International workshop on the High Energy CEPC
24-28 October 2022

Belle II

vertex detector upgrade with DMAPS

the VTX project

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on behalf of Belle II VTX collab.

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CNRS
Université de Strasbourg

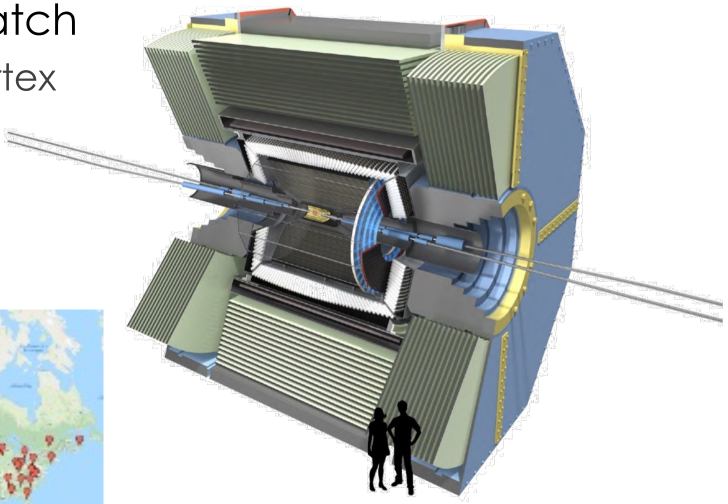
- → The SuperKEKB / Belle II project
- → Rationale & requirements for an upgrade
- → VTX proposal concepts
- → Full simulation results
- → OBELIX sensor & prototype ladders

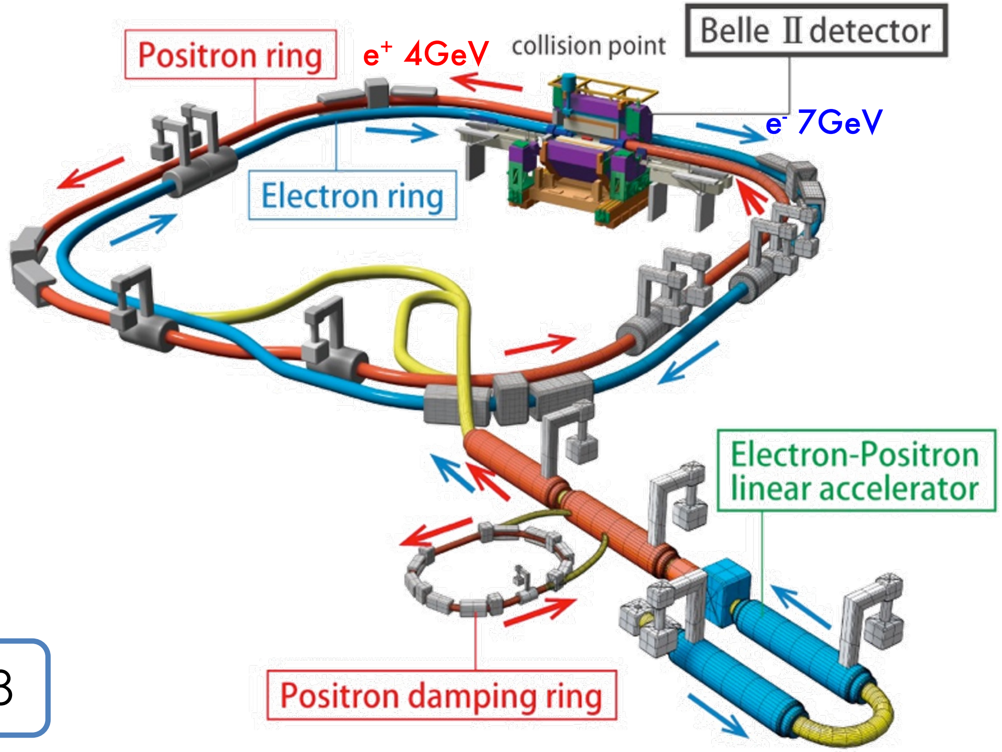
B,c,τ-factory: SuperKEKB + Belle II

- Initial physics program based on L_{int} = 50 ab^{-1} at $\sqrt{s} = M_{\Upsilon(4S)}$
  $\Rightarrow$ The Belle II physics book [PTEP 12 (2019) 123C01]

■ **High luminosity collider:**
- L_{peak} ~ multi 10^{35} $cm^{-2}.s^{-1}$ range
- High current / nano-beams / specific crossing features
- **Challenging background conditions**
  $\Rightarrow$ Snowmass contribution: [arXiv 2203.05731]

■ **Belle II detector:**
- Upgraded from Belle to match
  - Lower boost $\Rightarrow$ improved vertex
  - Higher rates & radiations
    $\Rightarrow$ faster det. & read-out

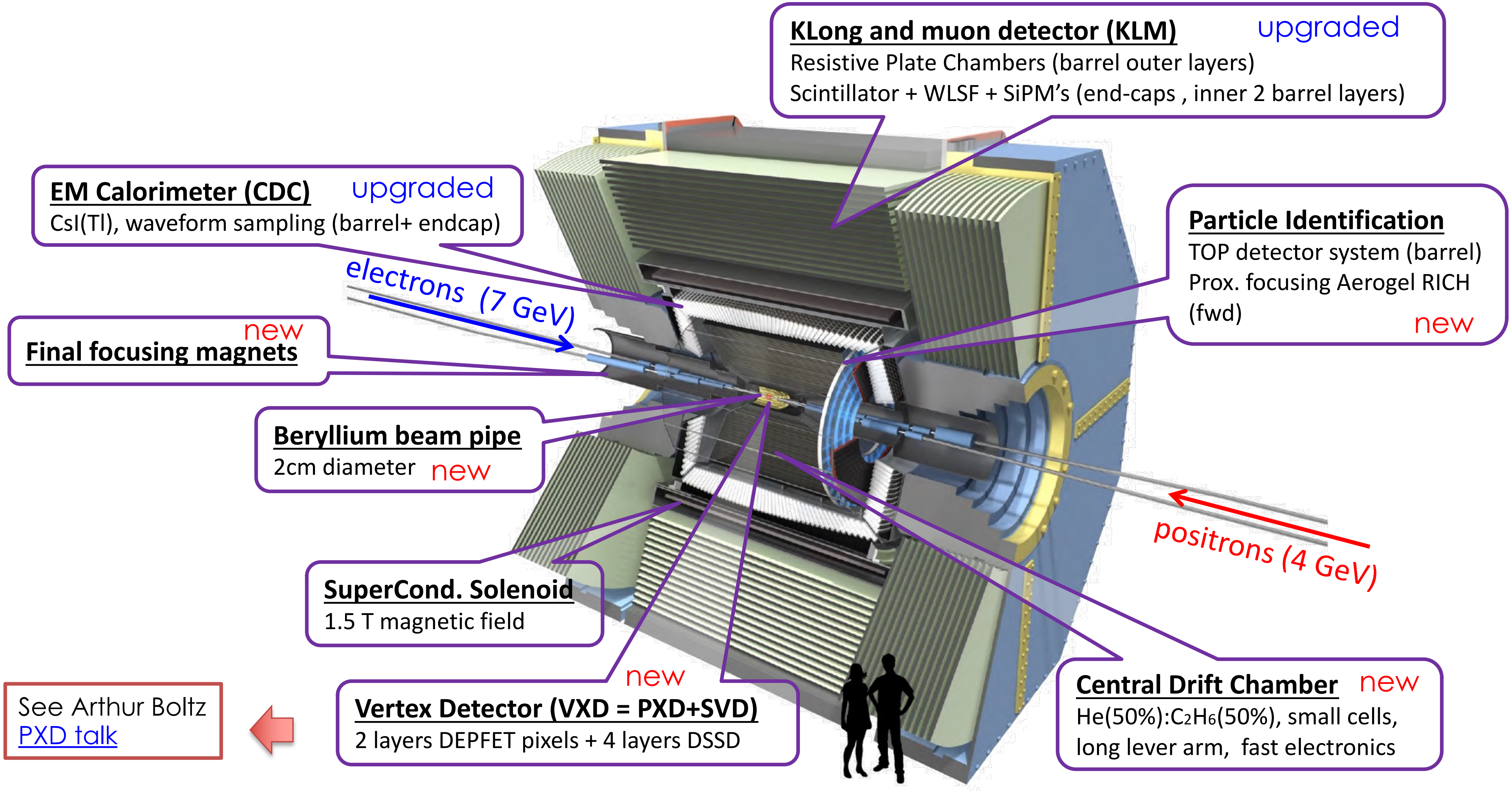




$\Rightarrow$ Started in 2018

Belle II detector

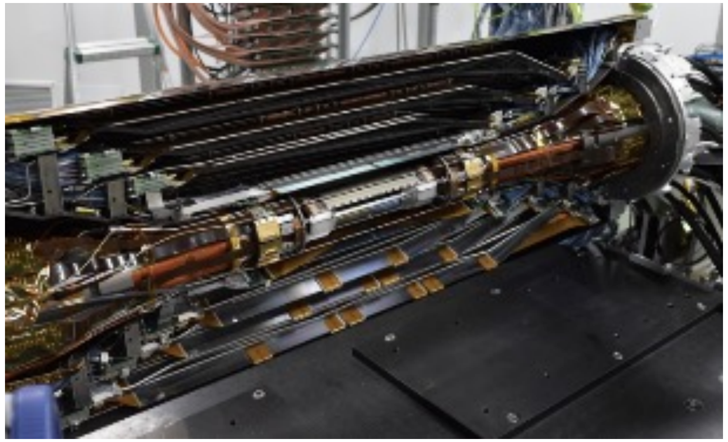
Upgraded or new / Belle



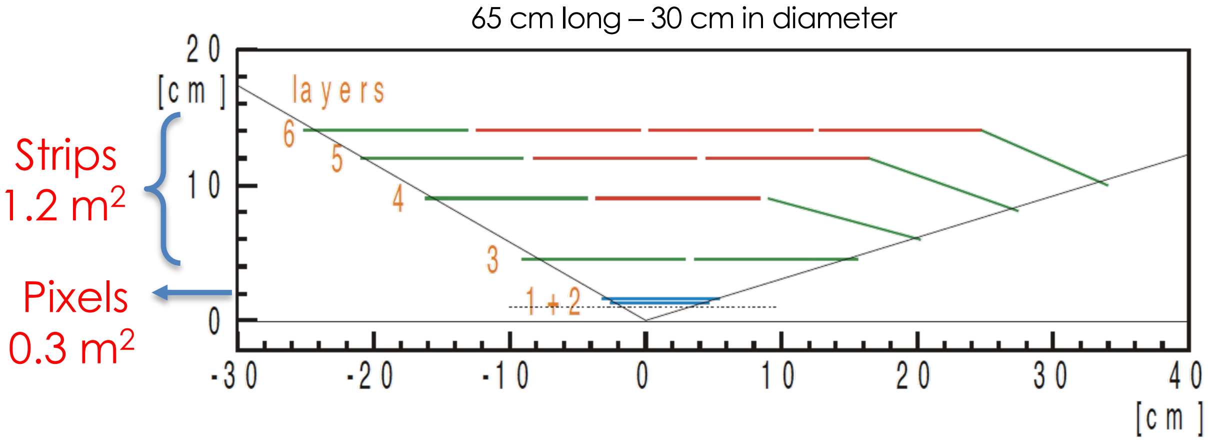
See Arthur Boltz
PXD talk

The current VXD

- Two technology system
  - **SVD = Double-Sided Strip Detector**
    - Read-out sensor connected on sensor = Origami
    - Hit time-stamping $\sigma_t \sim$ 2-3 ns
    - Spatial resolution $\sigma_{s.p.} \sim$ 20 µm



  - **PXD = DEPFET sensors**
    - Very low material budget 0.2 % X_0 / layer
    - Small first layer radius = 1.4 cm
    - Long integration time 20 µs / trigger rate & injection bkg



- VXD role
  - Standalone tracking (SVD) for low momentum
  - Vertexing from
    - PXD precision measurements
    - VSD interconnection from tracks to PXD hits

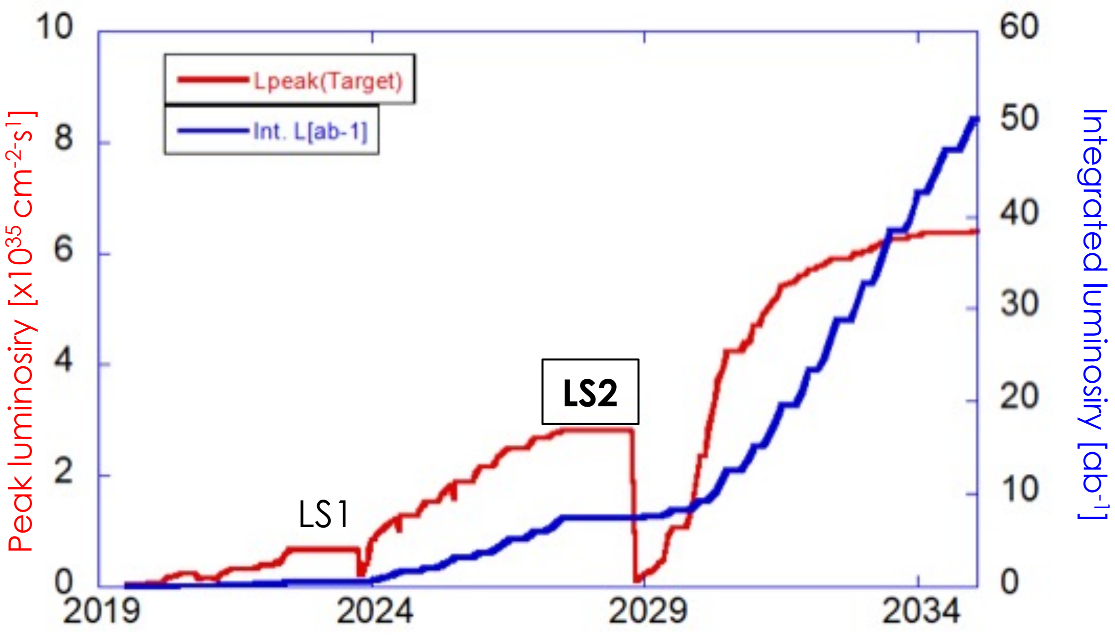
- The plan is successful so far with occupancy < 1 %
- At nominal luminosity, tracking at ~3% occupancy

Planning an upgrade for the Belle II-VXD

- Get ready for SuperKEKB luminosity increase
  - potential higher occupancy than currently predicted
  - Potential re-factoring of interaction region in **LS2**
- Additionally: improve performance of physics analysis

Increase granularity in space an/or time of VXD layers (occupancy << 1%)

No real robust predictions available!



- Various proposals
  - EOI Feb.2021 => CDR in 2023

General concepts	Technologies
Strips+Pixels ~ current Belle II concept	Thin & fine-pitch strips
	SOI pixel sensors
All pixel layers ~ ALICE ITS2 concept	CMOS pixel sensors

Installation in 2027
=> need known-working solution

Planning an upgrade for the Belle II-VXD

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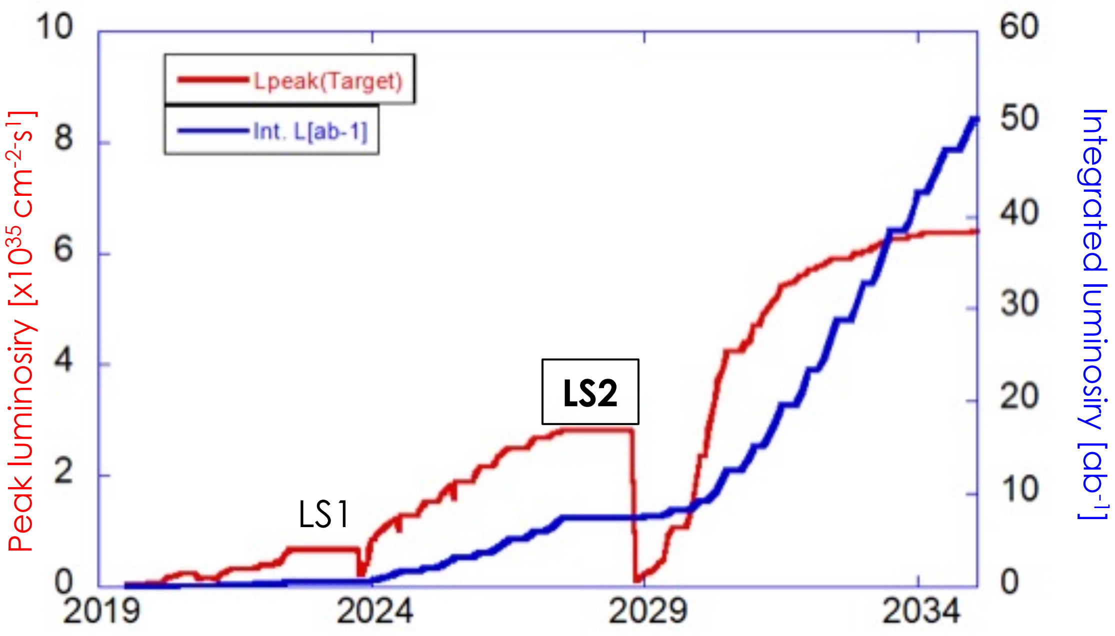

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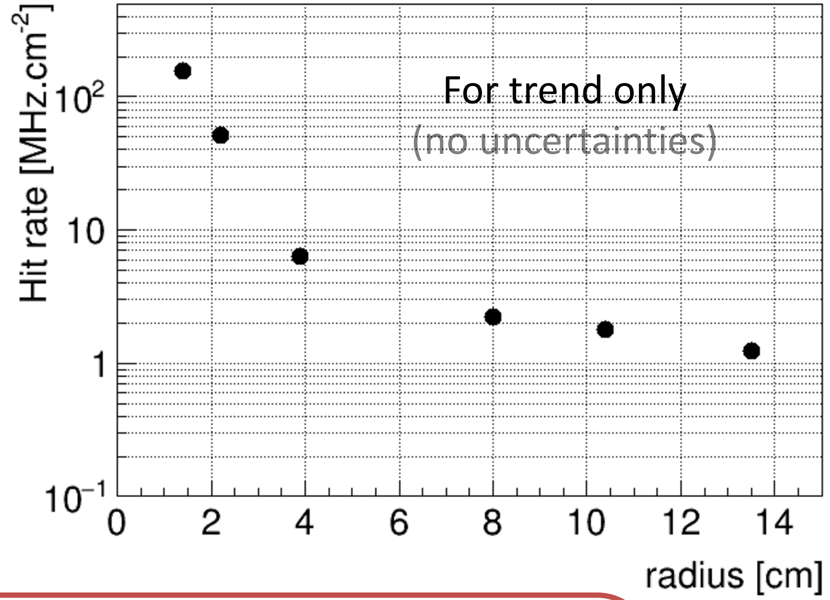
VTX proposal, features
- Larger granularity: pixels
- Simplification: single monolithic sensor
- In-line with ECFA R&D roadmap

Requirements for short-term VXD upgrade

- Vertexing & Tracking performances **at least** as good as current VXD
  - Radius range 14 – 135 mm
  - angle from 17 to 160 degrees
  - Single point resolution **≤10-15 μm**
  - Total material budget **< (2x 0.2 + 4x 0.7) % X_0**
    - total power budget < 1000 W

- **Robust** against environment for inner layer **(r=1.4 cm)**
  - **Hit-rate ~ 120 MHz.cm^{-2}**
  - Total Ionizing Dose ~ 10 kGy / year
  - NIEL fluence ~ 5×10^{12} n_{eq}.cm^{-2} / year

    Based on current extrapolation with safety factor (x5)
    bear In mind large uncertainties (previous slide)



- Possibly **improve** performances
  - Impact parameter resolution
  - Tracking efficiency (p_T < 100 MeV) & Fake rate
  - Faster High Level Trigger decision
    - Simplified track pattern recognition

Key sensor specifications:
- Pixel pitch 30-40 μm
- Integration time ≲100 ns
- Power dissipation ≲ 200 mW/cm^2

VTX general concept

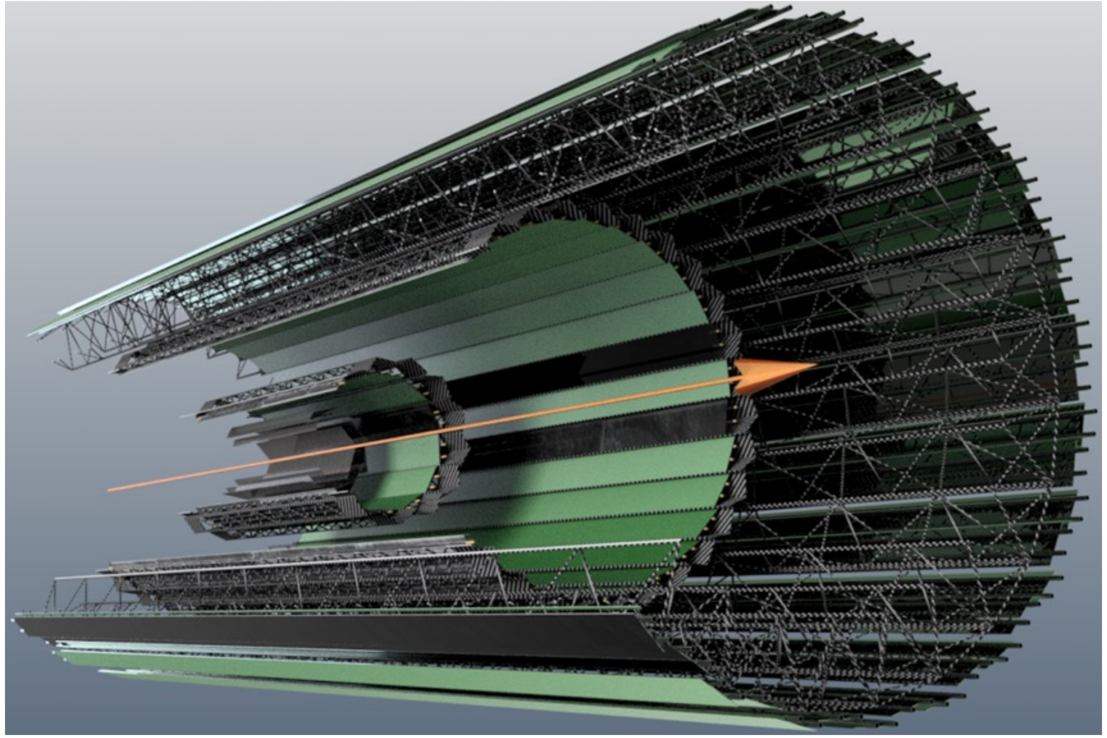
- 5 layers
  - About 2000 depleted-MAPS = OBELIX
  - Fast enough for including all layers in tracking
  - Services mostly on one side (backward region)
  - Total event size ~30 kBytes
  - Geometries adaptable to potential change of interaction region

- 2 inner ladders with radius < 3 cm
  - **iVTX**, ~0.1 % X_0
  - 12 cm long

- 3 outer ladders with radius > 3 cm
  - **oVTX**, 0.5-0.8 % X_0 (increasing with radius)
  - 20-70 cm long

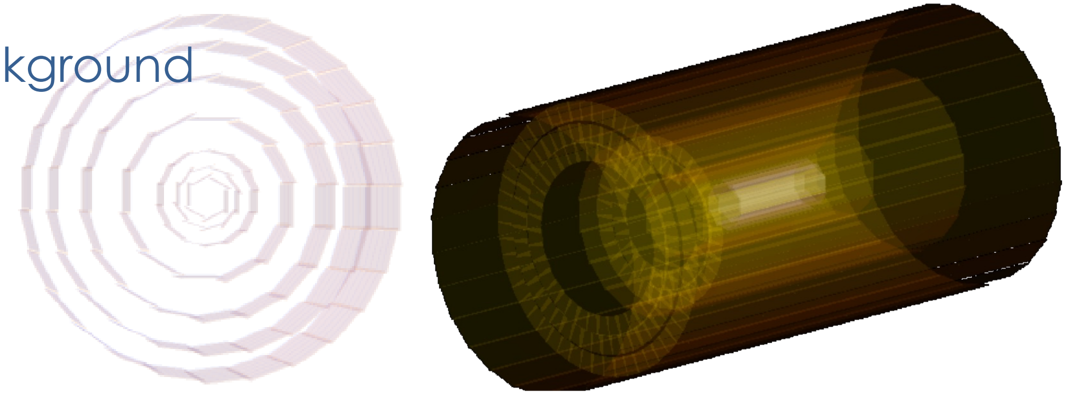
- VTX collaboration

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



VTX simulated tracking performances

Context = full Belle II simulation framework, including background

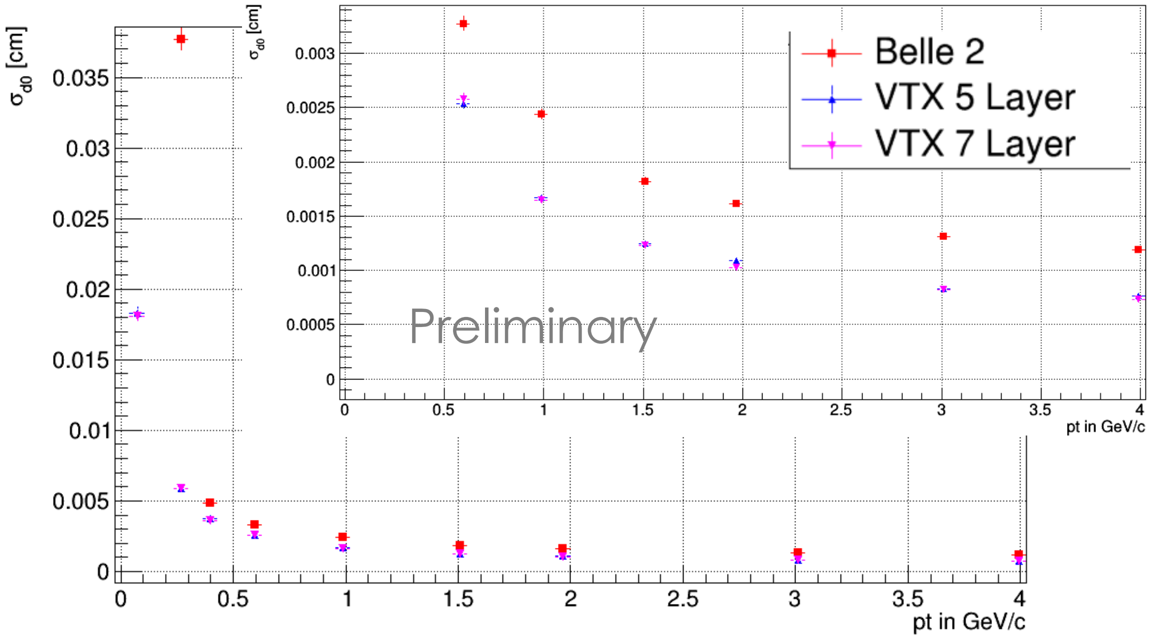


- Realistic pixel sensor model
  - Digitizer assuming
    - fully depleted thin layer 30 µm
    - Pixel 33x33 µm^2 with 7bits Time over Threshold
  - Tuned with Monopix-1 beam data

- Geometry
  - Taken from fast simulation
  - 5 or 7 barrel layers with/without 2 forward disks
  - Crude layer description but with targeted material budget
    → per layer: 0.1 % X_0 for radii <4 cm then 0.3 % X_0

- Full tracking chain
  - VTX standalone
  - CDC standalone

  } then combined



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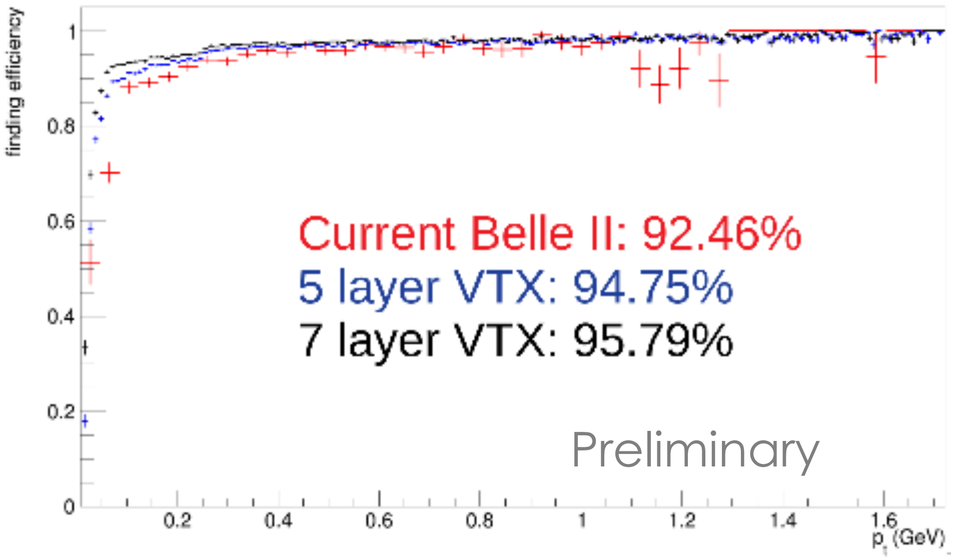
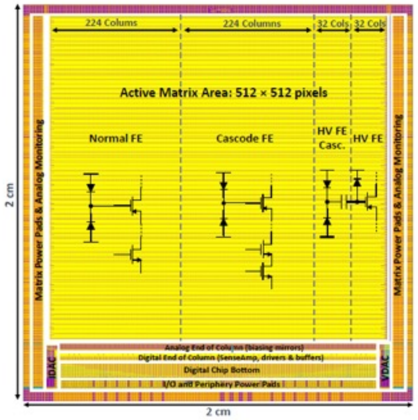
=> Occupancy < 0.002 % in first layer with current background estimate x 5

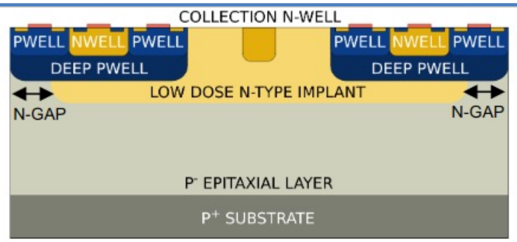


=> https://doi.org/10.5506/APhysPolB.52.909

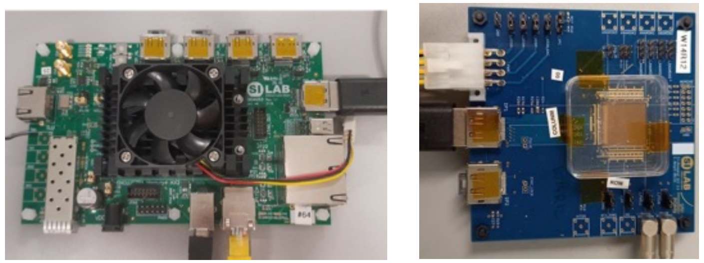
TJ-Monopix2 lab-test results

- Depleted MAPS technology choice
  - Tower 180 nm modified process (full Depletion) with small diode as sensing node
  - TJ-Monopix2 as forerunner of OBELIX
    - 33 µm pitch, 25 ns integration, 17x17 mm² matrix
    - 4 front-end flavours (gain, speed, depletion)
      - In-pixel detection threshold + Time-Over-Threshold (ToT)
    - Various sensing volume thickness CZ-bulk, epi-30 µm



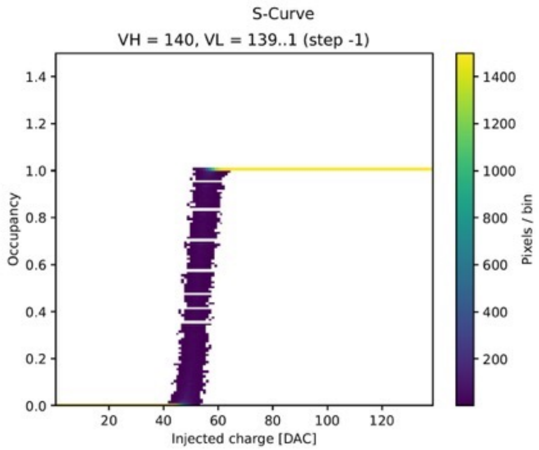


DOI: 10.1016/j.nima.2020.164403

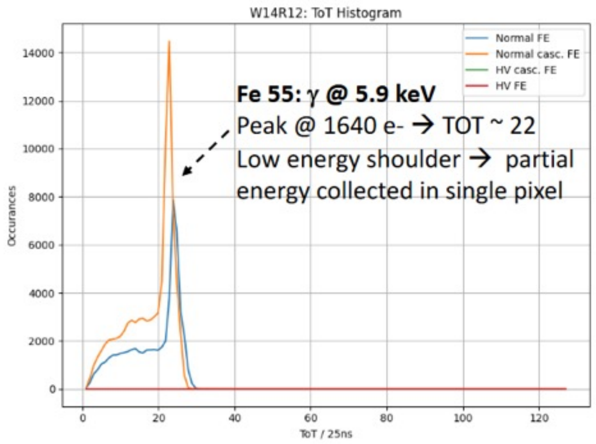


Bdaq53 acquisition system (also baseline for OBELIX)

- Calibration
  - S-curves ⟶ threshold (mean, dispersion)
    - Internal injection
  - ToT calibration
    - Internal injection + X-ray irradiations



Threshold ~ 500 e-
Dispersion ~18 e-

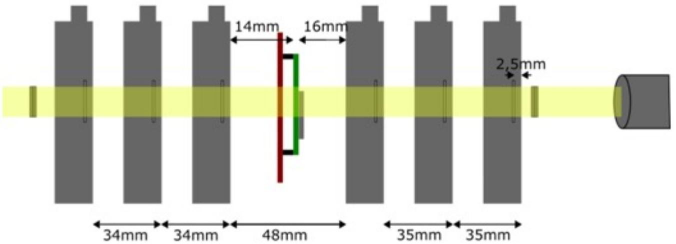


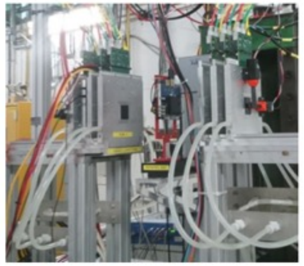
- Better and better understanding
  => Tuning of detection threshold / noise
  => Tuning of ToT dynamics & precision

Inputs for OBELIX design & next beam-test

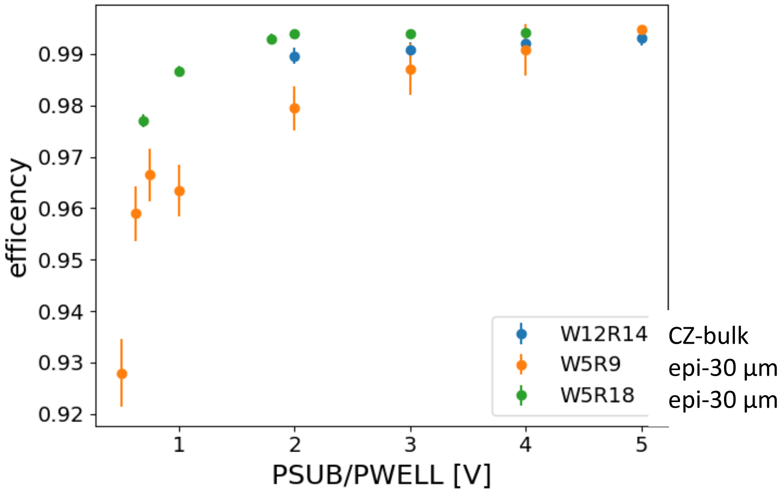
TJ-Monopix2 test beam results

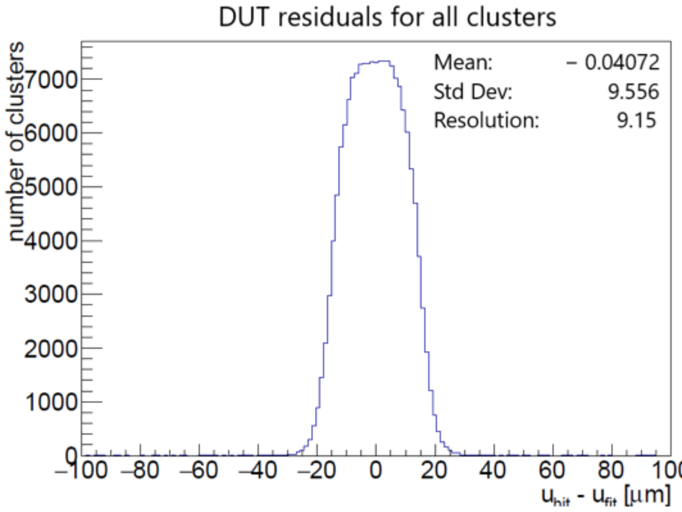
- DESY 5 GeV electron beam
  - Telescope (MIMOSA-26) extrapolation σ~3.5 μm





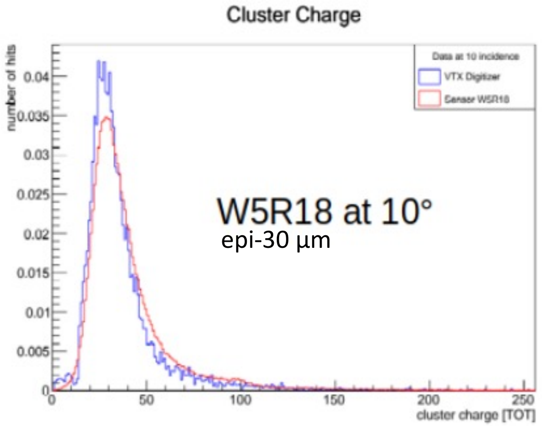
- Results with high threshold 500 e-
  - Detection efficiency 99.020 ± 0.040 %
  - Position resolution ~9 μm (< digital resolution)

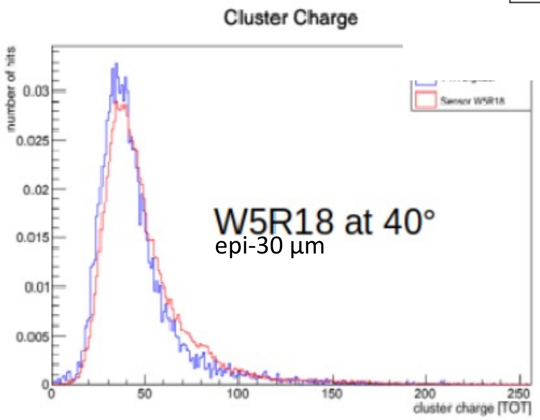




See: M.Schwickardi Belle2 Germany Workshop

- Simulation
  - Tuning of model in BASF2





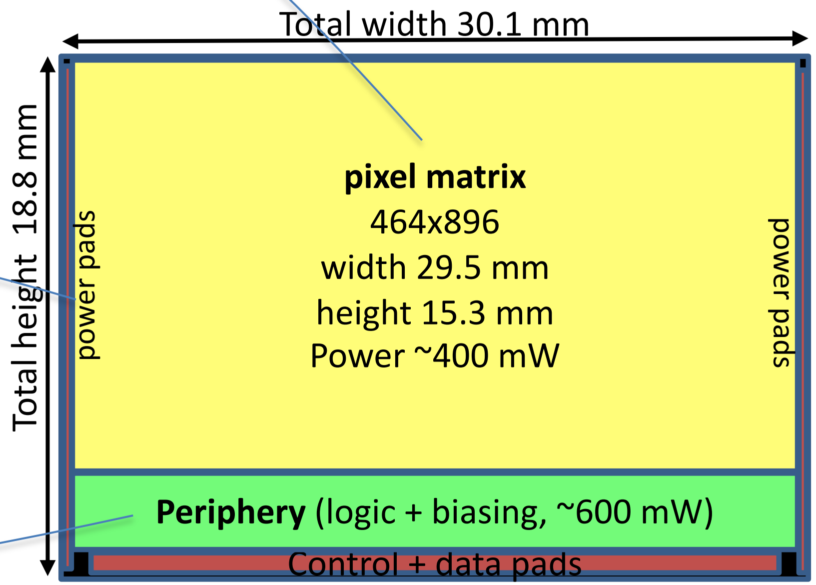
- Next steps
  - Lower detection threshold
  - Irradiation 10^{14}-10^{15} n_{eq}/cm^2
  - Next beam test in Q1-2023

OBELIX (Optimized BELle II pIXel) sensor

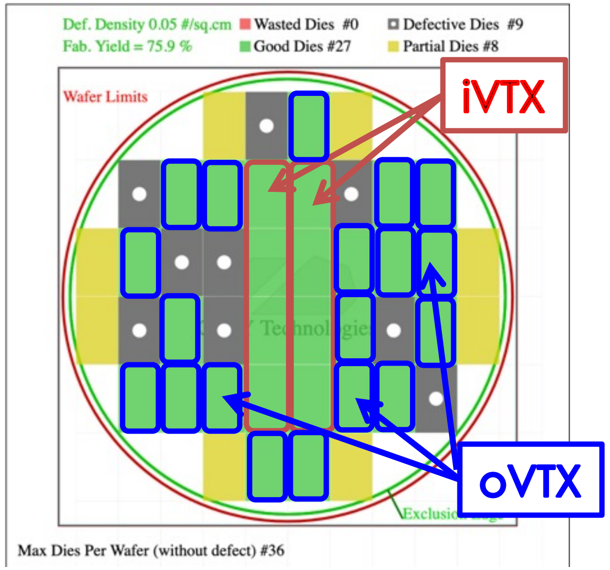
- **Pixel matrix**
  - Copied from TJ-Monopix2
    => radiation tolerance granted
  - Pitch possibly increased from 33 to <40 µm
    – for robustness & power dissipation
  - Frequency ~10-30 MHz
    => time-stamp precision 100 or 30 ns

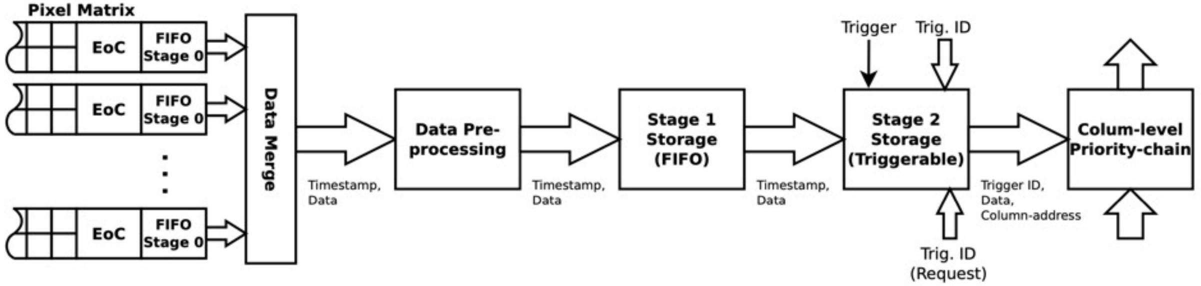
- **Power pads**
  - Power regulators added
    => simplified system integration
  - But area limited to <150 µm

- **Periphery**
  - New end-of-column adapted to Belle II trigger
    – Timestamped hits stored in memories
    – Read-out when timestamp matched with trigger
  - Single output at 320 MHz
    average bandwidth/sensor 140 Mbits/s
  - Biasing generation and monitoring



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

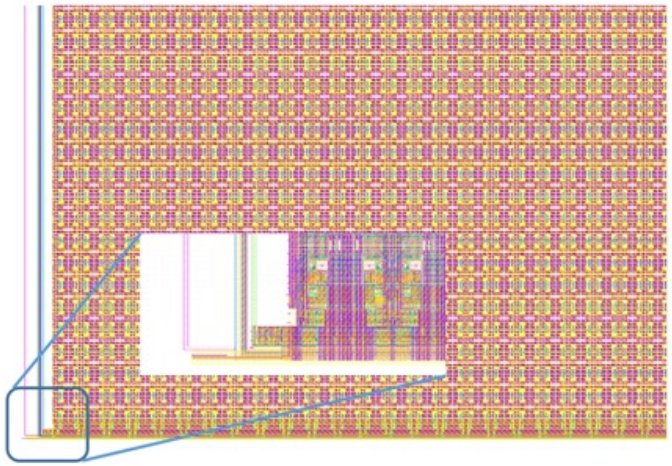




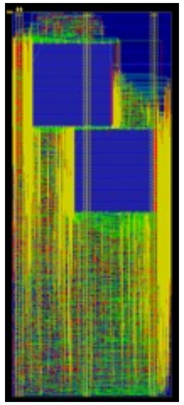
OBELIX-1 design

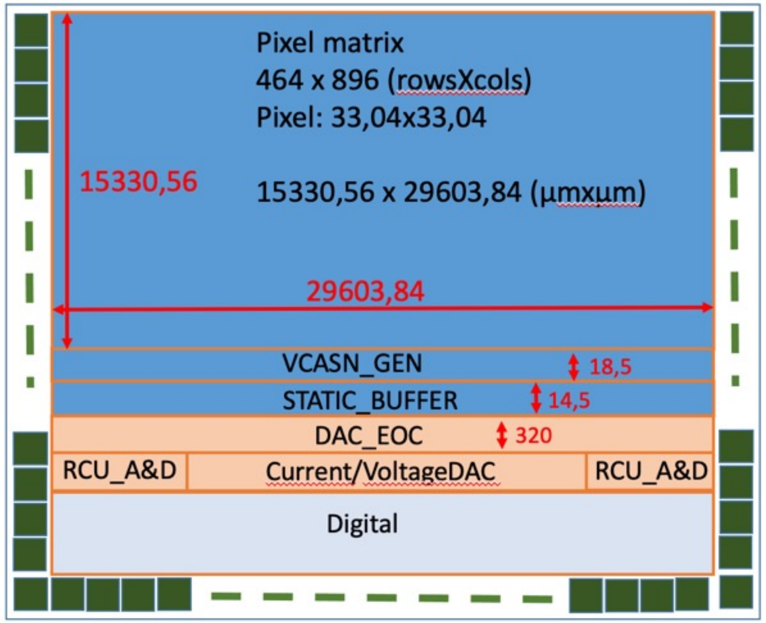
- Status
  - Main layouts (matrix, logic, regulators) almost ready
  - Power optimisation on-going for
    - In-pixel Front-End
    - Trigger logic
  - Control logic under development
  - Large verification effort ahead
  - Submission early in 2023

pixel matrix



trigger logic
16 columns
0.6x1.3 mm^2

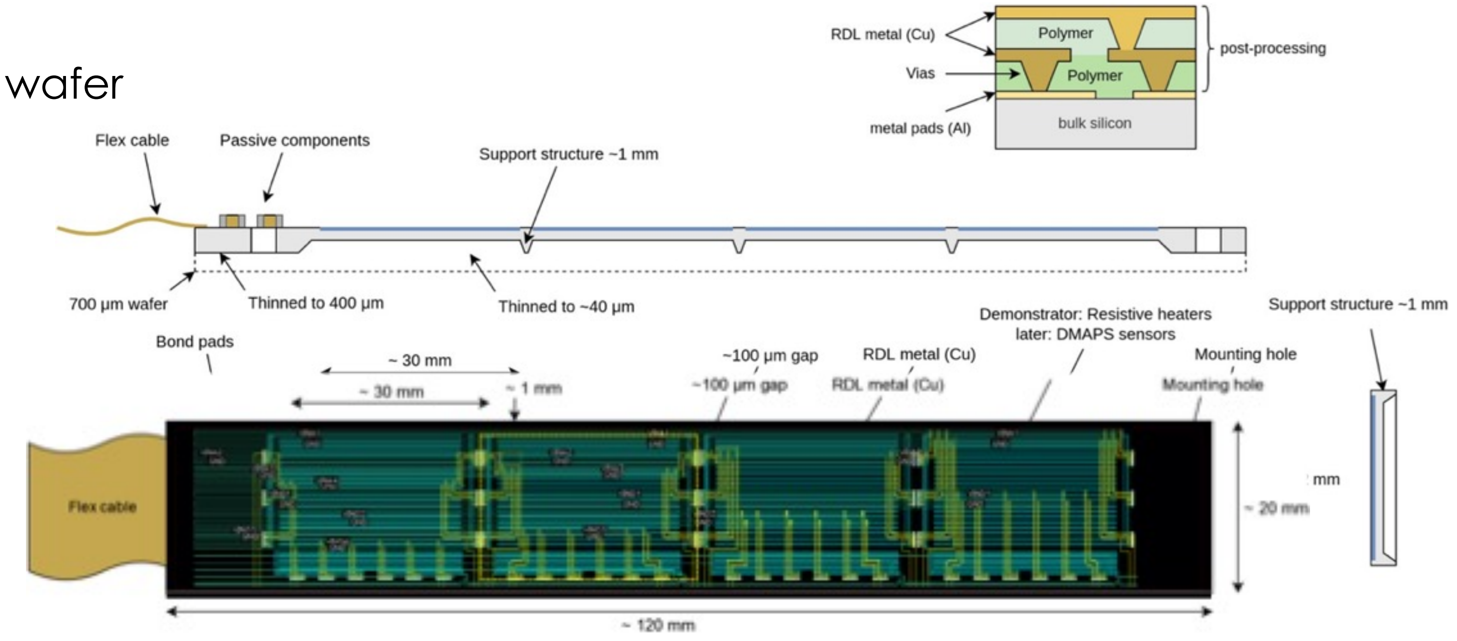




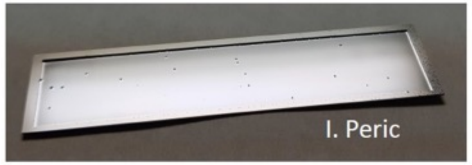
RCU_A/D: Regulator Control Unit Analog/Digital
REG_DAC: DAC Regulator
STATIC_BUFFER: BCID Buffers

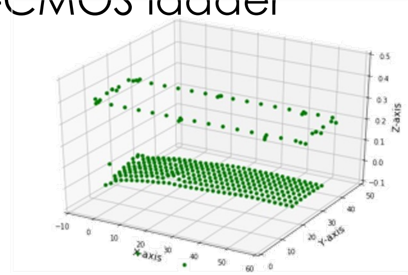
iVTX inner layer concept

- **All-silicon module < 0.15 % X0**
  - 4 contiguous sensors diced as a block from the wafer
  - Redistribution layer for interconnection
  - Heterogeneous thinning for thinness & stiffness



- **Prototyping**
  - With existing 10 cm2 HV-CMOS ladder
    - Planarity demonstration

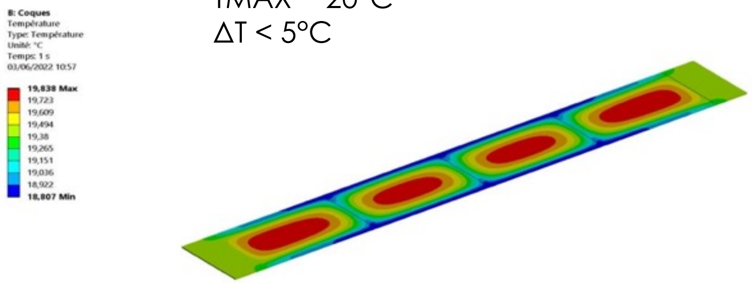




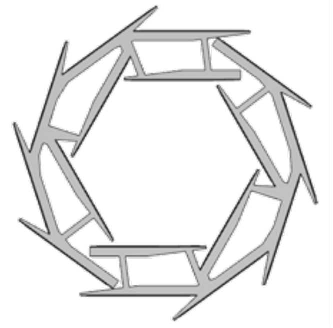
  - On-going at IZM-Berlin With dummy Si
    - True iVTX geometry => Spring 2023

- **Simulation on cooling**
  - Dry air cooling 15°C
  - Assume 200 mW/cm²

TMAX ~ 20°C
ΔT < 5°C

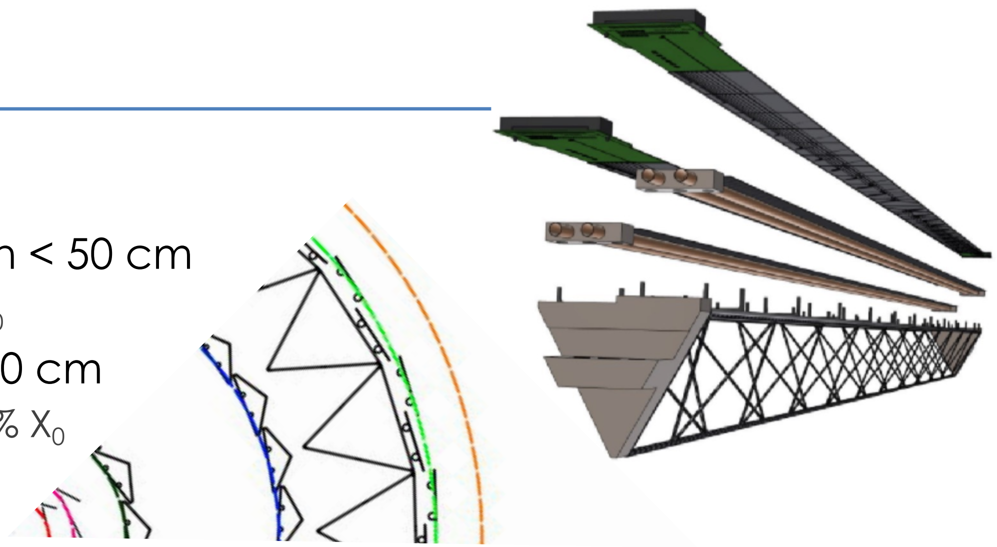


Windmill support structure
radii =14 + 22 mm

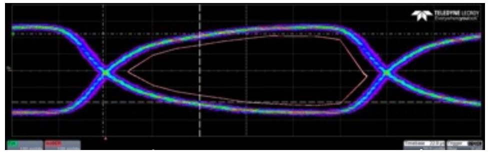


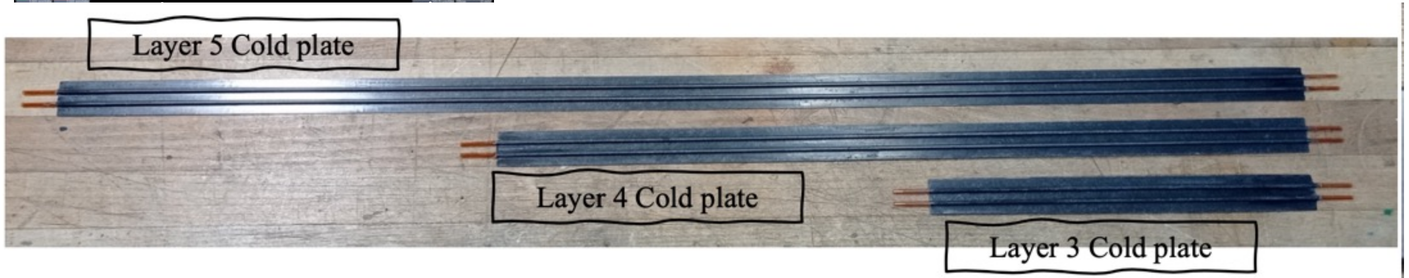
oVTX outer layer concept

- 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 < 50 cm
    - Single sensor row, ~0.5 % X_0
  - L5, radius 14 cm, length 70 cm
    - Double sensor rows , ~0.8 % X_0



- Prototypes for L5 under test
  - Deformation & vibration
    - Max sagitta ~500 µm
    - First resonance f=250 Hz
  - Signal propagation
  - Cooling at $T_{ambient}$ ~24°C
    - Leakless water flow at T_{in} = 10 C
    - Heaters dissipating 200 mW/cm^2
    - 22C < $T_{sensors}$ < 26

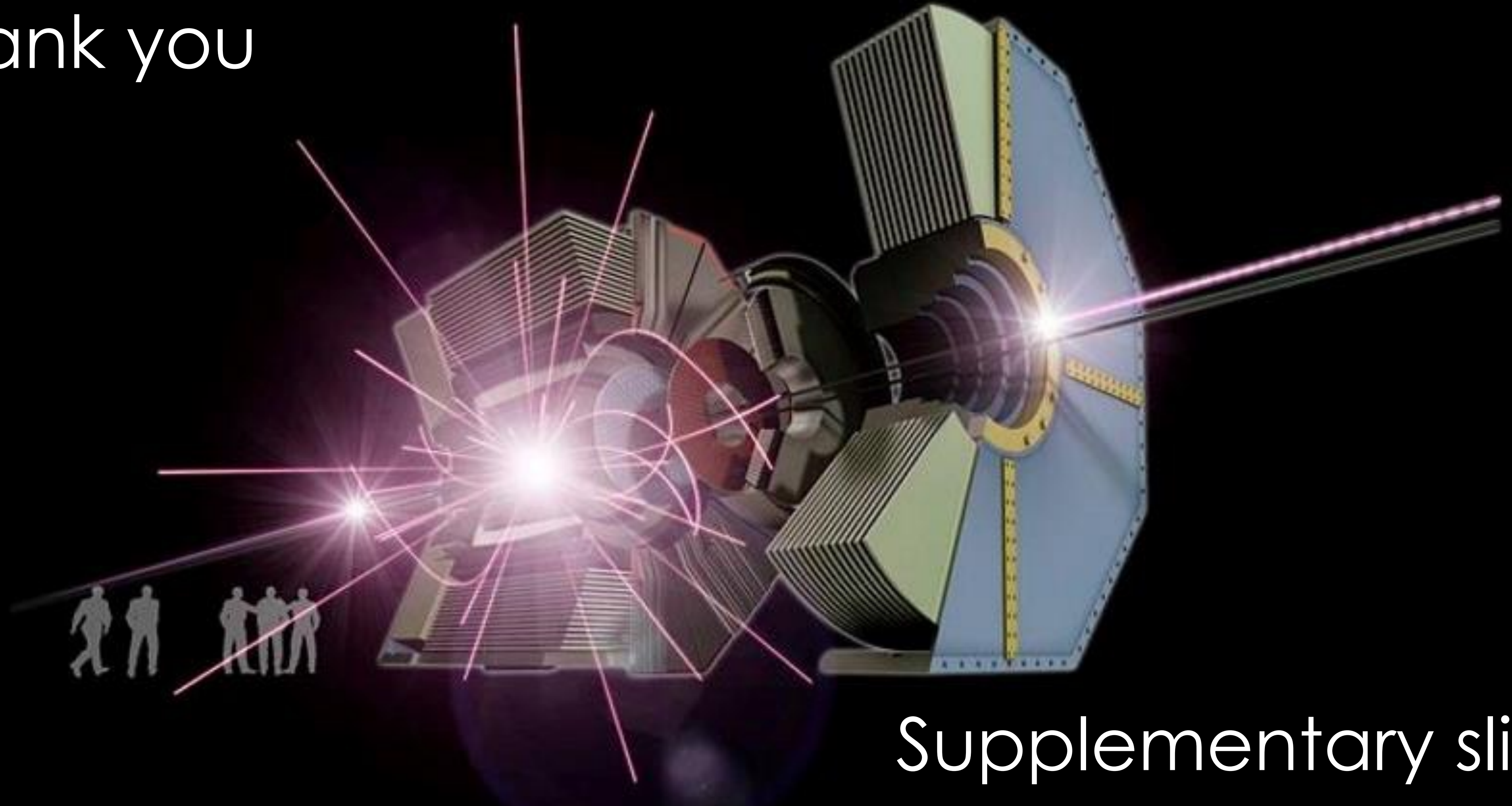




Conclusion

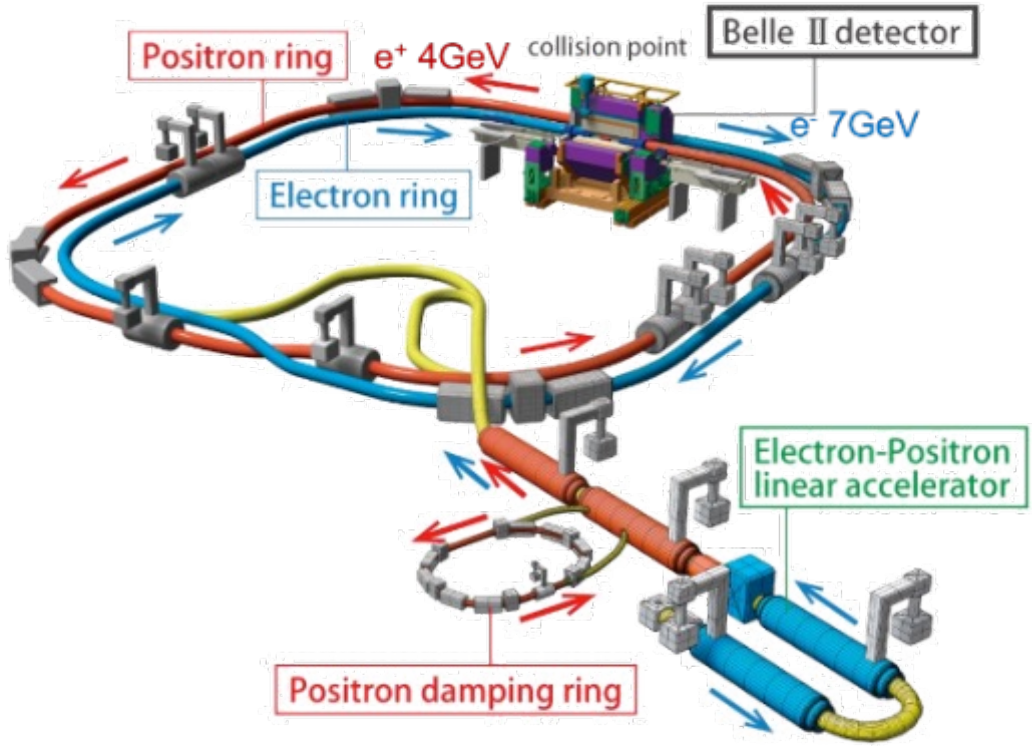
- **VTX could be the first vertex detector with MAPS for e+e- collisions < 2030**
- **Large prototyping & characterising effort**
  - Sensor, ladder
  - Critical milestones reached for Conceptual Design Report early 2023
- **Outlook on schedule**
  - VTX development phase completed around end of 2023 => Technical Design Report
  - Production phase may start in 2024

Thank you

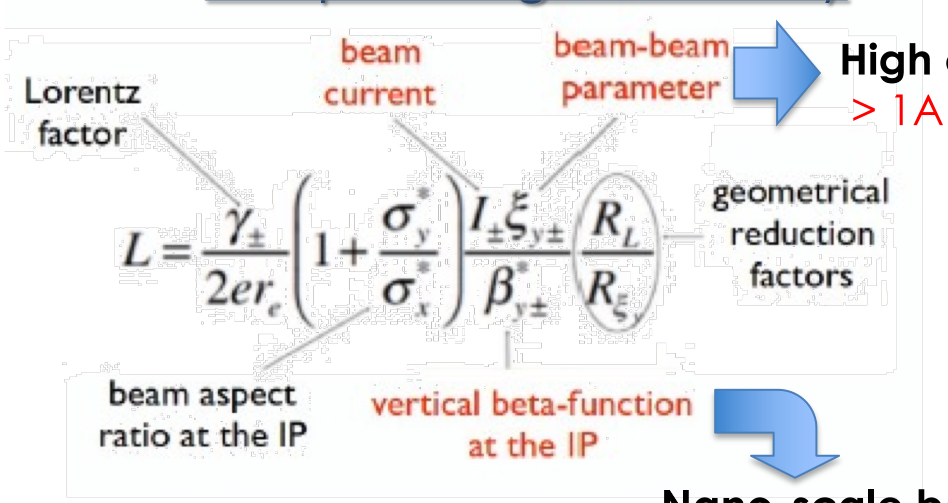


Supplementary slides →

SuperKEKB collider



- <u>Recipe to high luminosity</u>



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_\xi}\right)$$

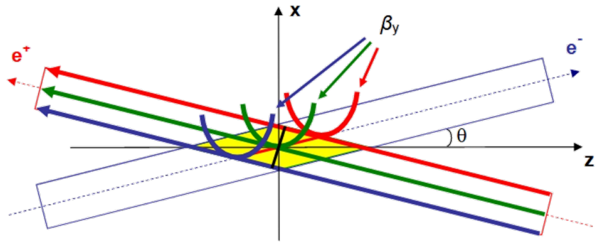
High currents:
> 1A

Nano-scale beam size:
$\sigma_x \times \sigma_y \sim 10\mu m \times 60\ nm$
$\beta_y^* << 1\ mm$

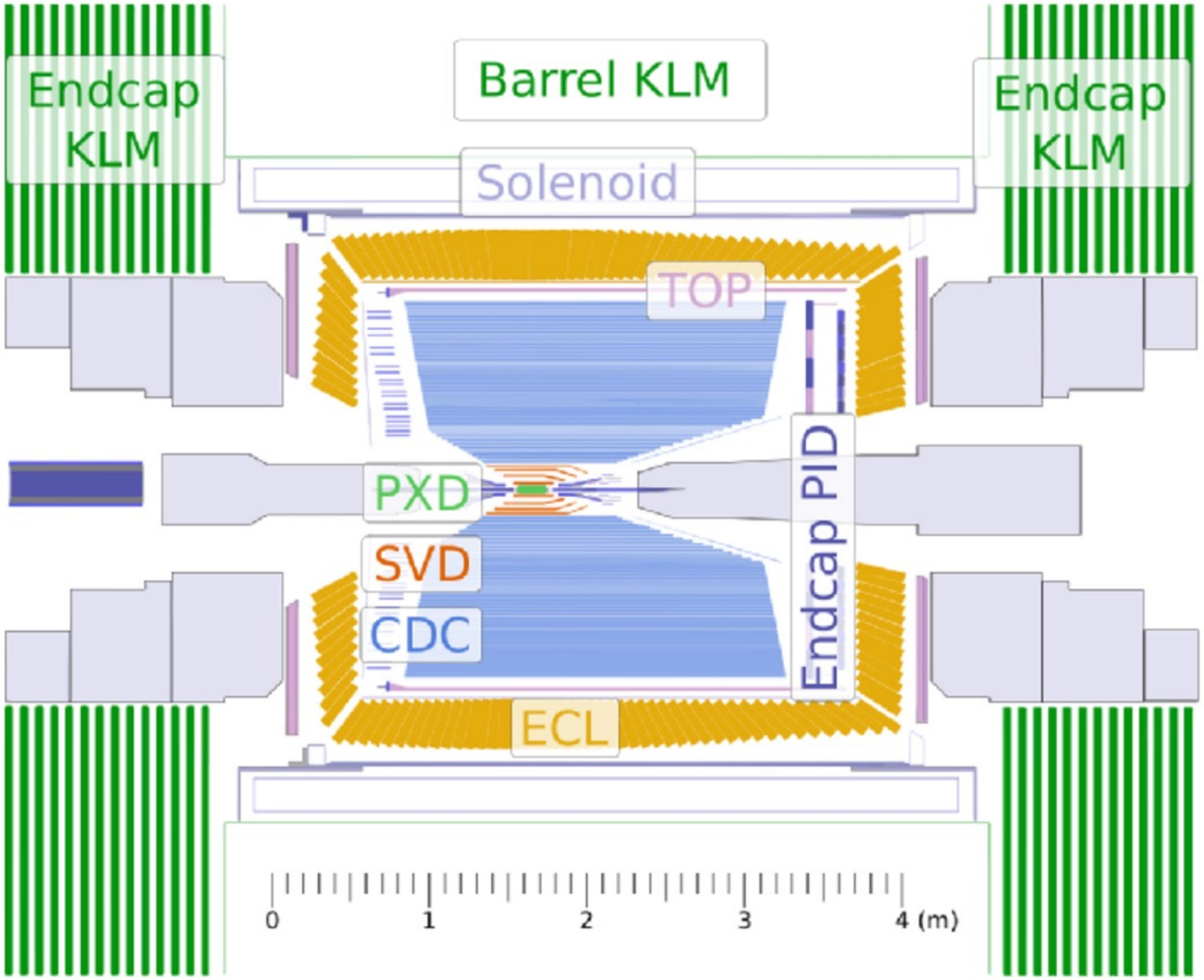
	KEKB	SuperKEKB	
		2020	Nominal
Energy (GeV) LER/HER	3.5 / 8	4 / 7	
Current (A) LER/HER	1.6/1.2	0.7/0.6	2.8 / 2.0
β_y^* (mm)	5.9	0.8	0.3
Instant. Lumi. ($cm^{-2}.s^{-1}$)	2.1×10^{34}	**2.4×10^{34}**	$\sim 6 \times 10^{35}$

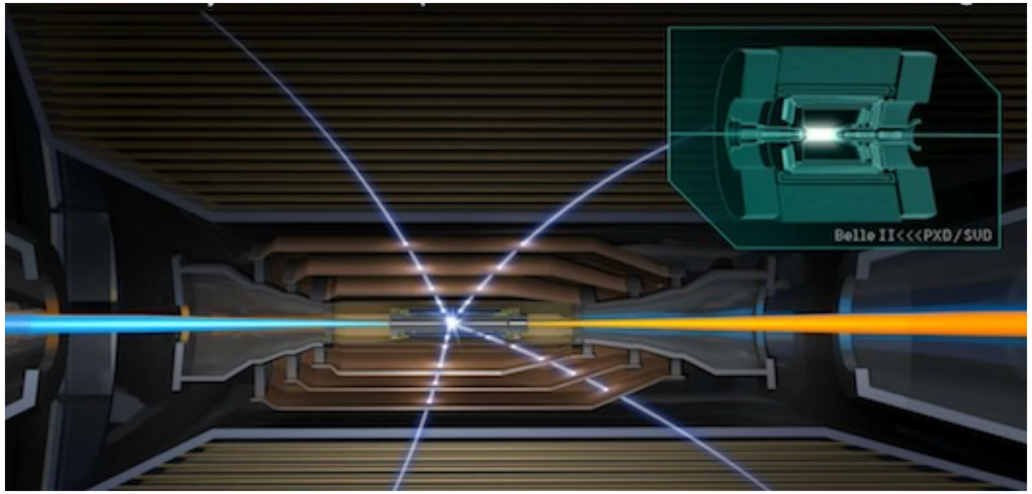
& specific beam crossing features
Crossing angle (83 mrad) + crab waist (80%)

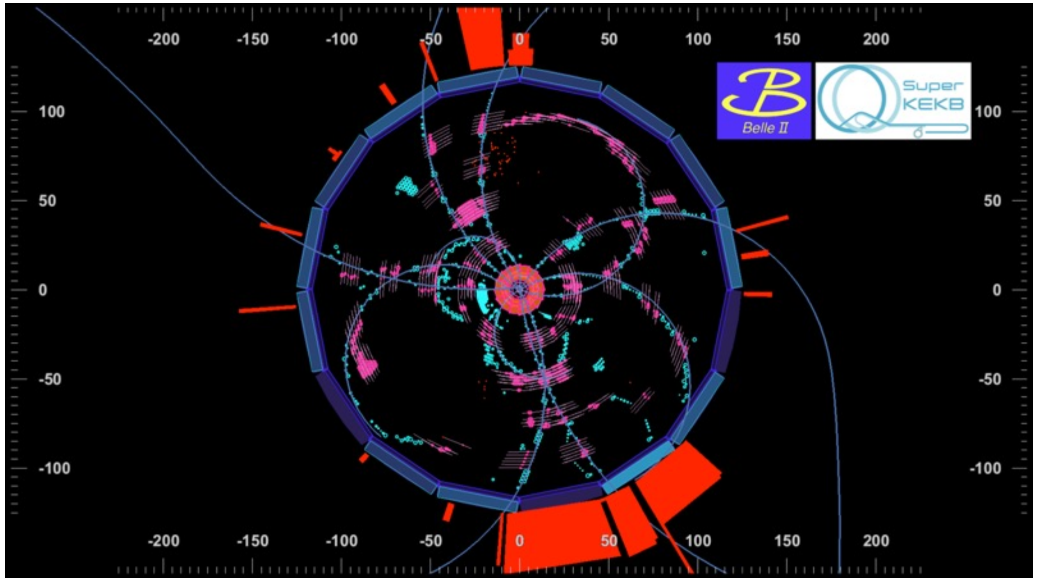
⚠ Cost = severe beam induced background



Belle II, another view







Impact on performance & physics

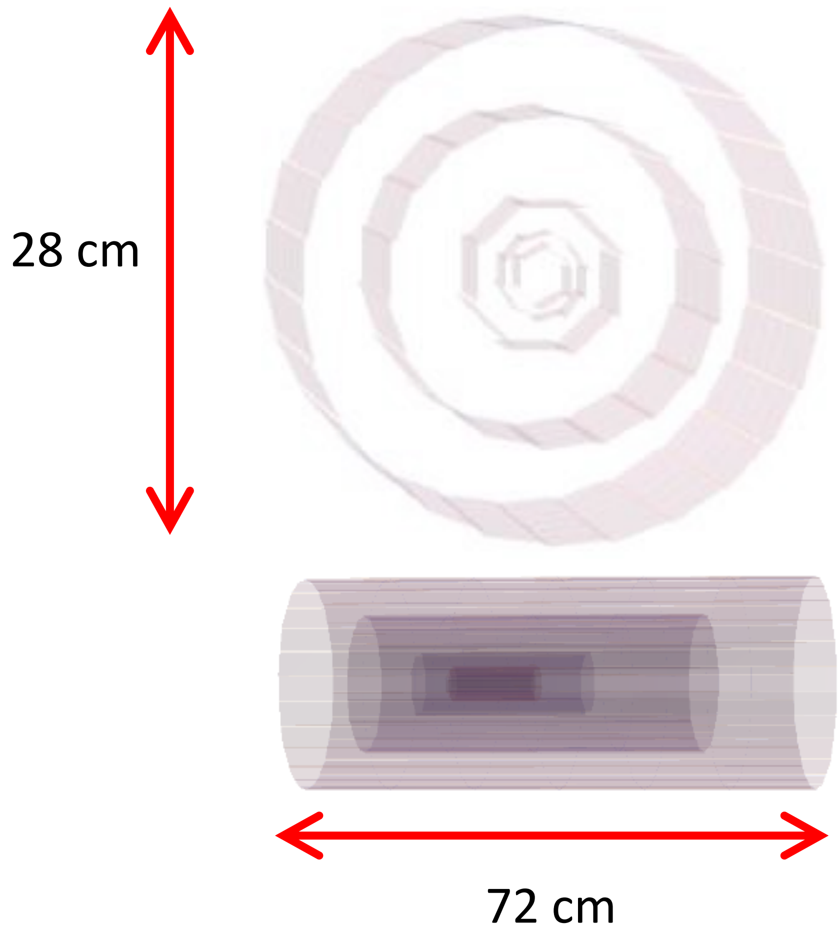
=> Snowmass Belle II : arXiv 2203.11349

Topic	VXD	CDC	PID	ECL	KLM
Low momentum track finding	✓	✓			
Track p, M resolution		✓			
IP/Vertex resolution	✓				
Hadron ID		✓	✓		
K_L^0 ID				✓	✓
Lepton ID		✓		✓	✓
π^0, γ				✓	
Trigger	✓	✓			

Topic	VXD	CDC (incl. Trigger)	PID	PID(Ω coverage)	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u \ell\nu)$	✓		✓	✓		✓
R, Polarisation$(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓		✓		
$S_{CP}, C_{CP}(B \to \pi^0\pi^0, K_S^0\pi^0)$	✓	✓			✓	
$S_{CP}, C_{CP}(B \to \rho\gamma)$		✓	✓		✓	
$S_{CP}, C_{CP}(B \to J/\psi K_S^0, \eta' K_S^0)$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches		✓			✓	✓

Details of the 5 layer VTX geometry

VTX 5 layers

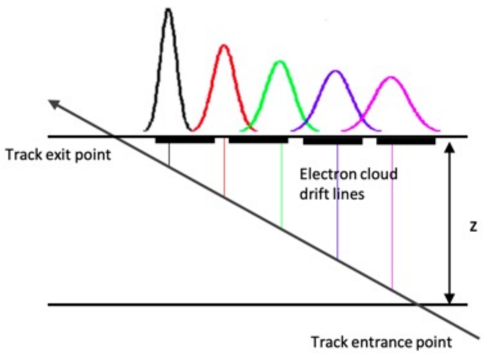


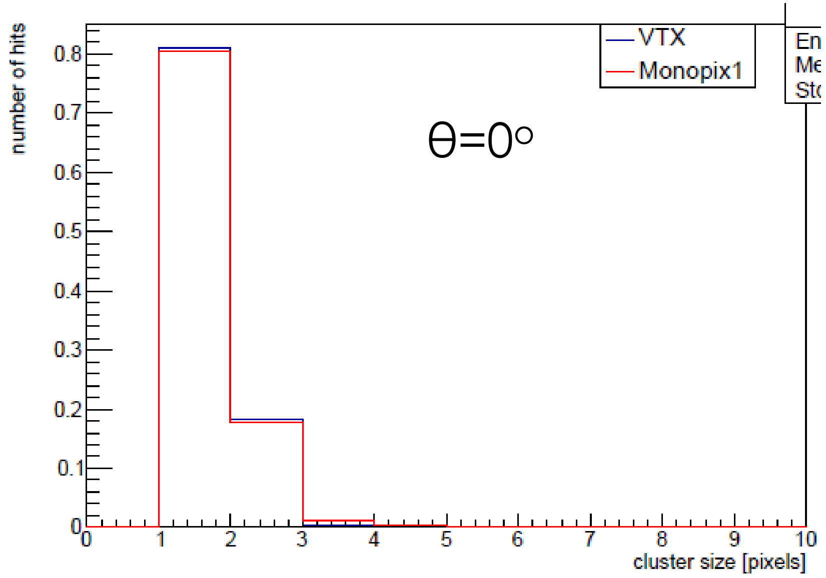
Layer no.	1	2	3	4	5
Radius (mm)	14.1	22.1	39.1	89.5	140.0
# Ladders	6	10	8	18	26
# Sensors per ladder	4	4	8	16	24

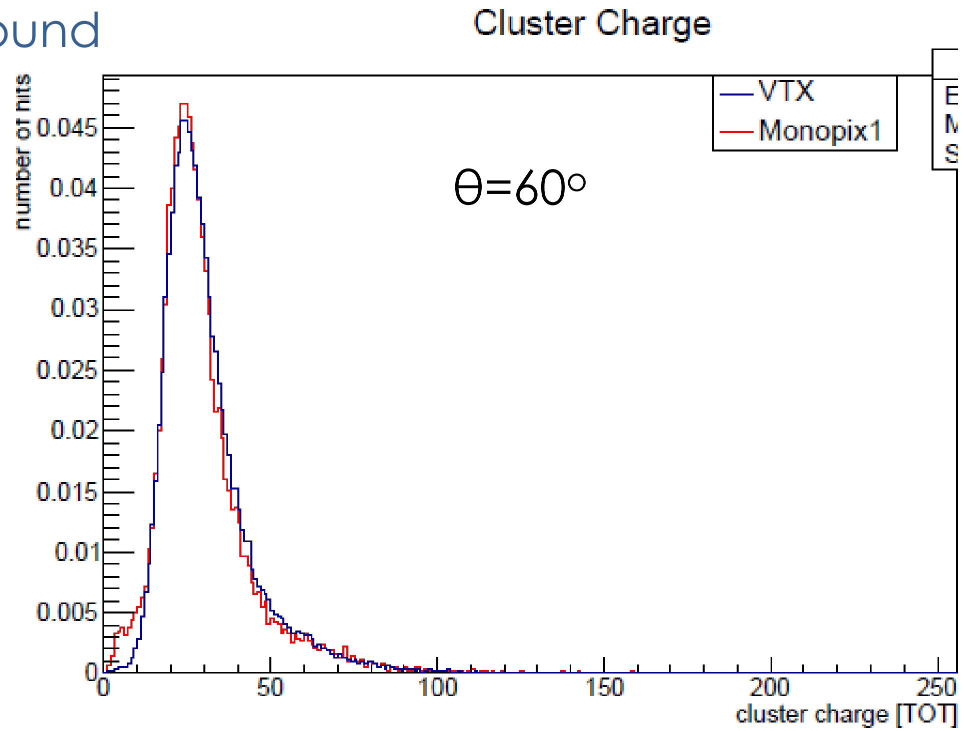
VTX simulated tracking performances

Context = full Belle II simulation framework, including background

- Realistic pixel sensor model
  - Digitizer assuming
    - fully depleted thin layer 30 μm
    - Pixel 33x33 μm^2 with 7bits Time over Threshold
  - **Tuned with Monopix-1 beam data**
    - JINST 14 (2019) C06006
    - Pitch 40x40 μm^2
    - ToT 6 bits







Monopix-1 data from **Bonn group**
Test-beam at DESY with 5 GeV e-

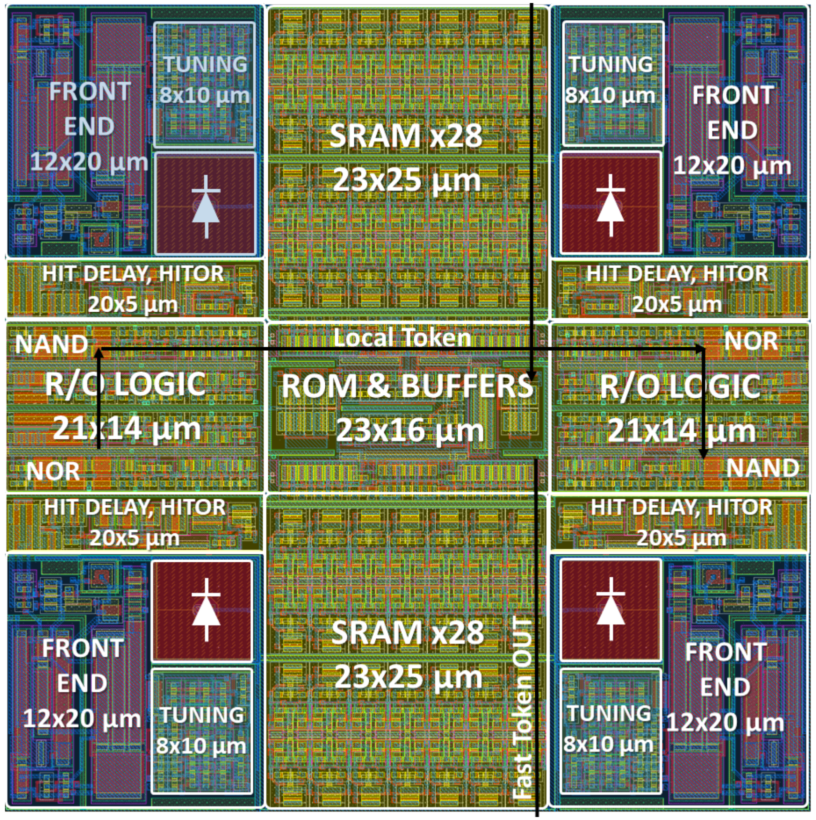
=> https://doi.org/10.5506/APhysPolB.52.909

TJ-Monopix in Tower 180 nm process

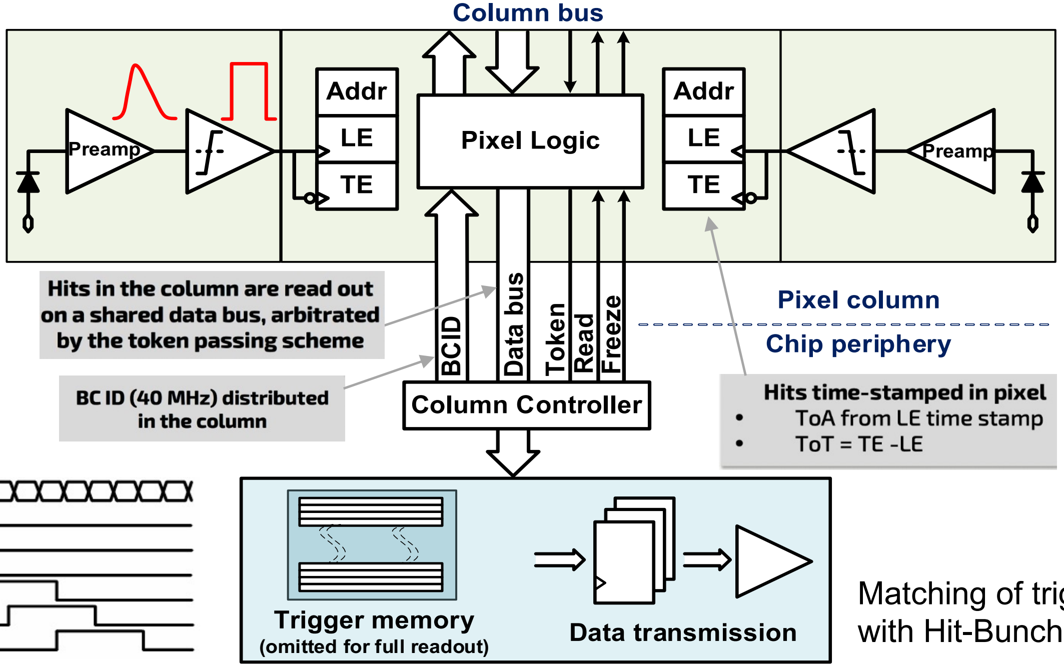
▪ Pixel matrix read-out architecture

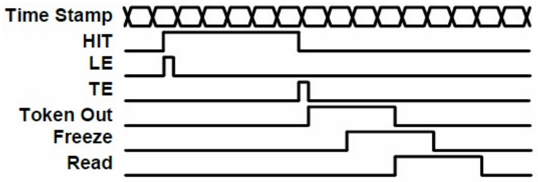
- Collaboration: Bonn, CERN, CPPM, CEA-IRFU
- Modified process for radiation tolerance
  DOI: 10.1016/j.nima.2020.164403
- Column-drain read-out Inherited from ATLAS FE-I3
- Capable to handle >100 MHz/cm^2
  - Fired pixel address moves fast down to periphery

The Layout:
2x2 pixels
each 33x33 µm^2



The logic:





Matching of trigger-ID
with Hit-BunchCrossingID

VTX sensor requirements

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

	Belle-II CMOS-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	25 to 100 ns	25 ns
Hit memory for trigger	< 100 kb	
Power	<200 mW/cm^2	200 mW/cm^2
TID fluence	<100 kGy < 10^{14} n_{eq}/cm^2	100 kGy 10^{15} n_{eq}/cm^2

Chosen as forerunner for OBELIX sensor