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The Belle II Tracker Upgrade

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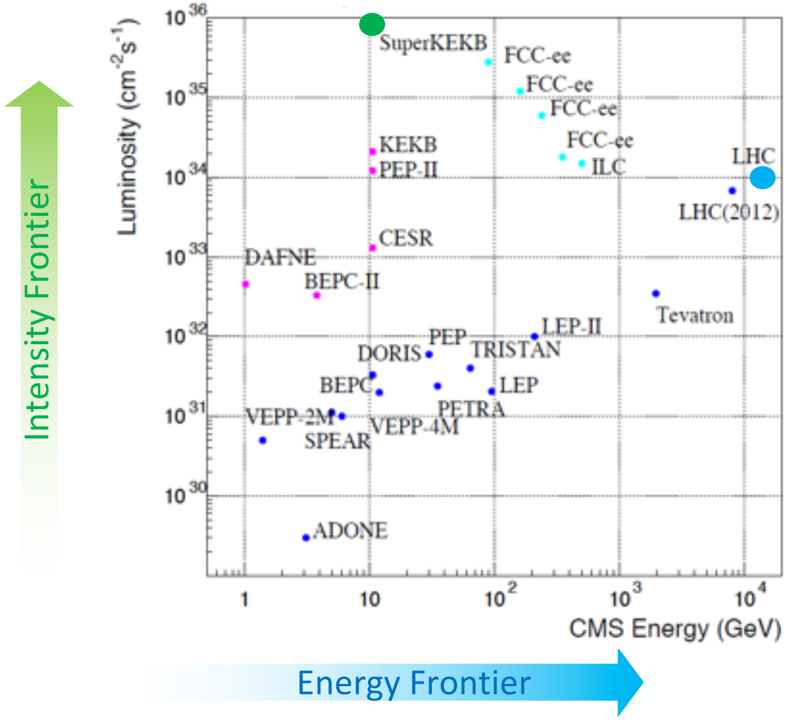
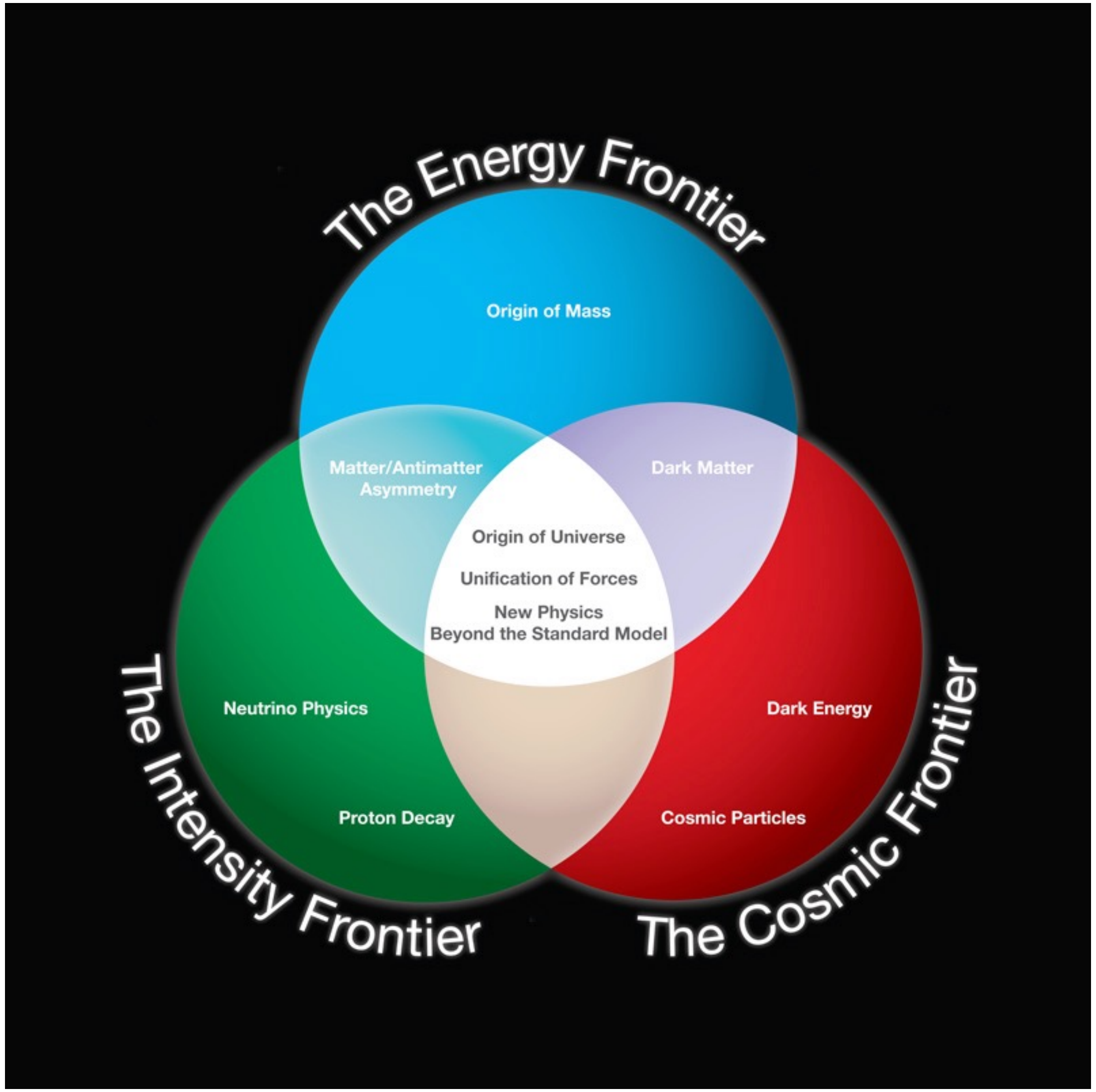
The Three Frontiers



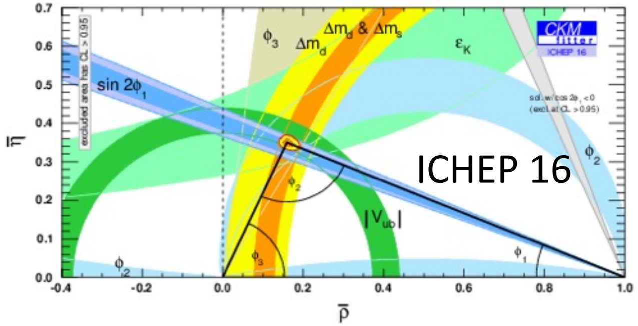
- The **Intensity Frontier**: Search for rare new phenomena using *medium-energy high-luminosity* machines

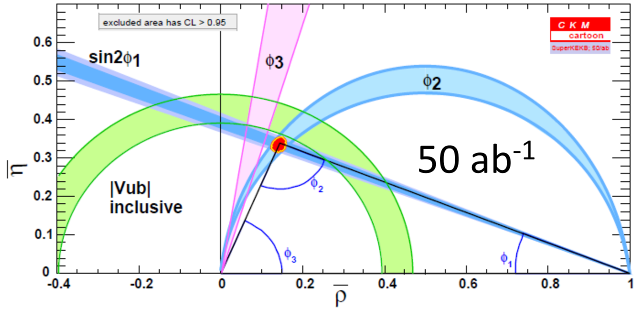


Super Flavor Factory

- Search for physics phenomena beyond SM in B, D and τ decays through precision measurements of the CKM sector and studies of rare or forbidden processes
- Many potential NP sources:
  - Flavor changing neutral currents
  - Lepton flavor violating decays
  - B → τ tree level new physics
  - New sources of CPV

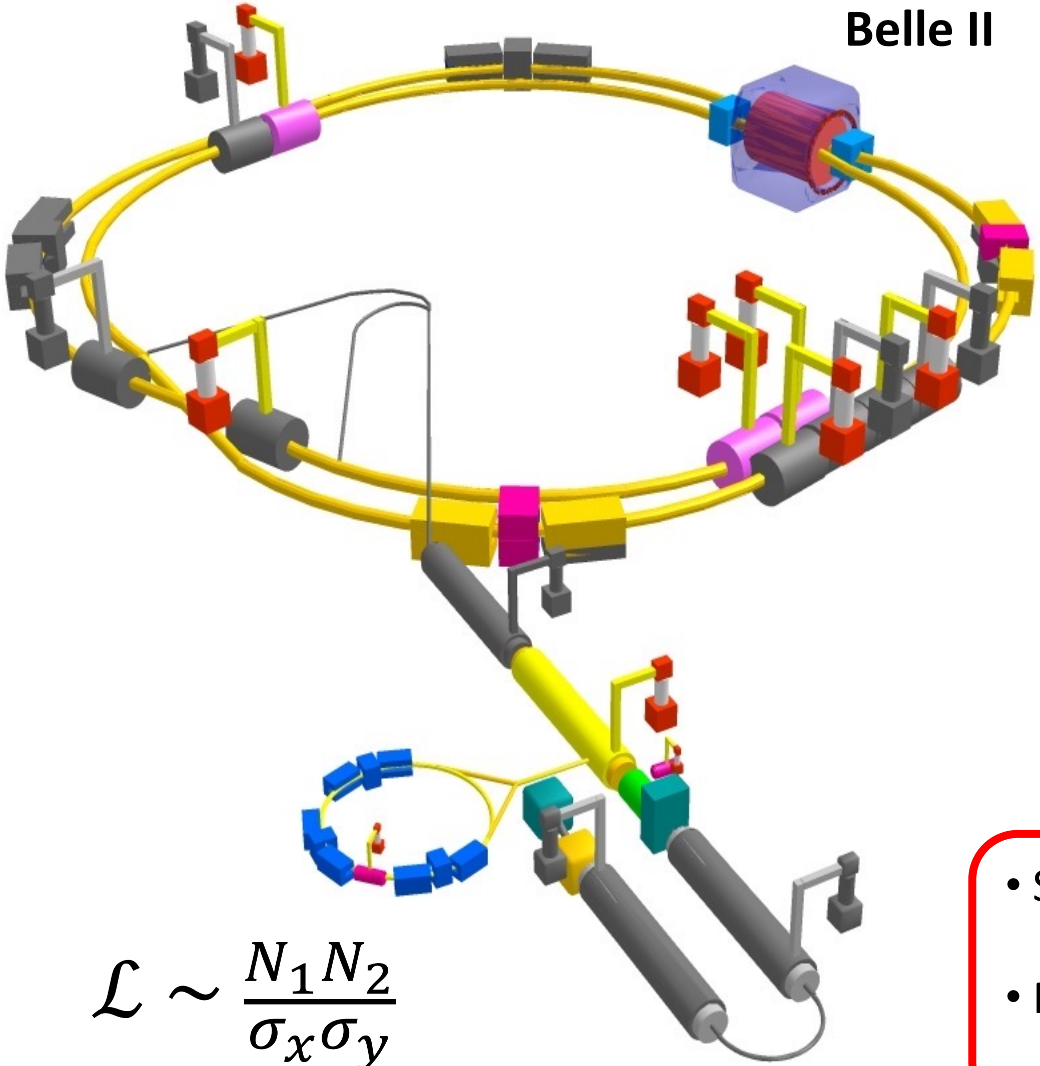
Observable	SM theory	Current measurement (early 2013)	Belle II * ($50\,ab^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.018
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.011
α from $B \to \pi\pi, \rho\rho$		$\pm 5.4°$	$\pm 1°$
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.035
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.07
$A_{CP}(B \to X_{s+d}\gamma)$	< 0.005	0.06 ± 0.06	± 0.005
A^d_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 3\%$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\gg 5\sigma$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 6\%$
$\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 30\%$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$ $(1 < q^2 < 6\,GeV^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{FB}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,GeV^2)$	9% → 2%	11%	2.1%



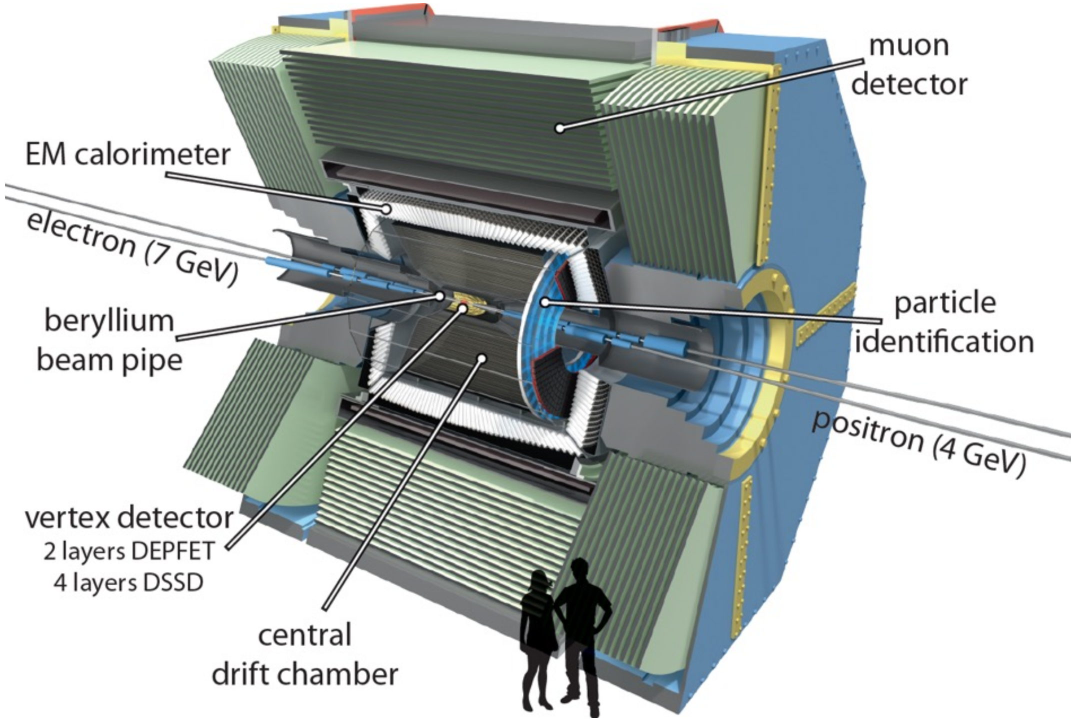


1. High luminosity accelerator
   SuperKEKB
2. High-resolution and large-coverage detector
   Belle II

SuperKEKB and the Belle II Experiment



Belle II



$$\mathcal{L} \sim \frac{N_1 N_2}{\sigma_x \sigma_y}$$

- SuperKEKB: Asymmetric energy e^+e^- collider
  $E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV
- Peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm^{-2} s^{-1} (x40 than KEKB)
  Beam size reduction. Higher current (x2 higher).

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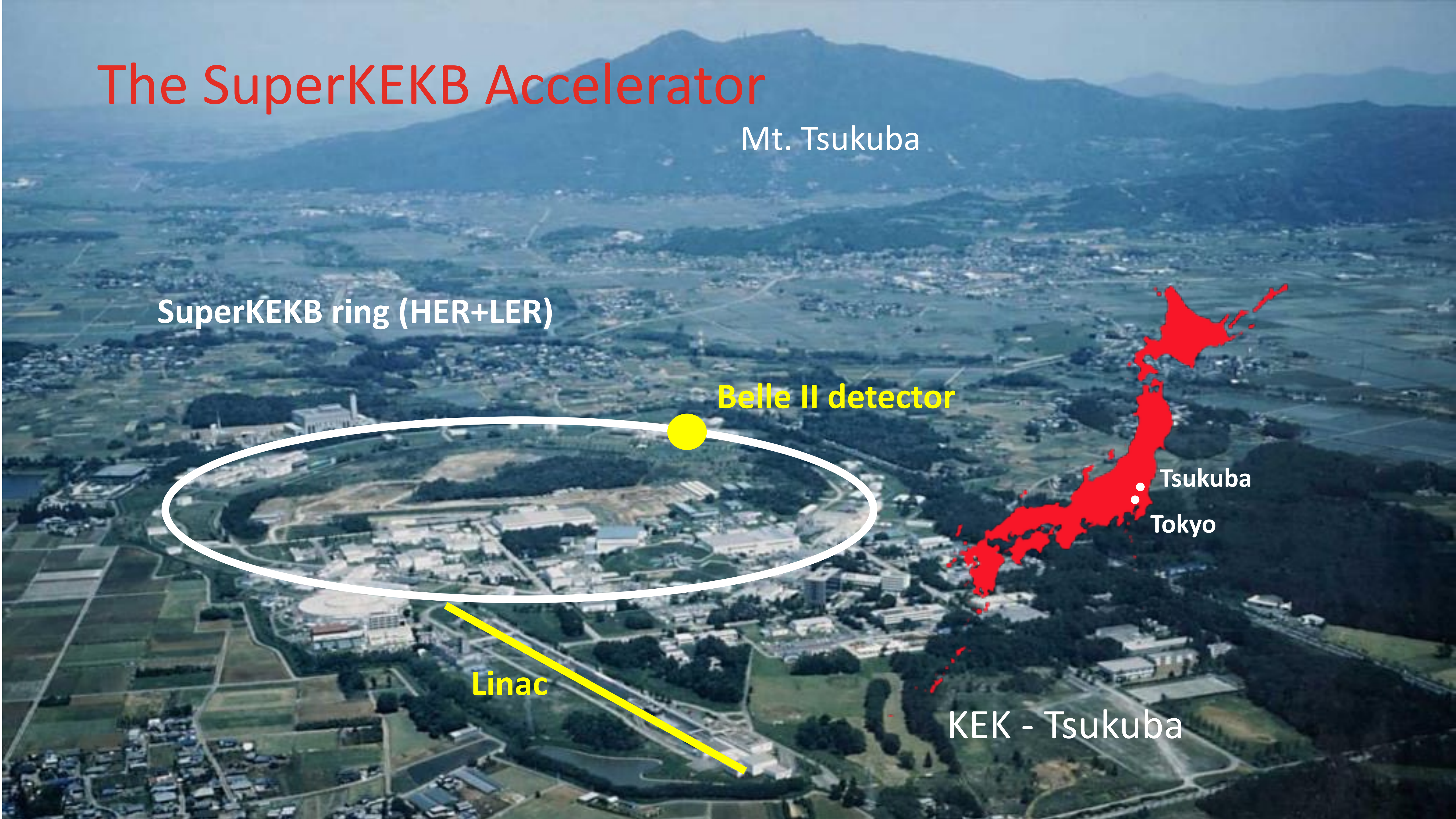
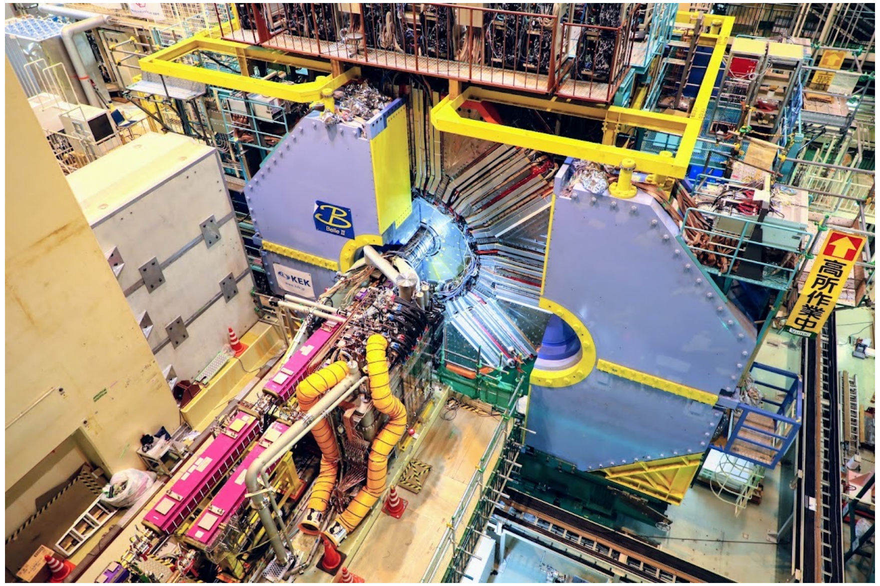
The SuperKEKB Accelerator

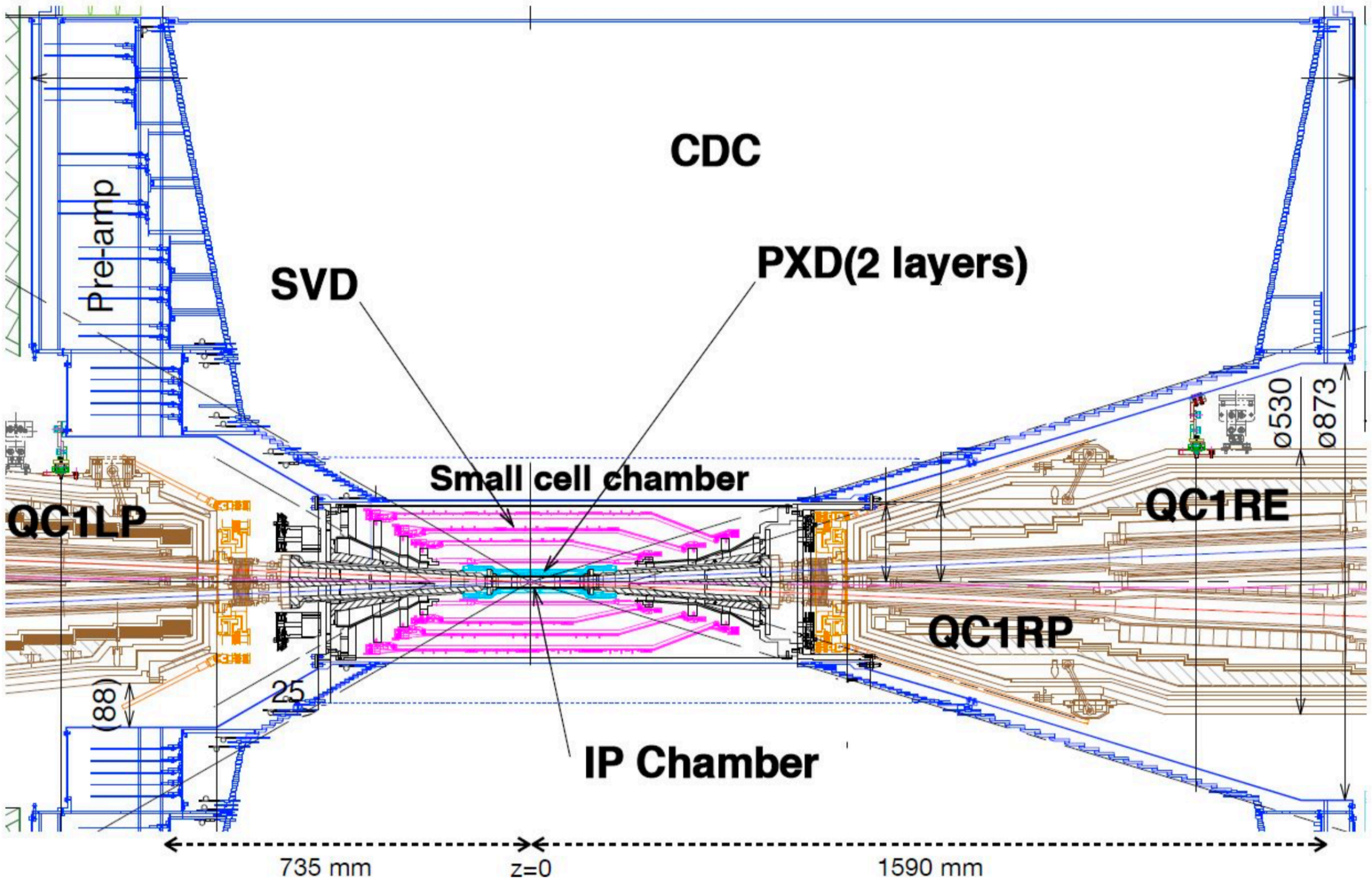


The Belle II Collaboration

- 27 countries
- 132 institutions
- 1175 members



Belle II Tracking System

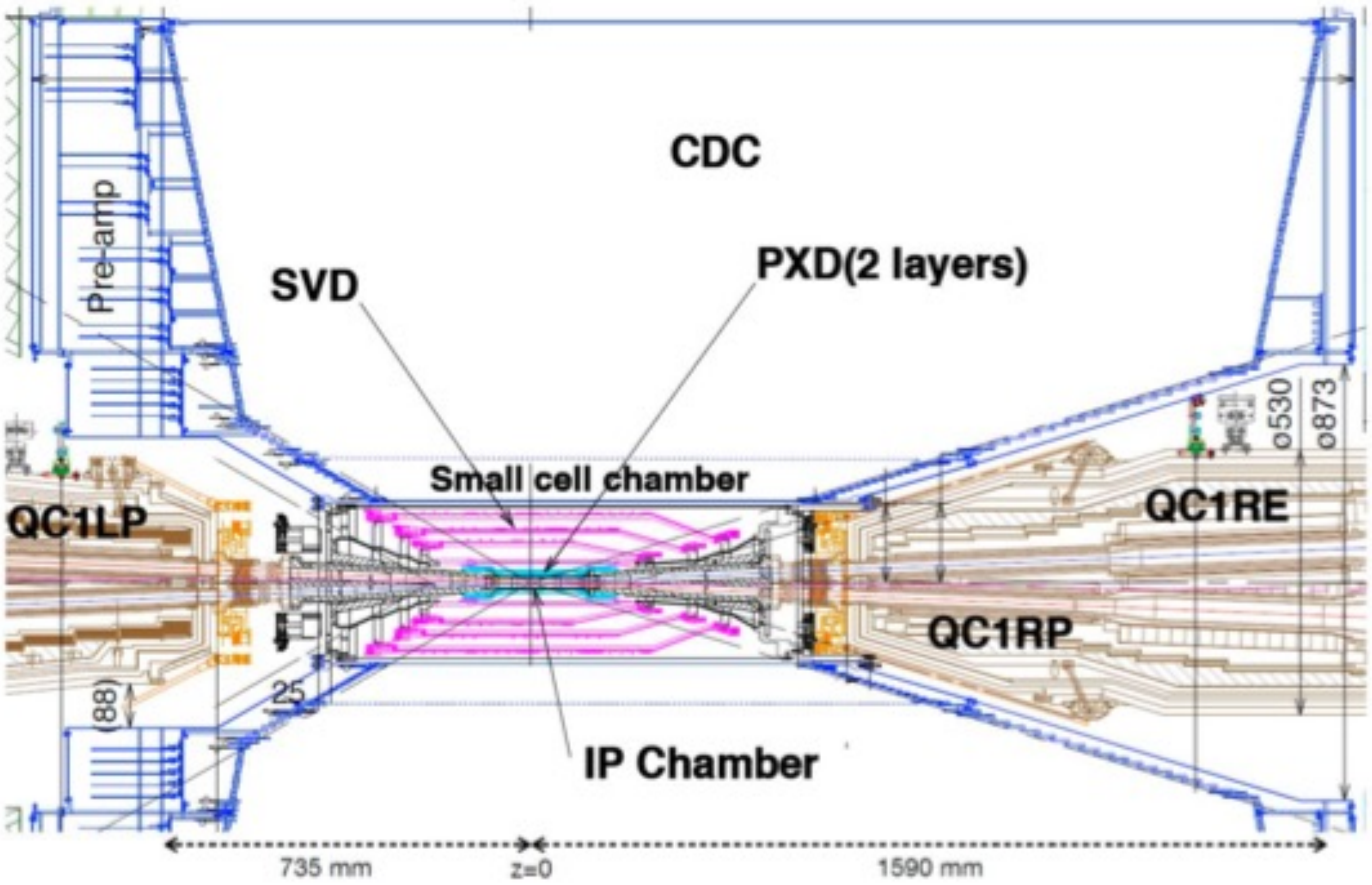


Three tracking sub-systems:

- Pixel Detector (PXD)
- Silicon Vertex Detector (SVD)
- Central Drift Chamber (CDC)

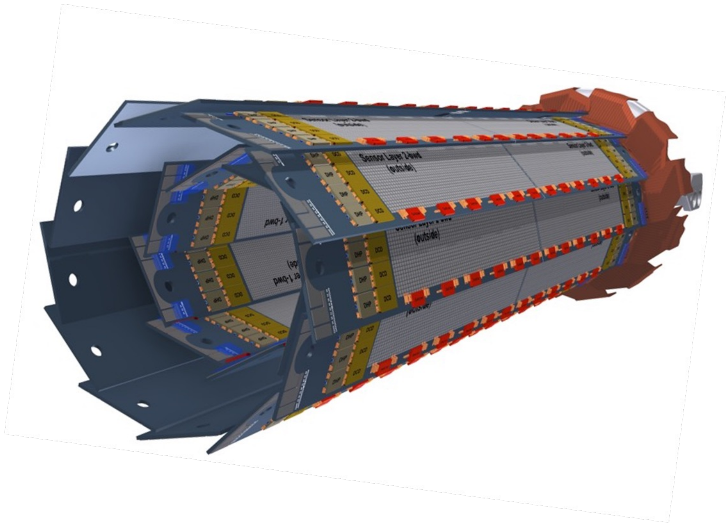
1.5 T solenoid and final focusing magnets inside detector volume

Belle II Tracking System

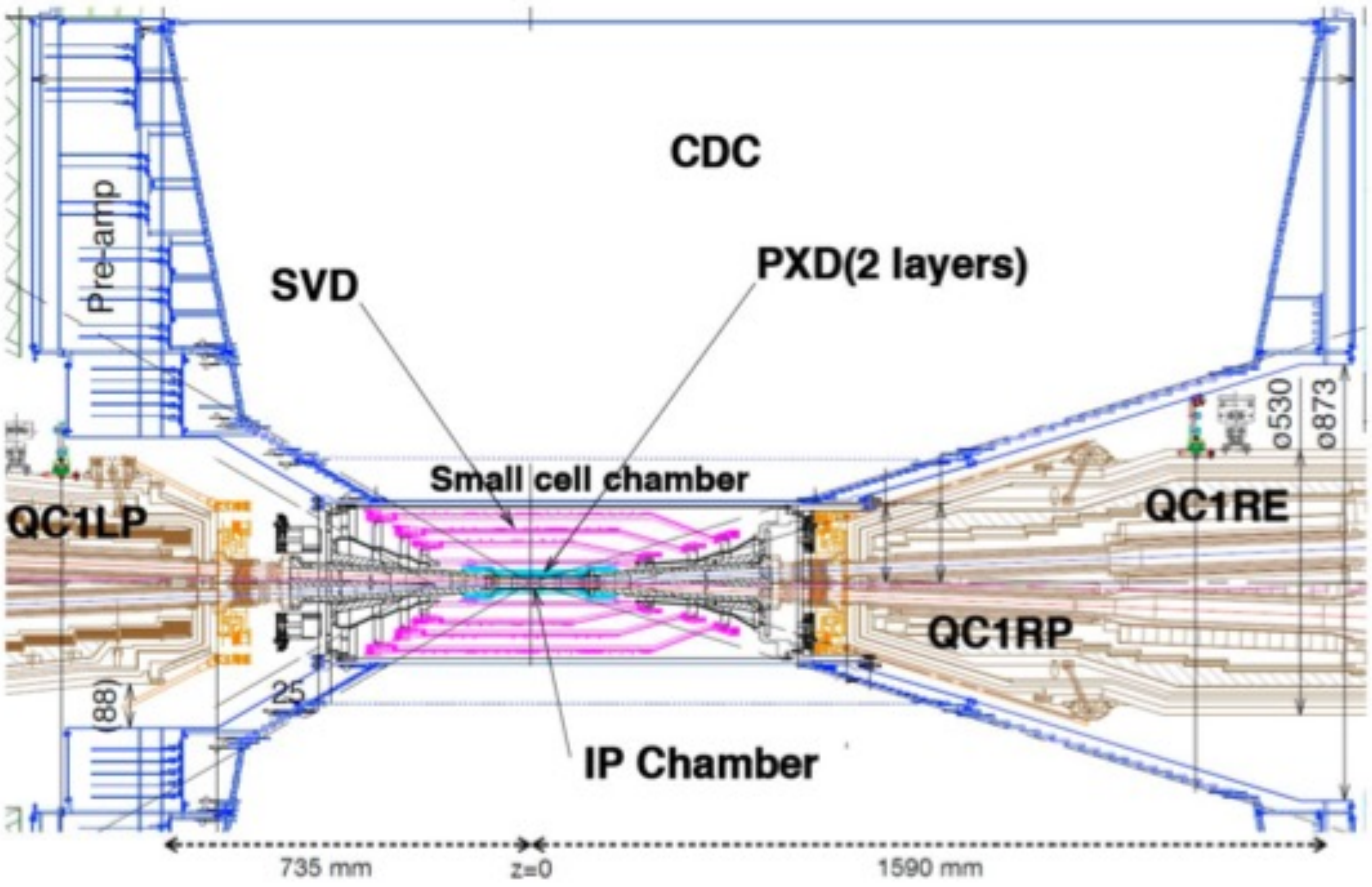


- PXD

  2 layers of DEPFET pixels
  r = 1.4 cm, 2.2 cm
  L = 12 cm
  ~ 0.027 m^2

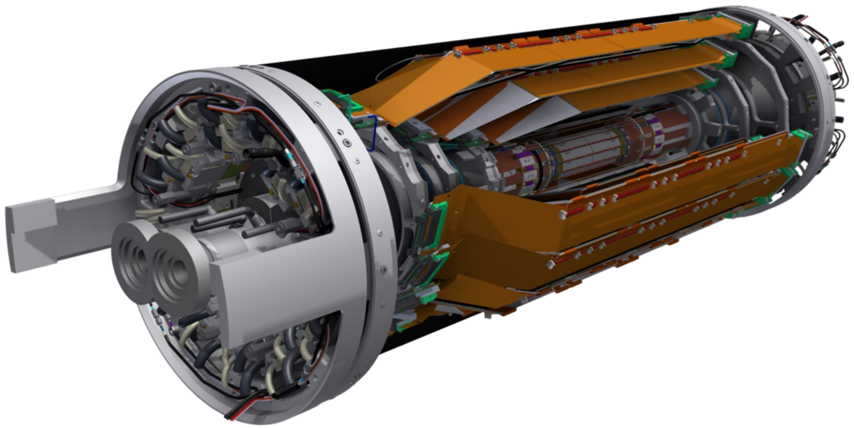


Belle II Tracking System

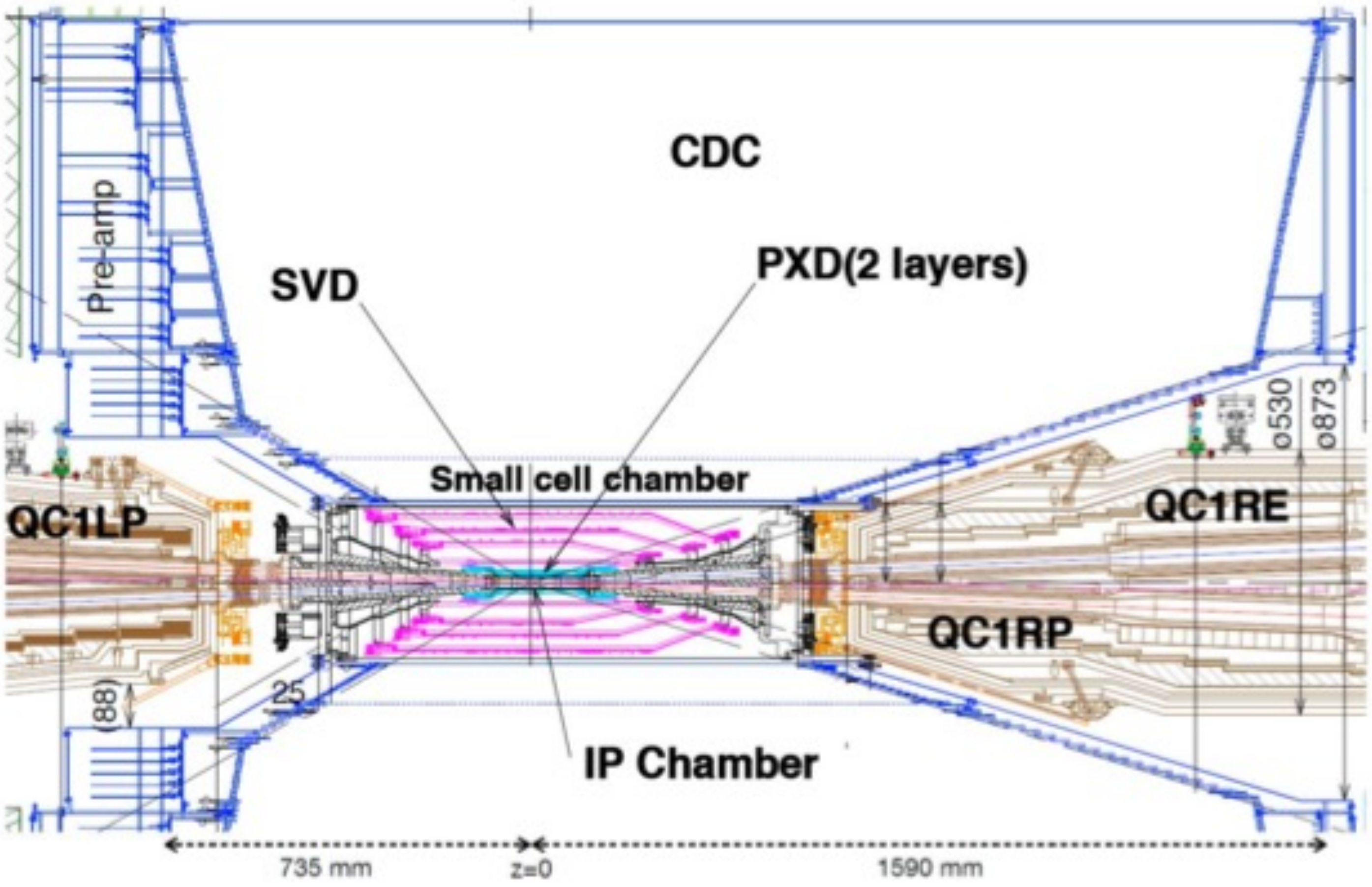


- SVD

  4 layers of DSSD (r = 39 - 135 mm)
  L = 60 cm
  $\sim$ 1 m^2

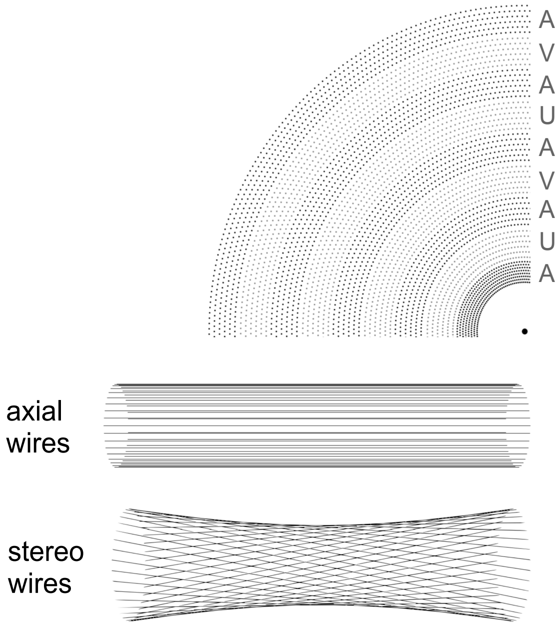


Belle II Tracking System



- CDC

  56 layers (r = 168 – 1111 mm)
  Arranged into superlayers of axial (A) and stereo (U, V) wires

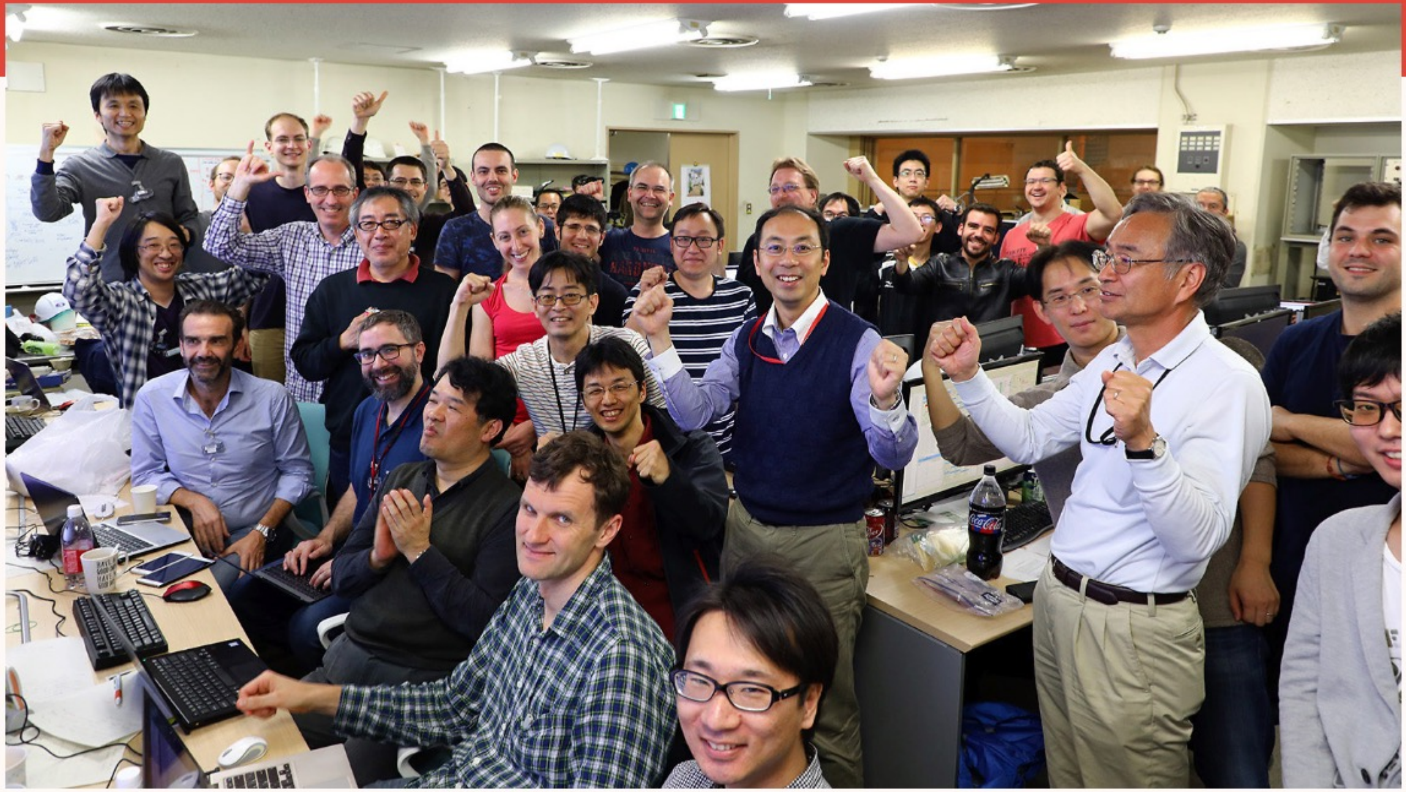


First Collisions (26 April 2018)

First collisions at Belle II

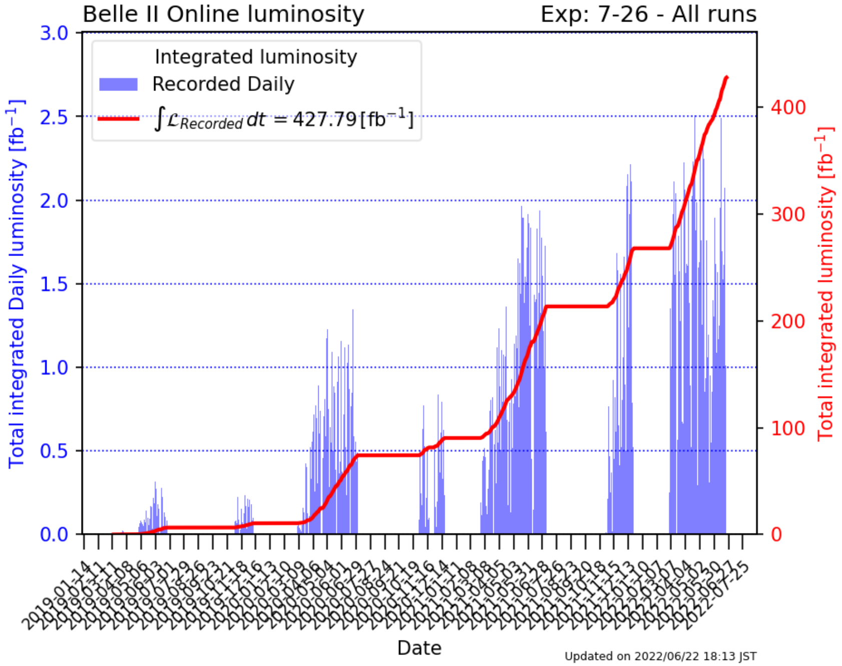
04/25/18 | By Sarah Lawhun

The Japan-based experiment is one step closer to answering mystifying questions about antimatter.

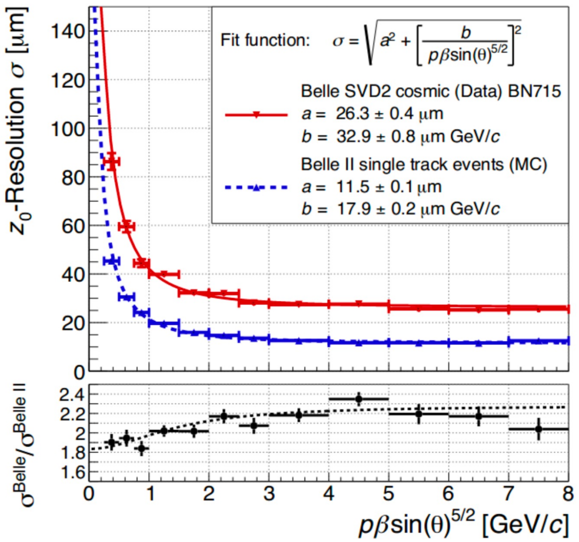


KEK/Belle II

Current Status – Performance Benchmarks



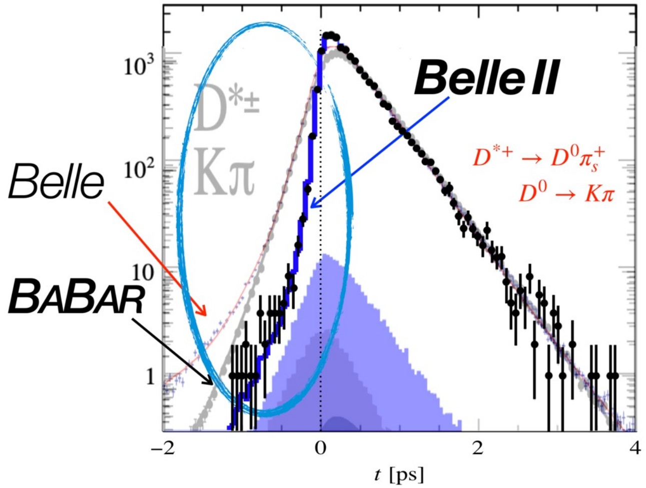
- L_{peak} = 4.7x10^{34} cm^{-2}s^{-1} (x2 KEKB)
- $L_{integrated}$ = 430 fb^{-1} (~BaBar)
- Data taking efficiency >90%
- Precision measurements



Excellent tracking performance (2x better single vertex resolution wrt Belle)

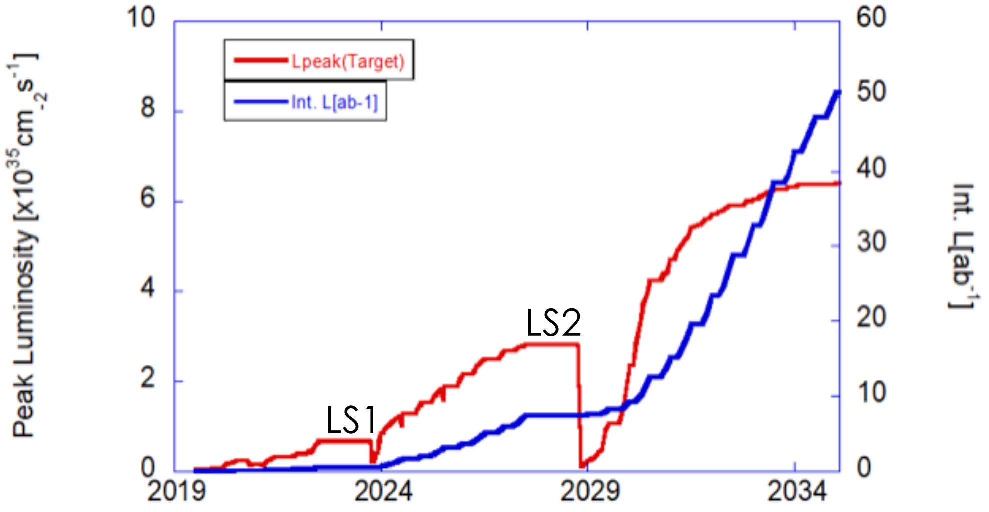
Decay time resolution x2 better than Belle and BaBar

World's best D lifetime measurement with only 72 fb^{-1}



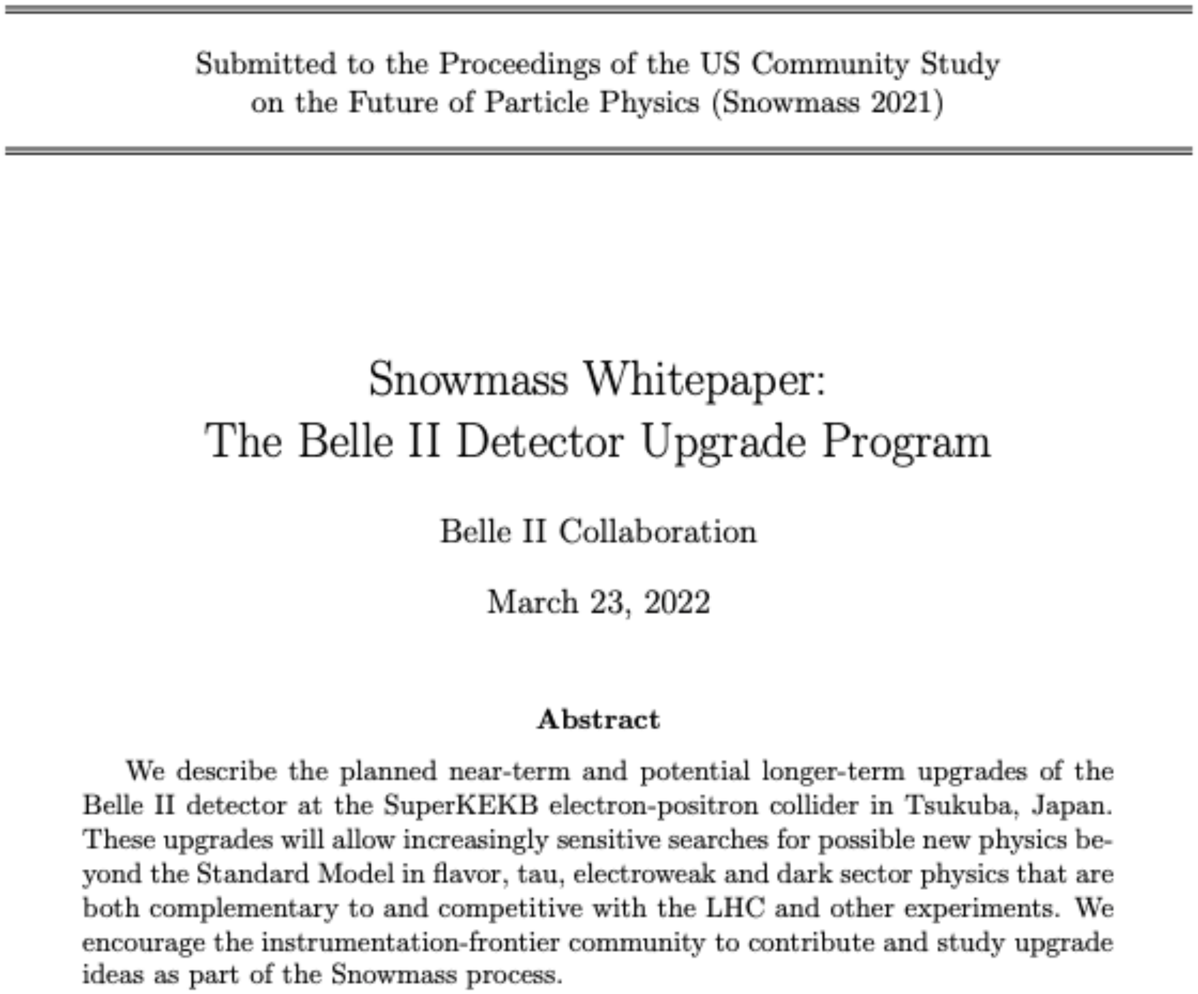
Important test of Belle II tracking performance
→ VXD reconstruction, track finding and vertex fitting

Belle II Upgrade Program



LS1: Actual detector consolidation
LS2: IR and detector upgrades

→ Currently: CDR preparation



Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Snowmass Whitepaper: The Belle II Detector Upgrade Program

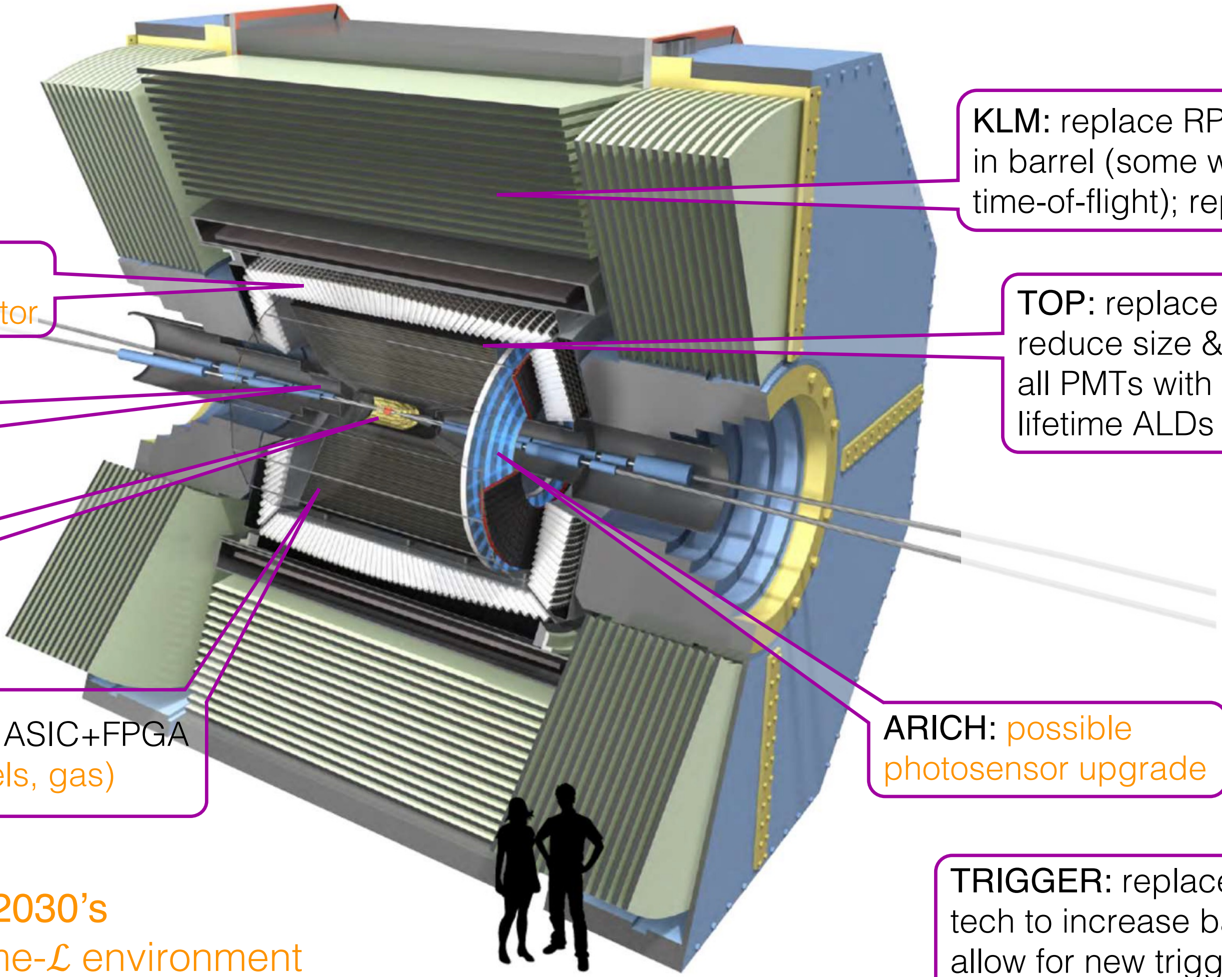
Belle II Collaboration

March 23, 2022

Abstract

We describe the planned near-term and potential longer-term upgrades of the Belle II detector at the SuperKEKB electron-positron collider in Tsukuba, Japan. These upgrades will allow increasingly sensitive searches for possible new physics beyond the Standard Model in flavor, tau, electroweak and dark sector physics that are both complementary to and competitive with the LHC and other experiments. We encourage the instrumentation-frontier community to contribute and study upgrade ideas as part of the Snowmass process.

Belle II Upgrade Program



KLM: replace RPCs with scintillators in barrel (some with fast timing for K_L time-of-flight); replace readout

ECL: replace crystals with pure CsI; APD readout; add pre-shower detector

TOP: replace readout to reduce size & power; replace all PMTs with extended-lifetime ALDs (or SiPMs?)

IR: accommodate QCS replacement and repositioning

VXD: all pixels
- DMAPS

CDC: replace r/o ASIC+FPGA
New tracker (pixels, gas)

ARICH: possible photosensor upgrade

TRIGGER: replace with latest tech to increase bandwidth, allow for new trigger primitives

More distant future: ~mid-2030's
✓ Detector R&D for extreme-$\mathcal{L}$ environment

Requirements for VXD Upgrade

Upgrade motivation:

- Cope with larger background activity
- Improve momentum and impact parameter resolution in low p_T region
- Simplify tracking chain with all layers involved
- Operation without special modes nor data reduction

Key sensor specifications:

- Pixel pitch 30-40 µm
- Integration time $\lesssim$100 ns
- Power dissipation $\lesssim 200\ \mathrm{mW/cm^2}$

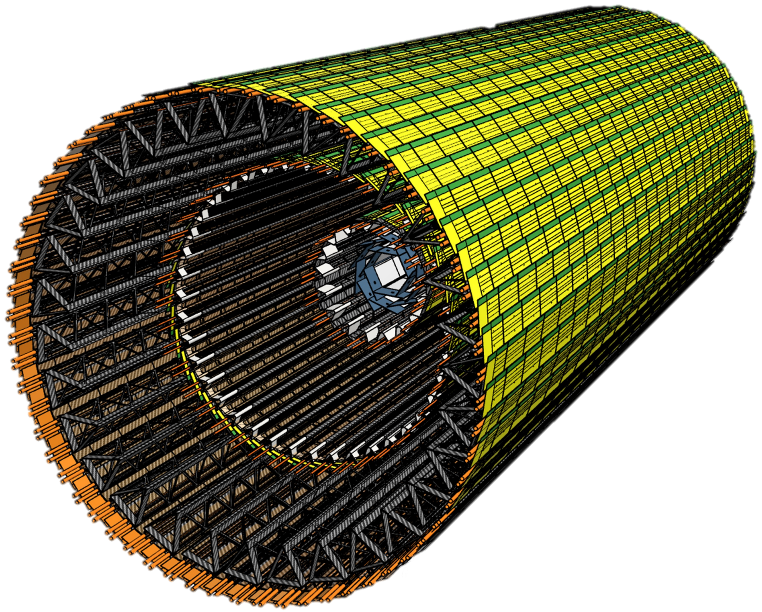
Improve physics reach per ab^{-1}

Radius range	14 – 135 mm
Tracking & Vertexing performance	
Single point resolution	< 15 µm
Material budget	0.2% X_0 / 0.7% X_0 inner- / outer- layer
Robustness against high radiation environment (innermost layer)	
Hit rate	~ 120 MHz/cm²
Total ionizing dose	~ 10 Mrad/year
NIEL fluence	~ 5e13 n_{eq}/cm²/year

Belle II Upgrade: VTX - DMAPS

SuperKEKB and Belle II LS2 Upgrade

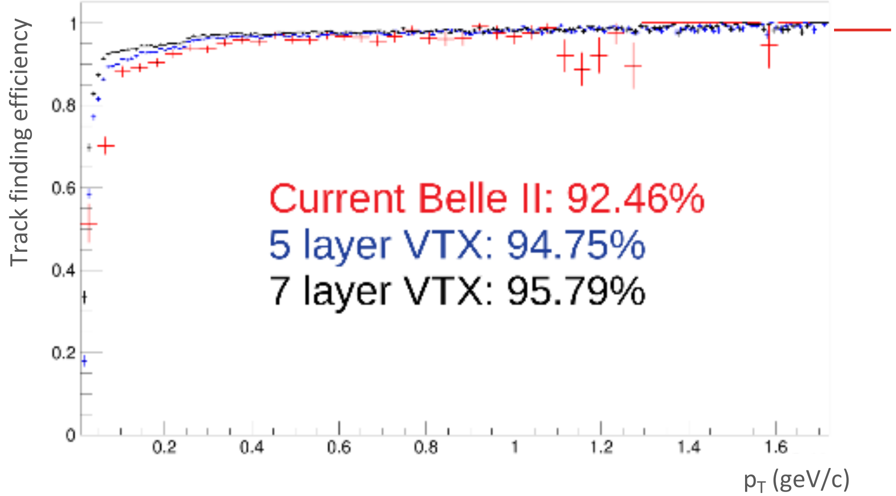
- 5 straight layers barrel, using CMOS pixel sensors
- Low material : 0.1% X_0 (L1+L2) - 0.4% (L3) - 0.8% X_0 (L4+L5)
- Moderate pixel pitch ~ 30 μm^2
- Fast integration time 50-100 ns
- iVTX: innermost 2 layers, self-supported, air cooled
- oVTX: 3 outer layers, CF structure, water cooled
- Overall service reduction and operation simplification

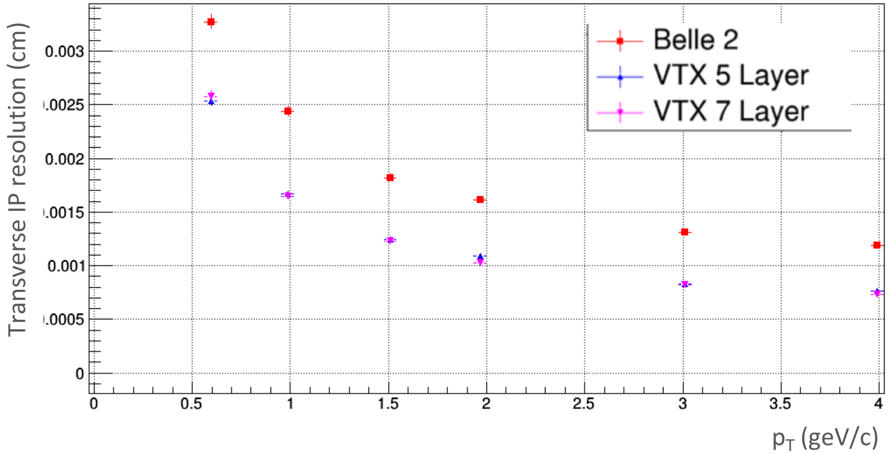


Performance Studies

- Full simulation in Belle II analysis software
  - 5 layer geometry implemented
  - Detailed digitizer model tuned from test beam data
  - Tracking algorithms re-trained
  - Estimated backgrounds at 8x10^{35} cm^{-2}s^{-1}

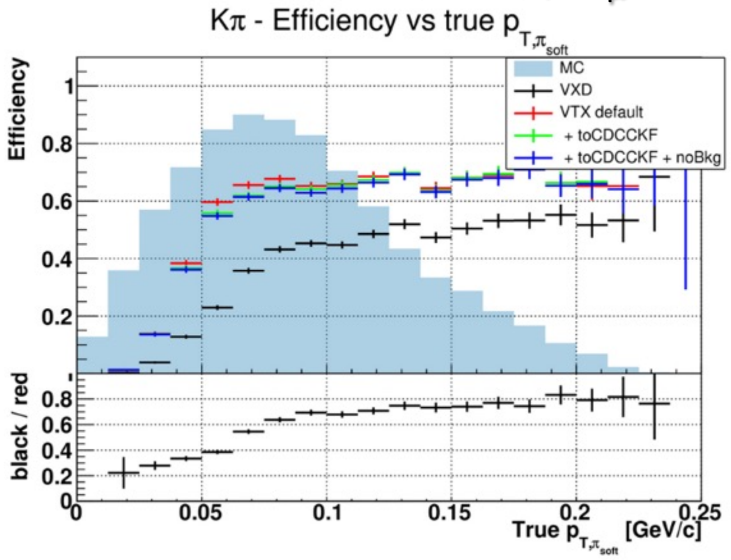
Tracking





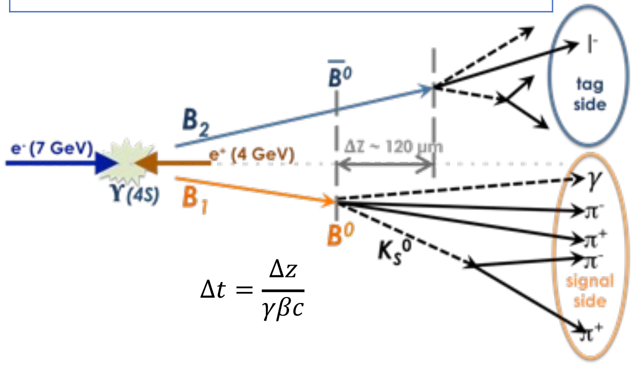
Physics Benchmarks

$B^0 \to D^{*-}(\bar{D}^0\pi^-)\,\mu^+\nu_\mu$



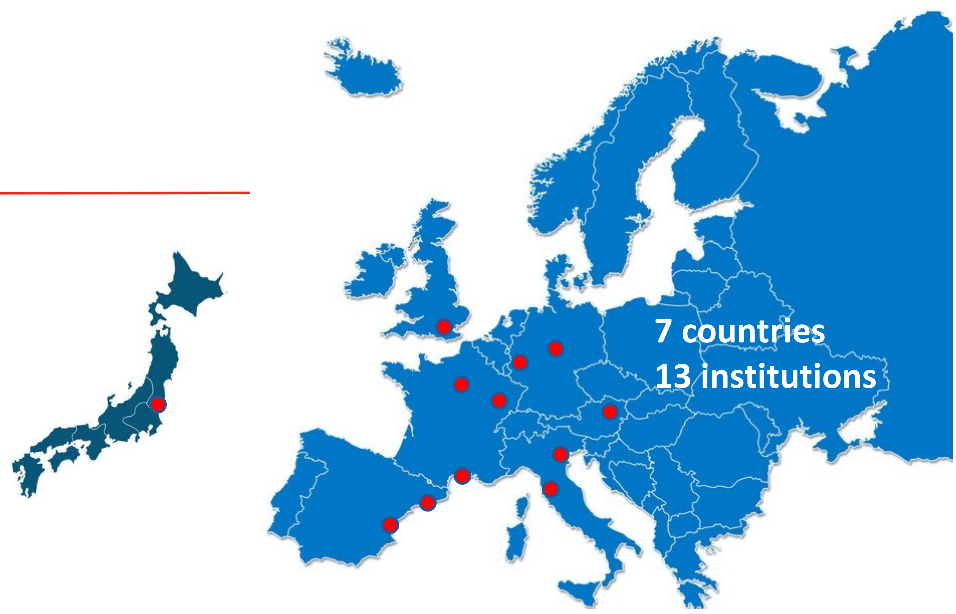
$B^0 \to K_S^0\,\pi^+\pi^-\gamma$

Geometry	Δt Resolution (ps)
VXD	1.12 ± 0.11
VTX 5 layers	0.82 ± 0.02



→ VTX performs slightly better / current VXD

Belle II VTX - Organization



Institutional Board

Project Leader
C. Marinas (Valencia)

WG1: Performance
B. Schwenker (Goettingen)

- Software
- Tracking
- Benchmarking

WG2: Sensor design
J. Baudot (Strasbourg)

- Analog
- Digital
- Verification
- Irradiations
- Test beam
- Lab Testing

WG3: Layer development
S. Bettarini (Pisa)

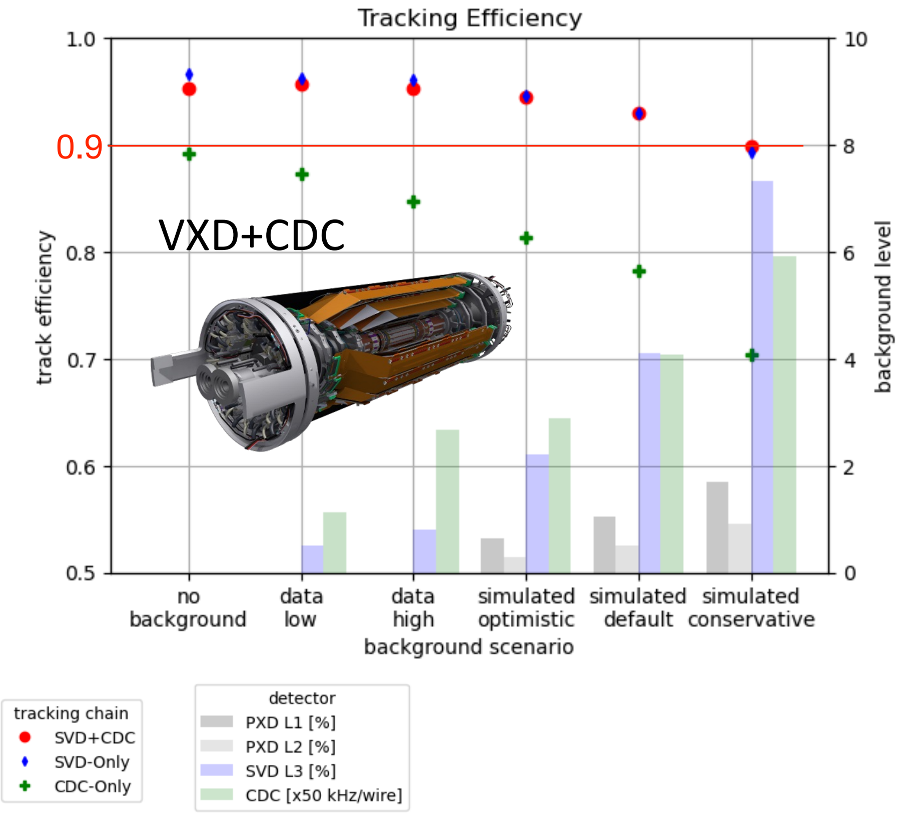
- iVTX Electrical
- oVTX Electrical
- iVTX Thermomech
- oVTX Thermomech

WG4: System integration

- Interfaces/links
- DAQ
- Power supplies
- Cooling/services
- Slow control

→ Strong French contribution in all WG

Tracking Efficiency under High Backgrounds

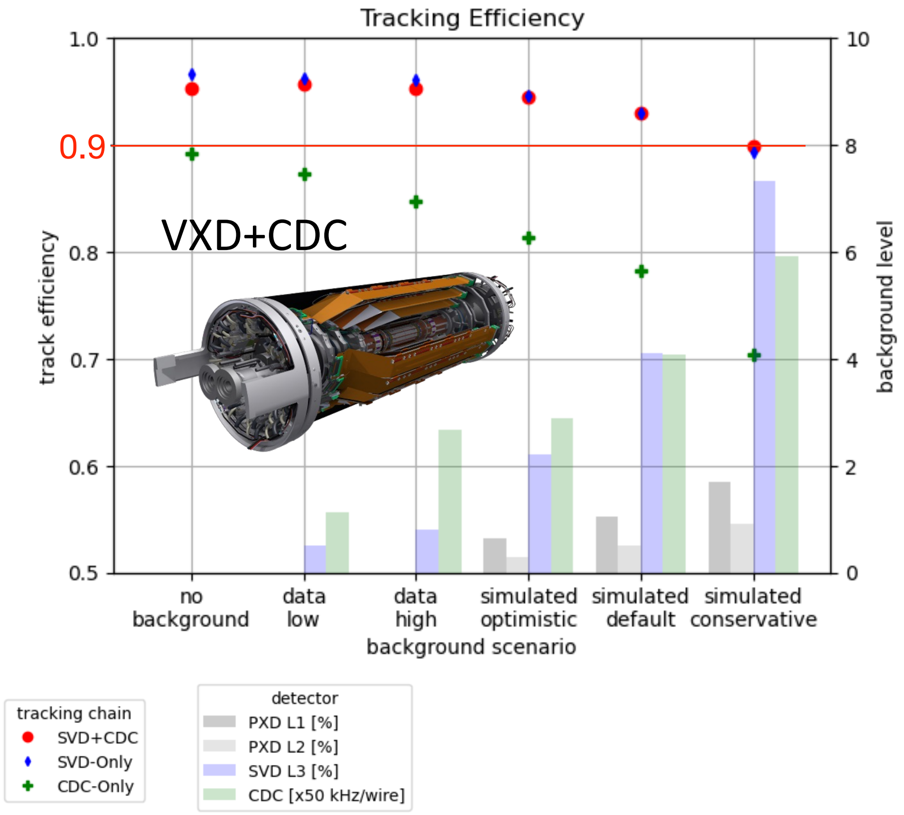


Tracking efficiency reaching 90% with current configuration with:

SVD at 7% occupancy

CDC at 300 kHz/wire hit rate

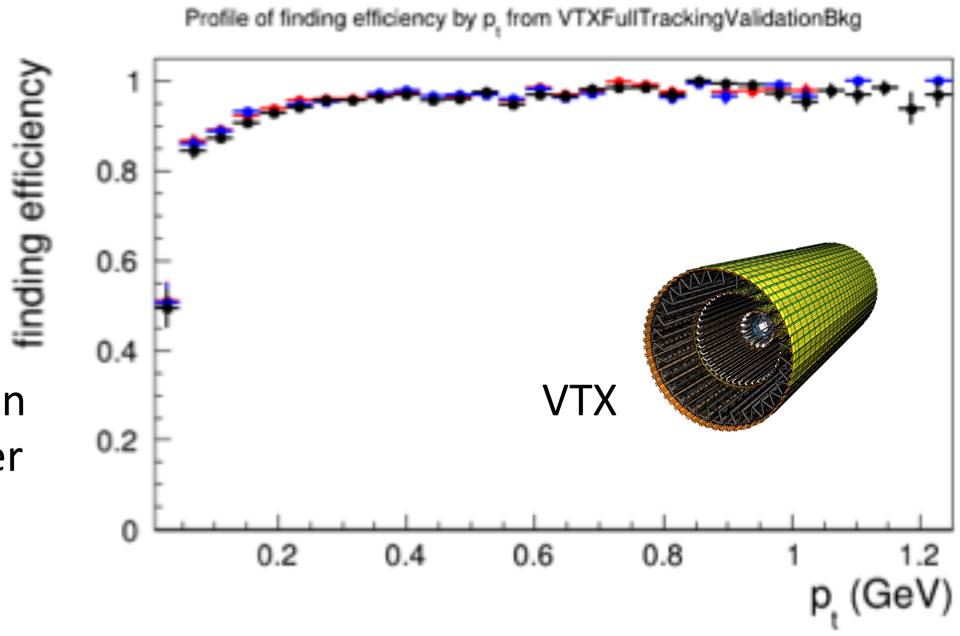
Tracking Efficiency under High Backgrounds



Tracking efficiency reaching 90% with current configuration with:

SVD at 7% occupancy
CDC at 300 kHz/wire hit rate

With new VTX: All-silicon tracking with x200 lower occupancy



→ VTX will take over CDC tracking at large background conditions

DMAPS for Belle II – LS2 and Beyond

Starting prospective ideas on simulation beyond VTX

- **Main tracker upgrade**

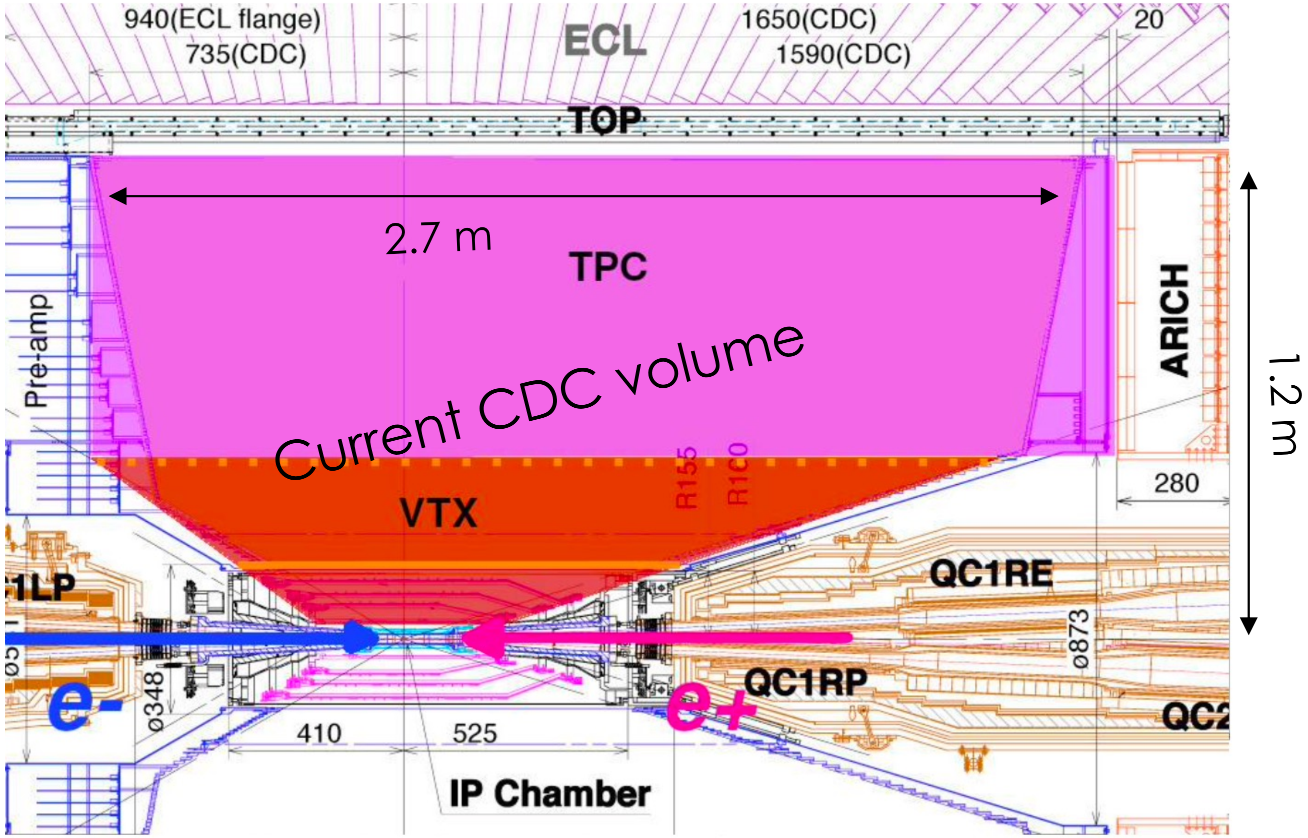
Replace totally/partially the CDC with DMAPS

Pitch 30-50 µm
1 ns time-stamping with TRG capability
50 mW/cm^2 power budget
1 MHz/cm^2 hit-rate
Low radiation hardness

- **Timing layers**

Trigger and PID (DMAPS?)

Time resolution 10-100 ps
Pad-like pixels



→ Large synergies with ECFA roadmap requirements

Belle II Vertex and Tracker: European Strategic Project

- Belle II upgrade identified as a strategic project on flavor collider experiments

Different environmental constraints

Strategic Projects	Tracking Vertex Detector (VD) Central Tracker (CT)	Timing Layer (TL) + Calorimeter
Heavy Ion	ALICE-3, EIC	ALICE-3 (LS4+), EIC
Flavour collider	BELLE-3	BELLE-3
Lepton collider	ILC, CLIC FCCee, Muon Collider	ILC, CLIC FCCee, Muon Collider
pp collider	LHCb-2, ATLAS, CMS FCC-hh	LHCb-2, ATLAS, CMS FCC-hh

DRD3 Workshop
22nd March 2023
CERN
D. Contardo

Milestone 1, 2028-2029
Strategic programs ALICE-3, LHCb-2, Belle-3, EIC: VD/CT
Highest position precision at lowest power dissipation up to large wafersize

New groups applying for joining Belle II Vertex Upgrade

European Strategy and Belle II (KEK)

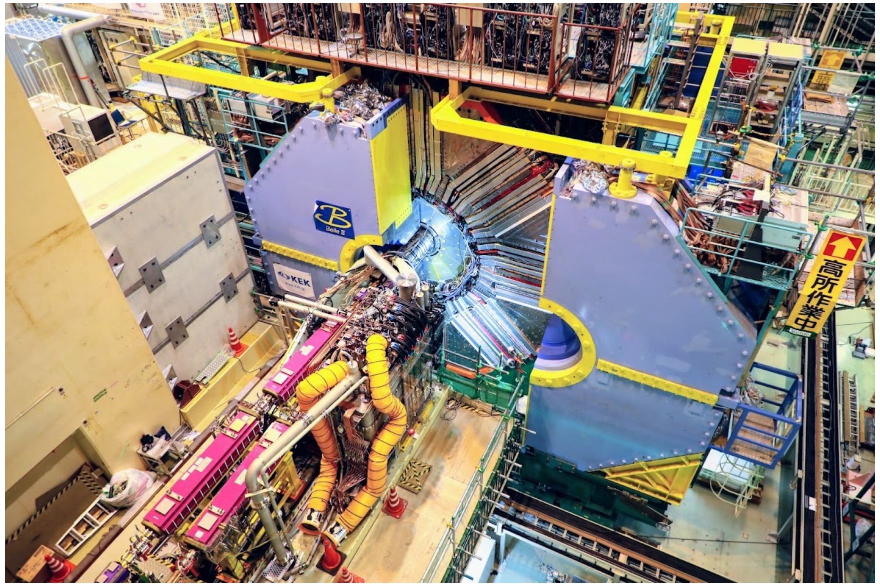
European Strategy recommends participation in flavor experiments outside Europe → Belle II

4

European Strategy Update

Other essential scientific activities for particle physics

A. The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***



MEXT Report on SuperKEKB/Belle II

Comprehensive Assessment

The SuperKEKB project is very urgent and strategic, and is highly ranked as a plan that can obtain the consensus of the domestic and international research community and the support of society and the public.

Three scientific goals:

1. Continuation of operation, performance improvement, and data accumulation
2. Maintenance and *improvement of apparatus*
3. Experimental data analyses and presentations of scientific outputs

- SuperKEKB/Belle II promoted as a large scale academic frontier project
- 10 years plan
- Long term support from hosting lab >2032

Summary

- Belle II physics goals is steering a rich instrumental program
- The detector operates efficiently at peak luminosities just below 10^{35} $cm^{-2}s^{-1}$
- LS1 (2023): Detector consolidation for entering $L_{inst} = 10^{35}$ $cm^{-2}s^{-1}$ regime in the next years
- LS2 (2027): Introducing new technologies for running safely at $6x10^{35}$ $cm^{-2}s^{-1}$ with enhanced performance
  → *Belle II VTX is baseline with CMOS technologies*
- Conceptual Design Report for medium-term detector upgrade ⟶ Fall 2023

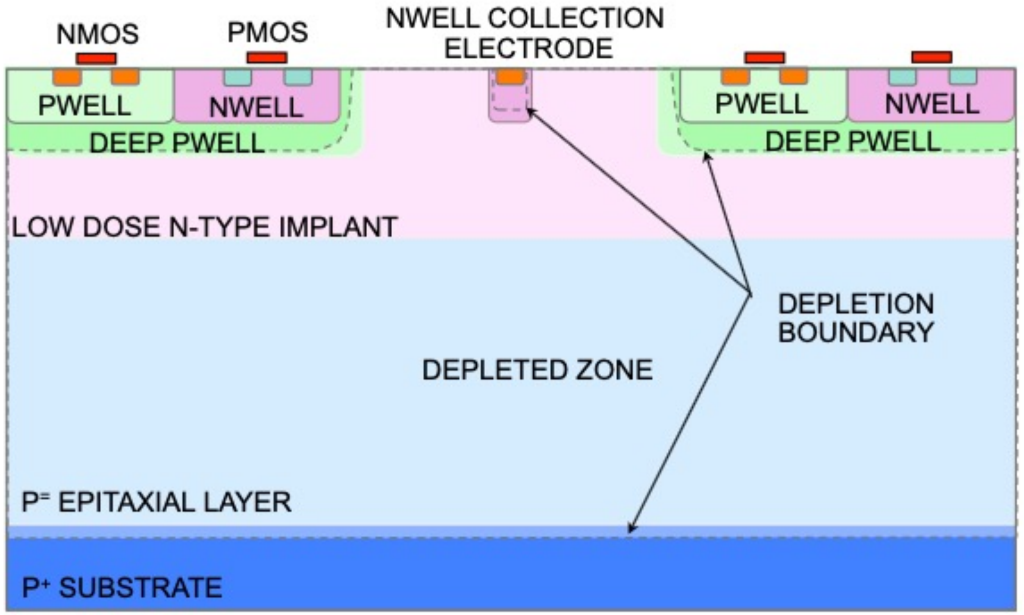
Essential to participate in DRD3, DRD7 and DRD8 for LS2 (VTX) and beyond (all-silicon tracker)
Belle II VTX: Well structured international community with expertise in large (CMOS) detector systems

Belle II long-term upgrade aligned with ECFA roadmap, with LS2 as critical intermediate step

THANK YOU

Small Electrode Sensor Design DMAPS

Monolithic detector: Combine sensor and readout on the same wafer



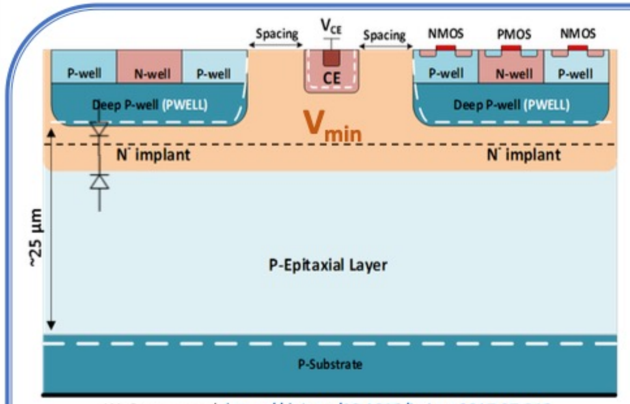
Electronics outside the collection well
Small fill factor

- Very small sensor capacitance
- Low noise and power

TowerJazz 180 nm CIS

- Deep pwell allows for full CMOS in pixel
- High resistivity epi-layer 1-8 kOhm.cm
  Epi thickness 18-40 µm
- 3 nm gate oxide for good TID
- Modified process: Additional planar n-type implant
  Full depleted volume
  Fast charge collection
- Derived from LHC developments

OBELIX: Growing the TJ-Monopix Family



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

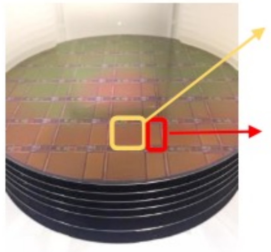
$C_d \leq 3fF$

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

DMAPS in TJ 180 nm: Concept

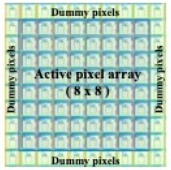
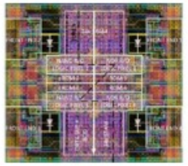
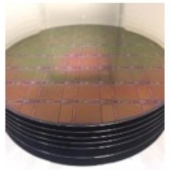
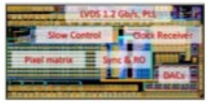
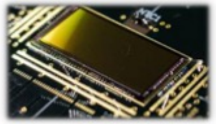
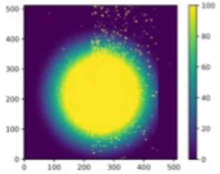
- Small sensor capacitance (Cd)
  - Key for low power/low noise
- Radiation tolerance challenges
  - Modified process
  - Small pixel size
- Design challenges
  - Compact, low power FE
  - Compact, efficient R/O

Large scale demonstrator chip development

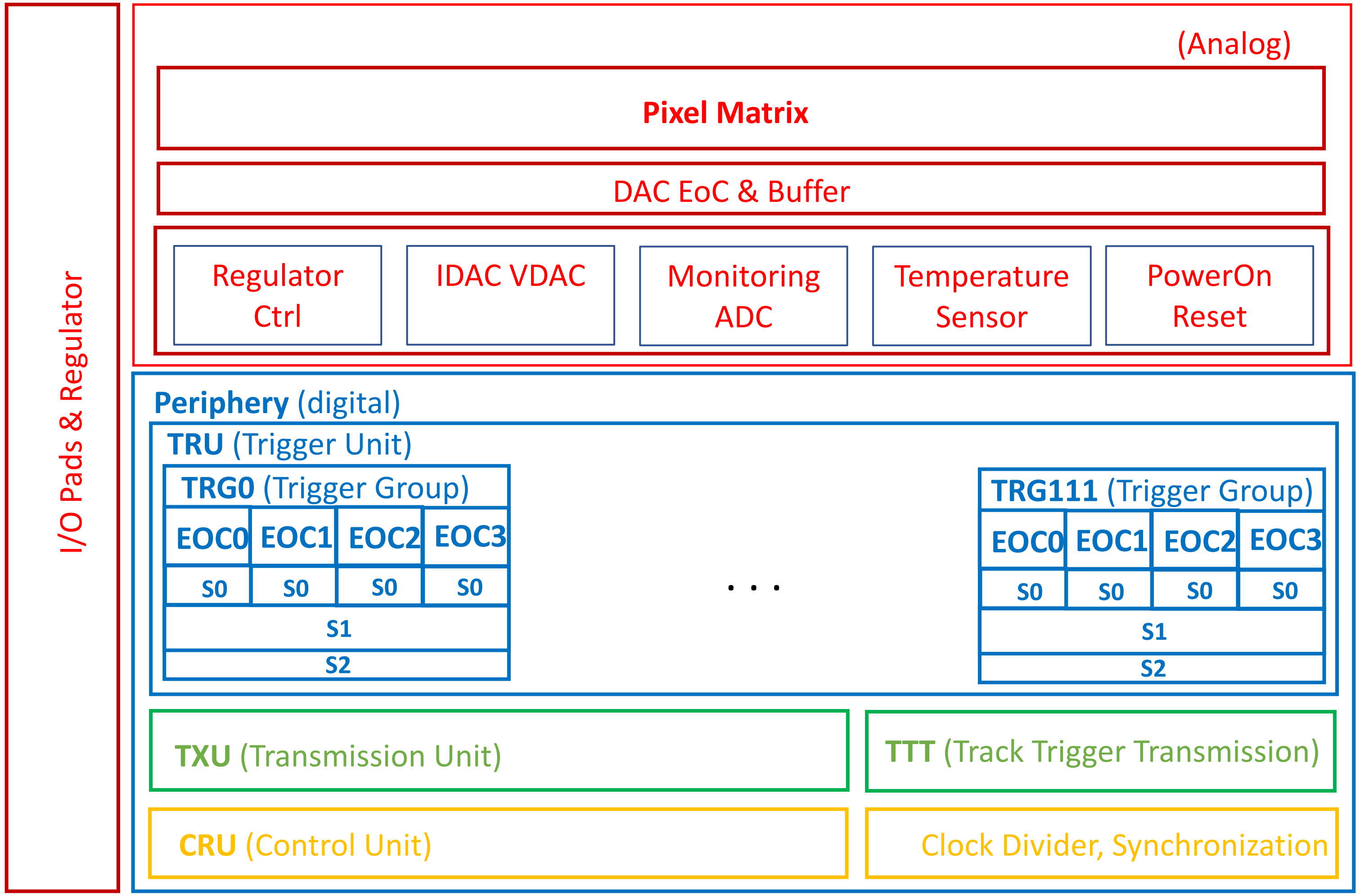


- MALTA
  - Asynchronous readout
- TJ-Monopix1
  - Synchronous column-drain R/O

- Process modification enhancements, Cz substrate ⟹ improved efficiency
- TJ-Monopix2: Improved full-scale DMAPS

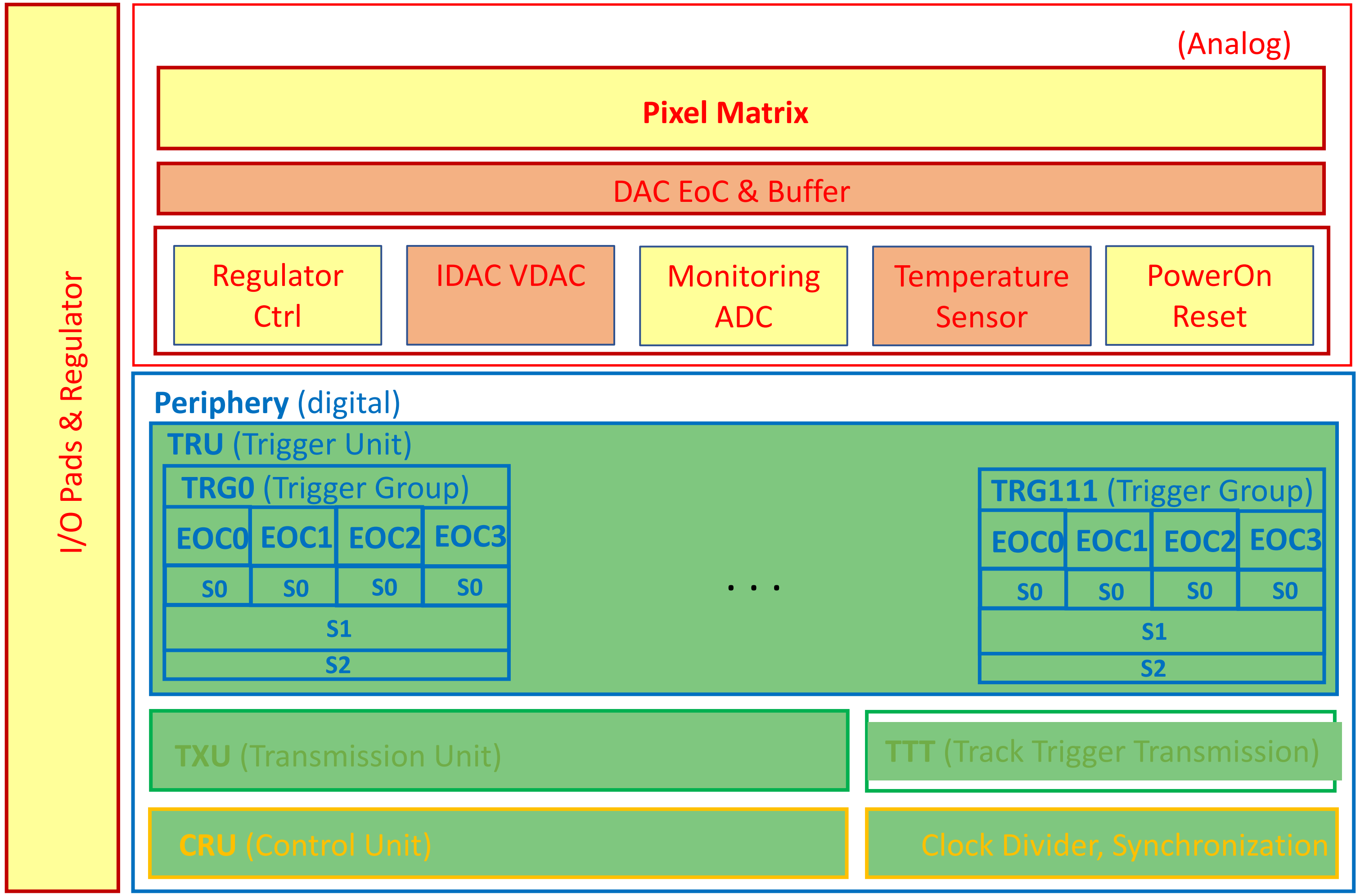
TJ-Investigator characterization	*TJ-Monopix1* & MALTA Design	*TJ-Monopix1* & MALTA Submission	Mini-MALTA sub. with process fixes	*TJ-Monopix1* resub. process fixes & Cz	*TJ-Monopix2* & *MALTA2* Design	*TJ-Monopix2* & MALTA2 Submission	*TJ-Monopix2* Characteriza tion	*"OBELIX"* Design
								Full scale System-ready: LDO, CDR, memory etc.
Q2 2016	Q4/2016	Q3/2017	Q3/2018	Q2/2019	Q2/2019	Q3/2020	Present	Future plans

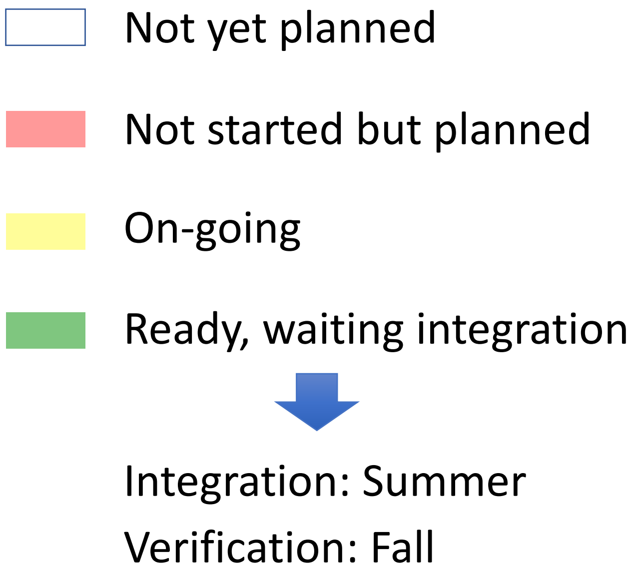
OBELIX – Design



- Pixel matrix
  - Extension from TJ-Monopix2
    - Radiation tolerance granted
  - Pitch kept at 33 µm
  - Operation point (I_{bias}) tuning on-going
  - Frequency ~10-20 MHz
    - Time-stamp precision 100 - 50 ns
- Power pads
  - Power regulators
    - Simplified system integration
  - But area limited to <150 µm
- Periphery
  - New end-of-column + trigger logic adapted to Belle II trigger
  - HitOR fast transmission (20 ns)
  - Control using RD53 protocol

OBELIX – Design Status



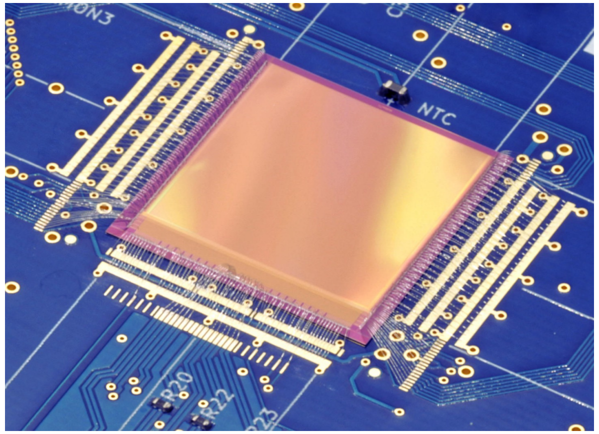


Contributors (still evolving):

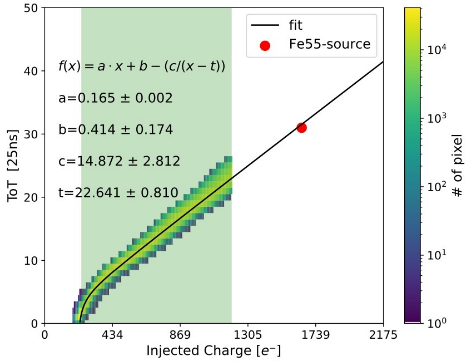
- Matrix: Bonn, IPHC, CPPM, Bergamo/Pavia
- DAC, IDAC, VDAC: IPHC + ?
- Regulator: Dortmund
- Monitoring: IFIC
- TRU: HEPHY
- TXU: HEPHY, CPPM
- CRU: CPPM
- Clock & Synchro: CPPM
- Power On Reset: IPHC

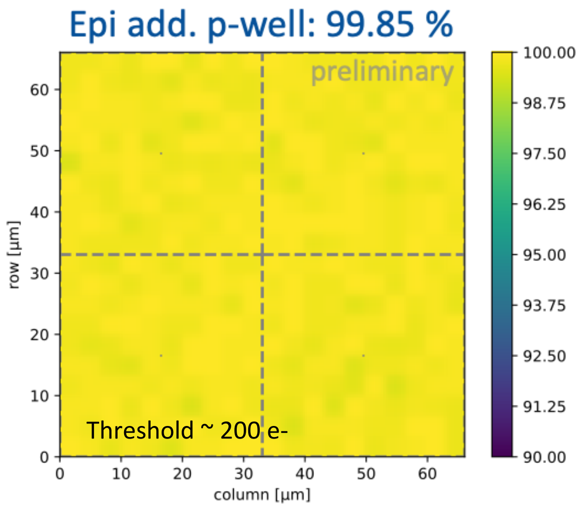
TJ-Monopix2 Characterization

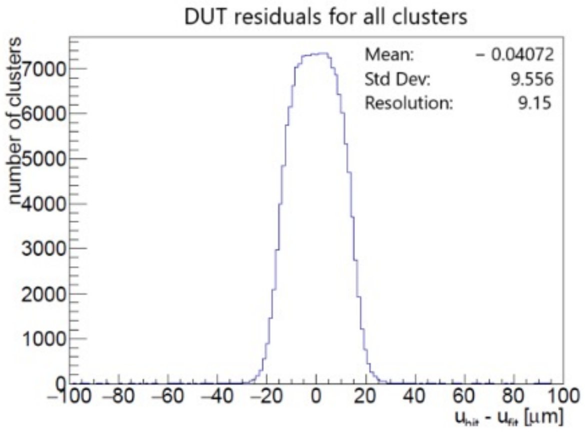
- TJ-Monopix2 as forerunner of OBELIX
  - 33x33 μm^2 pitch, 25 ns integration, 2x2 cm^2 matrix
  - 7 bit ToT information, 3 bit in-pixel threshold tuning
  - Various sensing volume thickness (CZ-bulk, epi-30 µm)



- Characterisation on-going
  - In-laboratory
    - Threshold / noise
    - ToT calibration
  - In-beam (DESY, 5 GeV electrons)
    - Efficiency ~99%
    - Position resolution ~9 µm

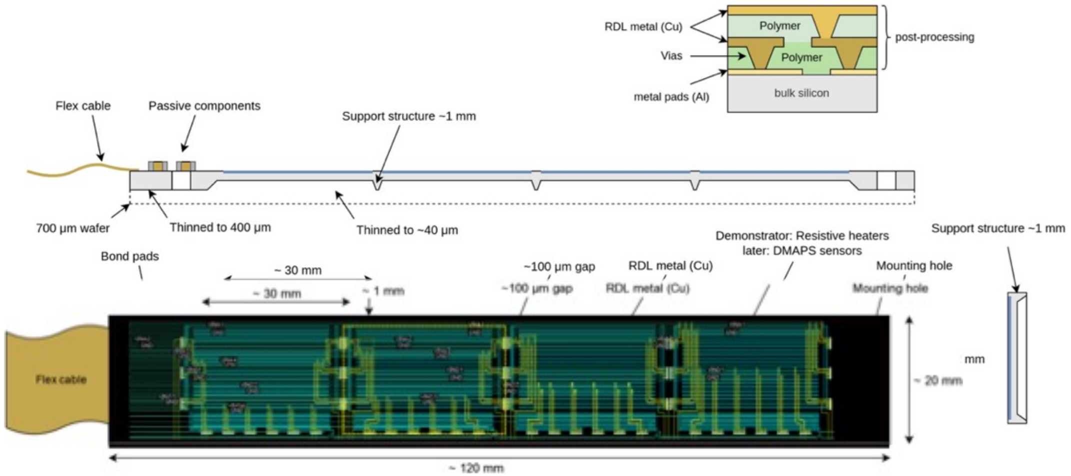






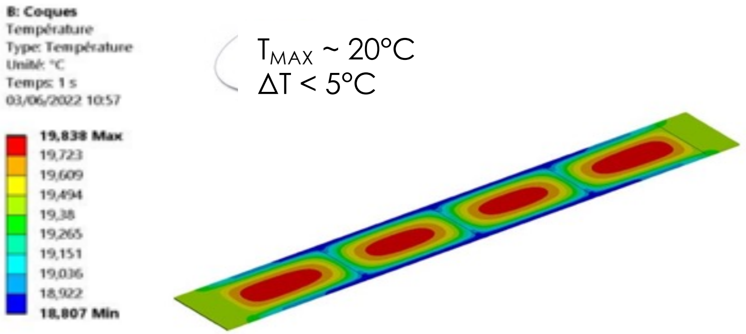
iVTX Inner Layer Concept

- All-silicon module < 0.15 % X_0
  - 4 contiguous sensors diced as a block from the wafer
  - Redistribution layer for interconnection
  - Heterogeneous thinning for thinness & stiffness

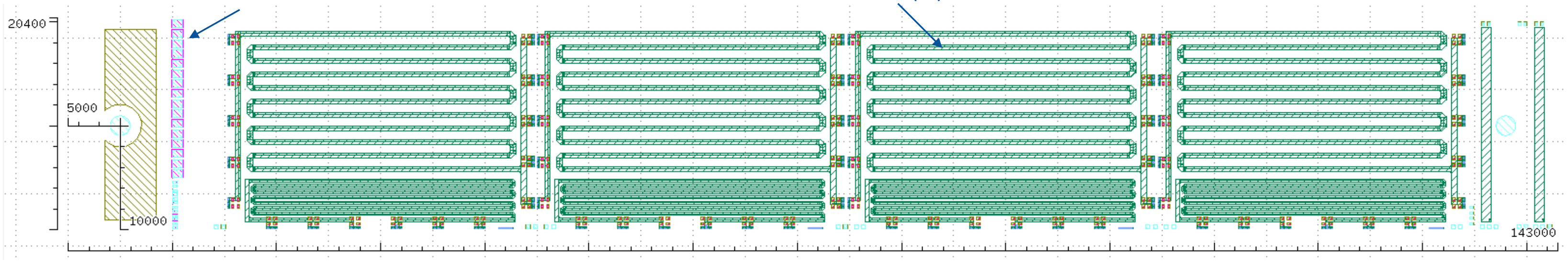


- Prototyping
  - With existing 10 cm^2 HV-CMOS ladder
    - Planarity demonstration
  - On-going at IZM-Berlin with dummy Si
    - True iVTX geometry → Summer 2023

- Simulation on cooling
  - Dry air cooling 15°C
  - Assume 200 mW/cm^2

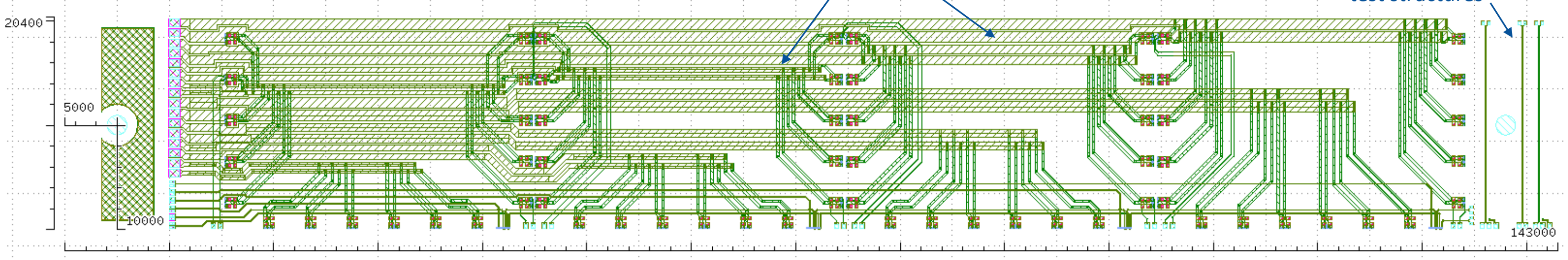


iVTX Ladder Demonstrator



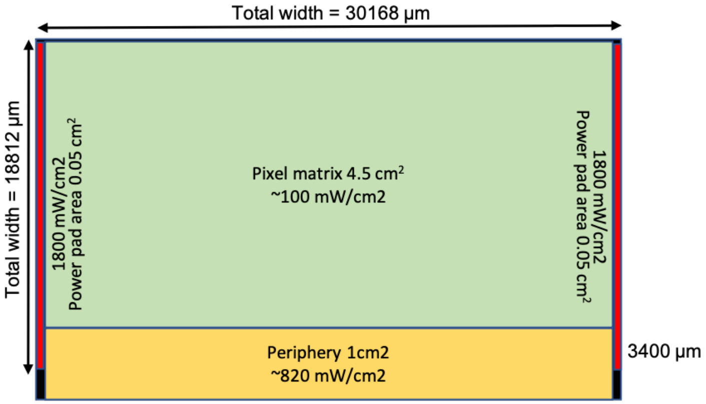
Metal system:

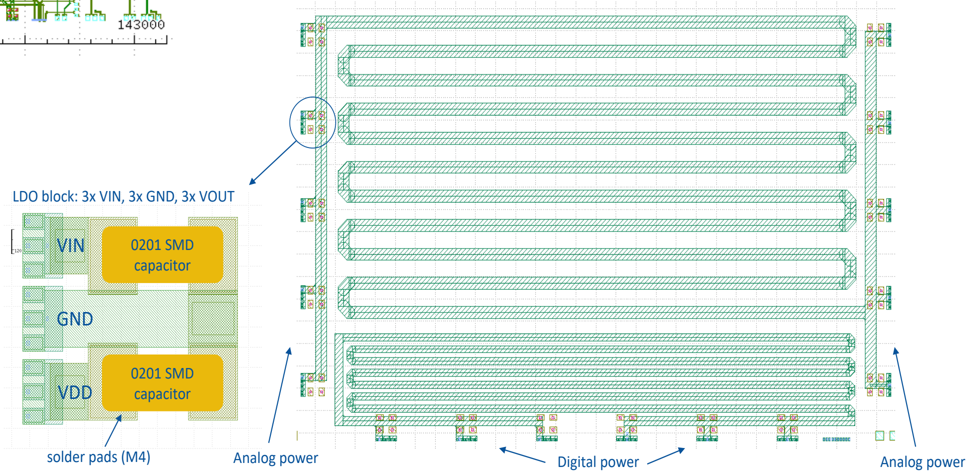
- Resistive heaters: 1.5 um Al (M1)
- 2 RDL metal layers: 3 um Cu (M2, M3)
- Top metal finish: NiAu (M4)
  Wirebonding, SMD soldering



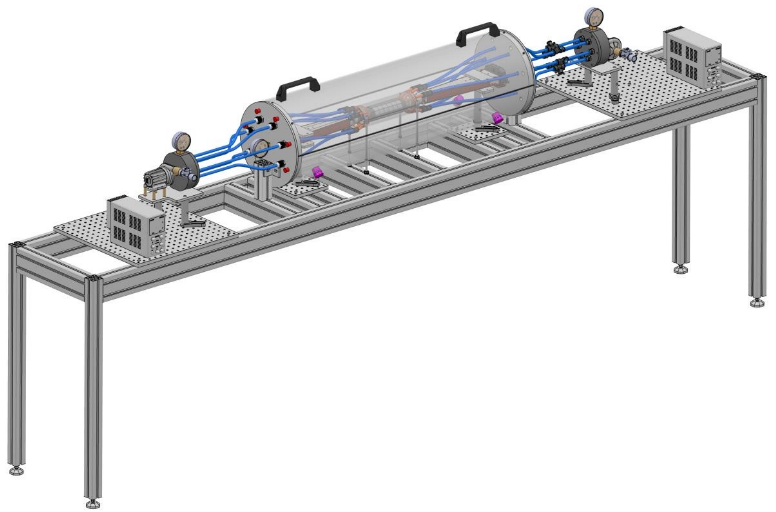
Final ladder dimension: 143 x 20.4 mm^2
Dummy heaters: 30 x 20 mm^2
Prepared for 1.7 mm mounting hole

Characterization electrical, mechanical and thermal performances of iVTX ladders

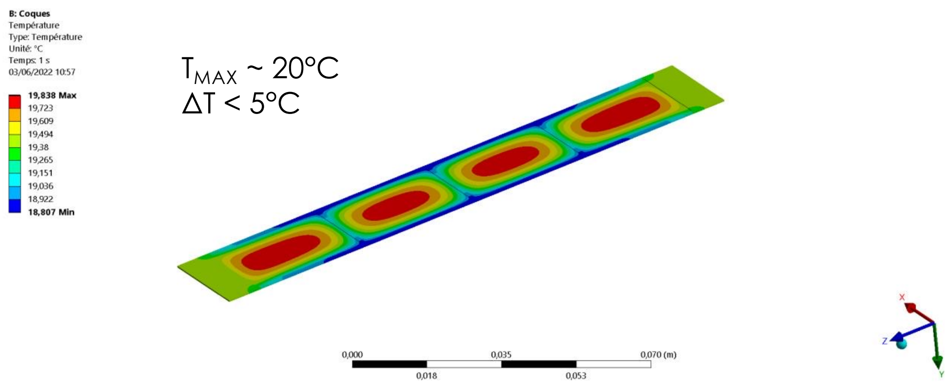


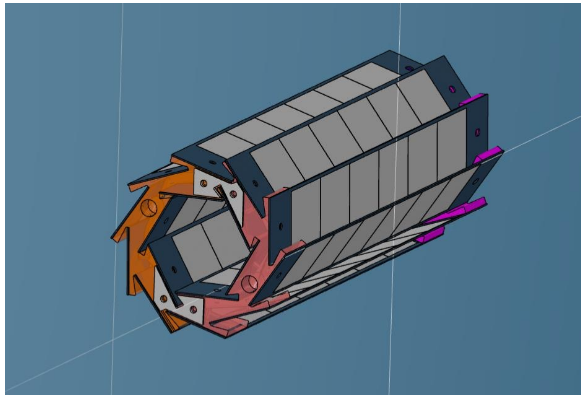


iVTX Cooling



Air cooling (10 m/s, 20 degC) seem feasible, but 9 mm tube seems necessary (3 l/s)



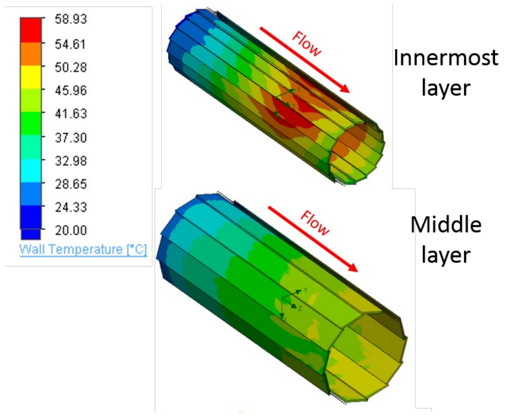


First conceptual air injector support

So far, standing single ladders with uniform power consumption.

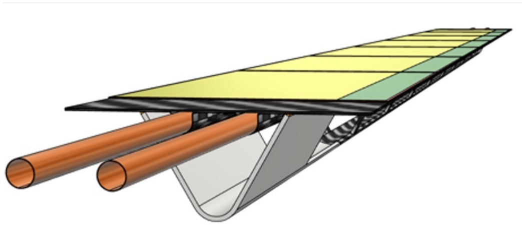
More realism to be added on the FEM…

→ Experience from CLIC wind tunnel:



oVTX Outer Layer Concept

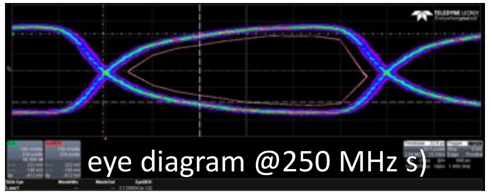
- Long ladders
  - Evolving from ALICE-ITS2
    - Carbon-fiber truss support frame
    - Cold-plate with water coolant
    - Long-flex for power & data



- 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

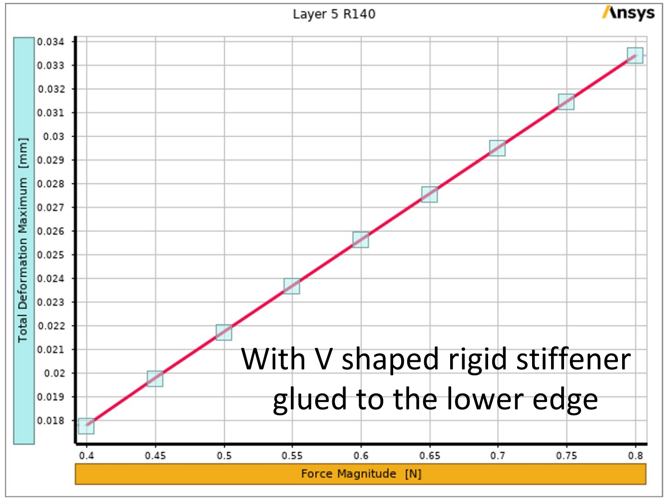
- Prototypes for L5 under test

  - Deformation & vibration
    - Max sagitta ~500 µm
    - First resonance f=250 Hz
  - Signal propagation

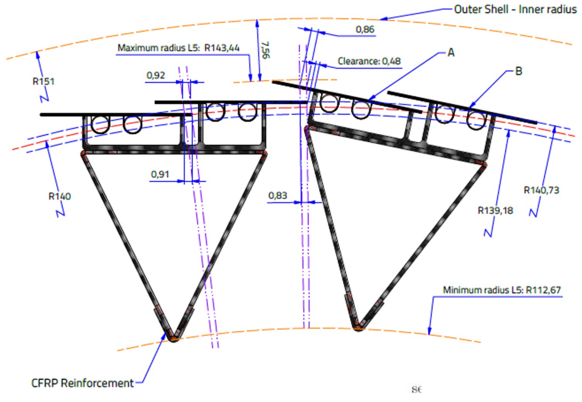


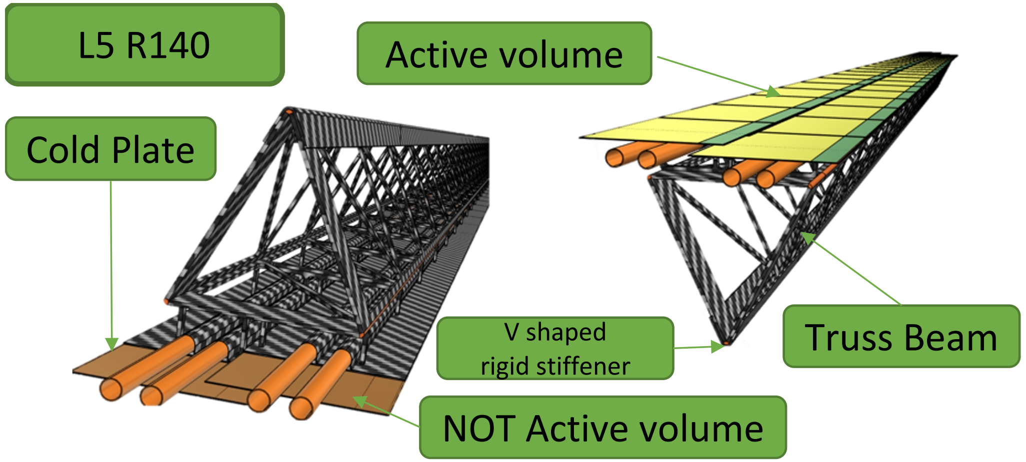
  - Cooling at T_{room} ~24ºC
    - Leakless water flow at T_{in} = 10ºC
    - Heaters dissipating 200 mW/cm^2
    - 22ºC < $T_{sensors}$ < 26ºC

oVTX Stave Integration



Realistic CAD model, including overlap studies





Studying mechanical properties with realistic models:

Tolerable max. deflection of the structure (40 µm)

Ladder concept compatible with X/X_0 expectations (0.4-0.8%)

Layer 3 R69 Radiation length summary 2 flex from FW and BW side (6 + 6 chips) - 12 chips

COMPONENT	X/X0 (%)
Support Structure	0,087%
Cold Plate	0,064%
Pipes & Coolant	0,048%
Glue	0,022%
Flex (FW + BW)	0,150%
Chips	0,066%
Grand Total	0,438%

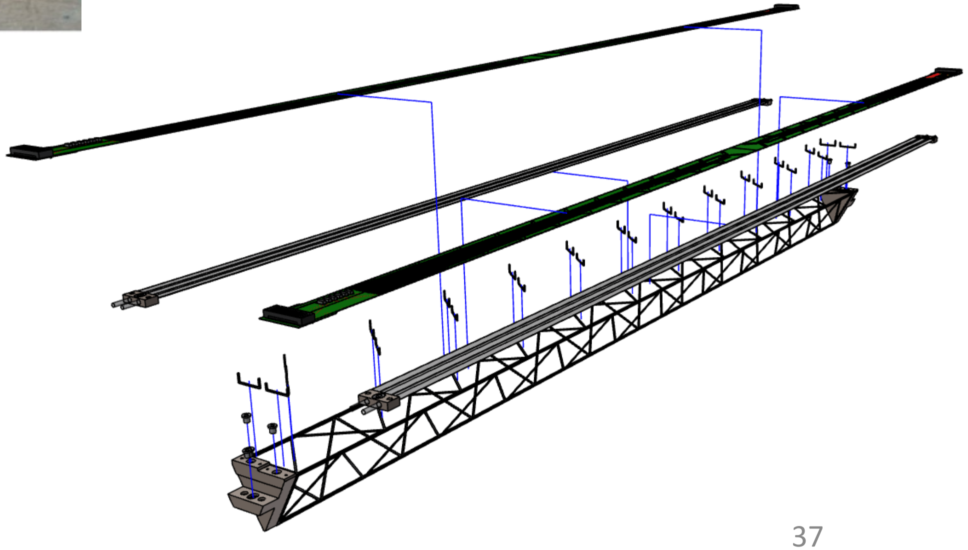
Layer 4 R89 Radiation length summary 2 flex FW and BW side (8 + 8 chips) - 16 chips

COMPONENT	X/X0 (%)
Support Structure	0,086%
Cold Plate	0,069%
Pipes & Coolant	0,048%
Glue	0,021%
Flex FW + BW	0,161%
Chips	0,067%
Grand Total	0,454%

Layer 5 R140 Radiation length summary 2 flex FW and BW side (12 + 12 chips) - 24 chips

COMPONENT	X/X0 (%)
Support Structure	0,169%
Cold Plate	0,093%
Pipes & Coolant	0,153%
Glue	0,127%
Flex FW + BW	0,186%
Chips	0,069%
Grand Total	0,796%

oVTX Stave Demonstrator



Completing a fully equipped L5 ladder (mechanical structure + cold plate + flex)

Assembly procedure well defined