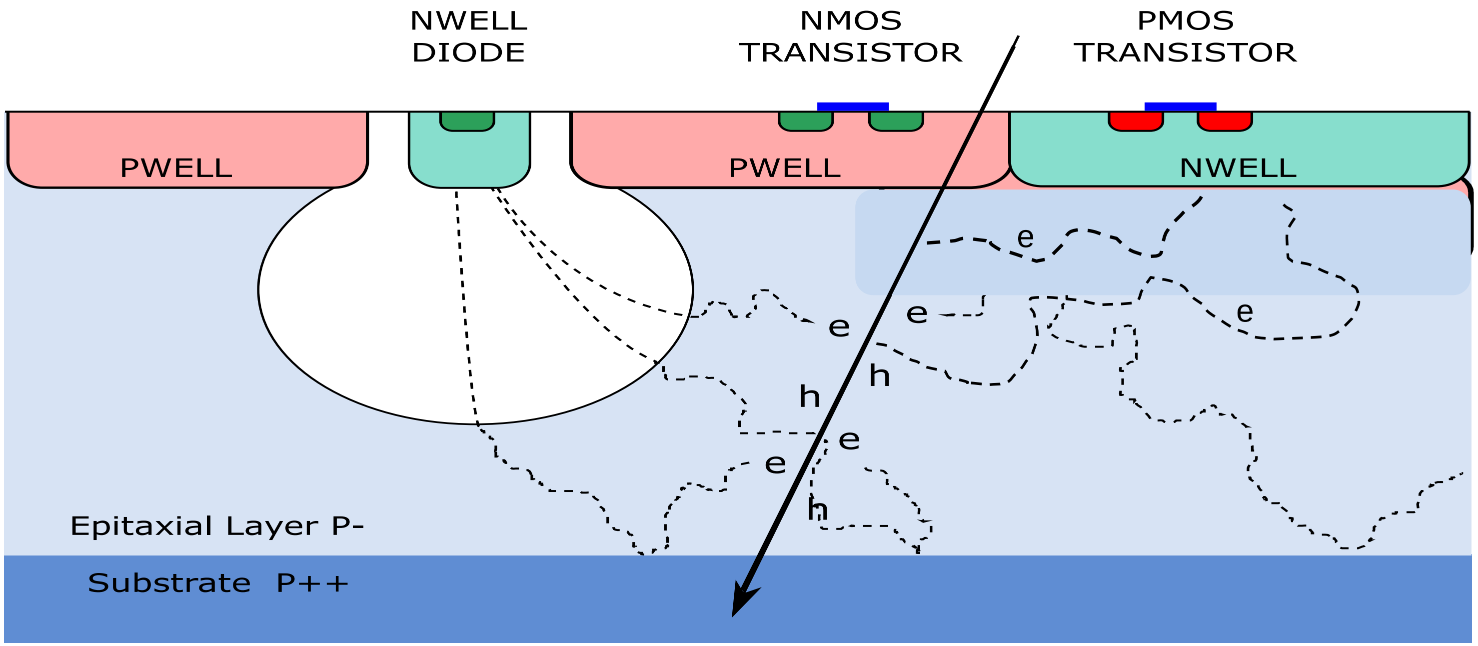
The innovation in monolithic and hybrid semiconductor 'micropattern' or 'reactive' pixel detectors for tracking in particle physics was actually to fit logic and pulse processing electronics with μW power on a pixel area of less than 0.04 mm^2, retaining the characteristics of a traditional nuclear amplifier chain. The ns timing precision in conjunction with local memory and logic operations allowed event selection at > 10 MHz rates with unambiguous track reconstruction even at particle multiplicities > 10 cm^{-2}. The noise in a channel was ~ $100e^-$ rms and enabled binary operation with random noise 'hits' at a level $< 10^{-8}$. Rectangular pixels from 75 μm × 500 μm down to 34 μm × 125 μm have been used by different teams. In binary mode a tracking precision from 6 to 14 μm was obtained, and using analog interpolation one came close to 1 μm. Earlier work, still based on charge integrating imaging circuits, provided a starting point. Two systems each with more than 1 million sensor + readout channels have been built, for WA97-NA57 and for the Delphi very forward tracker. The use of 0.5 μm and 0.25 μm CMOS and enclosed geometry for the transistors in the pixel readout chips resulted in radiation hardness of ~ 2 Mrad, respectively, > 30 Mrad.

Fig. 7. The analog signals allowed charge interpolation, and along the 34 μm direction a tracking precision with $\sigma = 2$ μm was measured on average. Further study revealed that an even better precision could be achieved on a subset of the events, as shown in Fig. 8. For a small summed pulse height only few pixels contributed and the interpolation was less precise, while for the largest pulse heights there was a delta-electron generated, which caused charge to be measured further away from the real track, degrading the precision. Better than 1.5 μm precision has been determined for the pulse heights between 0.9 and 1.4 times the peak of the Landau distribution. The charge distribution in multiple-hit clusters is a basic feature of pixel detectors, and requires more attention as the pixel size decreases. In spite of these promising results, Parker received only modest support to continue the exploration of monolithic detector structures, and as yet no (proposals for) applications in experiments have ensued.

Vanstraelen concluded in 1990 [54] that monolithic devices directly on high resistivity silicon, be it n-type as in his HRCMOS process, or p-type as in the Stanford process, would always be limited in circuit flexibility by lack of the complementary MOS transistor in the pixel area (at the periphery

How can we, today, build a Gpixel detector based on monolithic technology?


30 mm
15 mm
1024 x 29.24 um = 29941.76 um
Matrix
(sensitive area)
512 x 26.88 um = 13.76 mm
Digital Periphery (not sensitive)
1.208 mm

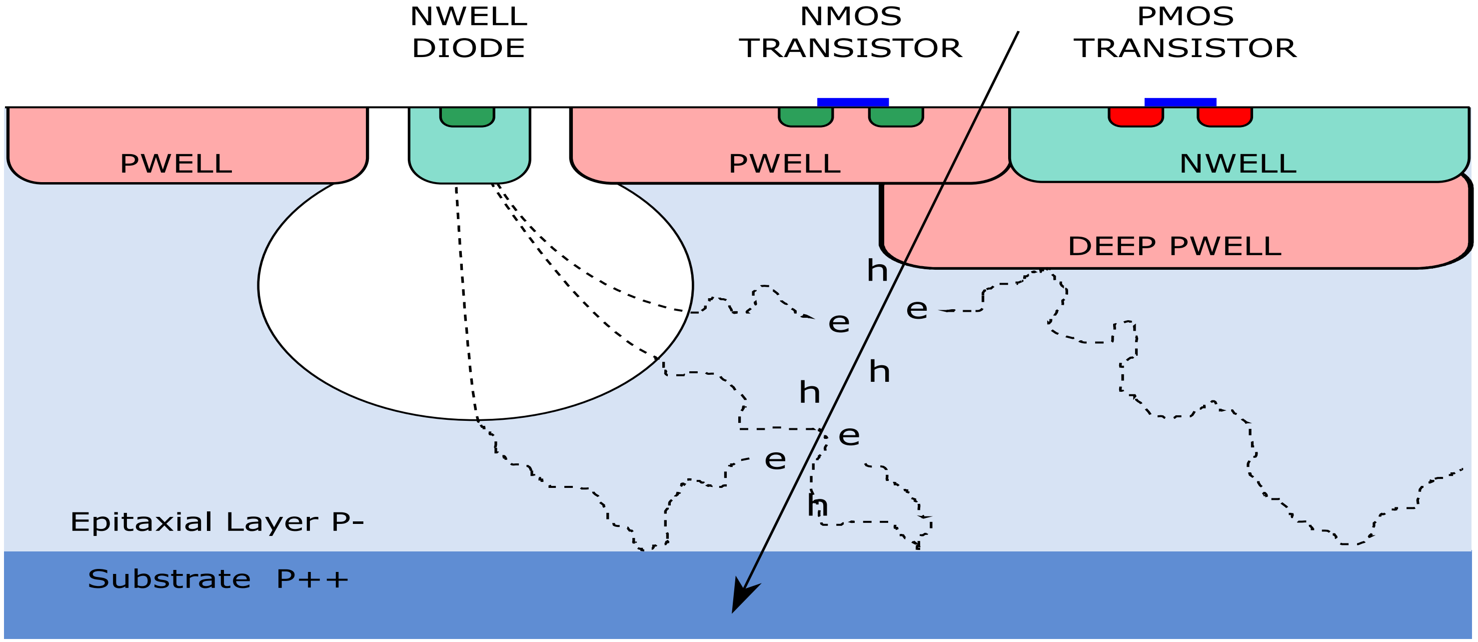


In order to implement full functionality both PMOS and NMOS transistors are needed

The NWELL of a PMOS trans behaves exactly as the NWELL of the collection diode

i.e. the electrons will drift or diffuse towards ALL NWELL in the pixel

The spreading of the already small signal (~1000 e^-) over many collection points makes the detector unusable



The introduction of a DEEP PWELL was the technological breakthrough

which make possible to overcome this limitation:

the transistors NWELL are now shielded and an unique collection electrode is present

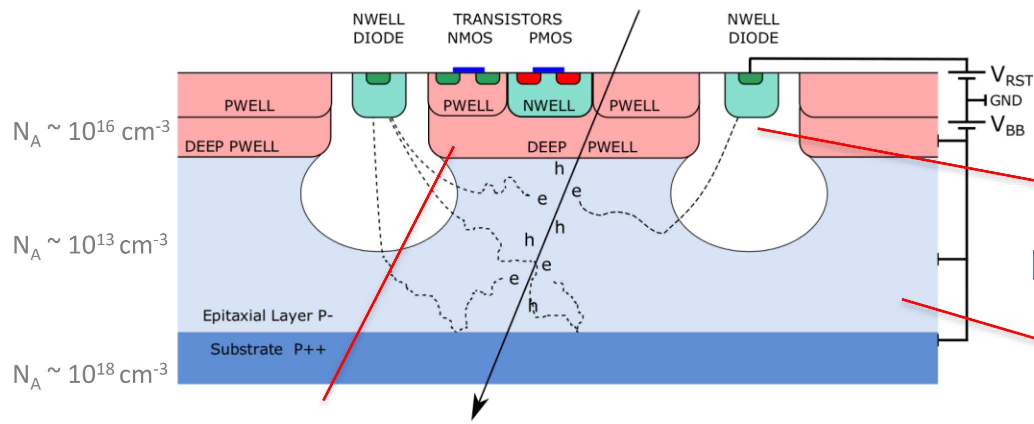
ALPIDE Requirements

Parameter	Inner Barrel	Outer Barrel
Chip size (mm x mm)	15 x 30	
Chip thickness (μm)	50	100
Spatial resolution (μm)	5	10 (5)
Detection efficiency	> 99%	
Fake hit rate	< 10^{-6} evt^{-1} $pixel^{-1}$ (ALPIDE << 10^{-6})	
Integration time (μs)	< 30 (< 10)	
Power density (mW/cm^2)	< 300 (~40)	< 100 (~30)
TID radiation hardness (krad)	270	10
NIEL radiation hardness (1 MeV n_{eq}/cm^2)	1.7×10^{12}	1.7×10^{11}
Readout rate, Pb-Pb interactions (kHz)	100	
Readout rate, pp interactions (kHz)	400	
Hit Density, Pb-Pb interactions (cm^{-2})	19	< 1

(*) In color: ALPIDE performance figure where above requirements

ALPIDE – Technology and Pixel Layout

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



Reverse bias voltage ($-6V < V_{BB} < 0V$) to substrate (contact from the top) to increase depletion zone around NWELL collection diode

Small n-well diode (2 μm diameter), 100 times < than pixel, low capacitance (~fF)

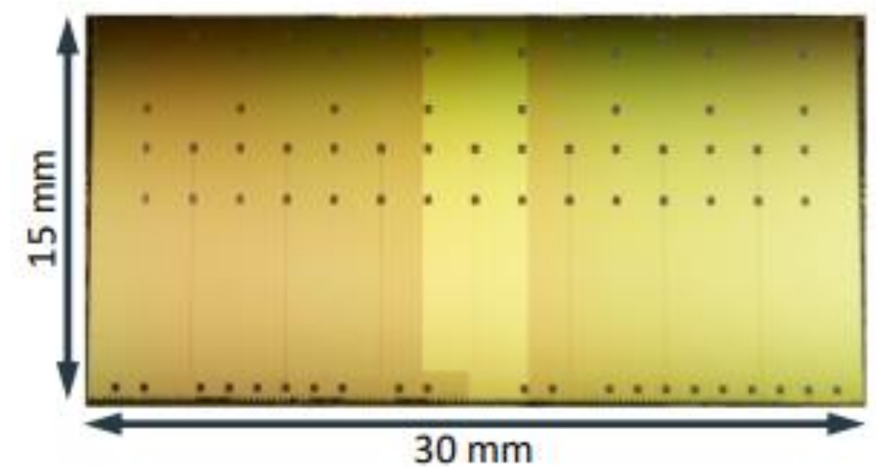
High-resistivity (> 1kΩ cm) p-type epitaxial layer (25μm) on p-type substrate

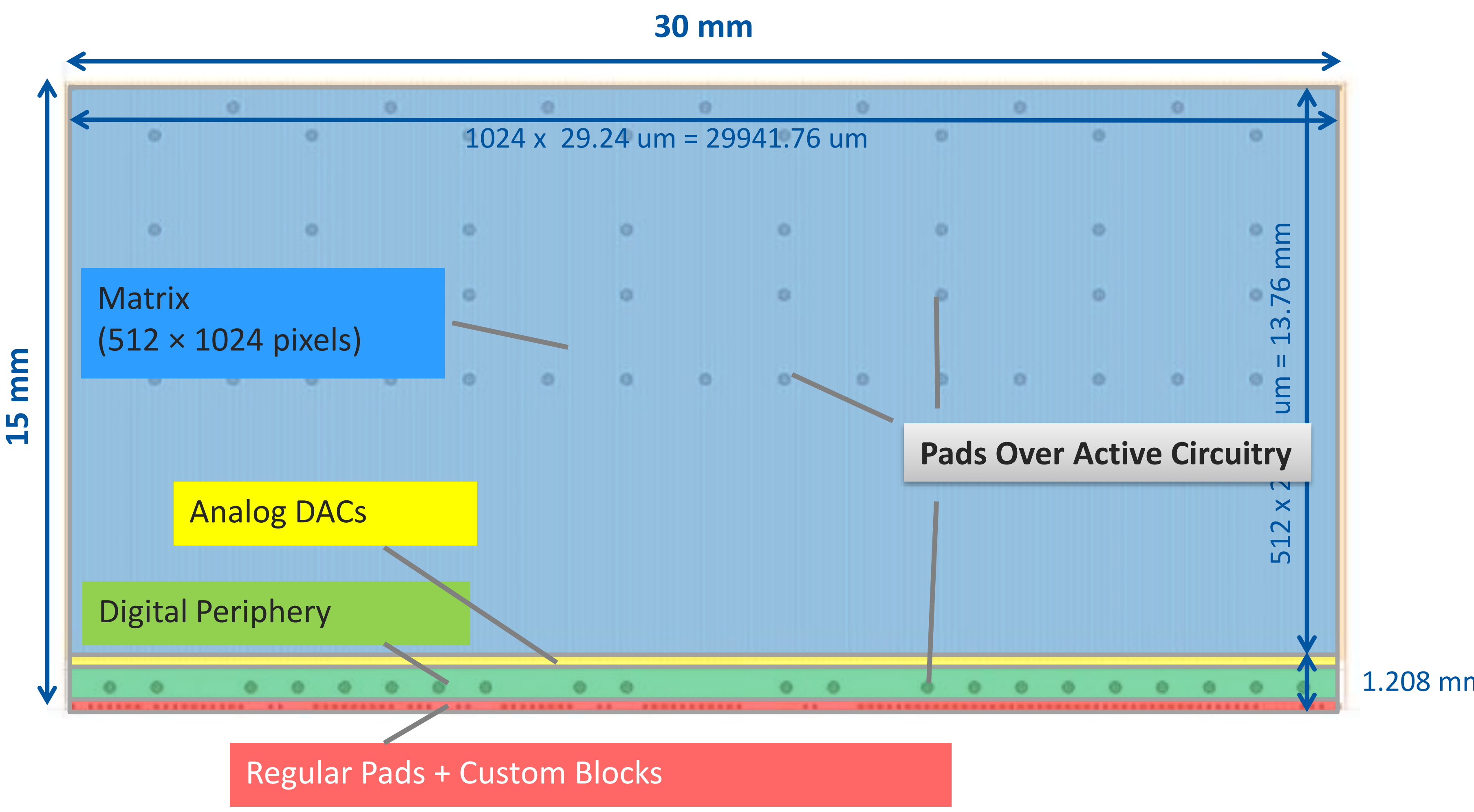
full CMOS circuitry within active area:

In-pixel:

- Amplification
- Discrimination
- 3-hit storage register (MEB)
- In-matrix sparsification

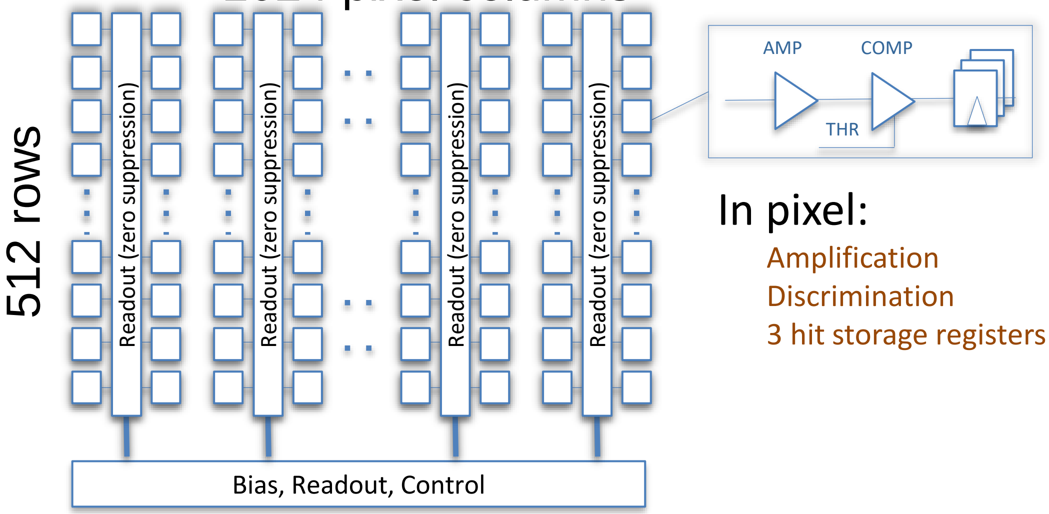
(only pixel w/ signal above a given threshold are R/O)





30 mm
1024 x 29.24 um = 29941.76 um
15 mm
512 x 26.88 um = 13.76 mm
Matrix
(512 × 1024 pixels)
Pads Over Active Circuitry
Analog DACs
Digital Periphery
1.208 mm
Regular Pads + Custom Blocks

ALPIDE Architecture (G. Aglieri Rinella)

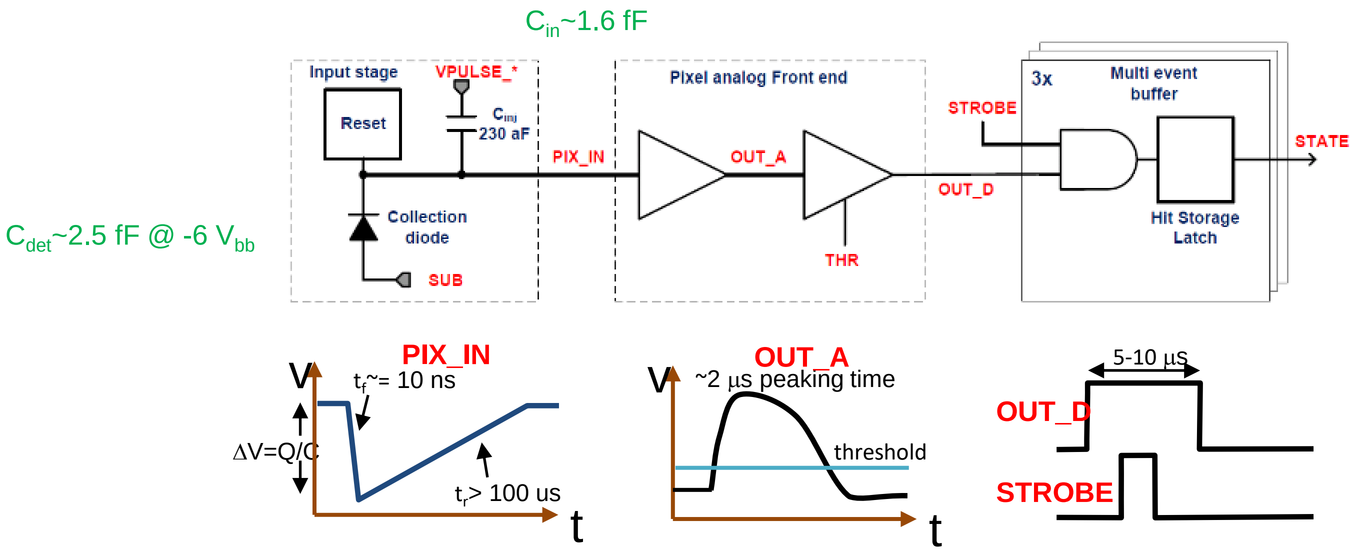


In pixel:

- Amplification
- Discrimination
- 3 hit storage registers (MEB)

- 29 μm x 27 μm pixel pitch
- Continuously active front-end
- Global shutter
- Zero-suppressed matrix readout
- Triggered or continuous readout modes

Pixel (G. Aglieri Rinella)



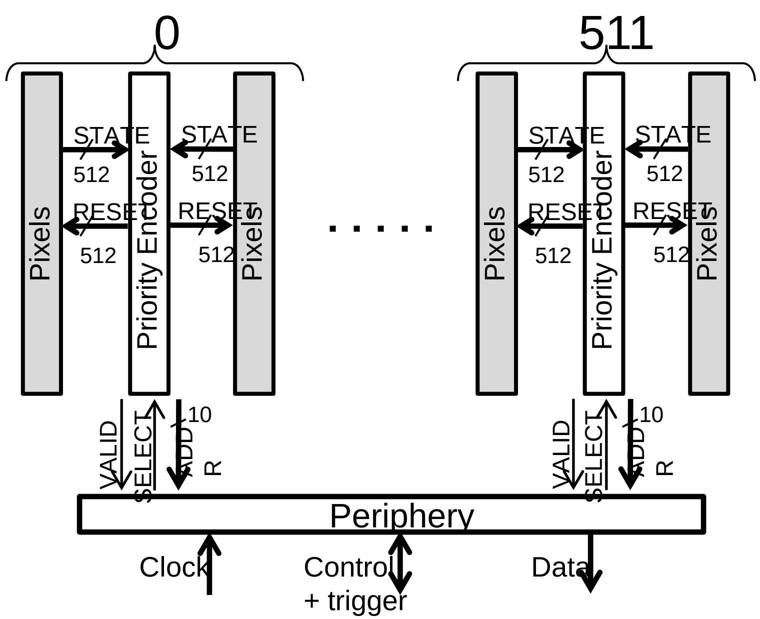
Analog front-end and discriminator continuously active

- Non-linear and operating in weak inversion. Ultra-low power: 40 nW/pixel
- The front-end acts as analogue delay line
- Test pulse charge injection circuitry
- Global threshold for discrimination -> binary pulse OUT_D

Digital pixel circuitry with three hit storage registers (multi event buffer)

Global shutter (STROBE) latches the discriminated hits in next available register In-Pixel *masking* logic

Matrix Readout (G. Aglieri Rinella)

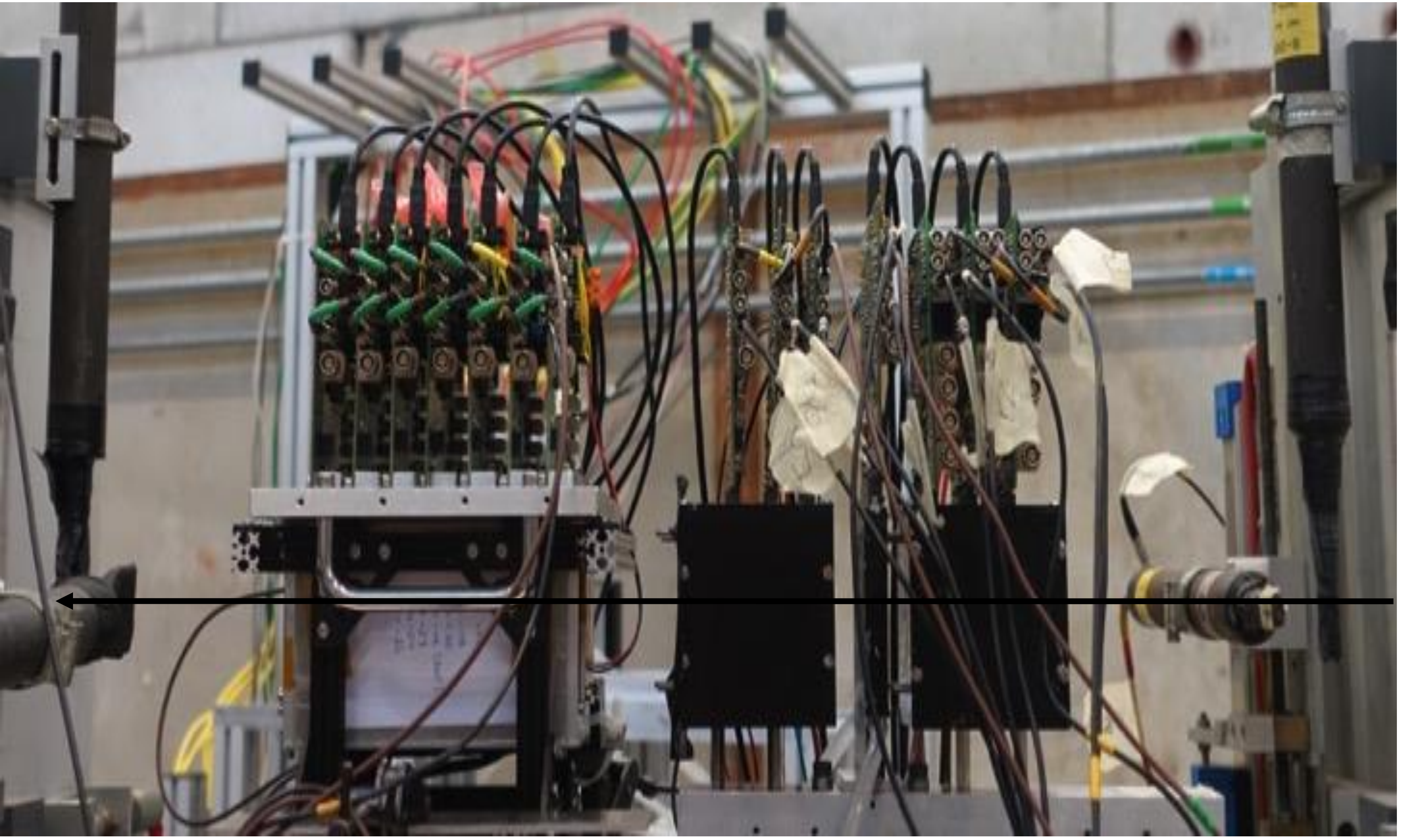


The Priority Encoder sequentially provides the addresses of all hit pixels in a double column

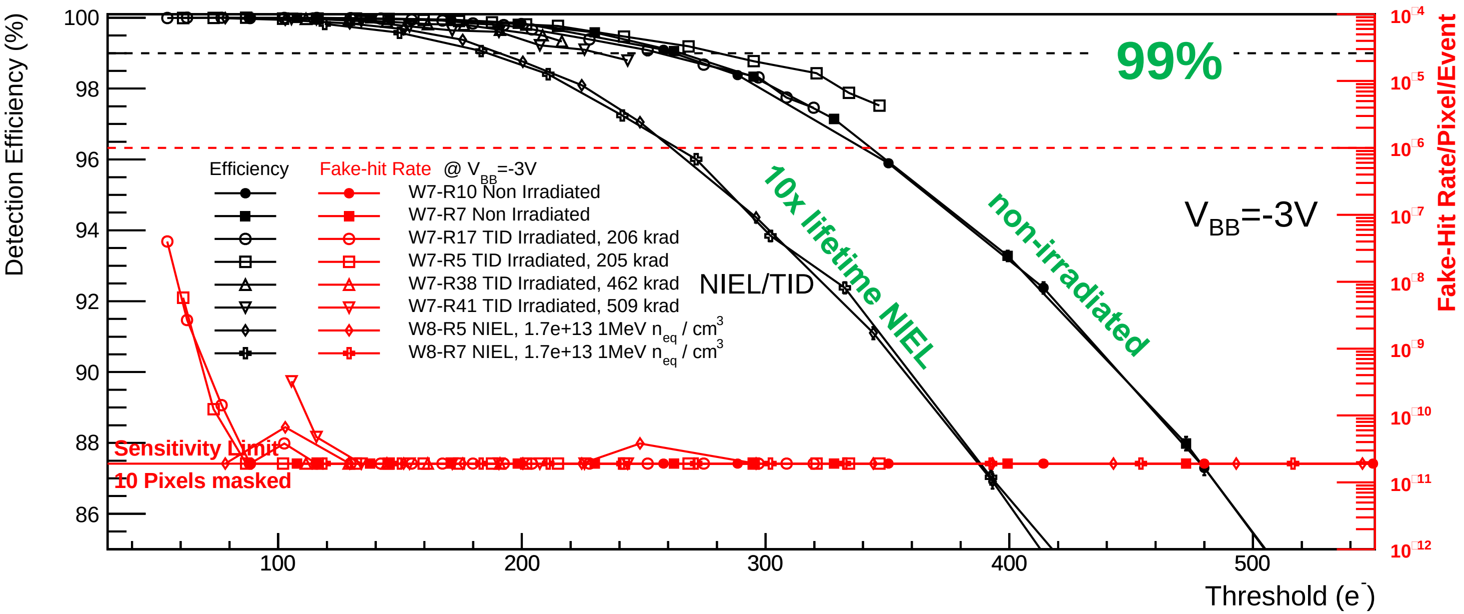
Combinatorial digital circuit steered by peripheral sequential circuits during readout of a frame

- No free running clock over matrix. No activity if there are no hits
- Energy per hit: E_h ~= 100 pJ -> ~3 mW for nominal occupancy and readout rate
- Buffering and distribution of global signals (STROBE, MEMSEL, PIXEL RESET)

ALPIDE performance

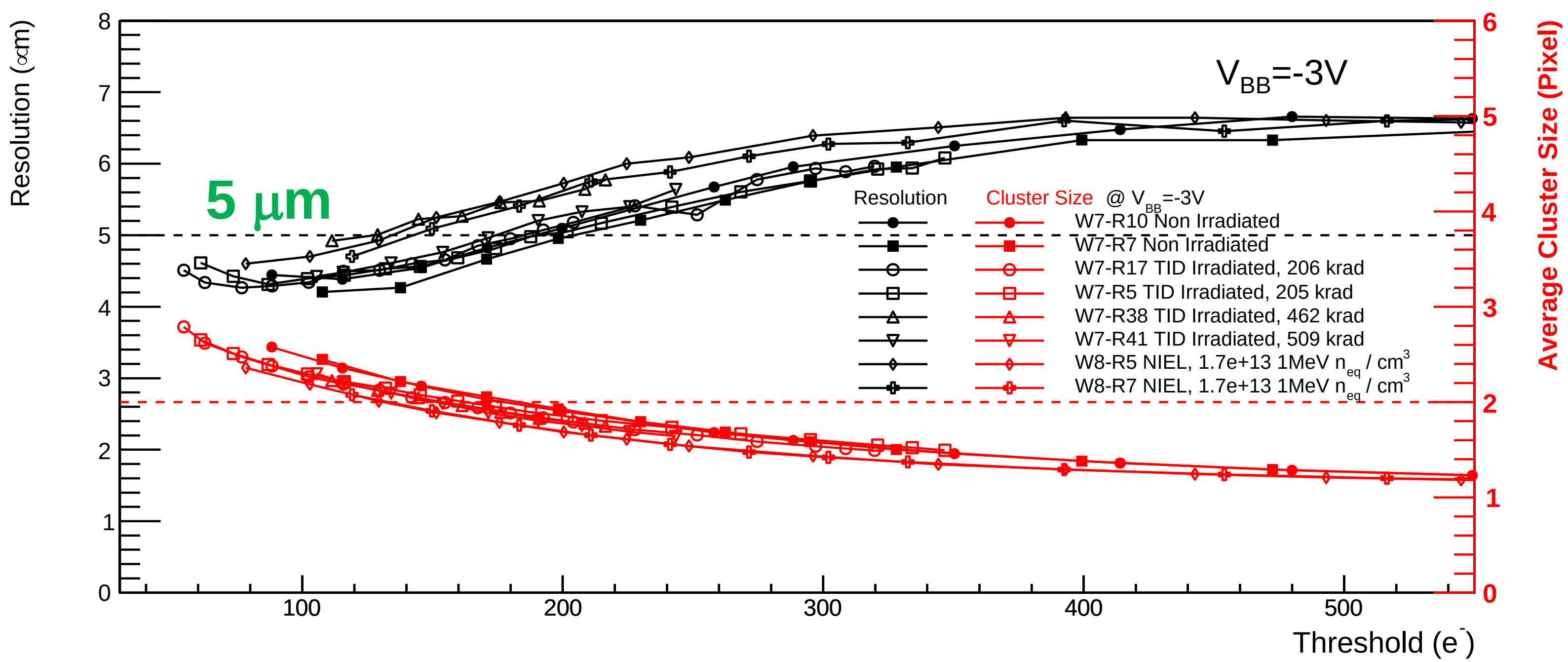


ALPIDE – Detection Efficiency and Fake-Hit Rate



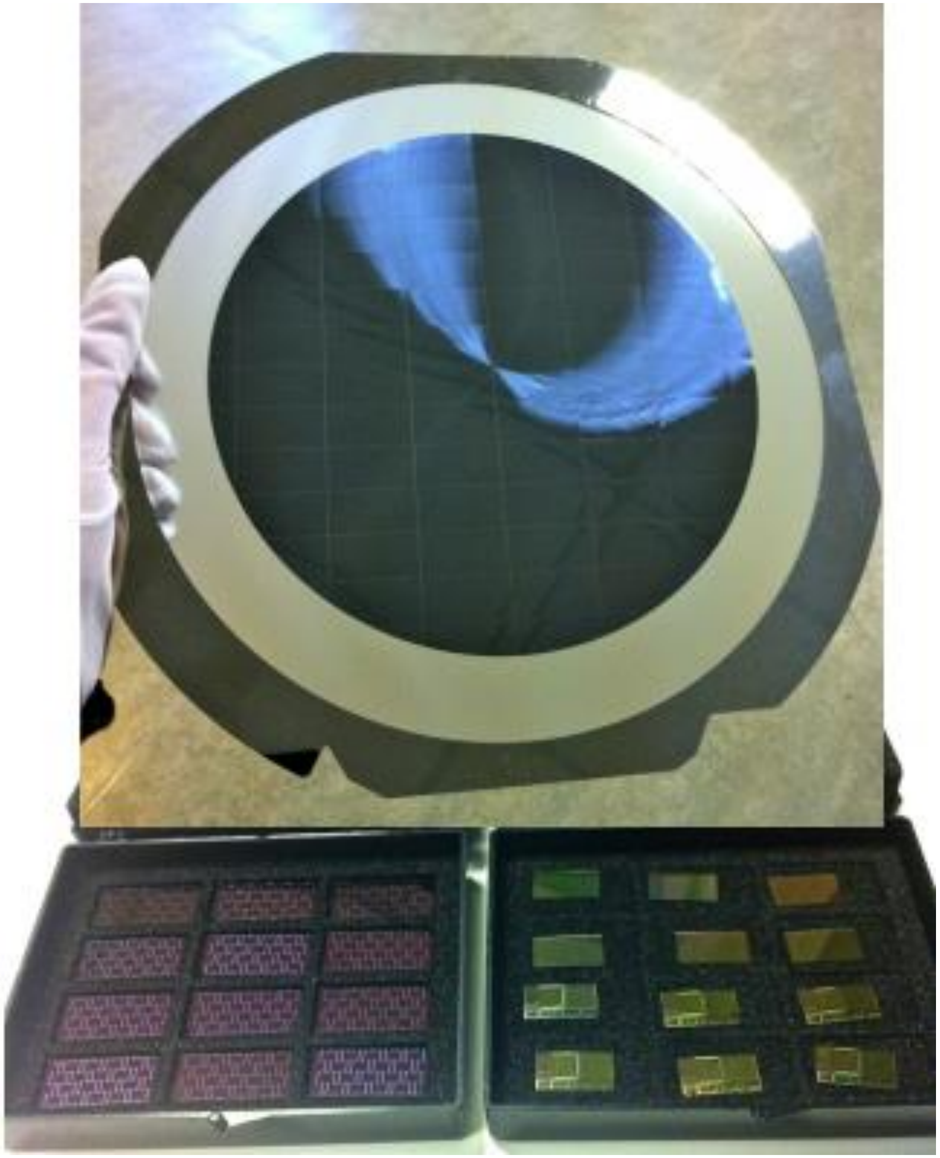
- Big operational margin with only 10 masked pixels (0.002%), fake-hit rate < 10^{-10} pixel/event (requirement < 10^{-6})
- Chip-to-chip fluctuations negligible
- Non-irradiated and NIEL/TID chips show similar performance
- Sufficient operational margin after 10x lifetime NIEL dose

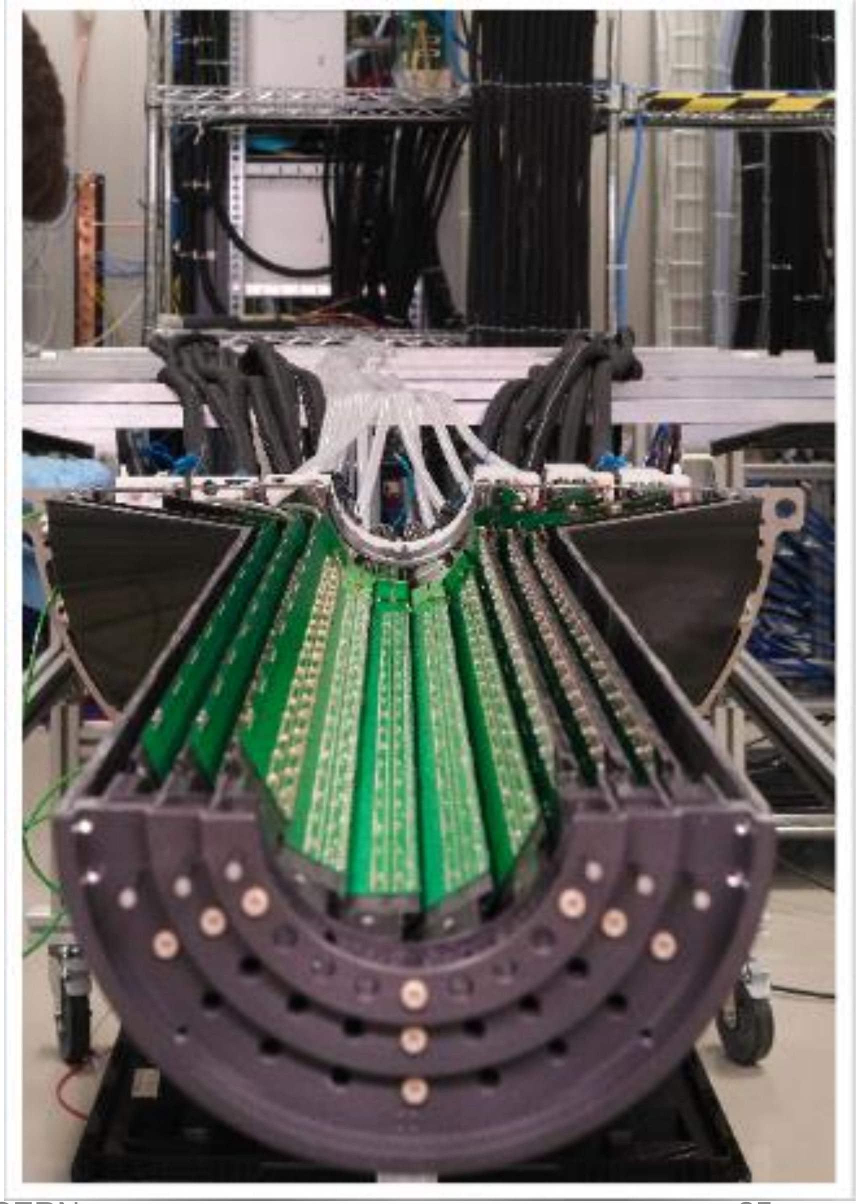
ALPIDE – Resolution and cluster size



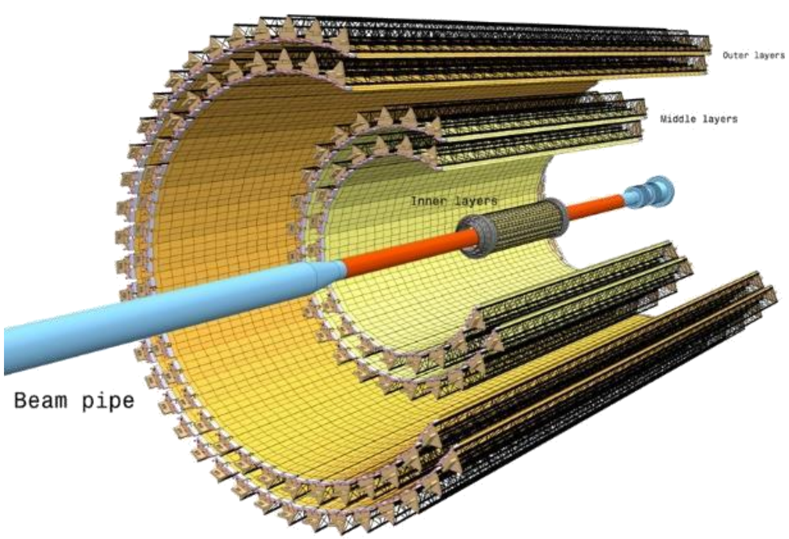
- Chip-to-chip fluctuations negligible
- Non-irradiated and TID/NIEL chips show similar performance
- Resolution of about 5µm at a threshold of 200 electrons
- Sufficient operational margin even after 10x lifetime NIEL dose

From chip to detector

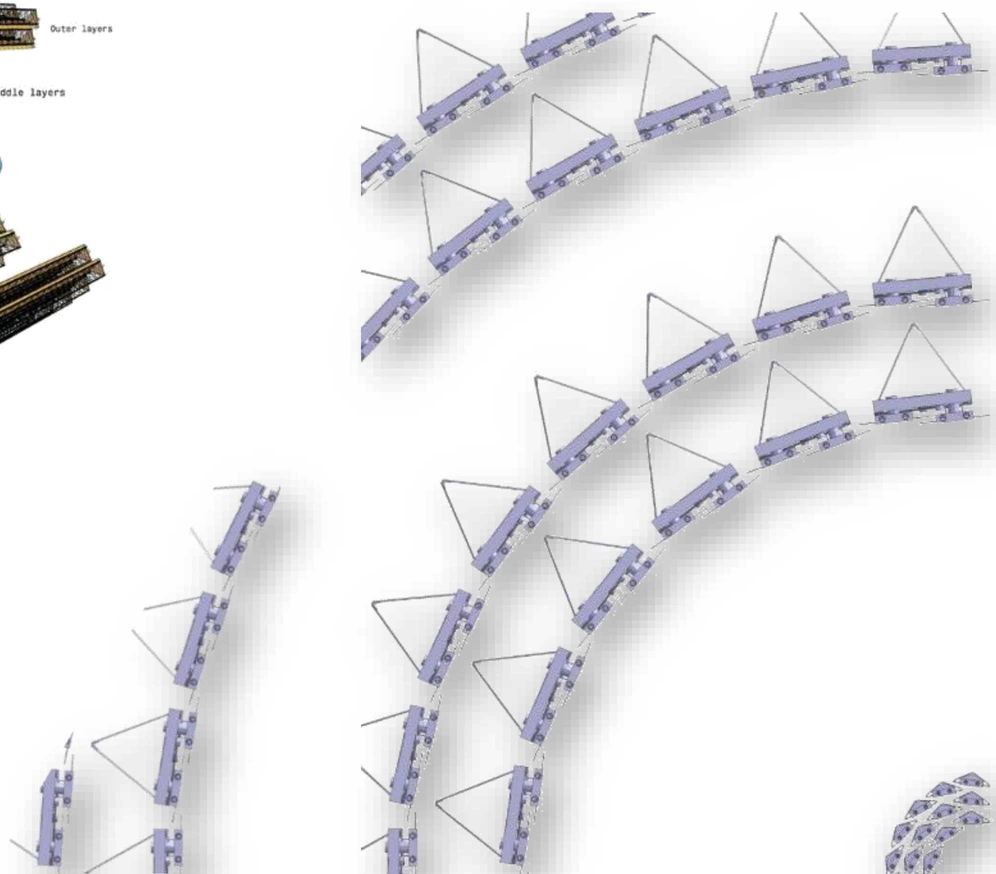




Detector Barrel Staves

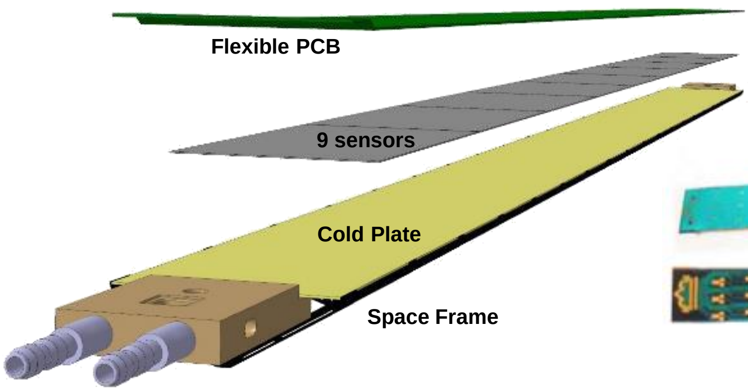


The ITS2 is constituted by
- 7 layers; 3 (IL), 2 (ML), 2(OL)
- 192 staves; 48 (IL), 54 (ML), 90 (OL)



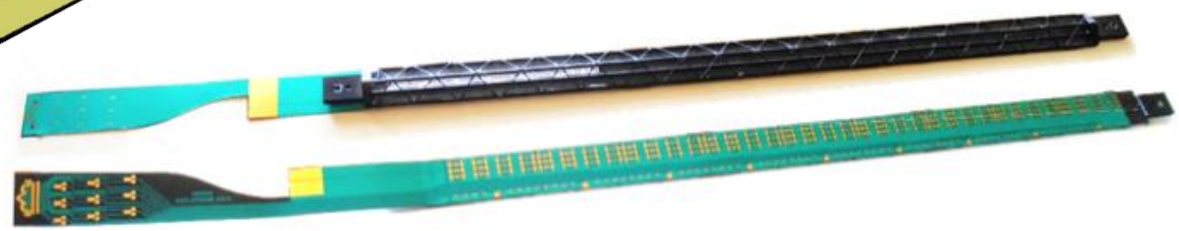
Layer #	6	5	4	3	2	1	0
n. of Staves	48	42	30	24	20	16	12

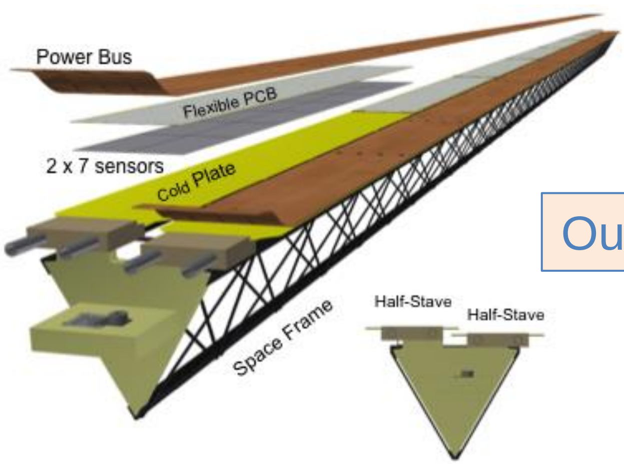
Stave Layout



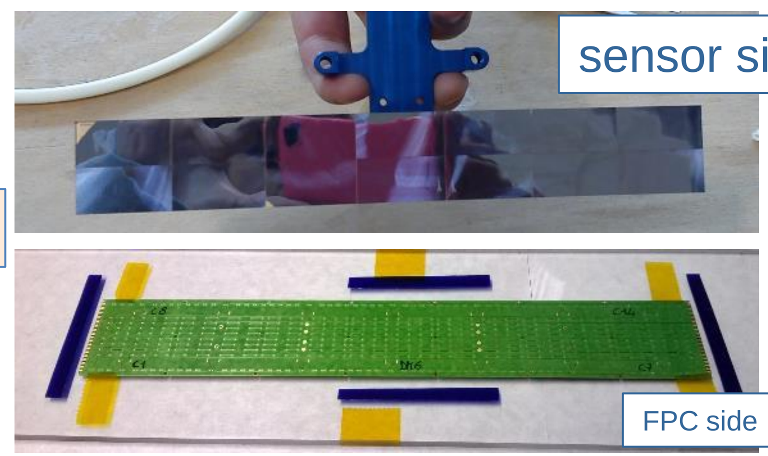
Inner Barrel

sensors thinned to 50μm





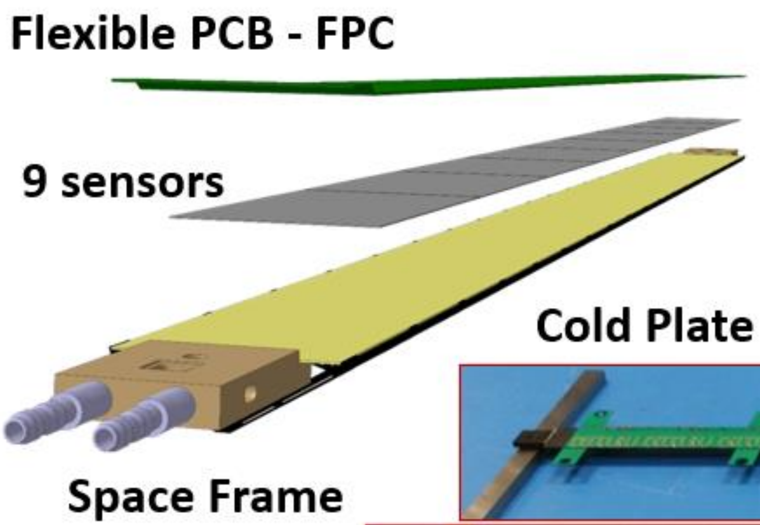
Outer Barrel

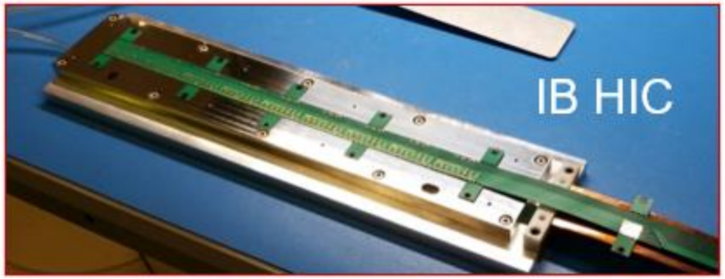


sensors thinned to 100 μm

Inner Barrel stave

HIC: Hybrid Integrated Circuit



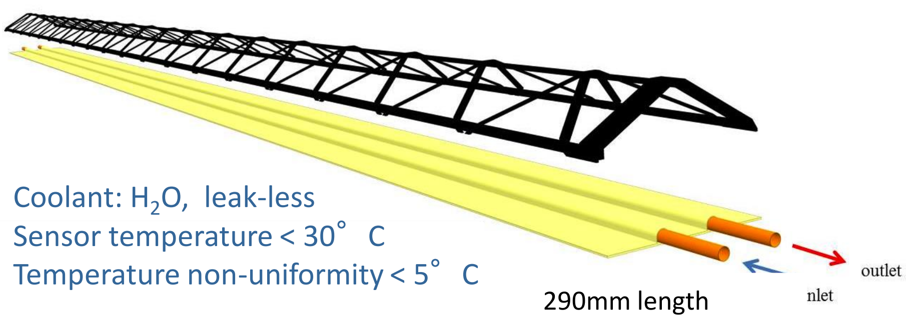


STAVE: HIC glued to the IB spaceframe & coldplate, such to provide HIC support, alignment, and thermal contact to the coldplate

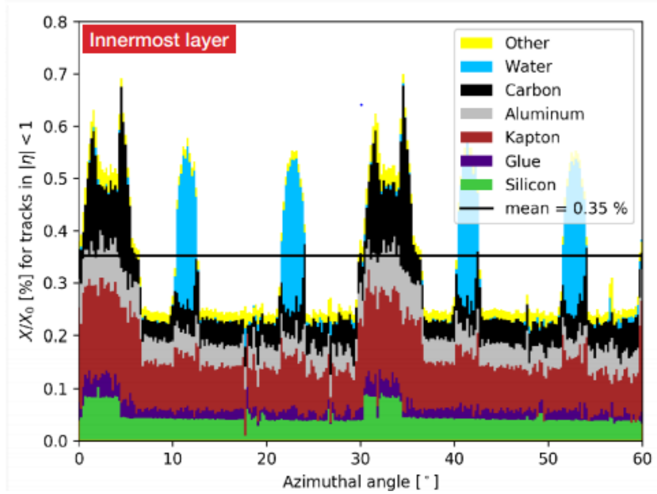
Adopted by sPHENIX & NA61

The ALICE Muon Forward Tracker (MFT) is also based on ALPIDE

Inner Barrel Stave Mechanics & Cooling



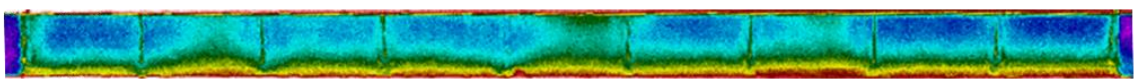
Coolant: H_2O, leak-less
Sensor temperature < 30° C
Temperature non-uniformity < 5° C



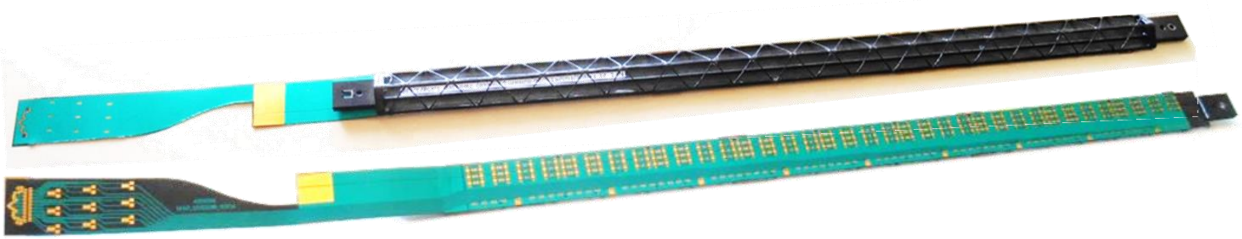
W = 100 mW / cm² (> x2 nominal) , H_2O flow rate = 3 Lh^{-1}

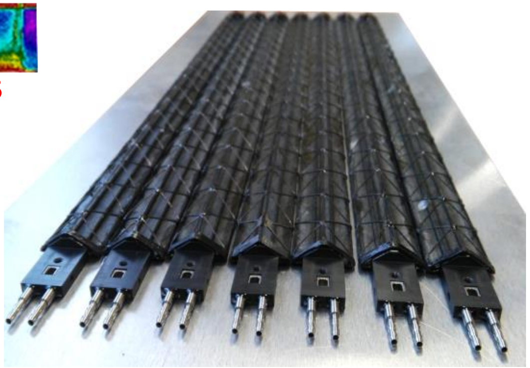
Tin=15.8° C

Tout=16.6° C

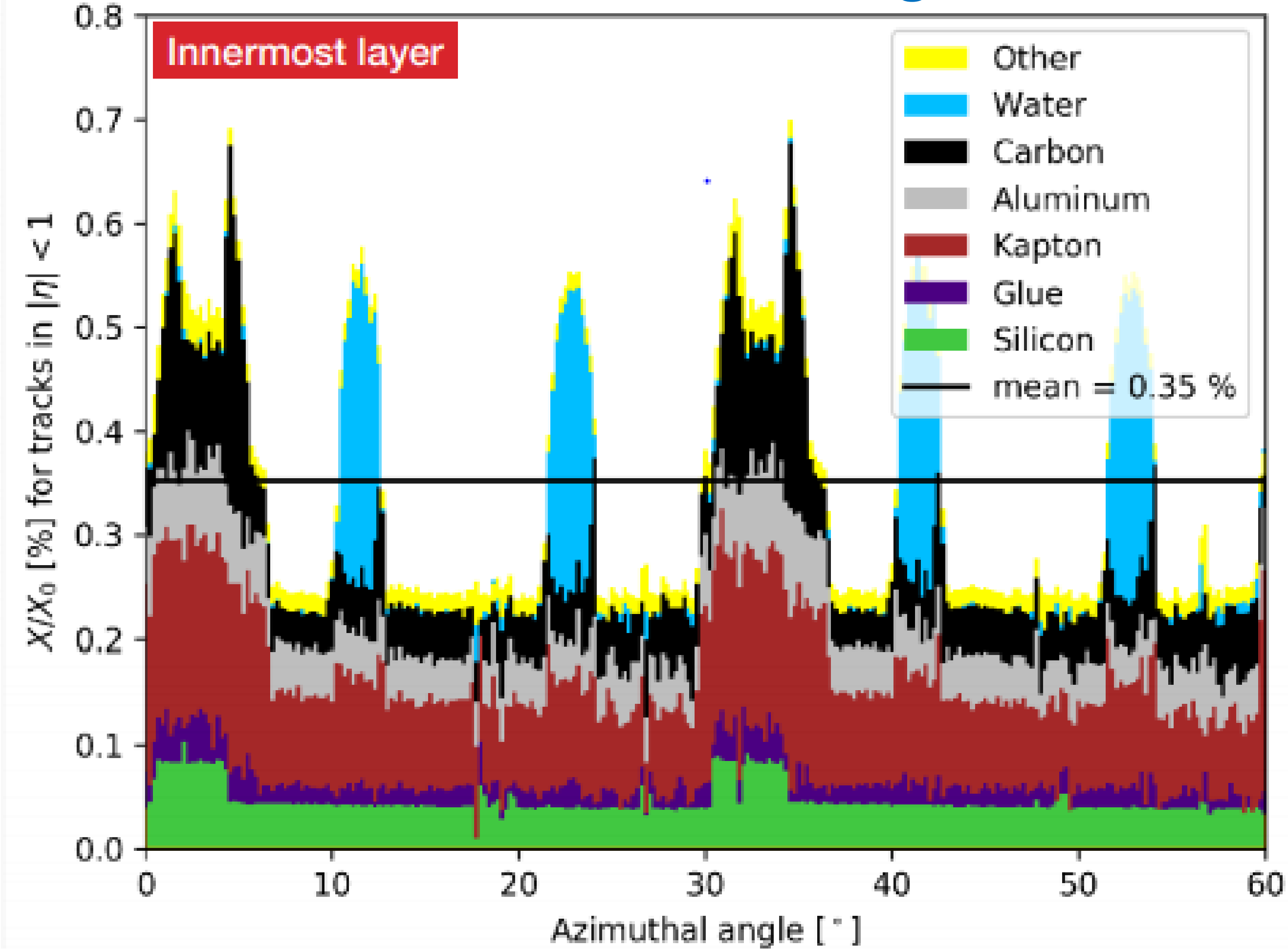


Max T periph=18.5

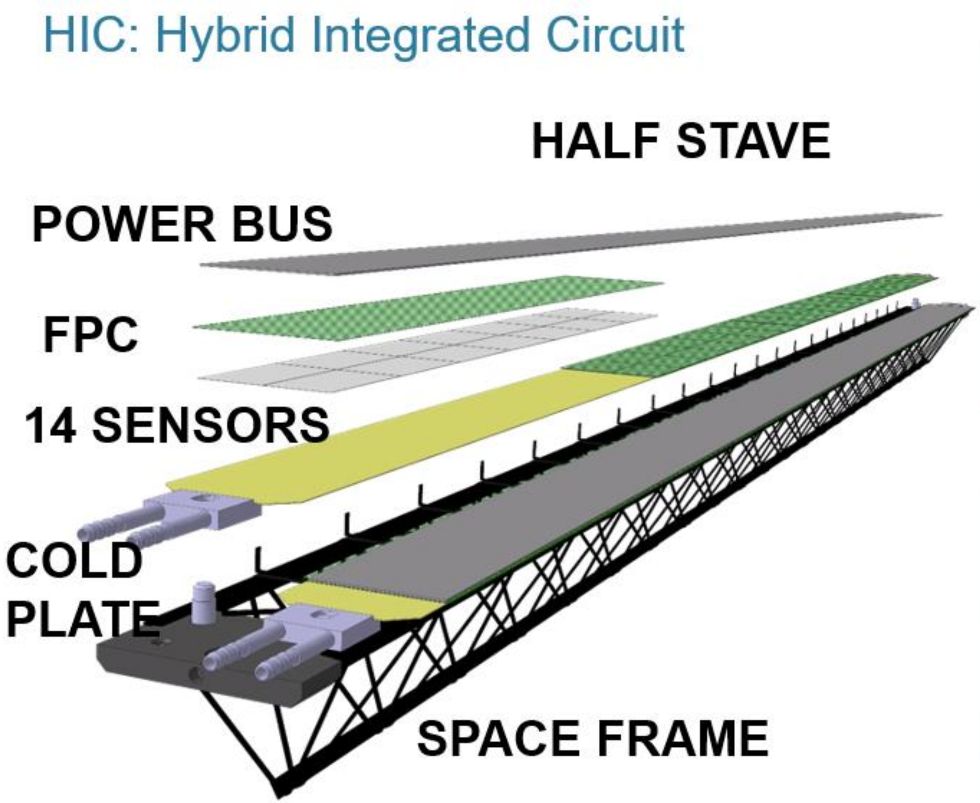


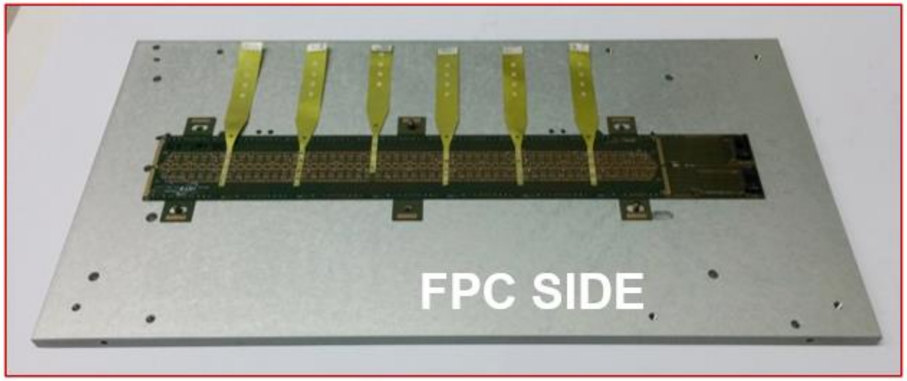


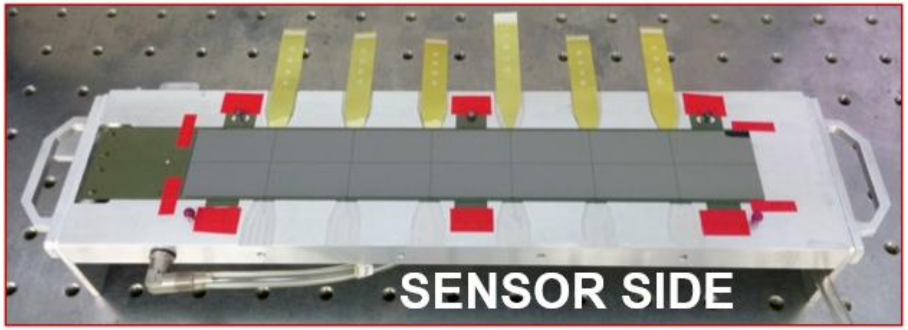
Material budget



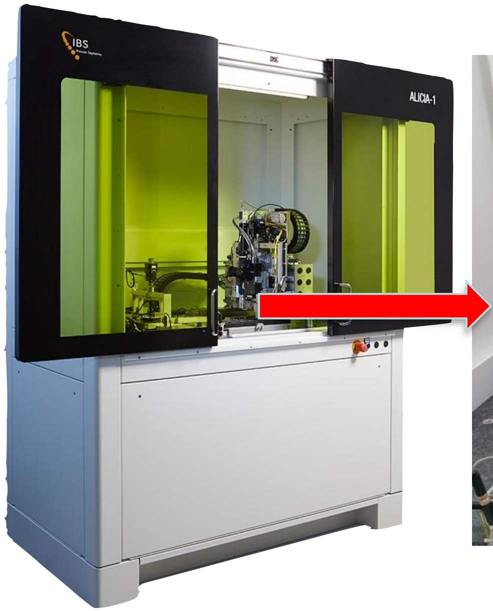
Outer Barrel stave

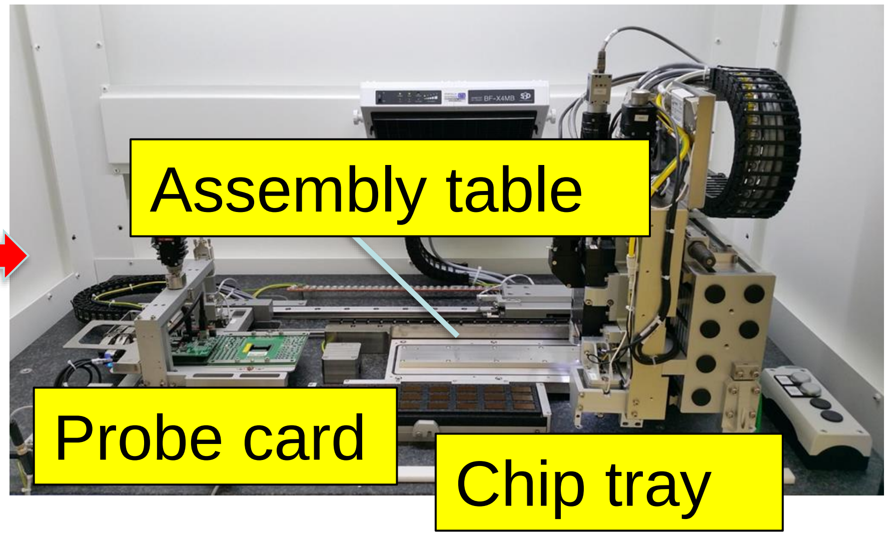






Chip series test and Hybrid Integrated Circuit (HIC) assembly





ALICIA (IBS)

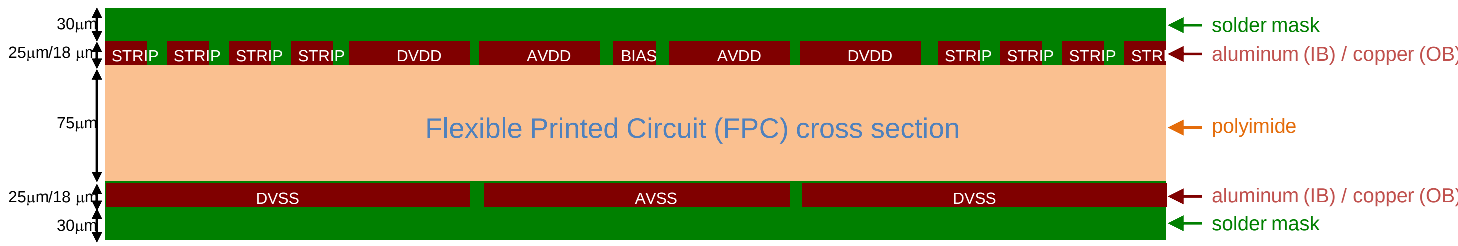
6 machines (+1 MFT)

(Chip probe testing & HIC assembly)

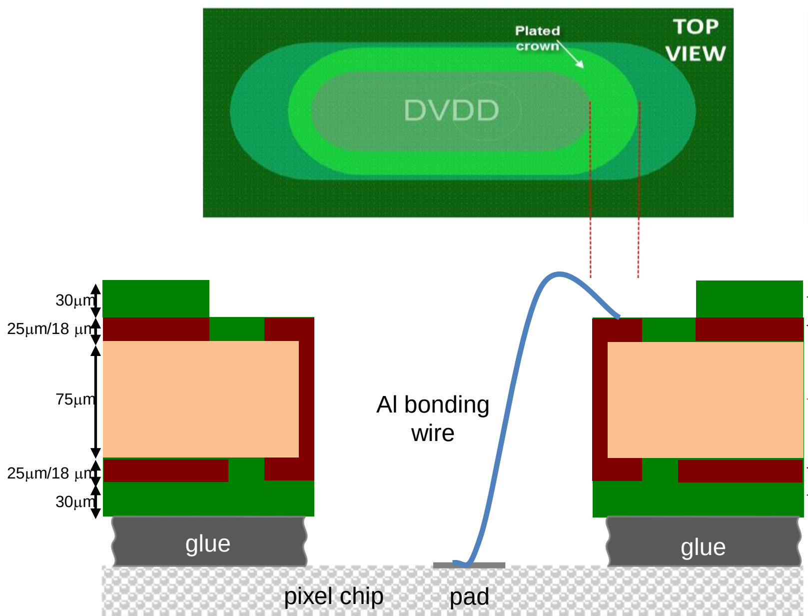
ALICIA = ALice Integrated Circuit Inspection and Assembly

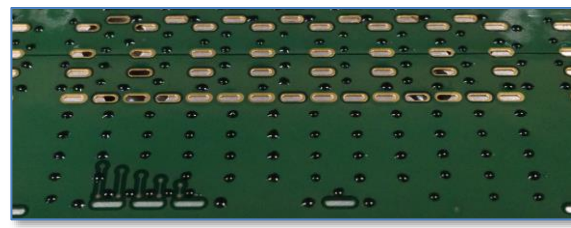
P. Martinengo, CERN

Wire Bonding

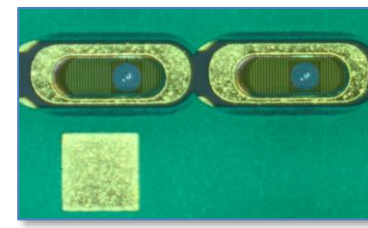


PCB conductor
aluminum Inner Layers
copper outer layers

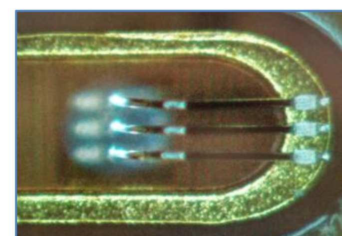




Droplets of glue (epoxy resin) dispensed on the FPC



chip pads aligned to FPC VIAs



FPC to Chip interconnection (Al wire bonding)

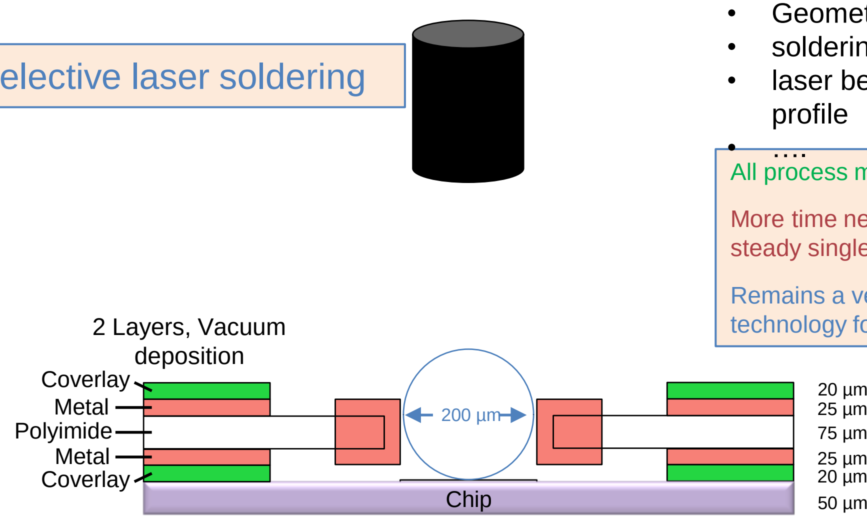
(3 wires: redundancy, lower resistance)

Laser Soldering

Laser soldering: connection of Pixel chip to flexible printed circuit

Laser soldering machine

Selective laser soldering



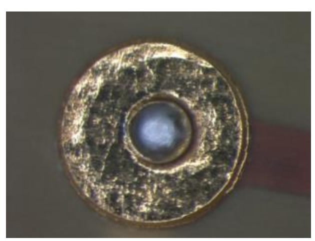
R&D addressed:

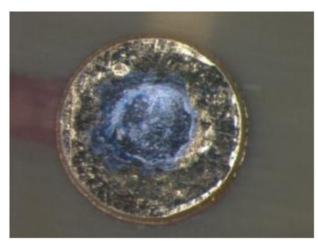
- Geometry of the interconnection
- soldering ball, interface pad and VIA
- laser beam profile and power time profile
- ….

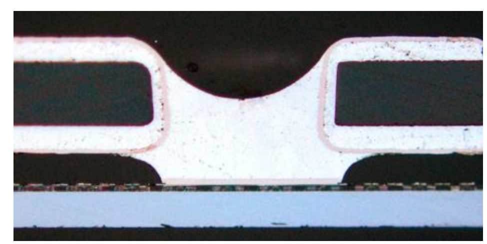
All process main issues were solved

More time needed to bring the process to a steady single interconnection yield of ~99.99%

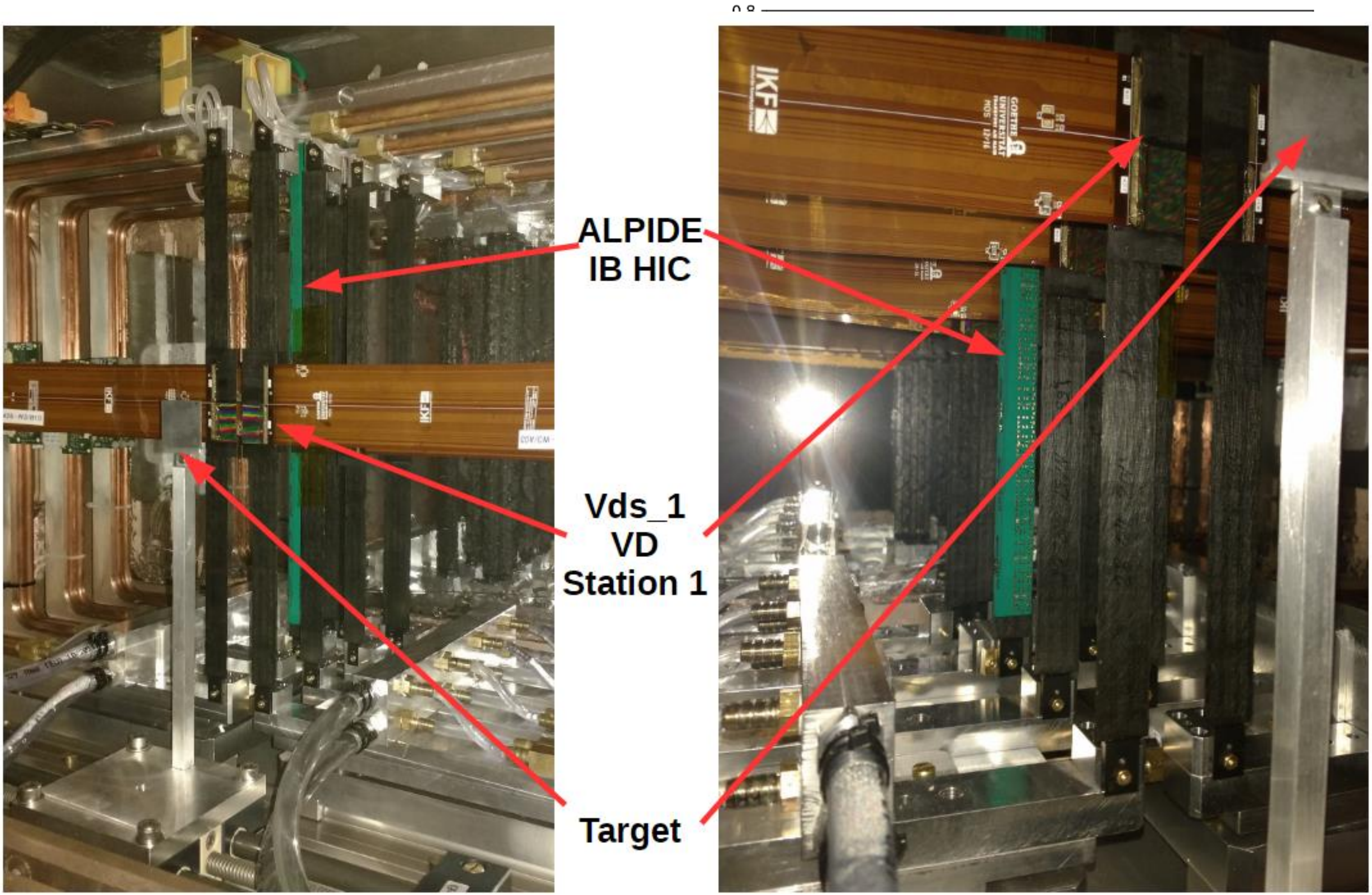
Remains a very promising interconnection technology for future applications



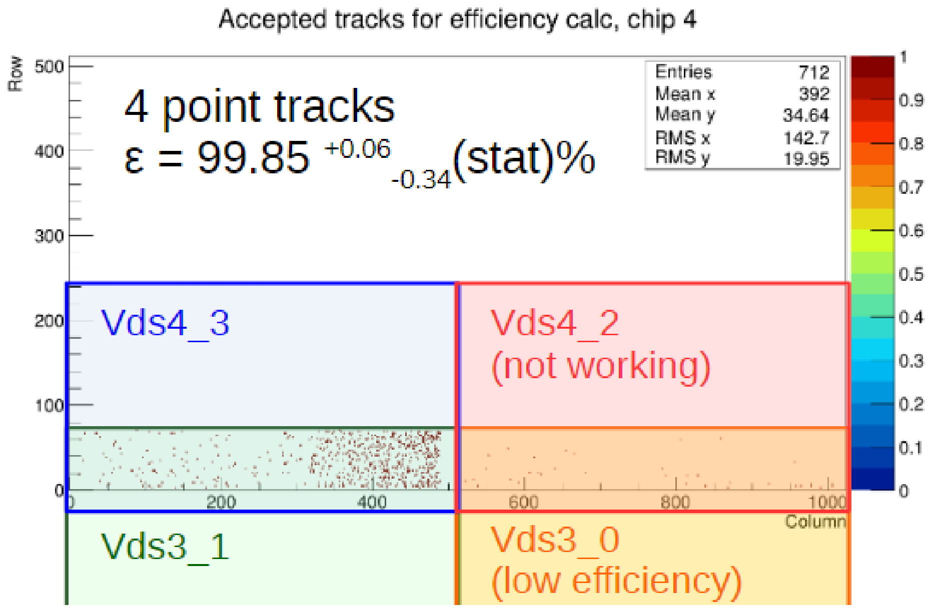


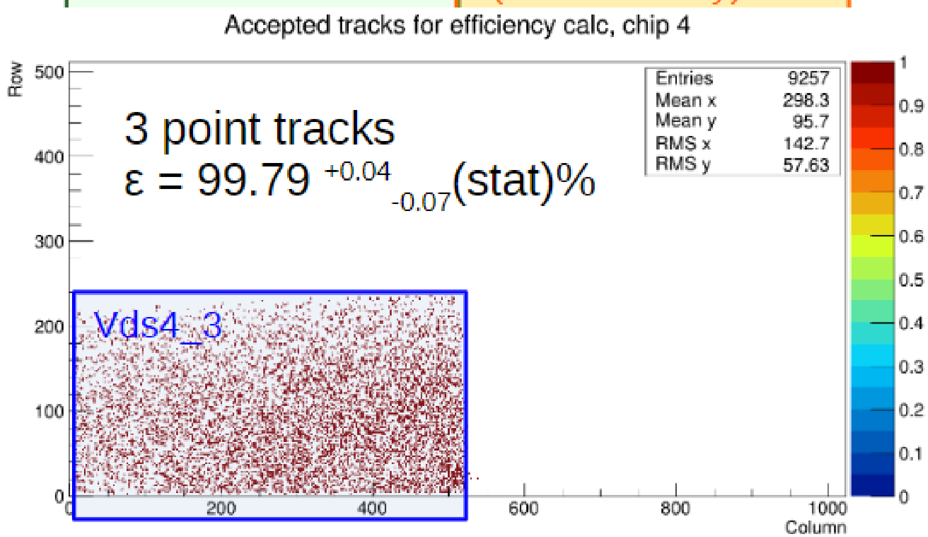


ALICE IB Stave in NA61 (2016)

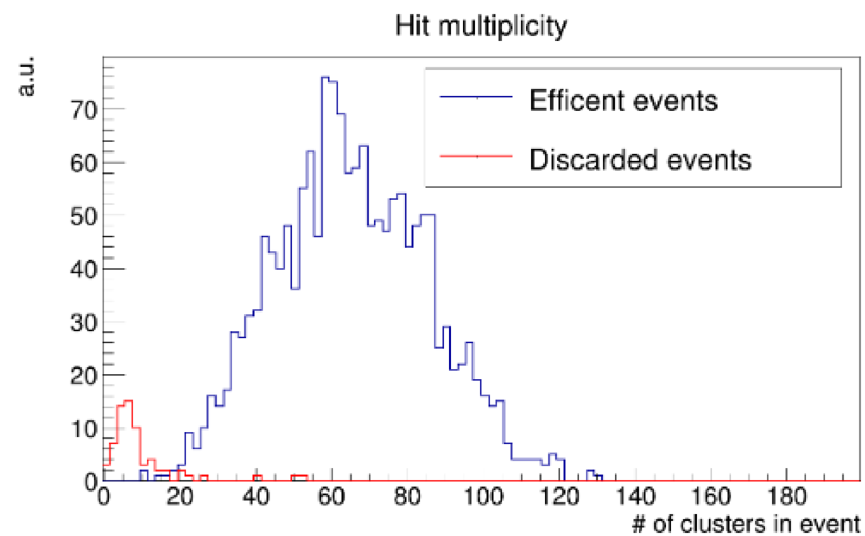

ALPIDE
IB HIC
Vds_1
VD
Station 1
Target

(M. Šuljić)



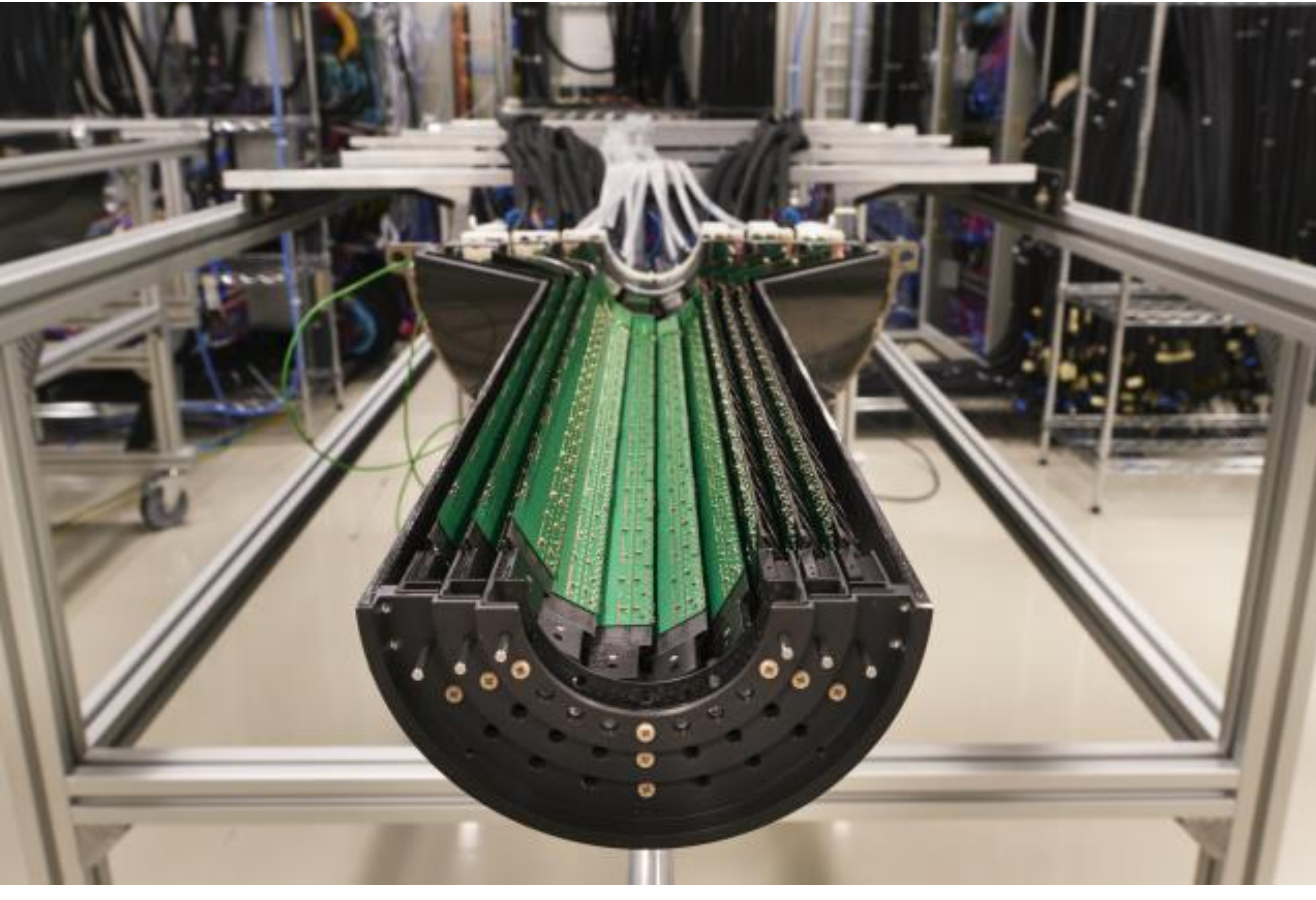


Up to 30 hit/cm^2

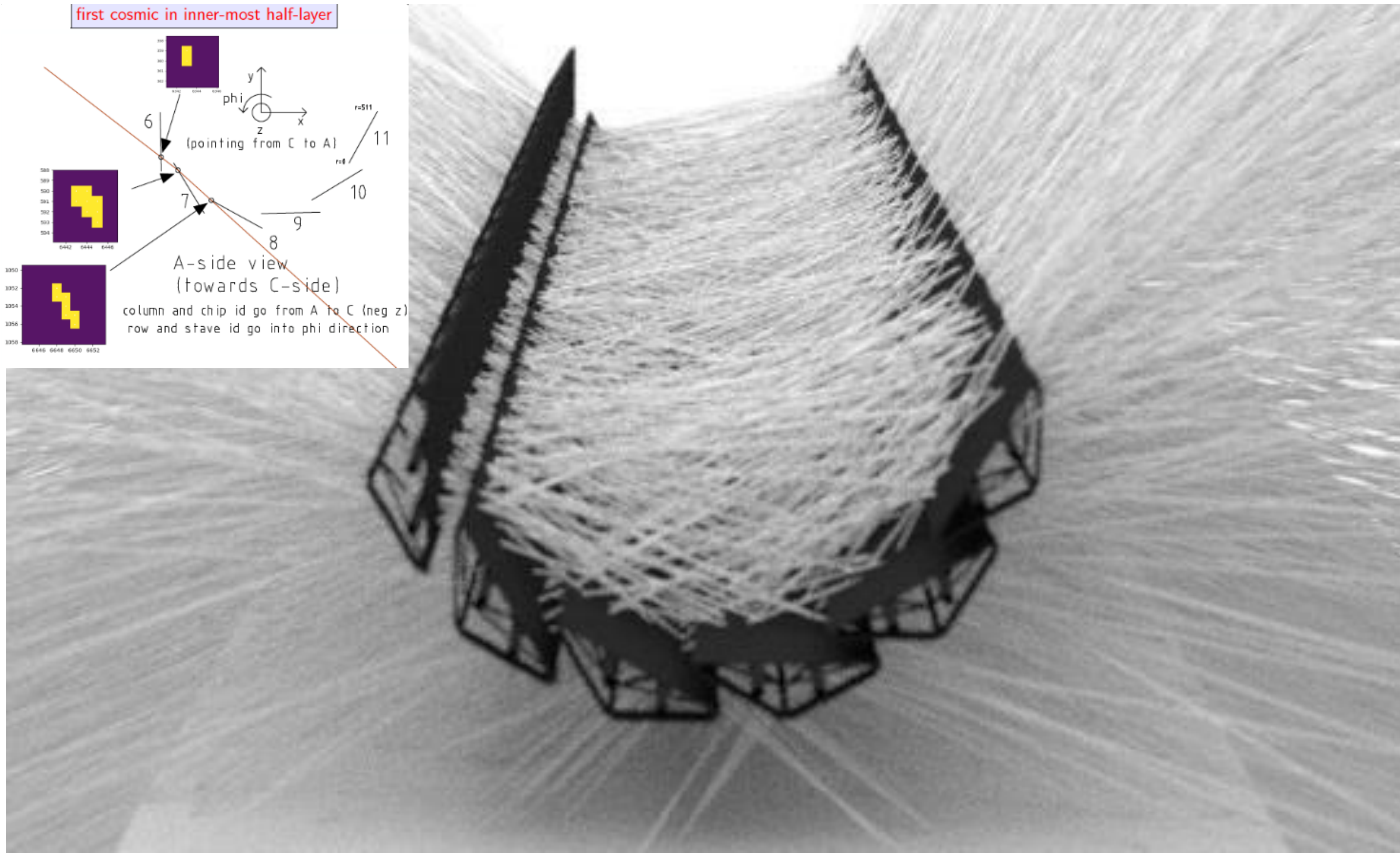


- Events with no efficent tracks have much lower hit multiplicity → consistent with off-time events
- Cuts introduce a systematic uncertainty (to be evaluated)
- Overall detection efficiency > 99%

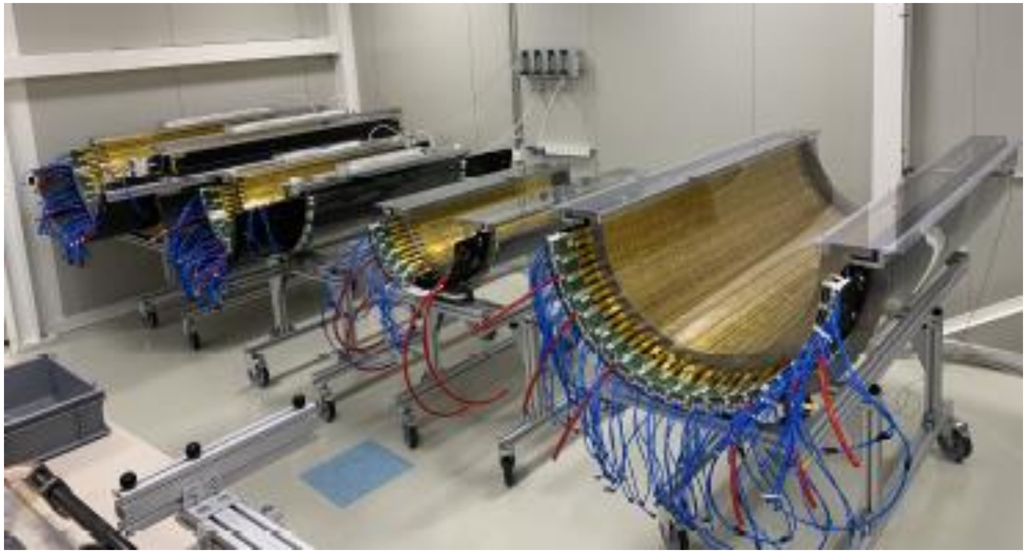
Half Inner Barrel

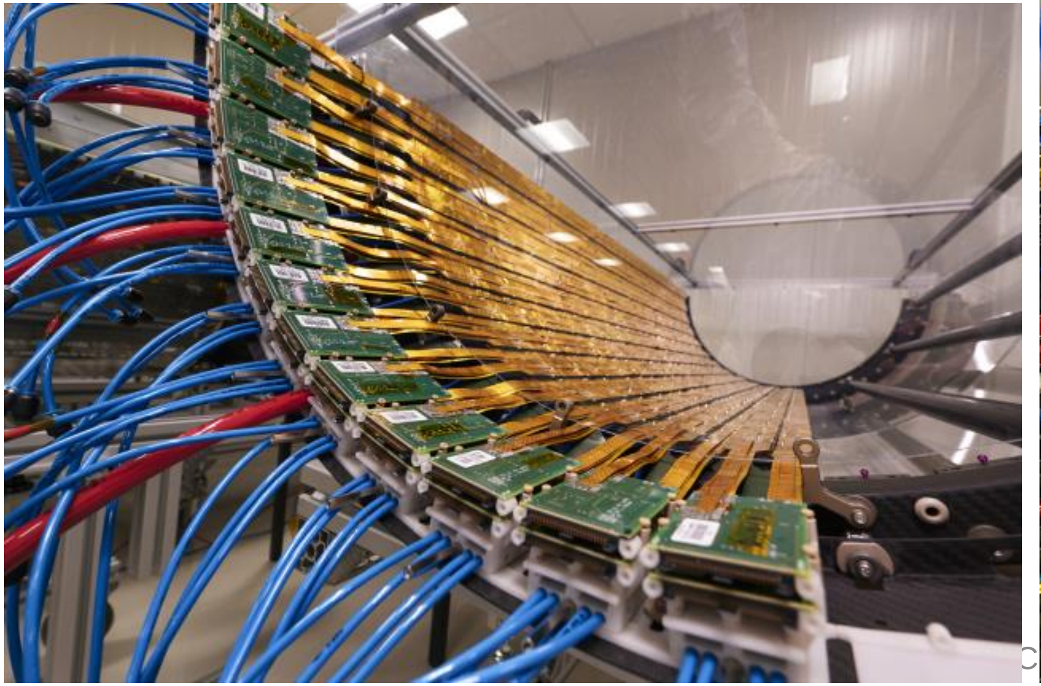


Cosmics tracks reconstructed in the Inner Barrel



Outer Barrel Assembly





CONCLUSIONS

- Silicon Pixel detector is a mature technology
- Present in (almost) all HEP experiments
- Silicon contribution to material budget already negligible
- Next: services & mechanics
- R&D for new generation started, including radiation hardness
- Smarter pixels but area shrink but also transistors, 3D ?
- Don’t forget interconnections !

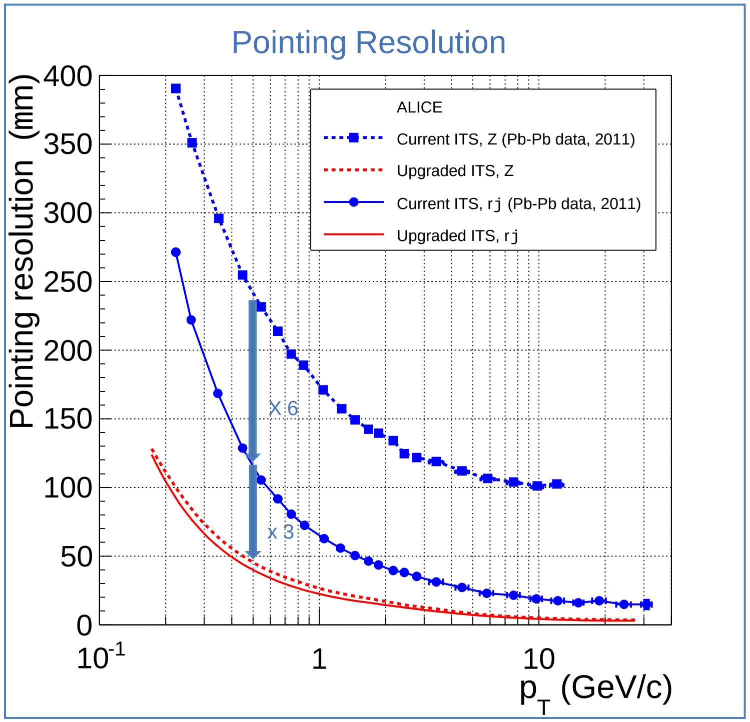
Thank you for your attention !

Back-up

Performance of new ITS (MC simulations)

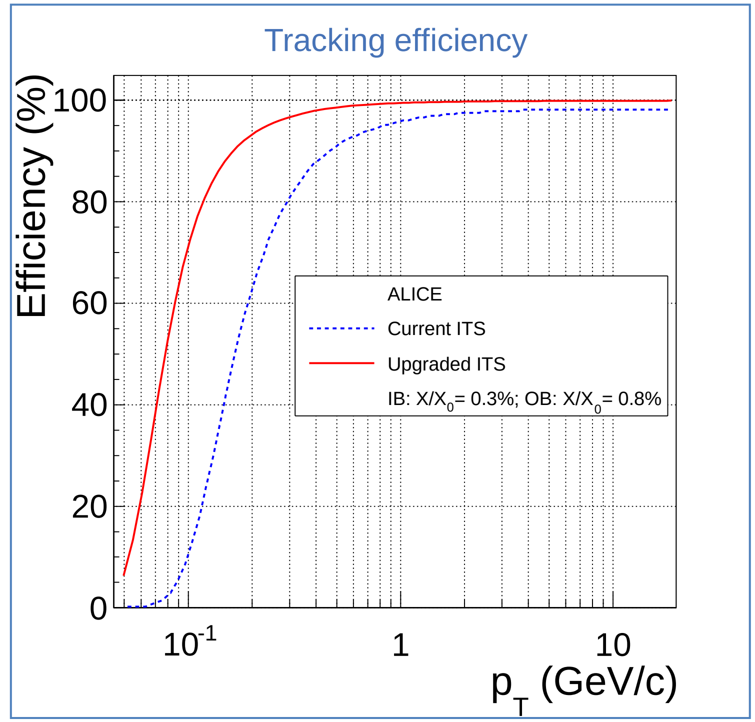
ALICE

Impact parameter resolution



~40 μm at p_T = 500 MeV/c

Tracking efficiency (ITS standalone)

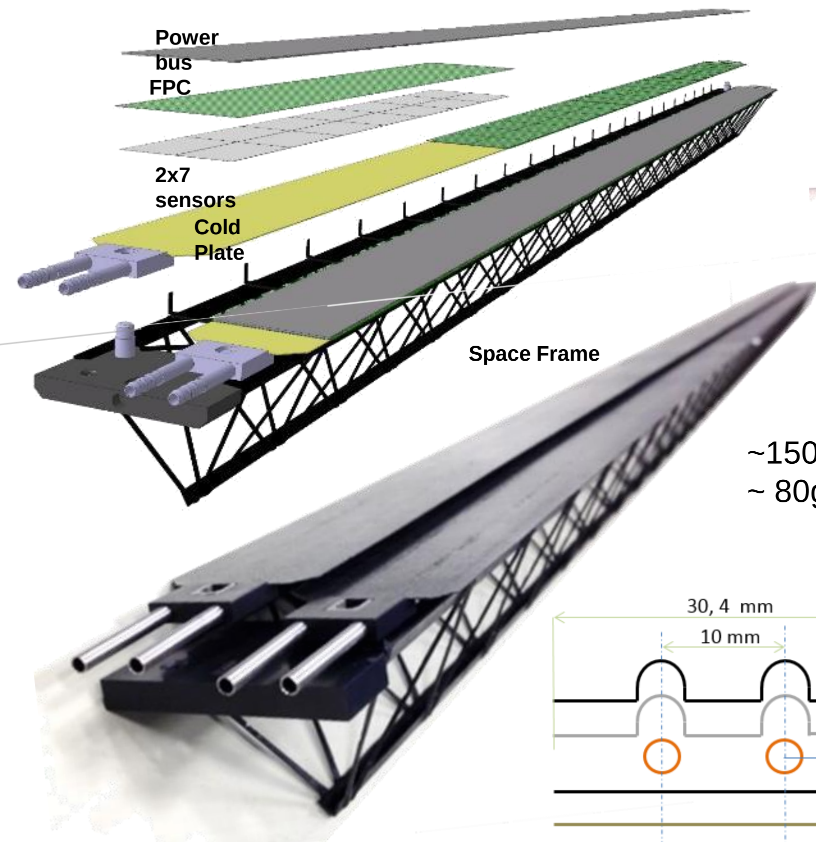


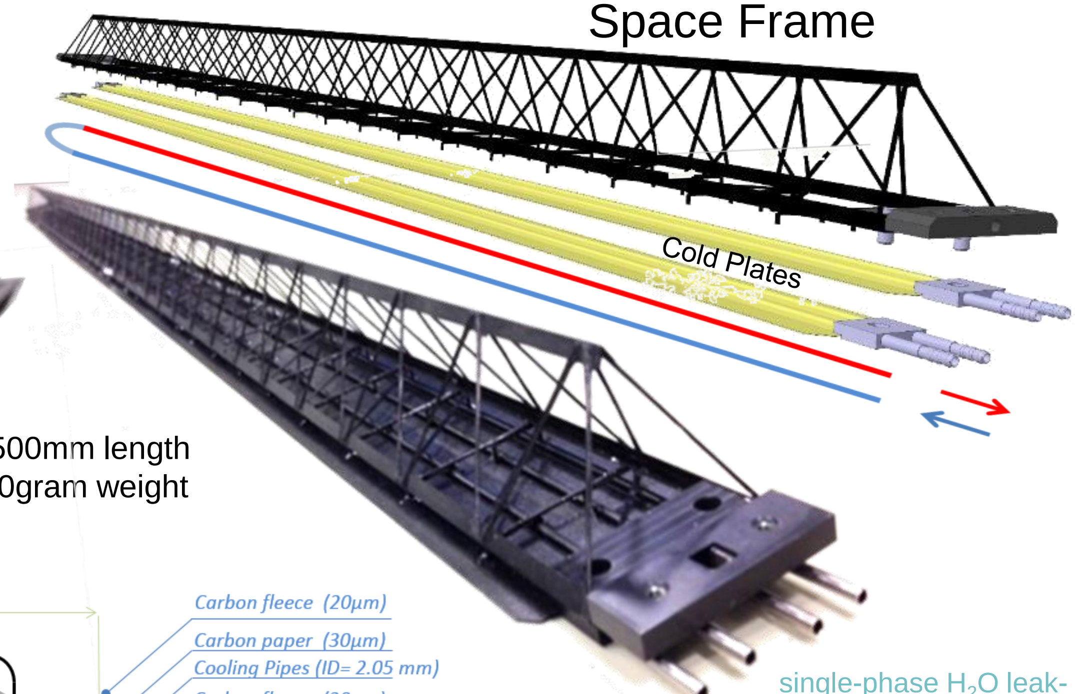
~70% at p_T = 100 MeV/c

P. Martinengo, CERN

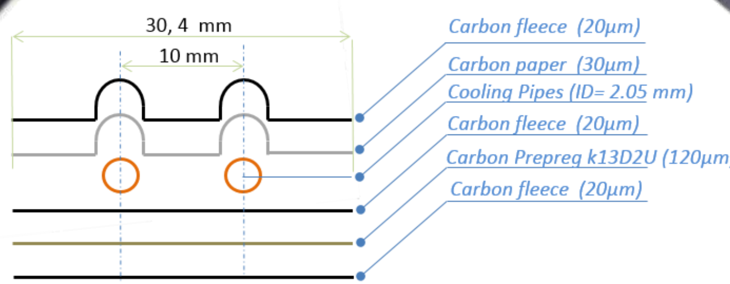
Outer Barrel Stave Mechanics & Cooling

ALICE





~1500mm length
~ 80gram weight

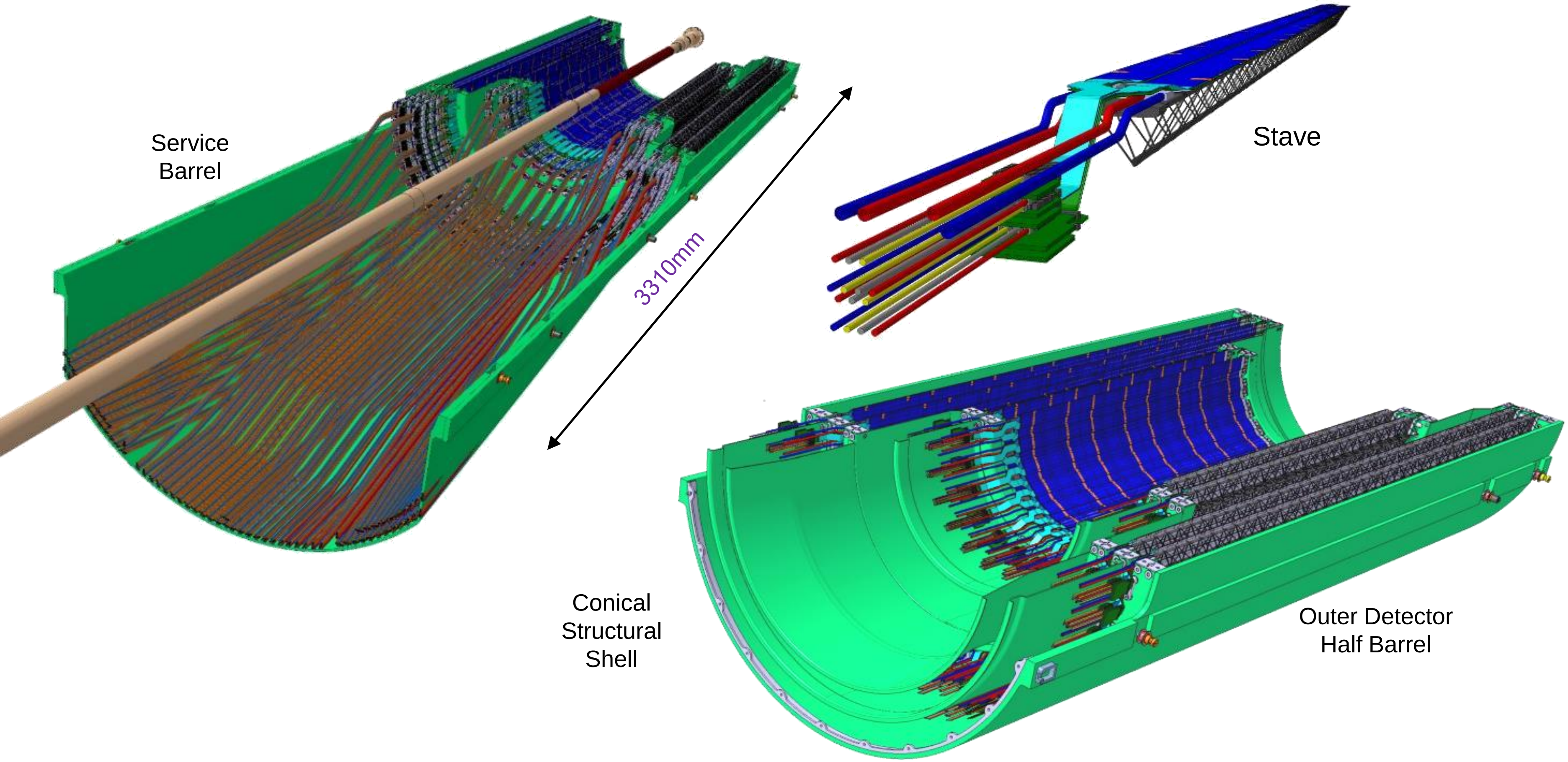


single-phase H_2O leak-less

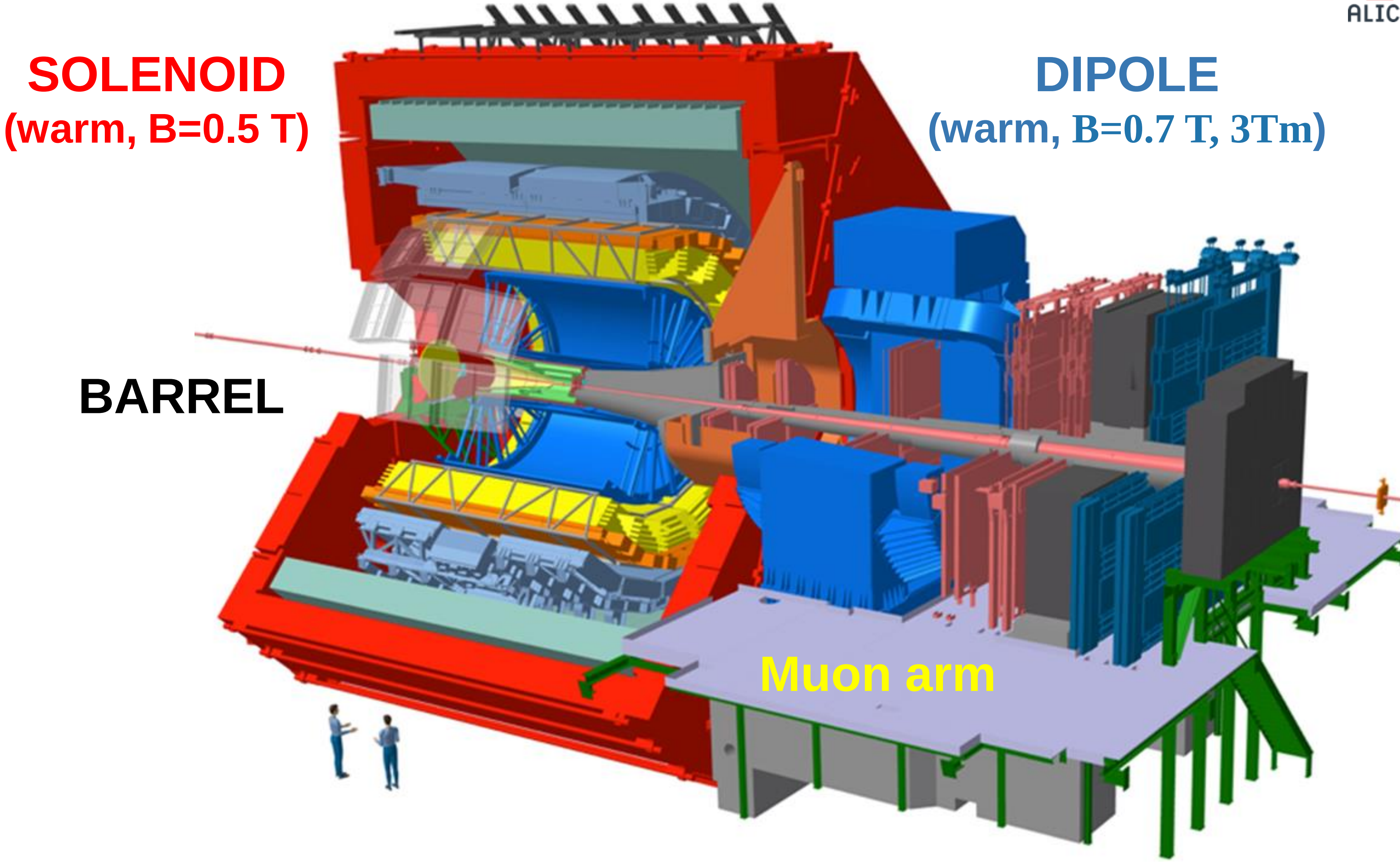
- temperature < 30° C
- non-uniformity < 5° C
- dissipation < 100mW/cm²

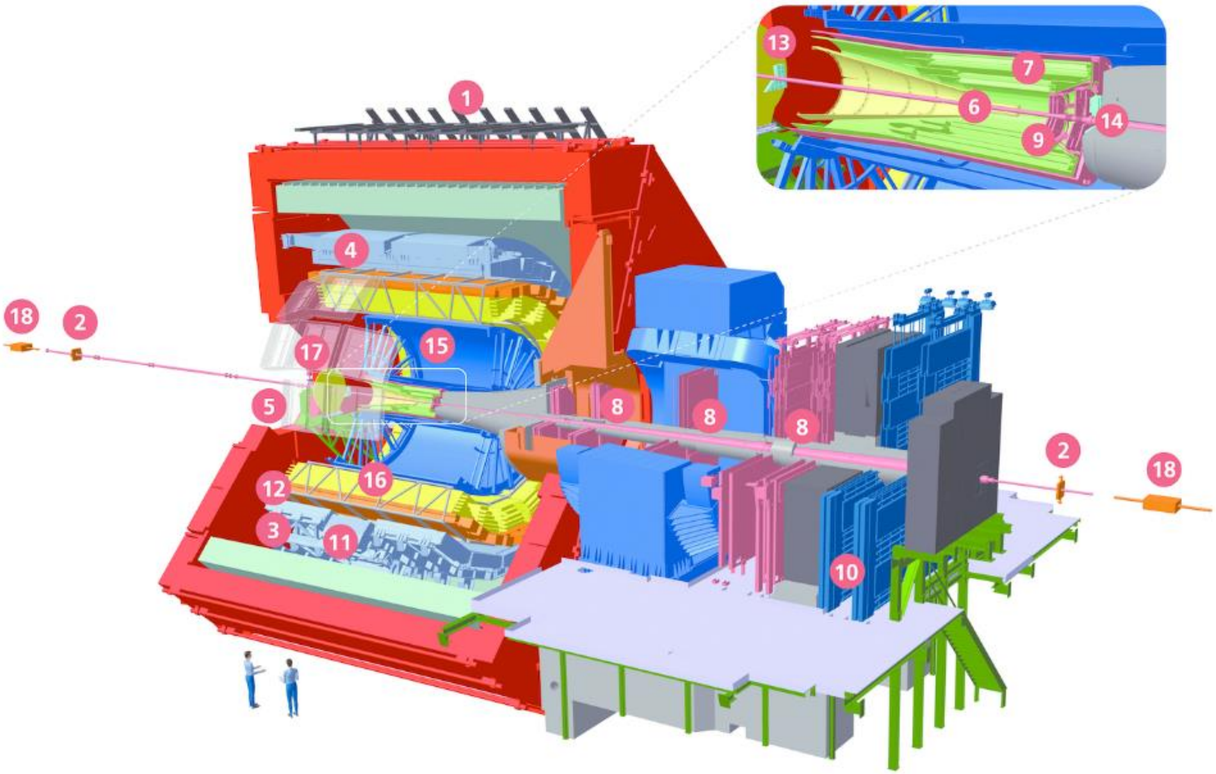
P. Martinengo, CERN

Outer Detector Barrel



P. Martinengo, CERN

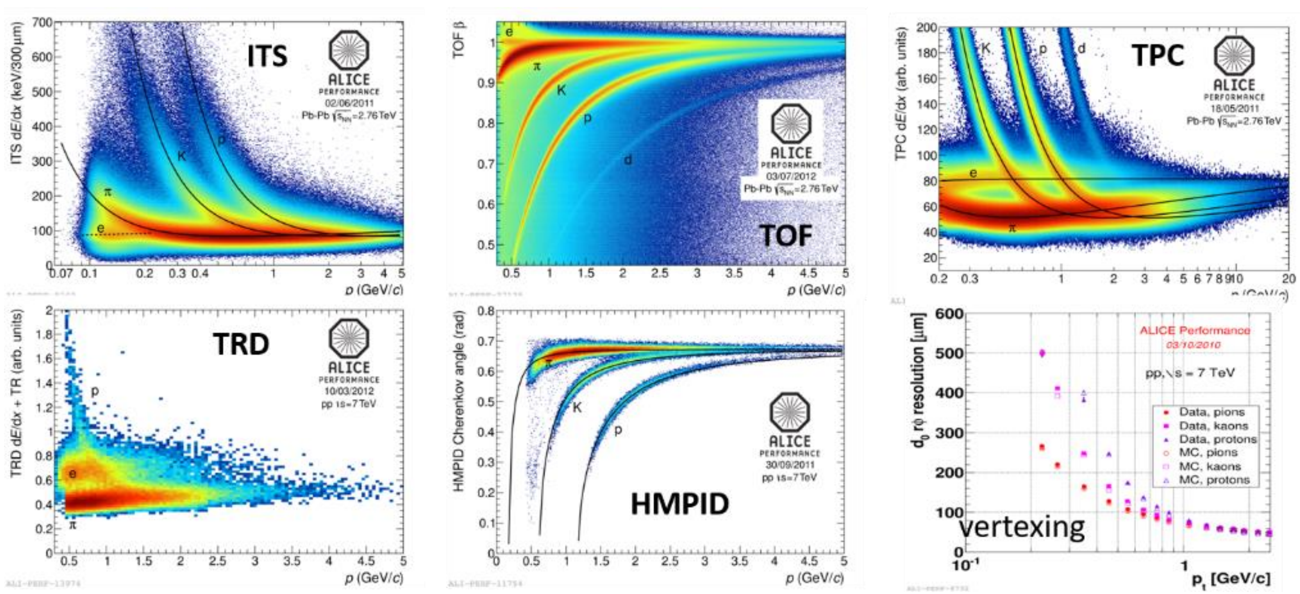

SOLENOID
(warm, B=0.5 T)
DIPOLE
(warm, B=0.7 T, 3Tm)
BARREL
Muon arm



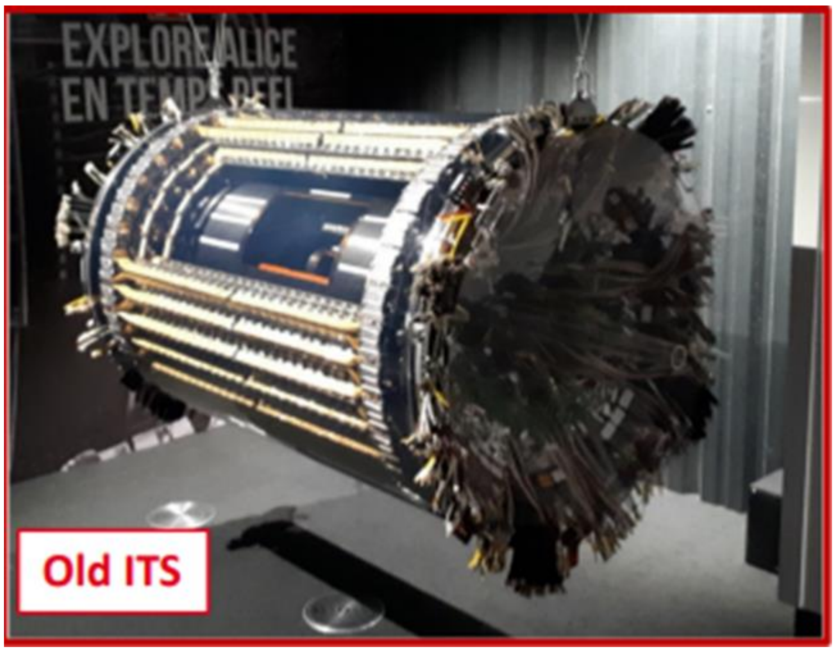
1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

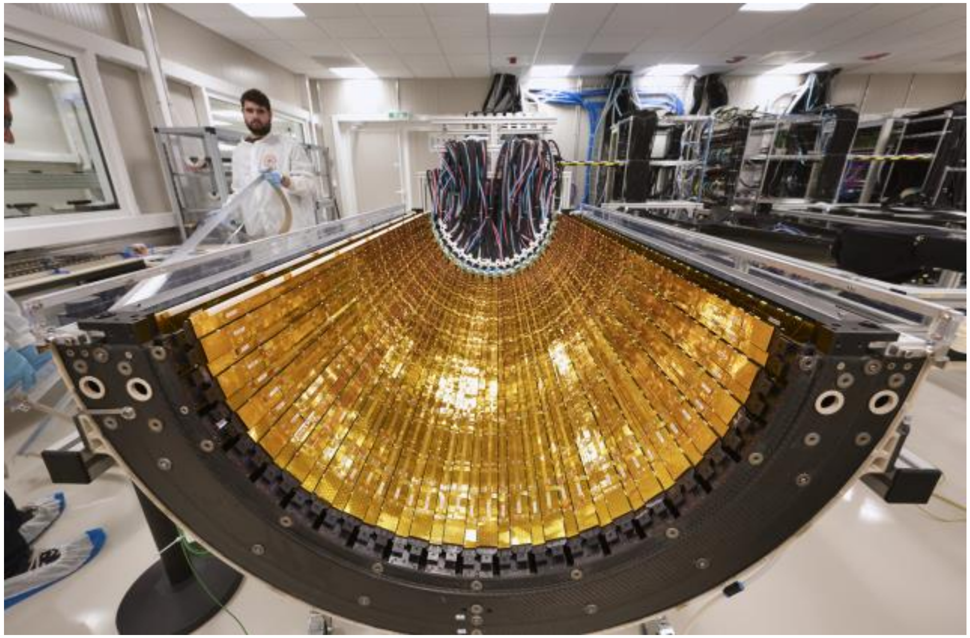
ALICE

Excellent tracking, vertexing and PID capabilities:

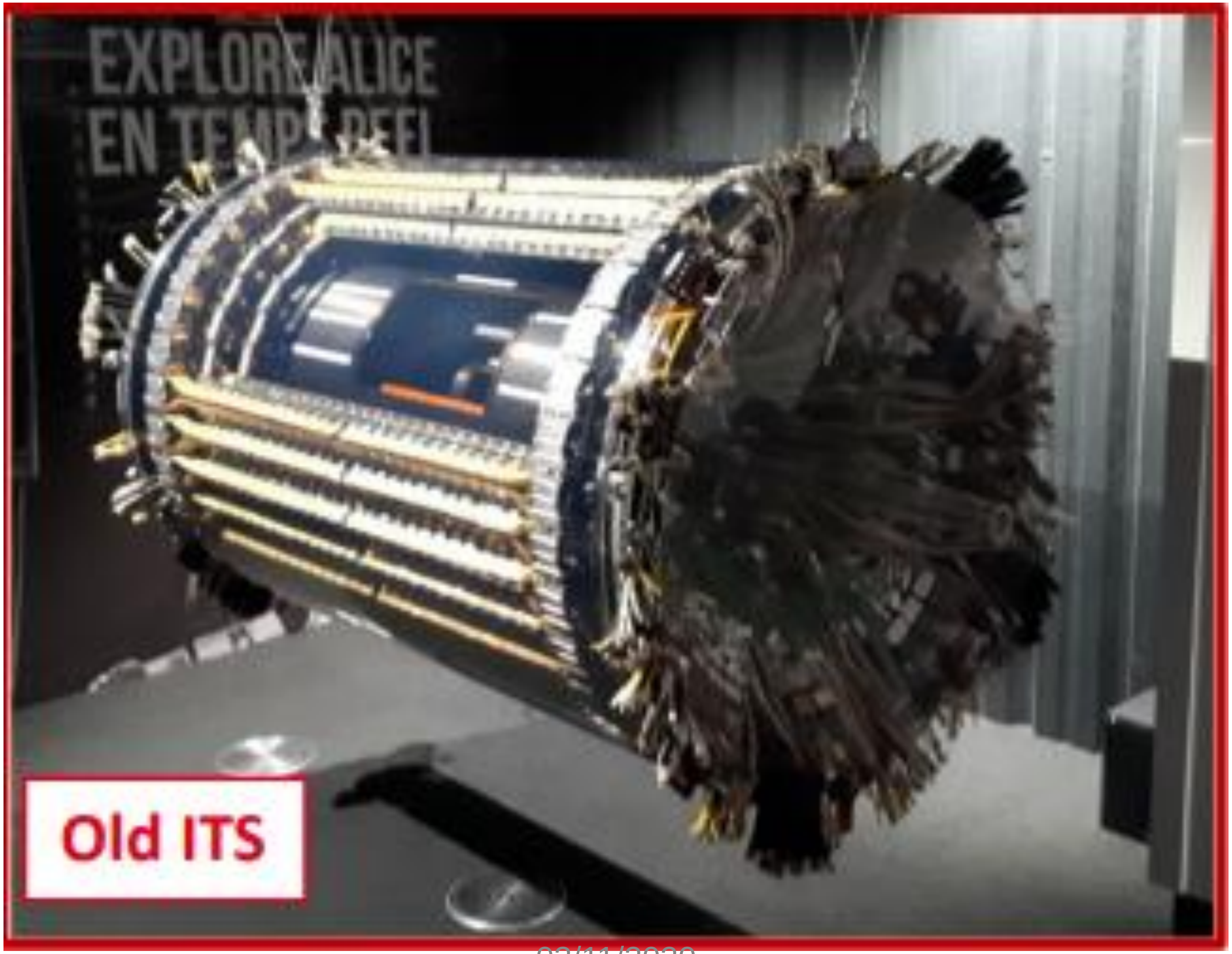


From ITS to ITS2





ITS took a well deserved retirement last year
Now in the ALICE exposition at P2



IB mechanics