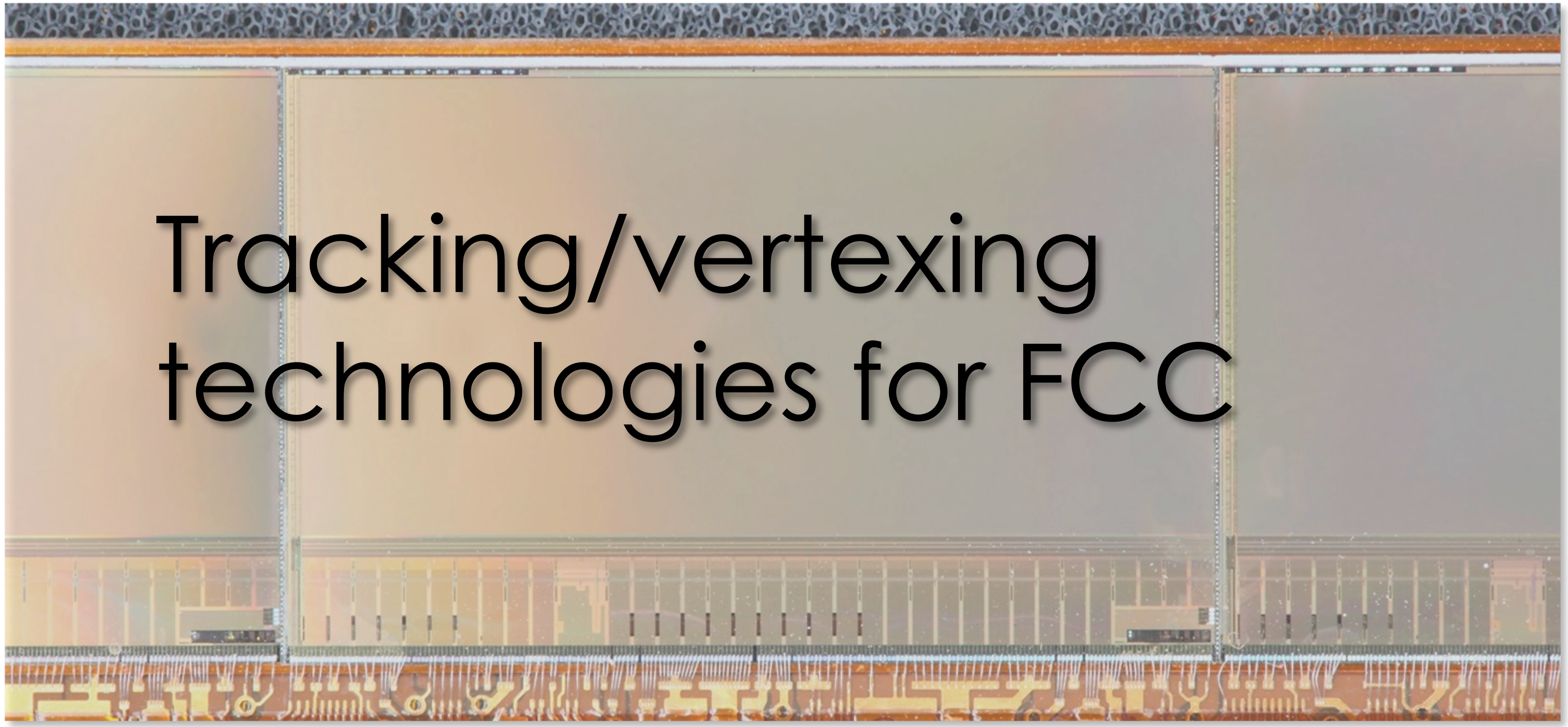
Prospectives IP2I
14 September 2023



Tracking/vertexing technologies for FCC

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cnrs

Université de Strasbourg

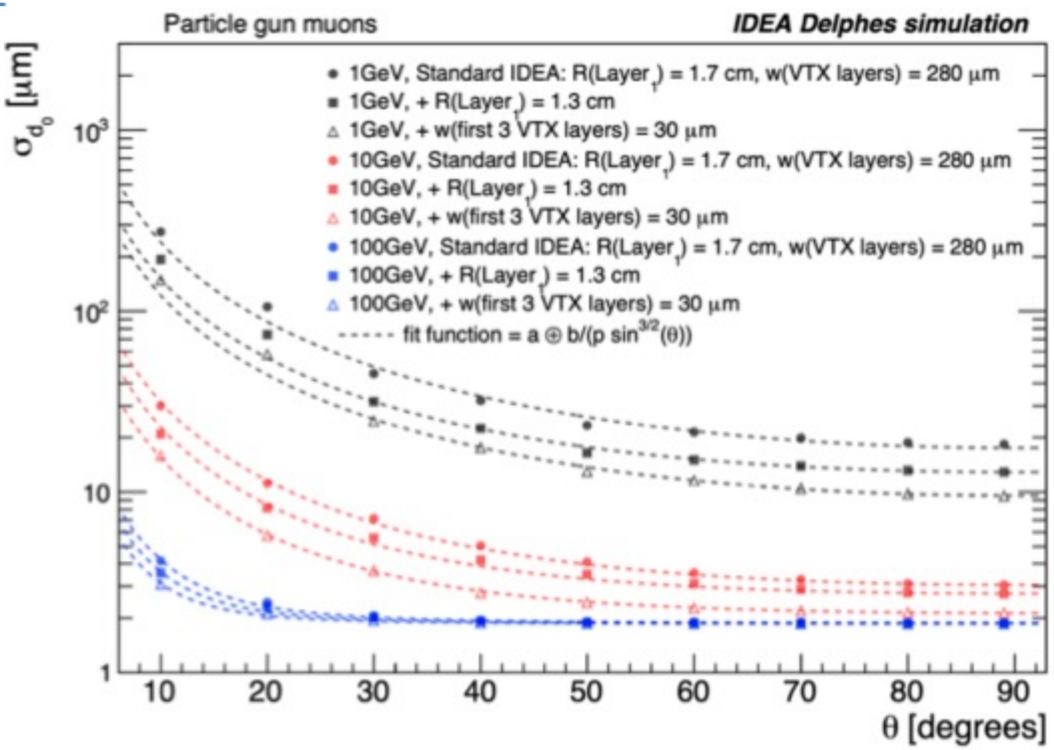
- Specifications: from physics to sensors
- First tour of technologies
- Monolithic sensors: detailed R&D roadmap
- R&D context in France & elsewhere

Specifications from physics to sensors

Vertexing

- **Goals**
  - Reconstruction of vertices: primary, secondary, tertiary
    - Possibly for long lived particle ⟶ tracker
  - Tagging jet flavour: impact parameter resolution
  - Low pT track reconstruction

- **Environment**
  - Beamstrahlung background dominating hit-rate
  - (radiations ignored: few 10^{11} n_{eq}/cm²/year & kGy/year)

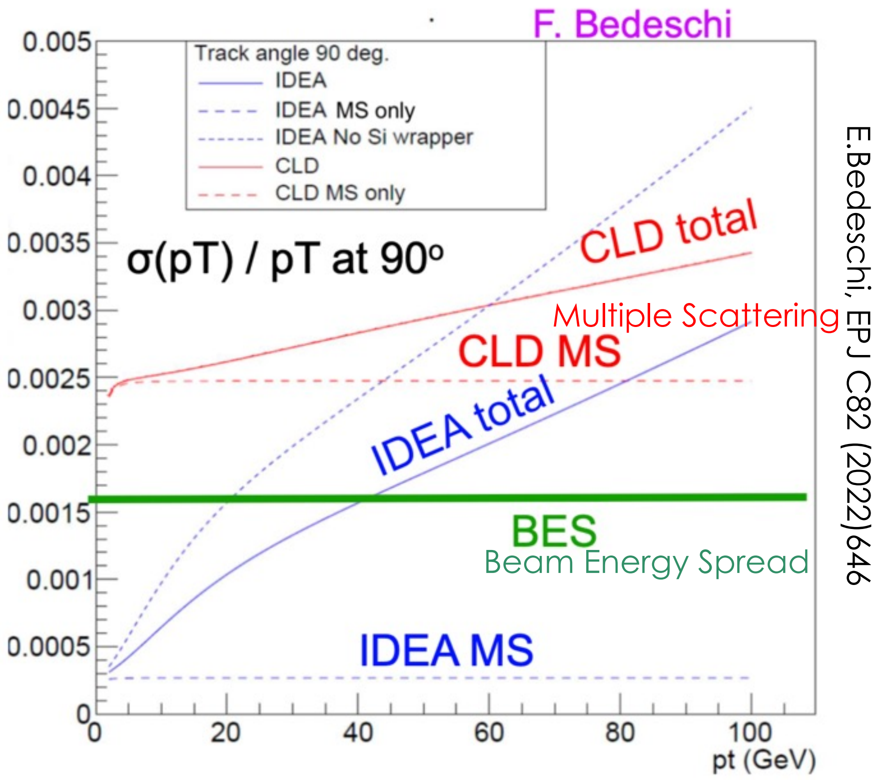


A.Ilg, L.Freitag: FCC workshop Jan 2023

- **Detector system**
  - 5 to 6 layers (< 0.5 m²)
  - Position resolution ≲ 3-4 μm
  - Material budget ≲ 0.2 % X_0 / layer
  - As close to collision as possible
    - Beam pipe radius 10 mm => 1st layer 12 mm

- **Sensors**
  - Small (17-25 μm) pitch and/or multi-bit digitization
  - Dimension compatible with small radius or bendable
  - Time binning 1 μs (Bunch ID with 30 ns, CLIC 3 ns)
  - Thinned to 50-100 μm (depends on other support)
  - Power budget < 20-50 mW/cm²

Tracking



- Goals
  - High track efficiency down to pT 100 MeV/c
  - Excellent momentum resolution

$$\frac{\sigma_{p_T}}{p_T} \leq 2.10^{-5}\, p_T + 1\text{to}2.10^{-3}$$

  - Particle Identification via dE/dx and/or Time of Flight
  - Compatible with Particle Flow Analysis

- Detector system
  - Radius coverage 200 cm
    - 10 m^2 for last layer
  - Multi-layer system
  - Position resolution ≲ 10 µm
  - Material budget ≲ 1-2 % X_0 / layer

- Sensors
  - Average to large pitch (30-100 µm)
  - Thinned to 50-100 µm (depends on other support)
  - Power budget < 20-50 mW/cm^2

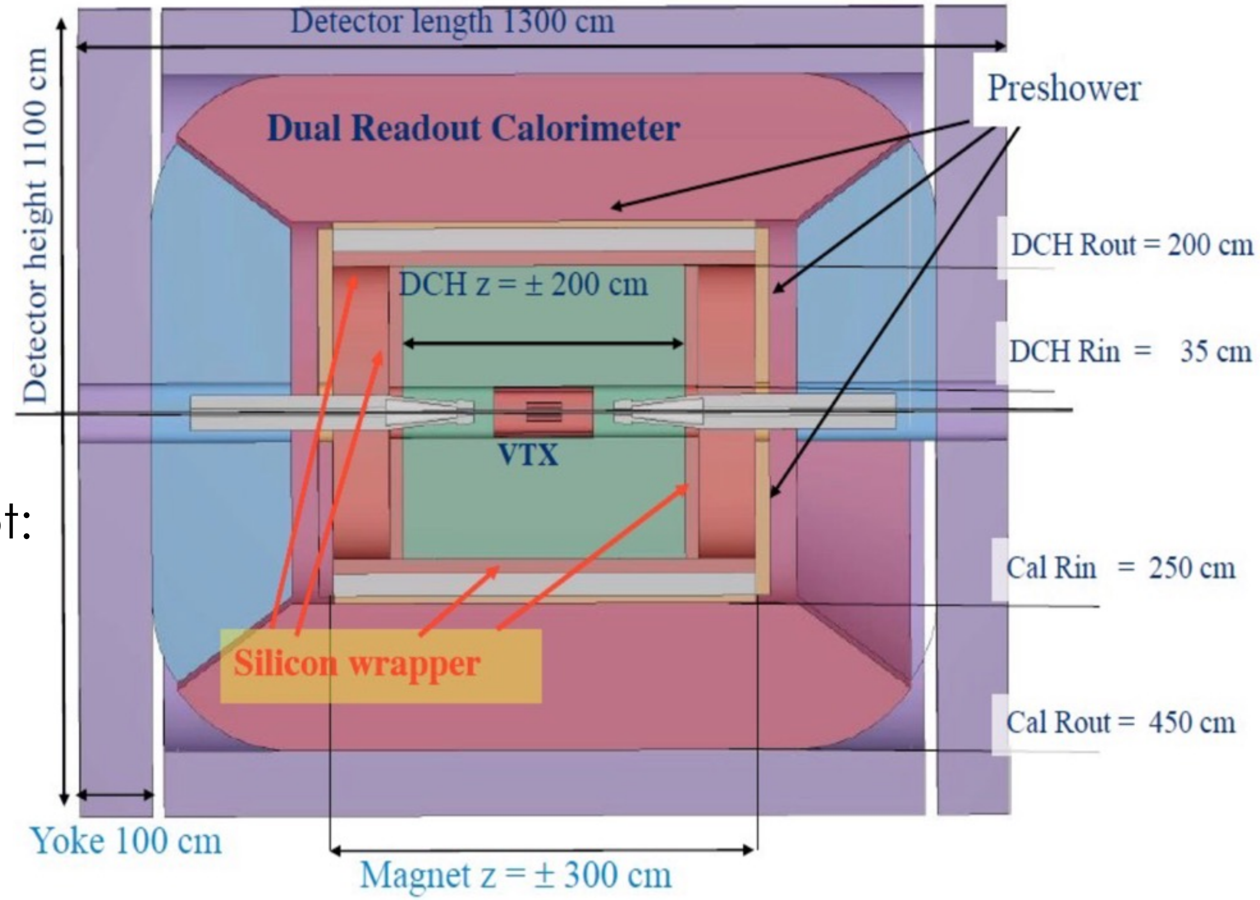
First tour of technologies

Gas detectors (tracking)

- Large volume
  - TPC / drift chambers
- Benefits
  - Easy coverage
  - No trade-off #points vs material budget
- Issues
  - 100 kHz

- Micro pattern
  - Individual layers with GEM or Micromegas

IDEA concept:



Hybrid silicon sensors

- **Sensors**
  - No internal amplification
    - strips, pixels, 3D, diamond
    - ELAD strips with enhanced lateral drift => position resolution
  - With amplification
    - Saturated: APD, SPADS => single photon sensitivity
    - Linear: LGAD => time resolution

- **Read-Out Chip**
  - RD53, Timepix4, VeloPix, … (CMOS 65 nm)
  - TimeSPOT, IGNITE (CMOS 28 nm)

- **Hybridization techniques**
  - Evolution of bump-bonding:
    pitch 25 µm with sensor thickness 50 µm (IZM)
  - Novel technique with anisotropic conductive films
    - Maybe only for prototyping?

- **Strong points**

  <= From functionalities optimised in different parts
  - Hit-rate
  - Radiation tolerance
  - Time resolution

- **Challenges**
  - Material budget (currennt limit ~1%)
  - Minimal pitch (current limit 25 µm)
  - Cost & time of production

Considered for

CLIC-tracking (nanosecond time resolution)

ToF with LGAD

But currently Monolithic preferred / FCCee

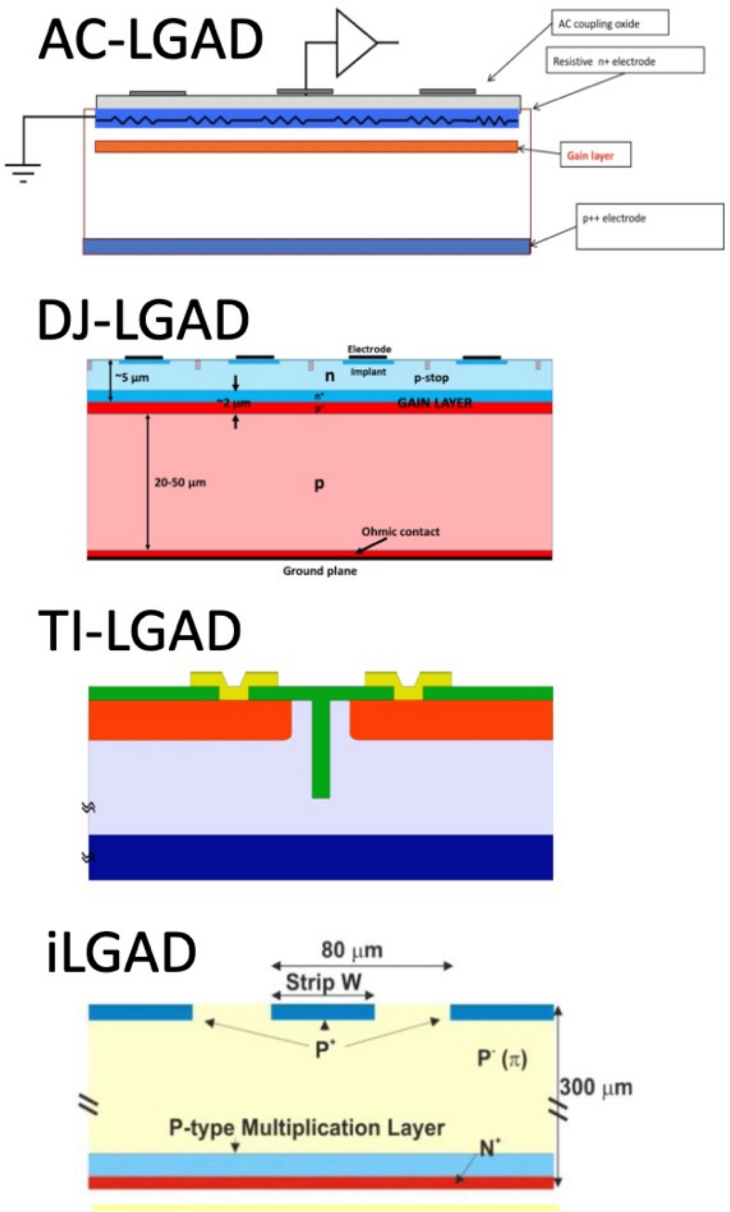
Low Gain Avalanche Detector

- <u>Success in ATLAS & CMS</u>
  - Time resolution ~70 ps
  - Limited granularity 1.3x1.3 mm^2

- <u>Various developments</u>
  - Improve timing
  - Improve granularity
  - Improve radiation tolerance

  - Capactive coupling (AC)
  - Deep junction
  - Trench isolation
  - Inverted
  - Resistive

R&D activities on sensors
part of ECFA-DRD3



Monolithic sensors: detailed R&D roadmap

Note:
CMOS-MAPS only
SOI, DEPFET ignored

Intro to CMOS-MAPS R&D

Sensitive layer / Collection node

- Drive charge collection

=> *defines collection pitch*

- Modifications depends on techno.
- Optimised by R&D cycle:
  - TCAD simulation
  - prototyping
  - characterisation

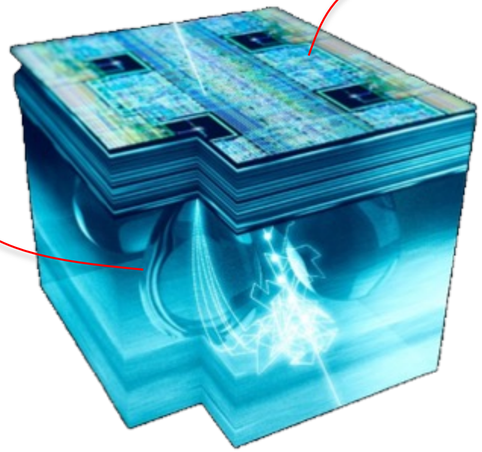
In-pixel & in-matrix µ-circuits

(Above sensitive layer)

- Convert charge collection properties into actual performance

=> *defines read-out pitch*

- Optimised by simulation & verification
  - prototyping still required to estimate for noise, pixel-to-pixel fluctuations, SEE

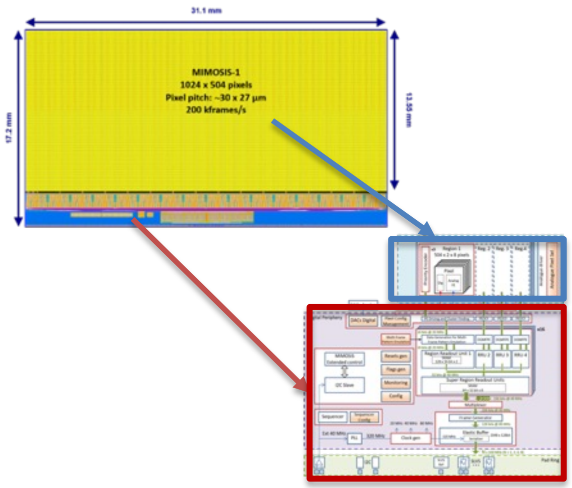


Periphery µ-circuits

- (Insensitive area, usually)

=> *defines interface to outside world*

  - Powering, configuration, signal transmission
- Optimised by simulation & verification
  - as complex as any large ASICS
  - Prototyping used to validate



Integration in det. modules

- Final sensor thickness, interconnection, geometrical arrangement

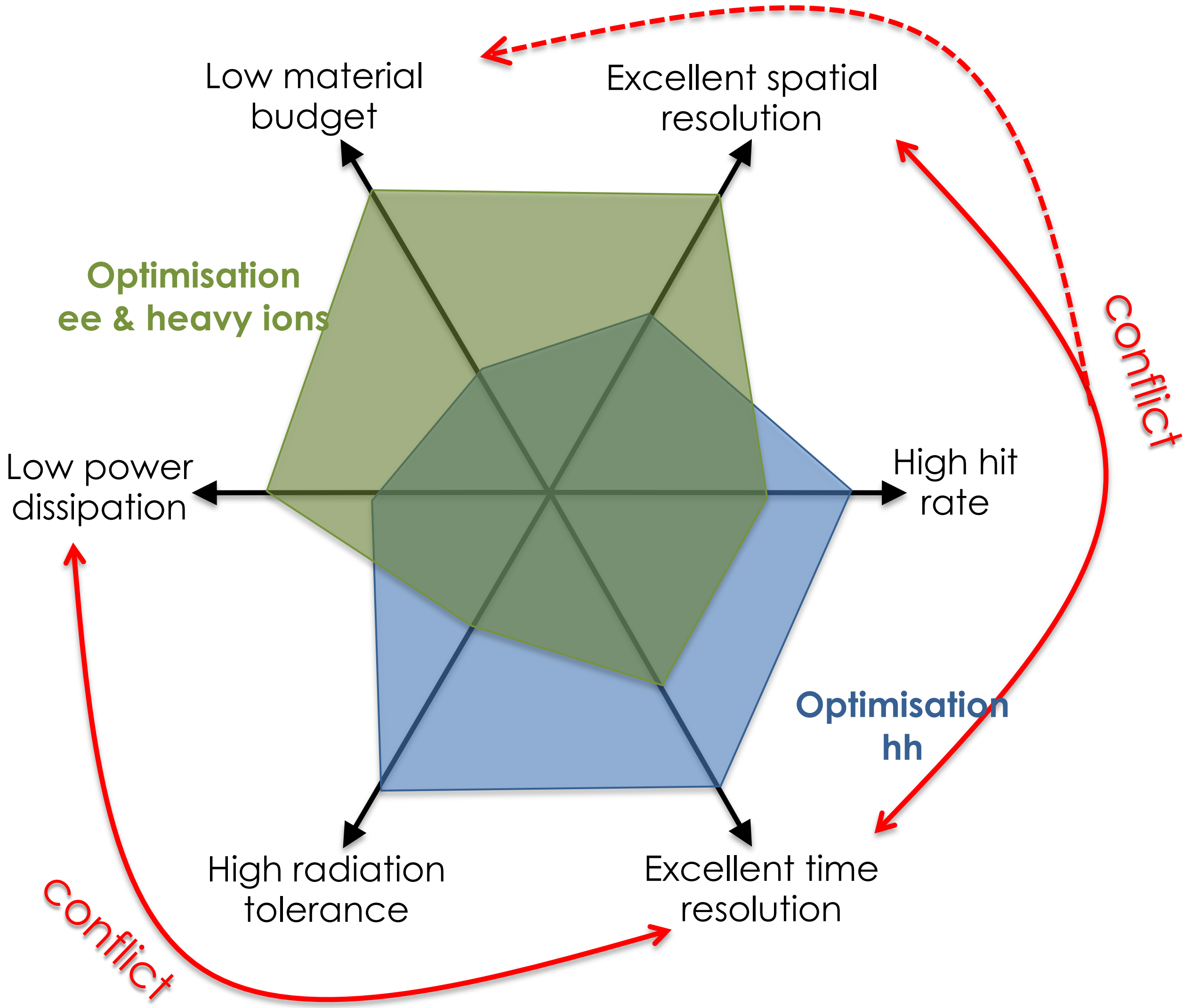
=> *Defines material budget & operability*

- Optimised by progressive prototyping in complexity

The curse of the monolithic approach

Stronger correlation between parameters than in other technologies

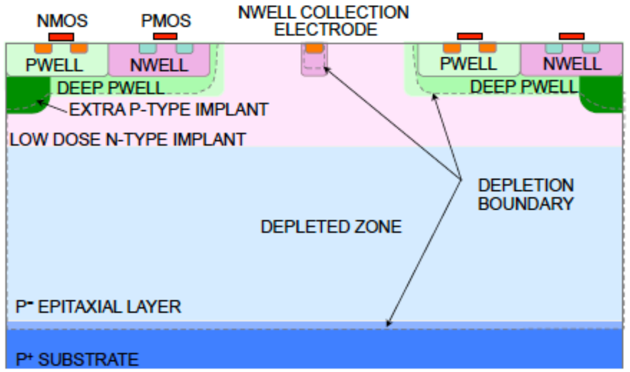
Any R&D is incomplete till all aspects addressed



MAPS technological processes

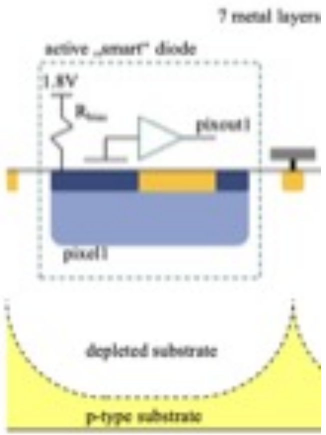
Small collection node (= small det. capacitance)

- Depletion through High-Resistivity material



Large collection node (→large det. Capacitance)

- Depletion through High-Voltage allowed by process



All in ECFA-DRD3 projects

- [Tower 180 nm]
  - ALPIDE, CBM, CLICTD, ATLAS-ITK, CEPC, LHCb-UT, TIIX
- [TPSCo 65 nm]
  - ALICE: MOSS -> MOSAIX
  - Various small prototypes

Note: *Single provider issue, similar to ASIC*

- [LF 150 nm]
  - ATLAS ITK, RD50, Cactus
- [LF 110 nm]
  - ARCADIA
- [TSI 180 nm]
  - Mu3e, LHCb-MT, ATLAS-ITK
- [SIGe BiCMOS]
  - Monolith, PicoAd, Faser

Beyond State-of-the-art Maps

- Foreword on technologies
  - MAPS developed on various technologies/processes (TSI-USA, Tower-Israel/Japan, LFoundry-Italy, IHP Germany, …)
  - For robustness & μ-electronics possibilities reasons => Tower processes are excellent choices

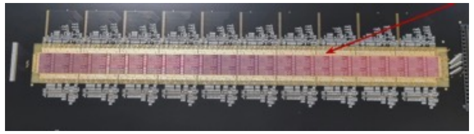
- The new horizon: TPSCo 65 nm ?
  - Foundry located in Hokuriku, Japan
  - Large consortium lead by CERN exploring the techno.
  - Strong connection with 180 nm techno. operated @ IPHC

Scheme from Francois Vasey (CERN, Feb. 2023)

- initial functional blocks
- 1st sensors (APTS, CE-65, DPTS)
- Structures to qualify techno

- Optimised sensors (APTS, CE-65, DPTS)
- Complementary functional blocks
- 1st stiched (1D sensors)

1.4x26 cm



- Optimised stiched sensor ALICE-ITS3
- Some chiplets for R&D

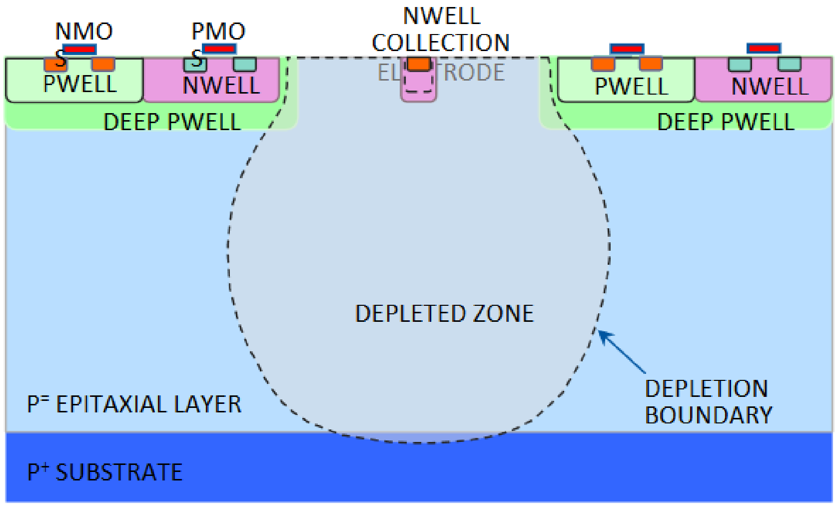
- **Start of the R&D program**

process modifications
position $\sigma \lesssim 3$ μm
power $\lesssim 20$ mW/cm^2
timing 10 -100 ps
LGAD in MAPS
hit rate > GHz/cm^2
new architectures
tolerance > 10^{16} n_{eq}/cm^2

- Integration studies !
  - Using existing large sensors from 180 nm techno

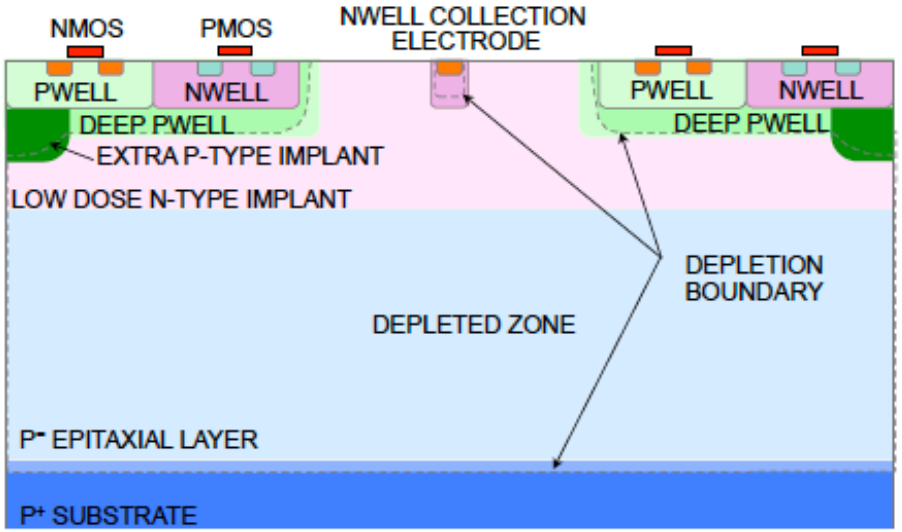
Charge collection: basic facts

Here on small collection node



- Fixed amount of charge generated by ionization in sensitive layer limited by substrate => all of it is collected over a cluster of pixels

- In **standard** process, **partial depletion** charges move by diffusion and drift



- In **modified** process, close to or **complete depletion** drift strongly dominates

Charge collection: basic facts

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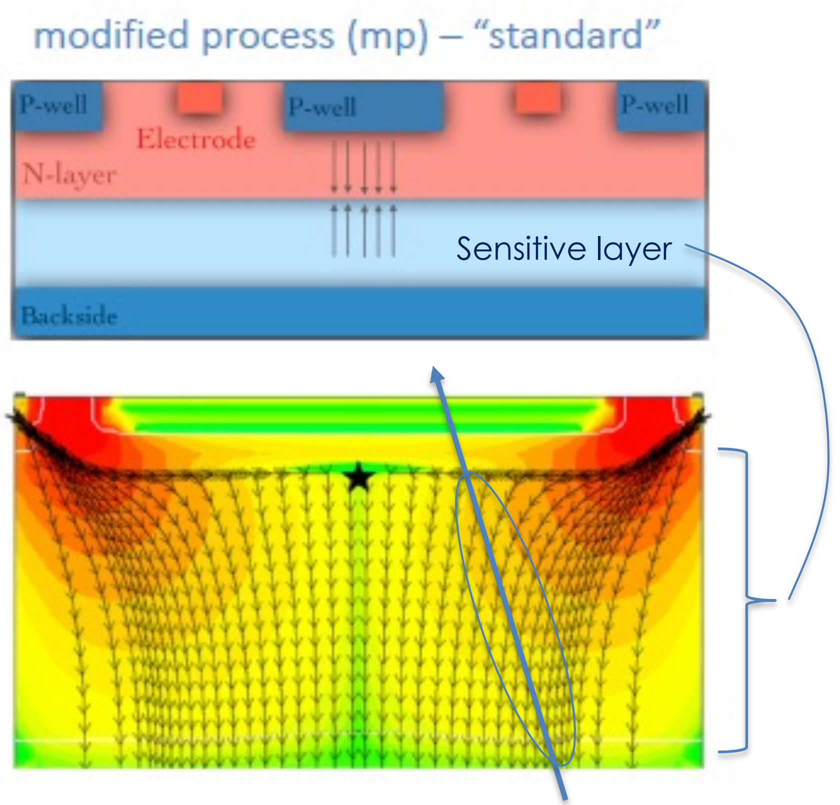


doi: 10.1016/j.nima.2017.07.046
doi: 10.1088/1748-0221/14/05/C05013

- Fixed amount of charge generated by ionization
  => all of it is collected over a cluster of pixels

- Electric field configuration & sensitive thickness drive charge sharing

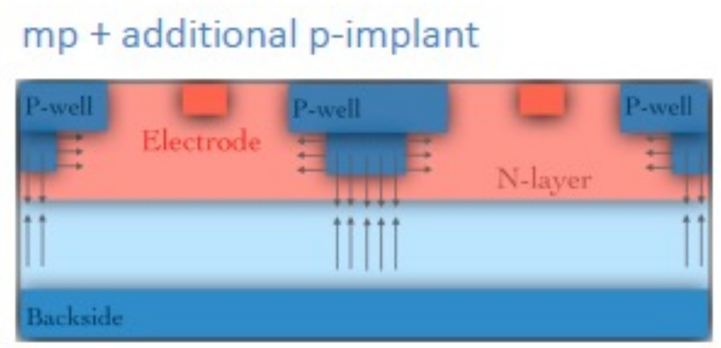
- **Sizeable sharing** =
  - Lower charge on seed pixel ⟶ low threshold for high efficiency
  - Slow collection ⟶ unfavourable / tolerance to radiation
  - More information to reconstruct position

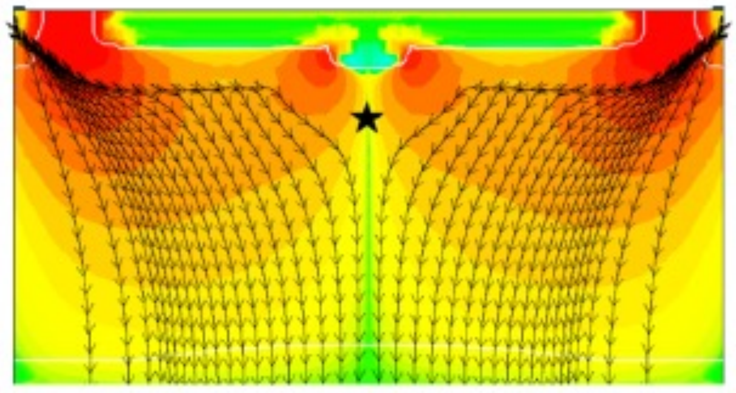
- **Low sharing** =
  - High charge on seed pixel ⟶ easy detection
  - Fast collection ⟶ beneficial for radiation tolerance & time resol.
  - Detrimental to position resolution

- !! Sharing depends on impact position within pixel

Charge collection: basic facts

Here on small collection node





Field configuration driven by (P/N)well geometries & dopings

- Fixed amount of charge generated by ionization => all of it is collected over a cluster of pixels
- Electric field configuration & sensitive thickness drive charge sharing
- **Sizeable sharing** =
  - Lower charge on seed pixel ⟶ low threshold for high efficiency
  - Slow collection ⟶ unfavourable / tolerance to radiation
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  - Detrimental to position resolution
- !! Sharing depends on impact position within pixel

Charge collection: beyond basics

Introduce amplification by impact in silicon

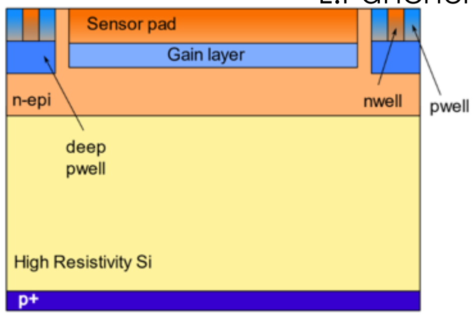
- Stronger signal ⟶ better radiation tolerance (caveat about behaviour of additional layers with fluence)
- Stronger signal ⟶ no need anymore for front-end: smaller pixels, lower power
- Faster signal ⟶ better time resolution (but just one of the ingredients)

Various current tentatives

- Mostly focused on timing (~10 ps) so far
  - ARCADIA project in INFN (LF 110 nm)
  - SiGe BiCMOS in U.Geneva
- Newcomers:
  - CERN starting with Tower 180 nm
  - ANR-APICS (IPHC, CPPM, ICube) starting with Tower soon

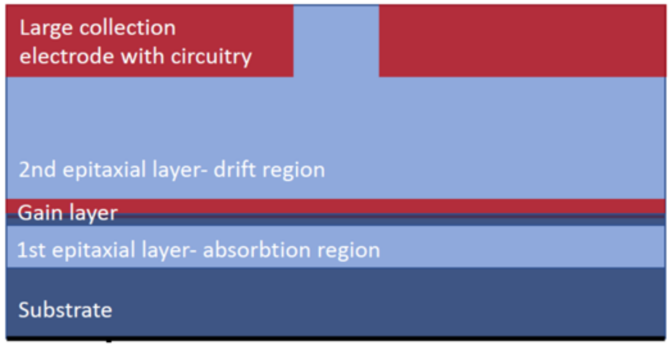
APD/LGAD-style

ARCADIA pad sensor with gain



L.Pancheri 2022

Schematic view of PicoAD sensor concept:



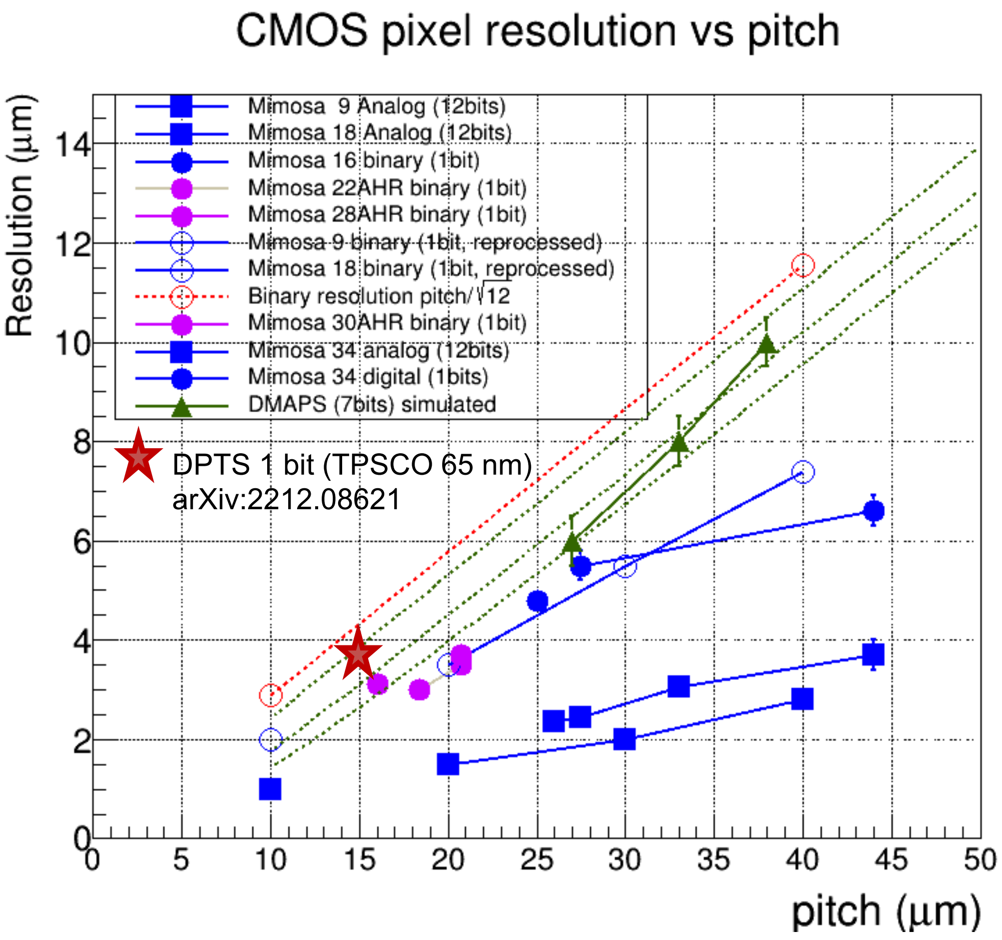
M. Munker, Trento Workshop 2022

Position resolution

- What we know
  - Resolution driven by
    - Charge sharing
    - Pixel-signal encoding resolution
    - Detection threshold
  - Best today still the 'slow' MIMOSA-26/28

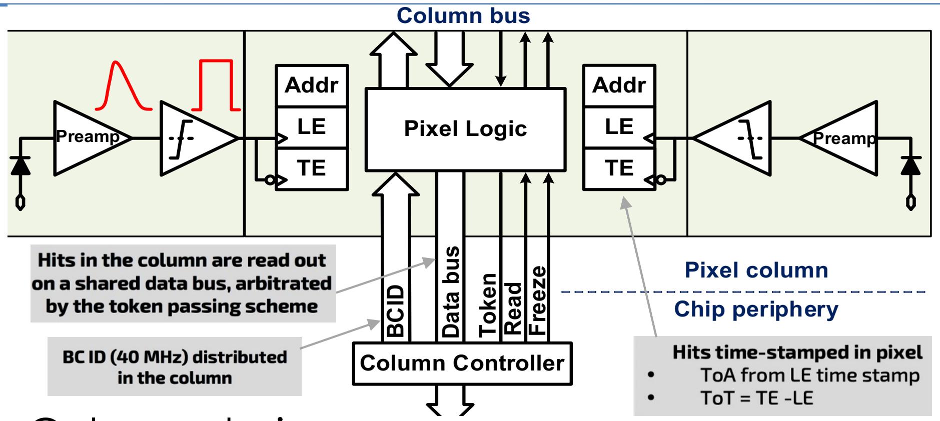
- Beyond state-of-the-art needs
  - ALICE 3 inner layers: 2.5 µm
  - Future lepton colliders: 3 µm

- R&D topics
  - CMOS process with smaller feature size ⟶ TPSCo 65 nm
    - But some work is still ahead of us
  - Removing front-end amplifier from pixel
    ⟶ requires amplification in silicon



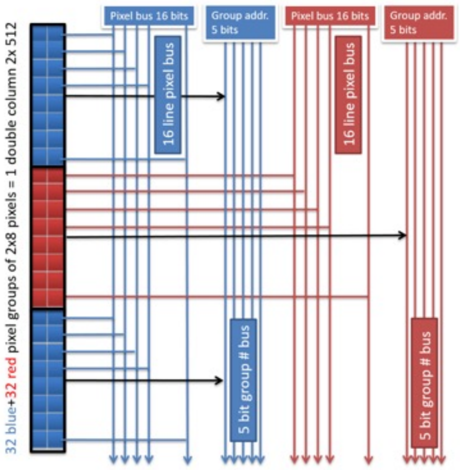
Read-out architecture

- **What we know**
  - Hit-rate capability & Power driven by
    - Front-end
    - Data-driven (position/charge/time) transmission out of the matrix
  - Best today Monopix/Malta/AtlasPix with 100 MHz/cm^2 and power > 100 mW/cm^2
- **Beyond state-of-the-art need**
  - ALICE-3, FCCee for power < 50 mW/cm^2
  - LHCB UT-MT for hit-rate 200 MHz/cm2 & timestamping (25 ns)
  - Belle3 for a combination of all
- **R&D topics**
  - Smaller CMOS process feature size
  - Asynchronous logic, expected to save power
  - Pixel ‘multiplexing’ to reduce granularity but keeping efficiency
    - 4:1 with 25x25 µm^2 50x50 µm^2
  - In-îxel generation of time resolution <100 ps ?



Column-drain doi: 10.1088/1748-0221/13/03/C03039

Priority encoder doi: 10.1016/j.nima.2015.02.063



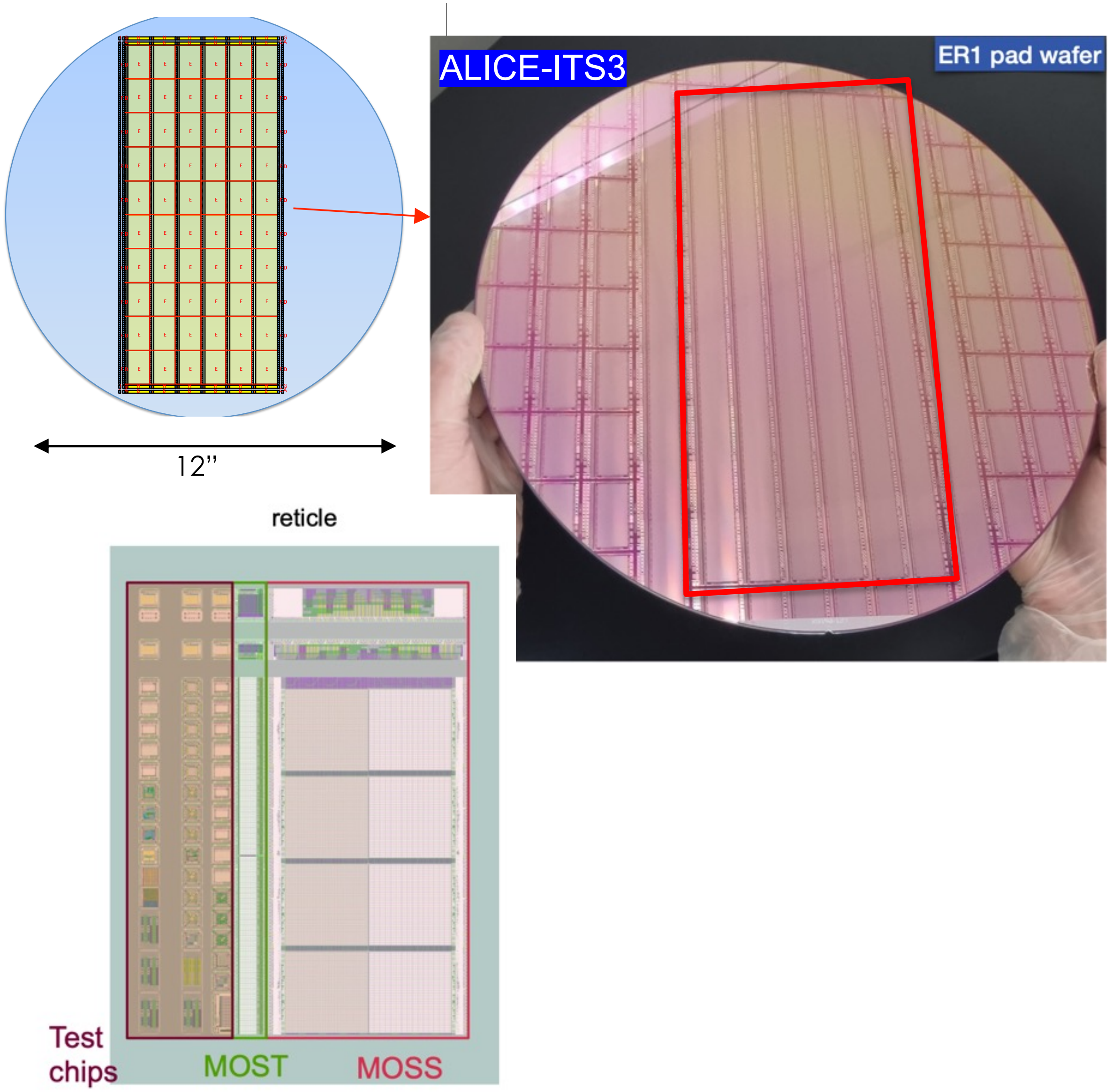
Asynchronous bus

doi:10.1088/1748-0221/13/01/C01023

Note: 3D interconnection (hybridisation) might be needed

Stitching or not-stitching?

- Benefits
  - Material budget with a single bent crystal
  - System simplicity
- Issues
  - Yield => expecting first result from MOSS this year
  - Insensitive area to drain data out
- Need
  - Small area innermost layers: ALICE-ITS2 + ALICE3 + FCC
  - Large area => no go because of yield ?
- R&D topic
  - 1D stitching with ALICE
    - Power domain local-failure proof
  - 2D stitching?



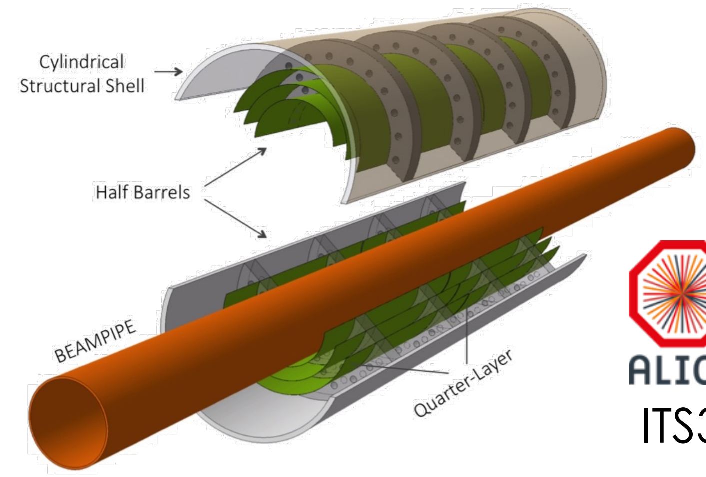
Integration:

- <u>Experience from</u>
  - STAR-PXL, PLUME, ALICE-ITS2, MALTA
  - FASER, MU3e, Belle II-VTX

PLUME: first double sided module
- 12 cm length, 8 Mpixels, 0.35 % X0

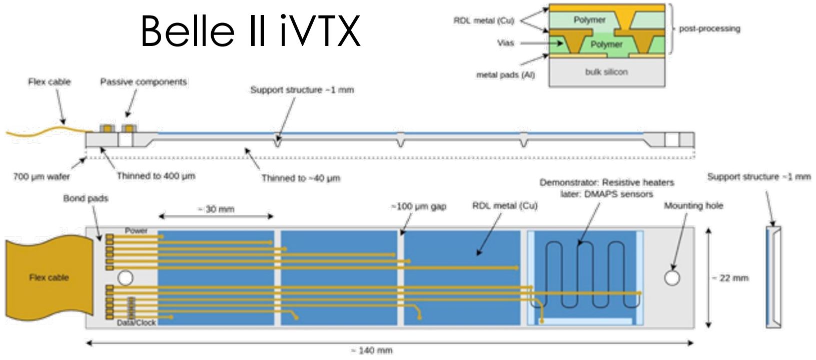
- Used in phase-2 SuperKEKB

- <u>R&D topics</u>
  - Stitching or pseudo-stitching
  - Connecting sensors on modules
    - For data and/or power
  - Regulating power



ALICE ITS3

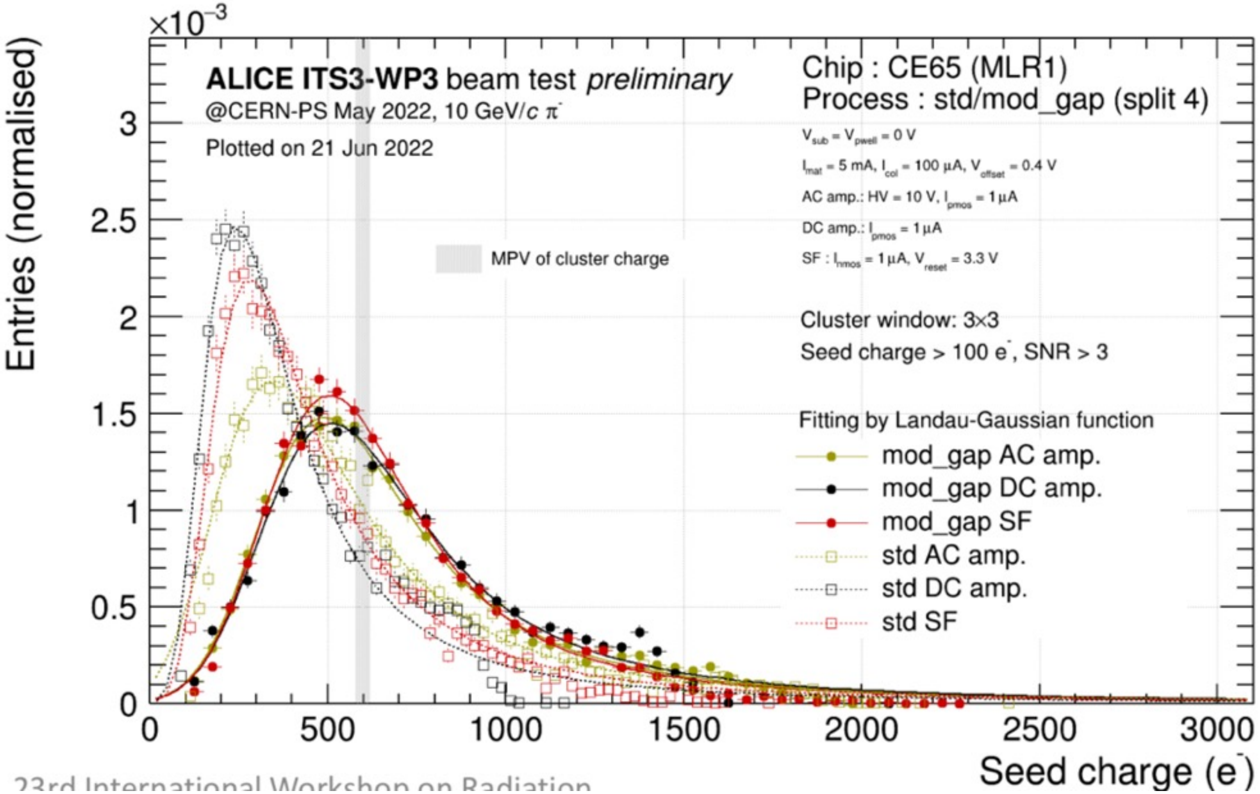
Belle II iVTX



Note: Quite difficult to have generic project
=> need an experiment to get practical

TPSCo 65 nm: current status

- From 1st submission in TPSCo 65 nm
  - Based on APTS, CE-65, DPTS: talks at IWoRiD2022, TREDI 2023, ULTIMA 2023, PSD 2023
  - Variety of pixel pitches: 10-25 µm
  - Successful sensitive layer depletion
    - From modified process



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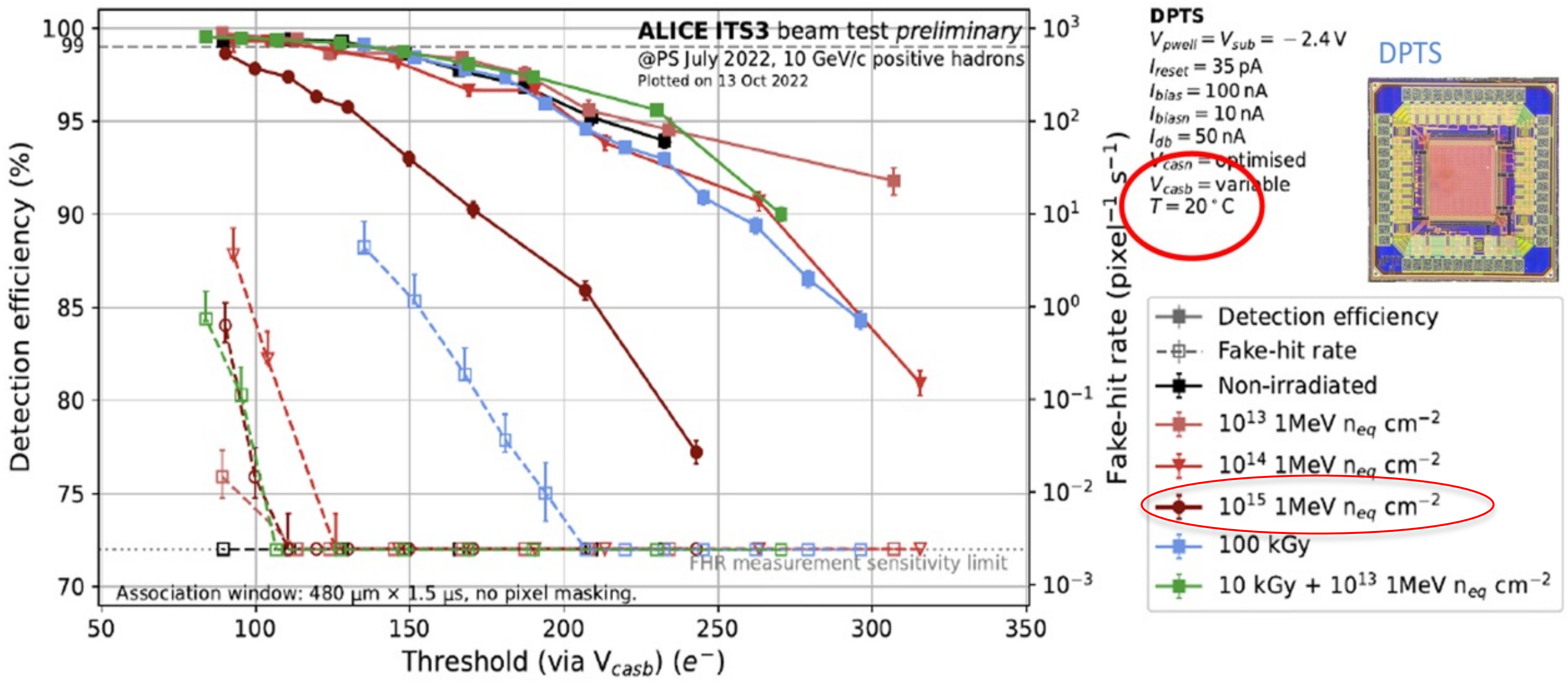

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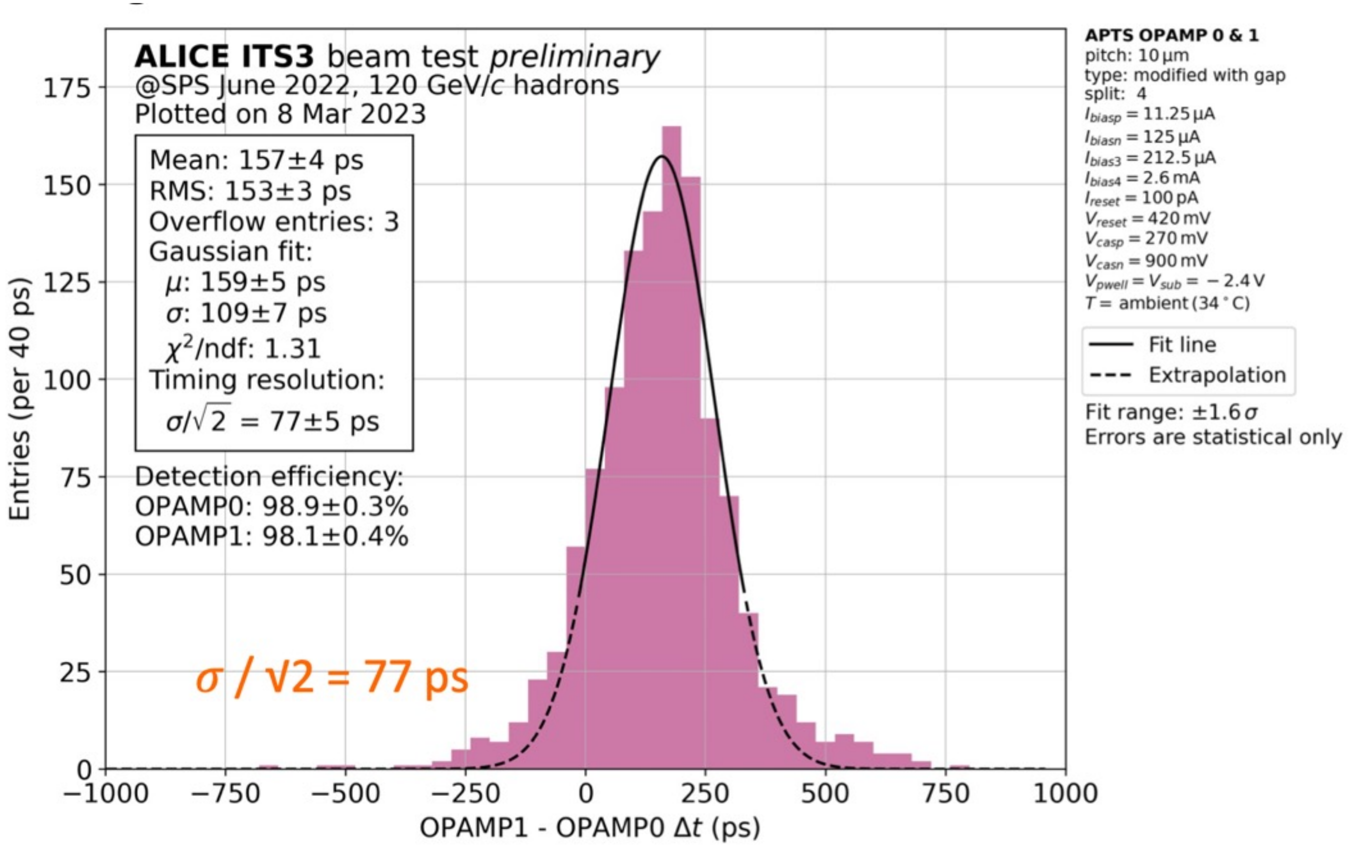
  - Promising radiation tolerance
  - Promising time resolution



R&D context in France & elsewhere

Context of MAPS R&D: the experiments

Attractive MAPS features for vertexing/tracking

=> small pitch, low mass & low power

- 1st applications
  - STAR-PXL@ RHIC 2014-16
    - MIMOSA-28 doi:10.1088/1748-0221/7/01/C01102
  - ALICE -ITS2 @ LHC (10 m2) 2022-32
    - ALPIDE doi:10.1016/j.nima.2016.05.016
  - sPHENIX-MVTX @ RHIC 2023- (also ALPIDE)
  - Mu3e detector @ PSI 2023-
    - MuPix10 doi:10.1016/j.nima.2020.164441
  - MVD in CBM @ FAIR for late 20s
    - MIMOSIS talk at Eurizon 2023 workshop
- Extended applications to higher radiation levels and/or hit rates
  - ATLAS-ITK @ LHC, successful R&D but not selected (yet)
    - MALTA, TJ-Monopix, LF-Monopix, ATLASPix
  - Belle II-VTX @ SuperKEKB upgrade project for late 20s
    - OBELIX talk at talk at AIDAinnova 2023 workshop

Pushing performances for more science

- Highly granular & light vertexing
  - ALICE-ITS3 XL-sensor (30x10 cm^2)
    - MOSS talk at PIXEL 2022
  - All future e+e- colliders at high energy with spatial resolution ≲ 3 µm
  - ALICE3 vertexing inside beam-pipe
- Tracking
  - Upgrades: Belle II @ SuperKEKB, LHCb @ LHC
  - New systems: EIC @ eRHIC, ALICE3 @ LHC
    Future e+e-/µµ/hh colliders

- Intensive R&D roadmap by ECFA
  - DRD3 for solid-state March Workshop at CERN
  - DRD7 for electronics March workshop at CERN

Context of Si sensors R&D: France

- Many IN2P3 labs with experience on silicon sensors for tracking in CMS, ATLAS, ALICE, …

MAPS developments

- historical contributors: IPHC, CPPM, IRFU
- More with ALICE-ITS2 & MFT: IP2I, LPSC, Subatech
- C4PI-Strasbourg: facility devoted to MAPS
  - 3 main projects: CBM-MIMOSIS, ALICE-ITS3, Belle II-VTX (to be decided)
    - ALICE & Belle II in collaboration with other IN2P3 labs
  - Already various R&D projects with other IN2P3 labs

- Clearly more laboratories interested in the context of ECFA-DRD3/7

ECFA-DRD3/7

The new horizon: TPSCo 65 nm ?

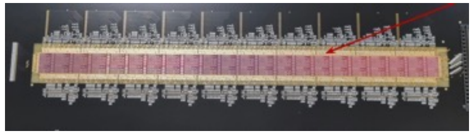
- Foundry located in Hokuriku, Japan
- Large consortium lead by CERN exploring the techno.
- Strong connection with 180 nm techno. operated @ IPHC

Scheme from Francois Vasey (CERN, Feb. 2023)

- initial functional blocks
- 1st sensors (APTS, CE-65, DPTS)
- Structures to qualify techno

- Optimised sensors (APTS, CE-65, DPTS)
- Complementary functional blocks
- 1st stiched (1D sensors)

1.4x26 cm



- Optimised stiched sensor ALICE-ITS3
- Some chiplets for R&D

- **Start of the R&D program**

process modifications — position $\sigma \lesssim 3$ µm — power $\lesssim 20$ mW/cm^2 — timing 10 -100 ps — LGAD in MAPS — hit rate > GHz/cm^2 — new architectures — tolerance > 10^{16} n_{eq}/cm^2

Conclusions

- Convergences des efforts de R&D sur la technologie MAPS
  - Plusieurs voies de développement
  - Ne pas oublier les outils de simulation !

- Ensemble d'opportunités pour les ~10 ans à venir
  - Structuration forte de la communauté R&D

- D'autres technologies vont continuer à progresser
  - détecteurs gaseux ou 'quantiques'

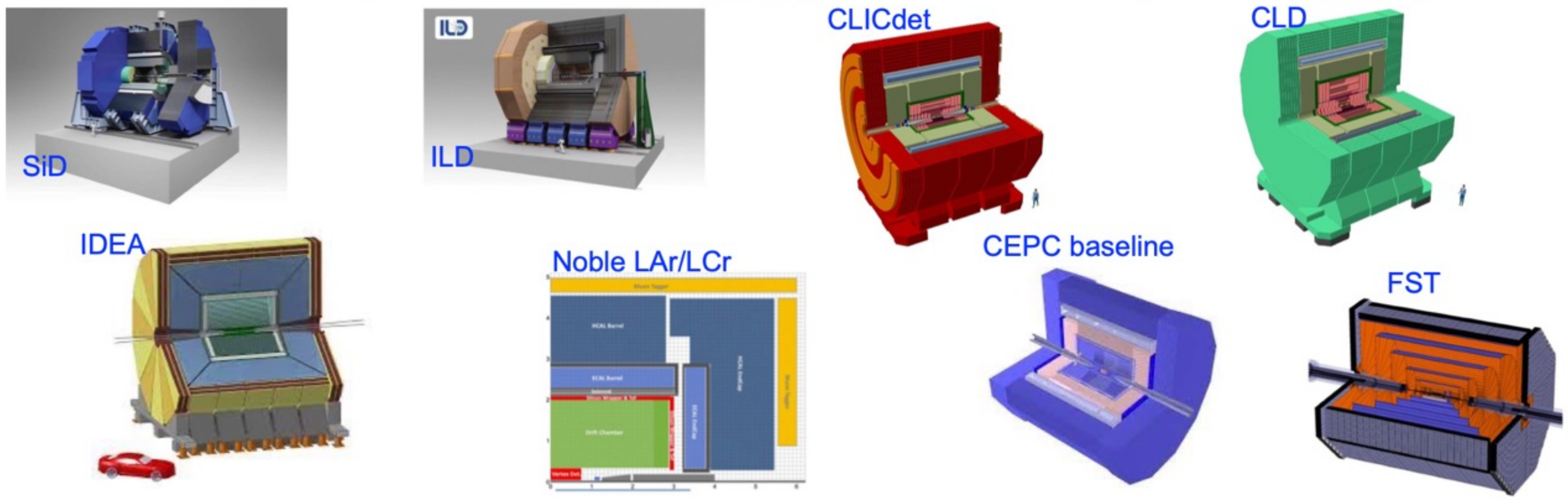
- A plus long terme
  - Quelque soit l'évolution/le changement du noeud de détection: densité d'information = paramètre majeur

Thank you for your attention

Spec

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

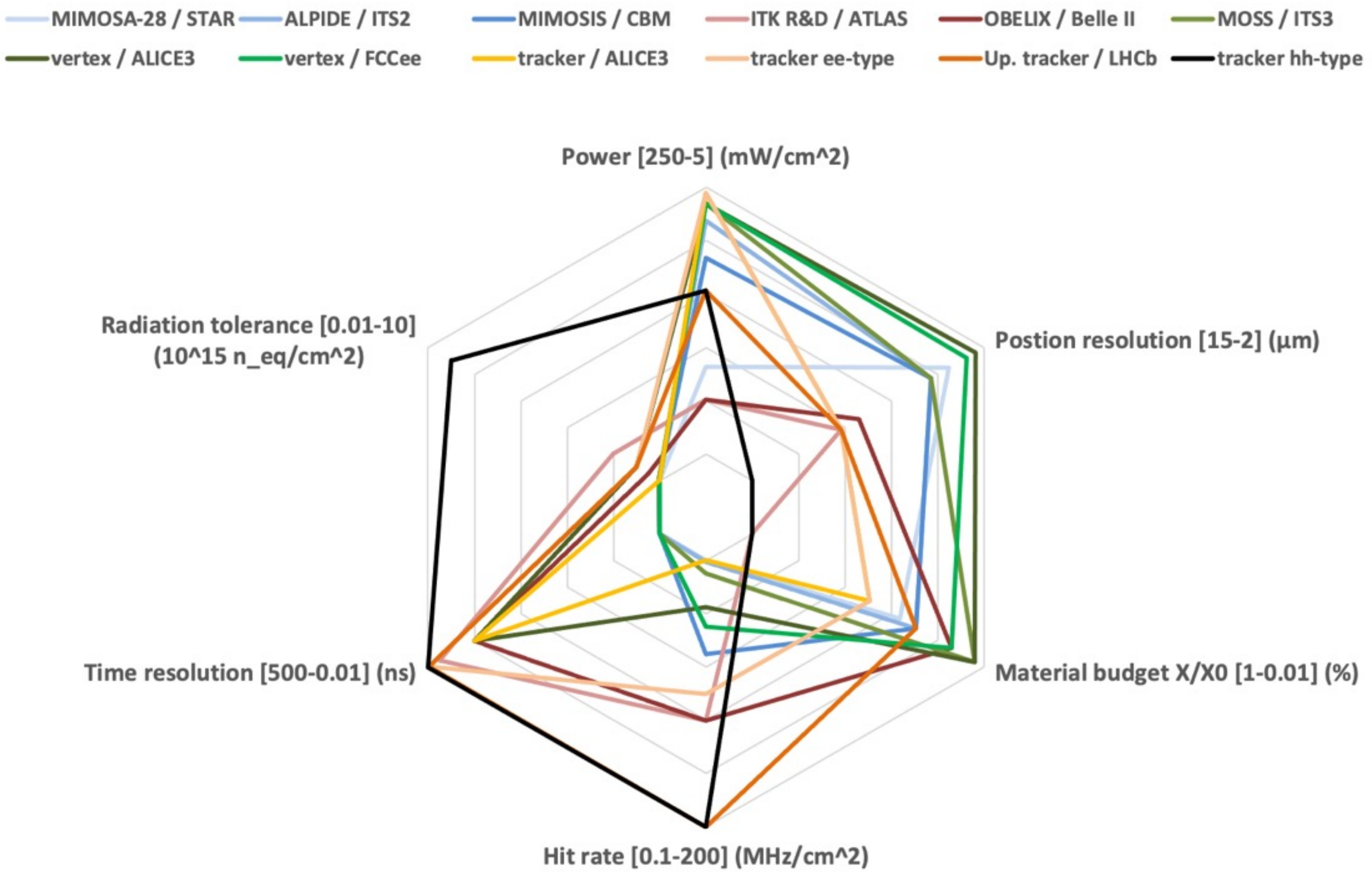
arXiv:1306.6329 arXiv:1812.07337 arXiv:1911.12230 doi.org/10.1140/epjst/e2019-900045-4 arXiv:1811.10545



D.Dannheim
PIXEL 2022

	STAR PXL	ALICE ITS2	HL-ATLAS ITK	CBM MVD	ALICE ITS3	Belle-II VXD	ALICE3 VTX	ALICE3 tacker	EIC tracker	LHCb UT	FCCee VTX	FCChh tracker
Data taking in	2014	2020	(2035)	2026	2029	2028	2035	2035	203?	2035	>2040	>2050
Total area (cm^2)												
Spatial res. (µm)	< 10	**~5**	10	**~5**	**~5**	< 10	**2.5**	10	pitch 10	O(10 µm)	**3** – 5	~10
Mat. budget (%X0)	0.37	0.35	<1	~0,3	**0.05**	**0.15**	**0.15**	0.3?	0.05-0.55	0.3?	**0.15**	~2
Hit rate (MHz/cm^2)	O(0.1)	O(1)	**200** triggered	15-70	~20	**100** triggered	35	0.005	?	20Gb/s	O(20)	
Time figure (ns)	200.10^3	5.10^3	**25**	5.10^3	5.10^3	~100	100	100	100 (?)	**O(1)**	10^2-10^3	**$5x10^{-3}$**
Trigger rate (kHz)						30			500			
Rad.hard. (kGy) (n_{eq}/cm^2)	2 10^{12}	30 $2x10^{13}$	800 10^{15}	30 /year < 10^{14} /y.	<100 <10^{14}	100 $5x10^{13}$	- $1.5x10^{15}$ /year	-	- 10^{15}	**2400 $3x10^{15}$**	20 $5x10^{11}$	100 **10^{16}**
nb of layers	2	7				5-6			5 + 5d			
radii (cm)	3-8					1.2-13.?						
bunchX (ns)			25		25	4			10			

Specifications (normalized to 0-100% score)



Time resolution

- What we know
  - Resolution driven by
    - Charge sharing
    - Time of arrival encoding
    - Time walk
  - Best today

- Beyond state-of-the-art need
  - 4D-tracking
  - Time of flight for particle identification

Maybe split in TWO domains?

- R&D topics
  - Fastpix
  - Monolith