Implementing ECFA-DRD7 workshop at CERN
2023 March 15th
https://indico.cern.ch/event/1214423

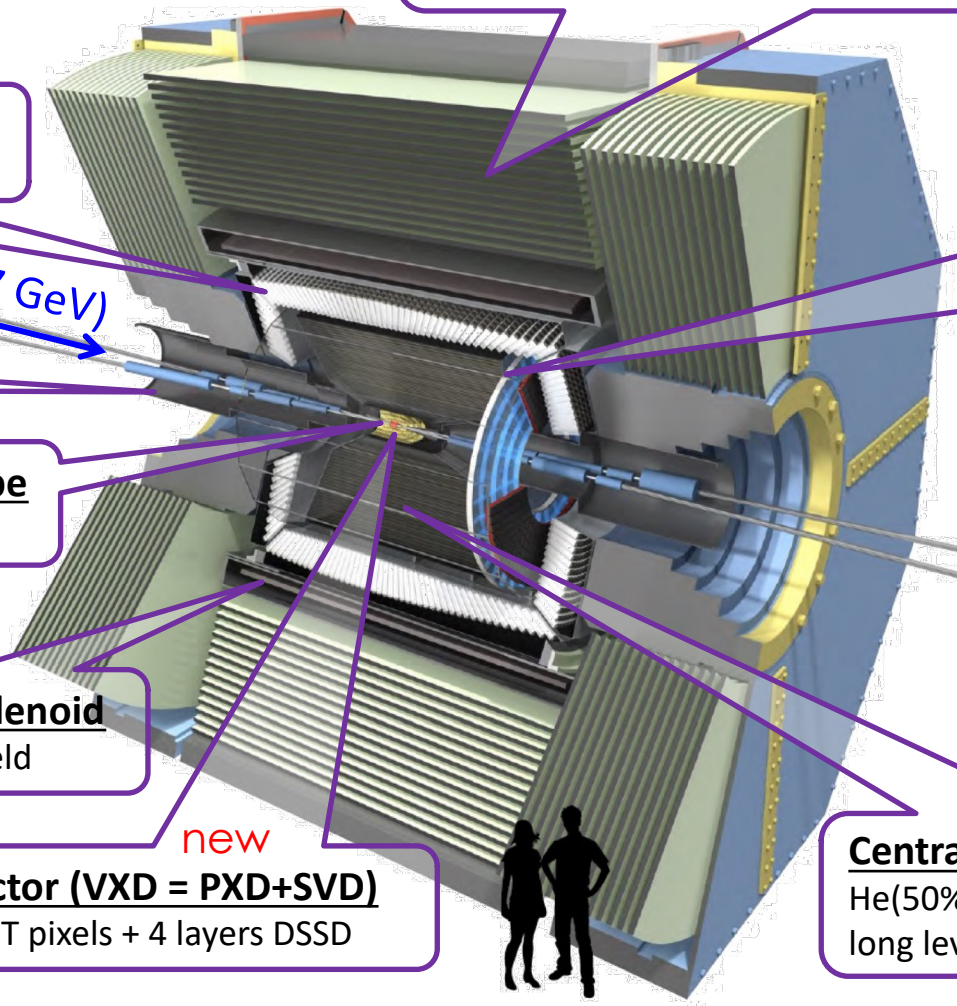
R&D perspective on MAPS

starting with the VXD upgrade

Jerome Baudot
Based on the work of the Belle II VTX collaboration

- Belle II context
- VXD upgrade: turning a pixel matrix into a detector
- Possibilities with MAPS beyond 2030

Belle II detector: upgraded or new sub-detectors with respect Belle



KLong and muon detector (KLM) upgraded
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter (CDC) upgraded
CsI(Tl), waveform sampling (barrel+ endcap)

electrons (7 GeV)

Particle Identification
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd) new

new
Final focusing magnets

Beryllium beam pipe
2cm diameter new

positrons (4 GeV)

SuperCond. Solenoid
1.5 T magnetic field

new
Vertex Detector (VXD = PXD+SVD)
2 layers DEPFET pixels + 4 layers DSSD

Central Drift Chamber new
He(50%):C_2H_6(50%), small cells,
long lever arm, fast electronics

The Belle II program & upgrades

Physics program @ SuperKEKB

- Based on accumulation of 50 ab^{-1} of e^+e^- at $\sqrt{s} = M_{\Upsilon(4S)}$
  => requires instantaneous luminosity close to $6x10^{35}$ $cm^{-2}.s^{-1}$

SuperKEKB collider implementing
the nano-beam scheme @ high currents

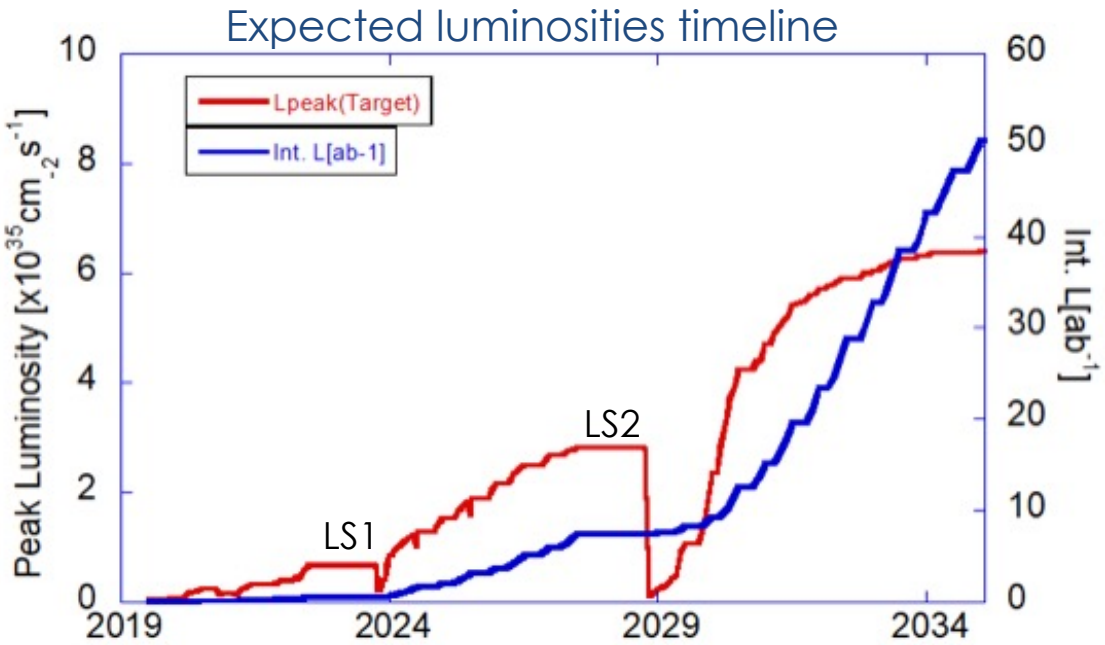
High collision rate High beam-induced BKG

Vertexing & tracking upgrades

- Getting more physics with increasing BKG
  => higher space-time granularity

- **Vertex upgrade ~LS2 (short-term)**
  - DEPFET + DSSD ⟶ MAPS (VTX proposal)
  - CDR being prepared for June 2023

- **Tracker upgrade > LS2 (long-term)**
  - CDC ⟶ partially/totally replaced by MAPS or TPC
  - Studies on-going



VTX general concept

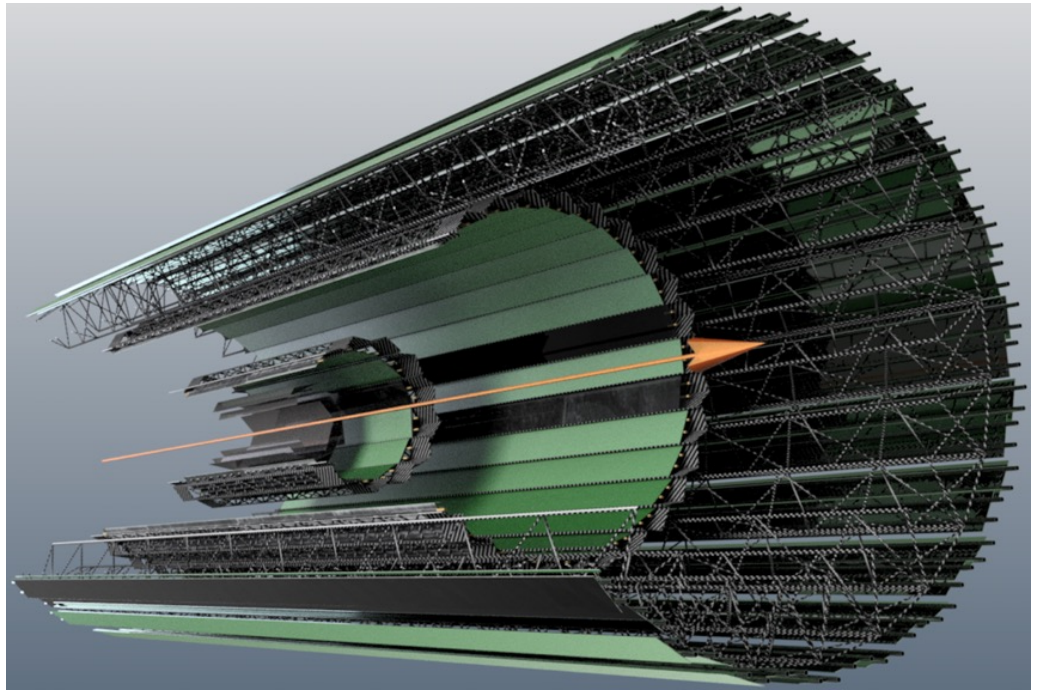
- **5 layers**
  - About 2000 OBELIX DMAPS
  - Fast enough for including all layers in tracking
  - Services mostly on one side (backward region)
  - Total event size ~30 kBytes

- **iVTX** = 2 inner ladders
  - radius 1.4, 2.2 cm
  - short length ~12 cm
  - material budget ~0.1 % X_0

- **oVTX** = 3 outer ladders
  - radius 4 ⟶14 cm
  - length ⟶ 70 cm
  - material budget 0.3 ⟶ 0.8 % X_0

- VTX collaboration

HEPHY, Vienna	University of Bergamo
CPPM, Marseille	INFN, Pavia
IJCLab, Orsay	INFN & University of Pisa
IPHC, Strasbourg	IFAE, Barcelona
University of Bonn	IMB-CNM-CSIC, Barcelona
University of Dortmund	IFCA (CSIC-UC), Santander
University of Goettingen	IMSE-CNM-CSIC, Seville
KIT, Karlsruhe	IFIC (CSIC-UV), Valencia
KEK, Tsukuba	ITAINNOVA, Zaragoza



VTX sensor requirements

FROM PHYSICS SIMULATION	Belle-II VTX
Spatial res.	< 10-15 µm
Mat. Budget inner-outer layers	0.1-0.8 % X_0/layer
Max hit rate	120 MHz/cm^2
Time precision	<100 ns
Trigger (freq) (delay)	30 kHz 5-10 µs
Rad.hard. (TID) 10years (fluence)	<1 MGy <5x10^{14} n_{eq}/cm^2

CHOOSING A MATRIX	Belle-II DMAPS	TJ-Monopix2	MIMOSIS-1	ATLASPix3
	exp ~2025	2020	2020	2019
Techno		Tower 180 nm	Tower 180 nm	TSI 180 nm
Sens. area	~30x15 mm^2	17x17 mm^2 ⚠	30x14 mm^2	20x19 mm^2
Sens. thick	~30 µm	25-100 µm	25-30 µm	<50 µm
Pitch	30 to 40 µm	33 µm	27x30 µm^2	150x50 µm^2 ⚠
Signal digits	1 to few bits	7 bits ToT	1 bit	7 bits ToT
Integration	25 to 100 ns	25 ns	5 µs ⚠	25 ns
Hit rate	120 MHz/cm^2	>100 MHz/cm^2	70 MHz/cm^2	>100 MHz/cm^2
Bandwidth	320 MHz	320 MHz	2.5 GHz	1.3 GHz
Power	<200 mW/cm^2	200 mW/cm^2	50 mW/cm^2	~140 mW/cm^2
TID fluence	<1 Mgy < 5x10^{14} n_{eq}/cm^2	100 kGy 10^{15} n_{eq}/cm^2	50 kGy 10^{14} n_{eq}/cm^2	100 kGy 10^{15} n_{eq}/cm^2

Forerunner for OBELIX sensor

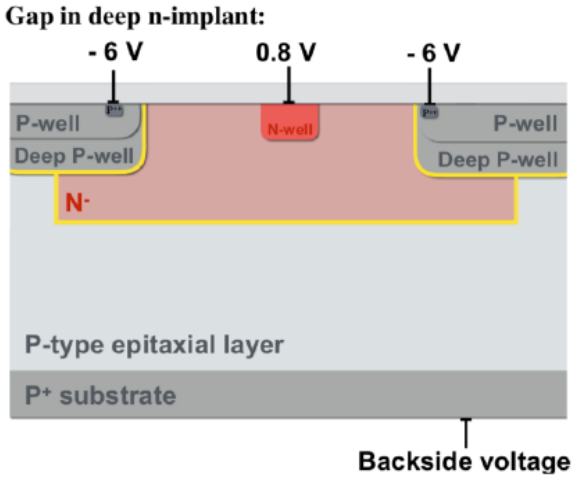
+ covering at least current VXD acceptance
  - radii from 1.4 to 14 cm
  - angle from 17 to 160 degrees

TJ-Monopix pixel matrix

- Collaboration: Bonn, CERN, CPPM, CEA-IRFU
  DOI: 10.1016/j.nima.2020.164403
- Column-drain read-out Inherited from ATLAS FE-I3
- Detection efficiency assessed up to 1^{15} n_{eq}/cm^2

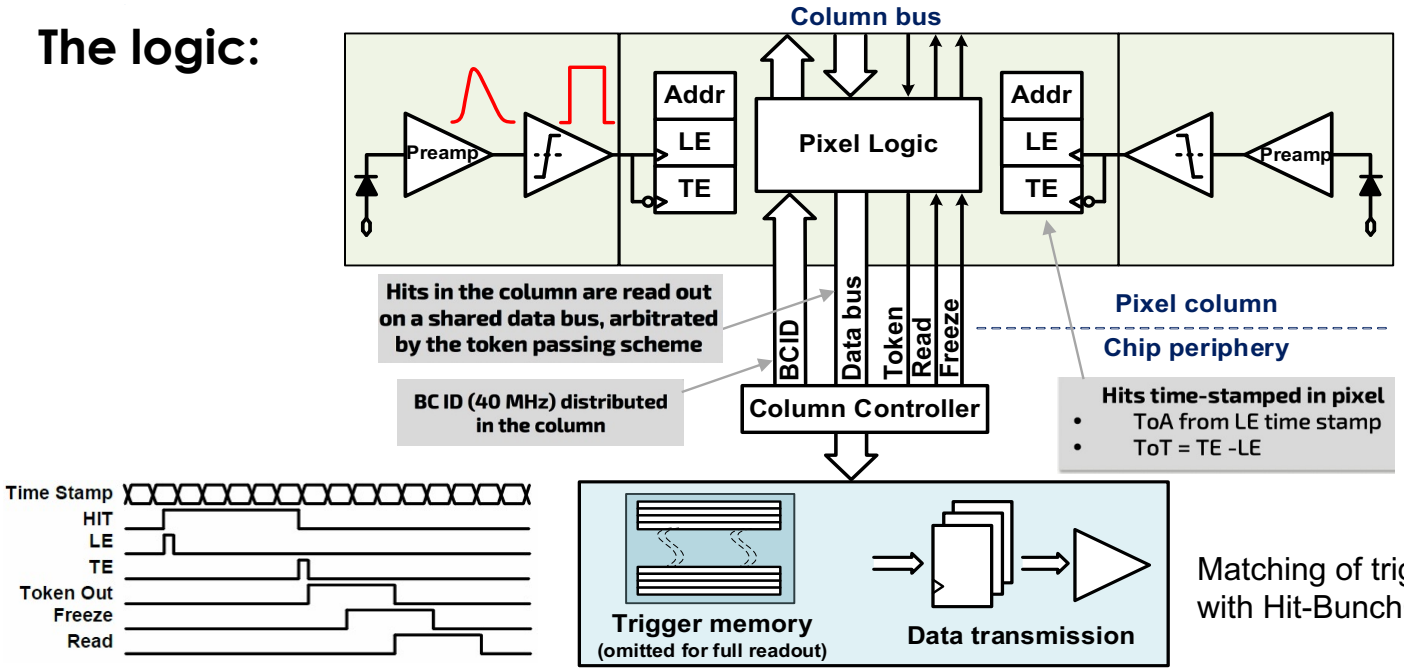
=> Latest characterisation results:
C.Bespin Pixel 2022, L.Massacesi TREDI 2023

The Pixel:
∃ variants



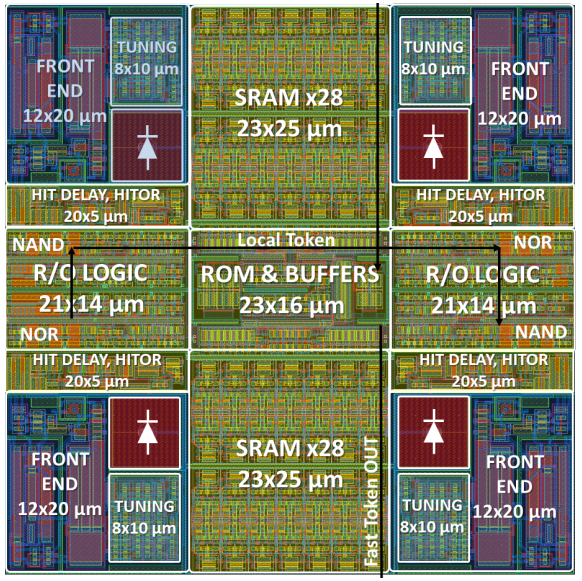
W.Snoeys et al.
doi: 10.1016/j.nima.2017.07.046

The logic:



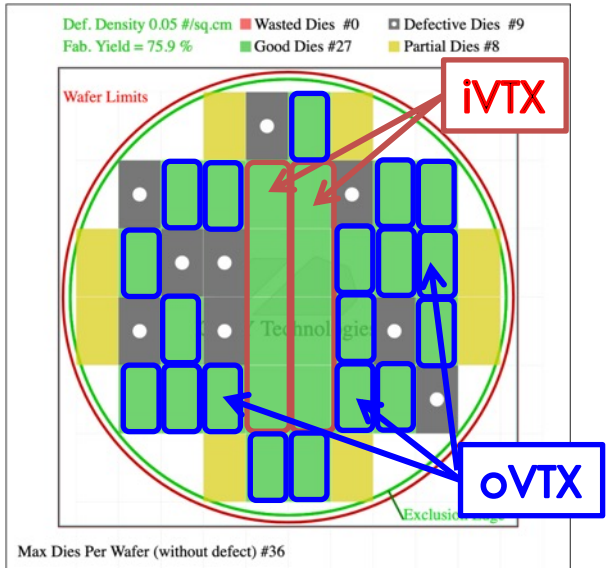
Matching of trigger-ID
with Hit-BunchCrossingID

The Layout:
2x2 pixels

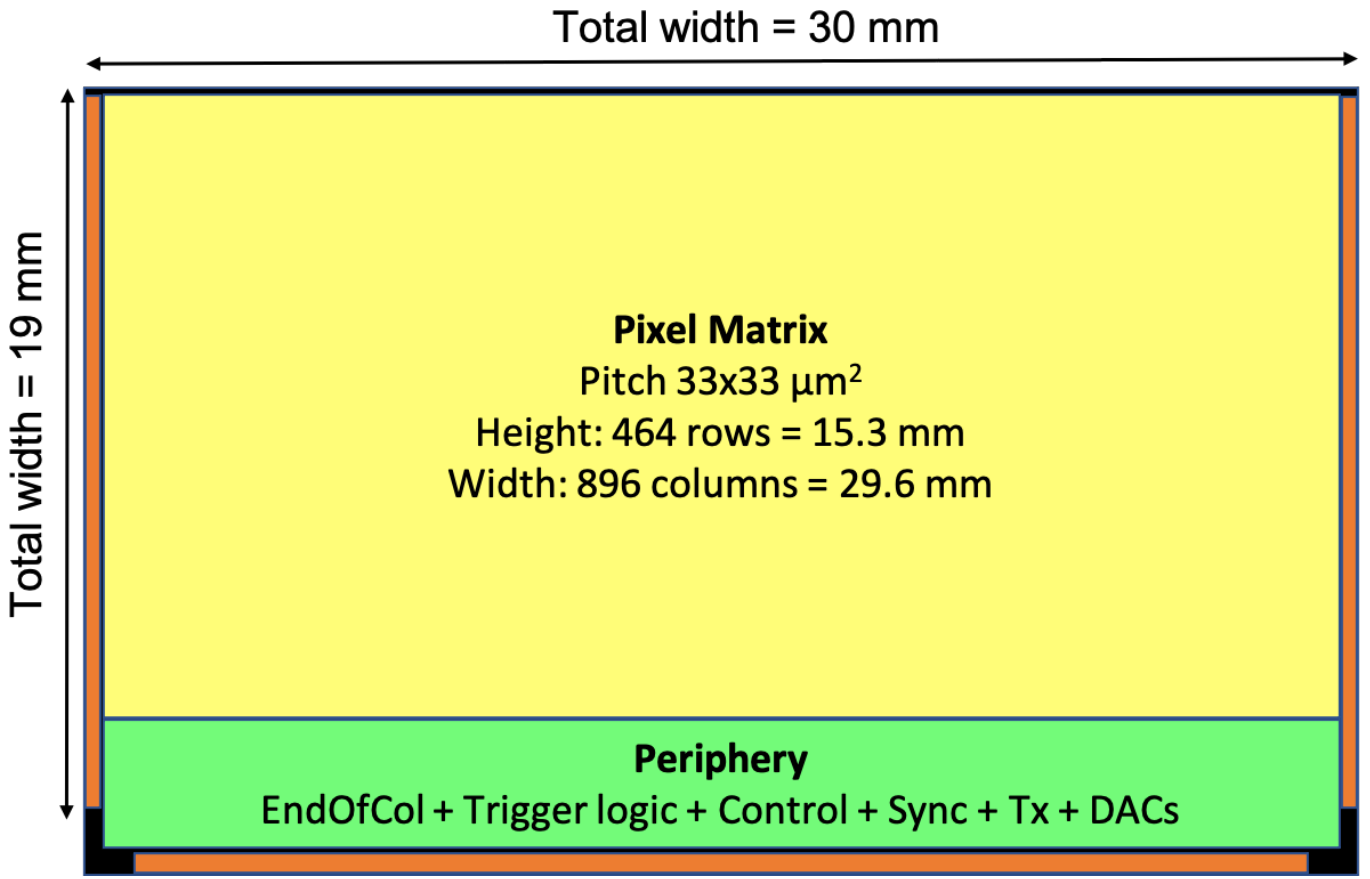


OBELIX (Optimized BELle II pIXel) sensor

Size optimized
to maximize (8) sets
of 4 contiguous sensors



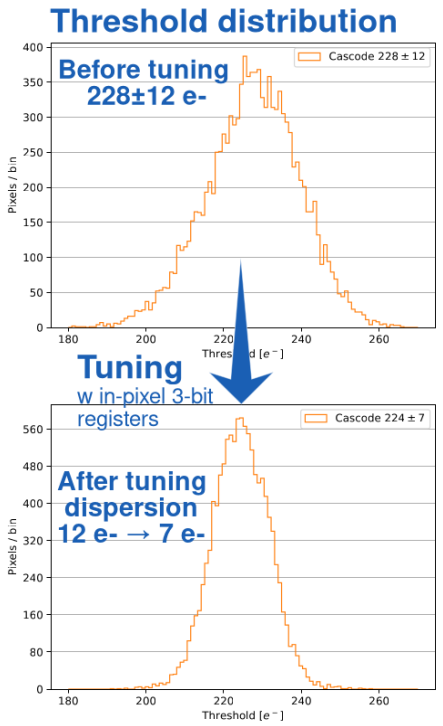
- Digital on-top design
  for continuous verification



OBELIX (Optimized BELle II pIXel) sensor

- Pixel matrix
  - Extension from TJ-Monopix2
    - Layout adapted to digital-tool design
  - Frequency ~10-20 MHz
    => time-stamp precision 100 or 50 ns
  - Operation point (I_{bias}) tuning on-going

- Strong on-going test effort on TJ-Monopix2
  - Critical to change any features
  - e.g. #trimming bits / pixel for threshold



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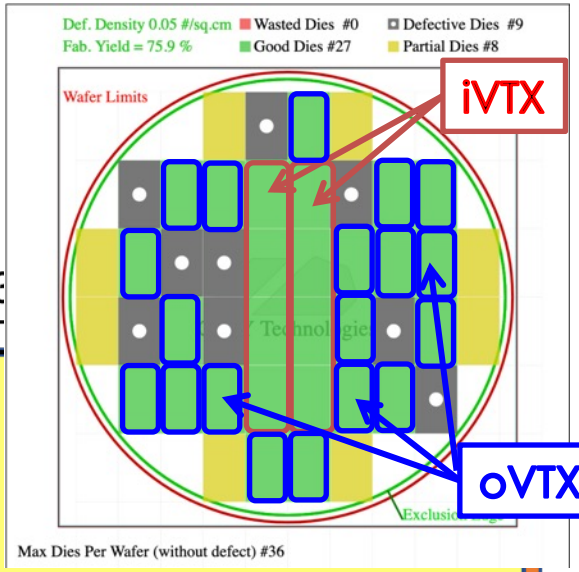

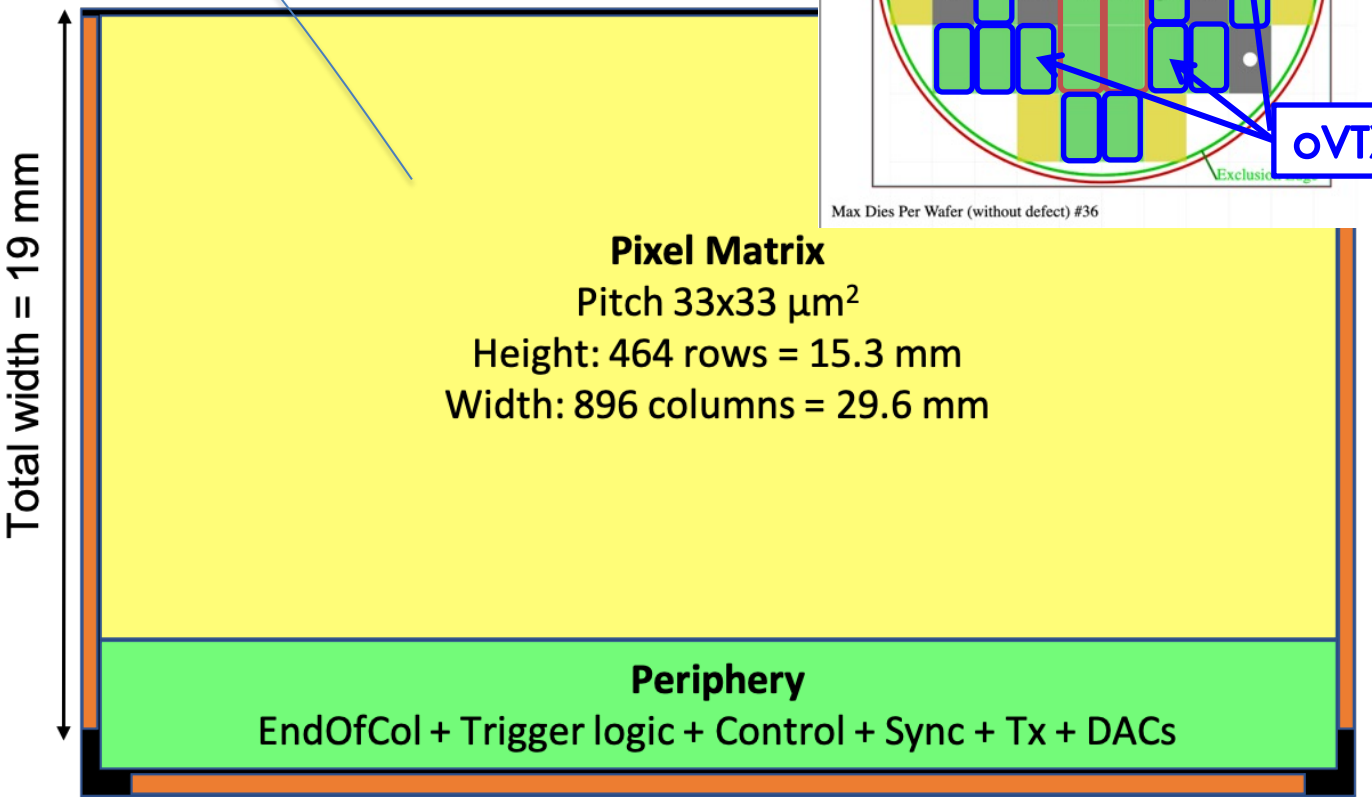

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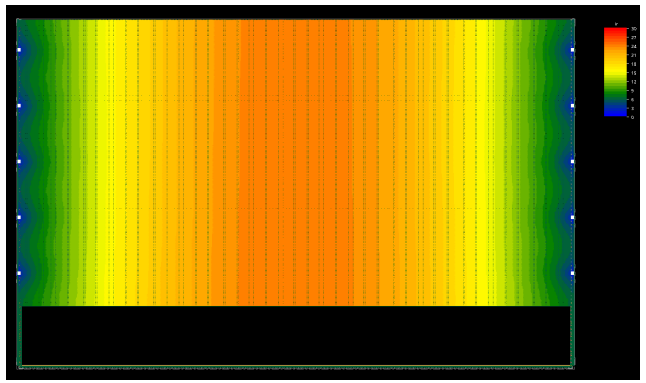
- **Power pads**
  - Power regulators added
    => simplified system integration
  - But area limited to <150 µm

GNDA IR drop (0-30 mV) simulation



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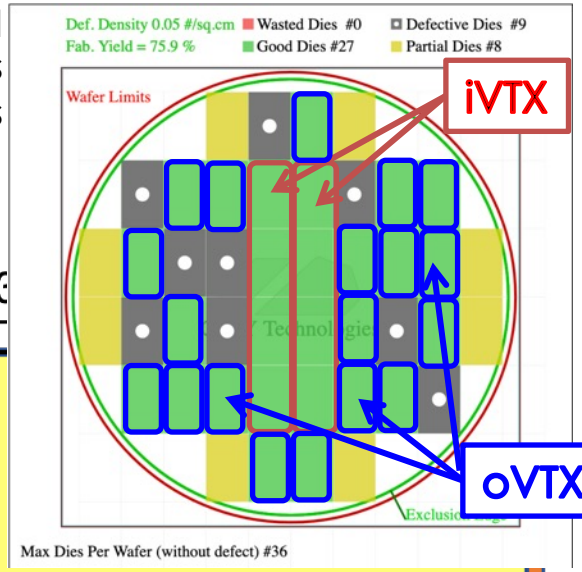

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- **Periphery**
  - New end-of-column + trigger logic adapted to Belle II trigger
  - HITor fast transmission ~20 ns (4 areas)
  - Control using protocol from RD53

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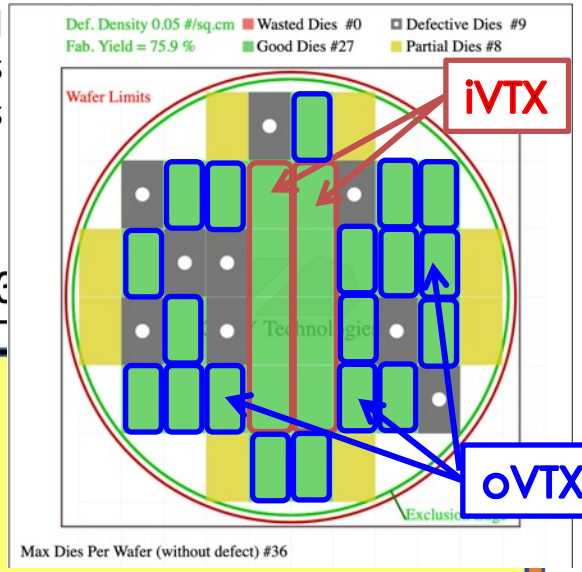

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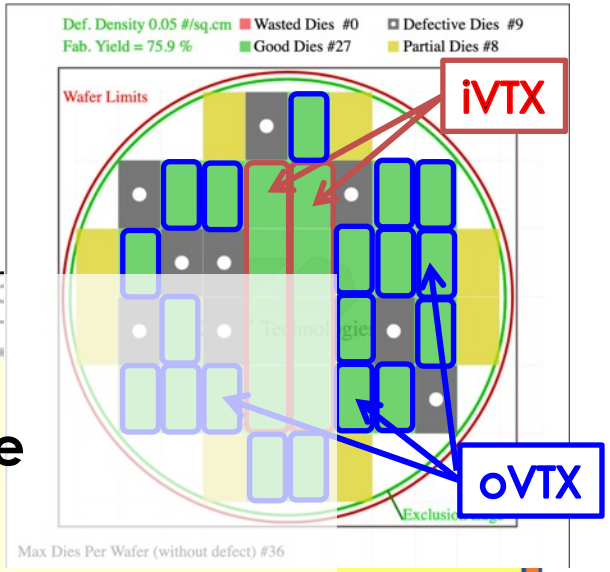
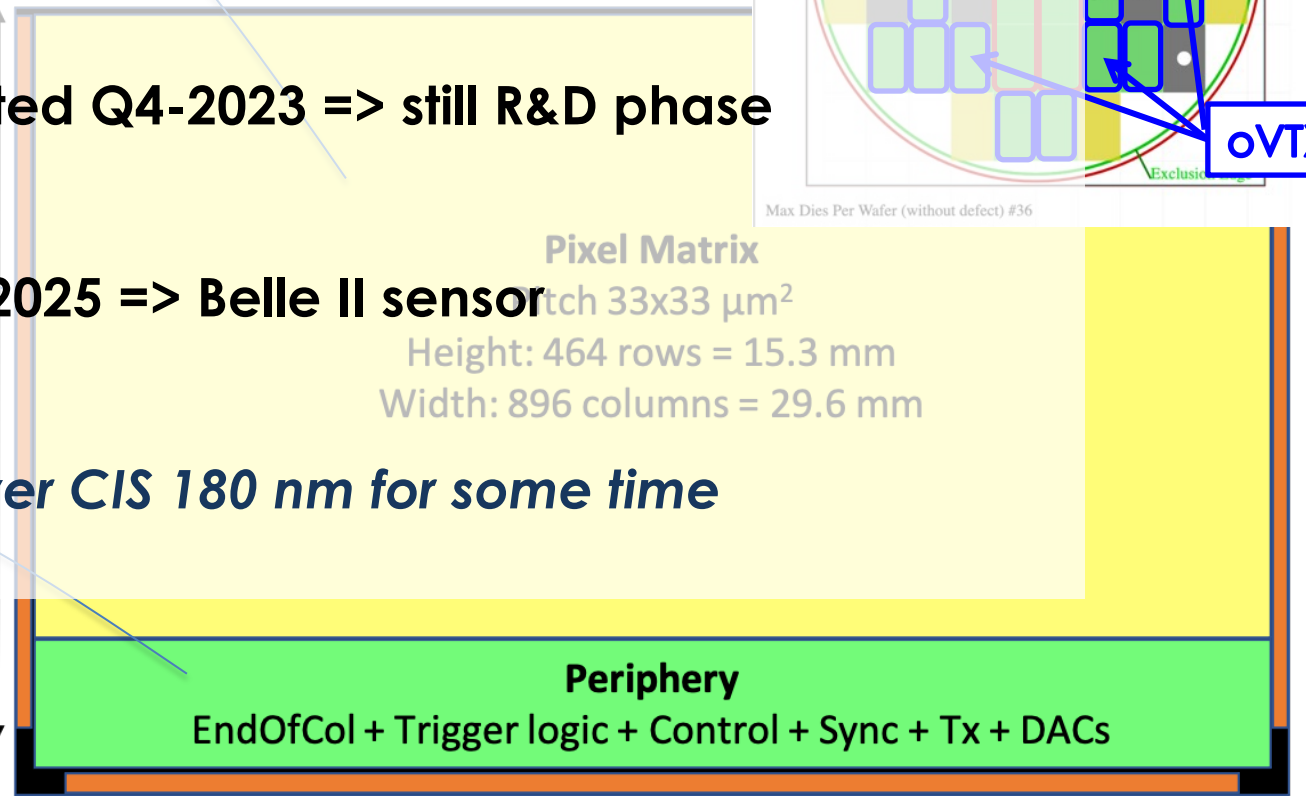


OBELIX-1 submission expected Q4-2023 => still R&D phase

OBELIX-2 for early 2025 => Belle II sensor

=> Keep working with Tower CIS 180 nm for some time

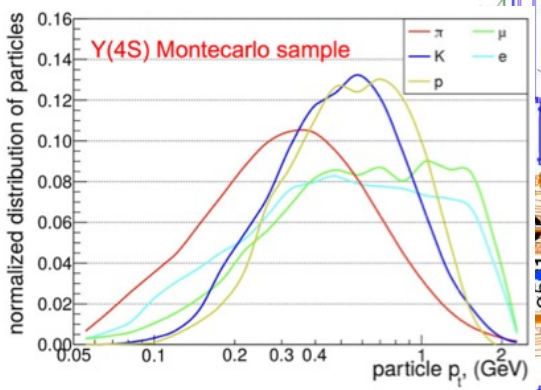


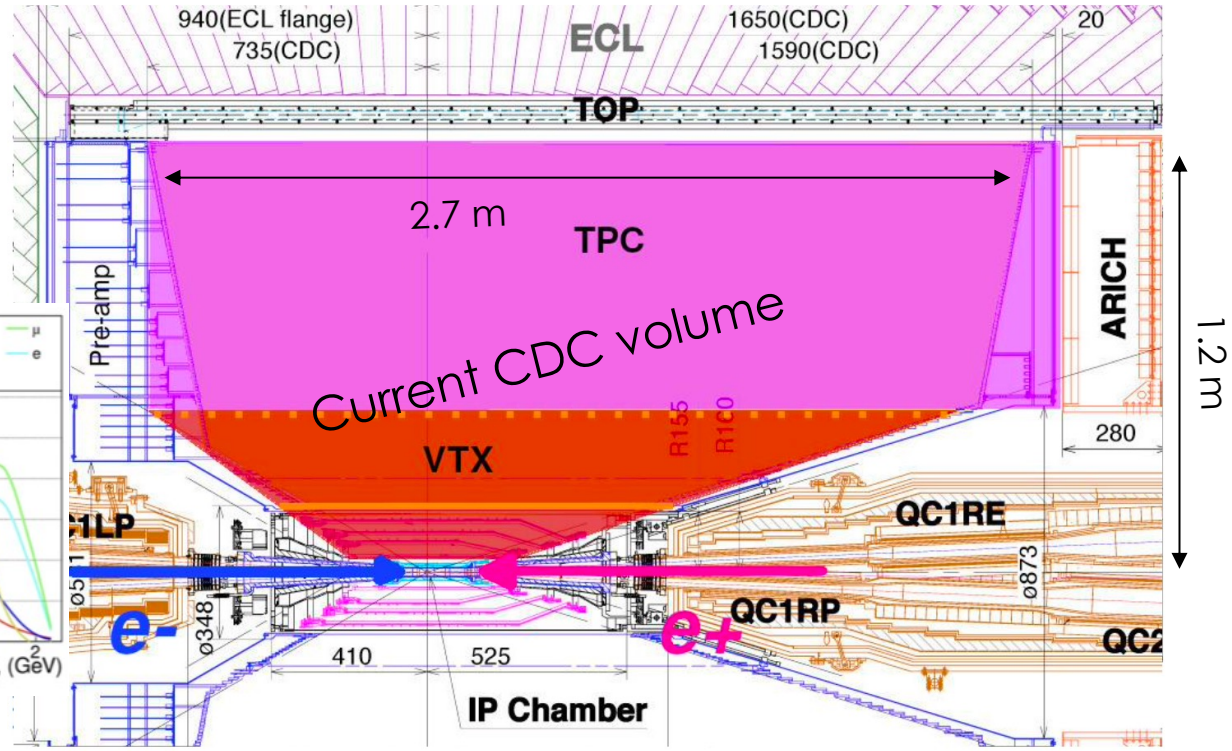
MAPS for Belle II beyond 2030

- For now, prospective ideas on simulation BUT strong interest for continuing

Change to the main tracker

- Replace partially or totally the CDC
- At least inner volume with MAPS
- Typical specs
  - Nanosecond timing
  - Provide trigger info swiftly (10 ns)
  - Large pixels OK





Introducing fast layer

- Goals: complement PID and provide trigger
  - A priori after main tracker (radius 1.2m)
  - Possibly within VTX volume as well
- Time resolution range 20-100 ps
- Could be MAPS

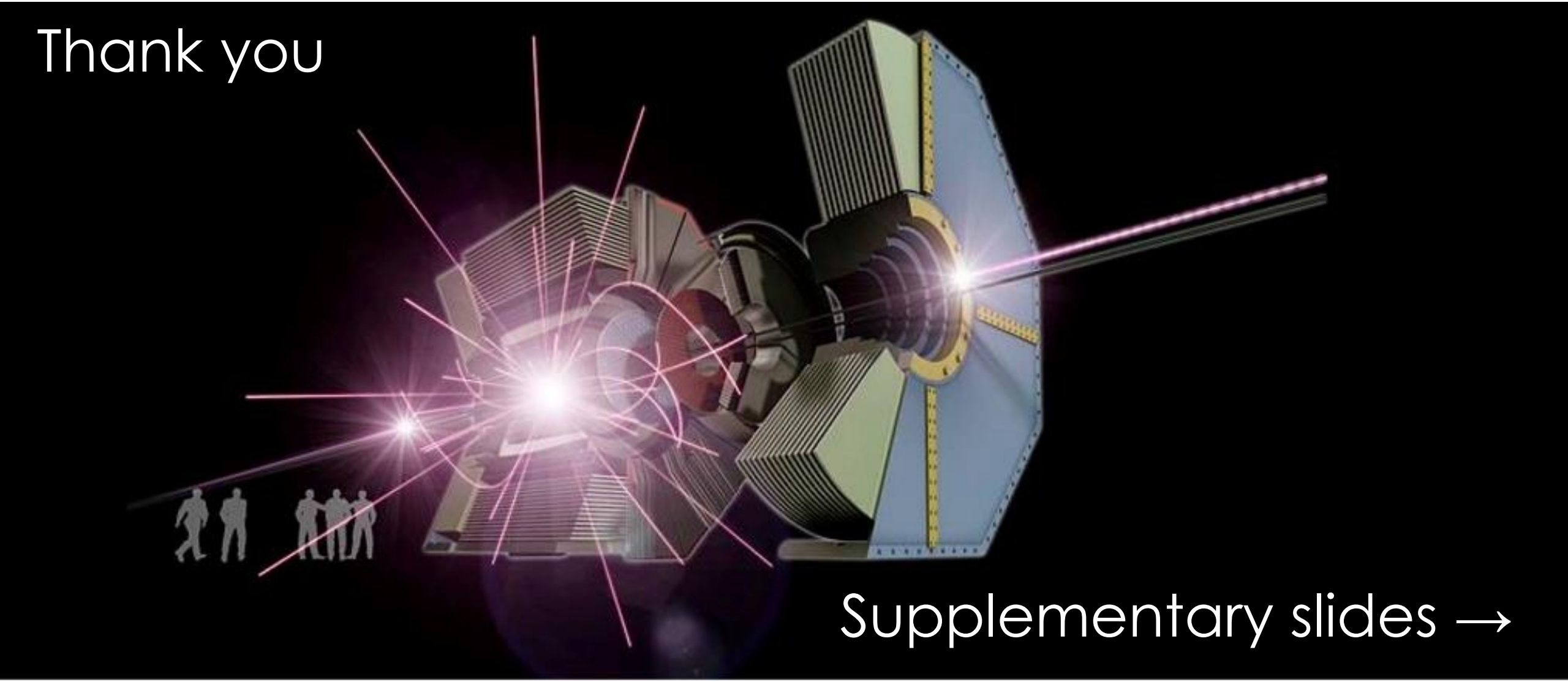
=> Large synergies with ECFA roadmap requirements

Take home messages

- A strong community issued from Belle II for R&D on MAPS
  - Across Europe & Japan
  - Expertise: design + characterisation + integration
    - Currently engaged in R&D with interest in long-term involvement

- Flying (i.e. proper detector perf for physics) is about balance
  - The difficult side to monolithic design: everything, everywhere, all at once

Thank you

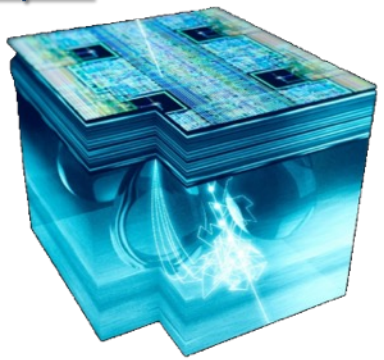


Supplementary slides →

CMOS-MAPS R&D in a nutshell

General concepts

2x2 submatrix view
thickness ~50 µm
© M.Mager



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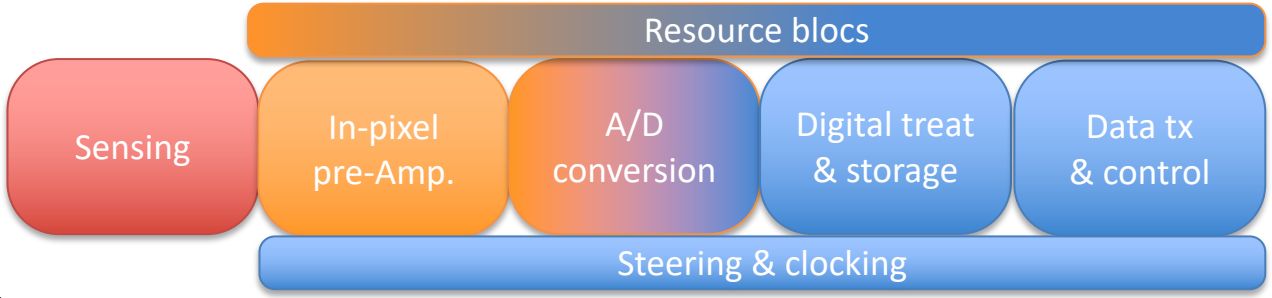
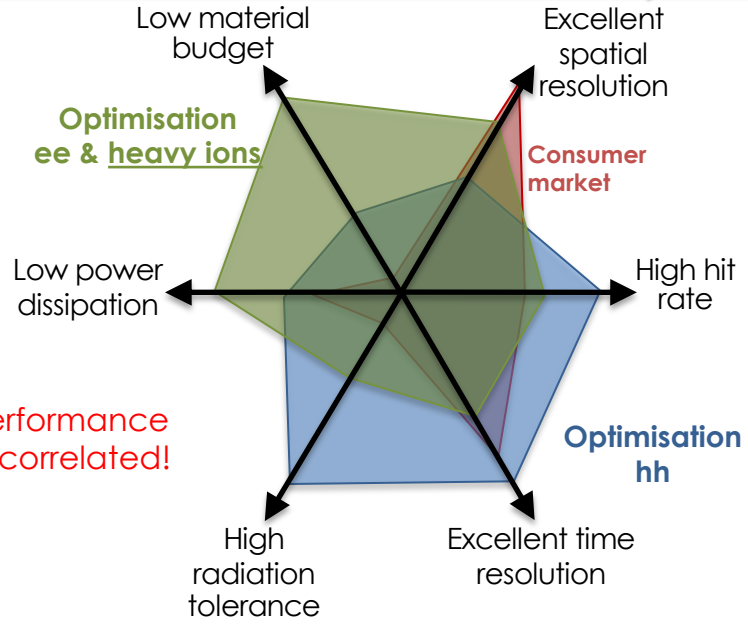
Monolithic active pixel sensor



R&D topics for each box

Performance is a matter of optimisation

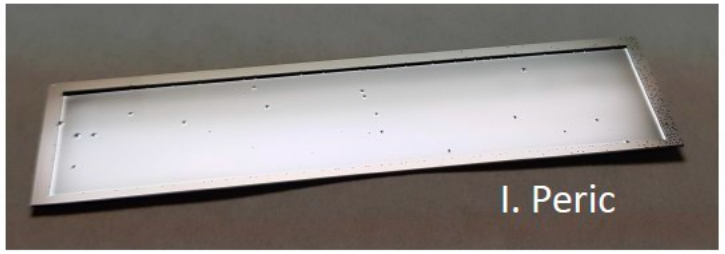


Some performance are anti-correlated!

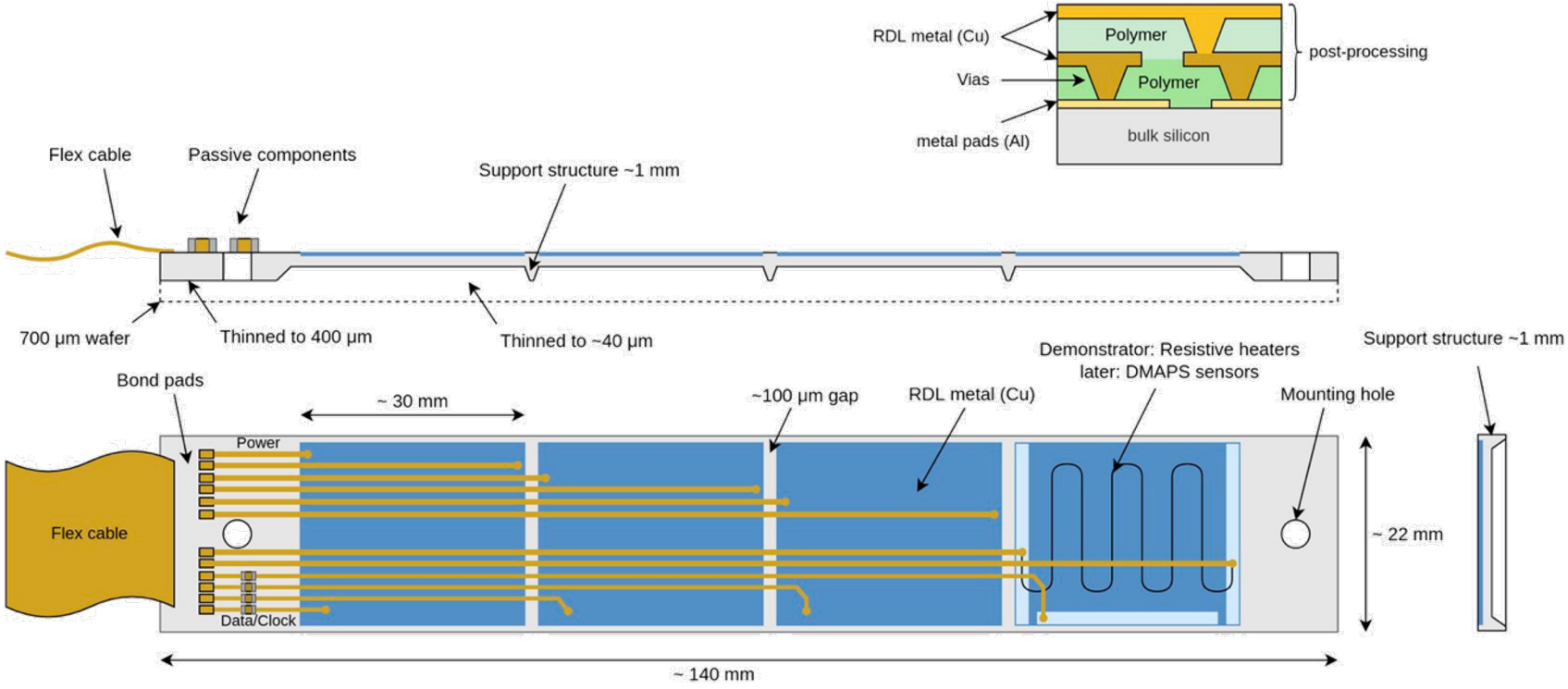
or

iVTX inner layer concept

- **Self-supported all silicon module**
  - Inherited from Belle II-PXD, also explored with ATLASPix →
  - 4 contiguous sensors diced out of wafer => 12cm long
  - Interconnected with redistribution layer
  - Heterogeneous thinning
    - "thick" edge walls for stiffness
    - thin (40 µm) sensitive area
  - Air-cooled
    - First simulations with 200 mW/cm^2 encouraging

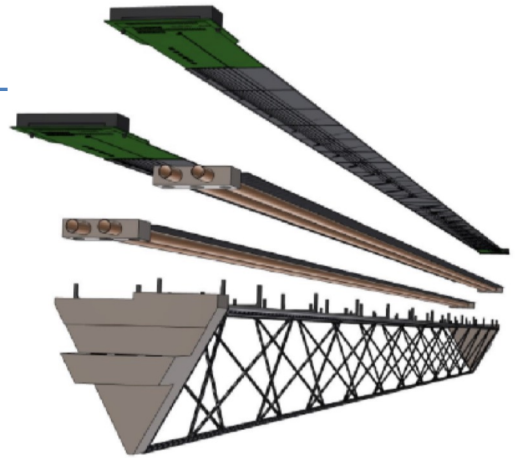


7.1x1.5 cm^2
Thickness (edge/center)
430/90 µm
Planarity ~17 µm

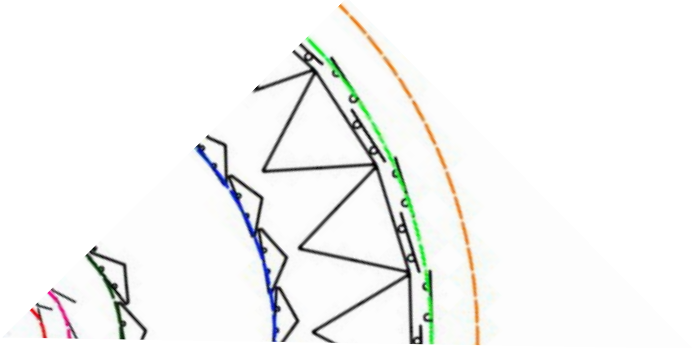


- **Prototyping on-going**
  - Process evaluation with dummy wafers
  - Thermo-mechanical tests
    - Using resistive heaters
  - Electrical tests with RDL
    - Signal integrity, power delivery

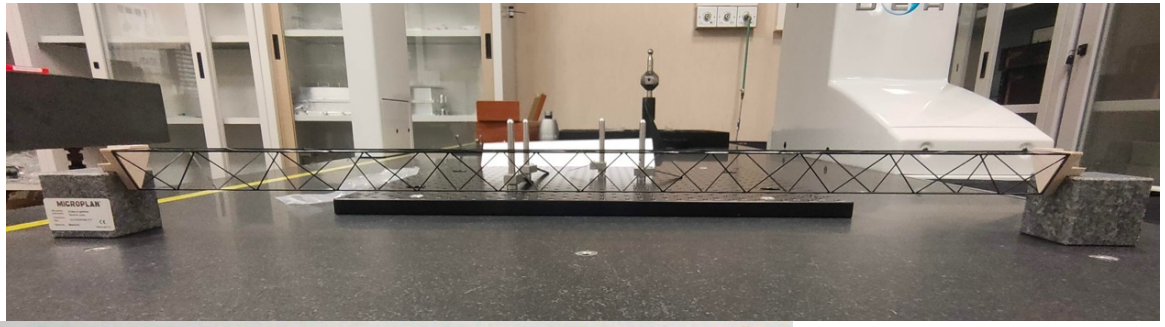
oVTX outer layer concept

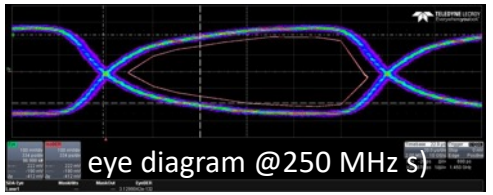


- **Long ladders**
  - Inherited from ALICE-ITS2
    - Carbon-fiber truss support frame
    - Cold-plate with water coolant
    - Long-flex for power & data
  - L3-4, radius 4-9 cm, length < cm
    - Single sensor row, ~0.5 % X_0
  - L5, radius 14 cm, length 70 cm
    - Double sensor rows , ~1 % X_0



- **Prototypes for L5 under test**
  - Truss fabricated
  - Flex cable

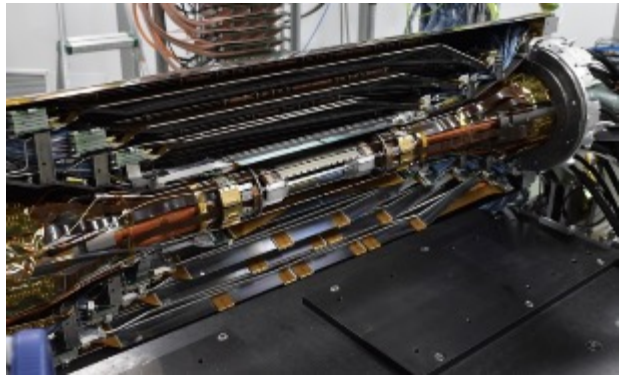




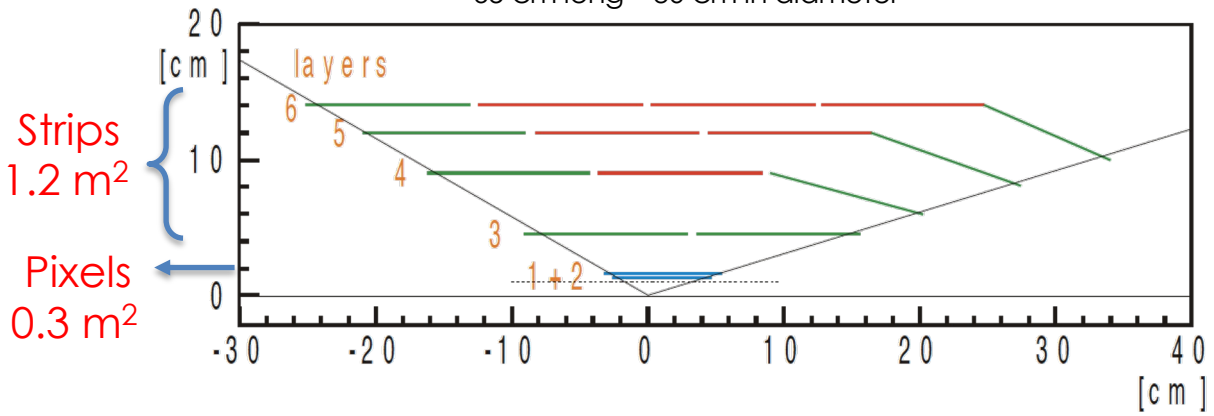
The current Belle II-VXD

- Two technology system
  - **SVD = Double-Sided Strip Detector**
    - Read-out sensor connected on sensor = Origami
    - Hit time-stamping σ_t <3 ns
    - Spatial resolution $\sigma_{s.p.}$~ 8-30 µm depending on pitch

=> SVD technical paper: arXiv:2201.09824



65 cm long – 30 cm in diameter



  - **PXD = DEPFET sensors**
    - Very low material budget 0.2 % X_0 / layer
    - Small first layer radius = 1.4 cm with pixel size 50x(55-85) µm2
    - Long integration time 20 µs / trigger rate & injection bkg