VERTEX 2020 Virtual ! October 5-8, 2020

Upgrade of the vertex detector of the Belle II experiment

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Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

CNRS

Université de Strasbourg

- 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

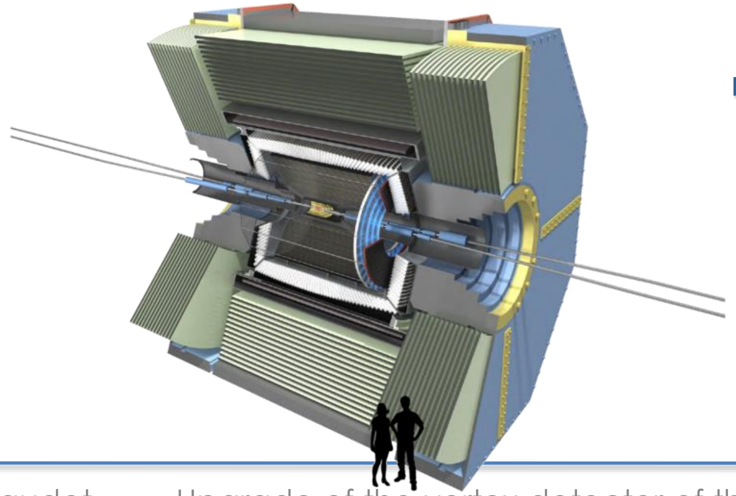
  - Based on accumulation of 50 ab^{-1} of e^{+}+e^{-} at $\sqrt{s}$ = $M_{\Upsilon(4S)}$
    - within ~10 years → instantaneous luminosity close to 10^{36} cm^{-2}.cm^{-1}

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

  ⇓

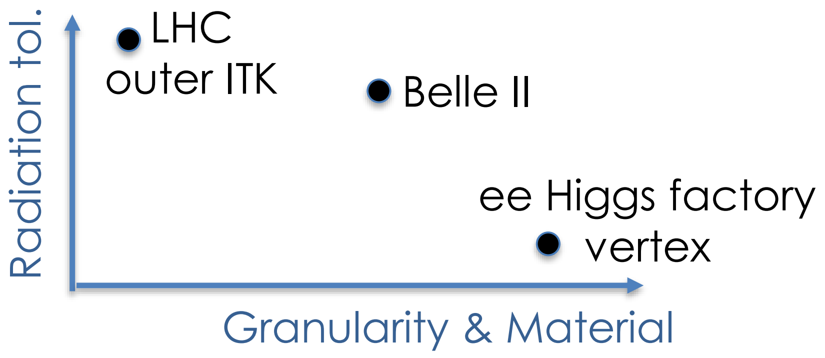
  High collision rate High beam-induced bkg

- **The Belle II experiment**
  - "classical" B-factory detector + enhanced features



- **The vertex detector (VXD)**
  - Better vertexing ← lower boost
    Smarter tracking ← higher hit rate

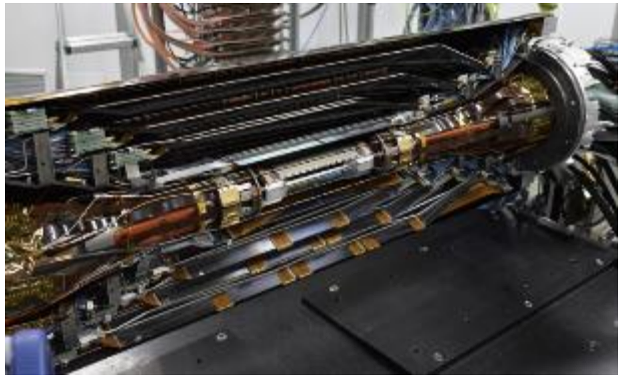
  \+ Harsher radiation environment
  \+ Belle II trigger rate ~ 30 KHz

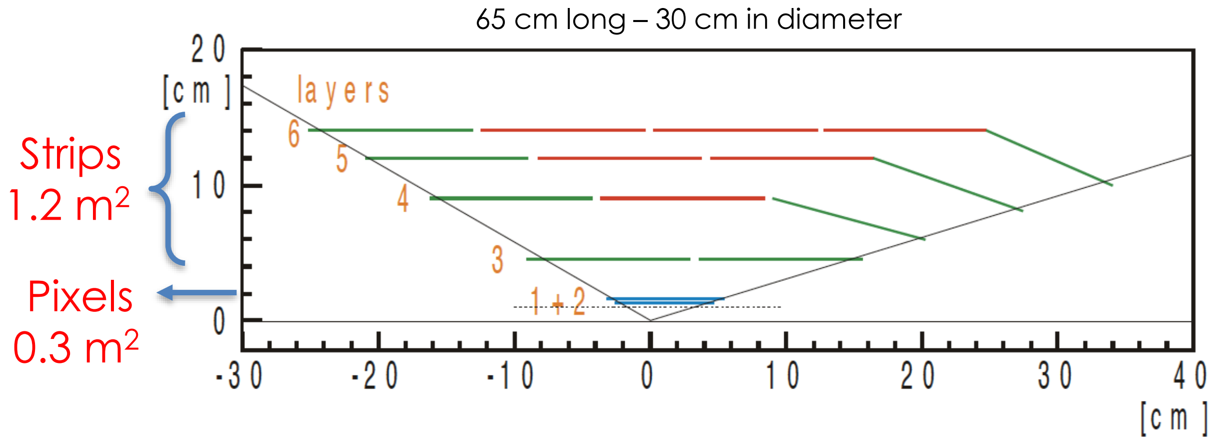


The current VXD

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

⇒ G.Rizzo SVD overview talk on Monday
+ Y.Uematsu Hit-time reconstruction poster
+ S.Hazra Particle identification Poster



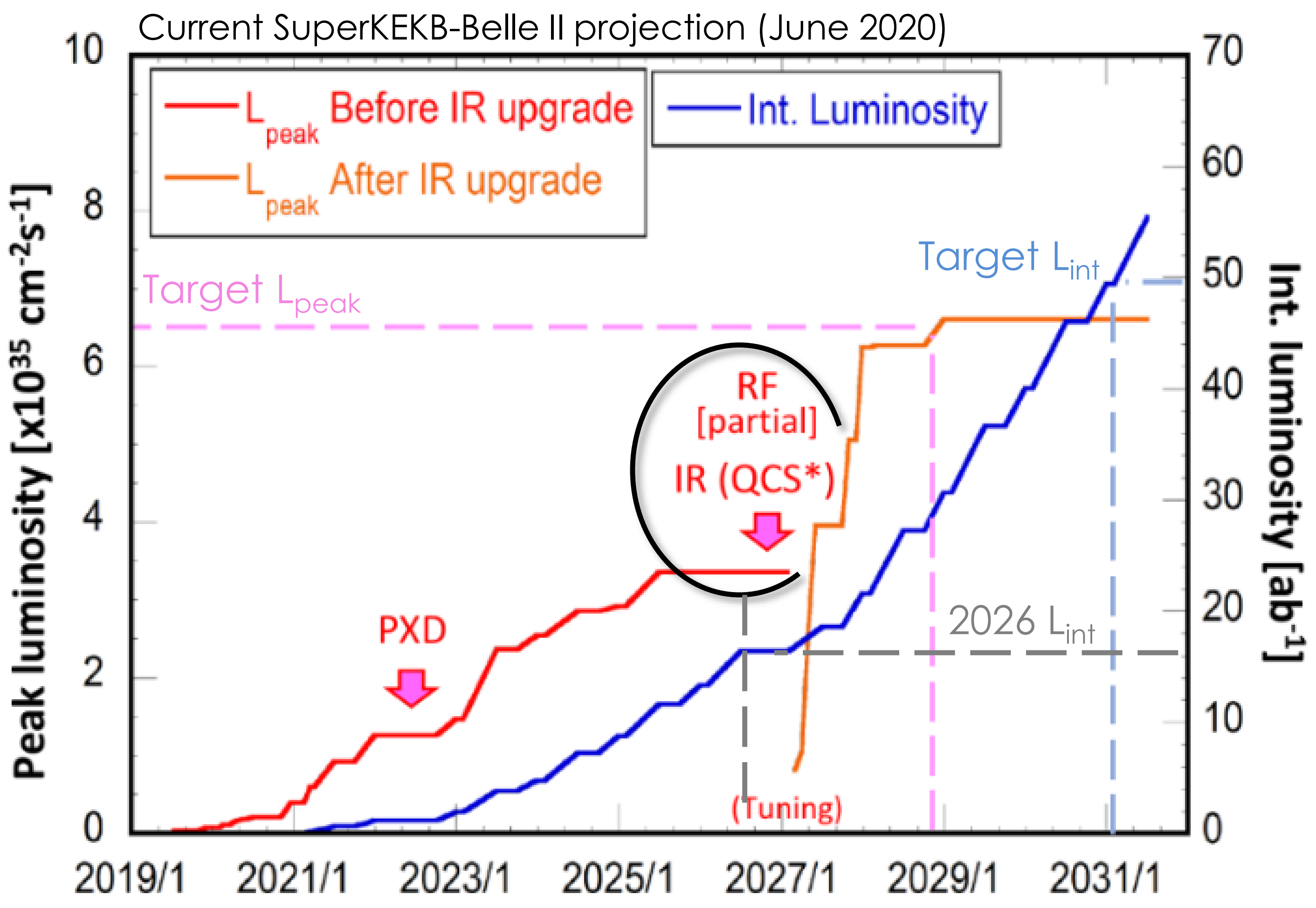


- **PXD = DEPFET sensors**
  - Very low material budget 0.2 % X_0 / layer
  - Small first layer radius = 1.4 cm
  - Long integration time 20 µs / trigger rate & injection bkg

⇒ Q.Liu PXD overview talk on Monday

The plan is successful so far! ⇒ C.Praz Tracking performance and interaction point properties talk on Tuesday

A decade of operation → Upgrades?

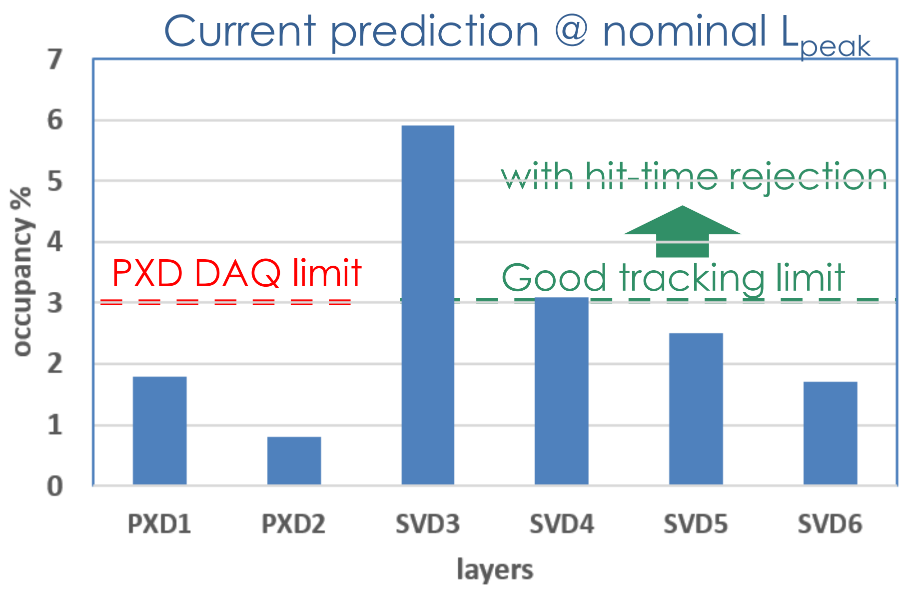


- Short term ~ 2026
  - Long shutdown for QCS upgrade
    - Needed before next jump in luminosity
  - Inner region needs to be opened up
    - Current VXD moved anyway
  - Opportunity for Belle II sub-det. upgrades
    - Let's investigate possibilities…
    - short time → with currently ~available techno.

- Longer term > 2030
  - Further increase of peak luminosity
    - Possibly beam polarization?
    - Enhanced physics program with 250 ab^{-1}
  - A renewed detector is needed
    - New set of requirements → not this talk!

Current VXD & nominal luminosity

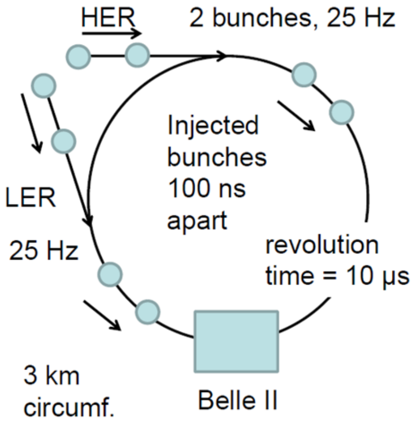
- [Beam-induced background extrapolations](#)
  - A long way to reach Data/MC ratio ~ O(1)



- **Still 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
    - currently too small for good estimate

⇒ Belle II VXD Open workshop July 2019

- 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.



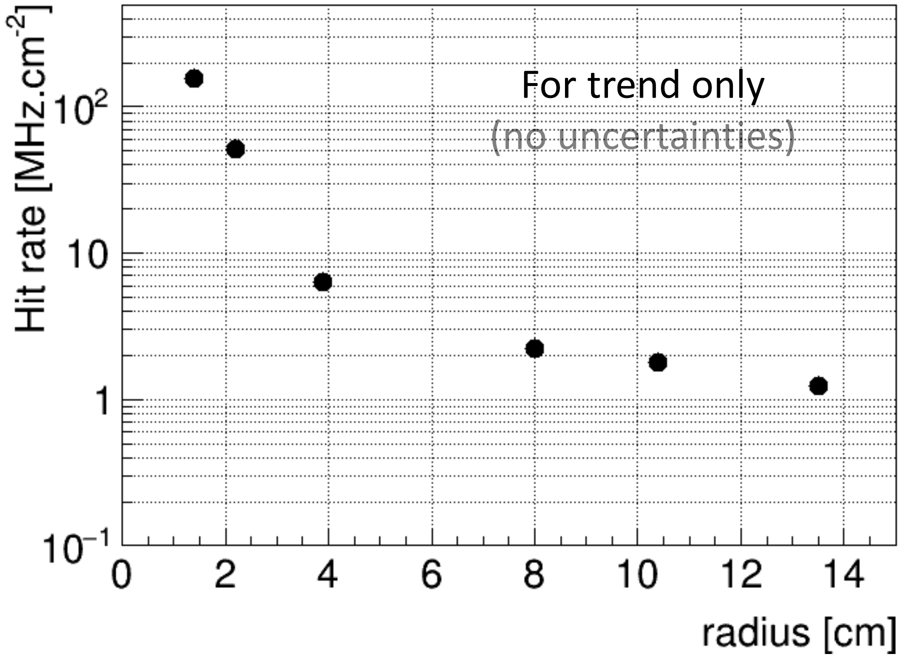
Performances within limits BUT without much margin

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 < 1000 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

Current strategy

General concepts discussed	Full simulation → performances	R&D efforts
Keep Strips+Pixels **with upgraded performances** ~ current Belle II concept	standard Belle II geometry	Thin & fine-pitch strips DEPFET pixel sensors
All pixel layers **with upgraded techno.** ~ ALICE ITS2 concept	New geometry implemented	SOI pixel sensors CMOS pixel sensors (various flavours)

+ *Integration concept for layer ~ 0.1-0.3 % X0*

within Belle II Upgrade group

R&D groups
(outside Belle II welcome!)

Effort built up to answer within ~1 year

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

→ 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
- Longer trigger latency & rate

R&D paths

- Shorter strips
- Finer pitch
- Thinner sensor

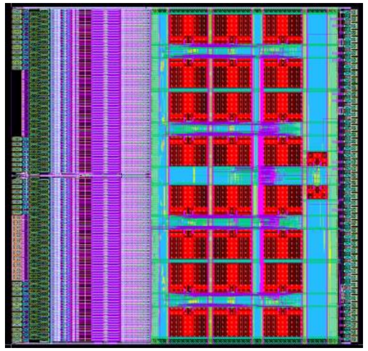
R&D challenges

- Heat dissipation (larger #chan.)
- Noise reduction (lower signal)

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

128 inputs



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

	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)

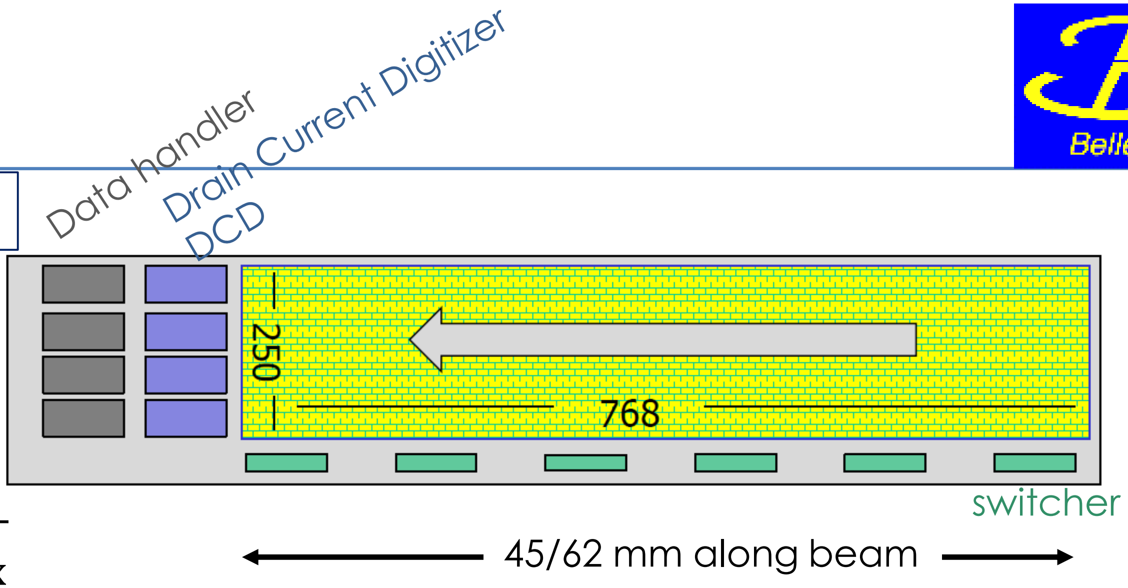
⇒ K.Nakamura Development of thin and fine-pitch DSSD poster

⇒ First Sensor+FEE in 2021

DEPFET pixel sensors

Belle II DEPFET collaboration

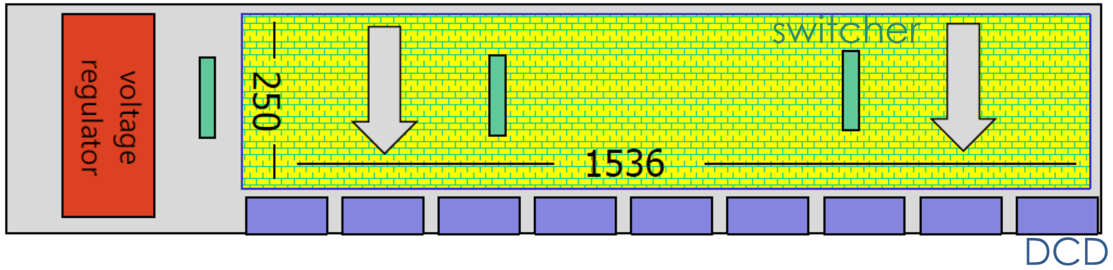
- **Current Belle II - PXD**
  - First use of the technology in HEP experiment
  - Many lessons learned



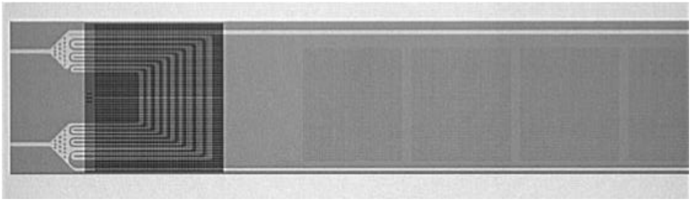
- **R&D directions**
  - Gain increase with shorter FET length L
    → thinner oxide
    → higher signal → improved rad. tolerance

$$g = \frac{dI_{drain}}{dQ} \propto \sqrt{\frac{t_{ox}}{L^3}}$$

  - 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 ↘ 3 μs
  - Improved σ_z
  - Mat. budget 0.21 ↘ 0.15 % X_0

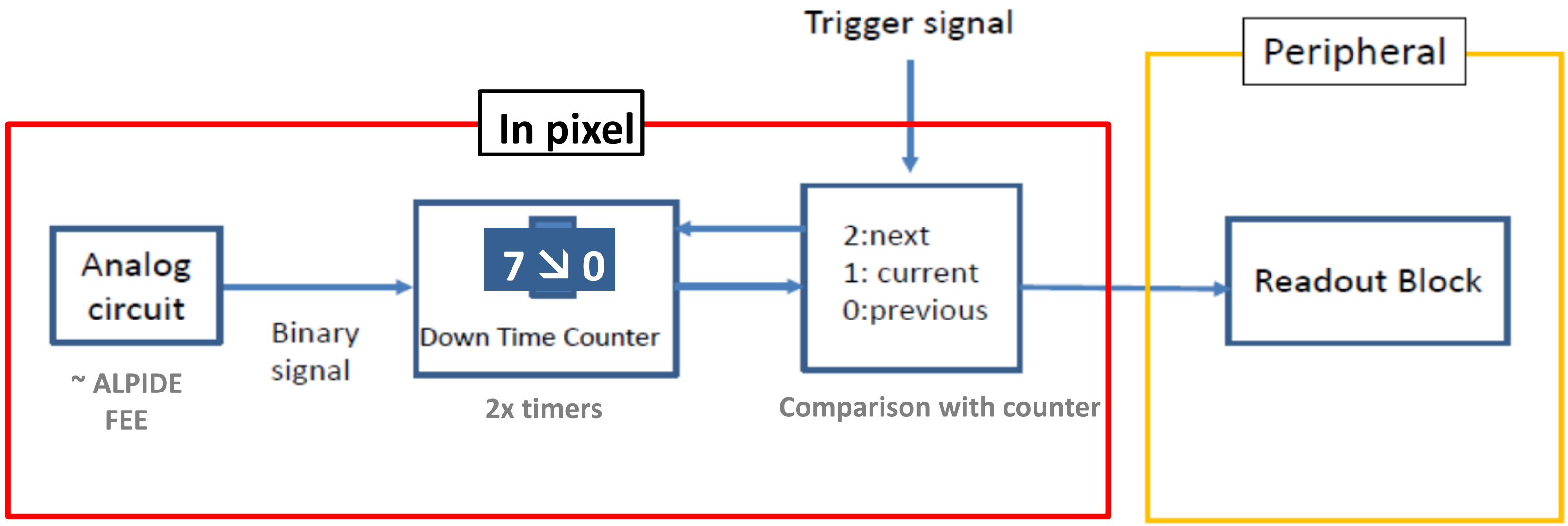
DuTiP - SOI pixel sensors

@ KEK

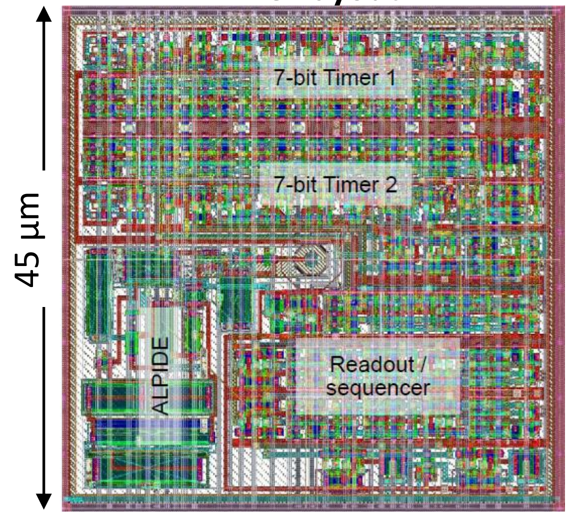
- **Main R&D targets**
  - Low material budget
    - Monolothic technolgy
  - Handling high-rate
    - Time-stamping < 100 ns
    - Global-shutter style

- **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 µm^2
  - Sensitive thickness 50-75 µm



Pixel layout



⇒ M.Yamada R&D status of monolithic SOI pixel sensor for vertex detector talk on Wed.

⇒ Initial prototype DuTIP 1 submission in Nov.2020

CMOS pixel sensor optionS

⇒ Various R&D on-going outside Belle II

⇒ Monolithic sessions on Wednesday

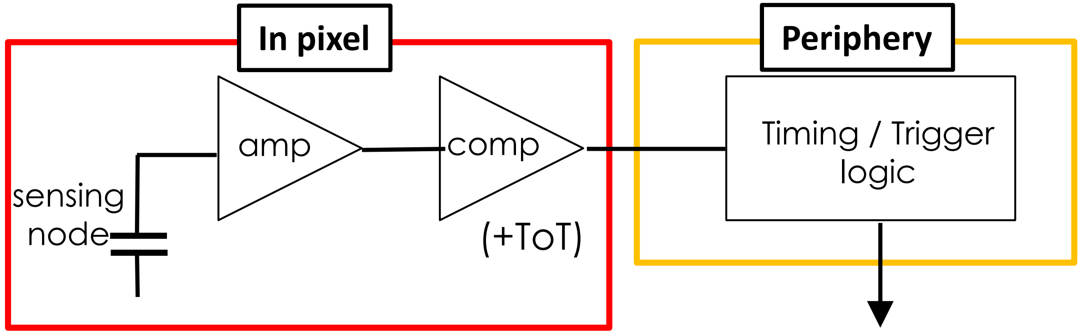
Sensor available 2020	MIMOSIS-1 (CBM-MVD)	Belle II requirements "First guess"	MONOPIX-2 (ATLAS-ITK)	ATLASPix3 (ATLAS-ITK)
Time precision (ns)	5000	**50 to 100**	25	25
Pixel pitch (μm^2)	30x27	**30x30 to 40x40**	33x33	150x50
TID (Mrad)	5	**10**	100	
Power (mW/cm^2)	~50	**< 100 to 200**	~150	?
Trigger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

MIMOSIS-1: In test IPHC

MONOPIX-2: Submitted Bonn, CERN, CPPM

ATLASPix3: Tested Barcelona, CPPM, Geneva, Heidelberg, KIT, Liverpool

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



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

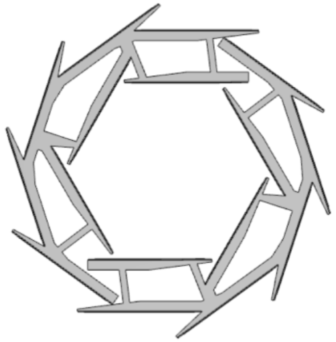
⇒ 1st dedicated version in 2021 ~ realistic

Integration concept

Context = new geometry with all VXD fully pixelated

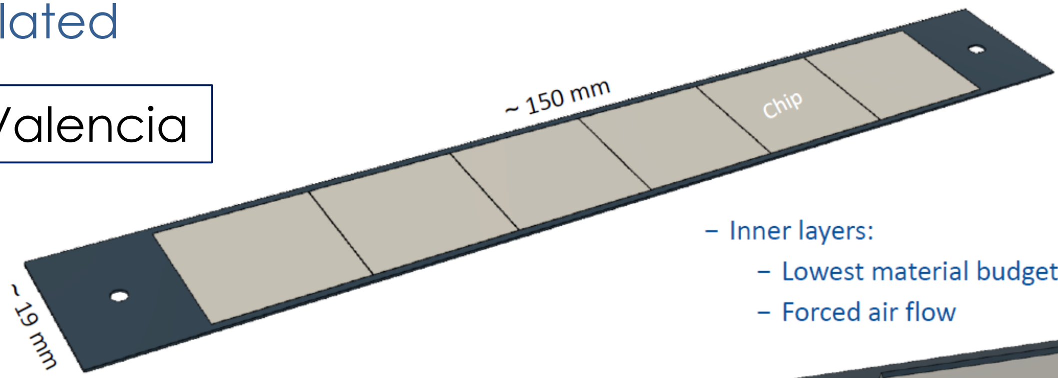
@ IFIC, Valencia

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



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

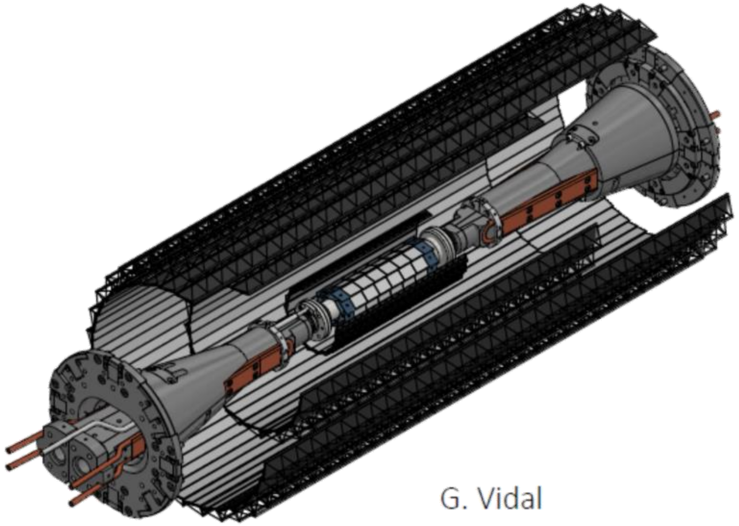
C.Gargiulo
CERN - ALICE



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

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

C.Marinas
G.Vidal



G. Vidal

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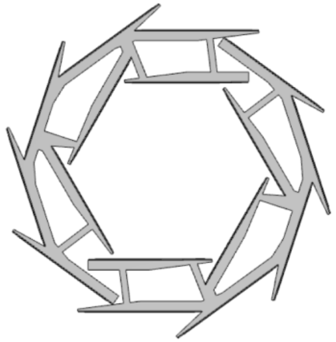

- Outer layers ~ ALICE-ITS ladder concept
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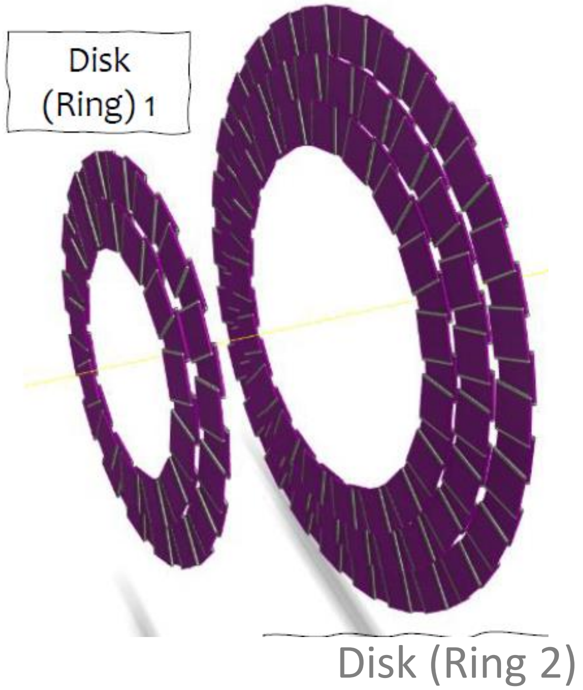
C.Gargiulo
CERN - ALICE

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

@ INFN-Pisa

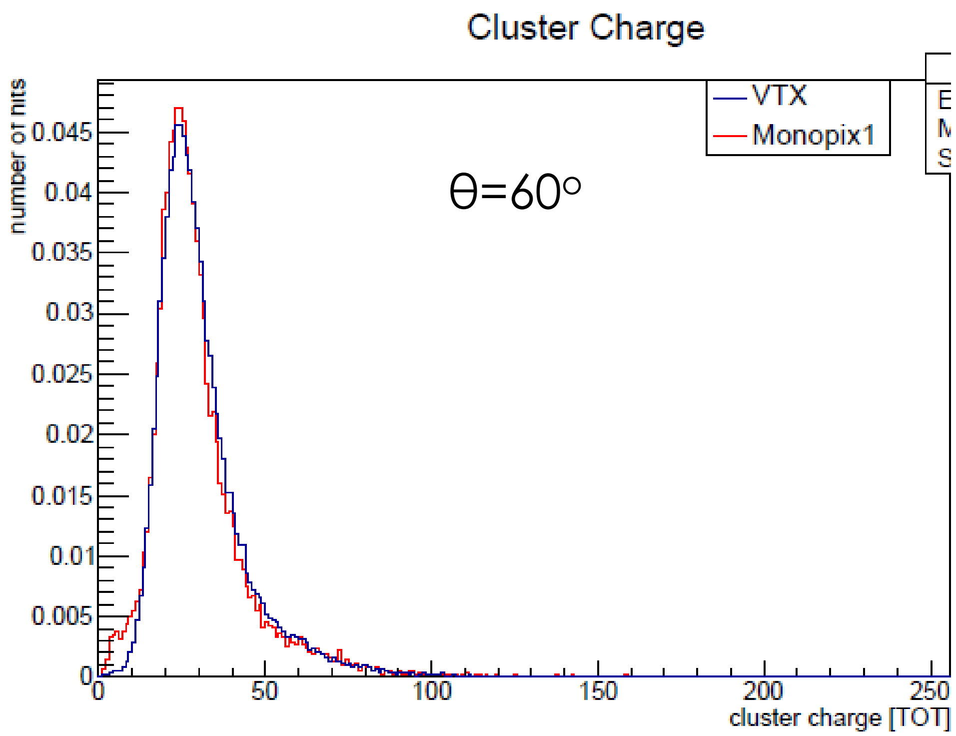
F.Bosi
M.Massa

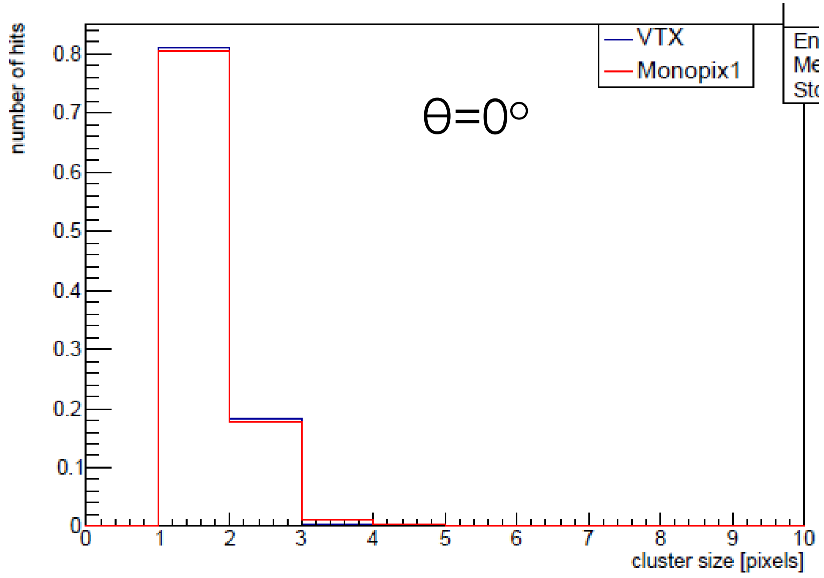


Simulated tracking performances

Context = new geometry 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.Schwenker (Göttingen), C.Wessel (Bonn)

Simulated tracking performances

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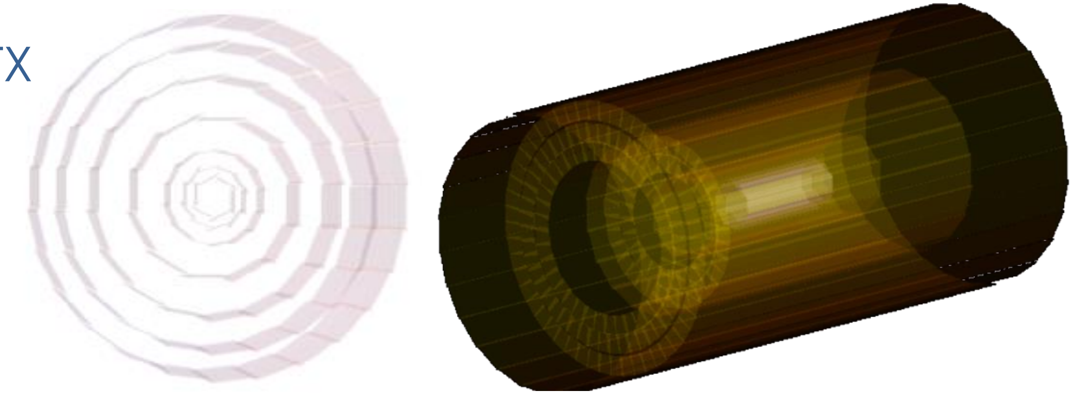

- Realistic pixel sensor model
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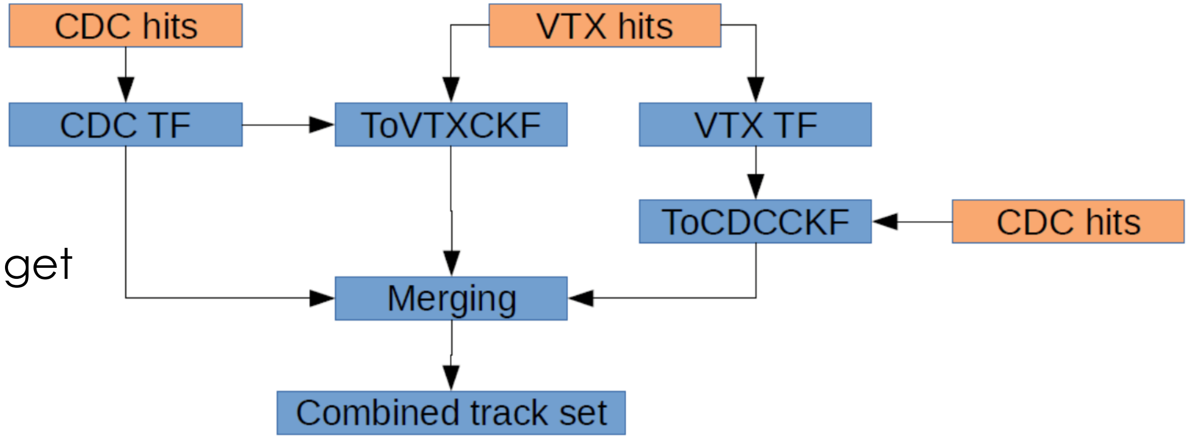
    - fully depleted thin layer 30 µm
    - Pixel 33x33 µm^2 with 7bits Time over Threshold
  - Tuned with Monopix-1 beam data

- 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

All VTX layers included in pattern-reco.
→ other possible simpler/faster scheme ⇒ beneficial to High Level Trigger

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

Simulated tracking performances

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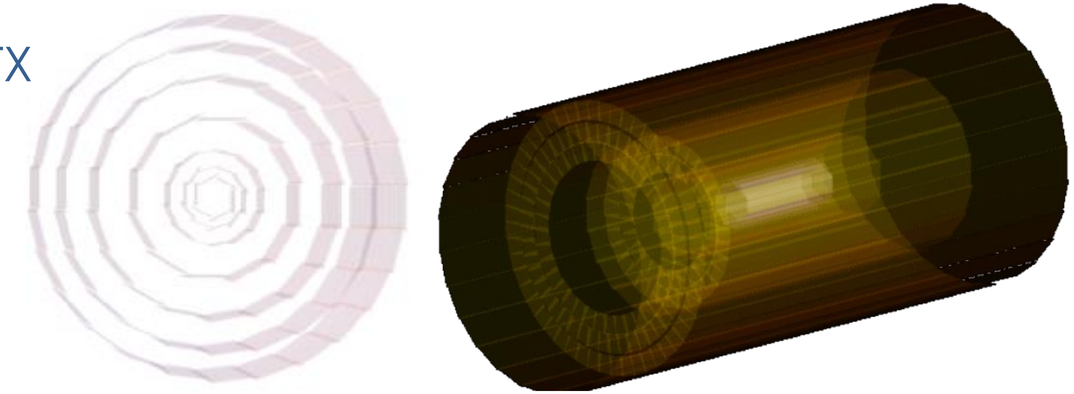

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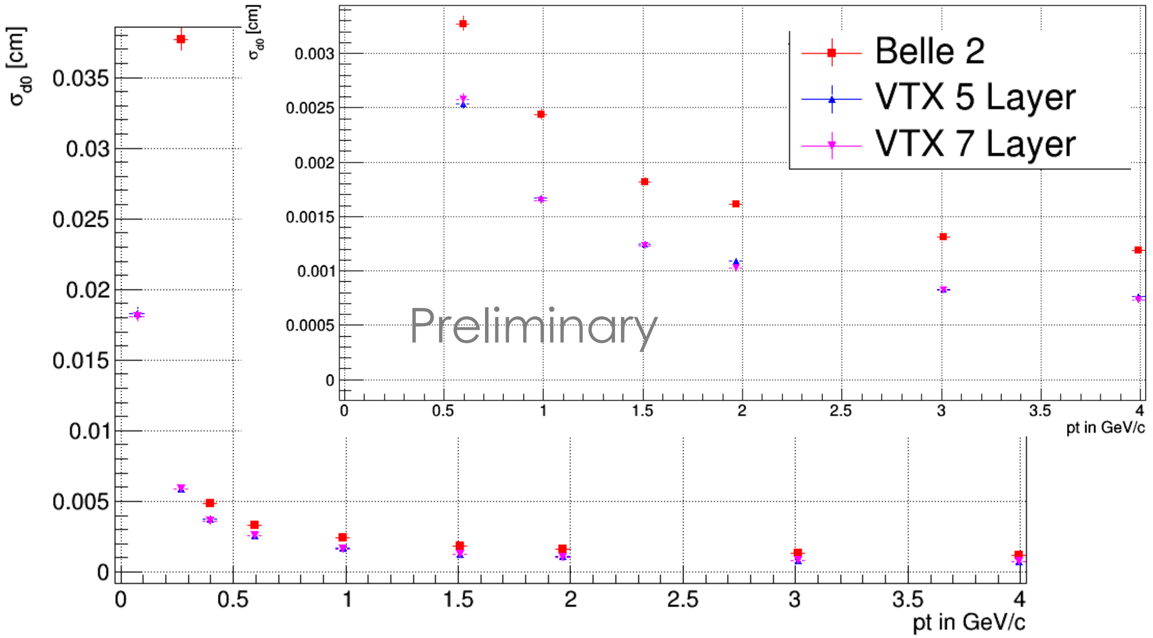

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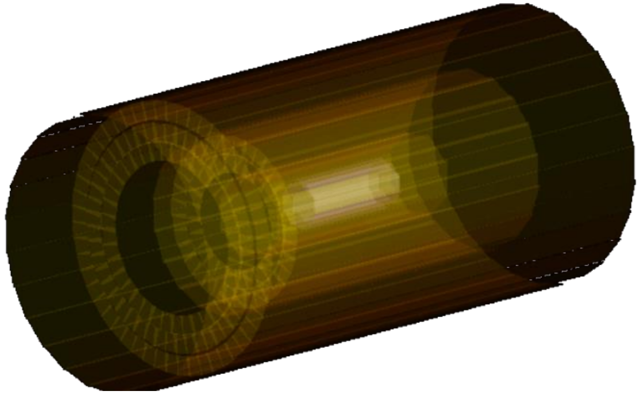

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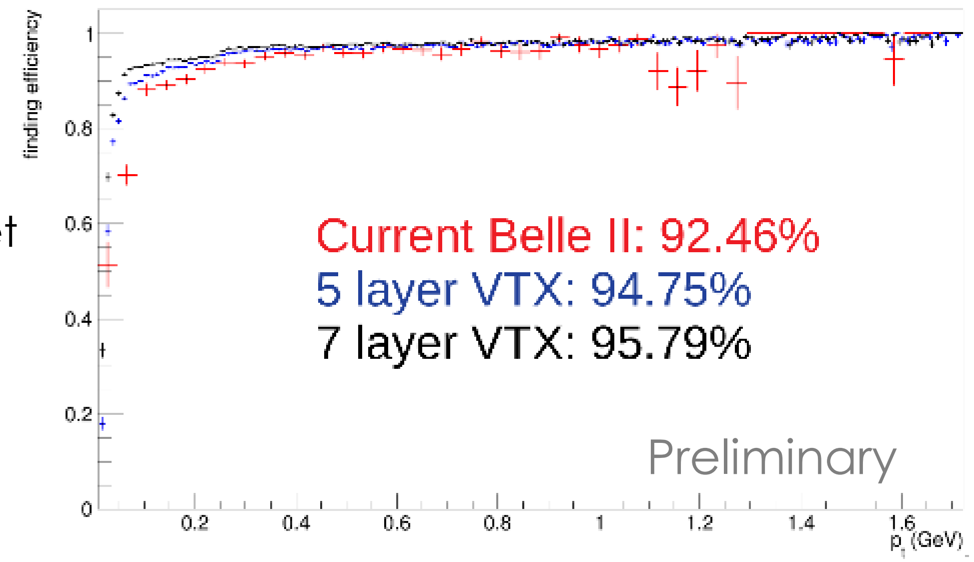


Results by T.Fillinger (Strasbourg), B.Schwenker (Giessen), C.Wessel (Bonn)

Summary & Outlook

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

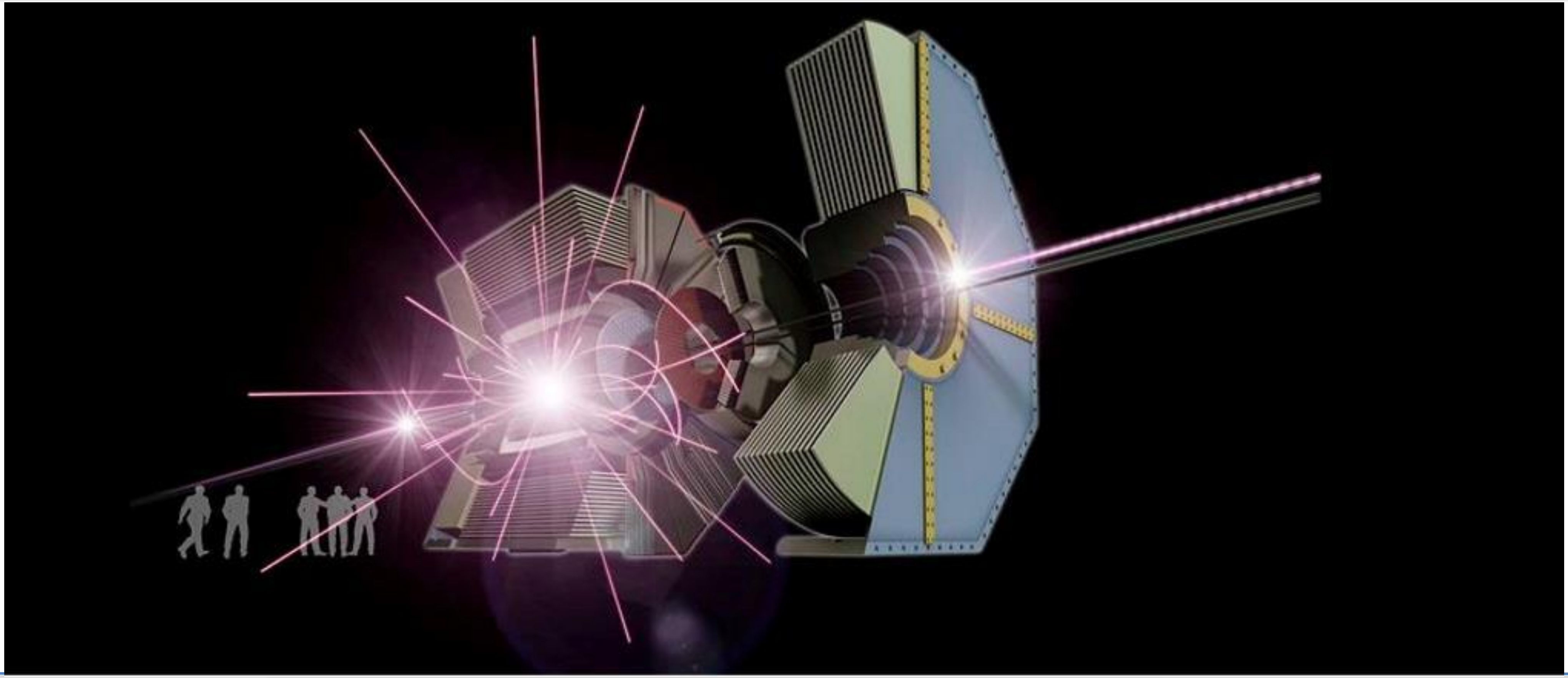
  ⇒ Will benefit to physics with > 30 ab^{-1} still to accumulate over expected 50 ab^{-1}

- Initial work status
  - R&D concepts on various strip / pixel & integration technologies on-going
  - **Full simulation for fully pixelated VXD option** → first evaluation of expected performances

- Still a lot to do in a short time
  - Letters of Intent describing draft proposals @ end of 2020
  - First dedicated prototypes in 2021 → CDR 2021
  - **Physics benchmarking with full simulation**
  - Then 5 years rush to development & install

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

SUPPLEMENTARY SLIDES



Related talks at VERTEX 2020

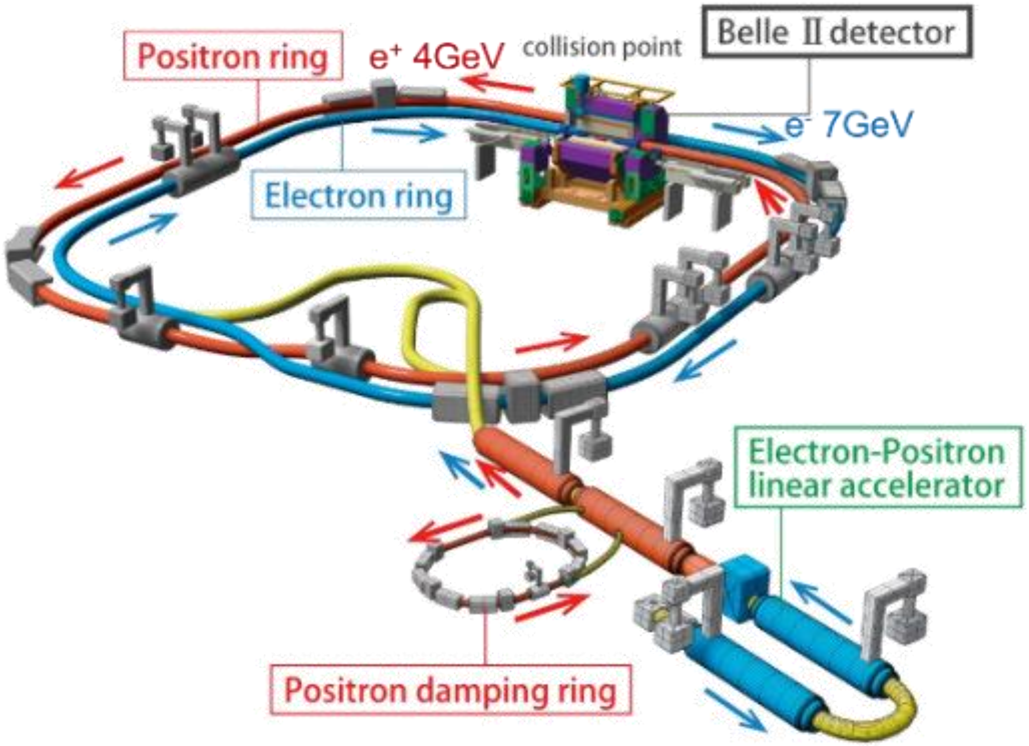
Belle II related talk

- **PXD**
  - Q.Liu Operational Experience and Performance of the Belle II Pixel Detector Talk on Monday 5th
- **SVD**
  - G.Rizzo The Belle II SVD performance and operational experience in the first data taking Talk on Monday 5th
  - Y.Uematsu A Study for Hit-time Reconstruction of Belle II Silicon Vertex Detector Poster on Monday 5th
  - S.Hazra Particle identification in Belle II silicon vertex detector Poster on Monday 5th
- **Tracking**
  - C.Praz Tracking performance and interaction point properties at the Belle II experiment Talk on Tuesday 6th
- **R&D**
  - K.Nakamura Development of the thin and fine-pitch silicon strip detector aiming for the Belle II upgrade Poster on Monday 5th

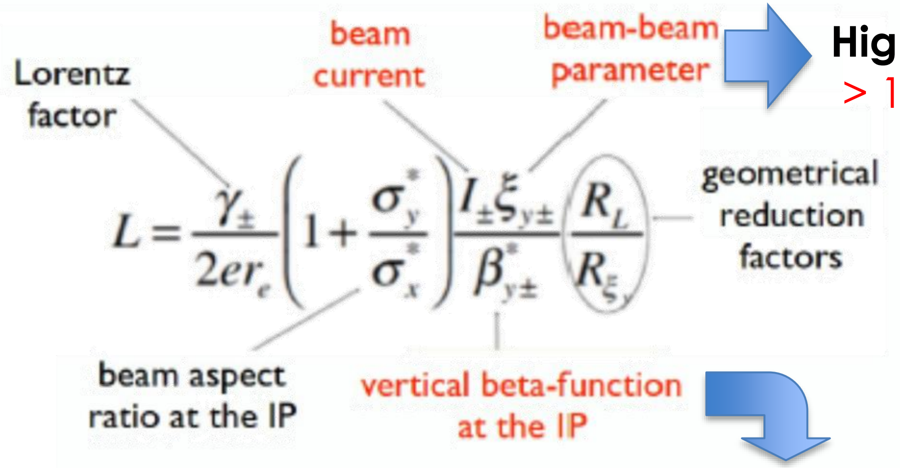
Generic R&D on pixel

- Sessions on Wednesday 7th morning: Monolithic I Monolithic II
  - M.Yamada R&D status of monolithic SOI pixel sensor for vertex detector Wednesday talk
  - M.Barbero Depleted Monolithic Active Pixel Sensors in LFoundry 150 nm and TowerJazz 180 nm CMOS technologies: The Monopix developments talk
  - H-C.Augustin MuPix10: First Results from the Final Design talk

SuperKEKB collider



- Recipe to high luminosity



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

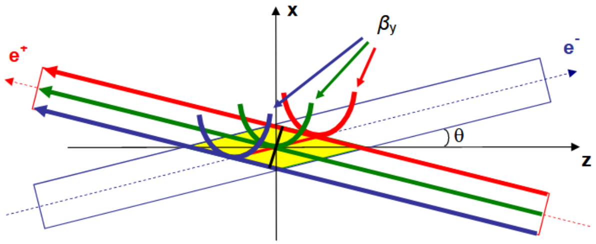
High currents:
> 1A

Nano-scale beam size:
$\sigma_x \times \sigma_y$ ~ 10μm × 60 nm
β_y^* << 1 mm

	KEKB	SuperKEKB 2020	SuperKEKB 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. ($cm^{-2}.s^{-1}$)	2.1x10^{34}	**2.4x10^{34}**	~6x10^{35}

⚠ Cost = severe beam induced background

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



Belle II detector

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

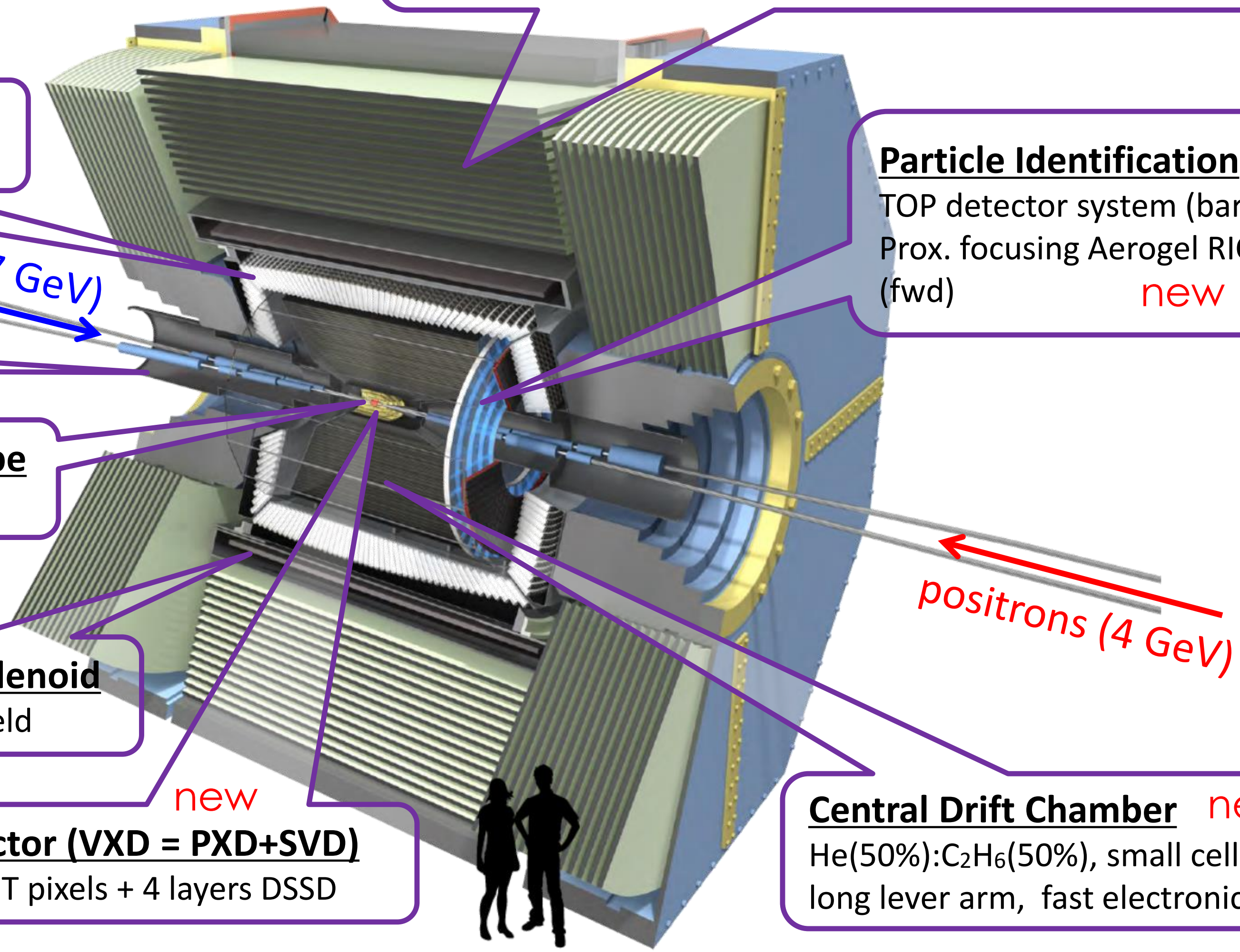
<u>KLong and muon detector (KLM)</u> upgraded
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

<u>EM Calorimeter (CDC)</u> upgraded
CsI(Tl), waveform sampling (barrel+ endcap)

<u>Particle Identification</u>
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd) new

new
<u>Final focusing magnets</u>

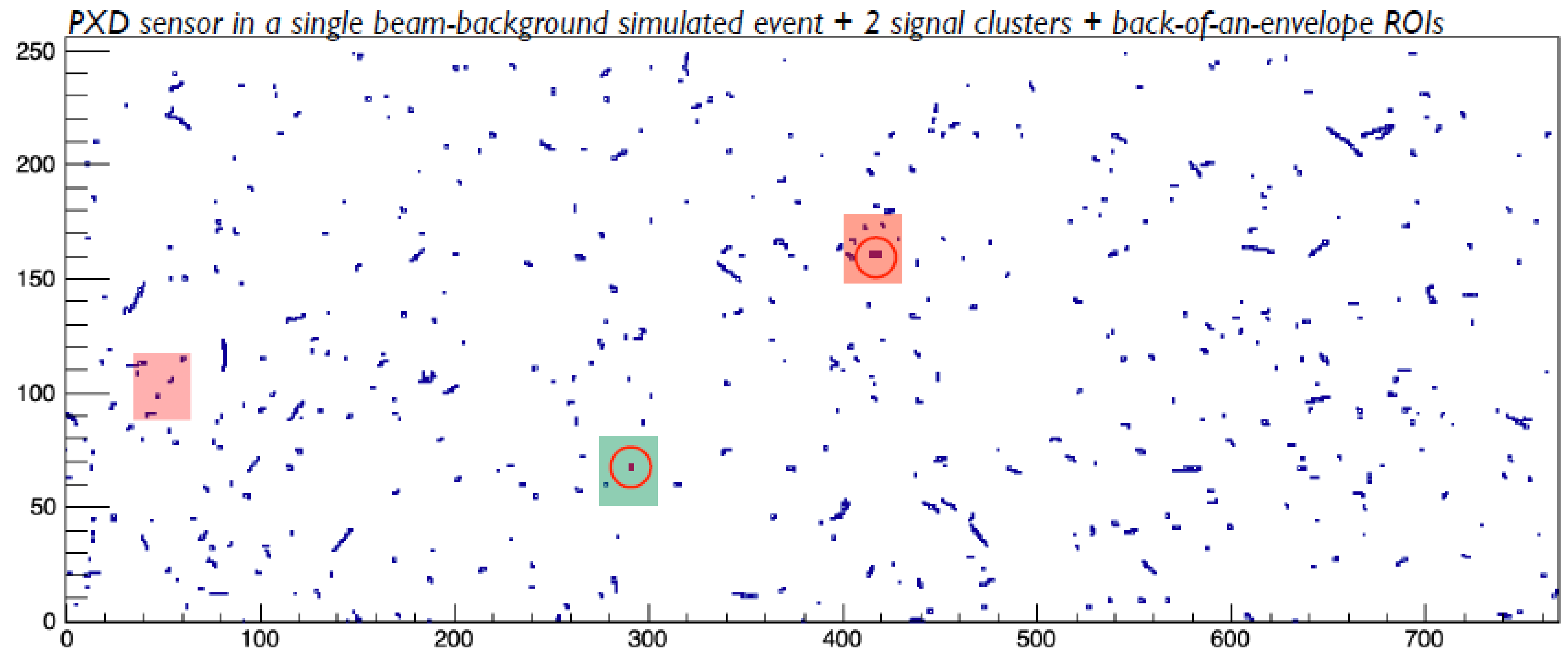
<u>Beryllium beam pipe</u>
2cm diameter new



<u>SuperCond. Solenoid</u>
1.5 T magnetic field

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

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



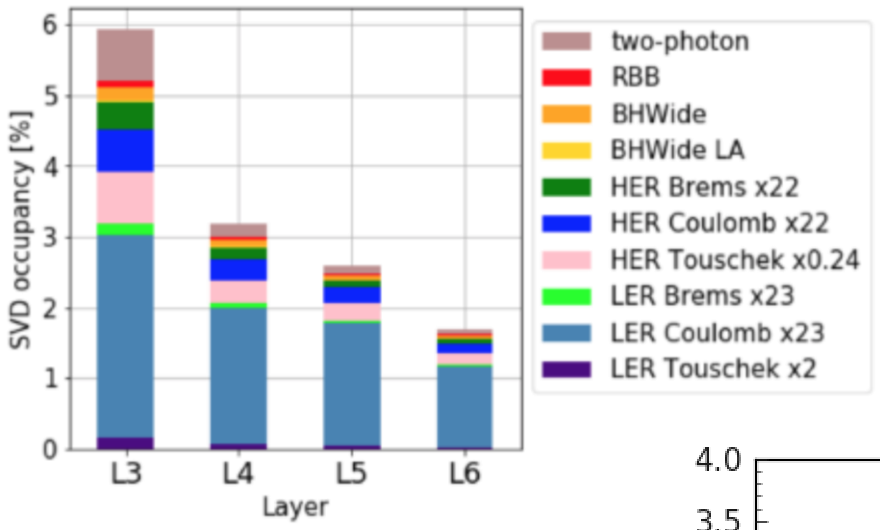
- A PXD sensor frame + the ROIs from the HLT + nominal expected background

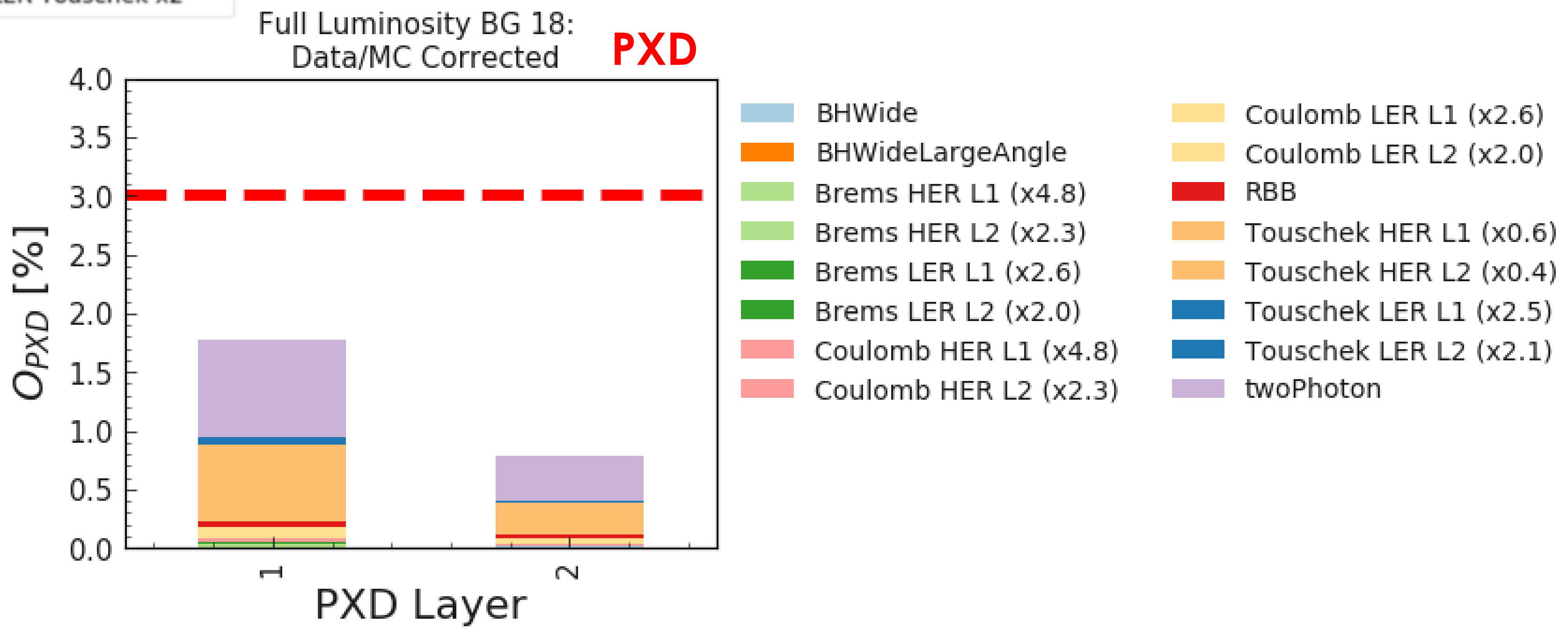
From Eugenio Paoloni, July 2019

Details on beam-induced background

Extrapolations still under progress

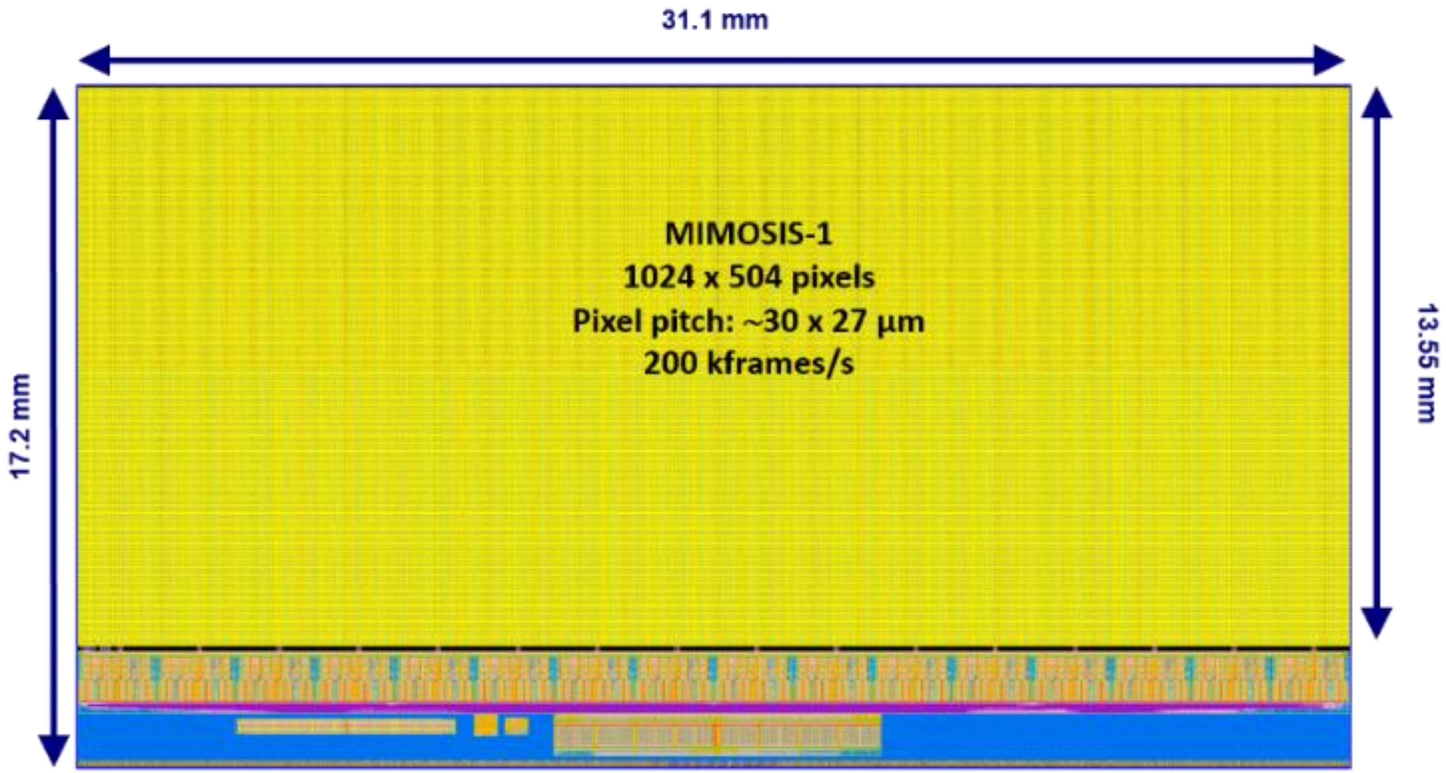
SVD BG estimation @ design luminosity





CMOS pixel sensor

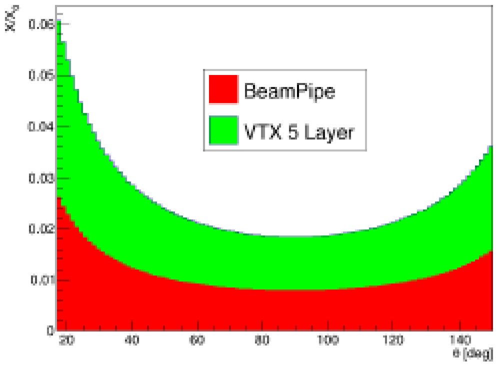
Typical application-ready sensor (180 nm techno)



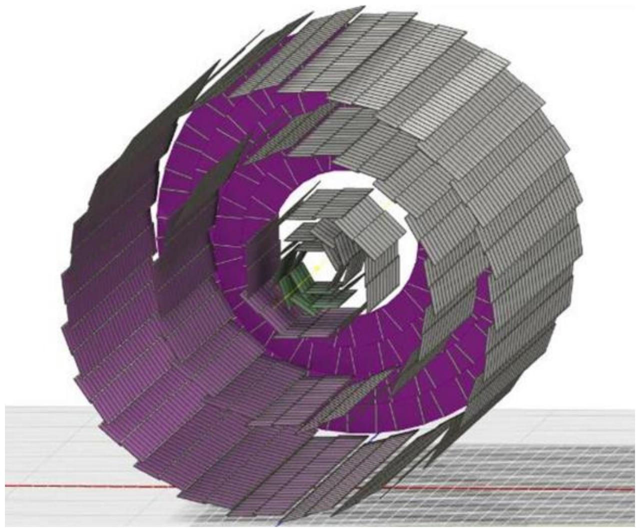
Full pixelated VXD: Geometry details

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

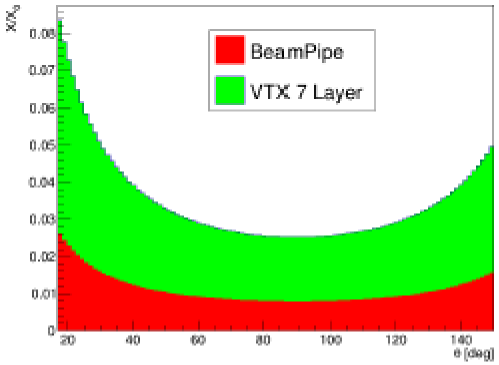


5 layers + 2 disks

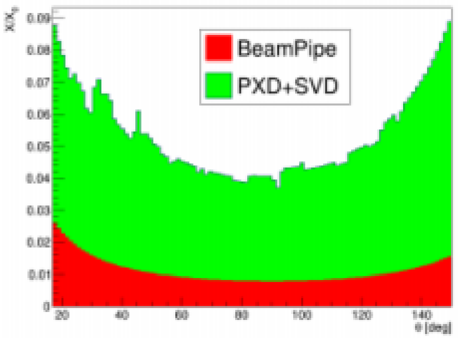


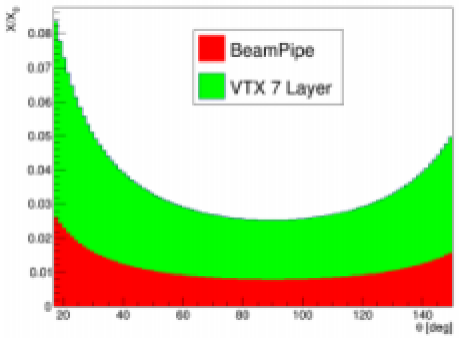
VTX with 7 pixelated layers

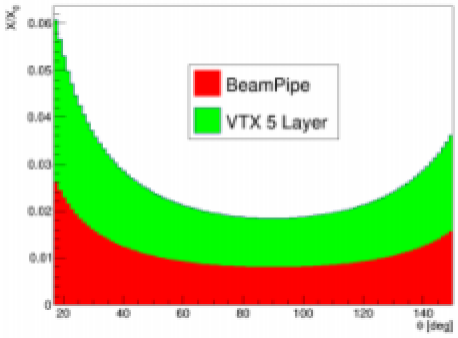
7 layers	1	2	3	4	5	6	7
Radius (cm)	1.4	2.2	3.5	6.0	9.0	11.5	13.5
# ladders	6	10	14	12	18	22	26
Sensor type	A	A	A	A'	A'	A'	A'
# Sensor rows along z direction	1	1	2	3	4	5	6

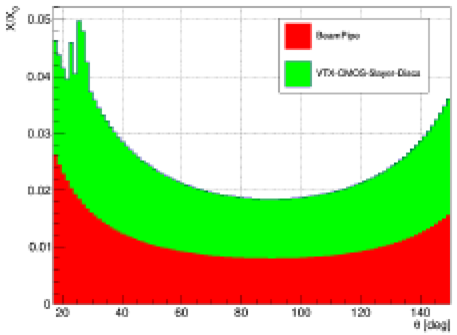


Material budget full pixelated VXD

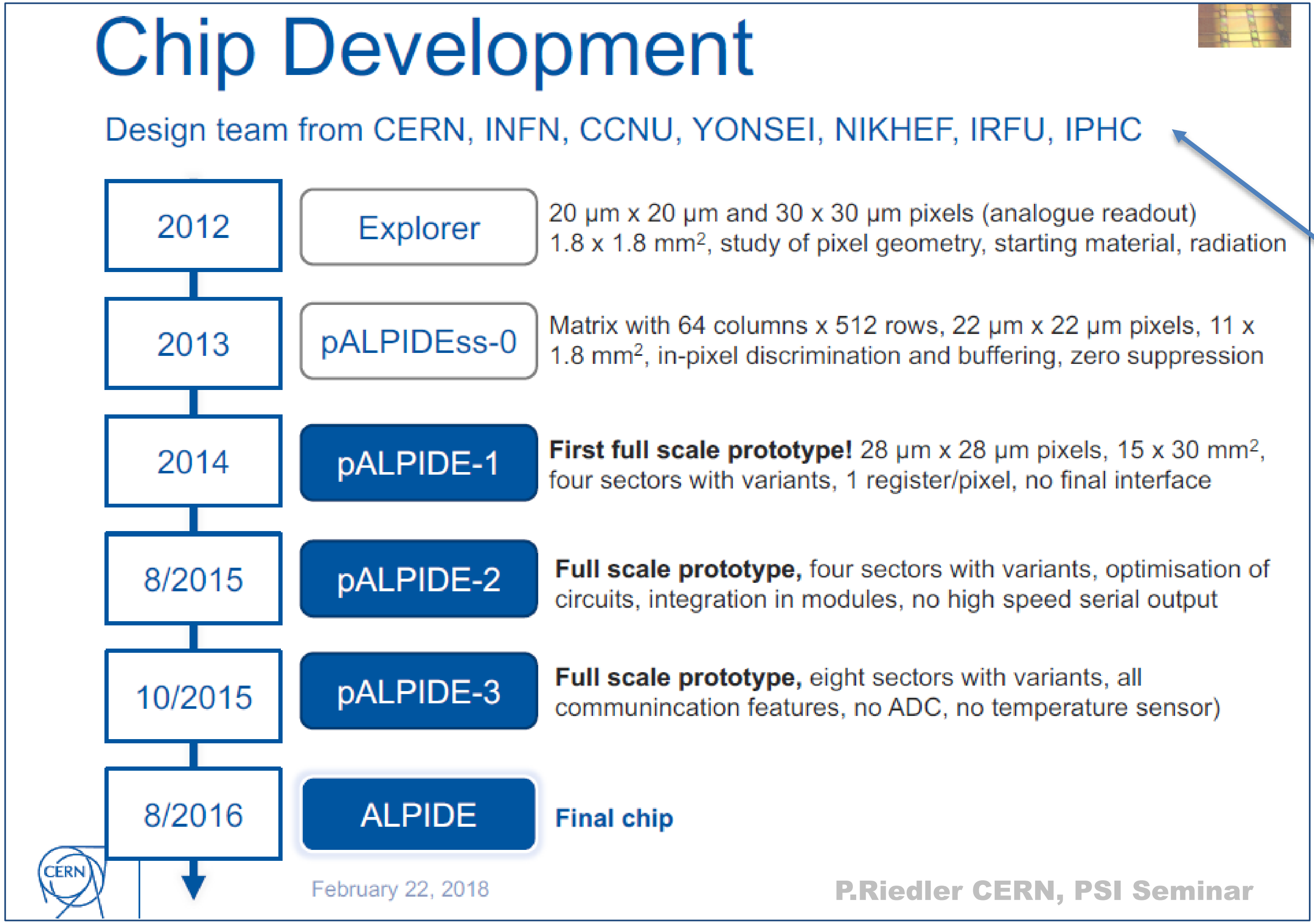








About timeline: the ALPIDE-ITS case



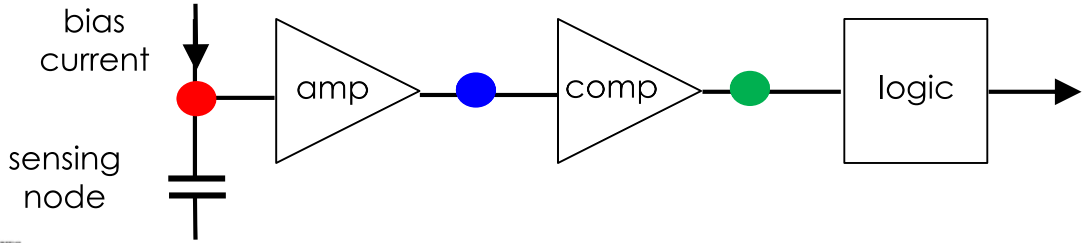
~4 years from tech-proto to final sensor

- Few remarks
  - TJ180 nm exploration started in 2011
  - This is not a small team

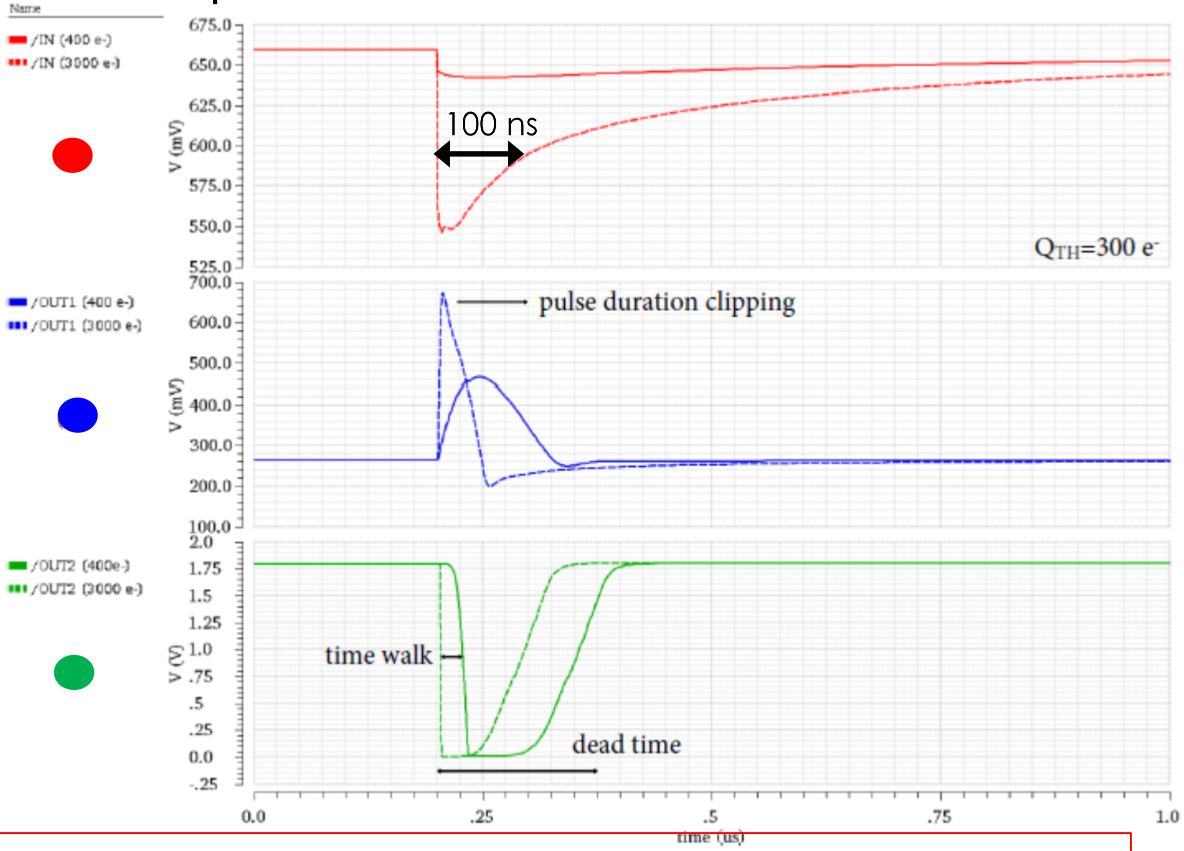
+3 years for assembly (ALICE-ITS ~10 m²)

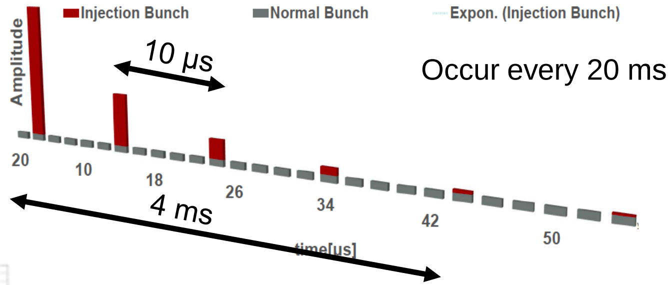
Tower Jazz 180 nm time response simulations

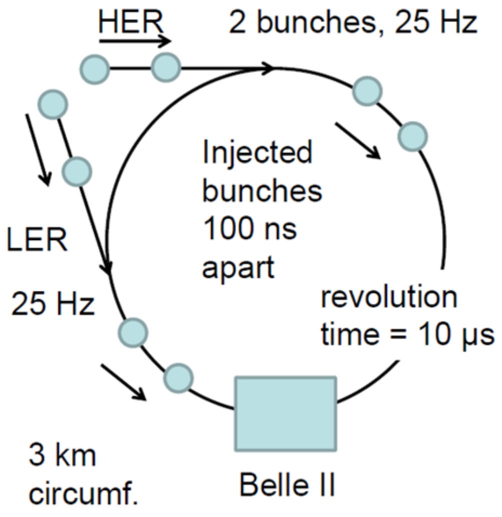
- Front-end structure in-pixel



- 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