Upgrade of the vertex detector of the Belle II experiment

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GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Belle II

LCWS2021 International Workshop on Future Linear Colliders

- Context of the current VXD
- Opportunity for a VXD upgrade
- On-going relevant R&Ds
- Full simulations for optimisation

The VXD roles within the Belle II setup

Physics program @ SuperKEKB with Belle II

- Thorough test of Std Model
- Direct/indirect search for New Physics
- Hadronic Physics

with billions of $B\bar{B}, c\bar{c}, \tau\bar{\tau}$ pairs
In "clean" environment of B-factory

⇒ The Belle II physics book
PTEP 12 (2019) 123C01

- Colliding e^++e^- at $\sqrt{s} = M_{\Upsilon(4S)}$ with luminosity $8\text{x}10^{35}\text{cm}^{-2}\text{s}^{-1}$

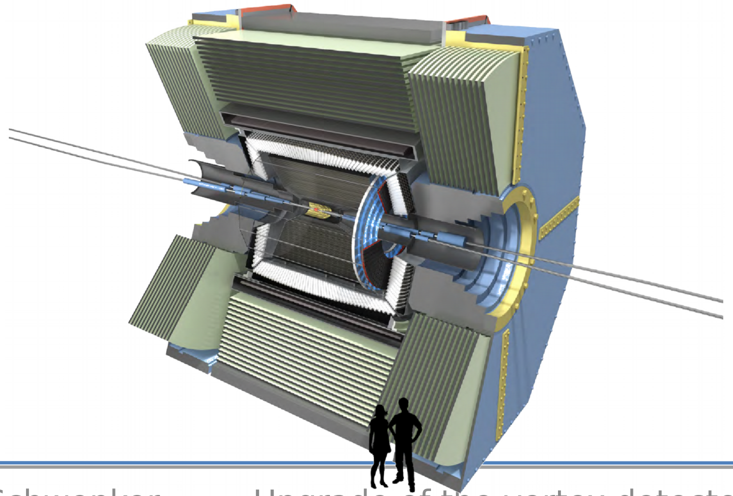
→ SuperKEKB collider implementing the nano-beam scheme @ high currents

↓

High collision rate   High beam-induced bkg

The Belle II experiment

- "classical" B-factory detector + enhanced features



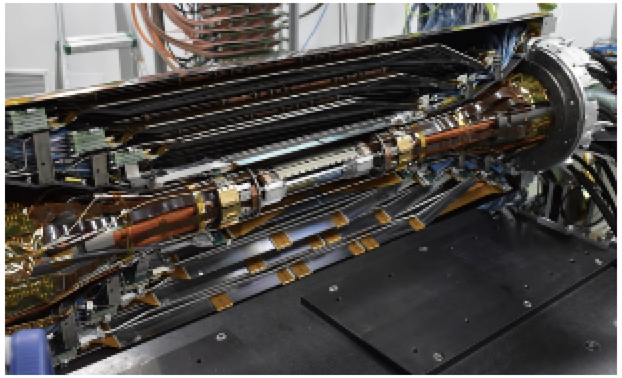
The vertex detector (VXD)

- Better vertexing ← lower boost
- Smarter tracking ← higher hit rate
- Tracking det.: VXD & Central Drift Chamber (CDC)

+ Harsher radiation environment
+ Belle II trigger rate ~ 30 KHz

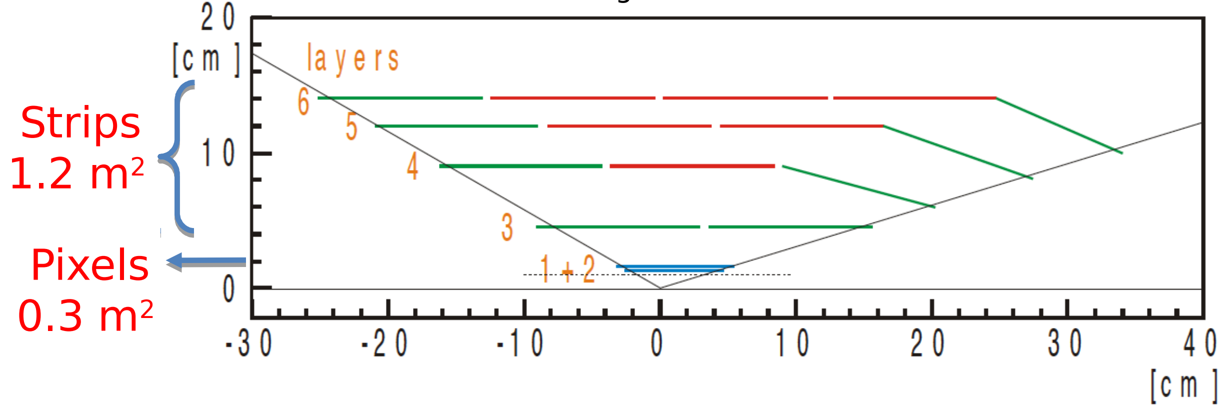
The current VXD

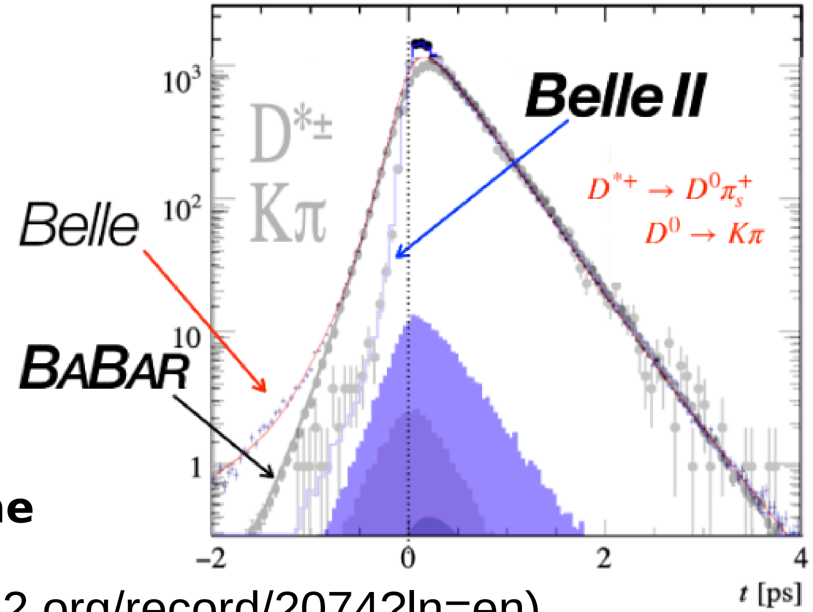
- <u>Two technology system</u>
  - **SVD = Double-Sided Strip Detector**
    - Read-out sensor connected on sensor = Origami
    - Hit time-stamping $\sigma_t \sim$ 2-3 ns
    - Spatial resolution $\sigma_{s.p.} \sim$ 20 µm



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

65 cm long – 30 cm in diameter

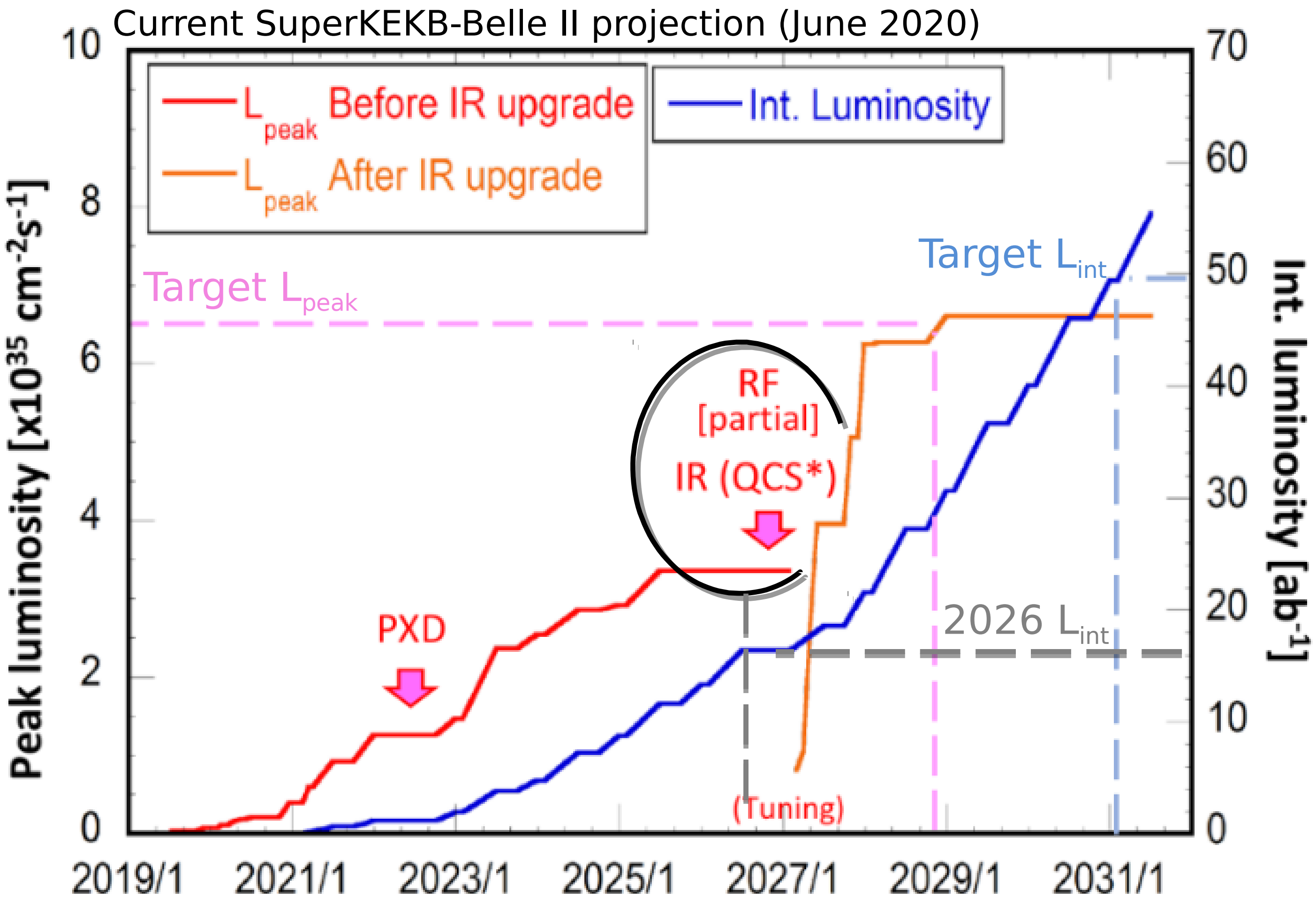




D meson lifetime

(https://docs.belle2.org/record/2074?ln=en)

A decade of operation → Upgrades?



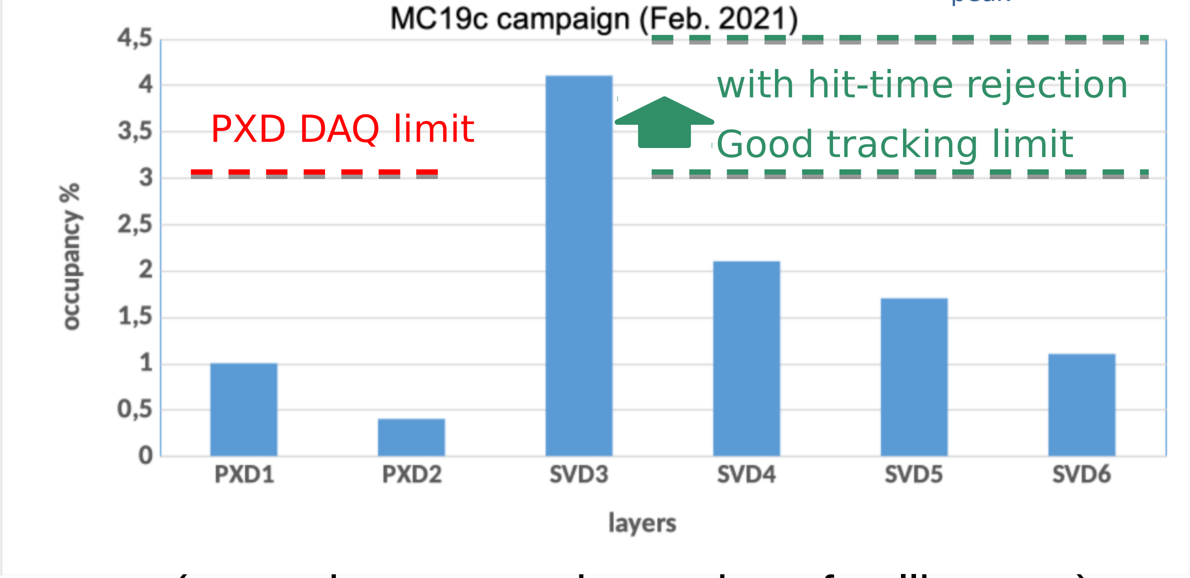
- Short term ~ 2026
  - Long shutdown for QCS upgrade
    - Needed before next jump in luminosity
  - Opportunity for Belle II sub-det. upgrades
    - Let's investigate possibilities…
    - short time → with currently ~available technology
- Longer term > 2030
  - Further increase of peak luminosity
  - Beam polarization?

Current VXD & nominal luminosity

⇒ Belle II VXD Open workshop July 2019

- Beam-induced background extrapolations
  - A long way to reach Data/MC ratio ~ $O(1)$

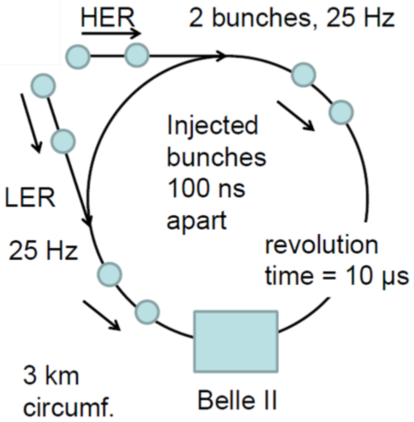
Current prediction @ nominal L_{peak}



(assuming aggressive tuning of collimators)

- **Optimistic case with large uncertainties**
  - Drastic change of beam optics for max L_{peak}
    - β_y* today 800 µm / nominal 300 µm
  - Continuous injection effect not predicted

- Tracking / vertexing
  - **Track pattern recognition with SVD hits only** required in // to tracking in Central Drift Chamber
  - Then extrapolation to match PXD hits
    - Also used for reduction of PXD output bandwidth
  - Final pointing resolution somewhat limited by beam-pipe thickness
    - 0.8 % X_0 ← partially required against synchrotron rad.



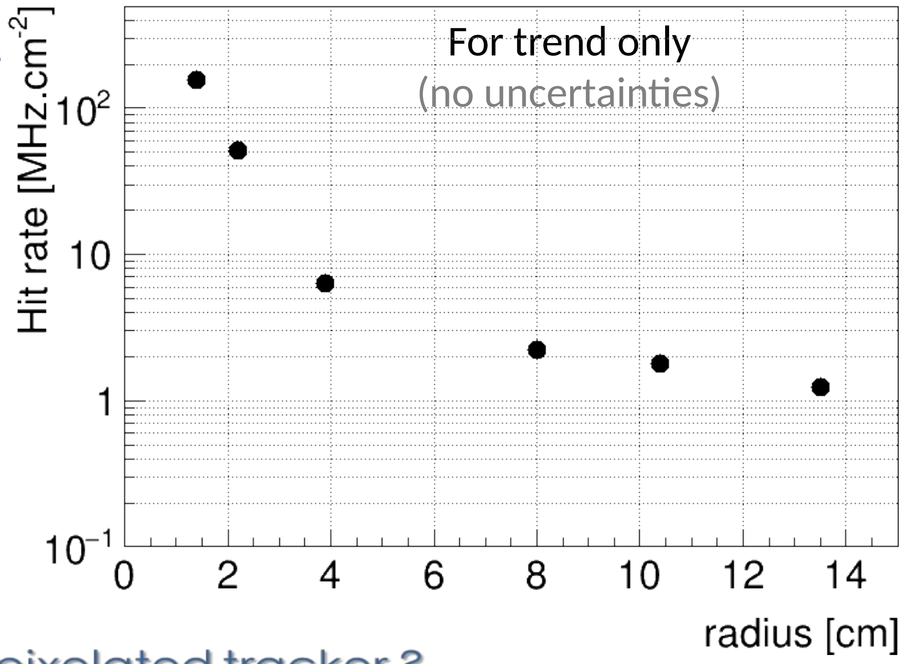
Performances within limits BUT without much margin

Requirements for short-term VXD upgrade

- Vertexing & Tracking performances **at least** as good as current VXD
  - Radius range 14 – 135 mm
  - Single point resolution **≤10-15 µm**
  - Total material budget **< (2x 0.2 + 4x 0.7) % X_0**
    - total power budget < 2000 W

- **Robust** against environment for inner layer (**r=1.4 cm**)
  - **Hit-rate ~ 120 MHz.cm^{-2}**
  - Total Ionizing Dose ~ 10 Mrad / year
  - NIEL fluence ~ 50x10^{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
    - Simplified track pattern recognition

- Timing if pixelated tracker ?
  rough estimate → $T_{int} \lesssim 100$ ns

Proposals for upgrades of Belle II

- Received expression of interest (EOI) documents related to vertex and CDC upgrade.

EOI	Upgrade ideas scope and technology	Time scale
RMBA	Improved diamond readout electronics. Integration with SKB abort system	< 2026
DEPFETs	Adiabatcally improved replacement of existing system	2026
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	2026
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	2026
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	2026
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< 2026

Effort built up to answer within ~1 year

- Which concepts bring best performances?
- Which technology fit requirements?
- Which technology can allow install in ~2026?

➡ EOI ➡ CDR

Thin and fine-pitch DSSD

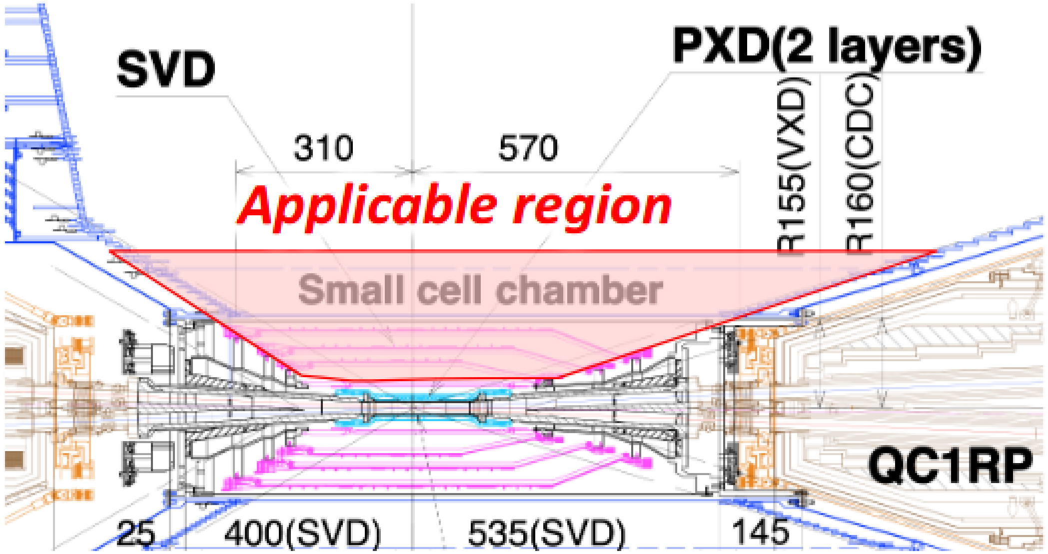
@ KEK

Main R&D targets

- Handling higher hit-rate / SVD
  - 10 MHz/cm^2 (radii>3 cm)
- Improved resolution σ_z & decrease material budget
- Extensible to small cell chamber of CDC
- Trigger capabilities (L1 trigger)

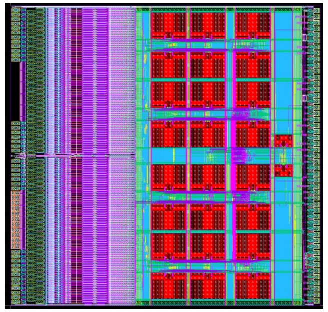
	Sensor dim.	Thickness	Pitch P-side	Pitch N-side
Current	40x125 mm^2 60x125 mm^2	300-320 µm	50-75 µm	160-240 µm
Upgrade	51.2x57.6 mm^2	140 µm	50 µm	75 µm

(with intermediate strip)



Solutions

- **Double-Sided Sensors** prototyped by Micron
- **Front-End ASIC = SNAP128A** under dvpmt
  - Based on SliT chip for g-2 (J-PARC experiment)
  - 180 nm CMOS process



- ENC = 650 e-
- Total power 2.8 mW/chan.
- 127 MHz output
- $\sigma_t \sim$ 8 ns
- 2k-depth memory → latency ~16 µs

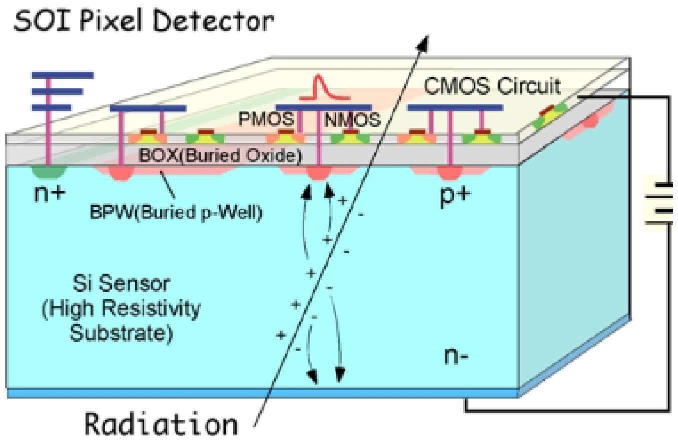
⇒ First Sensor+FEE in 2021

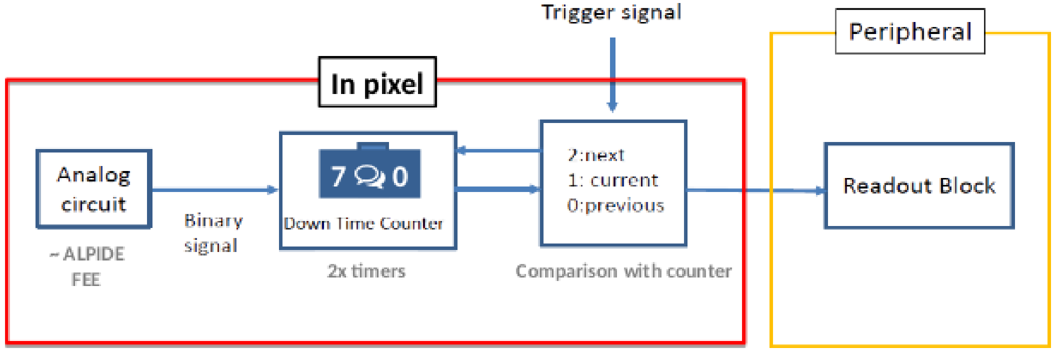
DuTiP - SOI pixel sensors @ KEK

- Main R&D targets
  - 7 layer tracker
  - Binary detector
  - Low material budget
    - Monolothic technolgy
  - Handling high-rate
    - Time-stamping < 100 ns
    - Global-shutter style

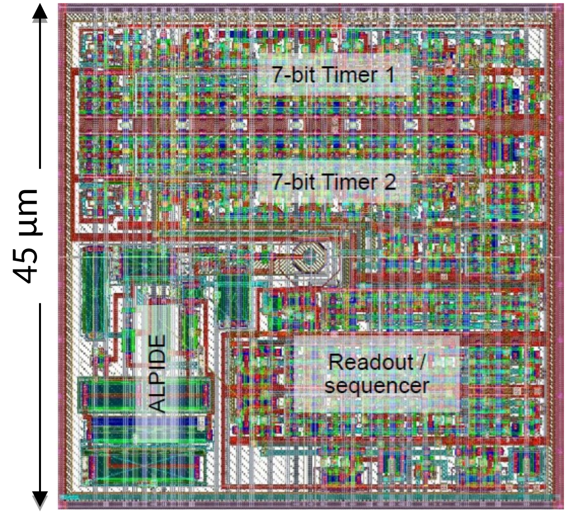
- Dual Timer Pixel concept
  - 16 MHz clock for TIMER
  - 2x 60 ns “integration” window
  - Trigger latency 8 µs
  - Occupancy << 0.1 %

- SOI Implementation
  - 0.2 µm LAPIS
  - Full depletion
  - Pixel pitch 45x45 µm²
  - Sensitive thickness 50-75 µm





Pixel layout

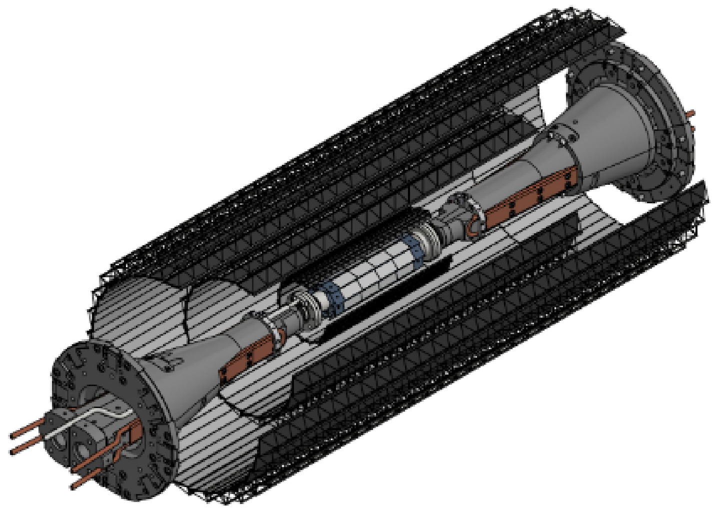


⇒ Initial prototype DuTIP 1 expected in March 2021

DMAPS – VTX

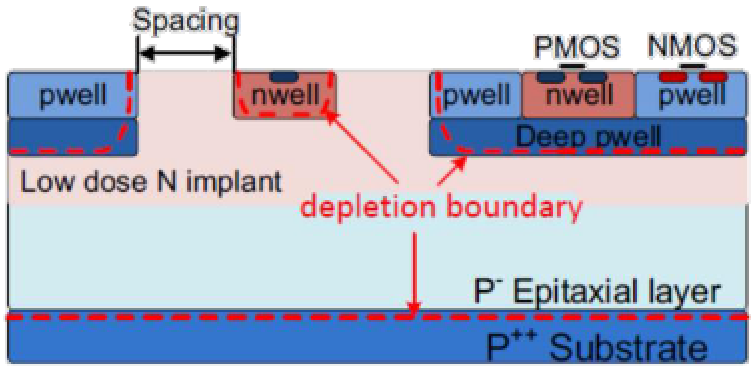
@ Bonn, CPPM, CERN, IRFU

- Main R&D targets
  - 5 (7) layer tracker
  - Monolithic and low power
  - Small and fast pixels in all layers
  - Rad. hard: TID 100Mrad & 10^{14} n_{eq} cm^{-2} NIEL



- 0.1% X_0 inner and 0.3-0.5% X_0 outer layers
- Simplified services, all layer for tracking on HLT

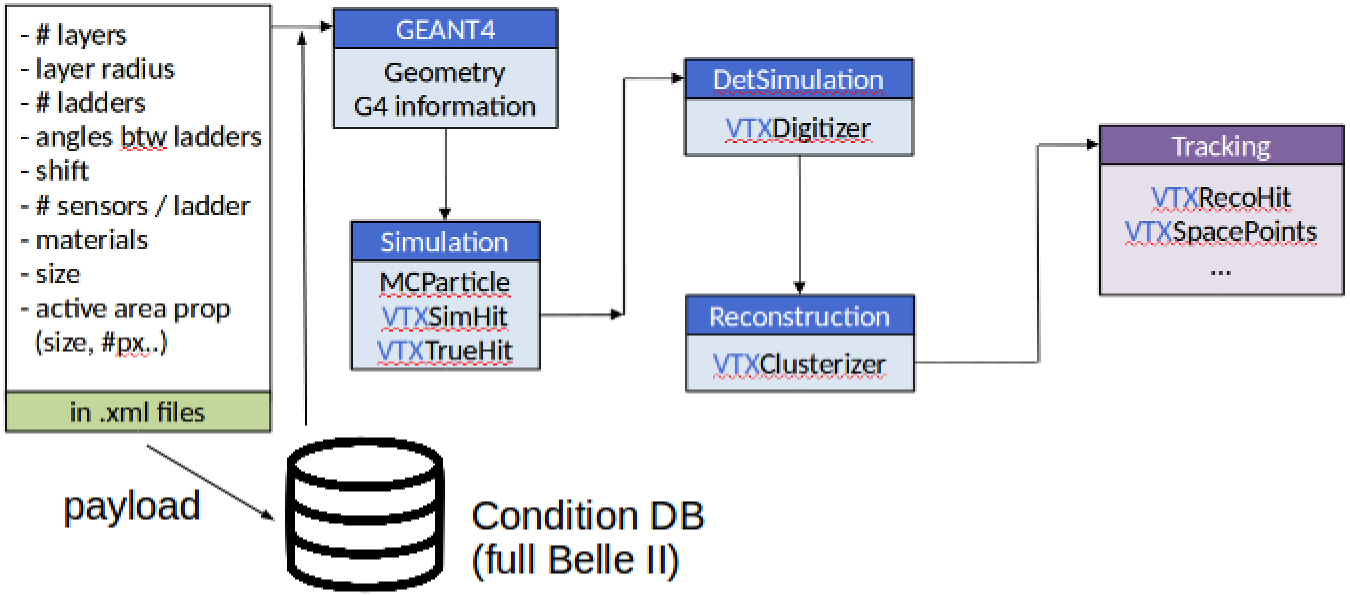
- Depleted monolithic active CMOS pixels
  - Evolution of TJ-Monopix and Mimosis chip families
    - TJ Monopix 2 matrix as workhorse
    - Column drain architecture ok for Belle II
    - R&D for Belle II EoC needed
  - Small pixels: 30x30µm^2
  - Fast: 25ns integration time (100ns time window sufficient)
  - Occupancy << 0.1 %



⇒ TJ-Monopix 2 being tested now.
1st Belle II dedicated chip (Obelix) in 2022

Full simulation of vertex upgrade in Belle II

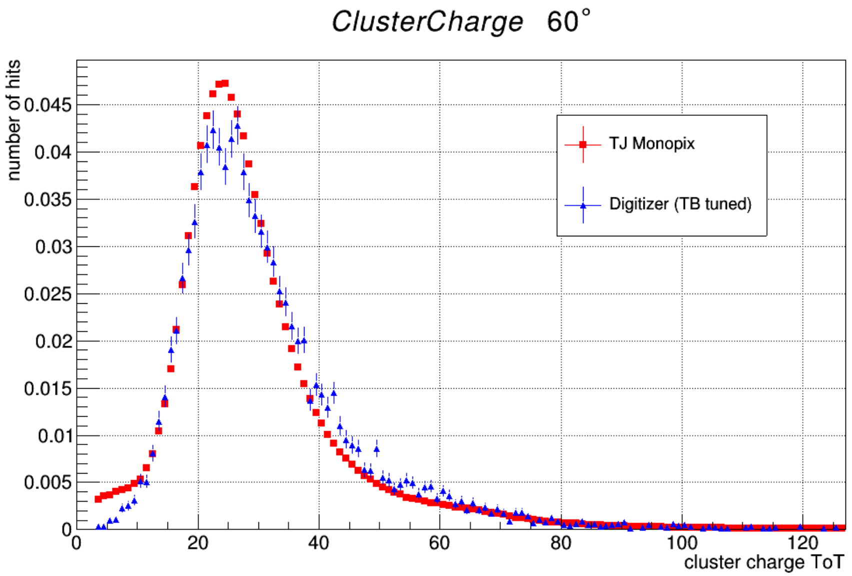
- Replace PXD & SVD with generic pixel layers and connect to tracking
  - Implemented in Belle II software as new sub-detector (VTX) of Belle II
  - Part of Geant4 detector simulation with realistic backgrounds
  - Part of overall event reconstruction => physics benchmarking

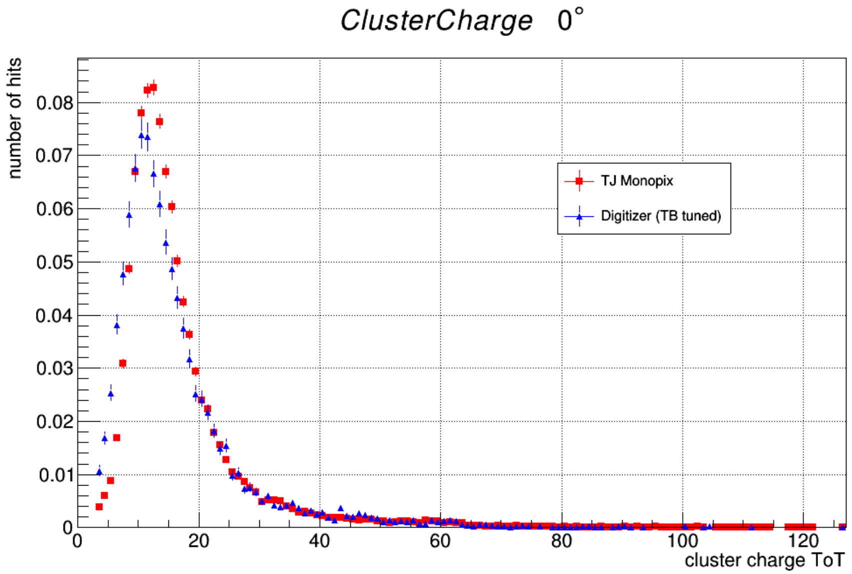


Simulated pixel response

Context = new vertex det. with all VXD fully pixelated = VTX

- Realistic pixel sensor model
  - Digitizer assuming
    - fully depleted thin layer 30 µm
    - Pixel 33x33 µm² with 7bits Time over Threshold
  - **Tuned with Monopix-1 beam data**
    - JINST 14 (2019) C06006
    - Pitch 40x40 µm²
    - ToT 6 bits



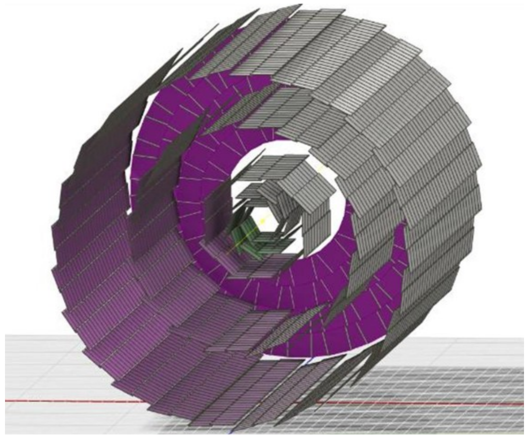


Monopix-1 data from **Bonn group**
Test-beam at DESY with 5 GeV e-

Results by T.Fillinger (Strasbourg), B.S. (Göttingen), C.Wessel (Bonn)

Simulated tracking performances

Context = new vertex det. with all VXD fully pixelated = VTX



- Realistic pixel sensor model
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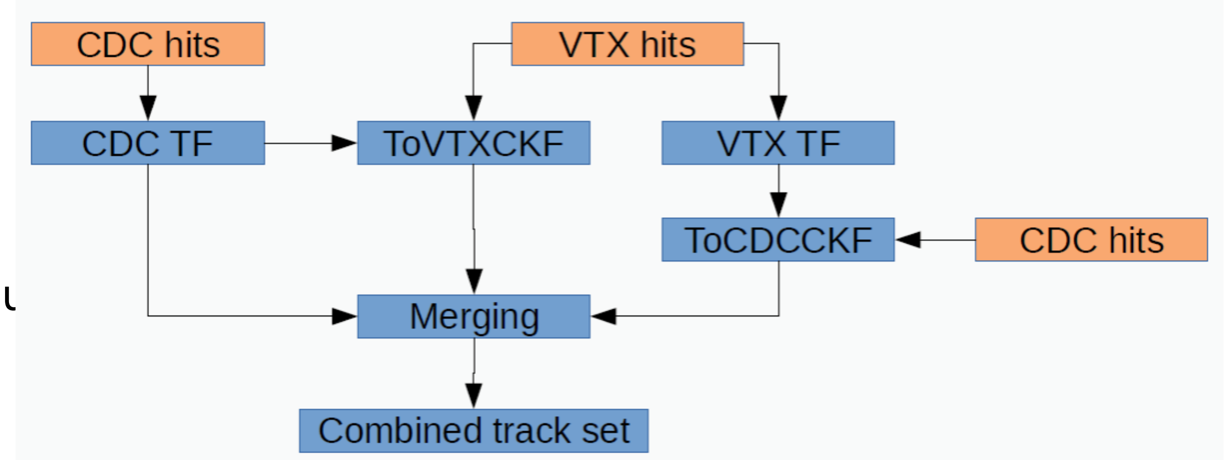
    - Pixel 33x33 µm² with 7bits Time over Threshold
  - Tuned with Monopix-1 beam data

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



- Full tracking chain
  - VTX standalone
  - CDC standalone

  } then combined

All VTX layers included in pattern-reco. ⇒ beneficial to High Level Trigger

Results by T.Fillinger (Strasbourg), B.S. (Göttingen), C.Wessel (Bonn)

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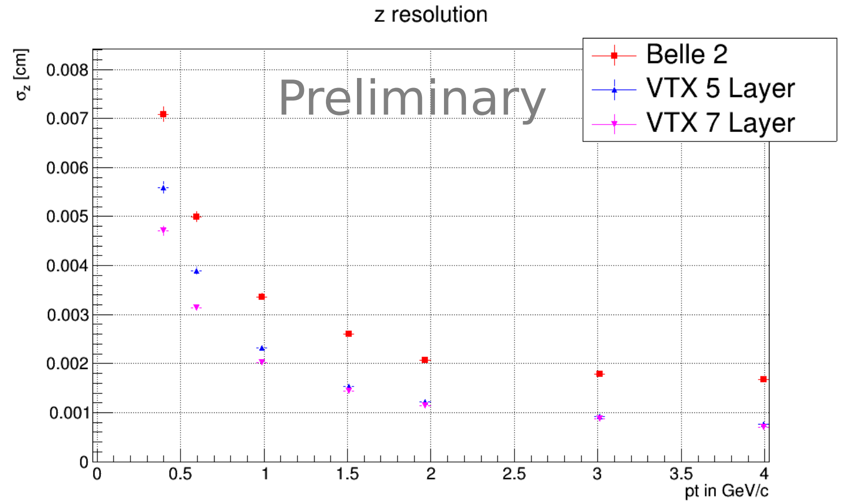

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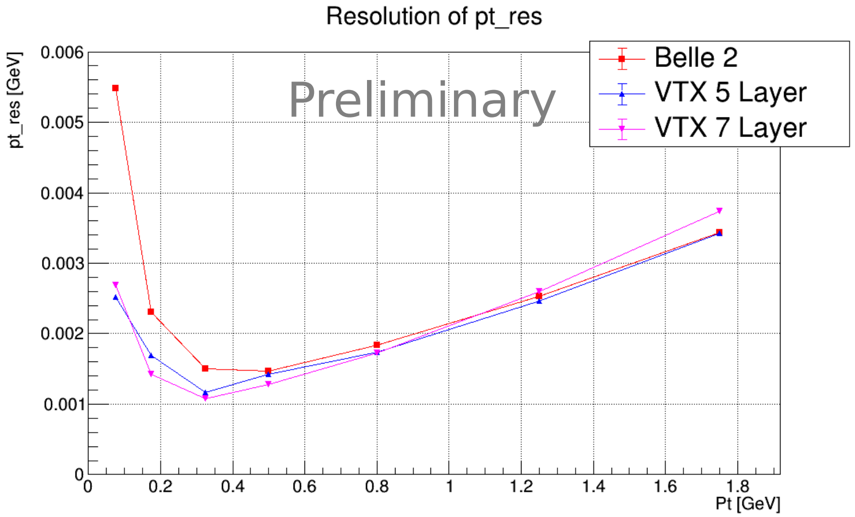

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Results by T.Fillinger (Strasbourg), B.S. (Göttingen), C.Wessel (Bonn)

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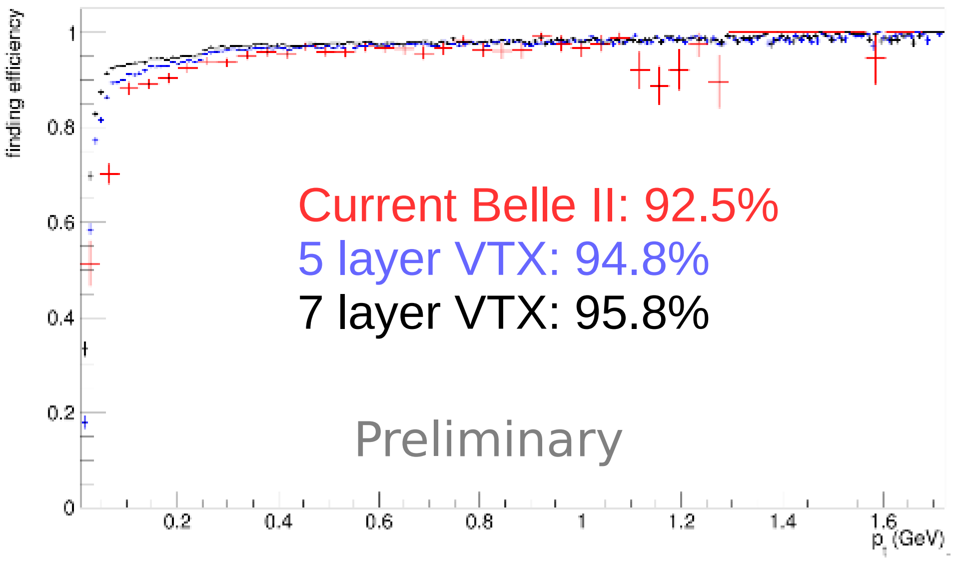

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- Full tracking chain
  - VTX standalone
  - CDC standalone

  } then combined

Summary & Outlook

- There is an opportunity for an upgraded vertex detector (VXD) in Belle II
  - Shor-term target QCS upgrade ~ 2026
  - Main requirement = additional robustness / hit-rate & radiation environment
  - Also opportunity to enhance vertexing & tracking performances

  ⇒ Large fraction of Belle II dataset will be collected after upgrade in 2026

- Present work status
  - Demonstrate feasibility of EOIs → test prototypes of submitted chips
  - **Full simulation for fully pixelated VXD option → physics benchmarking**

- Upgrade goals revolve on low material, low power, fast pixels to find signal tracks in large backgrounds
  - Common grounds with LC community

⇒ It is time to join,
R&D contributors outside
Belle II welcomed!

Full simulation of vertex upgrade in Belle II

- Replace PXD & SVD with generic pixel layers and connect to tracking
  - Implemented in Belle II software as new sub-detector (VTX) of Belle II
  - Part of Geant4 detector simulation with realistic backgrounds
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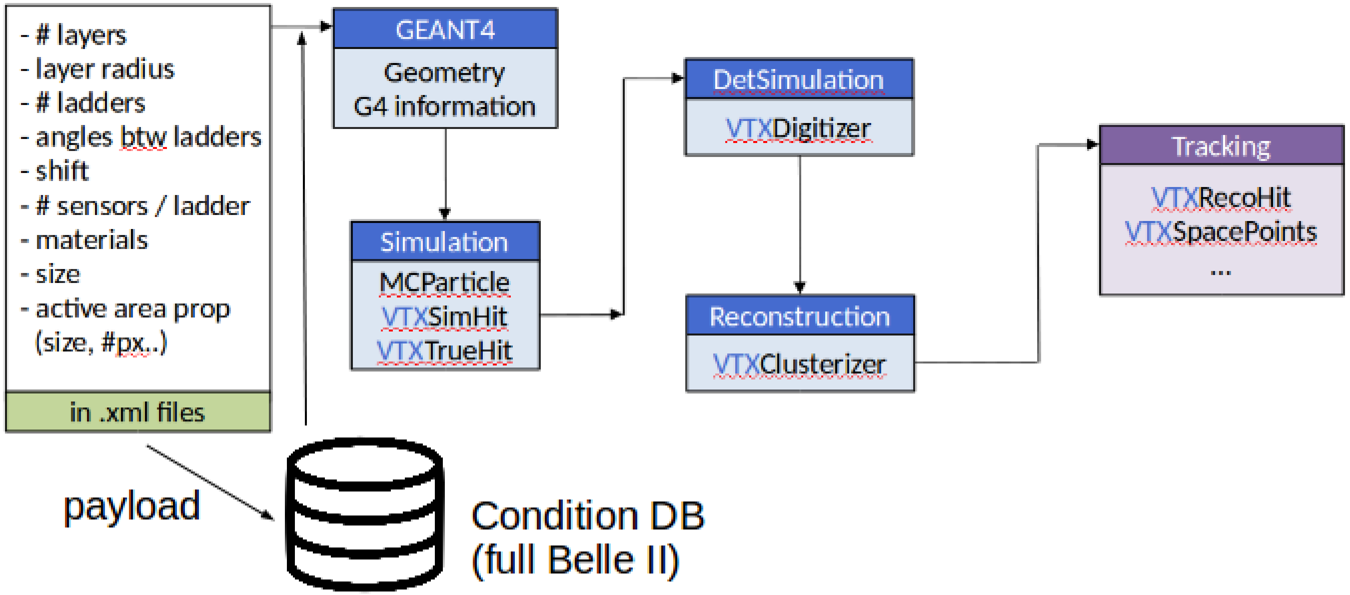
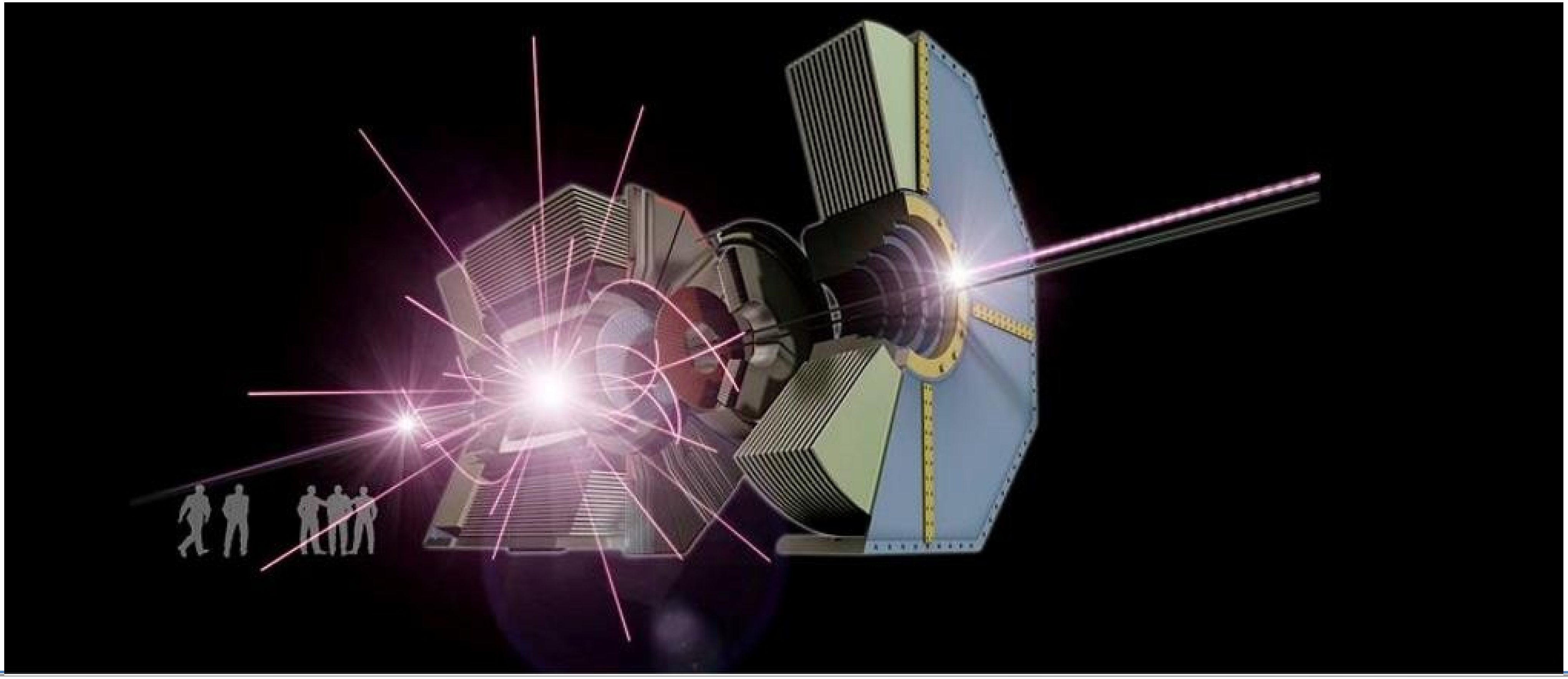
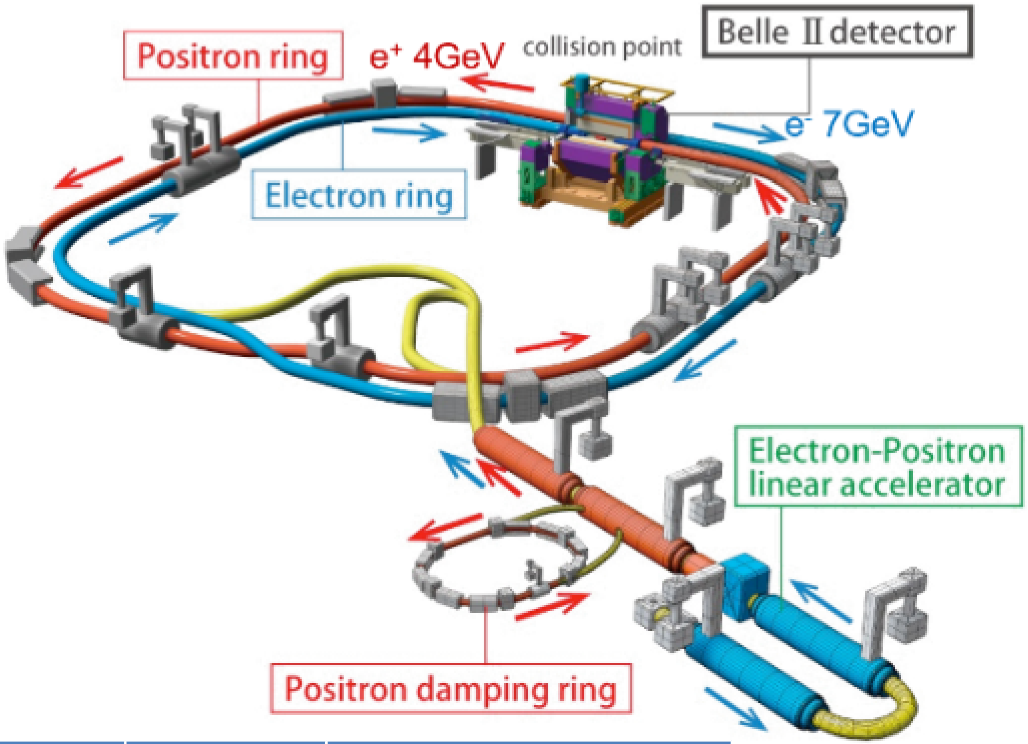


SUPPLEMENTARY SLIDES



SuperKEKB collider



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

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

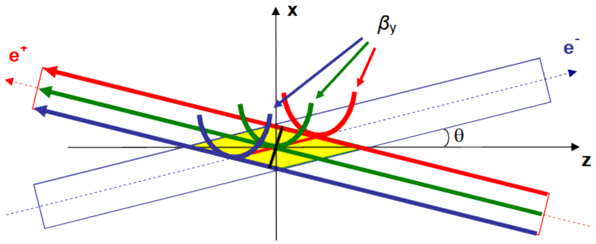
Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

High currents:
> 1A

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

& specific beam crossing features

Crossing angle (83 mrad) + crab waist (80%)

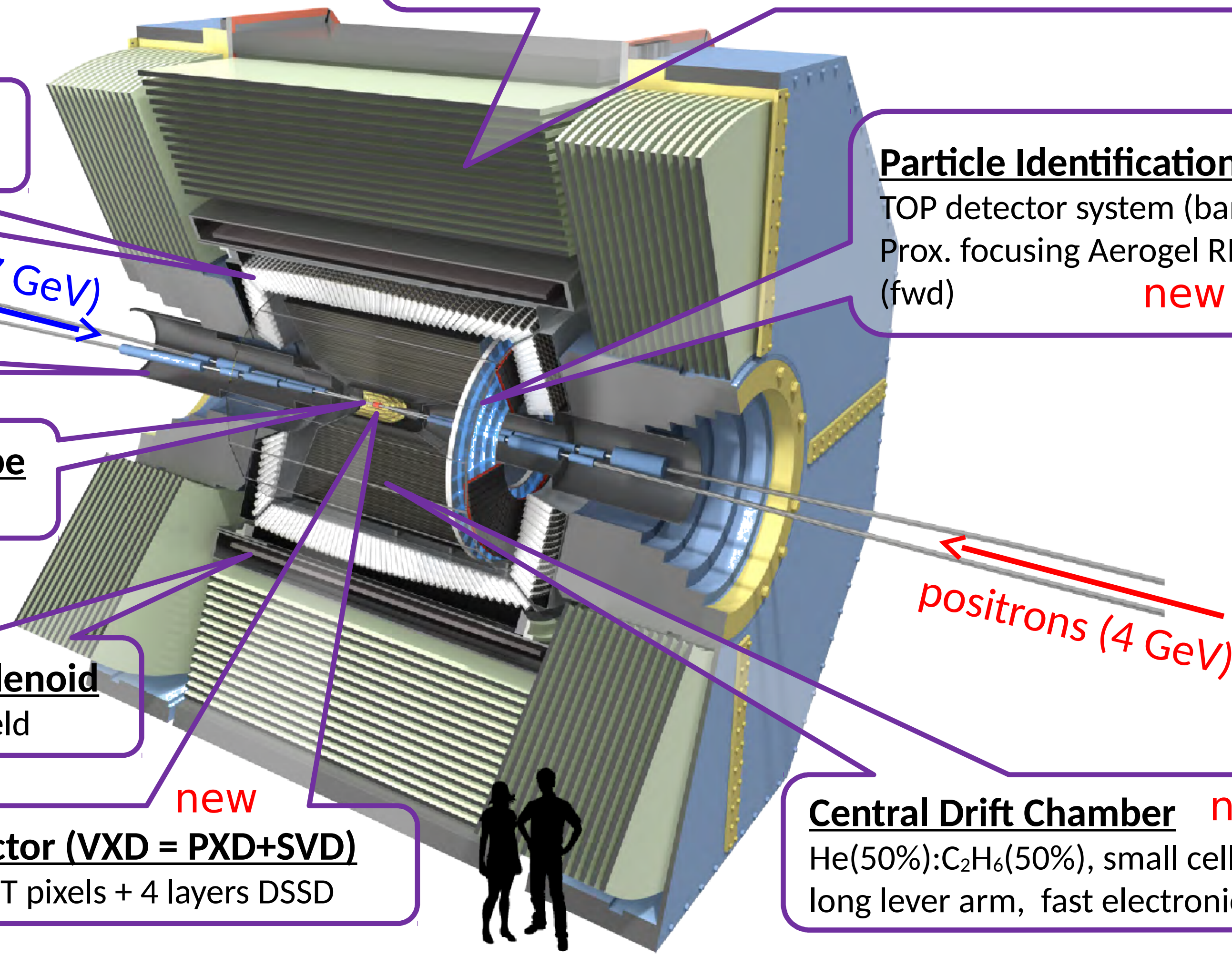


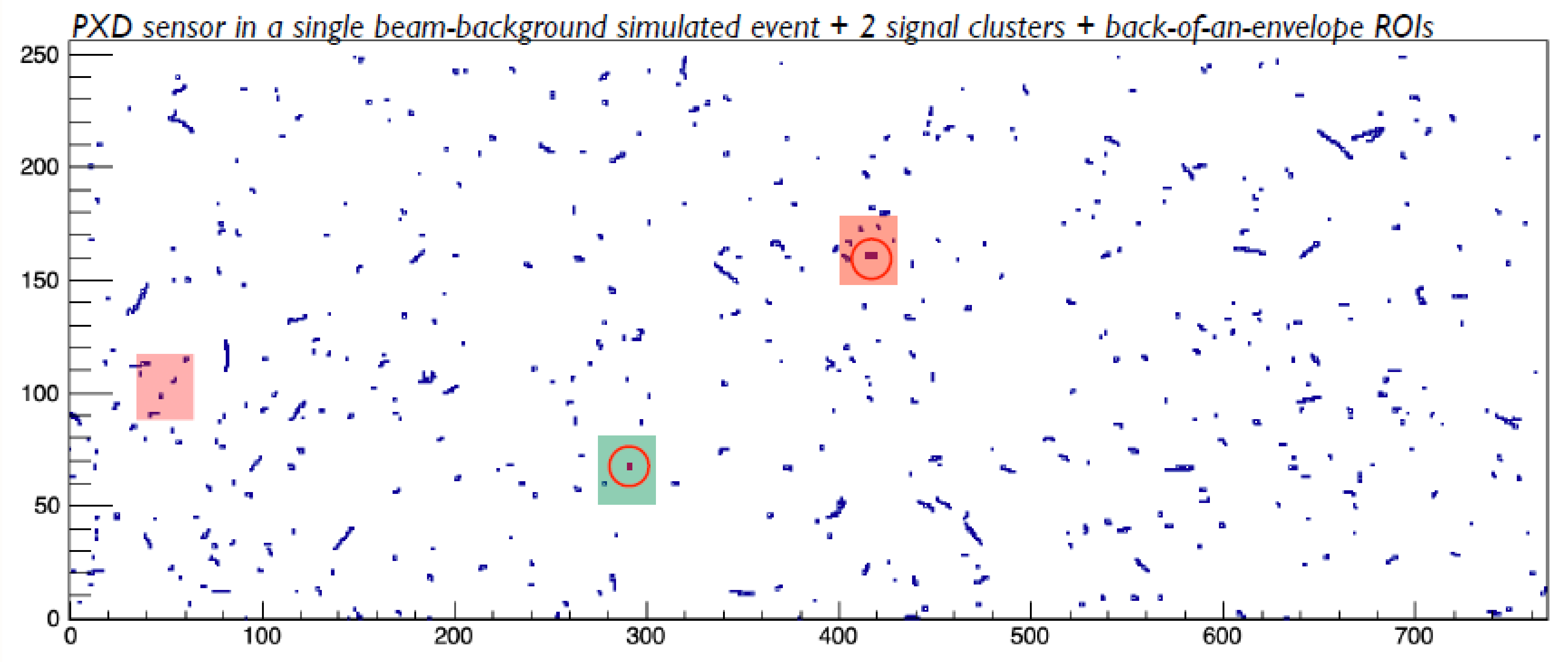
	KEKB	SuperKEKB	
		2020	Nominal
Energy (GeV) LER/HER	3.5 / 8	4 / 7	
Current (A) LER/HER	1.6/1.2	0.7/0.6	2.8 / 2.0
β_y^* (mm)	5.9	0.8	0.3
Instant. Lumi. ($cm^{-2}.s^{-1}$)	2.1×10^{34}	**2.4×10^{34}**	$\sim 6 \times 10^{35}$

Cost = severe induced beam background

Belle II detector

- <u>Planned for better performances / Belle under:</u>
  - Higher beam-background rate
  - Higher trigger rate (30 kHz)





- A PXD sensor frame + the ROIs from the HLT + nominal expected background

From Eugenio Paoloni, July 2019

CMOS pixel sensor options

⇒ Various R&D on-going outside Belle II

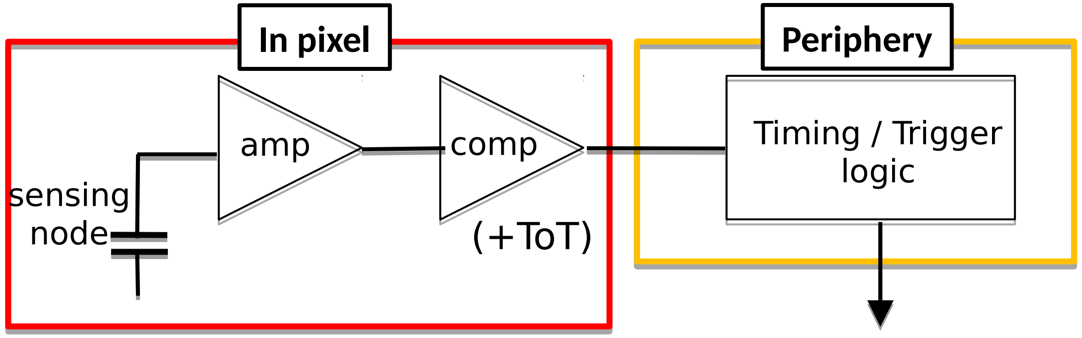
Sensor available 2020	MIMOSIS-1 (CBM-MVD)	Belle II requirements “First guess”	MONOPIX-2 (ATLAS-ITK)	ATLASPix3 (ATLAS-ITK)
Time precision (ns)	5000	**50 to 100**	25	25
Pixel pitch (μm^2)	30x27	**30x30 to 40x40**	33x33	150x50
TID (Mrad)	5	**100**	100	
Power (mW/cm^2)	~50	**< 100 to 200**	~150	~140
Trigger delay (μs)	No trigger	**5 → 10**	long	

In test
IPHC

Submitted
Bonn, CERN, CPPM

Tested
Barcelona, CPPM, Geneva, Heidelberg, KIT, Liverpool

180 nm HR-CMOS process → ~full depletion ← 180 nm HV-CMOS process



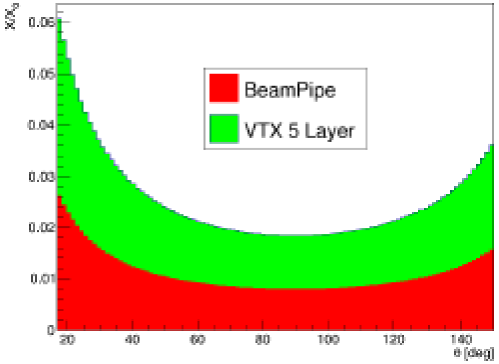
- <u>Demonstrated</u>
  - Monolithic & low power → low material budget granted
  - Excellent granularity → $\sigma_{s.p.} \sim$ 5-10 µm
  - Short integration → occupancy = $O(10^{-3})$

⇒ 1st dedicated version in 2022 ~ realistic

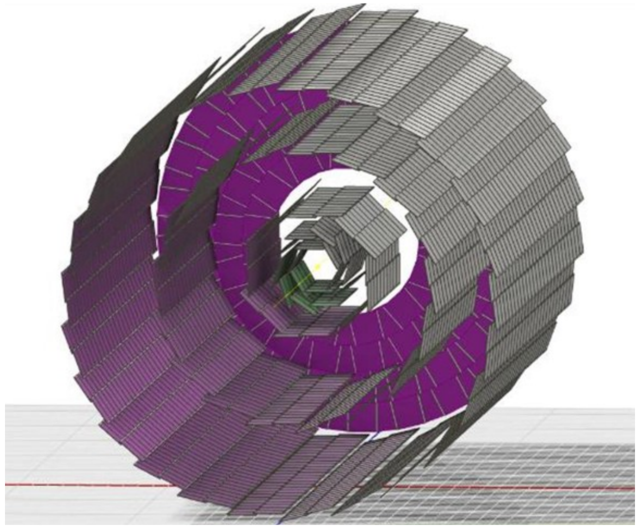
Full pixelated VXD: Geometry details

VTX with 5 pixelated layers

5 layers	1	2	3	4	5
Radius (cm)	1.4	2.2	3.9	8.9	14.0
# ladders	6	10	8	18	26
Sensor type	A	A	A'	A'	A'
# Sensor rows along z direction	1	1	2	4	6

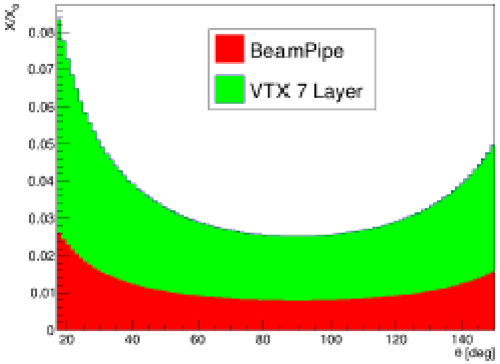


5 layers + 2 disks

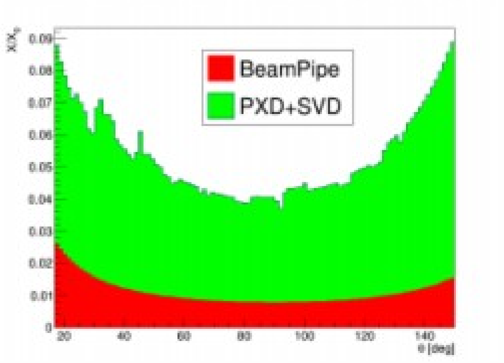


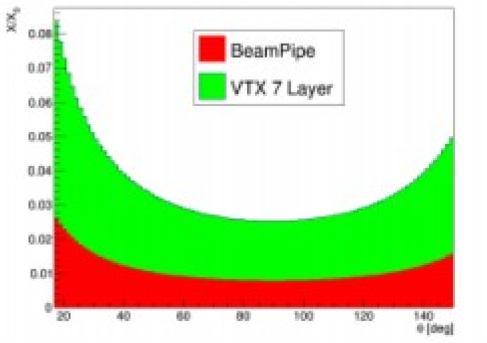
VTX with 7 pixelated layers

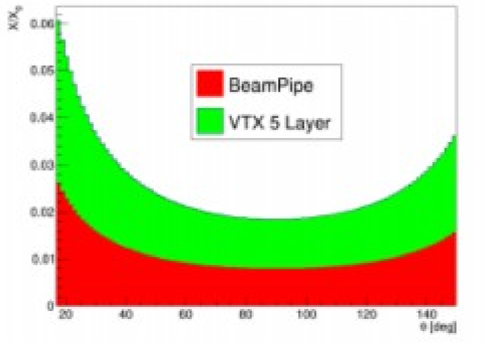
7 layers	1	2	3	4	5	6	7
Radius (cm)	1.4	2.2	3.5	6.0	9.0	11.5	13.5
# ladders	6	10	14	12	18	22	26
Sensor type	A	A	A	A'	A'	A'	A'
# Sensor rows along z direction	1	1	2	3	4	5	6

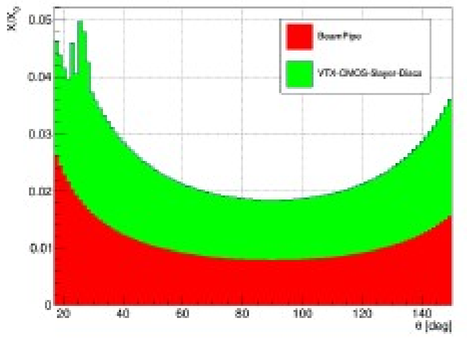


Material budget full pixelated VXD



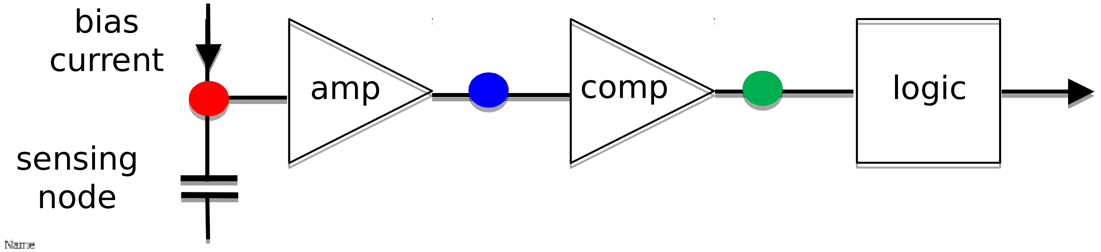


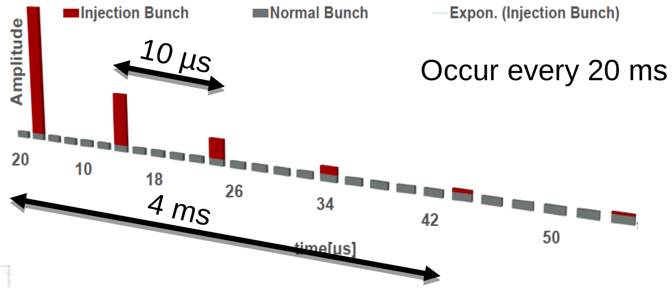




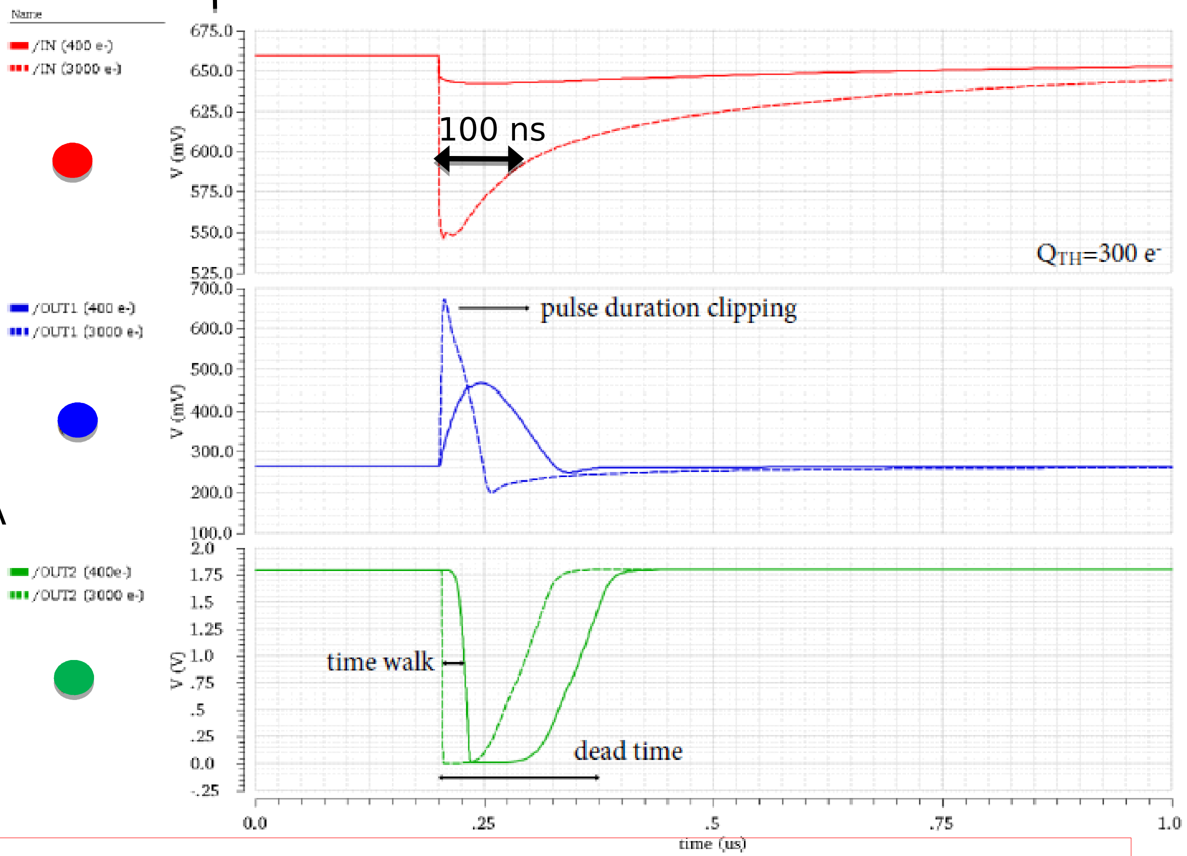
Tower Jazz 180 nm time response simulations

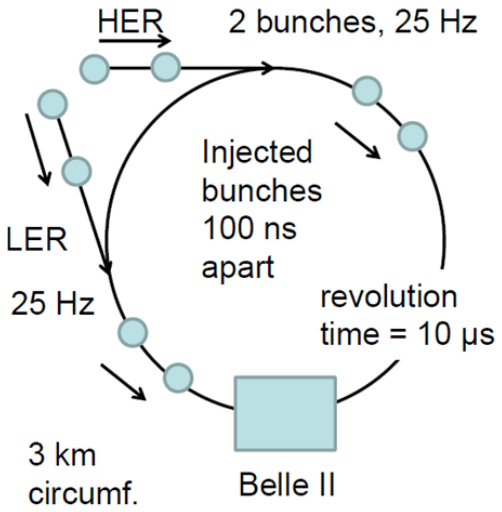
- Front-end structure in-pixel





- Simulated behavior (MALTA case)
  - From I. Berdalovich, JINST 13 (2018) C01023
  - Short recovery time for node requires I_{bias}~500 nA → 0.9 µW/pixel
  - ALPIDE with µs timing reaches 0.040 µW/pixel





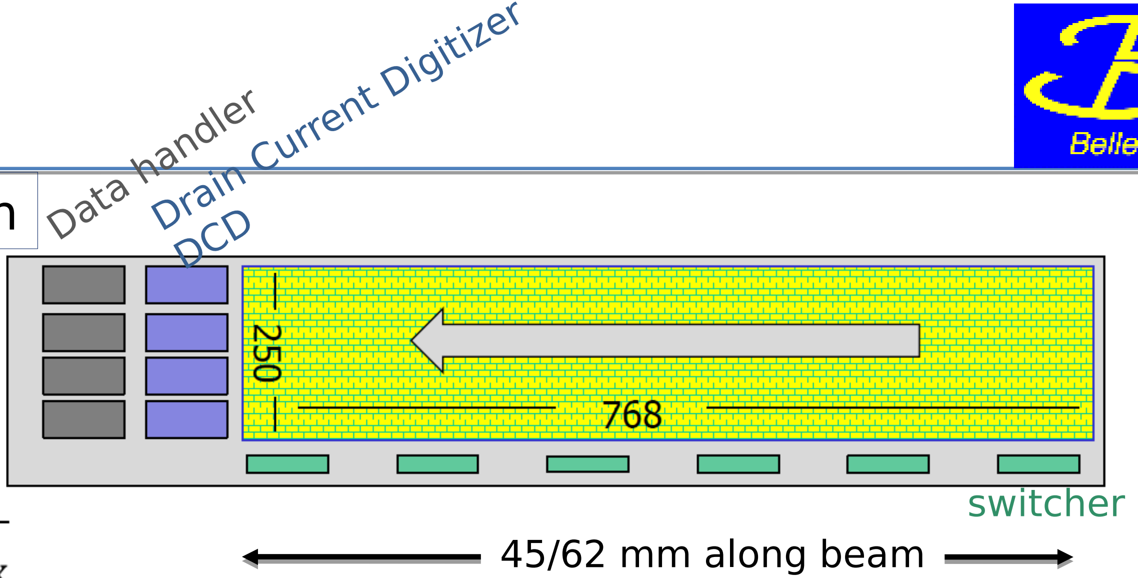
⇒ Suggest gating injection for ~100-200 ns doable after comparator

DEPFET pixel sensors

Belle II DEPFET collaboration

Current Belle II - PXD

- First use of the technology in HEP experiment
- Many lessons learned

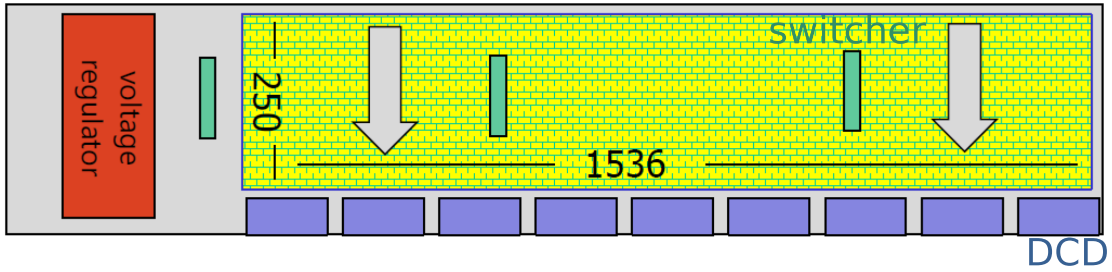


R&D directions

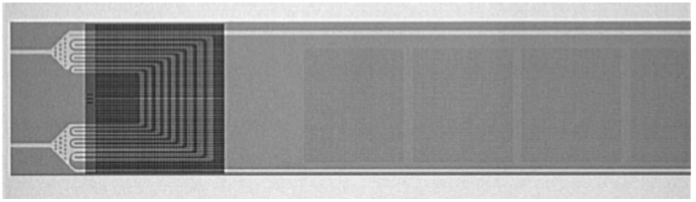
- Gain increase with shorter FET length L
  → thinner oxide
  → higher signal → improved rad. tolerance

$$g = \frac{\mathrm{d}I_{\mathrm{drain}}}{\mathrm{d}Q} \propto \sqrt{\frac{t_{\mathrm{ox}}}{L^3}}$$

- Rotating read-out direction + switcher intergration
  - Speed x3
  - Pixel size along beam x1/2



- Faster driving & read-out circuits
  - Require advanced processed
  - Speed x2
- **All-silicon module** improvements
  - Microchannel cooling
  - Thinner drivers



Within reach

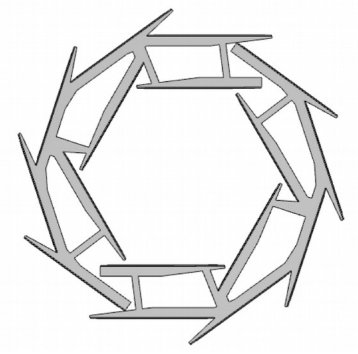
- T_{int}: 20 → 10 µs
- Improved σ_z
- Mat. Budget 0.21 → 0.15 % X_0

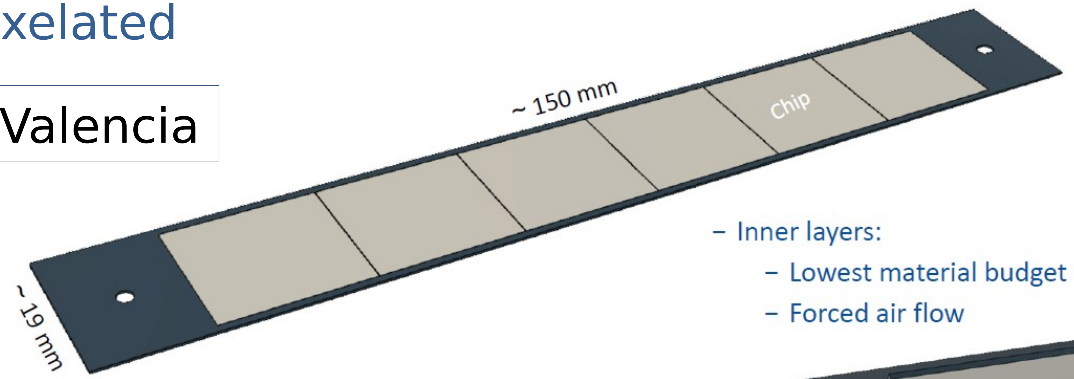
Integration concept

Context = new geometry with all VXD fully pixelated

@ IFIC, Valencia

- Inner layers = full silicon module
  - 2 to 3 layers, radius < 4 cm
  - Target 0.1 % X_0 / layer

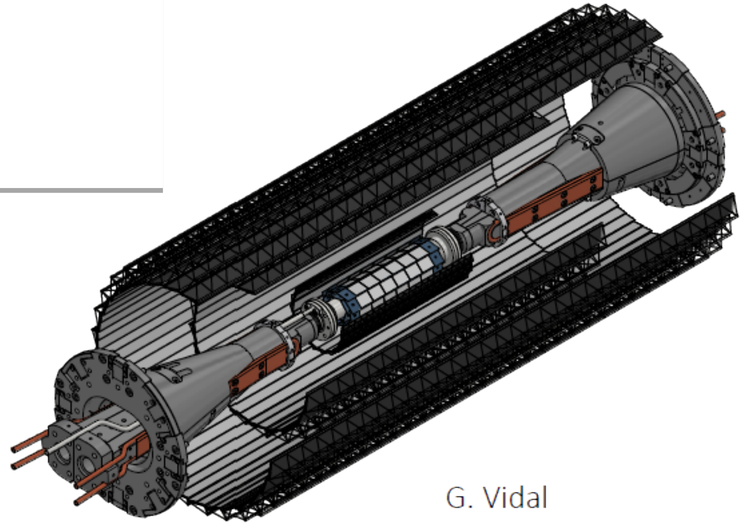




- Inner layers:
  - Lowest material budget
  - Forced air flow

Single piece of silicon
6 sensors per ladder
100 µm gap between sensors

C.Marinas
G.Vidal



G. Vidal

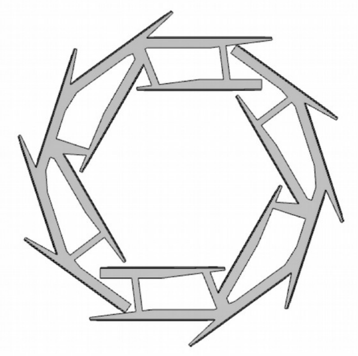
- Outer layers ~ ALICE
  - 3 to 4 layers, radius 4-14
  - Target 0.3 % X_0 / layer

C.Gargiulo
CERN - ALICE

Integration concept

Context = new geometry with all VXD fully pixelated

- Inner layers = full silicon module
  - 2 to 3 layers, radius < 4 cm
  - Target 0.1 % X_0 / layer



- Outer layers ~ ALICE-ITS la concept
  - 3 to 4 layers, radius 4-14 cm
  - Target 0.3 % X_0 / layer

C.Gargiulo
CERN - ALICE

- Forward disks
  - 2 disks at z= 16.5 & 25.6 cm
  - Target 0.3 % X_0 / layer

@ INFN-Pisa

F.Bosi
M.Massa