CMOS TPSCo 65 nm technology R&D

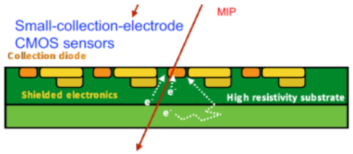
Motivations

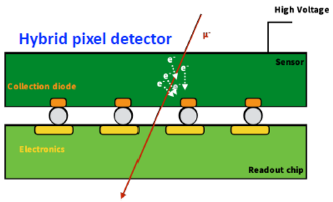
ALICE ITS-3

R&D with CE65 prototypes

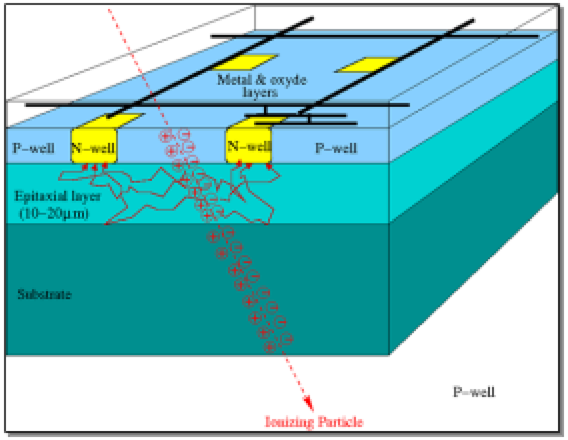
Future R&D & plans

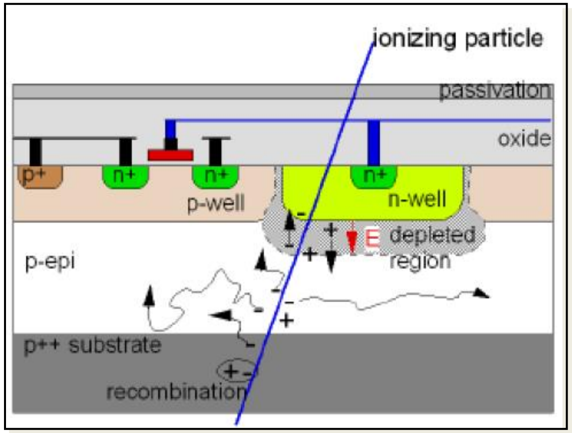
CMOS-MAPS for charged particle detection





- Main features
  - ✓ Monolithic, p-type Si
    - Signal created in low doped thin epitaxial layer ~O(10) μm
    - ~ 80 e- /μm ⇨ total signal ~ O(1000 e-) ⇨ low noise electronic
  - ✓ Charge collection: diffusion of e- ⇨ N-Well diodes
    - Partial depletion ⇨Charge sharing ⇨ resolution
    - Possible full depletion ⇨Higher S/N & rad. tol.
  - ✓ Continuous charge collection
- Main advantages
  - ✓ Granularity
    - Pixel pitch down to 10 x 10 μm^2 ⇨spatial resolution down to ~ 1 μm)
  - ✓ Material budget
    - Sensing part ~ 10-20 μm ⇨ whole sensor routinely thinned down to 50 μm
  - ✓ Signal processing integrated in the sensor
    - Compacity, flexibility, data flux
  - ✓ Flexible running conditions
    - From ≤ 0°C up to 30-40°C if necessary
    - Low power dissipation (~ 150-250 mW/cm^2) ⇨ material budget
    - Radiation tolerance: >~ MRad and O(10^{13-14} n_{eq}) ⇨f(T,pitch)
  - ✓ Industrial mass production
    - Advantages on costs, yields, fast evolution of the technology,
    - Possible frequent submissions
    - Smaller feature size, adapted epitaxial layers, doping profile to enhance depletion
- Main limitations
  - ✓ Industry addresses applications far from HEP experiments concerns
    - Different optimizations on the parameters on the technologies
    - R&D costs
  - ✓ High expertise needed (from design to tests & characterizations)
  - ✓ Long R&D needed for a given application





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

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

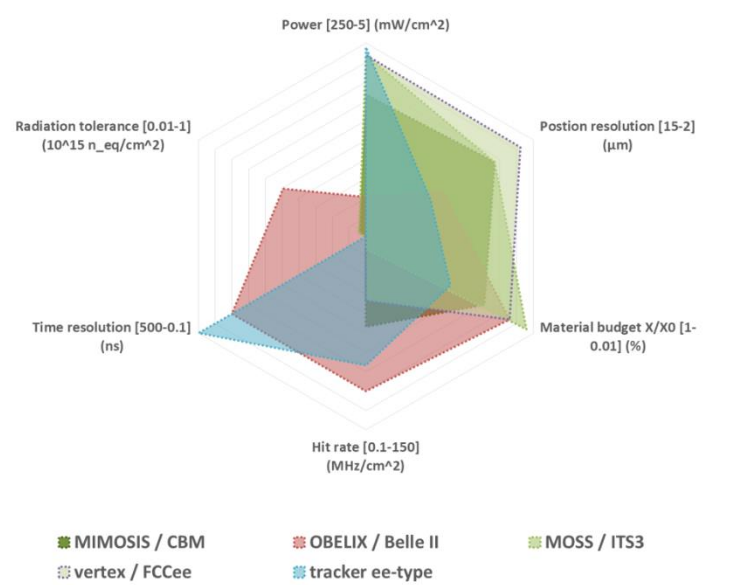
Important similarities between FCCee requirements & Heavy ions experiments (ALICE ITS3, ALICE3, EIC, etc.)

- Spatial resolution < 5 um
- Low material budget (~0.15% X_0/layer)
- Low Power (<100 mW/cm^2)

Pixel detector requirements

	past		present				future					
	MIMOSA28 STAR	ALPIDE ITS2	MIMOSIS CBM	OBELIX Belle II	MOSS ITS3 ALICE	ITK R&D ATLAS	Vertex ALICE3	vertex FCCee	Tracker ALICE3	tracker ee-type	Up. Tracker LHCb	Tracker hh-type
Power (mW/cm^2)	170	35	70	200	20	200,0	20	20	10	10	100	100
Postion res. (µm)	4	5	5	9	5	10,0	2,5	3	10	5-10	10	15
Mat. budget X/X_0 (%)	0,37	0,3	0,3	0,15	0,05	1,0	0,05	0,15	0,5	0,5	0,3	1
Hit rate (MHz/cm^2)	0,1	1	70	120	10	120,0	35	50	0,005	10-100	200	200
Time resolution (ns)	200000	5000	5000	100	5000	25,0	100	500	100	1-500	1	0,1
Rad. tolerance (10^{15} n_{eq}/cm^2)	0,001	0,05	0,05	0,5	0,05	2,0	1	0,0011	0,01	0,001-1	3	9
Sensor size (cm^2)	4,6	4,5	5,4	5,7	300,0	5,0	300,0	6,0	100,0	100,0	6,0	100,0

Figure made by J.Baudot



« high granularity vertex »
(MIMOSIS, ALICE ITS-3, FCCee vtx, ALICE3 vtx)

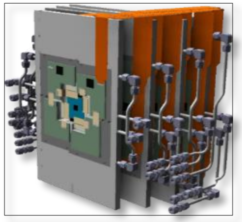
GRAM Master project

« outer trackers »
(Belle-II trk, ALICE-3 trk, FCCee trk)

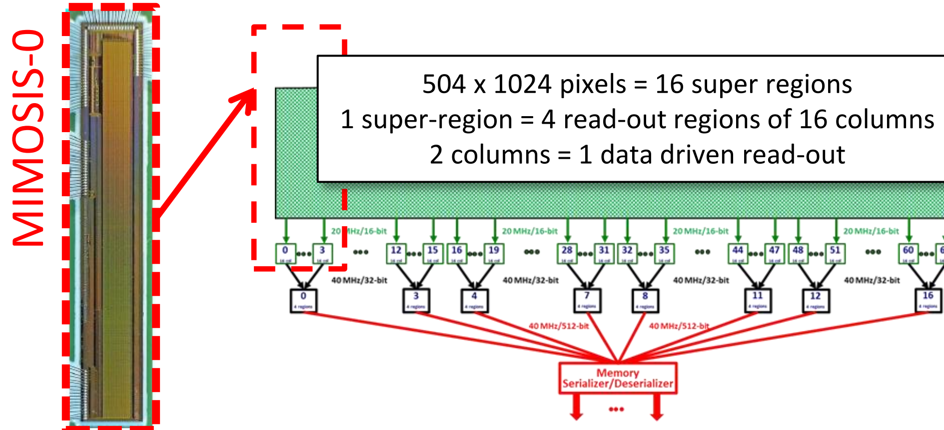
DEPHY Master Project

« high flux & rad. tol. »
(ATLAS, LHCb upgrades, FCChh)

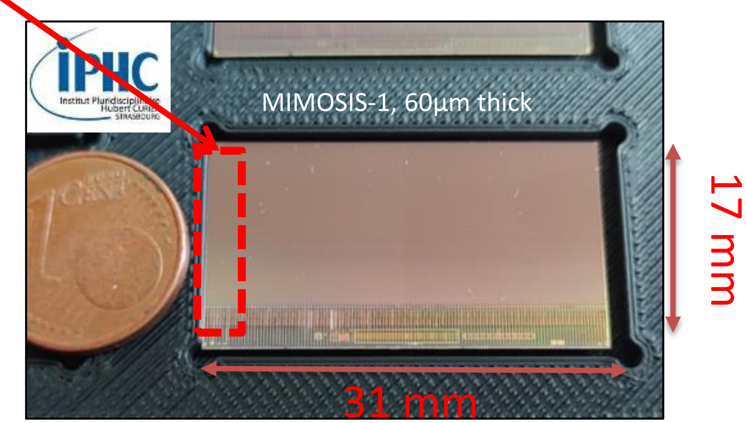
180 nm: MIMOSIS roadmap



Physics parameter	Requirements
Spatial resolution	~ 5 um
Time resolution	~ 5 us
Material budget	0.05% X_0
Power consumption	< 100 – 200 mW/cm^2
Operation temperature	- 40 °C to 30 °C
Temp gradient on sensor	< 5K
Radiation tol* (non-ion)	~ 7 x 10^{13} n_{eq}/cm^2
Radiation tol* (ionizing)	~ 5 MRad
Data flow (peak hit rate)	@ 7 x 10^5 / (mm^{2}s) > 2 Gbit/s



- MIMOSIS-0:
  - ✓ Tests (2018-2019)
- MIMOSIS-1: 1st full size prototype
  - ✓ Elastic buffer, SEE hardened
  - ✓ Fabricated in 2020
  - ✓ Intense test campaign in 2021-22
    - Lab and beam tests
    - Irradiations
    - Latchup tests



Parameter	Value
Technology	TowerJazz 180 nm
Epi layer	~ 25 µm
Epi layer resistivity	> $1k\Omega cm$
Sensor thickness	60 µm
Pixel size	26.88 µm × 30.24 µm
Matrix size	1024 × 504 (516096 pix)
Matrix area	≈ 4.2 cm^2
Matrix readout time	5 µs (event driven)
Power consumption	40-70 mW/cm^2

- MIMOSIS-2:
  - ✓ On-chip clustering
  - ✓ Triplication added
  - ✓ Back from foundry Q2 2023
  - ✓ Issues ⇨ resubmission of MIMOSIS 2.1 Q4 2023
- MIMOSIS-3: final pre-production sensor
  - ✓ ≥2025

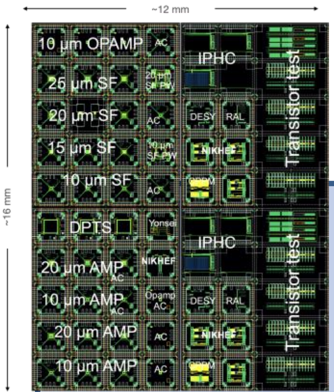
⇨ architecture adaptable to a fast sensor for a future e^+e^- collider vertex detector
⇨ Know-how maintained for large scale sensors
⇨ Opportunity to study different designs/options

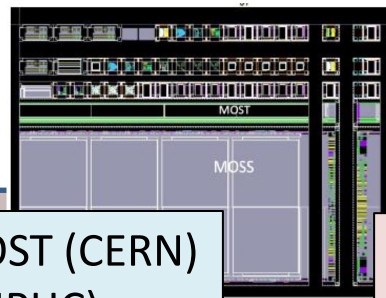
Moving from 180 nm to 65 nm

Technology	TowerJazz 180 nm	TPSCo 65 nm
Available since	2013 (mature technology)	2020 (access through CERN)
Large surface projects	• ALPIDE for ALICE ITS-2 • MIMOSIS for CBM-MVD • OBELIX for Belle-II upgrade	• MOSAIX for ALICE ITS-3 • DRD3/7 R&D ?
Price	affordable	More expensive
Wafer	• 8 inches (20 cm)	• Larger: 12 inches (30cm) ⇨ stitching + bent sensors
Epitaxial layer thickness	• 18/25/30/40/50 μm	• 10
Process options	• « standard » • « modified », « gap »	• « standard » • « modified », « gap »
Technology	• Feature size (180 nm) • V (1.8V) • 6 Metal Layers	• Feature size (65nm) • Lower V (1.2 V) • 7 Metal layers ⇨Pitch reduction, power saving, more functionnalites, etc.

⇨ Strong motivations to switch to a smaller feature size to increase the performances space

TPSCo 65nm Submissions





ALICE ITS-3

- MOSS/MOST (CERN)
- CE65_v2 (IPHC)
- Etc.

- MOSAIX (CERN)
- SPARCS ? (IPHC)
- Etc.

MLR1 (2020) → ER1 (2022) → ER2 (2024) → ER3 (2025?)

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- Ring oscillators (CPPM)
- Etc.

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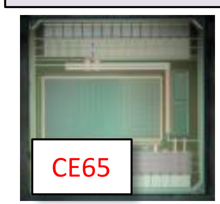
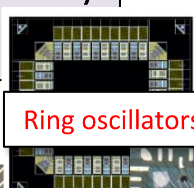
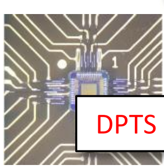
- Architectures exploration

- Fine pitch telescope
- Fast timing ?
- Power optimization ?

Generic R&D via DRD3/7


CE65


Ring oscillators


DPTS (CERN)


APTS (CERN)

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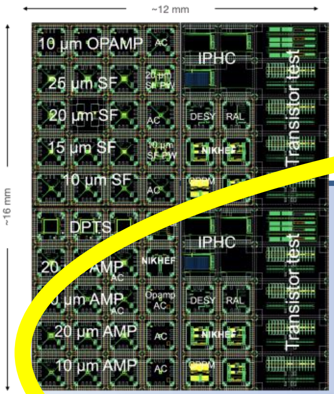

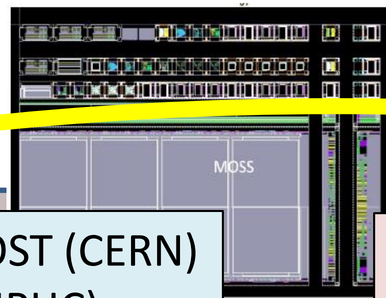

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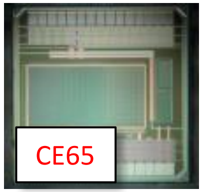
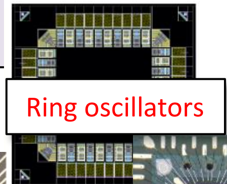

CE65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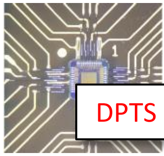
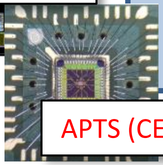
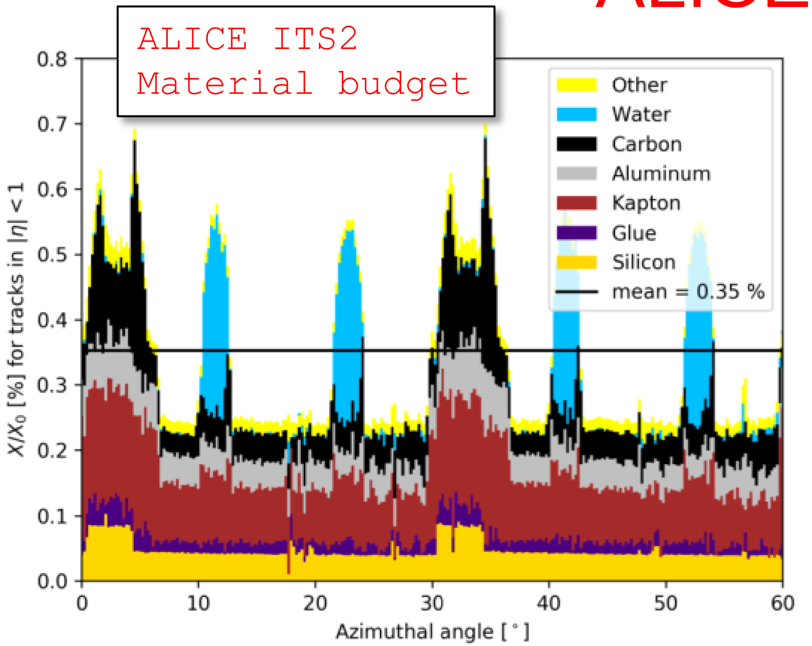
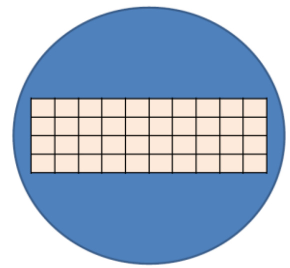
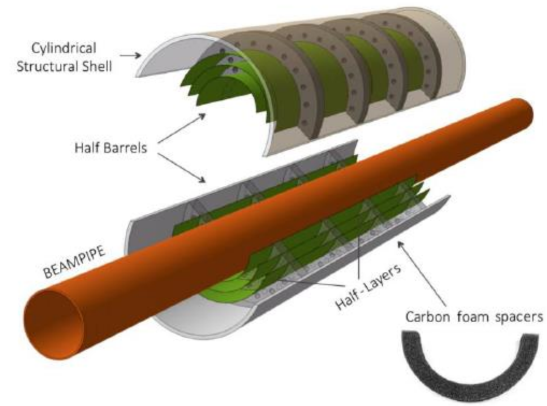

DPTS (CERN)

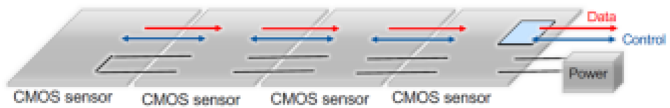

APTS (CERN)

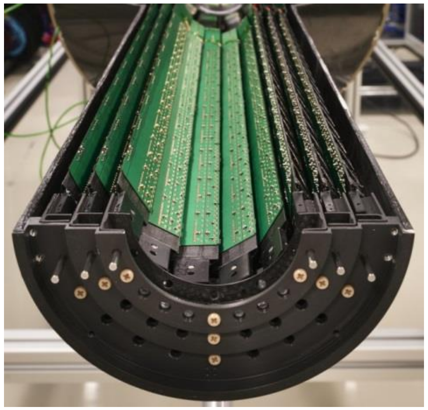
ALICE ITS-3 (Run4)





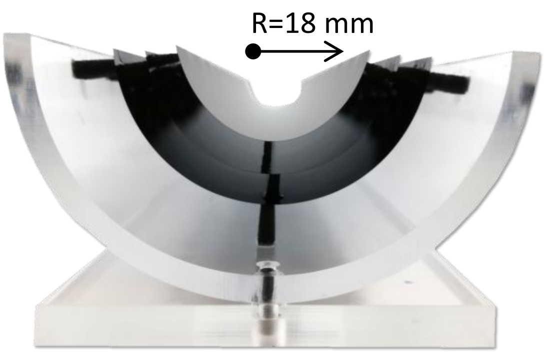






ITS2:

- 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:

- 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**

⇨ ALICE ITS-3 paves the road for the stitched sensor approach

How to adapt ITS-3 approach to FCCee ?

- ALICE-ITS3/CERN drives the R&D on stitching + bent sensors:
  - ✓ Sensor part ~15% of total material budget
  - ✓ Sensors thinned down to 50 μm or less ?
    - Tests performed by ALICE
  - ✓ Minimizing overlapping regions,
  - ✓ minimizing minimal radius around the beam pipe
- Challenges and caveats (for e^+e^- colliders)
  - ✓ Mechanics ? Bonding ? Air cooling only ?
  - ✓ Design: Minimizing peripheral circuits (Fill factor ~90%)
  - ✓ Bent sensor performances ? Yield ? Radiation hardness ?
  - ⇨ design rules constraints the minimal pitch (~22 μm)
  - ✓ ITS-3 do not have disk (chip periphery adds Z position constraint)
  - ✓ Approach validated in a limited radius range (R> 18mm) ?
    - Trials performed by ALICE down to R = 10mm
- ALIC ITS-3 Significant contributions from IPHC (C4PI, ALICE, PICSEL)
  - ✓ MOSS
    - Read-out line
    - Standard cells designs
    - DACs
  - ✓ MOSAIX
    - Feasibility studies
    - Matrix assembly (pixel analog + digital + readout
    - Column read-out in the matrix
    - Digital & Analog pixel (driven by CERN)
    - Standard cells with low leakage current
    - Biasing blocks (DACs)

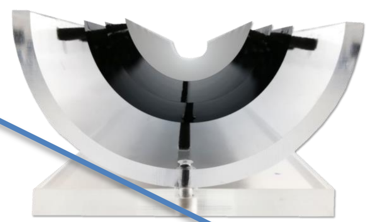
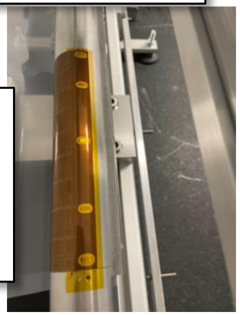
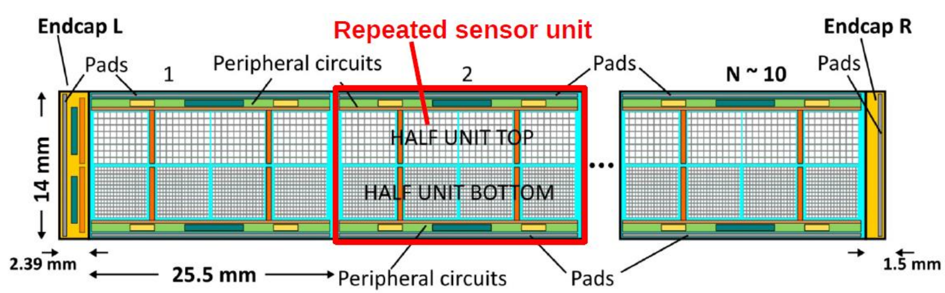


Figure 4.42: Setup for the bending strength measurements.

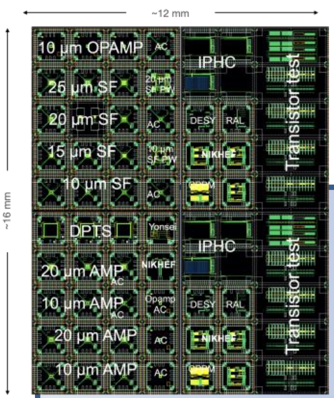
Questions potentially adressed by GRAM with MIMOSIS

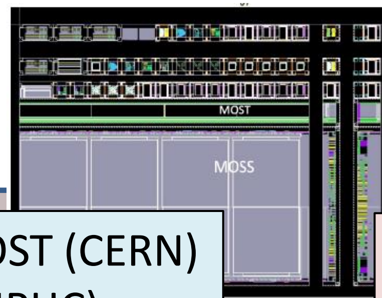


1st bending tests by C4PI microtechnics



TPSCo 65nm Submissions





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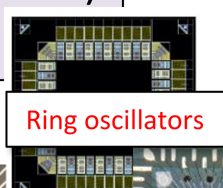
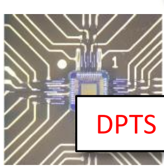
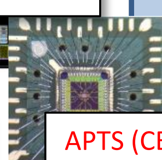
Generic R&D via DRD3/7


CE65

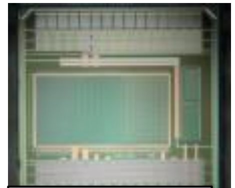

Ring oscillators


DPTS (CERN)


APTS (CERN)

CE65_v1

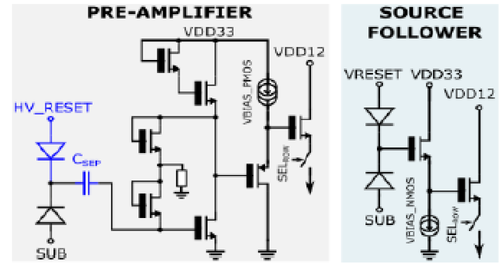
- CE_65v1 (MLR1 submission)
  - ✓ prototype designed @IPHC
  - ✓ Analog output, various designs (pitch, amplification)
- CE_65v2 (ER1 submission)
  - ✓ 18/22 μm pitch, hex design
  - ✓ Test beam next week @ DESY
- ✓ More results: PSD13, Oxford, El Bitar

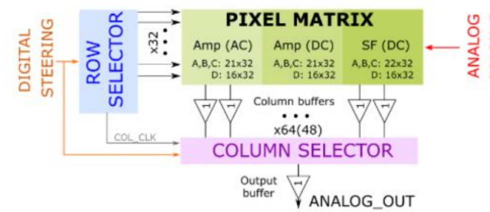


CE-65 (IPHC)

PICSEL C4PI-Platform CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG eurizon European network for developing new horizons for RIs AIDA innova cnrs IN2P3 Les deux infinis

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

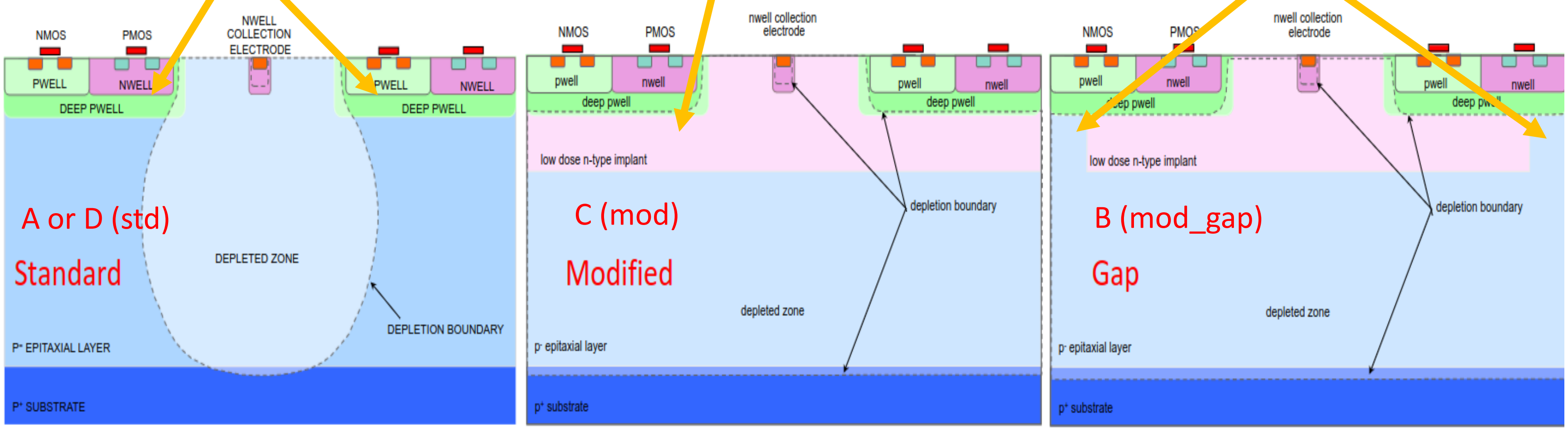




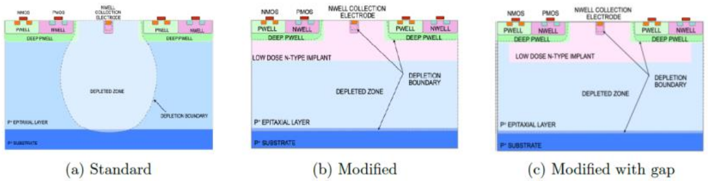
Prevent circuitry's nwells from collecting charge

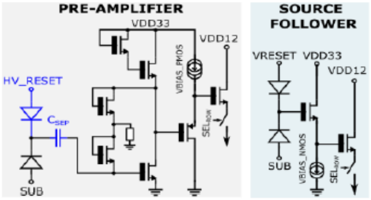
To obtain a full depletion

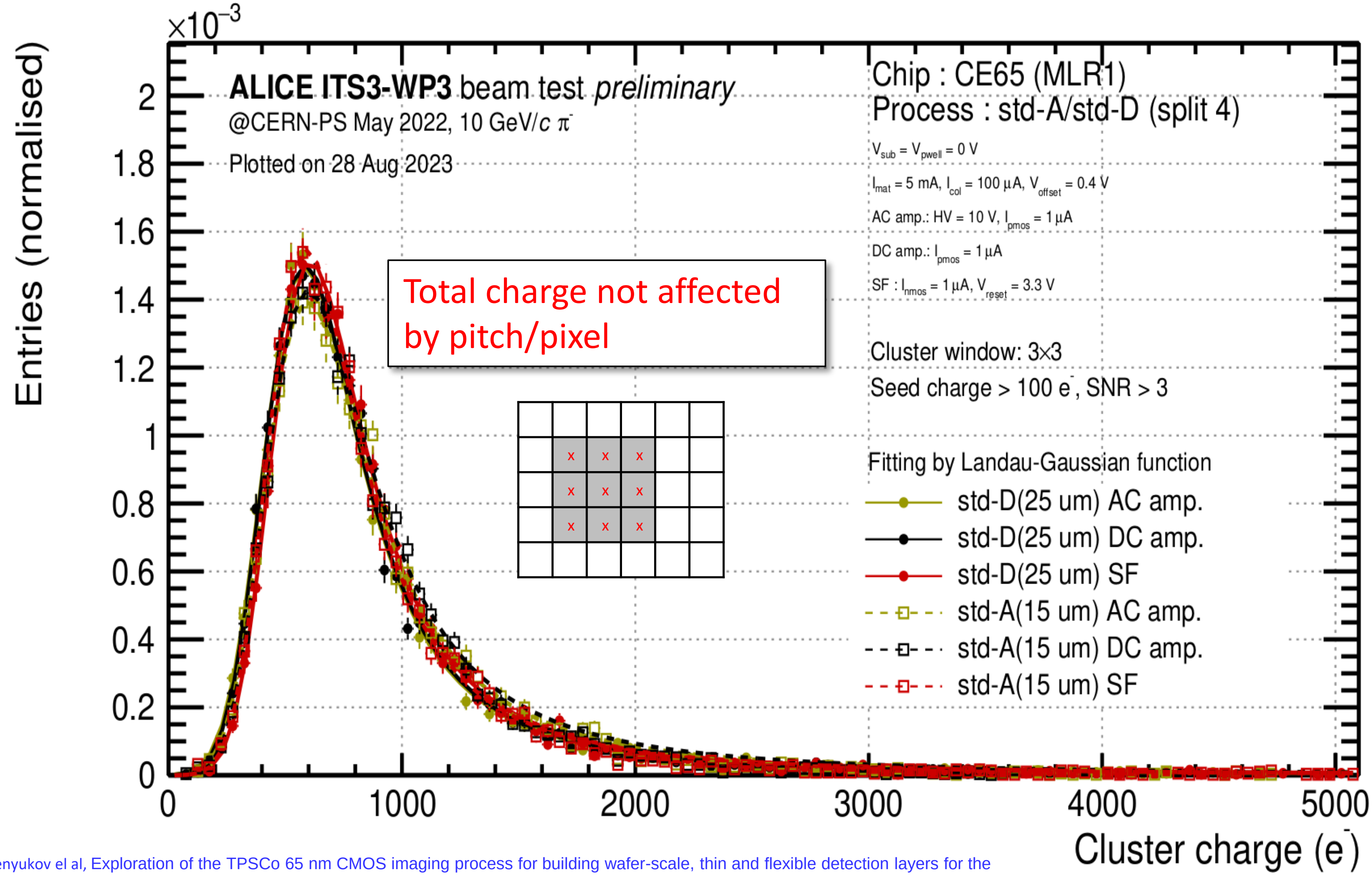
To overcome the weak electric field near the edges



Comparing the processes

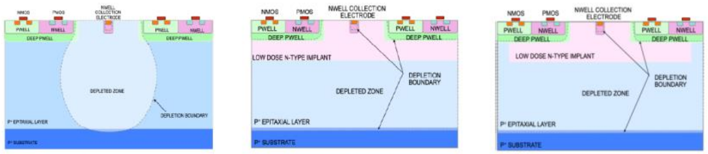




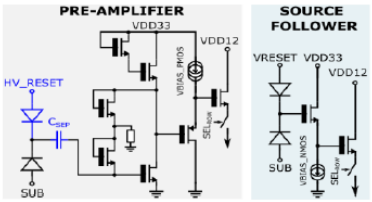


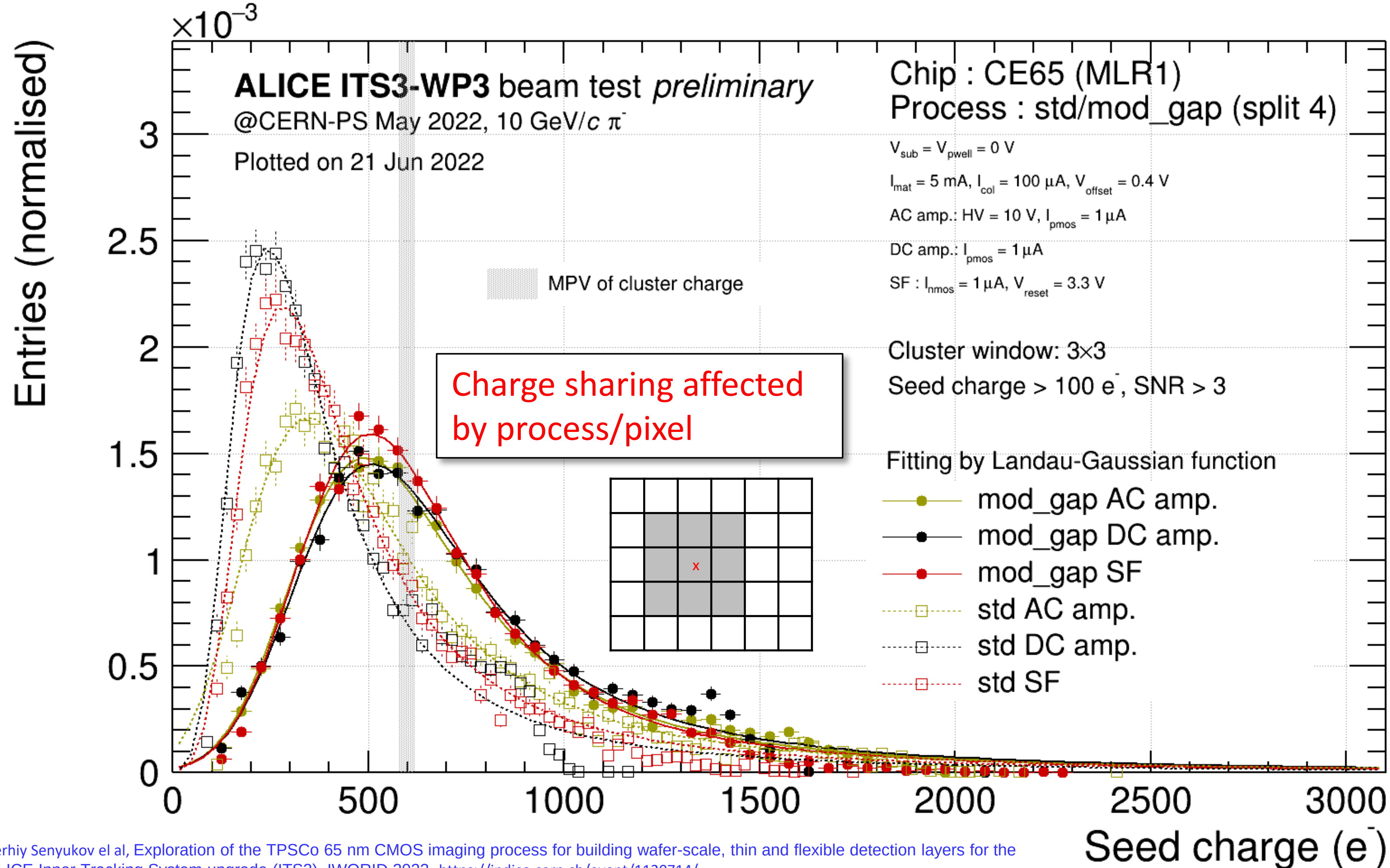
Serhiy Senyukov el al, Exploration of the TPSCo 65 nm CMOS imaging process for building wafer-scale, thin and flexible detection layers for the ALICE Inner Tracking System upgrade (ITS3), IWORID 2022 https://indico.cern.ch/event/1120714/

Comparing the processes



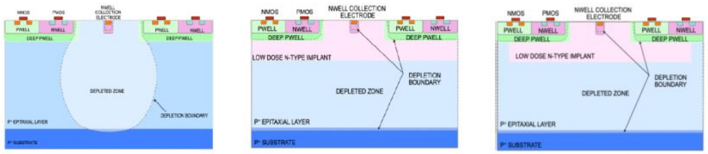
(a) Standard (b) Modified (c) Modified with gap





Serhiy Senyukov el al, Exploration of the TPSCo 65 nm CMOS imaging process for building wafer-scale, thin and flexible detection layers for the ALICE Inner Tracking System upgrade (ITS3), IWORID 2022 https://indico.cern.ch/event/1120714/

Comparing the pitch/pixel



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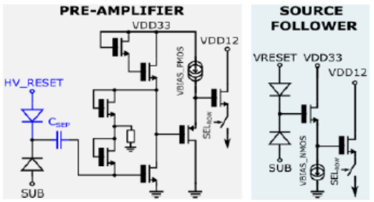
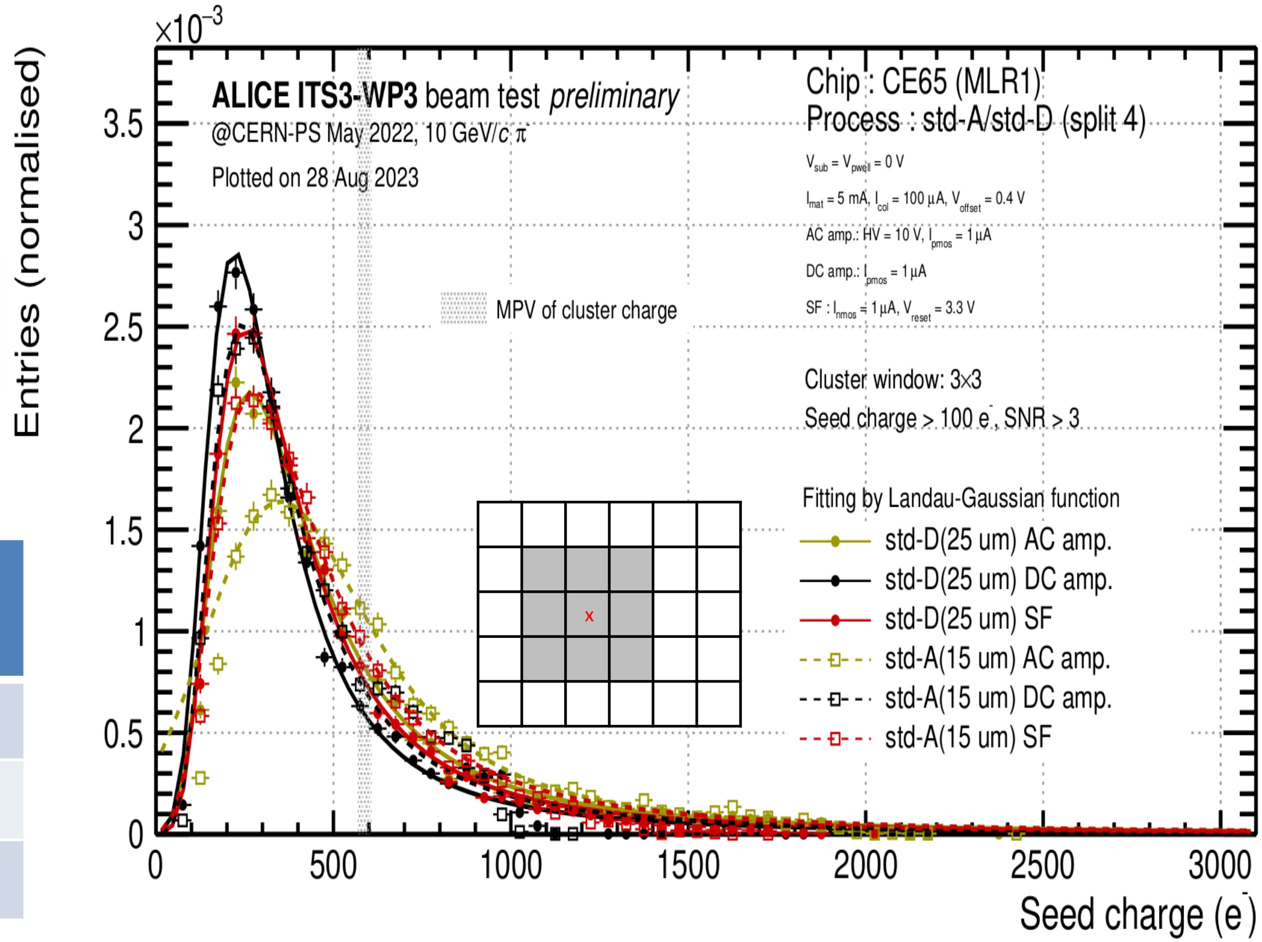


Charge sharing affected by pitch/pixel

Charge sharing increase →

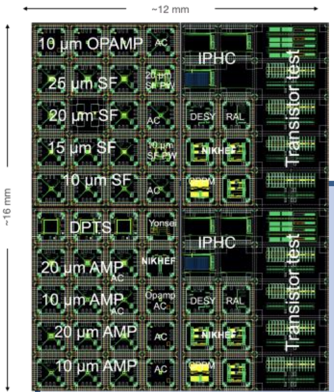
Charge sharing increase ↓

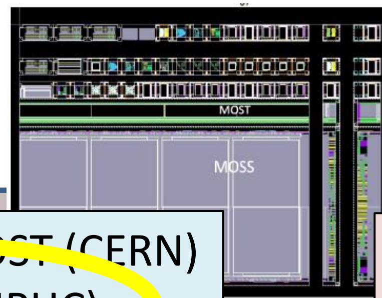
	A4-std 15 um	D4-std 25 um
AC	311	284
SF	297	269
DC	261	232



Serhiy Senyukov el al, Exploration of the TPSCo 65 nm CMOS imaging process for building wafer-scale, thin and flexible detection layers for the ALICE Inner Tracking System upgrade (ITS3), IWORID 2022 https://indico.cern.ch/event/1120714/

TPSCo 65nm Submissions





- MOSS/MOST (CERN)
- CE65_v2 (IPHC)
- Etc.

- MOSAIX (CERN)
- SPARCS ? (IPHC)
- Etc.

ALICE ITS-3

MLR1 (2020) → ER1 (2022) → ER2 (2024) → ER3 (2025?)

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

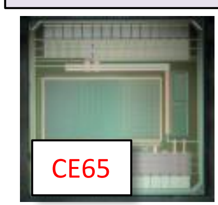
- CE65_v1 (IPHC)
- DPTS (CERN)
- APTS (CERN)
- TANGERINE (DESY)
- Ring oscillators (CPPM)
- Etc.

MPR2 (2025) → MPR3 (2027?)

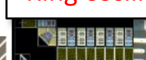
- Fine pitch demonstrator
- Architectures exploration

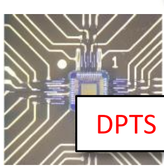
- Fine pitch telescope
- Fast timing ?
- Power optimization ?

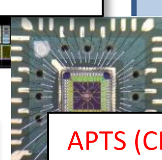
Generic R&D via DRD3/7


CE65

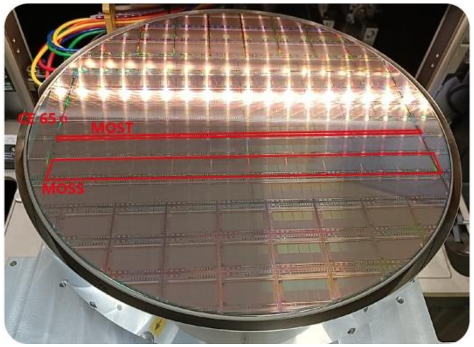

Ring oscillators



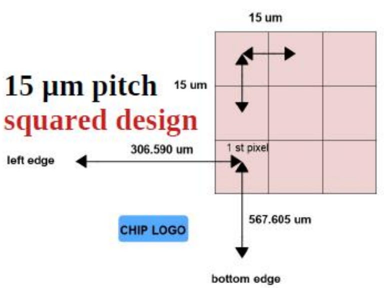

DPTS (CERN)

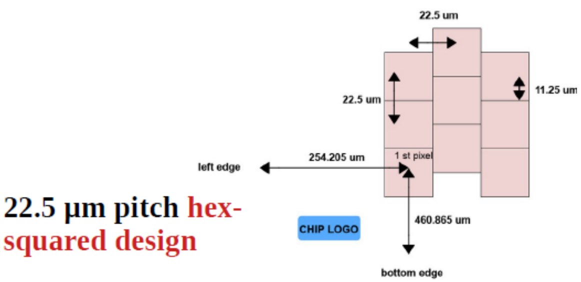

APTS (CERN)

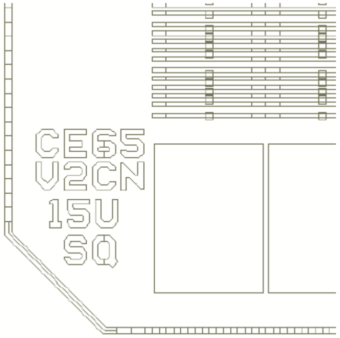
CE65_v2 (ER1 fabrication)



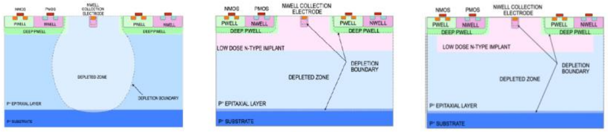
- New variants (x 15 !)
  - ✓ Back from foundry summer 2023
  - ✓ 48 col x 24 rows = 1152 pixels
  - ✓ 5 pixel geometries :
    - 15 µm, 18 µm squared & hexagonal, 22.5 µm squared & hexagonal





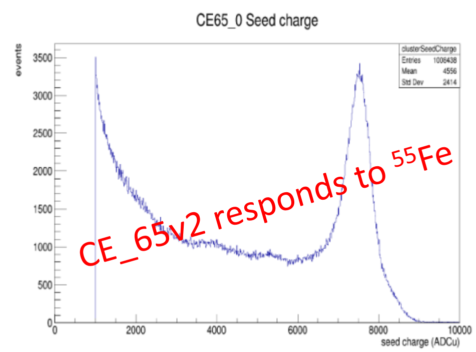


  - ✓ 3 process options (« standard », « Blanket », « Gap »)



(a) Standard (b) Modified (c) Modified with gap

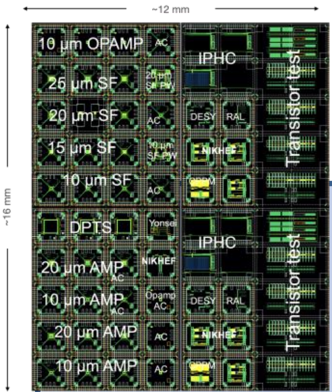
- First beam test next week (5 GeV e⁻ @ DESY)
  - ✓ ALPIDE telescope (DPTS trigger)

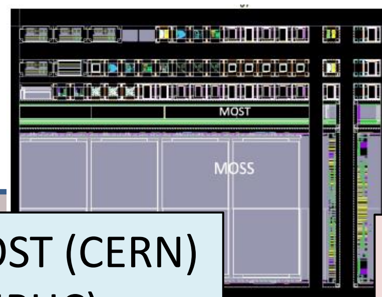


- Added value of CE65_v2: Charge collection model, resolution, efficiency, etc.

⇨ Deep understanding of the charge collection allows pixel optimization for various applications

TPSCo 65nm Submissions





ALICE ITS-3

- MOSS/MOST (CERN)
- CE65_v2 (IPHC)
- Etc.

- MOSAIX (CERN)
- SPARCS ? (IPHC)
- Etc.

MLR1 (2020) → ER1 (2022) → ER2 (2024) → ER3 (2025?)

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

ER1 (2022) → MPR2 (2025) → MPR3 (2027?)

- CE65_v1 (IPHC)
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- Etc.

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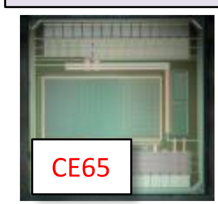
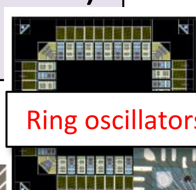
- Fine pitch telescope
- Fast timing ?
- Power optimization ?

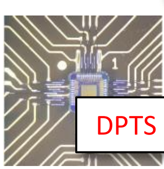
Generic R&D via DRD3/7



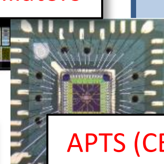
CE65



Ring oscillators



DPTS (CERN)



APTS (CERN)

CMOS 65 nm submissions and connexion with DRD3/DRD7

- 2 lines of submissions
  - ✓ Submissions dedicated to ALICE ITS-3 (ER2 & ER3)
  - ✓ Submissions for generic R&D, supported by CERN EP R&D WP1.2 (« MLR2 » and beyond)
    - Motivations to gather the Higgs factory community
- Solid state detector R&D framework = DRD3/7

- Generic R&D possible contributions
  - ✓ One expression of interest submitted with future e+e- collider vertex detectors as the main driver
    - Goal: gather groups to reach a critical size
    - Targets 3 μm spatial resolution, improved time resolution (5-500 ns), controlled Power (< 50 mW/cm^2), data flow (10-100 MHz/cm^2) and low material budget (50 μm thickness)
    - Demonstrator to equip new generation beam telescope
    - Proposing Institutes: CERN, DESY, IPHC, APC, etc.
    - Open to other participations
  - ✓ Other projects in discussion (tracking, timing, calorimeters)

DRD project: Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments

DRD technology area

DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.

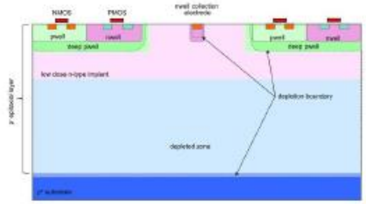
Proposing participants

Institute	Contact	Foreseen main areas of contribution
APC Paris	M. Bomben	Simulations, testing
CERN	D. Dannheim	Testing, DAQ, ASIC design support
DESY	S. Spannagel	ASIC design, testing, DAQ, simulations
IPHC Strasbourg	A. Besson	ASIC design, testing
Oxford University	D. Hynds	Testing, simulations
Zurich University	A. Macchiolo	Testing, DAQ, simulations

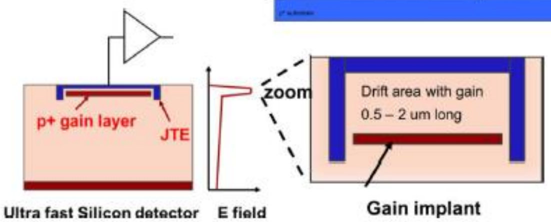
- MLR2 submission model ?
  - ✓ R&D submissions: ~ end 2025 (another expected > 2027)
  - ✓ Cost to be shared between EP R&D WP 1.2 and participating projects
  - ✓ Multi-year plan needed to allow significant contributions to the targeted submissions

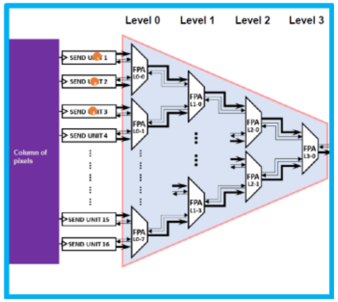
Other R&Ds

- Generic R&D
  - ✓ if fully generic ⇨ C4PI is the key player

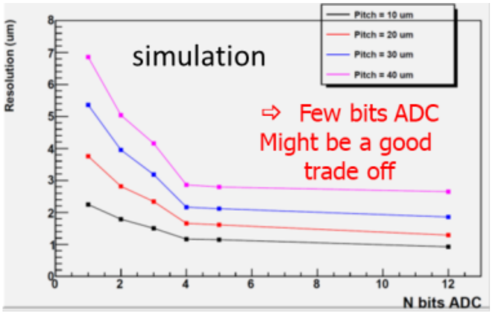


- CMOS with Preamplification
  - ✓ Carried by C4PI & ANR APICS 2023 (J. Baudot, CPPM/IPHC/ICUBE)
  - ✓ Interest: amplification of primary charges in the sensitive layer ⇨Spatial resolution, Fast time resolution & Power optimization





- Asynchronous read-out
  - ✓ Carried by C4PI/ICUBE + PhD
  - ✓ Interest: power, fast read-out architecture & increased bandwidth
  - ✓ Challenge: make it compatible wit small pitchs
  - ✓ Goal : compare the performances with other architectures



- In pixel ADCs
  - ✓ with APC
  - ✓ Interest: optimize the spatial resolution vs pitch figure of merit

- Fast timing (ToF via TDC)
  - ✓ with IP2I/APC
  - ✓ Interest: ⇨ MAPS with 4D measurements

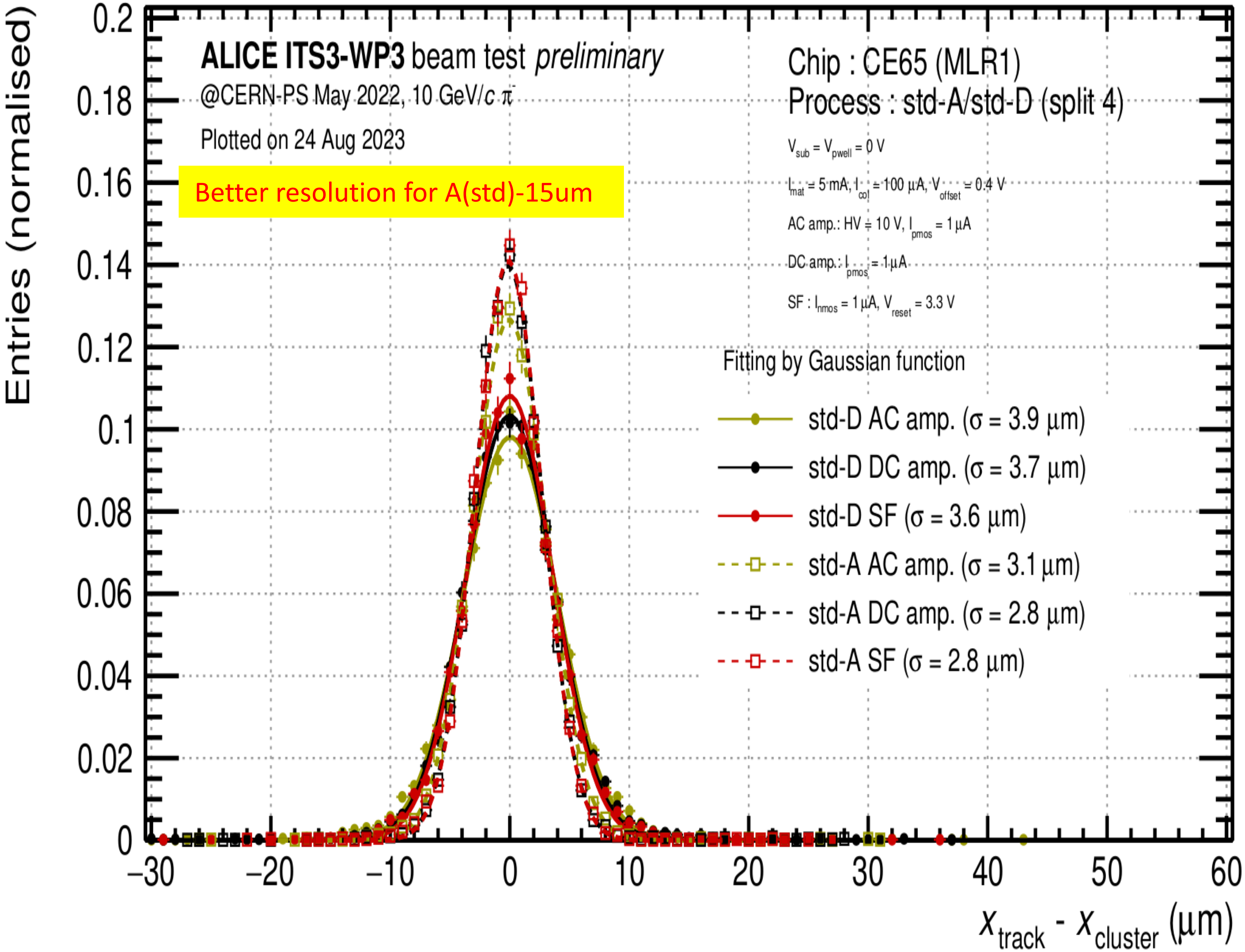
ANR 4D MAPS submitted in 2023 (IPHC/APC/IP2I, Bomben)

CMOS R&D for FCCee: Summary

- CMOS-MAPS technology:
  - ✓ After 20 years of R&D, the technology has reached a level of maturity which allows it to be widely used in HEP
  - ✓ The technology has not yet reached its full potential
- Scientific goals:
  - ✓ Exploit fully the potential of the technology, targeting future Higgs factory (FCCee) and any applications where granularity is a leading requirement
- Strategy definition:
  - ✓ Synergies: Mid-term projects are still the way to go
    - Carried by GRAM : MIMOSIS OR carried by other MPs: ALICE ITS-3, Belle-2 upgrade (Obelix)
    - Provides invaluable milestones, maintains/develops the know-how for full size chips
  - ✓ Leading technology: 65nm TPSCo R&D
    - Supported by CERN and DRDs
- Strategy implementation:
  - ✓ Local:
    - Crucial role of C4PI (e.g. R&D strategy coordination between GRAM & C4PI, manpower)
    - Strategy for Higgs factories/ALICE-ITS3/Belle II endorsed by IPHC scientific council (2023), HCERES.
  - ✓ National:
    - GRAM extended to emerging activities (IP2I, APC) and to other applications (e.g. outer trackers)
    - Complementarity of the 2 master projects : GRAM / DEPHY
    - Complementarity with projects carried by experiments (ALICE ITS-3, Belle-II) (e.g. technical coordinator of ITS-3 @ in2p3)
    - Continue to strengthen the community targeting FCCee (e.g. ANR submitted (Bomben, APC/ IP2I/IPHC)
    - Find the right balance between generic R&D and specific requirements & mid-term vs long term
    - Develop simulations & physics studies dedicated to FCCee
  - ✓ International:
    - DRD3/DRD7 and program of submission in 65 nm technology
    - Exploit synergies and maintain the network of partners (CERN, DESY, KEK, Zurich, etc.)

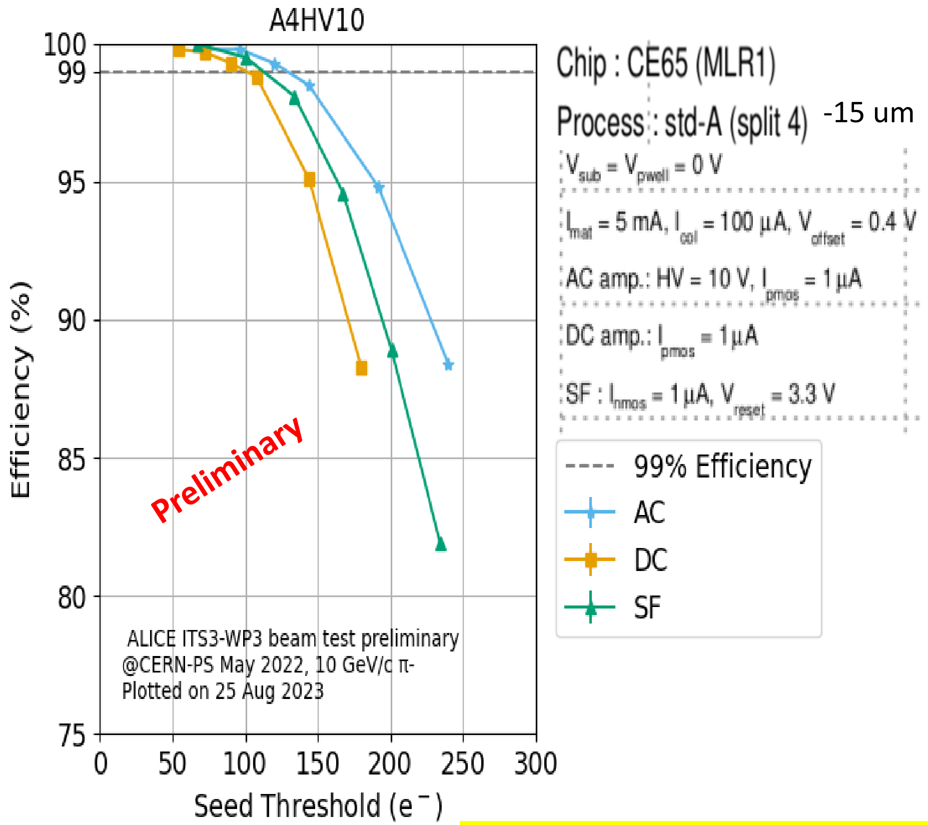
Back up

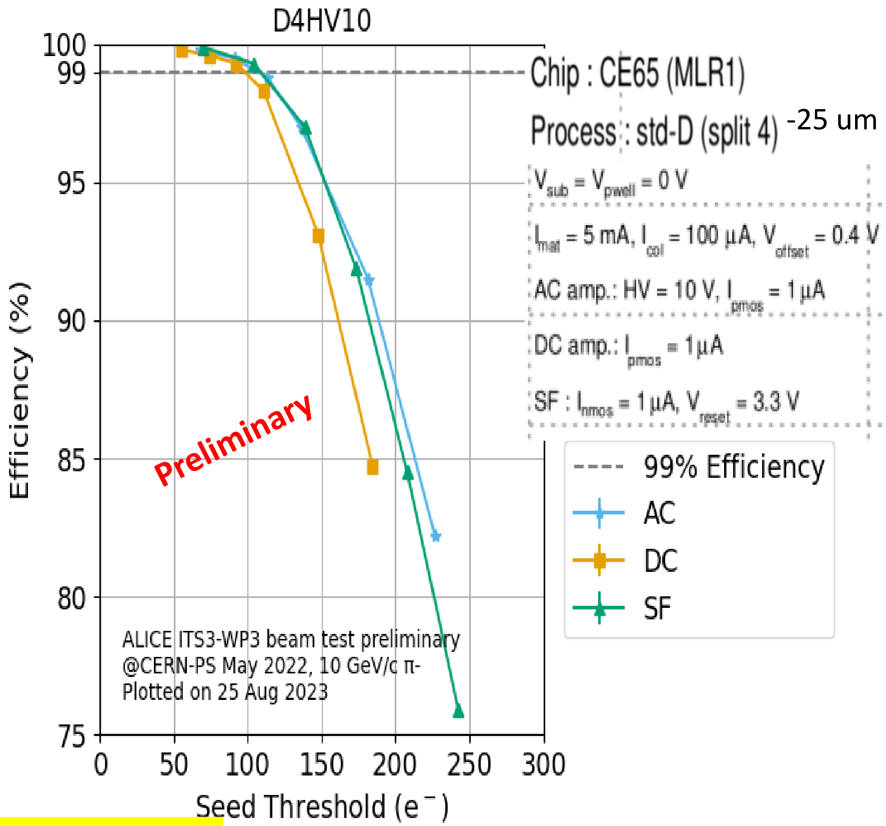
Residual



ALICE ITS3-WP3 beam test preliminary
@CERN-PS May 2022, 10 GeV/c π⁻
Plotted on 24 Aug 2023
Better resolution for A(std)-15um
Chip : CE65 (MLR1)
Process : std-A/std-D (split 4)
V_sub = V_pwell = 0 V
I_mat = 5 mA, I_col = 100 μA, V_offset = 0.4 V
AC amp.: HV = 10 V, I_pmos = 1 μA
DC amp.: I_pmos = 1 μA
SF : I_nmos = 1 μA, V_reset = 3.3 V
Fitting by Gaussian function
std-D AC amp. (σ = 3.9 μm)
std-D DC amp. (σ = 3.7 μm)
std-D SF (σ = 3.6 μm)
std-A AC amp. (σ = 3.1 μm)
std-A DC amp. (σ = 2.8 μm)
std-A SF (σ = 2.8 μm)
Entries (normalised)
x_track - x_cluster (μm)

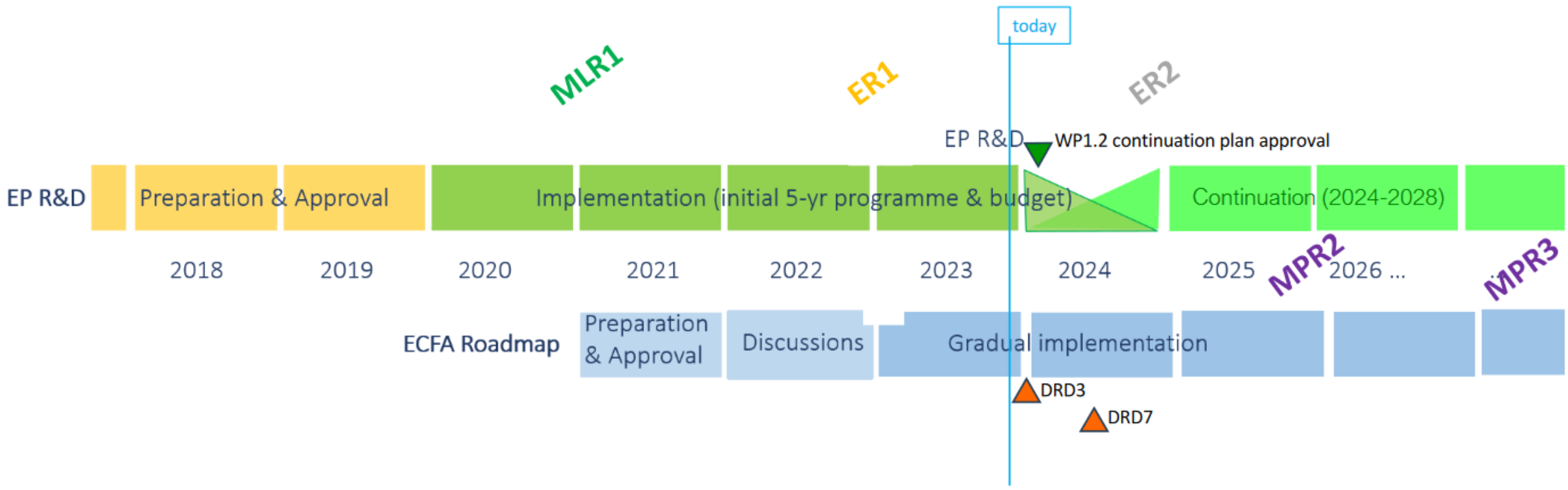
Detection efficiency





Charge sharing reduce efficiency

CERN WP 1.2



https://indico.cern.ch/event/1339888/