International workshop on the high energy Circular Electron Positron Collider
Hangzhou, 18-22 October 2024
https://indico.ihep.ac.cn/event/22089

Upgrading the Belle II vertex detector:
The VTX project

Belle II

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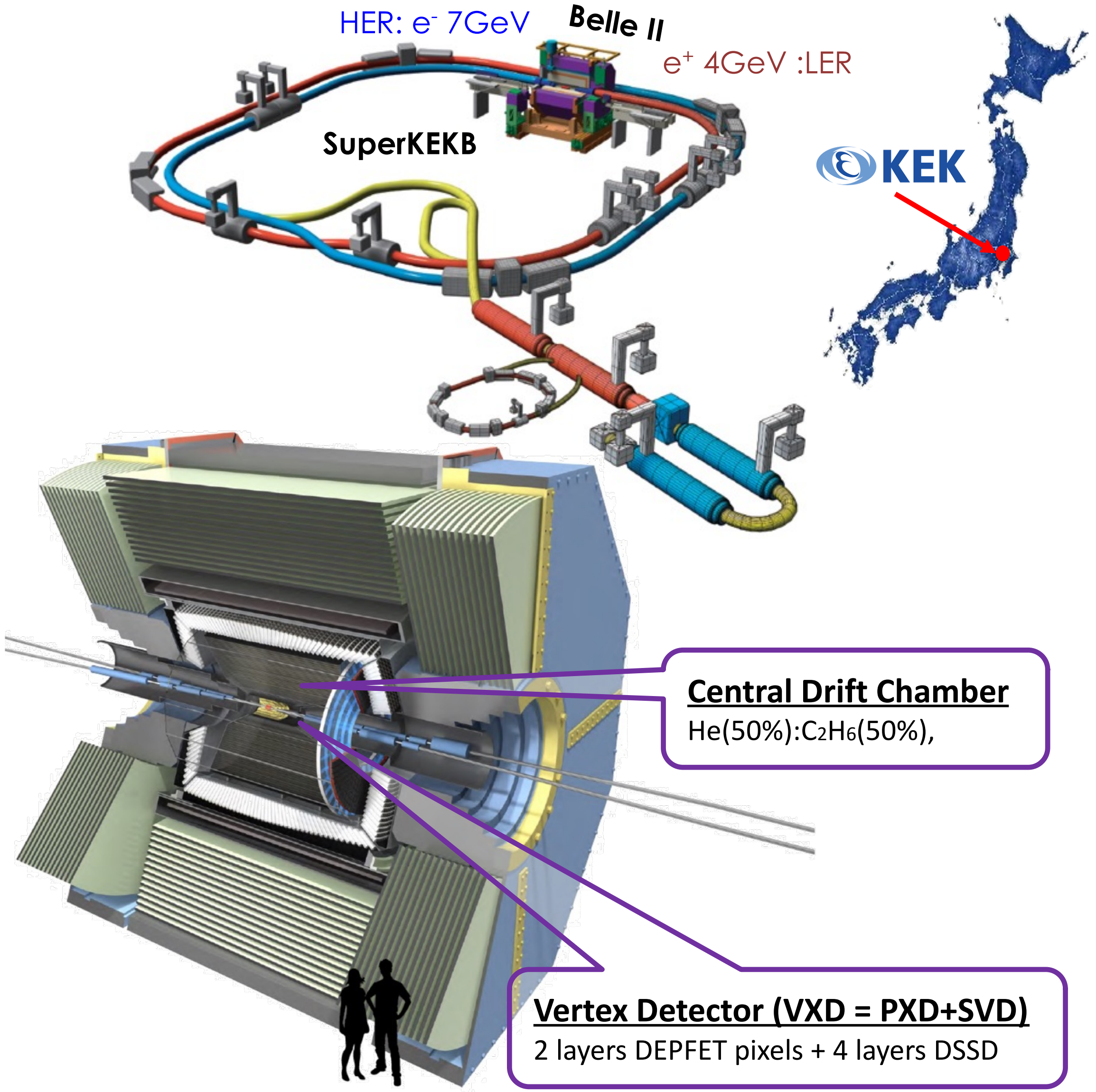
- Belle II & SuperKEKB program
- Motivations & requirements for a vertex detector upgrade
- Monolithic sensor development
- Inner & outer ladders developments
- Toward a system concept

The OBELIX / VTX collaboration

- 22 institutes over 8 countries

IGFAE, Barcelona
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
IPHC, Strasbourg
University of Tokyo
KEK, Tsukuba
IFIC (CSIC-UV), Valencia
HEPHY, Vienna

Belle II @ SuperKEKB



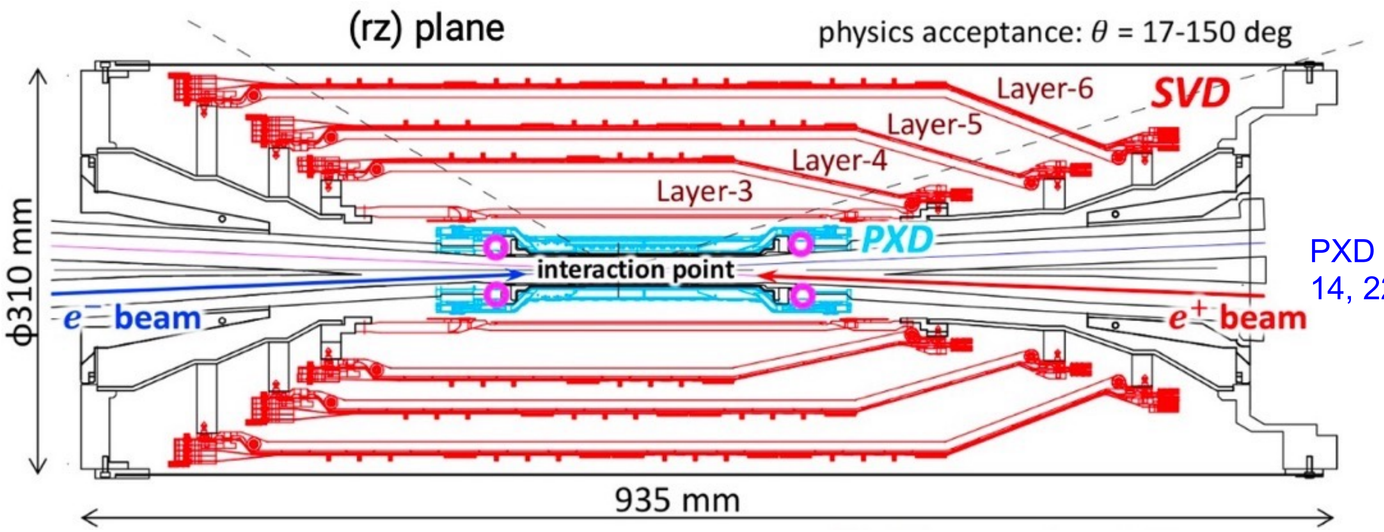
Luminosity driven program to search for physics beyond Standard Model with cc, bb, $\tau\tau$ pairs

- SuperKEKB: e+e- collider at $\sqrt{s} = M_{\Upsilon(4S)}$
  - High-lumi reach: nano-beams + high-current
  - Challenging beam-background conditions worsening with $\mathcal{L}$ but predictions suffer very large uncertainty
- Run I 2019-2022
  - **World record $\mathcal{L}$= 4.7 x10^{34} cm^{-2} s^{-1}**
  - 428 fb^{-1} integrated with full SVD + 80% PXD
- Run II 2024-
  - LS1: accelerator improvements, 100% PXD+SVD
  - **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**
    - Not triggered
  - full silicon layer (sensor 75 µm thick)
    - material budget: 0.25 % X_0 / layer
  - Occupancy limit 3%

- 4 outer layers: SVD
  - DSSD sensors
  - **Time resolution 3 ns, Strip length 6 cm**
  - Origami-concept, CO2 cooling
    - material budget: 0.75 % X_0 / layer
  - Triggered read-out, latency limited to 5 µs
  - Occupancy limit 6%



PXD radii
14, 22 mm

- Excellent performance @ occupancy ≲ 1%
  - Warning: PXD sensitivity to large dose from beam aborts

- 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	~1 m^2
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	Includes safety x4 / conservative scenario
Total Ionizing Dose (inner)	100 kGy / year	
NIEL fluence (inner)	$5x10^{13}$ n_{eq}/cm^2 / year	

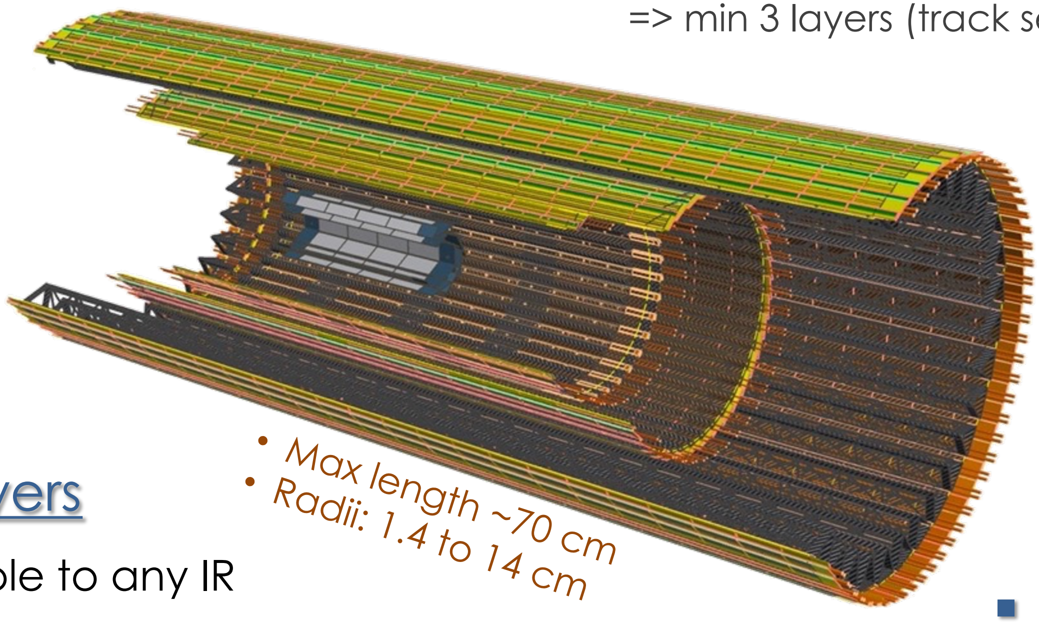
+ Strong interest for

- Time stamping < 5 ns
- Inputs to L1 trigger

VTX main concepts

- **Same sensor everywhere**
  - Space-time granularity => occupancy ≪ 1%
  - Depleted MAPS: **OBELIX**
    - alternative SOI: DuTIP
- **Low radius inner layers**
  - "On" beam pipe
  - Monobloc of Si: **iVTX**
  - Material ≲ 0.2 % X_0
- **Light & straight outer layers**
  - Straight sections => adaptable to any IR
  - "traditional" approach: **oVTX**
    - sensors + flex + cooling-plate + support
  - Material ≲ 0.8% X_0

- **Geometry for vertexing & tracking**
  - Inner layers as close to beam pipe as possible
    => 2 layers for redundancy
  - Outer layers overall material budget as low as possible
    => min 3 layers (track seed) up to 4 (pattern recognition)



- **Fast track reconstruction**
  - Impact on High Level Trigger
- **Simple services**
  - Single-side connexion whenever possible
  - Simple cooling (air or liquid)

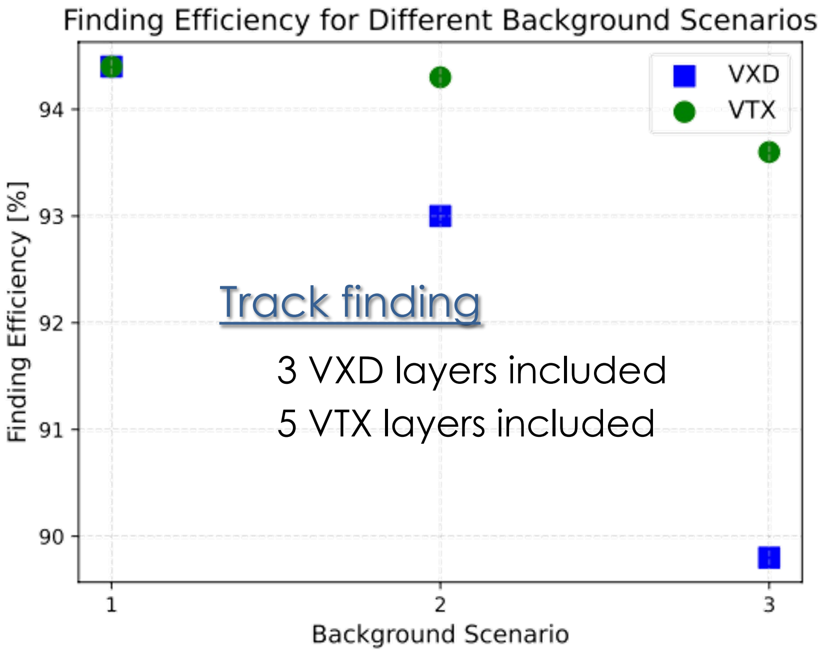
Framework Conceptual Design Report
arXiv:2406.19421 [hep-ex]

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

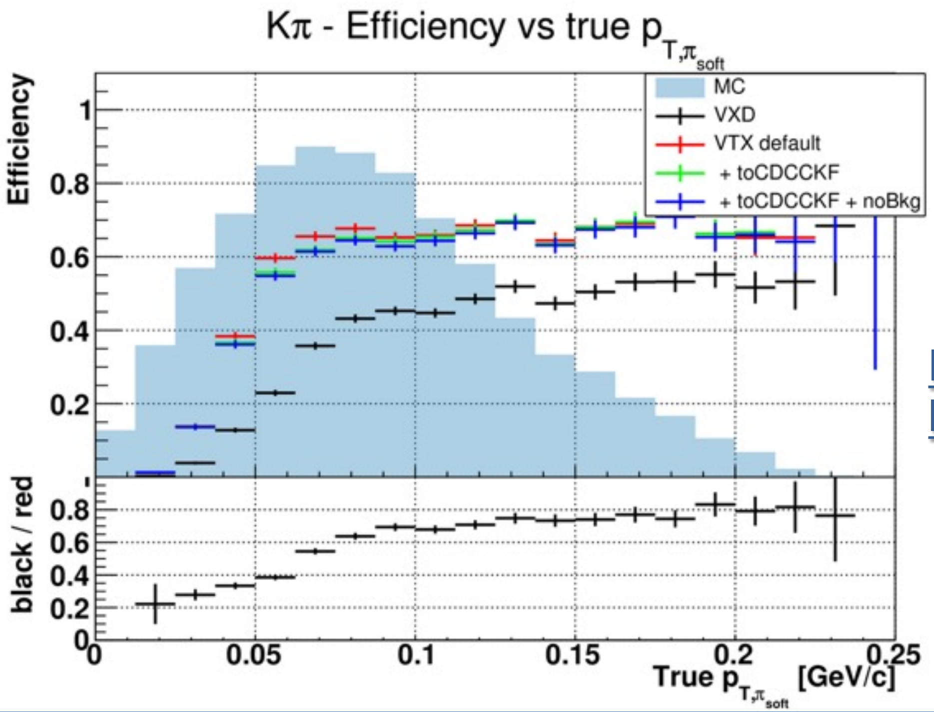
  => occupancy reduced /200 with VTX



Track finding

3 VXD layers included

5 VTX layers included



Resolutions studies

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

Improvement at low momentum

Soft π reconstruction in $B^0 \rightarrow D^{*-}\mu^+\upsilon_\mu$

$\quad\quad \hookrightarrow \overline{D^0}\pi^-$

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

=> Geometry optimisation on-going

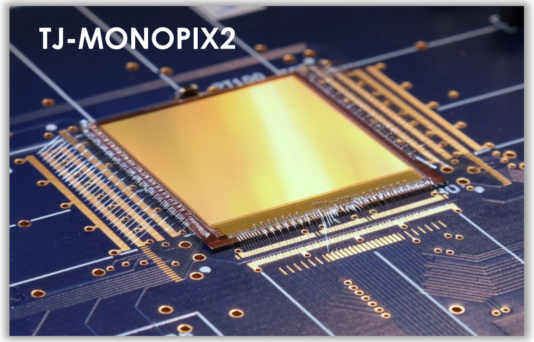
- 6 layers

VTX sensor requirements & strategy

	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

Large proto ~4 cm^2 chosen as pixel matrix

- TJ 180 nm CIS process
- Bonn, CERN, CPPM, CEA-IRFU
  DOI: 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)

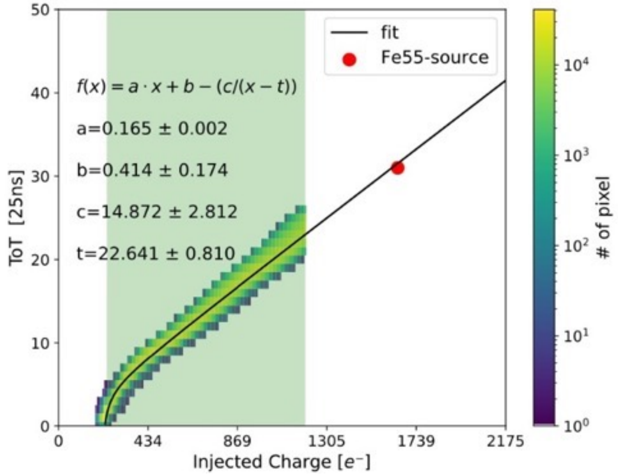
- Characterisation of TJ-Monopix2 pixel matrices
- Start design of **1st complete sensor OBELIX-1**
  - Extension of TJ-Monopix-2 pixel matrix
  - Completed with new digital logic + LDO regulator

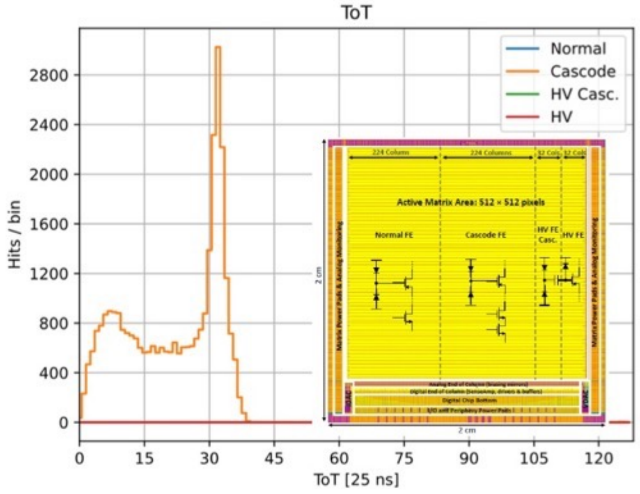
<===== now

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

Characterisation of TJ-Monopix2

- In laboratory
  - Stable threshold ~250 e-
  - Temporal noise ~8 e-
  - Threshold Dispersion ~17 e-
    - after tuning
  - ToT calibration





TJMP2 sensor is divided in 4 regions with different pixel FE

- In DESY beam, 5 GeV e-
  - Campaigns: 2022, 2023, 2024
  - Non irradiated sensors (Room temperature, thres. 500 e-)
    => uniform 99% det. efficiency, $\sigma_{position}$ ~9 µm
  - **Sensors irradiated with 5.10^{14} n$_{eq}$cm-^{2}**

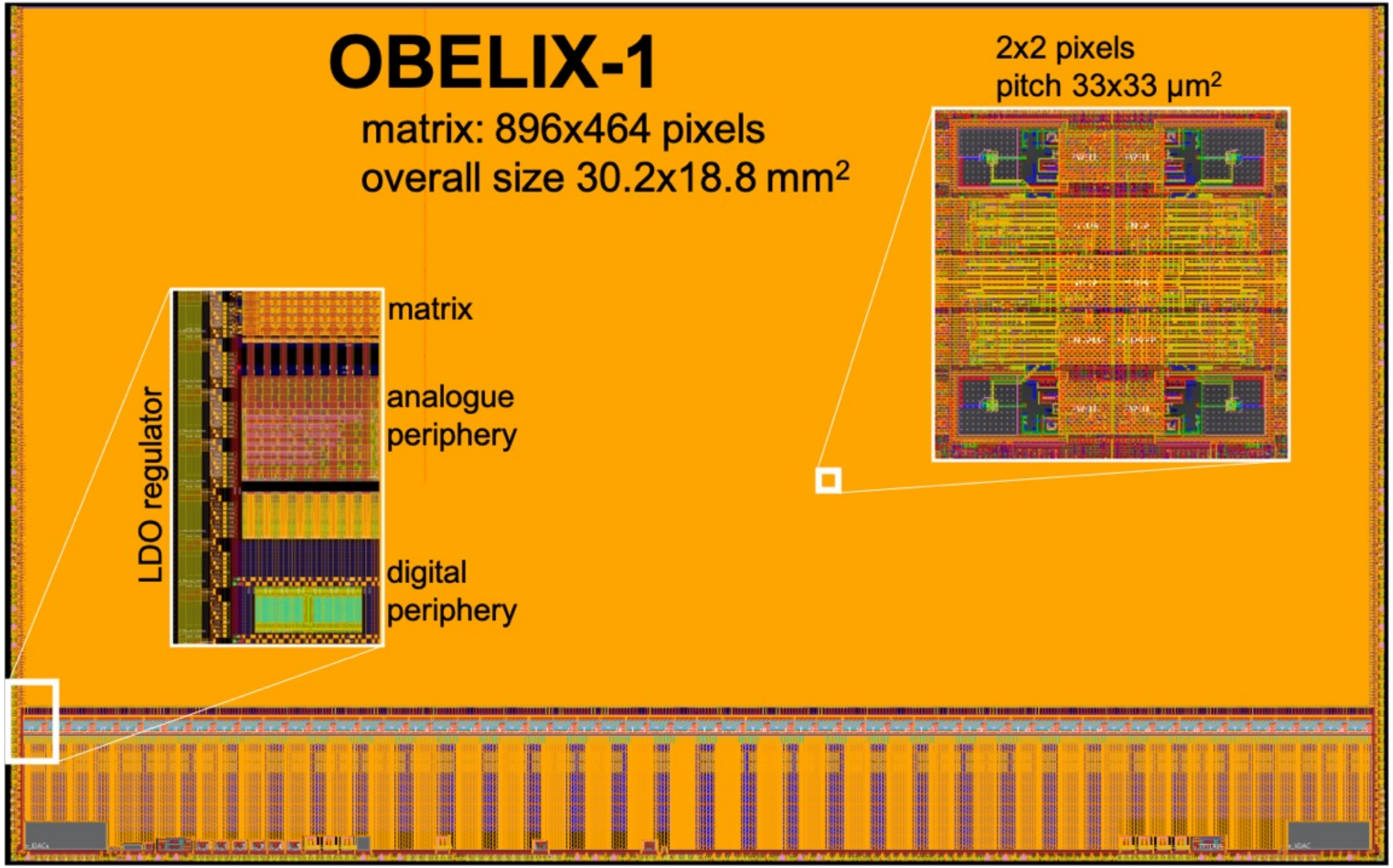
ampli	coupling	Efficiency (%)
Normal	DC	99.99
Cascode	DC	99.79
Normal	AC (HV)	99.13
Cascode	AC (HV)	98.11

2023 result
Room temp.
Thresh. ~300 e-

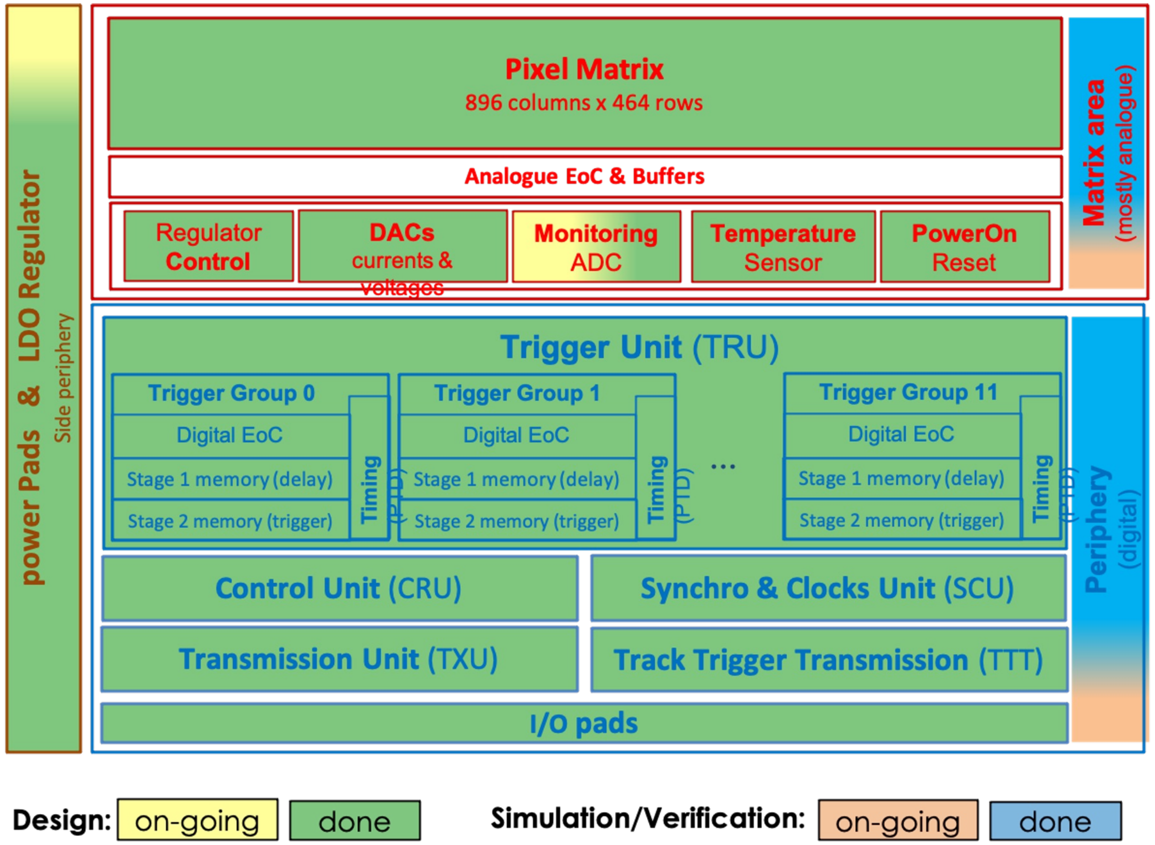
- 2024 measurements Temp ~45 ˚C
  - Different sensor
  - Threshold ~300-400 e-
  - Det. Efficiency 90-98 %
- **High temp & fluence = difficult!**
  - Leakage current

Further investigation in 2025
- Various Fluence-Temp combinations

Design of OBELIX-1



Design of OBELIX-1



DOI: 10.1016/j.nima.2023.168015

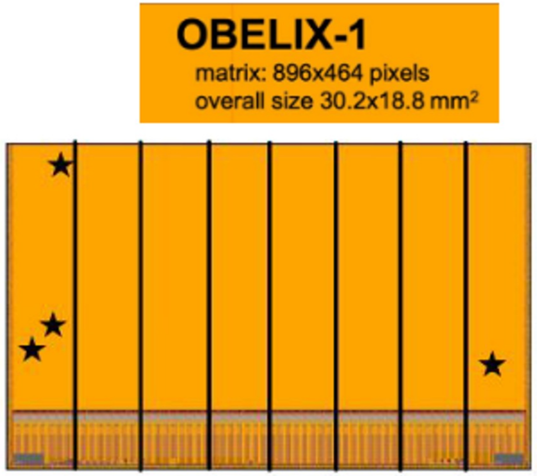
=> Fabrication in 2025

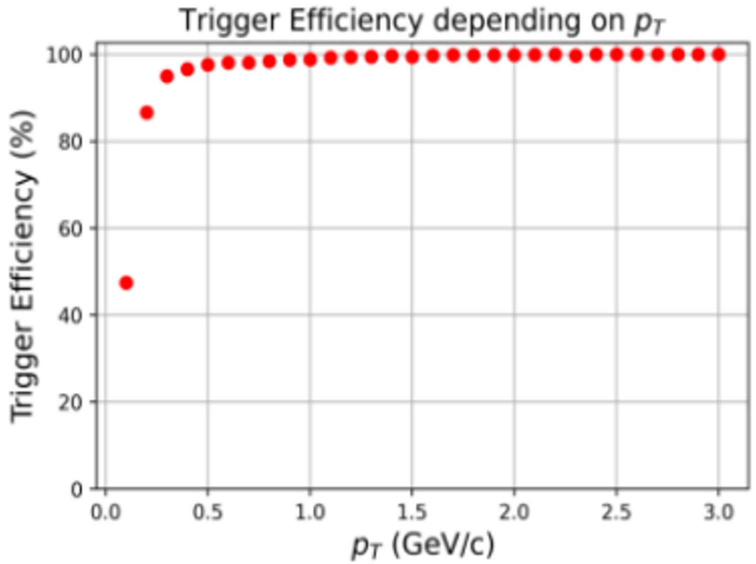
- **Matrix design**
  - Extended copy of TJ-Monopix2
  - Clock for time-binning slowed down: 100ns
- **Powering**
  - LDP regulator for easier voltage distribution
  - Overall power depends on hit rate: 200-300 mW/cm²
- **Trigger Unit**
  - Simulated with realistic inputs: 120 MHz/cm²
  - Can sustain 800 MHz/cm² for 0.5 μs
- **Fine time stamping**
  - 6 ns achievable with end-of-column fast clock
    - Limited to hit rate > 10 MHz/cm²
- **Track trigger**
  - Reduced granularity to 8 strplets (~4 x18 mm²)
  - Increased transmission rate: 30 ns

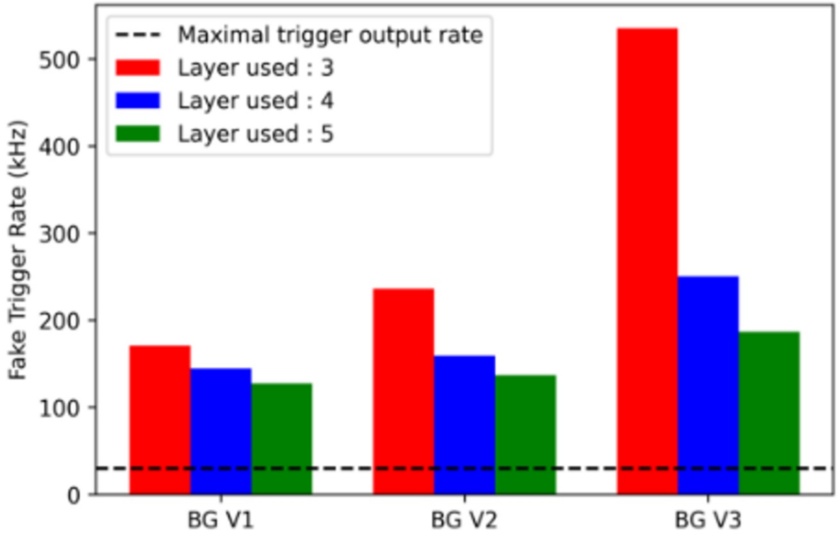
Track trigger performance

- 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

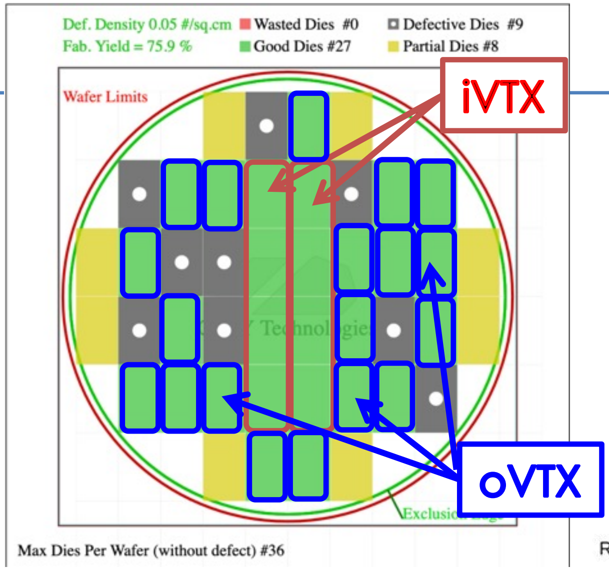
iVTX: inner layer design

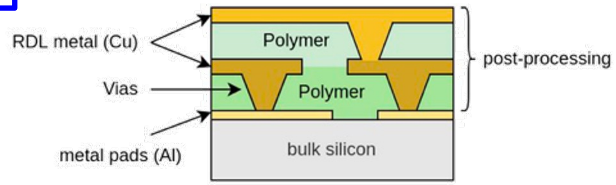
- Self-supported all silicon module
  - 4 contiguous sensors diced out of wafer => 12cm long
  - Interconnected with redistribution layer (IZM-Berlin)

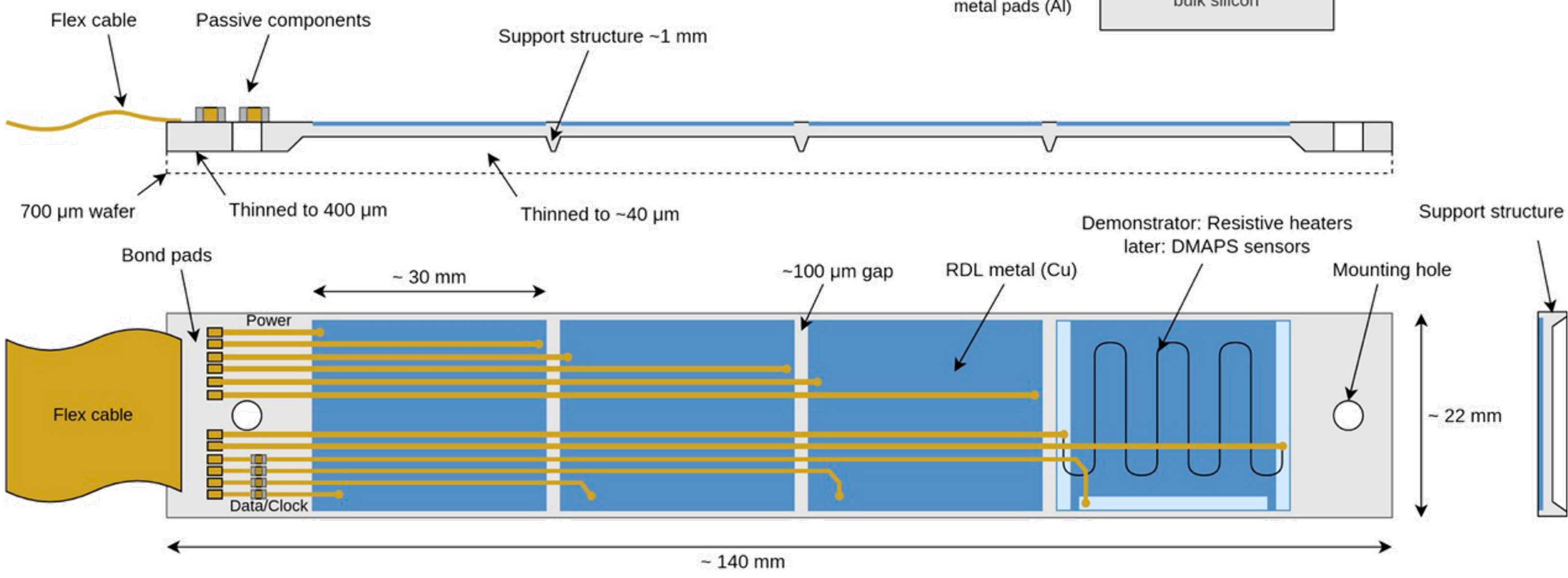
- Options for cooling under study
  - **Heterogeneous thinning**
    - thick edges versus thin matrix
    - Favoured for air cooling
    - Toperation ~45 C with large uniformity

    => minimal material ~0.1 % X_0
  - **Uniform Si thickness + 1 cooling tube**
    - Material ~ 0.2 to 0.3 % X_0

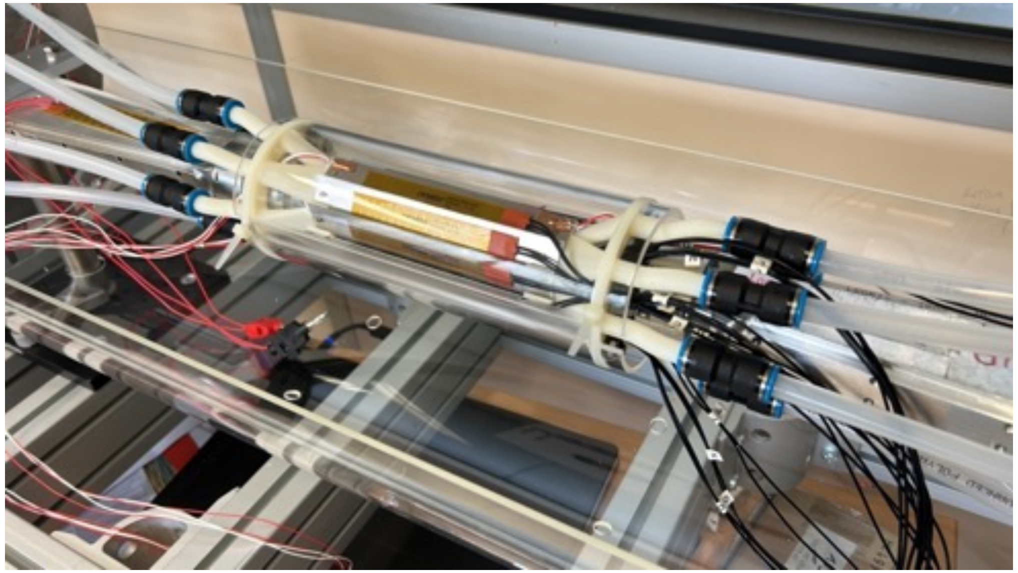
    => Toperation ~25 C, uniformity OK



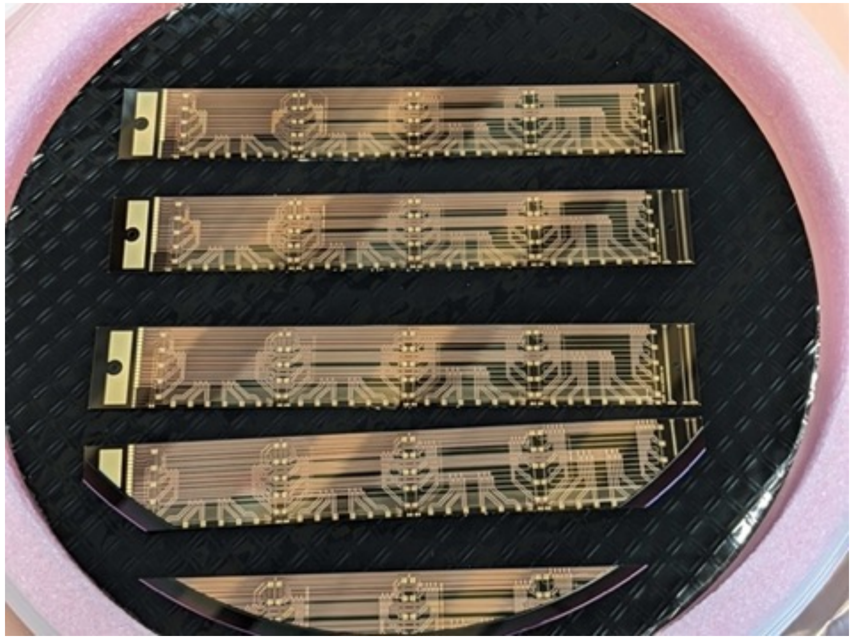




iVTX: Inner layer prototyping

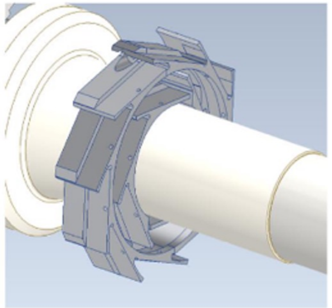


- [Instrumented wind tunnel]
  - Controlled air-flow, heaters, vibrations
  - Allow global investigation with layer interaction



- [First dummy wafers with redistribution layer]
  - Heaters integrated to reproduce OBELIX power
  - Thermal & electrical test on-going

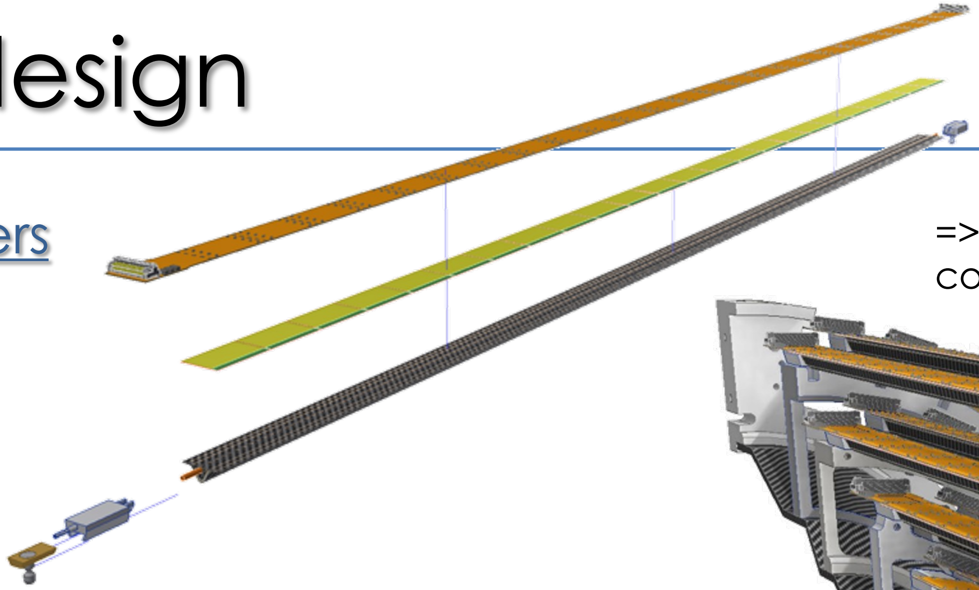
+ Investigation on support options
- On beam pipe
- From outer layers



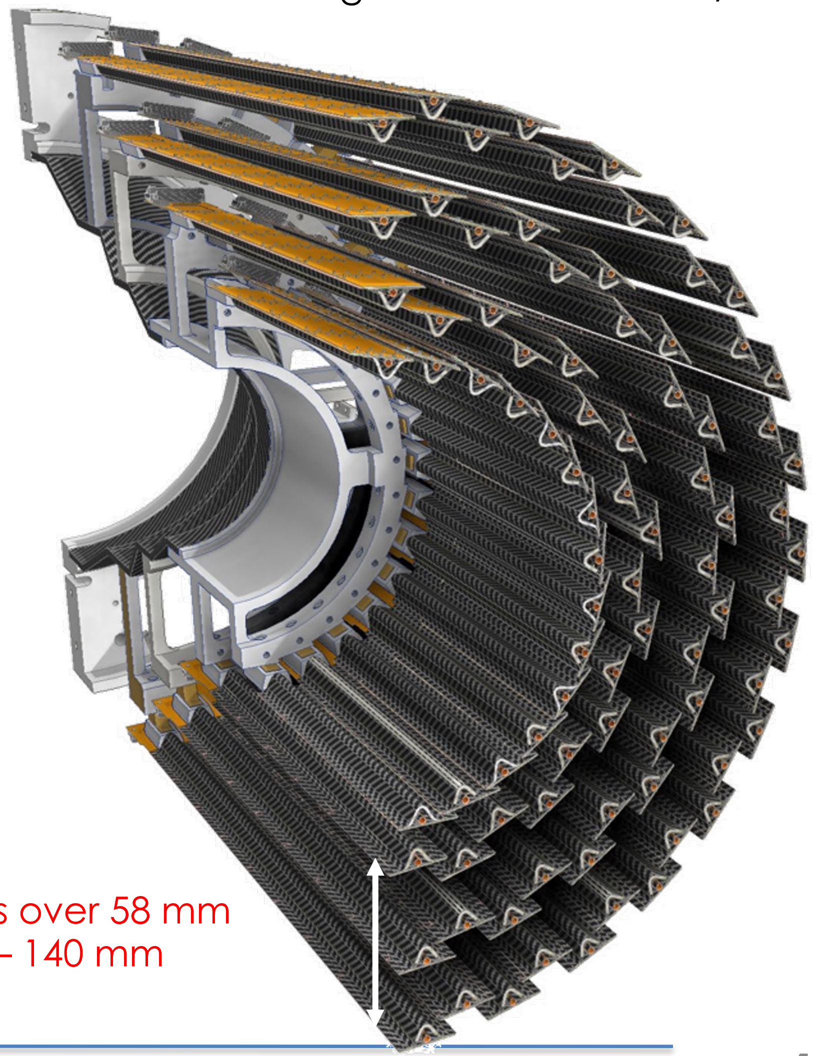
oVTX: outer layer design

- **Recipe for long and light ladders**

  (Inherited from ALICE-ITS2)
  - Carbon-fiber truss support frame
  - Cold-plate with 1 coolant tube
  - Long-flex for power & data



=> Early prototype demonstrated cooling OK for 200-300 mW/cm^2



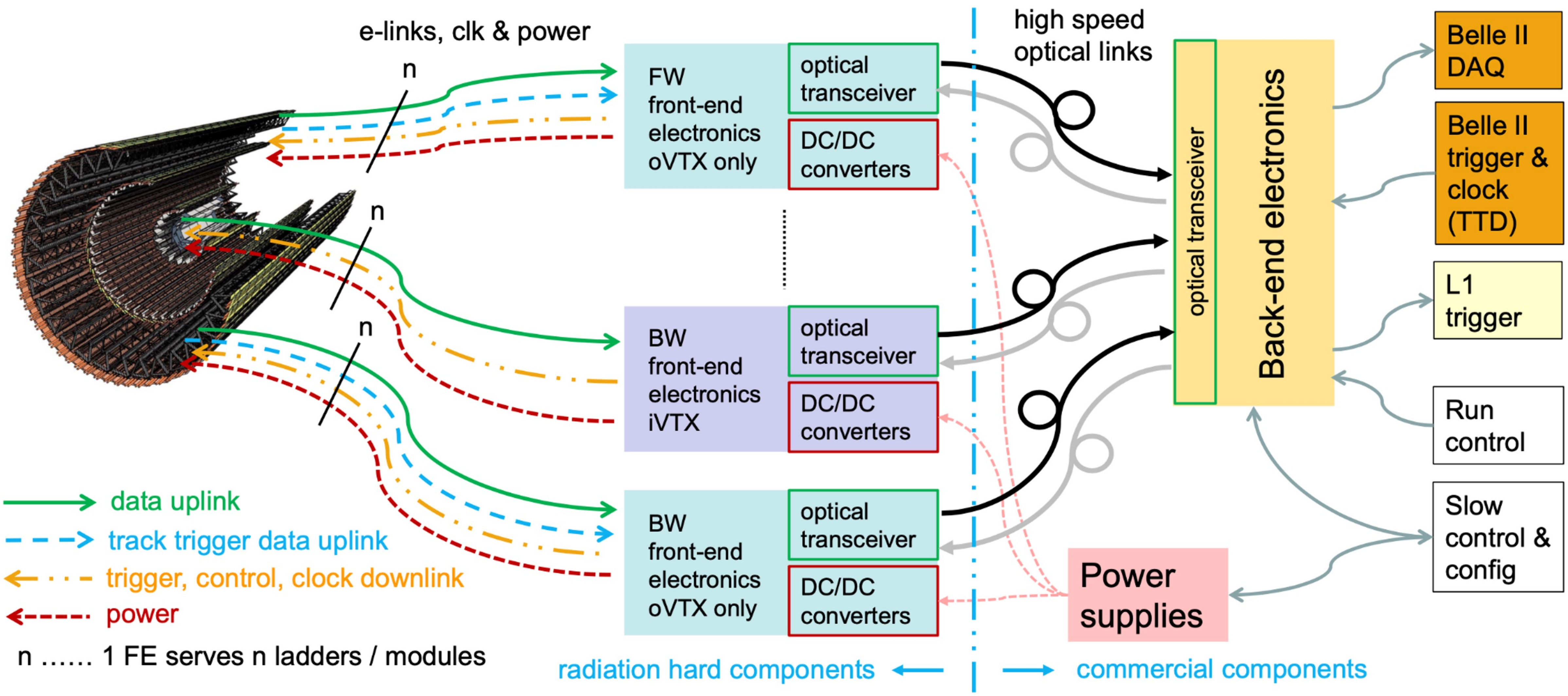
- **New Omega shape support**
  - Carbon fiber skin with rohacell core

    => way more compact / truss structure

    => material budget ~0.45% X_0 from L4 to L5
  - Current stagging measurements & comparison with simulation

- **Flex development**
  - 4 to 6 aluminium layers
  - Single or multiple-flex/layers not decided
  - Investigating CERN workshop & Japanese Co.

DAQ system concept



Rough schedule of VTX project

- 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**

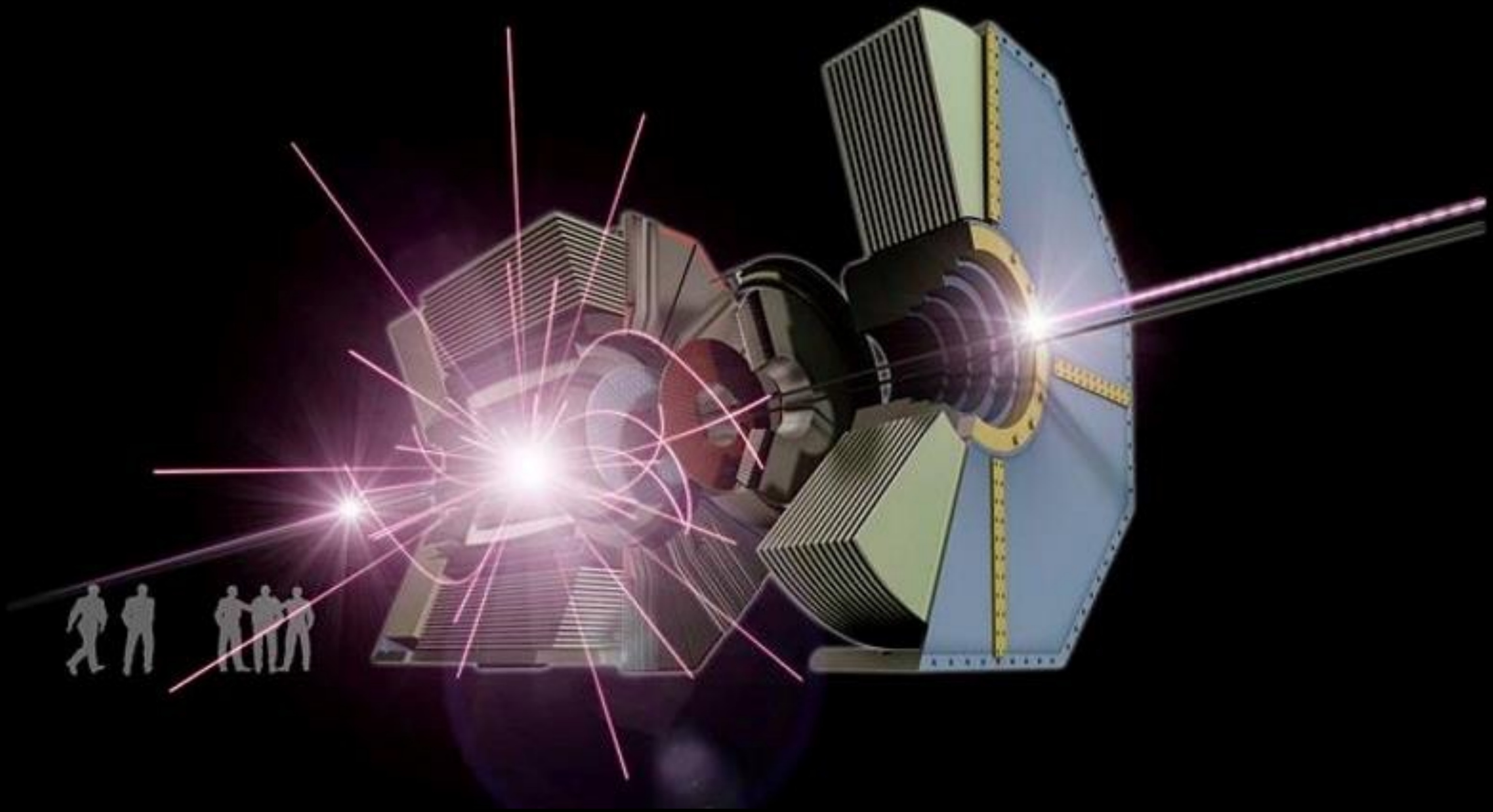
- Construction phase from ~2027
  - **Classical sequence: Pre-production / Production / Installation / Commissioning**

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)** ⇨ **In line with Detector R&D roadmap (DRD3)**
  - **Parallel to accelerator R&D for potential new interaction region**

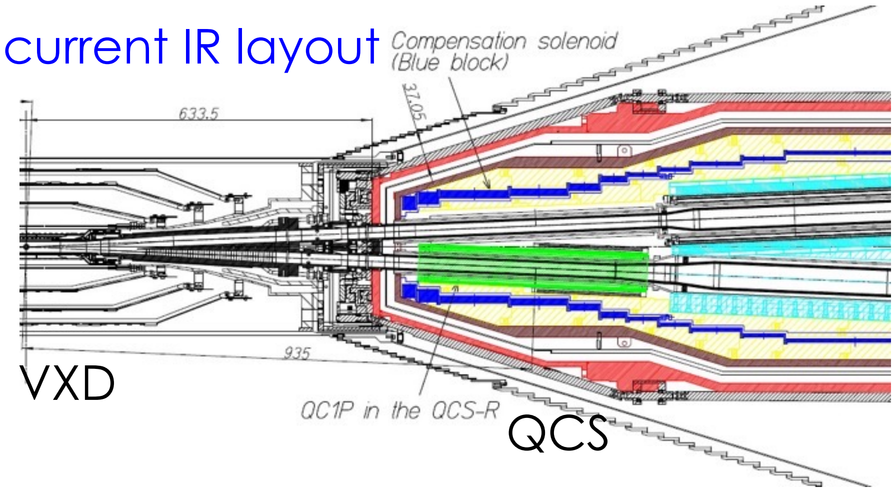
Thank you for your attention…



Interaction region for higher lumi

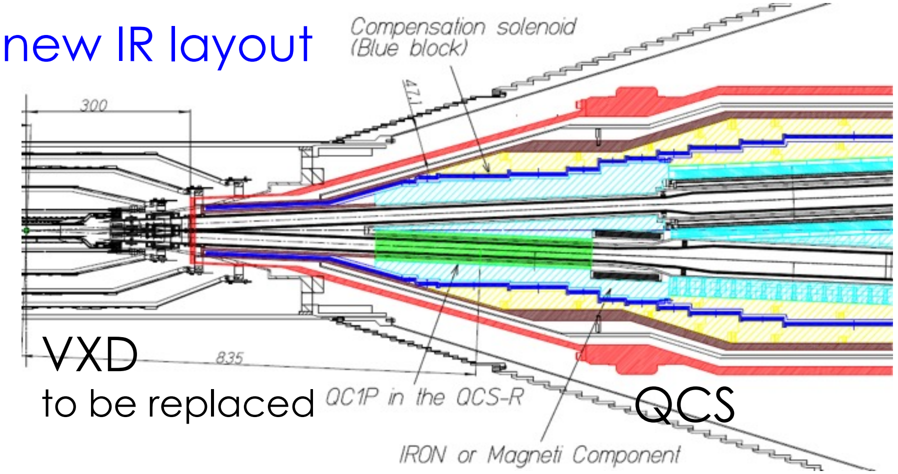
- **Current machine**
  - World luminosity record 4.7x10^{34} cm^{-2}.s^{-1} (2022)
  - Expected max lumi ~2x10^{35} cm^{-2}.s^{-1}
    - Main limit from dynamic aperture at Interaction Region (IR)

current IR layout

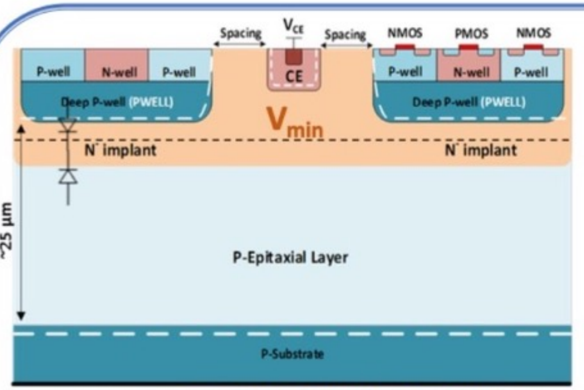


- **Potential road toword 6x10^{35} cm^{-2}.s^{-1}**
  - New final focusing magnet (QCS) required
    - To increase dynamic aperture at IR
    - On-going R&D for feasibility
  - **Foreseen new QCS conflicts with current VXD volume => new VTX length & support**

Potential new IR layout



Modified process & TJ-Monopix2 details



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

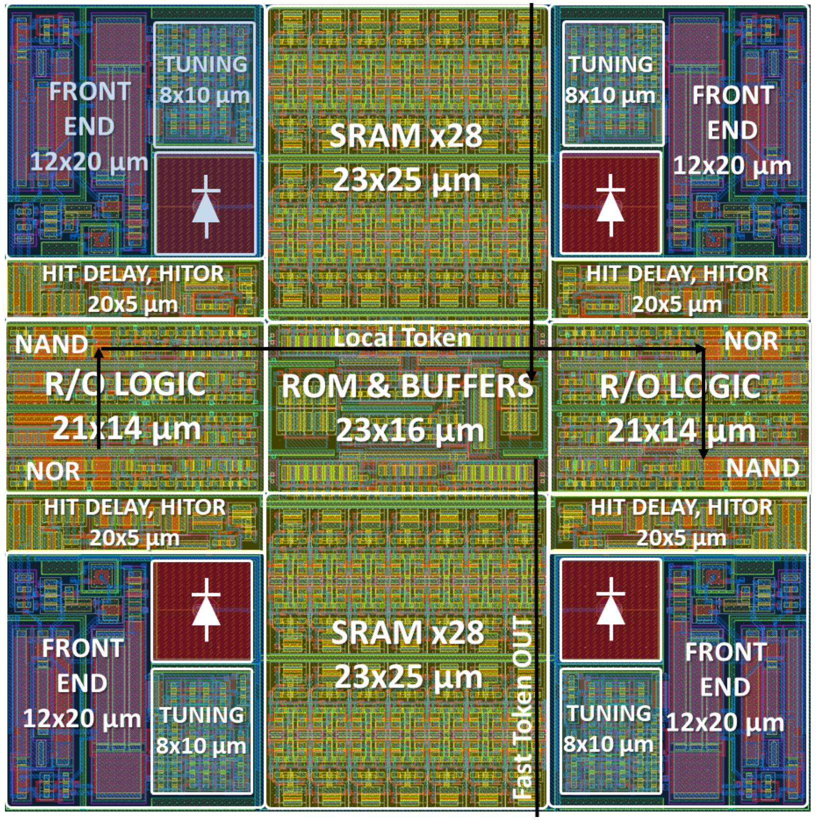
$C_d \leq 3fF$

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

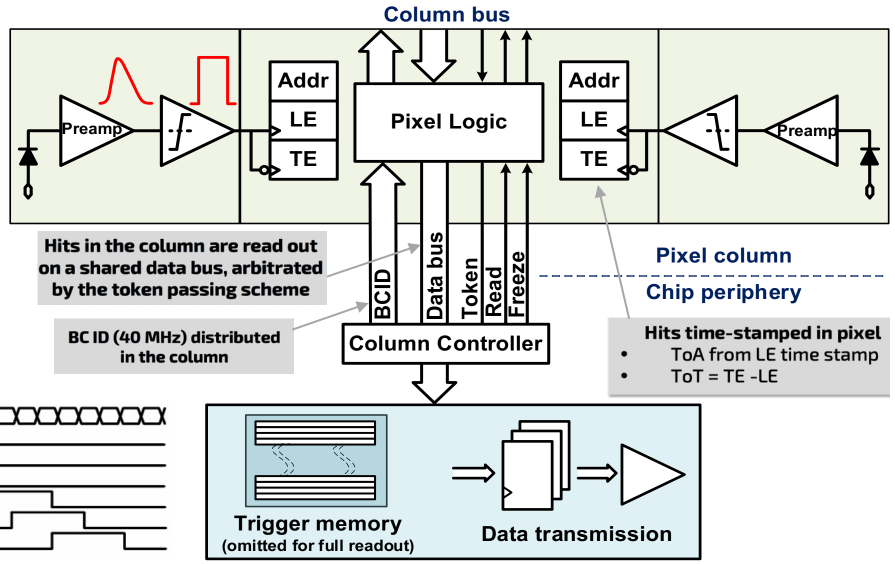
DMAPS in TJ 180 nm: Concept

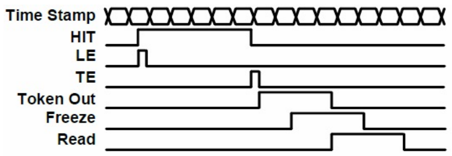
- Small sensor capacitance (Cd)
  - Key for low power/low noise
- Radiation tolerance challenges
  - Modified process
  - Small pixel size
- Design challenges
  - Compact, low power FE
  - Compact, efficient R/O

The matrix Layout:
2x2 pixels



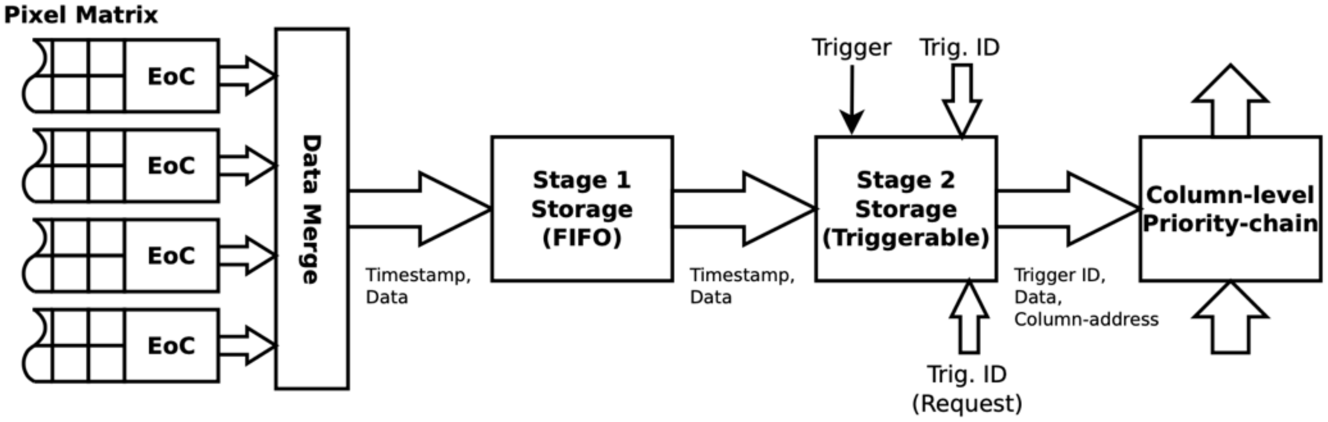
The logic:



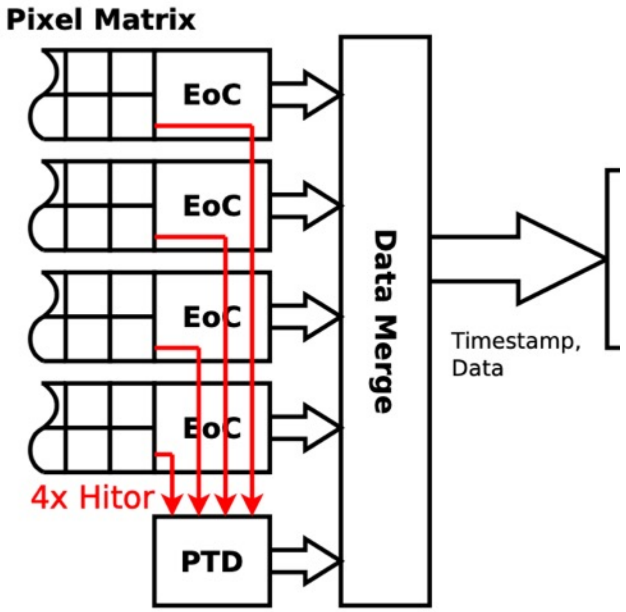


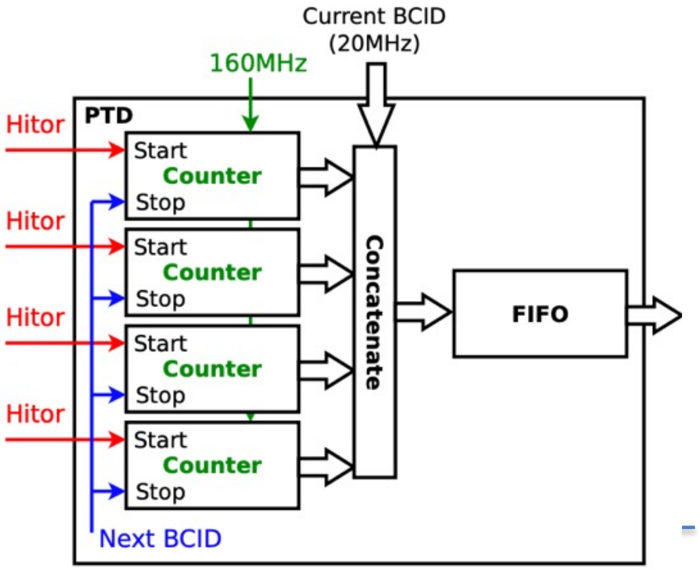
Logic detail within OBELIX-1

Trigger Unit



Peripheral Time to Digital



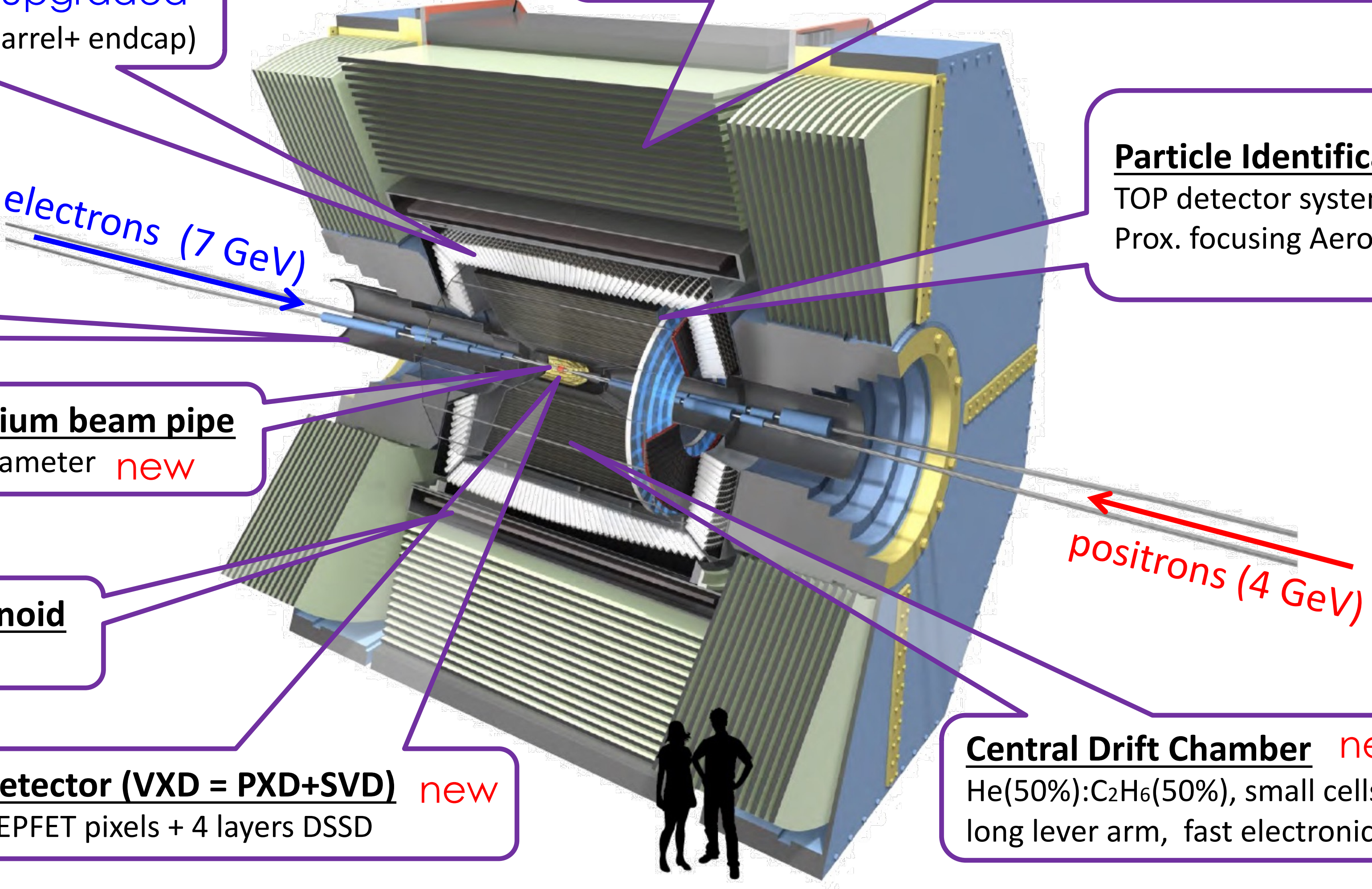


Belle II detector

Upgraded or new / 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 (ECL) upgraded
CsI(Tl), waveform sampling (barrel+ endcap)



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

new
Final focusing magnets

Beryllium beam pipe
2cm diameter new

SuperCond. Solenoid
1.5 T magnetic field

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

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