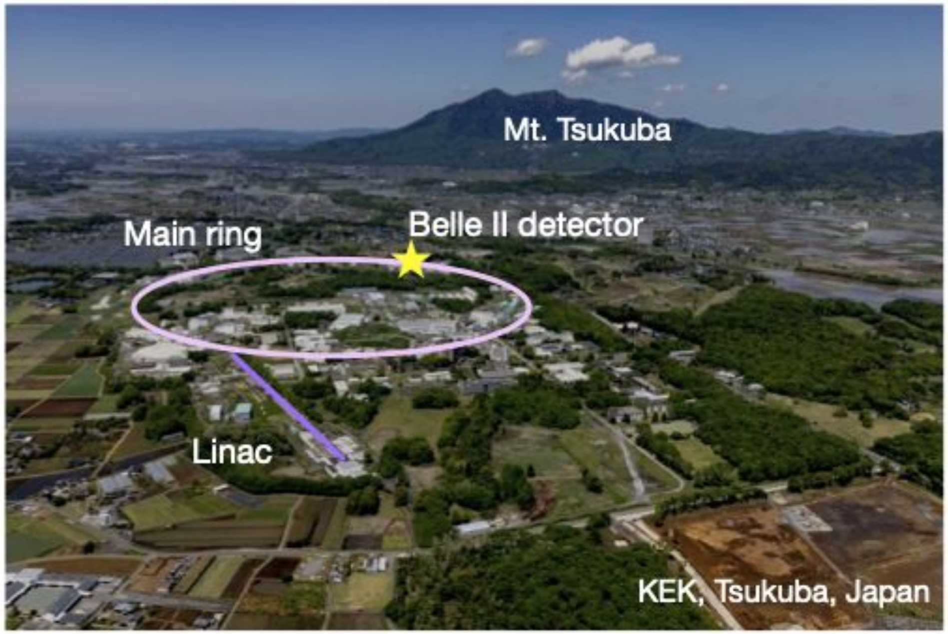
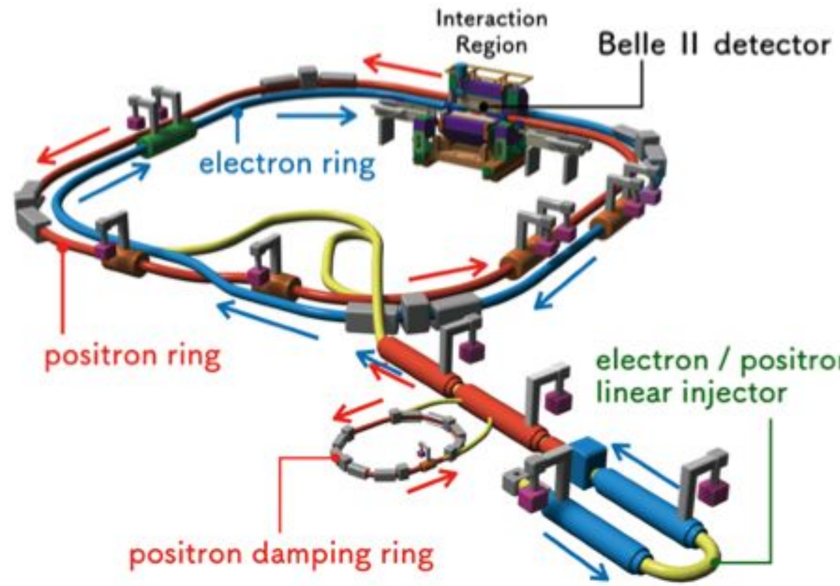
Belle II CDC

Operations and R&D

SuperKEKB and Belle II





e+e- asymmetric energy collider at Y(4S) mass

HER 7 GeV
LER 4 GeV

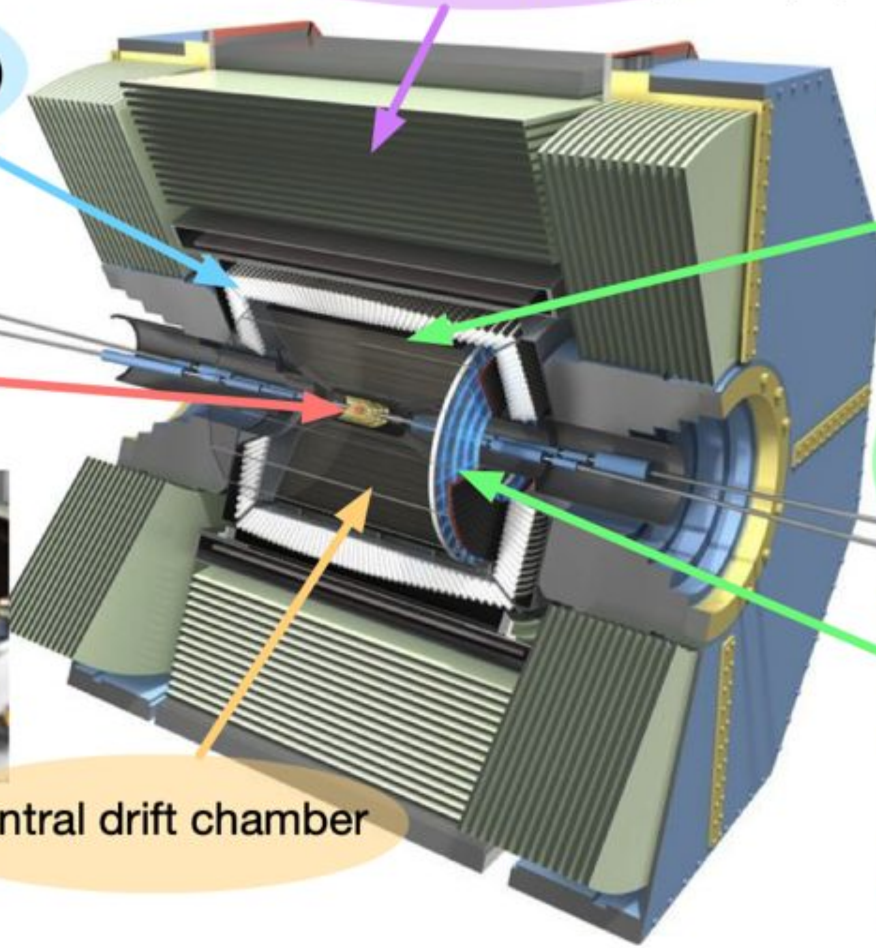
Target luminosity 6x10^35 cm-2 s-1

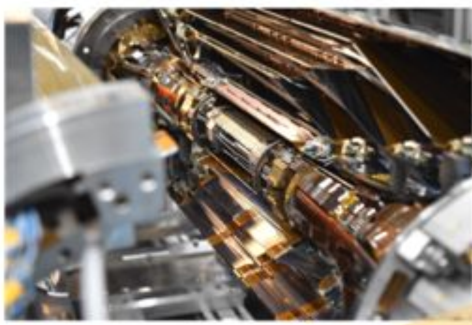
Belle II detector

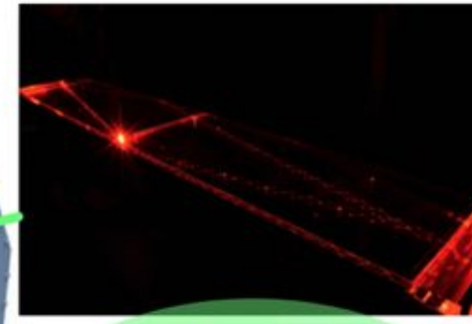
KL and muon detector
resistive plate counter (barrel)
scintillator+WLSF+MPPC (endcaps)

EM calorimeter; CsI(Tl)

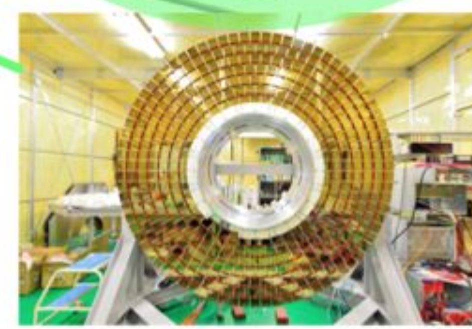
Vertex Detector
semiconductor
pixel + strip







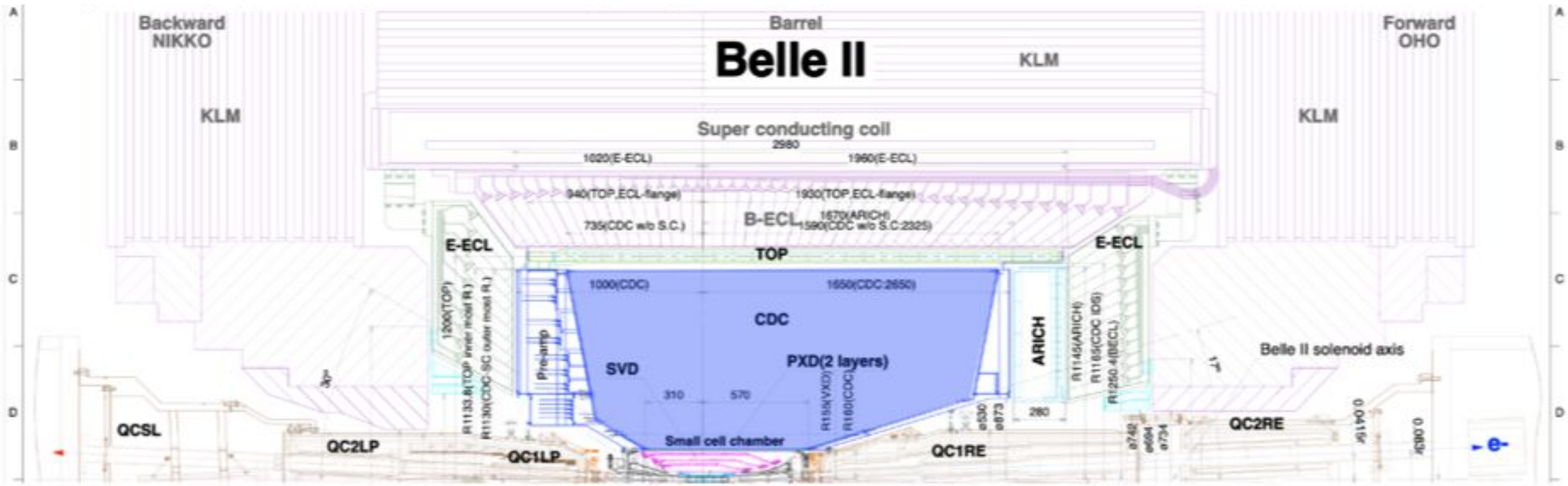
Particle ID
Time of propagation
counter (barrel)
aerogel RICH (endcap)



Central drift chamber

challenge ! preserve detector performance
while luminosity (beam background) increases

Design considerations



The volume should fit between the vertex detector and particle ID devices

The conical endplates machined to fit final focusing magnets

A small cell chamber constructed separately and installed without in between walls

Electronic boards located only on backward endplate

Main Functionalities

- Reconstruct charged tracks:

Measurement of track momentum under 1.5 T solenoid field

- Obtain information about particle identification:

Measurement of energy loss in the gas volume

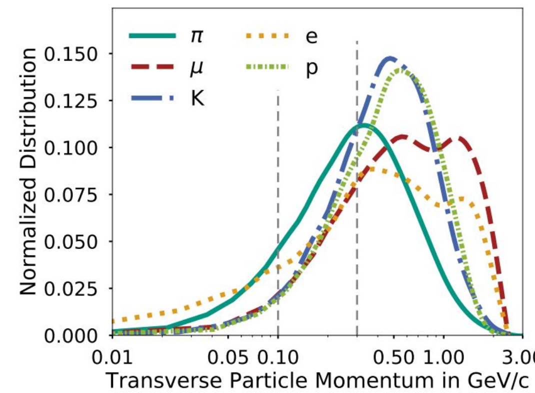
- Provide trigger signal (L1):

Short drift time and simple trigger logic

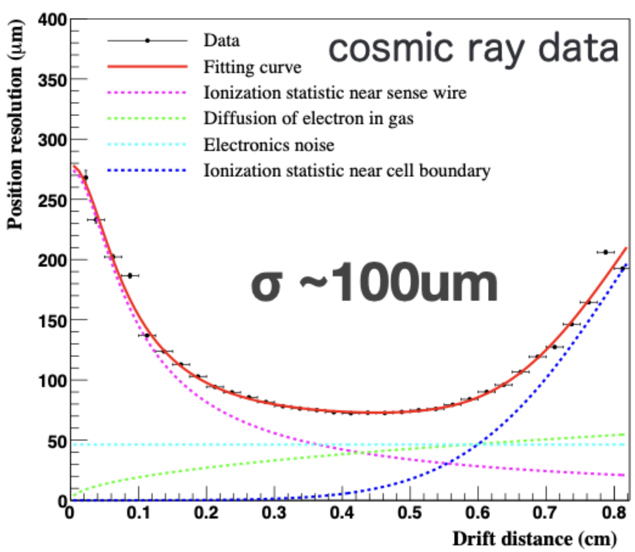
Performance

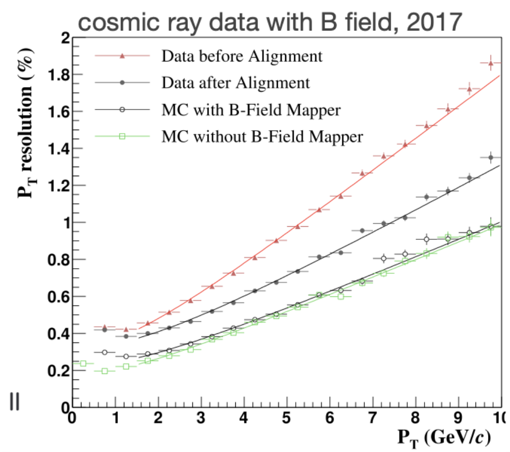
Momentum: spatial resolution and multiple scattering

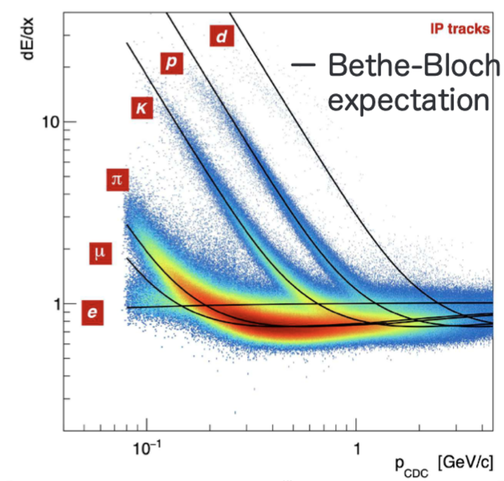
$$\frac{\sigma_p}{p} = \left(\frac{\sigma_p}{p}\right)_{\text{meas.}} \times p \oplus \left(\frac{\sigma_p}{p}\right)_{\text{MS}}$$



dE/dX: higher gas gain, good PID resolution

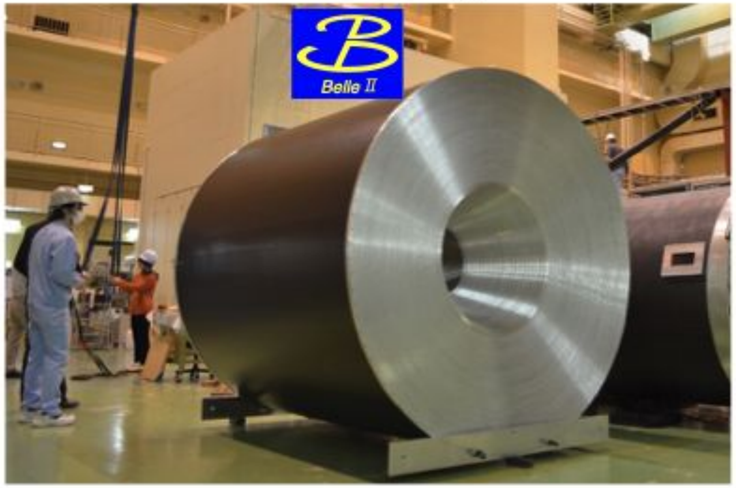


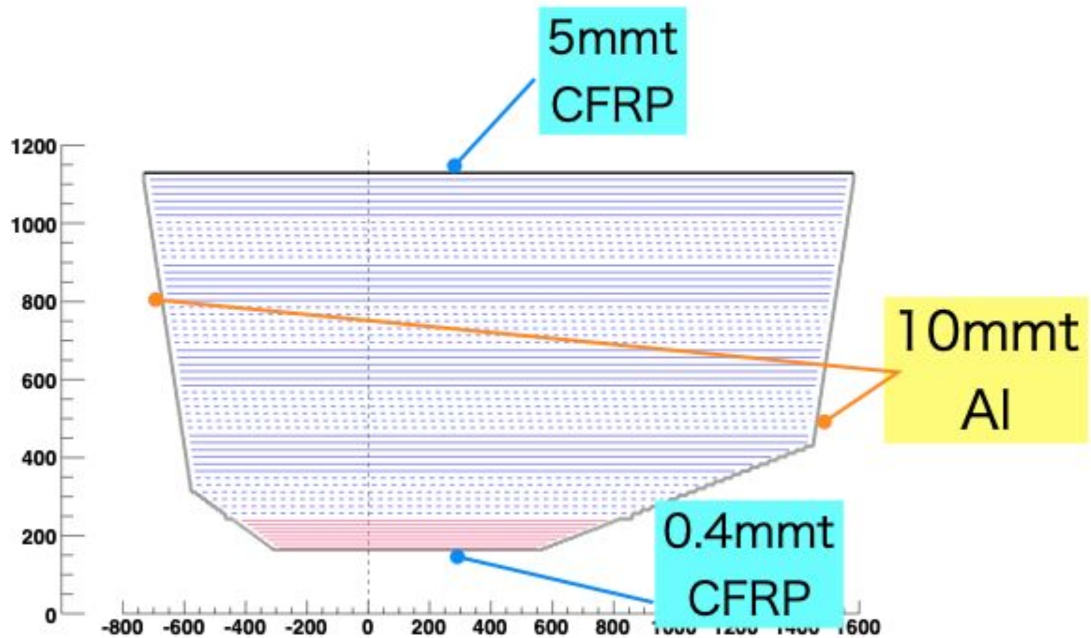




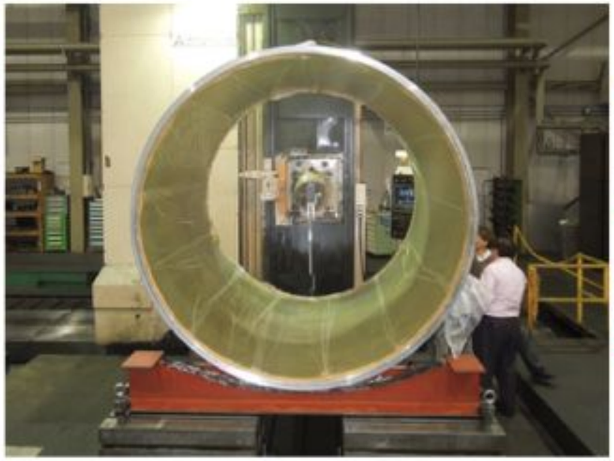
Material Budget

< 600kg





Aluminum endplate

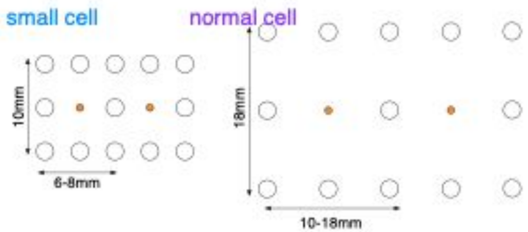


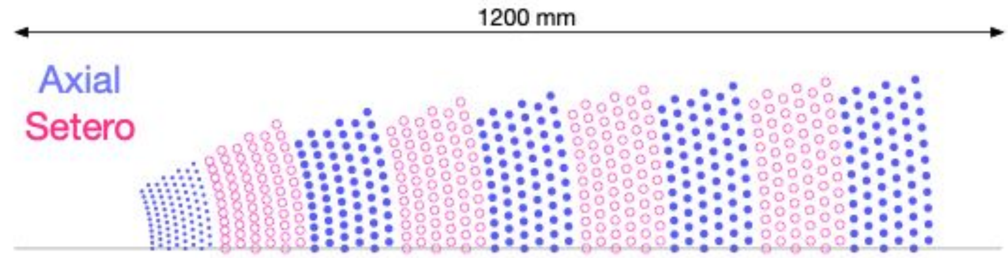
Carbon Fiber Reinforced Plastics (CFRP)

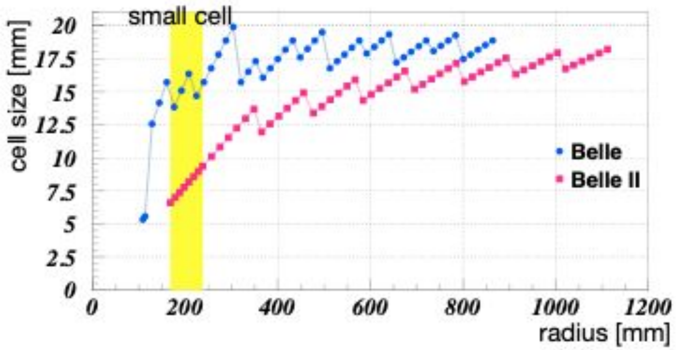
Au-W of ϕ30um; x14336
Al of ϕ126um; x 42240

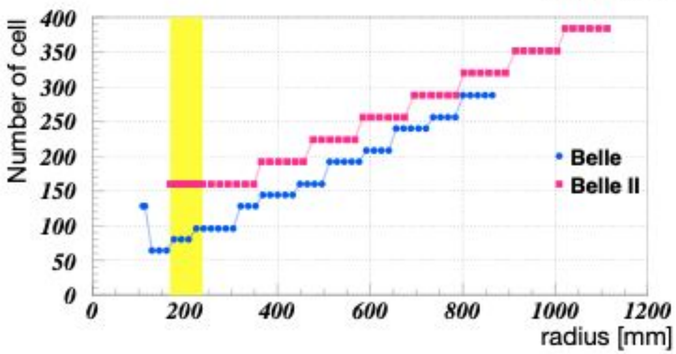
Gas; He:ethane (50:50)

Cell Configuration









- 56 layers in total
  - radius of innermost/outermost = sense wire 168/1111.4 mm
- ‘super layer’ structure
  - 5-axial super layers and 4-stereo super layers
    - stereo (+/-)45 ~ 74
  - innermost super layer = small cell (2+6 layers)
- 6 layer/super-layer; it is required by track trigger (CDCTRG)

Configuration / Structure

Anode: 30 um, Au-W, ~ 14k

- Thinner wires provide a higher electric field

Cathode: 126 um Al, ~42k

- Thicker wire reduce the cathode-side field and improve stability

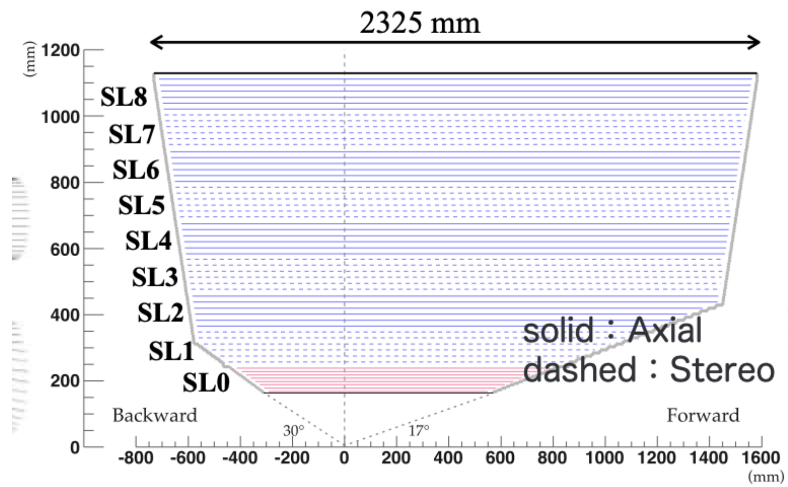
Gas: He: C_2H_6 = 50 : 50

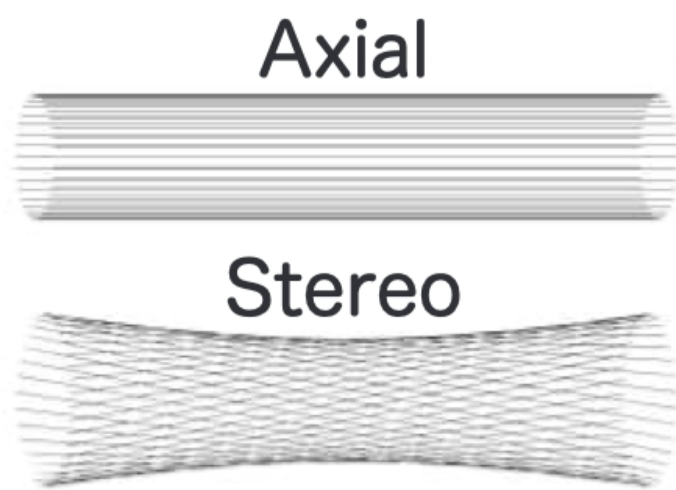
- Light gas mixture

HV: ~2300 V for 2 x 10^4 gain

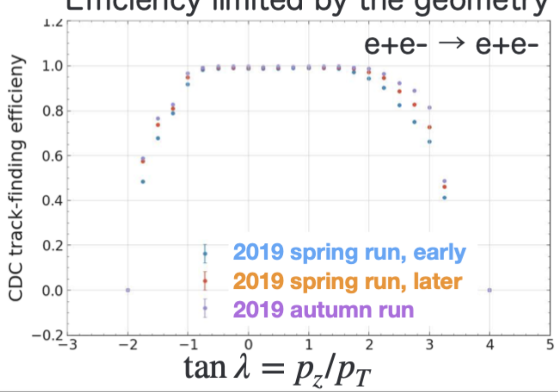
Stereo structure:

- With axial layers, only 2D
- Stereo layers also provide information along the z-axis

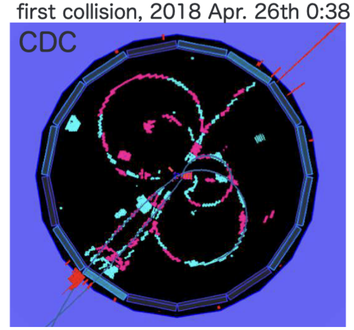




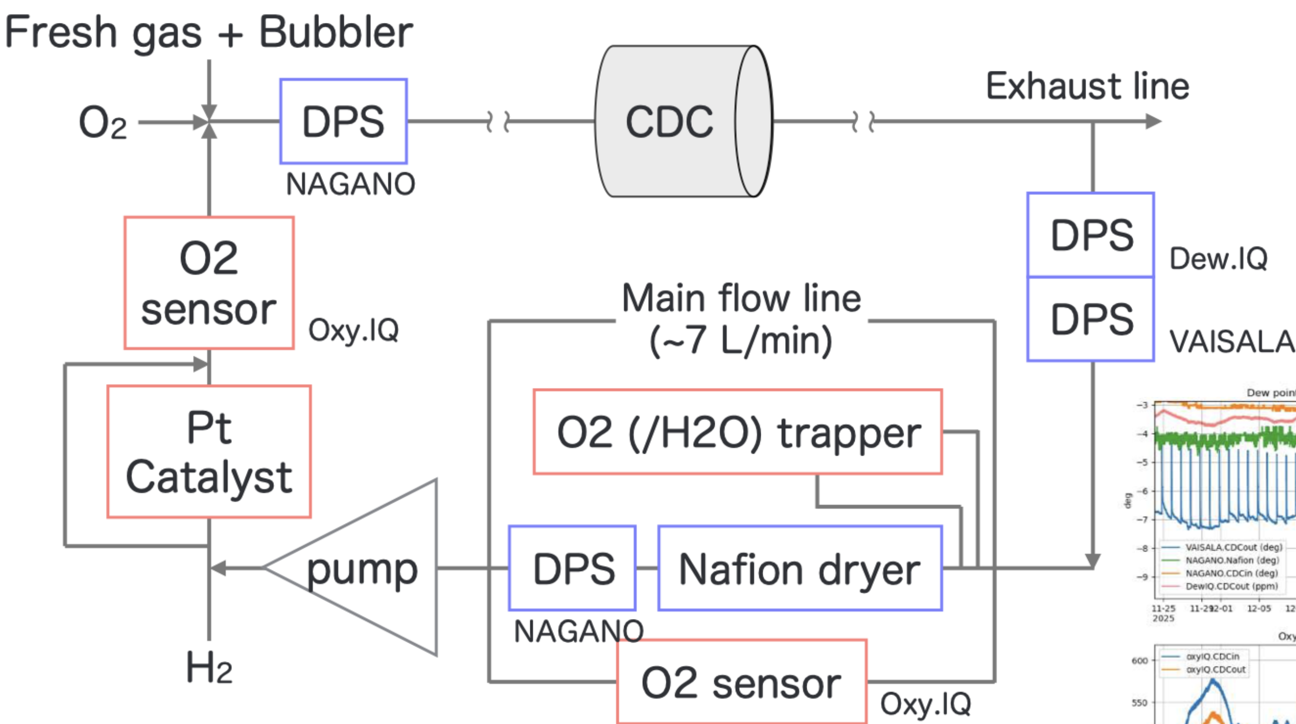
Efficiency limited by the geometry

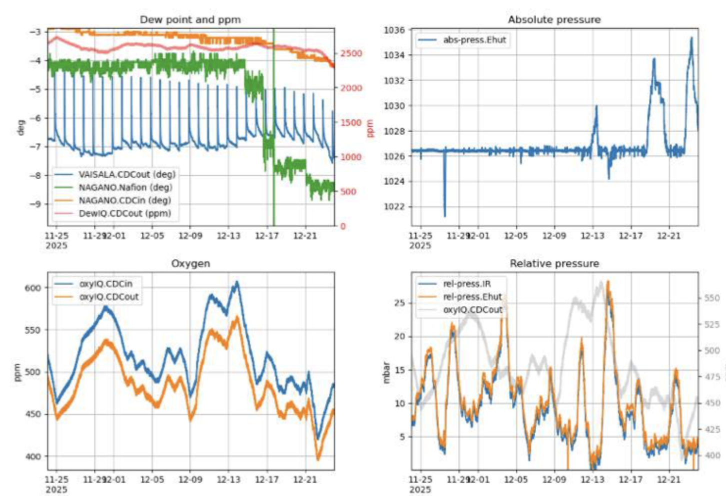


first collision, 2018 Apr. 26th 0:38



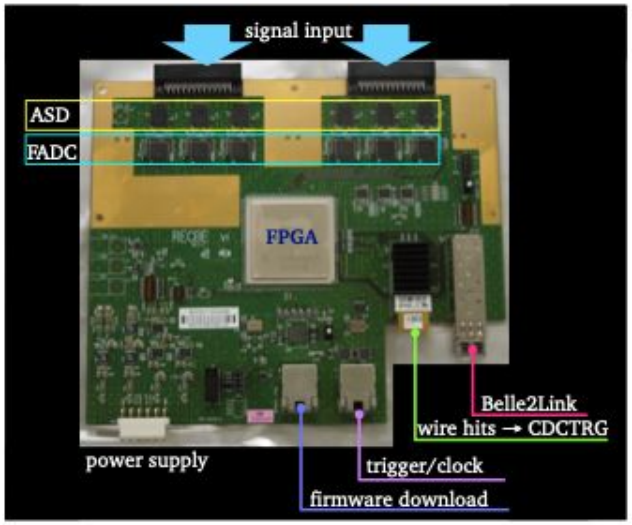
Sketch of gas system

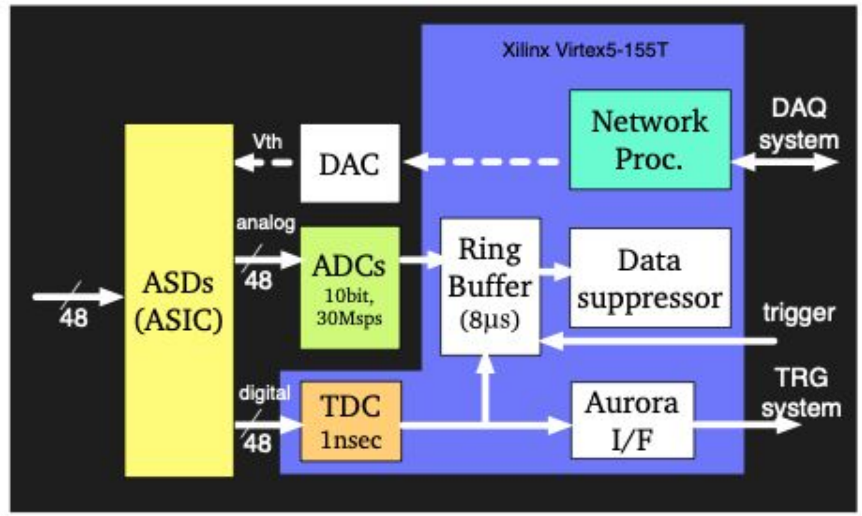




Transitioning from **~ 1 month full replacement** of **gas** to **~ 1 week** in current run *(and in the future want to achieve ~ 1 day, but need to upgrade system)*

Readout Electronics



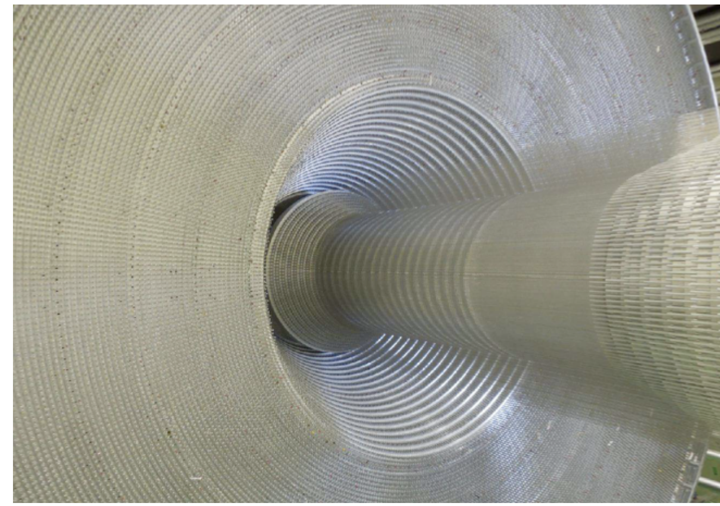


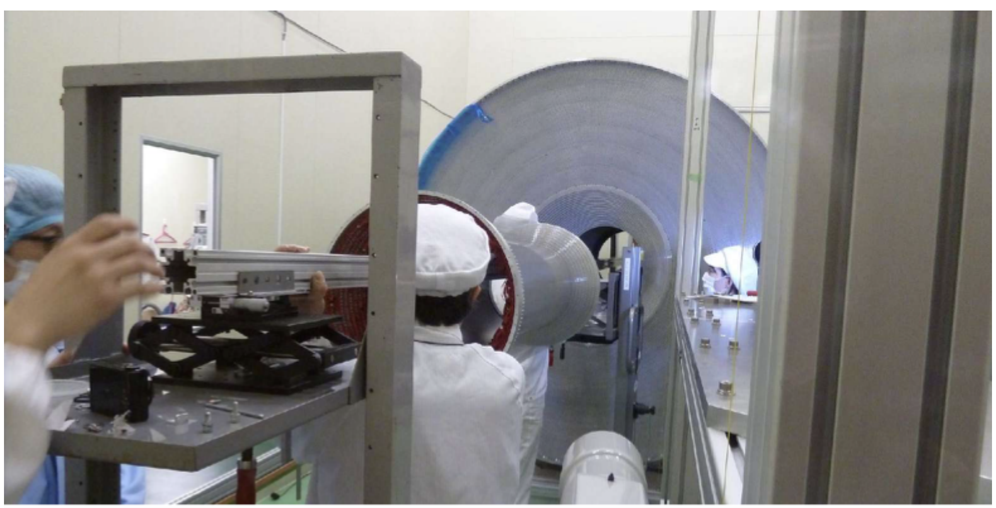
- The number of signals = 14336
- FPGA-based front-end electronics
  - TDC with 1 nsec resolution for drift time measurement
  - ADC with 32MHz sampling for dEdx (charge) measurement
  - 48ch/board

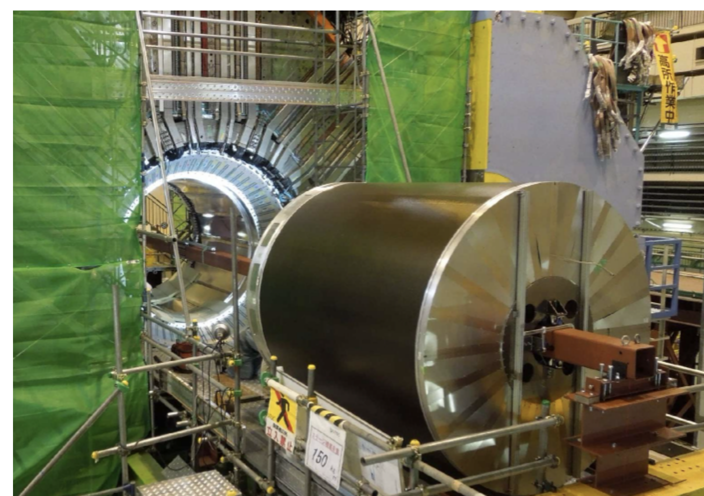
Recap Current CDC

Role: measurement of charged particles

- PID is performed using dE/dx
- From track reconstruction, determine # of particles, charge, momentum, and production vertex
- Using gas-based system keeps material budget low
    - Located centrally and has large volume
    - If the interaction rate is too high (due to e.g. large backgrounds) the correct trajectories may be degraded or lost.



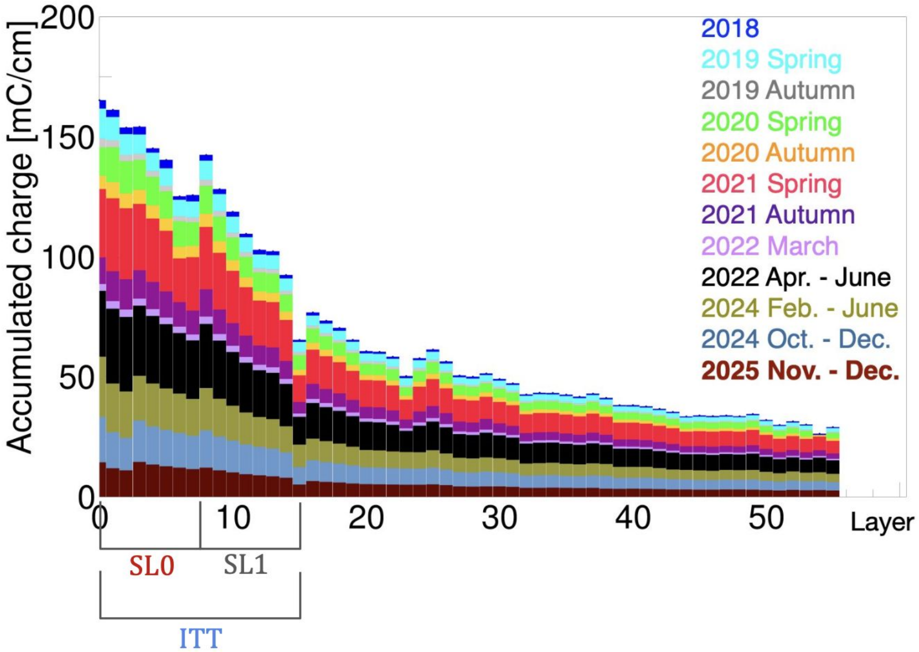




Current Situation

Large leak currents due to high backgrounds **(~300 uA → 20 nA/cm)** with luminosities of **>4.2 x 10^34**

- Near-term risk of **Malter** and gain degradation
- Long-term risk of **gain degradation** from aging effects due to accumulated charge



Innermost layers accumulate most charge (**~165 mC/cm**)

- So far, no significant gain drop observed
- Expected lifetime dose of chamber **~1-2 C/cm,** but need to investigate higher doses
- Added oxygen (500 ppm) to suppress growing of polymers and water (4000 ppm) to prevent start of polymerization
- Increased flow-rate so that the exchange rate is lowered from **1 month** to **1 week**

Current Operation strategy until 2032

Near-term risks and possible mitigation:

1. **Risk of Malter effect:**

Malter-like effect already seen in 2024c at high leak current (300 uA/layer → 20 nA/cm) and very dry conditions (1300 ppm water)

→ Mitigation via H2O/O2 control and lowered HV configuration

2. **Gain degradation due to accumulated charge:**

→ From Belle studies, 6% grain drop expected per 1 C/cm (tbc with Belle II)

3. **Gain degradation with increased leakage current**

→ Gain drop depending on current chamber is observed.

→ Origin not fully understood (voltage drop, space charge, …)

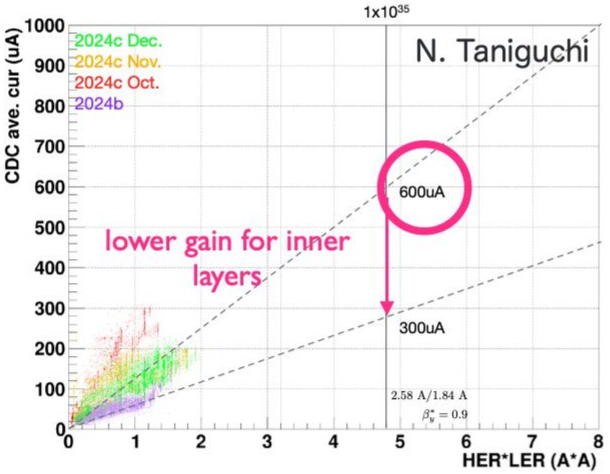
Risk of Malter effect

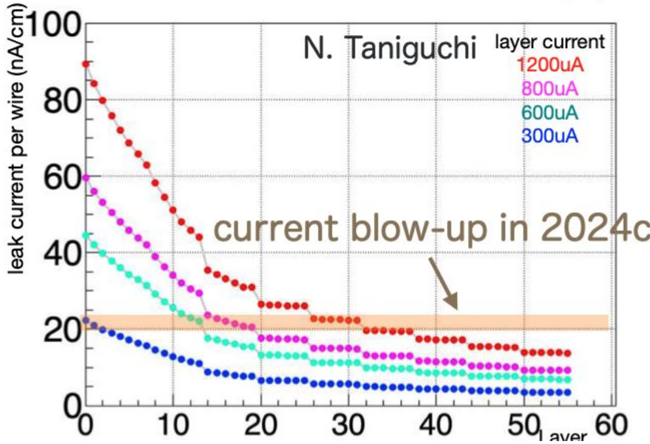
- Expected leak current in the future has large uncertainty, related to machine conditions, especially for long term projection.
  - In following tables extrapolation is based on Dec 2024 data, do not include effect of vacuum scrubbing.
  - Extrapolation based on BG simulation (CDR) is smaller, but also very uncertain due to unknown machine parameters.

	early Run 2	Run 2 target	Run 3 target
Luminosity ($cm^{-2}s^{-1}$)	$1x10^{35}$	$2.4x10^{35}$	$6x10^{35}$
HER*LER (A*A)	2.58*1.84	2.75*2.2	3.6*2.6
β_y* (mm)	0.9	0.6	0.3
leak current (uA/layer)	600	800	1200

$2.4x10^{35}$: Kyo Shibata, BPAC Sep. 24, 2024, $8x10^{35}$: design parameters

- The inner layers are at higher risk of current blow-up.
  - At the Run 3 target, even the outer layers have a potential risk of current blow-up.
- Decreasing HV reduces the risk by reducing the gain and current.





Gain degradation due to accumulated charge

- Expected gain degradation at layer 0
  - The aging effect is proportional to accumulated charge
  - Based on Belle-1 study:
    - Irradiation up to 160 mC/cm
    - 6% degradation at 1 C/cm
  - Assuming half-year operation with nominal HV

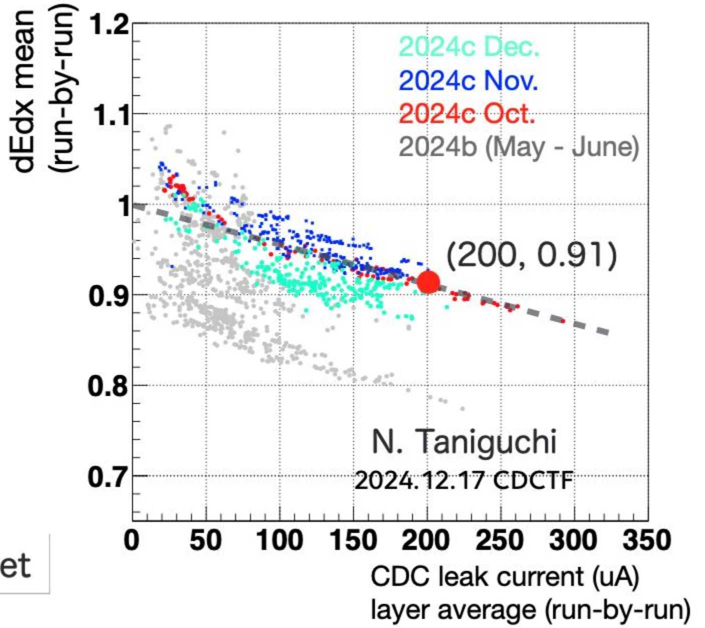
	early Run 2	Run 2 target	Run 3 target
Luminosity ($cm^{-2}s^{-1}$)	$1x10^{35}$	$2.4x10^{35}$	$6x10^{35}$
leak current (uA/layer)	600	800	1200
gain degradation per year at layer 0	~4.2%/yr	~5.6%/yr	~8.4%/yr

- The gain degradation will reach significant level by the end of Belle II.
- We plan to accelerate aging studies using two test chambers at two sites.
  - Using the current gas mixture to study the aging effect under conditions as close as possible to our own.
  - Exploring alternative candidates for future operations

Gain degradation depending on leakage current

- Gain drop depending on the wire current is observed.
  - Detailed mechanism is not understood well:
    - Voltage drop, space charge, ..?
  - Being investigated to find a possible mitigation.

- Gain drop in the future operation conditions are evaluated by linear extrapolation.



	early Run 2	Run 2 target	Run 3 target
Luminosity ($cm^{-2}s^{-1}$)	$1x10^{35}$	$2.4x10^{35}$	$6x10^{35}$
leak current (uA/layer)	600	800	1200
gain (dE/dx mean)	0.73	0.64	0.46

Understanding & treating malter ⇔ Lessons for Upgrade

Understand aging effects and study treatments; understand conditions that caused aging / malter (glue, contaminants, pollution in the gas system, etc.)

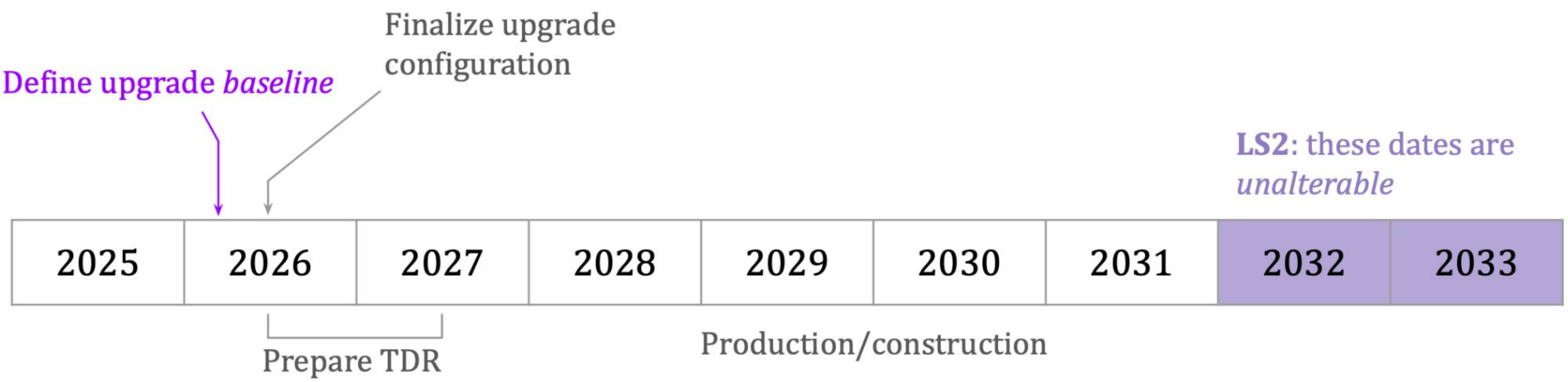
→ Imperative to keep current chamber in operational state until long shutdown 2 (LS2) in 2032

Also important lessons for post LS2 chamber design and upgrade activities

Upgrade

We are preparing a replacement of the CDC by LS2

- Need to keep the current CDC operational for at least 6 more years (until 2032)
- Need to learn all possible lessons from the current design and operation to understand where improvements can be made

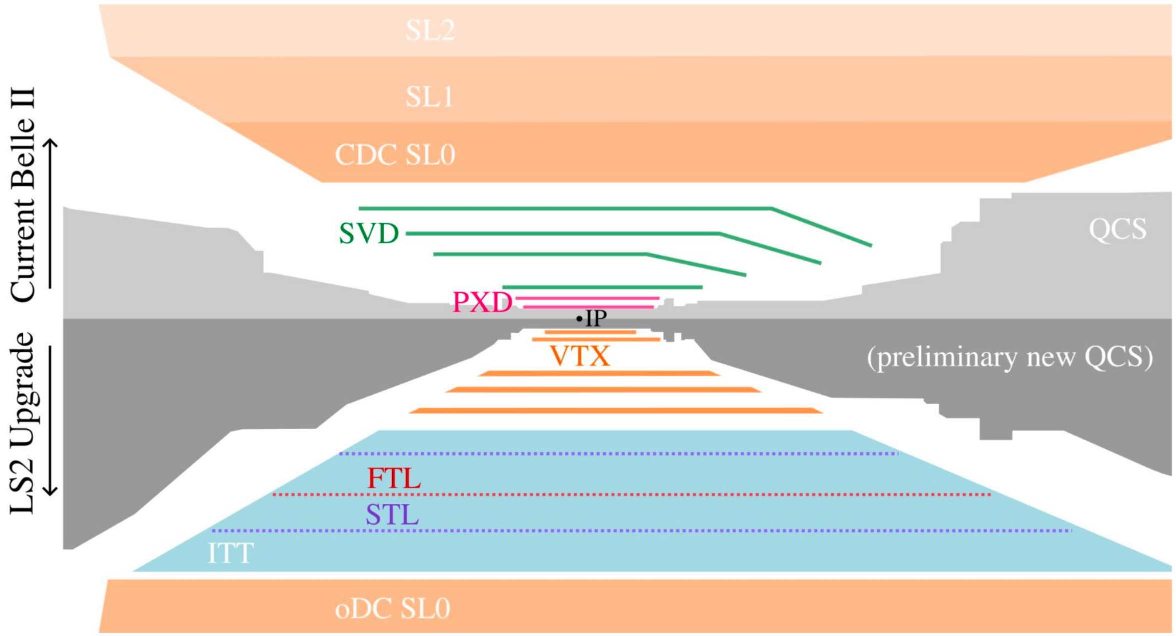


Upgrade Baseline detector

Construct only outer CDC (w/o approximately old SL0/1)

Instrument the regions with the highest occupancy with silicon detectors

- ITT: Inner tracking and timing volume
- FTL: Fast Timing Layer ; STL: Strip Transition Layer

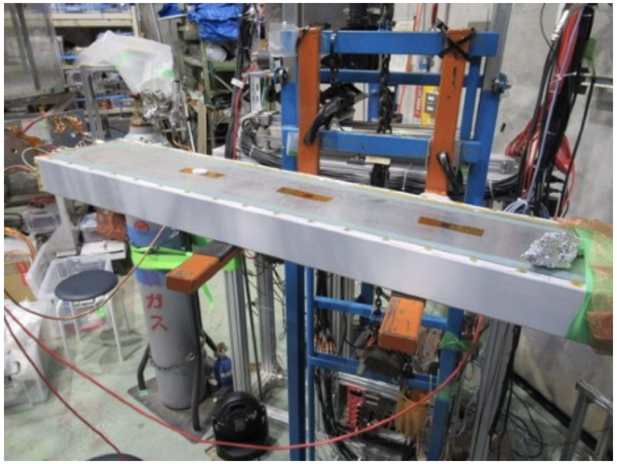


Area of Interest 1: Aging Studies

Ongoing and future accelerated aging studies with test chambers

Japan:

- Reach >1C/cm with X-ray source @ KEK
  - Intend to start this after end of 2026ab run (end of June)
  - Personpower to carry out these studies needed and outside help very welcome
- Reach ~1 C/cm with Tohoku e+/e- facility
  - Irradiated 1-m test chamber constructed with same material as CDC (wires, feedthrough, gas)
  - Same cell configuration and operational voltage as CDC
  - Gas exchange similar



Germany:

- Reach >1 C/cm with ELSA or Cyclotron in Bonn

Area of Interest 1: Aging Studies

Intend to organize new test chamber campaign in July 2026 (**proposed dates July 13th - 17th**) in Bonn to share knowledge on building test chambers

- Intend to design v2 of chamber that is shorter and easier to irradiate
- Easier to open to extract wire

Idea is to use these v2 chambers for an irradiation campaign at the GIF++ facility at CERN (possibly in Spring 2027, TBC)

These chambers will be used for aging and Malter healing studies

Intend to present plan and outcome of these studies at DRD1 meetings

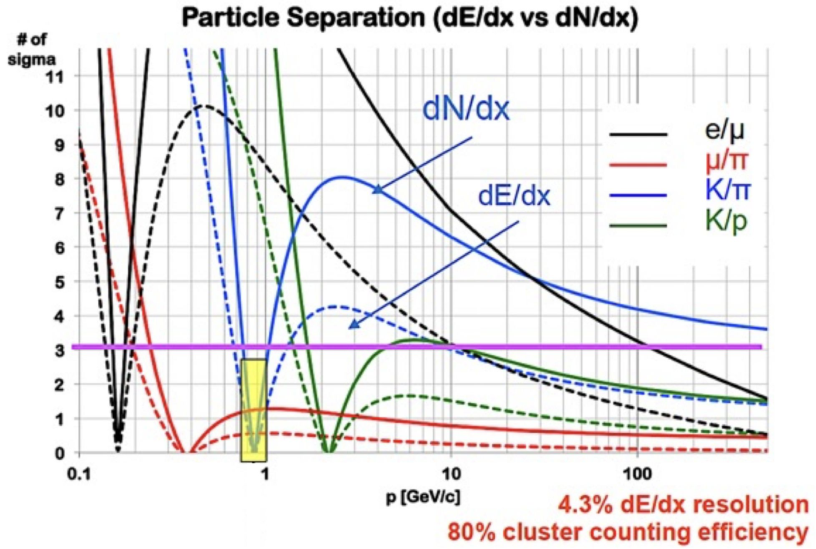
Area of Interest 2: Qualification Studies for LS2

Test of new materials, cell sizes and assembly techniques (e.g. two component glue)

- Simulation of field configurations with Garfield
  - Reoptimize cell size for helium dominant gas mixture (e.g. He:isobutane = 80-90:20-10)?
- Qualify new material and assembly techniques
- Study He:isobutane versus He:Ethane performance and aging effects
- Engineering aspects of new outer drift chamber

Area of Interest 3: Cluster Counting R&D

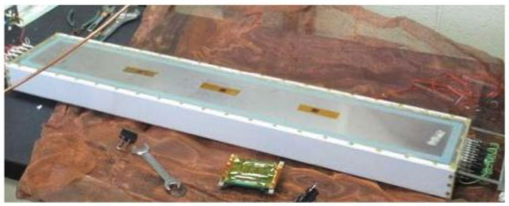
Demonstrate cluster counting with cell configuration and gas mixture using test chamber

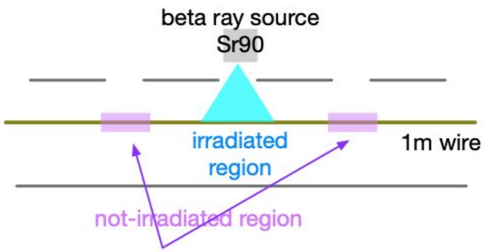


test chambers at KEK

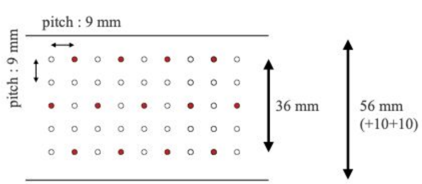
- purpose
  - (1) aging test (designed by K. Nakagiri-san)
  - (2) evaluation of electronics readout performance (by N. Taniguchi)
  - (3) measurement of analog signal from gas detector (by S. Uno)

(1) Aging Tests





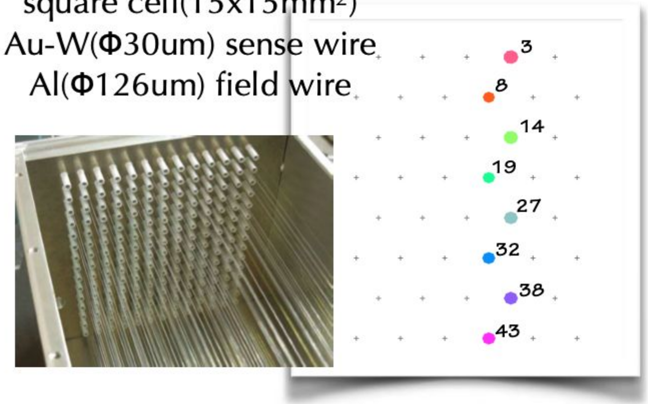
Cell structure of the test chambers



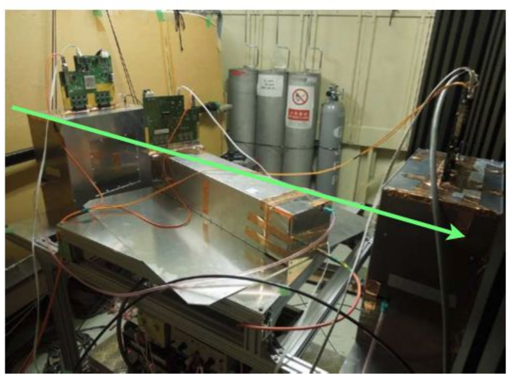
- Cell structure designed with a focus on aging tests, with the same size as the CDC itself
- Designed to irradiate the central wire
- Volume optimized considering the gas replacement rate
- Wires and feedthroughs taken from the remaining stock used for the Belle II CDC construction
- In aging tests, water and oxygen levels are critical, so the chamber is built to be gas-tight to minimize leaks from air.
- Guide strings were pre-installed, and the wire replacement was carried out with the chamber closed and glued.

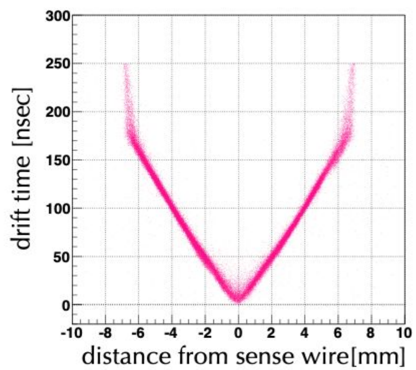
(2) Electronics Performance

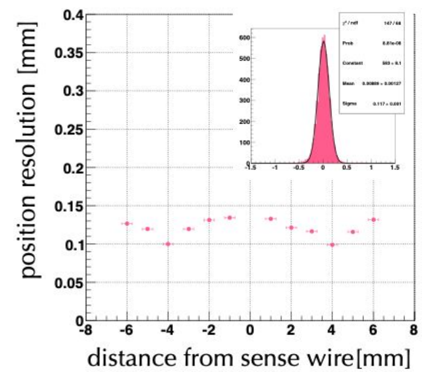
square cell(15x15mm^2)
Au-W(Φ30um) sense wire
Al(Φ126um) field wire



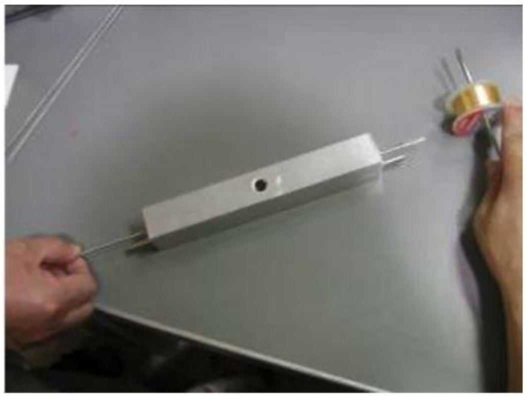
- 8 layers
- Attachment of the Belle II CDC readout board
  - full readout with 48 channels
- Gas-tightness is not required, as it is intended for short-term operation with a high gas flow rate, such as in beam tests.
- tracking
- Multiple layers were used to enable dE/dx evaluation as well

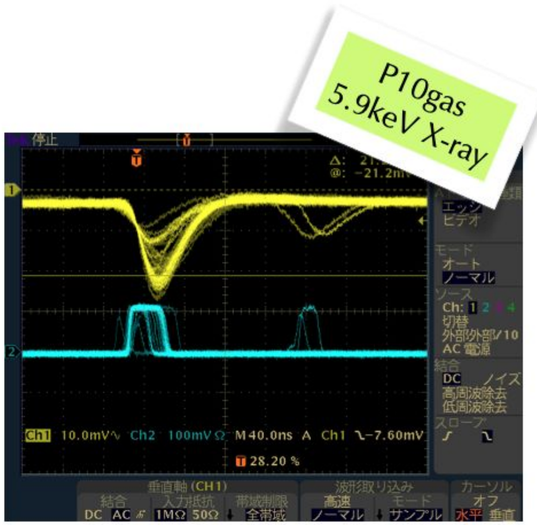






(3) Analog signal from gas detector





- single wire chamber
- measurement of analog signal using X-ray
  - gain curve, HV scan, analog signal shape..
-

Conclusion

Study of aging and Malter healing imperative for keeping current CDC operational until 2032

- Understanding these effects is also interesting for other drift chambers (e.g. for FCC, CEPC)
- Also will inform design and construction steps of new post-LS2 outer drift chamber

Belle II is very interested in collaborating on these subjects

For post-LS2 chamber, many possible studies relevant *[wire layout, cell size optimization, overall design, R&D of new read-out electronics if we want to use cluster counting], …*