11th Pixel workshop
Strasbourg, 18-22 November 2024
https://indico.in2p3.fr/e/pixel2024

The upgrade of the Belle II Vertex Detector: Thermomechanical characterization of prototype ladders and system integration

Jerome Baudot
on behalf of VTX collaboration

- → Motivation & Constraints
- → innerVTX: short full silicon ladders
- → outerVTX: long multi-element staves

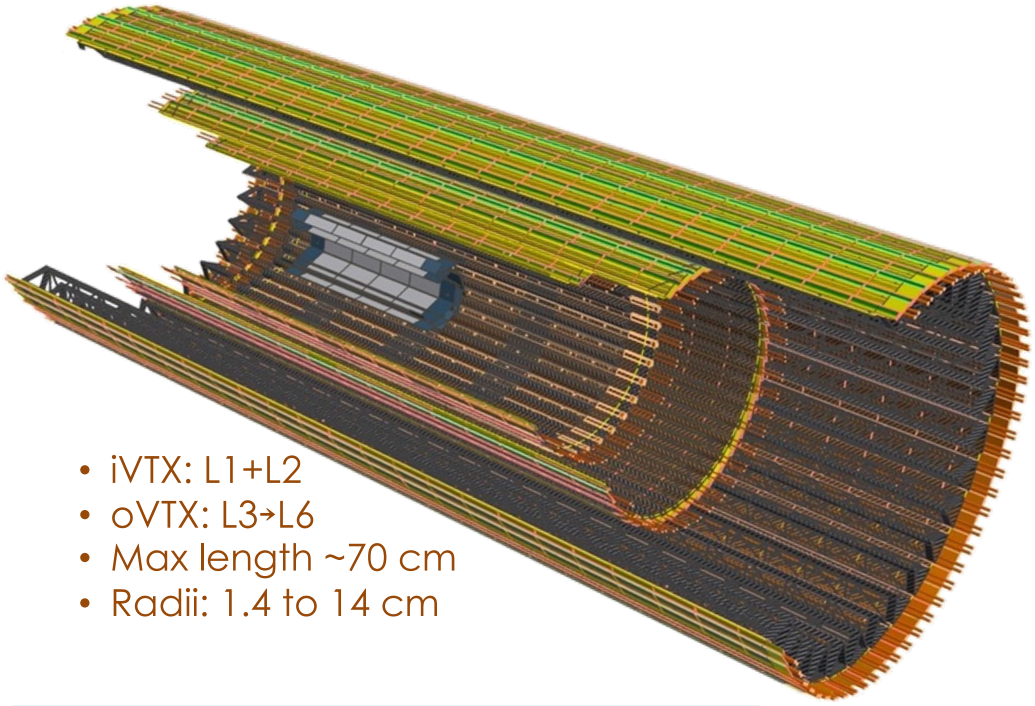
Motivation for an upgraded Belle II vertex detector

- See Alice Gabrielli's talk on Thursday morning
- **Robust tracking & vertexing for any beam-background**
- **Adapt to possible new Interaction region**
- **Possibly increase performance for physics**

VTX →
- **Higher space-time granularity**
- **Lighter material budget**
- **Higher radiation tolerance**
- **Simplified services**

- VTX/OBELIX collaboration: 19 institutes over 8 countries

University of Bergamo
University of Bonn
University of Dortmund
University of Göttingen
Jilin University
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
IGFAE, Santiago de Compostela
IPHC, Strasbourg
University of Tokyo
KEK, Tsukuba
IFIC (CSIC-UV), Valencia
HEPHY, Vienna



- iVTX: L1+L2
- oVTX: L3→L6
- Max length ~70 cm
- Radii: 1.4 to 14 cm

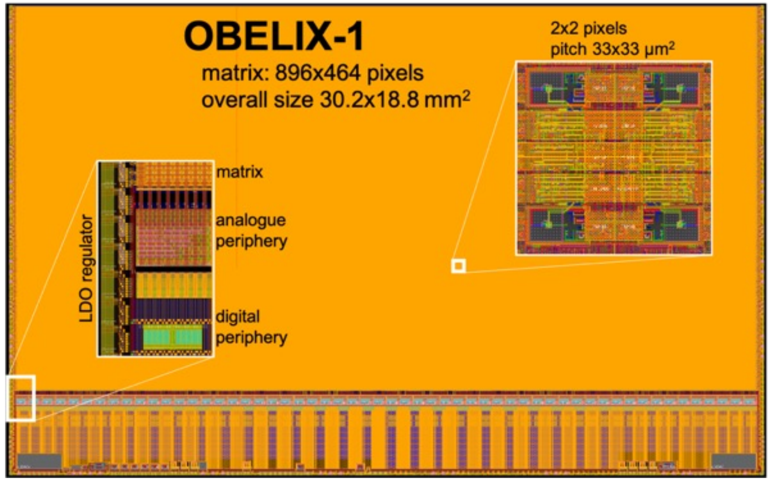
Framework Conceptual Design Report
arXiv:2406.19421 [hep-ex]

Upgrading the current VXD

Requirements

Acceptance r-φ	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	<= Goal for the system { 2 layers x ~0.2 % X_0 + 3-4 layers x ≲0.8 % X_0
Triggered read-out	30 kHz, latency 10 μs	
Average hit rate	up to 120 MHz/cm^2	
Total Ionizing Dose (inner)	1 MGy	=> Constraints to sensor
NIEL fluence (inner)	5×10^{14} n_{eq}/cm^2	

+ Strong interest for
  - Time stamping < 5 ns
  - Inputs to L1 trigger

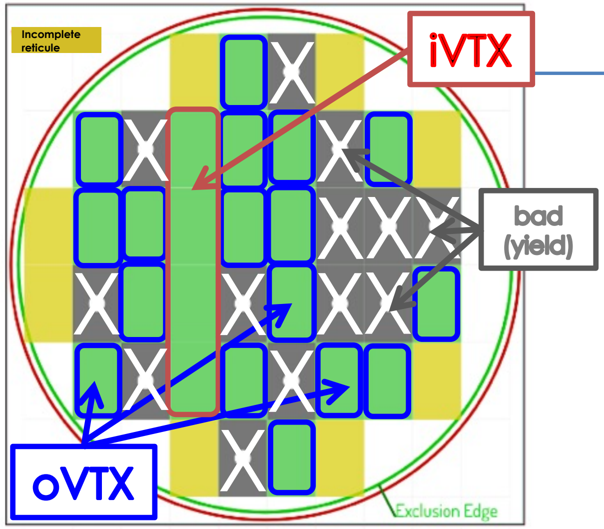


1st Belle II monolithic sensor in development

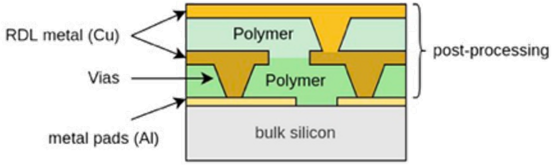
Powering

- On-sensor LDO regulator => facilitate voltage distribution
- Dissipation: 200 to 300 mW/cm^2 depending on hit-rate
  - Including power drop along ladder

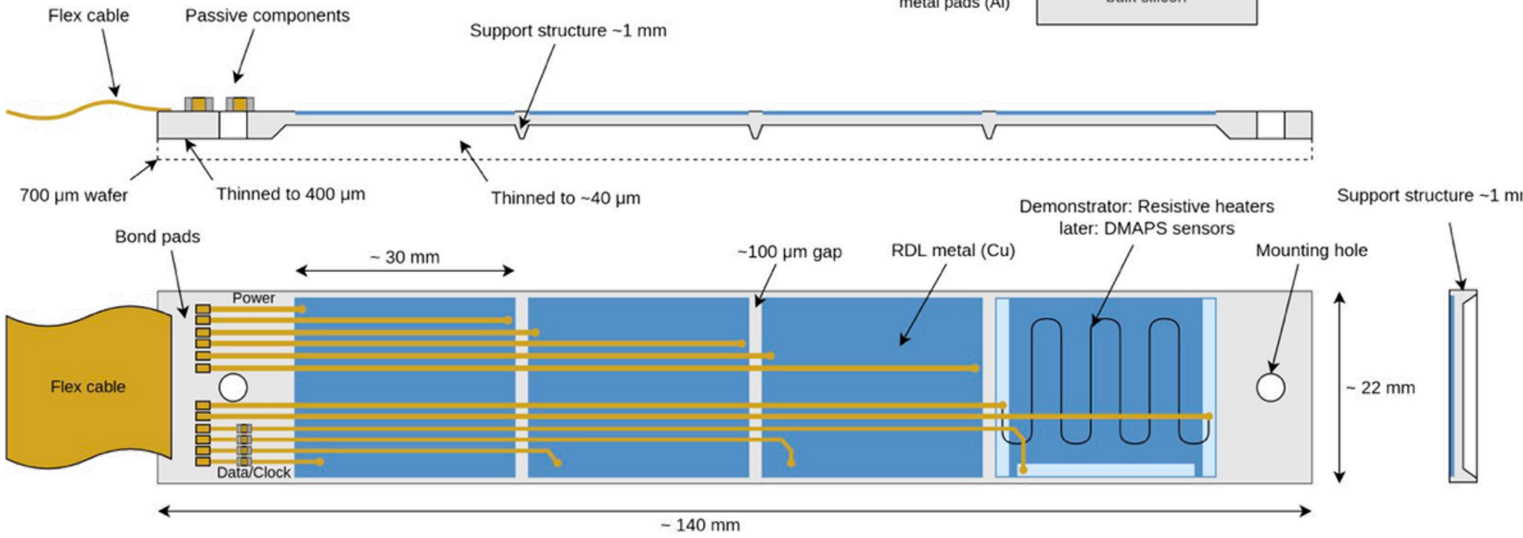
iVTX: inner layer design



- Self-supported all silicon module
  - 4 contiguous sensors diced out of wafer => 12 cm long
    - Insensitive distance from adjacent pixel matrices ~ 500 µm
  - Interconnected with redistribution layer
    - 2 metal layers
    - Single connexion at ladder end
  - Possible heterogenous thinning
    - thick edges versus thin matrix
    - Smallest material budget **~0.1 % X_0**



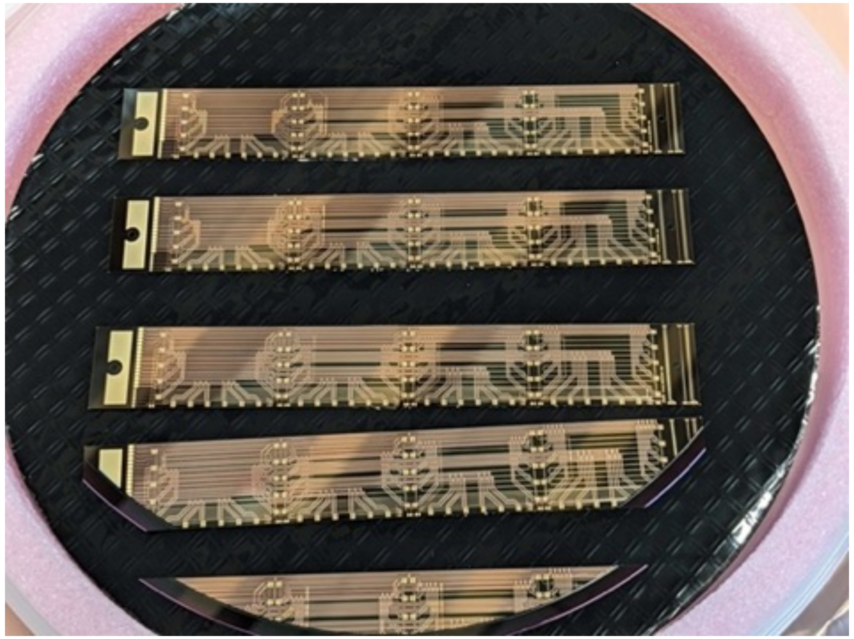
Dummy ladder design:

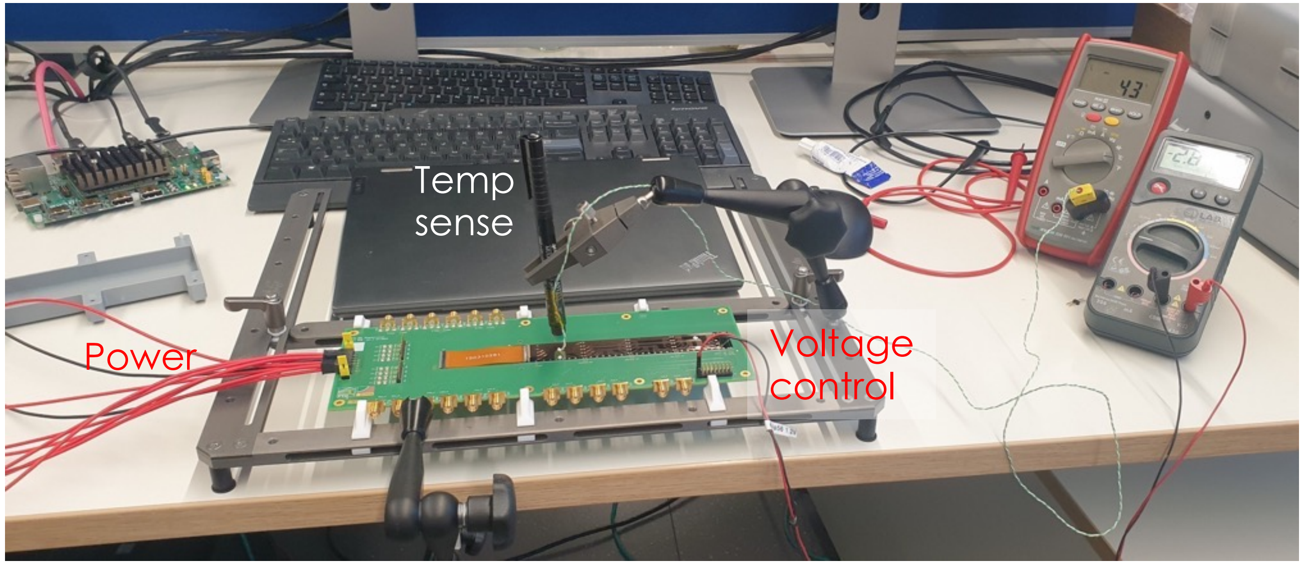


iVTX: Inner layer prototyping

Dummy ladders

- Full silicon wafers with resistive heaters
- RDL processed at IZM-Berlin
- Uniform thickness 700 μm



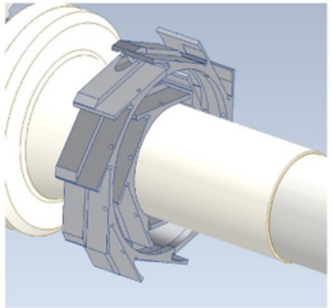


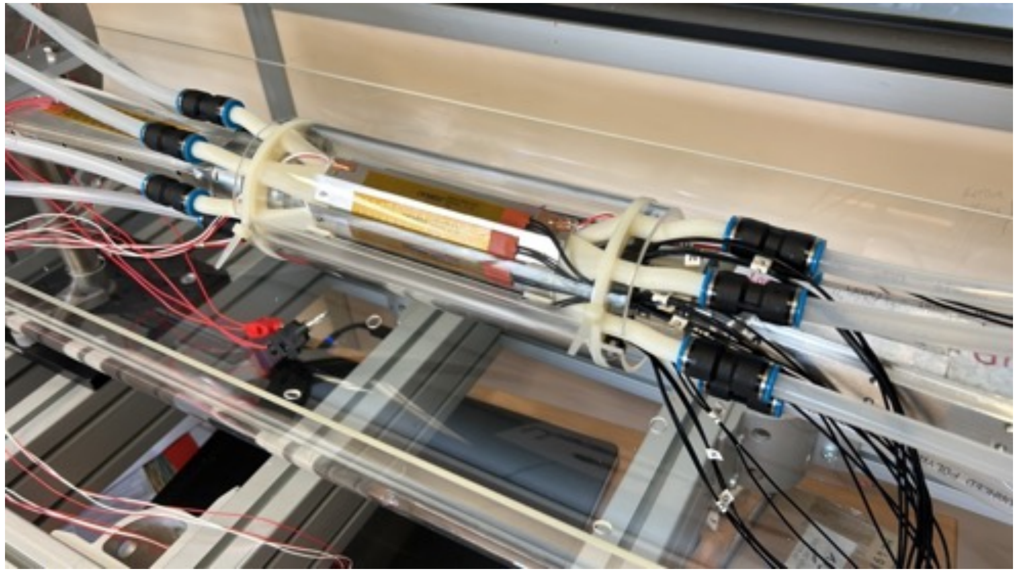
=> Initial tests: Temp ~53˚C for 1.5 W dissipated/sensor

- Mechanical, electrical test on-going …

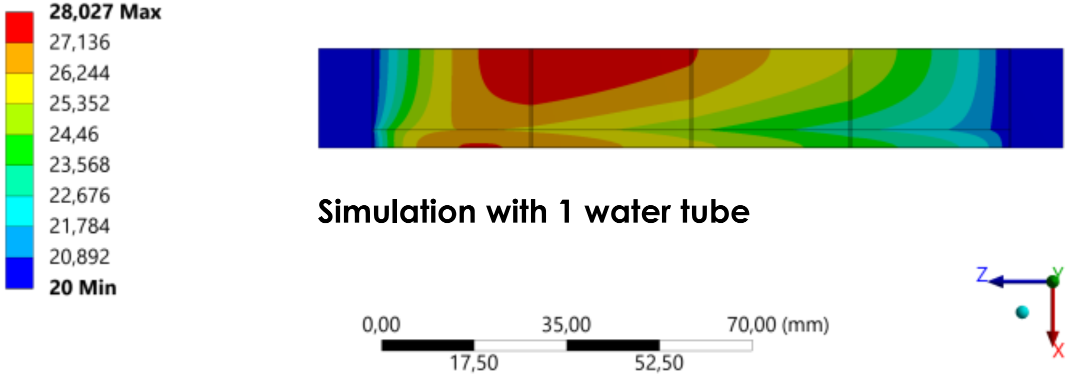
iVTX: options for cooling

- <u>Full air cooling</u>
  - Simulations (1 ladder):
    - Tmax ~50˚C, ΔT(1 sensor)~10 ˚C
  - Wind tunnel on dummy beam-pipe & 2 full-layers
    - Early tests with 70 W load & air speed 10 m/s
      => T ~50˚C
  - Bringing air to the iVTX volume
    - Solutions under study



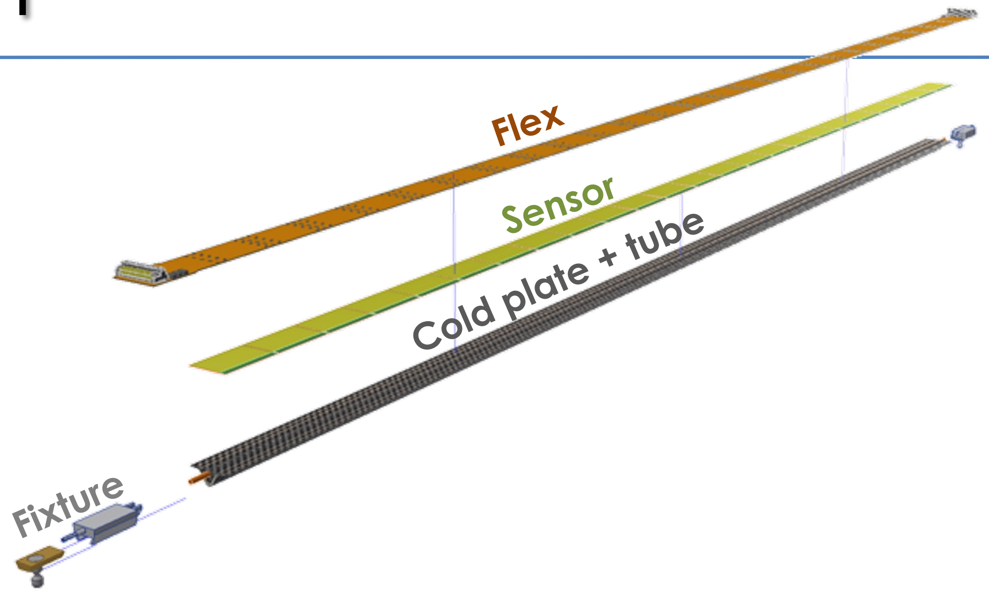


- <u>Cooling alternatives</u>
  - Water tube in contact with sensor periphery
    - Tube ø1.2mm, flow 0.2 µl/min
      => Tmax ~29˚C, ΔT(1 sensor)~5 ˚C
  - Additional flat heat sink for smaller ΔT
  - Material budget cost: 0.2 to 0.3 X_0
    => Physics performance simulation on-going



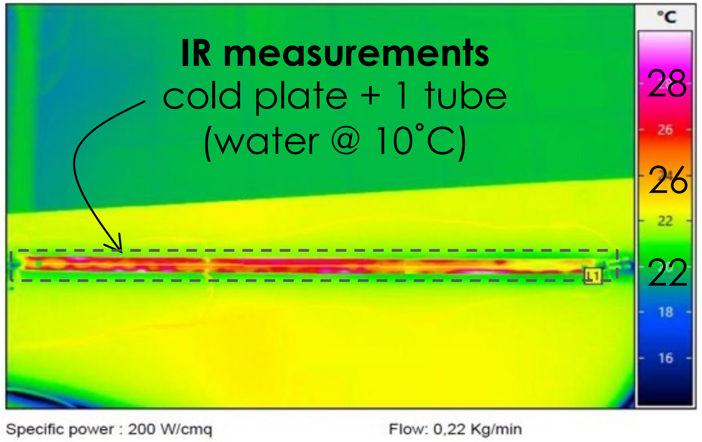
Simulation with 1 water tube

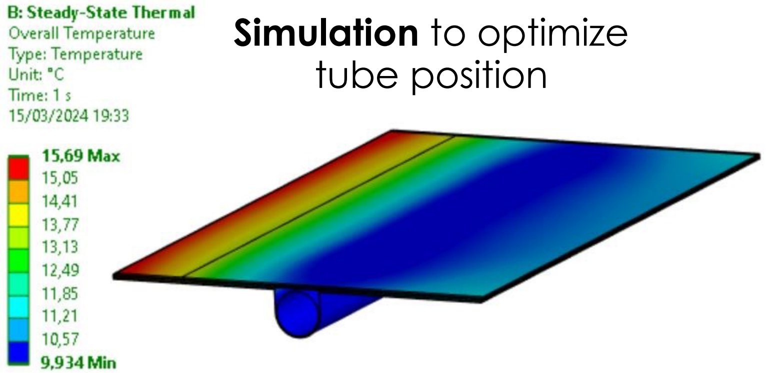
oVTX: outer layer design



- **Recipe for long and light staves**
  (Inherited from ALICE-ITS2)
  - Carbon fiber support frame
  - Cold-plate with 1 coolant tube
  - Long-flex for power & data
    - Longest flex: 1x12 sensors => 1-side output
    - Longest stave: 2x12 sensors => 2-side outputs

- **Cooling studies**
  - Early prototype tested with 200 mW/cm^2
  => Tmax < 30˚C, ΔT(1 sensor)~4 ˚C





Simulation to optimize tube position

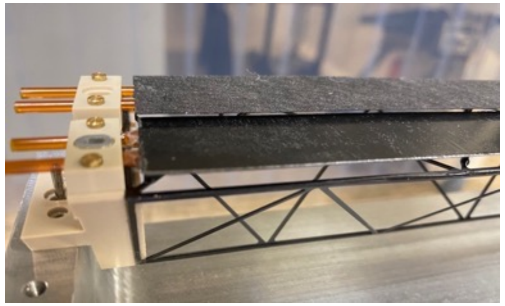
- **Flex development**
  - 4 to 6 aluminium layers
  - Investigating CERN workshop & Japanese Co.

oVTX: outer layer design

New Omega shape support

- Carbon fiber skin with rohacell core
  - way more compact / truss structure
  - Allow 3 to 4 layers at ~large radii
    => excellent for track-seeding & K_S^0

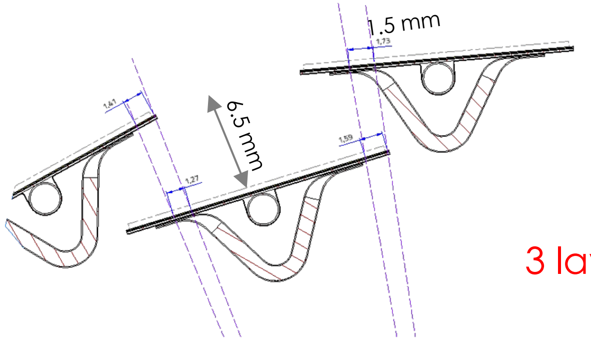
=> material budget ~0.45% X_0 from L3 to L5

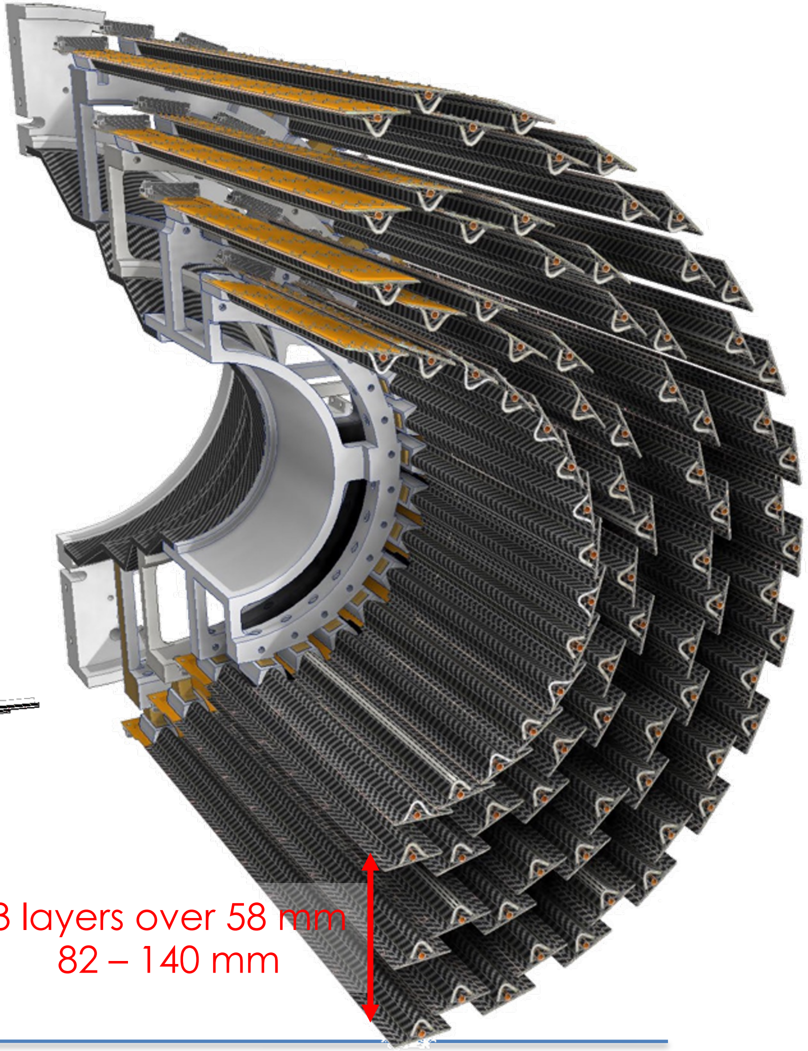


Truss structure + cold plate

Bending over 70 cm?

- Simulations: sagitta < 100 µm
- Measurement with prototype on-going



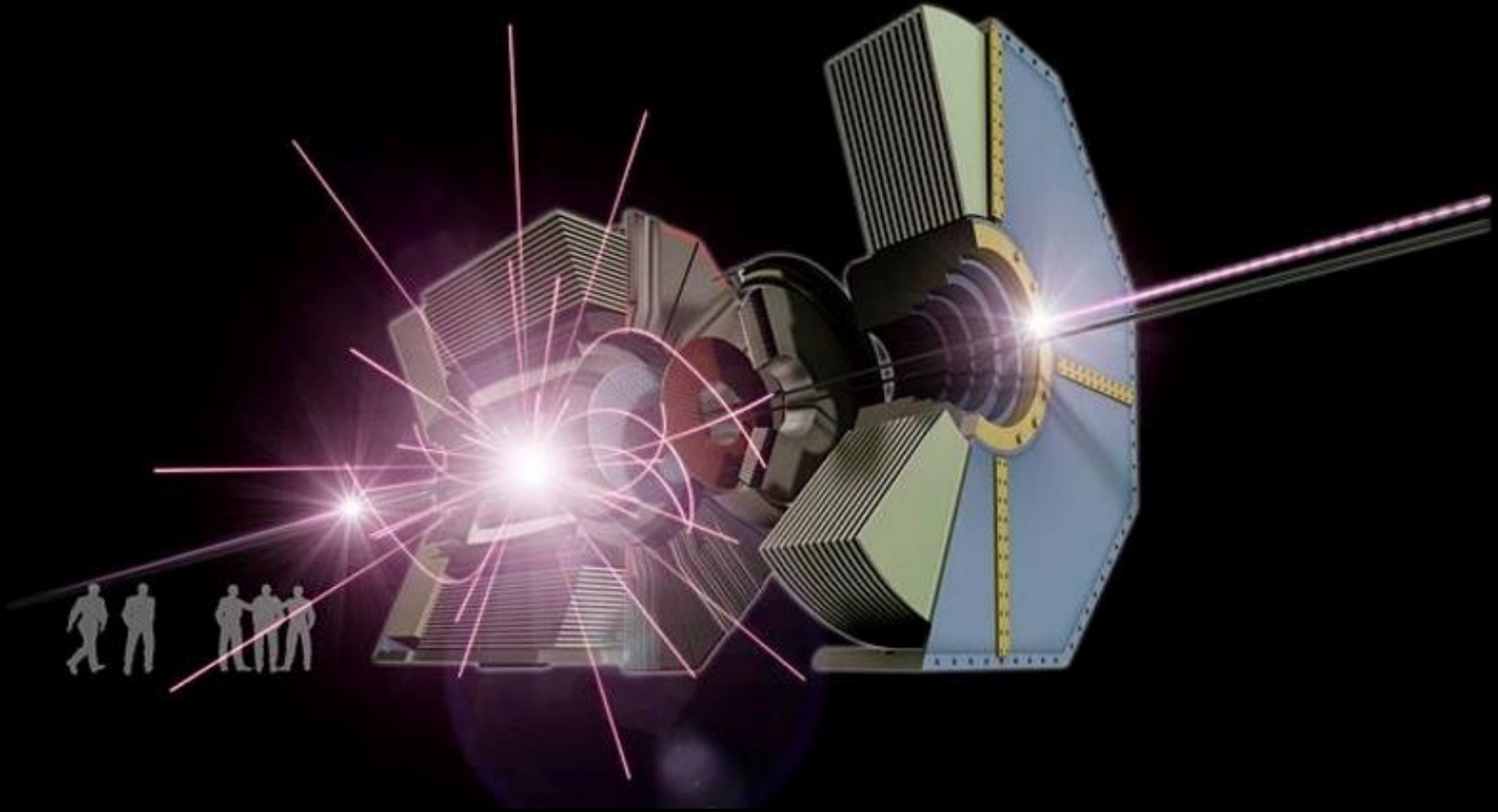


Conclusion

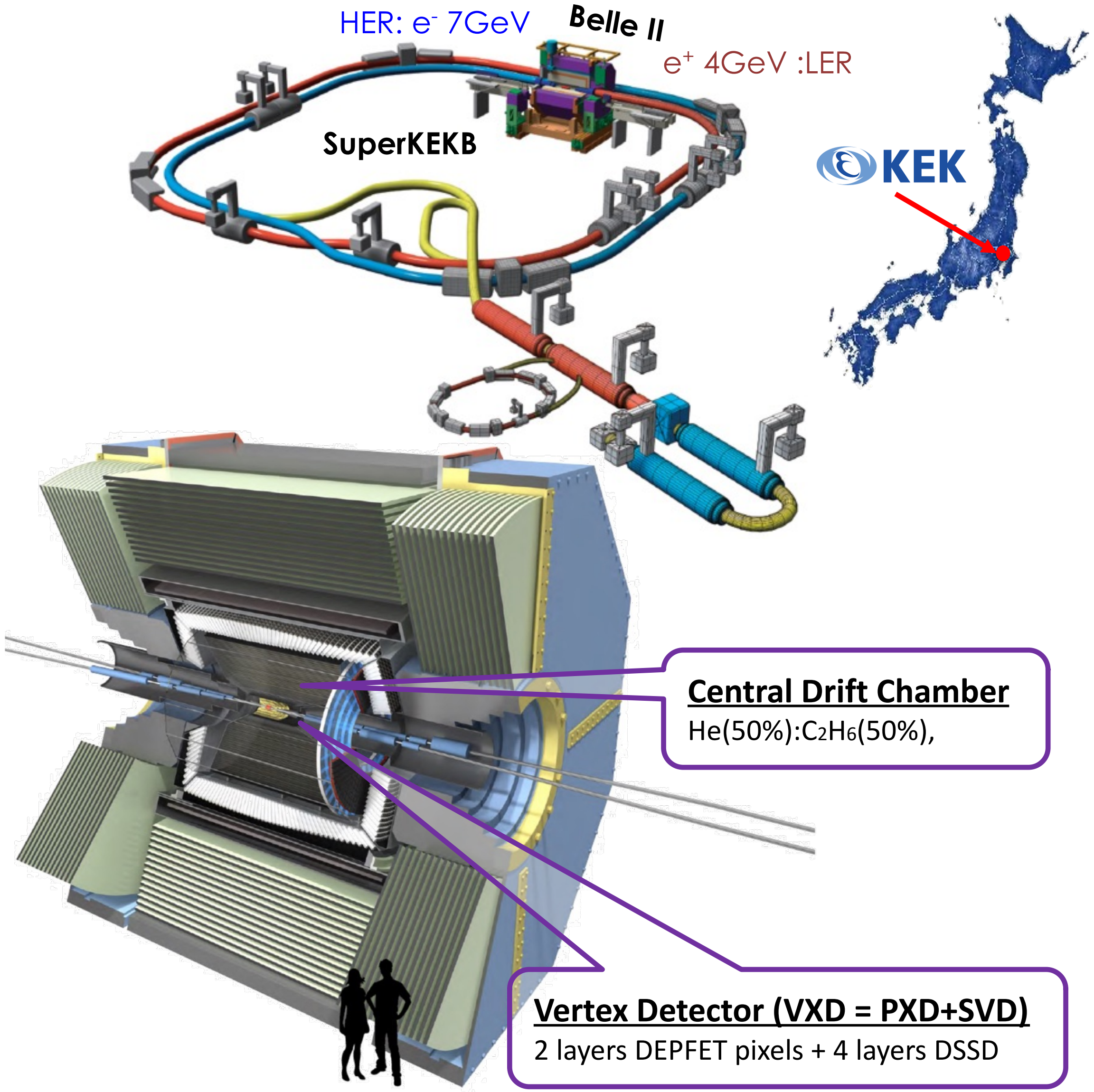
- Upgrade Belle II vertex detector
  - **Challenging requirements:**
    high hit rate / low material budget / low inner radius / 5-6 layers over small radial range
  - **Geometrical constraints: 5 to 6 layers within ~13 cm radius range**
  - **Operational conditions: Room temperature & Radiation tolerance**

- Status of R&D
  - **Early prototypes for iVTX & oVTX => measurements of key quantities**
  - **Optimising solutions for: cooling iVTX, supporting oVTX**
  - **Global integration concept starting…**

Thank you for your attention…



Belle II @ SuperKEKB



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

- SuperKEKB: e+e- collider at √s = $M_{Y(4S)}$
  - 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

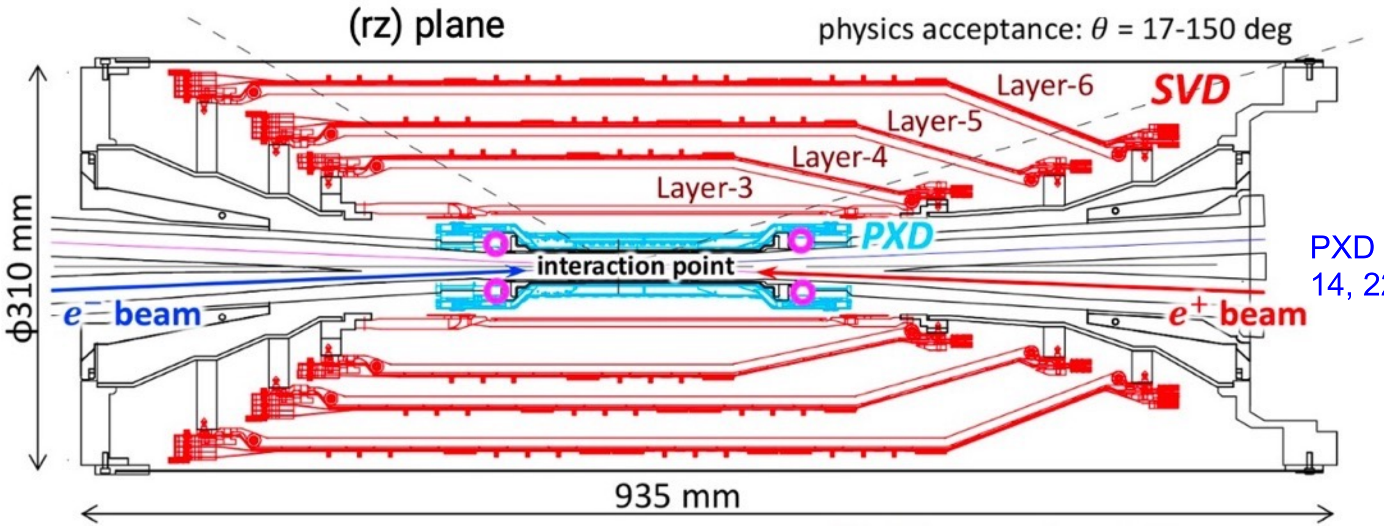
- 2 inner layers: PXD

See F. Becherer's talk on Monday morning

  - 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, CO_2 cooling
    - material budget: 0.75 % X_0 / layer
  - Triggered read-out, latency limited to 5 µs
  - Occupancy limit 6%

See L. Corona's talk at ICHEP 2024



PXD radii
14, 22 mm

VTX geometries

- Established layout

		L1	L2	L3	L4	L5
Radius	mm	14.1	22.1	39.1 or 69.0	89.5	140.0
# ladders		6	10	17 or 30	40	31
# sensors/ladder		4	4	7 or 12	16	2x24
Material budget	% X_O	~0.2	~0.2	0.3 or 0.4	0.5	0.8

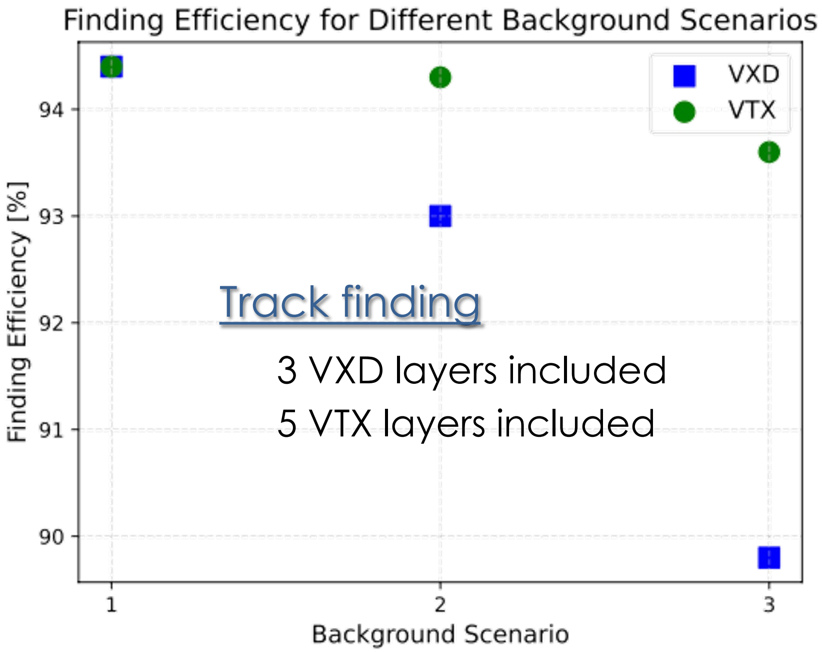
- Investigated layout

		L1	L2	(L3)	L4	L5	L6
Average radius	mm	14.1	22.1	39.1 or 69.0	85.8	109.3	136.8
# ladders		6	10	17 or 30	36	48	60
# sensors/ladder		4	4	7 or 12	16	20	24
Material budget	% X_O	~0.2	~0.2	~0.5	~0.5	~0.5	~0.5

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

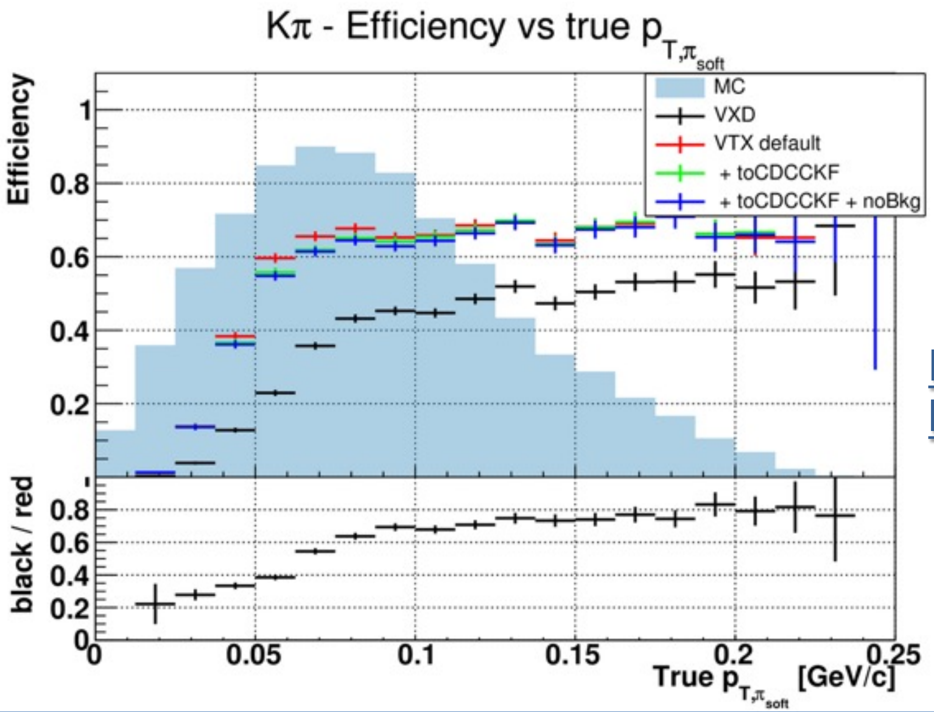


Track finding

3 VXD layers included
5 VTX layers included

Resolutions studies

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



Improvement at low momentum

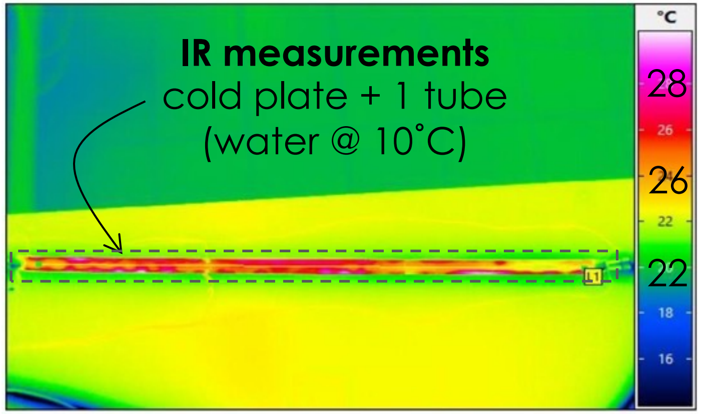
Soft π reconstruction in $B^0 \to D^{*-}\mu^+\upsilon_\mu$

↳ $\overline{D^0}\pi^-$

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

=> Geometry optimisation on-going
- 6 layers

Thermal test of long oVTX stave



Specific power : 200 W/cmq   Flow: 0,22 Kg/min

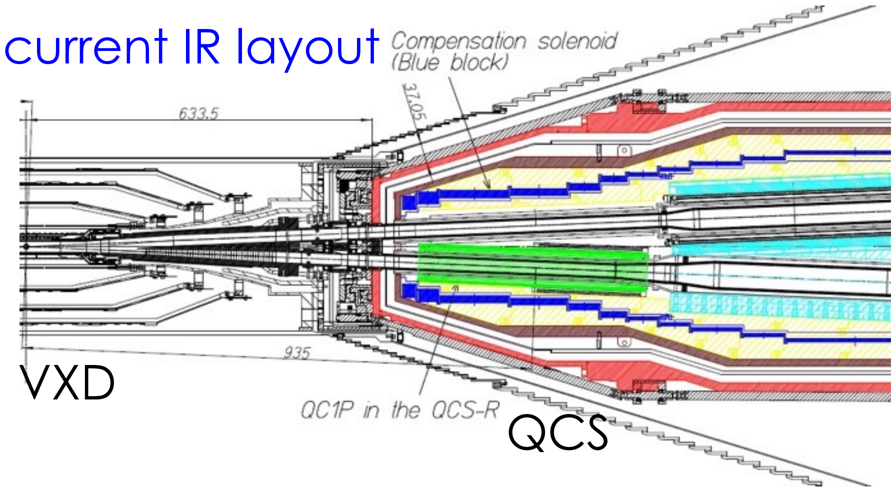
Specific power : 200 W/cmq   Flow: 0,22 Kg/min

ID	Avg	Min	Max	Span
L1	24,55	21,79	26,43	4,64

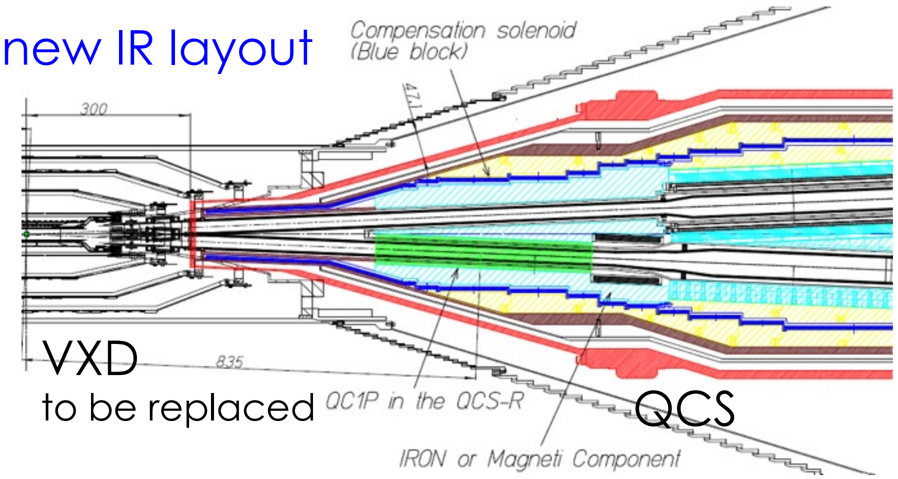
Interaction region for higher lumi

- Current machine
  - World luminosity record 4.7×10^{34} $cm^{-2}.s^{-1}$ (2022)
  - Expected max lumi ~2×10^{35} $cm^{-2}.s^{-1}$
    - Main limit from dynamic aperture at Interaction Region (IR)
- Potential road toward 6×10^{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**

current IR layout



Potential new IR layout

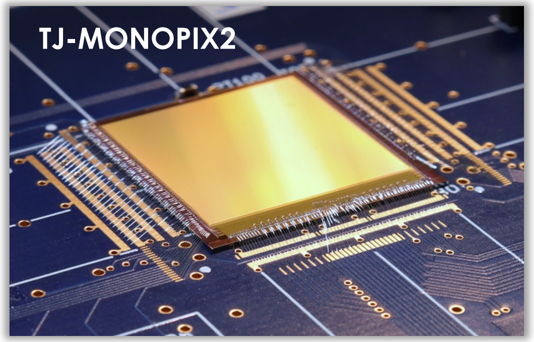


VTX sensor requirements & strategy

	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

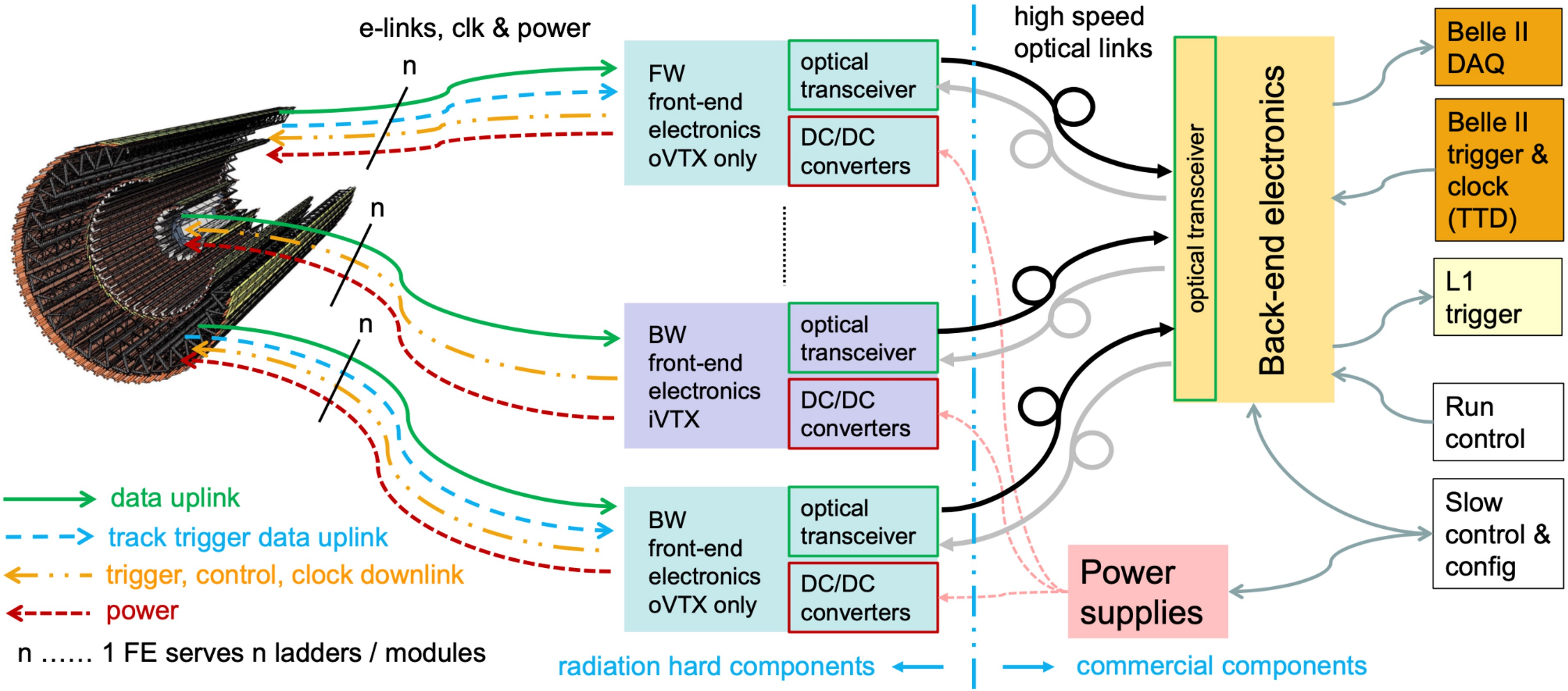
- TJ 180 nm CIS process
- Bonn, CERN, CPPM, CEA-IRFU
  DOI: 10.1016/j.nima.2020.164403
- Modified process for depletion => radiation tolerance
- Column-drain read-out inherited from ATLAS FE-I3



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

DAQ system concept



Belle II detector

Upgraded or new / Belle