Upgrade of the Belle II Vertex Detector with monolithic active pixel sensors

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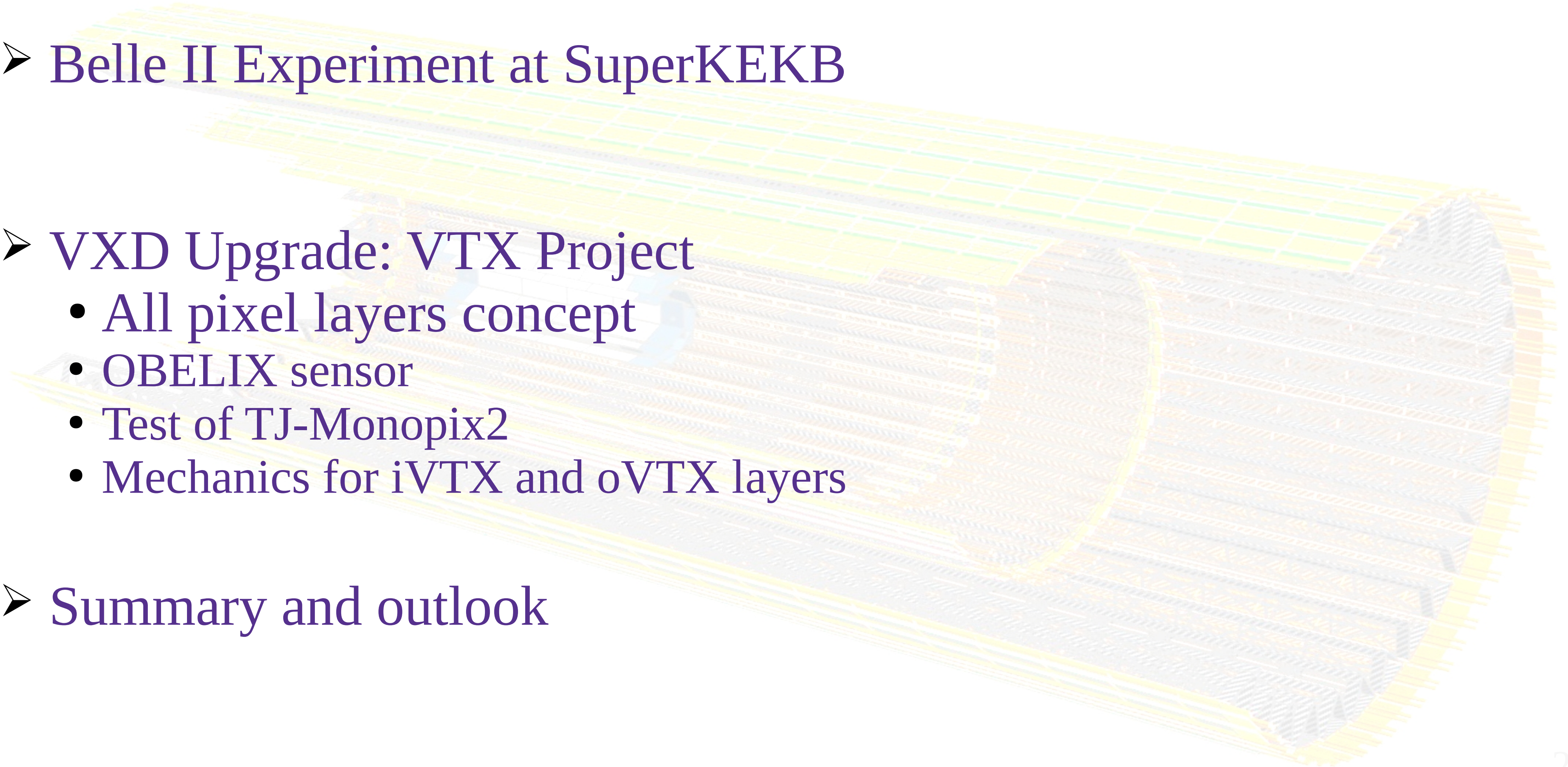
Outline



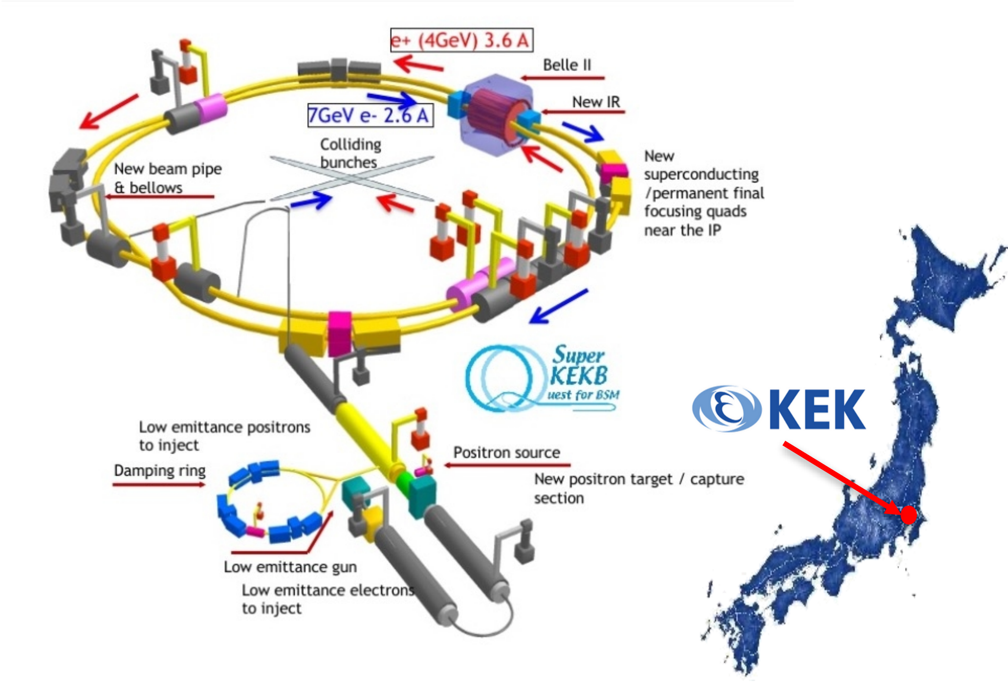
- Belle II Experiment at SuperKEKB

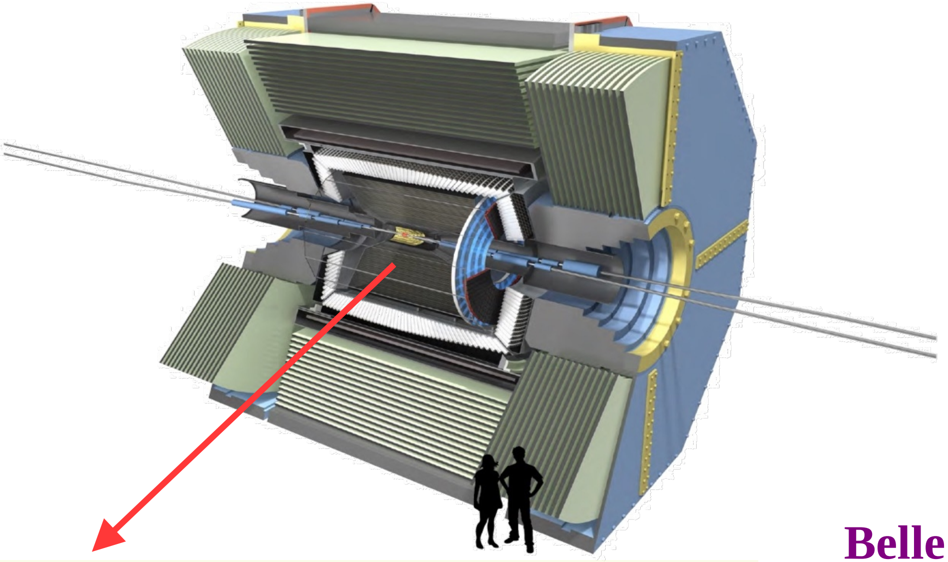
- VXD Upgrade: VTX Project
  - All pixel layers concept
  - OBELIX sensor
  - Test of TJ-Monopix2
  - Mechanics for iVTX and oVTX layers

- Summary and outlook

Belle II @ SuperKEKB

- SuperKEKB facility @ Tsukuba Japan:
  - $e^- + e^+$ collision with asymmetric energy $\sqrt{s} = M_{\Upsilon(4S)}$
  - Physics based on integrated luminosity
  - *World highest peak luminosity 4.7×10^{34} cm^{-2} s^{-1} in 2022*





Target
$\mathscr{L} = 6\times10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\int \mathscr{L}\, dt = 50\ \mathrm{ab}^{-1}$

Achieved (as of July 2024)
$\mathscr{L} = 4.7\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$\int \mathscr{L}\, dt = 530\ \mathrm{fb}^{-1}$

Belle II needs upgrade to operate at target luminosity

Current Vertex Detector (VXD) => Talk by L. Corona
PXD (2 layers DEPFET pixels) + SVD (4 layers DSSD)

"The Belle II Upgrade Program" by K. Nakamura

Need for VXD upgrade

✔ Excellent VXD performance in current conditions

- Large uncertainty on background extrapolation @ target luminosity
- Limited safety margin & performance degradation possible in the high BG scenario:
  - PXD layer1 up to 2% occupancy (32 MHz/cm^2 hit rate)
  - SVD layer3 up to 9% occupancy (9 MHz/cm^2 hit rate)

➢ May reach limits of current detector @ target Luminosity

➔ higher space & time granularity in all layers

■ Vertex detector upgrade requirements

- Hit rate up to 120 MHz/cm^2
- Fast time stamping: 50-100ns
- Spatial resolutions < 15 µm (pitch 30-40 µm)
- Power dissipation < 200 mW/cm^2
- Operation simplicity & reduced services
- Radiation levels:
  - TID ~ 100 Mrad
  - NIEL ~ $5x10^{14}$ n_{eq}/cm^2

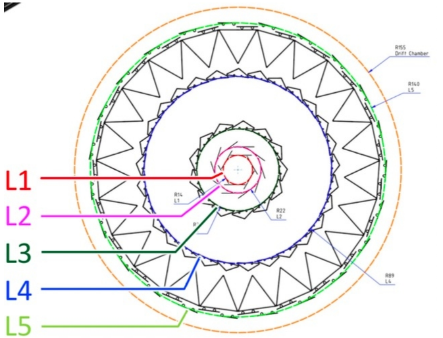
=> Requirements of VTX matches with **M**onolithic **A**ctive **P**ixel **S**ensor (MAPS)

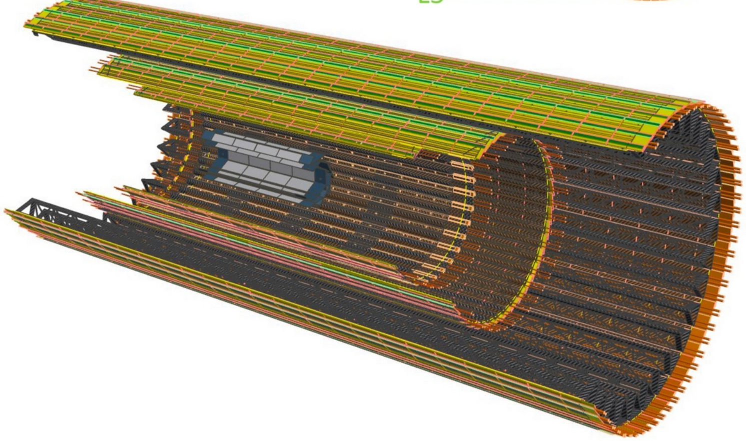
Vertex Detector Upgrade: The VTX Project

- 5 layers with pixel sensors (baseline)
  - High space-time granularity & low material budget
    - Very low occupancy < 10^{-4} => Better tracking efficiency at low momentum
  - Lighter service & easy geometry
    - adaptable to potential changes of Interaction Region

- Technical choice
  - **O**ptimized **BEL**le II p**IX**el (**OBELIX**) sensor
    - Thin DMPAS sensor (derived from TJ-Monopix2)
  - **The design and integration of the layers depends on the radius → two separate concepts have emerged**
  - **iVTX:** innermost two layers, all-silicon, self supported (inspired by PXD), air cooled (0.2 % X_0)
  - **oVTX:** 3 outer layers, carbon fiber frame (inspired by ALICE-ITS2), water cooled (0.3 - 0.8 % X_0)
  - Total material budget: ~2.0 % X_0

Max radius 18 cm & length 70 cm => 1 m^2



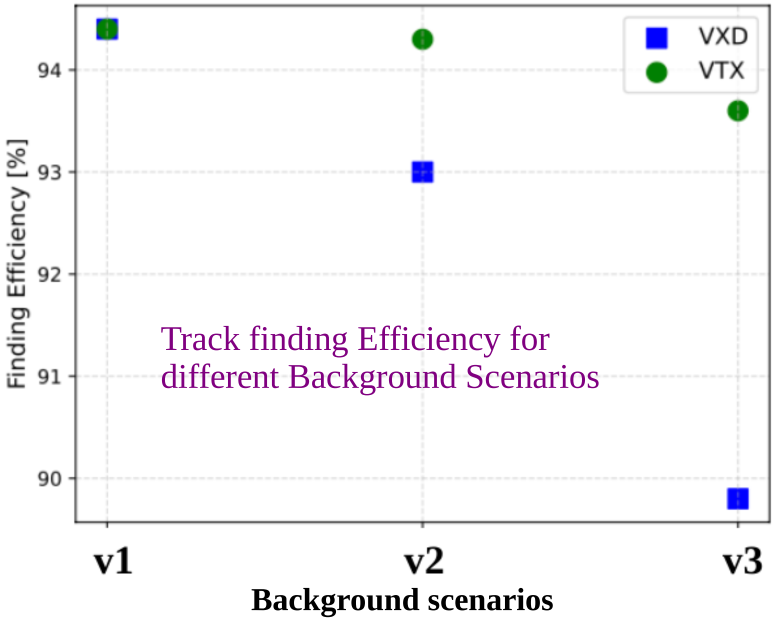


	L1	L2	L3	L4	L5	Unit
Radius (mm)	14.1	22.1	39.1	89.5	140	mm
# Ladders	6	10	17	40	31	
# Sensors	4	4	7	16	2x24	per ladder
Expected hit rate*	19.6	7.5	5.1	1.2	0.7	MHz/cm2

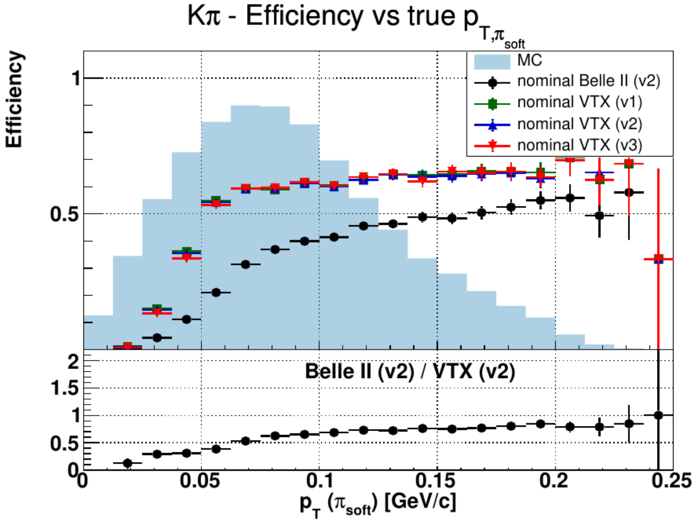
*Large uncertainty on BG extrapolation/possible changes in IR region

VTX tracking performance

- VTX performance studies: on benchmark channels, full simulations of signal events overlaying 3 possible background scenarios: optimistic:v1, intermediate:v2, conservative:v3
- Fully pixelated VTX with high space & time granularity in all layers
  - reduction in occupancy by a factor 200
  - all layers included in pattern recognition



Track finding Efficiency for different Background Scenarios



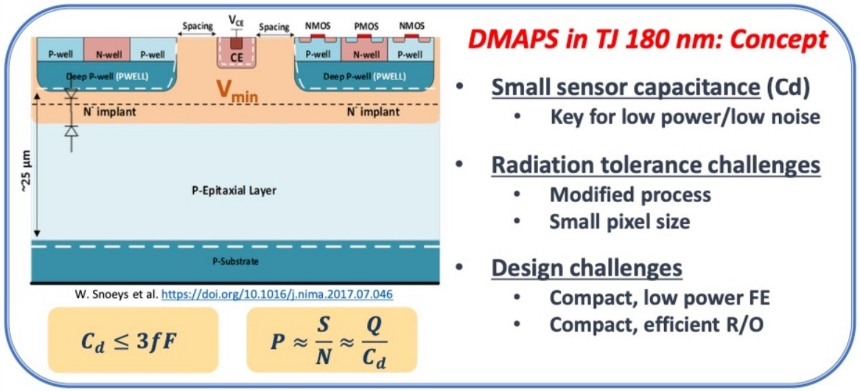
- VTX:
  - Better tracking efficiency than current VXD for full tracking (VTX tracking combined with Central Drift Chamber)
  - less sensitive to the background level than current VXD
  - Better (~70% improvement) low momentum tracking efficiency than current VXD

- Reconstruction efficiency for $B^0 \rightarrow D^{*-} l^+ \nu$ as a function of the π^- soft transverse momentum

MAPS for Belle II

❍ TJ-Monopix2 sensor as a prototype

- Developed for ATLAS (ITK outer layers), TJ 180 nm (same as ALPIDE) but modified process to improve rad hardness & faster readout
  - core features matching Belle II needs
    - 33x33 µm2 pitch, 25 ns integration, large matrix 2 x 2 cm^2
    - 7 bit ToT information, 3 bit in-pixel threshold tuning
    - Column drain readout capable to handle >> 120 MHz/cm^2 -> trigger-less in TJMP2



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

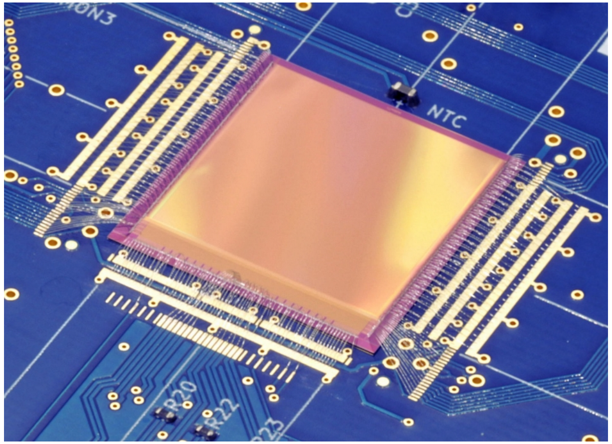
$C_d \leq 3fF$

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

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

TJ-Monopix2: Proof-of-principle for Belle II VTX – OBELIX



❒ OBELIX design with new digital periphery with trigger logic for Belle II
- optional features to allow Track Trigger capability
- additional finer time-stamping for outer layer hits (low rate)

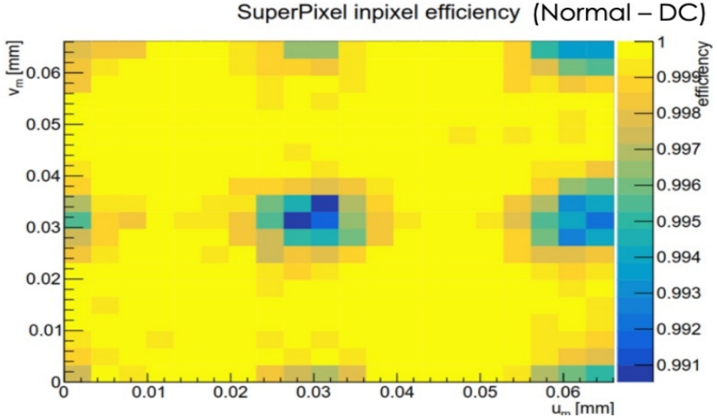
❒ Detailed characterization of TJ-Monopix2 to validate key performance crucial for OBELIX design

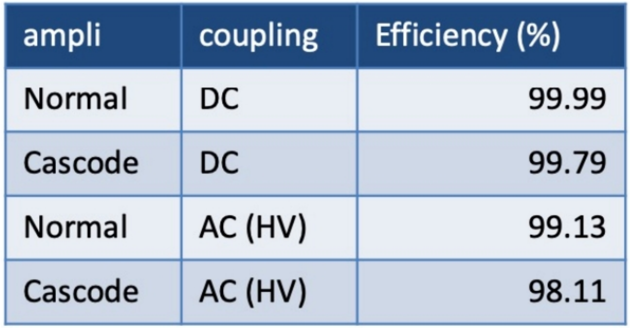
Characterization of TJ-Monopix2

- **Laboratory test:**
  - Threshold / noise
    - stable operation down to THR~ 250 e- (MIP signal in 30 um Si MPV~2500 e-)
    - THR dispersion 17e-
    - Noise ~ 8 e-

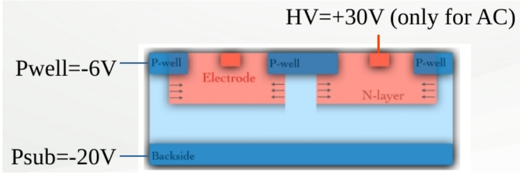
- **Beam test (DESY, 3-5 GeV, e^-):**
  - Several test-beam campaign
  - Measurement performed for not-irradiated sensors and irradiated sensor (5×10^{14} n_{eq}/cm^2, 24MeV protons)
    - Efficiency > 99%
    - Position resolution ~9 μm
    - Confirmed good performance & high efficiency after irradiation, increasing bias
  - Measurement of irradiated sensor with NIEL 5×10^{14} n_{eq}/cm^2 & TID 100 Mrad: **July 2024**
    - Understand operational range
    - Influence of temperature

Irradiated sensor



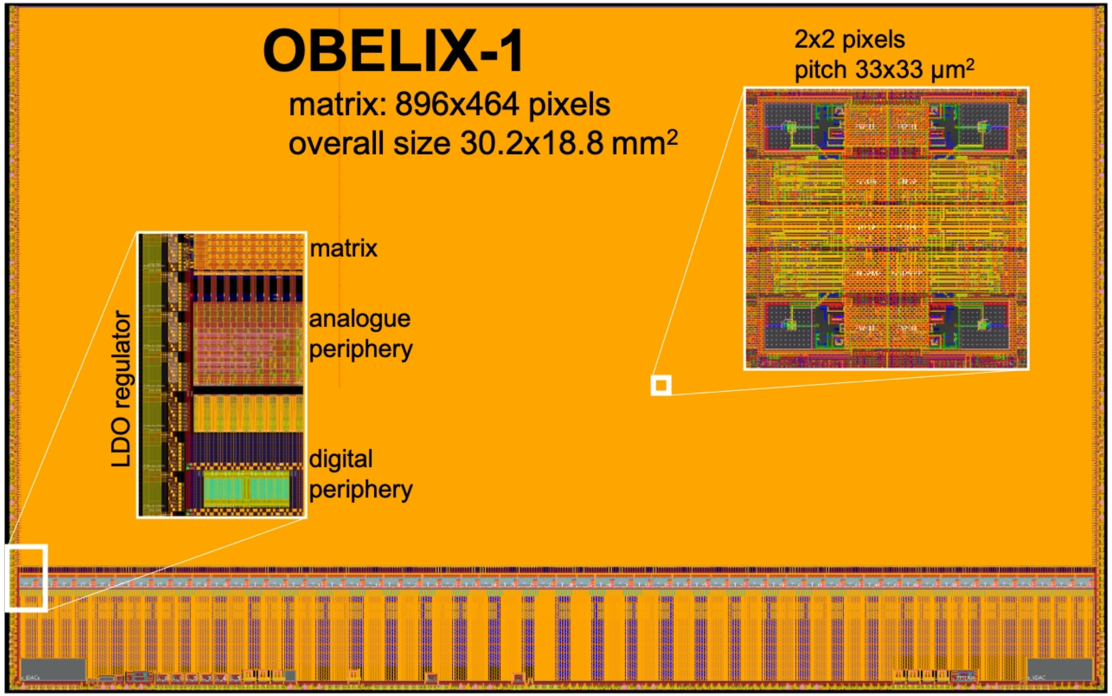


ampli	coupling	Efficiency (%)
Normal	DC	99.99
Cascode	DC	99.79
Normal	AC (HV)	99.13
Cascode	AC (HV)	98.11



Biasing for irradiated sensor

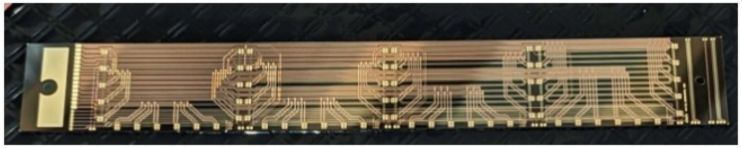
OBELIX for Belle II



- Pitch: 33 μm
- Trigger output: 10 ns resolution (reachable by combining 3 layers)
- PTD @ 3 ns
- Time stamping: 50 – 100 ns
- Power < 1.5 W per chip
- Fine time stamping: 5 ns for hit rate < 10 MHz/cm^2

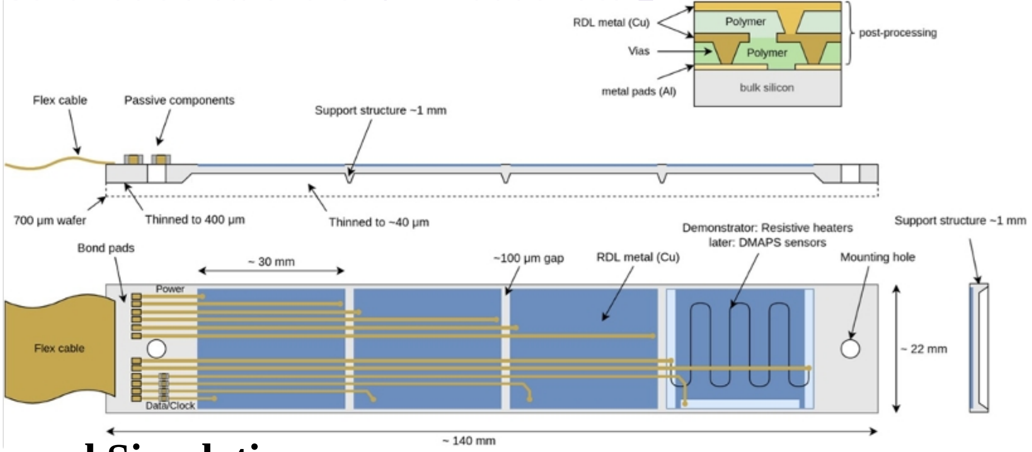
iVTX, Innermost Layer

- Material budget < 0.2X0
  - 4 contiguous OBELIX sensors diced as a block from the wafer, thinned to 50 um, except in some border area ~400 um thick, to ensure stiffness
- First real-size ladder at IZM-Berlin with dummy Si (dummy heater structures),
  - To characterize electrical, mechanical and thermal performance of the ladder design

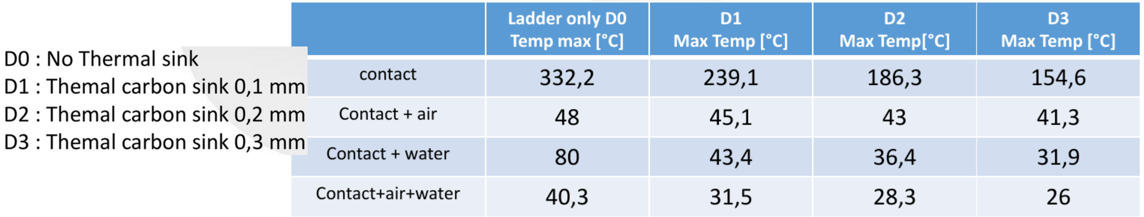


- Air cooling
  - Average power dissipation ~200 mW/cm^2
- Several options under evaluation

Schematic view of the iVTX ladder design

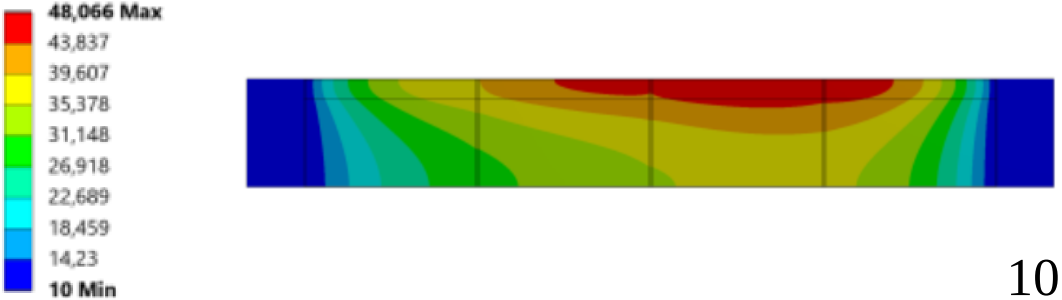


Thermal Simulation:



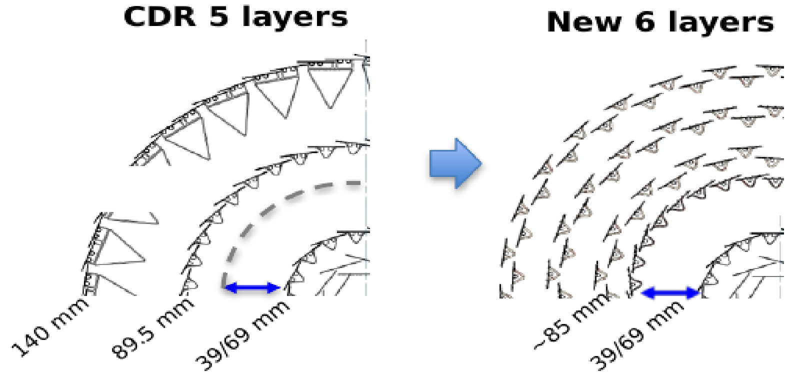
D0 : No Thermal sink
D1 : Themal carbon sink 0,1 mm
D2 : Themal carbon sink 0,2 mm
D3 : Themal carbon sink 0,3 mm

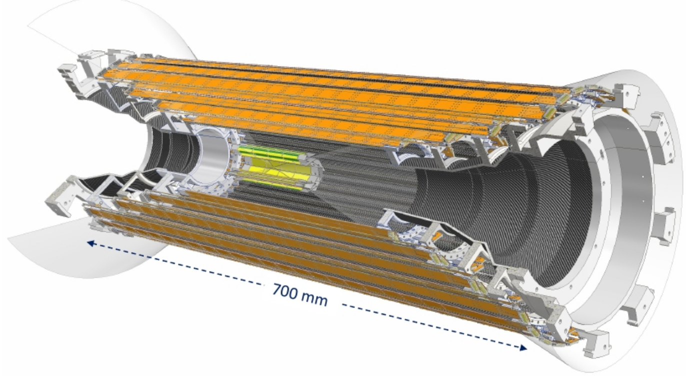
	Ladder only D0 Temp max [°C]	D1 Max Temp [°C]	D2 Max Temp[°C]	D3 Max Temp [°C]
contact	332,2	239,1	186,3	154,6
Contact + air	48	45,1	43	41,3
Contact + water	80	43,4	36,4	31,9
Contact+air+water	40,3	31,5	28,3	26

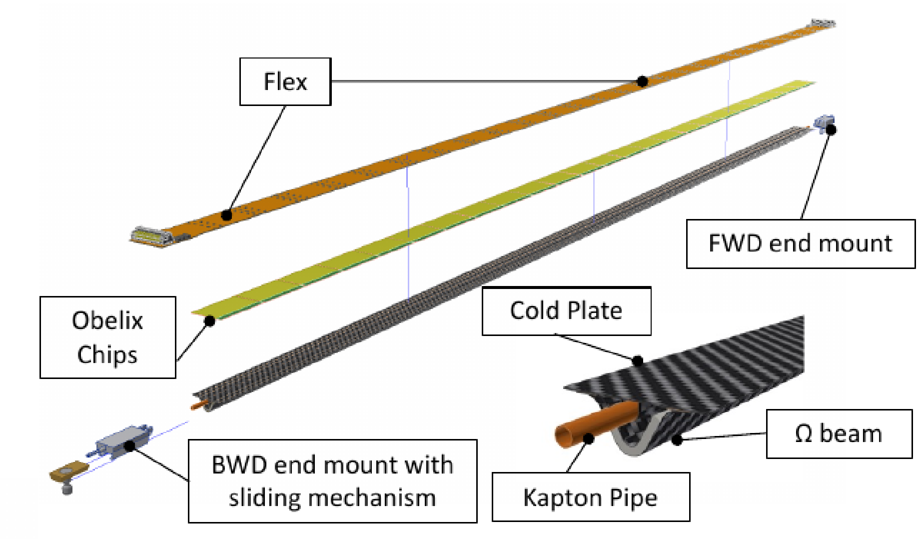


oVTX, Outer Layer

- ladder concept: inspired by ALICE ITS2
  - Each ladder is made of light carbon fiber support structure, a cold plate with pipes with liquid cooling
  - Sensor glued on cold plate, flex cables connecting each half ladder
- Prototypes:
  - Mechanical & thermal characterization done for the longer ladder ~70 cm (outermost layer)
- Mechanical design already advanced
- 6 layer design is also under consideration
  - More compact ladder design







Exploded view of the Layer 5 ladder

Summary and Outlook

- SuperKEKB will be upgraded to reach the target Luminosity, 6x10^{35} cm^{-2} s^{-1} with possible major redesign of the Interaction Region (IR)

- Current VXD detector has excellent performance, but limited safety margin for high BG

- LS 2 (2027-2028) is a good opportunity to upgrade the vertex detector

- DMAPS pixel sensor will be employed in proposed upgrade of VTX
  - VTX is more performant and resilient against higher machine backgrounds

- First submission full scale prototype OBELIX-1 sensor in Autumn 2024

- Framework CDR: Available on arXiv:2406.19421

VTX Collaboration

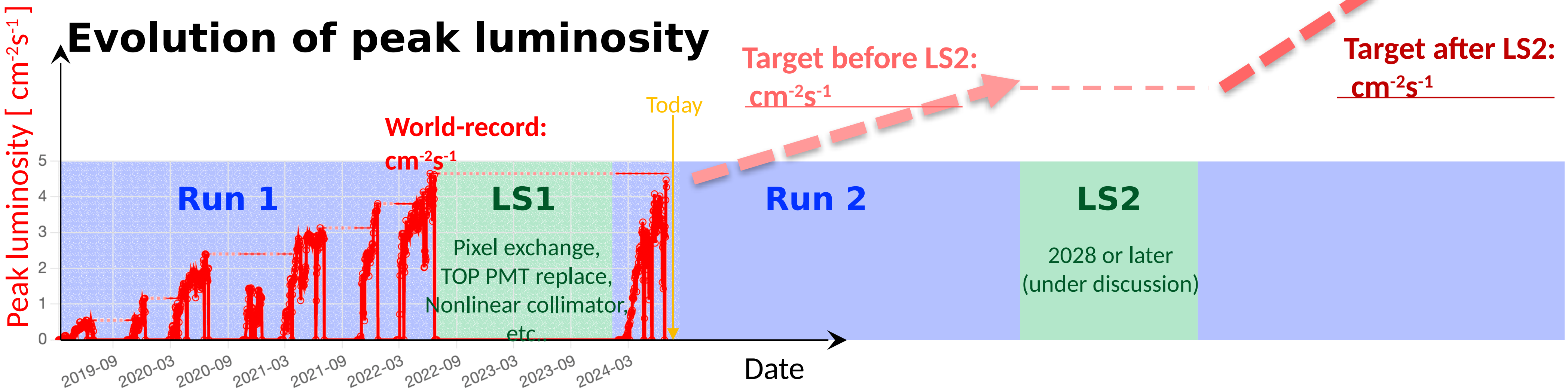
HEPHY (Viennna)
CPPM (Marseille)
IJCLab (Orsay)
IPHC (Strasbourg)
University of Bonn
QMU (UK)

IPMU (Kashiwa)
University of Tokyo
KEK (Tsukuba)
University of Goettingen
IFIC (CSIC-UV) Valencia
RAL (UK)

INFN & University of Bergamo
INFN & University of Pavia
INFN & University of Pisa
IFCA (CSIC-UC) Santander
ITAINNOVA (Zaragoza)
Jilin University (China)

Backup slides

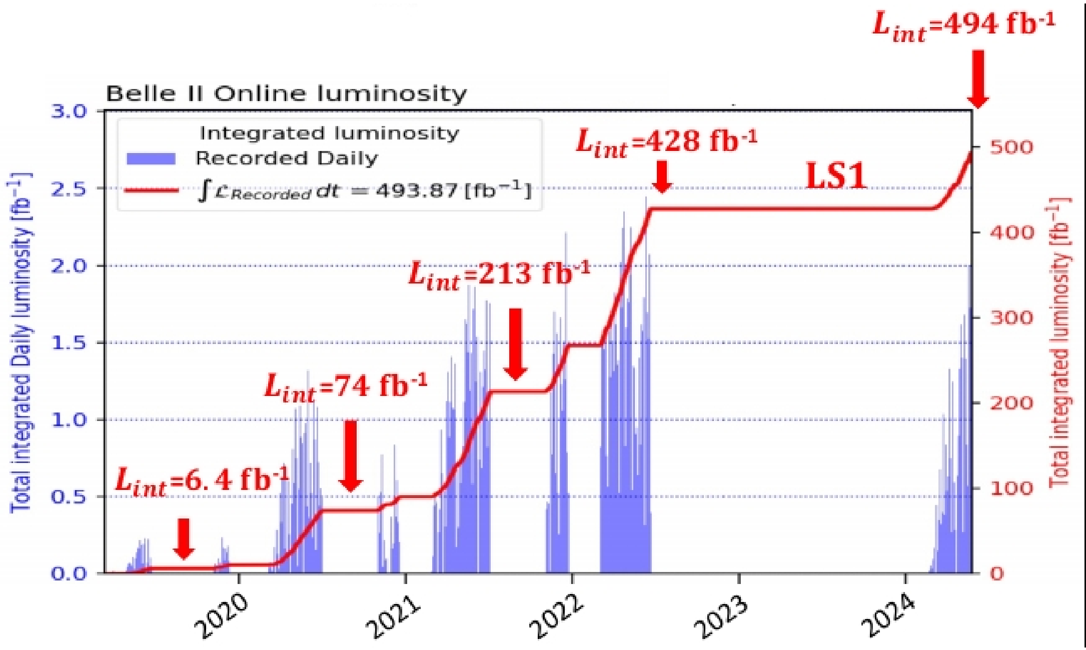
Belle II Upgrade Motivations



- Upgrade of accelerator complex required to reach 6×10^{35} cm^{-2} s^{-1} , it may include a major redesign of the Interaction Region (IR)
- LS2 (2027-2028) provides window of opportunity for significant detector upgrades
- Belle II upgrade program:
  - To improve detector robustness against backgrounds & provide larger safety factors to run at high luminosity
  - Increase longer term subdetector radiation resistance
  - Develop the technology to cope with a replacement of the VXD, needed in case of major IR redesign
  - Prepare a safety net in case of failure of detector components or accidents
  - Improve physics performance

Belle II @ SuperKEKB

- Run1: 2019-2022
  - Pixel Detector (PXD): layer 1 + only 20% of layer 2
  - Full 4-layers strip detector (SVD)
- Long Shutdown 1 (06/2022-12/2023)
  - several accelerator and detector maintenance & improvements
    → installation of the complete 2 layers PXD + current SVD
- Run2: started in Jan 2024
  - **Instantaneous luminosity ramping up > 10^{35} cm^{-2} s^{-1} in coming years**
  - Path to reach 2x10^{35} cm^{-2} s^{-1} identified but still large factors to reach peak target luminosity of 6x10^{35} cm^{-2} s^{-1}

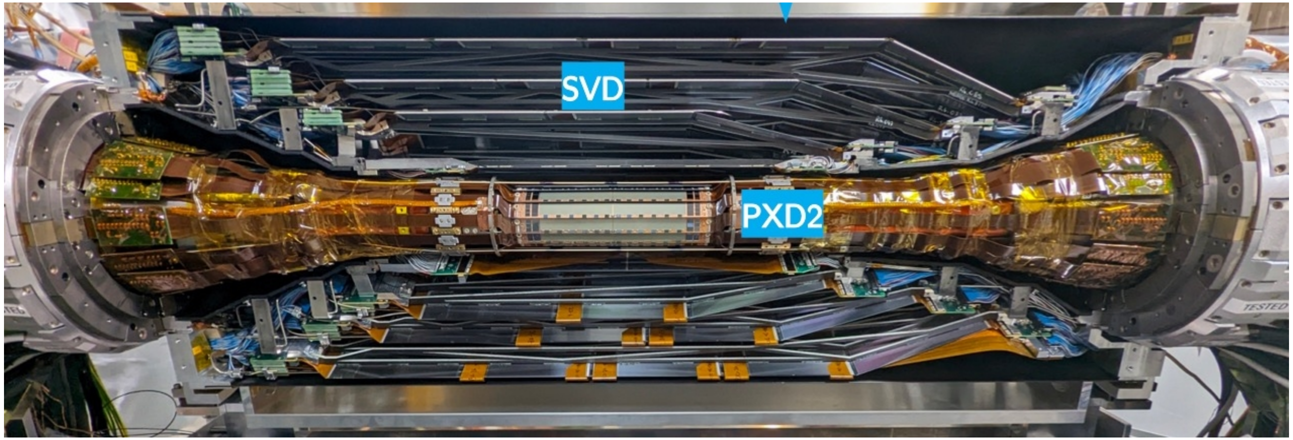


Current Vertext Detector (VXD)

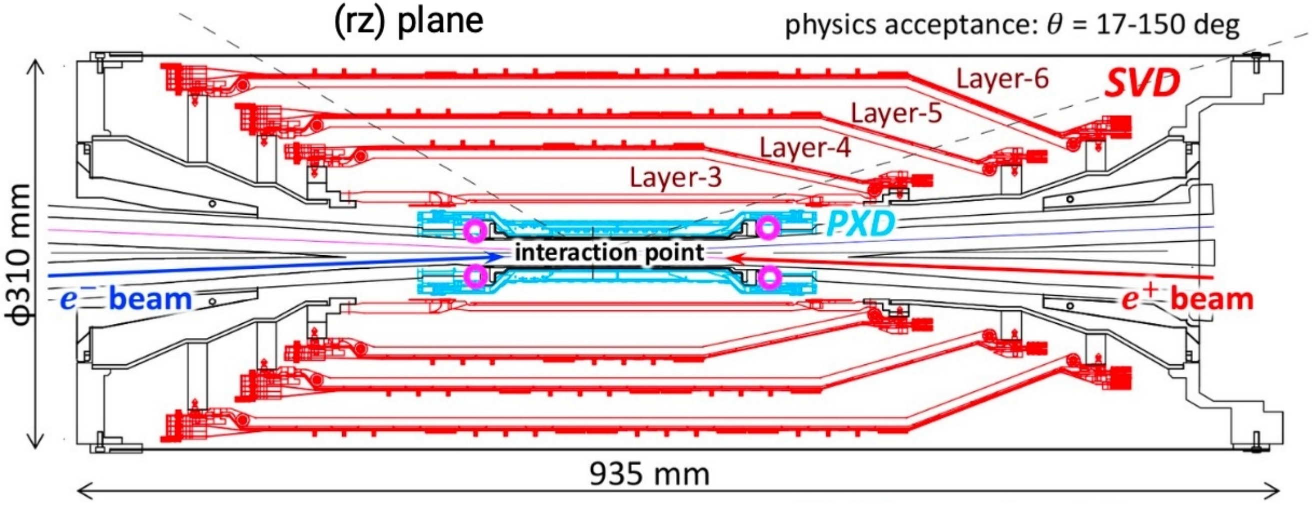
- Two technology system
  - Low mass ladder design with total material budget of 3.8%X_0
  - Spatial resolution: 10-25um

- PXD
  - 2 layers of DEPFET pixel sensor
  - Material budget → 0.25%X0
  - Small pixel pitch (50-75um) but long integration time (20us)
  - Delicate detector → damages in high dose beam aborts!

- SVD
  - 4 layers of double sided strip detector
  - Material budget → 0.75% X0/layer
  - Very good cluster time resolution (3ns), but long strips (6cm)

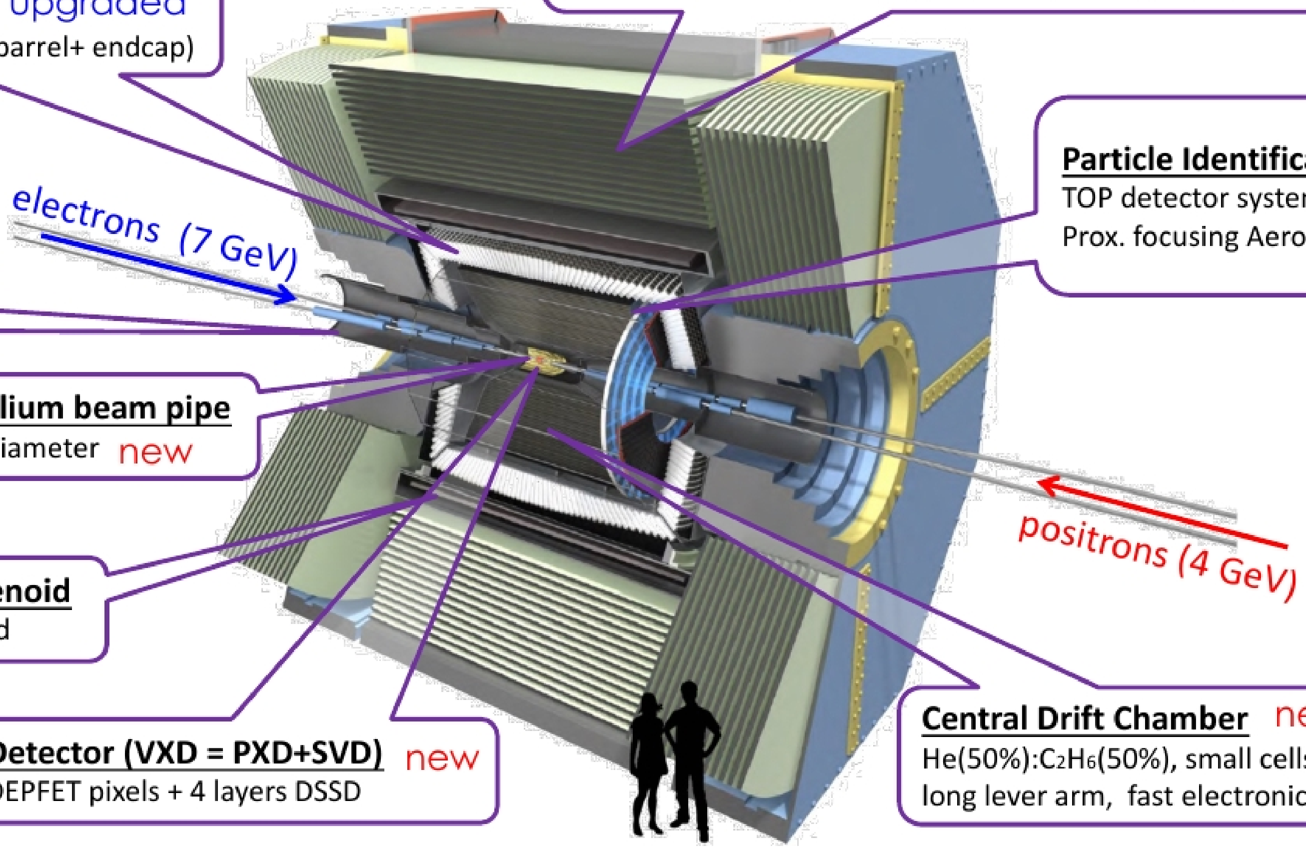


Talk by L. Corona in morning session



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

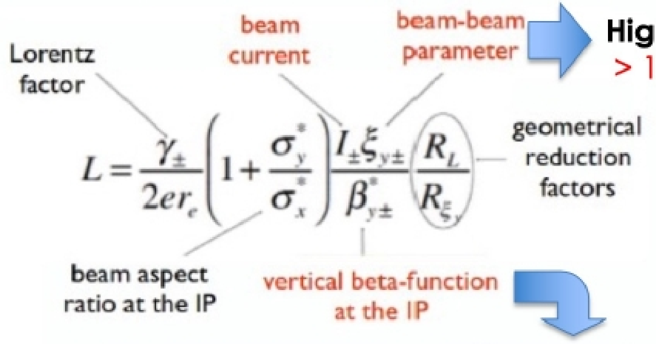
SuperCond. Solenoid
1.5 T magnetic field

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

SuperKEKB collider

Recipe to high luminosity



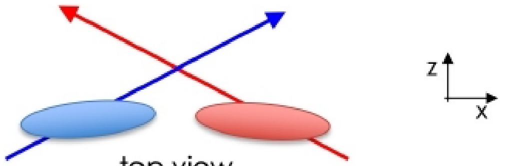
$$L=\frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

High currents:
> 1A

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

& specific beam crossing features

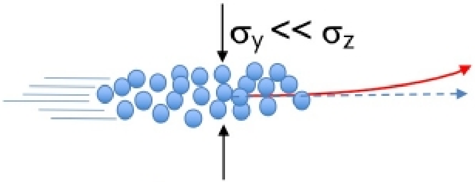
Crossing angle (83 mrad) + crab waist (80%)



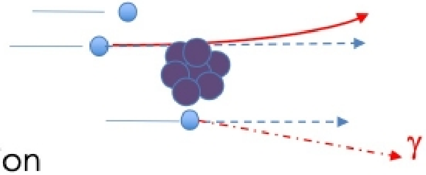
top view

Beam-induced backgrounds

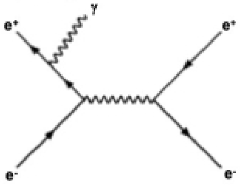
- Intra-beam scattering



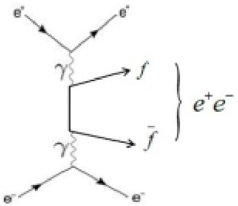
- Beam-gas interaction
- Synchrotron radiation



- Luminosity driven



Radiative Bhabha scattering



2-photon interaction

CDR OBELIX specs vs TJMP2

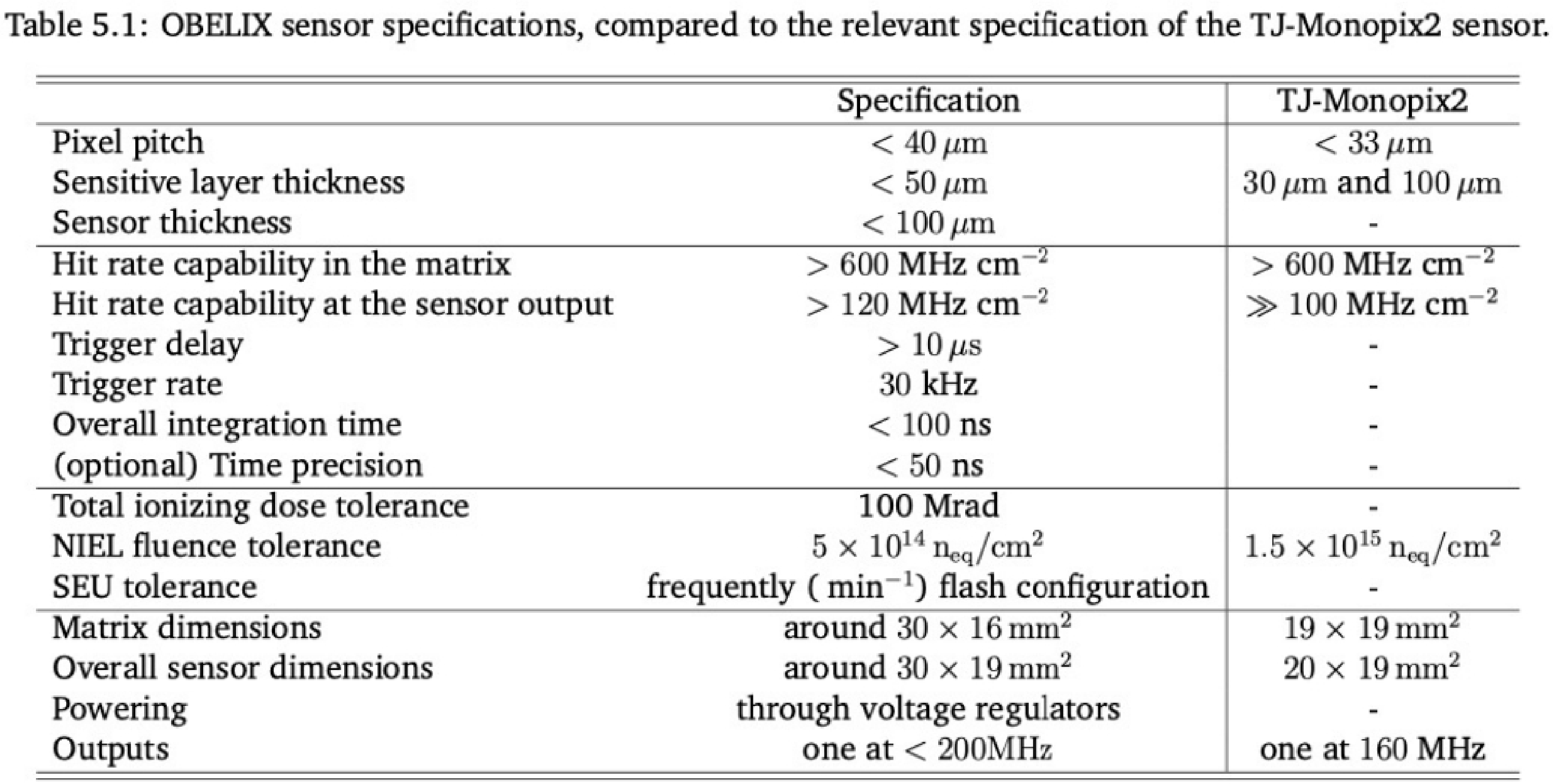


Table 5.1: OBELIX sensor specifications, compared to the relevant specification of the TJ-Monopix2 sensor.

	Specification	TJ-Monopix2
Pixel pitch	$< 40\,\mu$m	$< 33\,\mu$m
Sensitive layer thickness	$< 50\,\mu$m	$30\,\mu$m and $100\,\mu$m
Sensor thickness	$< 100\,\mu$m	-
Hit rate capability in the matrix	> 600 MHz cm^{-2}	> 600 MHz cm^{-2}
Hit rate capability at the sensor output	> 120 MHz cm^{-2}	$\gg 100$ MHz cm^{-2}
Trigger delay	$> 10\,\mu$s	-
Trigger rate	30 kHz	-
Overall integration time	< 100 ns	-
(optional) Time precision	< 50 ns	-
Total ionizing dose tolerance	100 Mrad	-
NIEL fluence tolerance	5×10^{14} n$_{\mathrm{eq}}$/cm^2	1.5×10^{15} n$_{\mathrm{eq}}$/cm^2
SEU tolerance	frequently (min^{-1}) flash configuration	-
Matrix dimensions	around 30×16 mm^2	19×19 mm^2
Overall sensor dimensions	around 30×19 mm^2	20×19 mm^2
Powering	through voltage regulators	-
Outputs	one at $<$ 200MHz	one at 160 MHz

Background scenarios

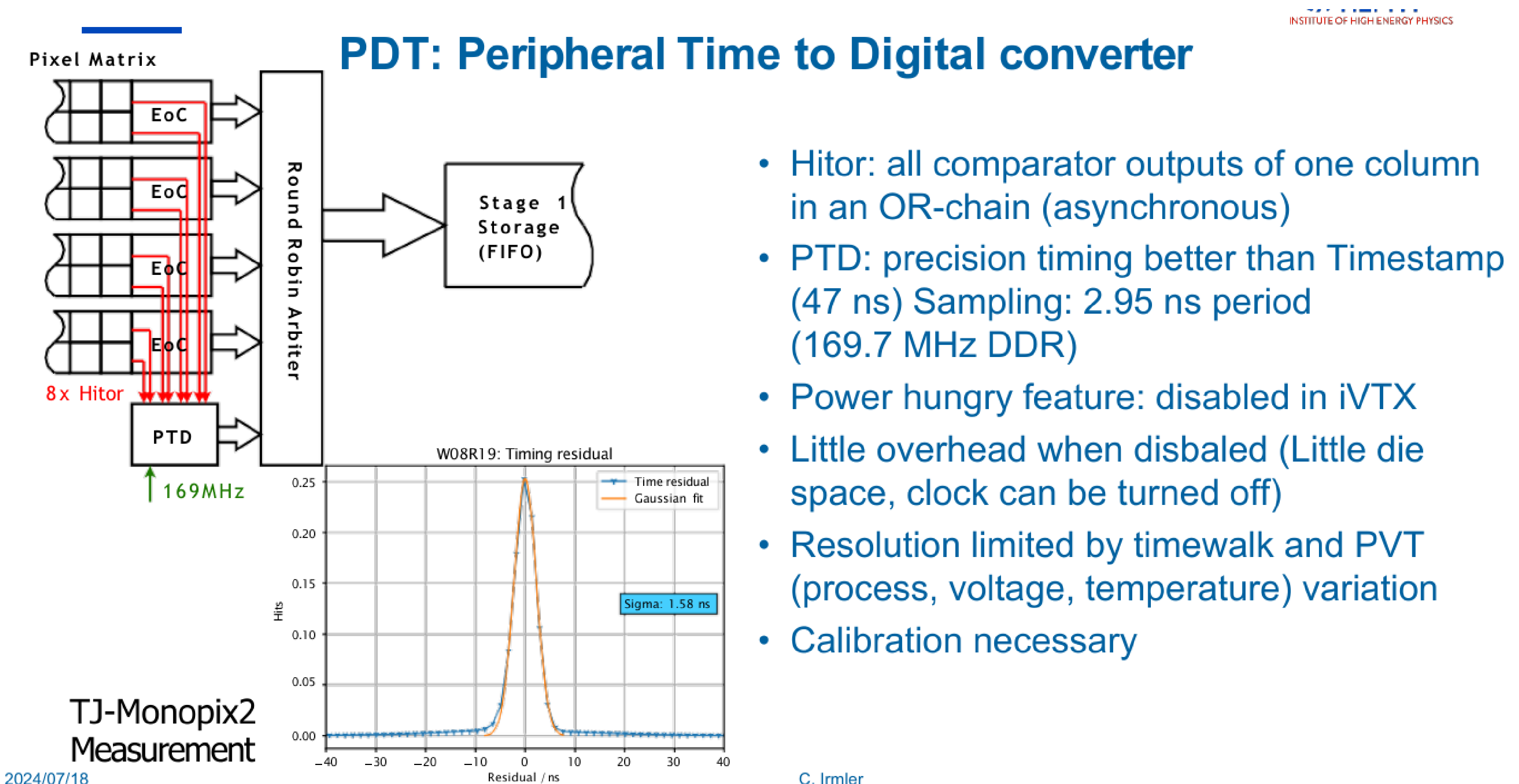
- **optimistic Scenario-1**, comes from a simple scaling of all single-beam background components from before LS2 to target beam parameters. scenario V1 optimistic (lumi 6e35), single beam scaled x2

- **x5 – intermediate Scenario-2.** scenario V2 nominal (lumi 6e35), single beam scaled x5

- **x10 – conservative Scenario-3.** scenario V3 conservative (lumi 6e35), single beam scaled x10

- An arbitrary factor assuming that all single-beam backgrounds will be elevated by order of magnitude after LS2. Luminosity BG terms are instead correctly simulated for the target luminosity after LS2 over the luminosity before LS2, applying the measured Data/MC ratio

PTD



PDT: Peripheral Time to Digital converter

- Hitor: all comparator outputs of one column in an OR-chain (asynchronous)
- PTD: precision timing better than Timestamp (47 ns) Sampling: 2.95 ns period (169.7 MHz DDR)
- Power hungry feature: disabled in iVTX
- Little overhead when disbaled (Little die space, clock can be turned off)
- Resolution limited by timewalk and PVT (process, voltage, temperature) variation
- Calibration necessary

TJ-Monopix2 Measurement

2024/07/18

C. Irmler