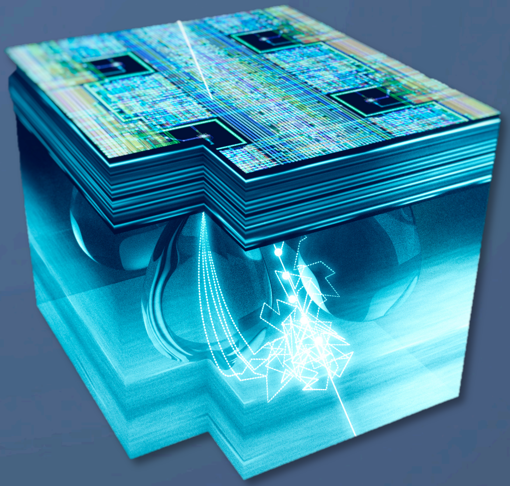
CERN – EP Department

CMOS Active Pixel Sensors
A Novel Detection Technology for Particle Physics

Luciano Musa – CERN



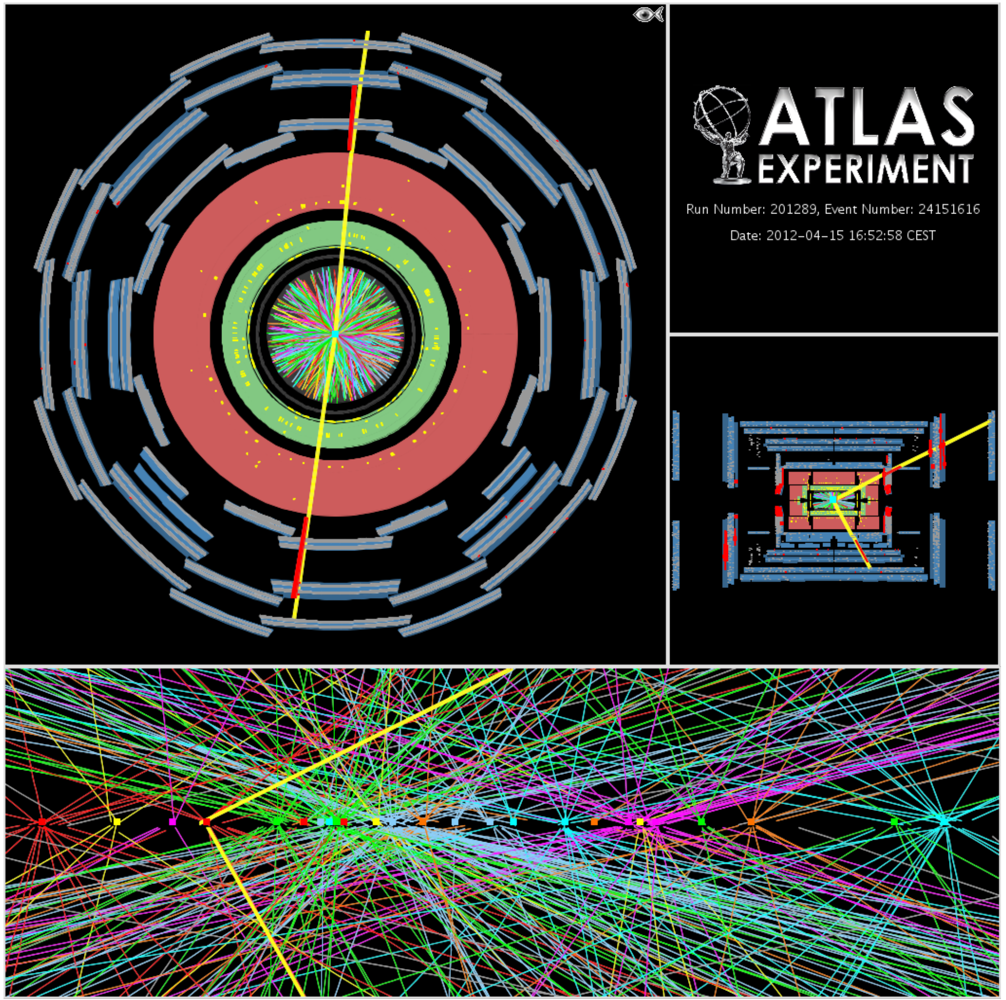
Physics Colloquium, Physikalishes Institut, Ruprecht-Karls-Universität Heidelberg, 27 April 2018

Outline

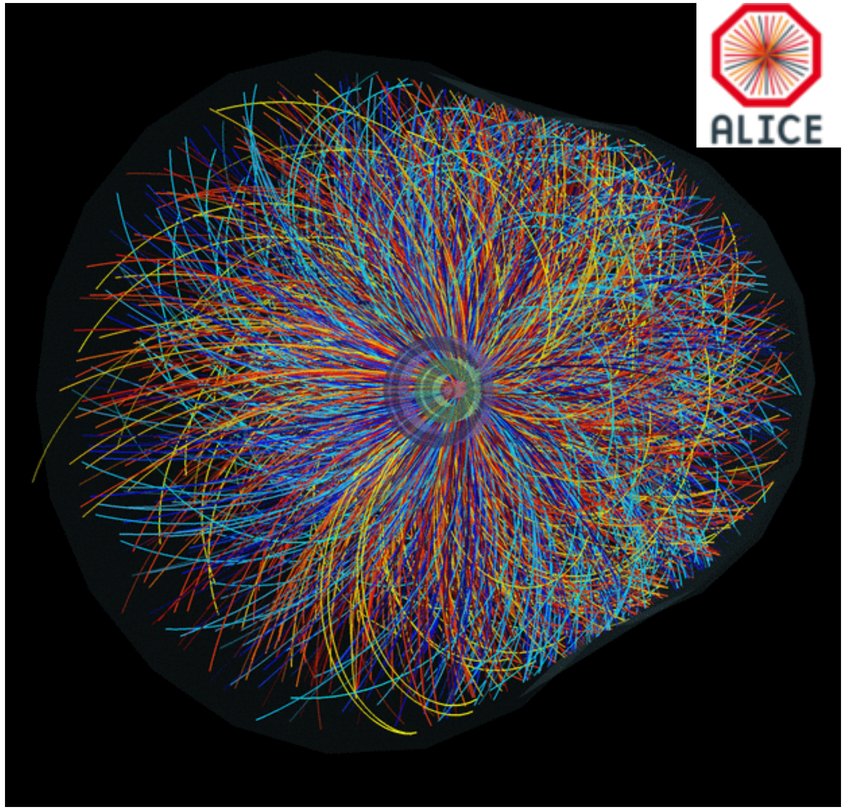
- Silicon detectors in HEP – a brief historical excursus
- First applications of CMOS APS in HEP (STAR, ALICE)
- CMOS APS Fully Depleted
- Novel developments and future applications in HEP
- Applications to medical imaging

Silicon detectors in HEP
Brief historical excursus

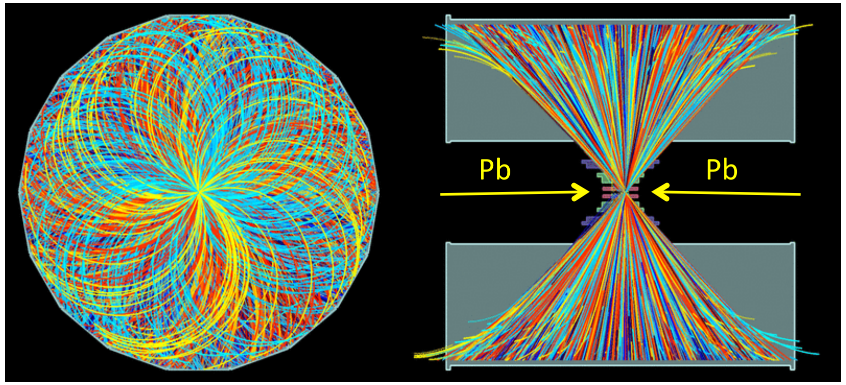
Silicon Trackers – Key to solve complex events close to IP



LHC pp collisions: a candidate Z boson event in the dimuon decay with 25 reconstructed vertices (ATLAS, April 2012)



LHC Pb-Pb collision (ALICE, Sep 2011)

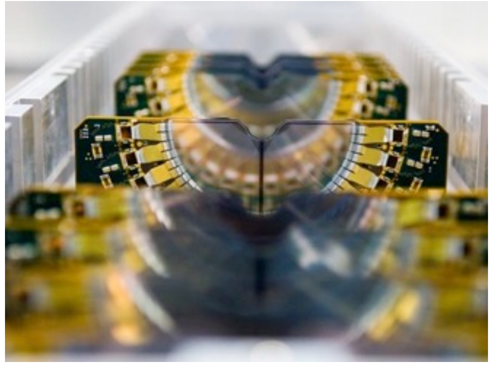


Silicon detectors at the hart of all LHC experiments

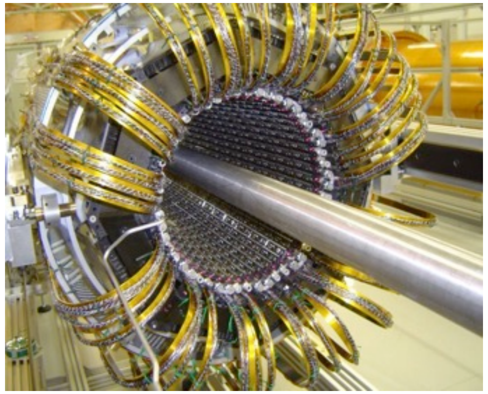
Complex systems operated in a challenging high track density environment

Innermost regions usually equipped with pixel detectors

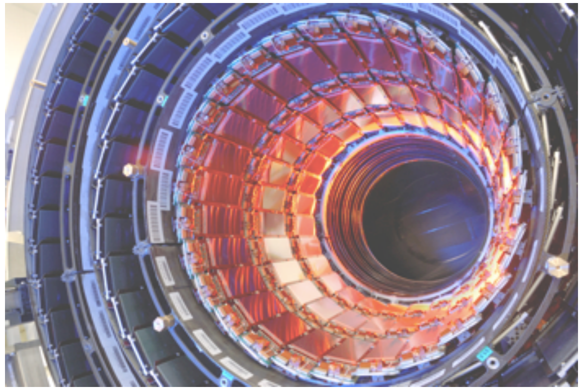
ALICE Pixel Detector



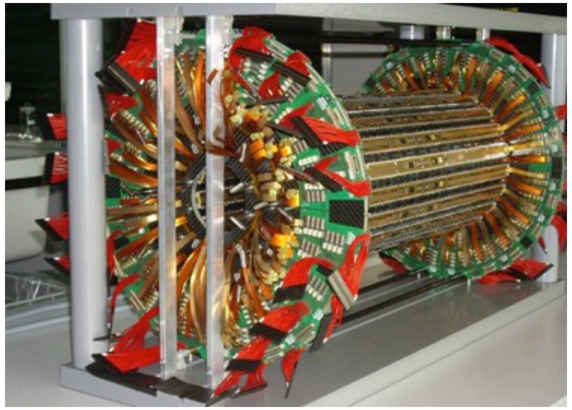
LHCb VELO



ATLAS Pixel Detector



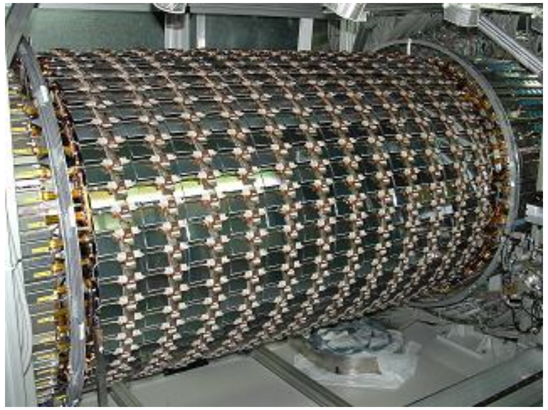
CMS Strip Tracker IB



CMS **Pixel** Detector

ALICE Drift Detector

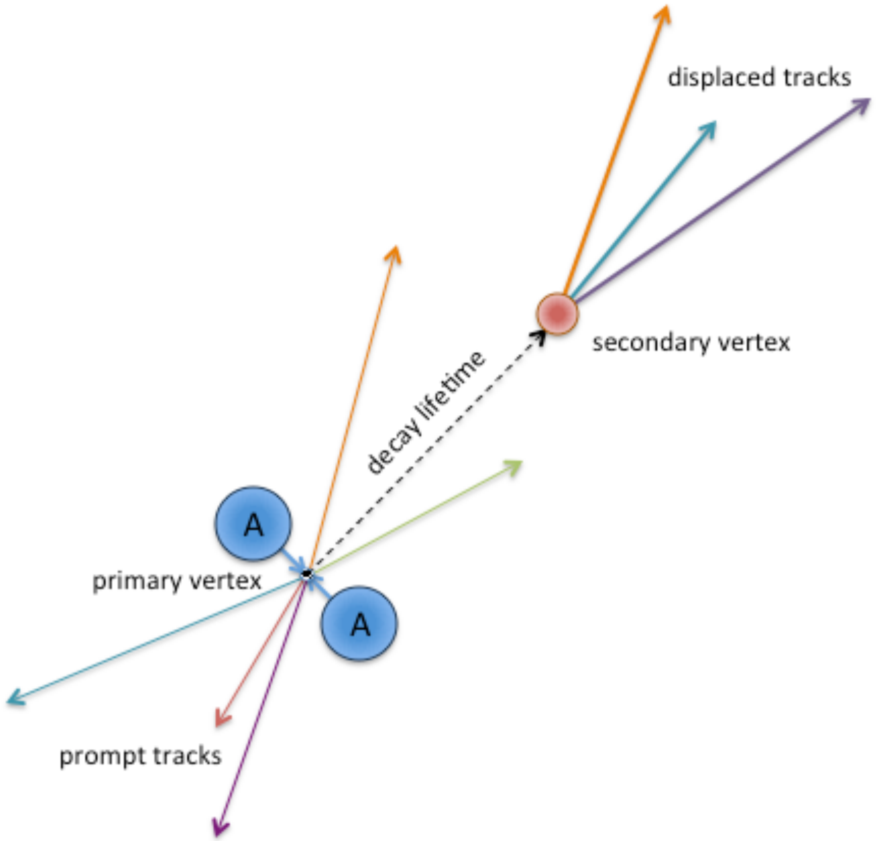
ALICE Strip Detector

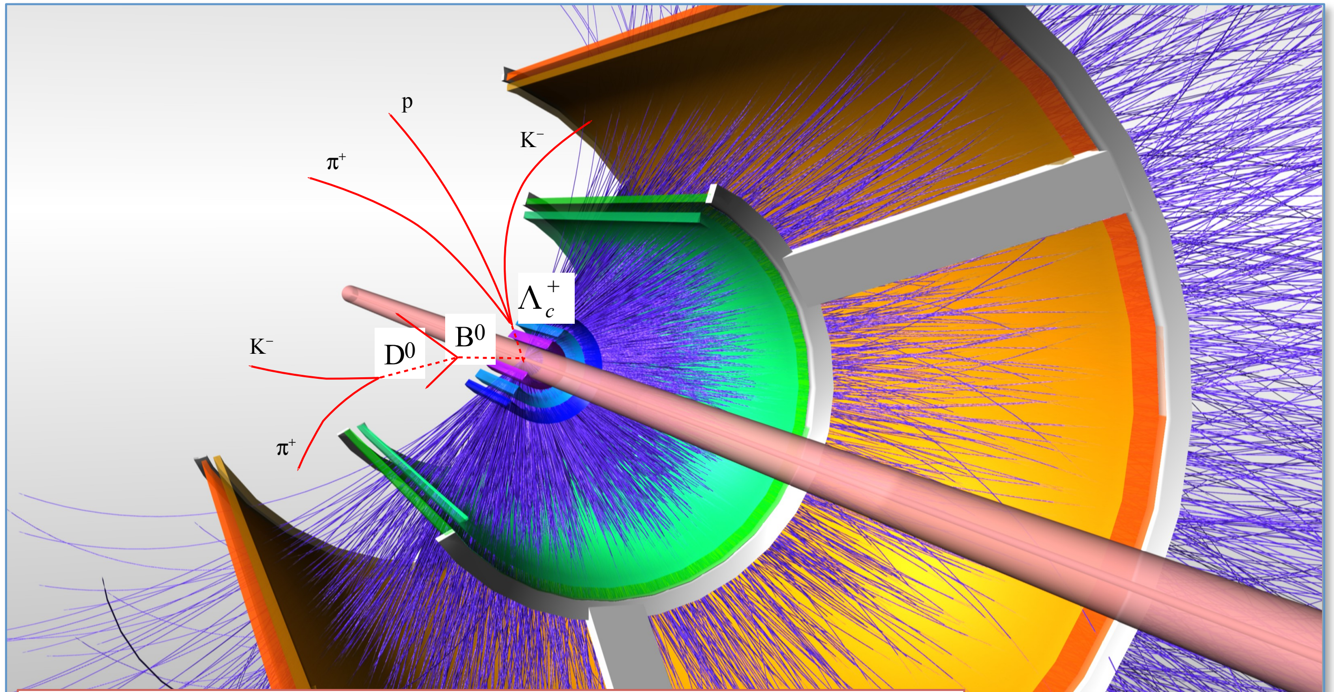


ATLAS SCT Barrel

Measurement of the decay topology of short-lived particles

The first detection layers, the closest to the IP, are crucial for the measurement of the interaction vertex (primary vertex) and the decay vertex of short-lived particles (secondary vertex)





radial distance of first detection layer > 20mm

typical (proper) decay length of charm and beauty hadrons: ≈100μm and ≈500μm respectively

The rise of silicon detectors in HEP

Towards end of 1970's: intensive R&D on devices which could measure short-lived particles (10^{-12} - 10^{-13} s)

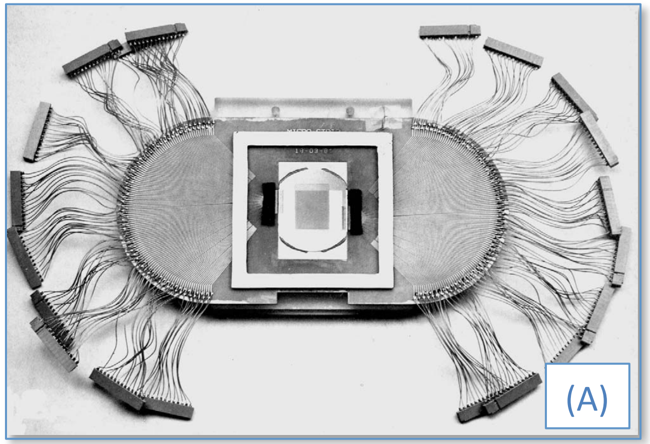
R&D at CERN(1) and Pisa(2) demonstrated that strip detectors (100-200μm pitch):

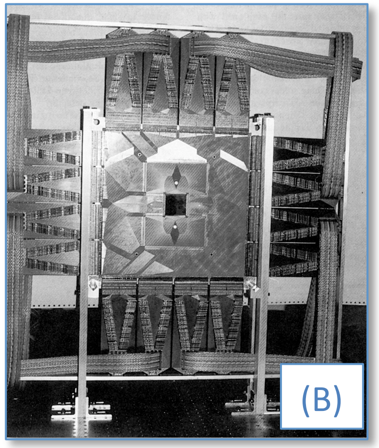
- exhibit high detection efficiency (>99%), good spatial resolution (~20μm) and good stability
- allow precise vertex reconstruction

However the technology for the fabrication of these devises was very tricky, thus limiting their availability

1980 – fabrication of silicon detectors using standard IC planar process (PIN diode ➔ μstrip detector)

J. Kemmer, et al., *"Development of 10-micrometer resolution silicon counters for charm signature observation with the ACCMOR spectrometer", Proceedings of Silicon Detectors for High Energy Physics, Nucl. Instr. and Meth. 169 (1980) 499.*





First use of silicon strips detectors by NA11(CERN SPS) and E706 (FNAL)

(A) NA11 (1981): 6 planes (24 x 36mm^2): resistivity 2-3 kΩcm, thickness 280μm, pitch 20μm

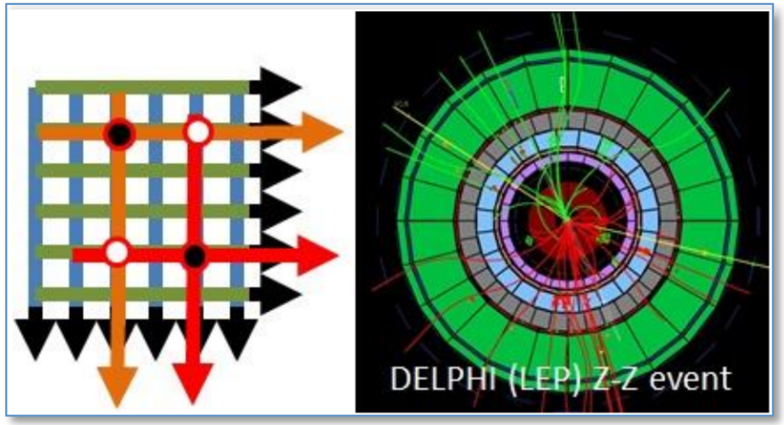
(B) E706 (1982): 4 planes (3x3 cm^2) + 2 planes (5x5cm^2)

The rise of silicon detectors in HEP

The next step forward came with the advent of the VLSI technology that allowed coupling ASIC amplifier chips directly to the detectors

1990s - LEP, first silicon vertex detectors were installed in DELPHI and ALEPH experiments, then OPAL and L3

1989 - first DELPHI vertex detector, consisting of two layers of single-sided strip detectors



Projective geometry ➔ ambiguity at high multiplicities (high occupancy)

This started to become apparent already at DELPHI:

- High number of ambiguities ➔ reconstruction efficiency suffered a lot, especially in the forward direction

Not usable close to IP in hadron colliders (LHC) or HI experiments at SPS

Another problem at (very) high particle load ➔ degradation of the sensor by the high radiation dose

This implies starting with a signal-to-noise ratio, which can only be obtained with detector with small capacitance

The Inception of Silicon Pixel Detectors

"The silicon micropattern detector: a dream?"

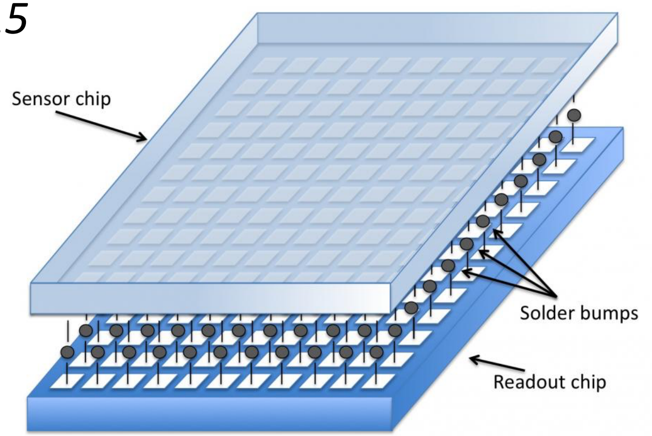
E.H.M Heijine, P. Jarron, A. Olsen and N. Redaelli , *Nucl. Instrum. Meth. A 273 (1988) 615*

"Development of silicon micropattern detectors"

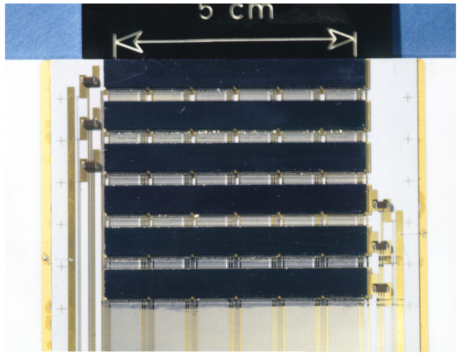
CERN RD19 collaboration, *Nucl. Instrum. Meth. A 348 (1994) 399*

1995 – First Hybrid Pixel detector installed in WA97 (CERN, Omega facility)

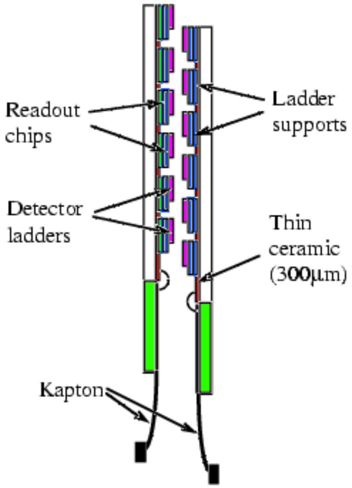
1996/97 – First Collider Hybrid Pixel Detector installed in DELPHI (CERN, LEP)



Hybrid pixel detector



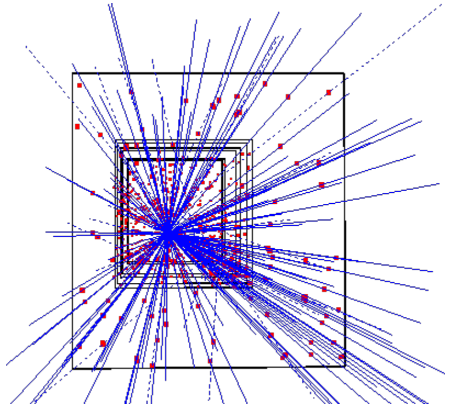
E. Heijne, E. Chesi



Work carried out by RD19 for WA97 and NA57/CERN

CERN – WA97 Experiment (1995)

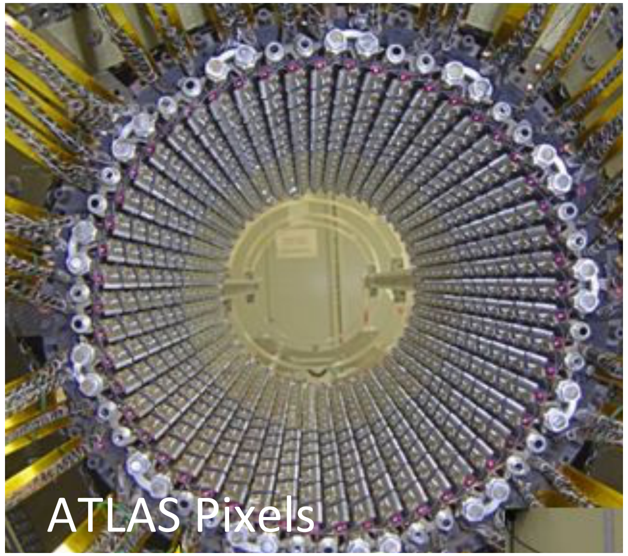
- 5 x 5 cm^2 area
- 7 detector planes
- ~0.5 M pixels
- Pixel size 75 x 500 μm^2
- 1 kHz trigger rate
- Omega2 chip

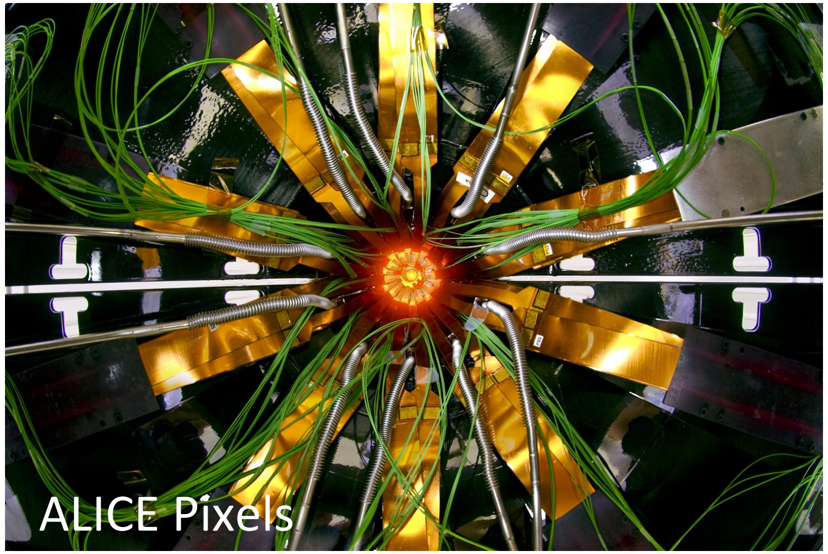


No-field, Pb-Pb, 153 reconstructed tracks

Pixel Detectors at the LHC experiments

10 years after the first use in WA97… silicon pixel detectors at the heart of the LHC experiments

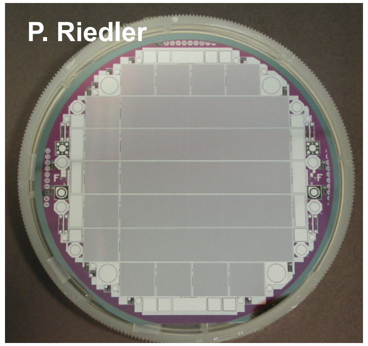


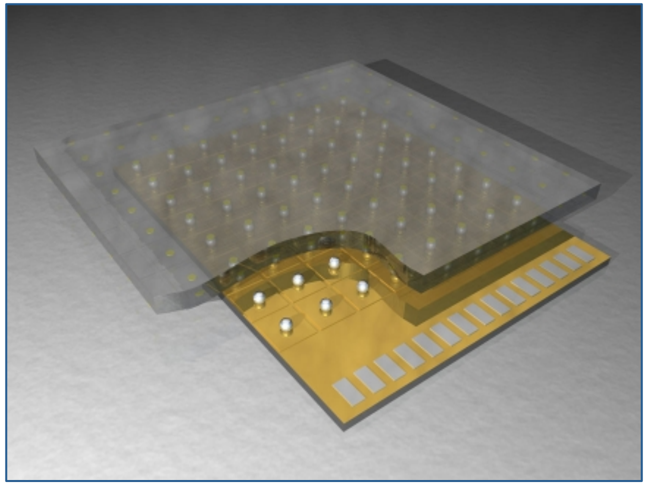


Parameters	ALICE	ATLAS	CMS
Nr. layers	2	3	3
Radial coverage [mm]	**39** - 76	**50** - 120	**44** – 102
Nr of pixels	9.8 M	80 M	66 M
Surface [m^2]	0.21	1.7	1
Cell size ($r\phi$ x z) [μm^2]	50 x 425	50 x 400	100 x 150
Silicon thickness (sens. + ASIC) - x/X_0 [%]	0.21 + 0.16	0.27 + 0.19	0.30 + 0.19

Beyond Hybrid Pixel Detectors …

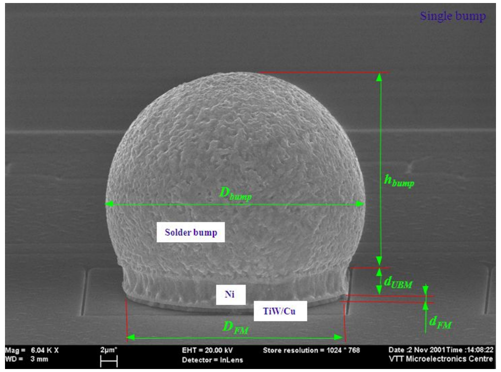
- Limited number of sensors producers (~10 world-wide)
- no industrial scale production ➔ high cost



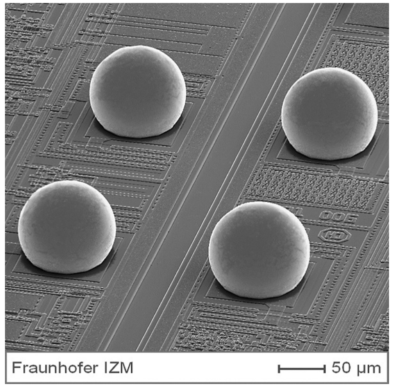


Azom.com

- Complex and costly interconnection between sensors and ASIC
- Interconnection technology (micro-bump bonding) limits:
  - pitch (currently ~30μm)
  - input capacitance ➔ power



VTT Microelectronics Centre



Fraunhofer IZM

Lower production cost

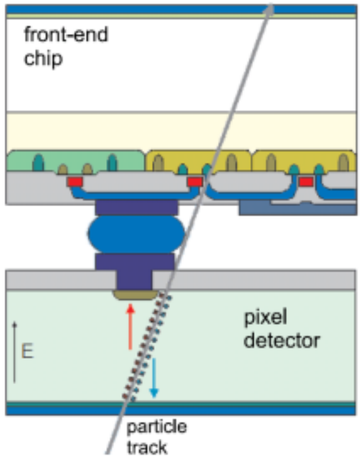
Higher integration (pitch, x/X_0)

Lower power (x/X_0, cost)

CMOS Pixel Sensors

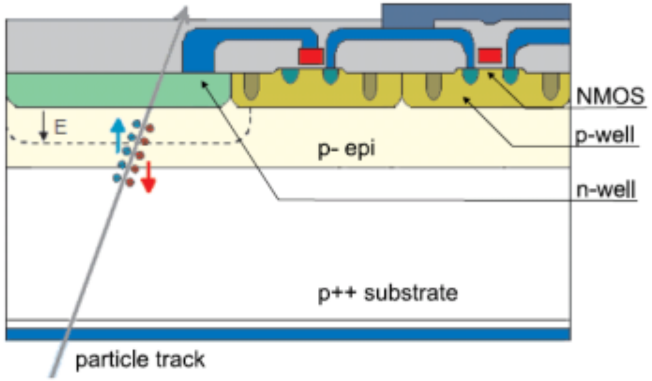
Beyond Hybrid Pixel Detectors …

Hybrid Pixel Detector



N. Wermes (Univ. of Bonn)

Monolithic Pixel Detector



N. Wermes (Univ. of Bonn)

Since the very beginning of pixel development (CERN RD 19):

dream to integrate sensor and readout electronics in one chip

Motivation to reduce: cost, power, material budget, assembly and integration complexity

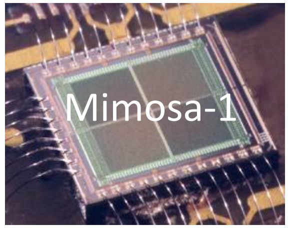
Several major obstacles to overcome:

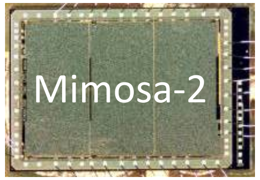
- CMOS generally not available on high resistivity silicon (needed as bulk material for the sensor) ✔
- Full CMOS circuitry not possible within the pixel area (only one type of transistor ➔ slow readout) ✔

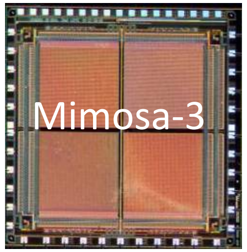
Exist in many different flavours: **CMOS**, HV CMOS, DEPFET, SOI

The following will cover only CMOS Active Pixel Sensors (CMOS MAPS) **= CMOS Active Pixel Sensors (CPS)**

Owing to the industrial development of CMOS imaging sensors and the intensive R&D work (IPHC, RAL, CERN)







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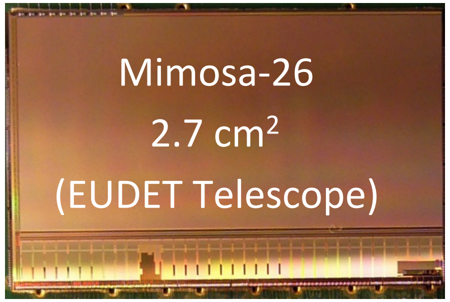
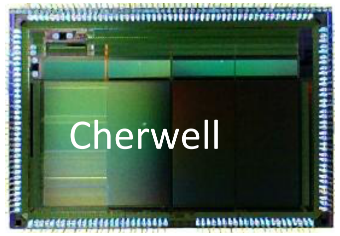
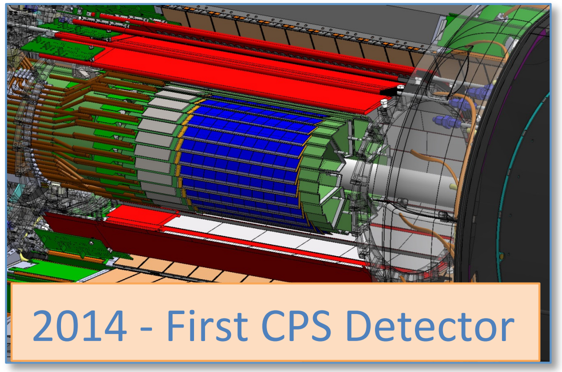




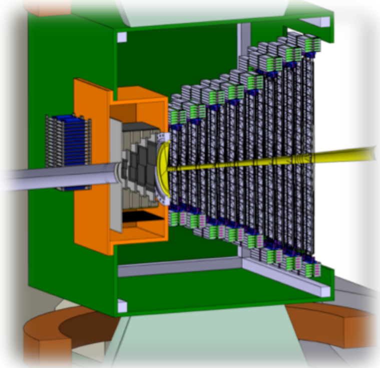
1999

2016

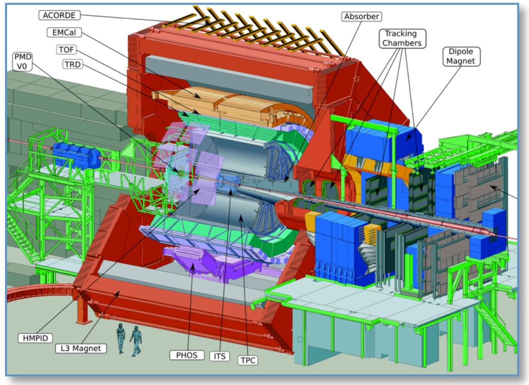
… several HI experiments have selected CMOS pixel sensors for their inner trackers



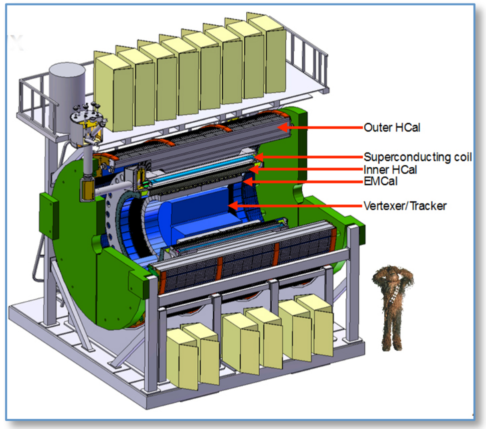
STAR HFT
0.16 m^2 – 356 M pixels



CBM MVD
0.08 m^2 – 146 M pixel



ALICE ITS Upgrade (and MFT)
10 m^2 – 12 G pixel



sPHENIX
0.2 m^2 – 251 M pixel

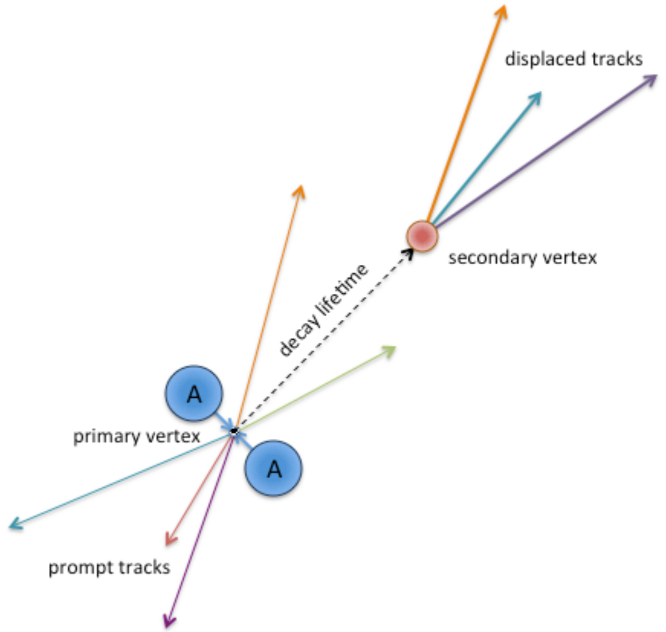
First application to Vertex Detectors

Measurement of short-lived particles

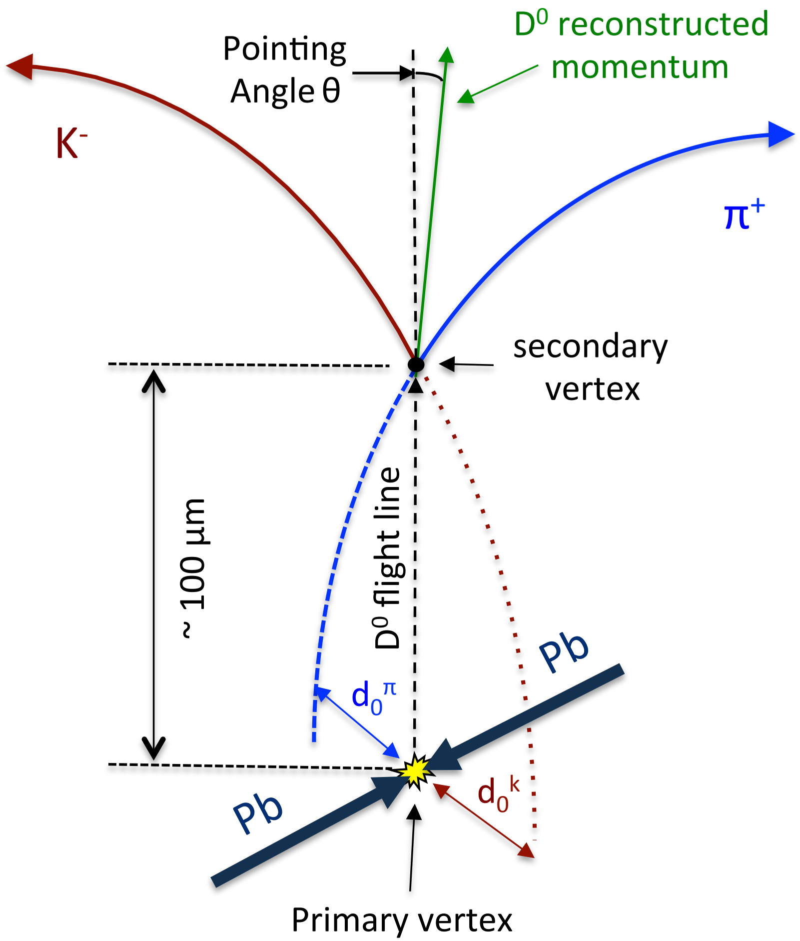
Secondary Vertex Determination

Open charm

Particle	Decay Channel	$c\tau$ (μm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p\, K^- \pi^+$ (5.0%)	60



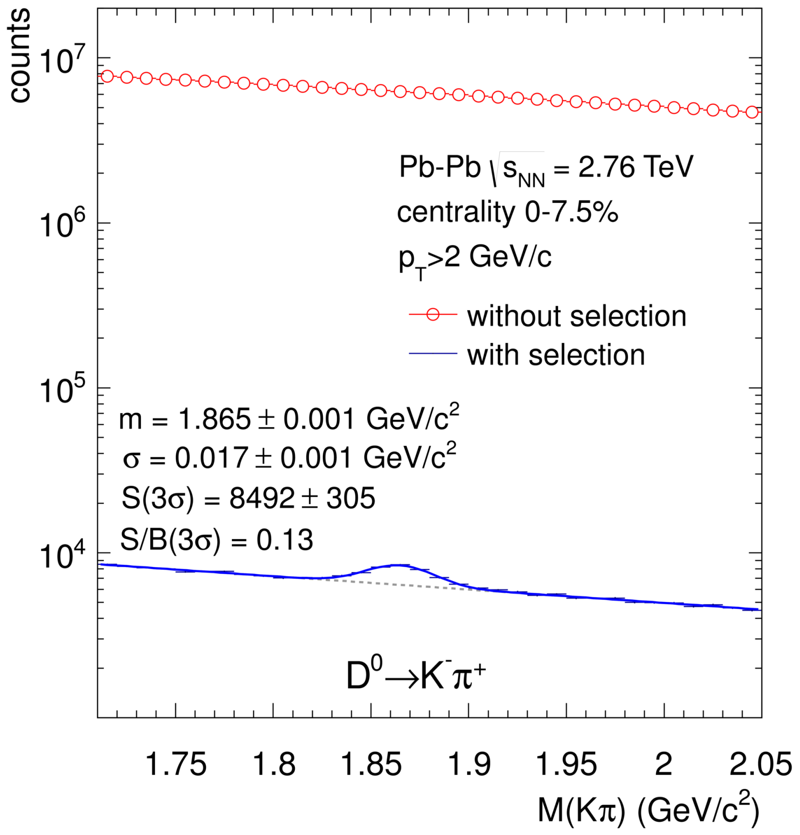
Example: D^0 meson



Analysis based on invariant mass, PID and <u>decay topology</u>

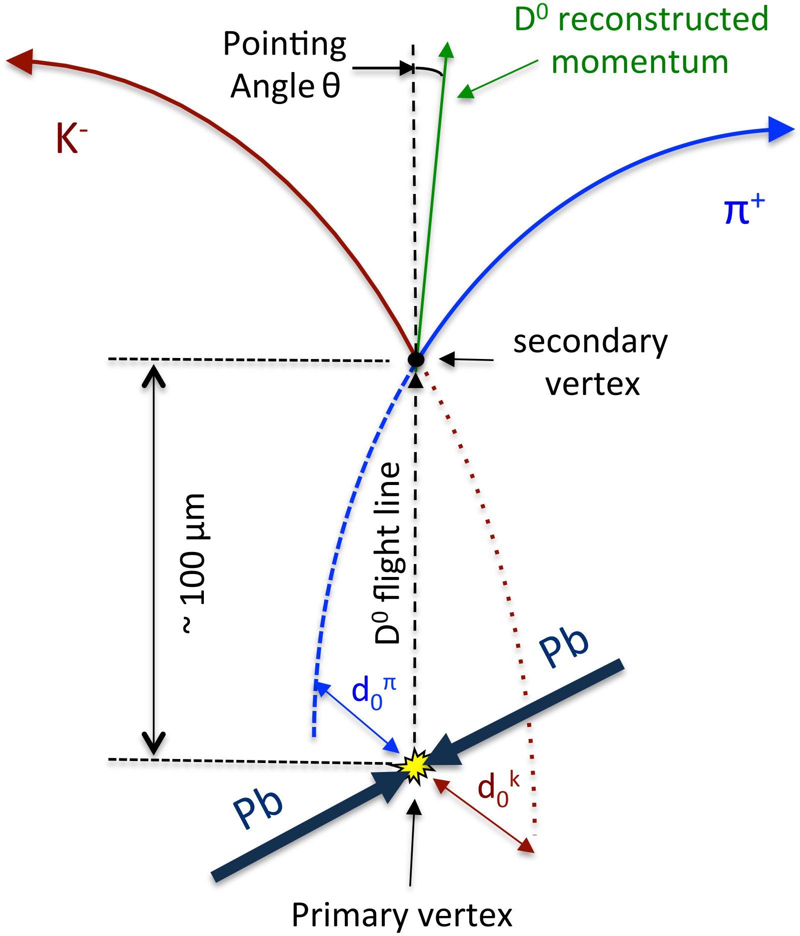
Secondary Vertex Determination

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044



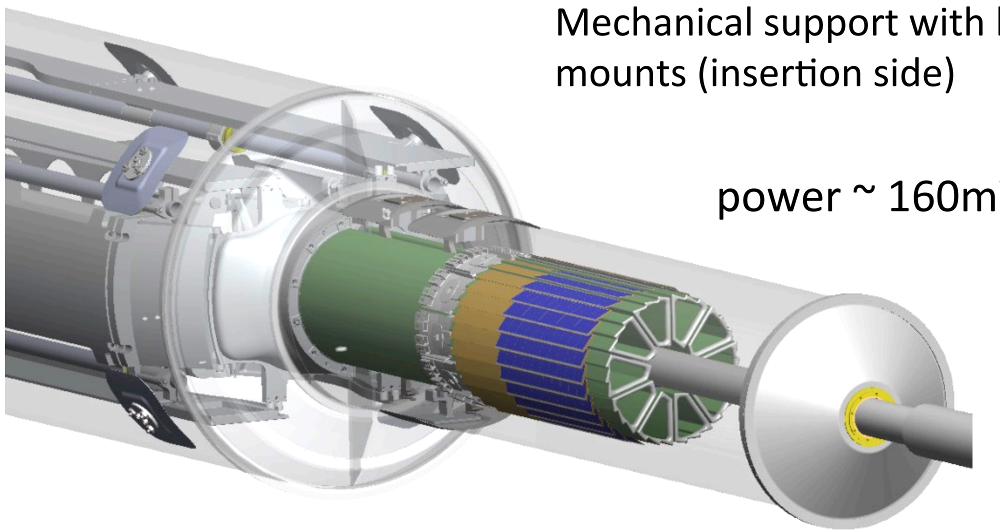
Invariant mass distribution of $K^-\pi^+$ pairs before and after applying selection criteria on the relation between the secondary (D^0 decay) and primary vertices

Example: D^0 meson



Analysis based on invariant mass, PID and decay topology

STAR Pixel Detector – First application of CMOS APS to HEP



Mechanical support with kinematic mounts (insertion side)

power ~ 160mW/cm²

- 2 layers
- 10 sectors total (in 2 halves)
- 4 ladders/sector

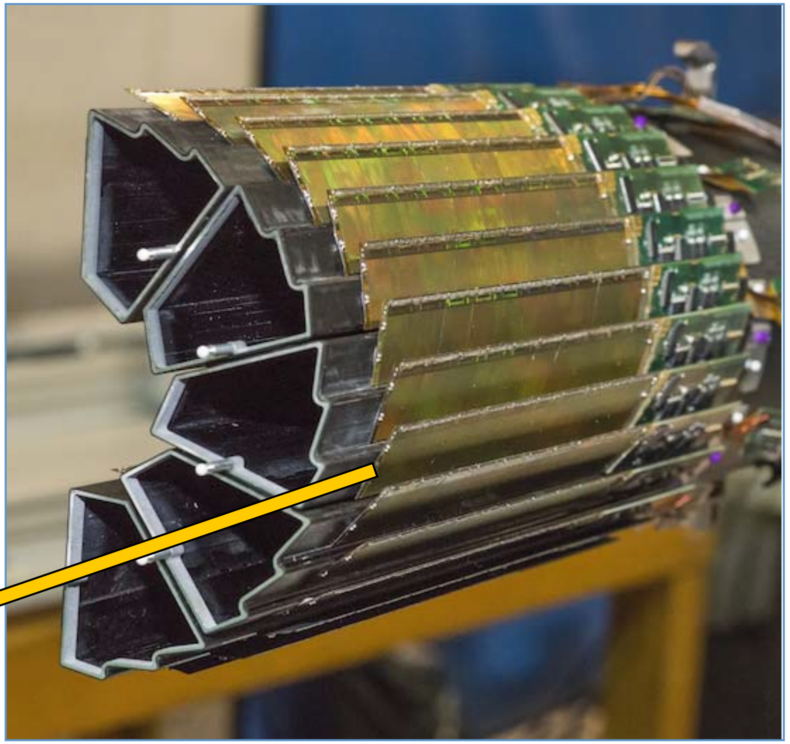
Rolling Shutter
~180μs integr. time

Ladder with 10 MAPS sensors (~ 2×2 cm² each)

2-layer kapton flex cable with Al traces

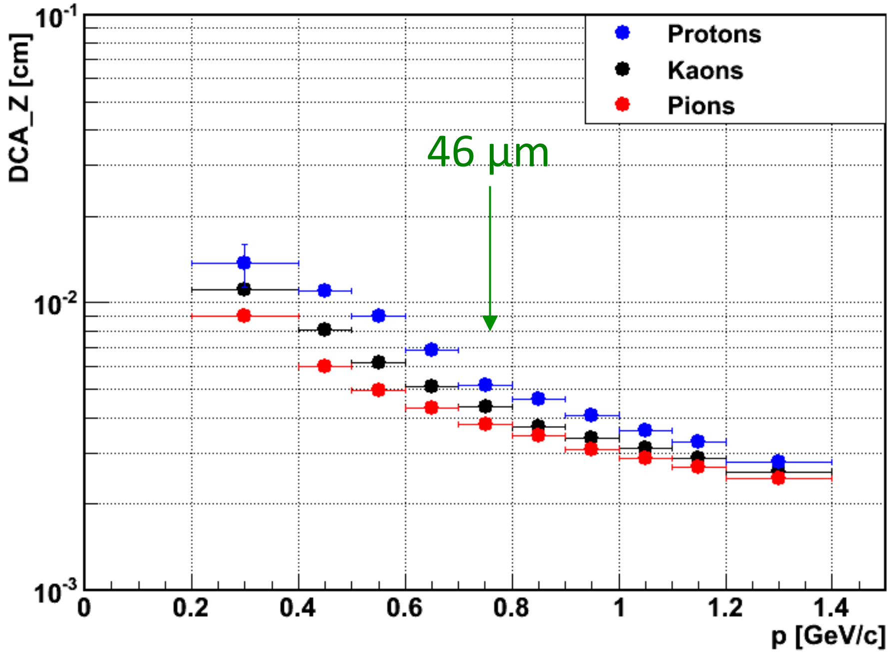
20 cm

Key dates
- 3-sector prototype May 2013
- **Full detector Jan 2014**



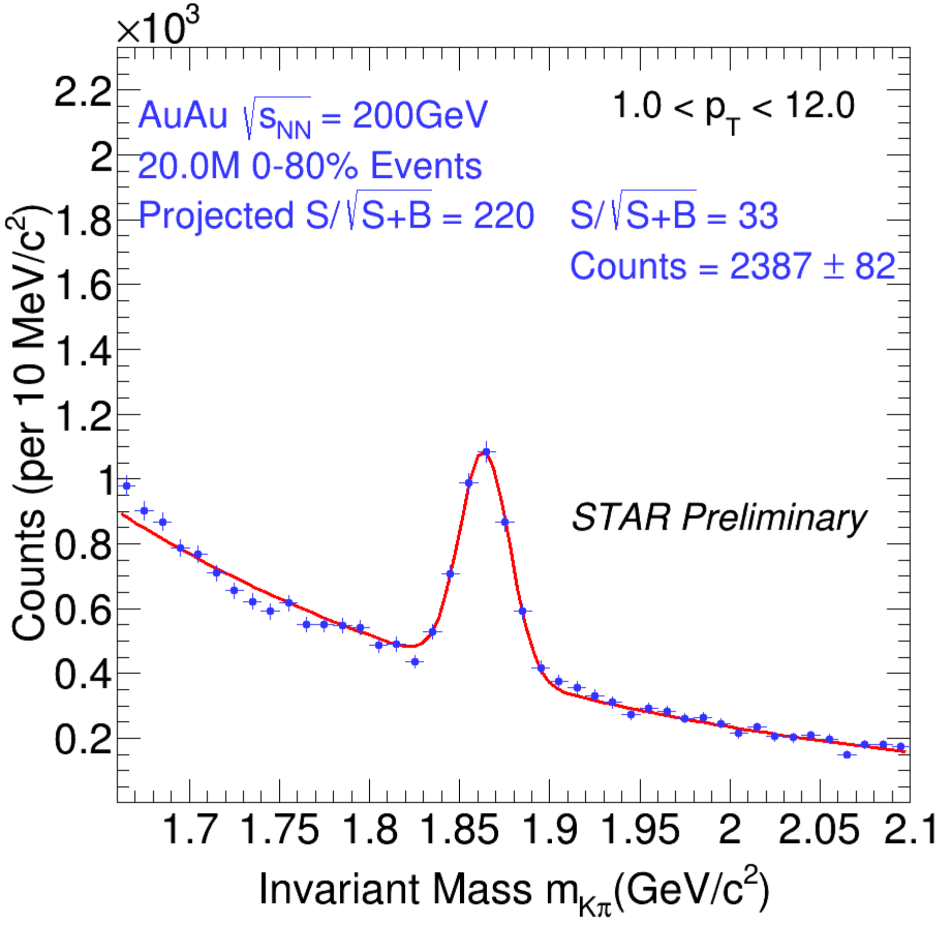
carbon fiber sector tubes
(~ 200 μm thick)

STAR Pixel Detector – Performance



DCA pointing resolution

- 46 µm for 750 MeV/c Kaons
- ~ 30 µm for p > 1 GeV/c



***$D^0 \rightarrow K\,\pi$ production** in $\sqrt{s_{NN}}$ = 200GeV Au+Au collisions*

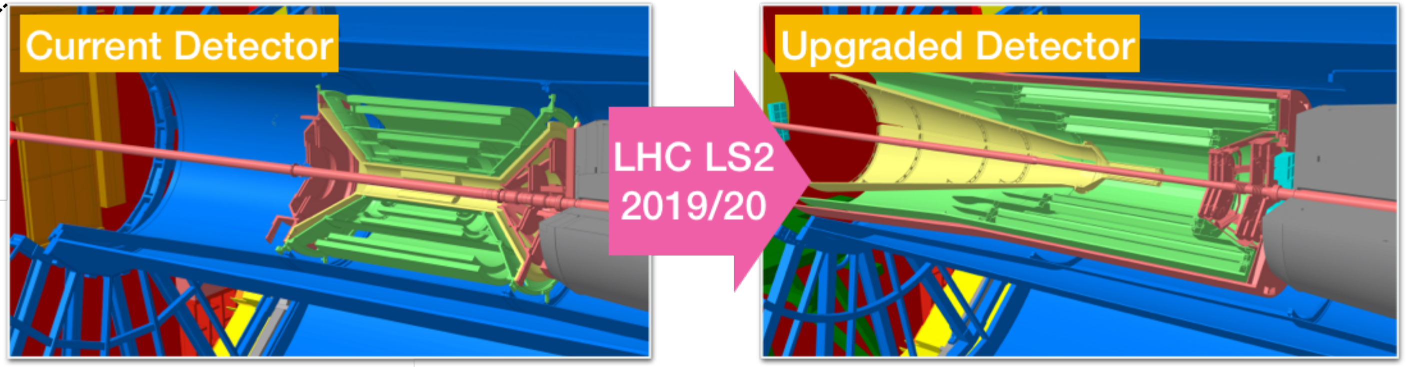
New Inner Tracking System based on CMOS sensors for ALICE

New Inner Tracking System (ITS)

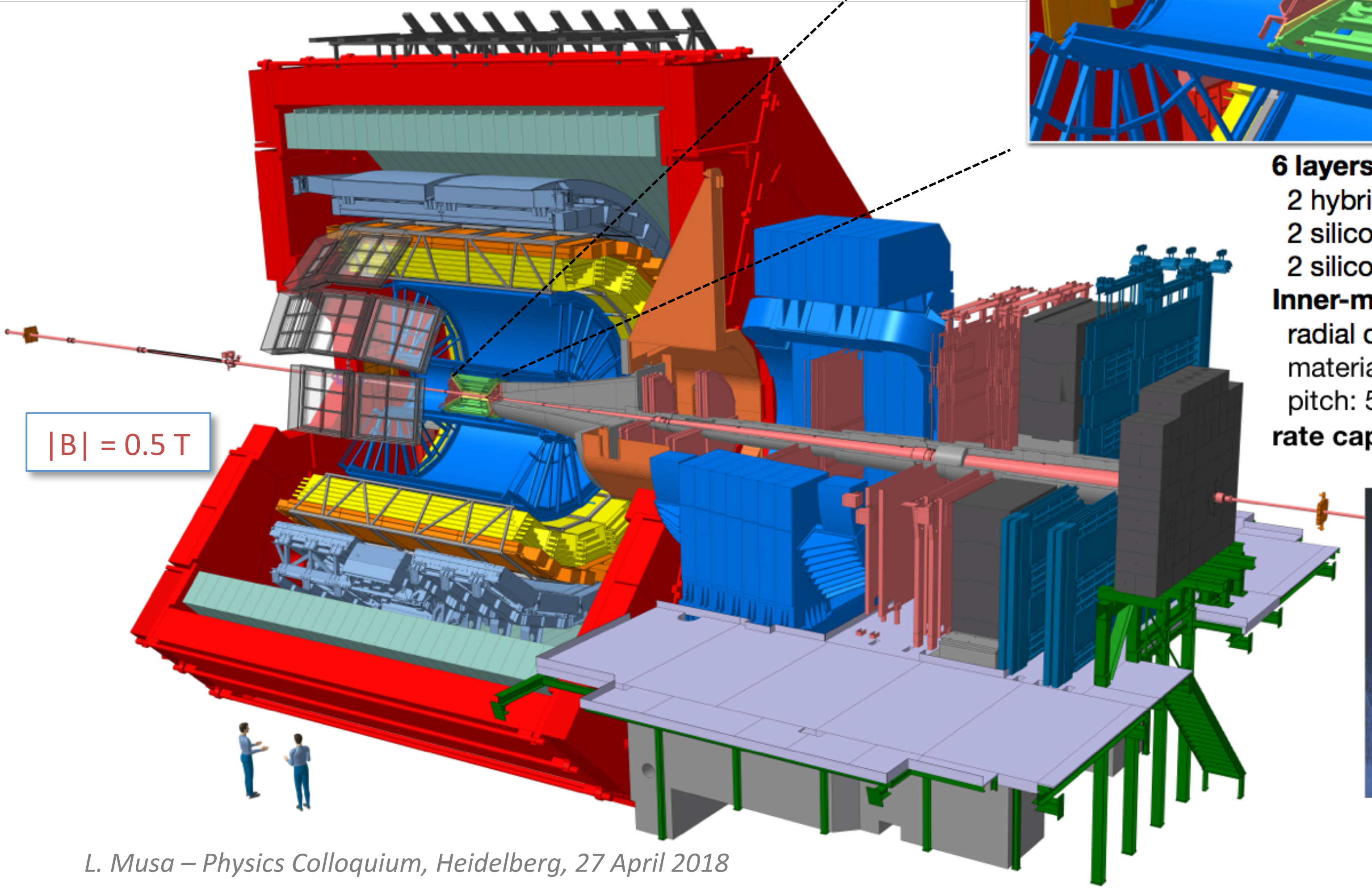
Novel MAPS technology

- CMOS Pixels

→ improved resolution, less material, faster readout



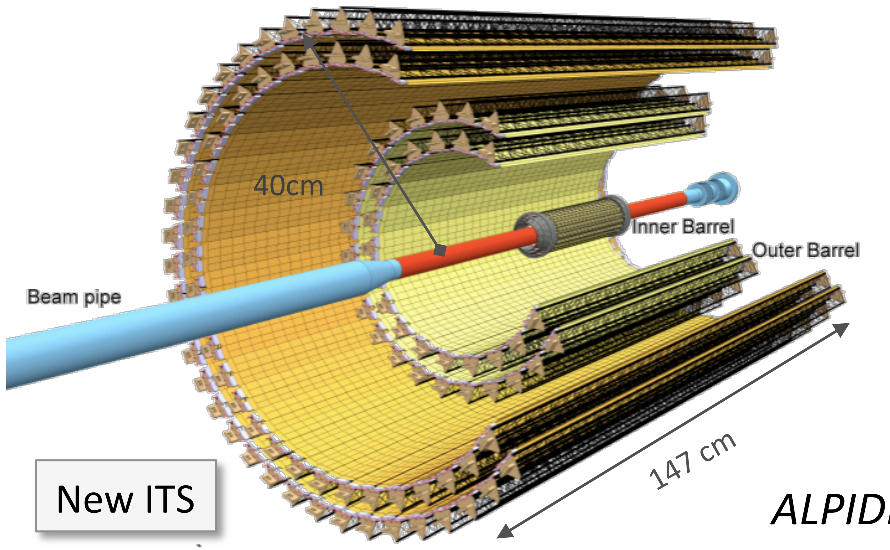
6 layers:	7 layers:
2 hybrid silicon pixel 2 silicon drift 2 silicon strip	all Monolithic Active Pixel Sensors
Inner-most layer:	**Inner-most layer:**
radial distance: 39 mm	radial distance: 23 mm
material: $X/X_0 = 1.14\%$	material: $X/X_0 = 0.3\%$
pitch: $50 \times 425\ \mu m^2$	pitch: $O(30 \times 30\ \mu m^2)$
rate capability: 1 kHz	**rate capability:** 100 kHz (Pb-Pb)



|B| = 0.5 T

ALICE LOI: https://doi.org/10.1088/0954-3899/41/8/087001
ITS TDR: https://doi.org/10.1088/0954-3899/41/8/087002

A new ITS: closer to IP, thinner, higher position resolution



$1.5 \leq \eta \leq 1.5$

Closer to IP: 39mm ➡ 22mm

Thinner: ~1.14% ➡ ~ 0.3% (for inner layers)

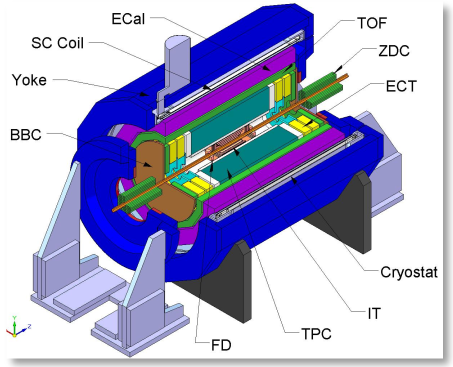
Smaller pixels: 50μm x 425μm ➡ 27μm x 29μm

Increase granularity (x 10^3): 20 chan/cm^3 ➡ 2k pixel/cm^3

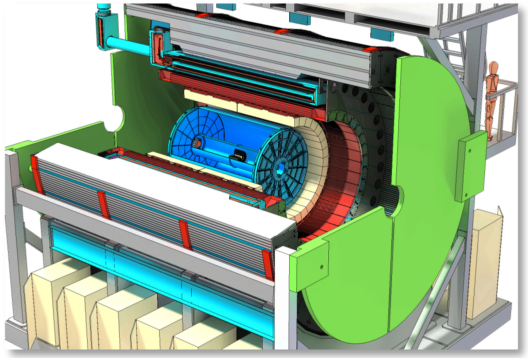
10 m^2 active silicon area: 12.5 G-pixels, $\sigma \approx 5\mu m$

*ALPIDE (**AL**ICE **Pi**xel **De**tector) - Developed for the ALICE upgrade (ITS and MFT) will be used (or it is proposed) for several other HEP detectors and non HEP applications*

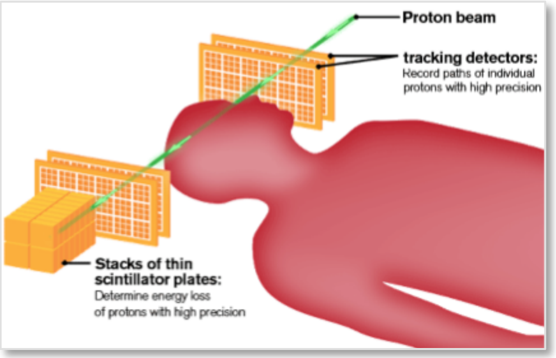
NICA MPD (@JINR)



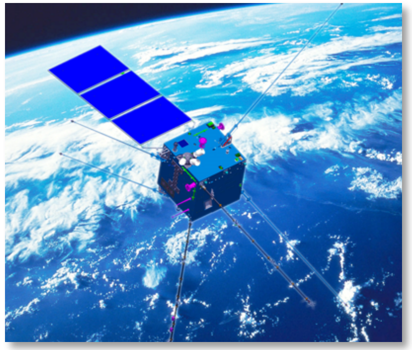
sPHENIX (BNL)



proton CT (tracking)



CSES – HEPD2



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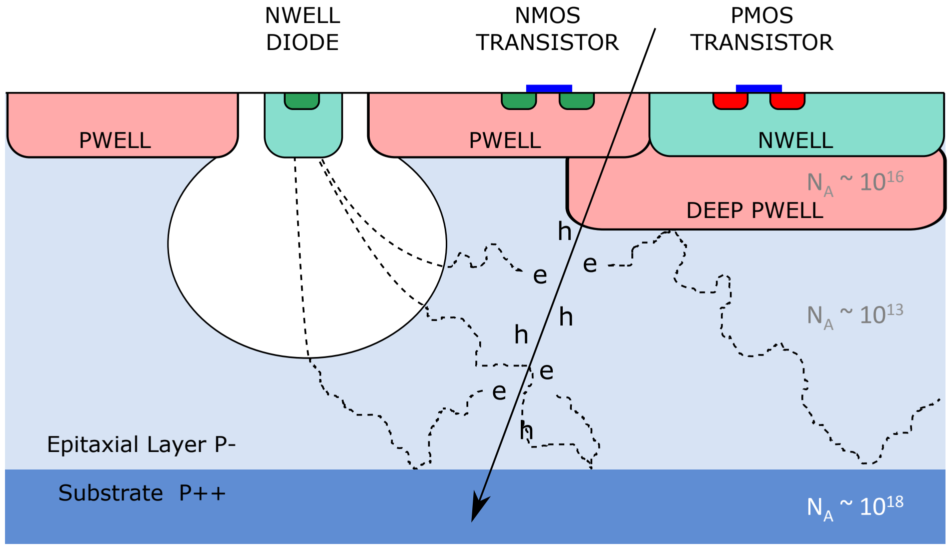
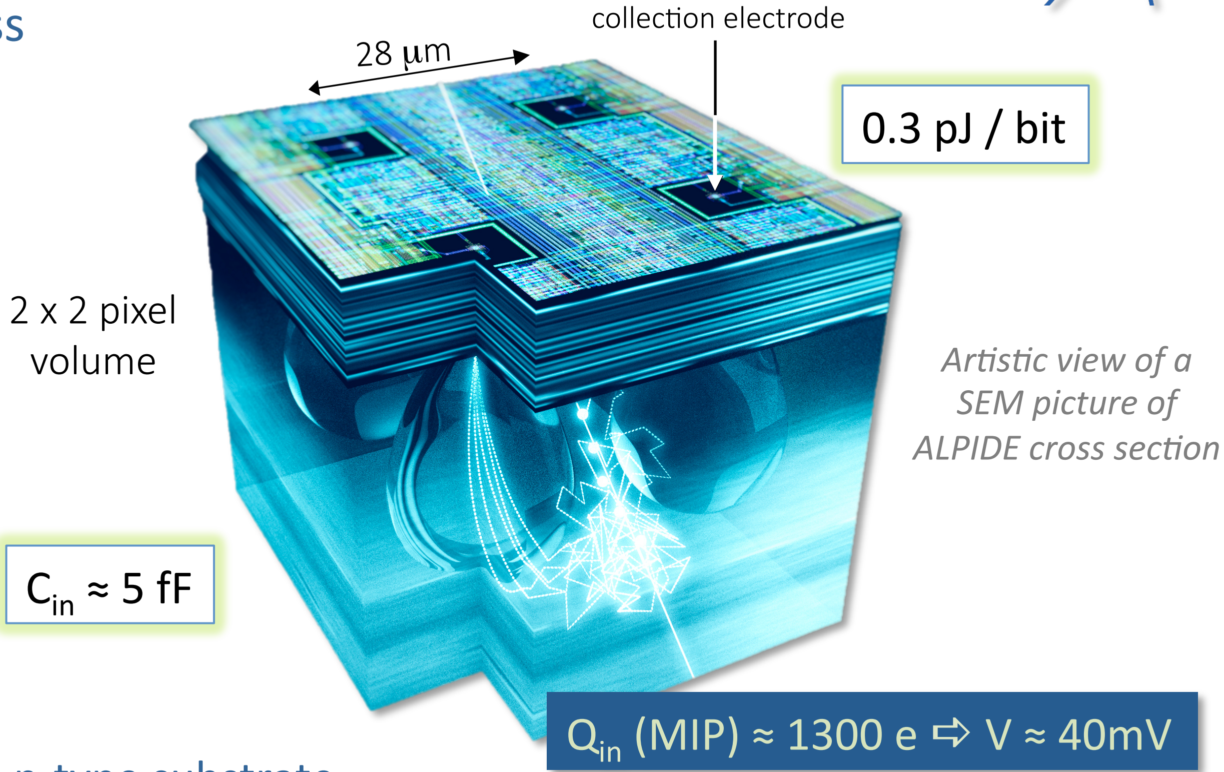
ALICE CMOS Pixel Sensor

CMOS Pixel Sensor using 0.18μm CMOS Imaging Process



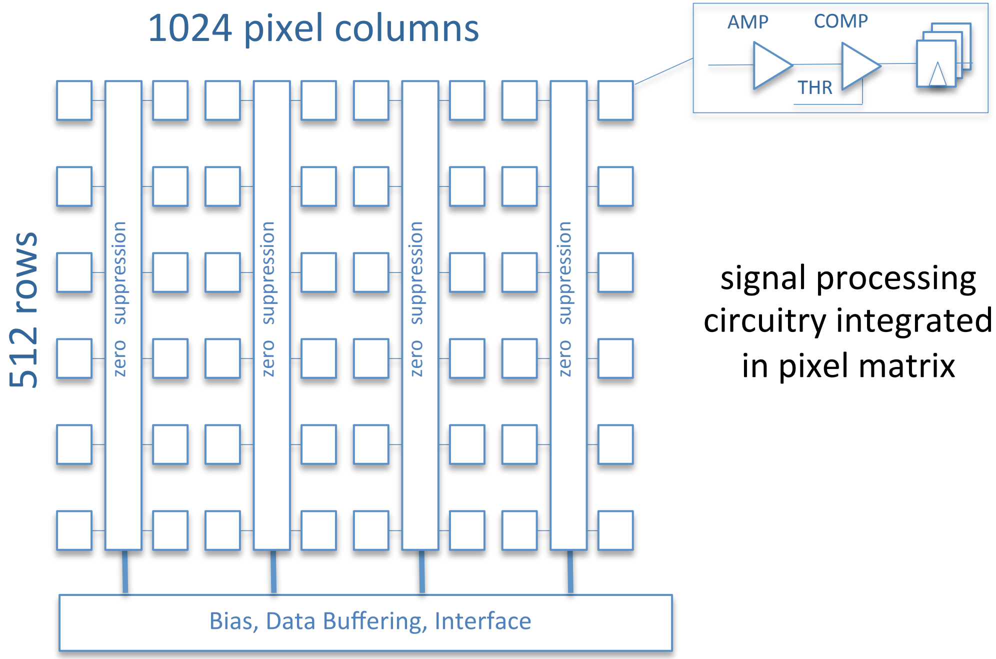
pixel capacitance ≈5 fF (@ V_{bb} = -3 V)



- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors

➔ full CMOS circuitry within active area

ALICE CMOS Pixel Sensor



signal processing
circuitry integrated
in pixel matrix

130,000 pixels / cm^2 27x29x25 μm^3

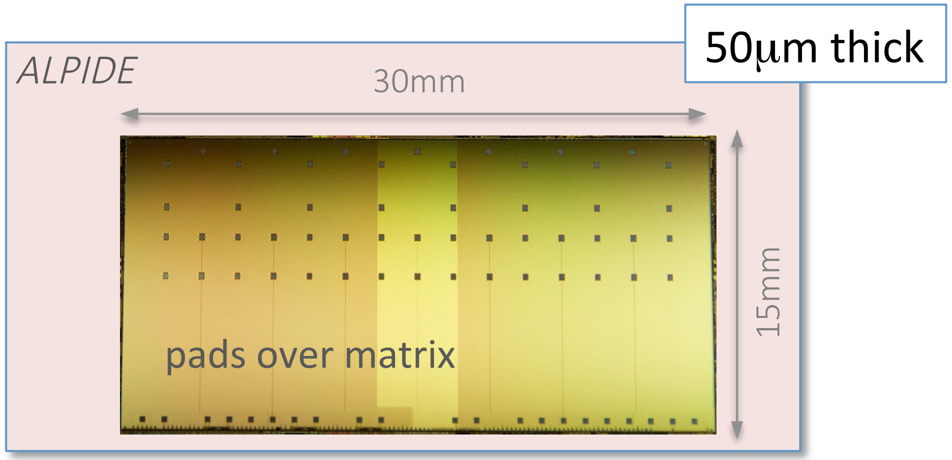
charge collection time <10ns (V_{bb} = -3V)

spatial resolution ~ 5 μm

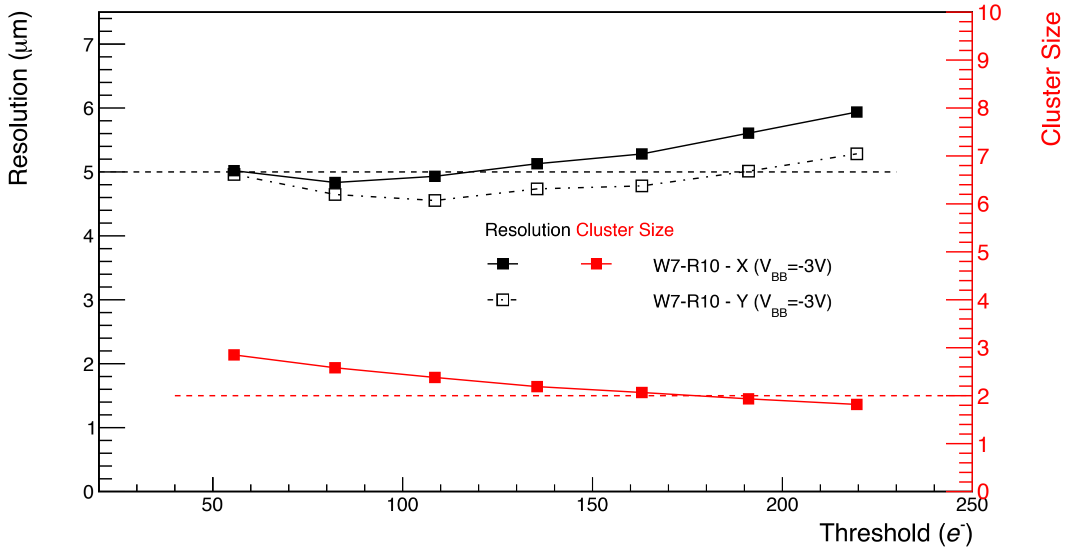
max particle rate ~ 100 MHz / cm^2

fake-hit rate: < 10^{-9} pixel / event

power : ≈300 nW /pixel



Spatial Resolution & Cluster Size

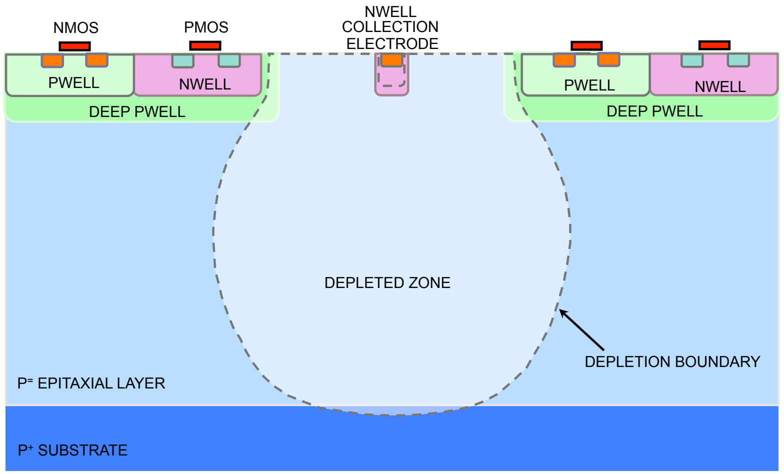


CMOS APS Fully Depleted

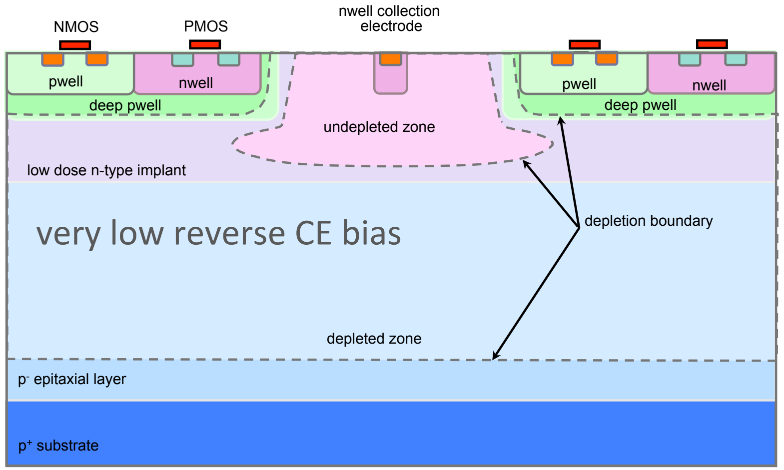
Improving timing performance and radiation tolerance

Fully depleted CMOS APS

A process modification for CMOS Active Pixel Sensors for enhanced depletion, timing performance and radiation tolerance



Standard Process (+DEEP PWELL)



Modified Process with low-dose n-type implant (+DEEP PWELL)

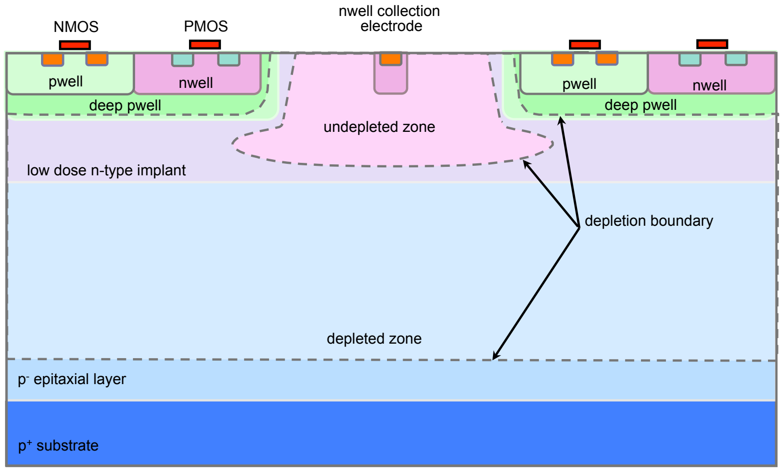
The process modification requires a single additional process mask with no changes on the sensor and circuit layout

For details on process modification and experimental results see: NIM, A 871C (2017) pp. 90-96 (CERN/Tower)

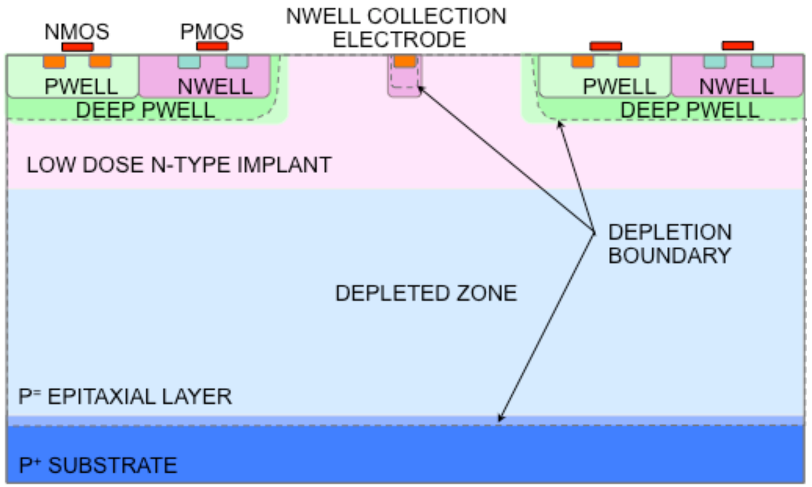
The ALICE test vehicle chip (investigator) and prototype ALPIDE chips exist with both flavors

A process modification for CMOS APS for full depletion

Depletion of the low-dose implant up to the Charge Collection Electrode (NWELL) is obtained at moderate reverse bias voltage (≈ -5V)



very low reverse CE bias



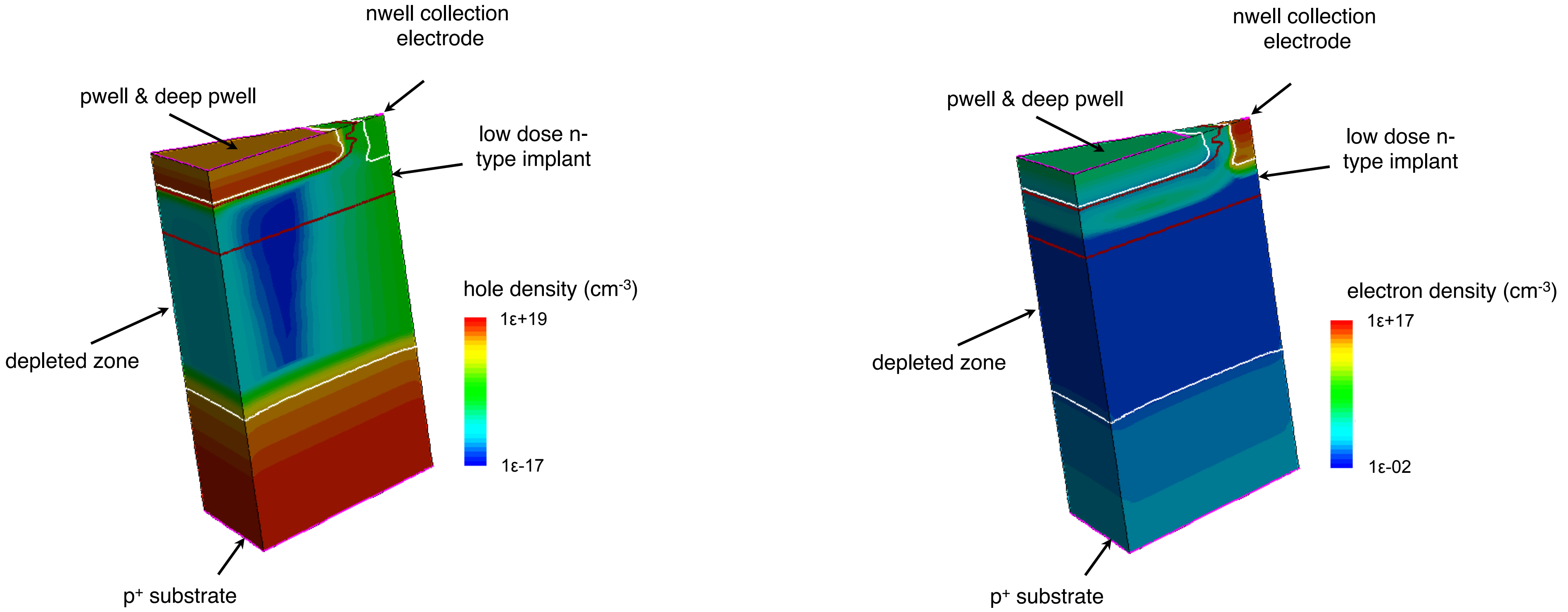
higher reverse CE bias

Punchthrough (pwell to substrate) sets in at > -30V for a high-res layer of 30μm

holes in the pwell entering the epitaxial layer

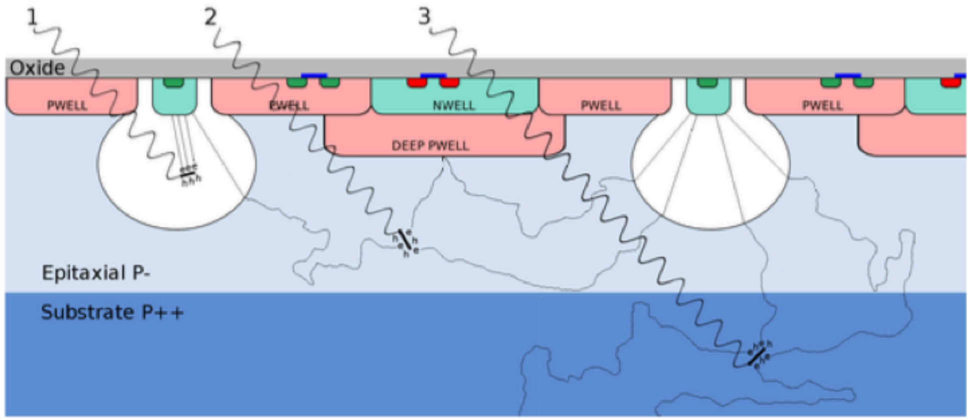
A process modification for CMOS APS for full depletion

Depletion of the epitaxial layer and the low dose implant



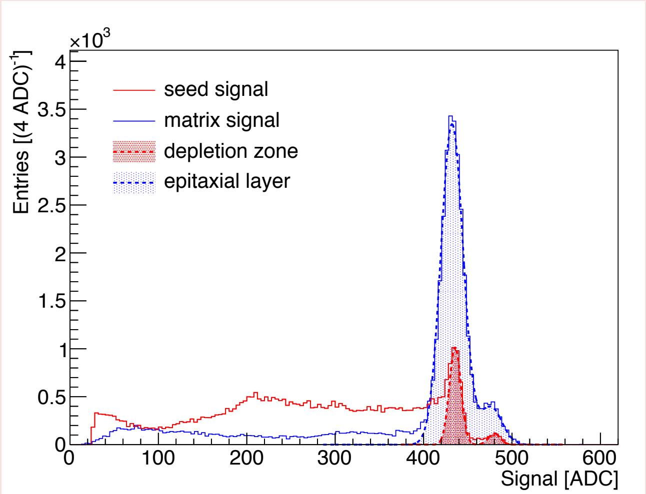
High-res = 18μm, V_{CE} = 5V, $V_{substrate}$ = -15V

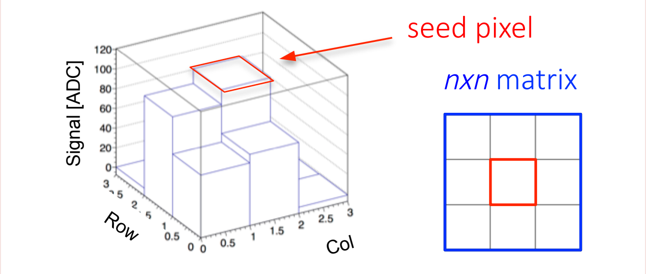
Simulated hole (left) and electron (right) densities. The junctions are indicated with a red line and the edge of the depleted cone with white lines.



^{55}Fe: two X-Ray emission modes:

1. K-α: 5.9 keV (1640 e/h), rel. freq.: 89.5% atten. length in Si: 29μm
2. K-β: 6.5 keV (1800 e/h), rel. freq.: 10.5% atten. length in Si: 37μm



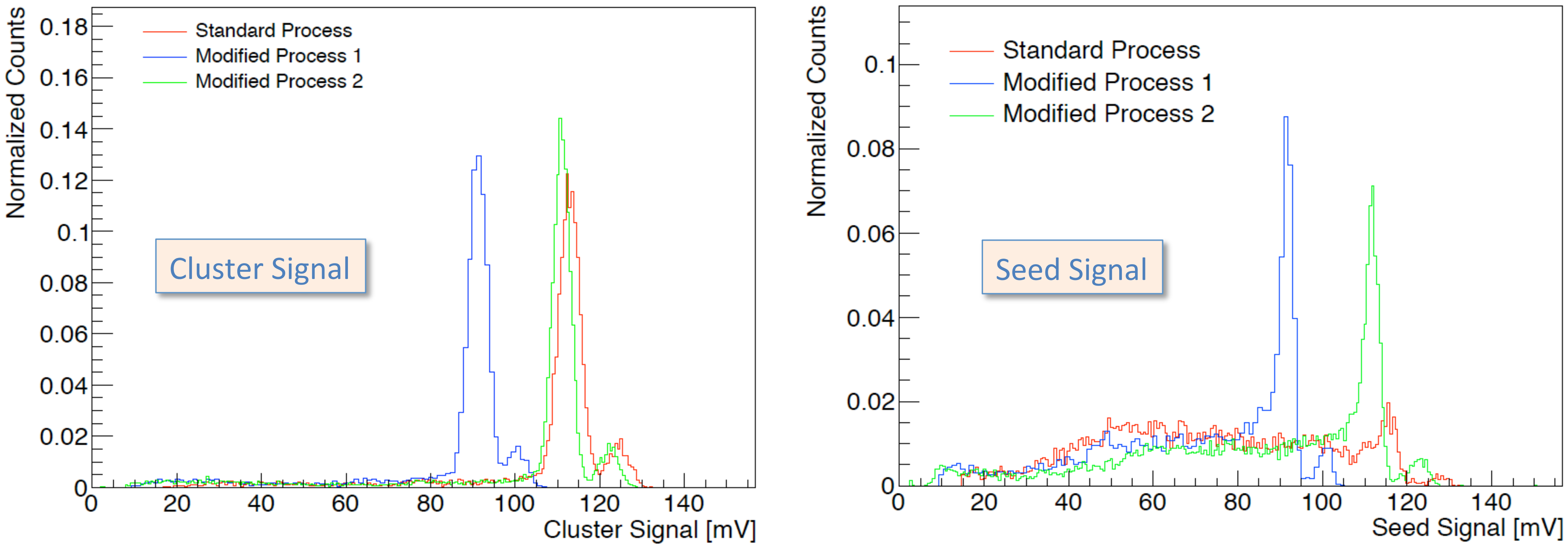


For X-Ray absorption in sensor with the std process three cases can be defined:

1. Absorption in depletion volume: charge collected by drift, no charge sharing, single pixel cluster:
   - Events populate the calibration peak in signal histograms
   - charge collection time expected to be ≈ 1ns
2. Absorption in epitaxial layer: charge partially collected by diffusion and then drift, charge sharing between pixels depending on position of X-Ray absorption
   - Charge collection depends on distance of the X Ray absorption from depletion
3. Absorption in substrate
   - Contribution depending on depth of X-Ray absorption position in substrate and charge carrier lifetime within substrate

A process modification for CMOS APS for full depletion

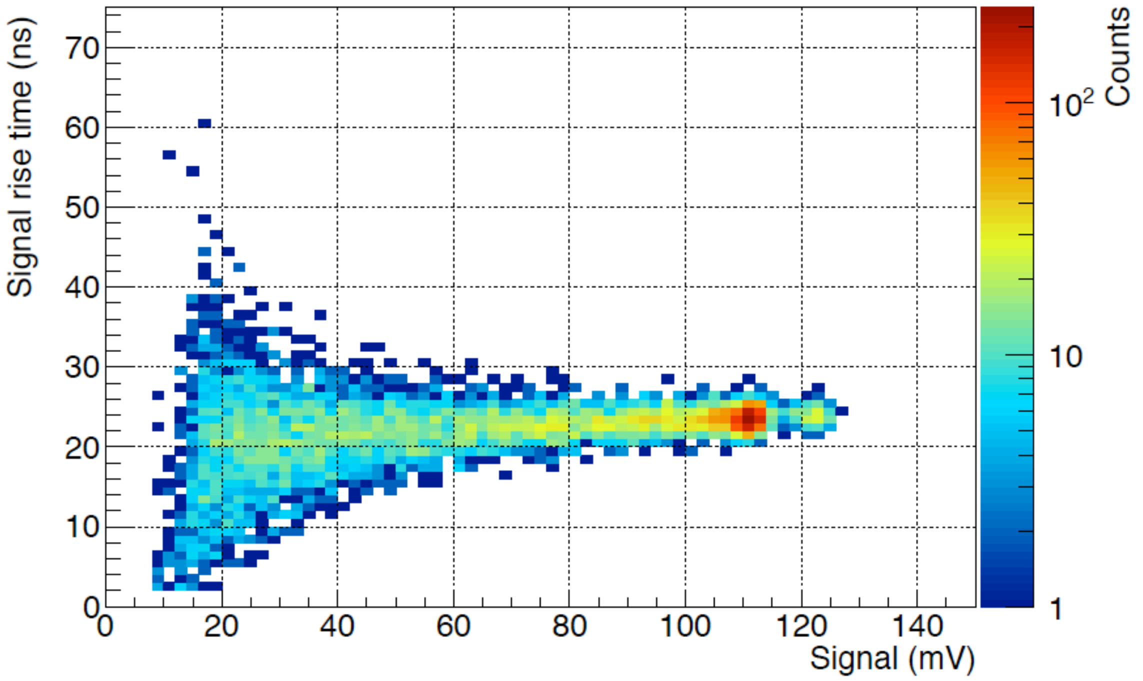
Experimental Results with the INVESTIGATOR CHIP (an ALICE test vehicle chip)

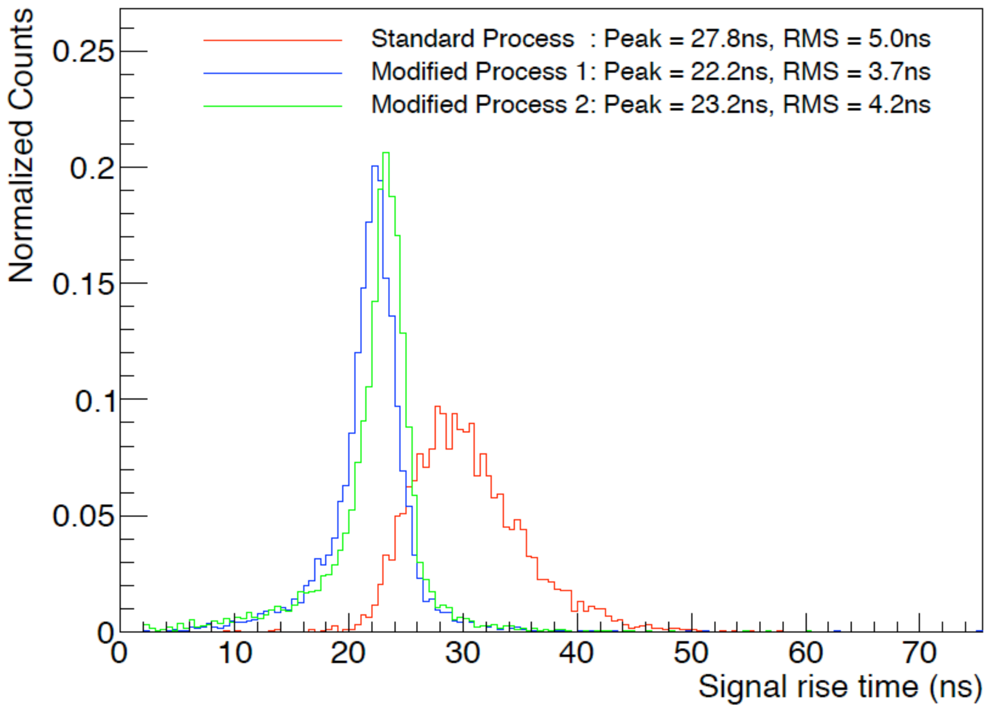


Signal and cluster distribution from a a ^{55}Fe radioactive source measured at room temperature for standard and modified process with higher (modified process 1) and lower (modified process 2) dose for the low-dose implant

A process modification for CMOS APS for full depletion

Experimental Results with the INVESTIGATOR CHIP (an ALICE test vehicle chip)





Charge collection time vs. signal (left) and signal rise time distribution (right) from a ^{55}Fe radioactive source for standard and modified process with higher (modified process 1) and lower (modified process 2) dose

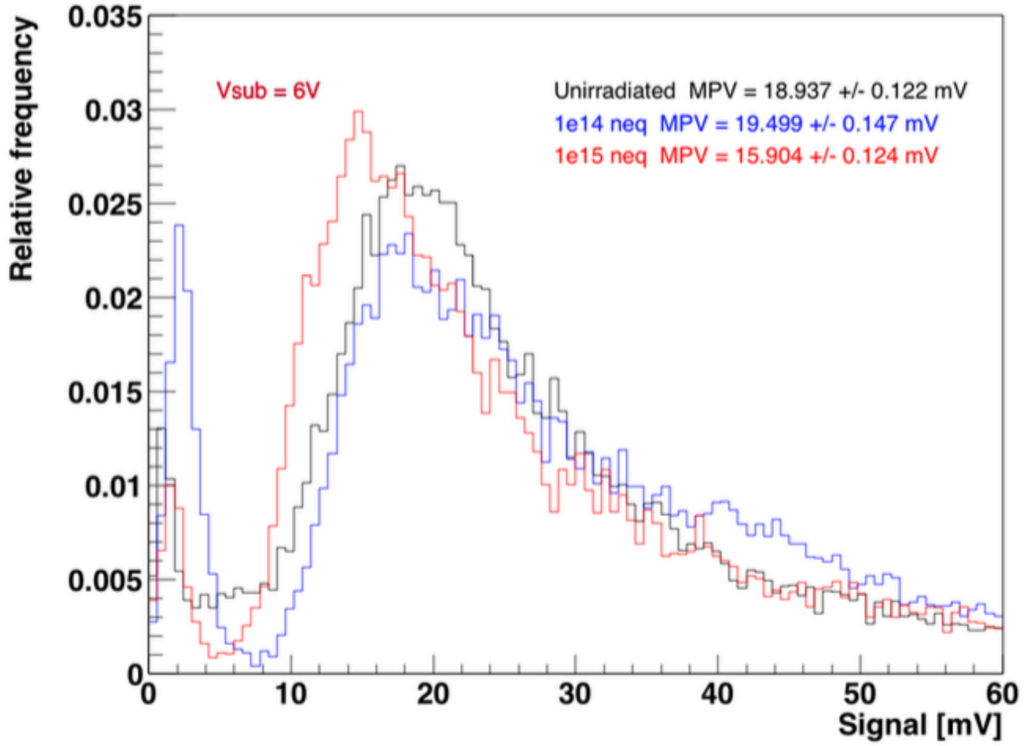
Time resolution limited by chip output buffer speed (≈ 20ns) and noise

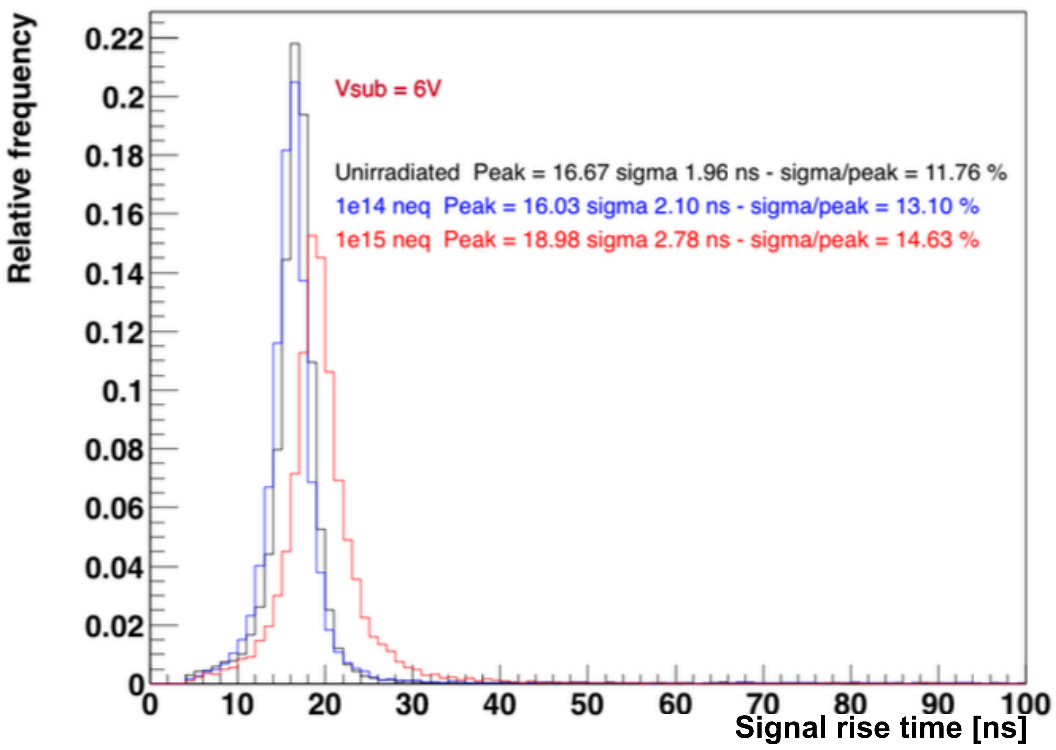
A new version of the investigator chip w/o buffer speed limitation is being tested now

A process modification for CMOS APS for full depletion

^{90}Sr measurements on modified-process (INVESTIGATOR chip)

Non-irradiated, 1x10^{14} 1MeV n_{eq}/cm^2 (NIEL) and 100 krad (TID), 1x1015 1 MeV n_{eq}/cm^2 (NIEL) and 1Mrad (TID)





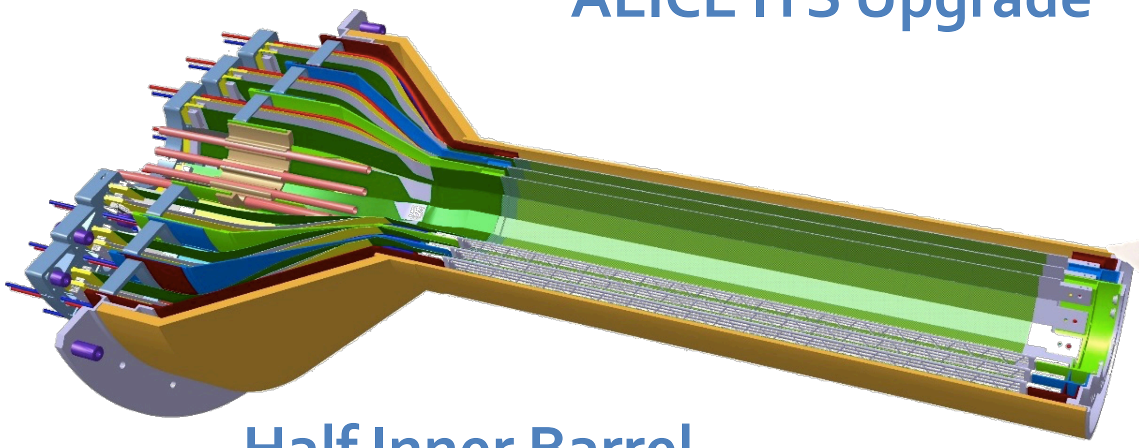
Little signal loss after irradiation, signal well separated from noise

Ultra-lightweight Vertex Detector

Approaching 0-mass detector

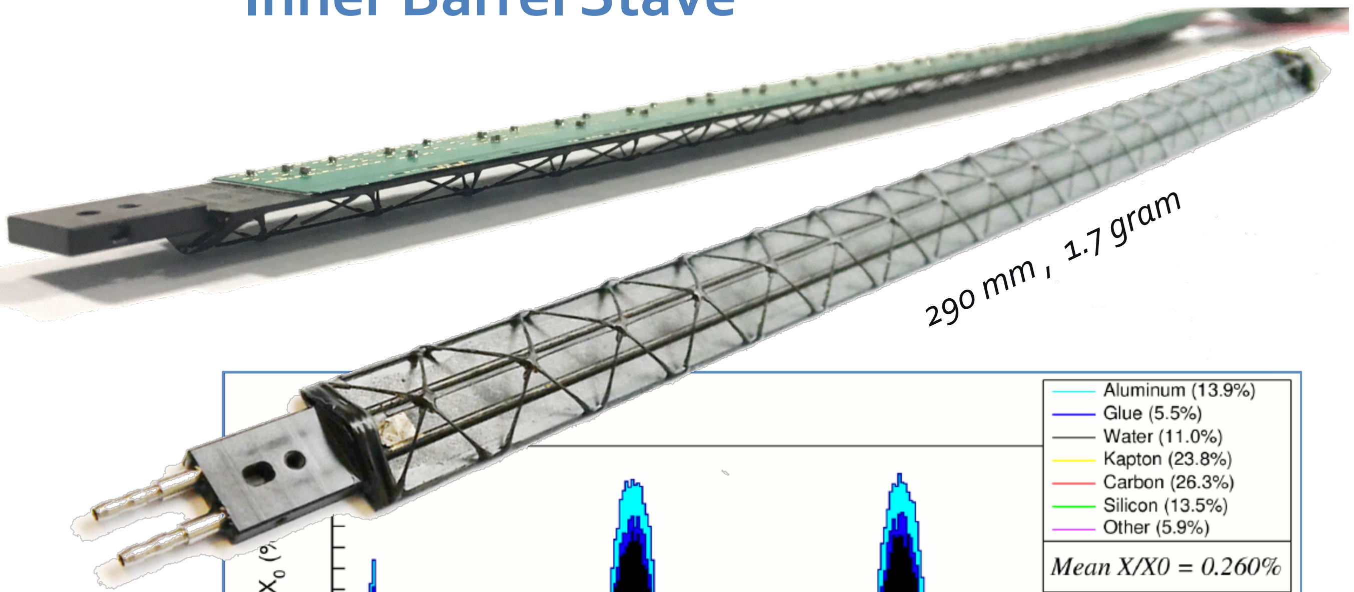
ALICE innovates: ultra lightweight support structures and cooling

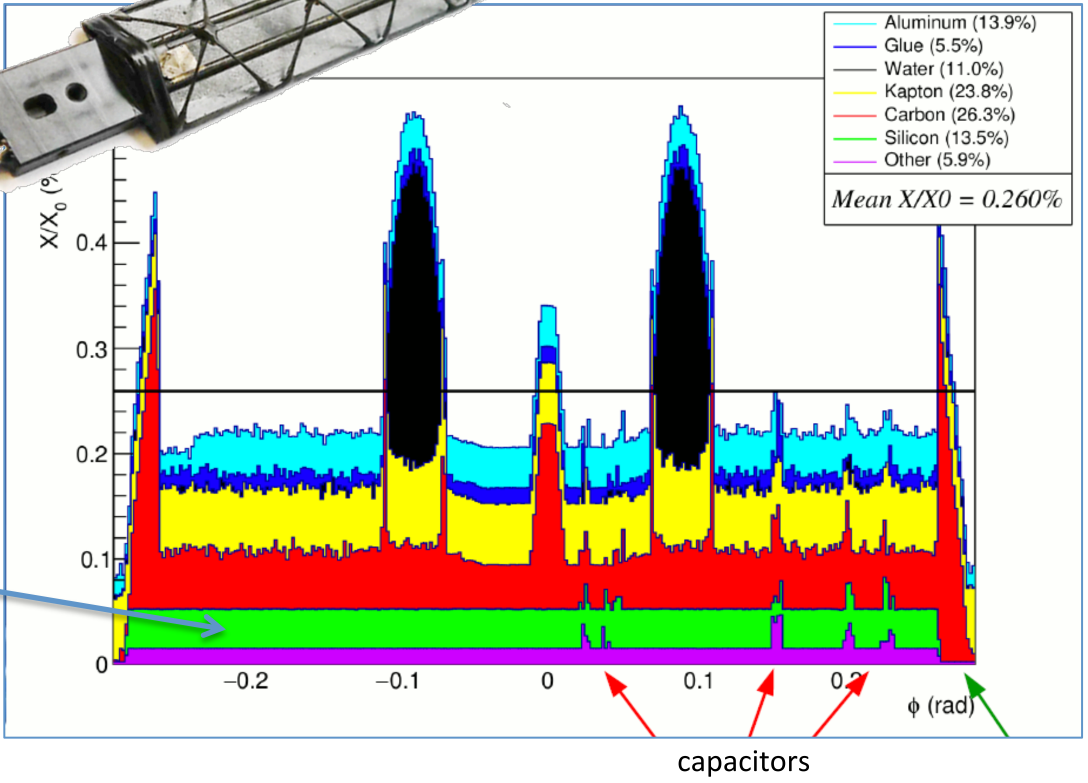
ALICE ITS Upgrade



Half Inner Barrel

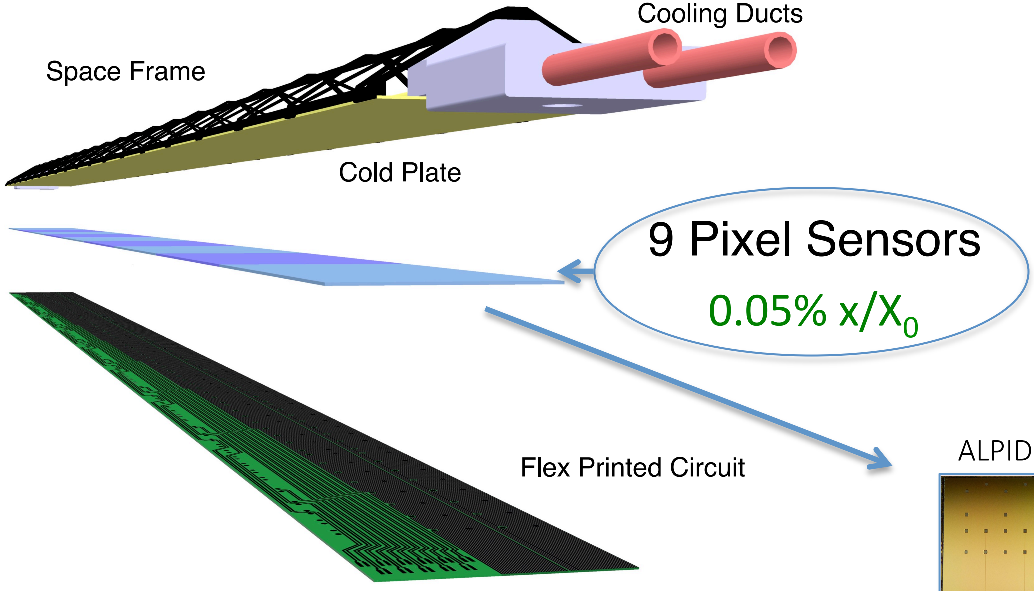
Inner Barrel Stave



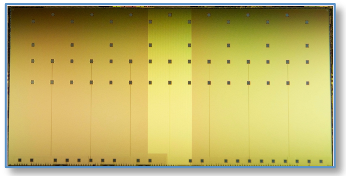


Silicon sensor + readout circuitry
only 13% of the total material budget

Can we further reduce the mass of a vertex detector?



ALPIDE



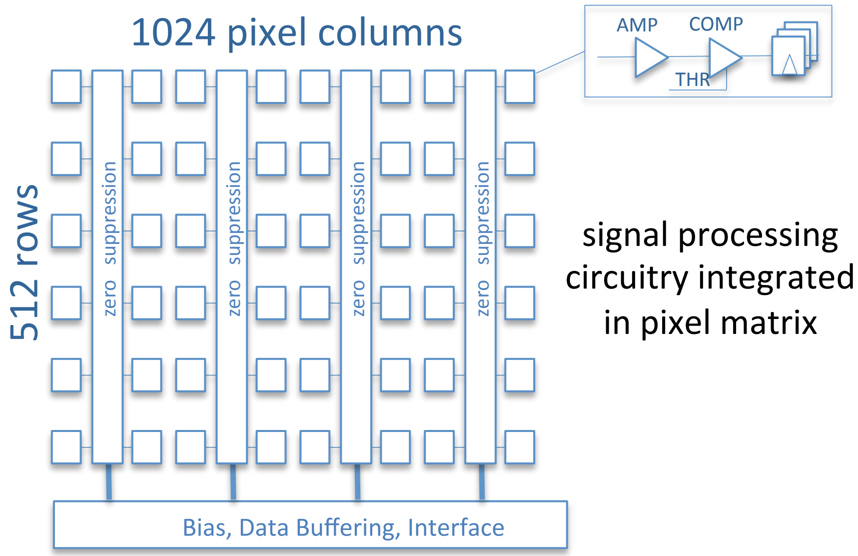
How to further reduce material budget?

Eliminate active cooling

→ possible for power densities below $20 mW/cm^2$

Eliminate electrical substrate

→ Possible if sensor covers the full stave length



signal processing circuitry integrated in pixel matrix

ALPIDE Chip: pixel matrix power ~$7 mW/cm^2$ …

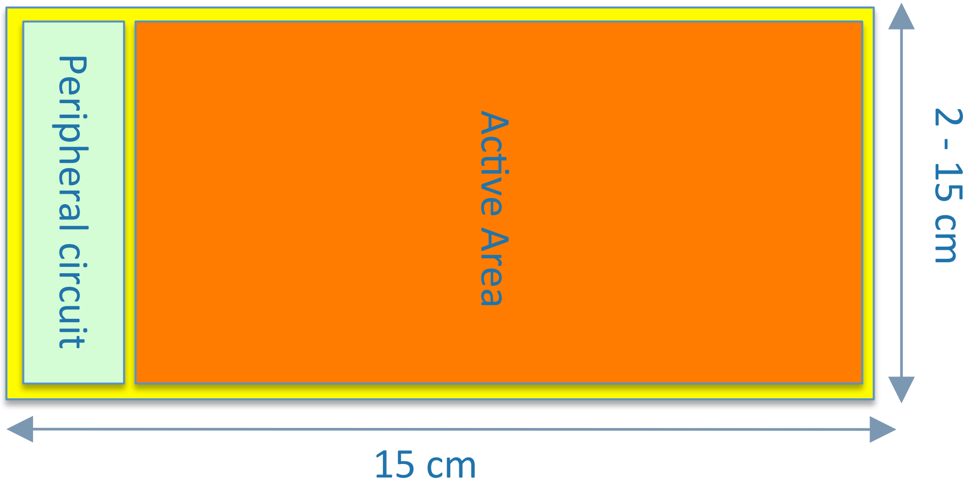
… the rest (~$30 mW/cm^2$) is dissipated at the sensor periphery

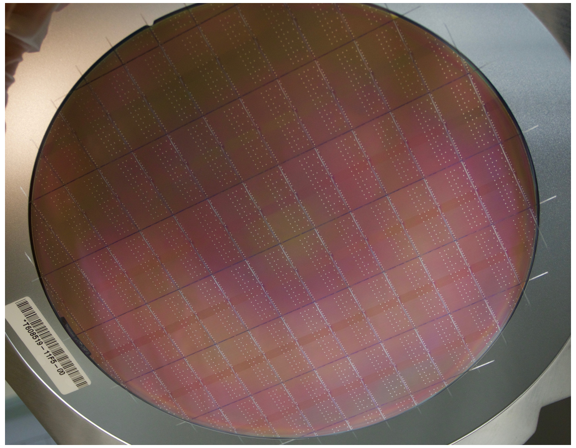
Can we put the circuit periphery at the periphery of the detector?

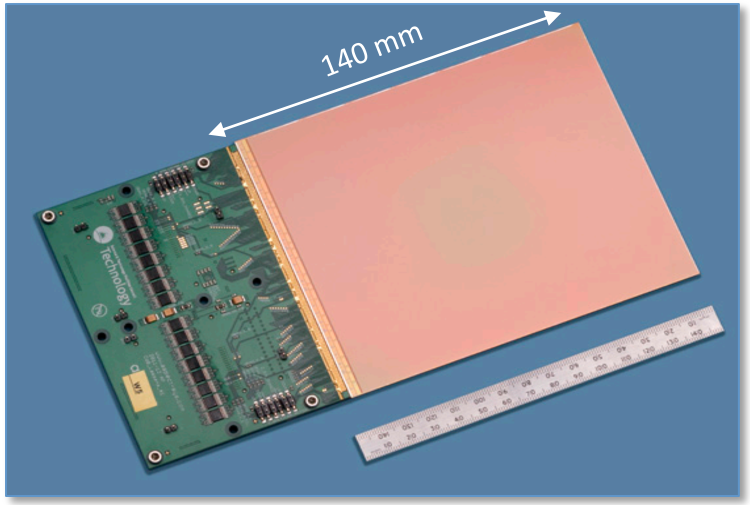
What’s next? - Future R&D opportunities using CMOS technologies

Stitching allows building circuits as large as an entire wafer (standard process for several CIS technologies)

1-D or 2-D stitched version of a sensor chip







Stitching available also for 300mm technologies

The use of CMOS and stitching technologies open new opportunities

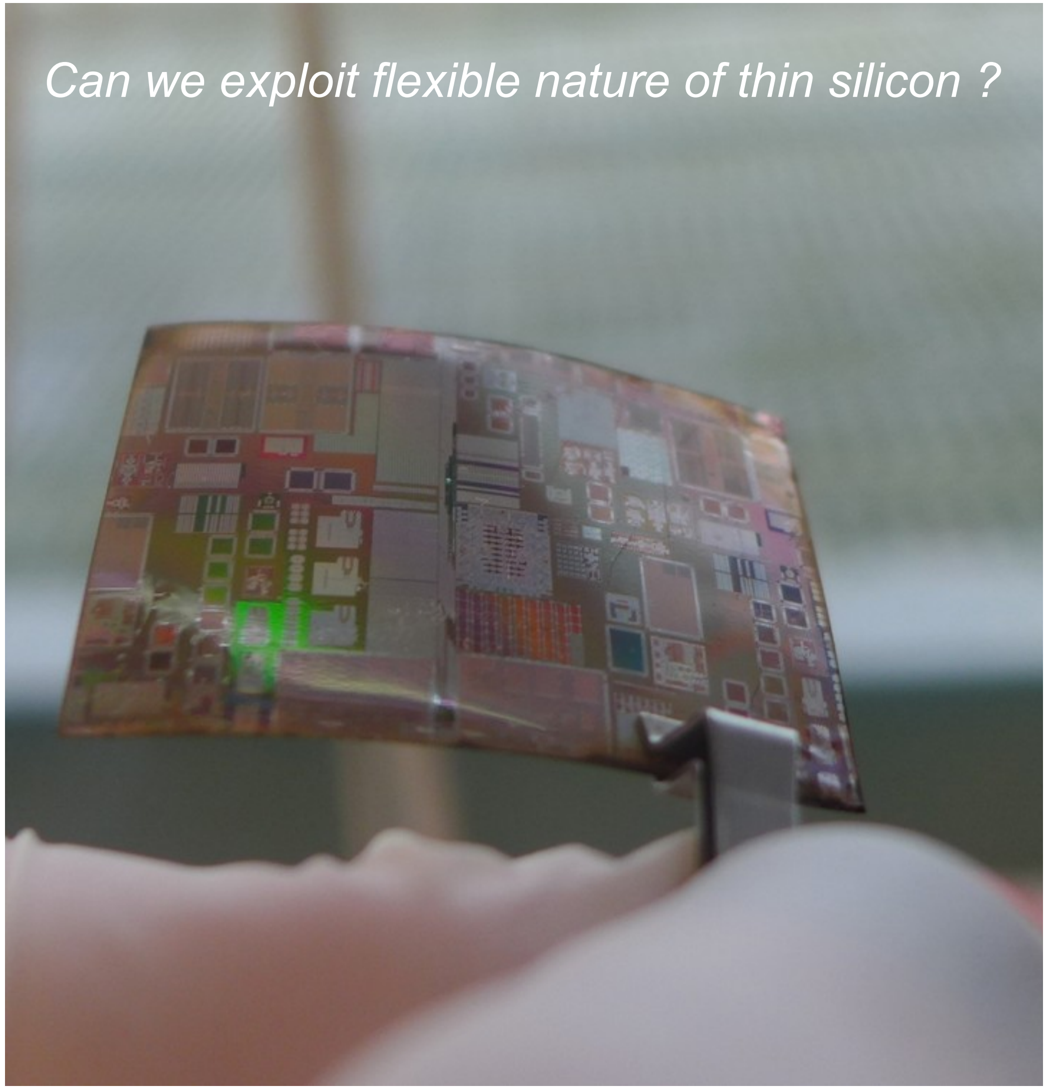
➪ **Vertex detectors, large area tracking detectors, digital caloremeters**

- enhanced performance (spatial and time resolution)
- reduction of power consumption and material budget

large cost saving due to low production costs

Migration to smaller technology nodes (180nm ➪ 65nm, 40nm) ➪ large power reduction

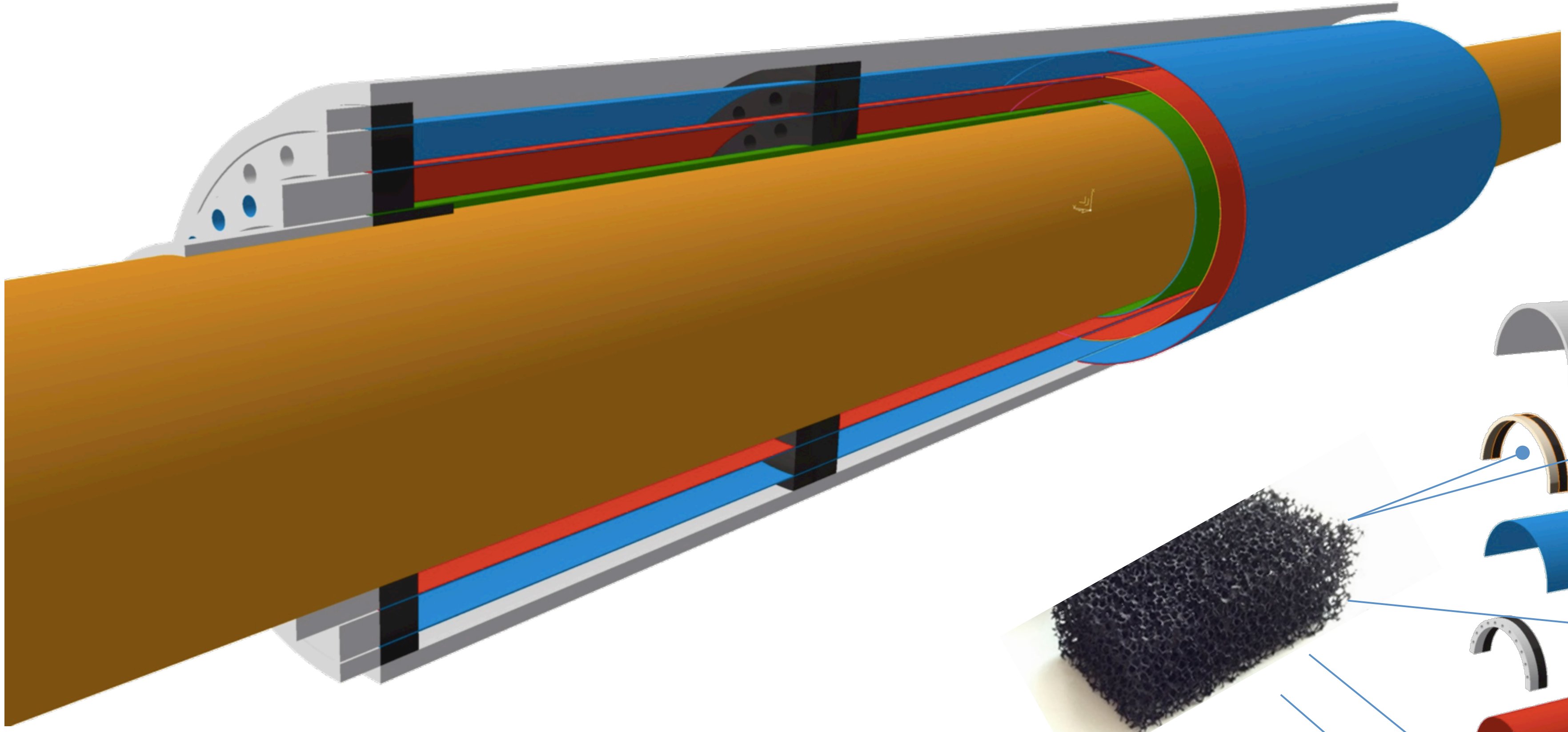
What's next? - Future R&D opportunities using CMOS technologies

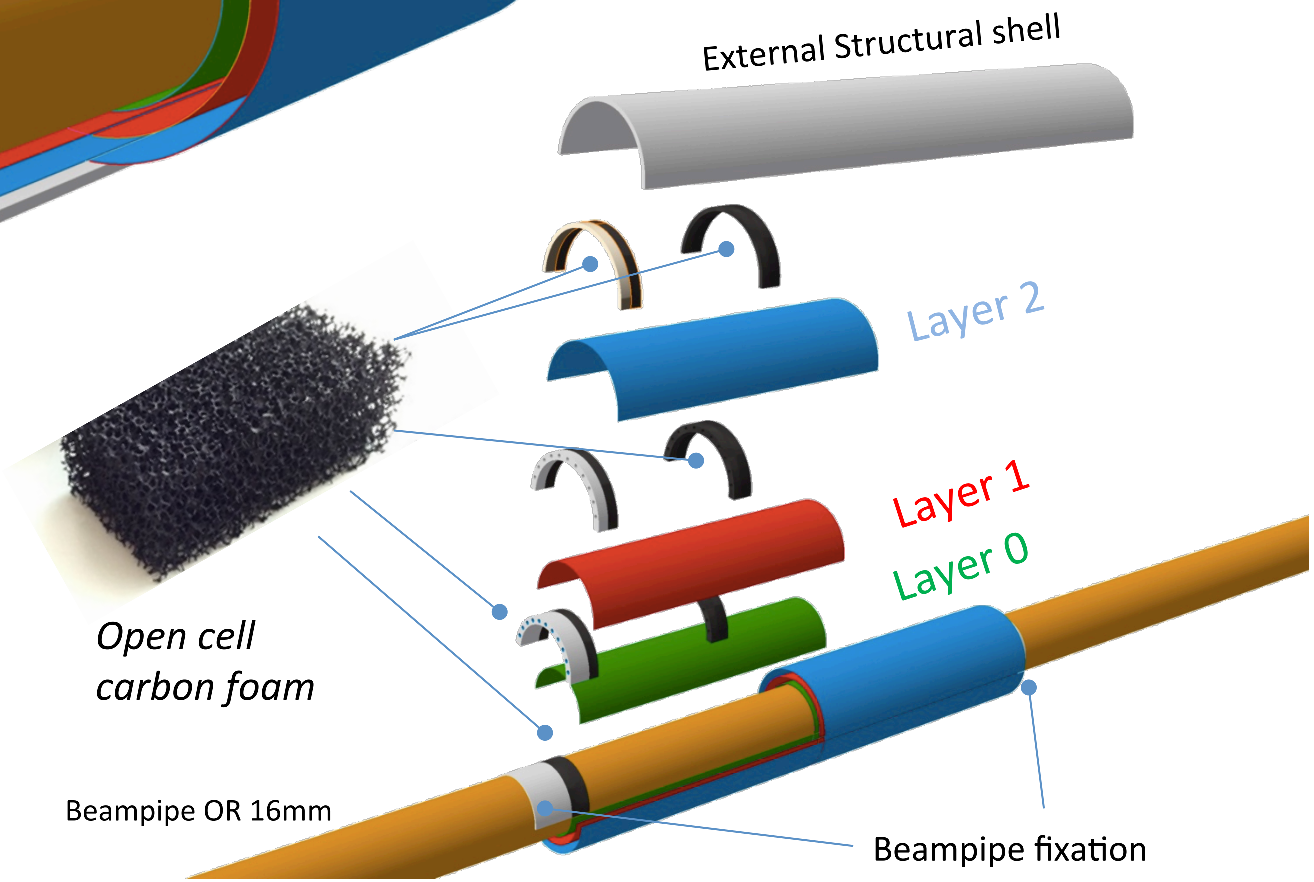


Chipworks: 30µm-thick RF-SOI CMOS

Silicon Genesis: 20 micron thick Si wafer

"Silicon-only" Cylindrical Vertex Detector (Inner Barrel)





Layers supported by high-thermal conductive carbon foam (half-ring)

Cooling is provided by air flow through the carbon foam.

A 3D Pixel Chamber

Active target using CMOS APS

A pixel chamber as heavy-flavour imager

Studies on 3D Pixel Chamber Imager for measuring charm and beauty at a fixed target experiment

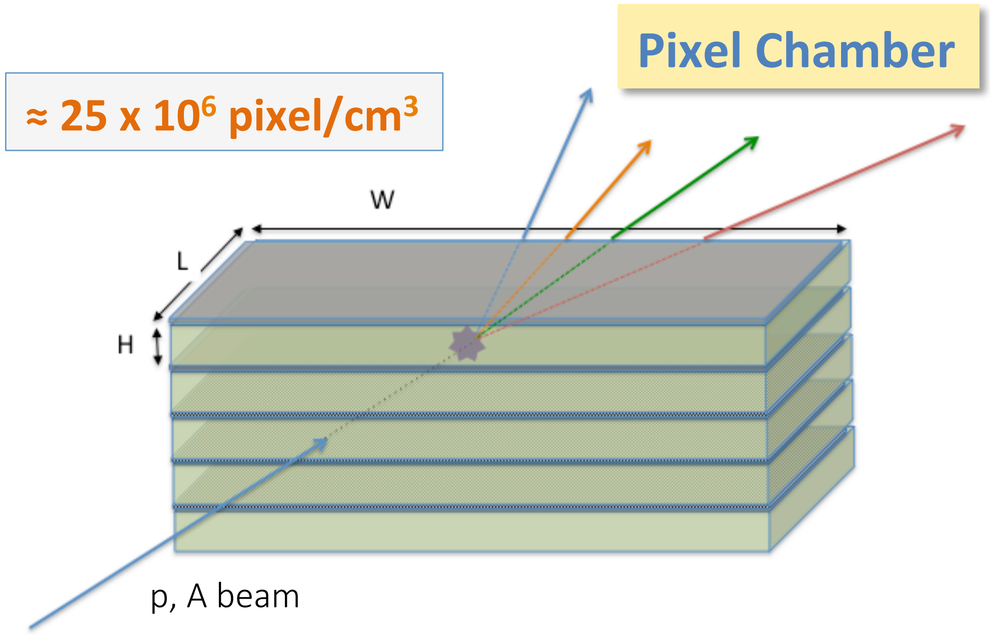
The heart is a **3D pixel chamber** used as active target

The idea is to have a detector able to provide the image of the proton-nucleus or nucleus-nucleus interaction and track the particles generated in the inelastic collision just starting at the interaction point

The pixel chamber is realized with a stack-up of thin CMOS sensors providing truly 3D (almost) continuous tracking with a precision of few microns for very high rate and multiplicity environment

Nuclear interaction inside a stack-up of N fine pitch pixel sensor

- N ≈ 100 , H ~ 50μm, L ≈ 0.1 nuclear collision length (≈30mm)
- *cm boost: ≈ 14 at 400 GeV/c (SPS), ≈60 at 7TeV (LHC)*



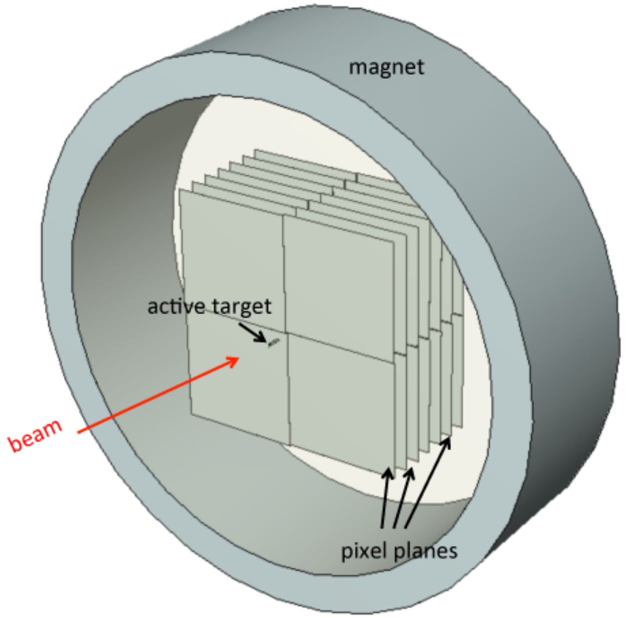
A pixel chamber as heavy-flavour imager

Using ALPIDE, Pixel Chamber Detector with a volume of about 15(w) x 30(L) x 5(H) mm^3

- segmented in pixels of about 27 x 29 x 50 μm^3
- providing the measurement of 25 x 10^6 space points / cm^3
- with a spatial resolution of ≈5μm in the three dimensions

Besides the huge granularity which ensures a three-dimensional image-like reconstruction of the event, this detector is sufficiently radiation hard (10^{14} - 10^{15} 1MeV n_{eq}) and fast for measurements in fixed-target mode (integration time O(1μs)).

The Pixel Chamber is coupled to a compact silicon telescope immersed in a magnetic filed of few tesla for precise measurement of particle momenta.

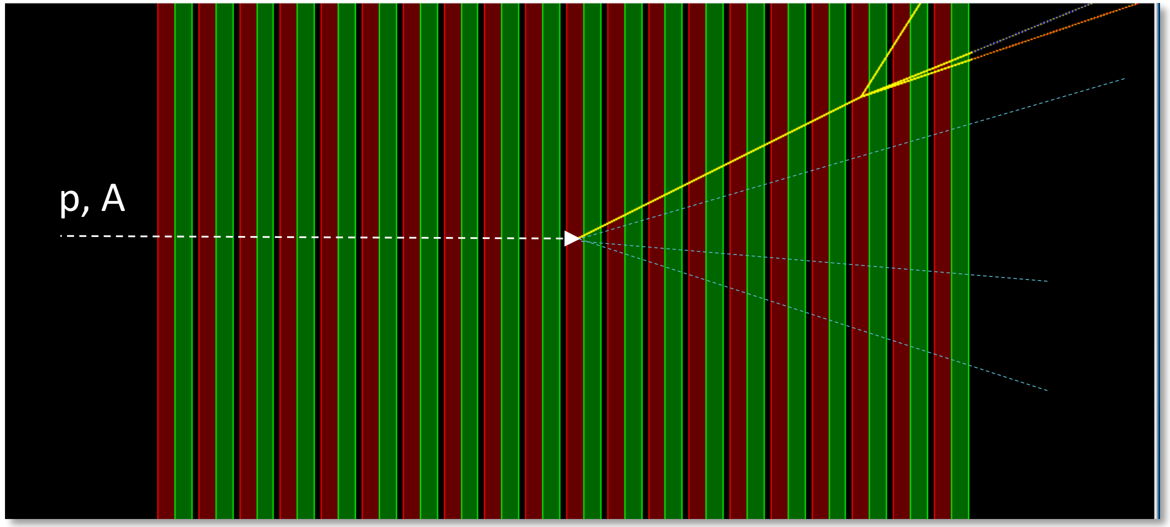


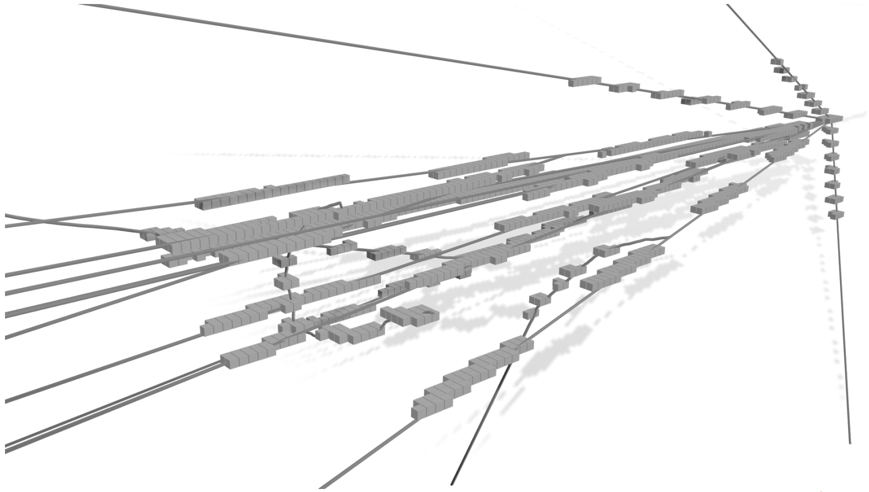
In this way a very compact instrument for imaging of heavy flavors with unprecedented precisions can be realized.

The detector could also be complemented with other detectors specialized for specific measurements (e.g. electrons, muons, photons)

Pixel Chamber - proof of principle demonstrator

A different configuration based on planes transverse to the beam direction



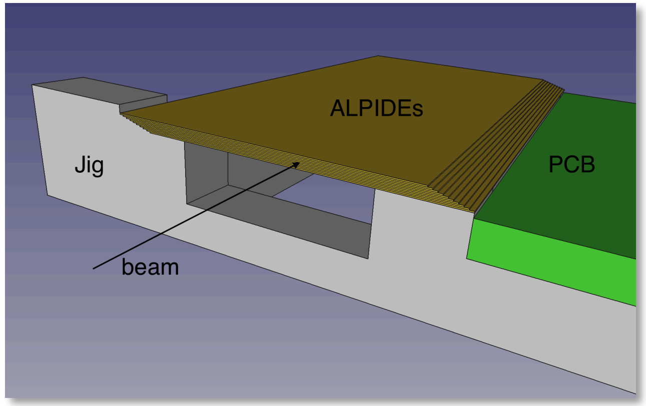


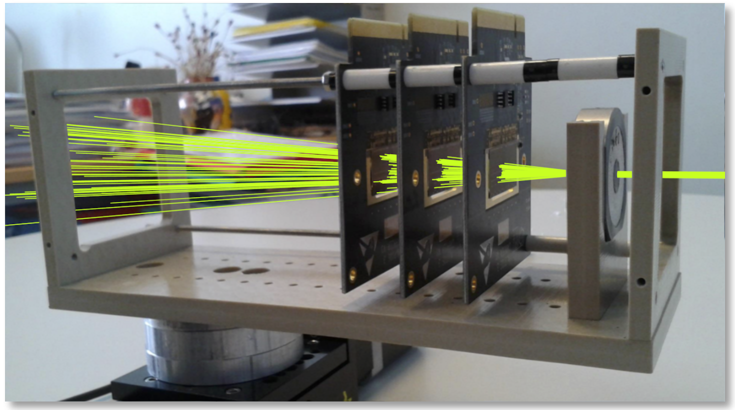
GEANT Simulation

The target is a different material, which is used as support and cold plate for the sensors

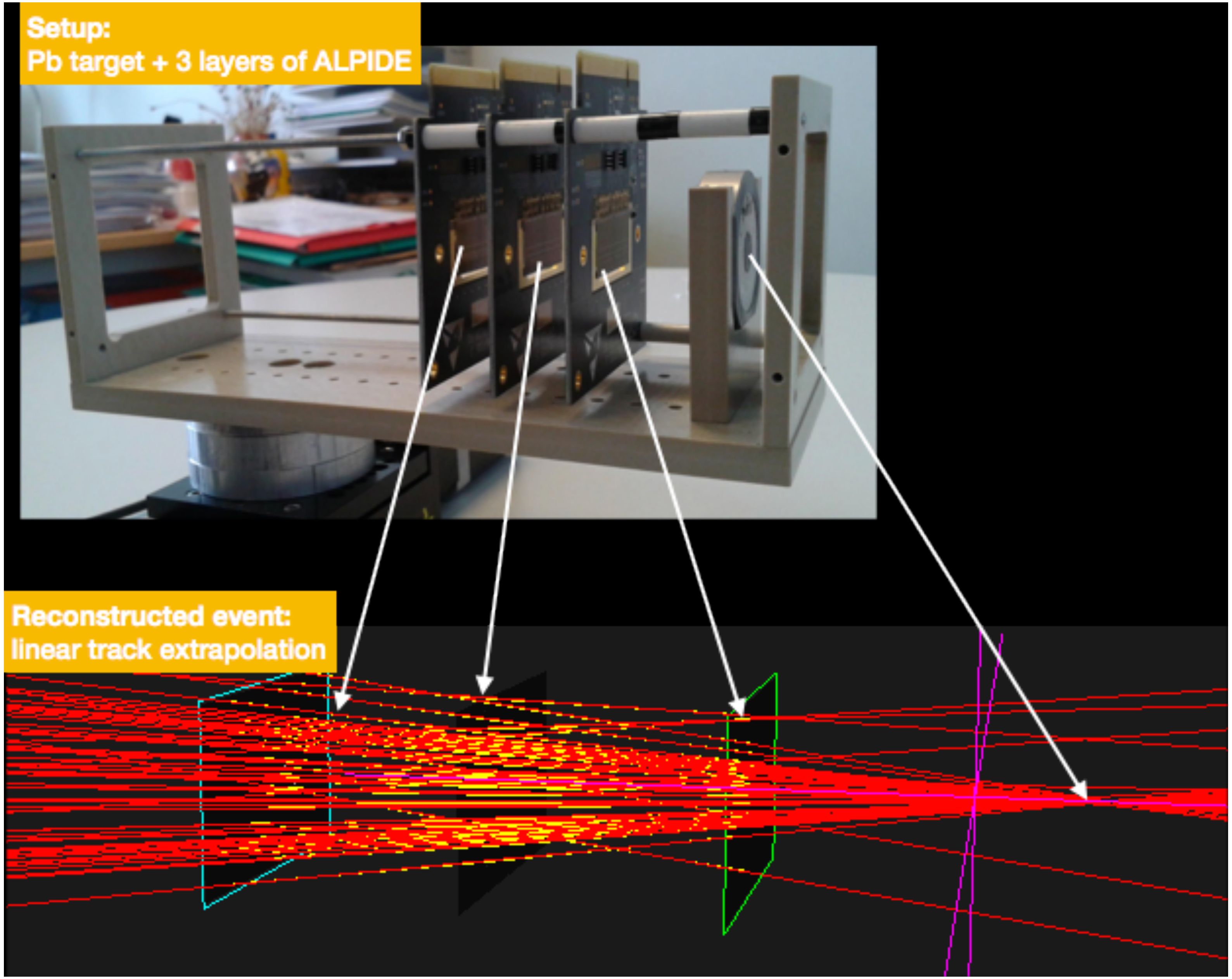
Demonstrator will be tested at SPS summer 2018

Pixel Chamber + telescope to measure beam position and emerging particles





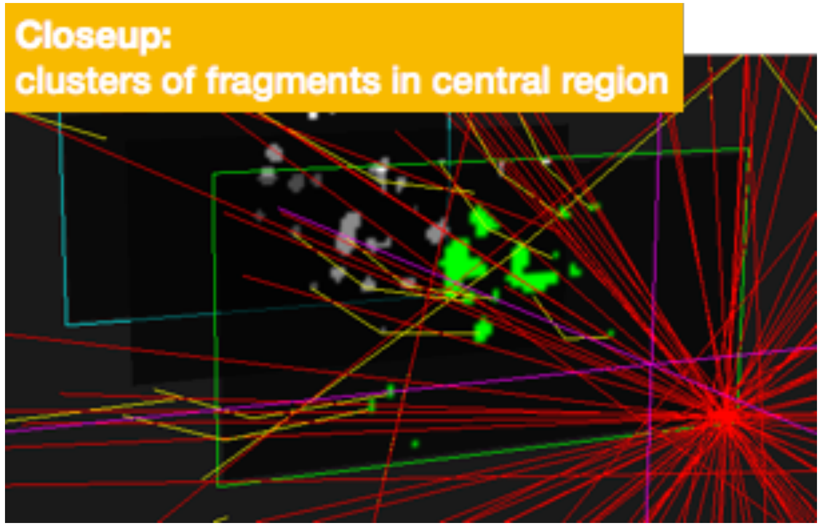
Xe-Pb measurements at SPS with ALPIDE



Xe – Pb @ SPS (2017)

- 15 AGeV/c Xe
- 10 mm Pb target, 3cm away
- 3 ALPIDE layers
- 2 cm plane spacing

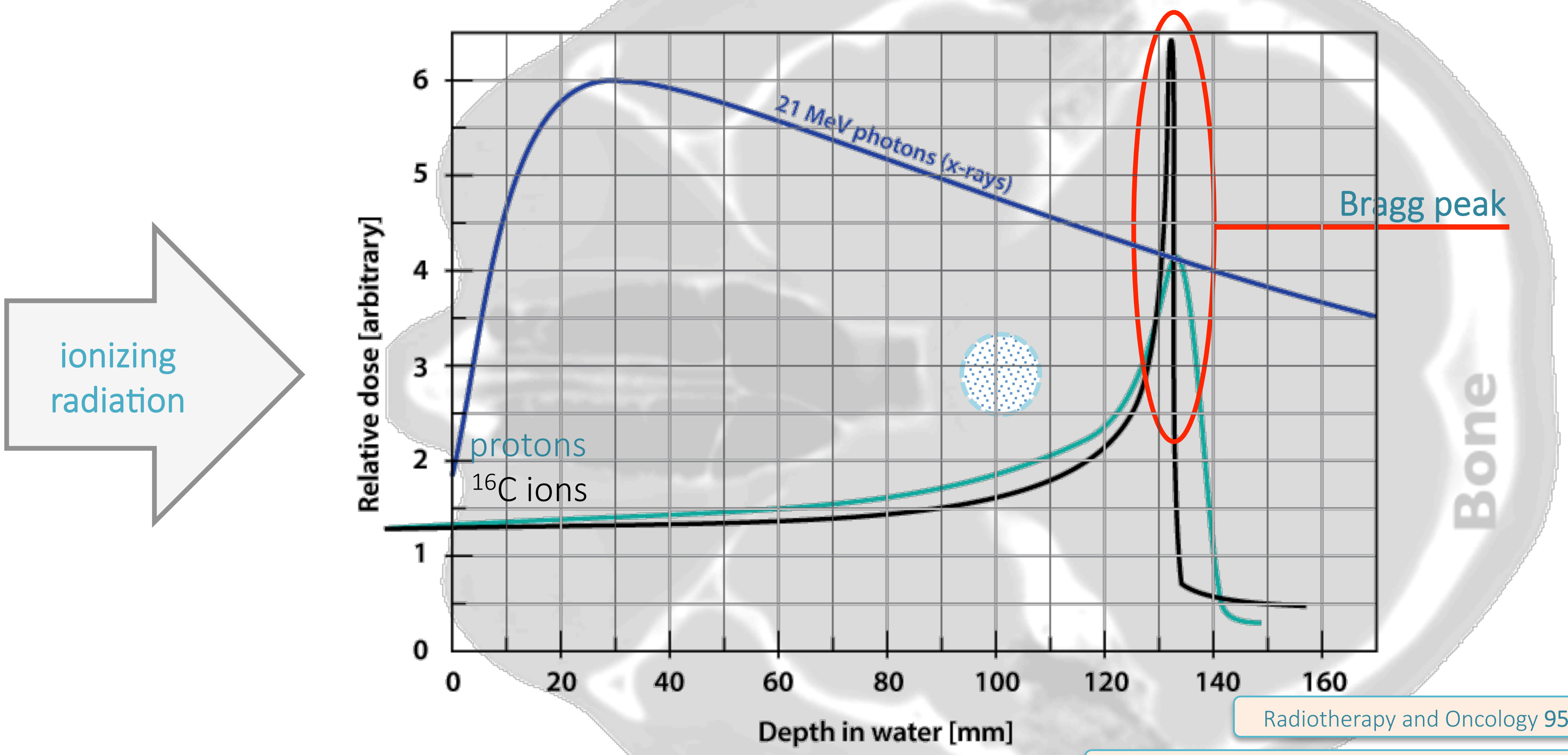
First look at data: plenty of events
some with interaction in silicon



Hadron Therapy

Use of CMOS APS for pCT

Proton (ion) energy transfer is highly localized (Bragg peak): greater effectiveness and much lower collateral damage respect to traditional x-rays therapy.

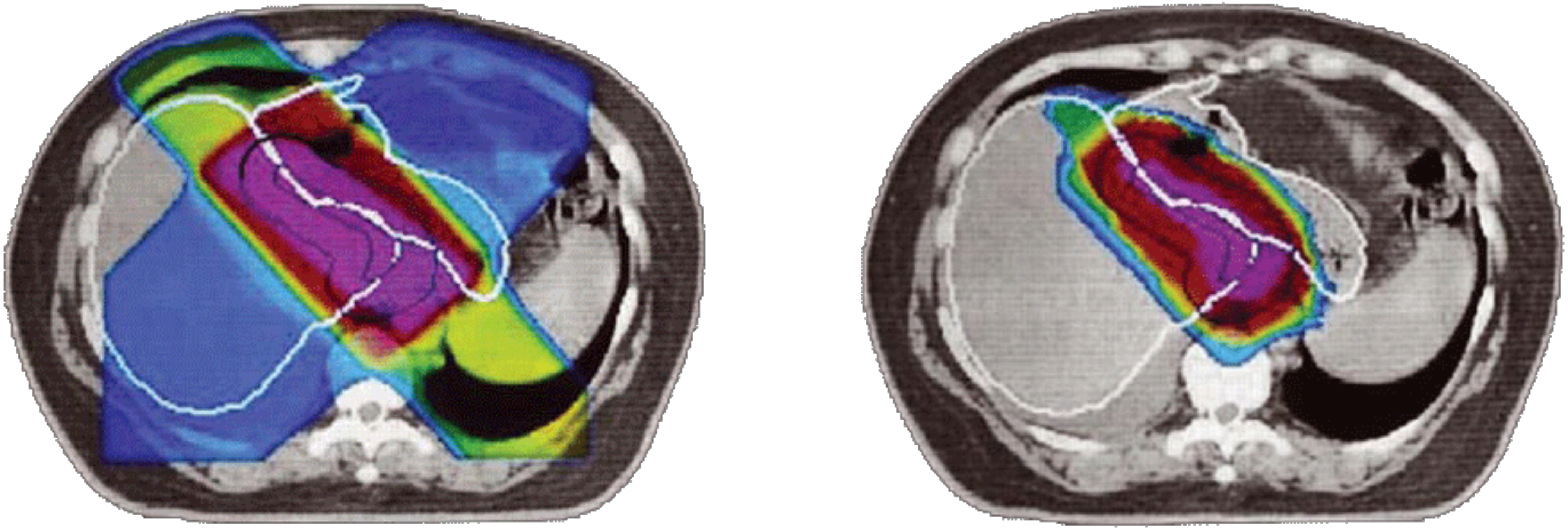


Radiotherapy and Oncology **95** (2010) 3–22

Radiation Oncology*Biology*Physics **83** (2012) 1549–1557

The Bragg peak position (depth) in the body depends on the ion energy and the tissue density it traverses. Changing energy determines the aiming depth.

Hadron therapy: reduced collateral damage



X-Rays treatment

Planned dose

0% 50% 100%

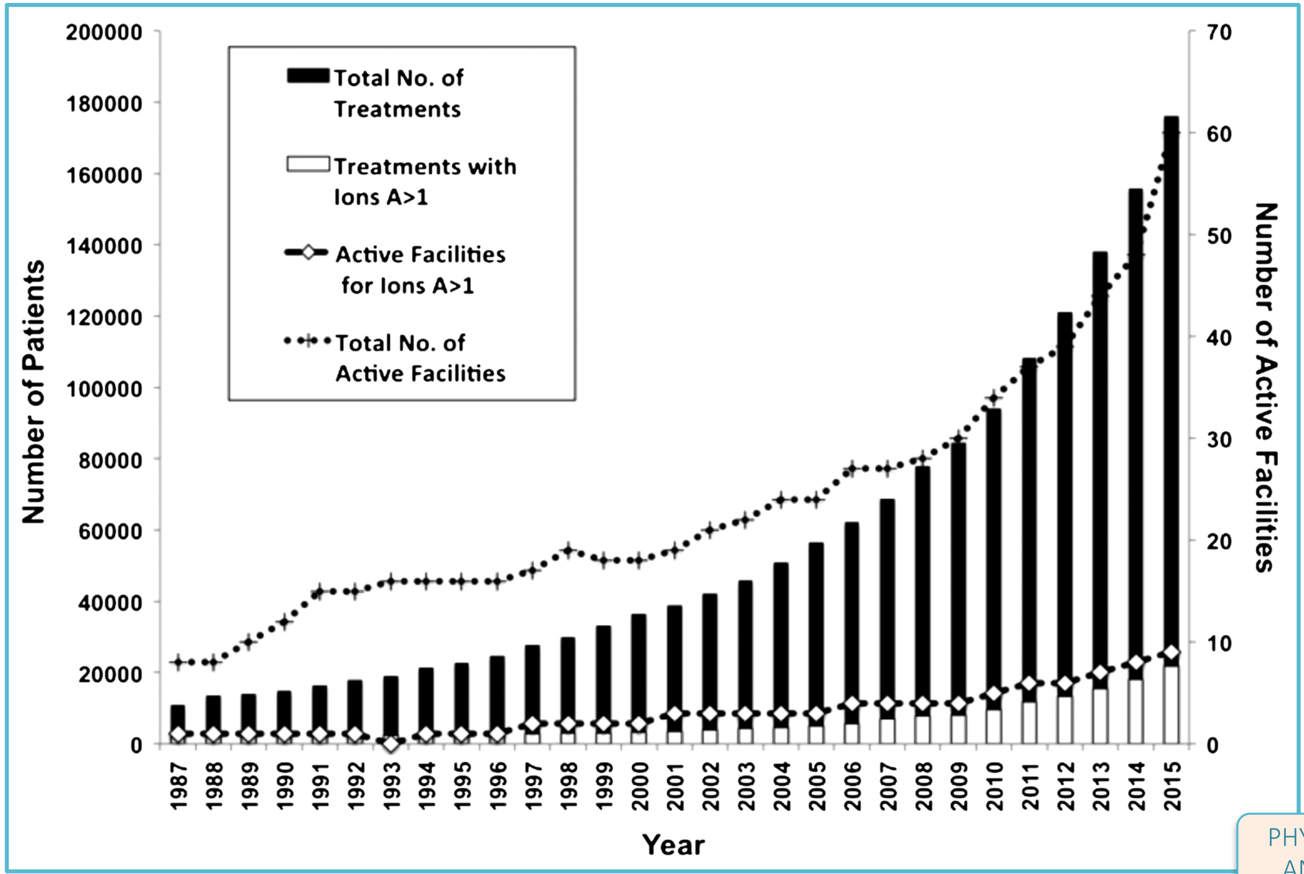
Protons treatment

JAMA **307** (2012) 1611-20

Radiation Oncology*Biology*Physics **83** (2012) 1549–1557

Hadron therapy facilities around the world

Only ≈1% of the candidates for proton therapy can be treated in the active facilities worldwide ….

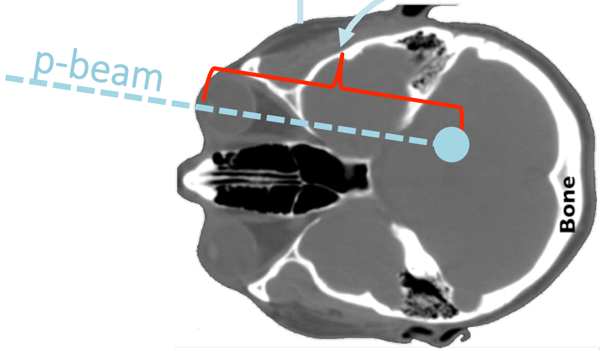


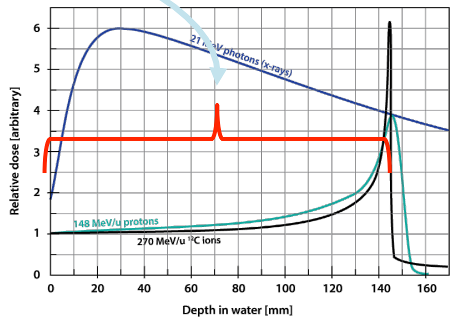
PHYSICAL REVIEW ACCELERATORS AND BEAMS **19**, 124802 (2016)

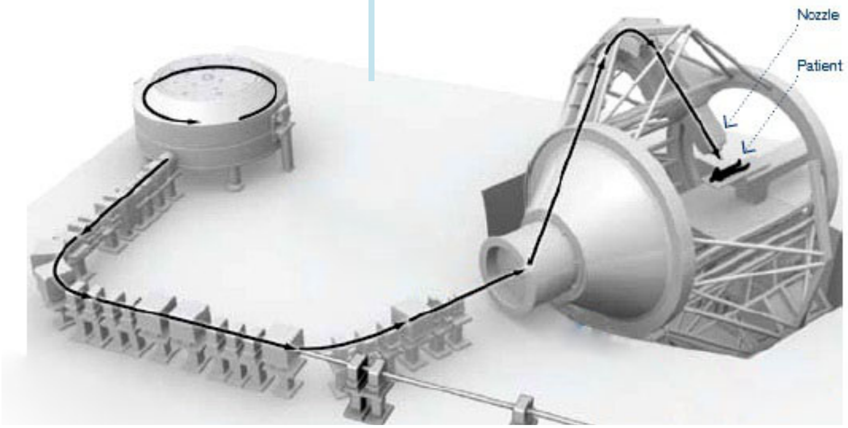
≈8000 more treatment rooms are needed around the globe

Hadron therapy: the aiming limit problem

Aiming the Bragg peak requires fine tuning of the proton energy to account for the tissue densities they have to traverse to reach the tumor.







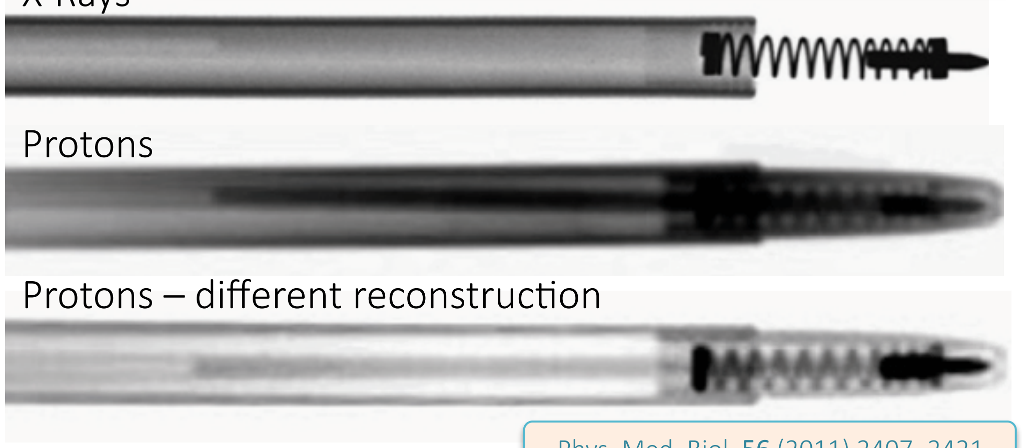
Poor tissue density resolution from X-Rays CT

Fine energy tuning better than 0.5%

NIM B **268** (2010) 3295–3305

Eur. Phys. J. Plus (2011) **126**: 78

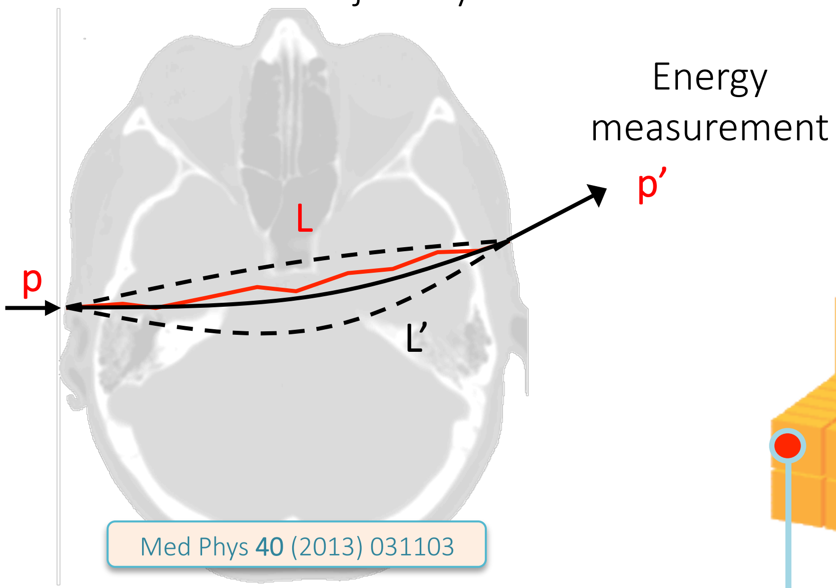
X-ray 3D CT cannot distinguish tissue densities with the required precision: proton therapy limit today (bigger systematic error, up to 5%). But protons actually can (and with much less dose, ≈ 1.5 mGy vs. 10-100 mGy).



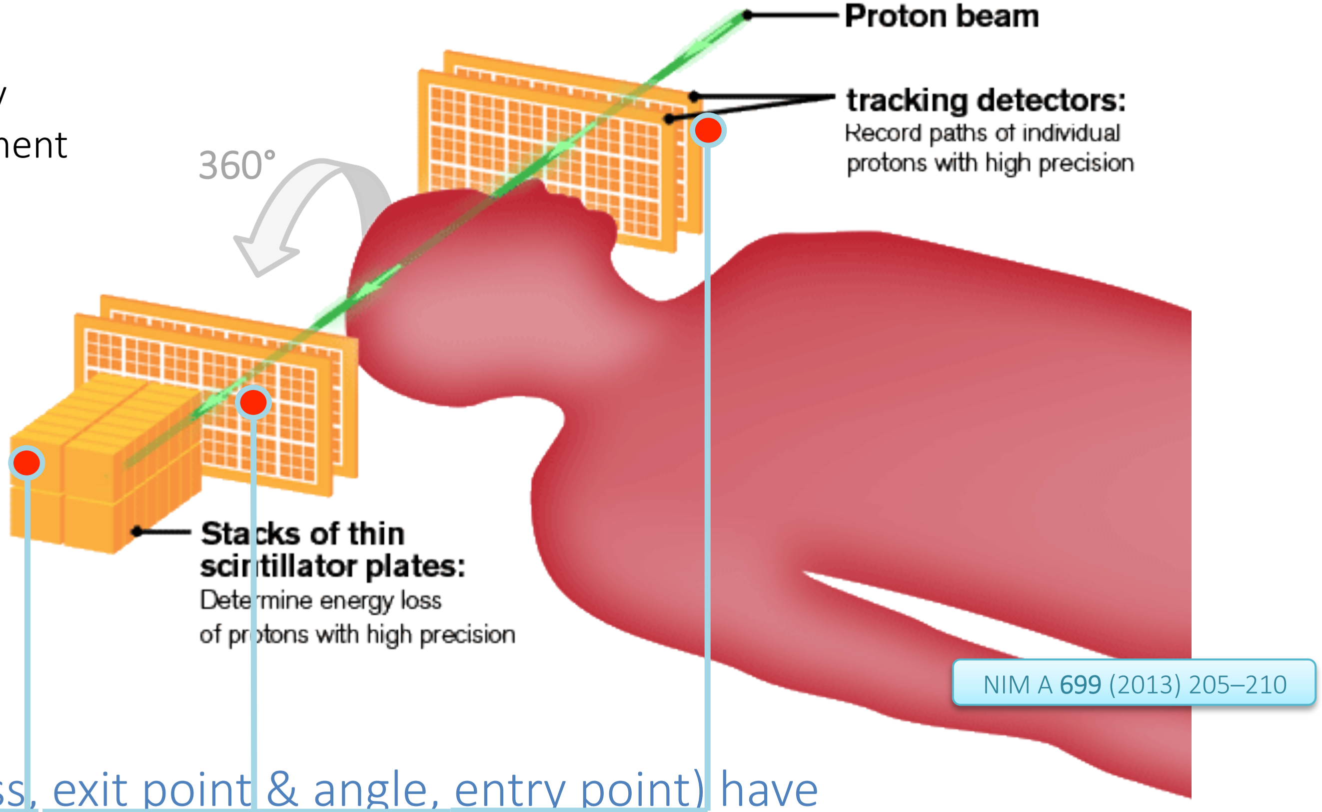
Phys. Med. Biol. **56** (2011) 2407–2421

The proton Computed Tomography (pCT) scanner

The pCT works on the same principle as a "standard" x-rays CT: recording particles passing through the target from different angles to reconstruct a 3D image. Main difference is that, while photons are simply absorbed, protons also scatter.



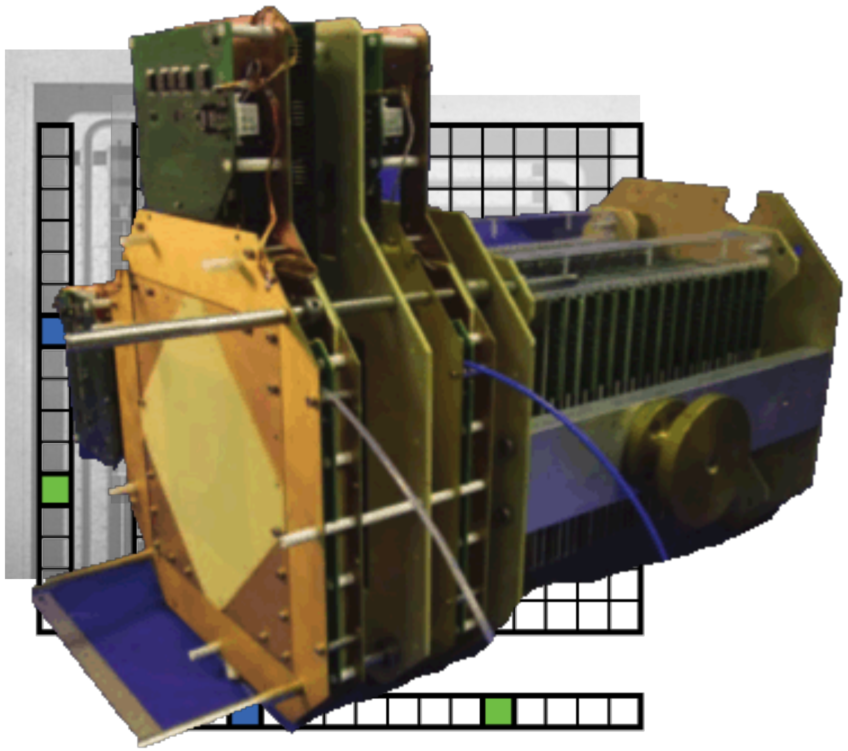
Entry and exit points + angle
Most Likely Path calculation



At least 10^9 proton tracks (energy loss, exit point & angle, entry point) have to be recorded to provide a detailed enough image. This leads to long exposure time (10s minutes) with current state of the art: limited to R&D only.

State-of-the-art: pCT scanner in R&D world

State of the art prototypes pCT trackers employ silicon micro-strips or scintillating fibers to get high speed readout over large area at reasonable bandwidth



Current state of the art, in-house built gaseous detector

1. "Slow", as readout speed of 10s MHz (and actual particles rate much less due to Poisson). 10 minutes for a full pCT!

NIM A **699** (2013) 205–210

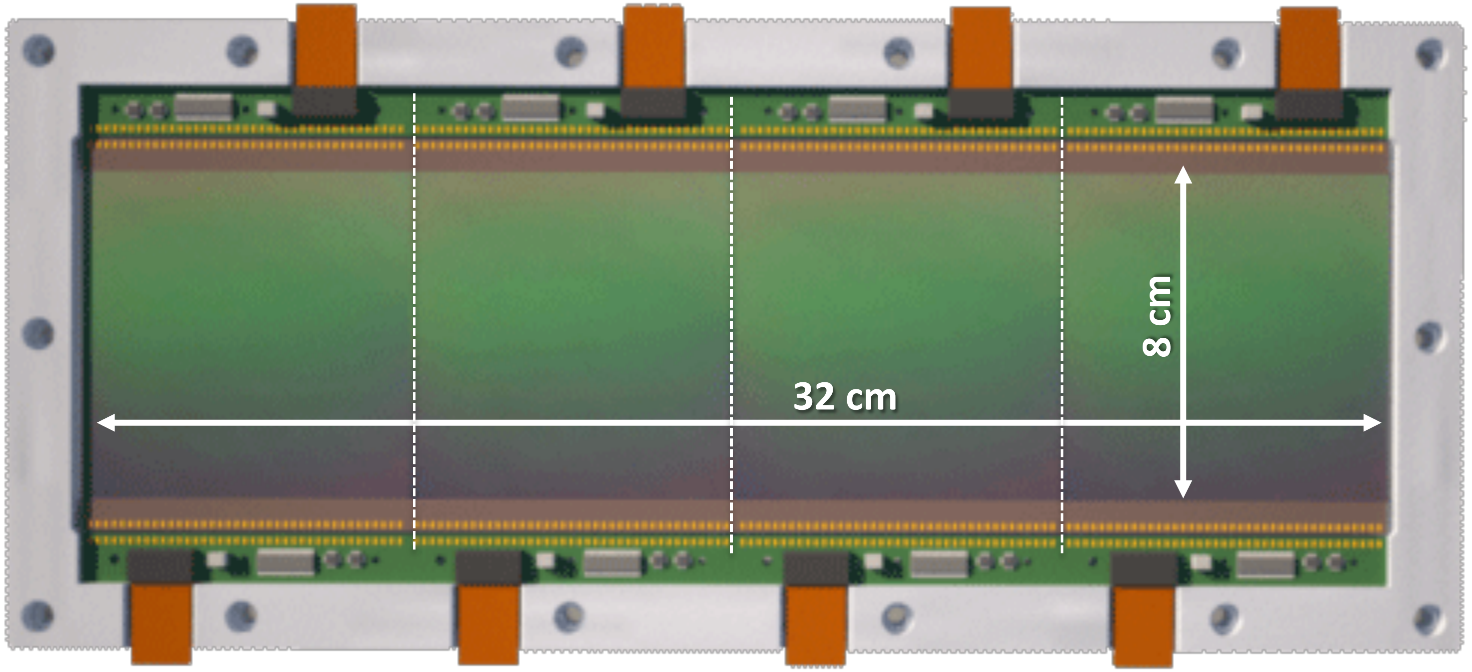
2. Requires two layers (x and y) for every station, material budget affects protons scattering + high voltage or gas.

3. Non commercial technology, built in house (scintillating fibers) or derived from HEP experiments (micro-strips).

Such approach covers the large area necessary to track particles over a head-sized target (≈10 × 30 cm^2) with "affordable" complexity and bandwidth. Effective for R&D, unlikely to meet the requirements of a commercially feasible pCT system

Large CMOS sensors – Tracking layer requirements for pCT

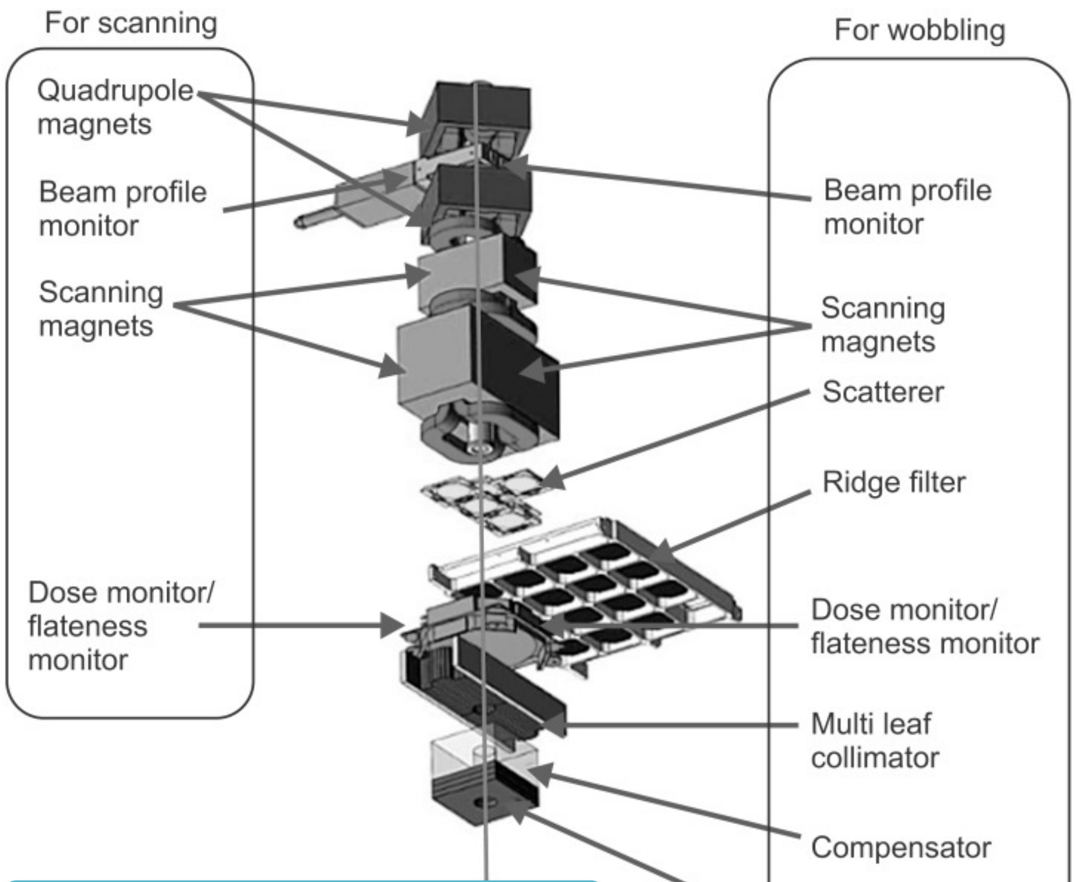
- Fast (> 10 MHz cm^{-2}) proton tracking at low power in silicon (50 mW cm^{-2})
- Monolithic, thinned (≤ 50 μm) and large area (> 16 cm^{2}) device to minimize proton scattering.
- No support structure behind the silicon.
- Cost effective, reliable, simplified commissioning & operations, commercial process (for large production)
- Low voltage for real clinical usage



Large sensors – broad beam useful for imaging purposes

Broad beam over the entire target area put lesser requirements on the tracking and calorimeter system

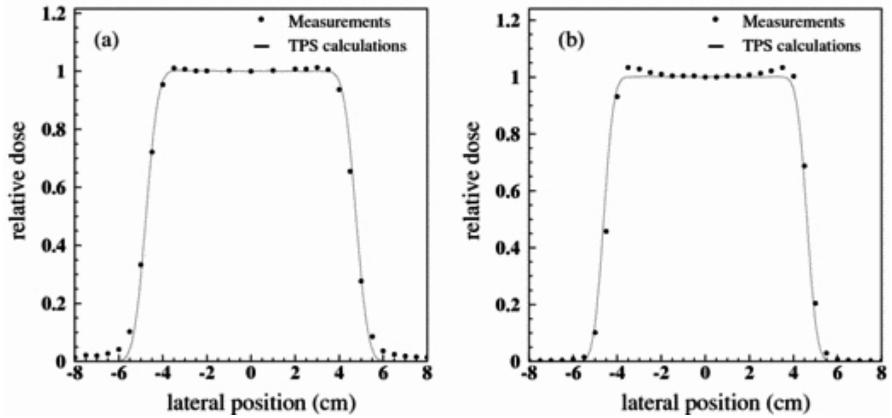
Mix of fast (MHz) wobbling magnets and scatterer(s) generates an almost uniform illumination profile (typical example reported in plot)



Radiation Oncology Journal 2015;33(4):337-343
http://dx.doi.org/10.3857/roj.2015.33.4.337

- Mitsubishi multi-purpose nozzle system
- Broad beam area: 25 × 25 cm^2
- Scanning beam area: 24 × 24 cm^2
- For a 20 × 20 cm^2 imaging area, 10^9 protons in 10 s exposure → 250 kHz cm^2
- Considering non uniformity, time fluctuations, etc...

≈ 1 MHz cm^{-2}

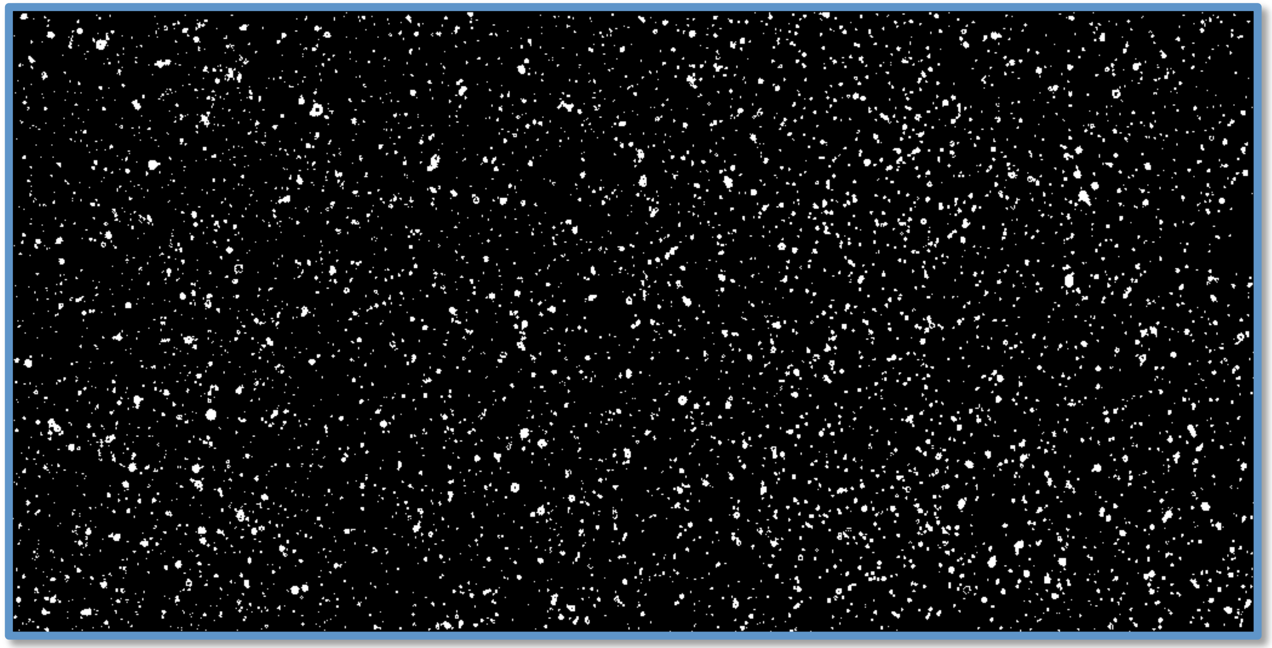


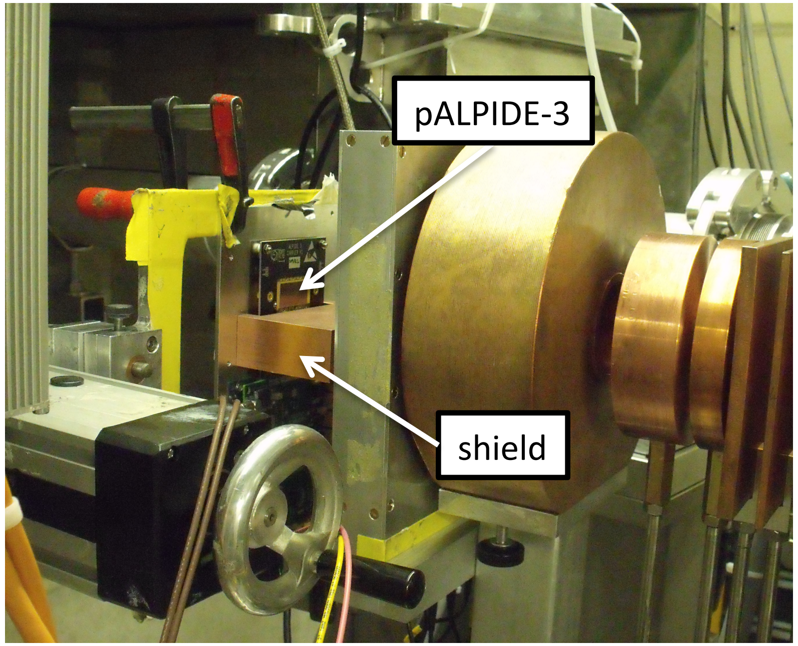
T Akagi et al 2006 Phys. Med. Biol. 51 1919
https://doi.org/10.1088/0031-9155/51/7/020

ALPIDE – proton rate capablities

ALPIDE pixel matrix can cope with particle rates of ≈100MHz cm^{-2} (power density 40mW/cm^2)

pALPIDE-3 Sensor (0V V_{sub})





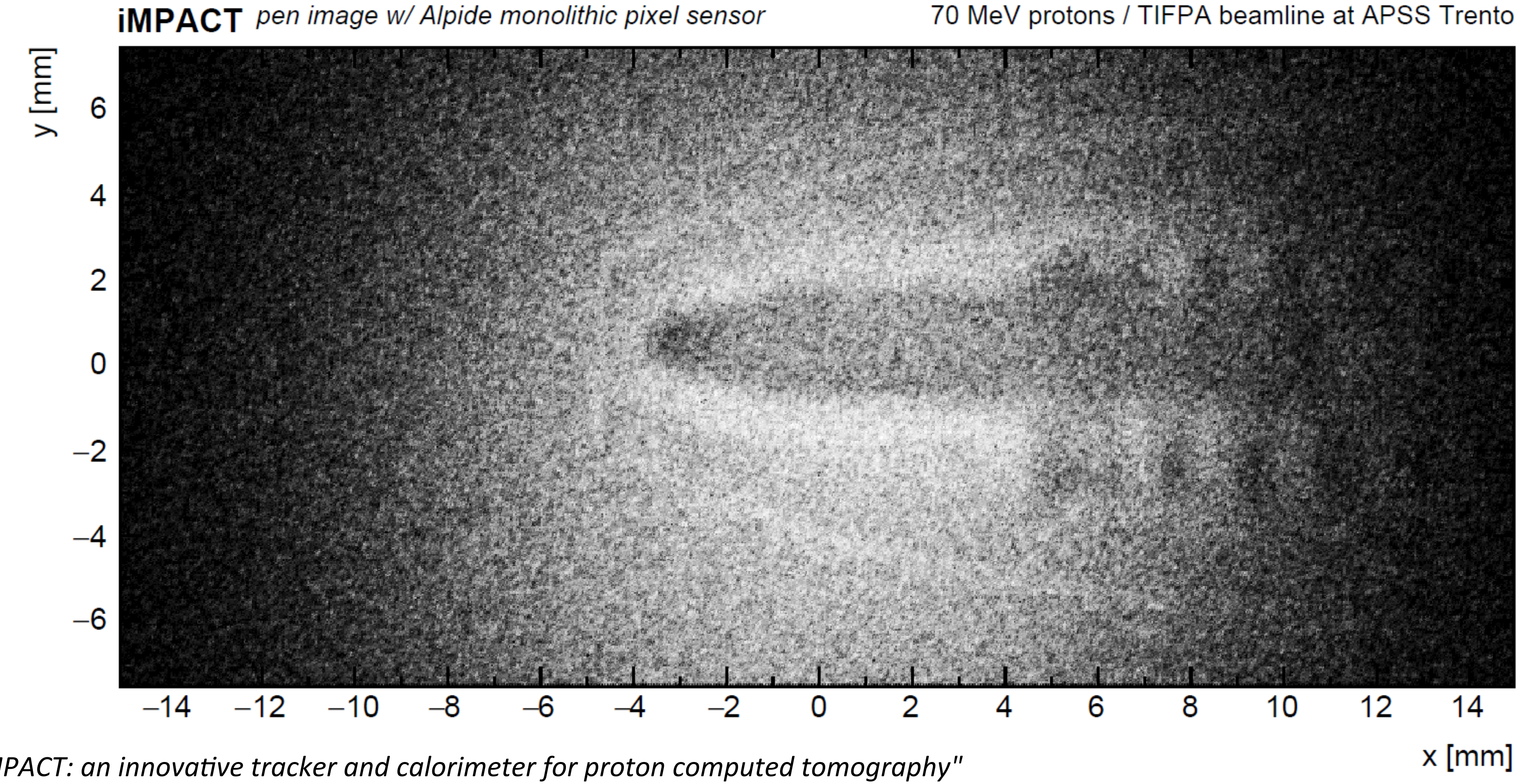
PIF @PSI - Nov 2015, 200 MeV protons, 1.6 x 10^8 $cm^{-2}s^{-1}$

Output bandwidth of ALPIDE (1 Gbit/s) limits maximum rate to 14 MHz cm^{-2}

Large sensors – ALPIDE first "proton" light

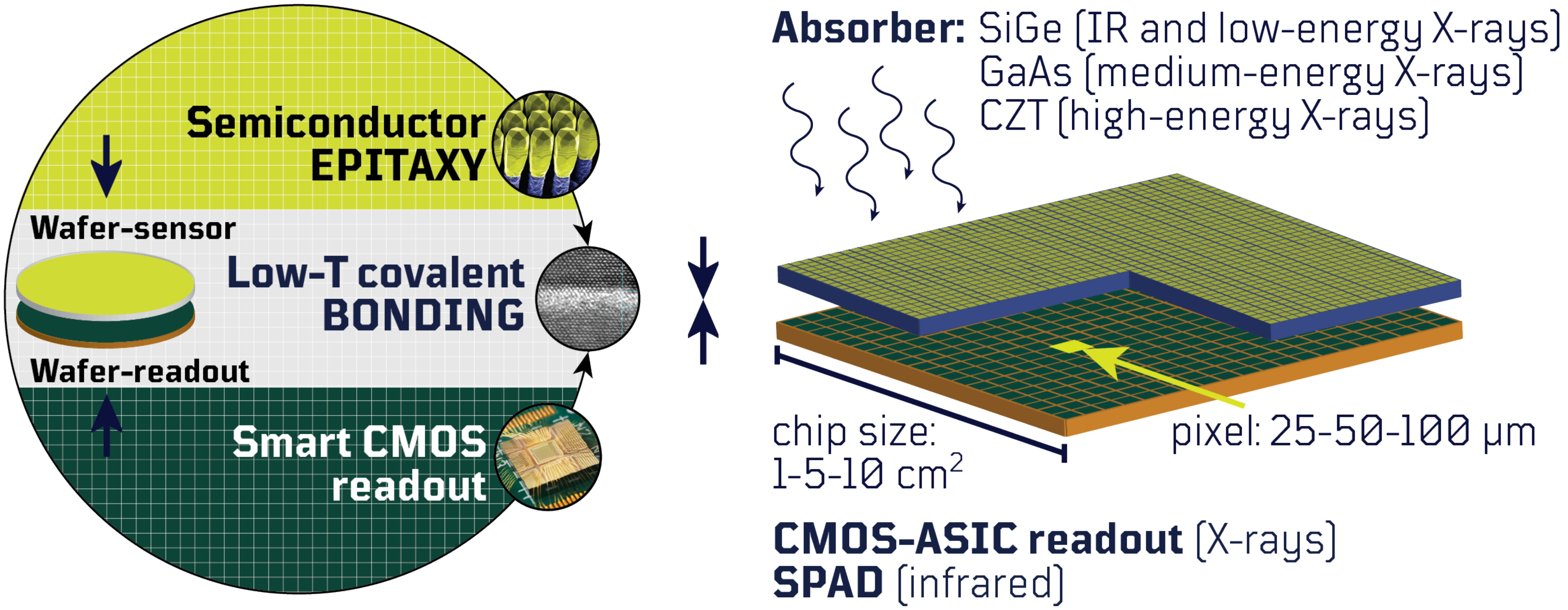
ALPIDE used to take a demonstrative proton radiography of a pen: metal, different plastic densities, air distinguishable

Raw data of a single projection (4.5 x 10^5 hits)



"iMPACT: an innovative tracker and calorimeter for proton computed tomography"
TRPMS-2018-0013.R1 Transactions on Radiation and Plasma Medical Sciences

Covalent bonding of optimized absorbers to CMOS chip



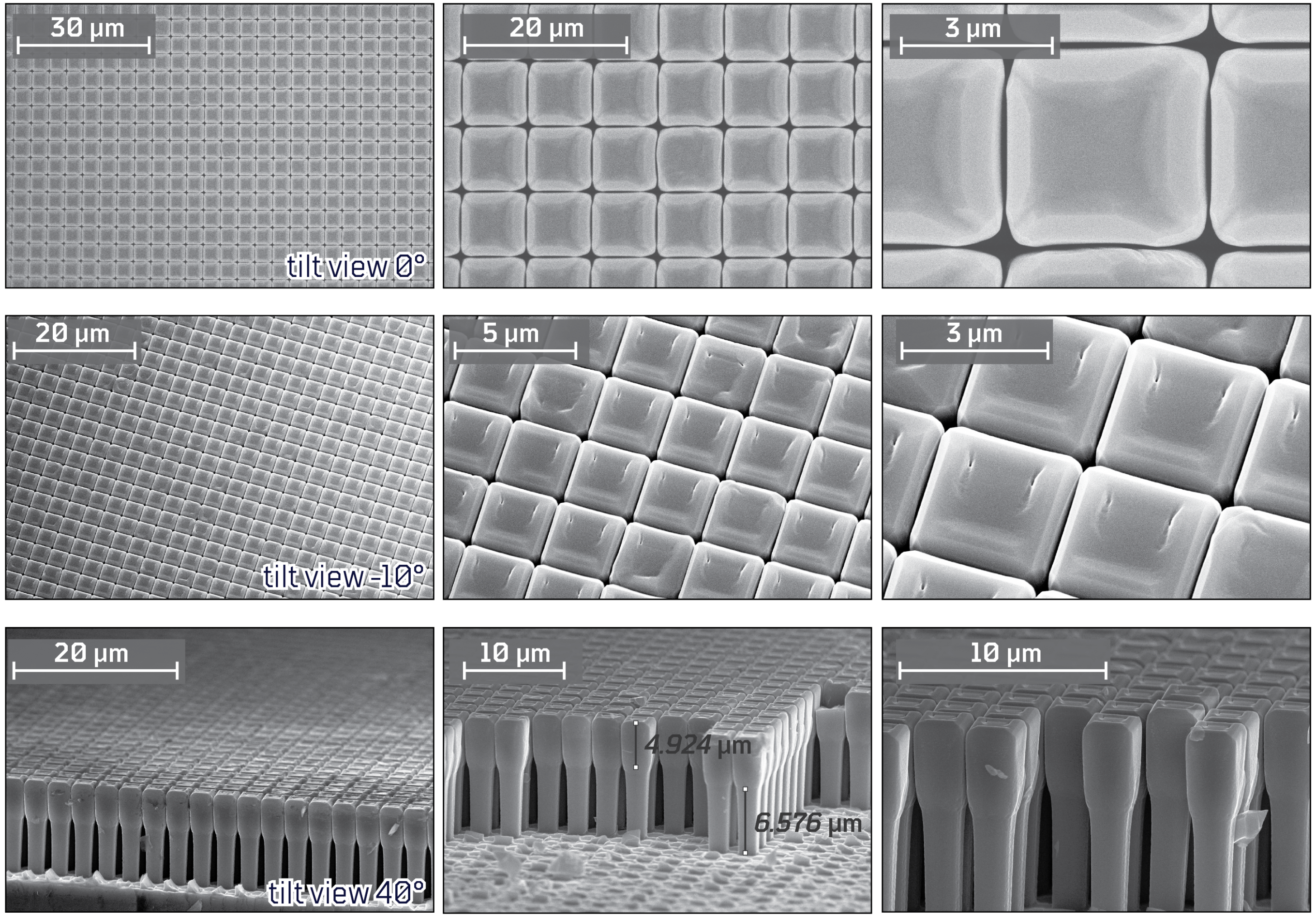
Courtesy of G-Ray

Covalent bonding of optimized absorbers to CMOS chip

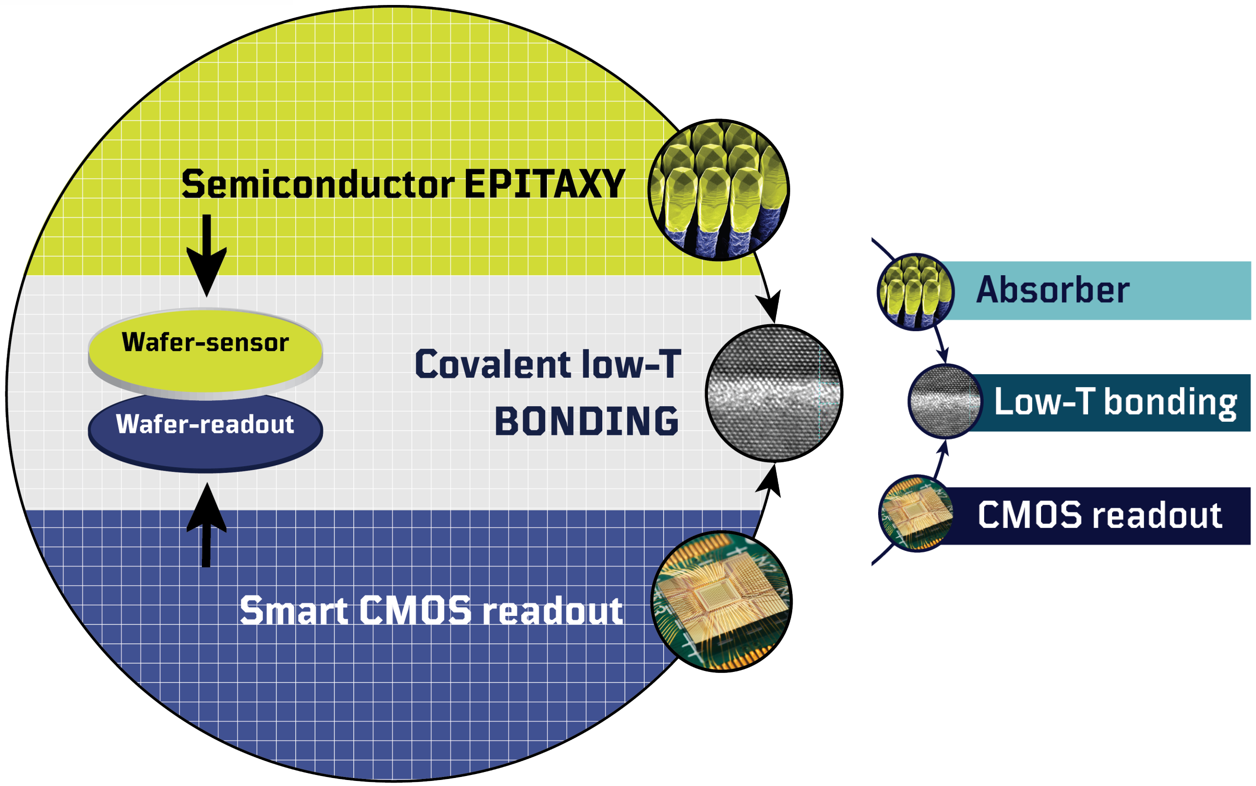
G-ray's unique and proprietary Epidavros™ system

Courtesy of G-Ray

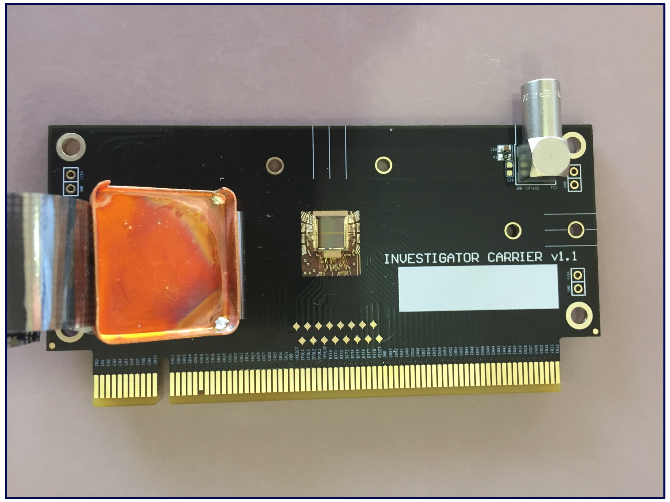
SiGe-pillar epitaxy by Epidavros™ system (April, 9th 2018)



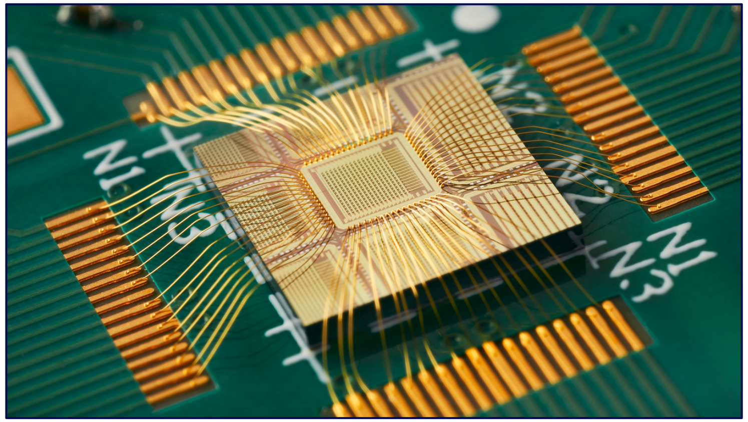
Covalent bonding of optimized absorbers to CMOS chip



for infrared and X-rays



INVESTIGATOR CHIP @ CERN

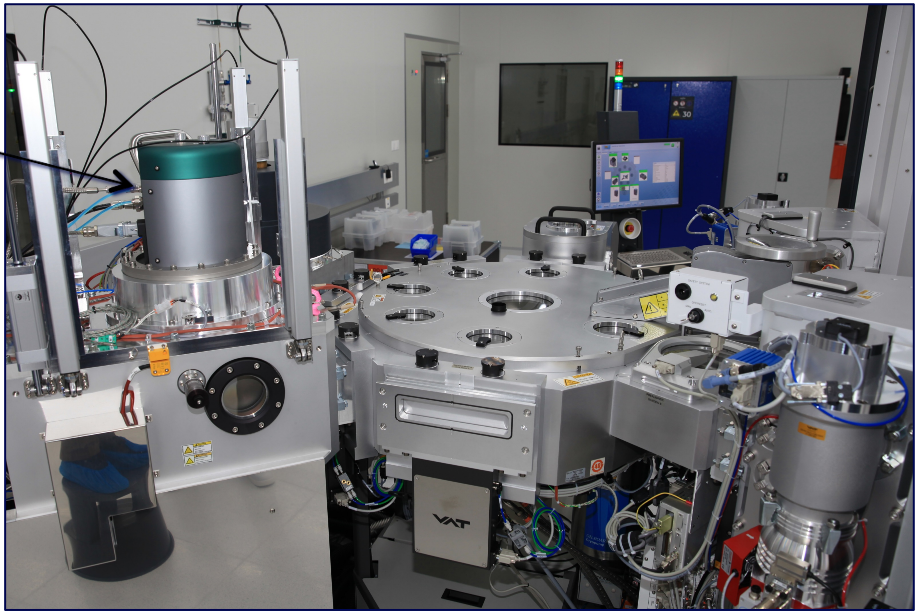


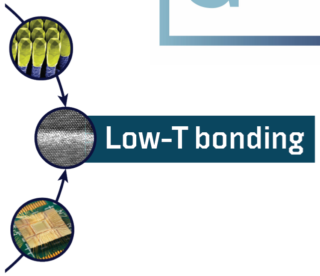
NOVIPIX CHIP @ CSEM & Empa

Low-temperature bonding: technology development

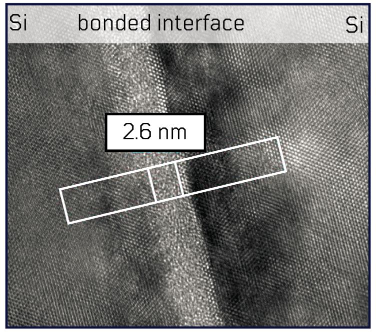
Modified EVG ComBond® System at G-ray

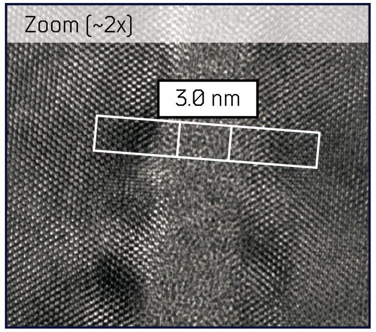
G-ray's Argon Plasma Module for atomic-scale wafer's surface cleaning

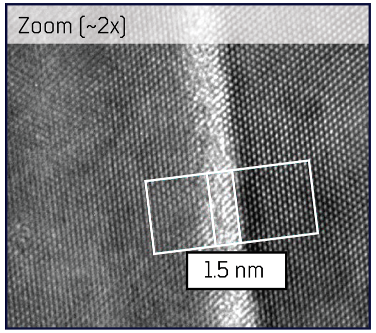


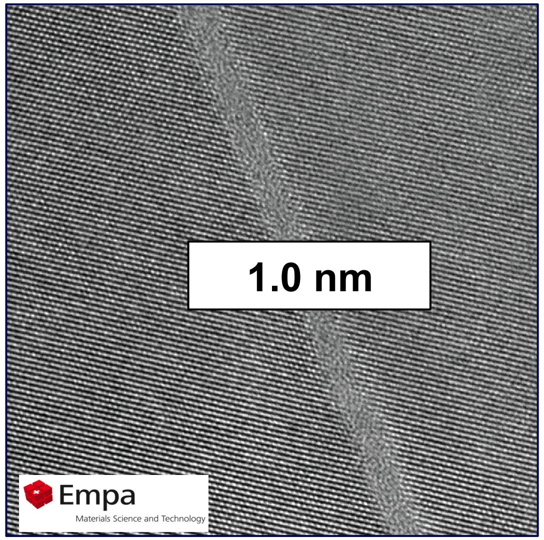


bonded interface reduced to a seamless 1 nm (Q1-2018)!







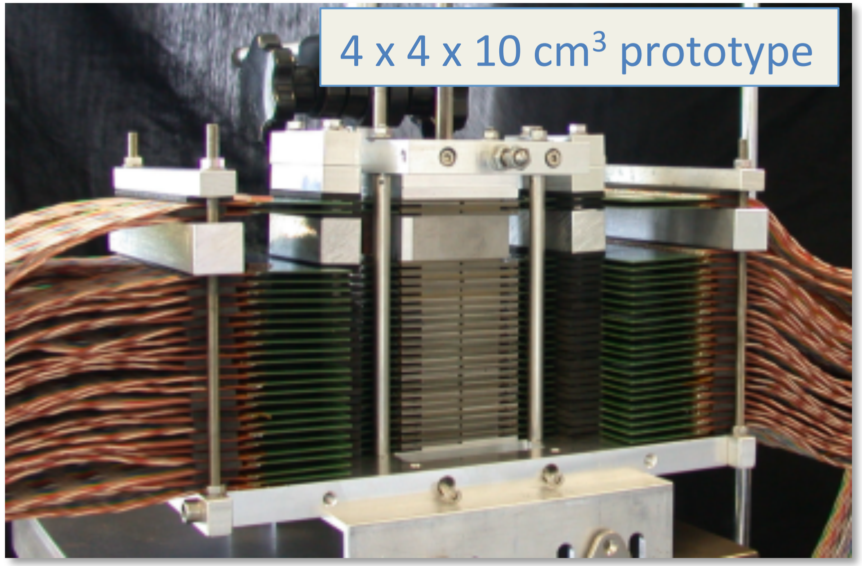


Experiments 2016 → Experiments 2017 → Experiments 2018 →

Picture (^{55}Fe) of a flower 30 x 1s
"photographed" with ALPIDE

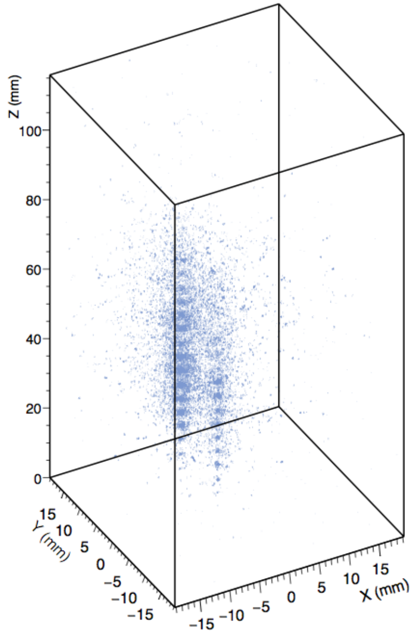
High-Granularity Digital Calorimeter Prototype

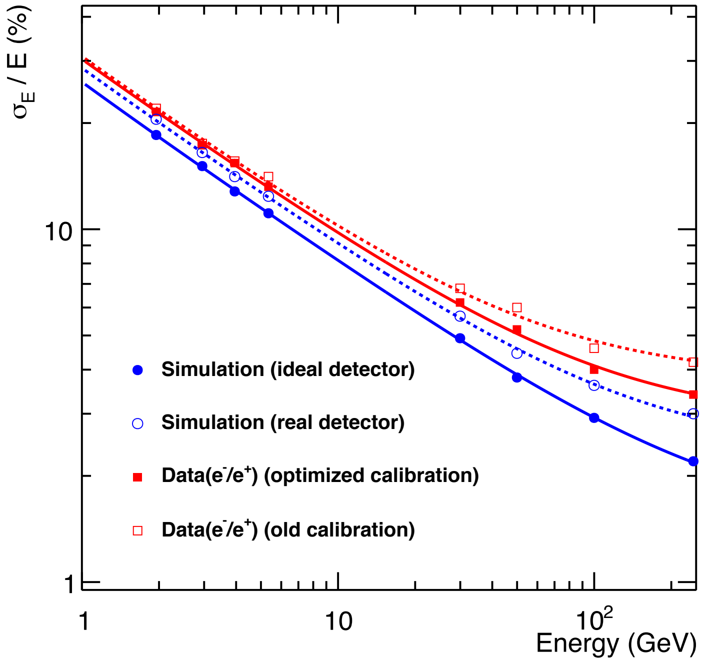
R&D in the context of FoCal in ALICE



Extremely compact design

Small Moliere radius (RM = 10.5 ± 0.5mm)





Prototype based on MIMOSA pixel chip

- 24 layers (1 X_0 W + MIMOSA23)
- 39M pixels, 30μm pitch
- Beam tests from 2 to 250 GeV/c (DESY, CERN PS & SPS,
- Cosmic muons

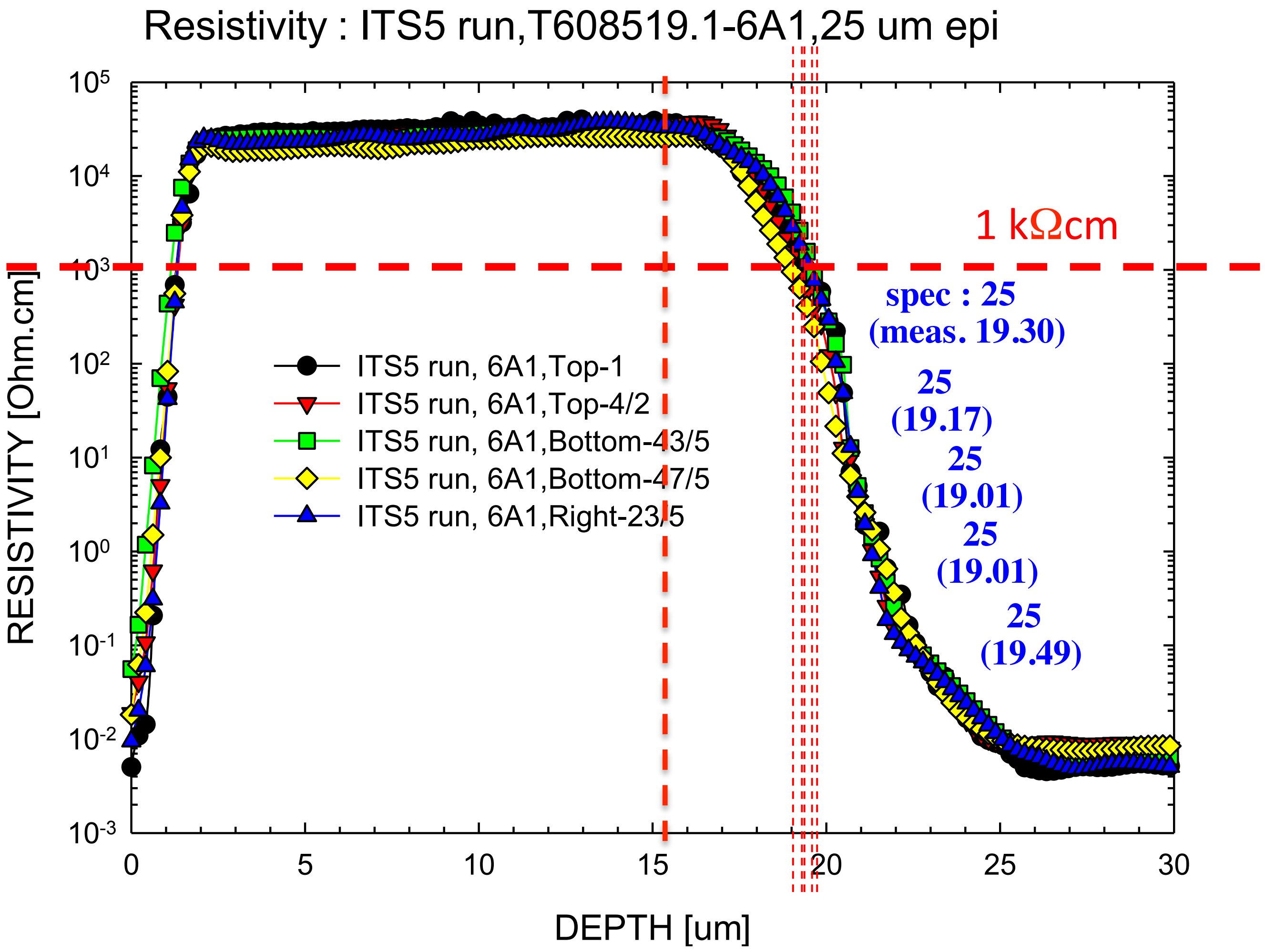
Very good energy linearity and resolution

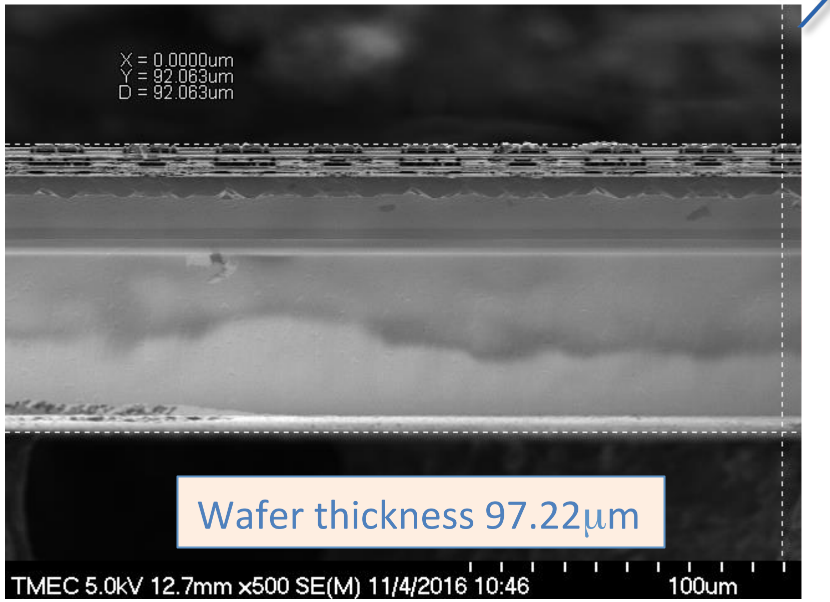
Extremely good position resolution

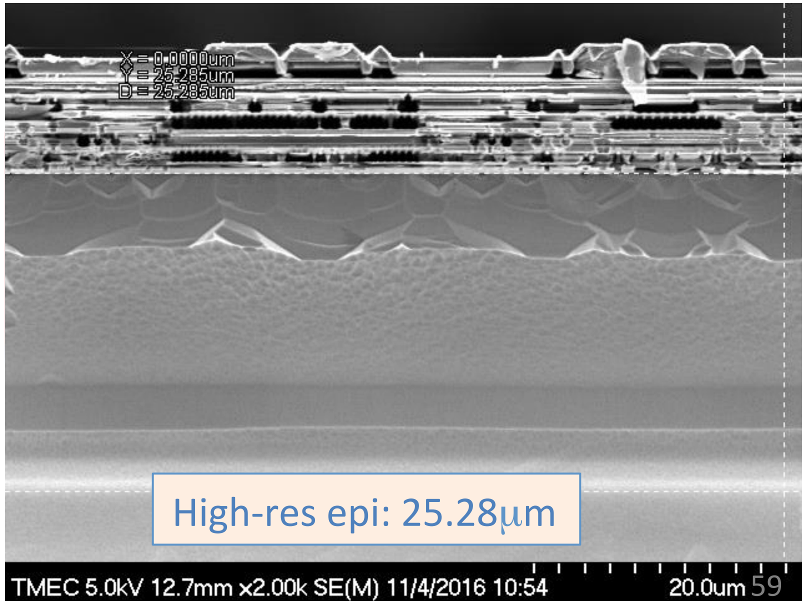
Preparing next generation prototype with ALPIDE

ALICE CMOS Pixel Sensor

Blank Wafers QA at TMEC (SRP and XSEM measurements)

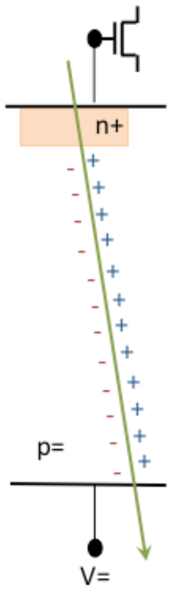






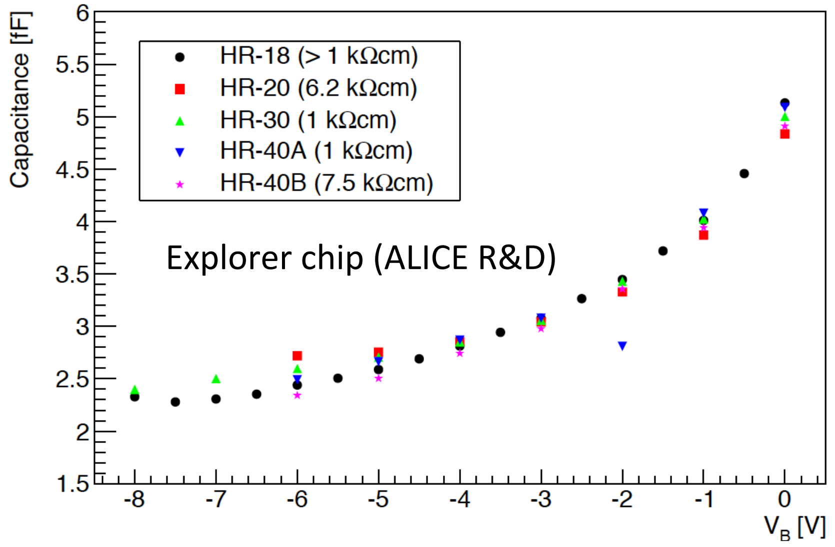
ALICE CMOS Pixel Sensor

Low capacitance ➔ large S/N at low power

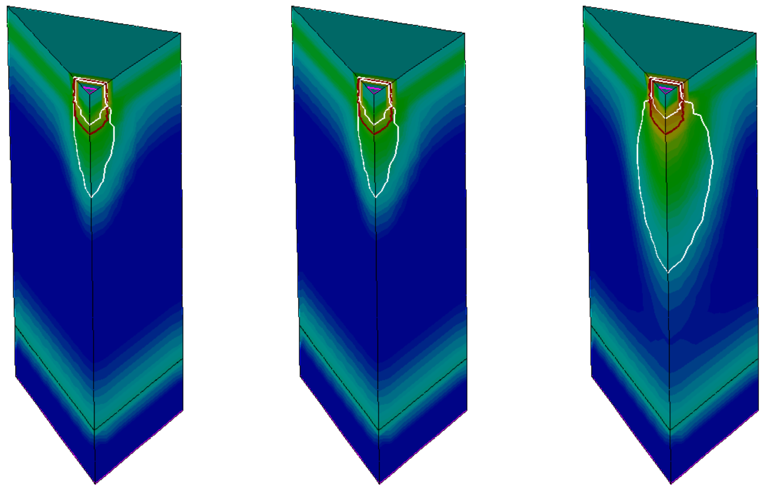


NWELL DIODE output signal = Q /C

- Minimize spread of charge over many pixels
- minimize capacitance:
  - ➡ small diode surface
  - ➡ large depletion volume



Diode 3µm x 3µm square n-well , White line: boundaries of depletion region



-1V, 1×10^{13} cm^{-3} | -1V, 1×10^{12} cm^{-3} | -6V, 1×10^{12} cm^{-3}

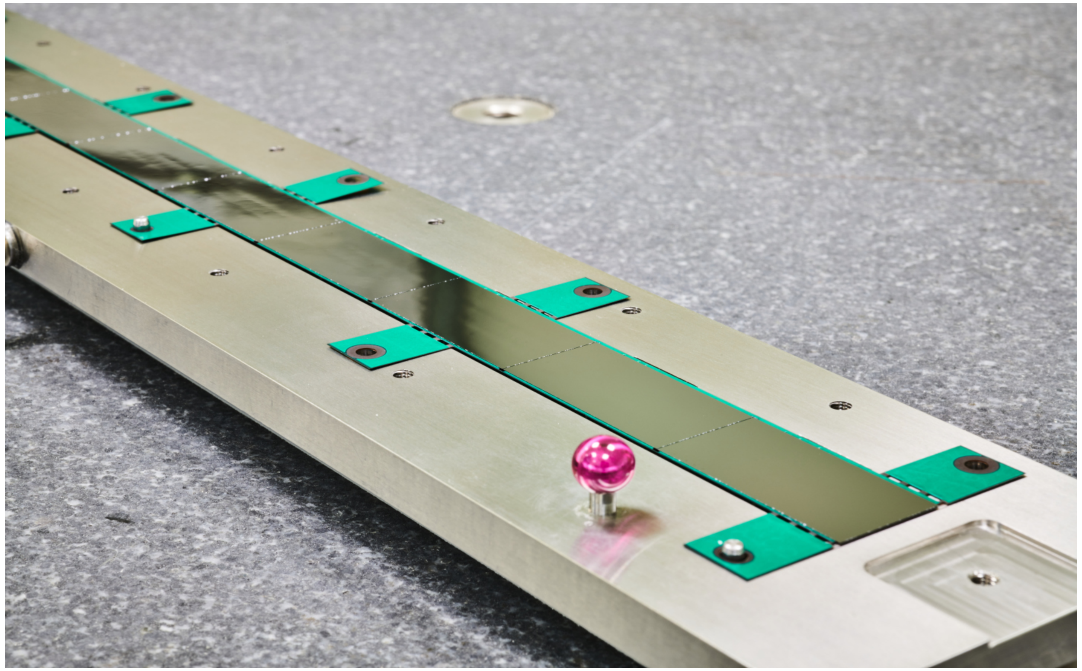
☞ Silicon strip capacitance: > 10 pF (~1.5 pF / cm)

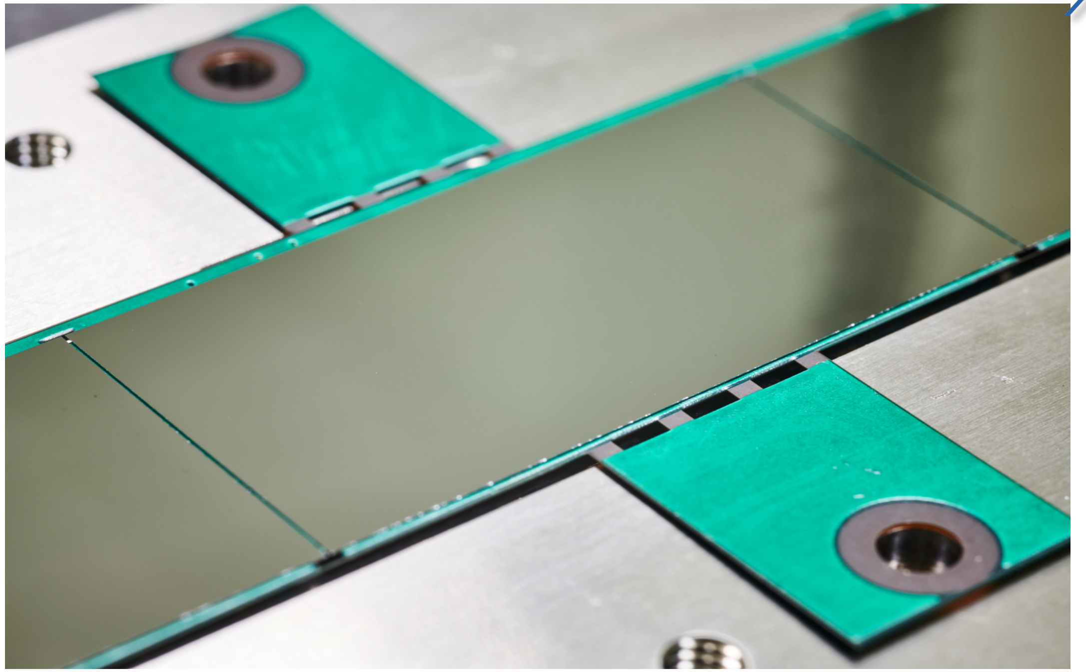
☞ Hybrid pixel capacitance: ~300 fF

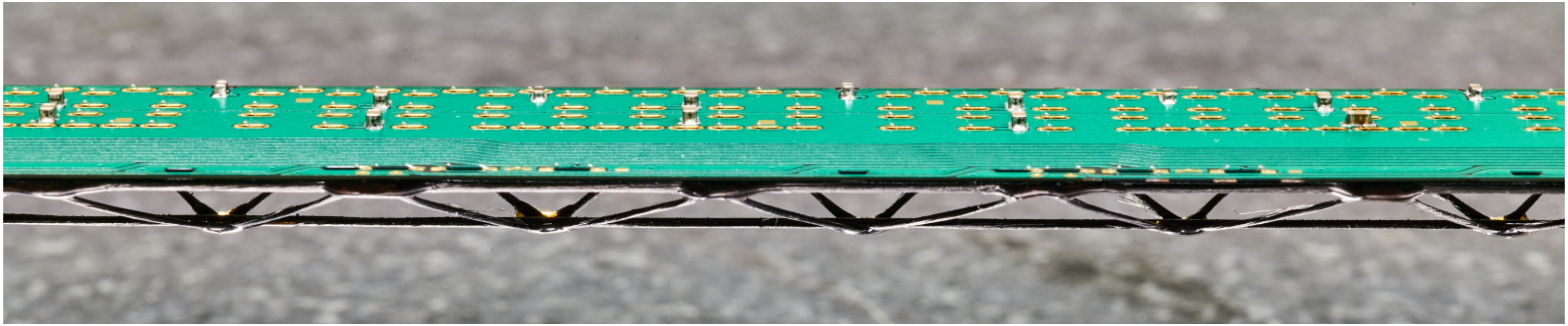
☞ Monolithic pixel capacitance: < 5 fF

C_d = 1fF: 1300 e^- ➔ 200mV (almost a digital signal)

Detector stave based on ALPIDE

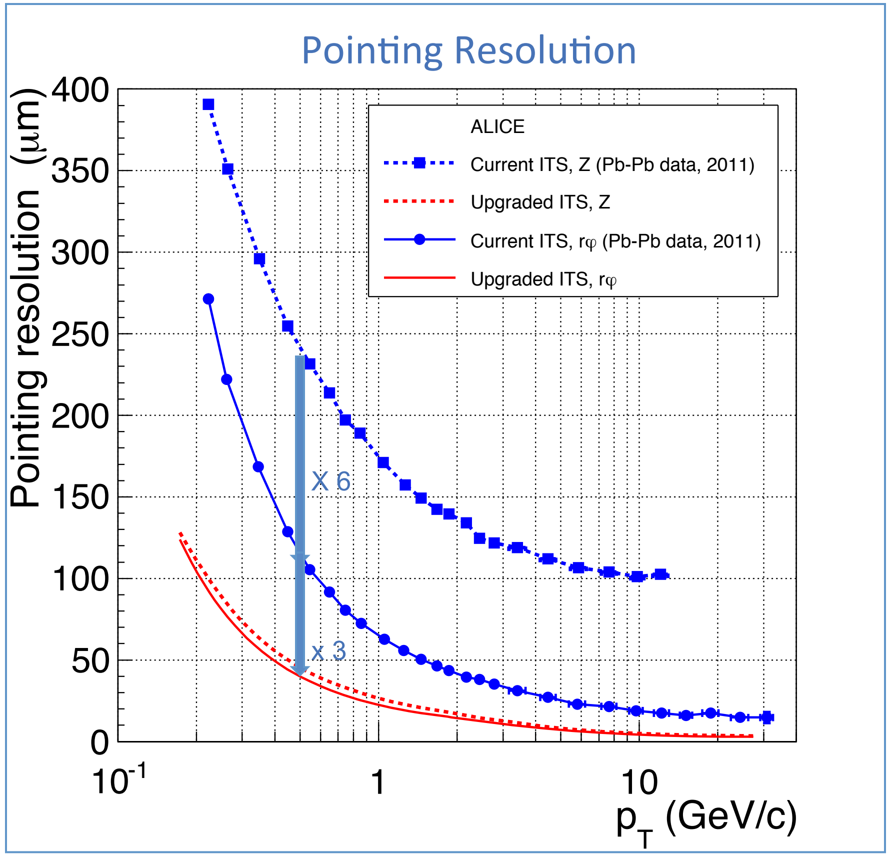




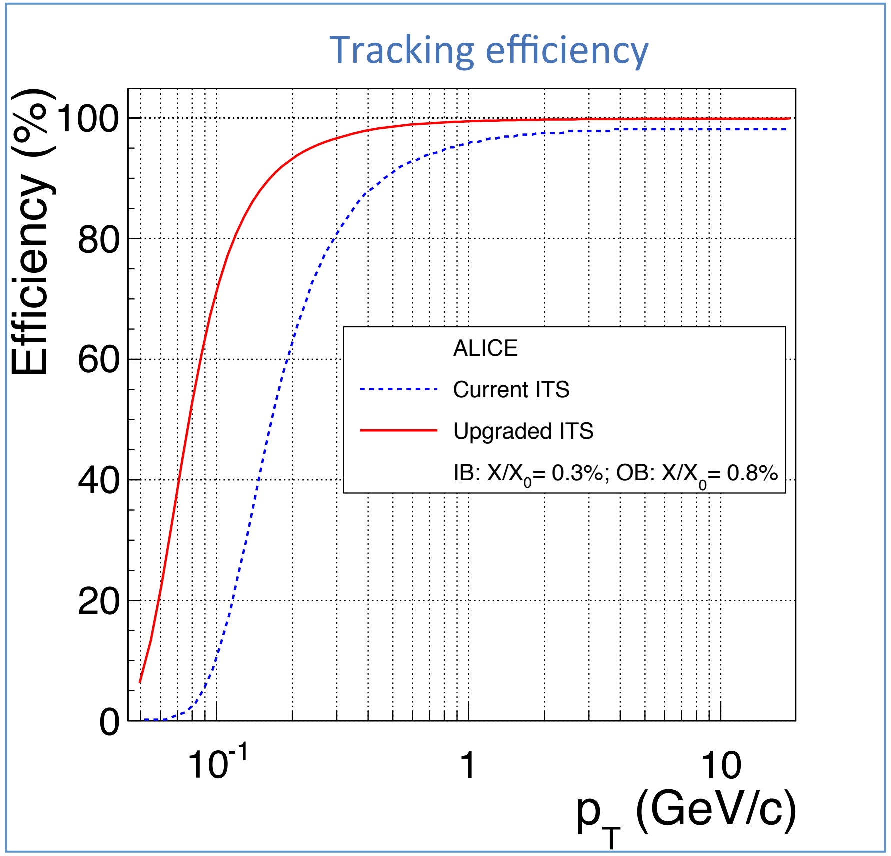


Projected performance of the ALICE ITS Upgrade

Impact parameter resolution



Tracking efficiency (ITS standalone)

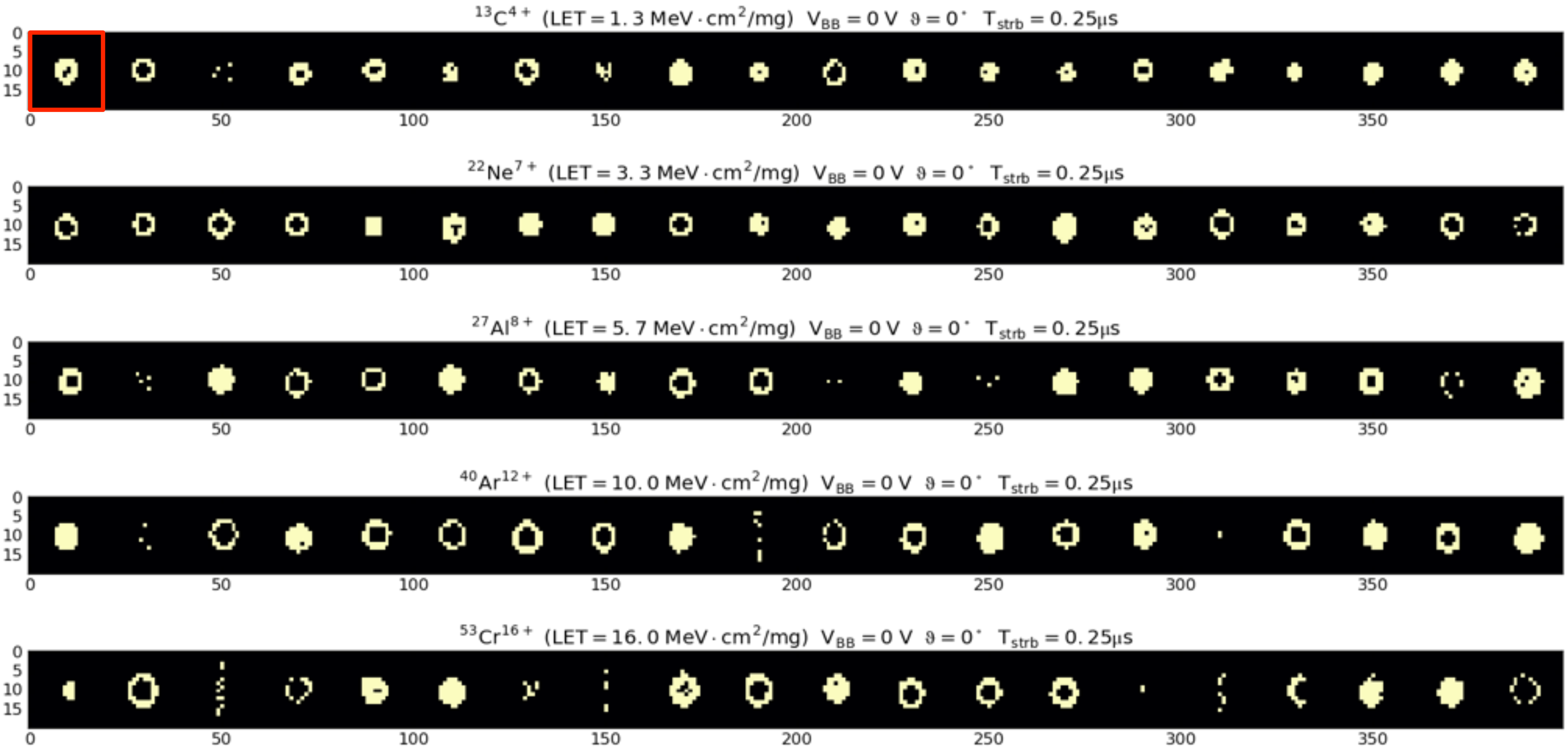


~40 μm at p_T = 500 MeV/c

LET Response studies – Lovain-la-Neuve

Sequence of images of single clusters. Each image corresponds to 20 x 20 pixels

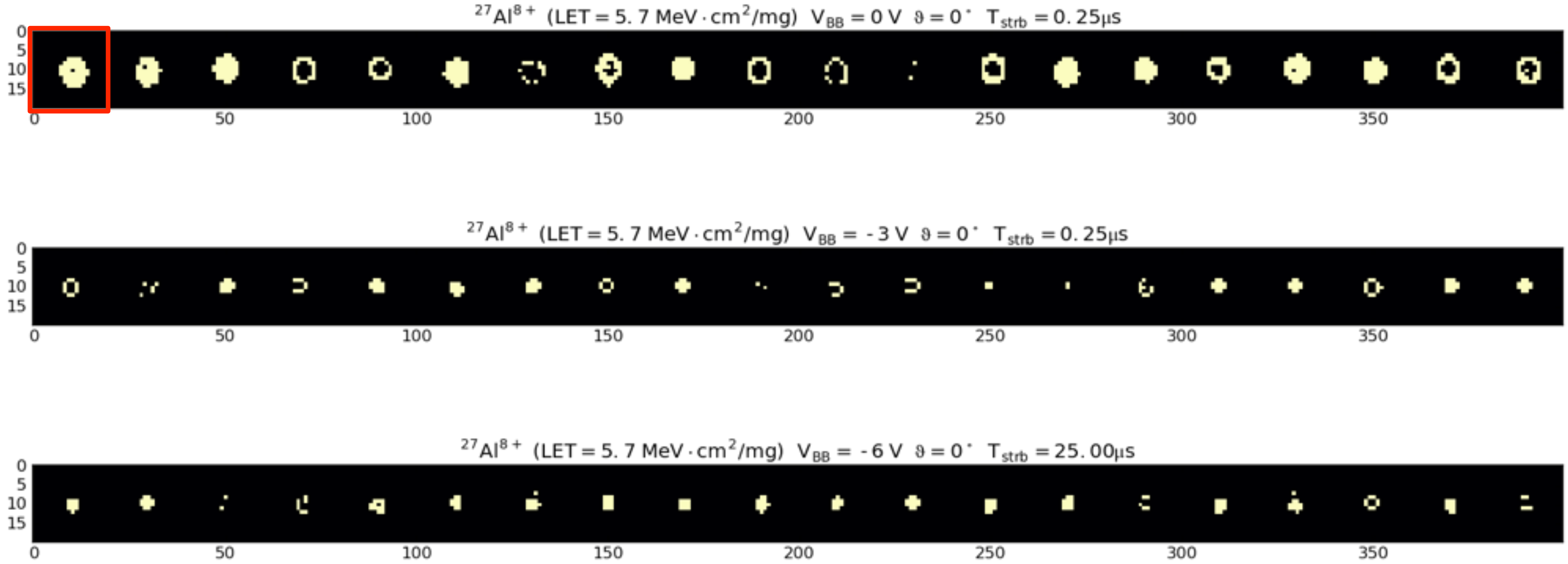
VS. LET @ V_{BB} = 0



LET Response studies – Lovain-la-Neuve

Sequence of images of single clusters. Each image corresponds to 20 x 20 pixels

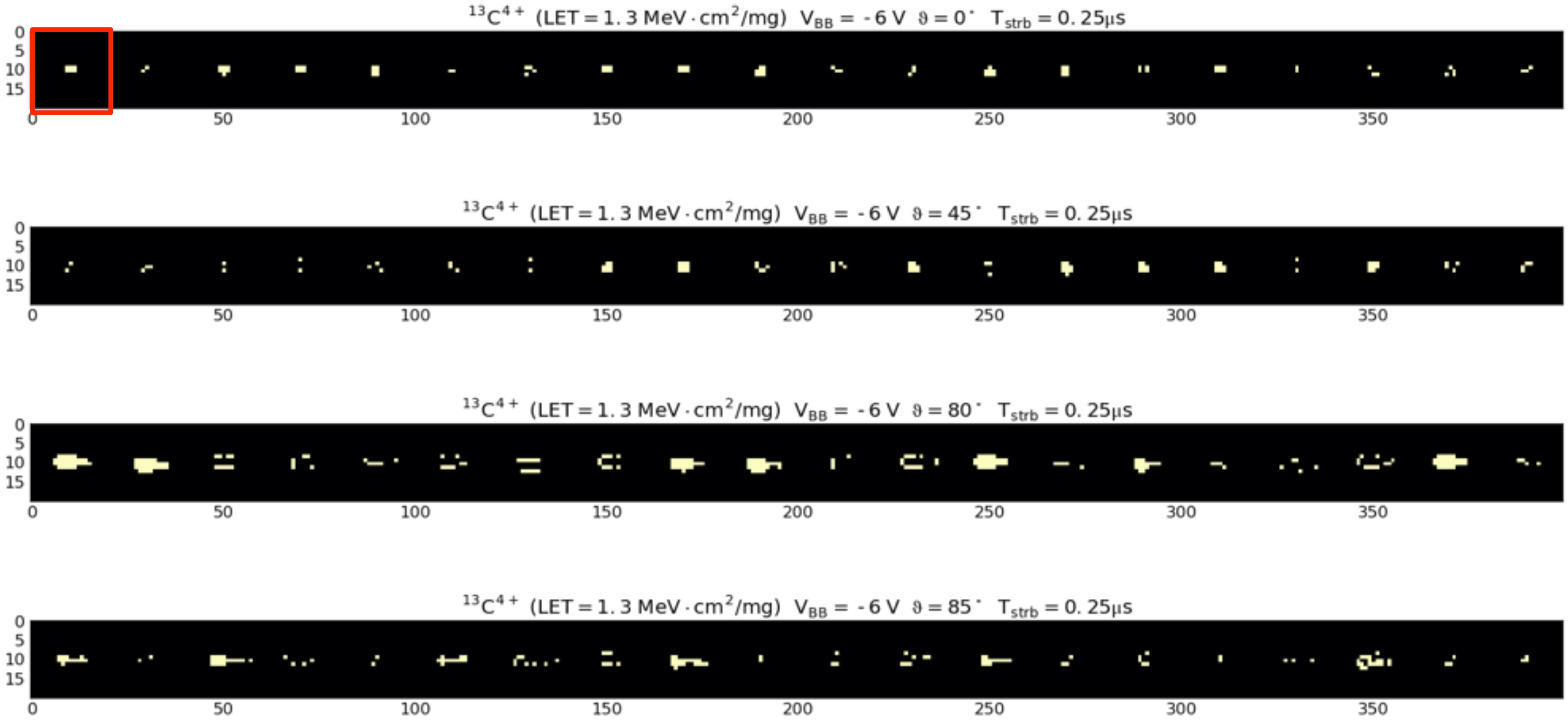
VS. V_{BB} @ LET = 5.7



LET Response studies – Lovain-la-Neuve

Sequence of images of single clusters. Each image corresponds to 20 x 20 pixels

VS. angle @ V_{BB} = -6



^{13}C: DUT energy [MeV] = 131, Range in Si [μm] = 269.3 (≈ 10 pixels)