CMOS pixel sensors (CPS) & FCC(ee)

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Inputs from

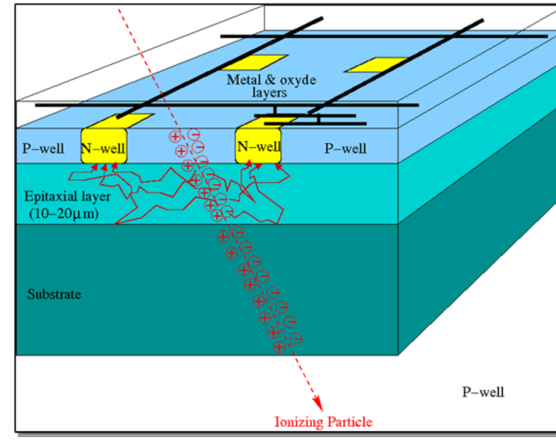
Projet CMOS: resp. M. Winter

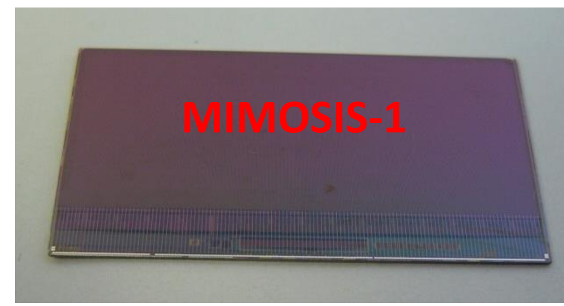
Projet DICE: resp. M. Barbero

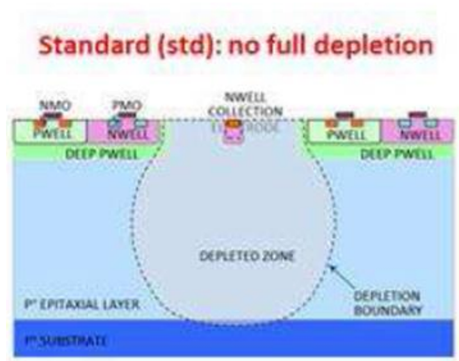
For more informations, please contact them

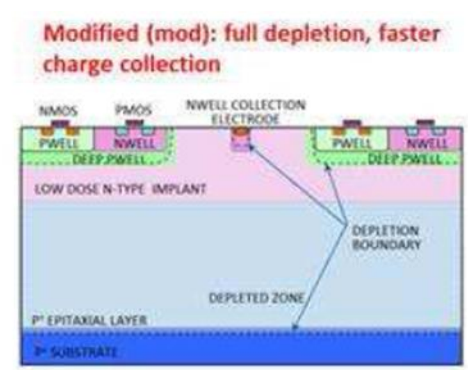
(thanks to them !)

- 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 ⇨ resolution)
  - ✓ 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





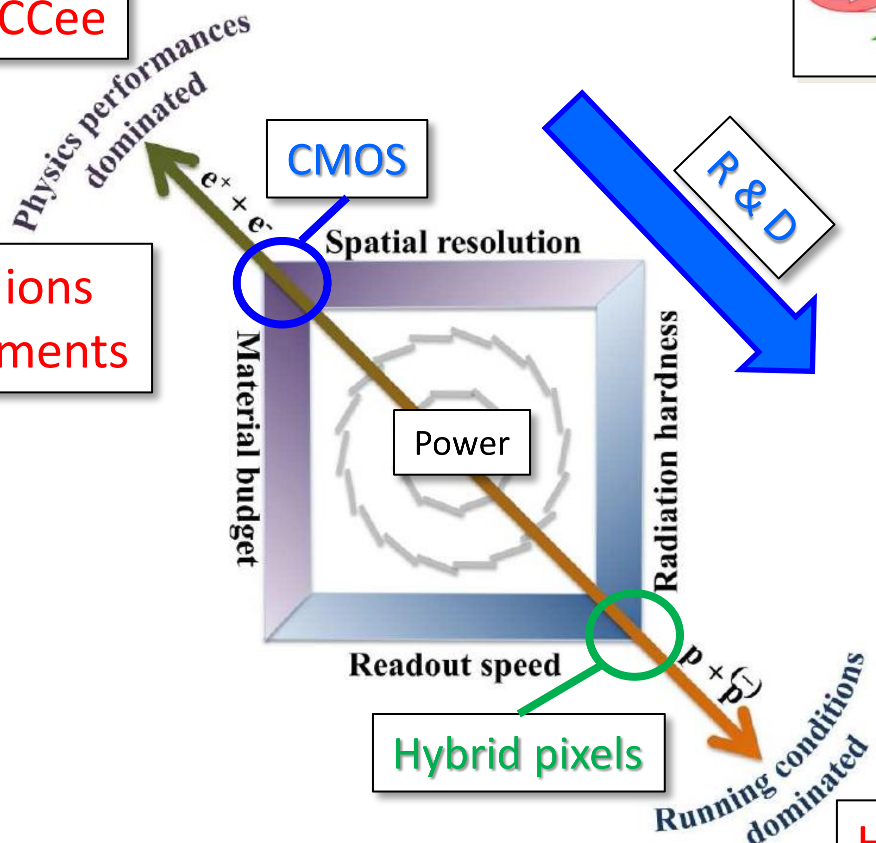


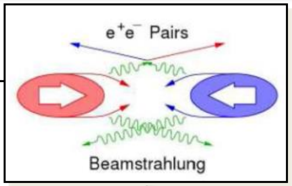


Vertex detector technology figure of merit

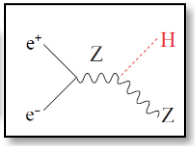
ILC, FCCee

Heavy ions experiments





e⁺e⁻ requirements



- Heavy flavor tagging (b, c, τ)
- Low momentum tracking (pT ~ 100 MeV/c)
- Vertex/Jet charge determination

Spatial resolution
σ_{sp} ~3 μm (pitch ~ 16 μm)

Low occupancy

Material Budget
~ 0.15% X_0 / layer

Impact parameter

$$\sigma_b < 5 \oplus \frac{10}{p\beta \sin^{\frac{3}{2}}\theta}\ \mu m$$

Time resolution
O(1-4 μs)

FCC-hh

HL-LHC

Challenge:

➯Keep excellent spatial resolution, low material budget, moderate Power consumption and push towards better time resolution

CPS @ IPHC (PICSEL & C4PI): on the road to Higgs factories

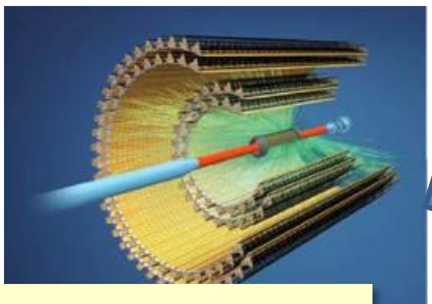
EUDET beam telescope
(Mimosa 26 by IPHC)
~ 15 copies since 2009

O(100 μs)

Process: 0.35 μm

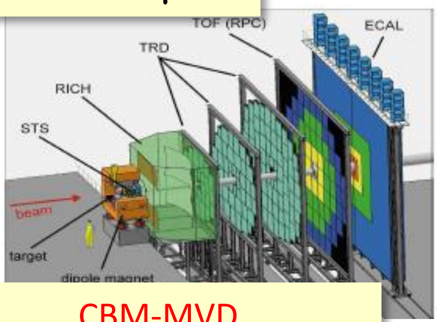
STAR-PXL detector
(ULTIMATE by IPHC)
2014-16

Process: 0.18 μm



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

O(10 μs)

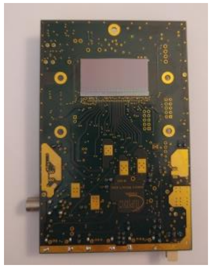


CBM-MVD
(MIMOSIS by IPHC & IKF)
Under development

ILC VXD & inner tracker
R & D

O(1 μs)

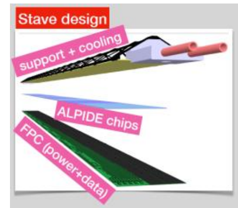
- IPHC: R&D started in ~1999
  - ✓ Take advantage of mid-term projects to get closer to ILC vertex detctor requirements
- Today (⇨~2023)
  - ✓ CBM-MVD: MIMOSIS chips
  - = Milestone for Higgs factories
  - ✓ Mimosis-1: Tests ongoing



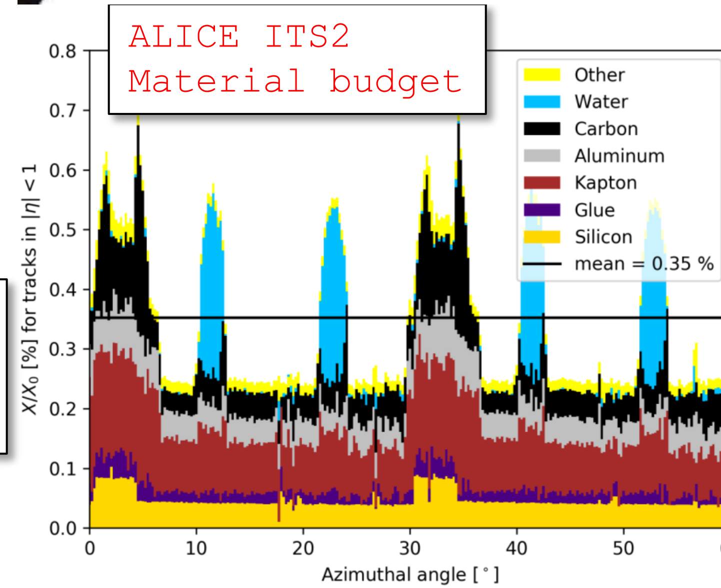
- Other activities:
  - ✓ Integration (double sided ladders)
  - ✓ SOI
  - ✓ Double-tier
  - ✓ multiples other applications (X-ray & β imaging, etc.)

Material budget

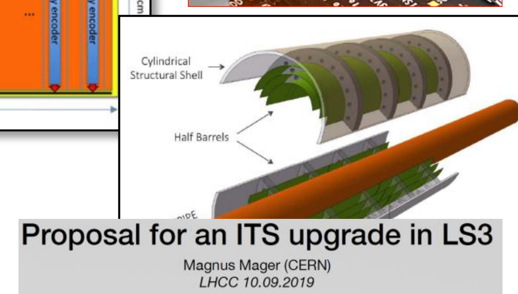
- PLUME (Bristol, DESY, IPHC)
- ALICE ITS-2
  - ✓ Water cooling ⇨ ~0.35% X_0



⇨ Contribution of sensors to total material budget ~ 20-30% (Majority from cables + cooling + support)



- Silicon is flexible
  - ✓ Self supported and bended circuits + detectors !
- Industry provides stitching
  - ✓ Multi-reticle size ladders
    - ~14 cm in 180 nm, 30 cm in 65 nm
    - Chip-to-chip interconnection
  - ✓ Very low material budget
    - ~0.05-0.10 % X_0/layer
  - ✓ Allows large surfaces O(100m^2)

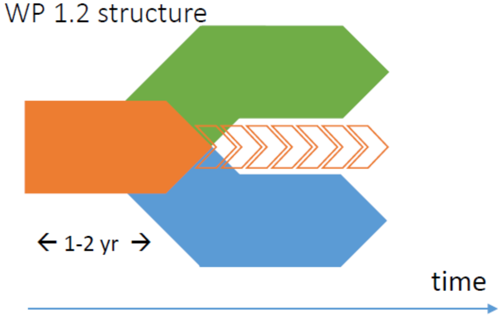


⇨ Stitching: strong interest for ALICE upgrades and Higgs factories

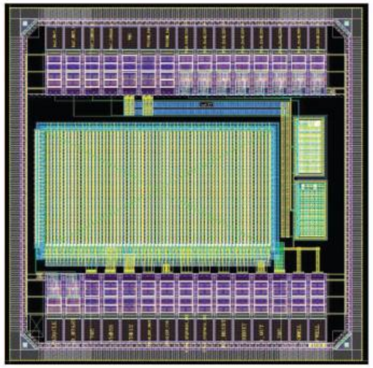
TJ-65 nm process: Le grand départ

- TJ-65 nm now available (since June 2020)
  - ✓ Main driver: CERN EP R&D WP 1 & ALICE ITS-3 upgrades (involves other labs)
  - ✓ Different requirements
    - EP: time resolution and radiation tol.
    - ALICE: granularity and material budget
    - Common R&D during the 1st years.

⇨ Synergy with Higgs factories requirements

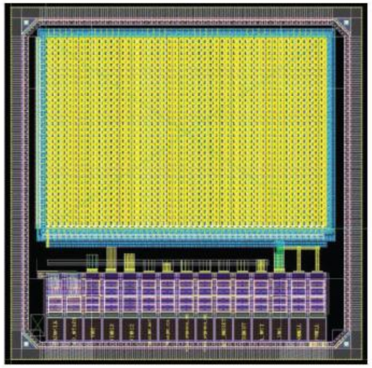


  - ✓ **First submission December 1st 2020** (MLR) !
    - Expected back from foundry in 6 months
- IPHC-Strasbourg involvement
  - ✓ Goal: **validate the process for charged particle detection**
    - **Caveat:** sensitive volume not yet optimised
  - ✓ Test structures, (DACs, etc.)
  - ✓ Technology exploration with single rolling shutter / analog output prototype
    - pitch, N-well variants, amps, etc.
    - Testable in beam
  - ✓ Part of Cremlin+ program (1 post-doc)



Variants A/B/C

64×32
15 µm pitch



Variant D

48×32
25 µm pitch

Le projet DICE

- DICE : Développement pixels pour les taux de comptage et niveau de radiation extrêmes.
  - Projet porté par le CPPM et l'IPHC, accepté pour 3 ans.
  - Une thématique générale:
    - « **Les détecteurs pixels de traces et de vertex développés dans des technologies pertinentes pour de futurs projets pour lesquels le taux de comptage et la résistance aux radiations sont des paramètres critiques** »
  - Se base sur la longue tradition de travail de conception au CPPM et à l'IPHC dans les technologies les plus fines, ainsi que sur l'historique de conception des capteurs DepMAPS.
  - 2 Work Packages:
    - **Les Pixels Hybrides**: Exploration de technologies mettant en œuvre des nœuds de process très avancés -e.g. 28 nm-. ResSci Barbero / ResTec Menouni.
    - **Les Pixels Monolithiques**: Exploration de la technologie Depleted MAPS dans deux directions principales, exploitation des développements et potentialité des nouvelles technologies. ResSci Baudot / ResTec Pangaud.
  - Partenaires et collaborations (hors DICE): Bonn/CPPM/CERN/IRFU, KIT, post-RD53, RD50, AIDAinnova, communauté Belle II… → prospective très active!

Work Packages

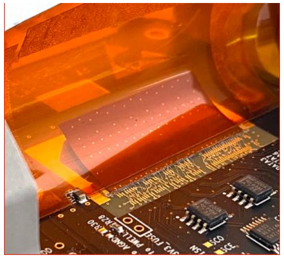
- Pixels hybrides:
  - Historique: 0.25µm IBM FE-I3/ → 130nm IBM FE-I4/IBL → 65nm RD53/ITk; lien à l'implication ATLAS du CPPM.
  - 28 nm en HEP: Démarrage 2015-16 Fermilab, mémoires associatives LPNHE, projet Timespot INFN… CERN 28nm forum, réunion démarrage 12 nov 2020.
  - But du projet: Conception complexe dans process (gain intrinsèque réduit, faible tension d'alim…), tolérance radiations… hybridation petits pixels → **implication IN2P3 nécessaire maintenant pour application dans les futurs projets**.
- Pixels monolithiques:
  - Historique: Mimosa/… série de capteurs MAPS développés par l'IPHC (expériences STAR/ALICE); depleted MAPS Monopix par le CPPM (développé initialement pour L4 ITk ATLAS) / Mimosis par l'IPHC (CBM).
  - 2 concepts principaux: petite diode (LF150nm, TSI180nm,…)/grande diode de collection de charge (TJ180nm…)
  - But du projet: **Continuité de l'étude** de ces technologies, soutien transition à l'**étude du démarrage d'une implication VXD Belle II**, implication dans des **technologies plus fine -TJ65nm-** (lien avec la CERN R&D roadmap, premières soumissions TJ65 CPPM et IPHC en commun avec le CERN il y a quelques jours..)

CMOS technology for Higgs factories: FCC(ee)

- FCCee requirements (w.r.t. ILC)
  - ✓ Beam backgroung (drives occupancy)
    - Same order of magnitude (possibly a bit lower @ FCCee)
  - ✓ Same detector performances required (time & spatial resolution, material budget)
  - ✓ Beam structure ⇨ « continuous » data taking
    - no Power pulsing
  - ✓ Magnetic field (~ 2 T) ⇨ less bended tracks
  - ✓ Z peak : ⇨ lower radius doable
- Overall:
  - ✓ Performances requirements comparable though more challenging @FCCee in terms of Power dissipation
- The R&D can be considered as generic for all Higgs factories (CLIC excepted)

Summary: Synergies in CMOS R&D

- Not discussed: integration ⇨ many open issues here !
- FCCee requirements more challenging w.r.t. ILC (no power pulsing allowed)
  - ✓ Price to pay might translate into
    - Additional material budget
    - And/or slightly degraded spatial resolution
- However, ILC & FCCee requirements are comparable
  - ✓ Common R&D towards faster time resolution while keeping low power, small granularity and low material budget
- CMOS pixel Sensors R&D in a strong dynamic
  - ✓ Strong synergies with
    - CERN R&D (ALICE and EP)
    - R&D programs (e.g. AIDA2025, CREMLIN+)
    - Heavy ion experiments (e.g. ALICE beyond LS3/4 proposal, EIC @ Brookhaven, etc.)
  - ✓ 65 nm technology exploration
    - First submission done this week (driven by CERN and involved IPHC & CPPM)
    - Expression d'intérêt (IPHC/CPPM/IP2I)
  - ✓ Stitching & large surface for very low mass detectors
    - e.g. bended ALPIDE tests
  - ✓ Other experiments: Belle-II, EIC, etc.



Back up

Vertex detector

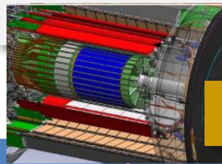
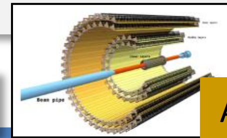
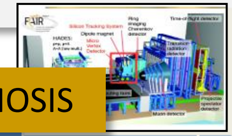
- VXD has to be precise, thin, low power (no pulsing), readout electronics should integrate over less than O(1 μs) (backgrounds)
- Current requirements on impact parameter resolution inherited from former Higgs studies :

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

$$a \simeq 5\,\mu\text{m}; \quad b \simeq 15\,\mu\text{m GeV}$$

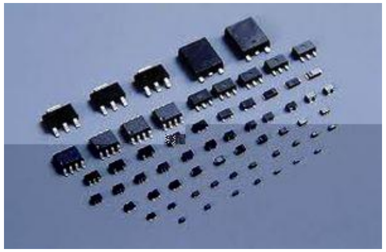
- Will be revisited in the FCC-ee context: precise Hcc, Hbb, Hgg determination
- Requirements from B-physics on the reconstruction of primary, secondary and tertiary vertices
  - E.g. with σ(PV) = 3 μm, σ(SV – TV) = 5 -7 μm, a large signal of $B \to K^* \tau\, \tau$ can be seen, likely unique to FCC
- Requirements from EW Heavy Flavor observables R_b, R_c, $A_{FB}^{b,c}$
- Requirements from lifetime measurements
  - E.g. potential to measure tau lifetime to sub-10^{-5} (i.e. GT from τ ! Universality test)
  - Requirements on (offline) alignment to be determined

Evolving CPS

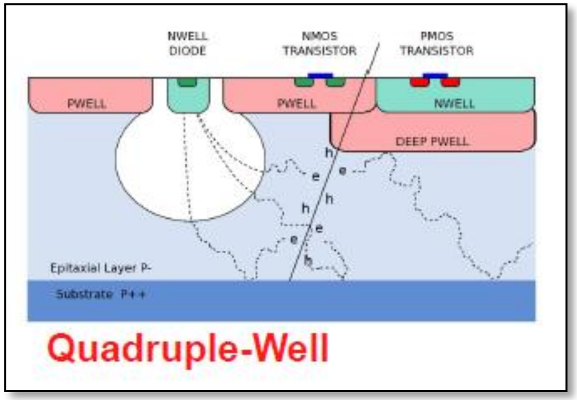





	ULTIMATE STAR-PXL	ALPIDE ALICE-ITS	MIMOSIS CBM-MVD	PSIRA proposal ILD-VXD
Data taking	2014-2016	>2021-2022	>2021	>2030
Technology	AMS-opto 0.35 μm	0.18 μm	0.18 μm	0.18 μm (conservative) < 0.18 μm ?
	4M	HR, V_{bias} ~-6V Deep P-well	HR, Deep P-well	?
Architecture	Rolling shutter + sparsification + binary output	Data driven r.o. In pixel discri.	Data driven r.o. In pixel discri.	Data driven r.o. (conservative)
Pitch (μm^2) / 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/cm^2/s Peak data rate ~ 0.9 Gbits/s	peak hit rate @ 7 x 10^5 /mm^2/s >2 Gbits/s output (20 inside chip)	~375 Gbits/s (instantaneous) ~1166Mbits / s (average)
Radiation	O(50 kRad)/year	$2x10^{12}$ n_{eq}/cm^2 300 kRad	$3x10^{13}$ $n_{eq}/cm^2/yr$ & 3 MRad/yr	O(100 kRad)/year & O($1x10^{11}$ n_{eq}(1MeV)) /yr
Power (mW/cm^2)	< 150 mW/cm^2	< 40 mW/cm^2	< 200 mW/cm^2	~ 50-100 mW/cm^2 + Power Pulsing
Surface	2 layers, 400 sensors, $360x10^6$ pixels 0.15 m^2	7 layers, $25x10^3$ sensors > 10 m^2	4 stations Fixed target	3 double layers 10^3 sensors (4cm^2) 10^9 pixels ~0.33 m^2
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

65nm: Towards faster time resolution



- Feature size of the technology
  - ✓ 0.35 µm (past)
  - ✓ ⇨ 0.18 µm (present)
  - ✓ ⇨ 0.065 µm (near future)
- Smaller feature size allows
  - ✓ More functionalities inside the pixel
    - Keep pixel dimensions small
  - ✓ Faster read-out
  - ✓ Lower Power consumption
  - ✓ Other tech. options matters
    - Epitaxial layer properties
    - # metal layers
    - Deep N-well, etc.

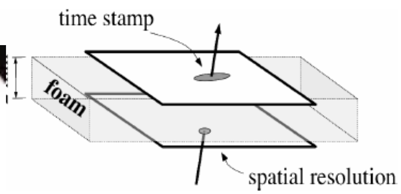


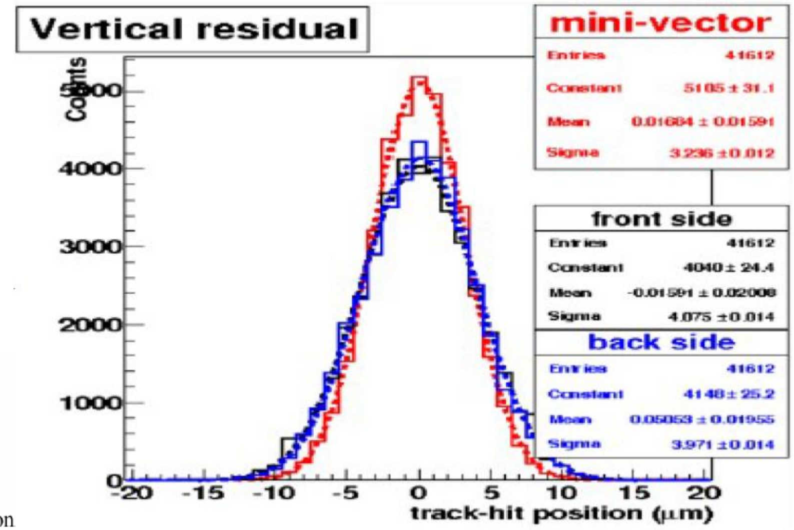
- The 65 nm qualification for charged particle detection needs to be done in the coming years

⇨ Relation with foundries and access to options is a key
⇨ Current technology: time resolution potential of O(100 ns)
⇨ Ultimate limit down to O(100 ps)

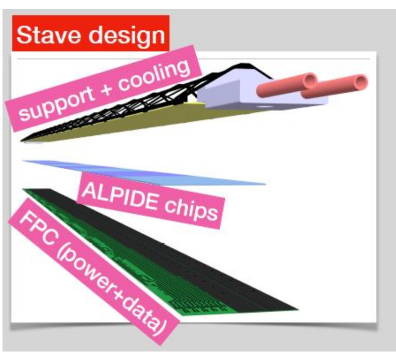
Material budget

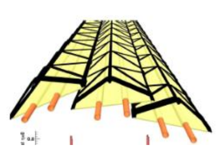
- PLUME (Bristol, DESY, IPHC)
  - ✓ Double sided ladders with minimized material budget
  - ✓ 0.35% X_0 reached ⇨ ~0.3 X_0 doable (with air flow cooling)
  - ✓ Combining each side for improved resolution



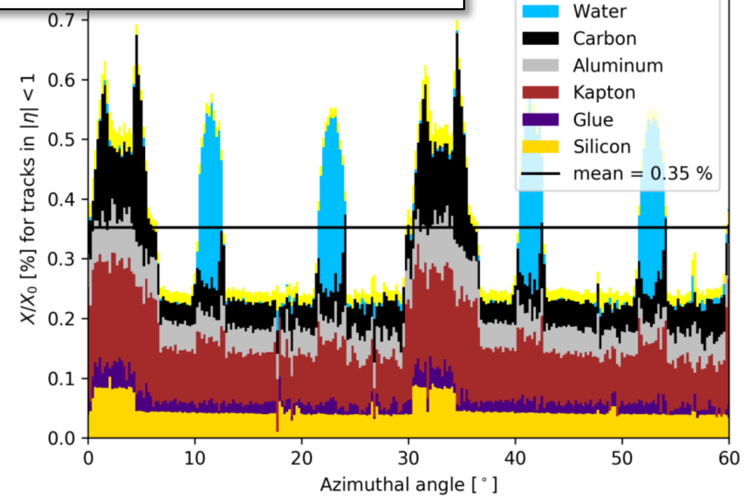


- ALICE ITS-2
  - ✓ Water cooling ⇨ ~0.35% X_0





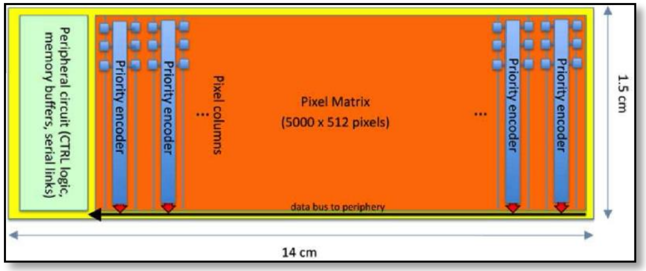
ALICE ITS2 Material budget



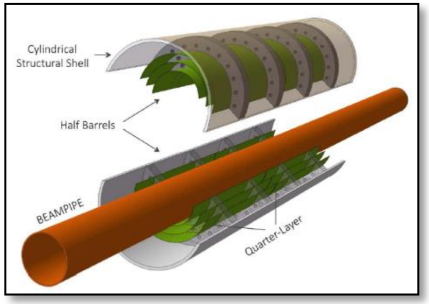
⇨ Contribution of sensors to total material budget ~ 20-30%
(Majority from cables + cooling + support)

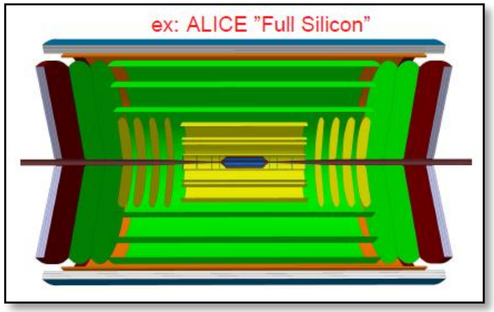
A possible answer: stitching

- Silicon is flexible
  - ✓ Self supported and bended circuits + detectors !
- Industry provides stitching
  - ✓ Multi-reticle size ladders
    - ~14 cm in 180 nm, 30 cm in 65 nm
    - Chip-to-chip interconnection
- Added value:
  - ✓ Very low material budget (~0.05-0.10 % X_0)
    - Flex cable ? Cooling ? Support ?
  - ✓ Large area detectors
    - Constant R = No overlaps or acceptance loss
    - Beam pipe as mechanical support
- ALICE R&D program
  - ✓ ALICE ITS upgrade beyond LS3
    - Exploit stitching
  - ✓ Proposal beyond LS4
    - 10 double sided layers
    - 100 m^2
- Challenge & potential issues
  - ✓ Bias voltage drops
  - ✓ Extended signal distance transport

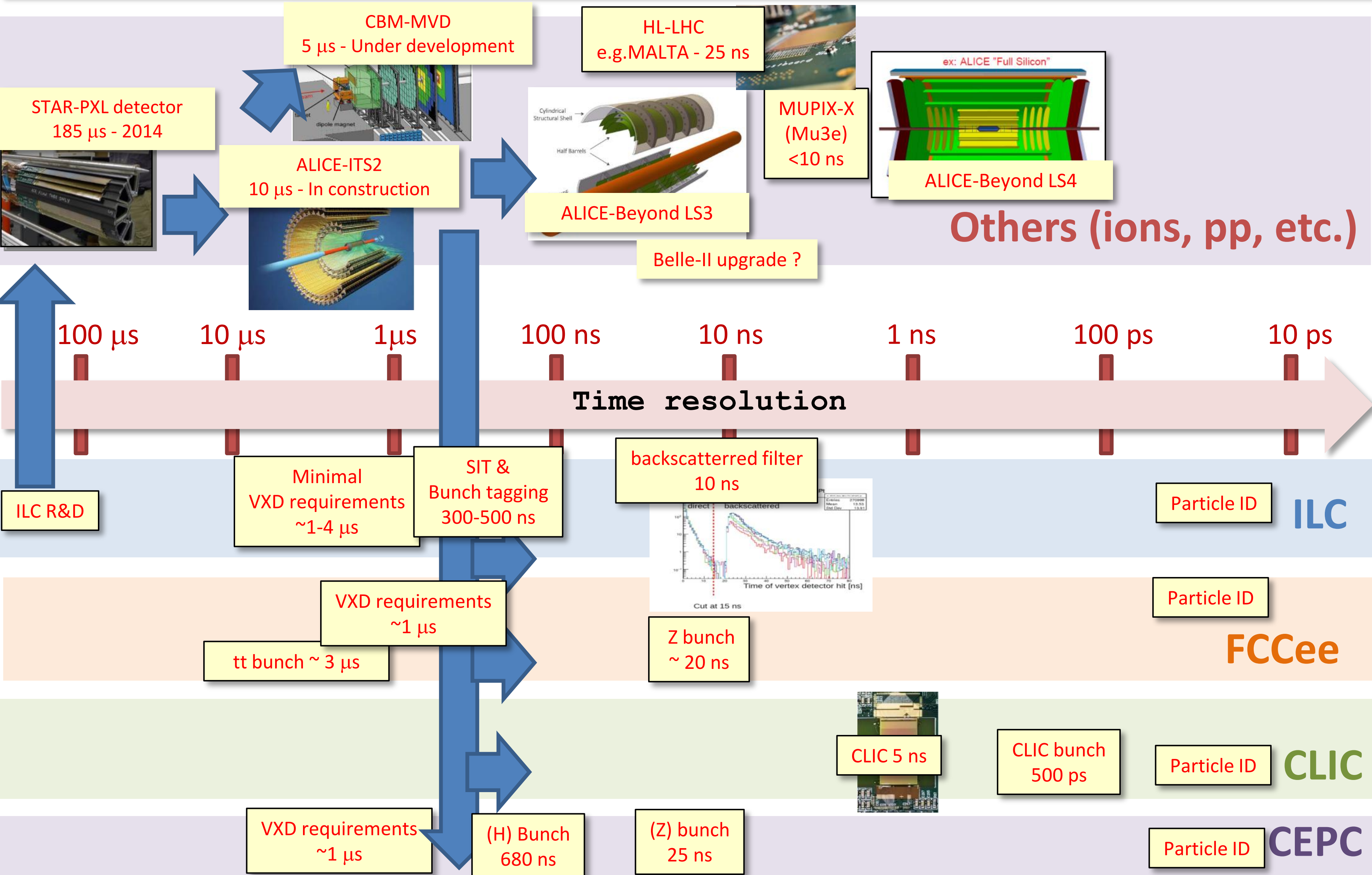


Proposal for an ITS upgrade in LS3
Magnus Mager (CERN)
LHCC 10.09.2019

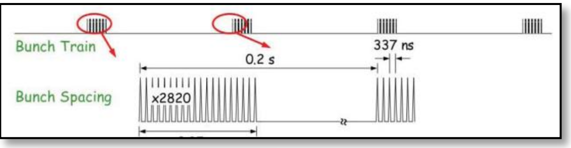




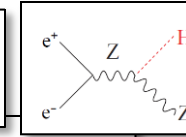
Time resolution in the context of e^+e^- colliders



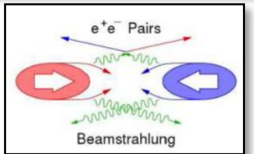
ILC VXD requirements



$$\sigma_b < 5 \oplus \frac{10}{p\beta \sin^{\frac{3}{2}}\theta} \ \mu m$$

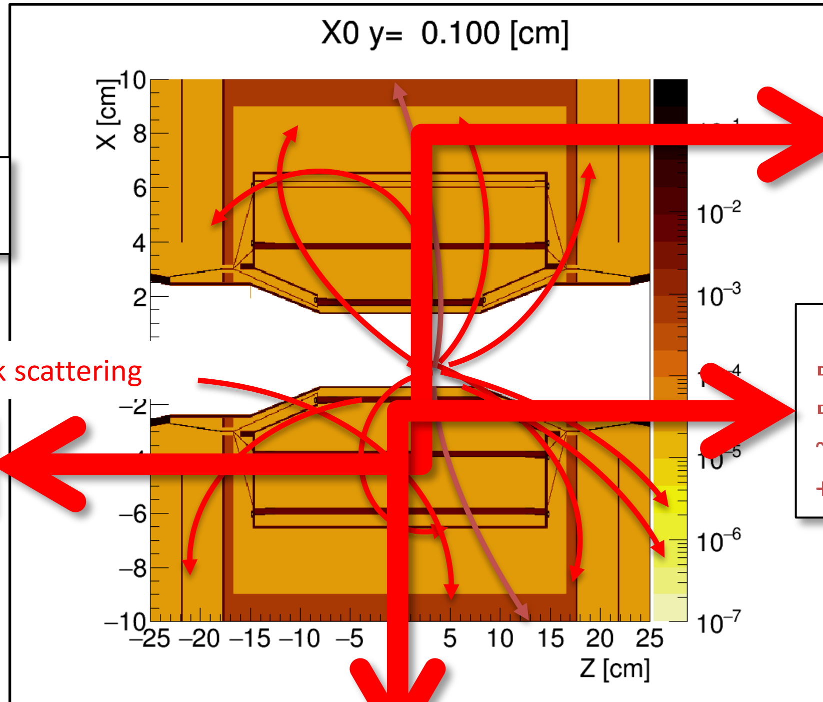


Physics
⇨ Flavour tagging
⇨ Low pT tracks



Physics (<Hz/cm²)

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



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

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

Cooling
Stiffness / Alignment

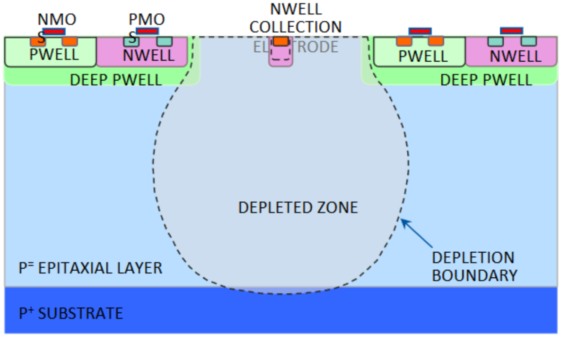
Low material detectors & supports structures

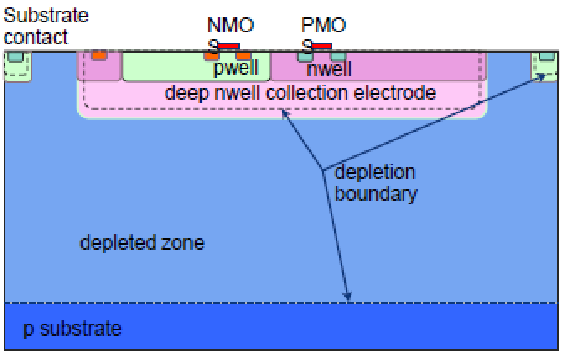
Challenge : meet the requirements all together

CPS: Large vs small nwell collection electrode

Small electrode — Large electrode

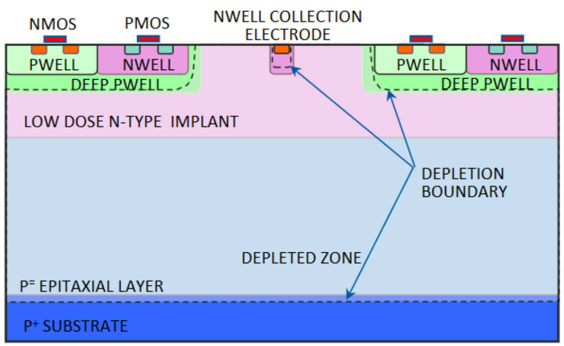
Standard : no full depletion





- Partial depletion
  - ✓ Charge sharing ⇨resolution

Modified : full depletion, faster charge collection



- Full depletion
  - ✓ No Charge sharing ⇨ S/N
  - ✓ Charge collection time ⇨ very fast timing
  - ✓ Radiation hardness (not an issue in e^+e^- colliders)

- Capacitance
  - ✓ Analog power ~ $(C/Q)^2$

⇨ Design should favor spatial resolution and power consumption w.r.t. radiation hardness and charge collection time*

⇨ Small electrodes more adapted for Higgs factories

*Exception: CLIC

e+e- collider beam parameters

Linear

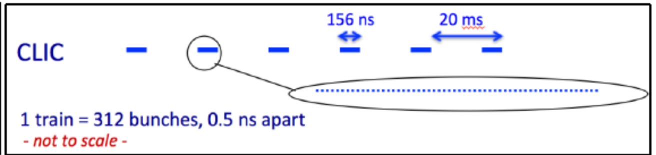
Parameter	ILC 250 GeV	ILC 500 GeV	CLIC 380 GeV	CLIC 1.5 TeV	CLIC 3 TeV
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	1.35	1.8	1.5	3.7	5.9
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	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)

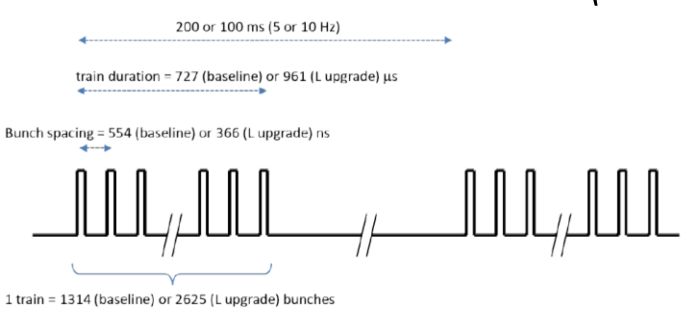
At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
⇒ **Statistical accuracies at 10^{-4} -10^{-5} level ⇒ drives detector performance requirements**
⇒ **Small systematic errors required** to match
⇒ This also drives requirement on **data rates** (physics rates 100 kHz)
⇒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

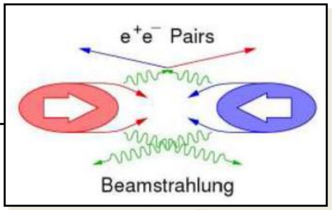
Mogens Dam / NBI Copenhagen AIDA++ Open Meeting, CERN 4 September, 2019 6

(slide from Mogens Dam/Lucie Linssen)



Occupancy and beam background (Guinea Pig)

- Assuming the same time resolution (~1-4 μs), background rates (and therefore occupancy) are comparable



ILD @ 250 GeV

	hits/BX			hits/BX/cm^2		
	mean	±	RMS	mean	±	RMS
VXD 1	914	±	364	6.64	±	2.65
VXD 2	545	±	207	3.96	±	1.51
VXD 3	129	±	60	0.213	±	0.100
VXD 4	107	±	53	0.177	±	0.088
VXD 5	40	±	26	0.043	±	0.029
VXD 6	34	±	24	0.037	±	0.026

Daniel Jeans, Akiya Miyamoto

Pitch ~ 17-25 μm
Cluster multiplicity ×5
Safety factor ×3-5
Time resolution ~few μs
⇨ ~Per mil level occupancy
⇨ Bunch separation ?

FCCee occupancies

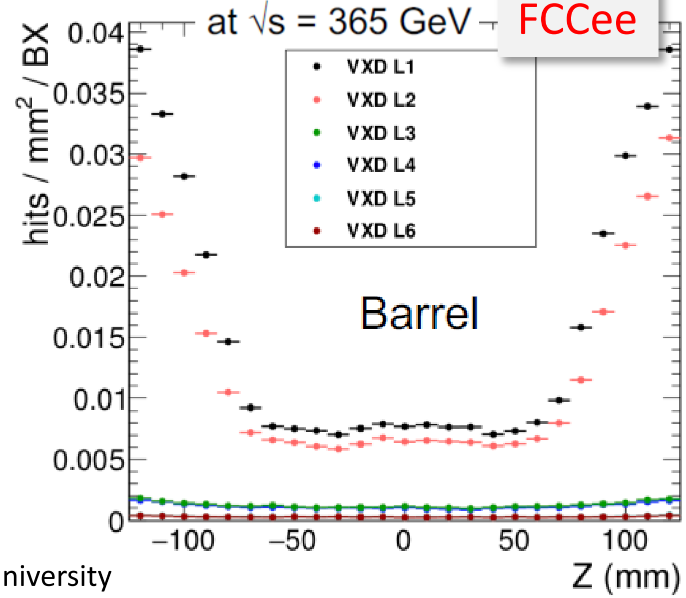
CLD max. occ. / subdetector, IPC & SR		
$\sqrt{s}$ [GeV]	91.2	365
VXDB	$\sim 10^{-5}$	$\sim 4 \times 10^{-4}$
VXDE	$\sim 4.7 \times 10^{-6}$	$\sim 4 \times 10^{-4}$
TE	$\sim 1.8 \times 10^{-5}$	$\sim 3 \times 10^{-4}$

The presented occupancy / BX is rather low for VXD and Si tracker

However bunch spacing at the Z peak is 20ns

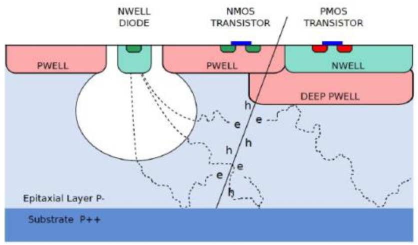
- Might be that we have to integrate over several Bxs
- Still with a time resolution of $1\mu s \rightarrow$ occupancy stays $\leq 6 \times 10^{-4}$

FCCee

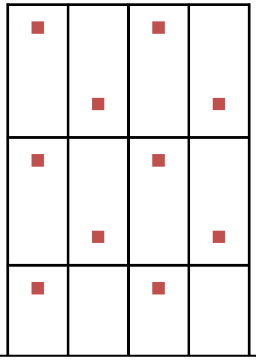


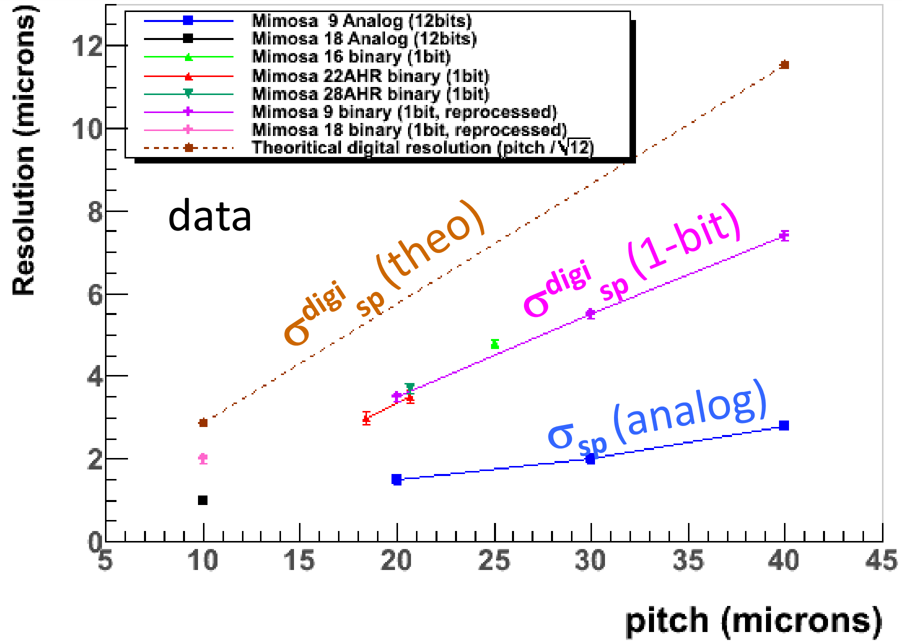
Spatial Resolution: Optimizing the sensing element

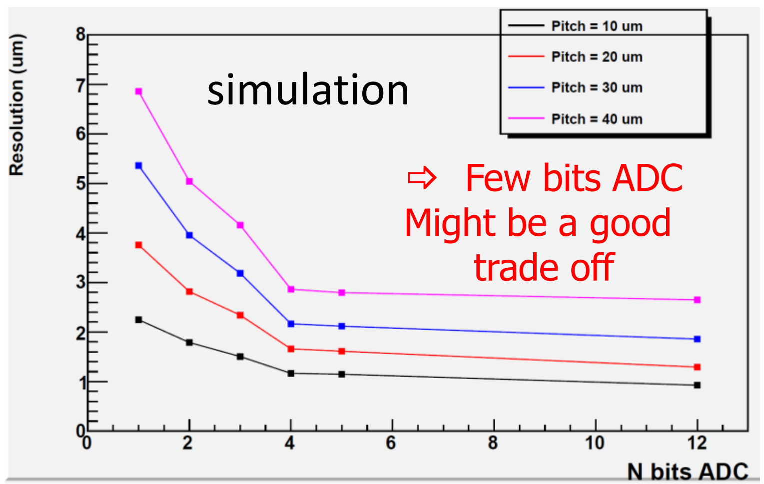
- Epitaxial layer
  - ✓ Pitch
  - ✓ Thickness
    - ▪ >~ 20 um
  - ✓ Depletion
  - ✓ Doping profile
  - ✓ Collecting diode & preamp.
  - ✓ N bits to encode the charge



- Effects on:
  - ✓ Q_{signal} & SNR
  - ✓ Radiation tolerance
  - ✓ Charge collection time
  - ✓ Cluster size & spatial resolution
- Staggering ?
  - ✓ Minimizing distance to diode
- ADCs ?





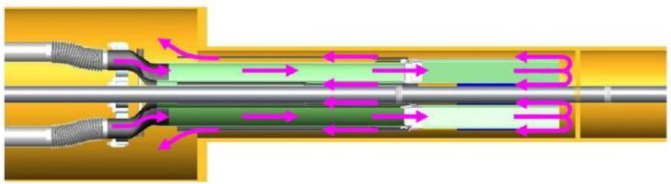


⇨ σ_{sp} ~ 3 µm ⇦⇨ pitch ~ 17 µm (not 25 µm !)

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

FCCee: Power discussion

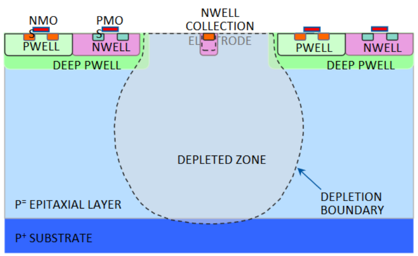
- No power pulsing has significant consequences
- How much power can we extract with air flow cooling ?
  - ✓ Probably ~20-25 mW/cm^2
  - ✓ STAR HFT did ~150 mW/cm^2 @ 10m/s but without disks !



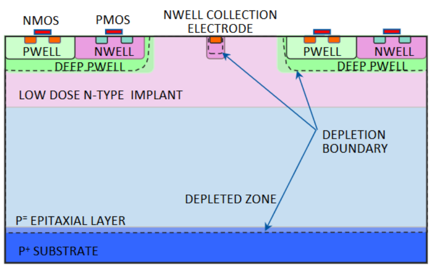
The STAR MAPS-based PiXeL Detector NIM, A 907 (2018) 60-80

- What would be the power in FCCee with the current know how ?
  - ✓ Probably in the range ~ 80-100 mW/cm^2
- Is air flow cooling only possible ?
  - ✓ Yes with compromise or significant Tech. progress
  - ✓ Possible other approaches (micro-channels, etc.)
  - ✓ Don't forget power drops along cables (~50 W ?)
- How to optimize Power ?
  - ✓ Dependence on
    - Time resolution
    - Data flow (# outputs, clock frequency, etc.)
    - Spatial resolution
  - ✓ Outer layers responsible for the majority of power dissipation
    - Allow slightly degraded performances in the outer layers ?

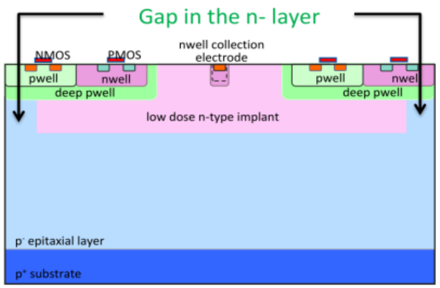
Charge collecting time simulations



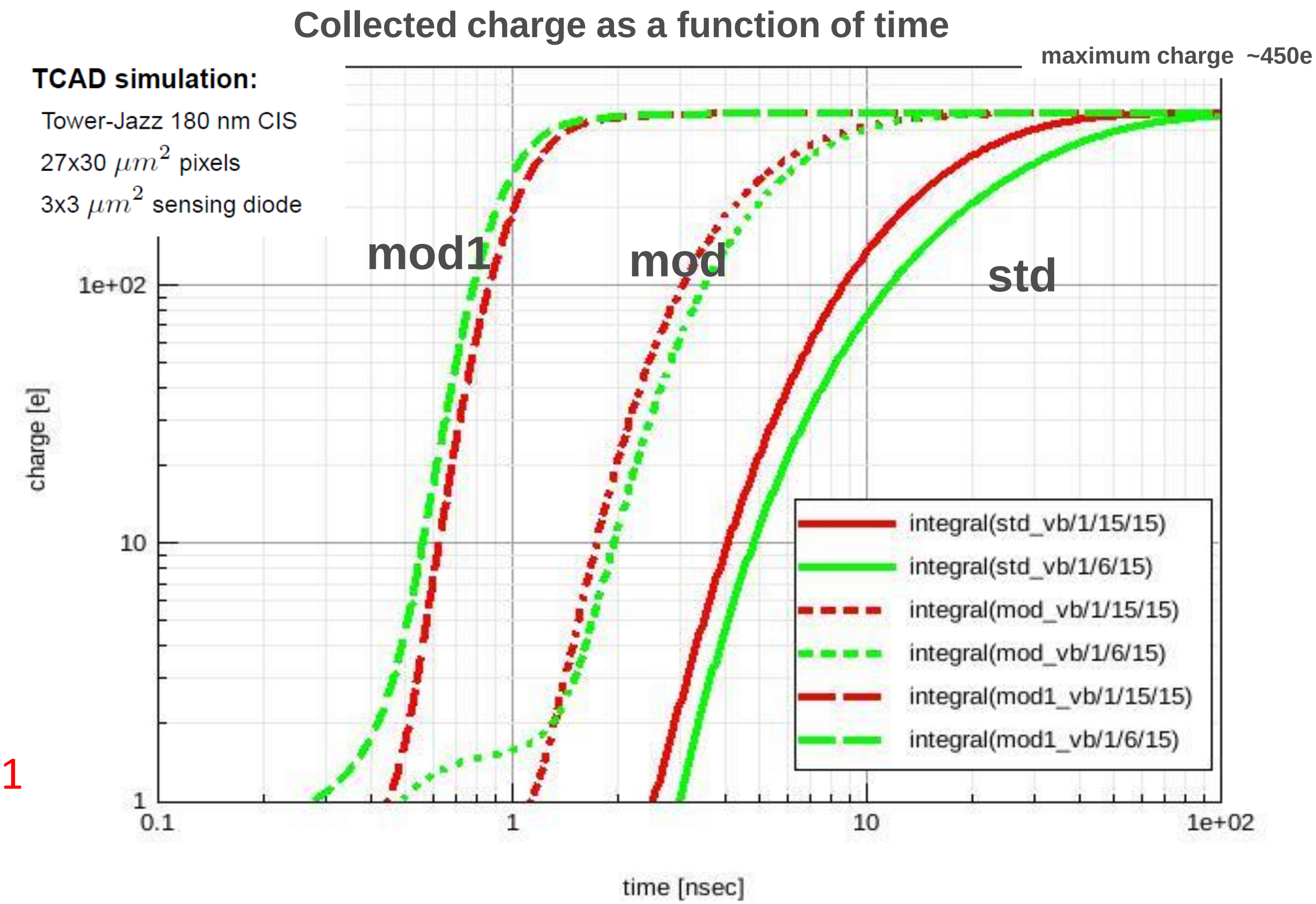
std



mod



mod1



- Shorter collection time
  - ✓ Improves radiation tolerance
  - ✓ Necessary for ultimate time resolution < 100 ns
    - "QUARTET", R&D transverse project of IN2P3 (IPHC, CPPM, OMEGA)