The 2020 International Workshop on the High Energy Circular Electron Positron Collider
October 26-28.2020, Shanghai Jiao Tong University, Shanghai, China

Current and future developments of CMOS pixel sensors

Focus on activities at C4PI, Strasbourg

Jerome Baudot
with Christine Hu-Guo's help

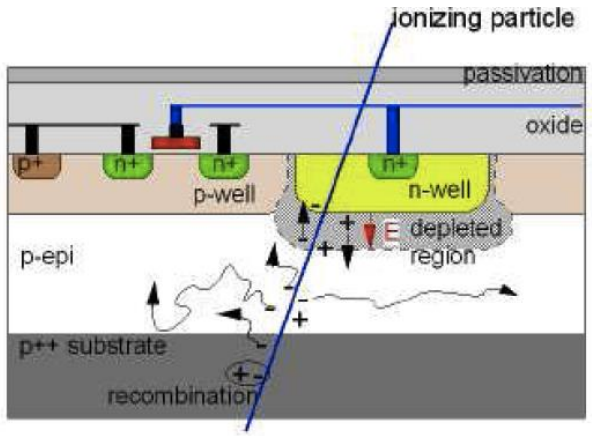
iPHC
Institut Pluridisciplinaire Hubert CURIEN
STRASBOURG

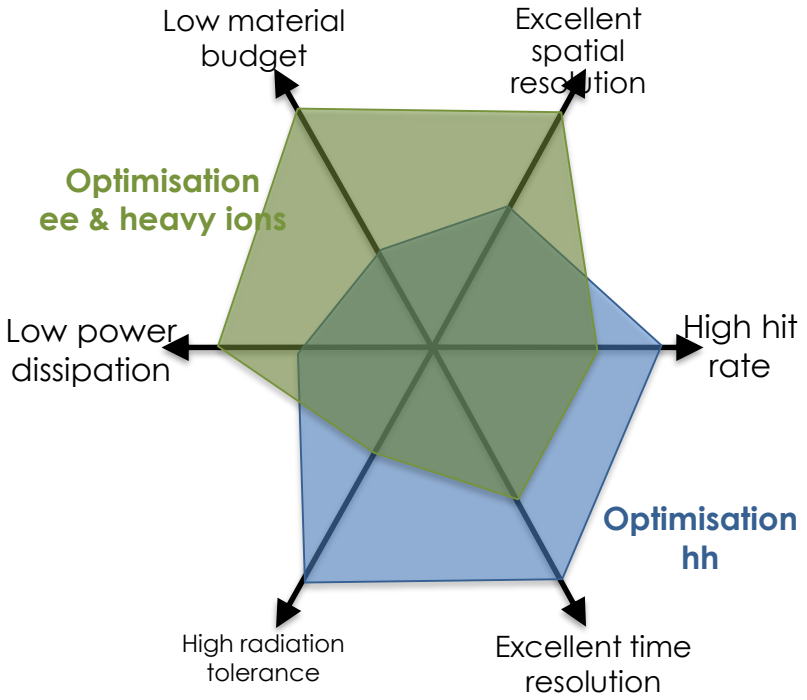
cnrs
Université de Strasbourg

- → Brief overview of activities in the past 20 years
- → The spatial resolution "case"
- → Sensors driven by spatial resolution

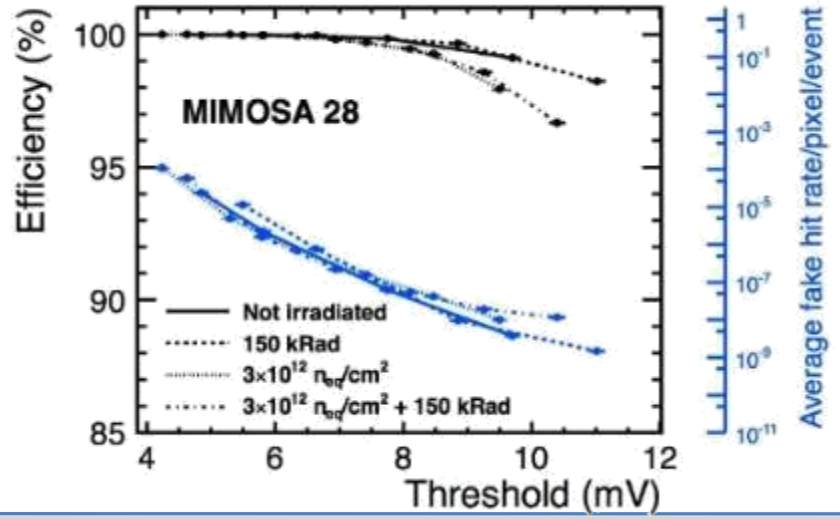
Overview: the ~10 first years

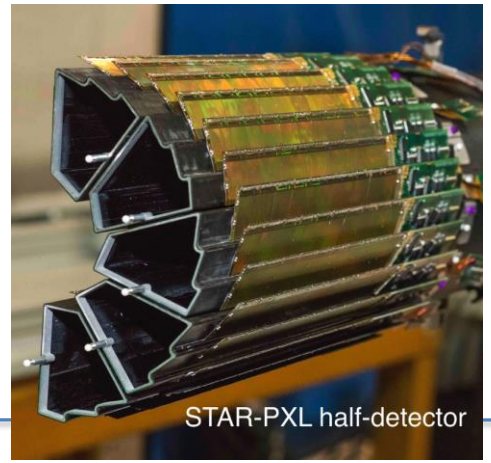
- Initial motivation = new optimization for ILC vertex detector
  - Late 90's
  - R.Turchetta NIM A 458 (2001) 677





- The STAR – PXL
  - Collab. IPHC – BNL
  - MIMOSA-28 sensor
    - AMS 350 nm technology
    - already with resistivity > 400 Ω.cm
  - **50 µm thick, 20.7 µm pitch**
  - 160 mW/cm^2
  - Hit-rate > MHz/cm^2
  - Operation 2014-2016
  - I.Valin JINST 7 (2012) C01102
  - G.Conti A 907 (2018) 60

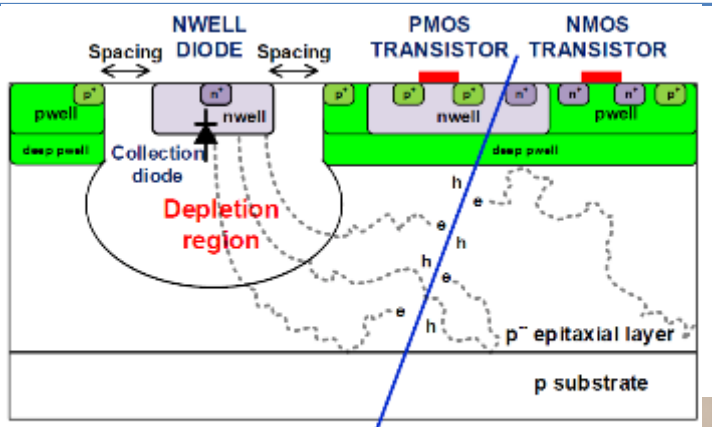




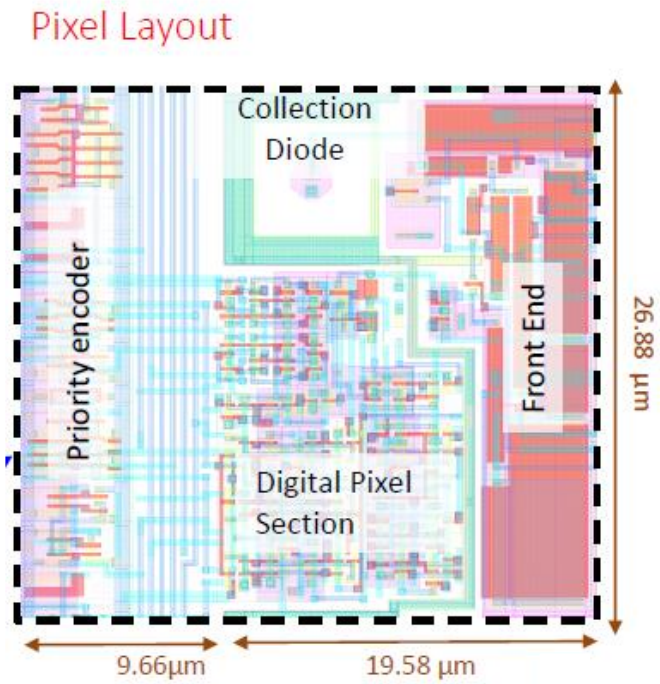
Overview: the past ~10 year – part 1

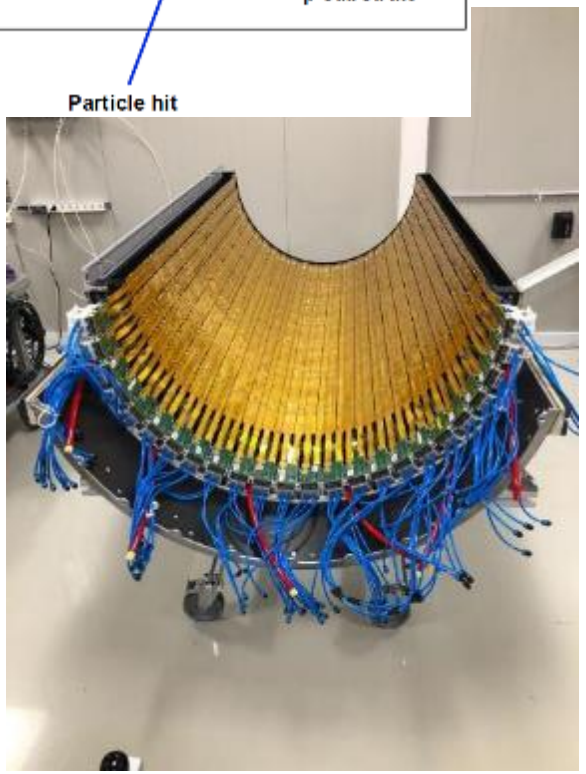
- Exploration of new CMOS process
  - Quadruple well
  - or High-voltage
    - Large collection diode
    - **See next talk by H.Zhang**

Powerful in-pixel treatment
& read-out architecture



- The ALICE - ITS2
  - Large collab. around CERN
  - ALPIDE sensor
    - Tower-Jazz 180 nm
  - **40 mW/cm²**
  - **hit rate 100 MHz/cm²**
  - Total surface covered **10 m²**
  - A.Rinella NIM A 845 (2017) 583

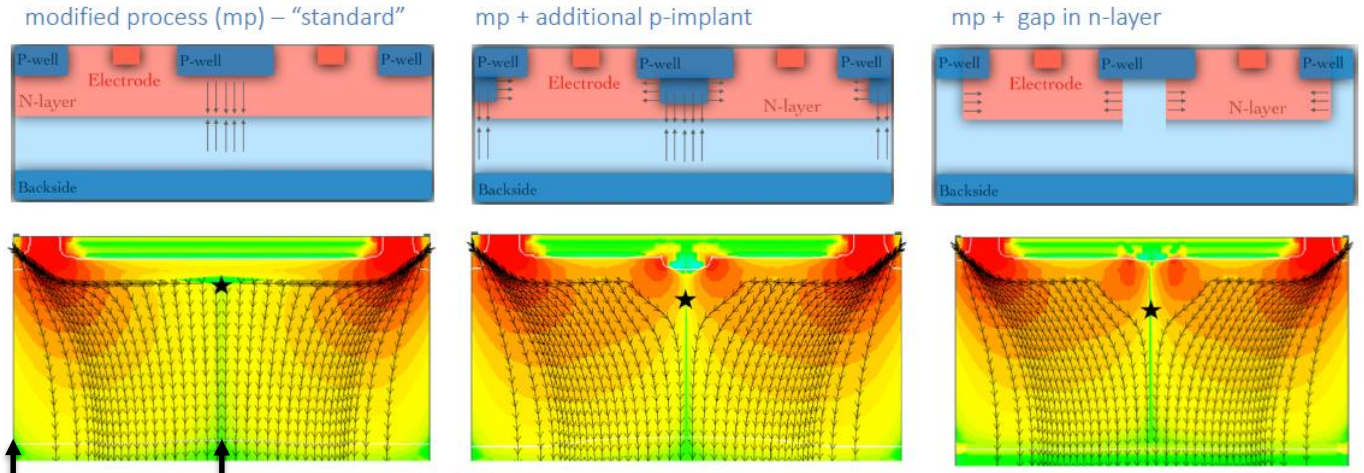




Overview: the past ~10 year – part 2

- **New sensitive layer**
  - High resistivity epitaxy combined with
  - Shallow but N-implant
  - W.Snoeys NIM A 871 (2017) 90

Short collect. time ~ns



M.Munker JINST 14 (2019) C05013

- **Higher radiation tolerance**
  - Interest in ATLAS – ITK community
  - **Toward tolerance to**
    - **Fluence 10^{15} n_{eq}/cm^2**
    - **TID ≥1 MGy**
  - Large sensors (~2x2 cm^2)
    - MONOPIX-2
    - MALTA
    - ATLASPix3 / MuPix

Pixel pitch

33x33 μm^2

36x36 μm^2

50x150 μm^2

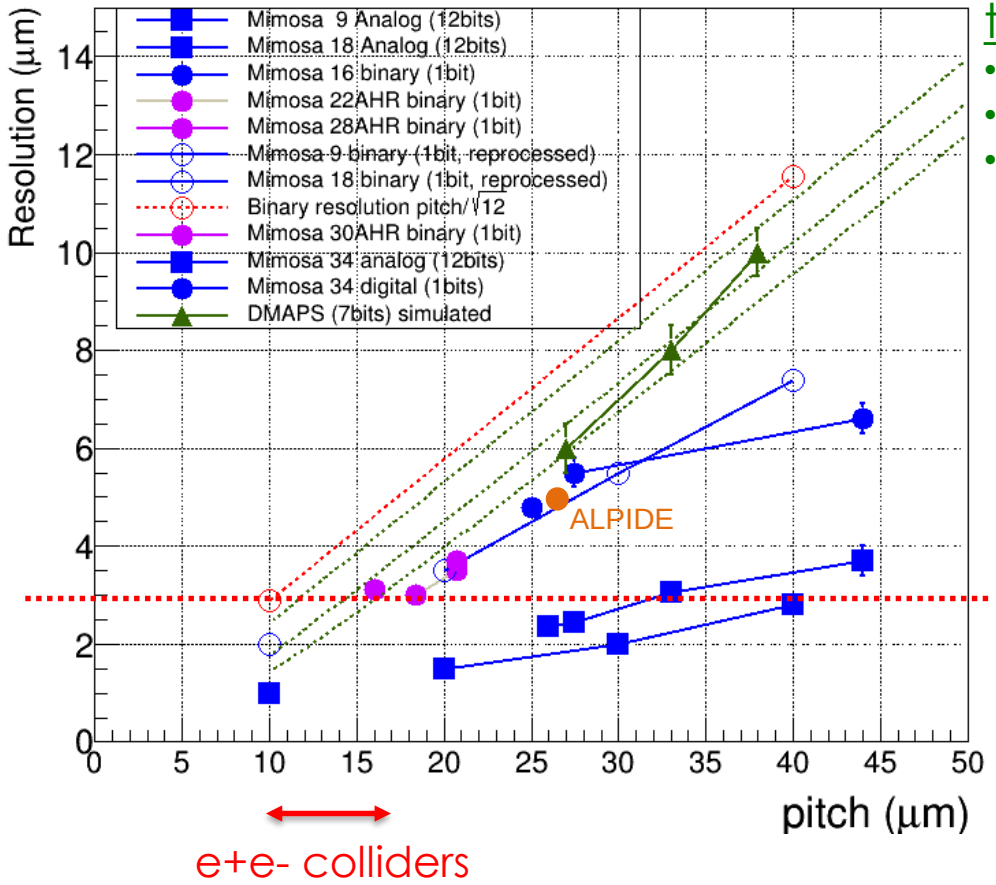
- **Not to forget, closely related R&Ds**
  - SEED & ARCADIA projects at INFN
    - LFoundry 110 nm, HR sensitive layers
    - See P.Giubilato's talk on Monday
  - SOI technology
    - LAPIS 200 nm
    - See M.Yamada monolithic SOI @ Vertex 2020

The spatial resolution "case"

A well-known fact ⇒ Charge sharing drives heavily spatial resolution

- **Partial depletion**
  - Charge collection shared between diffusion and E-drift
  - Rather strong charge sharing ☺
  - Not easy to simulate!
    - Still strong progresses: TCAD+Allpix²
    - Ex: D.Dannheim NIM A964 (2020) 163784
- **Full depletion**
  - Charge collection dominated by E-drift
  - Charge sharing limited ☹
    - Still more comfortable / SNR
  - Relatively easy to simulate and understand
    - Gaussian transverse diffusion ⊗ pixel size

Measurements & simu. from MIMOSA series



Simulation inspired by Monopix-1 sensor with **full-depletion** thickness

- 10 µm
- 20 µm
- 30 µm

Focus on activities in Strasbourg

Scientific groups @ IPHC ⇒

	ALICE ITS3	Belle-II VXD upgrade	CBM MVD	ILC VTX	CEPC VTX
Spatial res. (µm)	~5	< 10	~5	≲ 3	~3
Mat. budget (%X0)	0.05	0.15	~0,3	0.15	0.15
Hit rate (MHz/cm²)	100	100	15-70	~20	~10
Time figure (ns)	100-10^3	~100	5.10^3	10^2-10^3	10^2-10^3
Rad.hard. (kGy) (n_{eq}/cm²)		10/year $5x10^{12}$/y	5 /year < $7x10^{13}$ /y	1 /year 10^{11}/y	1 /year $6x10^{12}$ /y
Power diss. (mW/cm²)	20	< 200	< 200 in vaccum	~20 pow-puls.	<50

Common key feature →

→ **PICSEL group**

- A.Besson
  M.Winter
  & al.

IN2P3 core facility C4PI

- Dedicated to CMOS sensors
- Tech. & Scient. direction: Christine Hu-Guo & J.Baudot

⇐ Material budget

Hit-rate

Spatial resolution

⇒ **MIMOSIS sensor**

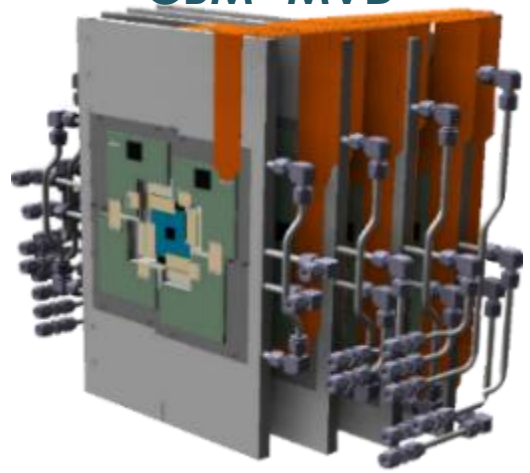
MIMOSIS sensor - Context

- Goal
  - Exploiting known TowerJazz 180 nm technology
  - combining low-power & high hit-rate
  - Follows ALPIDE FEE & priority encoder read-out

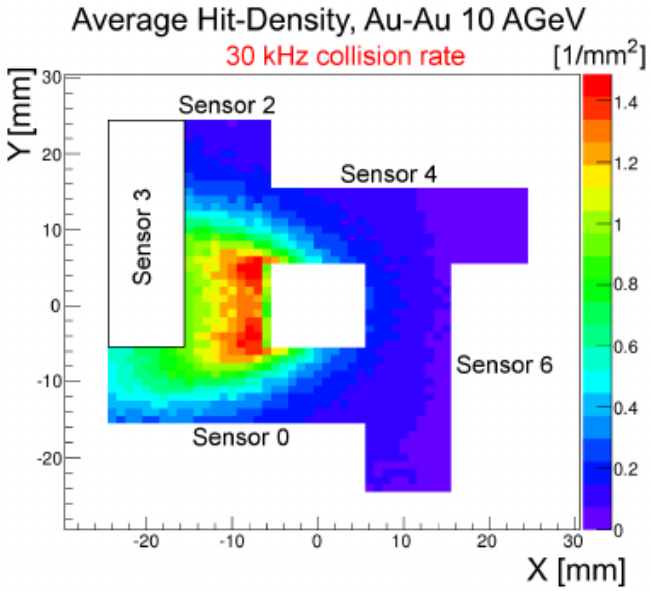
- Dedicated experiment
  - CBM MicroVertexDetector (MVD)
  - Collaboration: IPHC, IKFrankfurt, GSI, H2020-CREMLIN+

- Timeline
  - 2020: MIMOSIS-1
  - 2021: MIMOS-2
  - ~2023: final chip=MIMOSIS-3

CBM -MVD



J.Stroht Bormio 2018
M.Koziel, DPG 2017



MIMOSIS sensor - Design

- **Pixel matrix**
  - Pixel area = 26.88 x 30.24 µm^2
  - 504 x 1024 pixels structured in regions
  - Global shutter: 5 µs integration time

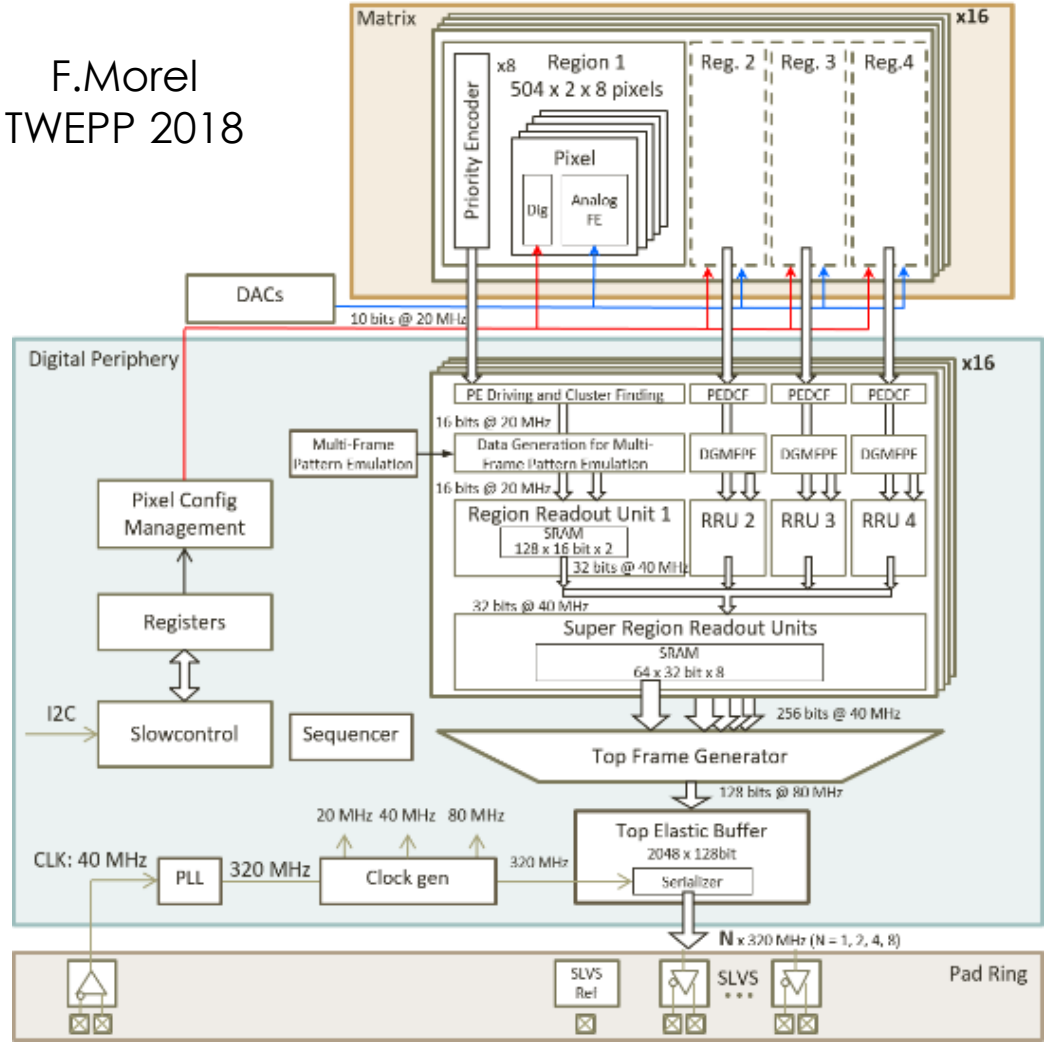
- **Read-out architecture**
  - Elastic memory concept (9 events storage capacity)
  - 8 outputs (320 Mbps) for ~2.5 Gb/s

- **Single-Event-Effects resilience**
  - Triple Modular Redundanc
    + Error Correction Code (PhD. Y.Zhou)

- **Power budget**

Pixel/frame	1	640
Analogue (mW)	30	30
Digital (mW)	150	200
Total (mW/cm^2)	**43**	**55**

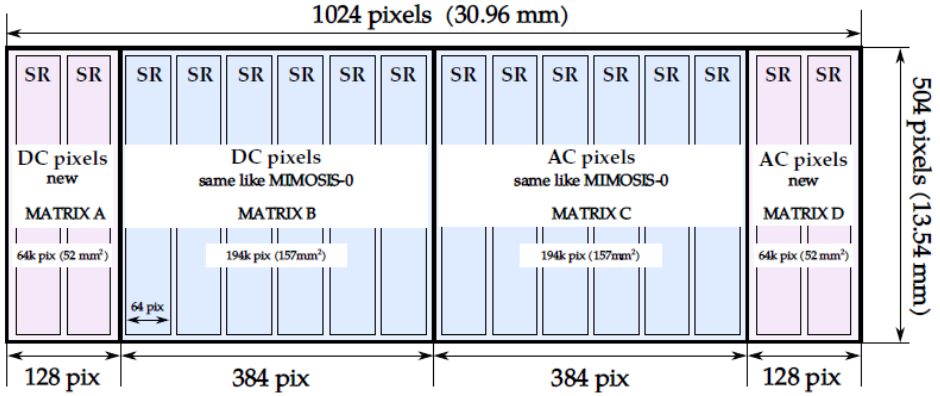
F.Morel
TWEPP 2018

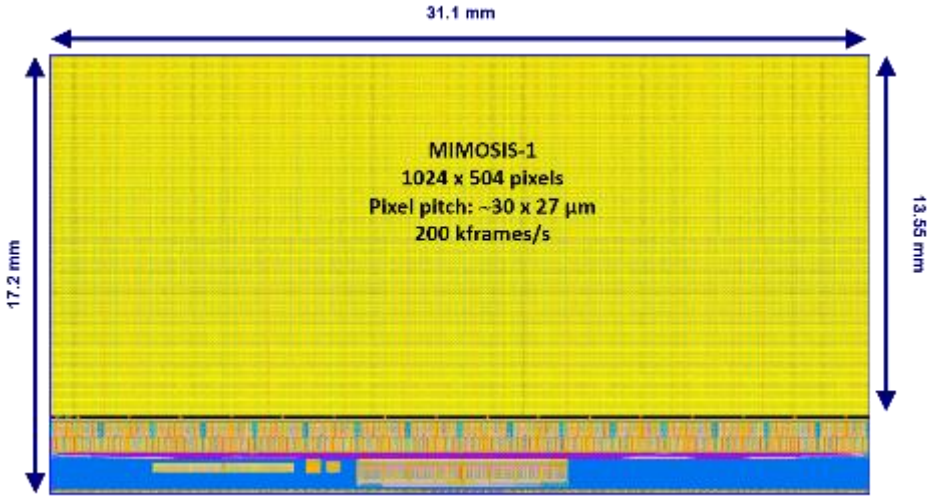


MIMOSIS-1

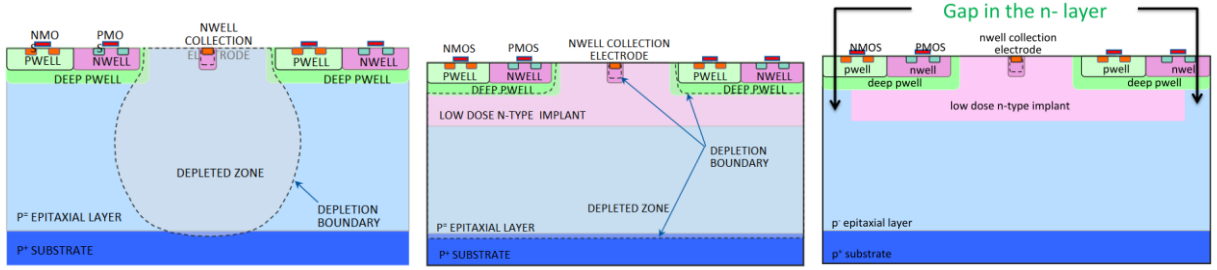
Full-size sensor, still exploring variants

- Pixel amplification



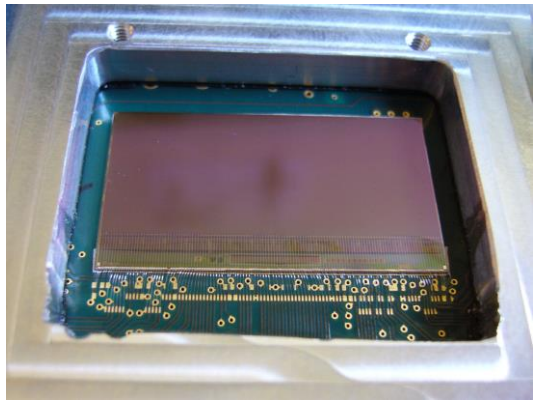


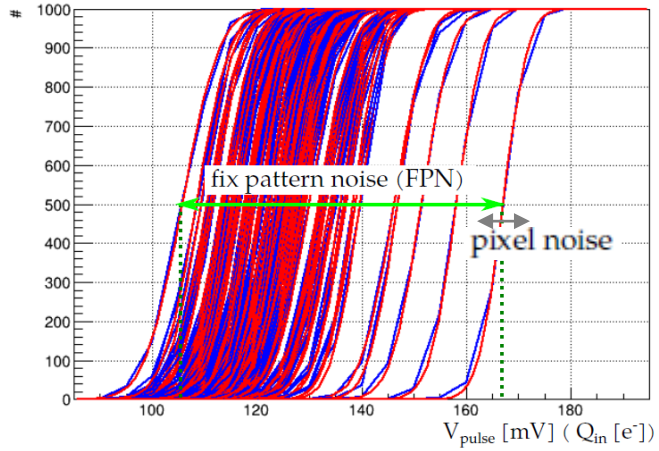
- Sensitive layer



- Tint ~ µs → no in-time efficiency issue expected
  - Still need radiation tolerance assessment
- Careful study on spatial resolution dependence
  - With substrate modification
  - With biasing voltage
  - In connection with large analogue output sensor (Monolithic Imager, 20 µm pitch by M.Kachel)

- Initial tests on-going @ IPHC



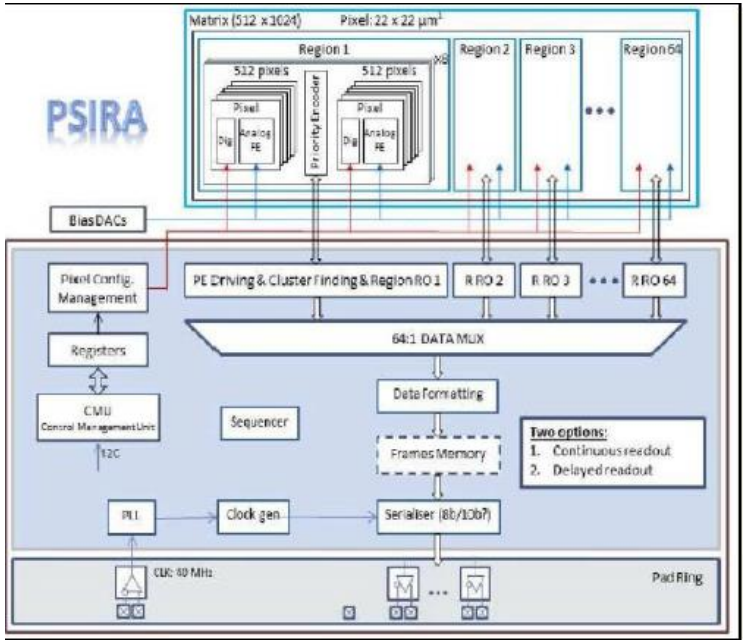


Spatial resolution ≲3µm : 1st path

- The 180 nm solution
  - Evolution of MIMOSIS architecture for ILC → **PSIRA**
    - 4 µs integration time → 4-8 Bunch & 100 hits/cm²/µs
    - ILC time-structure → power-pulsing
    - Interest to resolve BX
      → ~500 ns integration time
      MIMOSIS-0Fast prototype (2021)
    - Minimal pitch ~22 µm → spatial res. ~4 µm

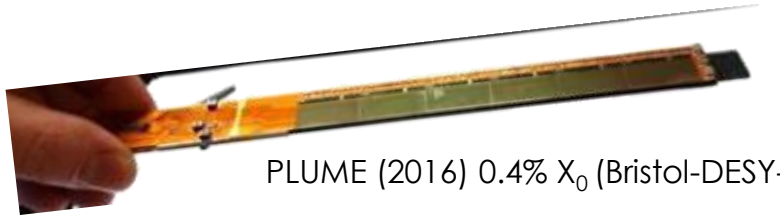
Power pulsing	Total det power
Without	100-120 W
With	15-30 W

From Auguste Besson



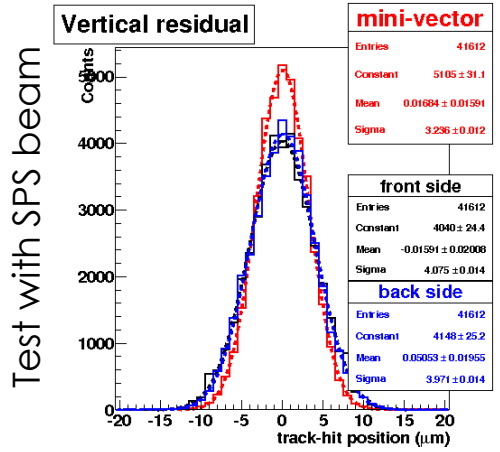
- **Requires double-sided layer *a la* PLUME**
  - Resolution x 1/√2: 4 → 2.8 µm
  - More studies with MIMOSIS (CREMLIN+)

- **or 3D-bonding integration**
  - Currently exploring 2-tiers bonding with
  - 20x20 µ m2 pixels
  - T-micro technology
    (applied to SOI-SOFIST prototype)



PLUME (2016) 0.4% X_0 (Bristol-DESY-IPHC)

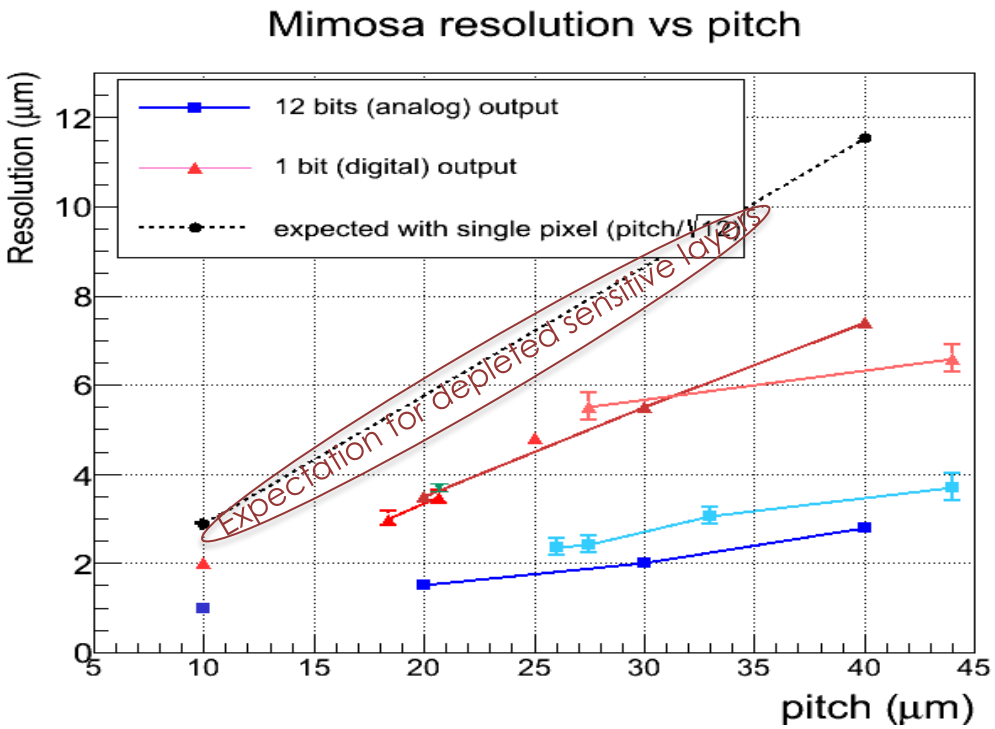
Successfully operated
6 months during 2018
Belle II commissioning



Spatial resolution ≲3µm : 2nd path

- The 65 nm solution
  - The road to pixel size < 20 µm
  - According to "predictions" 3 µm requires ⇒
    ~10 µm fully depleted
    ~18 µm without depletion
    - Reachable assuming x2 size-reduction potential
  - Current technology evaluation
    - With CERN EP-R&D Roadmap + partners
      - See Laura Gonella's talk on Monday
    - Small exploratory matrices being submitted (Nov.2020)
      - pixel size 10-25 µm, Various amplifications, AC/DC coupling
  - Other benefits?
    - Lower power dissipation $\propto CV^2$ (power supply 1.2 V)
    - Stitching avalaible

- Lesson from techno 350 & 180 nm without depletion



Conclusion

- CMOS pixel sensor: a mature technology
  - Example: ALICE-ITS2 10 m^2 detector being commissioned
  - Growing number of experiments opting for or considering the techno.
  - Many active groups over the 3 regions

- Still full potential to be further developed / explored
  - Large sensors in known (TJ 180 nm & others) process pushing performances
    - However getting to 3 m with hit-rate>> MHz/cm^2 seems a hard limit
  - A new 65 nm technology possibly a solution for the 3 µm spatial resolution
    - Should not be the only option explored
  - **Not the end-of-story / colliders after 2030 ⇒ Continuous effort needed**

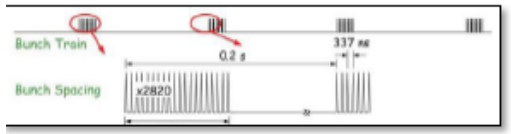
For full benefit

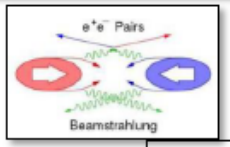
Specific integration studies required
See talks by F.Bosi & M.Mager


Thank you…
…bones slides

	STAR PXL	ALICE ITS2	HL-ATLAS ITK	CBM MVD	ALICE ITS3	Belle-II Lnom	ILC VTX	FCCee VTX	CLIC SiTrack	FCChh SiTrack
Spatial res. (µm)	< 10	~5	10	~5	~5	< 10	≲ 3	3 – 5	7	~10
Mat. budget (%X0)	0.37	0.35	<1	~0,3	0.05	0.15	0.15	0.15	~1	~2
Hit rate (MHz/cm²)	O(0.1)	O(1)	200	15-70	2x better / ITS2	100	20	O(20)	O(0.1)	
Time figure (ns)	200.10^3	5.10^3	25	5.10^3		~100	10^2-10^4	10^2-10^3	5	$5x10^{-3}$
Rad.hard. (kGy) (n_{eq}/cm^2)	2 10^{12}	30 $2x10^{13}$	500 10^{15}	30 /year $< 10^{14}$ /y.		100 $5x10^{13}$	10 $< 10^{12}$	20 $5x10^{11}$	< 10 $< 10^{12}$	100 $5x10^{15}$
Sensor	**MIMOSA 28**	**ALPIDE**	**R&D MONOPIX MALTA**	**MIMOSIS**	**R&D**	**R&D**	**R&D**		**R&D**	
Techno (nm)	350	180	180 (150) modif.	180 modif.	65	180	180 / 65		180	
Pixel pitch (µm²)	20x20	28x28	33x33 36x36	27x30	target stitching	< 40x40	target 17x17		30x300	
Power (mW/cm²)	150	45	O(200)	< 55		target ~100	~3 Pow.Puls			

Scientific requirements: ILC - VTX





Reminder: ILC VXD requirements

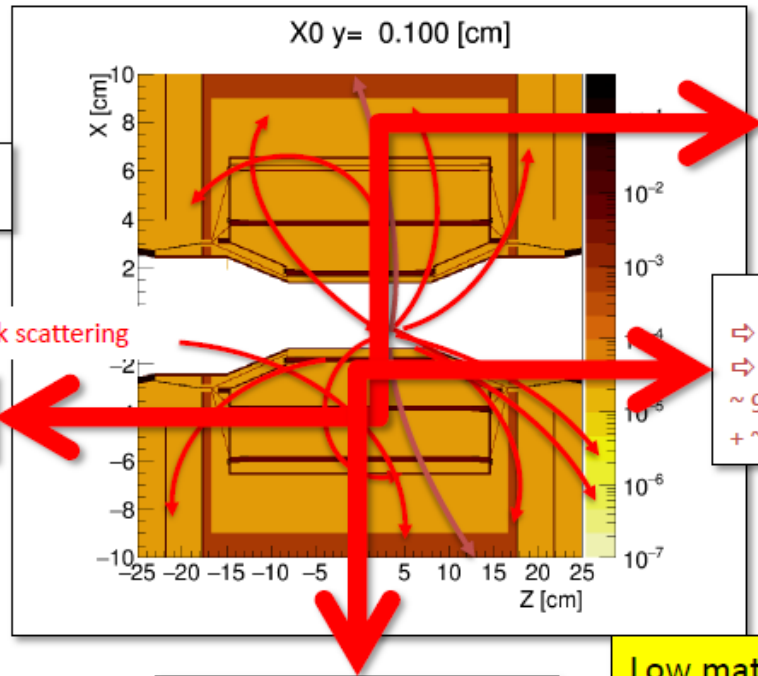
Physics (<Hz/cm²)

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

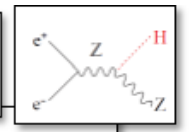
Read-out speed
O(1-10 µs)

Power consumption
~< 50mW/cm²

Fast read-out & low Power architectures

Cooling
Stiffness / Alignment

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



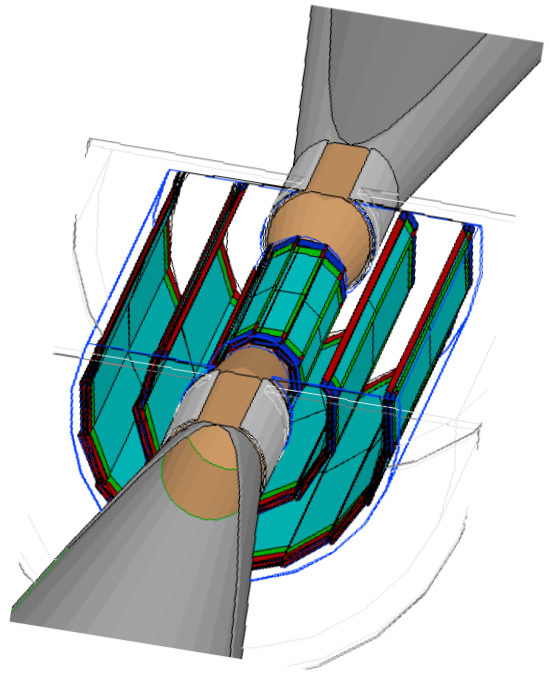
Physics
- Flavour tagging
- Low pT tracks

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

Low material detectors & supports structures

Challenge : meet the requirements all together

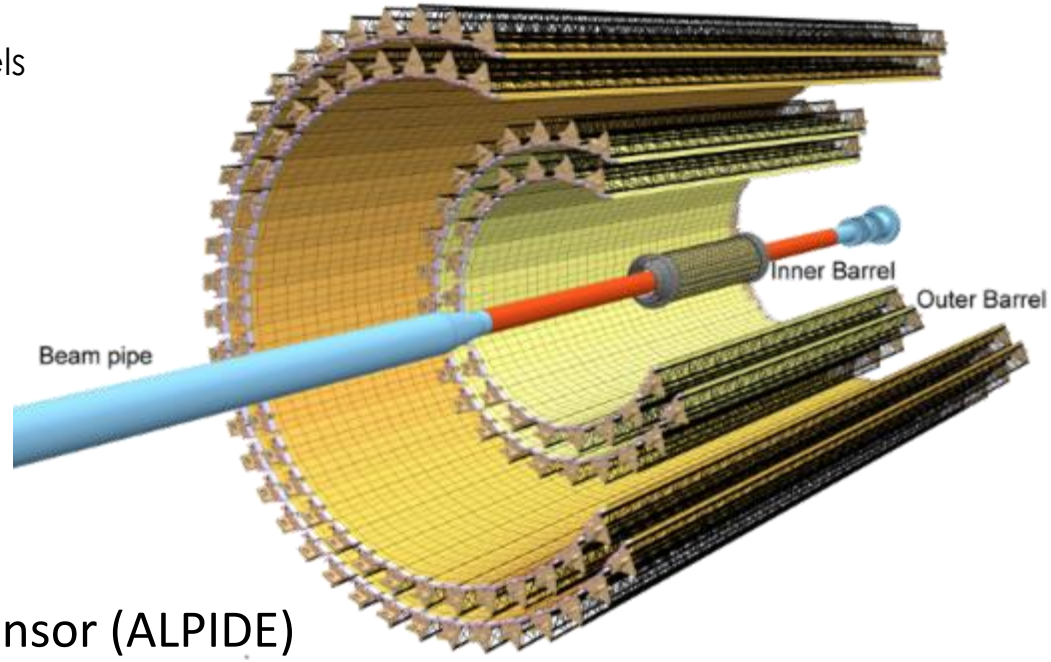


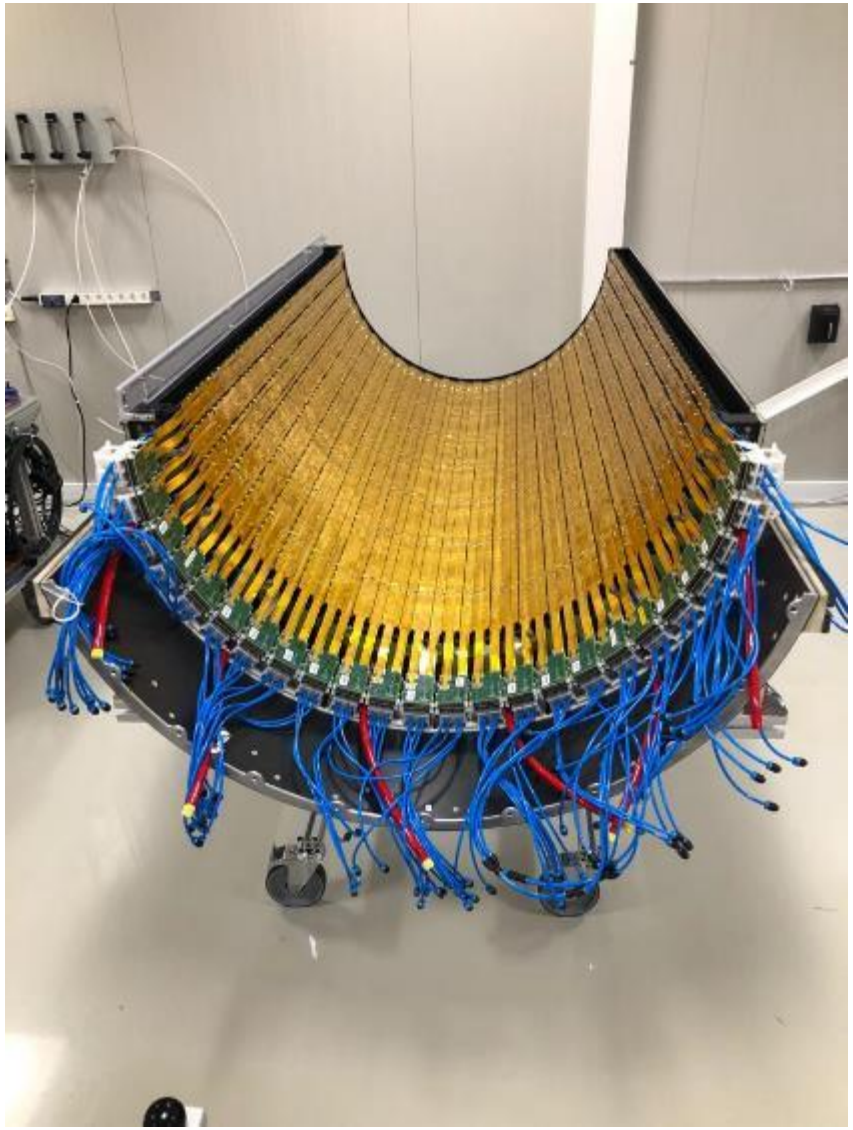
- CEPC / FCCee
  - Many similarities with ILC
    - ~ hit rates
    - granularity, mat.budget, rad.tol.
  - Main difference: time structure

How to control power without power pulsing ?

ALICE – ITS2

10 m^2, 12.5 Gpixels





CMOS Pixel Sensor (ALPIDE)

- 10 m^2 active silicon area (12.5 G-pixels)
- 130,000 pixels / cm^2 (27x29x25 μm^3)
- Spatial resolution ~5μm
- Power density < 40mW / cm^2
- Max particle rate ~ 100MHz /cm^2 (pile-up)
- Max readout rate ~ 10 MHz/cm^2 (bandwidth)
- Fake-hit rate < 10^{-9} pixel/event

About timeline: the ALPIDE-ITS case

Chip Development

Design team from CERN, INFN, CCNU, YONSEI, NIKHEF, IRFU, IPHC

2012	Explorer	20 µm x 20 µm and 30 x 30 µm pixels (analogue readout) 1.8 x 1.8 mm², study of pixel geometry, starting material, radiation
2013	pALPIDEss-0	Matrix with 64 columns x 512 rows, 22 µm x 22 µm pixels, 11 x 1.8 mm², in-pixel discrimination and buffering, zero suppression
2014	pALPIDE-1	**First full scale prototype!** 28 µm x 28 µm pixels, 15 x 30 mm², four sectors with variants, 1 register/pixel, no final interface
8/2015	pALPIDE-2	**Full scale prototype,** four sectors with variants, optimisation of circuits, integration in modules, no high speed serial output
10/2015	pALPIDE-3	**Full scale prototype,** eight sectors with variants, all communincation features, no ADC, no temperature sensor)
8/2016	ALPIDE	**Final chip**

February 22, 2018 **P.Riedler CERN, PSI Seminar**

~4 years from tech-proto to final sensor

- Few remarks
  - TJ180 nm exploration started in 2011
  - This is not a small team

+3 years for assembly (ALICE-ITS ~10 m²)

+

Belle II-VXD potential upgrade

⇒ J.Baudot
VERTEX 2020

Motivations

- ~10^{36} cm^2.s^{-1} luminosity →serious beam induced backgrounds
  - Might challenge current VXD operation & performances
- All the more true if lumi upgraded x5

=> Consider/prepare for upgrade for ~2026 or beyond

Requirements

- Safe side of current extrapolation: hit-rate ~100 MHz/cm^2
- Full-pixelated system → more robust/precise track reconstruction
- Difficult to get smaller/thinner beam-pipe (mm / 0.5%X_0)
  - Limit interest for small pixels
  - Still lighter layers usefull

Current VXD		Upgraded VXD
2 DEPFET layers	4 DSSD layers	5 to 7 full-pixel layers
50x70 µm^2	25x60000 µm^2	30x30 to 40x40 µm^2
20 µs	~5 ns (offline)	50 to 100 ns
0.2 % X_0	0.7 % X_0	0.1 % (inner) - 0.3 % (outer) X_0