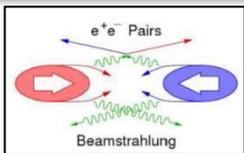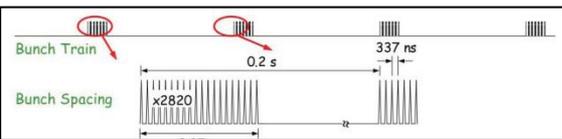# CMOS pixels sensors R&D for the vertex detector in a Higgs factory

Auguste Besson

On behalf of the PICSEL group & C4PI Platform
@IPHC – Strasbourg

- Introduction: requirements & strategy
- MIMOSIS chip development (IPHC-IKF-GSI Collaboration)
- 65 nm R&D (with CERN EP R&D WP 1.2 & ALICE ITS-3)

# ILC/FCCee Vertex detector requirements

Bunch Train
Bunch Spacing
0.2 s
337 ns
x2820

$e^+e^-$ Pairs

Beamstrahlung

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

$e^+$ $e^-$ $Z$ $Z$ $H$

Physics (<Hz/cm$^2$)

Beam background (~ 5 hits/BX/cm$^2$ on layer 0, ILC)
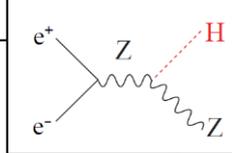
Beam background

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

Rad.Tol. devices

Back scattering

Read-out speed
O(1-10 μs)

X0 y= 0.100 [cm]

Power consumption
~< 50mW/cm$^2$

Fast read-out & low Power Architectures (~ 20 mW/cm$^2$)

Cooling
Stiffness / Alignment

Power pulsing (ILC) vs continuous beam (FCCee)
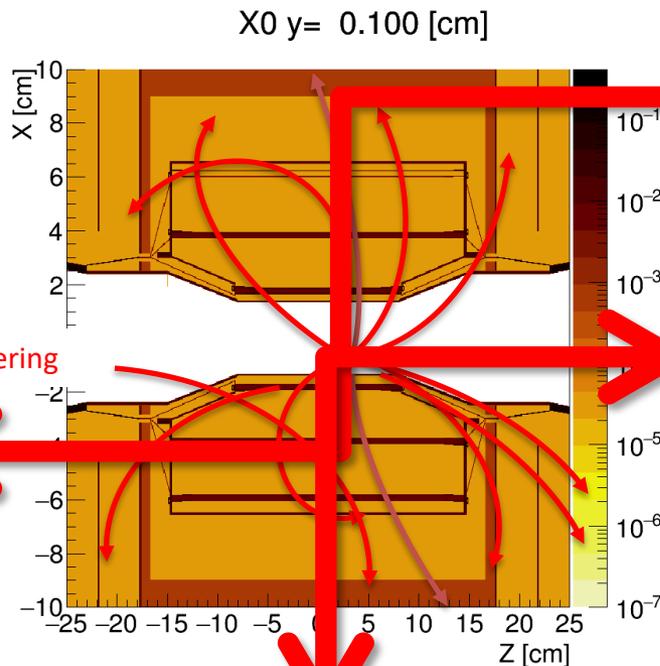
Vertex reconstruction
⇨ granularity
⇨ Pitch ~17 um
⇨ ($\sigma_{sp}$ ~3 um)

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

**Challenge:**

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

CMOS Master Project

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

Approach the Higgs factories vertex detector requirements

Input for detector simulations

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

Exploit fully the potential of the CMOS technology

MIMOSIS chip family (180 nm)

Maintain & develop the know how to build sensors to be installed in real experiments
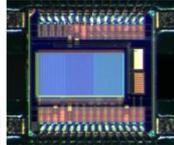
R&D 65 nm

Large surfaces (stitching)

Bent sensors

Integration

Emerging technologies (e.g. double tier)

ECFA Detector Technology roadmap
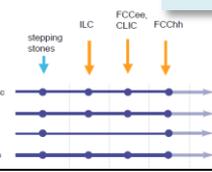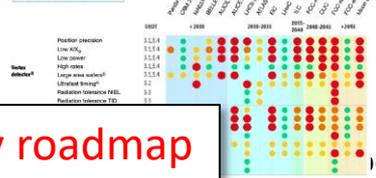
# History & Future: On the road to Higgs factories

O(100 μs)

Process: 0.35 μm

EUDET beam telescope
(Mimosa 26 by IPHC)
~ 15 copies since 2009

STAR-PXL detector
(ULTIMATE  by IPHC)
2014-16
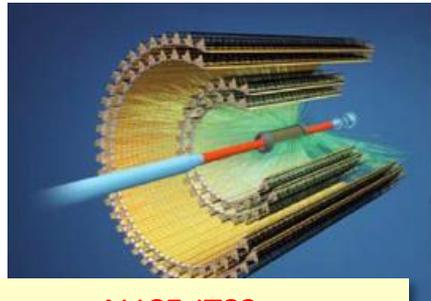
Process: 0.18 μm

ALICE-ITS2
(ALPIDE by CERN & IPHC)
In installation

O(10 μs)
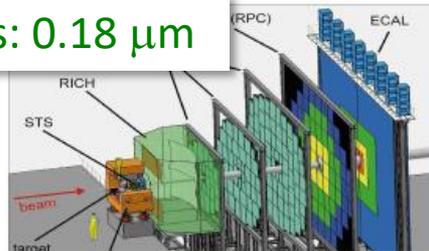
CBM-MVD
(MIMOSIS by IPHC -IKF-GSI)
Under development

O(1 μs)

Process: 65 nm ?

O(100 ns)?

ILC VXD & inner tracker
R & D

- IPHC: R&D started in ~1999
  - ✓ Take advantage of mid-term projects to get closer to ILC vertex detector requirements
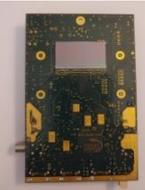
- Today (⇨~2023)
  - ✓ CBM-MVD: MIMOSIS chips
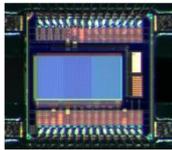
  - ✓ 65 nm technology exploration with CERN
    - • + stitching

- Long term (> 2025⇨2035)
  - ✓ Higgs factories development line

# Time resolution in the context of e⁺e⁻ colliders

CBM-MVD
5 µs - Under development

HL-LHC
e.g.MALTA - 25 ns

STAR-PXL detector
185 µs - 2014

ALICE-ITS2
10 µs - In construction

MUPIX-X
(Mu3e)
<10 ns

ex: ALICE "Full Silicon"

ALICE-Beyond LS4

ALICE-Beyond LS3

**Others (ions, pp, etc.)**

Belle-II upgrade ?

| 100 µs | 10 µs | 1µs | 100 ns | 10 ns | 1 ns | 100 ps | 10 ps |

**Time resolution**

ILC R&D

Minimal
VXD requirements
~1-4 µs

SIT &
Bunch tagging
300-500 ns

backscatterred filter
10 ns

Particle ID  **ILC**

VXD requirements
~1 µs

tt bunch ~ 3 µs

Z bunch
~ 20 ns

Particle ID  **FCCee**

CLIC 5 ns

CLIC bunch
500 ps

Particle ID  **CLIC**

VXD requirements
~1 µs

(H) Bunch
680 ns

(Z) bunch
25 ns

Particle ID  **CEPC**

A.Besson, IPHC-Strasbourg University

# Requirements

Vacuum



CBM-MVD@ FAIR

**simulations**

**Average Hit density**

1/mm²/collision

| Physics parameter | Requirements |
|---|---|
| Spatial resolution | ~ 5 um |
| Time resolution | ~ 5 us |
| Material budget | 0.05% $X_0$ |
| Power consumption | < 100 – 200 mW/cm² |
| Operation temperature | - 40 °C to 30 °C |
| Temp gradient on sensor | < 5K |
| Radiation tol* (non-ion) | ~ 7 x $10^{13}$ $n_{eq}$/cm² |
| Radiation tol* (ionizing) | ~ 5 MRad |
| Data flow (peak hit rate) | @ 7 x $10^5$ / (mm²s) > 2 Gbit/s |
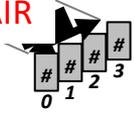
- 4 double-sided thin planar detector stations
- 100 kHz Au+Au @ 11 AGeV and 10GHz p+Au @ 30 AGeV
- Non uniform hit density in time and space
- High radiation environment, operating in vacuum

# 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 | $\sim 25\,\mu m$ |
| Epi layer resistivity | $> 1 k\Omega cm$ |
| Sensor thickness | $60\,\mu m$ |
| Pixel size | $26.88\,\mu m \times 30.24\,\mu m$ |
| Matrix size | $1024 \times 504$ (516096 pix) |
| Matrix area | $\approx 4.2\,cm^2$ |
| Matrix readout time | $5\,\mu s$ (event driven) |
| Power consumption | 40-70 mW/cm² |

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

- 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



504 x 1024 pixels = 16 super regions
1 super-region = 4 read-out regions of 16 columns
2 columns = 1 data driven read-out

MIMOSIS-1, 60µm thick

17 mm

31 mm

⇨ 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.**
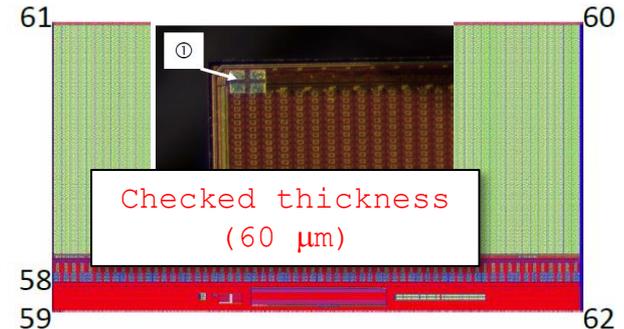    - ▪ Explore performances after **irradiation**

- 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



1024 pixels (30.96 mm)
504 pixels (13.54 mm)

DC pixels MATRIX A — 64k pix (52 mm²)
DC pixels MATRIX B — 194k pix (157 mm²)
AC pixels MATRIX C — 194k pix (157 mm²)
AC pixels MATRIX D — 64k pix (52 mm²)

128 pix | 384 pix | 384 pix | 128 pix — 64 pix

Sensing part — Amplification — In-pixel Memory

AC coupling — Bias2 — MV Bias1 — Charge inj. 160 aF

Shaping time few μs — Amp — Comp

Full custom digital — Dual Port 2 words of 1 bit — Pixel output

DC coupling — Bias1 — Charge inj. 160 aF

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

Checked thickness (60 μm)

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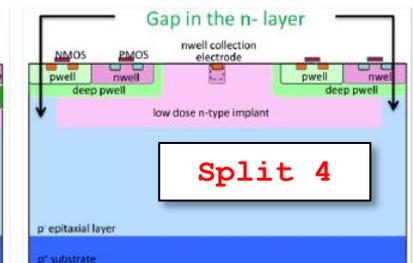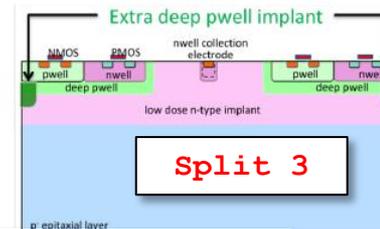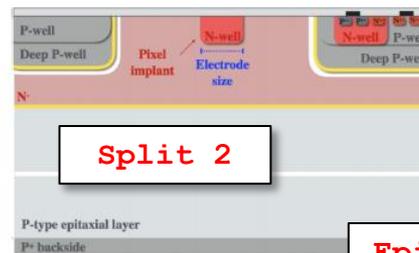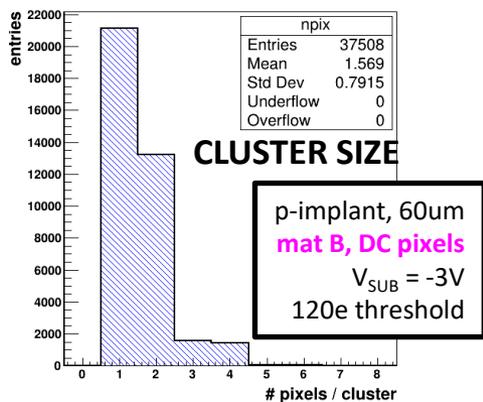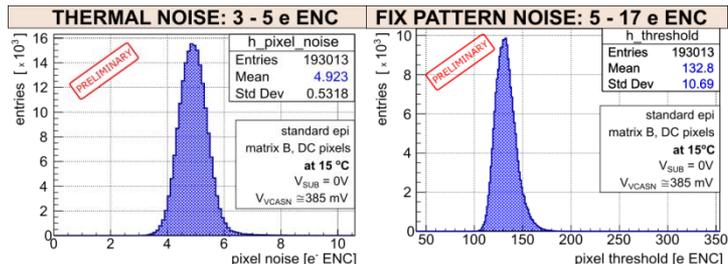
- standard process (3 available wafers)
- continuous n-layer (blanket) (3 wafers)
- additional p-implant (3 wafers)
- gap in n-layer (3 wafers)

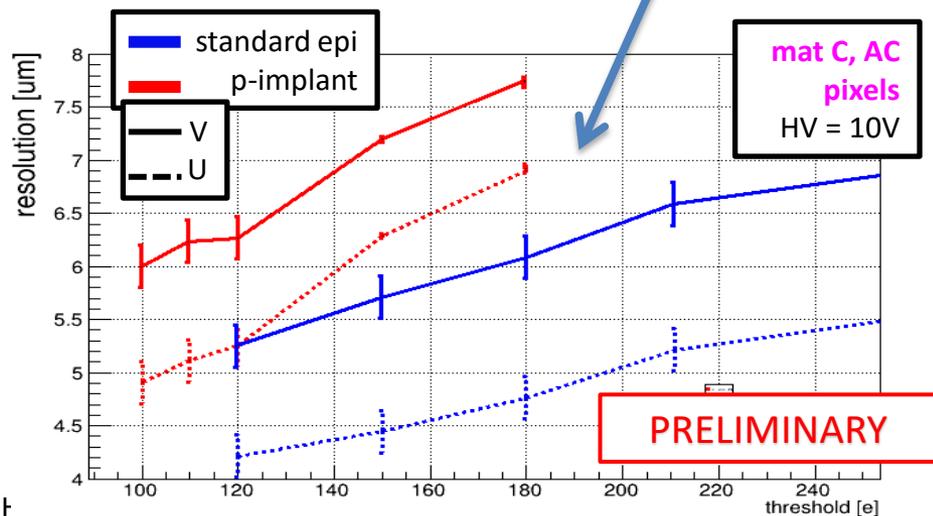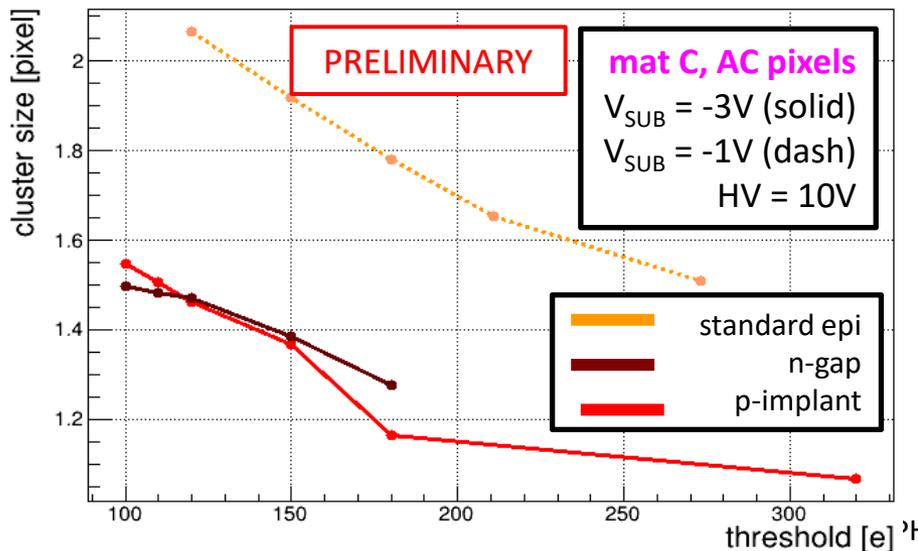**Split 2**

**Split 3**

**Split 4**

**Epitaxial variants**

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
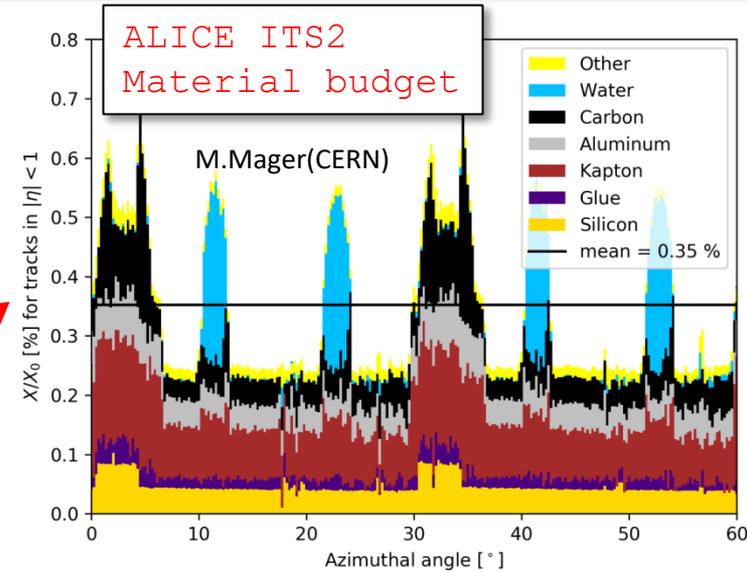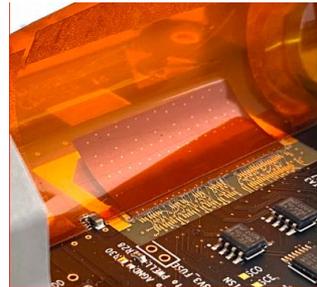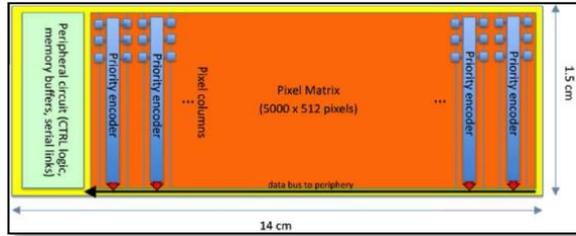- Resolution as expected
- Fake rate probably very low
  - ✓ (< $10^{-6}$, tbc)



THERMAL NOISE: 3 - 5 e ENC

h_pixel_noise
Entries 193013
Mean 4.923
Std Dev 0.5318

standard epi
matrix B, DC pixels
at 15 °C
$V_{SUB}$ = 0V
$V_{VCASN}$ ≅ 385 mV

FIX PATTERN NOISE: 5 - 17 e ENC

h_threshold
Entries 193013
Mean 132.8
Std Dev 10.69

standard epi
matrix B, DC pixels
at 15°C
$V_{SUB}$ = 0V
$V_{VCASN}$ ≅ 385 mV



npix
Entries 37508
Mean 1.569
Std Dev 0.7915
Underflow 0
Overflow 0

CLUSTER SIZE

p-implant, 60um
mat B, DC pixels
$V_{SUB}$ = -3V
120e threshold

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



PRELIMINARY

mat C, AC pixels
$V_{SUB}$ = -3V (solid)
$V_{SUB}$ = -1V (dash)
HV = 10V

standard epi
n-gap
p-implant



standard epi
p-implant
V
U

mat C, AC pixels
HV = 10V

PRELIMINARY

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





ALICE ITS2
Material budget

M.Mager(CERN)



- ALICE-ITS3/CERN drive the R&D
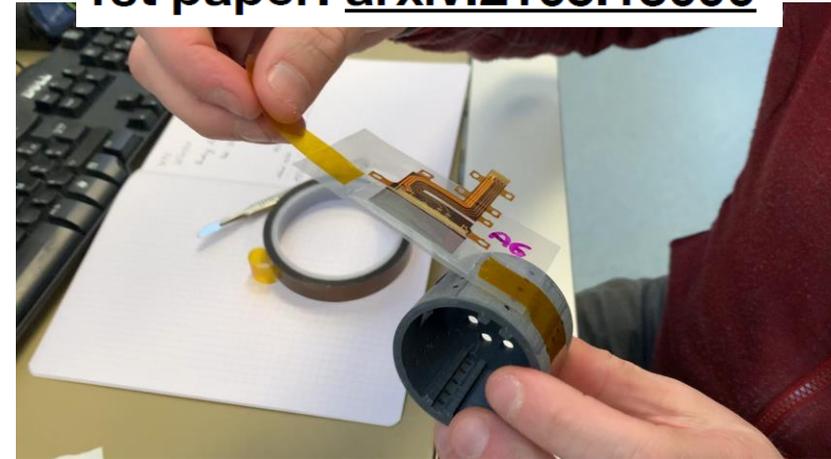  - ✓ Cf. M. Mager Seminar: *ALICE ITS3 – a next generation vertex detector based on bent, wafer-scale CMOS sensors*
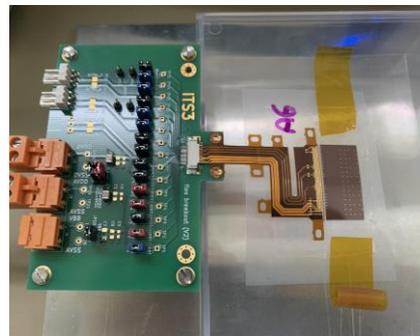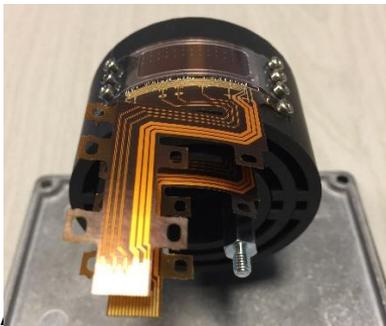    - ▪ https://indico.cern.ch/event/1071914/

- 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

# TJ-65 nm process: smaller feature size

- 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 (involves other labs) ⇨ LS3 ~ 2024-26
  - ✓ Different requirements
    - ▪ EP: time resolution and radiation tol.
    - ▪ ALICE: granularity and material budget
    - ▪ Common R&D during the 1st years.
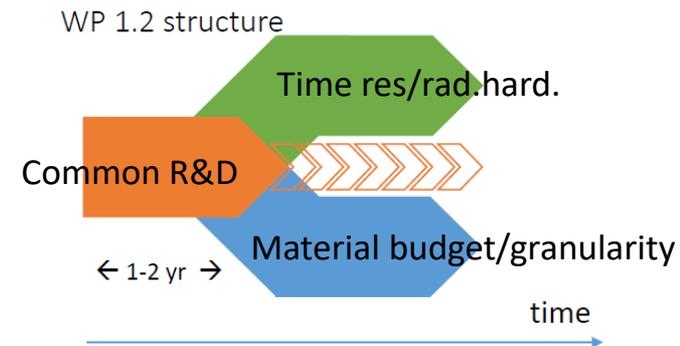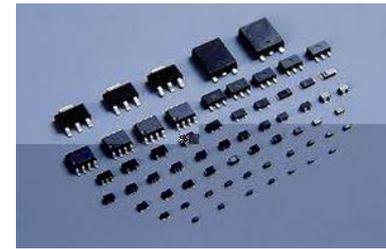
⇨ First submission: MLR1 (Q4 2020)
⇨ Synergy with Higgs factories requirements
⇨ Relation with foundries and access to options is a key factor



WP 1.2 structure





A.Besson, IPHC-Strasbourg University

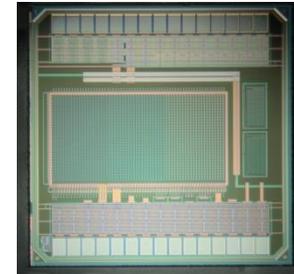- IPHC-Strasbourg (Part of Cremlin+ program)
  - ✓ Goal: **validate the process for charged particle detection**
    - ▪ Sensitive volume not optimised for Higgs factories
  - ✓ + Test structures (DACs, amplifiers, etc.)
  - ✓ **4 matrices submitted: CE-65**
    - ▪ Technology exploration with single 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 (ITS3 WP3 & Cagliari) @ CERN/DESY Q4 2021

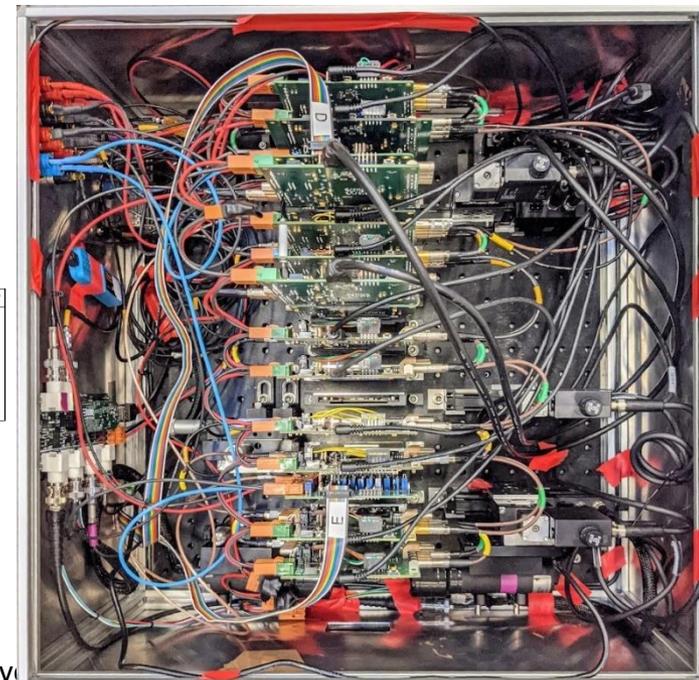**CE-65 prototypes**

Variants A/B/C
64 × 32
15 μm pitch
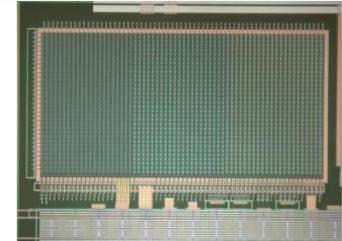
Variant D
48 × 32
25 μm pitch

AC pixels with amplifier

preliminary

Test beam data

preliminary

signal

preliminary

Seed pixel charge of plane 1 - DUT

DC AMP    B4

$^{55}$Fe data

preliminary

charge (ADCu)

A.Besson, IPHC-Strasbourg Univ
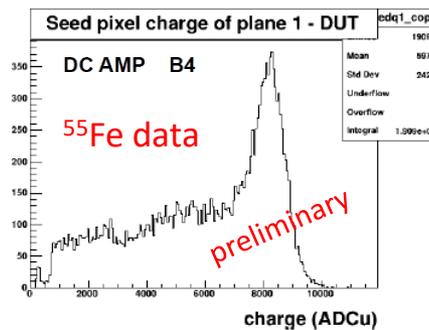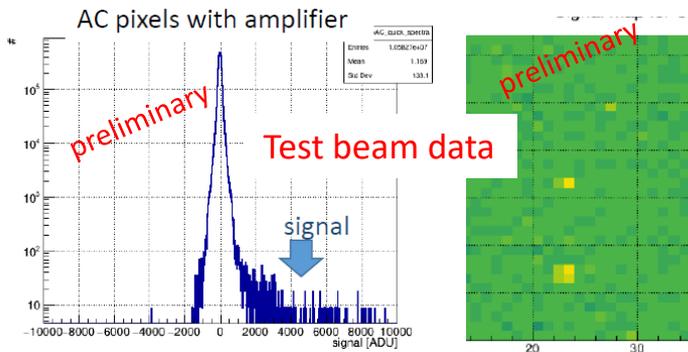
- Next submission: ER1
  - ✓ CERN EP R&D WP 1.2 & ALICE ITS-3 upgrades
  - ✓ Submission: Q1 2022
  - ✓ Monolithic Stitched Sensor(MOSS) driven by CERN
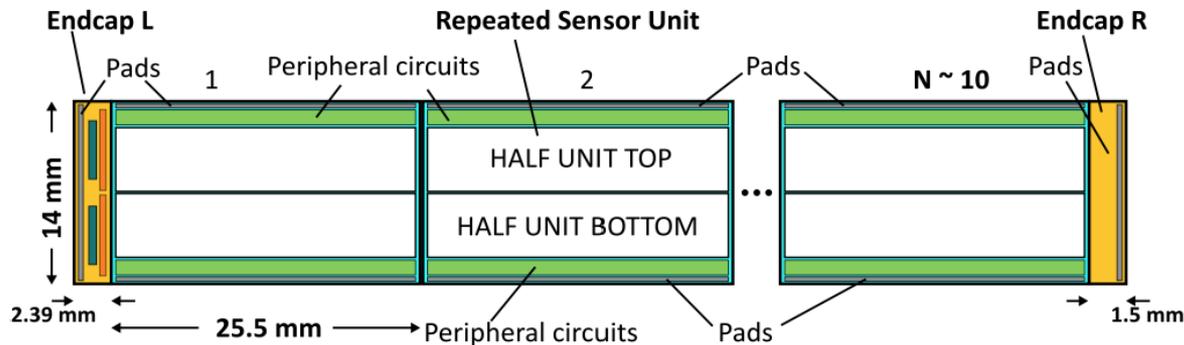


  - ▪ Goal: study Power distribution, signal routing, yield, Noise, etc.
  - ✓ IPHC contributions to
    - ▪ New matrices with analog output CE_65+ (e.g. Staggered pixels)
    - ▪ Matrices with disciminators
    - ▪ Contribution to the Stitching exploration (MOSS & MOST)
- Beyond ER1 ➪ ER2 (2022-23)

# Summary: Synergies in CMOS R&D

- Integration ➪ not discussed here!
- CMOS Pixel Sensors are the baseline for Higgs factories
  - ✓ Requirements are within reach
- Strong dynamic of CMOS pixel Sensors R&D:
  - ✓ **180 nm : MIMOSIS series**
    - ▪ **(5μm spatial res./ ≤5μs time res./ 60μm thickness / < 70 mW/cm$^2$)**
    - ▪ **MIMOSIS-1 ➪ full size prototype being tested**
    - ▪ **MIMOSIS-2 to be submitted (Q4 2021)**
  - ✓ **65 nm technology exploration**
    - ▪ First submission dec.2020 (MLR1)
    - ▪ Techno validation: first indices are encouraging (DPTS)
    - ▪ **First test beam on CE_65 chips ongoing @ CERN/DESY**
    - ▪ **2$^{nd}$ submission (ER1, Q1 2022): Stitching**
  - ✓ **Stitching** & large surfaces for very low mass detectors ➪ Priority for Higgs factories in the future
    - ▪ Bent sensors test beam performed by ALICE
    - ▪ Material budget & Large pixelated surfaces
  - ✓ **Synergies** with
    - ▪ CERN R&D (ALICE ITS upgrades and EP R&D WP1.2)
    - ▪ R&D programs (e.g. AIDA-Innova, CREMLIN+, etc.)
    - ▪ Heavy ion experiments (e.g. ALICE beyond LS3/4 proposal, CBM, EIC)
    - ▪ Other experiments: Belle-II, etc.
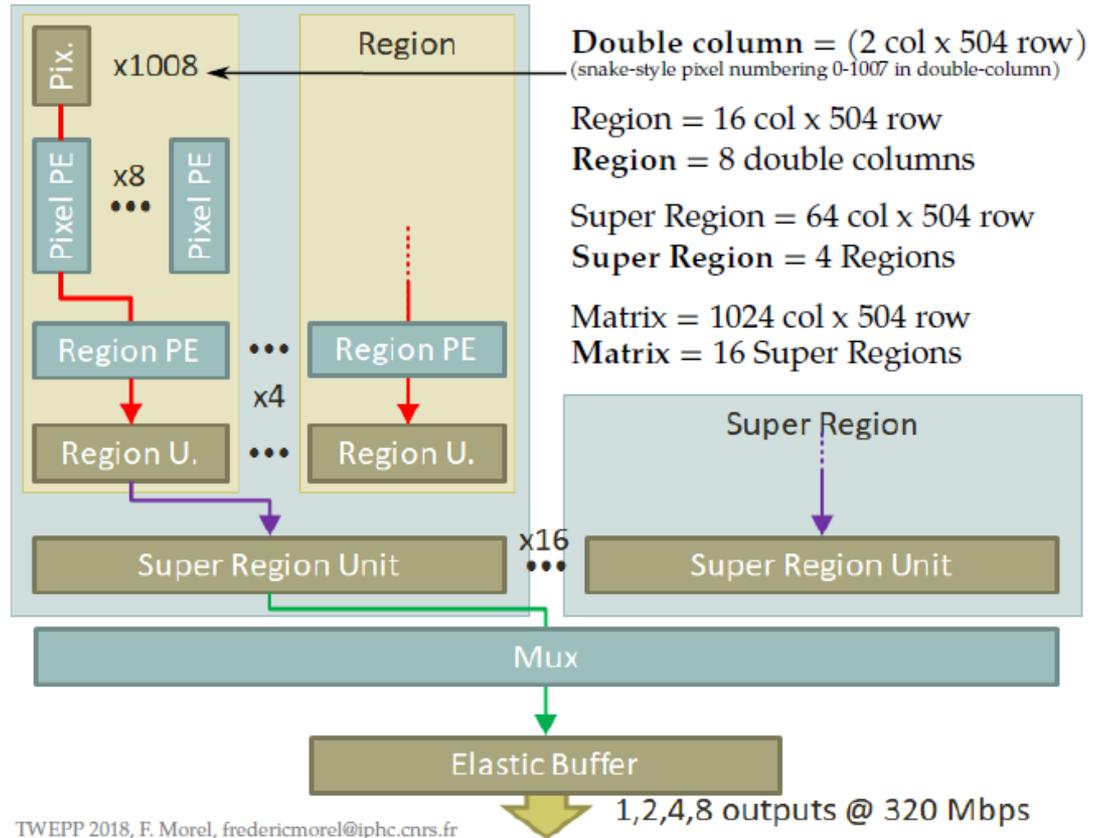    - ▪ DICE MP (see Marlon's talk)

# Back up

# 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 ?



Beam Pipe wall — 0.6mm Be — 0.5mm $H_2O$ — 0.6mm Be — 0.005mm Au — 15mm — Beam line

- 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)

- 3-stage buffering allows to handle with data rate fluctuations

- 8 double-columns forms 1 Region (8064 pixels) → read out by priority encoder @ 20 MHz.

- each region has a region buffer (capacity up to 100 words).

- 4 Regions (1 Super Region) → data sent @ 40 MHz to Super Region Buffer

- 16 SR (whole matrix) → data goes through frame generator to elastic buffer @ 80 MHz

- elastic buffer – can store up to 16384 words and outputs the data on 8 differential data links

**Double column** = $(2 \text{ col} \times 504 \text{ row})$
(snake-style pixel numbering 0-1007 in double-column)

**Region** = 16 col x 504 row
**Region** = 8 double columns

**Super Region** = 64 col x 504 row
**Super Region** = 4 Regions

**Matrix** = 1024 col x 504 row
**Matrix** = 16 Super Regions



TWEPP 2018, F. Morel, fredericmorel@iphc.cnrs.fr

- MIMOSIS-1 has 8 outputs each 320 Mb/s providing a required data throughput for MVD

# AC / DC pixels
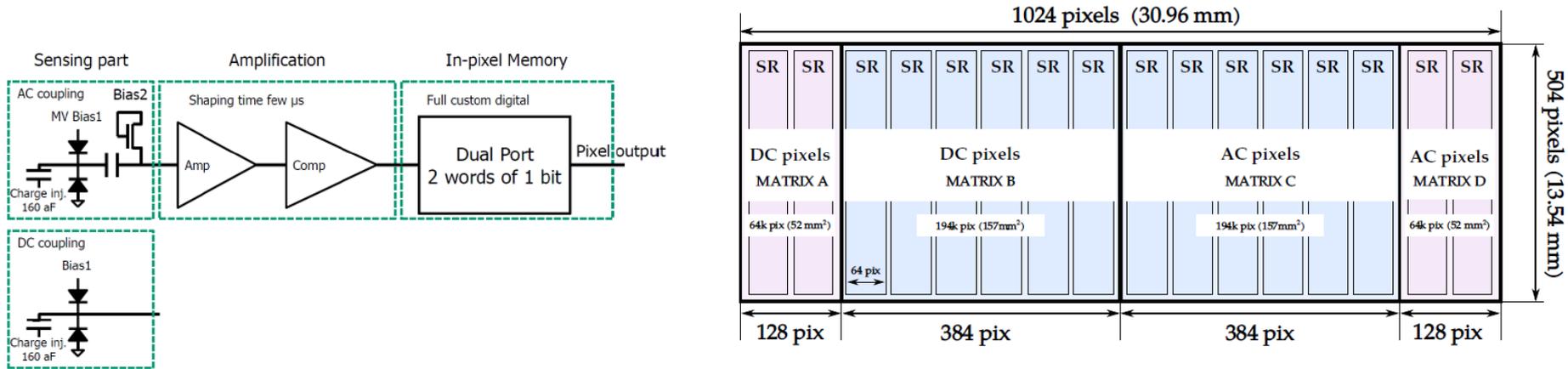


- DC Pixels (~ALPIDE) & AC pixels (top bias up to > 20V)
  - ✓ Amplifier / shaper / discriminator chain similar to ALPIDE in both scheme
  - ✓ Data driven readout
  - ✓ Pulse injection for calibration
  - ✓ Pixel masking options

# CMOS pixel sensor (CPS) for charged particle detection

- 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-1



Standard (std): no full depletion

Modified (mod): full depletion, faster charge collection
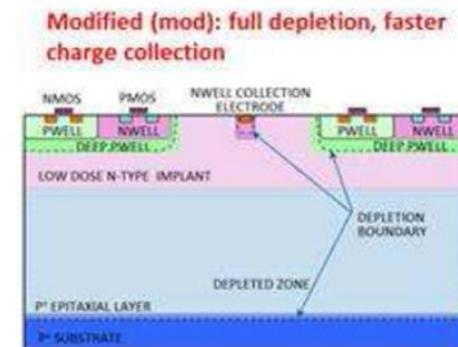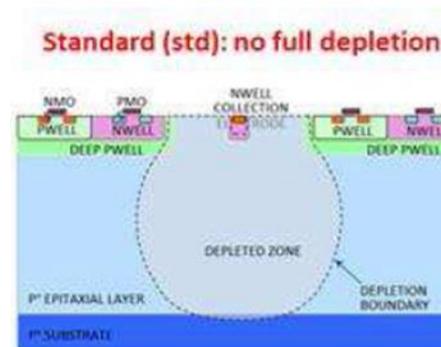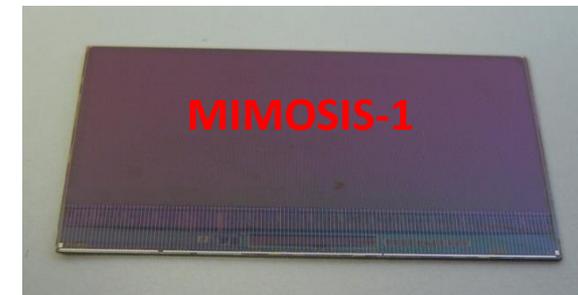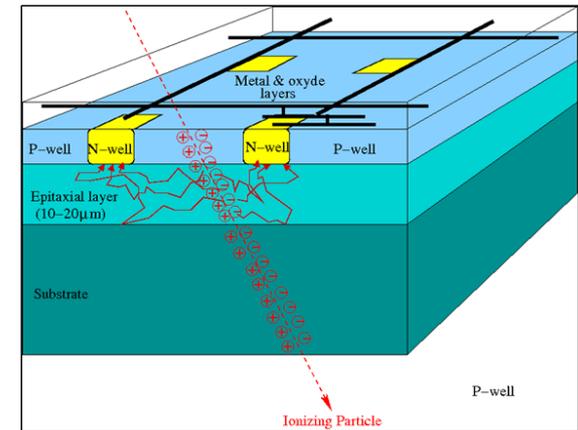
# Evolving CPS
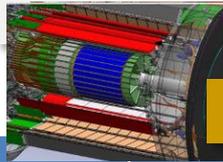
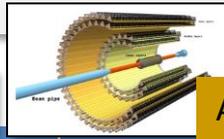| | ULTIMATE STAR-PXL | ALPIDE ALICE-ITS | MIMOSIS CBM-MVD | PSIRA proposal ILD-VXD |
|---|---|---|---|---|
| Data taking | 2014-2016 | >2021-2022 | >2022 | >2030 |
| Technology | AMS-opto 0.35 μm | 0.18 μm | 0.18 μm | 0.18 μm (conservative) < 0.18 μm ? |
| | 4M | HR, $V_{bias}$ ~-6V Deep P-well | HR, 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 | 2x$10^{12}$ $n_{eq}$/cm² 300 kRad | 3x$10^{13}$ $n_{eq}$/cm²/yr & 3 MRad/yr | O(100 kRad)/year & O(1x$10^{11}$ $n_{eq}$(1MeV)) /yr |
| Power (mW/cm²) | < 150 mW/cm² | < 40 mW/cm² | < 100 mW/cm² | ~ 50-100 mW/cm² + Power Pulsing |
| Surface | 2 layers, 400 sensors, 360x$10^6$ pixels 0.15 m² | 7 layers, 25x$10^3$ 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 |

20

# e⁺e⁻ collider beam parameters

**Linear**

**ILC** | **CLIC**

| Parameter | 250 GeV | 500 GeV | 380 GeV | 1.5 TeV | 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 $\sigma_x/\sigma_y$ (nm) | 515/7.7 | 474/5.9 | 150/2.9 | ~60/1.5 | ~40/1 |
| Beam size at IP $\sigma_z$ (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**

CLIC
156 ns   20 ms

1 train = 312 bunches, 0.5 ns apart
- not to scale -
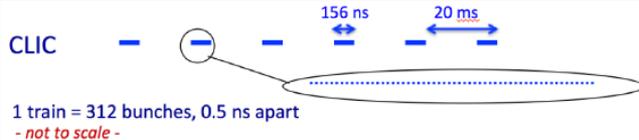
**Circular**

**FCC-ee** | **CEPC**

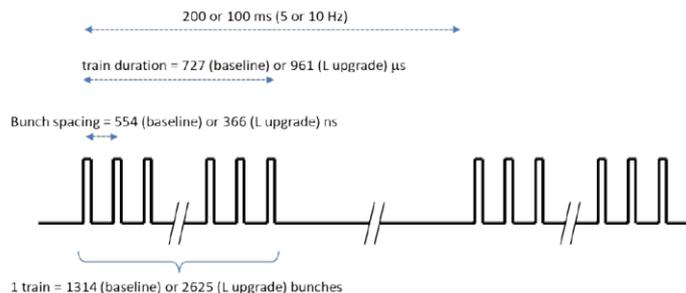| | Z | Higgs | ttbar | Z (2T) | Higgs |
|---|---|---|---|---|---|
| √S [GeV] | 91.2 | 240 | 365 | 91.2 | 240 |
| Luminosity / IP ($10^{34}$cm$^{-2}$s$^{-1}$) | 230 | 8.5 | 1.7 | 32 | 1.5 |
| no. of bunches / beam | 16640 | 393 | 48 | 12000 | 242 |
| Bunch separation (ns) | 20 | 994 | 3000 | 25 | 680 |
| Beam size at IP $\sigma_x/\sigma_y$ (µm/nm) | 6.4/28 | 14/36 | 38/68 | 6.0/40 | 20.9/60 |
| Bunch length (SR/BS) (mm) Beam size at IP $\sigma_z$ (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

*(slide from Mogens Dam/Lucie Linssen)*

200 or 100 ms (5 or 10 Hz)

train duration = 727 (baseline) or 961 (L upgrade) µs

Bunch spacing = 554 (baseline) or 366 (L upgrade) ns

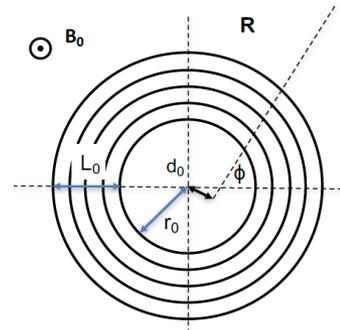1 train = 1314 (baseline) or 2625 (L upgrade) bunches

- Why do we need vertexing and tracking ?
  - ✓ 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

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

$$\Delta d_0|_{res.} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1 + \frac{8r_0}{L_0} + \frac{28r_0^2}{L_0^2} + \frac{40r_0^3}{L_0^3} + \frac{20r_0^4}{L_0^4}}$$
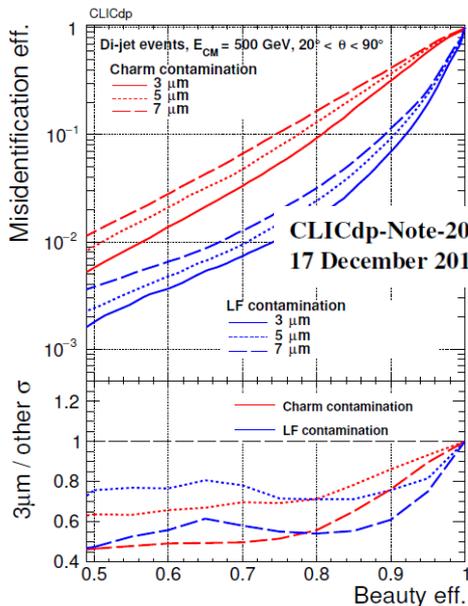
$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\text{GeV/c}}{\beta p_T}r_0\sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

Level arm !

**Sensitivity to b/c-tagging performances**

CMOS pixel resolution vs pitch

*Increasing depletion*
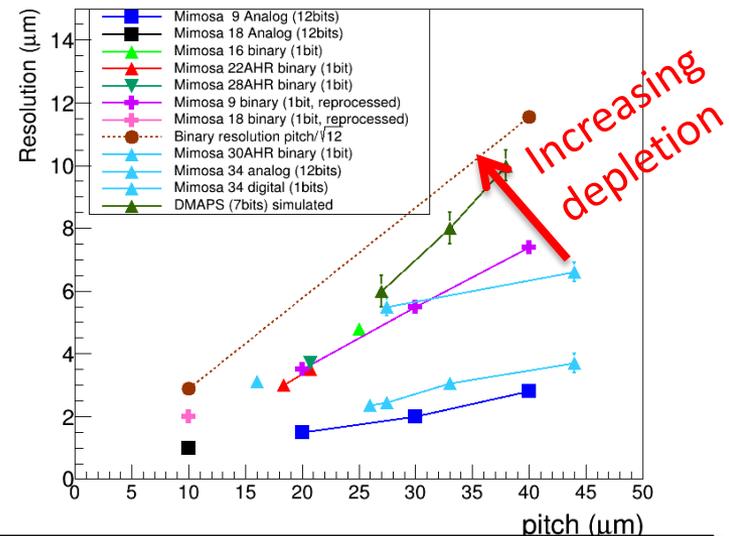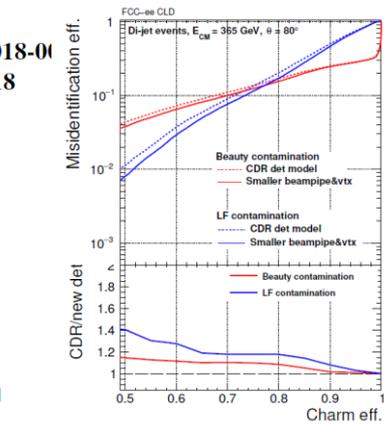
⇒  σ_sp ~ 3 μm  ⇔⇒  pitch ~ 17 μm
(assuming binary output, ~20 μm epi.thickness
& partial depletion in 180nm tech.)

CLICdp-Note-2018-0(
17 December 2018

LCD-Note-2019-001
25 November 2019

A.Besson, IPHC   22

# 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
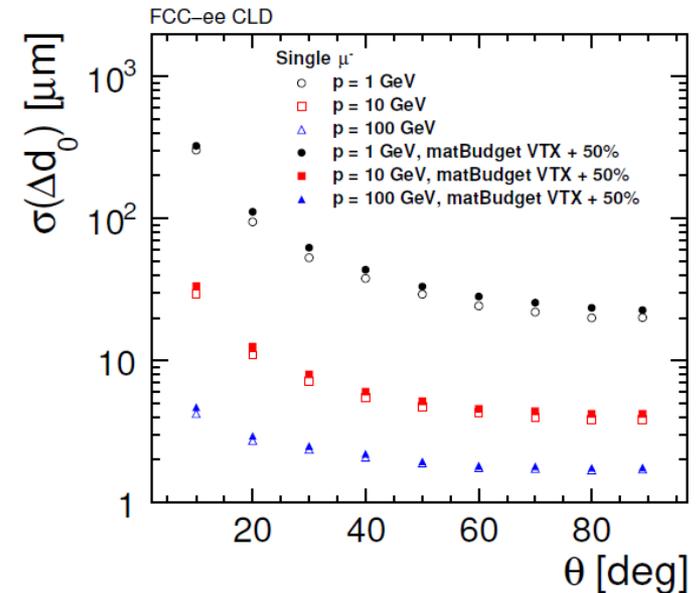  - ✓ Stitching (see later)
    - ▪ Larger surfaces
  - ✓ Bent sensors (see later)
    - ▪ Optimize
  - ✓ Integration
    - ▪ Cooling system, mech. Support, cabling, Powering scheme, etc.



(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

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

**Challenge: Air flow cooling only**

| | |
|---|---|
| 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 % |

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

No Beam ~ 199 ms

Train 1 ms

Train 1 ms

Layer 0

1 ms : DATA 82 mW/cm$^2$

~3 ms : Chip ON but no data ~40mW/cm$^2$

196 ms: Chip OFF ~ 2.8 mW/cm$^2$

<P> ~4 mW/cm$^2$

Besson, IPHC Strasbourg University