EU grant n.101183137

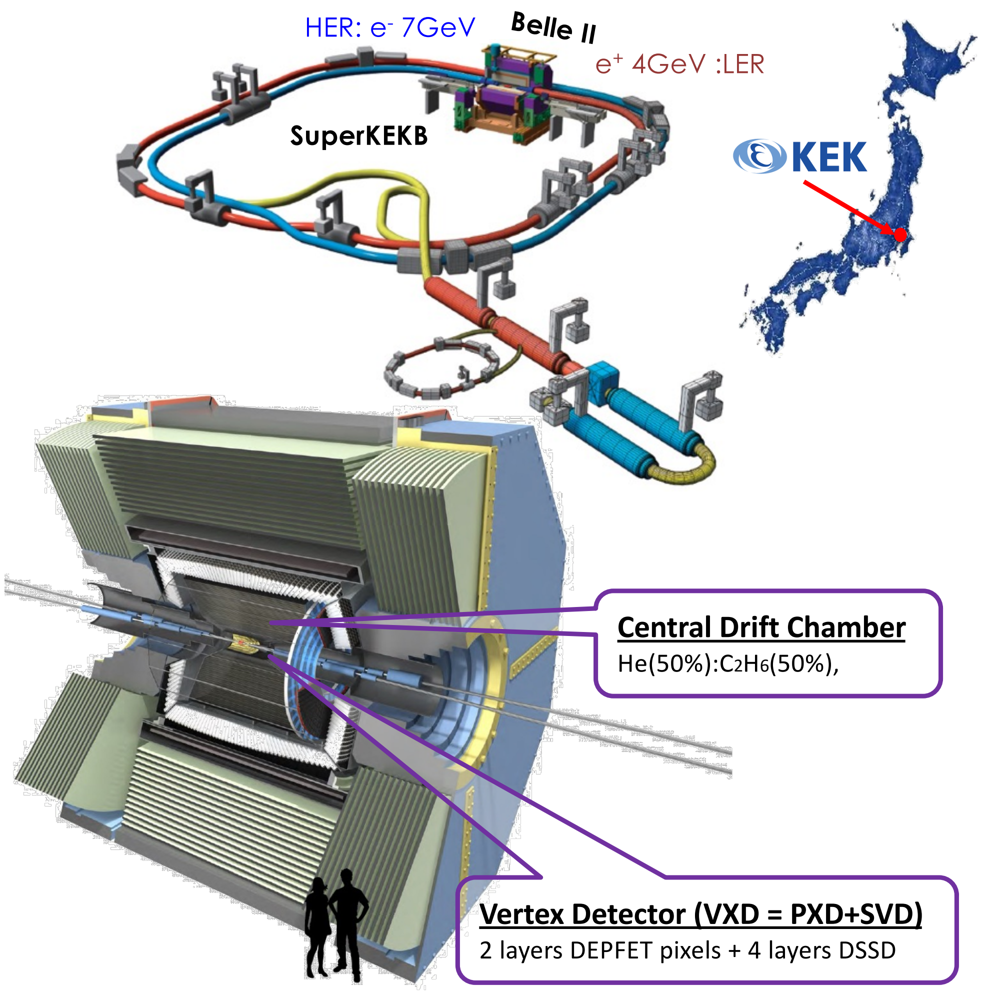
**JENNIFER3 kickoff meeting**
IFAE, Barcelona, 27-28 January 2025
https://agenda.infn.it/event/44427/

# Upgrading the Belle II vertex detector:
## *The VTX project*

Jerome Baudot
on behalf of VTX collaboration

- → Belle II & SuperKEKB program
- → Motivations & requirements for a vertex detector upgrade
- → Monolithic sensor development
- → Inner & outer ladders developments
- → Toward a system concept

# Belle II @ SuperKEKB

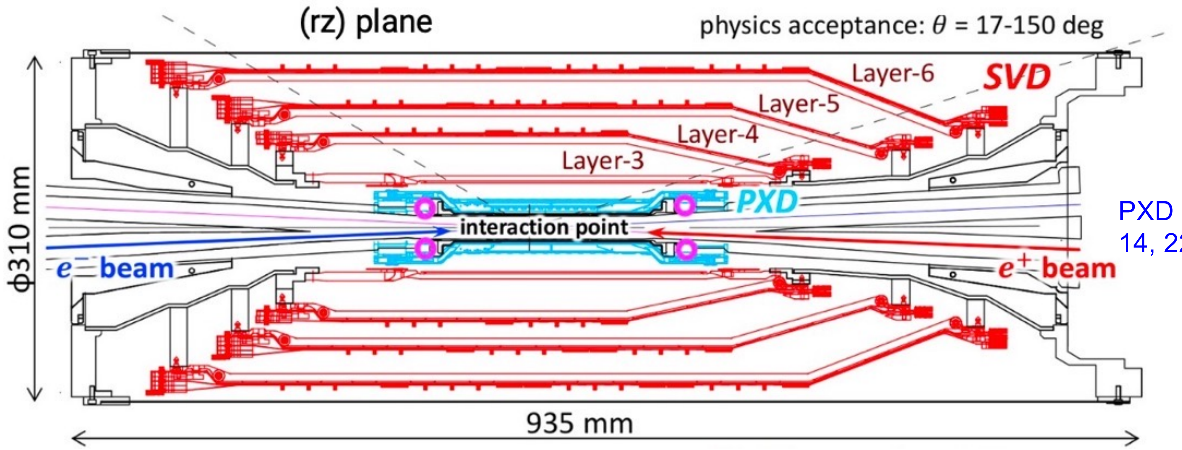



**Luminosity driven program to search for physics beyond Standard Model with cc, bb, $\tau\tau$ pairs**

- SuperKEKB: e+e- collider at $\sqrt{s} = M_{\Upsilon(4S)}$
  - High-luminosity <= nano-beams + high-current
  - Challenging beam-background conditions worsening with $\mathcal{L}$ + predictions with large uncertainty
- Run I 2019-2022
  - 428 fb$^{-1}$ integrated with full SVD + 80% PXD
- Run II 2024-
  - LS1: accelerator improvements, 100% PXD+SVD
  - **World record $\mathcal{L}$ = 0.5 x10$^{35}$ cm$^{-2}$ s$^{-1}$**
  - Push toward 2 x10$^{35}$ cm$^{-2}$ s$^{-1}$
- Further planning
  - Target 6 x10$^{35}$ cm$^{-2}$ s$^{-1}$
  - Requires interaction region improvements

# Current vertex detector: VXD

- 2 inner layers: PXD
  - DEPFET sensors
  - **Pitch 50-75 µm, Integration time 20 µs**
  - Read-out not triggered
  - full silicon layer (sensor 75 µm thick)
    - material budget: 0.25 % $X_0$ / layer
  - Occupancy limit 3%




PXD radii 14, 22 mm

- 4 outer layers: SVD
  - DSSD sensors
  - **Time resolution 3 ns, Strip length 6 cm**
  - Origami-concept, $CO_2$ cooling
    - material budget: 0.75 % $X_0$ / layer
  - Triggered read-out, latency limited to 5 µs
  - Occupancy limit ~6%

- Excellent performance @ occupancy ≲ 1%
  - Warning: PXD sensitive to large dose from sudden beam loss
- Prospect for the $10^{35}$ $cm^{-2}$ $s^{-1}$ lumi regime
  - High uncertainty on beam induced background level
  - Occupancy limits may be reached (SVD-L3)

# Upgrading the current VXD?

- Motivations
  - **Robust tracking & vertexing for any beam-background**
  - **Adapt to possible new Interaction region**
  - **Possibly increase performance for physics**

⇨
- **Higher space-time granularity**
- **Lighter material budget**
- **Higher radiation tolerance**
- **Simplified services**

- Requirements

| | |
|---|---|
| Same r-φ acceptance | 14-135 mm / 17-150 deg |
| Spatial resolution | < 15 μm |
| Time-stamping | 50-100 ns |
| Total material budget | < 3.5% $X_0$ |
| Triggered read-out | 30 kHz, latency 10 μs |
| Average hit rate | up to 120 MHz/cm$^2$ |
| Total Ionizing Dose (inner) | 1 MGy |
| NIEL fluence (inner) | $5\times10^{14}$ $n_{eq}$/cm$^2$ |

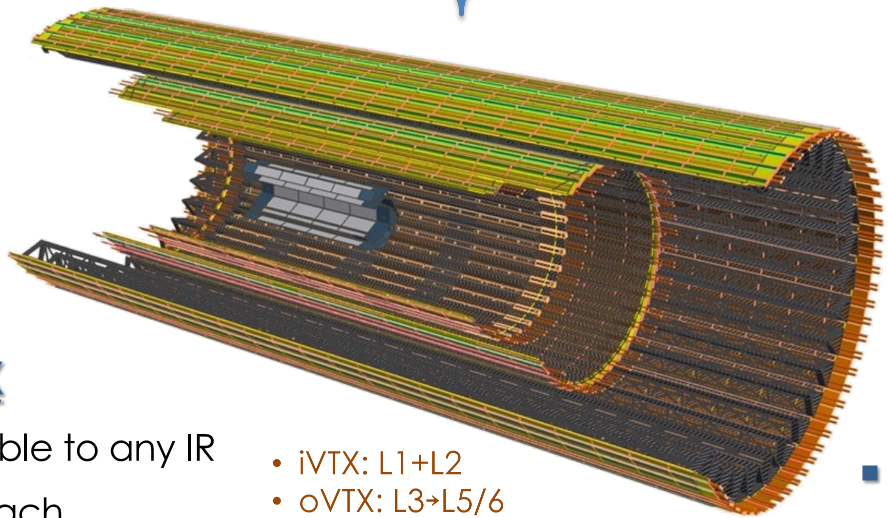
~1 m$^2$

Includes safety x4
conservative scenario

**+ Strong interest for**
- Time stamping < 5 ns
- Inputs for L1 track-trigger

# VTX main concepts

- **Geometry for vertexing & tracking**
  - Inner layers @ minimal radius & with redundancy
  - MIn 3 outer layers as light & as far as possible
- **Simple services**
  - Single-side connexion whenever possible
  - Simple cooling: air or liquid



- **2 inner layers: iVTX**
  - “On“ beam pipe
  - Full-silicon concept
  - Material $\lesssim$ 0.2 % $X_0$ /layer
- **3 to 4outer layers: oVTX**
  - Straight sections => adaptable to any IR
  - Support+Flex+Sensor approach
  - Material $\lesssim$ 0.8% $X_0$ / layer

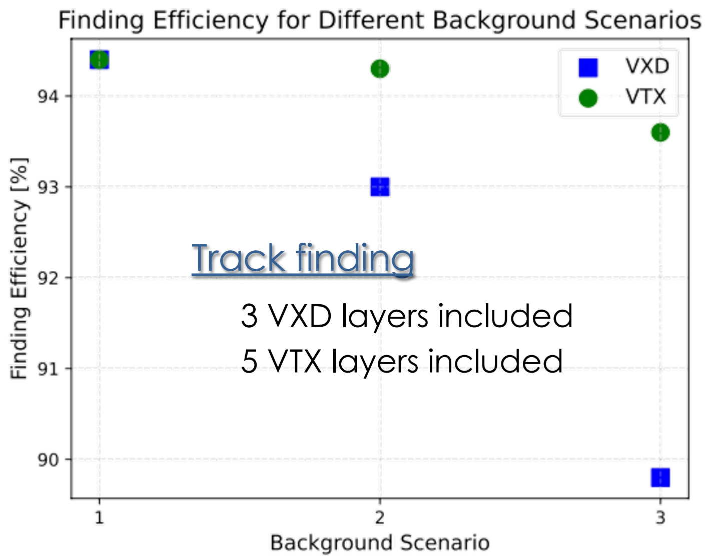
- iVTX: L1+L2
- oVTX: L3→L5/6
- Max length ~70 cm
- Radii: 1.4 to 14 cm

- **Same sensor everywhere**
  - Space & time granularity
    => occupancy ≪ 1%
  - Depleted MAPS: **OBELIX**
    – alternative SOI: DuTIP
- **Fast track reconstruction**
  - Full resolution in SW High Level Trigger
  - Reduced granularity for L1

**Framework Conceptual Design Report** arXiv:2406.19421 [hep-ex]

# Expected VTX performance

- **Full simulation**
  - Pixel response modeled + Simplified 5 layer geometry
  - Belle II Reconstruction SW (BASF2)
  - 3 Beam-induced background scenarios
    **V1: optimistic, v2 intermediate, v3: conservative**
  
  => occupancy reduced /200 with VTX

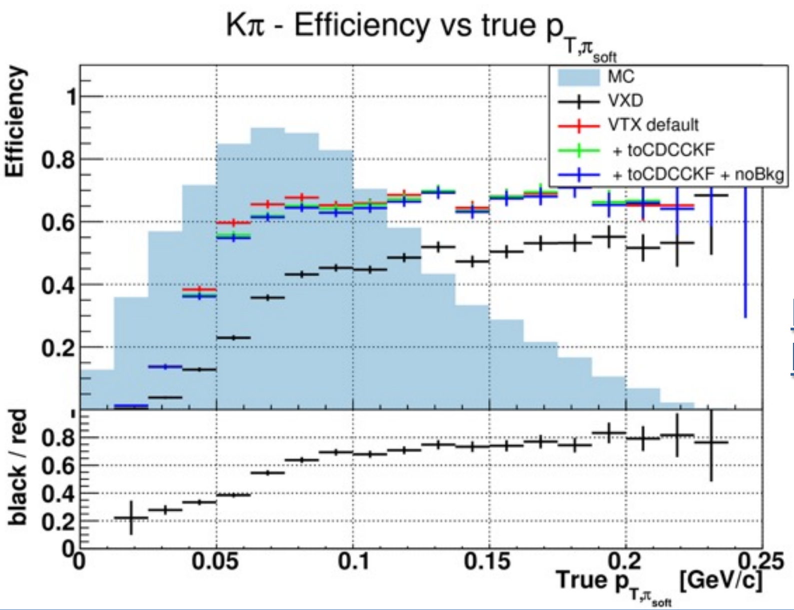



**Track finding**

3 VXD layers included
5 VTX layers included

**Resolutions studies**

- $B^0 \to J/\psi(\mu\mu)K_S(\pi\pi)$ and $B^0 \to K_S\pi\pi\gamma$
- B vertex resolution 20 to 50%
- Flavour tagger ~ performance




**Improvement at low momentum**

Soft π reconstruction
in $B^0 \to D^{*-}\mu^+\upsilon_\mu$
↳ $\overline{D^0}\pi^-$

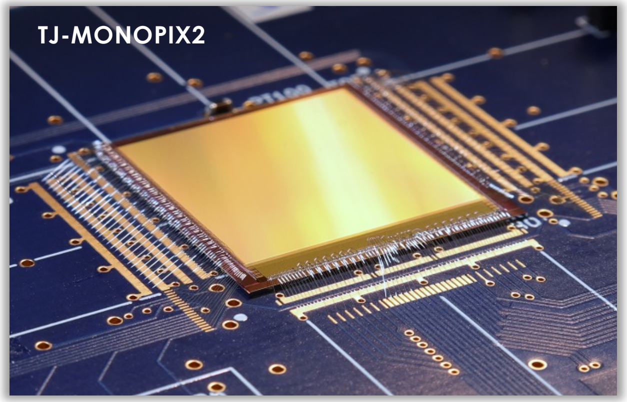
- ➢ **Strong resilience to background**
- ➢ **Improved performances**

**=> Geometry optimisation on-going**
- 6 layers

# VTX sensor

**TJ-Monopix2 Large proto ~4 cm² chosen as pixel matrix**

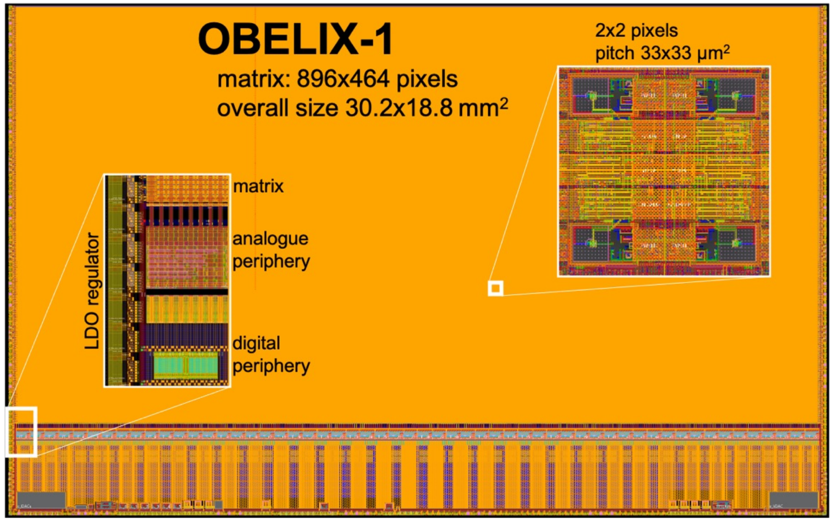
- TJ 180 nm CIS process
- Bonn, CERN, CPPM, CEA-IRFU
  [DOI: 10.1016/j.nima.2020.164403](https://doi.org/10.1016/j.nima.2020.164403)
- Modified process for depletion
  => radiation tolerance
- Column-drain read-out
  inherited from ATLAS FE-I3




**Steps toward Optimised BELle II pIXel sensor (OBELIX)**

- **Characterisation of TJ-Monopix2 pixel matrices**
- **Design of 1st complete sensor OBELIX-1**
  - Extension of TJ-Monopix-2 pixel matrix
  - New digital logic + voltage regulator

  **=> Submission Q1 2025**
- Characterisation of OBELIX-1
- From OBELIX v1 to v2
  - corrections & option choice driven by tests
  - Addition of SEU protection



# Characterisation of TJ-Monopix2

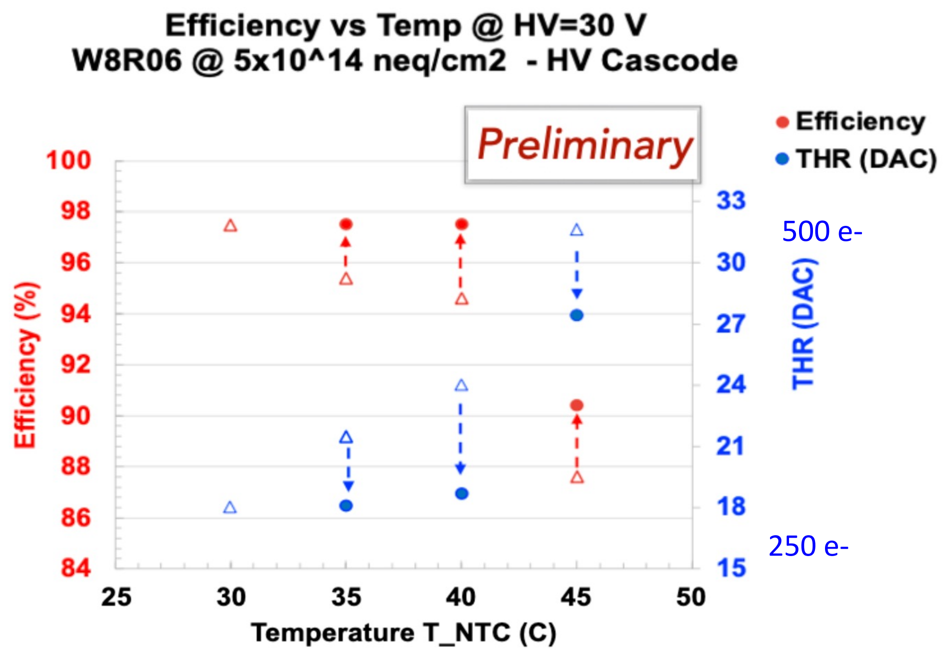
## Sensor tuning

- Detection threshold range: 250 to 500 e-
- Temporal noise ~8 e-
- Threshold Dispersion ~17 e-

## Detection efficiency

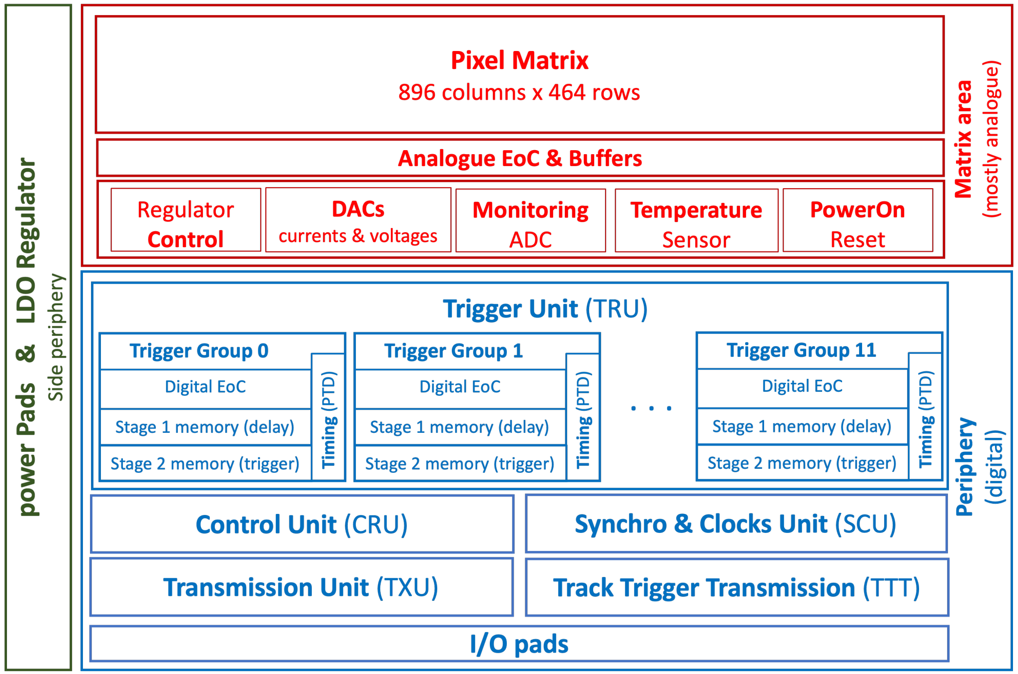
- Tests @ DESY & KEK, 4-6 GeV e- beams
  - 2023, 23, 24, (25)
- Non irradiated sensors
  - uncontrolled temperature, threshold ~500 e-
  
  => uniform 99% det. efficiency, $\sigma_{position}$ ~9 µm
- **Sensors irradiated with $5.10^{14}$ $n_{eq}cm^{-2}$**
  - temperature 40 to 60 ˚C, threshold 250 to 400 e-

  => Preliminary: ~40 ˚C on sensor required



10-15 ˚C below T_sensor

# Design of OBELIX-1

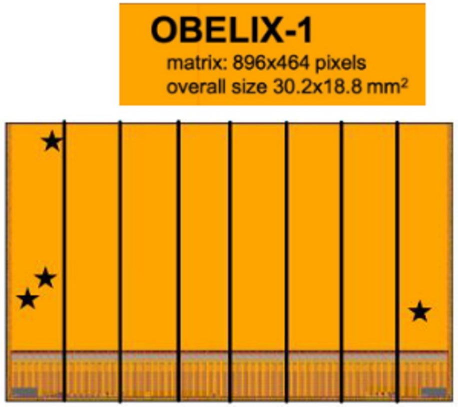



DOI: 10.1016/j.nima.2023.168015

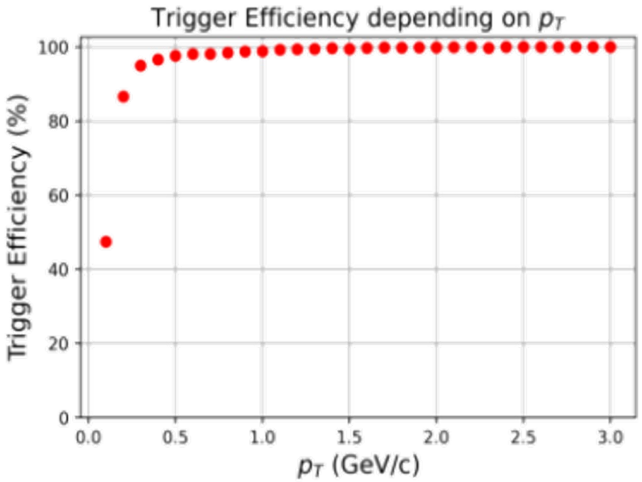
- **Matrix design**
  - Extended copy of TJ-Monopix2
  - Clock for time-binning slowed down: 100ns
- **Powering**
  - LDO regulator for easier voltage distribution
  - Overall power depends on hit rate: 200-300 mW/cm$^2$
- **Trigger Unit**
  - Simulated with realistic inputs: 120 MHz/cm$^2$
  - Can sustain 800 MHz/cm$^2$ for 0.5 μs
- **Fine time stamping**
  - 6 ns achievable with end-of-column fast clock
    - Limited to hit rate <^ 10 MHz/cm$^2$
- **Track trigger**
  - Reduced granularity to 8 striplets ( ~4 x18 mm$^2$)
  - Increased transmission rate: 33 MHz

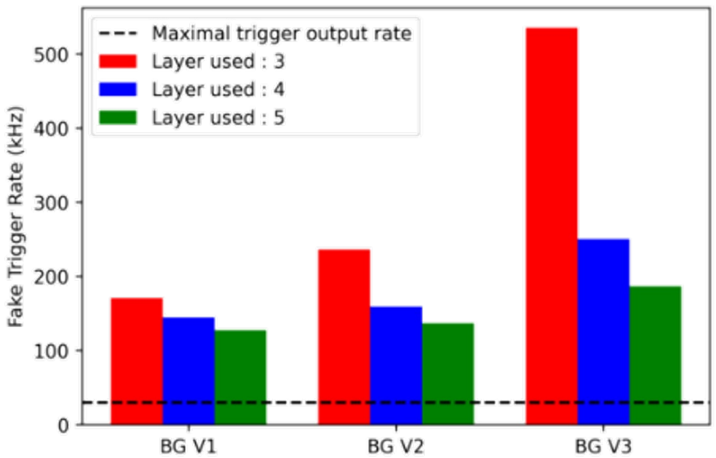
# Track trigger performance

- A software estimation
  - Exploit Full 5 layer geometry simulation
  - Granularity reduced to 8 striplets/sensor




- Track reconstruction
  - Training: store track hit-patterns in Look-up table
  - Reco: search hit-pattern in table => track



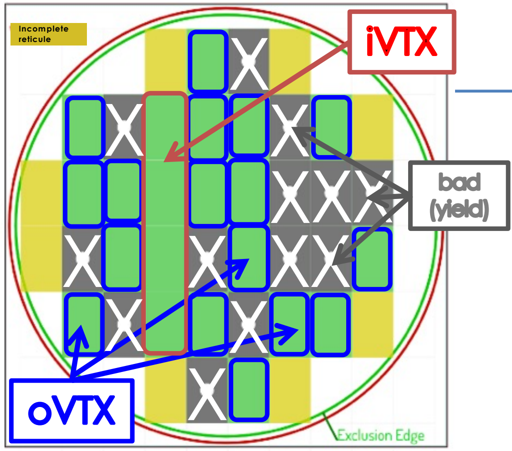



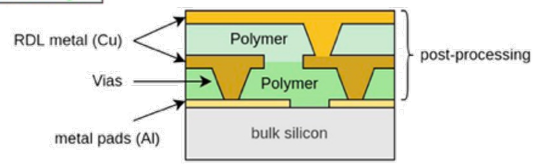

- Excellent standalone efficiency
- Fake track rate too high for standalone trigger

BUT ok with drift-chamber
=> improved z-resolution

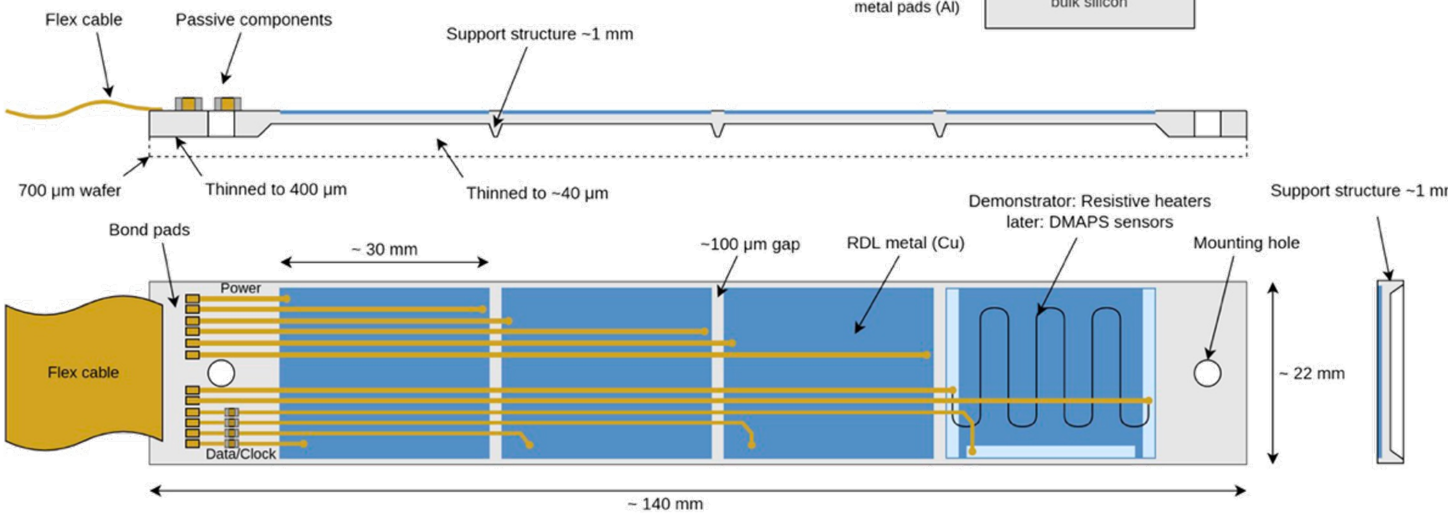
# iVTX: inner layer design

- Self-supported all silicon module
  - 4 contiguous sensors diced out of wafer => 12 cm long
    - Insensitive distance from adjacent pixel matrices ~ 500 µm
  - Interconnected with redistribution layer
    - 2 metal layers
    - Single connexion at ladder end
  - Possible heterogenous thinning
    - thick edges versus thin matrix
    - Smallest material budget **~0.1 % $X_0$**



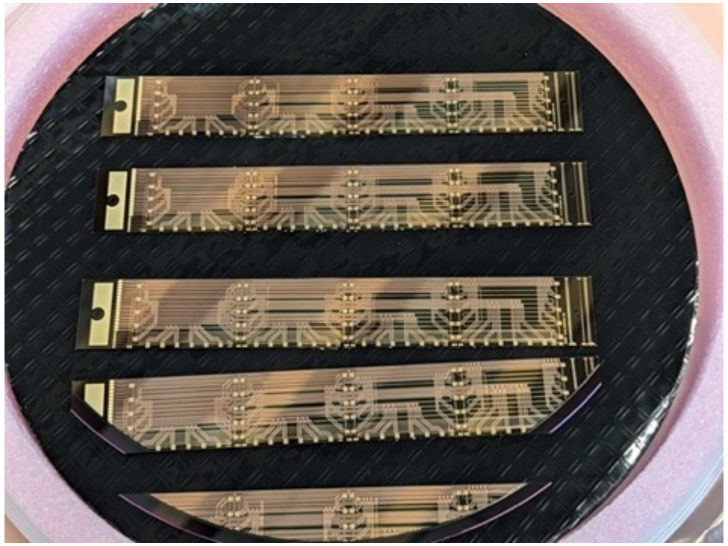

**Dummy ladder design:**



# iVTX: Inner layer prototyping

## Dummy ladders

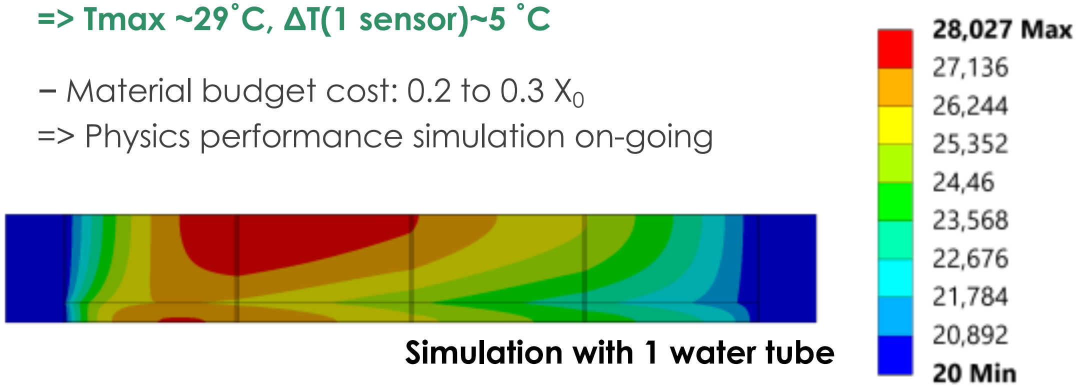
- Full silicon wafers with resistive heaters
- RDL processed at IZM-Berlin
- Uniform thickness 700 µm



- Currently under test

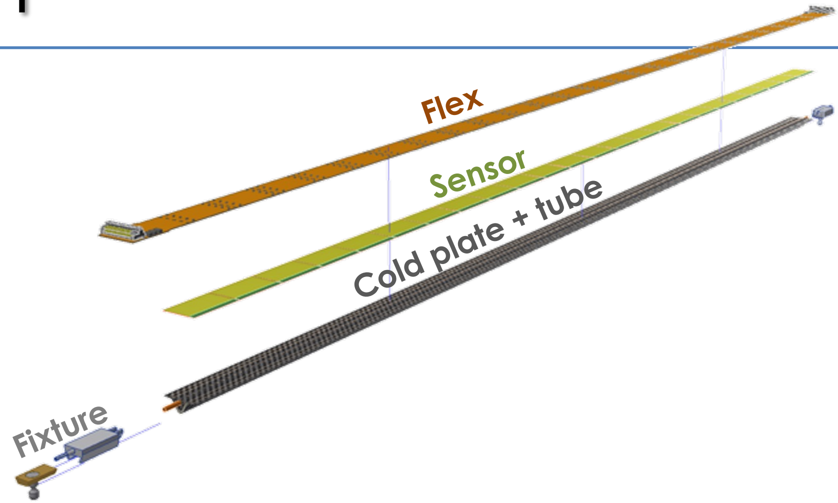
## Cooling studies

- **Full air cooling**
  - Simulations
    & wind tunnel measurements on dummy ladder
  - Air speed 10 m/s
  
  => Tmax ~50˚C, ΔT(1 sensor)~10 ˚C
  - Solutions under study to bring air to inner volume
- **Water tube** in contact with sensor periphery
  - Tube ø1.2mm, flow 0.2 µl/min
  
  **=> Tmax ~29˚C, ΔT(1 sensor)~5 ˚C**
  - Material budget cost: 0.2 to 0.3 $X_0$
  
  => Physics performance simulation on-going




**Simulation with 1 water tube**

# oVTX: outer layer design




## Recipe for long and light staves

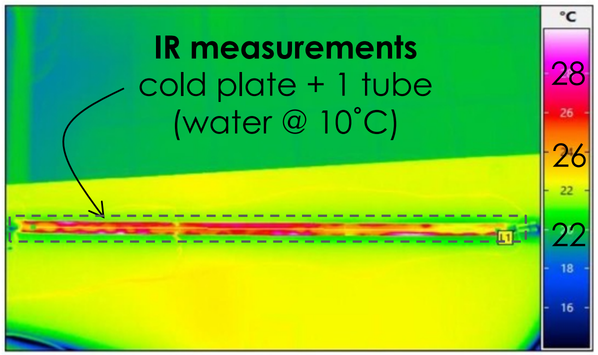
(Inherited from ALICE-ITS2)

- Carbon fiber support frame
- Cold-plate with 1 coolant tube
- Long-flex for power & data
  - Longest flex: 1x12 sensors => 1-side output
  - Longest stave: 2x12 sensors => 2-side outputs

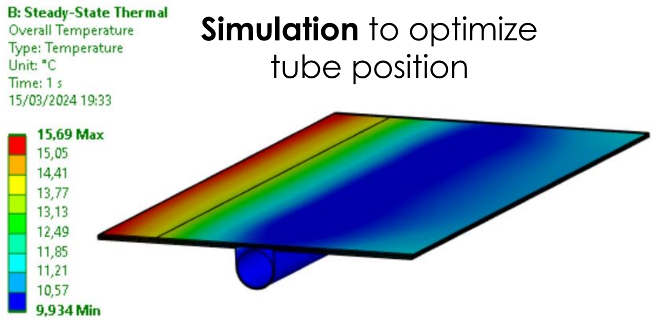
## Cooling studies

- Early prototype tested with 200 mW/cm$^2$

=> Tmax < 30˚C, $\Delta$T(1 sensor)~4 ˚C




Specific power : 200 W/cmq        Flow: 0,22 Kg/min




**Simulation** to optimize tube position

## Flex development

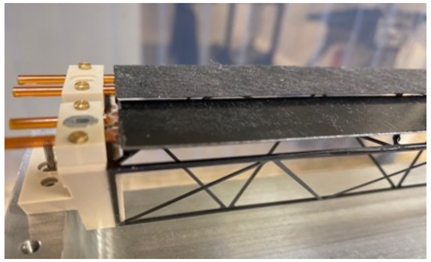
- 4 to 6 aluminium layers
- Investigating CERN workshop & Japanese Co.

# oVTX: outer layer design

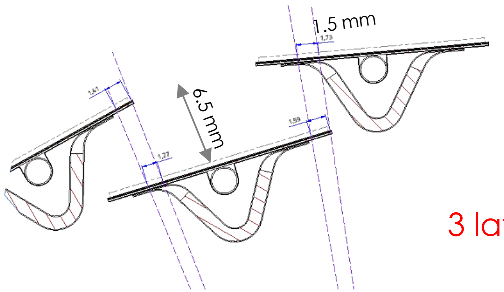
- <u>New Omega shape support</u>
  - Carbon fiber skin with rohacell core
    - way more compact / truss structure
    - Allow 3 to 4 layers at ~large radii
      => excellent for track-seeding & $K_S^0$

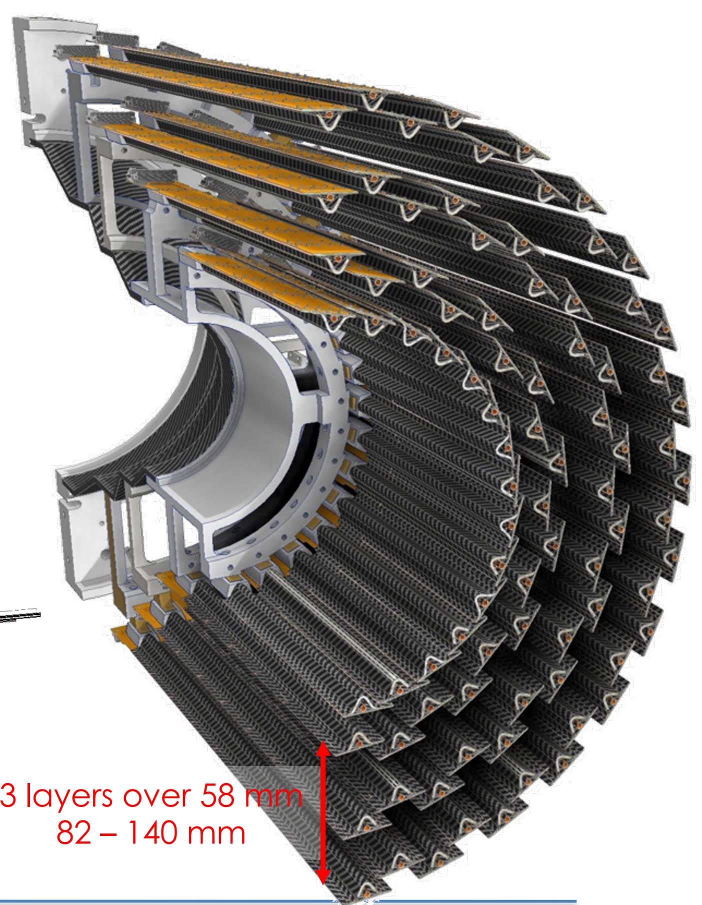
  **=> material budget ~0.45% $X_0$ from L3 to L5**

- <u>Bending over 70 cm?</u>
  - Simulations: sagitta < 100 μm
  - Measurement with prototype on-going

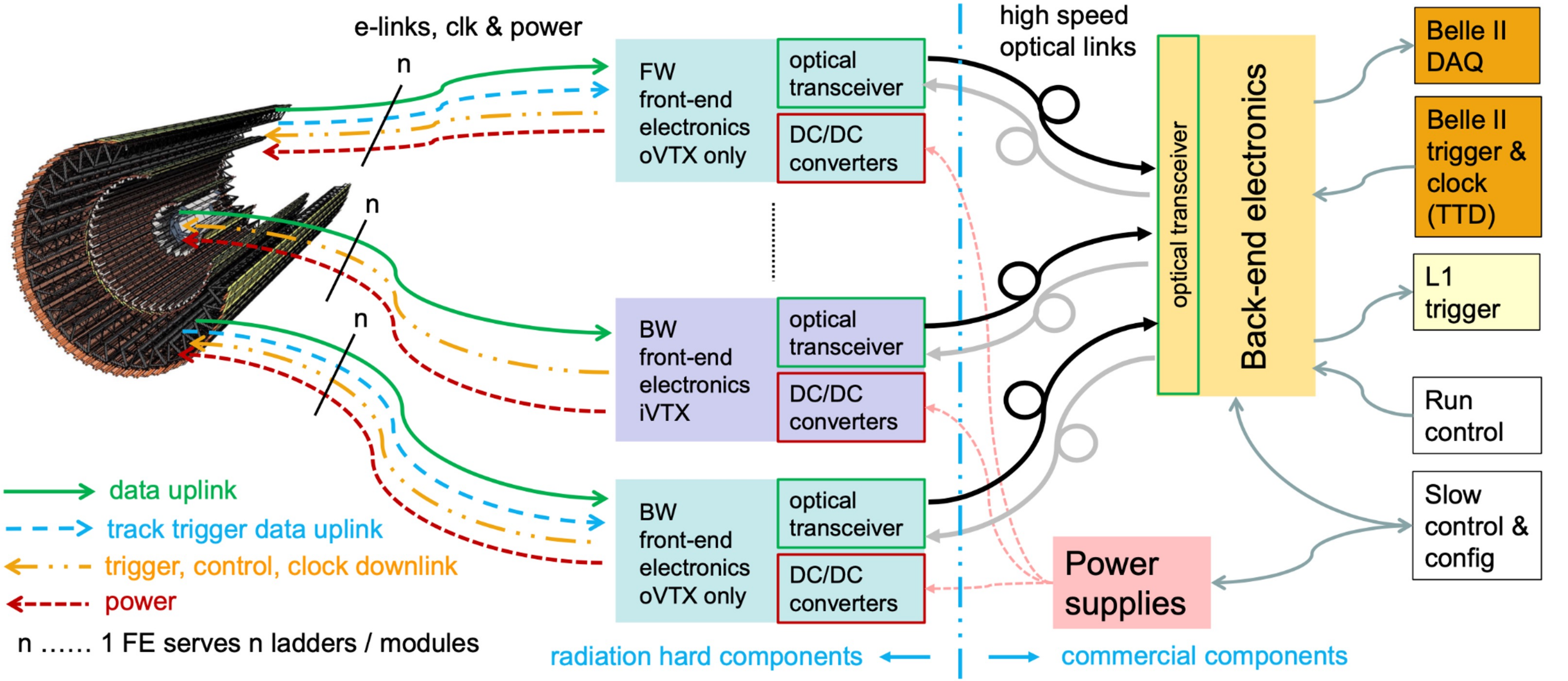


Truss structure + cold plate

# (Early) DAQ system concept



# Rough schedule & Collaborators

- R&D phase till 2027
  - Fabrication and extensive tests of OBELIX-1 => **design of final sensor OBELIX-2**
  - Prototyping of detection layers with OBELIX-1 => **design of final iVTX and oVTX layers**
  - Prototyping of DAQ / Environment control systems => **demonstrator**
  - Prototyping of mechanical support in parallel with interaction region potential change

  - => Construction phase from ~2027

- 22 institutes over 8 countries

University of Bergamo
IHEP, Beijing
University of Bonn
University of Dortmund
University of Göttingen
DESY, Hamburg
Jilin University
KIT, Karlsruhe
IPMU, Kashiwa
Queen Mary University of London
CPPM, Marseille
IJCLab, Orsay
RAL, Oxford
INFN & University of Pavia
INFN & University of Pisa
IFCA (CSIC-UC), Santander
IGFAE, Santiago de Compostela
IPHC, Strasbourg
University of Tokyo
KEK, Tsukuba
IFIC (CSIC-UV), Valencia
HEPHY, Vienna

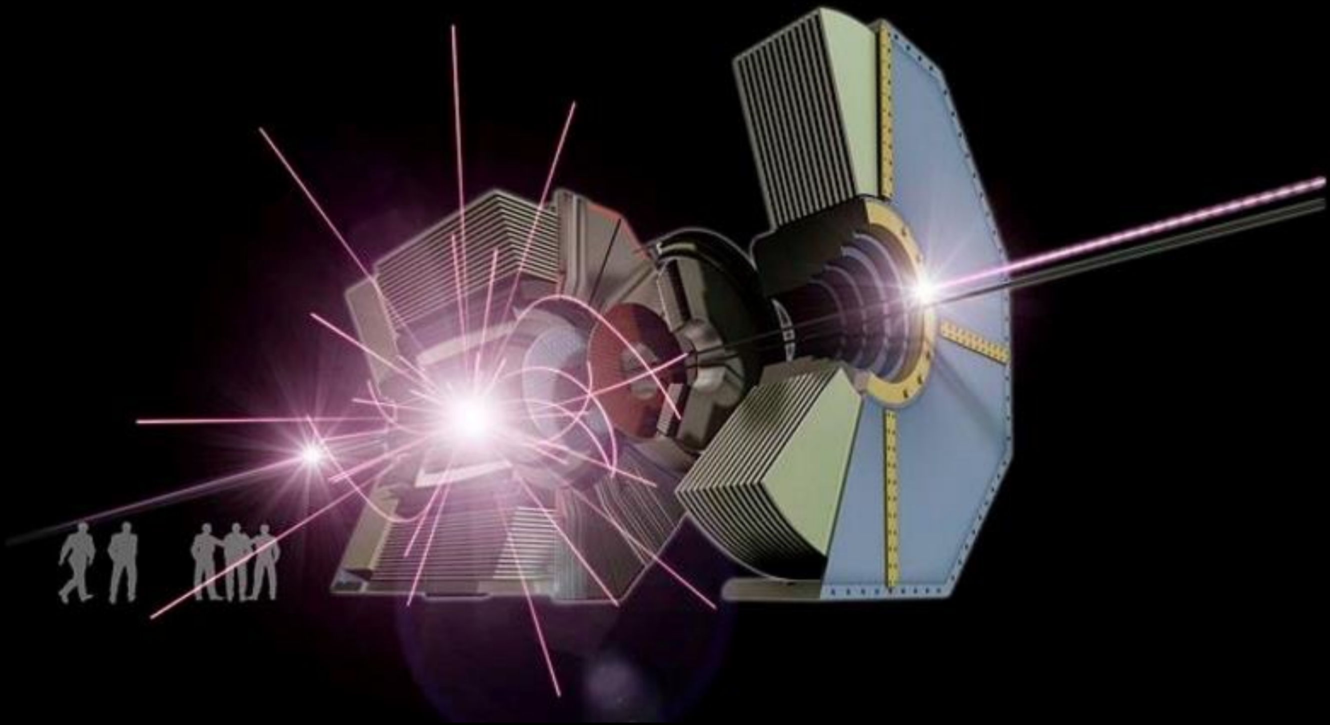
# Conclusion

- The VTX is a new generation of MAPS vertex detector
  - **Requirements combine: High hit rate / low material budget / low inner radius**
  - **Challenging operational conditions: Room temperature & Radiation tolerance**

- Intense detector R&D program still for ~3 years
  - **Phase transition with OBELIX-1 fab in 2025**
  - **Full system concept ⟶ demonstrator system (telescope / VTX sector)**
  - **Parallel to accelerator R&D for potential new interaction region**

⇨ **In line with Detector R&D roadmap (DRD3)**

# Thank you for your attention…

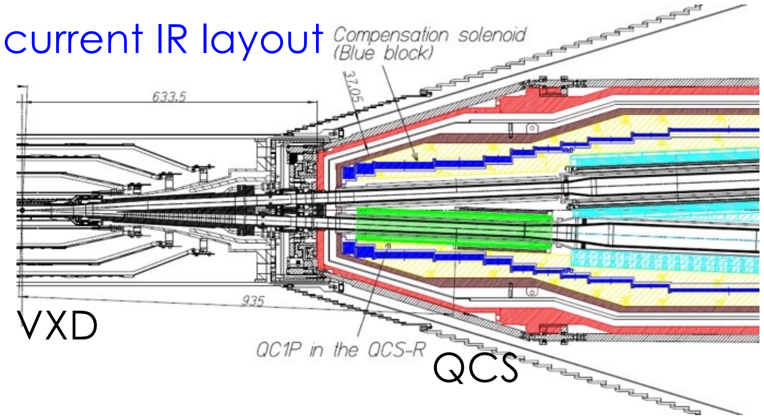


# Interaction region for higher lumi

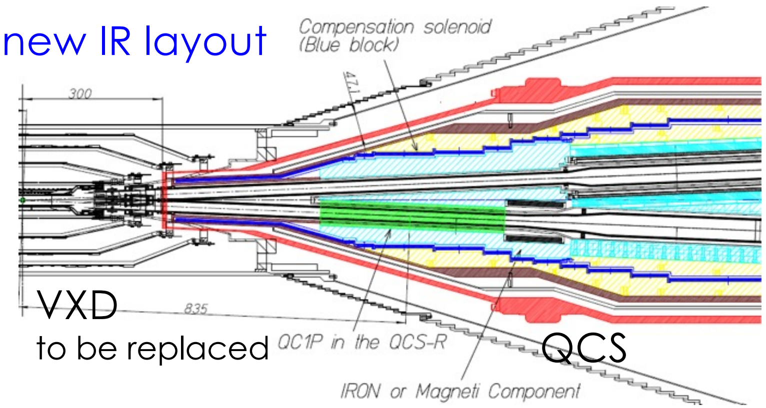
- Current machine
  - World luminosity record $4.7 \times 10^{34}$ $cm^{-2}.s^{-1}$ (2022)
  - Expected max lumi $\sim 2 \times 10^{35}$ $cm^{-2}.s^{-1}$
    - Main limit from dynamic aperture at Interaction Region (IR)

- Potential road toword $6 \times 10^{35}$ $cm^{-2}.s^{-1}$
  - New final focusing magnet (QCS) required
    - To increase dynamic aperture at IR
    - On-going R&D for feasibility
  - **Foreseen new QCS conflicts with current VXD volume => new VTX length & support**

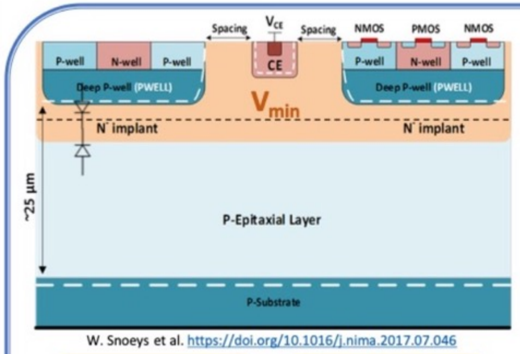
current IR layout




Potential new IR layout



# Modified process & TJ-Monopix2 details




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

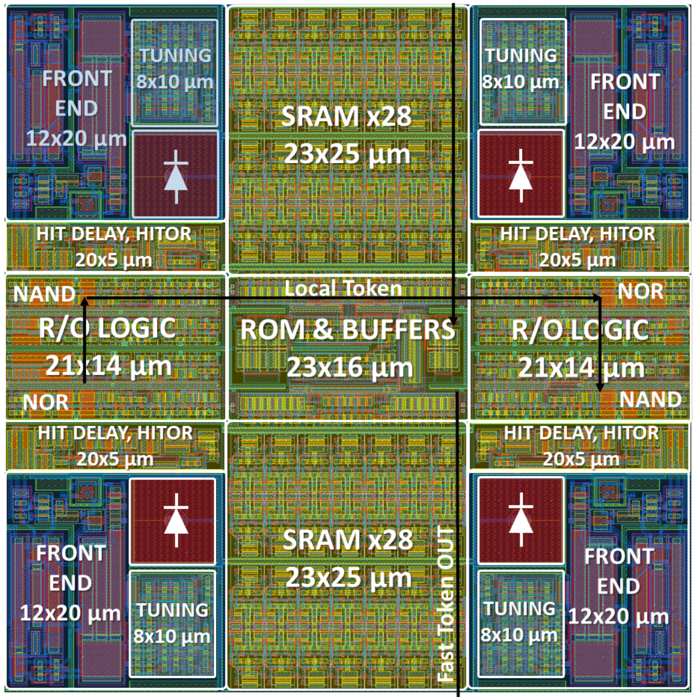
$C_d \leq 3fF$

$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$

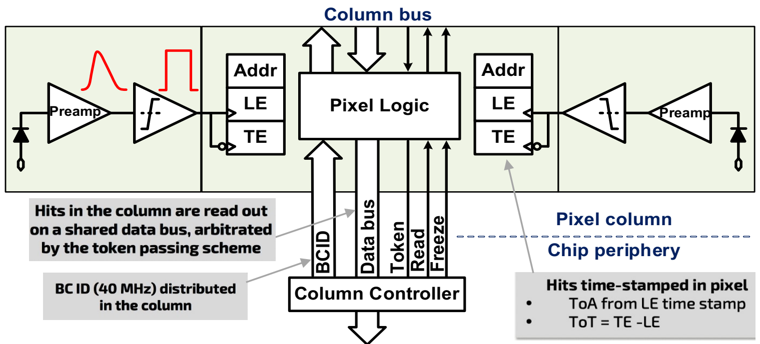
***DMAPS in TJ 180 nm: Concept***

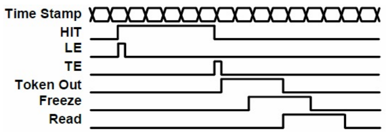
- **Small sensor capacitance (Cd)**
  - **Key for low power/low noise**
- **Radiation tolerance challenges**
  - **Modified process**
  - **Small pixel size**
- **Design challenges**
  - **Compact, low power FE**
  - **Compact, efficient R/O**

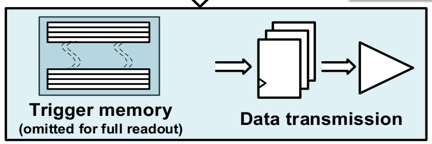
**The matrix Layout:**
2x2 pixels




**The logic:**

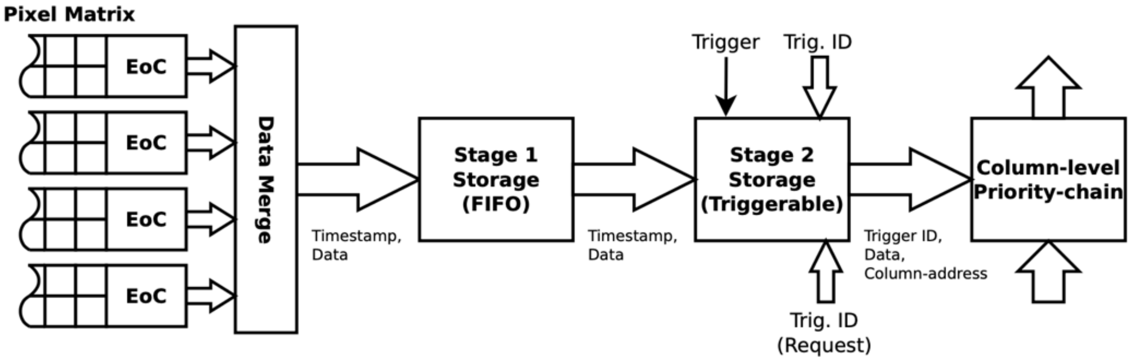


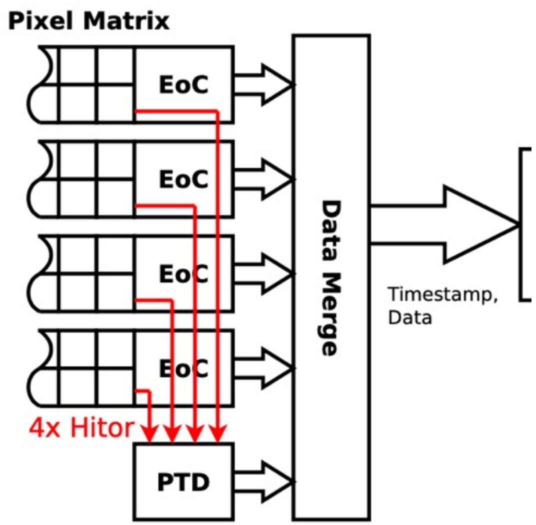



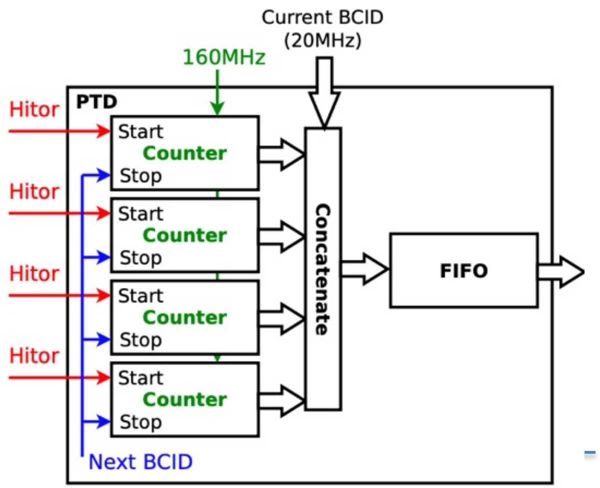
# Logic detail within OBELIX-1

**Trigger Unit**




**Peripheral Time to Digital**



# Choosing TJ-Monopix2

| | Belle-II depleted MAPS | TJ-Monopix2 |
|---|---|---|
| **Sensitive area** | ~30x17 $mm^2$ | 17x17 $mm^2$ |
| **Sensitive thickness** | ~30 µm | 25-100 µm |
| **Pitch** | 30 to 40 µm | 33 µm |
| **Signal digits** | 1 to few bits | 7 bits ToT |
| **Integration time** | 50 to 100 ns | 25 ns |
| **Hit rate (average)** | 120 $MHz/cm^2$ | > 100 $MHz/cm^2$ |
| **Triggered read-out** | 30 kHz, lat. 10 µs | |
| **Power** | ~200 $mW/cm^2$ | 200 $mW/cm^2$ |
| **TID fluence** | ~1 MGy ~$5.10^{14}$ $n_{eq}/cm^2$ | 1 MGy $3.10^{15}$ $n_{eq}/cm^2$ |
| **Oper. Temp.** | room+ | -20 ˚C |

# Belle II detector
Upgraded or new / Belle