Silicon detectors for tracking and vertexing

Ziad EL BITAR

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Outline

- Vertex and tracker requirements
- Detector concepts
- DRDT and WGs
- R&D in progress
- Summary

APOLOGIES
if your favorite R&D is not presented !!

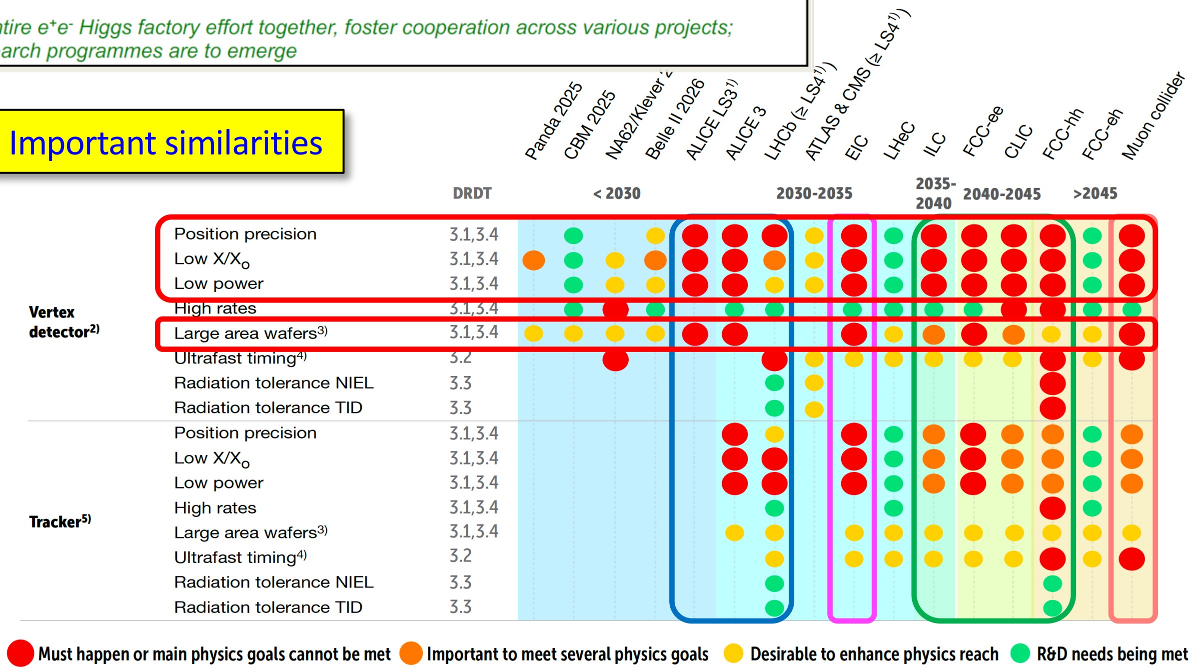
ECFA recommendation & synergies

ECFA recognizes the need for the experimental and theoretical communities involved in physics studies, experiment designs and detector technologies at future Higgs factories to gather. ***ECFA supports a series of workshops*** *with the aim to* ***share challenges and expertise, to explore synergies in their efforts*** *and to respond coherently to this priority in the European Strategy for Particle Physics (ESPP).*

Goal: bring the entire e^+e^- Higgs factory effort together, foster cooperation across various projects; collaborative research programmes are to emerge

K. Jakobs, FCC Physics Workshop, Feb 2022

Important similarities



		DRDT	Panda 2025	CBM 2025	NA62/Klever 2	Belle II 2026	ALICE LS3$^{1)}$	ALICE 3	LHCb (≥ LS4$^{1)}$)	ATLAS & CMS (≥ LS4$^{1)}$)	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
					< 2030					2030-2035			2035-2040	2040-2045			>2045	
Vertex detector$^{2)}$	Position precision	3.1,3.4		🟢		🟡	🔴	🔴	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low X/X_0	3.1,3.4	🟠	🟢	🟡	🟠	🔴	🔴	🟠	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	Low power	3.1,3.4		🟢	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟢	🔴	🔴	🔴	🔴	🟢	🔴
	High rates	3.1,3.4		🟢	🔴	🟢		🟢	🟢		🟢	🟢	🟢	🟢	🔴	🔴	🟢	🟢
	Large area wafers$^{3)}$	3.1,3.4	🟡	🟡	🟡	🟡	🔴	🔴			🔴	🟡	🟠	🔴	🟠	🟡	🟡	🔴
	Ultrafast timing$^{4)}$	3.2			🔴				🔴	🟡	🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢	🟡						🔴		
	Radiation tolerance TID	3.3							🟢	🟡						🔴		
Tracker$^{5)}$	Position precision	3.1,3.4						🔴	🟡		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low X/X_0	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	Low power	3.1,3.4						🔴	🔴		🔴	🟢	🟠	🔴	🟠	🟠	🟢	🟠
	High rates	3.1,3.4							🟢			🟢				🔴	🟢	
	Large area wafers$^{3)}$	3.1,3.4						🟡	🟡		🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟡
	Ultrafast timing$^{4)}$	3.2							🟡		🟡	🟡	🟡	🟡	🟡	🔴	🟡	🔴
	Radiation tolerance NIEL	3.3							🟢							🟢		
	Radiation tolerance TID	3.3							🟢							🟢		

🔴 Must happen or main physics goals cannot be met 🟠 Important to meet several physics goals 🟡 Desirable to enhance physics reach 🟢 R&D needs being met

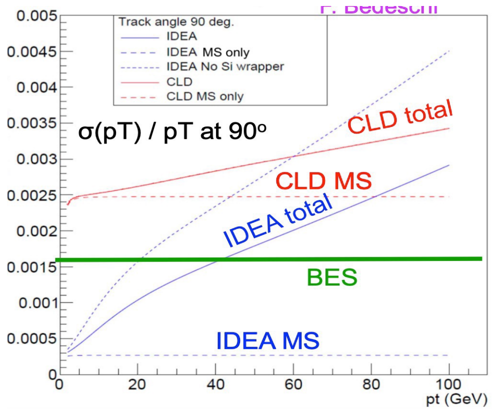
ECFA 2021: R&D Detector Roadmap

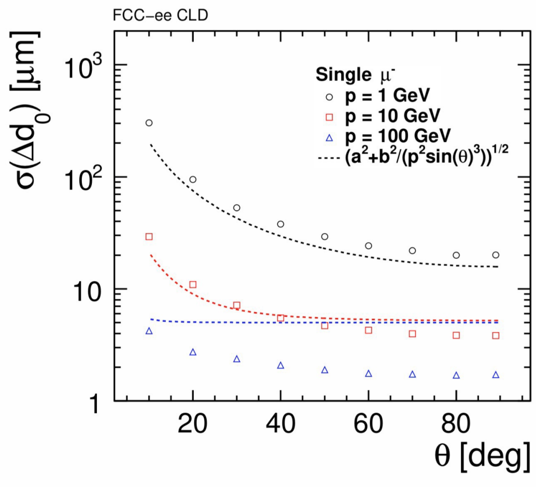
Requirements

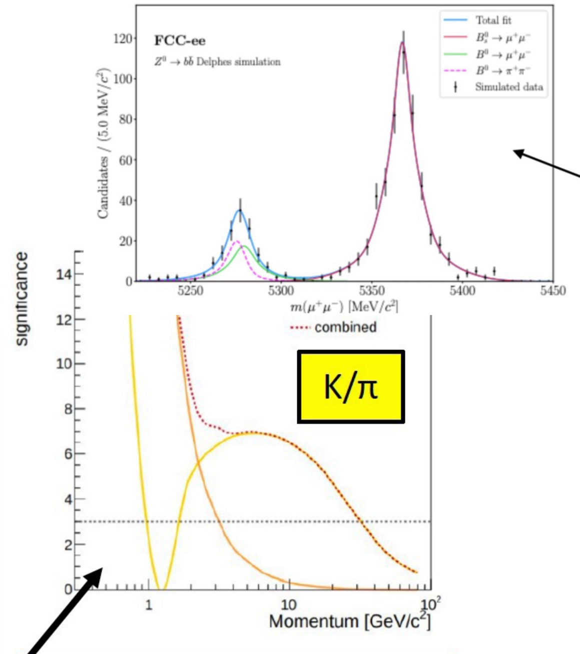
ECFA 2021: R&D Detector Roadmap

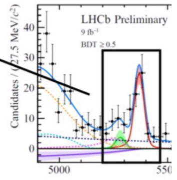
"Technical" Start Date of Facility (This means, where the dates are not known, the earliest technically feasible start date is indicated - such that detector R&D readiness is not the delaying factor)				**< 2030**					**2030-2035**					**2035 - 2040**	**2040-2045**		**> 2045**		
				Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3 [1]	ALICE 3	LHCb (≳LS4)[1]	ATLAS/CMS (≳ LS4)[1]	EIC	LHeC	ILC [2]	FCC-ee	CLIC [2]	FCC-hh	FCC-eh	Muon Collider
Vertex Detector[3]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (µm)		$\simeq 5$		$\lesssim 5$	$\simeq 3$	$\lesssim 3$	$\lesssim 10$	$\lesssim 15$	$\lesssim 3$	$\simeq 5$	$\lesssim 3$	$\lesssim 3$	$\lesssim 3$	$\simeq 7$	$\simeq 5$	$\lesssim 5$
			X/X_0 (%/layer)	$\lesssim 0.1$	$\simeq 0.5$	$\simeq 0.5$	$\lesssim 0.1$	$\simeq 0.05$	$\simeq 0.05$	$\simeq 1$		$\simeq 0.05$	$\lesssim 0.1$	$\simeq 0.05$	$\simeq 0.05$	$\lesssim 0.2$	$\simeq 1$	$\lesssim 0.1$	$\lesssim 0.2$
			Power (mW/cm^2)		$\simeq 60$			$\simeq 20$	$\simeq 20$			$\simeq 20$		$\simeq 20$	$\simeq 20$	$\simeq 50$			
			Rates (GHz/cm^2)		$\simeq 0.1$	$\simeq 1$	$\lesssim 0.1$		$\lesssim 0.1$	$\simeq 6$		$\lesssim 0.1$	$\simeq 0.1$	$\simeq 0.05$	$\simeq 0.05$	$\simeq 5$	$\simeq 30$	$\simeq 0.1$	
			Wafers area (")[4]					12	12			12			12		12		12
		DRDT 3.2	Timing precision σ_t (ns)[5]	10		$\lesssim 0.05$	100		25	$\lesssim 0.05$	$\lesssim 0.05$	25	25	500	25	$\simeq 5$	$\lesssim 0.02$	25	$\lesssim 0.02$
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							$\simeq 6$	$\simeq 2$						$\simeq 10^2$		
			Radiation tolerance TID (Grad)							$\simeq 1$	$\simeq 0.5$						$\simeq 30$		
Tracker[6]	MAPS Planar/3D/Passive CMOS LGADs	DRDT 3.1 DRDT 3.4	Position precision σ_{hit} (µm)						$\simeq 6$	$\simeq 5$		$\simeq 6$	$\simeq 6$	$\simeq 6$	$\simeq 6$	$\simeq 7$	$\simeq 10$	$\simeq 6$	
			X/X_0 (%/layer)						$\simeq 1$	$\simeq 1$		$\simeq 1$	$\simeq 1$	$\simeq 1$	$\simeq 1$	$\simeq 1$	$\lesssim 2$	$\simeq 1$	
			Power (mW/cm^2)						$\lesssim 100$	$\simeq 100$		$\lesssim 100$		$\lesssim 100$	$\lesssim 100$	$\lesssim 150$			
			Rates (GHz/cm^2)							$\simeq 0.16$									
			Wafers area (")[4]						12			12		12	12	12	12		12
		DRDT 3.2	Timing precision σ_t (ns)[5]						25	$\lesssim 25$		25	25	$\lesssim 0.1$	$\lesssim 0.1$	$\lesssim 0.1$	$\lesssim 0.02$	25	$\lesssim 0.02$
		DRDT3.3	Radiation tolerance NIEL (x 10^{16} neq/cm^2)							$\simeq 0.3$							$\lesssim 1$		
			Radiation tolerance TID (Grad)							$\simeq 0.25$							$\lesssim 1$		

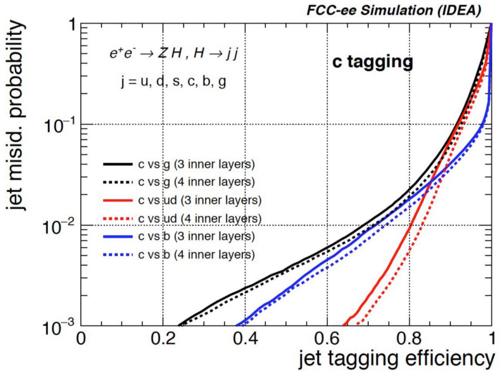
Exploring new physics…



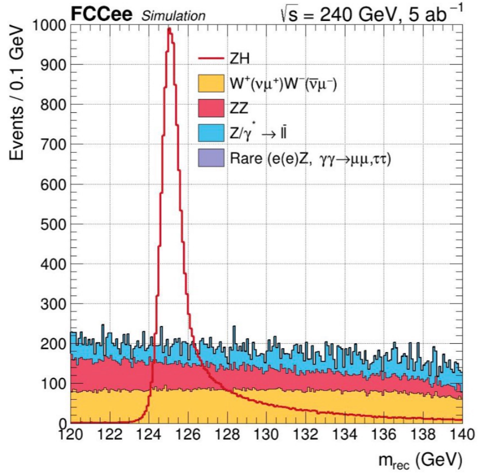




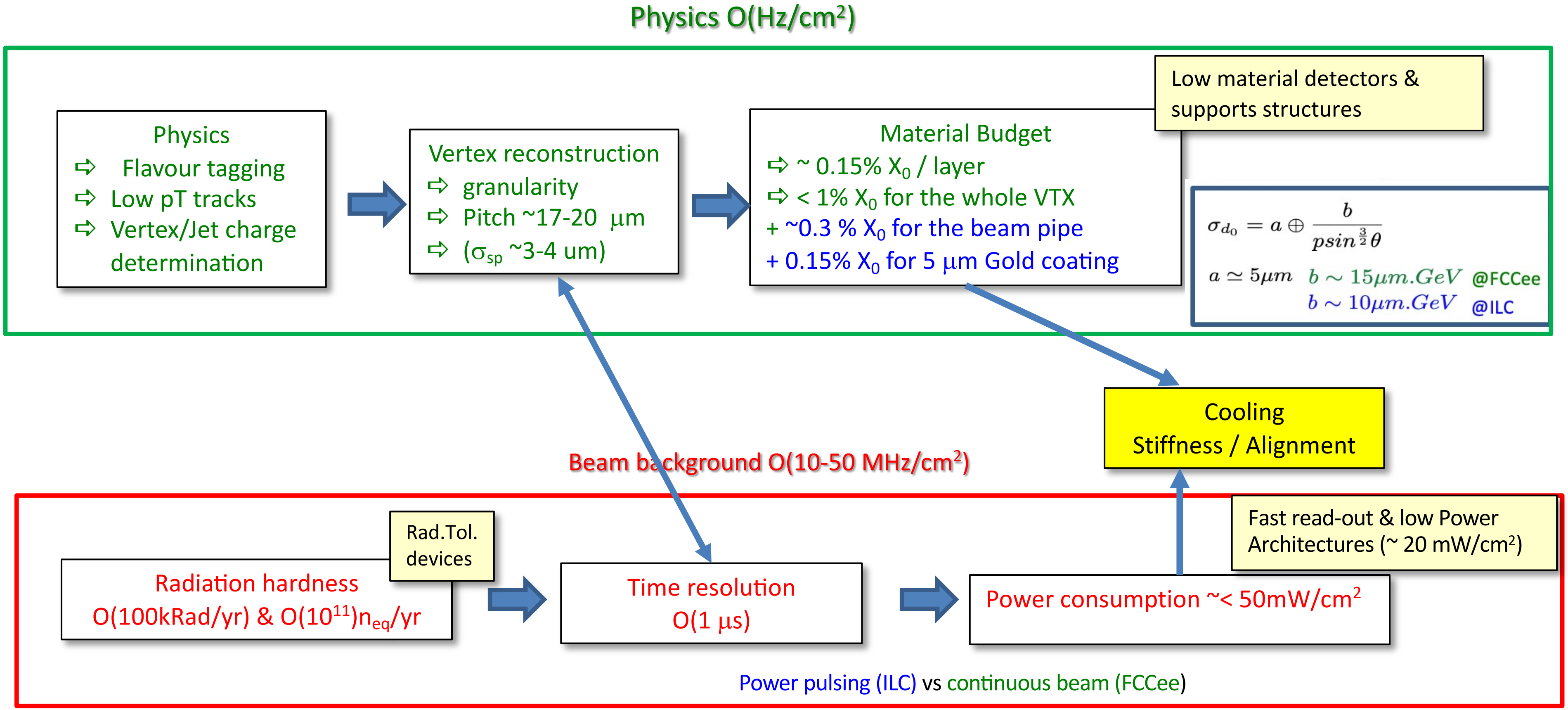




3-sigma separation for tracks with **p < 30GeV**



Constraints on vertex and tracker



Physics O(Hz/cm²)

Physics
- ➪ Flavour tagging
- ➪ Low pT tracks
- ➪ Vertex/Jet charge determination

Vertex reconstruction
- ➪ granularity
- ➪ Pitch ~17-20 µm
- ➪ (σ_{sp} ~3-4 um)

Material Budget
- ➪ ~ 0.15% X_0 / layer
- ➪ < 1% X_0 for the whole VTX
- + ~0.3 % X_0 for the beam pipe
- + 0.15% X_0 for 5 µm Gold coating

Low material detectors & supports structures

$$\sigma_{d_0} = a \oplus \frac{b}{p\sin^{\frac{3}{2}}\theta}$$

$a \simeq 5\mu m$ $b \sim 15\mu m.GeV$ @FCCee

$b \sim 10\mu m.GeV$ @ILC

Cooling
Stiffness / Alignment

Beam background O(10-50 MHz/cm²)

Rad.Tol. devices

Radiation hardness
O(100kRad/yr) & O(10^{11})n_{eq}/yr

Time resolution
O(1 µs)

Power consumption ~< 50mW/cm²

Fast read-out & low Power Architectures (~ 20 mW/cm²)

Power pulsing (ILC) vs continuous beam (FCCee)

Requirements in summary

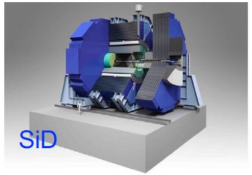
- Spatial resolution : ~ 3 um (except LHCb, FCChh and Muon Colliders)
- Low material budget : 0.05 to 0.15 % X_0
- Fast readout, low power consumption (< 20 mW/cm^2 except for CLIC) compatible with air cooling.
- Increase Radiation Hardness and more R&D for Ultra-Fast timing for future Hadrons and Muon Colliders

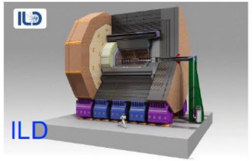
Vertex/tracking detector concepts

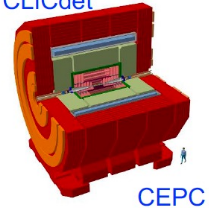
D. Dannheim., 11th BTTB 2023

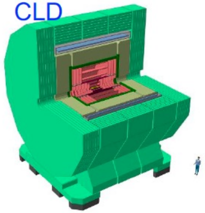
Collider	ILC		CLIC	FCC-ee			CEPC	
Detector Concept	SiD	ILD	CLICdet	CLD	FCC-ee IDEA	Noble LAr/LKr	CEPC baseline	CEPC IDEA
B-field [T]	5	4	4	2	2	2	3	2
Vertex inner radius [mm]	14	14	31	17 → 12	17 → 12	17 → 12	16	16
Tracker out. radius [m]	1.25	1.8	1.5	2.2	2.0	2.0	1.81	2.05
Vertex	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel
Tracker	Si-strips	TPC/Si-strips	Si-pixel	Si-pixel	DC/Si-strips	DC/Si-strips or Si-pixel	TPC/Si-strips or Si-strips	DC/Si-strips

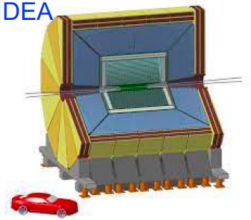
arXiv:1306.6329 arXiv:1812.07337 arXiv:1911.12230 doi.org/10.1140/epjst/e2019-900045-4 arXiv:1811.10545


SiD

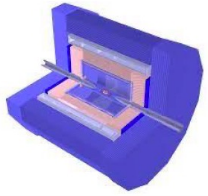

ILD

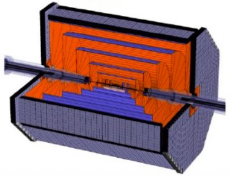
CLICdet


CLD


IDEA


Noble LAr/LCr

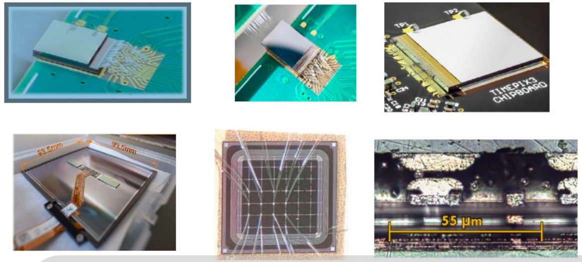

CEPC baseline


FST


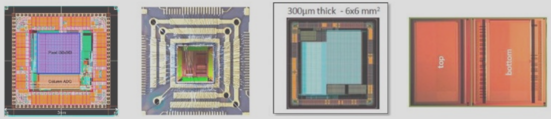
Silicon Pixel R&D examples

D. Dannheim., 11th BTTB 2023

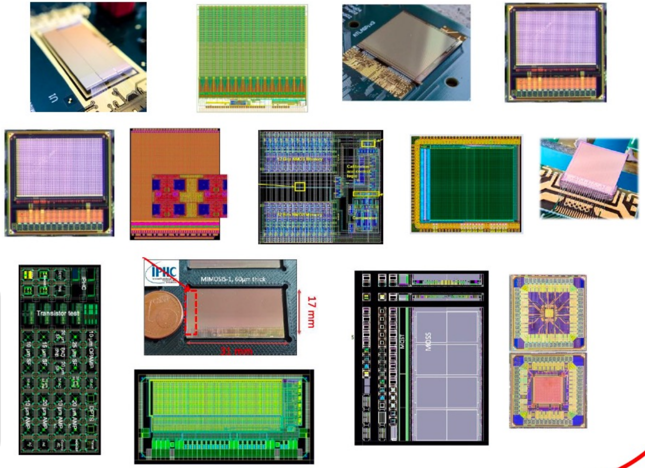
Hybrid detectors



Silicon on Insulator

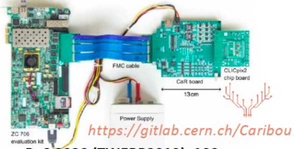


Monolithic Sensors



Tools

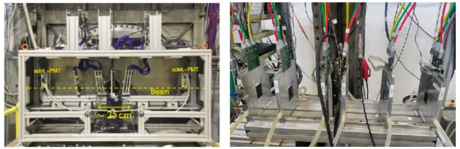
Caribou readout system



https://gitlab.cern.ch/Caribou

PoS 2020 (TWEPP2019), 100

CLICdp + AIDA telescopes



MC Simulation framework: Allpix Squared

https://gitlab.cern.ch/allpix-squared/allpix-squared

NIM A 901 (2018) 164-172

Analysis & reconstruction framework: Corryvreckan

https://gitlab.cern.ch/corryvreckan/corryvreckan

2021 JINST 16 P03008

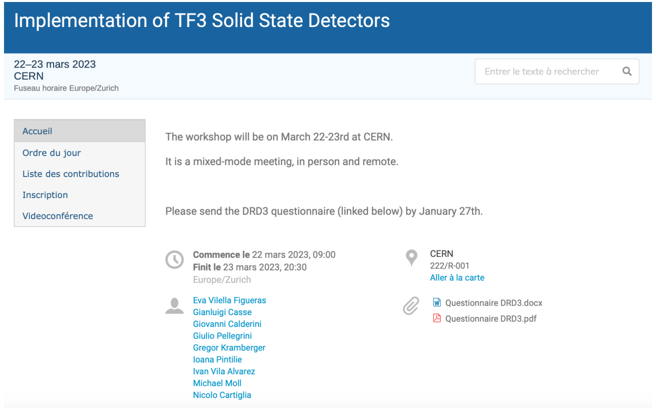
- Diverse R&D performed within various collaborative frameworks (ILD, SiD, CLICdp, IDEA, CERN EP R&D, AIDAinnova, DRD3/7, …), with strong links to other developments (HL-LHC, Belle II, Mu3e, CBM@FAIR, …)
- Mostly focusing on conceptual studies + technology demonstrators

→ Flexible tools developed, to support the R&D and exploit synergies between the various R&D lines

DRDT

Task Force 3 Solid State Detectors has identified the essential Detector R&D Themes (DRDT) which capture the most critical requirements:

- DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.
- DRDT 3.2 - Develop solid state sensors with 4D-capabilities for tracking and calorimetry.
- DRDT 3.3 - Extend capabilities of solid state sensors to operate at extreme fluences.
- DRDT 3.4 - Develop full 3D-interconnection technologies for solid state devices in particle physics.



Implementation of TF3 Solid State Detectors

22–23 mars 2023
CERN
Fuseau horaire Europe/Zurich

The workshop will be on March 22-23rd at CERN.

It is a mixed-mode meeting, in person and remote.

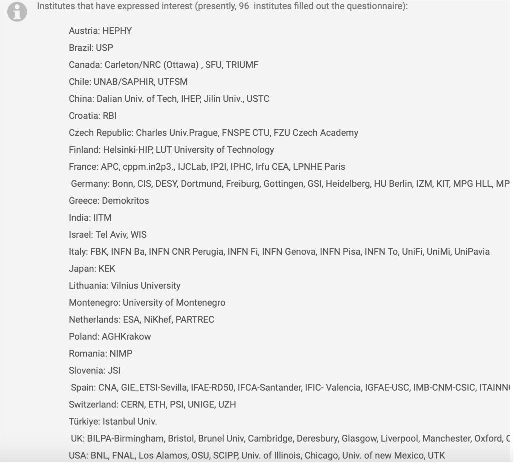
Please send the DRD3 questionnaire (linked below) by January 27th.

Commence le 22 mars 2023, 09:00
Finit le 23 mars 2023, 20:30
Europe/Zurich

CERN
222/R-001

Eva Vilella Figueras
Gianluigi Casse
Giovanni Calderini
Giulio Pellegrini
Gregor Kramberger
Ioana Pintilie
Ivan Vila Alvarez
Michael Moll
Nicolo Cartiglia

Questionnaire DRD3.docx
Questionnaire DRD3.pdf



Institutes that have expressed interest (presently, 96 institutes filled out the questionnaire):

Austria: HEPHY
Brazil: USP
Canada: Carleton/NRC (Ottawa) , SFU, TRIUMF
Chile: UNAB/SAPHIR, UTFSM
China: Dalian Univ. of Tech, IHEP, Jilin Univ., USTC
Croatia: RBI
Czech Republic: Charles Univ.Prague, FNSPE CTU, FZU Czech Academy
Finland: Helsinki-HIP, LUT University of Technology
France: APC, cppm.in2p3., IJCLab, IP2I, IPHC, Irfu CEA, LPNHE Paris
Germany: Bonn, CIS, DESY, Dortmund, Freiburg, Gottingen, GSI, Heidelberg, HU Berlin, IZM, KIT, MPG HLL, MP
Greece: Demokritos
India: IITM
Israel: Tel Aviv, WIS
Italy: FBK, INFN Ba, INFN CNR Perugia, INFN Fi, INFN Genova, INFN Pisa, INFN To, UniFi, UniMi, UniPavia
Japan: KEK
Lithuania: Vilnius University
Montenegro: University of Montenegro
Netherlands: ESA, NiKhef, PARTREC
Poland: AGHKrakow
Romania: NIMP
Slovenia: JSI
Spain: CNA, GIE_ETSI-Sevilla, IFAE-RD50, IFCA-Santander, IFIC- Valencia, IGFAE-USC, IMB-CNM-CSIC, ITAINN
Switzerland: CERN, ETH, PSI, UNIGE, UZH
Türkiye: Istanbul Univ.
UK: BILPA-Birmingham, Bristol, Brunel Univ, Cambridge, Deresbury, Glasgow, Liverpool, Manchester, Oxford,
USA: BNL, FNAL, Los Alamos, OSU, SCIPP, Univ. of Illinois, Chicago, Univ. of new Mexico, UTK

[Implementation of TF3 Solid State Detector @ CERN, March 22-23, 2023]

Working Groups

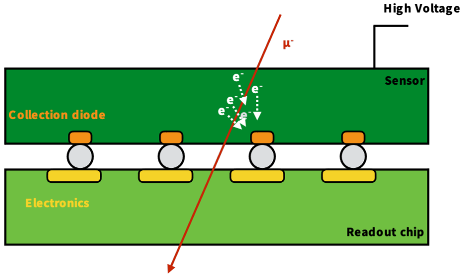
- WG1 Monolithic CMOS Sensors
- WG2 Sensors for Tracking and Calorimetry
- WG3 Radiation damage and extreme fluences
- WG4 Simulation
- WG5 Characterization techniques, facilities
- WG6 Wide bandgap and innovative sensor materials
- WG7 Interconnect and device fabrication
- WG8 Dissemination and outreach

R&D

Hybrid pixel detectors

P. Svihra et al., BTTB 2023

- Enable to factorise R&D on sensors and readout ASICs.
- Take advantage of advancements in ASIC technologies and performances
- Bumping remains the main challenge as well as material budget, cost and minimal pitch achieving.



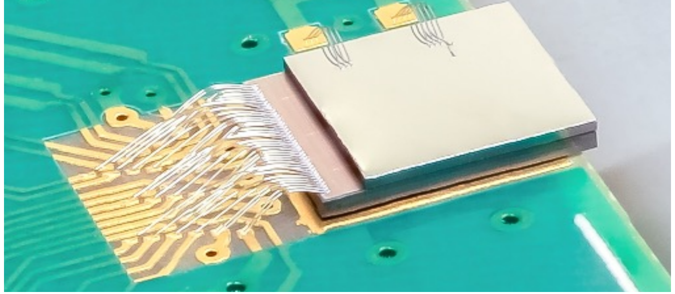
Reference 1

Reference 2

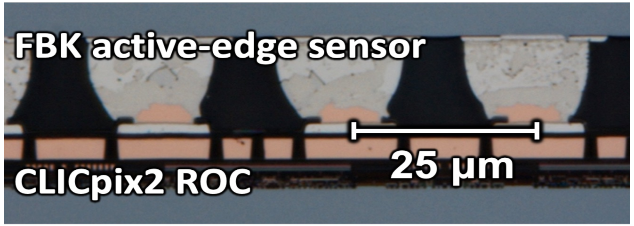
- R&D with Fraunhofer IZM for development of single-die bonding process
  - Based on support wafer processing with SnAg bumps
  - Verified for multiple CLICpix2 assemblies in lab and beam-test
    - 128x128 pixels with **25 µm pixel pitch**
    - 50 µm, 100 µm, 130 µm sensor thickness

Fraunhofer IZM

CLICpix2 ASIC bump-bonded to an active edge silicon sensor



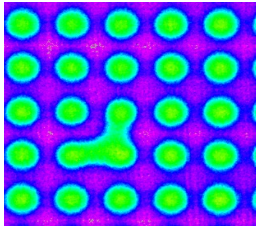
Cross-section of bonded assembly



Interconnection yield above **99.7%** for four tested devices

10.1088/1748-0221/18/03/C03008

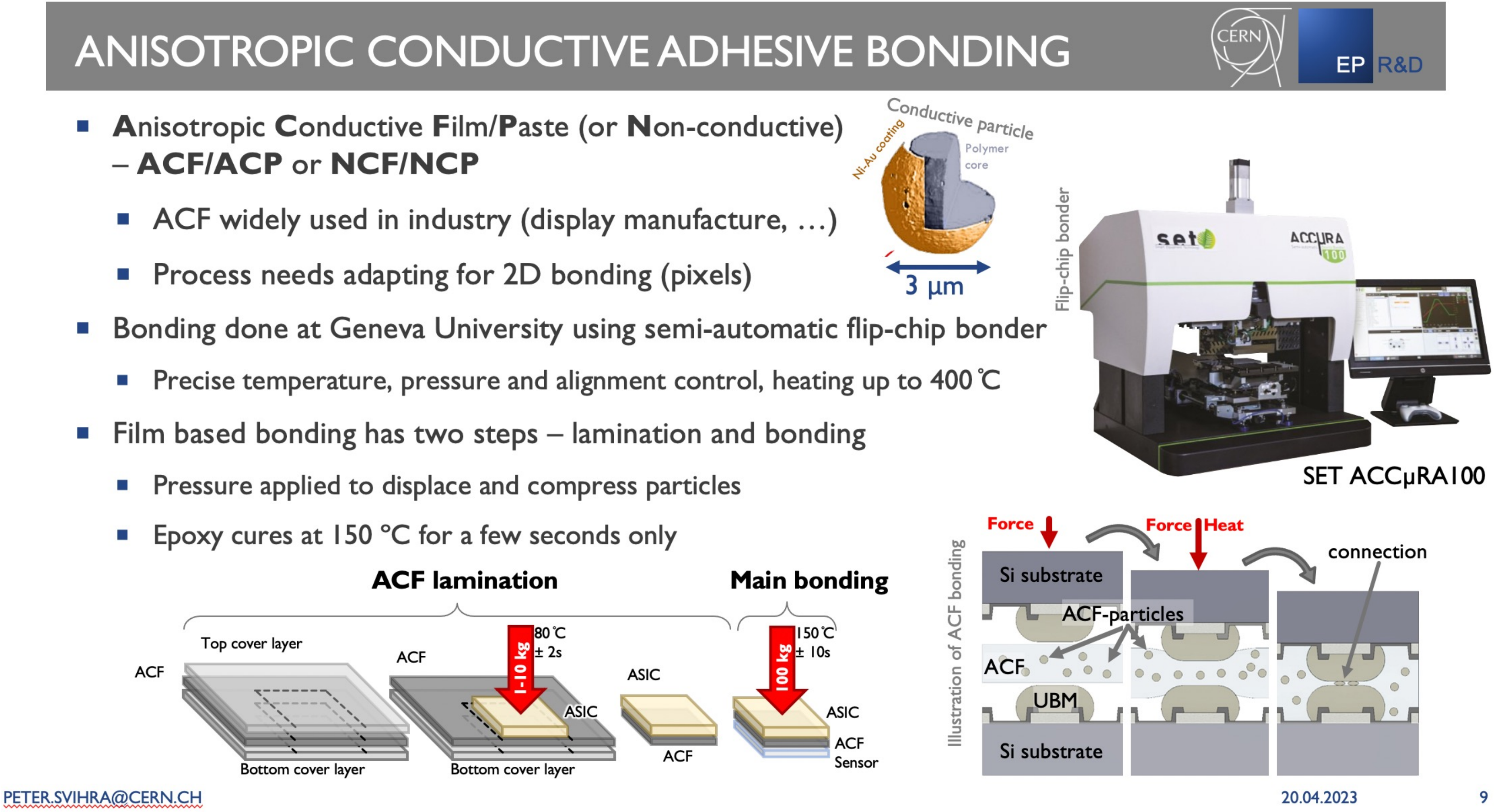
X ray image of bumps



provided by Nikon XT V 160
by Abishek Sharma

Hybrid pixel detectors

P. Svihra et al., BTTB 2023



ANISOTROPIC CONDUCTIVE ADHESIVE BONDING

CERN EP R&D

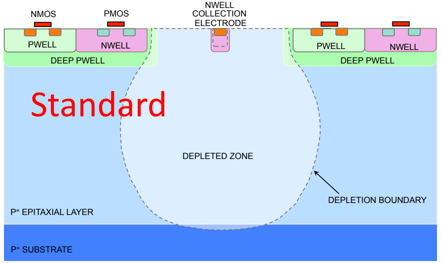
- **A**nisotropic **C**onductive **F**ilm/**P**aste (or **N**on-conductive) – **ACF/ACP** or **NCF/NCP**
  - ACF widely used in industry (display manufacture, …)
  - Process needs adapting for 2D bonding (pixels)
- Bonding done at Geneva University using semi-automatic flip-chip bonder
  - Precise temperature, pressure and alignment control, heating up to 400 ̊C
- Film based bonding has two steps – lamination and bonding
  - Pressure applied to displace and compress particles
  - Epoxy cures at 150 °C for a few seconds only

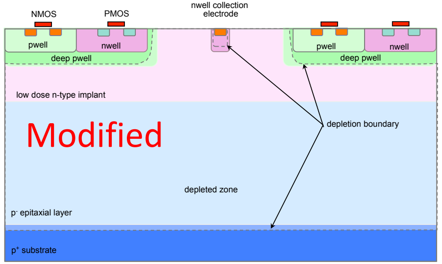
PETER.SVIHRA@CERN.CH

20.04.2023 9

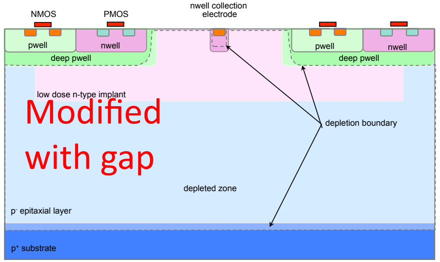
Exploring the TPSCo 65 nm

- Benefits : 65 nm vs 180 nm
  - Better spatial resolution due to smaller feature size.
  - Larger wafers : 300 mm vs 200 mm => final sensor : 27x9 cm^2.
  - Lower power supply : 1.2 V vs 1.8 V => Low power consumption.
  - Lower material budget : thinner sensitive layer ($\sim 10\mu m$).
- Provides 2D stitching
- 7 metal layers
- Process modifications for full depletion:
  - Standard (no modifications)
  - Modified (low dose n-type implant)
  - Modified with gap (low dose n-type implant with gaps)





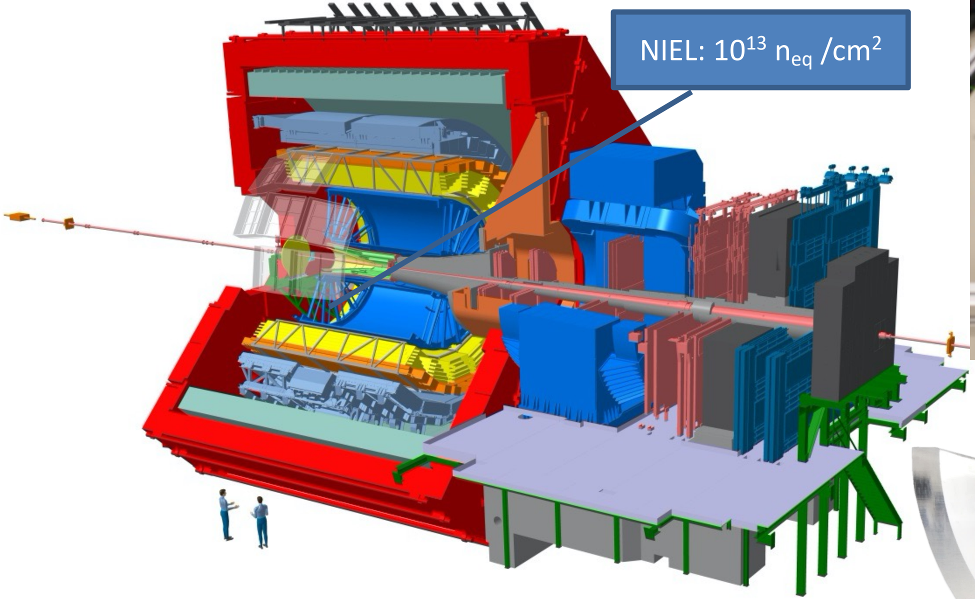
https://doi.org/10.1016/j.nima.2017.07.046



https://iopscience.iop.org/article/10.1088/1748-0221/14/05/C05013

Alice detector LS3 upgrade: ITS2 (180 nm) → ITS3 (65nm)

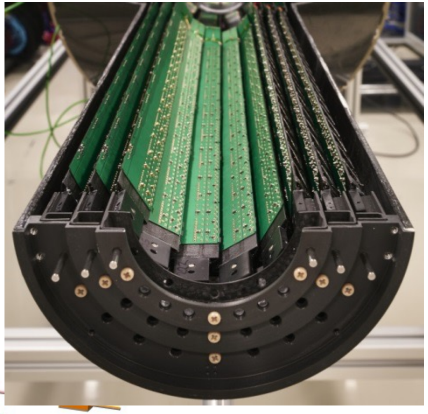
R. Ricci, PSD 2023



NIEL: 10^{13} n_{eq} /cm^2

ALICE – general purpose detector at LHC:

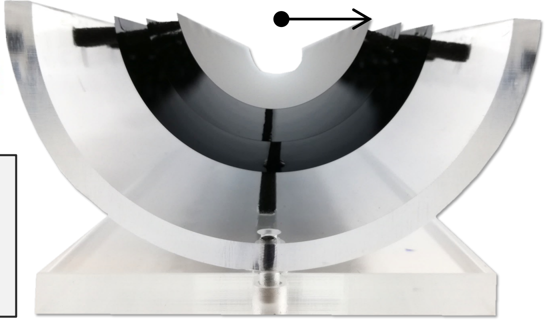
- Tracking (100 MeV/c – 100 GeV/c)
- Particle identification: π, K, p, e (0.1 – 50 GeV/c)



ITS2:

(S.Beolé, iWoRiD 2022)

- 7 layers of MAPS
- TJ 180 nm CMOS
- 12.5 Giga pixels
- Pixel size: 27×29 μm^2
- Water cooling
- **0.3 % X_0 / inner layer**



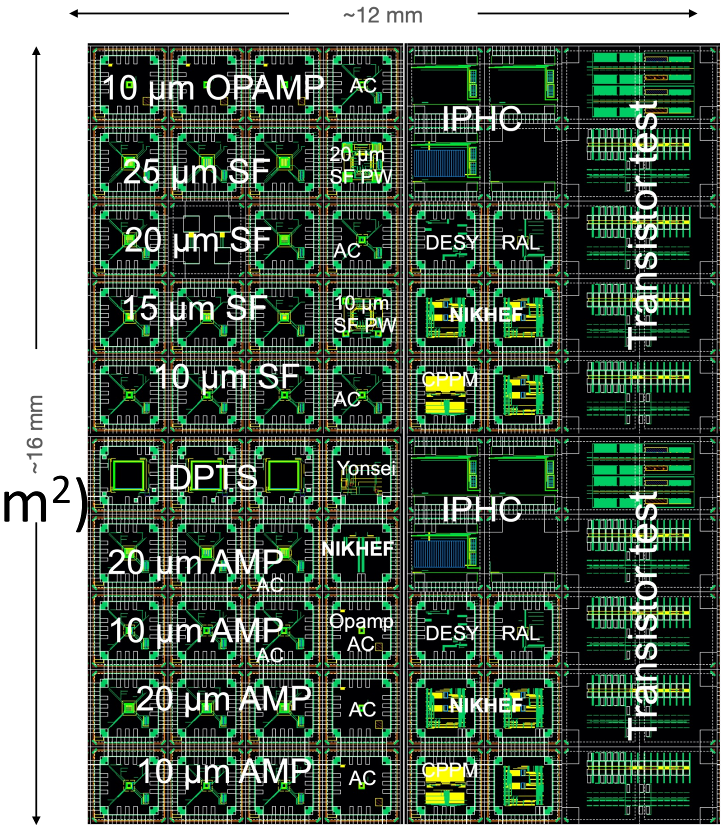
ITS3

(M. Šuljić, iWoRiD 2023)

- 4 outer layers of ITS2
- 3 new fully cylindrical inner layers
  - Sensor size up to 27×9 cm
  - Thickness 30-40 µm
  - No FPCs
  - Air cooling in active area
- **0.05 % X_0 / inner layer**

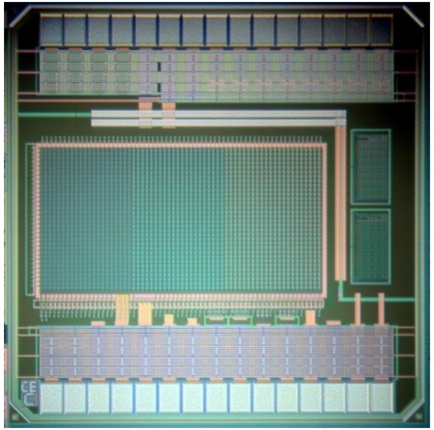
First Test Submission : MLR1

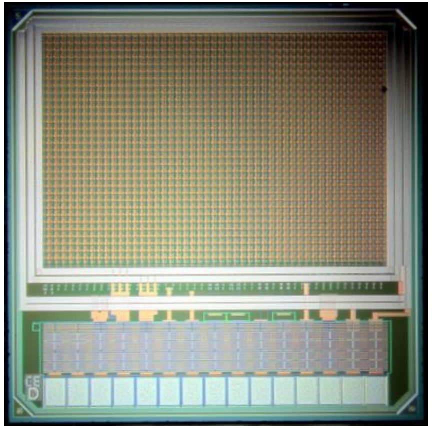
- Submitted in December 2020
- Main goals:
  - Learn technology features
  - Characterize charge collection
  - Validate radiation tolerance
- Each reticle (12×16 mm^2):
  - 10 transistor test structures (3×1.5 mm^2)
  - 60 chips (1.5×1.5 mm^2)
    - Analogue blocks
    - Digital blocks
    - **Pixel prototype chips: APTS, CE65, DPTS**



CE65 : Circuit Exploratoire 65 nm

- 2 matrix sizes
  - 64×32 with 15 µm pitch
  - 48×32 matrix with 25 µm pitch
- Rolling shutter readout (50 µs integration time)
- 3 in-pixel architectures:
  - AC-coupled amplifier
  - DC-coupled amplifier
  - Source follower
- 4 chip variants:
  - **Standard process 15 µm pitch**
  - Modified process 15 µm pitch
  - **Modified process with gaps 15 µm pitch**
  - Standard process 25 µm pitch
- Fabrication in September 2021
- Presented results from CERN PS beam test : May 2022



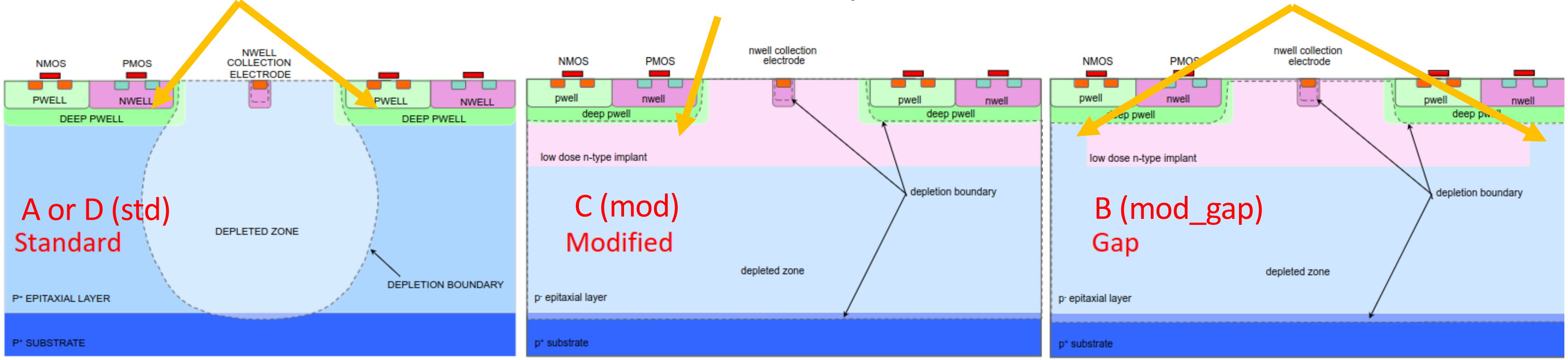


1.5×1.5 mm²

CE65 variants

Variant	Process	Pitch	Matrix	Sub-matrix
CE65-A	std	15μm	64×32	AC/21, DC/21, SF/22
CE65-B	mod_gap	15μm	64×32	AC/21, DC/21, SF/22
CE65-C	mod	15μm	64×32	AC/21, DC/21, SF/22
CE65-D	std	25μm	48×32	AC/16, DC/16, SF/16

Pixel pitch impact was evaluated on standard process only



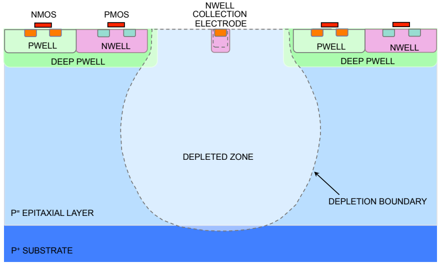
Prevent circuitry's nwells from collecting charge

To obtain a full depletion

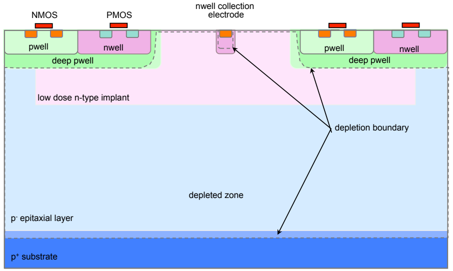
To overcome the weak electric field near the edges

S. Senyukov, iWoRiD 2022

Process modification impact

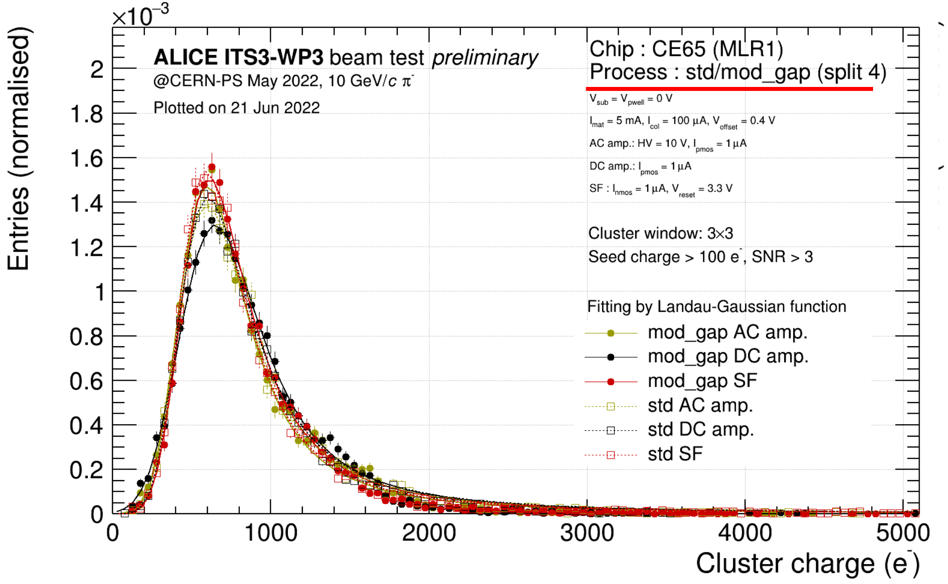


Standard

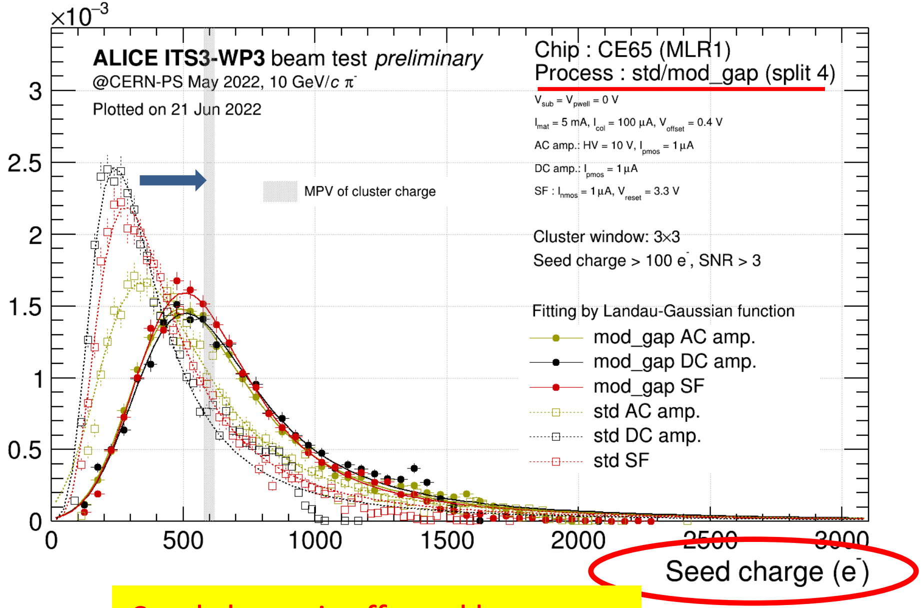


Modified with gap

Modified process effective for depletion…

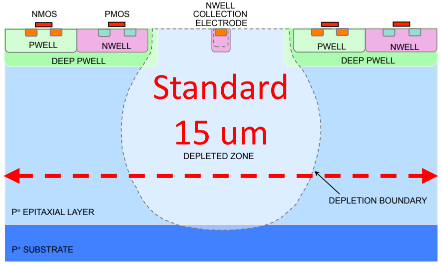


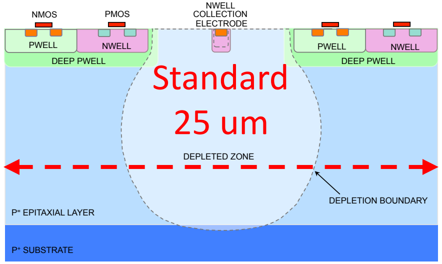
Cluster charge is not affected by process modification



Seed charge is affected by process modification

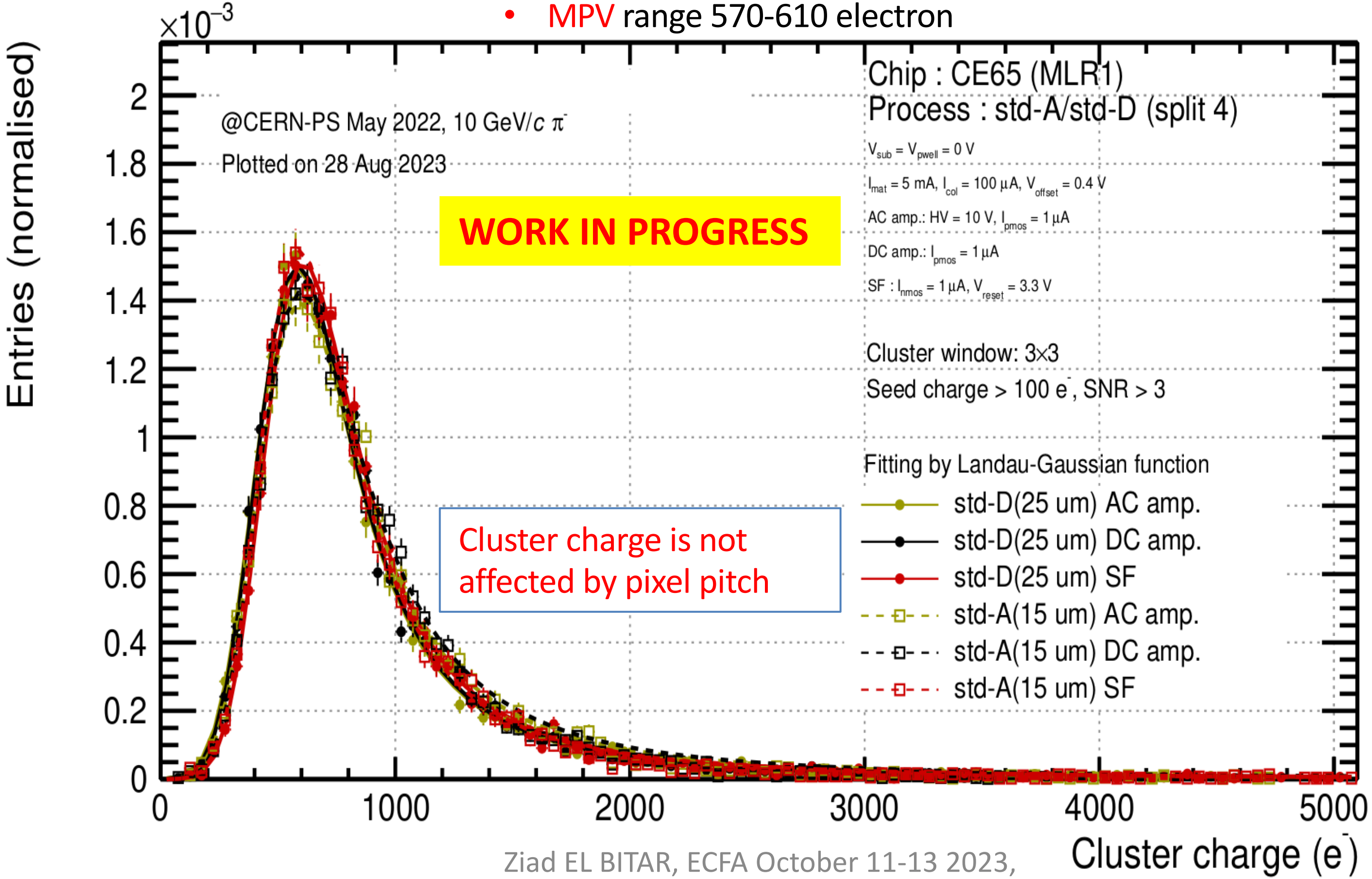
Pixel pitch impact





Cluster charge

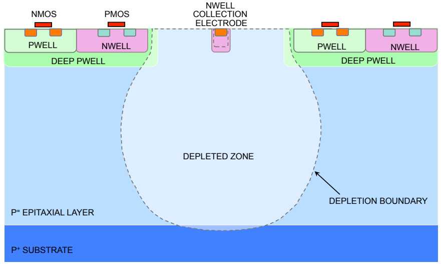
- MPV range 570-610 electron



WORK IN PROGRESS

Cluster charge is not affected by pixel pitch

Pixel pitch evaluation for standard process only



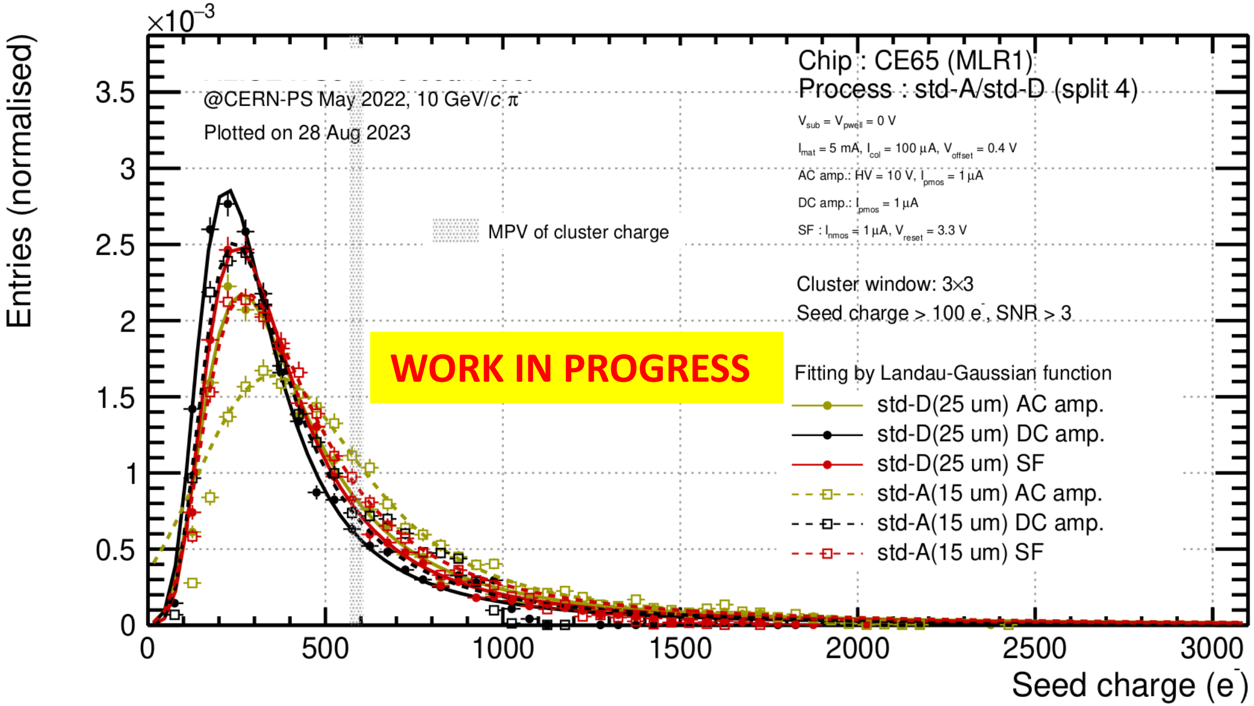
Seed charge

- Seed peaks

Charge sharing increase

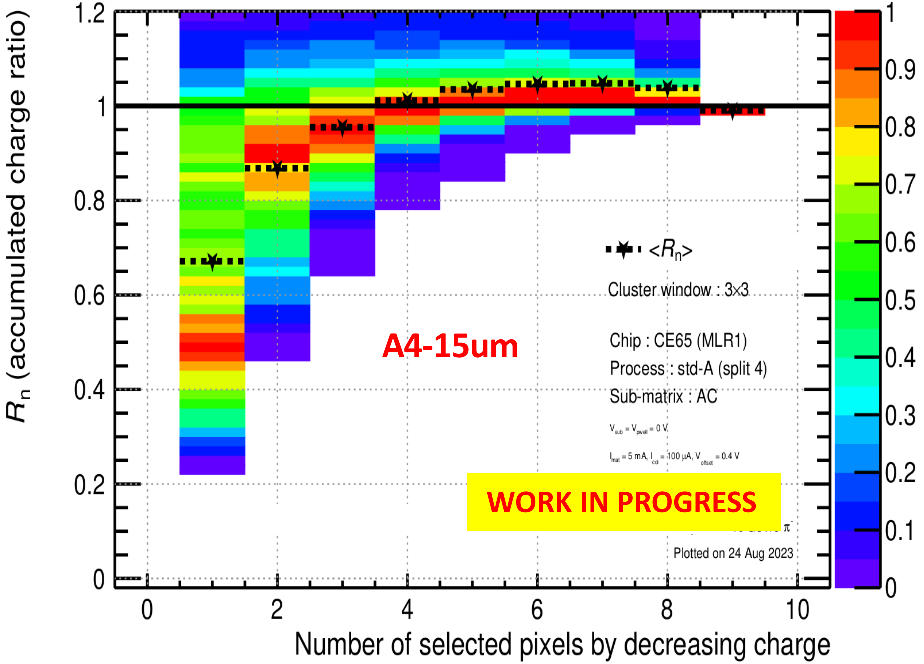
Charge sharing increase

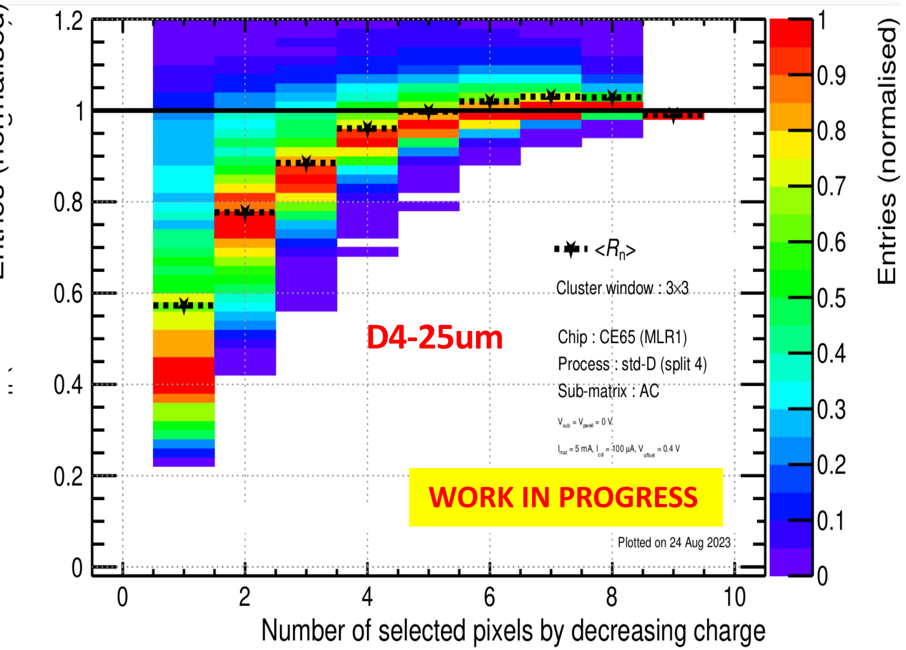
	A4-std 15 um	D4-std 25 um
AC	311	284
SF	297	269
DC	261	232



Charge sharing

- 4 pixels contain all cluster charge for AC submatrix in A4-15um where it needs 5-6 pixels for D4-25um.
- Seed pixel contains: **more** then 60% in average for A4
  a little bit **less** then 60% in average for D4





Simulations: ALLPix + TCAD

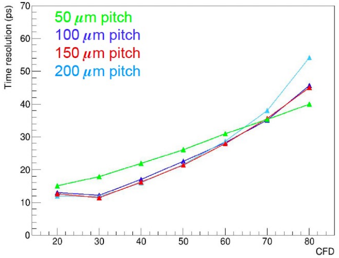
C. Ferrero et al., TREDI, 2023

ARCADIA fully-depleted monolithic active pixel sensors optimised for sub-nano second timi

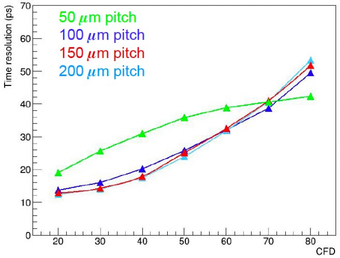
TCAD
- Numerical simulation tool for sensor modeling
- Describes carriers motion and electromagnetic fields
- Very demanding on computing time

ALLPIX²
- Monte Carlo simulations
- High statistics
- Geant4 for energy deposition
- Telescope and complex detector geometries

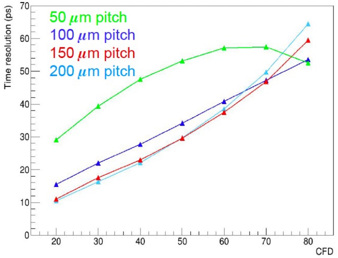
Sentaurus TCAD



Thickness 25 µm



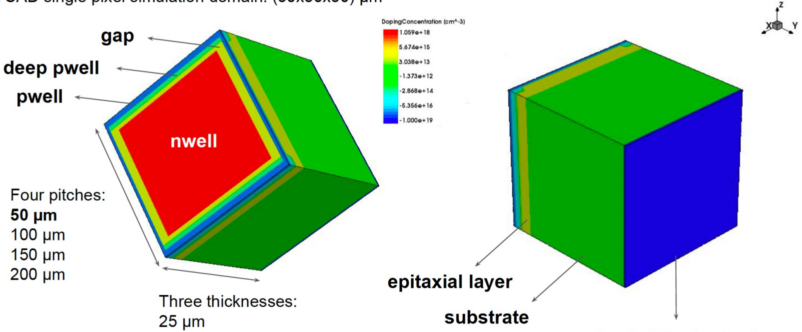
Thickness 35 µm



Thickness 50 µm

ARCADIA pad diode monolithic sensor

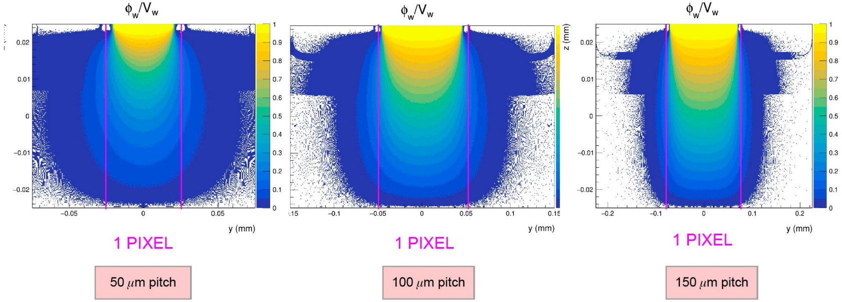
TCAD single pixel simulation domain: (50x50x50) µm^3



Four pitches:
50 µm
100 µm
150 µm
200 µm

Three thicknesses:
25 µm
35 µm
50 µm

Weighting Potential - 3x3 simulation domain
50 / 100 / 150 μm pitch

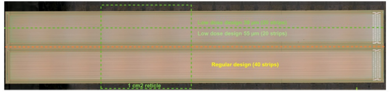


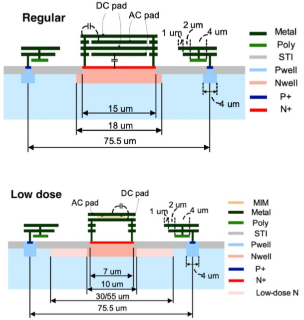
Stitching passive strip CMOS

I. Zatocilova et al., iWoRiD 2023

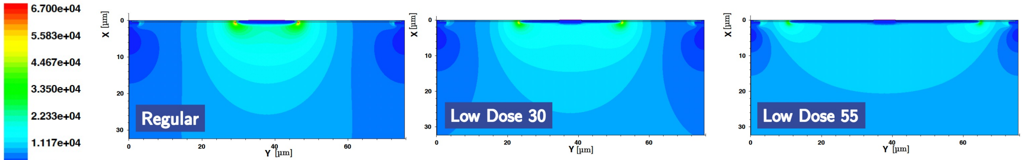
Passive CMOS Strips

- Sensors fabricated in LFoundry in a 150 nm process
- Passive → no electronics included
- 150 µm thick silicon wafer
- Two lengths of strips 2.1 and 4.1 cm
    - 1 cm^2 reticle used → strips had to be stitched
    - Up to five stitches in each sensor
- Three different designs
    - Regular – similar to the ATLAS strip design
    - Low dose 30 & 55 – low dose implant and NIM capacitor

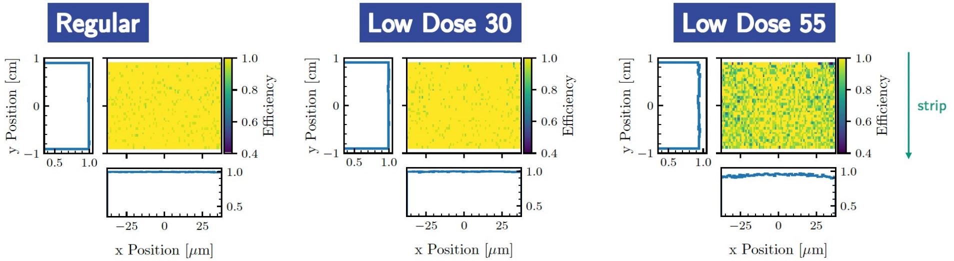




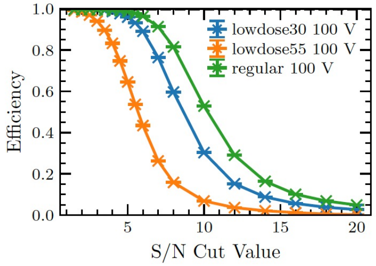
Electric Field @ 100 V, Sentaurus TCAD simulation



Test Beam, Unirradiated



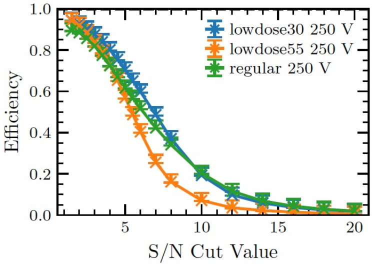
Unirradiated



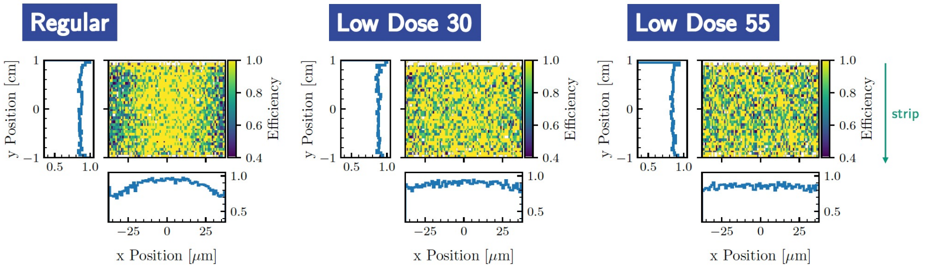
Irradiated

by 23 MeV neutrons

$\Phi_{eq} = 3{\cdot}10^{14}\ \mathrm{n_{eq}/cm^2}$



Test Beam, irradiated

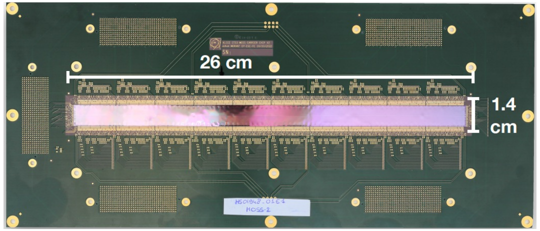


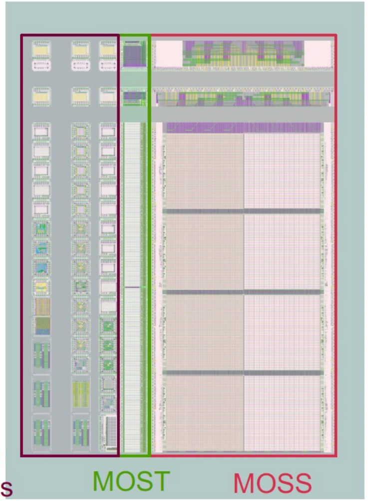
Stitching active pixel CMOS

M. Suljic et al., iWoRiD 2023

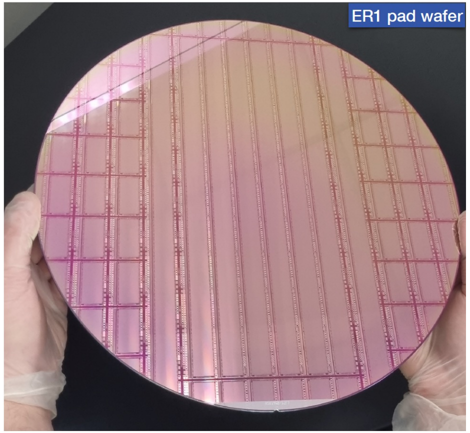
- First MAPS for HEP using stitching - one order of magnitude larger than previous chips

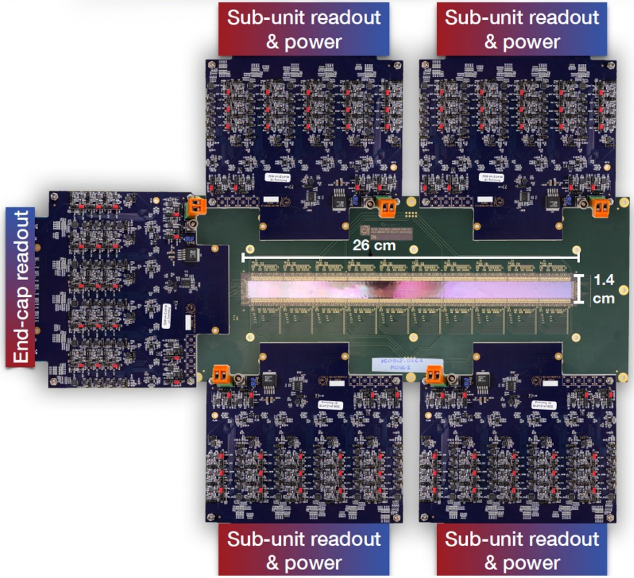
- **“MOSS”** : 14 x 259 mm, 6.72 MPixel (22.5 x 22.5 and 18 x 18 μm^2)
  - conservative design, different pitches
- “MOST” : 2.5 x 259 mm, 0.9 MPixel (18 x 18 μm^2)
  - more dense design
- Plenty of small chips (like MLR1)





W. Snoeys, PSD 2023

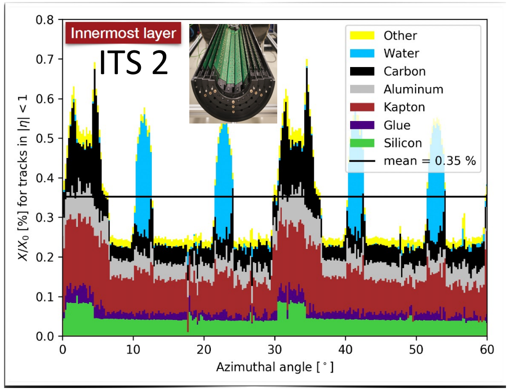


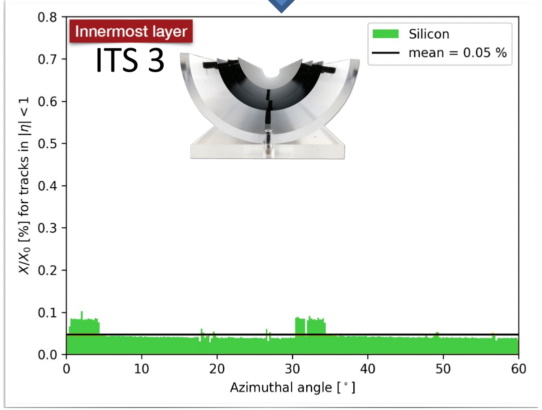


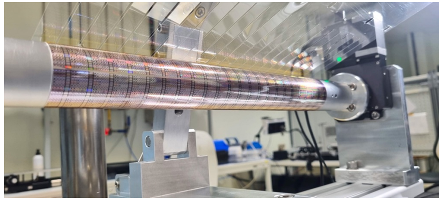
Bent sensor: reducing material budget

M. Suljic et al., iWoRiD 2023

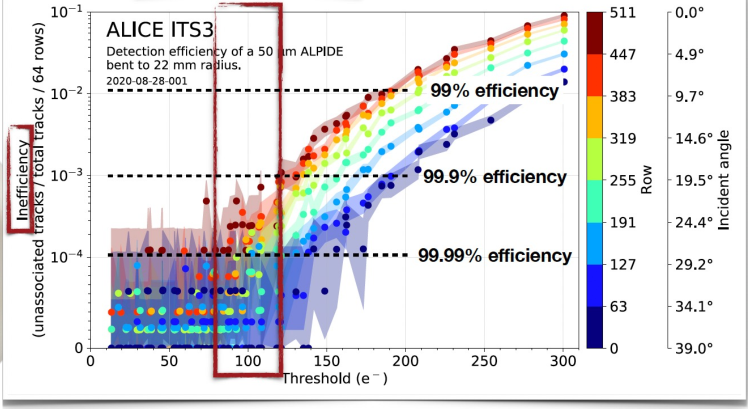
- Observations: - Si makes only 1/7-th of total material budget - Non-uniformity due to support, cooling & overlaps
- Removal of water cooling: - If **power consumption < 20 mW/cm2**
- Removal of the circuit board for power & data: - If **integrated on chip**
- Removal of mechanical support: **- Self-supporting arched structure**







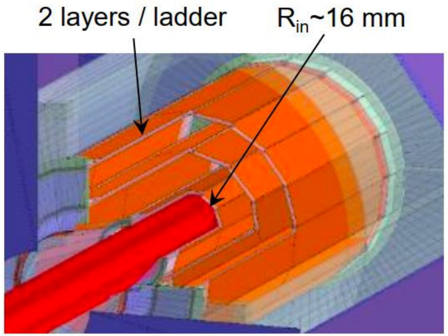
Nominal operating point

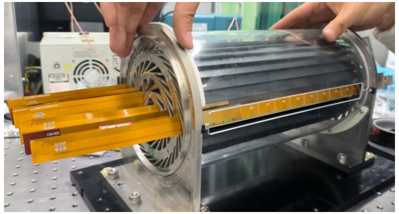


Clearly proving that bent MAPS are working!

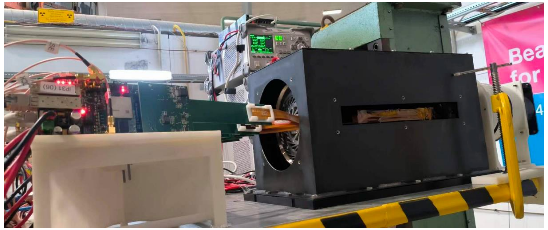
VXD Prototype - CEPC

S. Li et al., BTTB 2023
T. Wu et al., PSD 2023

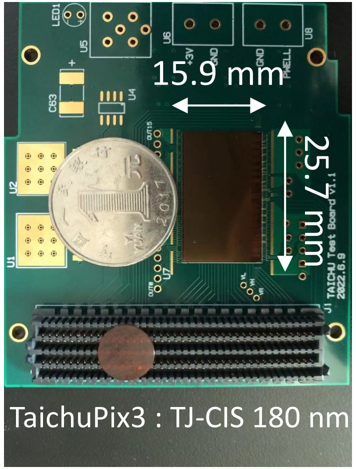




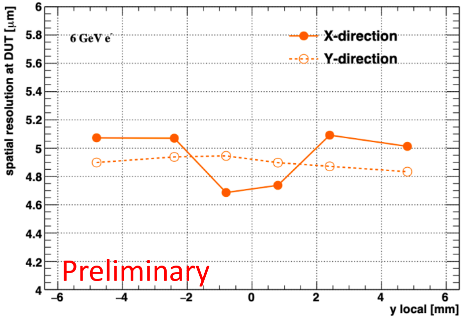
Vertex Prototype

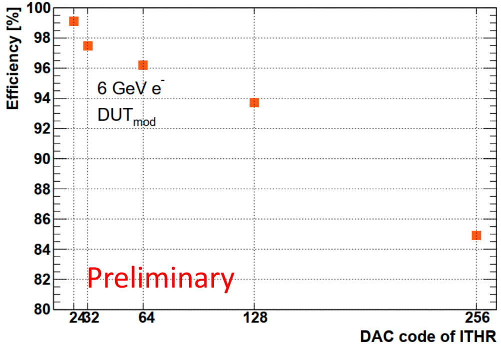


Test Beam @ DESY



Pixel size: 25 µm x 25 µm





https://doi.org/10.1016/j.nima.2018.11.133

Summary

- Plenty of R&D to follow carefully.
- Exploring new technologies is very promising (TPSco65 nm).
- Some detector requirements are achieved: spatial resolution (~5 um).
- Material budget is drastically reduced (bent sensors).
- Stitching sensors is very well advanced.

THANK YOU