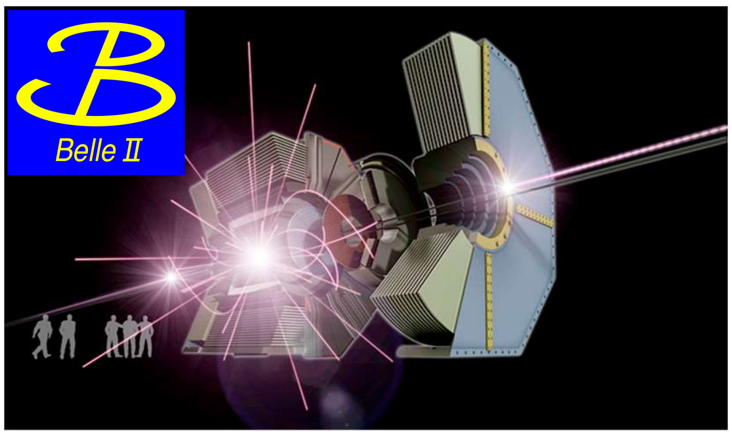
Nagoya, 29-30 March 2023

B1 Heavy Flavor and Dark Matter Joint Unit Symposium



The Belle II Upgrade Program

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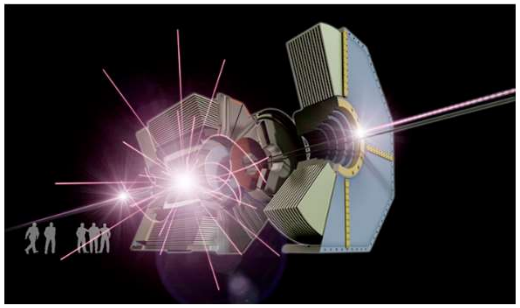
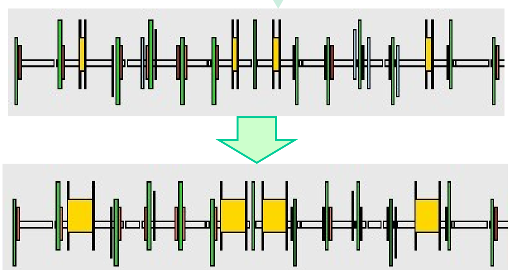
Contents

- The Belle II and SuperKEKB Program
- Timescales for upgrades
- Motivations and opportunities
- Upgrades overview
- Perspectives

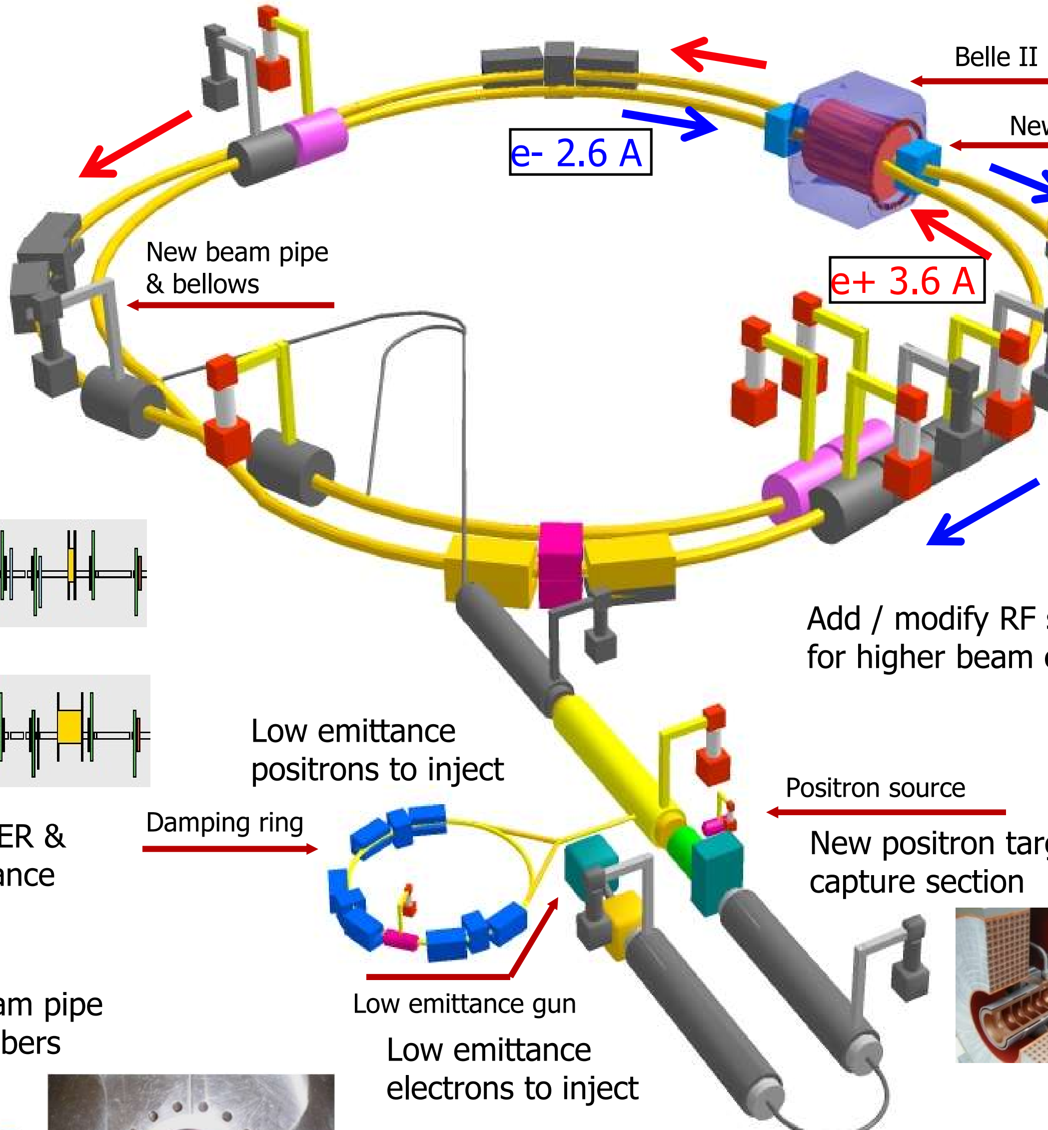


KEKB → SuperKEKB

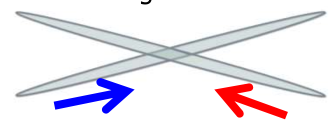
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance



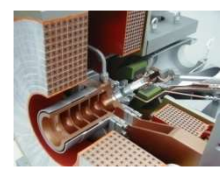
Colliding bunches



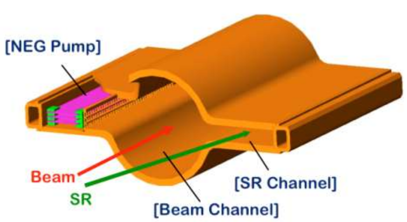
New superconducting /permanent final focusing quads near the IP

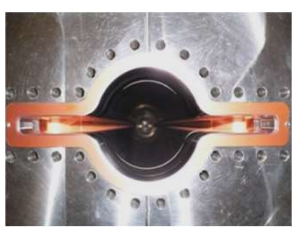
Add / modify RF systems for higher beam current

New positron target / capture section



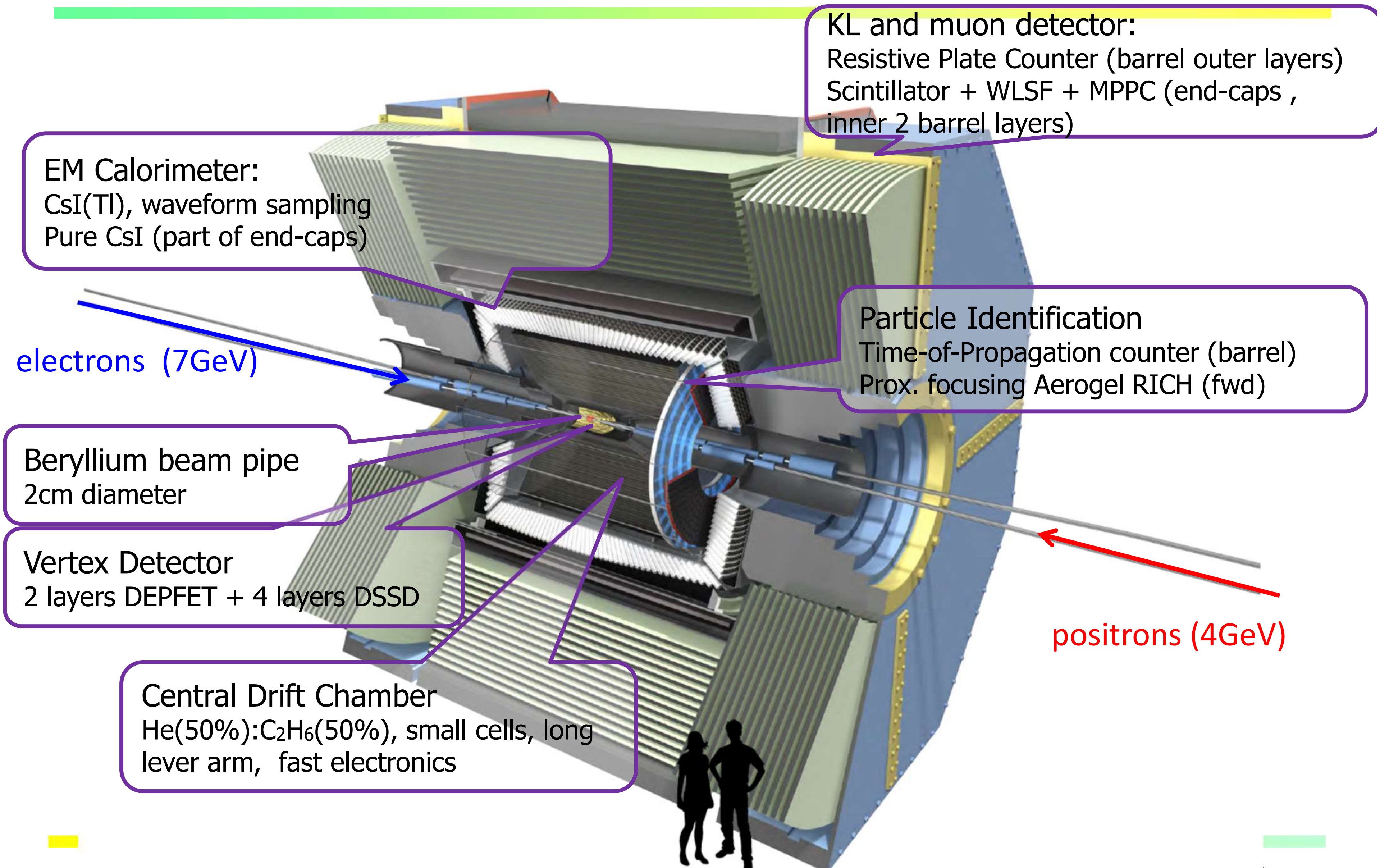
TiN-coated beam pipe with antechambers





To get x30 higher luminosity

Belle → Belle II Detector



The SuperKEKB/Belle II program

- Phase 1(2016): no detector, no collision, test the rings, baking the 3km of the accelerator vacuum chambers

- Phase 2 (2018): first collisions with complete accelerator
  - Incomplete detector: Vertex detector replaced by dedicated background detector (Beast 2)

- Phase 3 (2019-): luminosity run with complete detector
  - Pixel Detector (PXD): layer 1 + only 2 ladders in layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper appeared in January 2020

- New and difficult accelerator. Additional operational complexity during the pandemic
- Record peak luminosity 4.7×10^{34} cm^{-2} s^{-1}
- Path to reach 2×10^{35} cm^{-2} s^{-1} identified.
- Still large factors to reach the target peak luminosity of 6×10^{35} cm^{-2} s^{-1}

Path to the future

Steep path to higher luminosity

A. Machine performance and stability
- Beam blow up due to beam-beam effects
- Lower than expected beam lifetime
- Transverse mode coupling instabilities
- Low machine stability
- Injector capability
- Aging infrastructure

B. Backgrounds in the detector
- Single beam: Beam-gas, Touchek,
- Luminosity: Radiative Bhabha, two-photon processes
- Injection backgrounds

Mitigation measures

A. Consolidate machine
- International task force at work to help
- Many countermeasures under development
- A major redesign of the Interaction Region may be required to go beyond $\sim 2 \times 10^{35}$ cm^{-2} s^{-1}

B. Consolidate the detector
- Install a complete PXD
- Complete installation of more robust TOP PMTs

C. Improve detector
- Upgrade program to make the detector more robust against backgrounds and with improved performance

Timeline of upgrade work

Long Shutdown 1 (LS1) - 2022-23

- Motivated by the installation of a complete PXD.
- Well underway

Long Shutdown 2 (LS2): 2027-28

- Motivated by a (still to be defined) redesign of the IR, possible with a replacement of the superconducting quadrupoles.
- Window of opportunity for significant detector upgrades, but large uncertainties
- Prepare technology choice for a full VXD replacement

Longer term upgrades: >2032

- Not clear at this time how to realize a significant luminosity increase
- Study the physics case and start technology R&D for an extreme-luminosity detector
- Interesting possibility of beam polarization under active study; maybe possible on a more rapid timescale

Status and plan

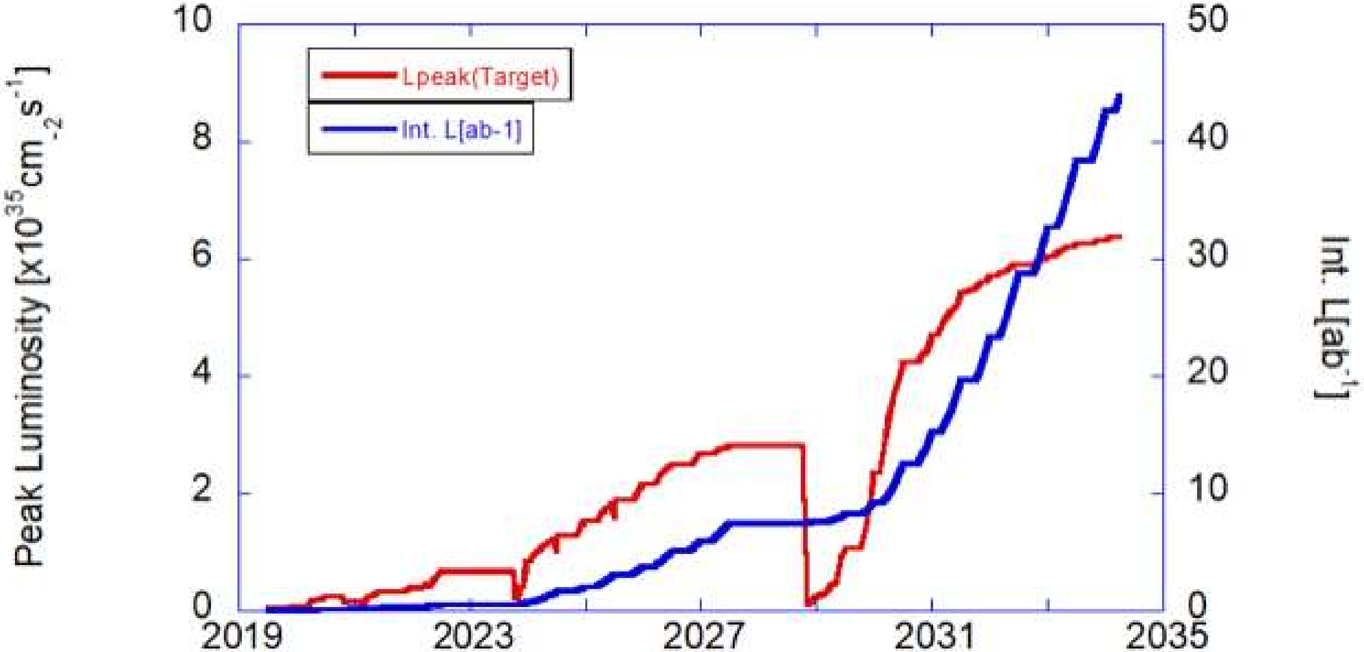
- LS1 well underway to replace VXD and a part of the photosensors in the TOP detector. In addition, other maintenance/improvement work on the machine and detector.

Status and plan

• LS1 well underway to replace VXD and a part of the photosensors in the TOP detector. In addition, other maintenance/improvement work on the machine and detector.

• We will resume machine operation end of 2023.

• An International Taskforce is discussing additional improvements needed for the operation in the target scenario (displayed below).



Motivation for Belle II upgrades

Improve detector robustness against backgrounds

- Provide larger safety factors for running at higher luminosity

Increase longer term subdetector radiation resistance

Develop the technology to cope with different future paths

- For instance if a major IR redesign is required to reach the target luminosity

Improve physics performance: get more physics per ab^{-1}.

A number of ideas are being developed and reviewed internally for the different time scales

Logo: Copyright F. Forti

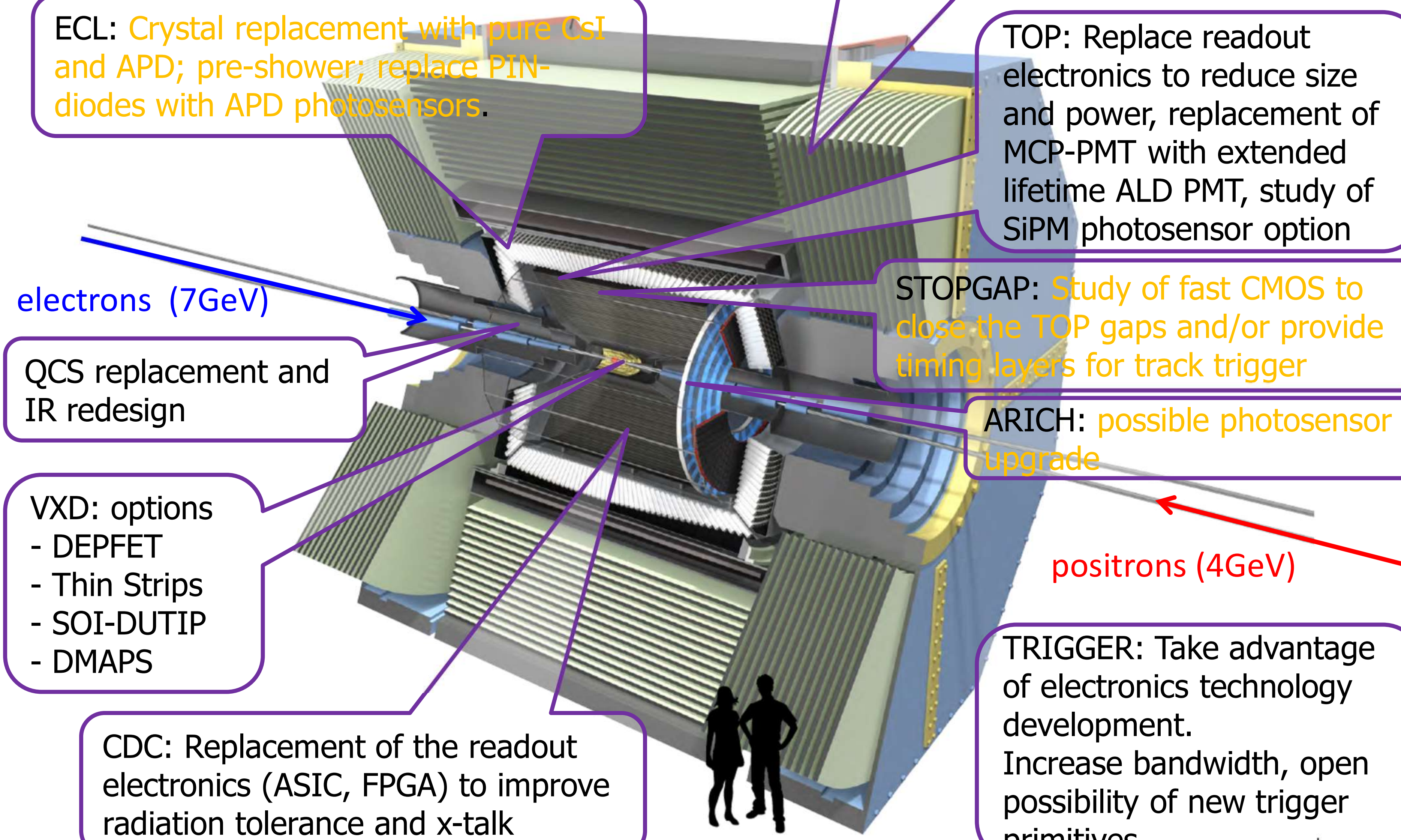
Belle II upgrades

- During LS2
- Options beyond LS2

KLM: Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF

ECL: Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.

TOP: Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option



STOPGAP: Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger

QCS replacement and IR redesign

ARICH: possible photosensor upgrade

VXD: options
- DEPFET
- Thin Strips
- SOI-DUTIP
- DMAPS

CDC: Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk

TRIGGER: Take advantage of electronics technology development.
Increase bandwidth, open possibility of new trigger primitives

Upgrades main ideas and time scale

Snowmass Upgrades White Paper Table (https://arxiv.org/abs/2203.11349)

Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	short-term
		new DEPFET	medium-term
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
		replace inner part with silicon	medium/long term
		replace with TPC w/ MPGD readout	long-term
TOP	PID, barrel	Replace conventional MCP-PMTs	short-term
		Replace not-life-extended ALD MCP-PMTs	medium-term
		STOPGAP TOF and timing detector	long-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	γ, e *ID*	add pre-shower detector in front of ECL	long-term
		Replace ECL PiN diodes with APDs	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		on-detector upgraded scintillator readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		firmware improvements	continuos
DAQ		PCIe40 readout upgrade	ongoing
		add 1300-1900 cores to HLT	short/medium-term

Table 1.1: Known short and medium-term Belle II subdetector upgrade plans, starting from the radially innermost. The current Belle II subdetectors are the Silicon Pixel Detector (PXD), Silicon Strip Detector (SVD), Central Drift Chamber (CDC), Time of Propagation Counter (TOP), Aerogel Rich Counter (ARICH), EM Calorimeter (ECL), Barrel and Endcap K-Long Muon Systems (BKLM, EKLM), Trigger and Data aquistion (DAQ). DAQ includes the high level trigger (HLT).

VXD Upgrade -Requirements

Radius range: R	14 – 135 mm (**)
Tracking & Vertexing performance at least as good as current VXD	
Single point resolution(*)	< 15 um
Total material budget	< (2x 0.2% + 4x 0.7%) X_0
Robustness against radiation environment	
Hit rate(*)	~ 120 MHz/cm^2
Total Ionizing Dose(*)	~ 10 Mrad/year
NIEL fluence(*)	~ 5.0×10^{13} $n_{eq}/cm^2/year$

* For the innermost layer at 14 mm
** Option: include the inner region of the CDC (135 mm – 240 mm)

Be prepared for a major interaction region redesign

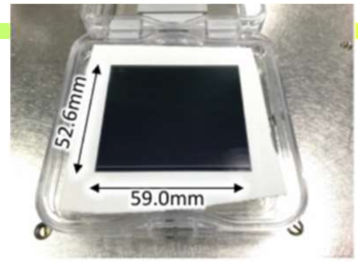
- Allow large safety factors against backgrounds

Take advantage of technology development

Possible performance improvements

- Improve impact parameter and vertexing resolution
- Improve tracking performance for low pT tracks
- Triggering: possible contribution to the L1 trigger

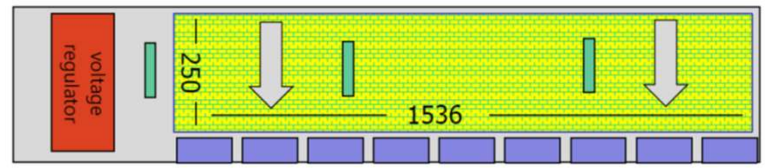
VXD – several proposals have been studied



Thin and fine-pitch DSSD

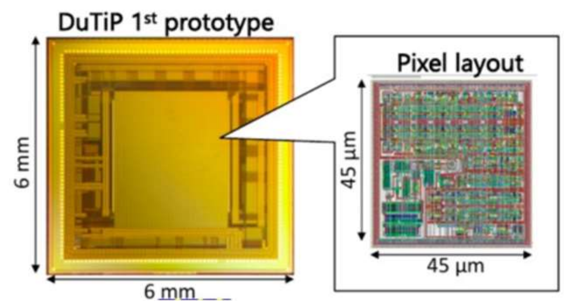
- Sensor 140 μm thin & z-pitch < 80 μm
- New ASIC for low noise

Upgraded DEPFET



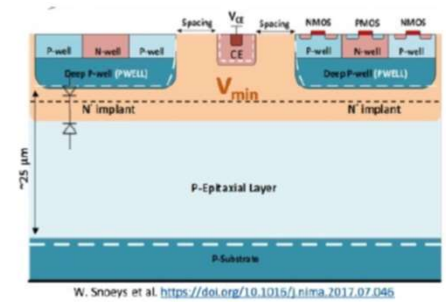
- Higher radiation tolerance through higher gain
- Faster read-out (few μs) with new ASICs
  and a possible R/O re-orientation

SOI pixels

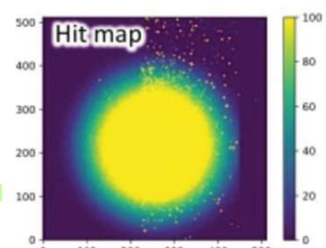


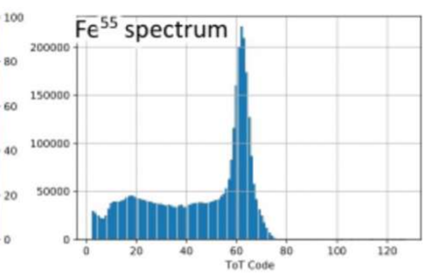
- Lapis 200 nm process
- Dual Time pixel sensor (DuTiP)
- pitch 45 μm, 2x60 ns integration

CMOS-MAPS



- Tower 180 nm process
- Extension of TJ-MONOPIX2⟶ OBELIX sensor
- Pitch <40 μm with 100 ns integration
- Fully pixelated VXD concept = VTX
with all-Si modules or ALICE-ITS-like ladders

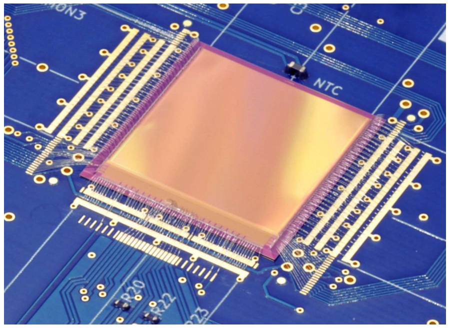




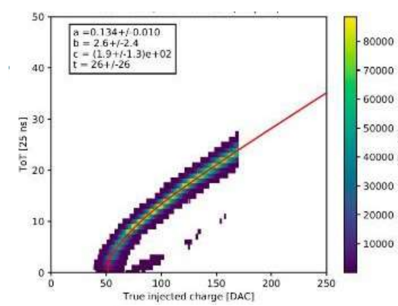
VXD upgrade – lab and beam tests

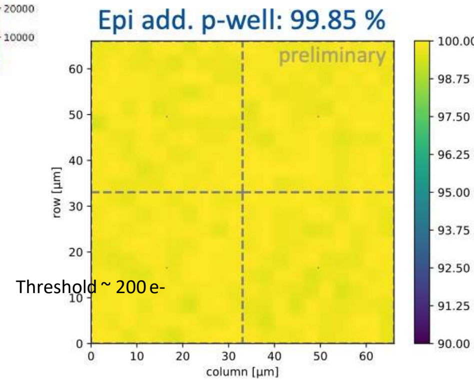
TJ-Monopix2 Characterization

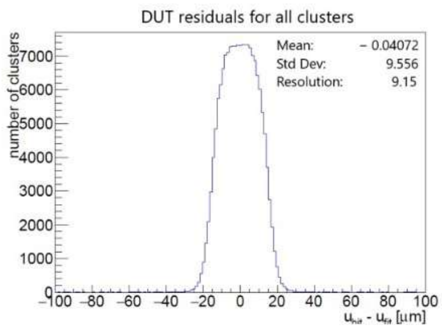
- TJ-Monopix2 as forerunner of OBELIX
    - 33x33 μm^2 pitch, 25 ns integration, 2x2 cm^2 matrix
    - 7 bit ToT information, 3 bit in-pixel threshold tuning
    - Various sensing volume thickness (CZ-bulk, epi-30 μm)



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







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Tracking: CDC

Central Drift Chamber Electronics upgrade:

- Improve radiation tolerance,
- Reduce cross-talk and power consumption
- New ASIC, new FPGA, optical modules
- Installation in LS2

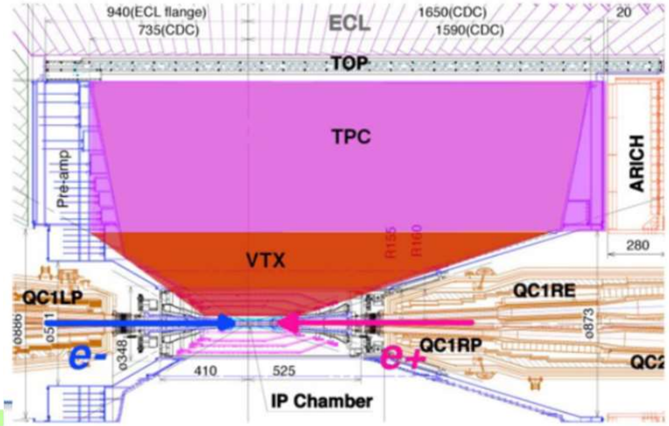
	the present board	upgrade	status
power consumption (ASIC of ASD)	separated chips, ASD and FADC	functions of ASD and FADC are in one chip. ~60% reduction is expected in ASD+FADC	design is almost finalized (M. Miyahara, KEK Esys) mass production from 2023
cross talk (ASIC of ASD)	~100mV pulse height induced in neighbor ch with 7pC input	~10mV pulse height induced in neighbor ch with 7pC input + double thresholds	
FPGA soft error	Virtex-5	Kintex-7	purchased and fabricated on the prototype board. irradiation test is planed in 2022.
radiation tolerance of optical transceiver	SFP for DAQ (1kGY) Avago HFBR-7934WZ for TRG (300-400Gy)	QSFP	purchased several QSFPs to be tested with irradiation
bandwidth of optical transceiver	SFP for DAQ Avago HFBR-7934WZ for TRG (3.125Mb/s)	one QSFP in stead of two different optical transceivers	basic test is done with TRG system

Long-term studies

- Sustaining higher rates & backgrounds

→ Exploring options

- Extended VTX
- TPC tracker with pixel read-out Gridpix-like 200^2 μm^2
- Full silicon tracker



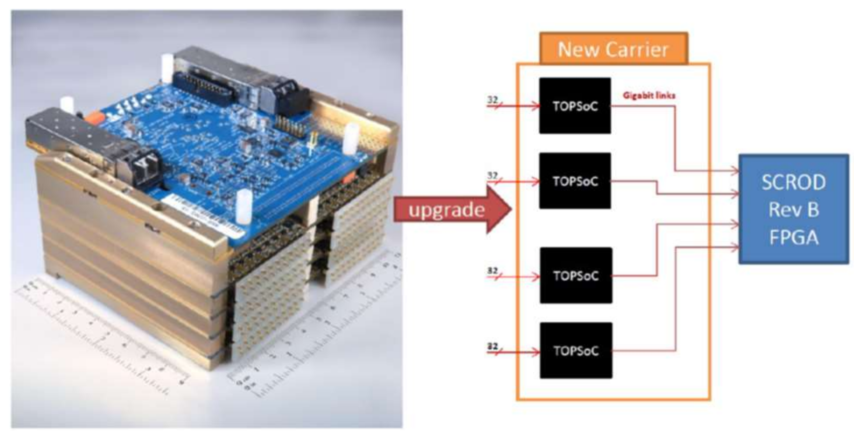
PID: TOP

Install Life-extended Atomic Layer Deposition MCP PMTs
- in LS1 for standard MCP PMT,
- possibly in LS2 for ALD MCP PMTs

Study of SiPM as possible MCP PMT replacement
- Require cooling system
- Longer time scale

Electronics upgrade
- IRSX ASIC 8-channel 250 μm CMOS

→ TOPSoC ASIC 32-channel 130 μm CMOS
- Feature extraction inside ASIC
- Reduced power consumption



→ Talks by J. Kandra and K. Matsuoka

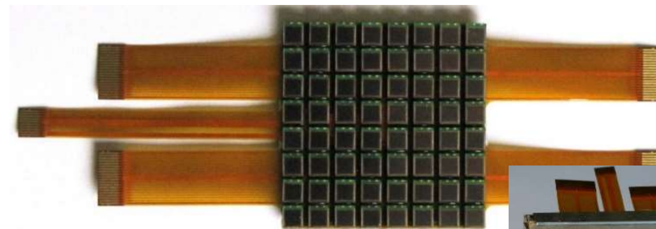
PID: ARICH

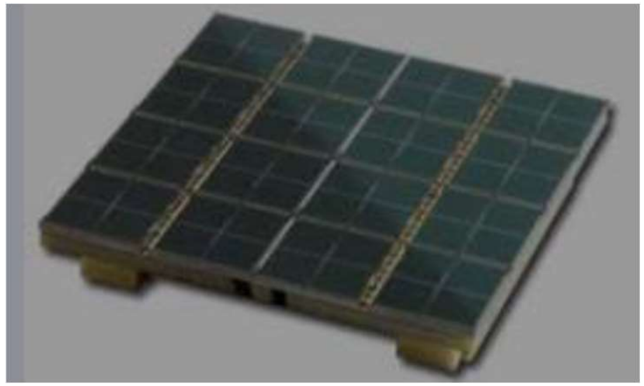
No modifications planned for the LS1+LS2.

Long term studies:

-Photon detector upgrade (SiPMs or MCP-PMTs/LAPPD)

- SiPMs: irradiation tests underway of various Hamamatsu sensors
- LAPPD 20cm x 20cm at hand since end of Dec 2021, first studies
- Read-out: two options under study, custom development and FASTiC (developed for the next upgrade of LHCb RICHes)





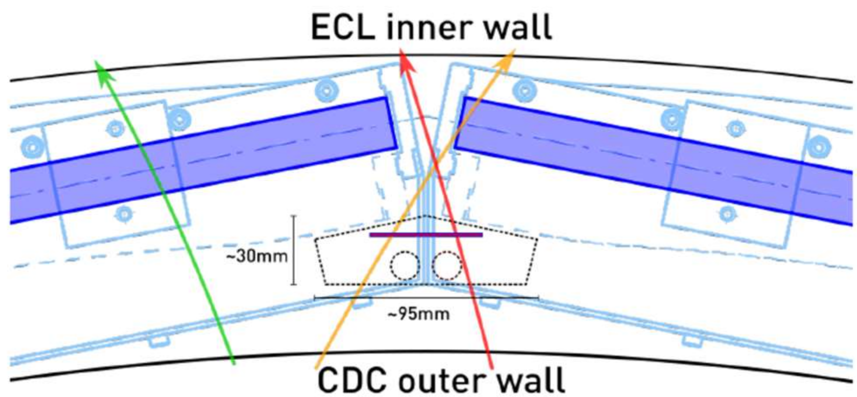
-Impact of possible aerogel upgrade is under investigation

→ Talk by Samo Korpar

PID: STOPGAP

Take advantage of development of fast CMOS sensors

1) Proposal to fill the gaps in the TOP detector with a ~1cm^2 granularity: improve K detection efficiency in TOP by covering the full solid angle - kaon ID coverage increased by O(10%).



2) Proposal to add one or two full timing layers at lower radii (250mm, 450mm) to provide PID for low momenta in the context of a larger VXD; trigger

Interesting concept for longer term upgrades. R&D needed

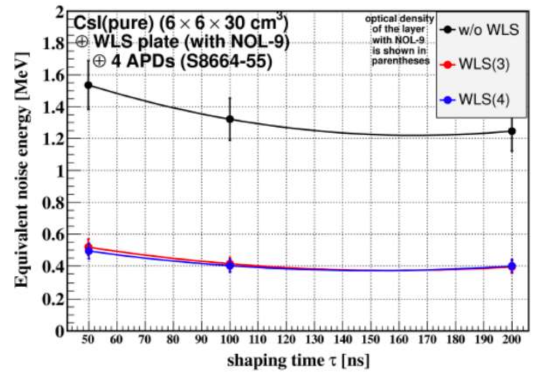
Calorimetry: ECL

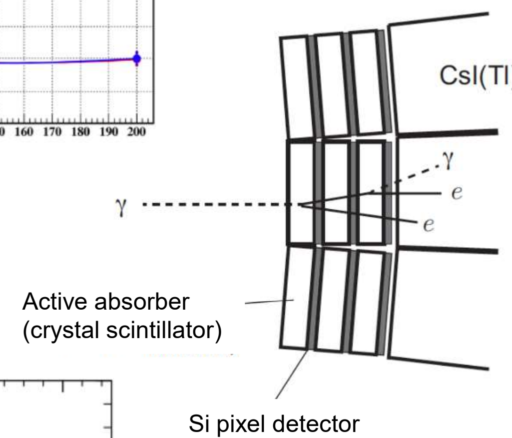
Hypotheses for long term upgrades

CsI(Tl) --> pure CsI

- Improves pile-up
- WLS employed to improve

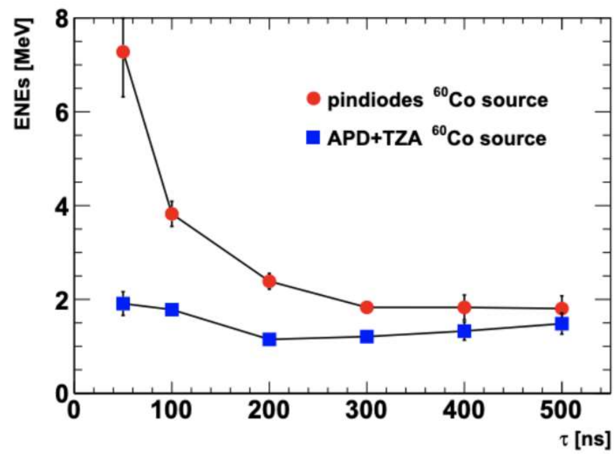
Equivalent Noise Energy





Preshower detector

- Help reduce background and pileup
- Determine photon direction, timing



PiN diodes --> APDs

- Reduce ENE, improve resolution

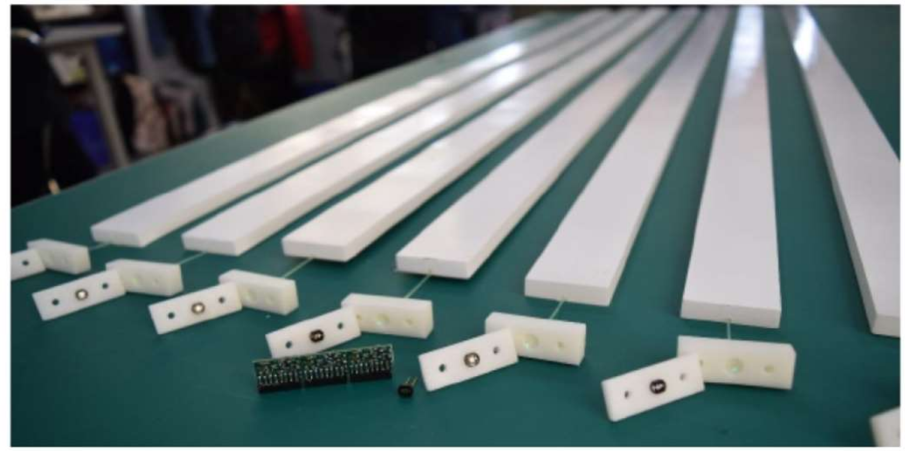
All complex and expensive options

→ Longer time scale

Muon and K_L detector: KLM

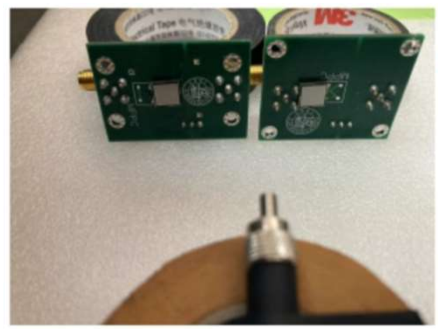
RPCs → scintillator bars + WLS fiber + SiPM

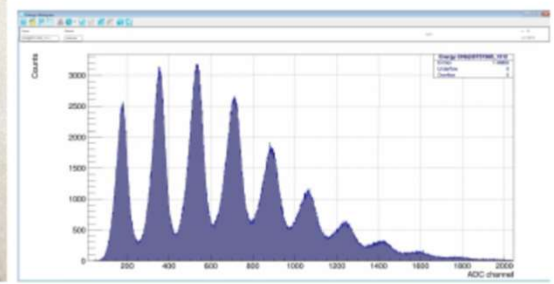
- Already done in first layers and endcap
- Increase rate capability



Readout electronics upgrade

- More compact readout
- Data push architecture possible





SiPM sensors with newly designed PAs, tested by laser light

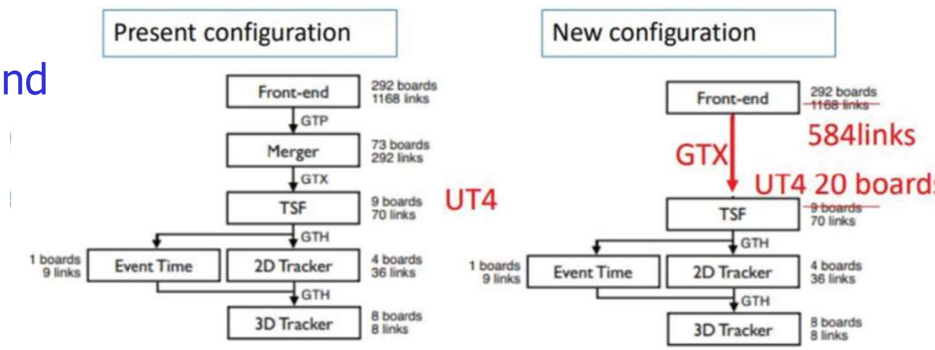
Possible use as TOF detector

- Required time resolution around 100ps
- Improve K_L identification
- Ongoing studies of scintitllators and SiPMreadout arrangement for high time resolution

Trigger

Upgrade

- More powerful UT4 board for new CDC Front End
- Avoid merger boards, more bandwidth, use all CDC TDC and ADC information
- Many trigger improvements possible.
- Detailed technical documents in preparation



Component	Feature	Improvement	Time	#UT
CDC cluster finder	transmit TDC and ADC from all wires with the new CDC front end	beamBG rejection	2026	10
CDC 2Dtrack finder	use full wire hit patterns inside clustered hit	increase occupancy limit	2022	4
CDC 3Dtrack finder	add stereo wires to track finding	enlarge θ angle acceptance	2022	4
CDC 3Dtrack fitter (1)	increase the number of wires for neural net training	beamBG rejection	2025	4
CDC 3Dtrack fitter (2)	improve fitting algorithm with quantum annealing method	beamBG rejection	2025	4
Displaced vertex finder	find track outside IP originated from long loved particle	LLP search	2025	1
ECL waveform fitter	improve crystal waveform fitter to get energy and timing	resolution	2026	–
ECL cluster finder	improve clustering algorithm with higher BG condition	beamBG rejection	2026	1
KLM track finder	improve track finder with 2D information of hitting layers	beamBG rejection	2024	–
VXD trigger	add VXD to TRG system with new detector and front end	BG rejection	2032	–
GRL event identification	implement neural net based event identification algorithm	signal efficiency	2025	1
GDL injection veto	improve algorithm to veto beam injection BG	DAQ efficiency	2024	–

Table 14: TRG firmware upgrade plan.

Options down-selection & LS2 focus

Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	now
		~~new DEPFET~~	~~medium-term~~
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
		inner part with silicon (full silicon?)	medium/long term
		~~replace with TPC w/ MPGD readout~~	~~long-term~~
TOP	PID, barrel	Replace conventional MCP-PMTs	now
		Replace not-life-extended ALD MCP-PMTs	medium-term
		STOPGAP TOF and timing detector	long-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	*γ, e ID*	add pre-shower detector in front of ECL	long-term
		Replace ECL PiN diodes with APDs	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		on-detector upgraded scintillator readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		firmware improvements	continuos
DAQ		PCIe40 readout upgrade	now
		add 1300-1900 cores to HLT	short/medium-term

future

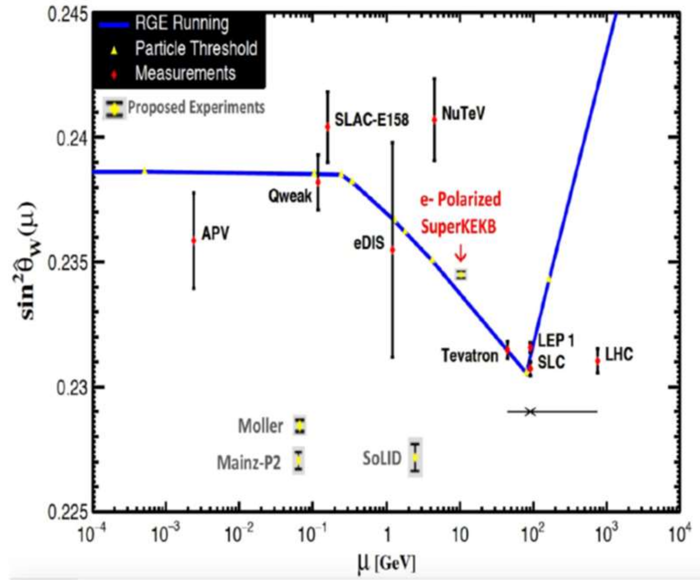
Polarized electron beam

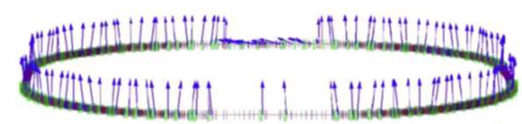
Physics case: precision $\sin^2\theta_W$ measurements at ~10GeV with b, c, e, μ & τ, probing its running and universality.

Planning 70% polarization with 80% polarized source.

New hardware for the polazation upgrade:

- Low emittance polarized Source: electron helicity can be flipped bunch-to-bunch by controlling circular polarization of source laser illuminating a GaAs photocathode. Inject vertically polarized electrons into the 7 GeV e- ring, needs a low enough emittance source to be able to inject.
- Spin rotators: Rotate spin to longitudinal before Interaction Point (IP) in Belle II, and then back to vertical after IP using solenoidal and dipole fields
- Compton polarimeter: monitors longitudinal polarization with <1% absolute precision, provides real-time polarimetry. Use tau decays from e+e-→ τ+ τ- measured in Belle II to provide high precision absolute average polarization at IP.





e- spin vector around ring

→ Project under active development

Summary and outlook

Belle II and SuperKEKB have started a successful physics run

Machine improvements are being studied and implemented to reach target luminosity

Detector upgrade ideas are being explored and R&D is in progress

- more robustness against background and radiation damage
- more physics performance
- readiness for interaction region redesign

The Belle II upgrade organization is in place

- Upgrade Working Group and Upgrade Advisory Committee have been established to help establish priorities and direct the effort
- Belle II Upgrades Whitepaper submitted to the Snowmass process

The transition to a construction project

- The preparation of an Upgrades Conceptual Design Report is well underway, ready in June 2023

Longer term perspectives

- Important to start exploring a longer term plan for SuperKEKB and Belle II

There is lots of physics at high luminosity

Additional slides

Physics and performance challenges

Identify crucial performance challenges impacting physics reach

- Tracking at low momentum
- Vertex and IP resolution
- Calorimetry energy resolution and lepton ID
- Trigger efficiency
- K/π separation
- K_L detection

Topic	VXD	CDC	PID	ECL	KLM
Low momentum track finding	✓	✓			
Track p, M resolution		✓			
IP/Vertex resolution	✓				
Hadron ID		✓	✓		
K_L^0 ID				✓	✓
Lepton ID		✓		✓	✓
π^0, γ				✓	
Trigger	✓	✓			

TABLE II. Key performance requirements vs subdetector upgrades.

Topic	VXD	CDC (	PID	PID Ω	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u \ell\nu)$	✓			✓		✓
$R, P(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓				
$S, C(B \to \pi^0\pi^0, K_S^0\pi^0)$	✓	✓			✓	
$S, C(B \to \rho\gamma)$		✓			✓	
$S, C(B \to J/\psi K_S^0, \eta' K_S^0)$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches					✓	✓

TABLE III. Selected key physics channels and the subdetector upgrades that would make substantial impacts to measurement reach.

Polarized electron beam – possible scenario

Implementation Staging Planning - Initial thoughts

Stage 1: Install source and Wien Filter to produce transverse beam polarization

Stage 2: Take beam data with transverse polarization

- Single beam studies:
  - Measure transverse polarization with Touscheck effect
  - Measure transverse polarization lifetime with Touscheck effect
  - HER beam energy calibration via resonant depolarization at Υ(1S, 2S, or 3S) HER energy setting
- Colliding beams studies:
  - LER beam energy calibration at Υ(1S, 2S or 3S) using precision mass
  - Use Belle II data to study possible e+ polarization from azimuthal dependencies in di-lepton events
- In parallel, complete development of longitudinal Compton polarimeters and Spin Rotator

Stage 3: Install and Commission Compton Polarimeters and Spin Rotators

Stage 4: Collect collision data with longitudinally Polarized e- beam at IP

- find operational conditions for maximizing the luminosity
- Operation with Compton Polarimeter, cross-calibrate with Tau Polarimetry
- Initial precision physics program (electroweak, tau g-2,.. etc)

Stage 5: Program of High luminosity running with polarization

- Ultimate reach of electroweak precision; ppm tau g-2 informing mu g-2 SM tension; …

Potentially rewarding program with an injection of new ideas and resources.
Need to ramp up attention and interaction with SKB and KEK.