Vertex (& tracking) detector @FCCee (CMOS technology)

Requirements, R&D, open questions

Not covered here, Various R&D e.g.:

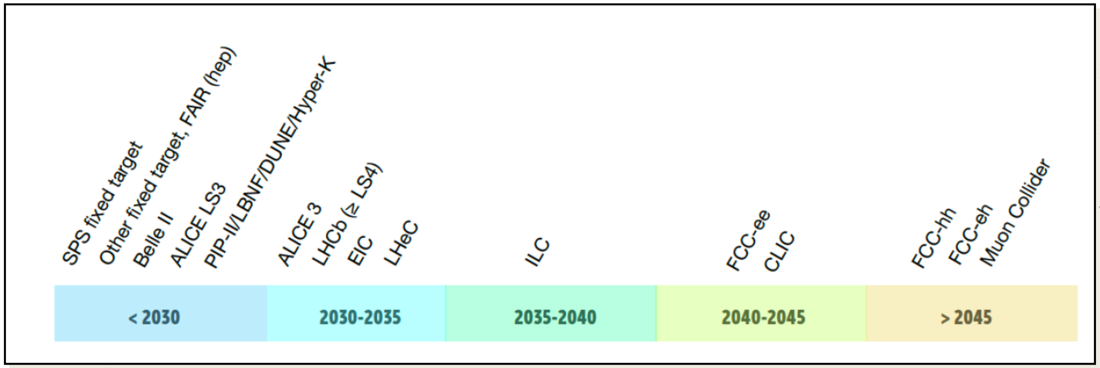
➪AIDAInnova kickoff meeting (65nm: J.Baudot talk)
https://indico.cern.ch/event/1104064/timetable/#20220329.detailed

➪VCI 2022 (CLIC R&D: D. Dannheim, 180nm: A. Dorokhov, 65nm: S. Bugiel, Tangerine: H. Wennlöf, Belle-2, ALICE ITS-3, EIC, etc.)
https://indico.cern.ch/event/1044975/contributions/?config=0d068a40-df13-42c0-b415-7cf8db16ac6c

➪ALICE ITS-3 CERN seminar (Stitching, bent sensors, 65nm: M. Mager)
https://indico.cern.ch/event/1071914/

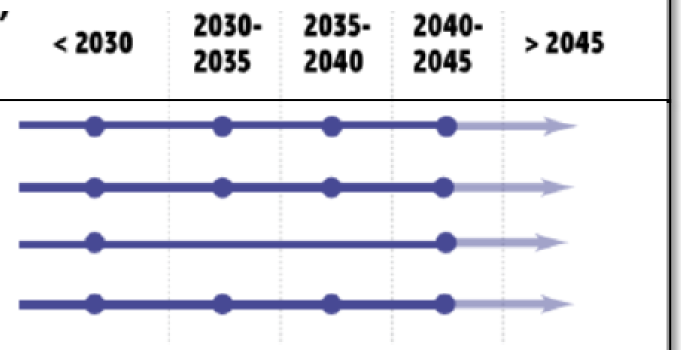
Global strategy for vertex-tracking R&D

Detector R&D Roadmap: themes (DRDTs)



References: ECFA/RC/21/510
CERN-ESU-017
DOI: 10.17181/CERN.XDPL.W2EX

Solid state		
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	



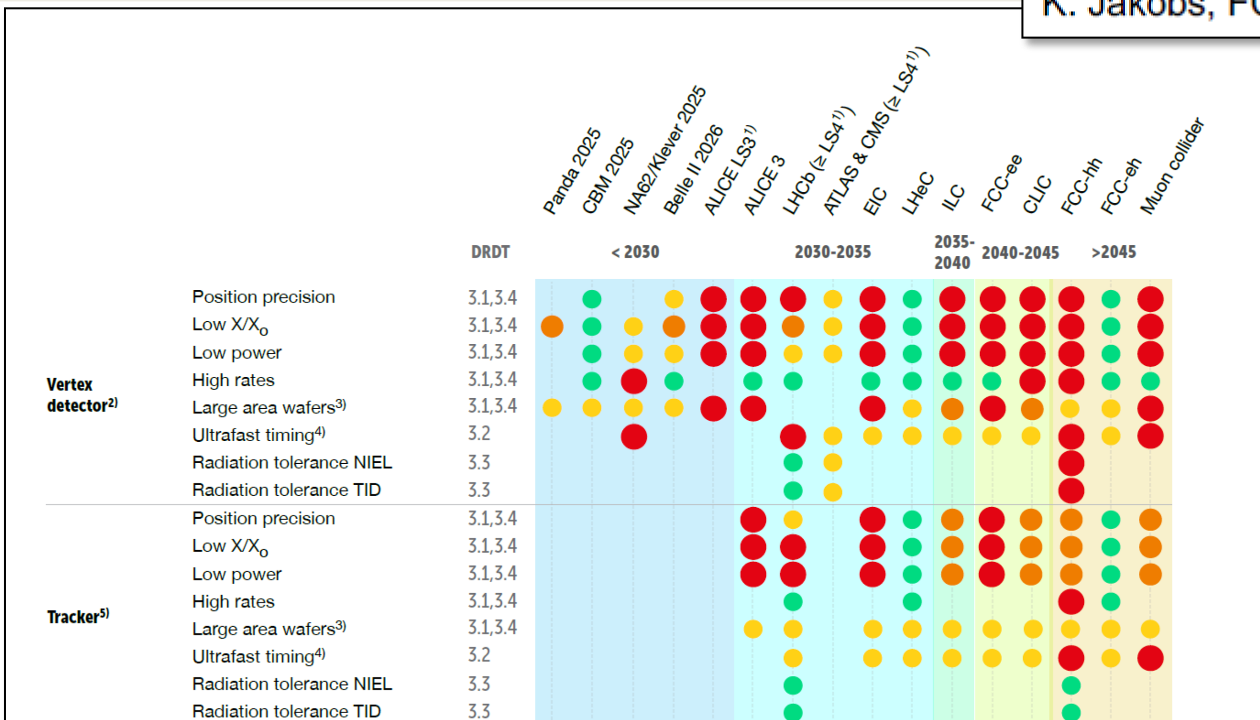
DRDT 3.1 - Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors.
Developments of Monolithic Active Pixel Sensors (MAPS) should achieve very high spatial resolution and very low mass aiming to also perform in high fluence environments. To achieve low mass in vertex and tracking detectors, thin and large area sensors will be crucial. For tracking and calorimetry applications MAPS arrays of very large areas, but reduced granularity are required for which cost and power aspects are critical R&D drivers. Passive CMOS designs are to be explored, as a complement to standard sensors fabricated in dedicated clean room facilities, towards hybrid detector modules where the sensors is bonded to an independent ASIC circuit. Passive CMOS sensors are good candidates for calorimetry applications where position precision and lightness are not major constraints (see Chapter 6). State-of-the-art commercial CMOS imaging sensor (CIS) technology should be explored for suitability in tracking and vertex detectors.

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

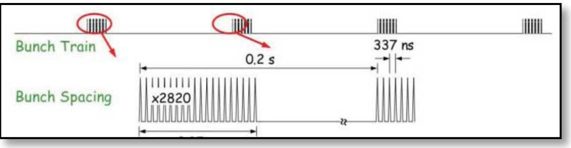
K. Jakobs, FCC Physics Workshop, Feb 2022

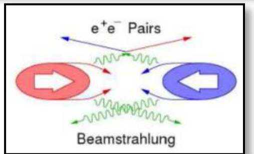


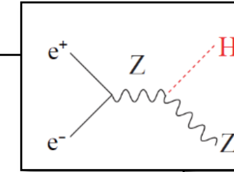
Must happen or main physics goals cannot be met | Important to meet several physics goals | Desirable to enhance physics reach | R&D needs being met

+ integration know-how (e.g. ALICE, Belle-2)

ILC/FCCee Vertex detector requirements



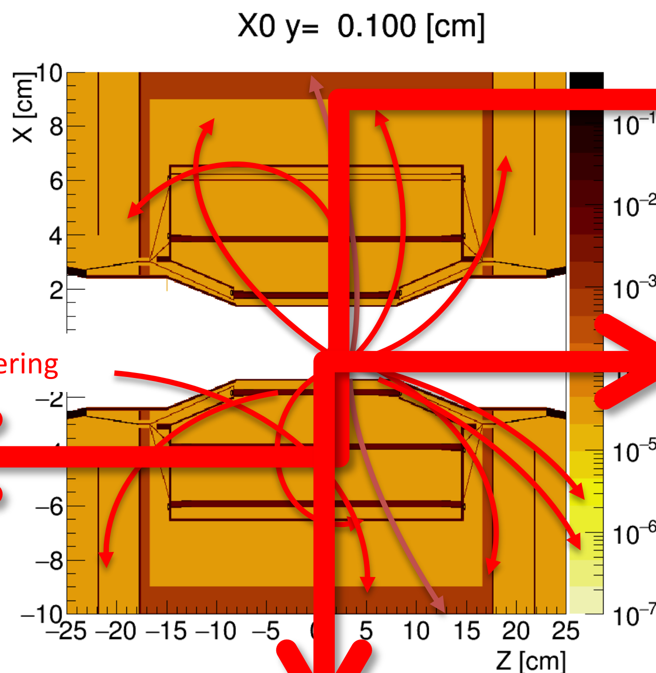




Physics
- ⇨ Flavour tagging
- ⇨ Low pT tracks
- ⇨ Vertex/Jet charge determination

Physics (<Hz/cm²)

Beam background (~ 5 hits/BX/cm² on layer 0, ILC)



Beam background

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

Rad.Tol. devices

Back scattering

Read-out speed
O(1-10 μs)

Power consumption
~< 50mW/cm²

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

Cooling
Stiffness / Alignment

Vertex reconstruction
- ⇨ granularity
- ⇨ Pitch ~17 um
- ⇨ (σ_{sp} ~3 um)

Material Budget
- ⇨ ~ 0.15% X_0 / layer
- ⇨ < 1% X_0 for the whole VTX
- ~ 900 μm Si
- + ~0.14% X_0 for the beam pipe (ILC)
- + ~0.3 % X_0 for the beam pipe (FCC)

Low material detectors & supports structures

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

$a \simeq 5\,\mu m$; $b{\sim}15\,\mu m.GeV$ FCCee

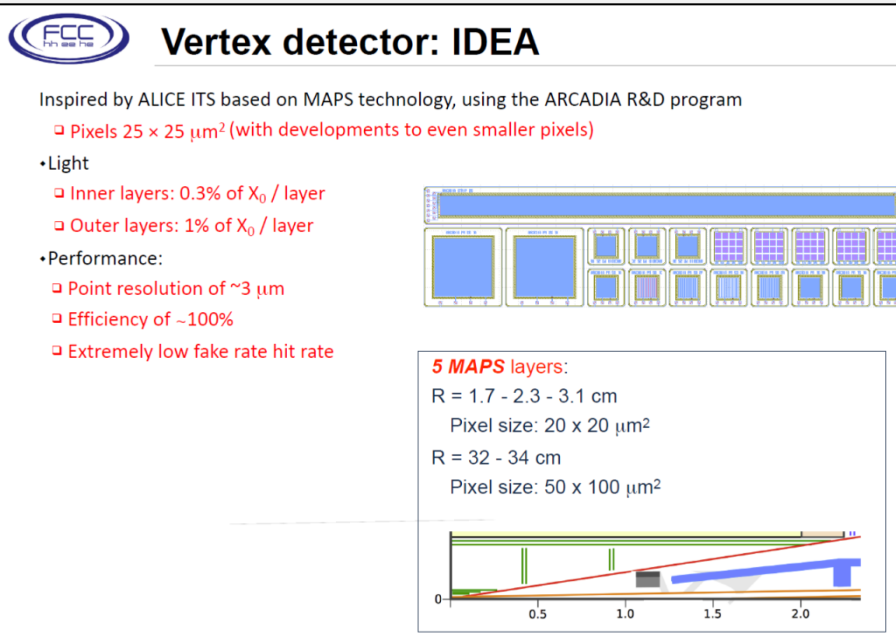
$b{\sim}10\,\mu m.GeV$ ILC

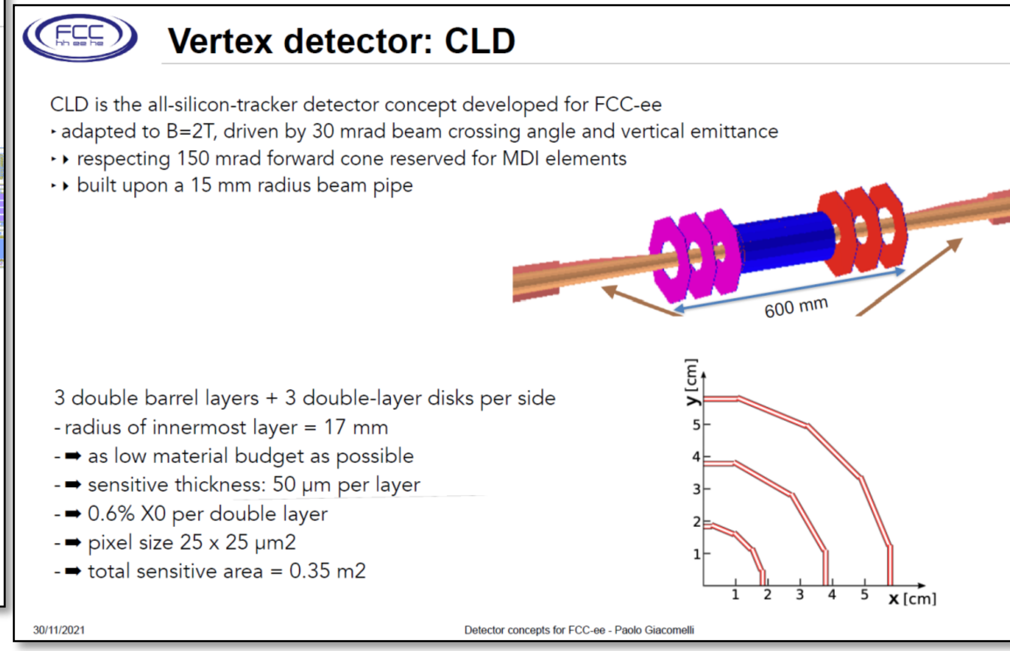
Power pulsing (ILC) vs continuous beam (FCCee)

Challenge:

⇨Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution (BX)

Vertex detector IDEA/CLD





Paolo Giacomelli (Annecy 2021)

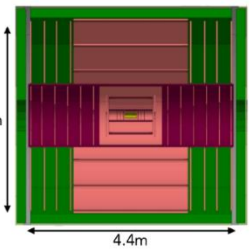
- Comments:
  - ✓ 25 μm pitch vs 3μm resolution
    - Needs: high S/N and/or no binary output
  - ✓ Material budget 0.3% X_0/layer:
    - Conservative value
    - Beam pipe material budget ~ 0.3%X0
  - ✓ 5 layers vs 3 double layers
    - Robustness (standalone tracking), low momentum vs high momentum,
    - New player: Stitching & bent sensors vs double sided approach
  - ✓ Inner and outer radius are key factors

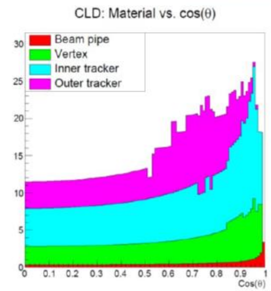
Tracking

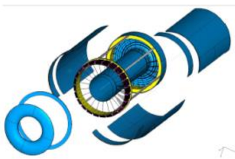
Central tracker

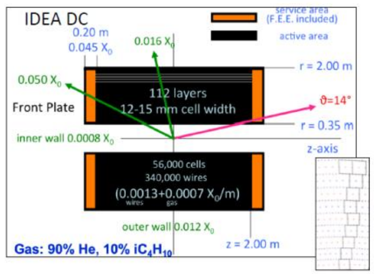
Two solutions under study

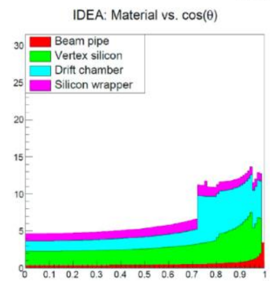
- CLD: All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube (2.5% X_0)
- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si "wrapper"











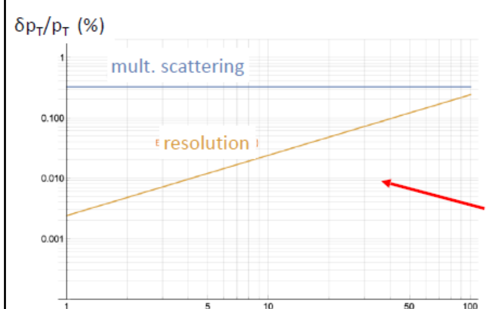
30/11/2021 Detector concepts for FCC-ee - Paolo Giacomelli 6

Paolo Giacomelli (Annecy 2021)

In reality, there is of course a resolution term (*a*) and a multiple scattering term (*b*)

$$\sigma(p_T)/p_T^2 = a \oplus \frac{b}{p\sin\theta}$$

For "standard" ultra-light detectors (e.g. full Si), multiple scattering dominates up to p_T of ~100 GeV



Here illustrated for the CLD detector at 90° :
Total material budget = 11% of X_0

From analytic expressions for track parameter resolutions.

Drasal, Riegler, https://doi.org/10.1016/j.nima.2018.08.078

$$\left.\frac{\Delta p_T}{p_T}\right|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV}/c}{0.3\beta B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\sin\theta}} \qquad \left.\frac{\Delta p_T}{p_T}\right|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

Often, the "canonical" requirement is expressed as

$$\sigma_{p_T}/p_T^2 \simeq 2\times10^{-5}\,\mathrm{GeV}^{-1}$$

Questions: CLD material budget ?
Gaseou vs silicon ?

Question: Low or high momentum priority ?

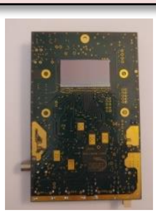
Strategy: on the road to Higgs factories

CMOS Master Project

Design, build and exploit CMOS pixels sensors
with <u>low material budget</u> & <u>high granularity</u>
In order to contribute to the construction of a vertex & a tracking detector in a Higgs factory.

Approach the Higgs factories vertex detector requirements

MIMOSIS chip family (180 nm)



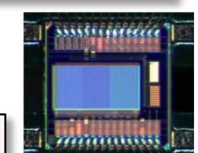
Input for detector simulations

Optimize the parameters of the technology (e.g. sensitive layer)

Maintain & develop the know how to build sensors to be installed in real experiments

Exploit fully the potential of the CMOS technology

R&D 65 nm

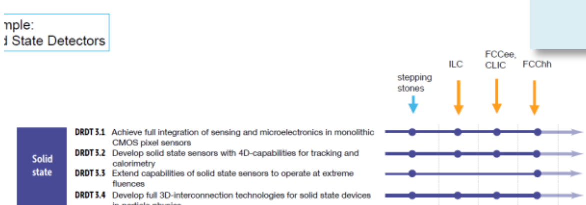


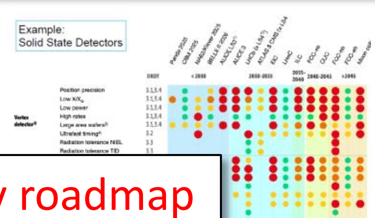
Large surfaces (stitching)

Bent sensors

Integration

Emerging technologies (e.g. double tier)

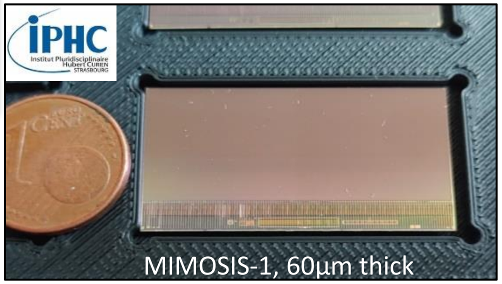


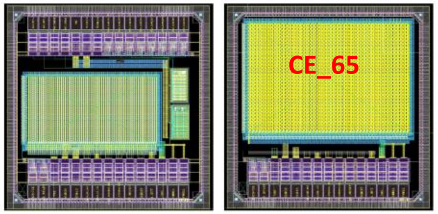


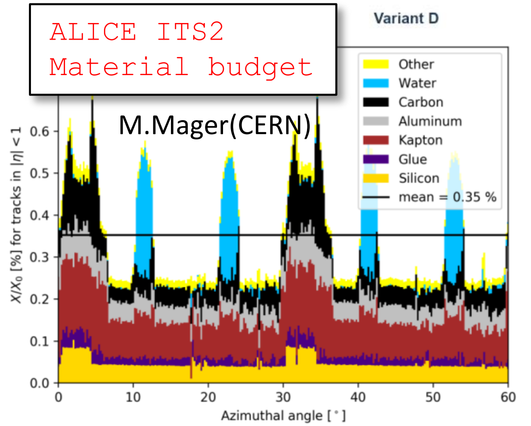
ECFA Detector Technology roadmap

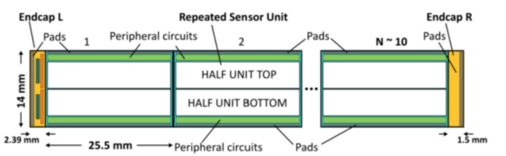
CMOS R&D lines

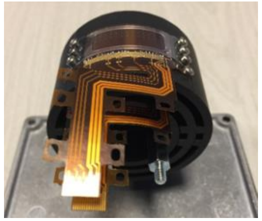
- 180 nm technology: **MIMOSIS chips** for CBM-MVD@ FAIR
  - ✓ = a milestone for Higgs factories **(5µm spatial res./ ≤5µs time res./ 60µm thickness)**
  - ✓ MIMOSIS-1 (1st full scale prototype) under tests
  - ✓ 3 test beam campaigns performed in 2021, 3 in 2022
    - Results match expectation
  - ✓ Absolutely crucial to maintain know-how
- **65 nm tech. Exploration**
  - ✓ Main driver: CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades
  - ✓ Priority: Validate the technology then optimize time resolution & granularity while keeping power low
    - Test beam (CE_65 prototype)
  - ✓ Financial support to ER1 (ER2 ?)
  - ✓ Involvement in design and test: CE_65
- **Stitching** & large surfaces for very low mass detectors
  - ✓ Priority for Higgs factories in the future ⇨ Material budget & Large pixelated surfaces
    - Reassess double sided approach ?
  - ✓ Next submission in 65 nm technology (eng.run 1) with CERN in Q1 2021: prototypes to explore stitching (MOSS/MOST)
- Bent sensors (with ALPIDE – ALICE ITS-3)
  - ✓ https://indico.cern.ch/event/1071914/
- **Mid term** (~2025-26)
  - ✓ Complete MIMOSIS program
  - ✓ Establish a demonstrator for Higgs factories in 65 nm
  - ✓ Develop simulation & integration activities





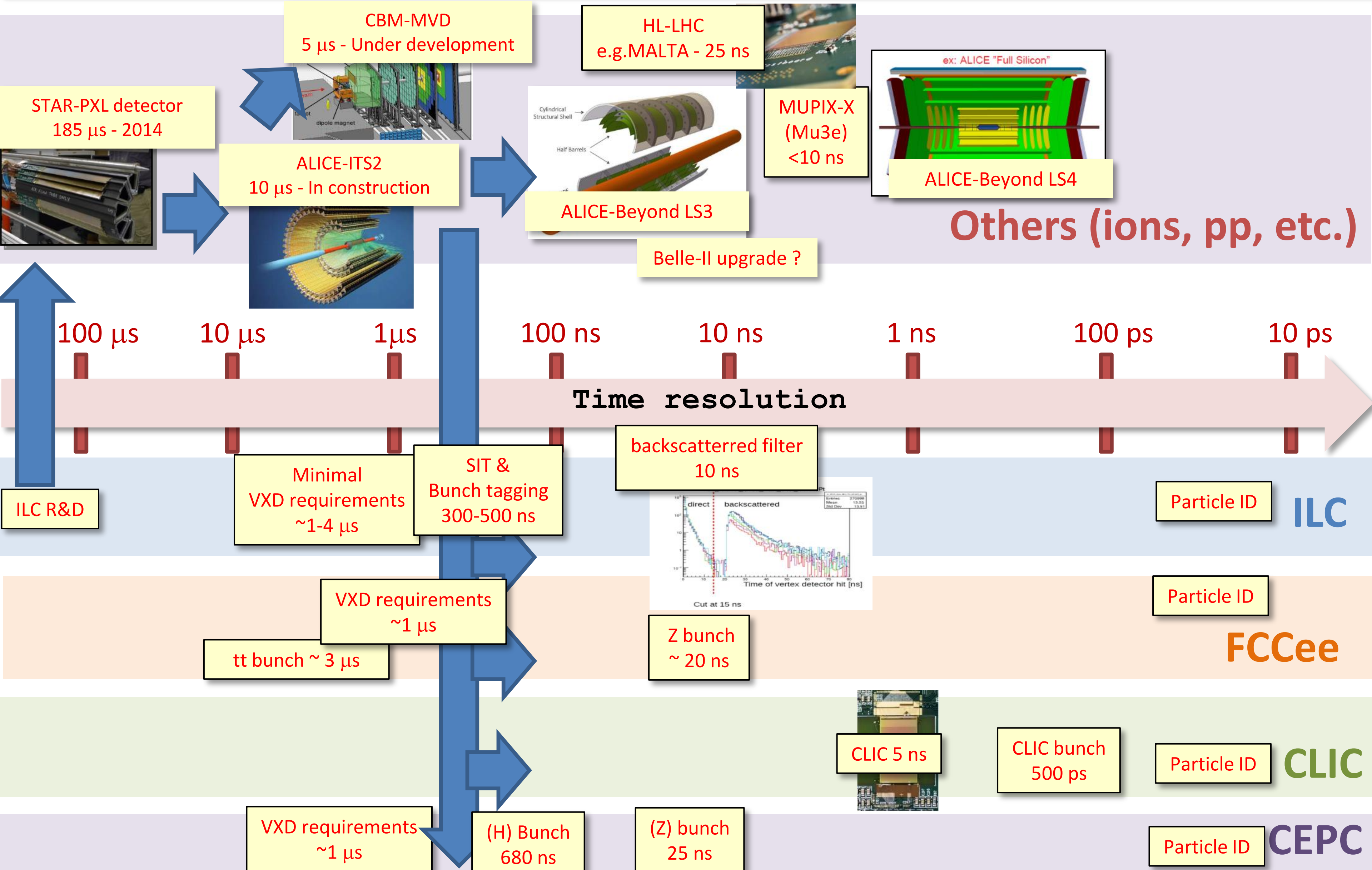






Requirements

Time resolution in the context of e^+e^- colliders



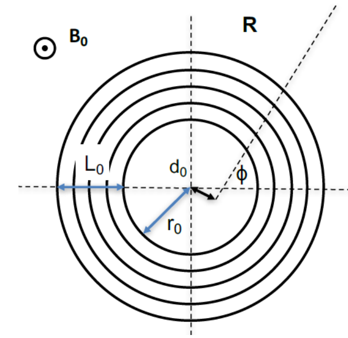
Spatial resolution in Higgs factories

- Vertex detector roles
  - ✓ Reconstruct Primary and secondary vertex
    - ▪ Heavy flavor tagging (b, c, τ)
    - ▪ Order of magnitude: O(1µm)- O(10µm)
  - ✓ Low momentum tracking
    - ▪ pT ~< 100 MeV/c - 1 GeV/c
  - ✓ Vertex/Jet charge determination

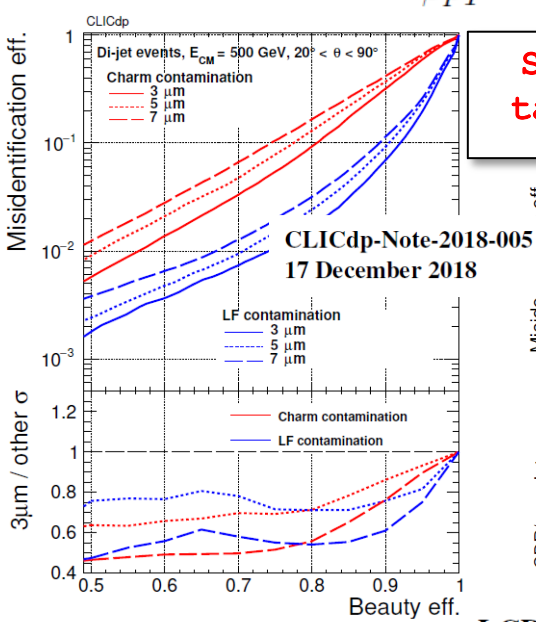
$$\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\sin^{3/2}\theta}\right)^2$$

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

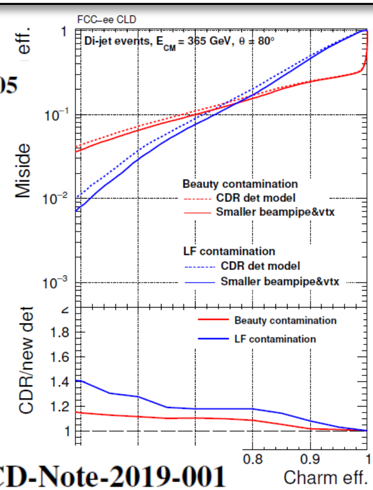


Level arm !



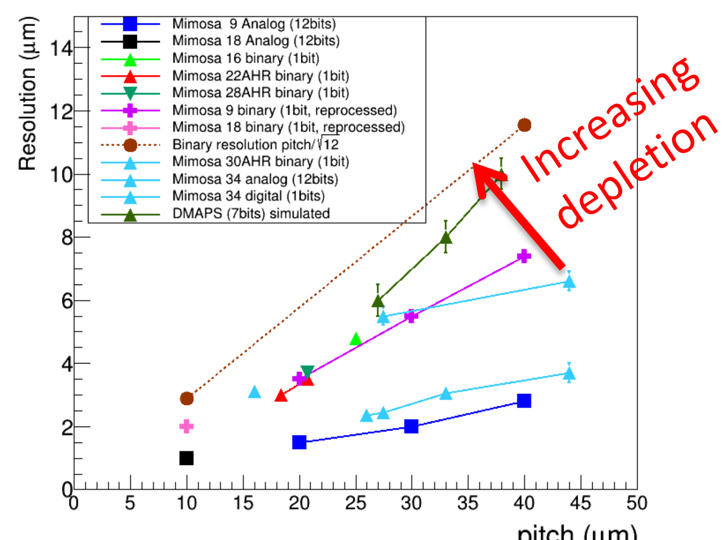
CLICdp-Note-2018-005
17 December 2018

Sensitivity to b/c-tagging performances



LCD-Note-2019-001
25 November 2019

CMOS pixel resolution vs pitch



⇨ σ_{sp} ~ 3 µm ⇦⇨ pitch ~ 17 µm

(assuming binary output, ~20 µm epi.thickness & partial depletion in 180nm tech.)

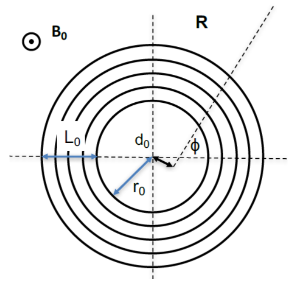
Material budget in Higgs factories

$$\sigma_{d0}{}^2 = a^2 + \left(\frac{b}{p.\sin^{3/2}\theta}\right)^2$$

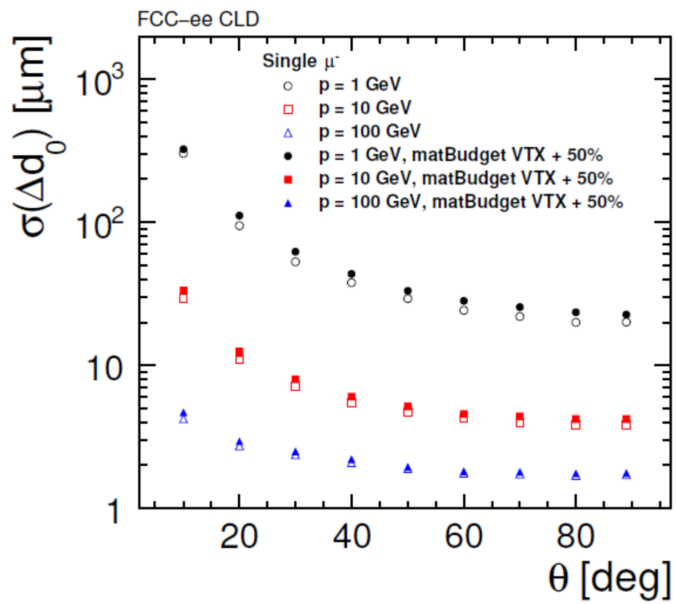
- Driving parameter
  - ✓ Inner radius

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\text{GeV}/c}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin\theta}} \sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

  - ✓ Beam pipe
    - Constant term ~ 0.15-0.3 % X_0
  - ✓ Material budget / layer
    - Requirement ~ ~0.15% X_0 /layer



- Material budget optimization
  - ✓ Double sided approach
    - PLUME prototypes
  - ✓ Stitching (see later)
    - Larger surfaces (fill factor ?)
  - ✓ Bent sensors
    - Optimize inner layers
  - ✓ Integration
    - Cooling system, mech. Support, cabling, Powering scheme, etc.



(a) d_0 resolution

Sensitivity to impact parameter resolution

Power & cooling in Higgs Factories

- Baseline:
  - ✓ air flow cooling only to minimize material budget
  - ✓ Up to ~ 20 mW/cm^2
- Driving parameters:
  - ✓ # channels, Time resolution / data flux
  - ✓ Surface (VXD ~ 3500 cm^2)
- Power Pulsing (ILC/CLIC)
  - ✓ Constraints more relaxed w.r.t. FCCee

Power Analog ($mW/chip$)	49.22
Power Bias ($mW/chip$)	4.5
Power PriorityEncoder ($mW/chip$)	4.219
Power DigitalPeriphery ($mW/chip$)	64.27
Power PLL ($mW/chip$)	18.5
Power Serializer With Data ($mW/chip$)	86.06
Power Serializer With No Data ($mW/chip$)	0
Power LVDS ($mW/chip$)	56.4

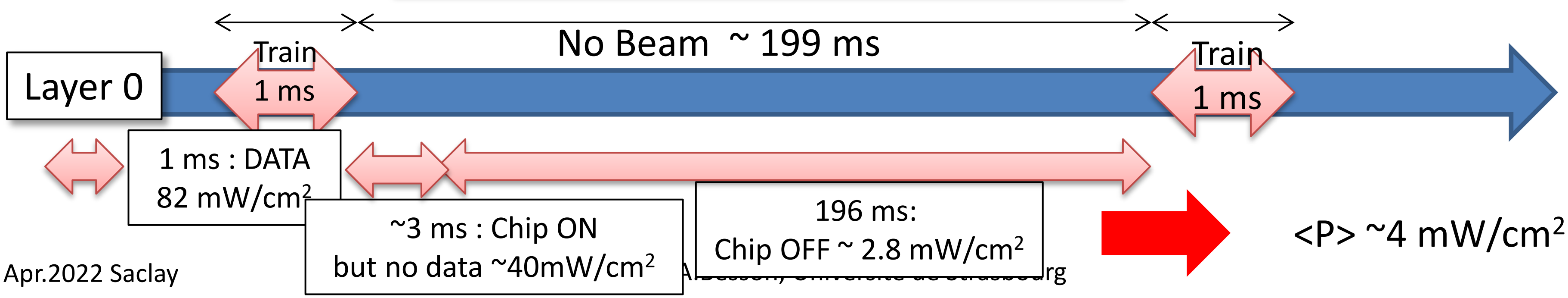
MIMOSIS like architecture, 180 nm

Period	Relative Energy
E during train	225 mJ ~ 4 %
E between train (Power ON)	380 mJ ~ 6 %
E between train (Power OFF)	5740 mJ ~ 90 %

Beam background rate	Read-out speed	<Power (NO P.P.)	<Power> (P.P.)	
	(µs)	(W)	Conservative	Ambitious
DBD	4 µs	102 W (~30mW/cm^2)	~31 W (~10 mW/cm^2)	~12 W
DBD	2 µs	122 W (~33mW/cm^2)		
DBD x 2	4 µs	107 W		
DBD x 2	2 µs	127 W		

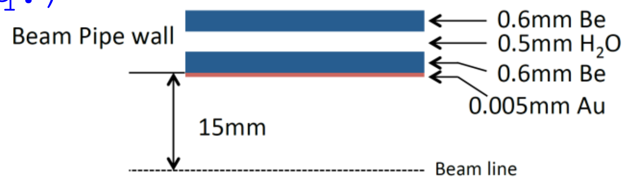
Layers	Relative Power
Layers 0/1	~ 10 %
Layers 2/3	~ 35%
Layers 4/5	~ 55 %

Challenge: Air flow cooling only



Being generic: ILC & FCC differences

- Beam structure: « continuous » vs trains
  - ✓ Power Pulsing: allows a factor O(10) reduction in average power
  - ✓ ILC: However, avoiding PP is desirable (alignment)
- Beam pipe shape and material
  - ✓ ILC: ~0.14% X_0 for the beam pipe (500 μm)
  - ✓ FCCee: Sync. Radiations ⇨ Cooling of the beam pipe ⇨ higher Mat.Budget
  - ⇨ 800 (2 pipes) + 400 (water) ~ 1200 um Be eq.)
  - ⇨ Smaller inner radius @ FCCee ?

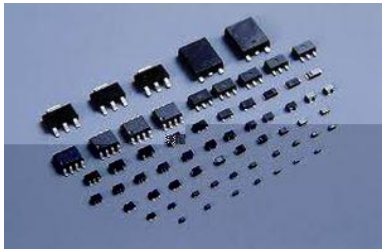


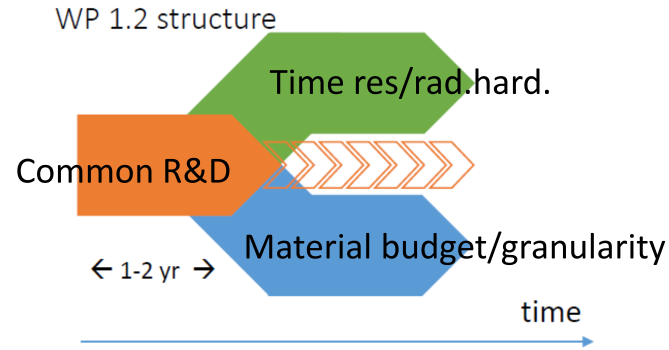
- MDI:
  - ✓ CLD: Forward acceptance limited to 150 mradian (8.6°)
  - ✓ ILD: Froward acceptance (disks) ~ 5°
- TeraZ vs Giga Z
  - ✓ Specific timing and impact parameter resolution ?
    - e.g. lower radius ?
- Magnetic field:
  - ✓ ILC: 3.5/4 T (R_{max} ~1.8m)
  - ✓ CLIC: R_{max}(CLIC): 1.5m
  - ✓ FCC: 2 T max ⇨ compensate by larger level arm (R_{max} ~ 2.15m)

⇨ Overall most of the R&D can be fruitfully made common

More details on 65nm

- 65 nm feature size technology
  - ✓ (ALPIDE & MIMOSIS fabricated in 180 nm)
  - ✓ Larger wafers (⇨ 30 cm)
  - ✓ More functionalities inside the pixel
  - ✓ Keeps pixel dimensions small ⇨ spatial res.
  - ✓ Potentially faster read-out
  - ✓ Lower Power consumption
- **TJ-65 nm available** (since June 2020)
  - ✓ Main driver: CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades ⇨ LS3 ~ 2024-26
  - ✓ involves IPHC/CPPM & R&D CMOS + DICE
  - ✓ Different requirements
    - EP: time resolution and radiation tol.
    - ALICE: granularity and material budget
    - Common R&D during the 1st years.

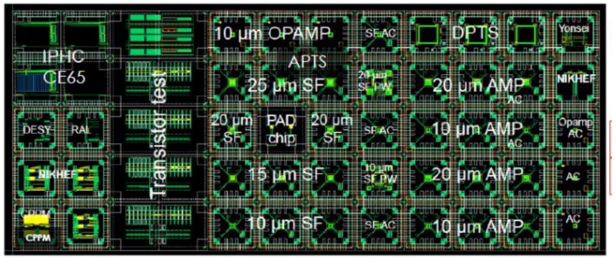




⇨ First submission: MLR1 (Q4 2020)

⇨ Synergy with Higgs factories requirements

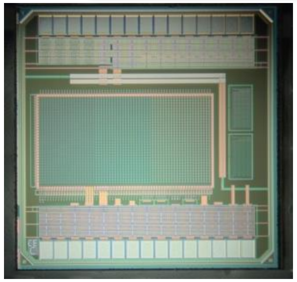
⇨ Relation with foundries and access to options is a key factor



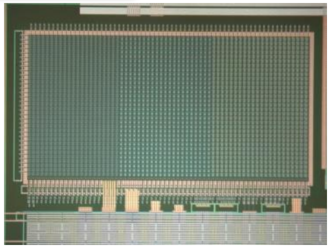
65nm: CE_65 prototypes

- IPHC-Strasbourg (Part of Cremlin+ program)
  - ✓ Goal: **validate the process for charged particle detection**
    - Sensitive volume not optimised for Higgs factories
  - ✓ + Test structures (DACs, amplifiers, etc.)
  - ✓ **4 matrices submitted: CE-65**
    - Technology exploration with single rolling shutter / **analog output**
    - Pitch: 15/25 µm
    - 3 N-well variants
    - Amps (AC/DC), SF
    - **Testable in beam**
  - ✓ CE_65 tests:
    - Back from foundry ~ **May-2021**
    - Beam tests with ALICE groups

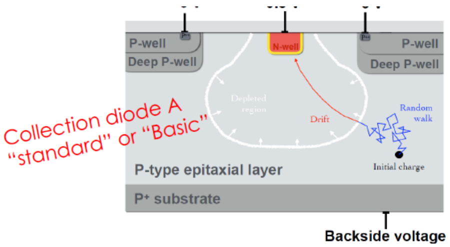
CE-65 prototypes

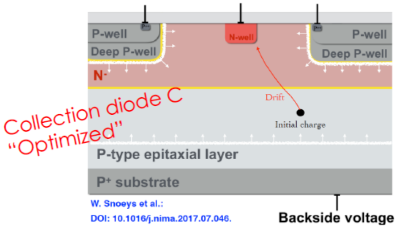


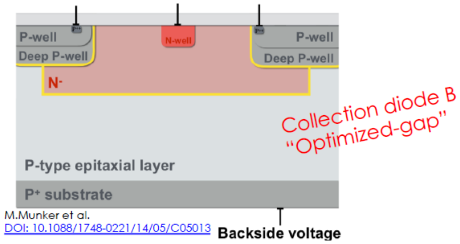
Variants A/B/C
64 × 32
15 µm pitch

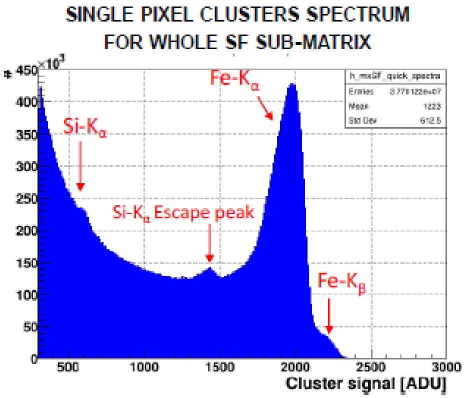


Variant D
48 × 32
25 µm pitch





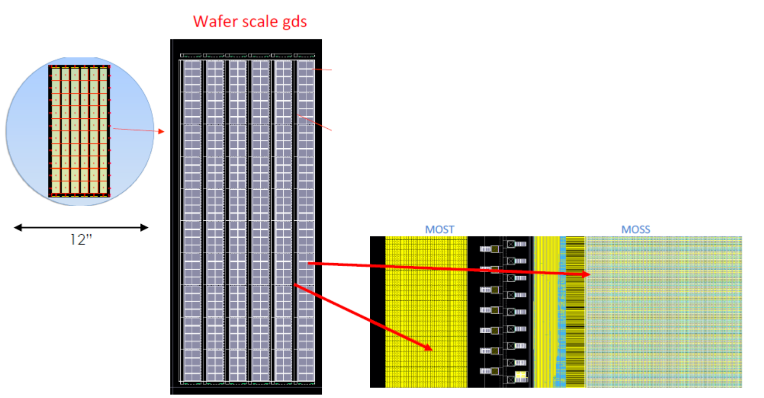


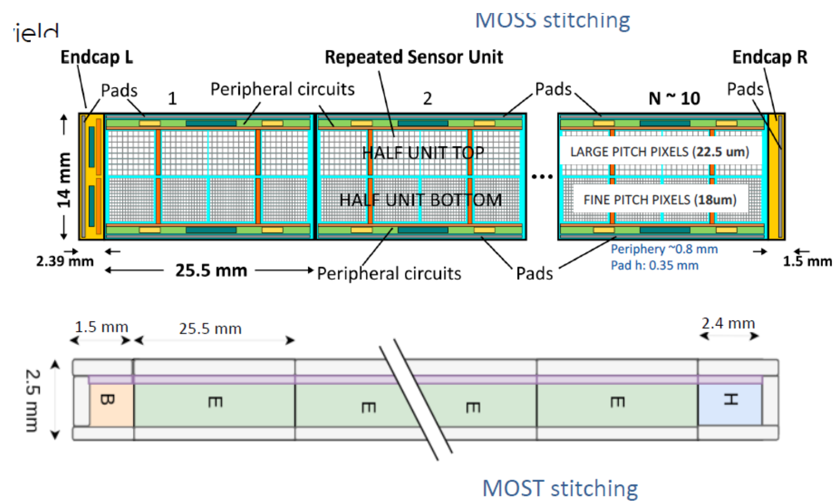


- ✓ **Excellent charge collection efficiency**
- ✓ **no showstopper**
- ✓ **Performances to be validated in beam test**

65 nm future plans

- Next submission: ER1
  - ✓ Goal: study Stitching/yield ➪ Power distribution, signal routing, yield, Noise, etc.
    - CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades
    - Submission: Q1 2022
    - Monolithic Stitched Sensor (MOSS) driven by CERN





  - ✓ IPHC contributions to
    - New matrices with analog output CE_65+ (e.g. Staggered pixels)
    - Matrices with discriminators
    - Contribution to the Stitching exploration (MOSS & MOST)
- Beyond ER1 ➪ ER2 (2022-23) dedicated to ITS-3

Summary

- VTX and tracking R&D
  - ✓ CMOS/MAPS = baseline for inner tracking in Higgs factories
    - probably still true up to next European strategy update
    - Mid-term applications (ALICE ITS-3, Belle-2 upgrade, etc.)
  - ✓ Efforts needed towards
    - Improved Power consumption (~20-50 mW/cm^2), time resolution (0.5-1 µs) and spatial resolution (~3 µm)
    - Material budget (~0.1-0.2%X_0/layer) ➪ Bent sensors + stitching
    - Targeting a FCCee demonstrator ~ 2025-26
  - ✓ Longer term: emerging technologies (e.g. interconnexion, wireless, etc.)
- Detector optimization
  - ✓ Specialist or general purpose ?
- « Parents pauvres » (manpower issues)
  - ✓ R&D groups mostly focused on chip designs
  - ✓ Software studies:
    - Design choice-Detector performances-physics performances
  - ✓ Integration
    - Strong interplay between beam pipe, services, barrel-disks forward detectors (e.g. lumi)
    - Monitoring, cooling, cable routing, Alignment, Powering scheme, mechanics, data flow, etc.
    - Global strategy needed ➪ federate French contribution ?

e^+e^- collider beam parameters

Linear

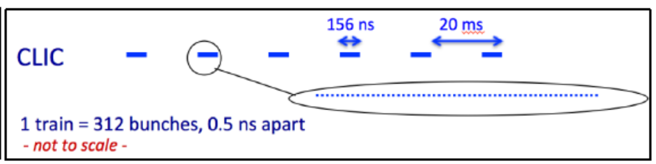
Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Beam size at IP σ_z (μm)	300	300	70	44	44

ILC: Crossing angle 14 mrad, e^- polarization ±80%, e^+ polarization ±30%
CLIC: Crossing angle 20 mrad, e^- polarization ±80%

Very small beams + high energy => beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
Triggerless readout
Power pulsing



Circular

	FCC-ee Z	FCC-ee Higgs	FCC-ee ttbar	CEPC Z (2T)	CEPC Higgs
√s [GeV]	**91.2**	**240**	**365**	**91.2**	**240**
Luminosity / IP ($10^{34}cm^{-2}s^{-1}$)	**230**	**8.5**	**1.7**	**32**	**1.5**
no. of bunches / beam	16640	393	48	12000	242
Bunch separation (ns)	**20**	994	3000	**25**	680
Beam size at IP σ_x/σ_y (μm/nm)	6.4/28	14/36	38/68	6.0/40	20.9/60
Bunch length (SR/BS) (mm) Beam size at IP σ_z (mm)	3.5/12.1	3.3/5.3	2.0/2.5	8.5	4.4

Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV)

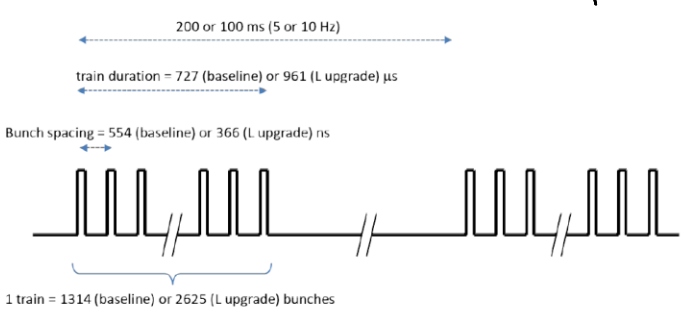
At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
⇒ **Statistical accuracies at 10^{-4} -10^{-5} level** ⇒ **drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
⇒ Triggerless readout likely still possible

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Mitigated through MDI design and detector design

Modified from Lucie Linssen, ESPPU, 2019

Mogens Dam / NBI Copenhagen   AIDA++ Open Meeting, CERN   4 September, 2019   6

(slide from Mogens Dam/Lucie Linssen)

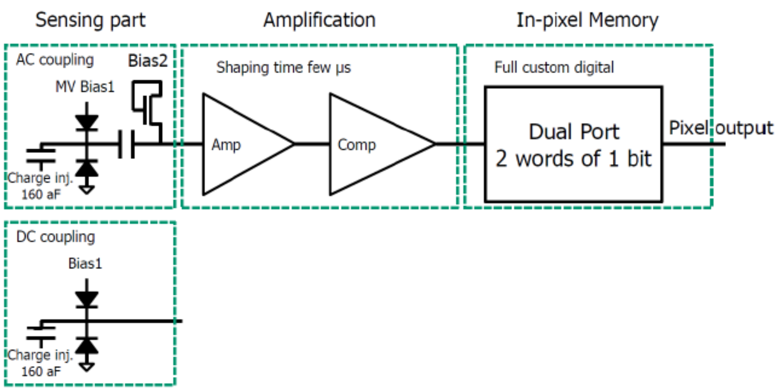


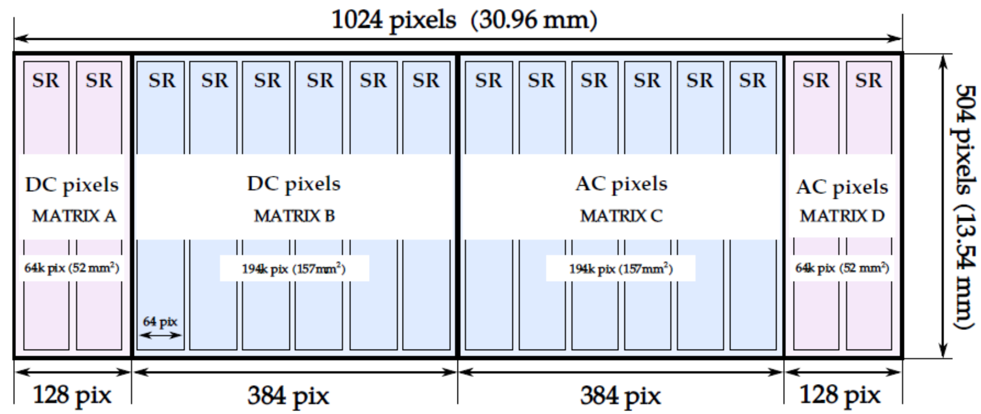
Collider parameters

FCC-ee collider parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} cm^{-2}s^{-1}]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

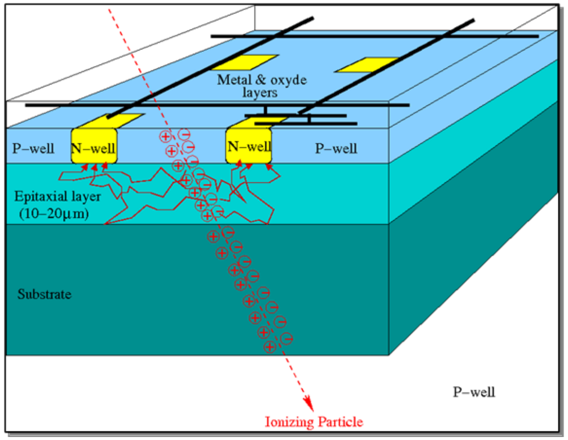
AC / DC pixels

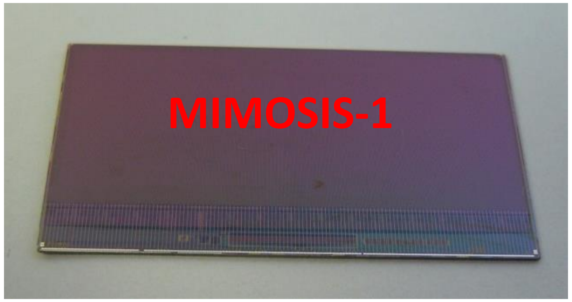


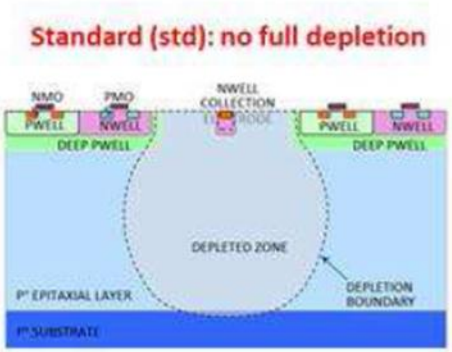


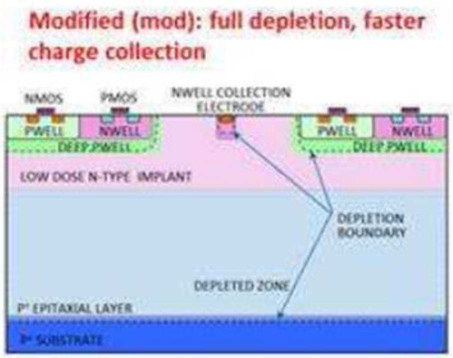
- DC Pixels (~ALPIDE) & AC pixels (top bias up to > 20V)
  - ✓ Amplifier / shaper / discriminator chain similar to ALPIDE in both scheme
  - ✓ Data driven readout
  - ✓ Pulse injection for calibration
  - ✓ Pixel masking options

- Main features
  - ✓ **Monolithic** (Signal created in low doped thin epitaxial layer ~10-30 µm)
  - ✓ Thermal diffusion of e- (Limited depleted region) + drift
  - ✓ Charge collection: N-Well diodes (Charge sharing)
  - ✓ Continuous charge collection (No dead time)
- Main advantages
  - ✓ **Granularity**
  - ✓ **Material budget**
  - ✓ Signal processing integrated in the sensor
    - Low signal & **Low Noise**
  - ✓ Flexible running conditions (Temperature, Power, Rad. Tol.)
  - ✓ **Industrial** mass production
    - Advantages on costs, yields, fast evolution of the technology,
    - Possible frequent submissions
- Main limitations
  - ✓ Industry addresses applications far from HEP experiments concerns
  - ✓ **Needs adapted processes**



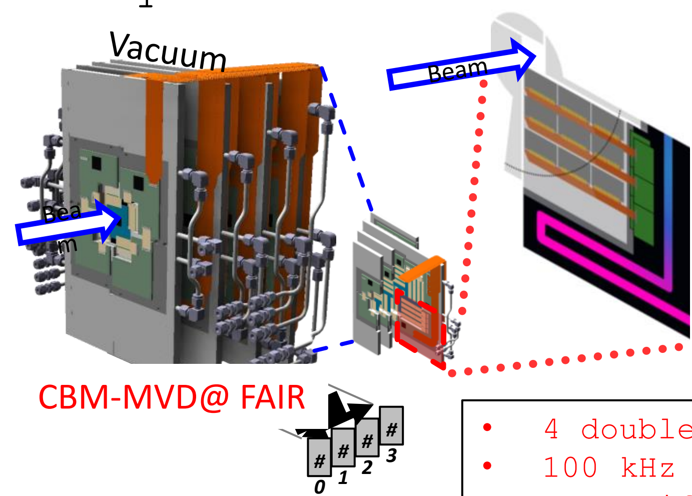


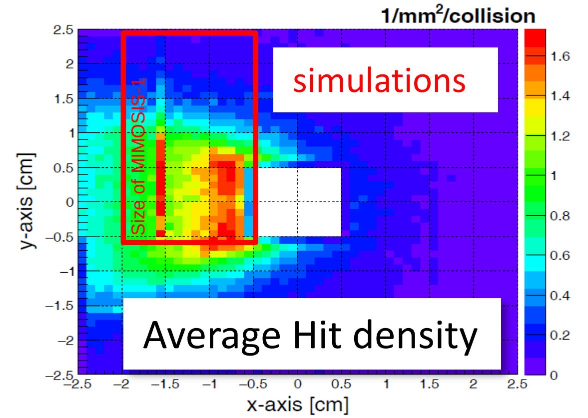




MIMOSIS requirements

- Requirements





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

- 4 double-sided thin planar detector stations
- 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
- Non uniform hit density in time and space
- High radiation environment, operating in vacuum

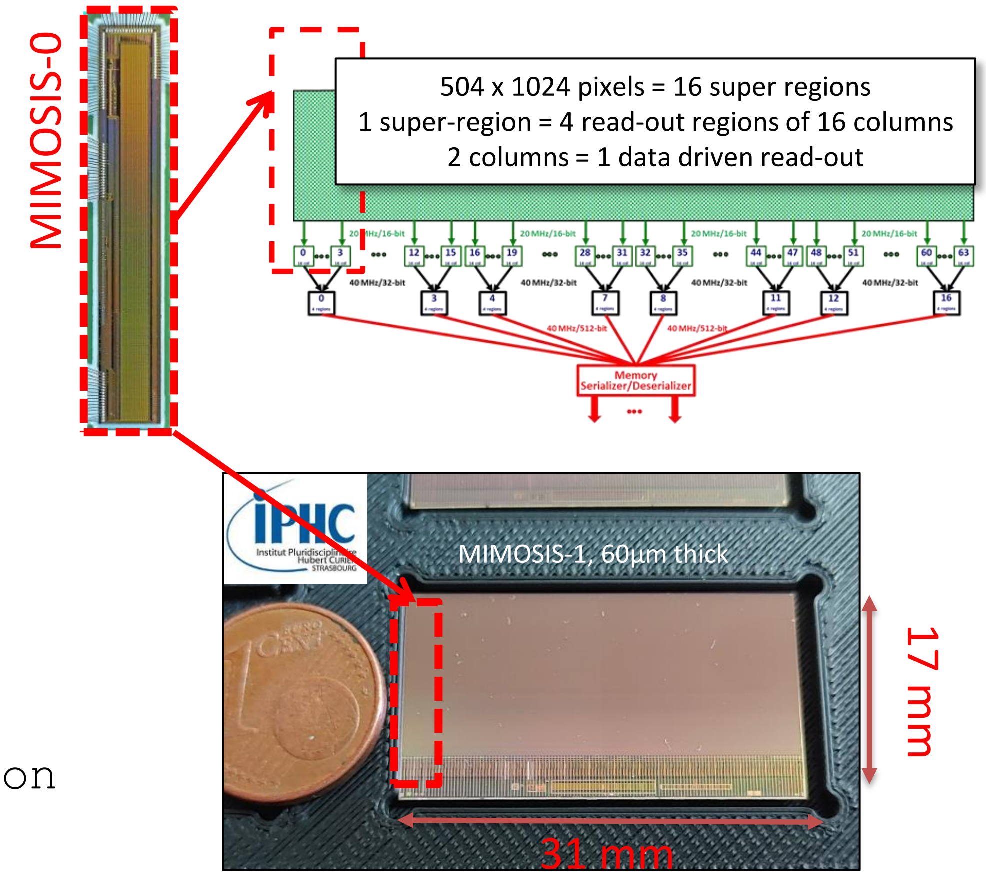
- MIMOSIS chip
  - ✓ Based on ALPIDE architecture
  - ✓ Discriminator on 27x30µm² pixel
  - ✓ Multiple data concentration steps
  - ✓ Elastic output buffer
  - ✓ 8 x 320 Mbps links (switchable)
  - ✓ Triple redundant electronics

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 = a milestone for Higgs factories (5 µm / ≤5 µs)

MIMOSIS roadmap

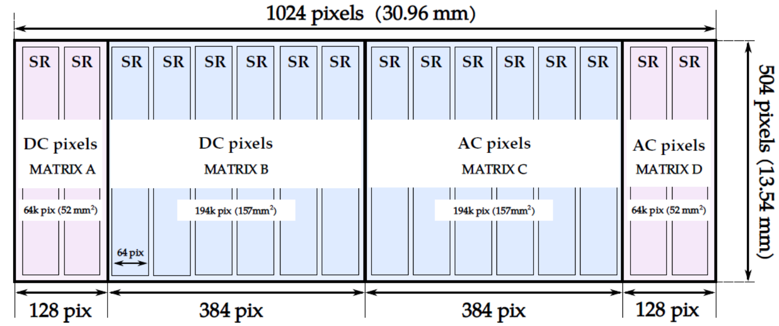
- 4 prototypes:
- MIMOSIS-0: = 2 regions
  - ✓ Tests (2018-2019)
    - ▪ Testability
- **MIMOSIS-1: 1st full size prototype**
  - ✓ **Elastic buffer, SEE hardened**
  - ✓ **Fabricated in 2020**
  - ✓ **Lab/beam test campaign in 2021**
- MIMOSIS-2:
  - ✓ On-chip clustering
  - ✓ Q4 2021 ⇨ tests in 2022
- MIMOSIS-3: final pre-production sensor
  - ✓ ≥2023

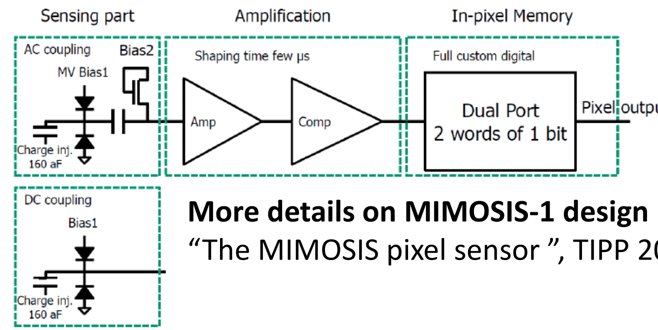


⇨ architecture adaptable to a fast sensor for an ILC vertex detector
⇨ Opportunity to study different designs/options

MIMOSIS-1

- MIMOSIS tests
  - ✓ Submatrices: DC/AC pixels
    - DC pixels: ALPIDE-derived
    - **AC pixels: top bias up to > 20V**
  - ✓ 6 epitaxial variants (18 wafers)
    - Thinned down to 60 µm
    - Study **Yield**
    - Study **charge collection / spatial res.**
    - Explore performances after **irradiation**



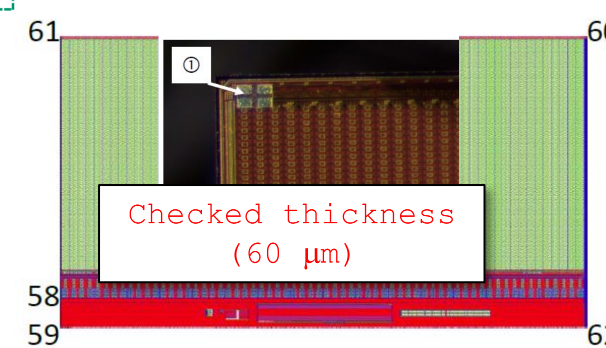


More details on MIMOSIS-1 design → F. Morel, "The MIMOSIS pixel sensor ", TIPP 2021

- Intense test program in 2021:
  - ✓ Laboratory tests
  - ✓ Irradiation tests

Ljubjana (TRIGA)	~1 MeV reactor neutrons
Karlsruhe (KIT)	~10 keV X-rays

  - ✓ Beam tests @ DESY/CERN (3 campaigns)
  - ✓ Latchup / SEE tests at GSI

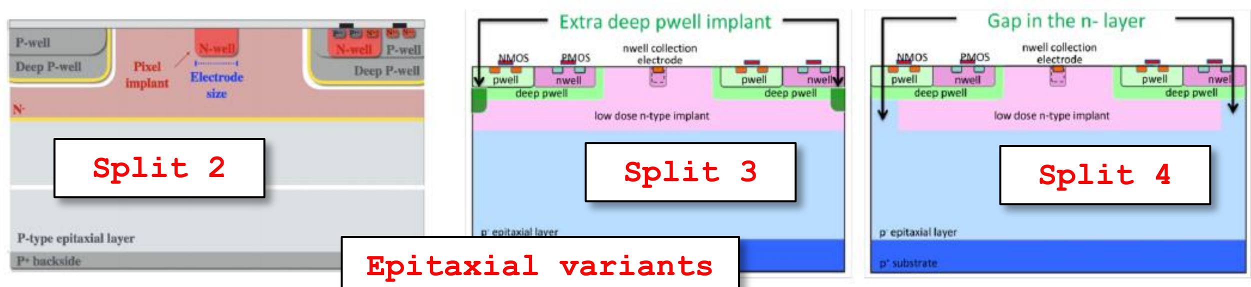


continuous n-layer

additional p-implant

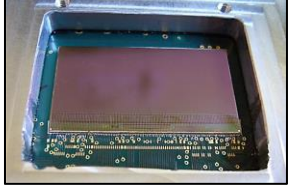
gap in n-layer

- standard process (3 available wafers)
- continuous n-layer (blanket) (3 wafers)
- additional p-implant (3 wafers)
- gap in n-layer (3 wafers)

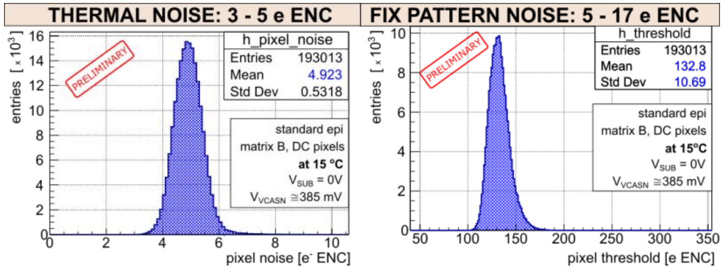


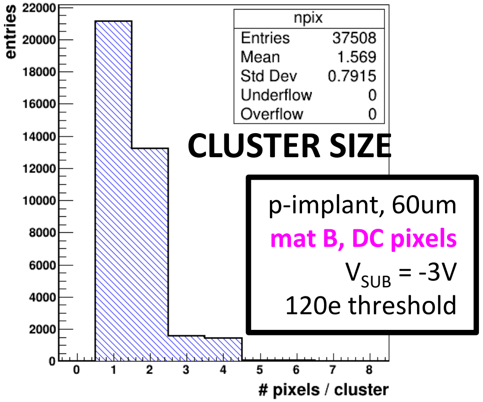
Pic from: Munker, Vertex 2018, Status of silicon detector R&D at CLIC
Carlos, TREDI 2019, Results of the Malta CMOS pixel detector prototype for the ATLAS Pixel ITK

MIMOSIS beam test preliminary results

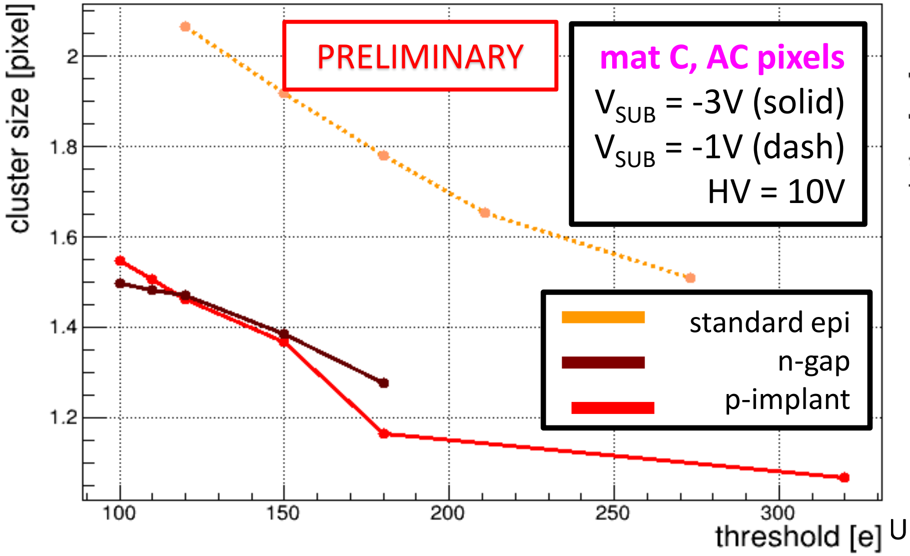


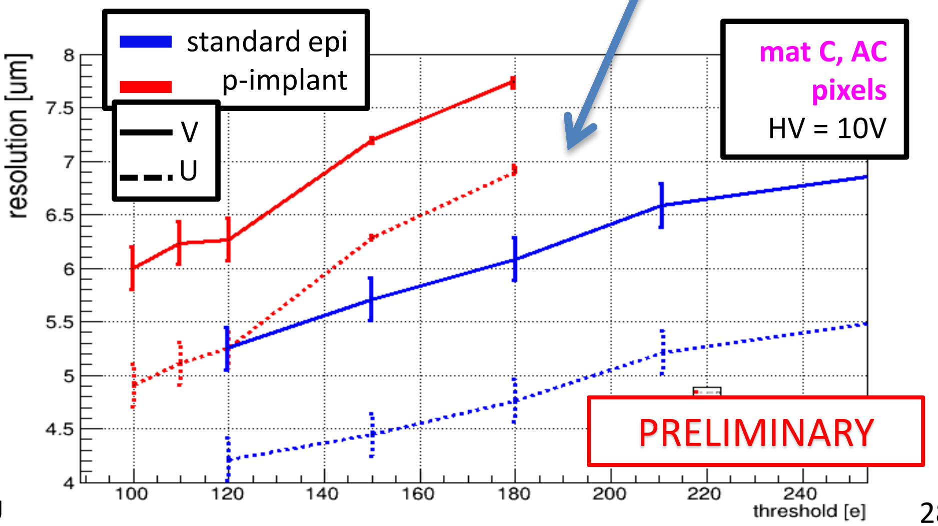
- Noise
  - ✓ DC pixels, no back bias applied) @ room T°C
  - ✓ Pixel Noise ~ 3-5 e⁻ ENC
  - ✓ FPN ~5-17 e⁻ ENC
- Efficiency
  - ✓ ≥ 99.5 % (work in progress)
  - ✓ Time walk correction
- Cluster multiplicity
  - ✓ Typically in the 1-2 range
- Resolution as expected
- Fake rate probably very low
  - ✓ (< 10^{-6}, tbc)





Pixel dimensions
~26.9 µm x 30.2 µm
Binary resolution
~ 7.8 (U) x 8.3 (V) µm
Depletion - Cluster size - resolution dependencies observed

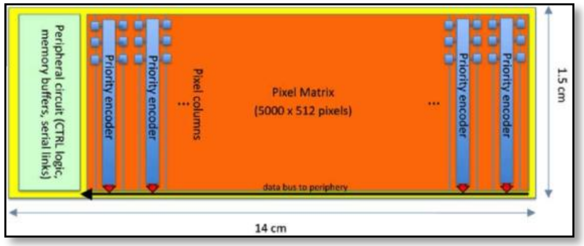


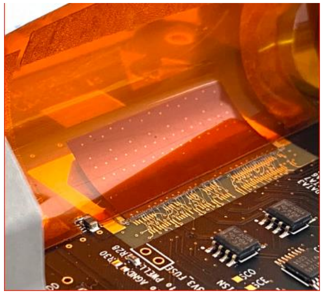


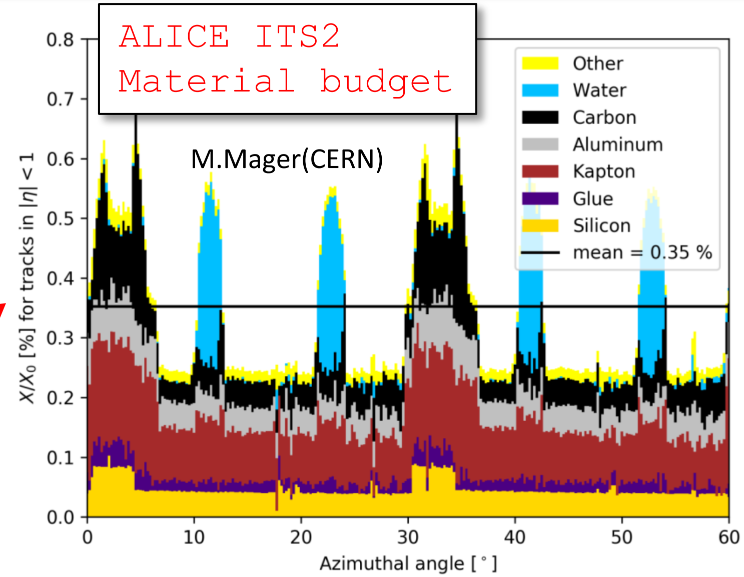
A U

Material budget: Bent sensors & stitching

- Stitching:
  - ✓ The way to go to minimize material budget

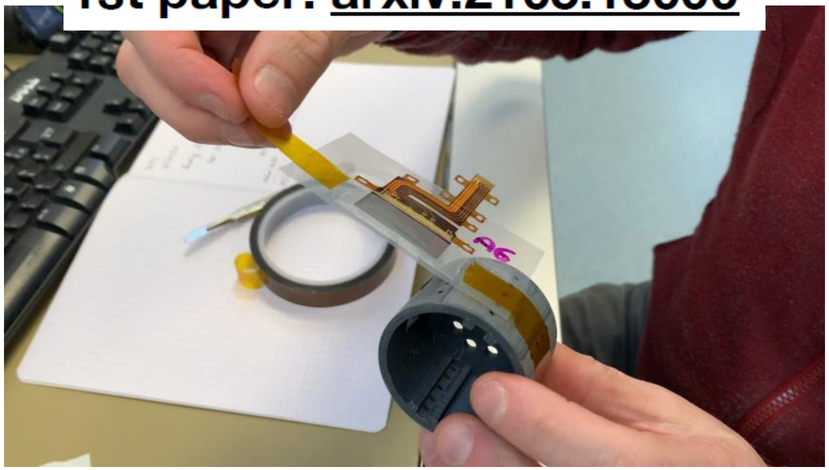


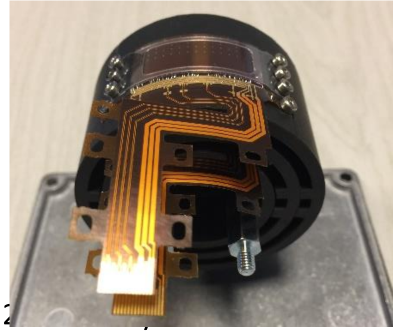


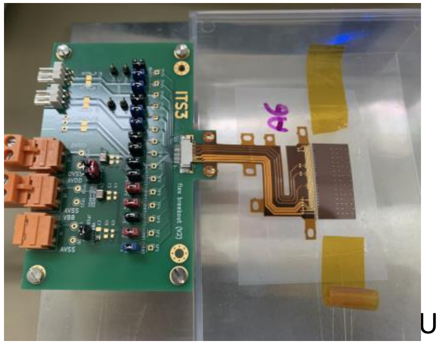


- ALICE-ITS3/CERN drive the R&D
  - ✓ Cf. M. Mager Seminar: *ALICE ITS3 – a next generation vertex detector based on bent, wafer-scale CMOS sensors*
    - https://indico.cern.ch/event/1071914/
- Micro-technics tests @IPHC
  - ✓ collaboration with ALICE-ITS3
  - ✓ Know-how acquired for bent bonding.

1st paper: arxiv:2105.13000

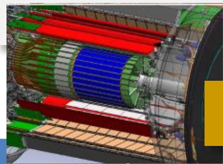
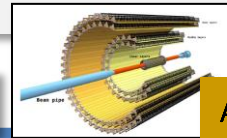
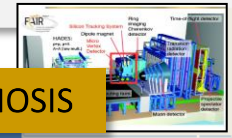






Bending / bonding
Or Bonding / bending
⇨Functionnal tests

Evolving CPS


	ULTIMATE STAR-PXL	ALPIDE ALICE-ITS	MIMOSIS CBM-MVD	PSIRA proposal ILD-VXD
Data taking	2014-2016	>2021-2022	>2021	>2030
Technology	AMS-opto 0.35 μm	0.18 μm	0.18 μm	0.18 μm (conservative) < 0.18 μm ?
	4M	HR, V_{bias} ~-6V Deep P-well	HR, Deep P-well	?
Architecture	Rolling shutter + sparsification + binary output	Data driven r.o. In pixel discri.	Data driven r.o. In pixel discri.	Data driven r.o. (conservative)
Pitch (μm²) / Sp. Res.	20.7 x 20.7 / 3.7	27 x 29 / 5	27 x 30 / <5	~ 22 / ~ 4 OR ~ 17/3
Time resolution (μs)	~185	5-10	5	1 – 4
Data Flow		~10^6 part/cm²/s Peak data rate ~ 0.9 Gbits/s	peak hit rate @ 7 x 10^5 /mm²/s >2 Gbits/s output (20 inside chip)	~375 Gbits/s (instantaneous) ~1166Mbits / s (average)
Radiation	O(50 kRad)/year	$2x10^{12}$ n_{eq}/cm² 300 kRad	$3x10^{13}$ n_{eq}/cm²/yr & 3 MRad/yr	O(100 kRad)/year & O($1x10^{11}$ n_{eq}(1MeV)) /yr
Power (mW/cm²)	< 150 mW/cm²	< 40 mW/cm²	< 200 mW/cm²	~ 50-100 mW/cm² + Power Pulsing
Surface	2 layers, 400 sensors, $360x10^6$ pixels 0.15 m²	7 layers, $25x10^3$ sensors > 10 m²	4 stations Fixed target	3 double layers 10^3 sensors (4cm²) 10^9 pixels ~0.33 m²
Mat. Budget	~ 0.39 % X_0 (1st layer)	~ 0.3% X_0 / layer		~ 0.15-0.2 % X_0 / layer
Remarks	1st CPS in colliding exp.	(with CERN)	Vacuum operation Elastic buffer	Evolving requirements