Status of CDC (Central Drift Chamber) at Belle II

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The 3rd DRD1 meeting

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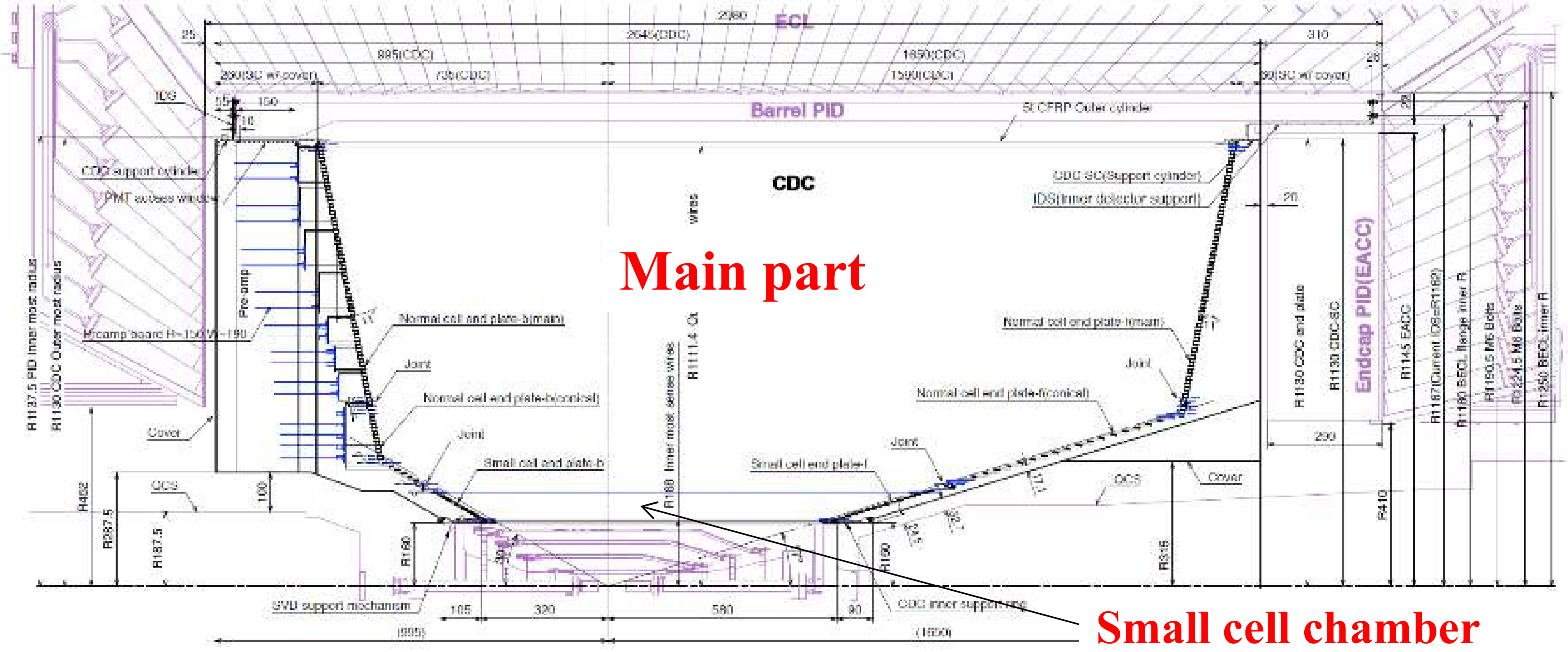
Main Features of Belle CDC

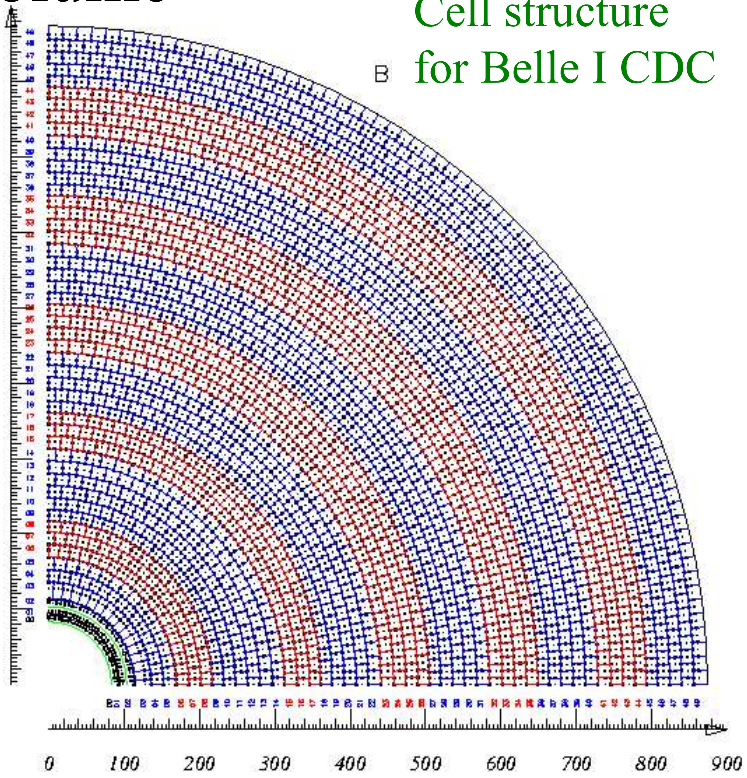
- **The volume should be fitted between vertex detector and particle ID devices.**
- The conical endplates were machined to meet final focusing magnets.
- **A small cell chamber was constructed separately and was installed without any walls between the main part.**
- Electronics boards are located at only backward end plate.
- 3D charged trigger scheme is adopted (Belle II).

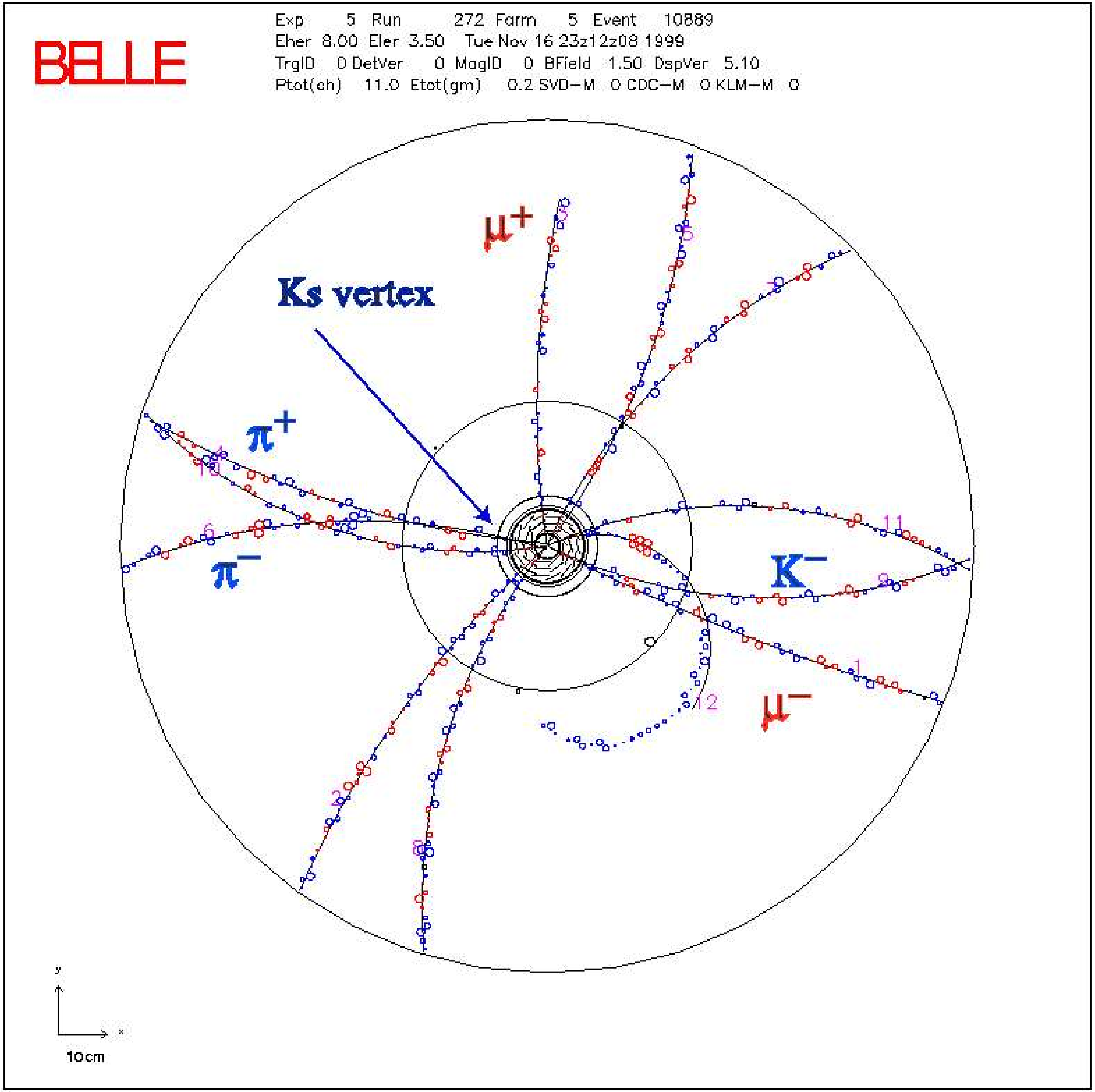


Functions of CDC

- To reconstruct charged tracks
  - Measurement of track momentum precisely under magnetic field
    - Position resolution : ~0.1mm
- To obtain information about particle identification
  - Measurement of energy loss in the gas volume
- To provide the trigger signal (L1)
  - Multi small cell type for both CDCs
    - Shorter maximum drift time
    - Simple trigger logic
  - Not TPC and not Jet cell type
    - Two track separation is not essential for the B factory.

Cell structure for Belle I CDC





BELLE
Exp 5 Run 272 Farm 5 Event 10889
Eher 8.00 Eler 3.50 Tue Nov 16 23z12z08 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.0 Etot(gm) 0.2 SVD-M 0 CDC-M 0 KLM-M 0
Ks vertex
μ+
π+
π−
K−
μ−
10cm

Accuracy on momentum measurement

$$\left(\frac{\sigma_{Pt}}{Pt}\right)^2 = (aPt)^2 + b^2$$

$$a = \frac{\sigma_{r\phi}}{0.3BL^2}\sqrt{\frac{720}{N+5}} \qquad b = \frac{0.054}{LB}\sqrt{\frac{L}{X_0}}\left[1 + 0.038\ln\frac{L}{X_0}\right]$$

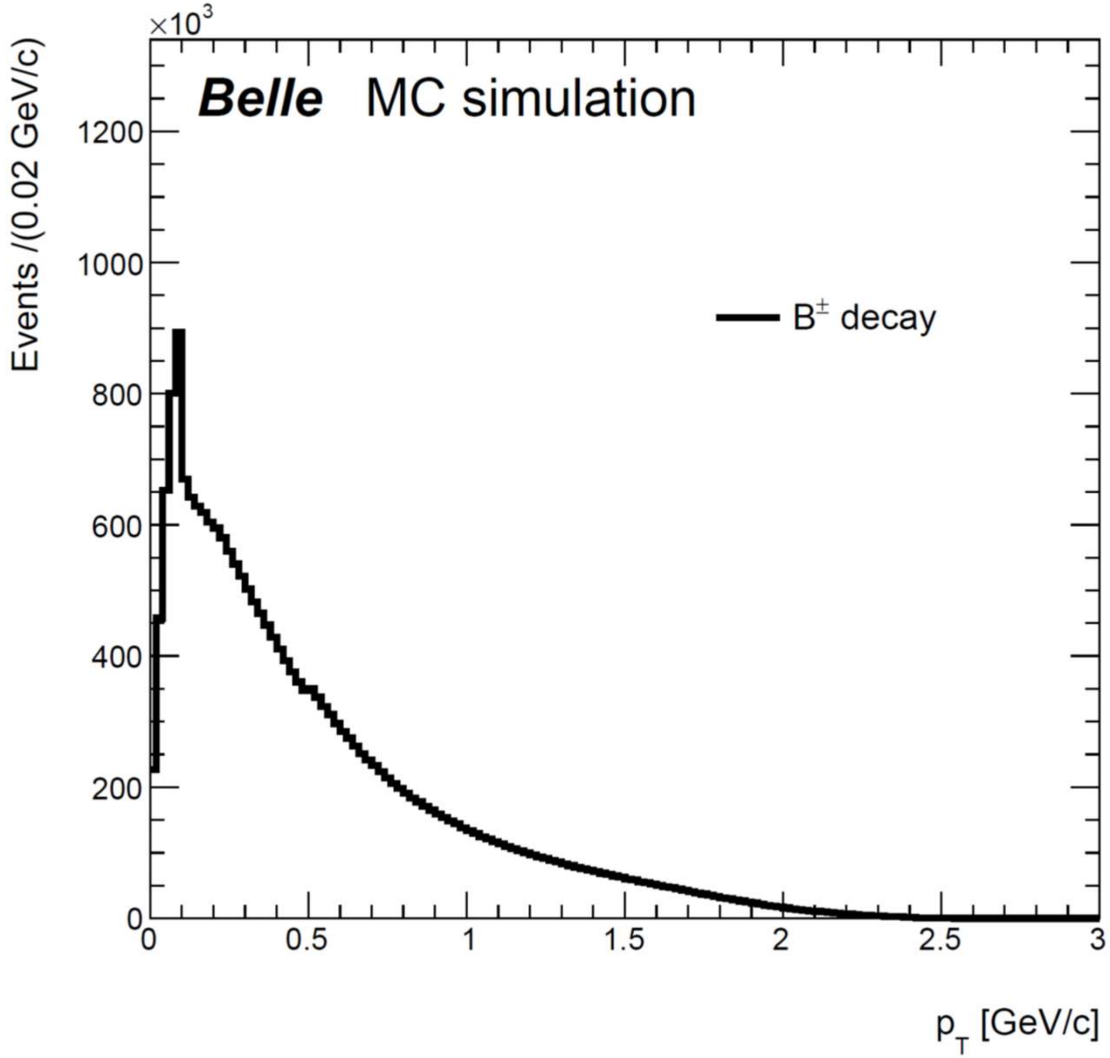
B : Magnetic field strength (Tesla)
L : Measurement lever ar (m) m (Size of chamber)
$\sigma_{r\phi}$: Measurement error for each point (m)
N : Number of measurement points
X_0 : Radiation length in gas volume (m) (material)
Pt : Transverse momentum (GeV/c)

The parameter (a) is important in higher energy experiment.
The parameter (b) is crutial in relatively lower energy experiment.

Pt distribution in B factory

- Pt for most of decay particles in the B factory is less than 1 GeV.

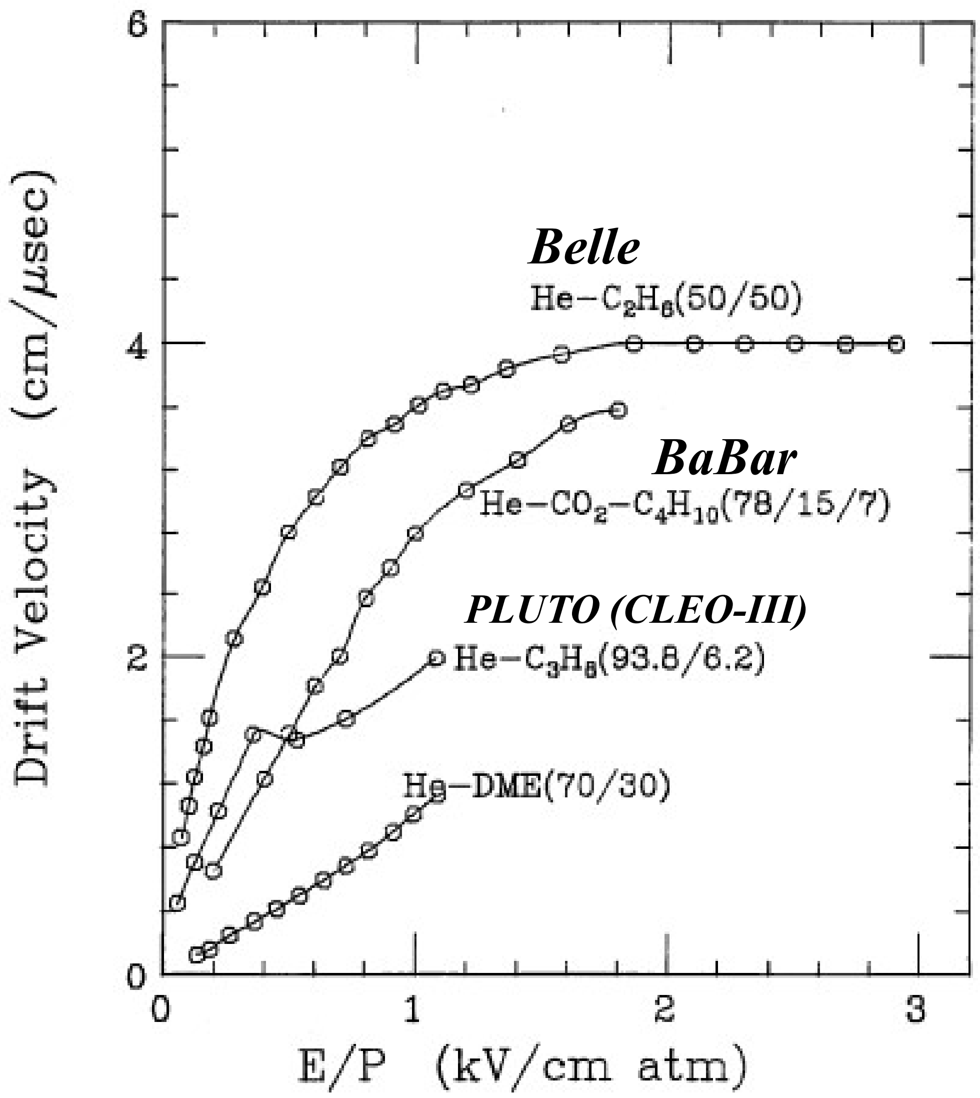
- Less material is a key to get better momentum resolution.



Chamber Gas

- He(50%)-C_2H_6(50%)

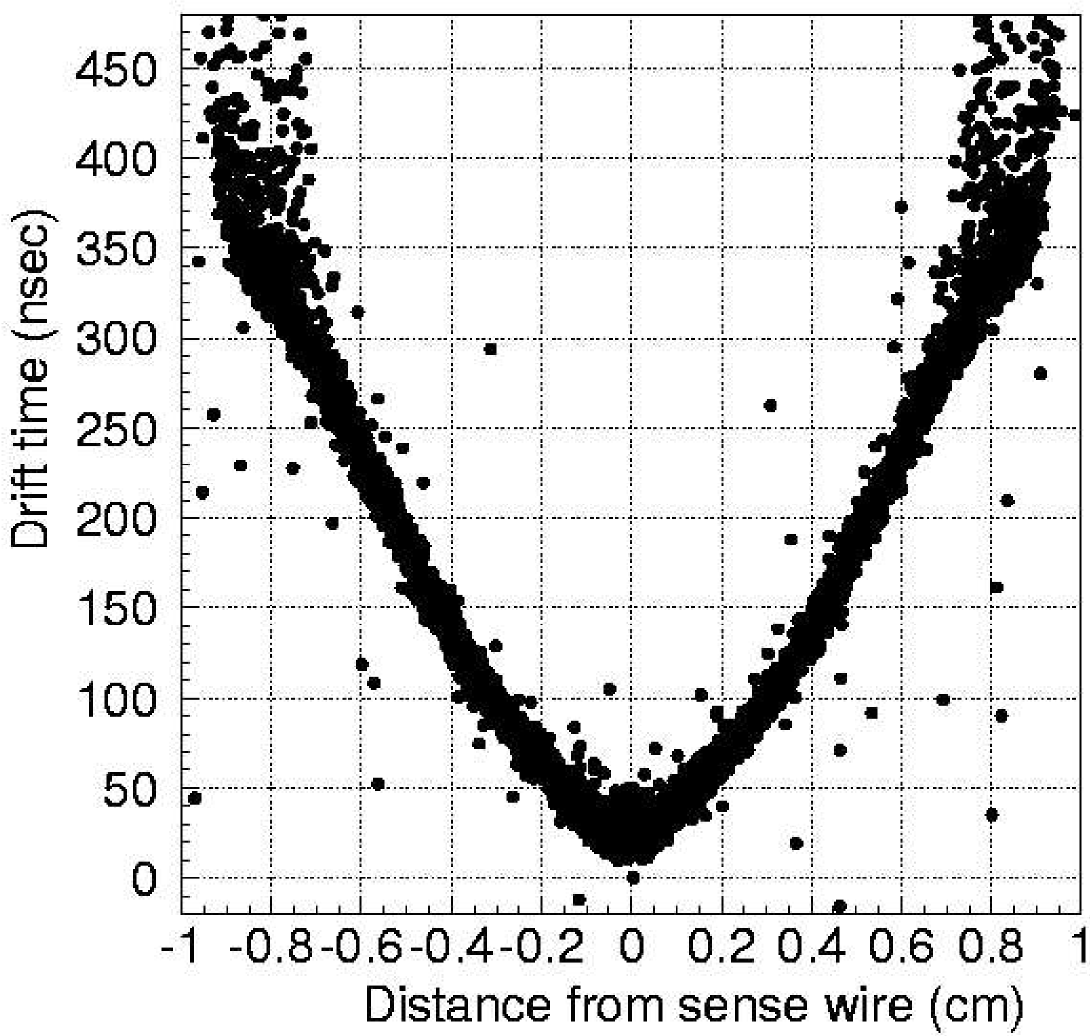
 for both CDCs
  - Longer radiation length(680n
    - 0.139% X0 in total gas volume
  - Drift velocity is higher than other He-based gas.
    - Average drift velocity :
      - ~3.3cm/μsec in the chamb cell.
    - Maximum drift time :
      - ~400nsec for 18mm cell si
  - Good dE/dx resolution.



X-T Curve

- $He(50\%)\text{-}C_2H_6(50\%)$
- B=1.5Tesla
- HV : 2.3KV
- Cell Size:18mm

- Maximum Drift Time : ~400nsec

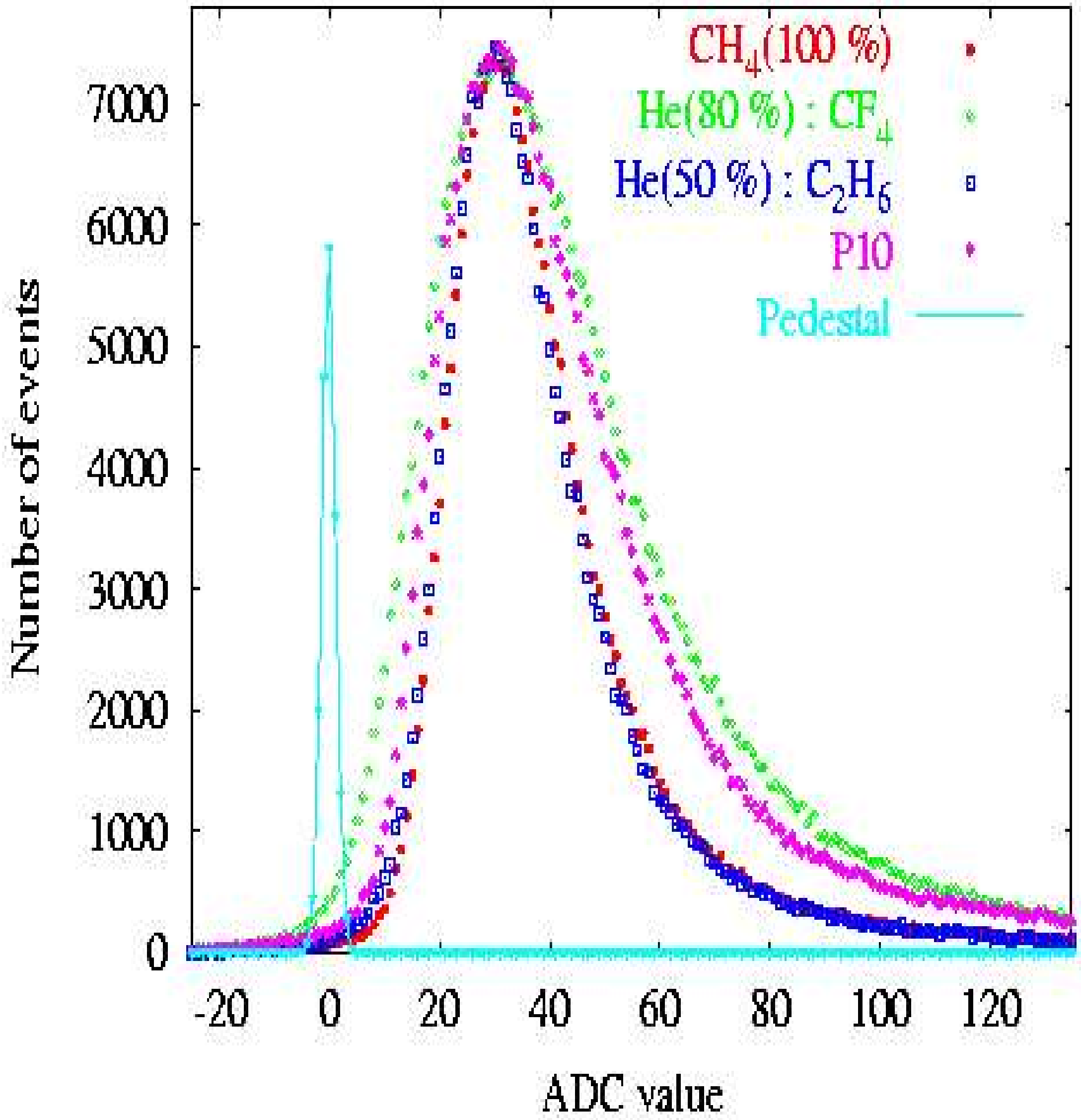


dE/dx Resolution

- The pulse heights for electron tracks from ^{90}Sr were measured for various gases.

- The resolutions for CH_4 and He(50%)-C_2H_6(50%) are same.

- The resolution for He-CF_4 is worse than Ar-based gas(P-10).



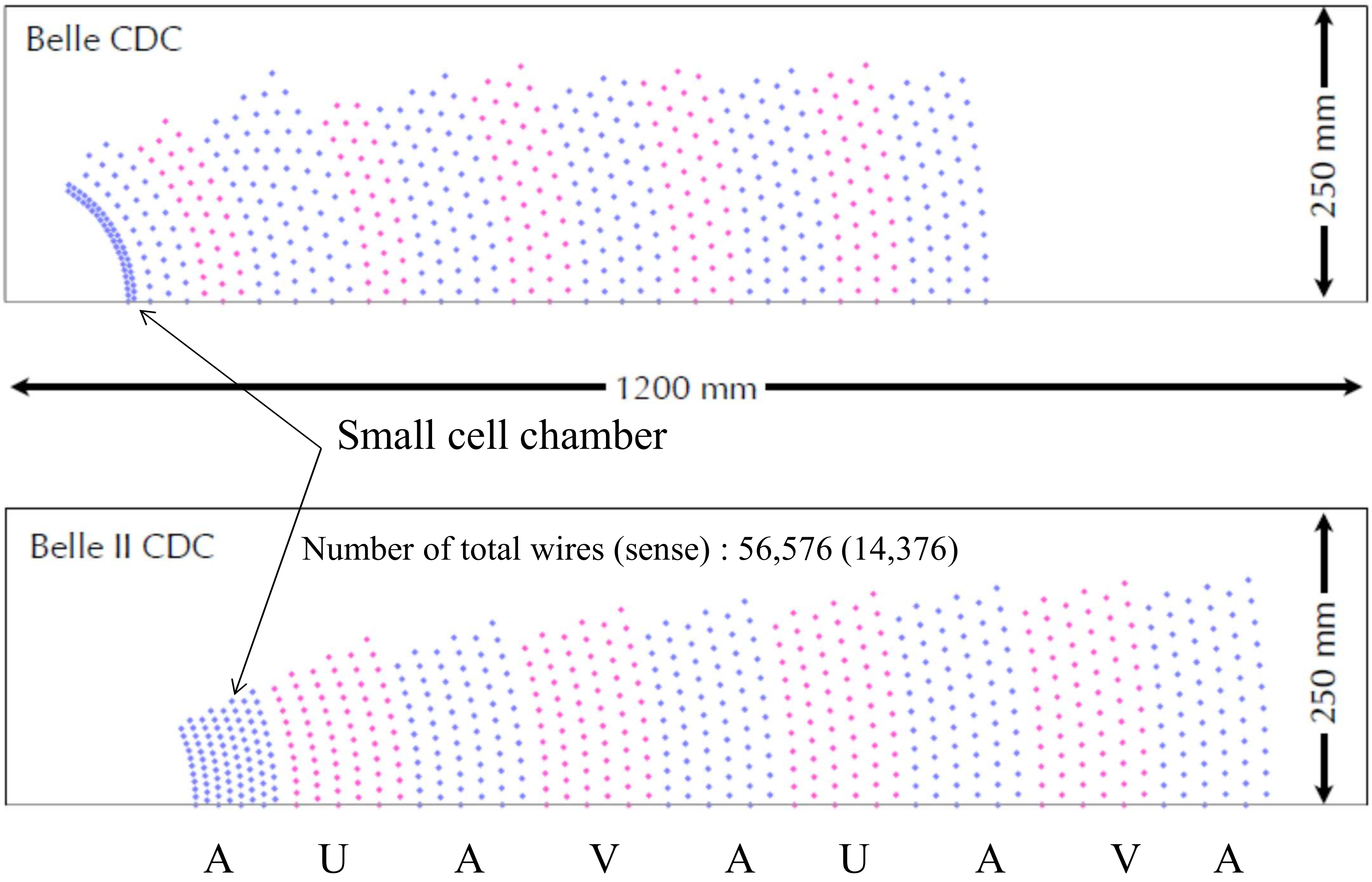
Selection of wires

- Thicker diameter is better as following reasons.
  - Sense wire : Stronger drift field
    - Drift velocity tends to saturate
    - Diffusion constant smaller
    - Lorentz angle smaller
  - Field wire : Maximum electric field on the surface should be less than 20 kV/cm to avoid radiation damage (Malter effect).

↓

- Au-W 30 μm diameter for sense wire
  - 0.072% X_0 < Al field wire
- Al (without any plating) 126 μm diameter for field wire
  - 0.147% X_0 ~ Chamber Gas (He(50%)-C_2H_6(50%))

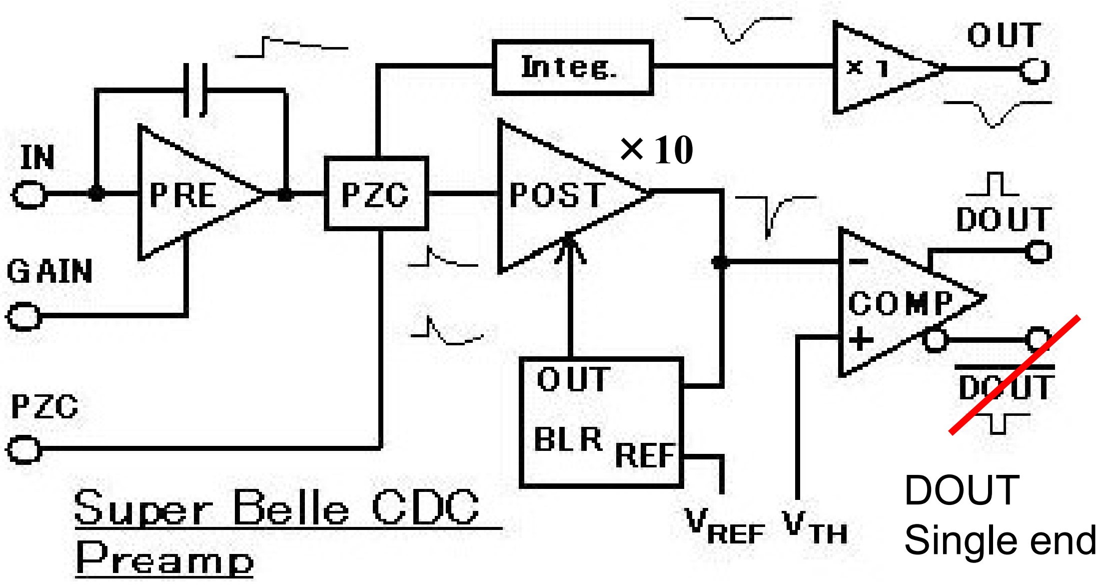
Wire configuration



9 super-layers : 5 axial + 4 stereo(2U+2V) 56 layers in total

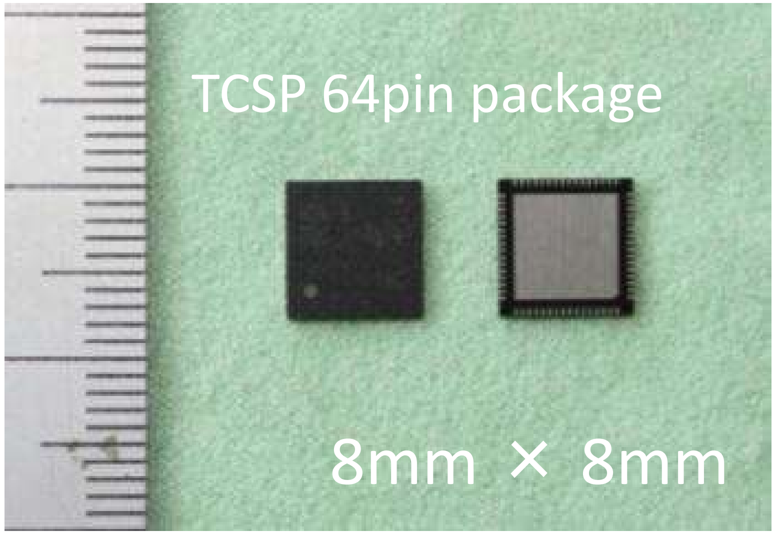
ASIC

Amp-Shaper-Discriminator (ASD) chip

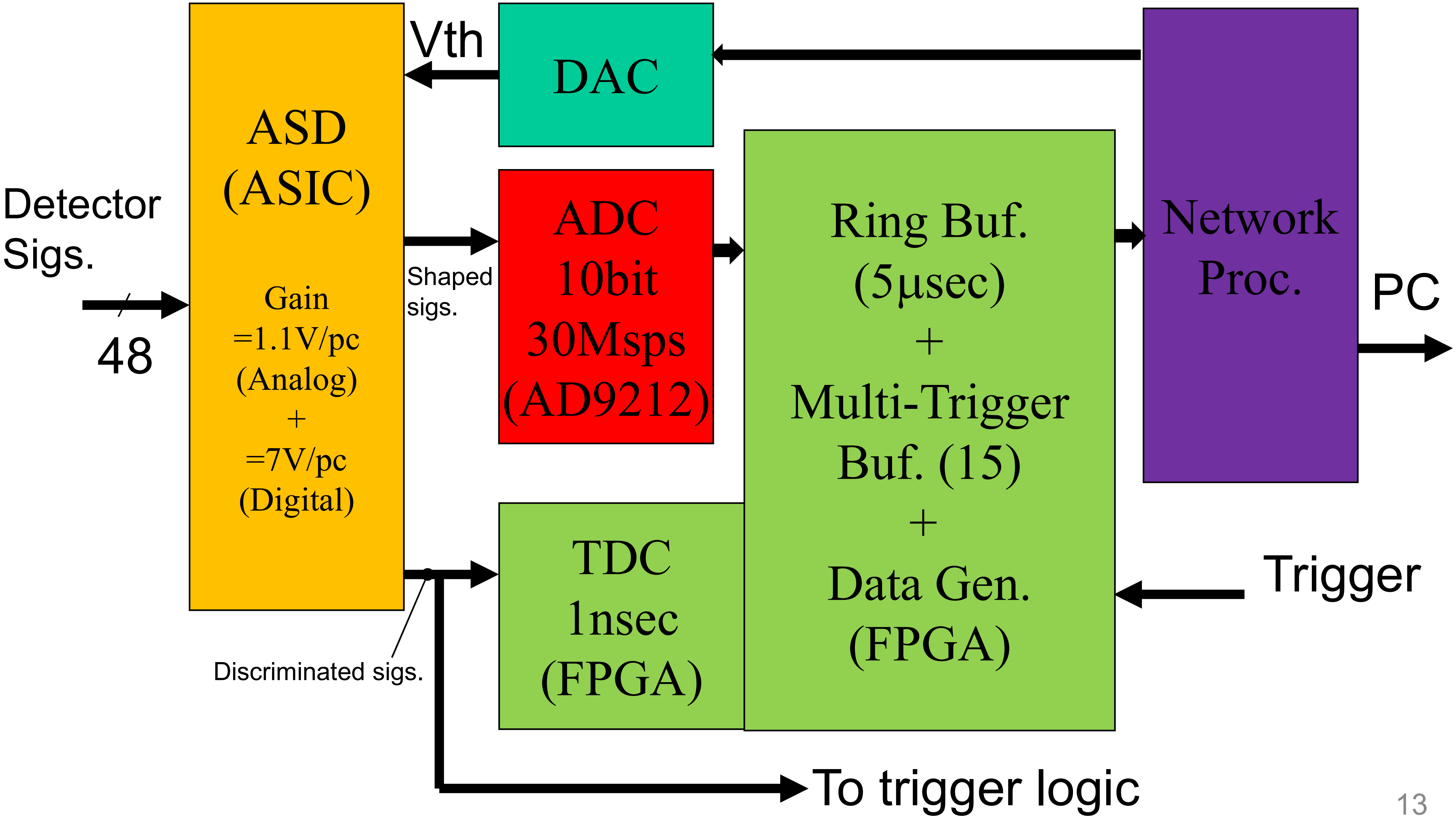


Specifications

Parameter	Value
# of Chs.	8
Analog gain	-1.1V/pC
Peaking time	8 ns
Noise	4000 e @Cd=20 pF
Power	+5V, +3.3V
Power consumption	34mW/ch
Process	BiCMOS 0.8 μm

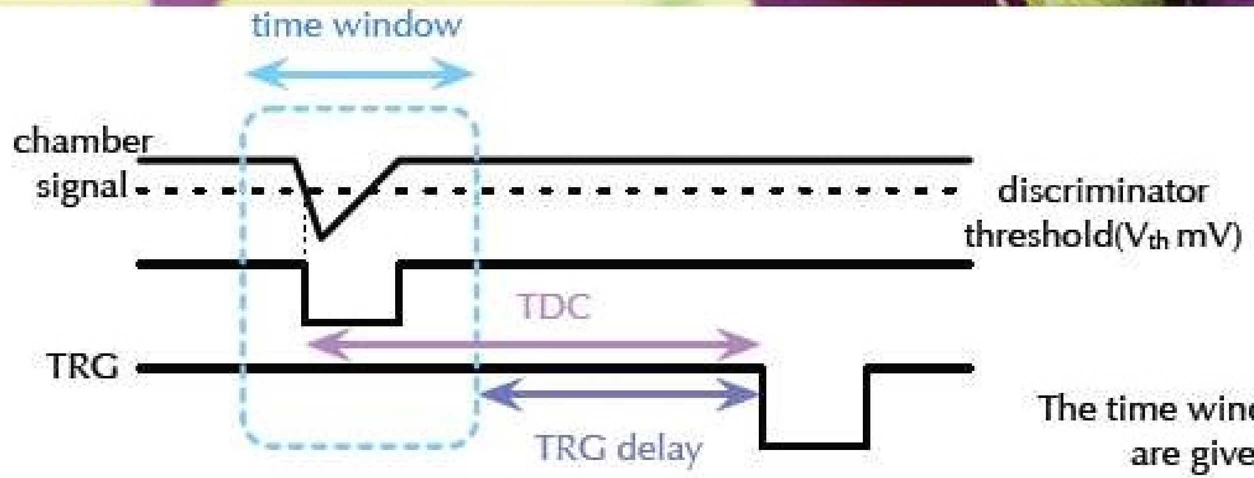


Block diagram for readout board

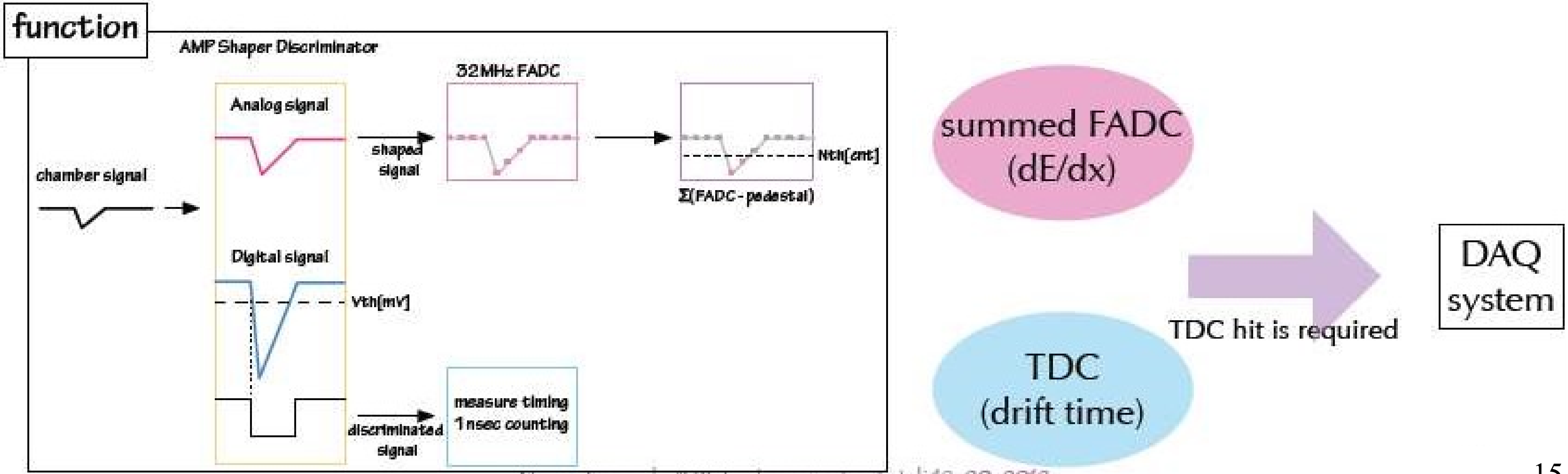


Readout electronics board

CDC readout electronics

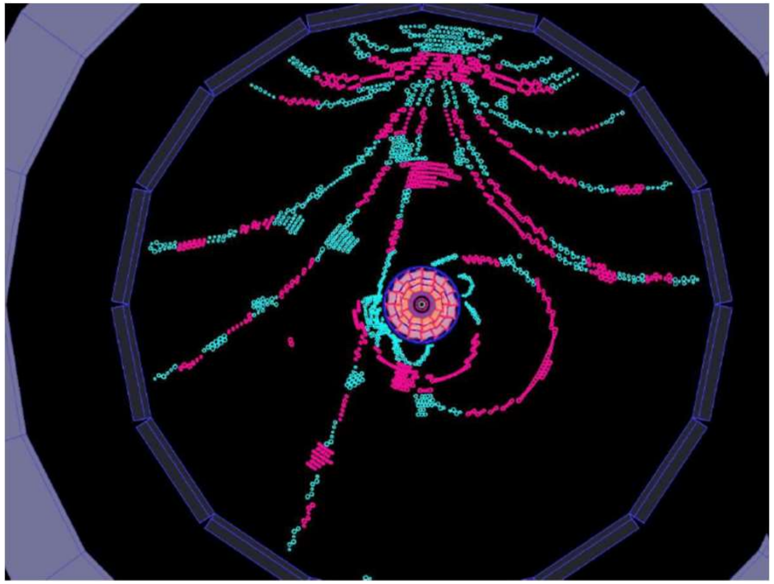


The time window and TRG delay are given in advance.

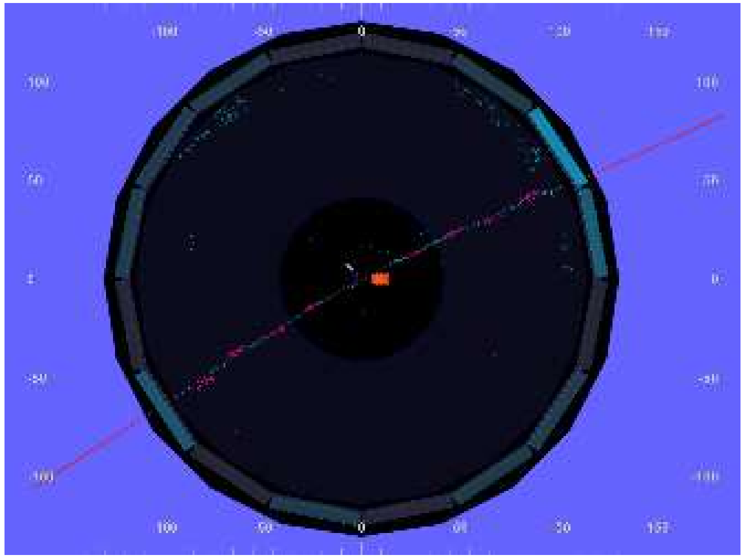


Belle-II CDC

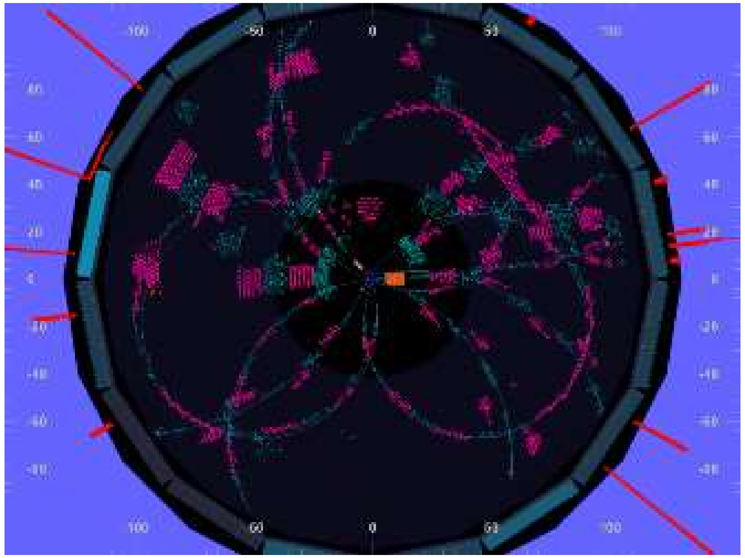
Installation into Belle II structure
with inner bar without touching Barrel PID



Comic ray

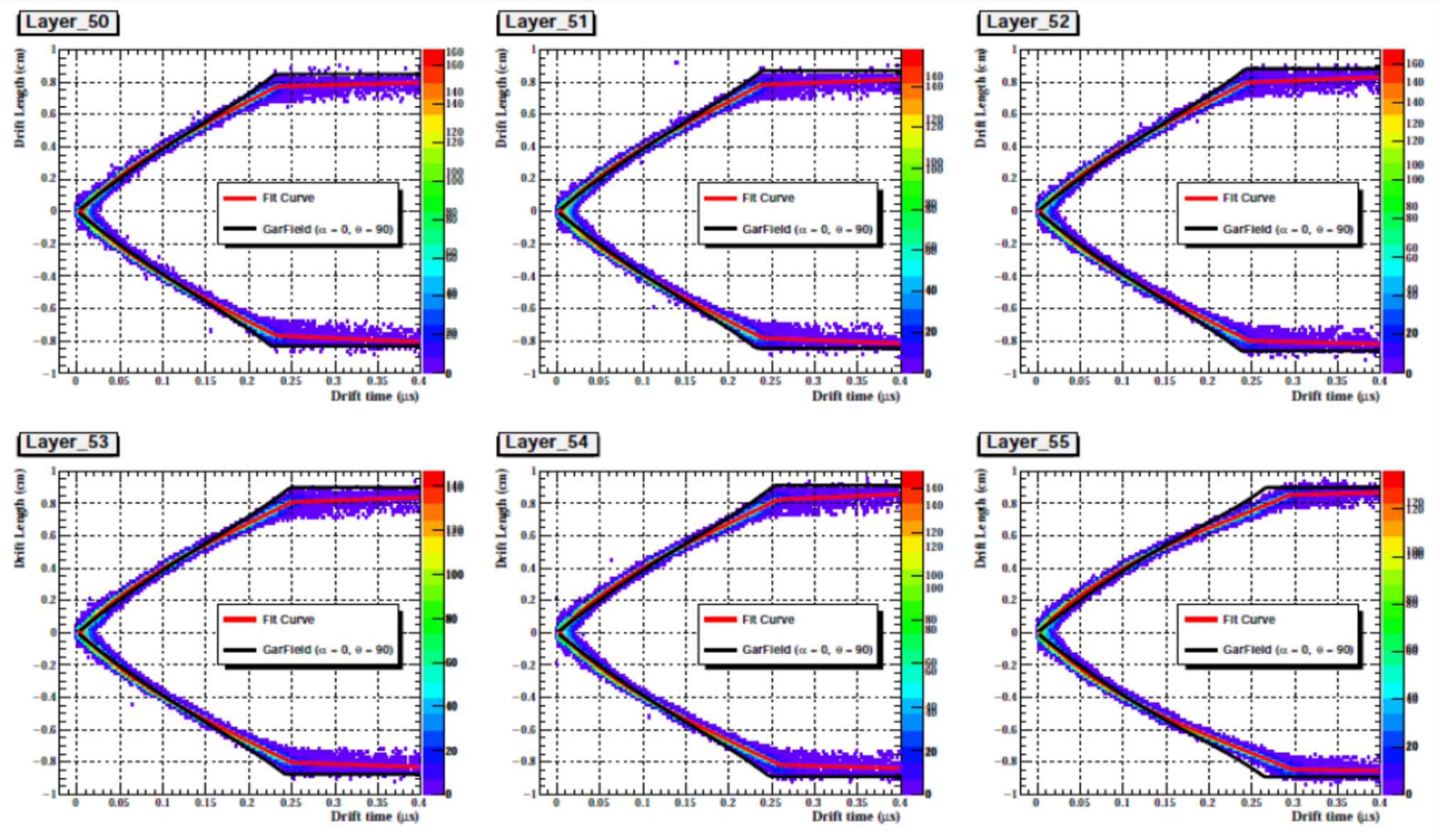


Barbar event



B-like event

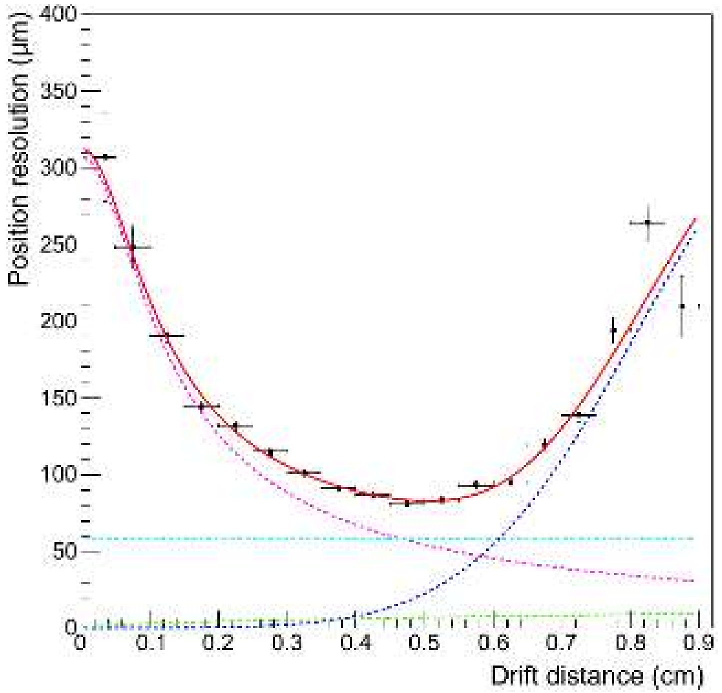
XT-Curve for Belle II CDC



- Function: 5 order polynomial + liner function
- Theta : 7, α:18, Layer:56, LR: 2 Total: 14,112

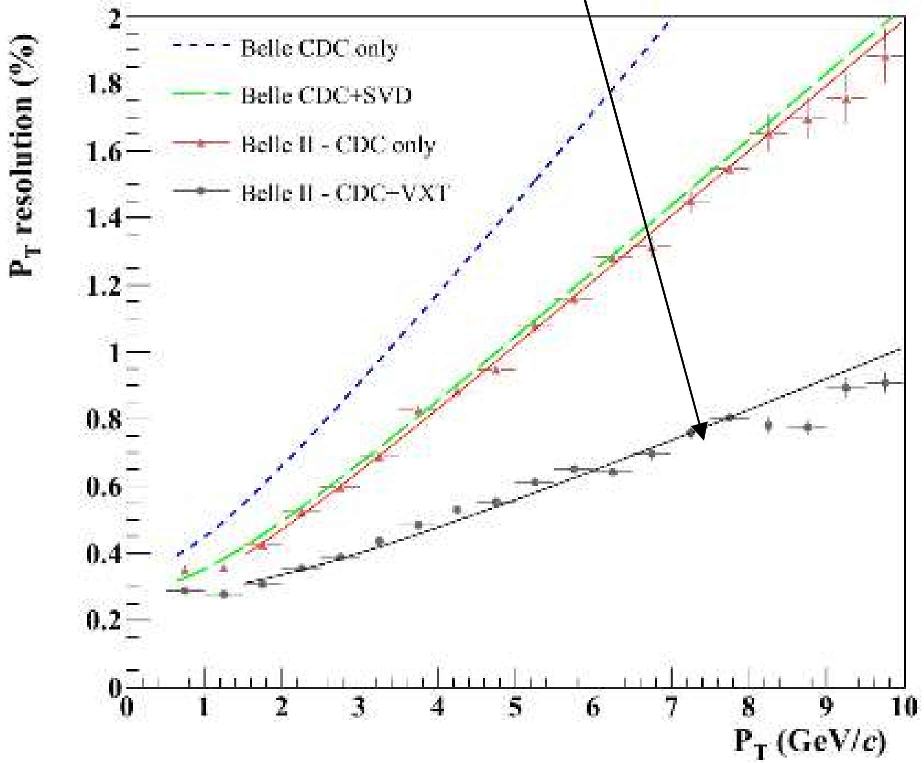
Performance under 1.5 Tesla magnetic field

Position resolution



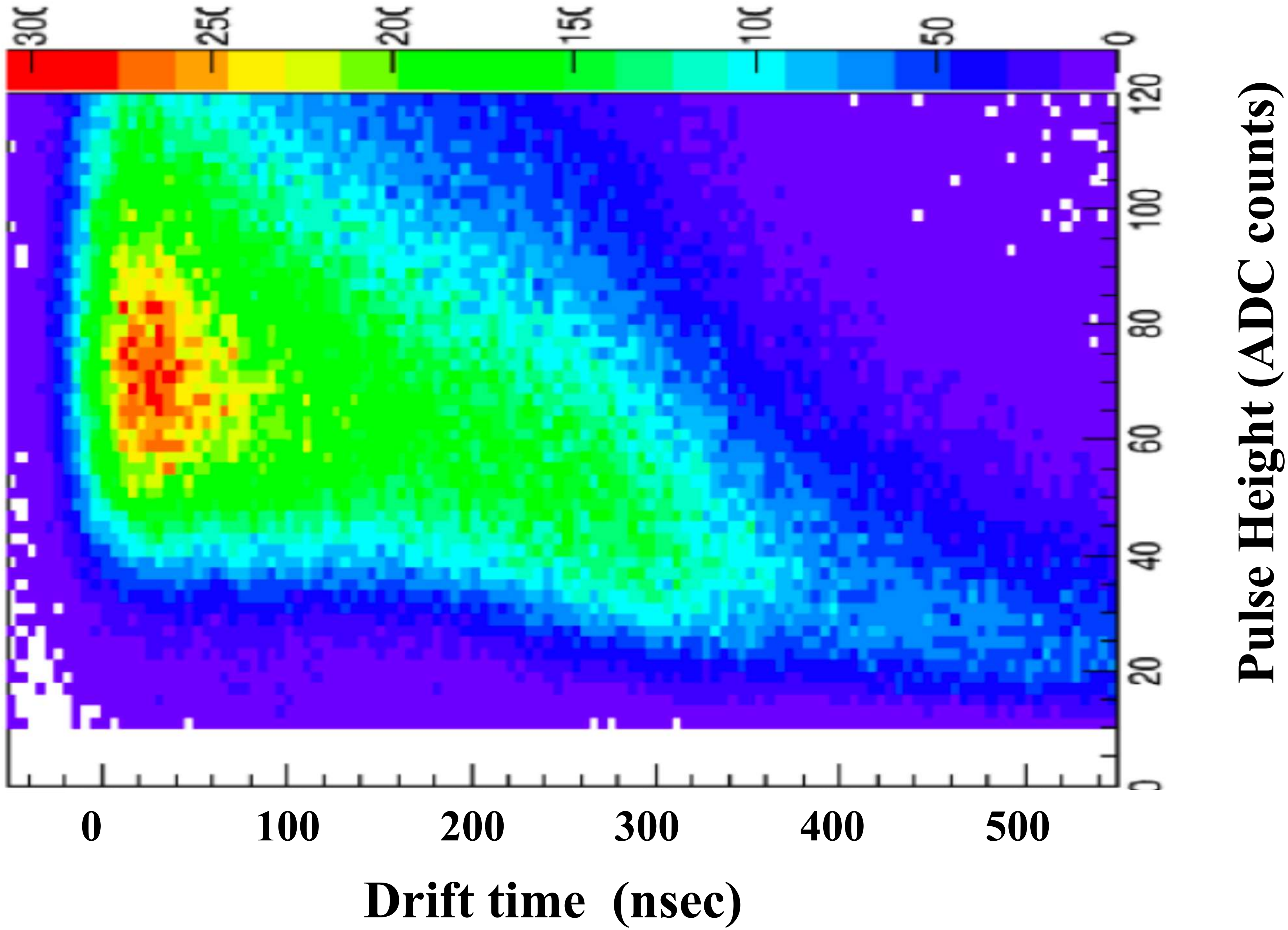
Layer 51, right, θ = 130º, α = -85º

Pt resolution:
$((0.098pt)^2 + (0.27)^2)^{1/2}$ (%)



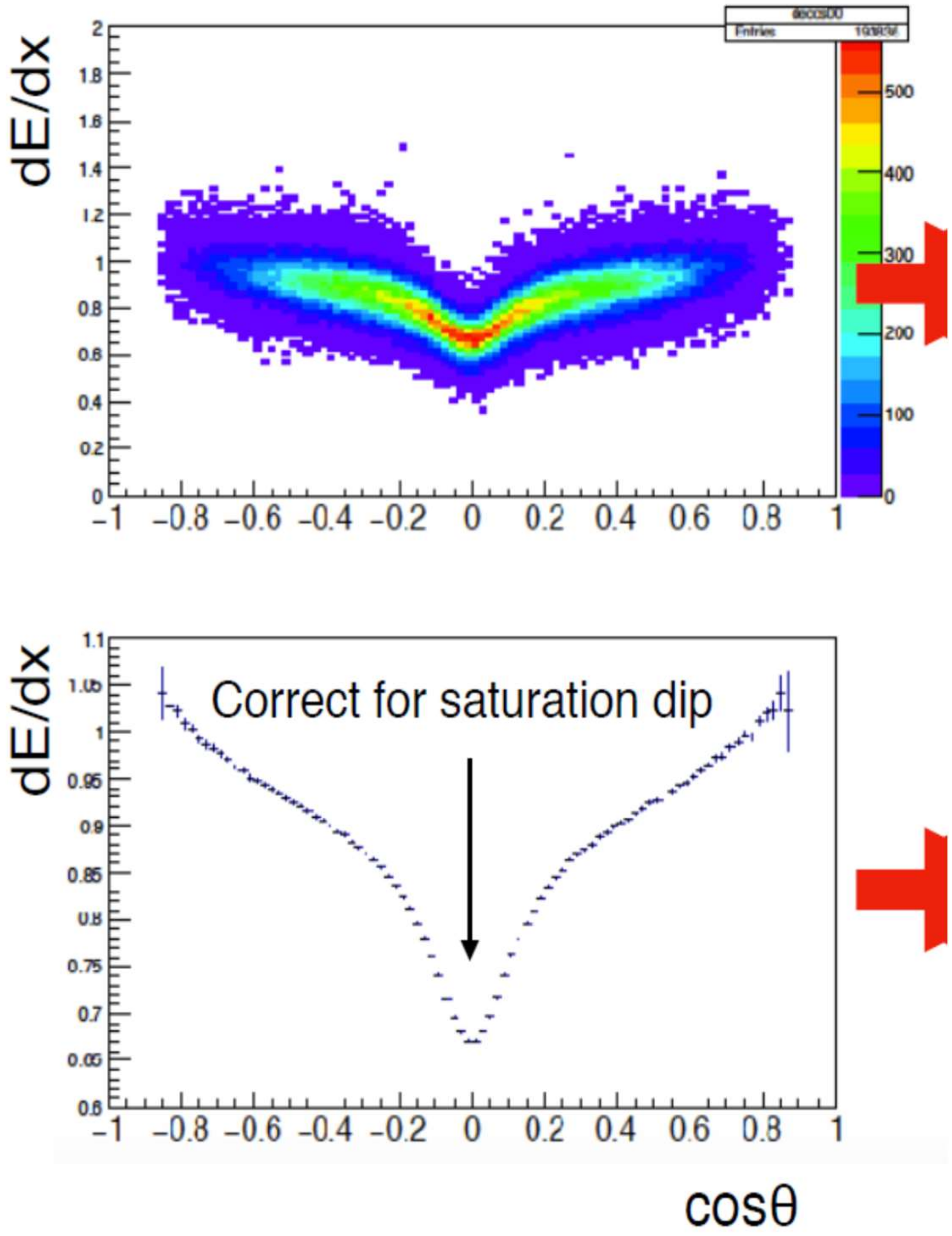
The small constant term(b) could be obtained in Belle II CDC.

Pulse height as a function of drift time

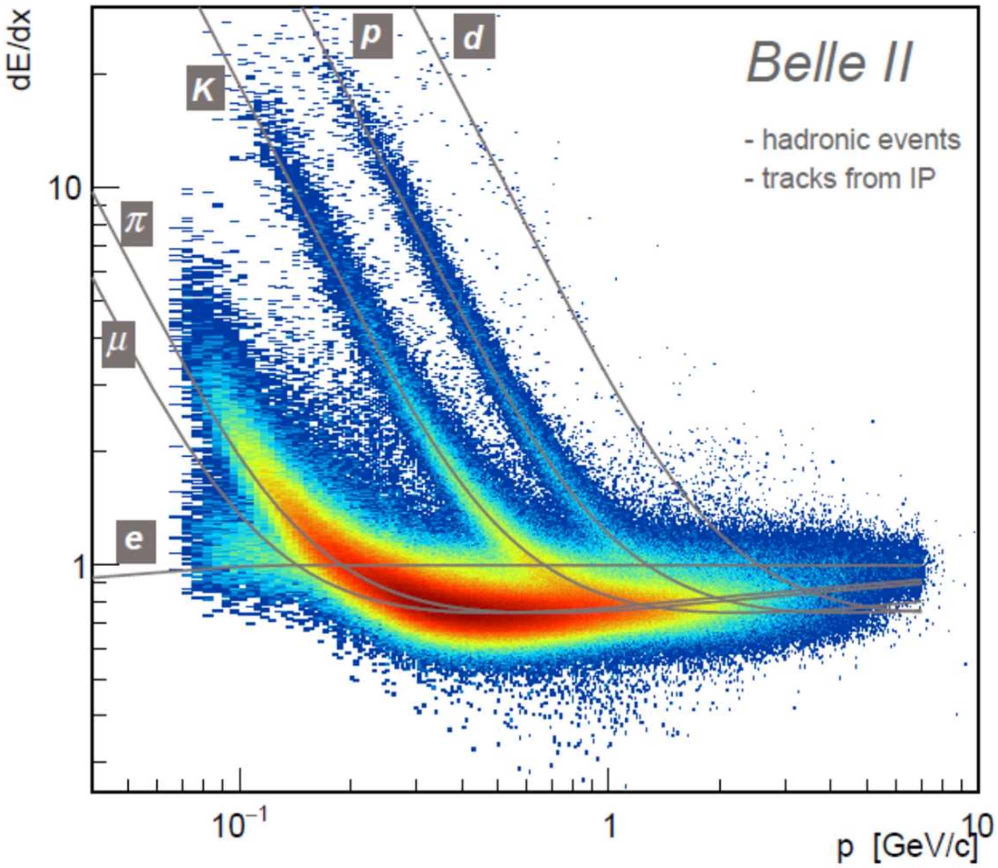


Calibration

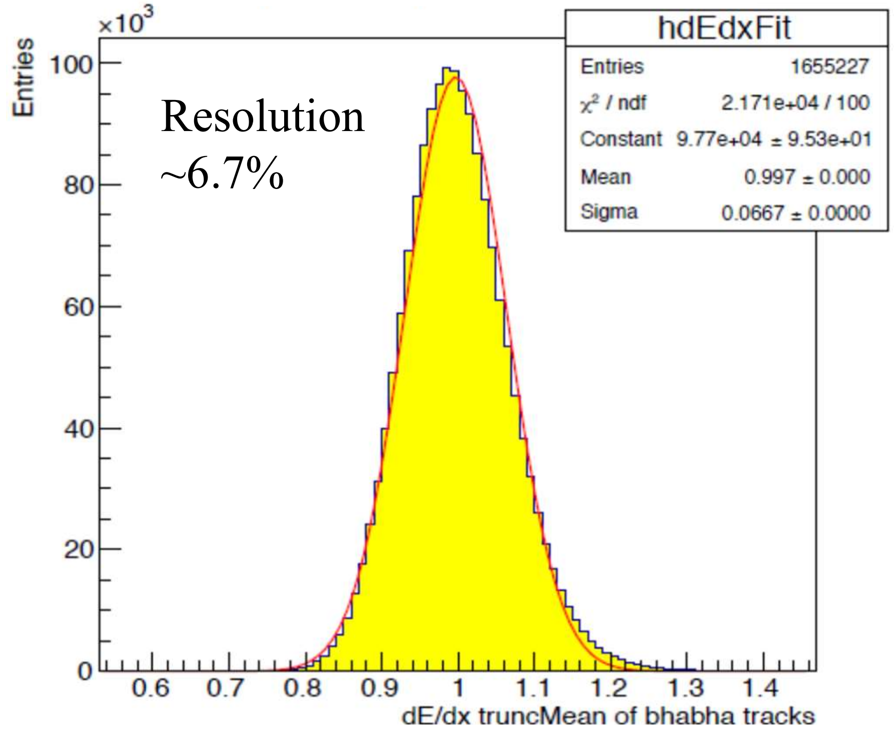
- The gas gain tends to saturate for high charge density.
- The track pass though in the chamber perpendicularly (cosθ ~ 0) and the created ionization electrons reaches in the small region on the sense wire. Then, the gas gain saturation occurs.
- This effect should be correct to obtain better dE/dx resolution. It is slightly complicate. Since, the saturation effect depend on the amount of energy loss itself.



dE/dx performance



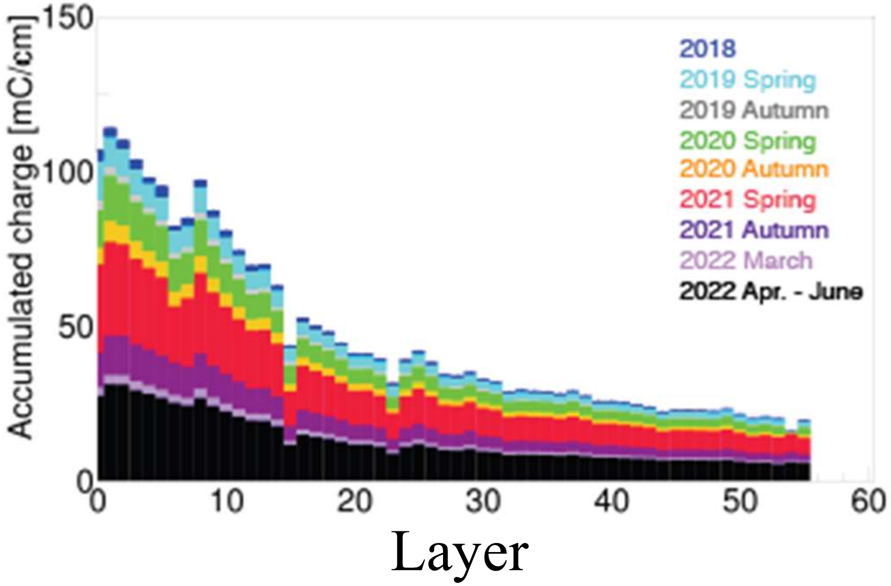
Bhabha events

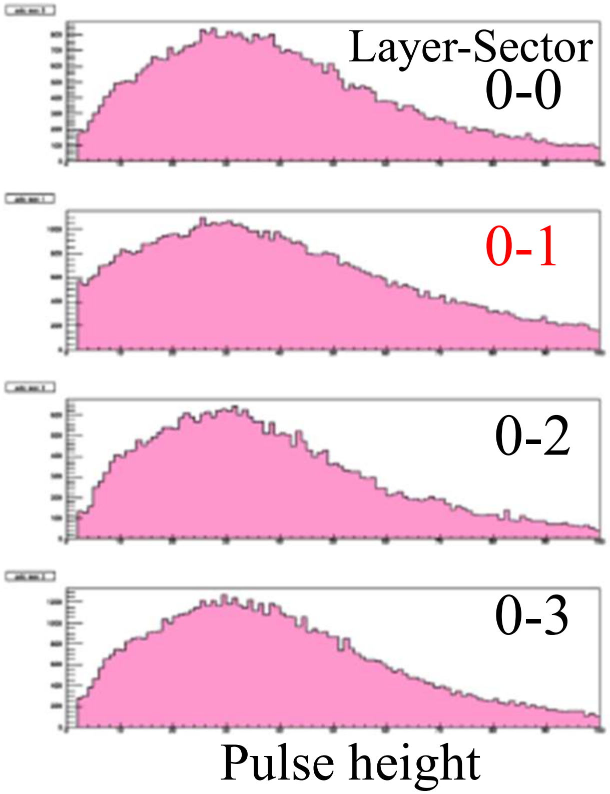


Resolution ~6.7%

Radiation damage

- Total accumulated charge had reached up to ~1 C/cm in the inner most layer for10 years Belle I CDC operation.
  - No serious performance degradation had not been observed.
- For Belle II CDC, total accumulated charge is reaching up to ~0.1 C/cm for the inner most layer.
  - Also, no serious radiation damage has not been observed, so far.
  - Total accumulated charge is small in the layer 0 – sector 1 due to HV trouble during the past operation. Recently, the trouble was fixed. Then, no difference is observed in the pulse height distribution as comparing with other normal sectors.



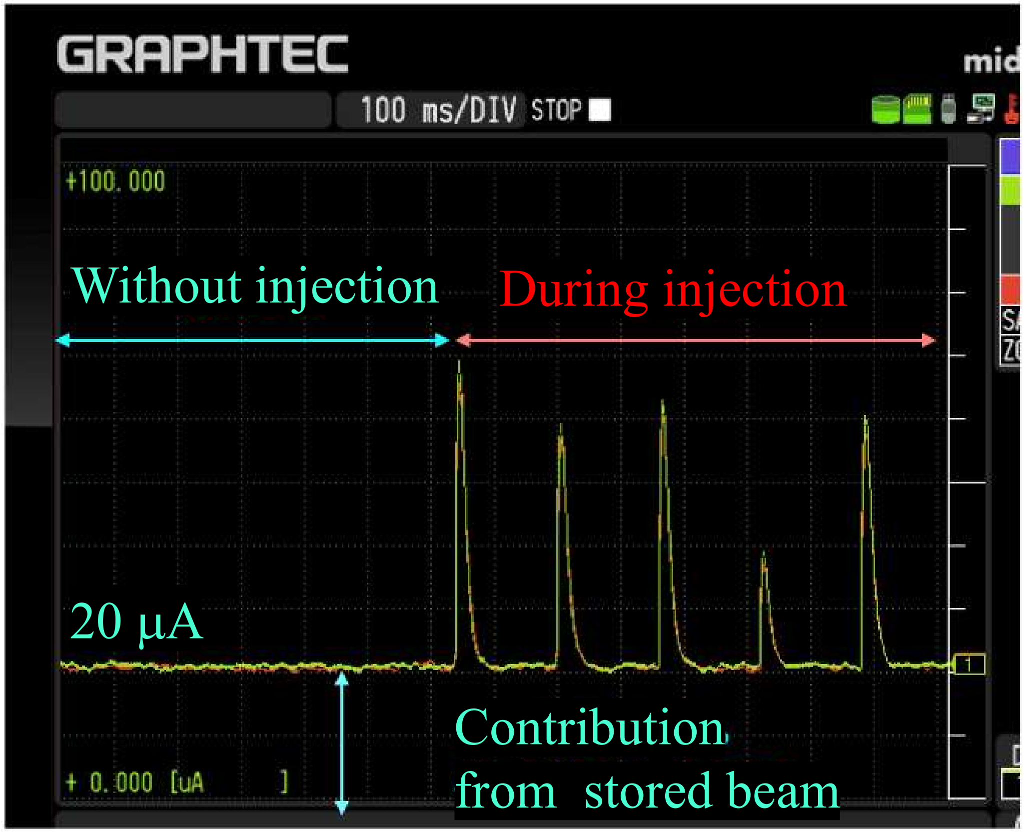


Huge injection background

- The continuous injection (top-up) is adapted in the SuperKEKB operation to obtained higher integrated luminosity.
  - Belle II are taking data during the beam injection with the injection veto.

- The CDC leak current jumps up just after the injection. The CDC condition is not stable. We should manage this situation.

CDC current (inner layer)



Summary

- Belle (I & II) CDC was/is working fine.
  - Small constant term for Pt resolution was obtained using low Z gas, aluminum field wire and thin inner CFRP wall.
  - Good dE/dx resolution.
- Some problems for Belle II CDC.
  - Crosstalk
    - Inside ASIC chip
      - →New chip was designed and was tested.
      - →New boards with new ASIC chips will be installed in the future.
  - Sudden current increase occurred in 2018
    - Have not occurred later after adding ~1500 ppm water.
    - Recently (2024 October), it happened once in the different region. After ~3000 ppm water, not occurred. The reason is not clear for me.

Backup

To minimize material

- Lighter gas (lower pressure)
- Lighter material of wires
- Smaller number of wires
- Thinner diameter of wires

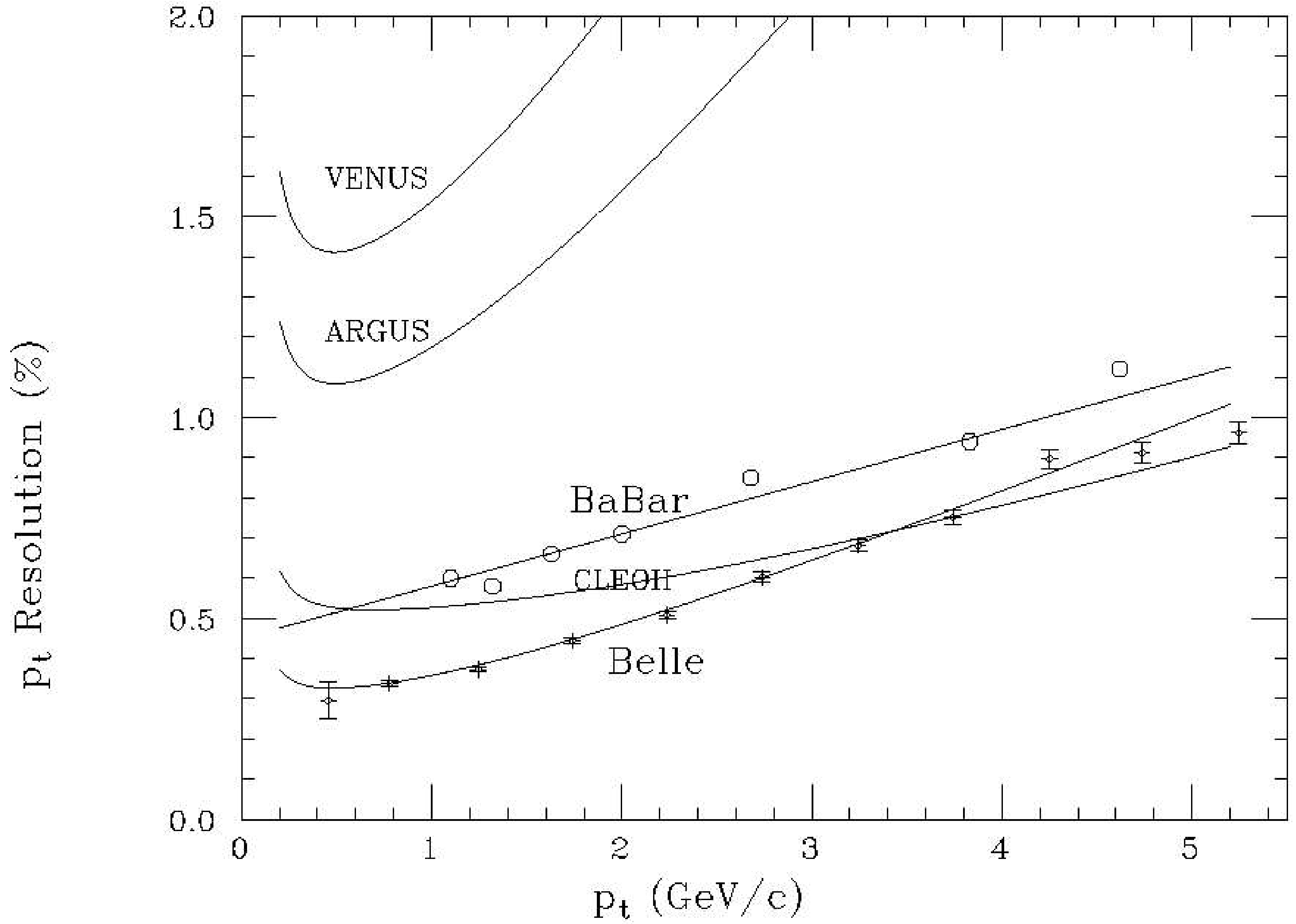
↕

- Better position resolution
- Better resolution of energy loss in gas volume
- Less radiation damage
- Longer stability
- Easier construction and cheaper

Selection of gas mixture

- Lower Z (atomic number) gas
  - Radiation length is proportional to square of Z.
- Drift velocity tends to saturate even in low electric field.
  - Stable performance and less calibration.
- Smaller diffusion constant
- Better resolution of energy loss.
- Less radiation damage.

Momentum resolution (Belle I)



The smallest constant term(b) could be obtained in Belle CDC.

Selection of wires II

- Material of wires
  - Sense wire
    - does not affect on total material so much.
    - Au-W (which is used in the world, generally)
      - $30\mu m^{\phi}$: 0.072% X_0 < Al field wire
  - Field wire
    - Cu-Be : too heavy
    - Al : Worry about creep → test → OK
      - $126\ \mu m^{\phi}$: 0.147% X_0 ~ Chamber Gas (He(50%)-C_2H_6(50%))
    - C : Diameter is not suitable.
    - Be : too difficult to string wire and expensive

Structure of CDC

- How to support huge total wire tension (more 3 tons)?
- How to string many wires?
- How much material is allowed for inner cylinder?
- What value is used for operation gas pressure?
  - Absolute pressure or relative pressure?

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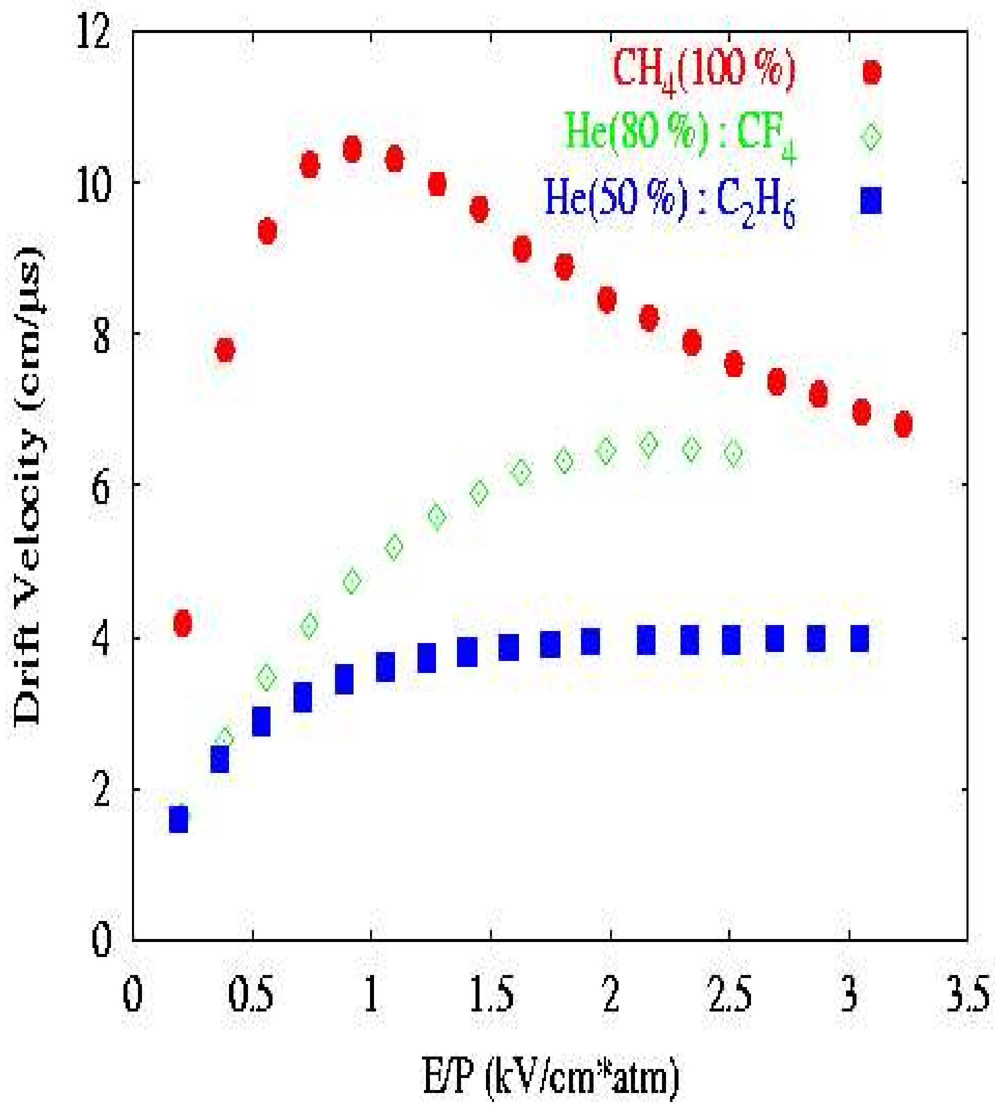
- Outer cylinder should support whole wire tension.
  - Curved aluminum endplate (thinner endplate with 10 mm thickness)
  - Pre-stress technique
- One piece of outer CFRP cylinder with 5 mm thickness
  - Thin aluminum sheet (0.1mm thickness) is attached for the electric shield.
- Thickness of inner cylinder should be minimized and it can be installed after wire stringing for main part.
  - CFRP (+ aluminum) with 0.5 (+0.1) mm thickness

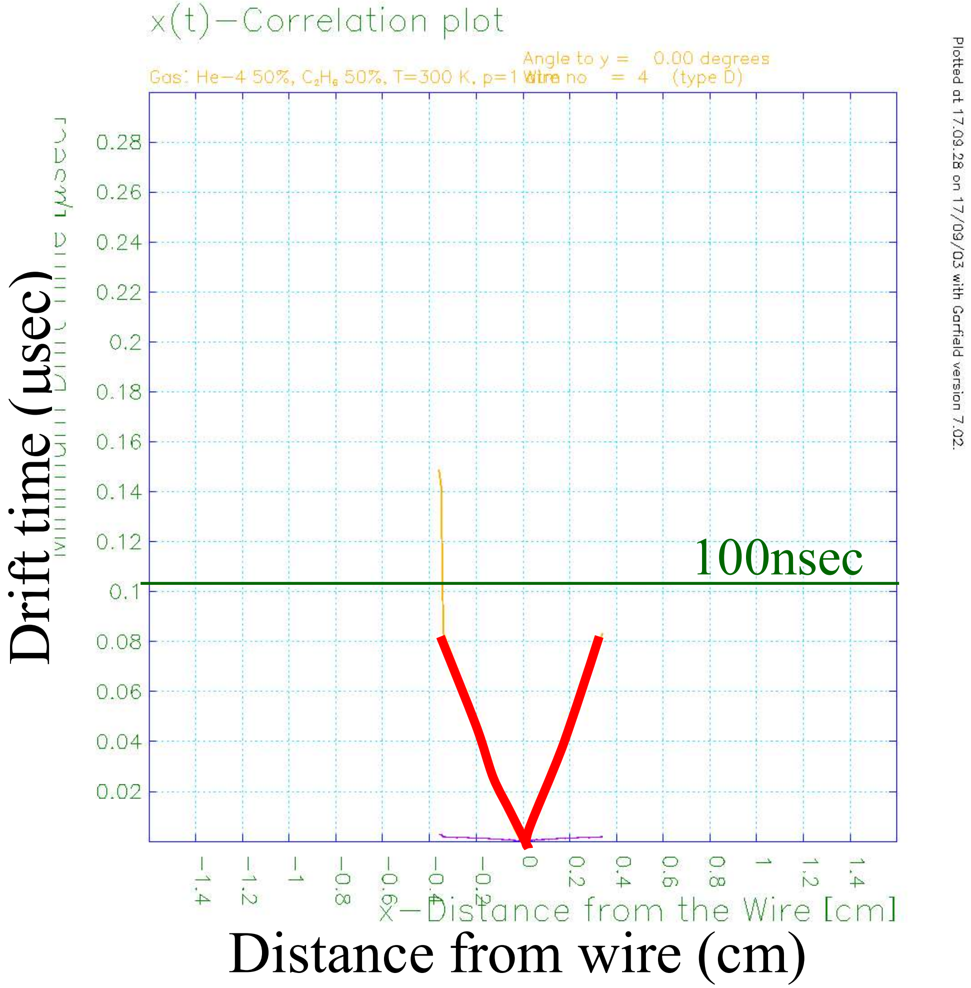
Drift Velocity

- Two gas candidates for faster drift velocity were tested for Belle II CDC to obtain shorter maximum drift velocity.
  - CH_4 and He-CF_4
- In case of He-CF_4, higher electric field is necessary to get fast drift velocity.
- In case of CH_4, faster drift velocity by factor two or more can be obtained, even in rather lower electric field. But, Lorentz angle is too larger.

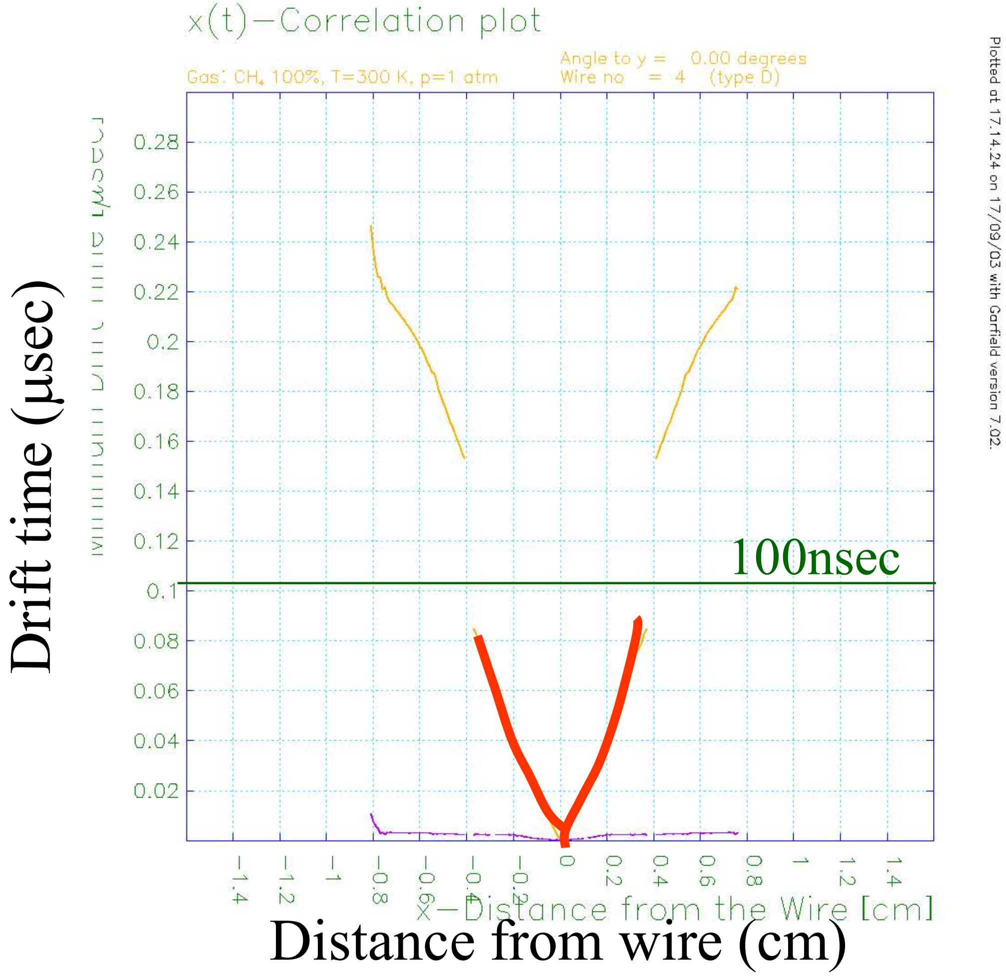


xt curve for new gas in 7mm cell under 1.5 Tesla magnetic field

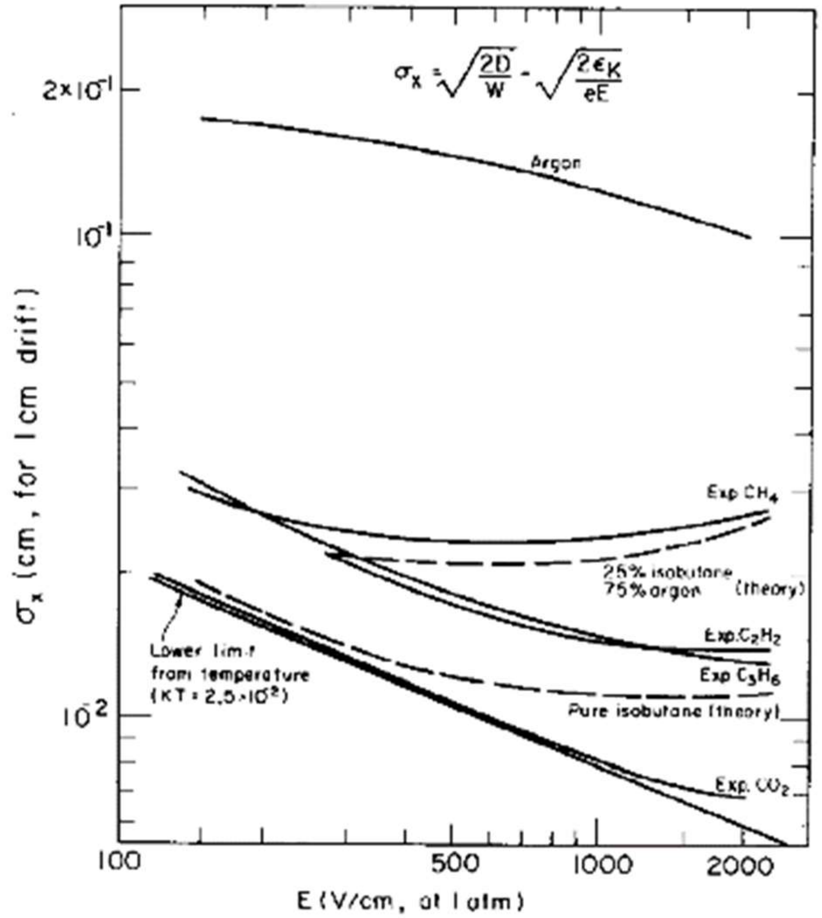
He/C_2H_6 = 50/50



Pure CH_4



Diffusion coefficient for one electron



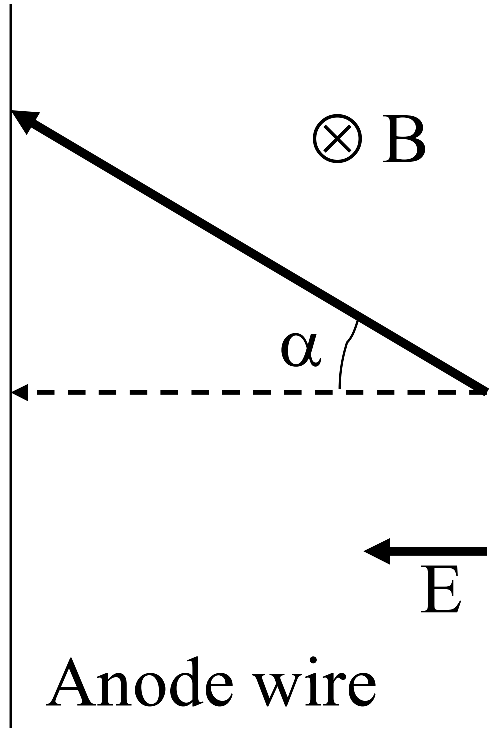
1 mm

0.1 mm

Remark : Rather large for just one electron
Diffusion is smaller in higher electric field.

Lorentz angle

$$\tan\alpha = c\frac{B\cdot v_0}{E}$$



α : Lorentz angle

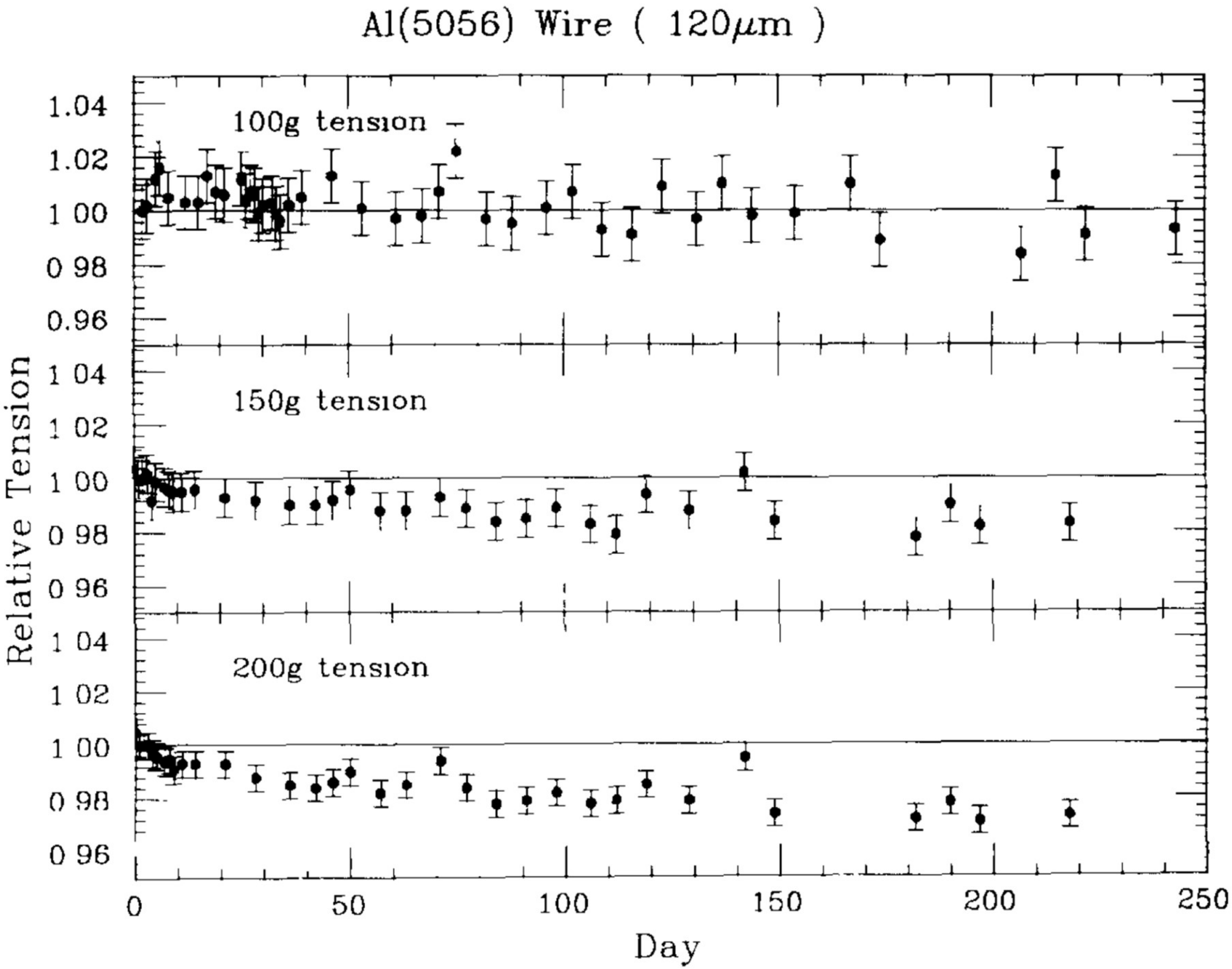
B : Magnetic field (T)

E : Electric field (V/m)

v_0 : Drift velocity without magnetic field (m/s)

Lorentz angle becomes smaller in higher electric field.

Creep test



Al(5056) Wire (120μm)
100g tension
150g tension
200g tension
Relative Tension
Day
1.04
1.02
1.00
0.98
0.96
0
50
100
150
200
250

Wires

- Sense wire
  - 30 μm$^{\phi}$ gold-plated W
- Field wire
  - 126 μm$^{\phi}$ Aluminum (A5056) without any plating
- For both CDCs

Cell structure

- Rectangular shape or Hexagonal shape?
  - Number of wires
  - Goodness of electric field
  - Pass length difference along drift distance

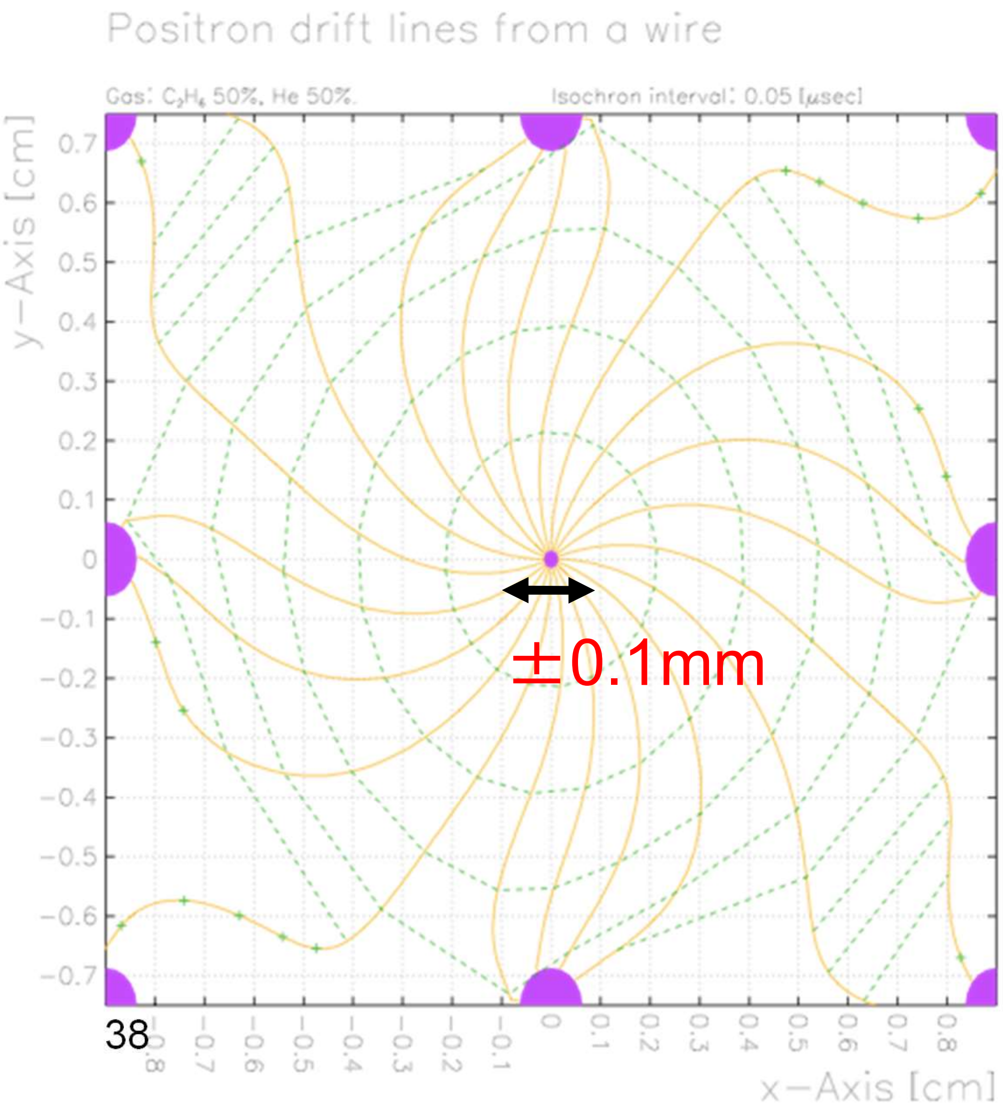
- Cell size?
  - In case of larger cell size,
    - Number of wires decreases.
    - Increase good electric field region.

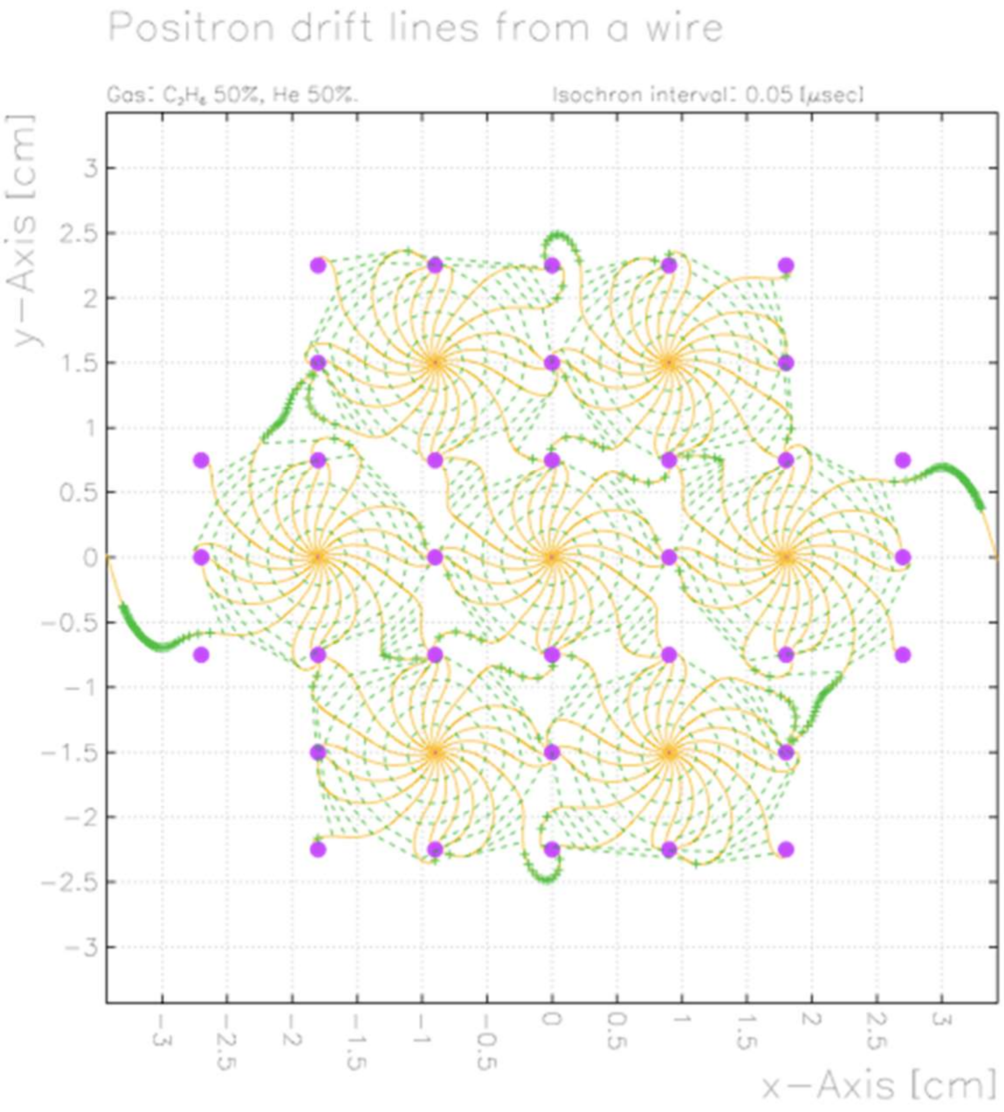
      ↕

    - Higher voltage is required on the sense wires.
    - Electric field deceases in the drift region.

Simulation using Garfield

HV=2.3kV (sense wire)
B = 1.5 T, C_2H_5:50% He:50%





Wire configuration 1

- Super-layer structure
- 6 layers for each super-layer (Belle II)
  - at least 5 layers are required for track reconstruction.
  - Even number is preferred for preamp arrangement on support board to shorten signal cable between feed-through and preamp.
- Additional two layers in inner most super-layer (Belle II).
  - Higher hit rate in a few layers near wall.
  - Two inner most layers are considered as active guard wire.

Wire configuration 2 (Belle II)

- 9 super-layers : 5 axial + 4 stereo(2U+2V)
  - A 160*8, U 160*6, A 192*6, V 224*6,
  - A 256*6, U 288*6, A 320*6, V 352*6, A 388*6
- Number of layers : 56
- Number of total sense wires : 14336
- Number of total wires : 56576

Deformation of endplate

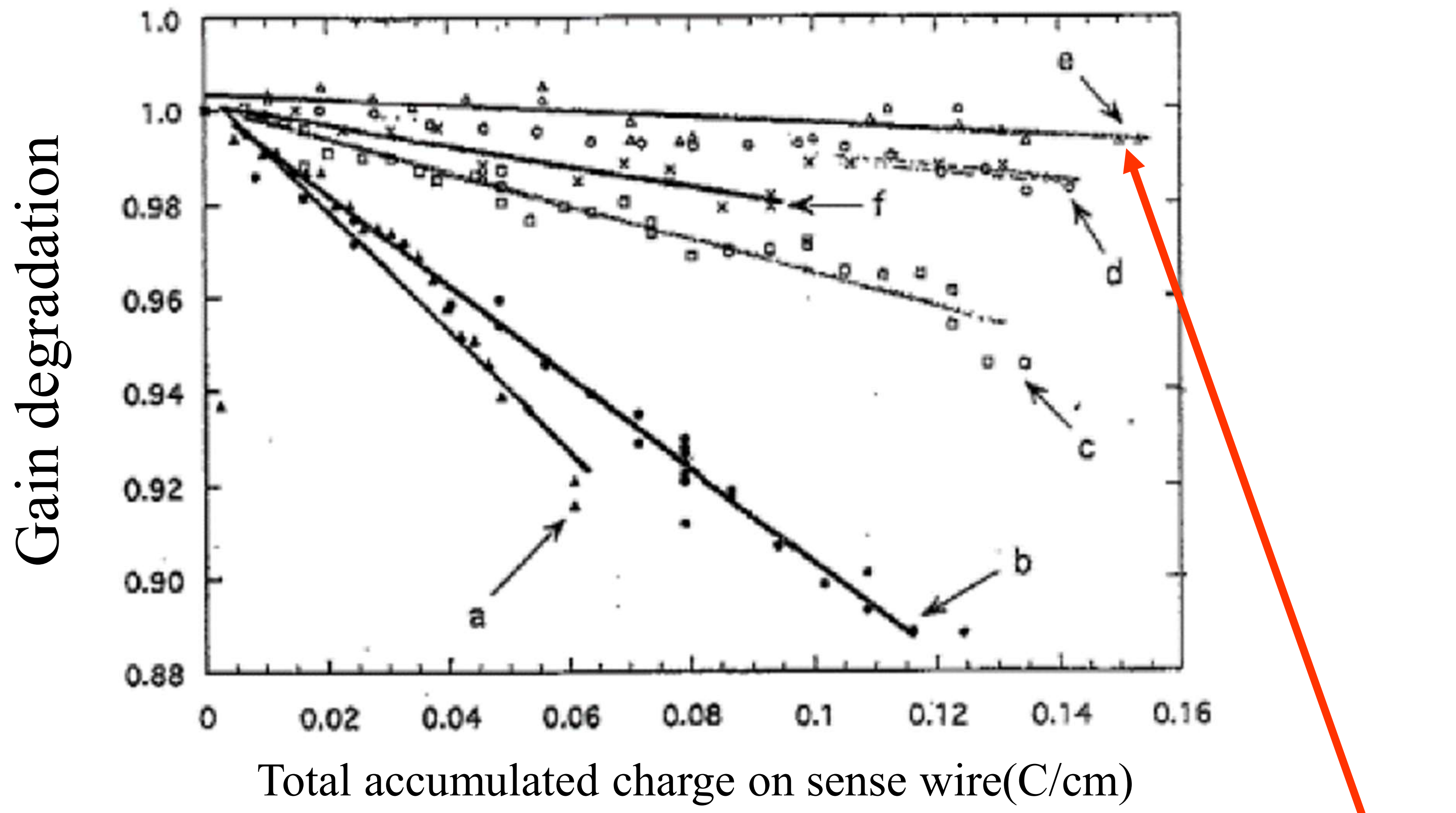
- Number of wires increase by factor 2 as compared with Belle I.
  - Larger deformation of endplate is expected.
  - It may cause troubles in a wire stringing process and other occasions.
- Number of holes increases, but a chamber radius also enlarges. Cell size is changing as a function of radius to reduce number of wires.
  - The fraction of holes respect to total area is not so different, as comparing with the present CDC.
    - 11.7% for present CDC
    - 12.6% for Super-Belle CDC
- In order to reduce deformation of endplates,
  - The endplate with a different shape is considered.
  - Wire tension of field wires will be reduced.
- Anyway, we can arrange the wire configuration and can make a thin aluminum endplate.

Radiation damage

- Radiation damage depends on various condition dramatically.
- No problem for usual gas (Argon Methane).
- Impurity and out gas from chamber material may cause troubles.

- There are two different types of damages on cathode wire surface and anode wire surface.
  - When electric field on the surface of cathode wire exceeds some level (>20kV/cm), gas multiplication occurs. Then, something accumulate on the surface of the cathode wires quickly.
    - This is so-called Malter effect. Frequent sparks occur suddenly and high voltage cannot be supplied.
  - Gas gain decreases continuously due to accumulation of something on the surface of anode wires.

Radiation Damage Test



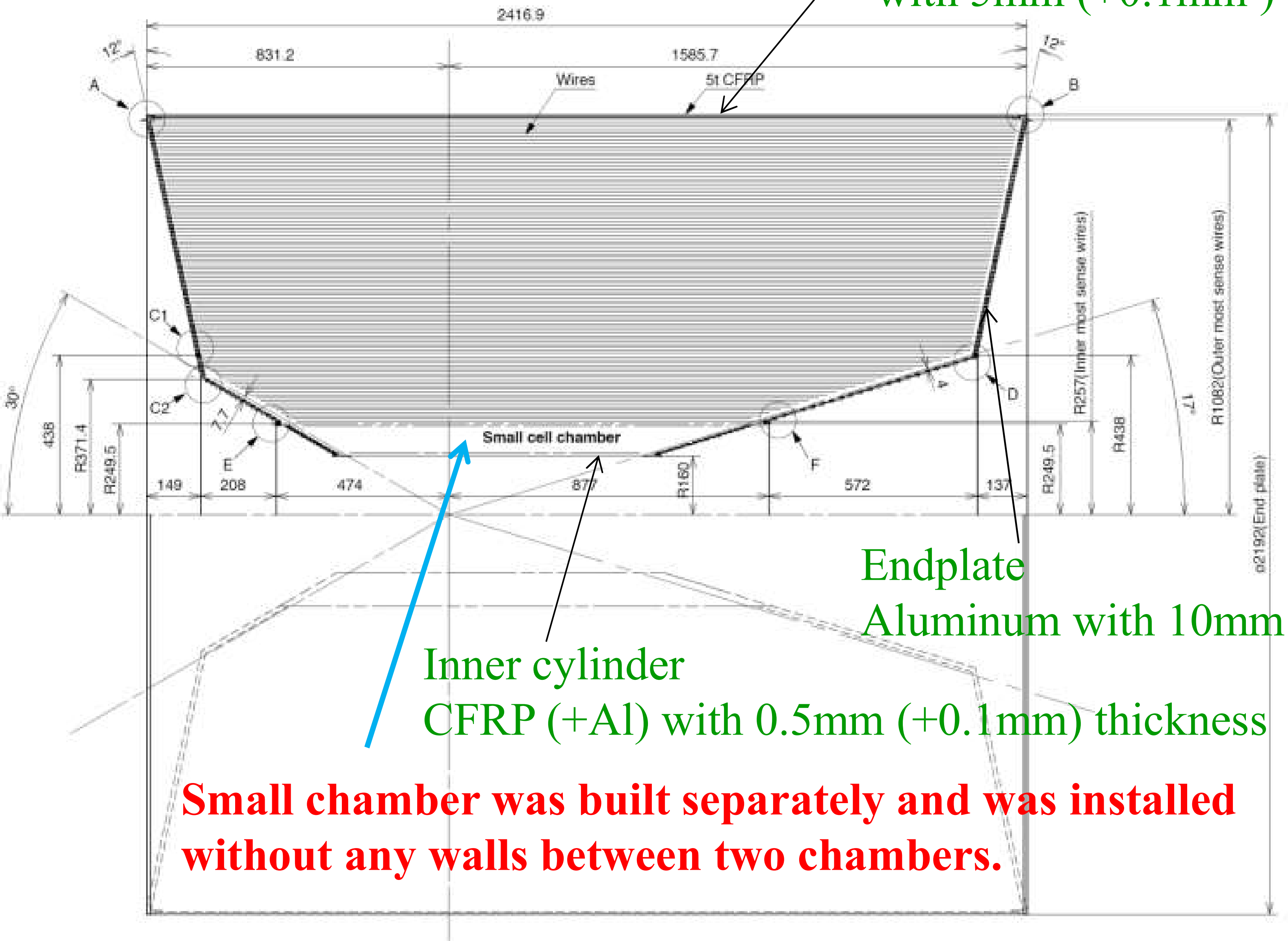
a: '93 Plastic tube
b: '93 Plastic tube + O2 filter
c: '94 Plastic tube
d: '94 SUS tube
e: '94 SUS tube + O_2 filter
f: '94 Plastic tube

Main parameters

	Belle	Belle-II
Radius of inner boundary (mm)	77	160
Radius of outer boundary (mm)	880	1130
Radius of inner most sense wire (mm)	88	168
Radius of outer most sense wire (mm)	863	1111.4
Number of layers	50	56
Number of total sense wires	8400	14336
Effective radius of dE/dx measurement (mm)	752	944
Gas	$He\text{-}C_2H_6$	$He\text{-}C_2H_6$
Diameter of sense wire (μm)	30	30

CDC Structure

Outer cylinder
CFRP (+Al)
with 5mm (+0.1mm) thickness



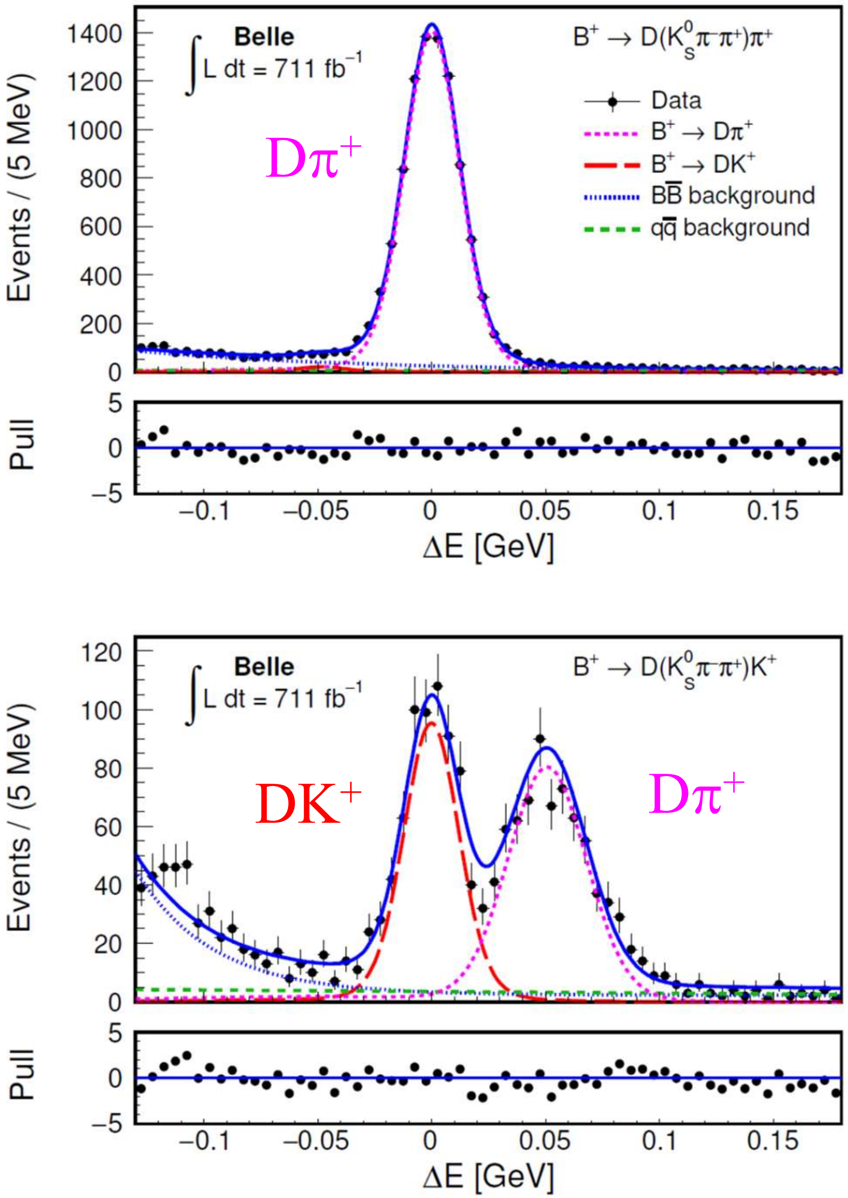
Endplate
Aluminum with 10mm thickness

Inner cylinder
CFRP (+Al) with 0.5mm (+0.1mm) thickness

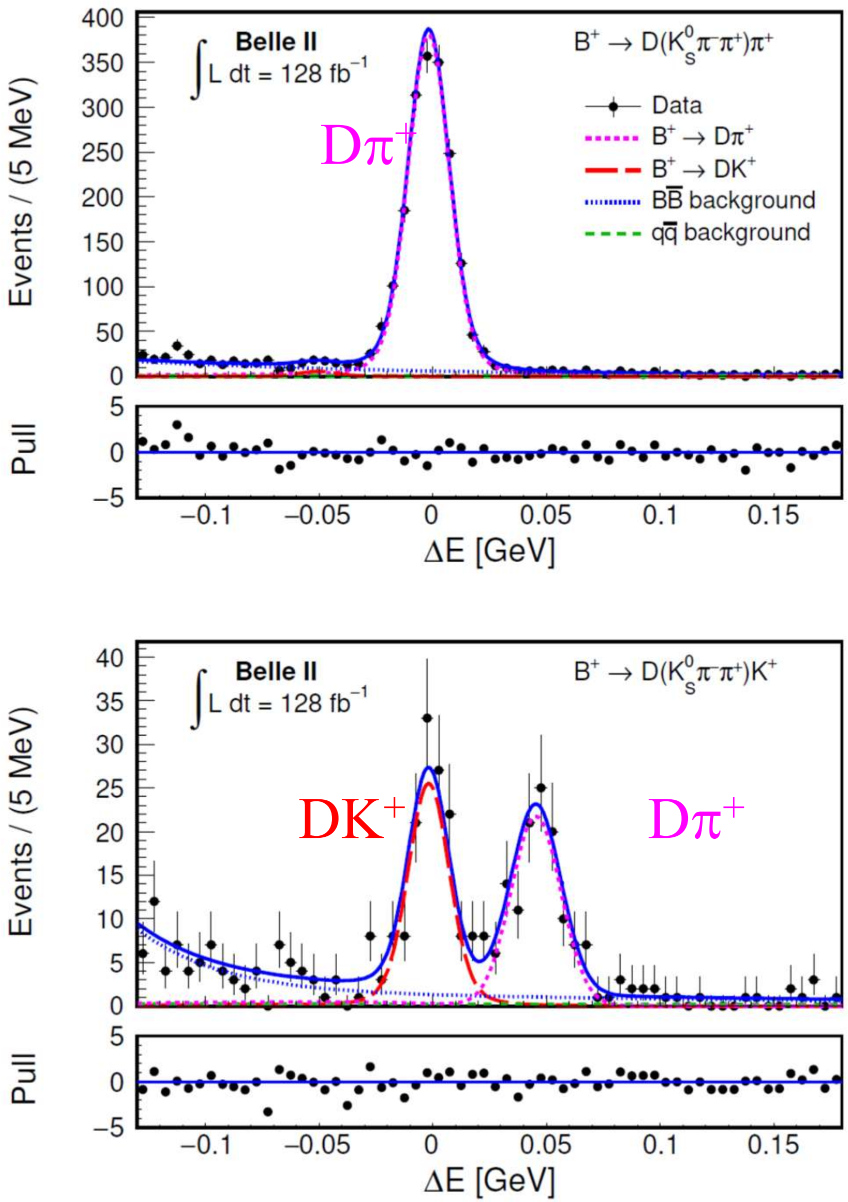
Small chamber was built separately and was installed without any walls between two chambers.

$B^+ \rightarrow Dh^+$

Belle



Belle II



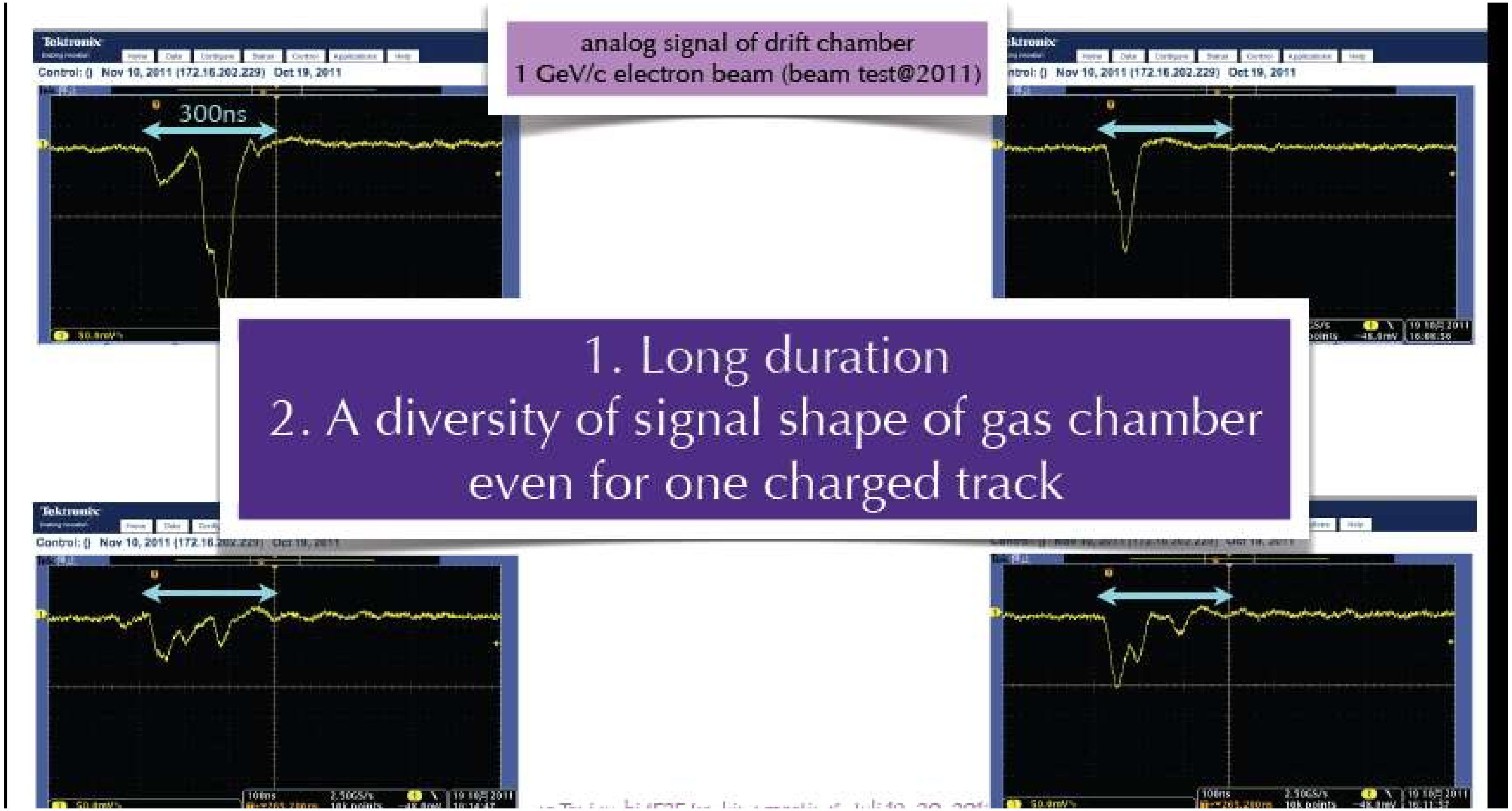
Electronics for Belle-II CDC

About readout electronics

- **For Belle-I CDC,**
  - S/QT + multi-hit TDC
  - S/QT : Q to Time conversion
  - FASTBUS TDC was replaced with pipeline COPPER TDC.
- **Three options,**
  - High speed FADC(>200MHz)
  - Pipeline TDC + Slow FADC(~20MHz)
  - ASD chip + TMC(or new TDC using FPGA) + slow FADC near detector.
    - ASIC group of KEK Detector Technology Project is developing new ASD chip.
    - New TDC using FPGA is one candidate for TDC near detector.

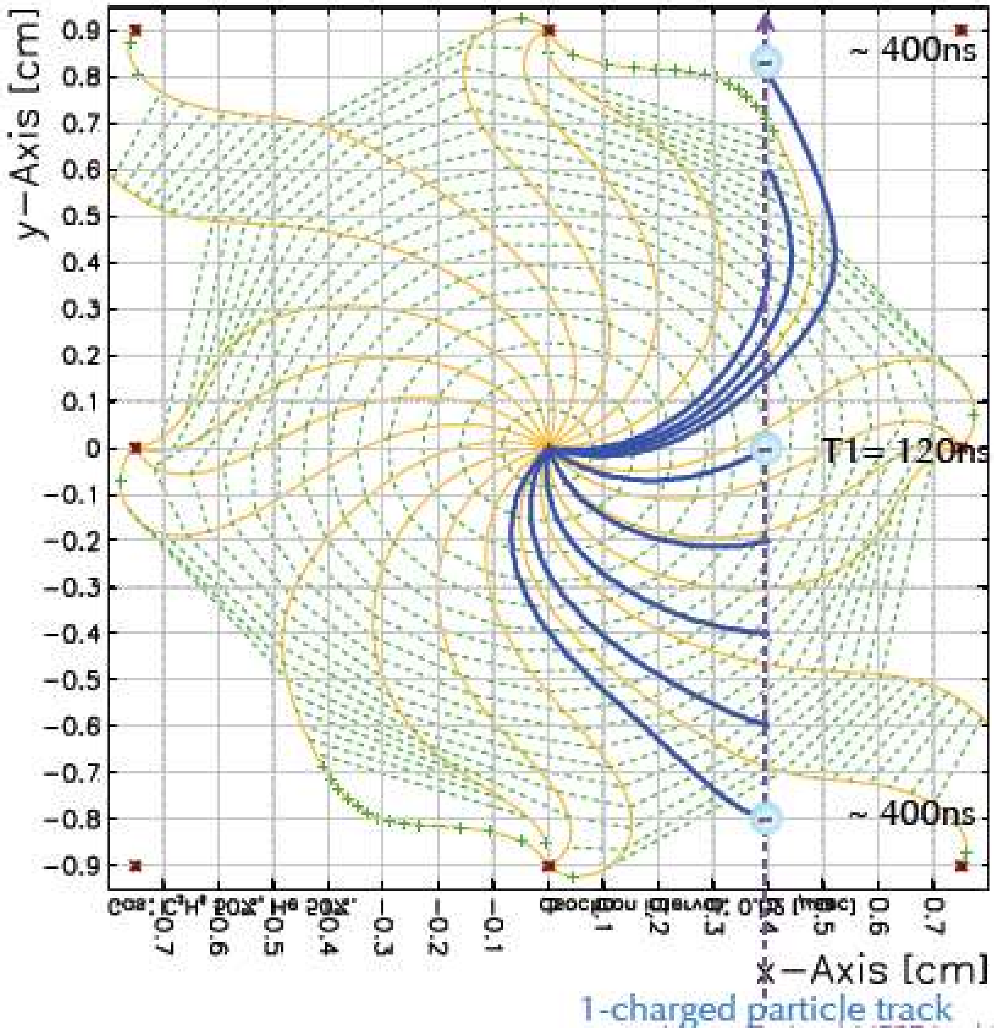
Signal Shape

- **Each signal shape is not same.**
- **Rise time : ~10nsec, Pulse width : ~300nsec.**
- **Maximum drift time : ~300nsec**

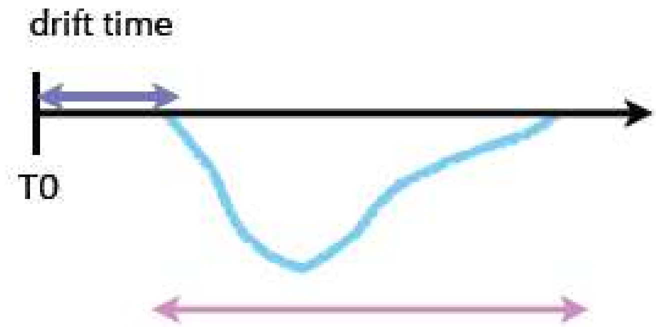


Signal shape

B=1.5T



arrival time difference > 300nsec



pulse width >~300nsec

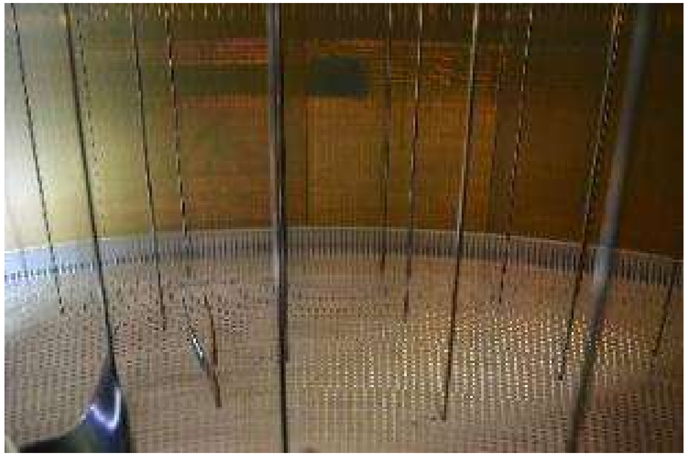
duration becomes longer

Nanae Taniguchi "F2F tracking meeting", Juli 19-20, 2012

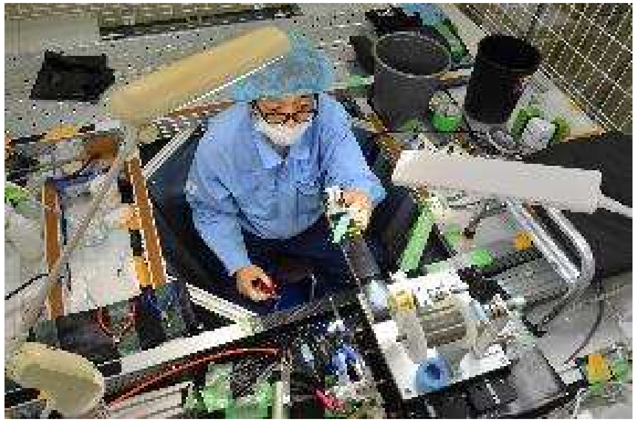
Wire stringing for main part

Vertical stringing

One person could access inside
to string wires.



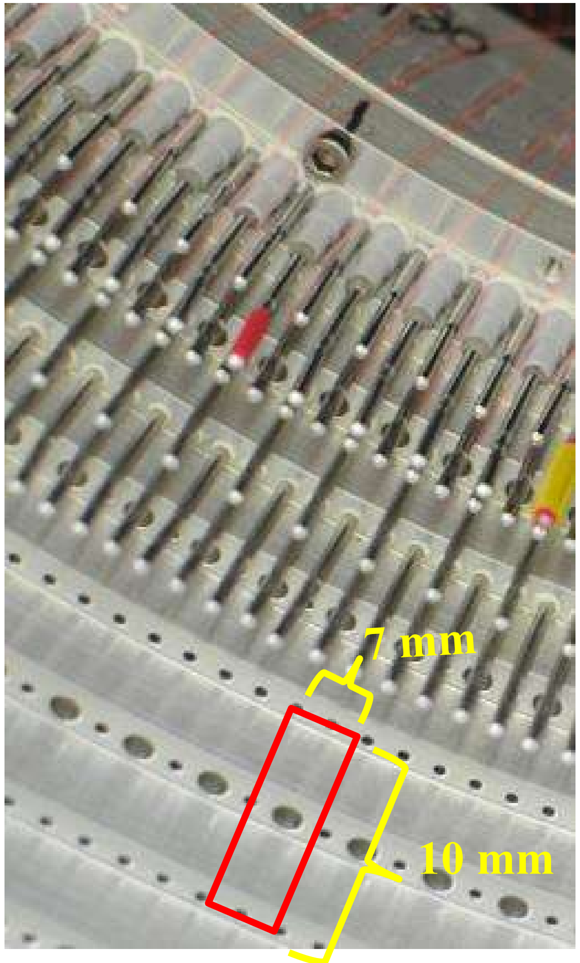
One person could handle wires
inside chamber.



One person could sit with hanging device
without touching the endplate
to string wires for the conical part.

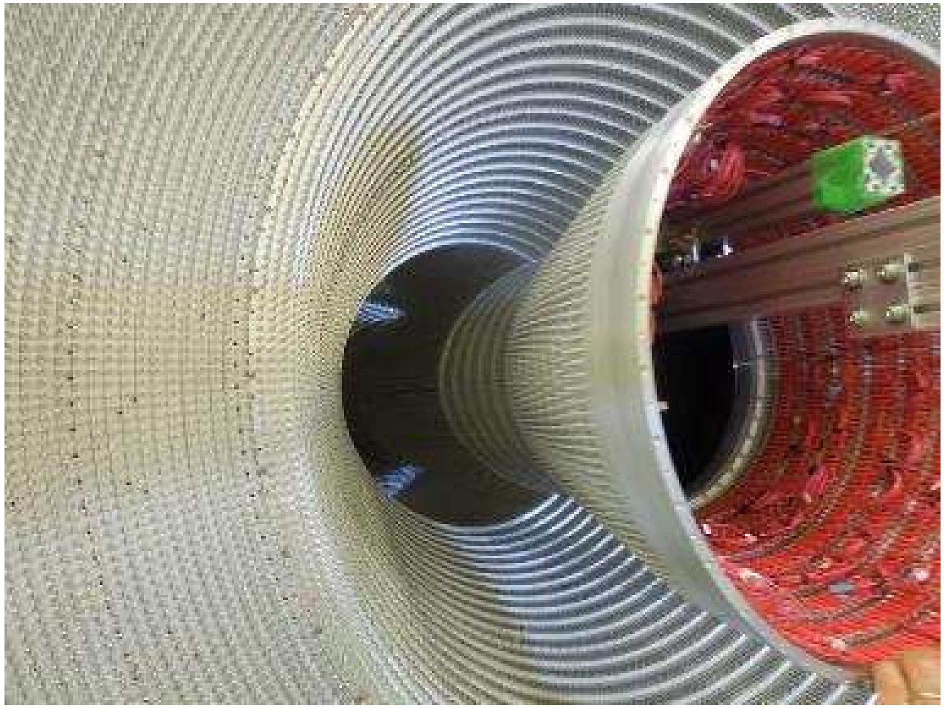
Wire stringing for small cell chamber

Horizontal stringing
Whole wire tension is supported with thin inner CFRP cylinder.



Sense : Feedthrough

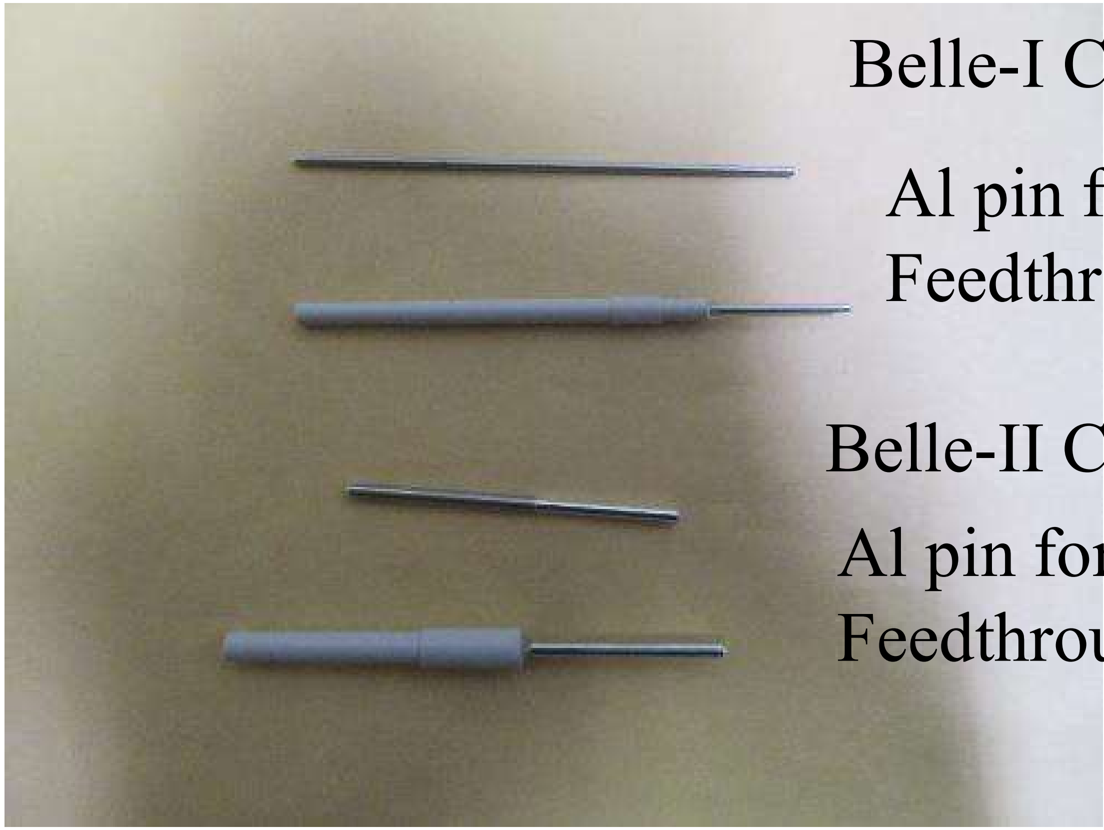
Field : without feedthrough, Al pin only



Installation of small cell chamber

Small cell chamber

Feedthrough



Belle-I CDC small cell chamber

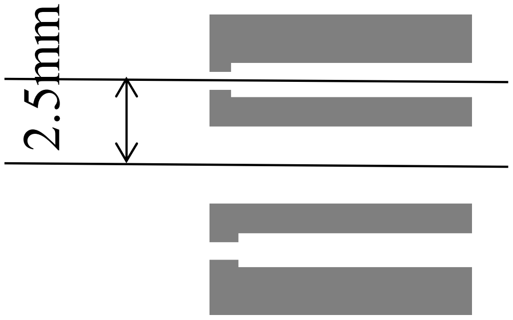
Al pin for field wire 1mm$^{\phi}$
Feedthrough for sense wire 3mm$^{\phi}$

Belle-II CDC small cell chamber

Al pin for field wire 1.6mm$^{\phi}$ + 1.4mm$^{\phi}$
Feedthrough for sense wire 4mm$^{\phi}$

Material of aluminum pin : A5052
Material of feedthrough : Noryl

Shape and diameter for holes

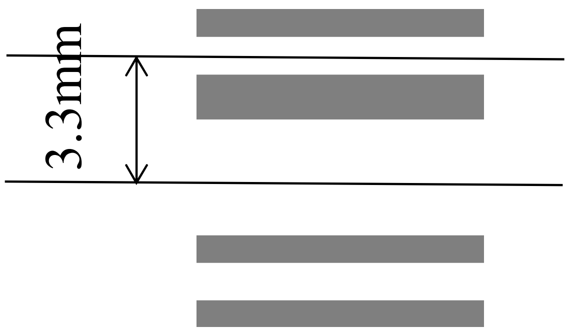


Belle-I

$1.0mm^{\phi}$+ $0.8mm^{\phi}$ for field wire

$3.0mm^{\phi}$ for sense wire

Minimum distance
between two holes:2.5mm



Belle-II

$1.6mm^{\phi}$ for field wire

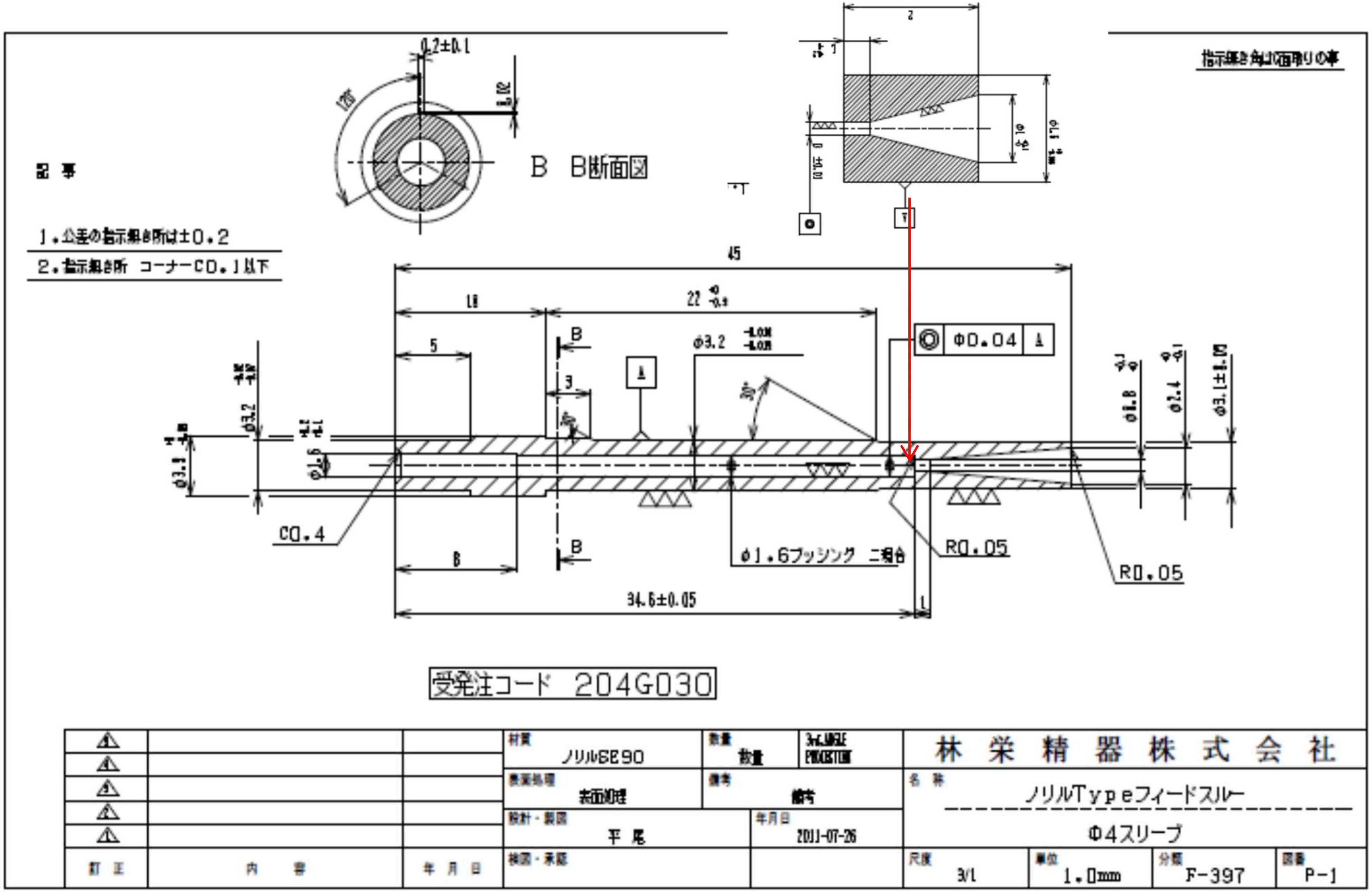
$4.0mm^{\phi}$ for sense wire

Minimum distance
between two holes:3.3mm

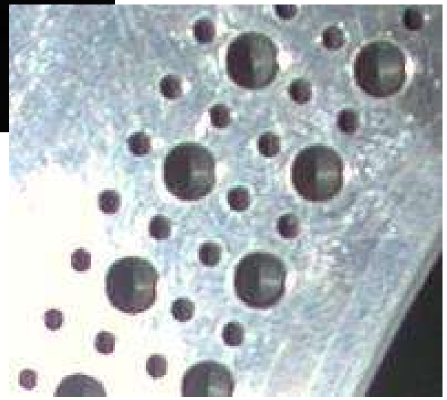
How to fix the wire

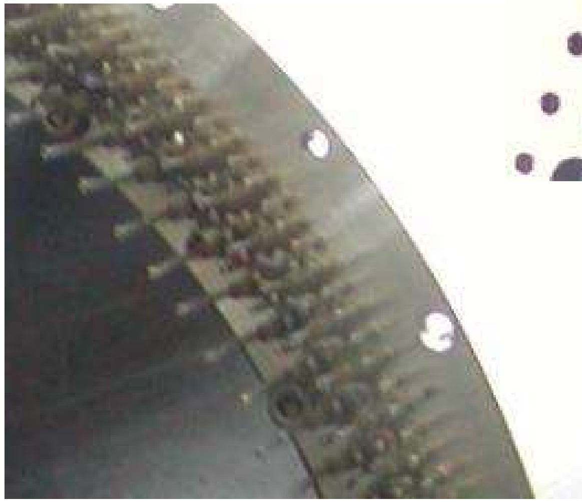
- Wire pass through the hole (~0.3mm$^{\phi}$) and is fixed by crimping.
- Feedthrough has a taper shape from the gas side.
  - We can put the wire easily into the hole of the aluminum pin with feedthrough for the sense wire.
- For the field wire,
  - There is aluminum pin only without feedthrough.
  - It is slightly difficult to put the field wire into the hole of aluminum pin directly. But, it is possible for Japanese and a student from Thailand.

Shape of one of feedthroughs

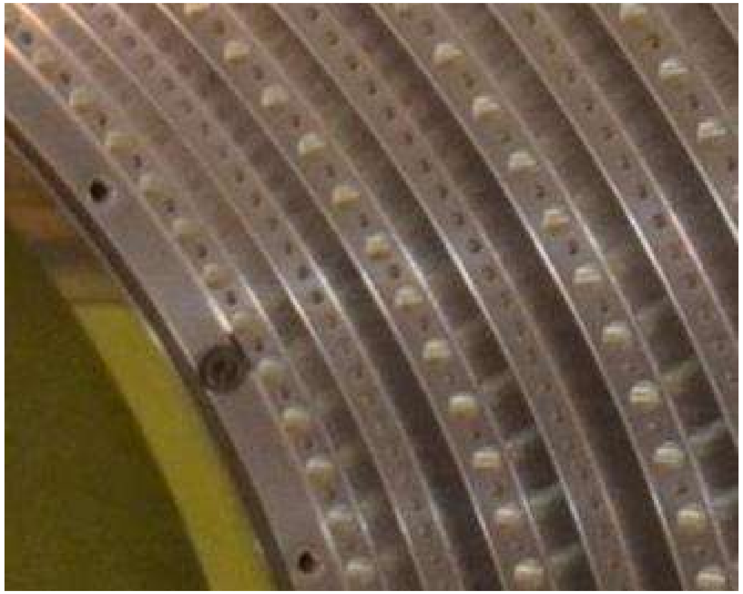


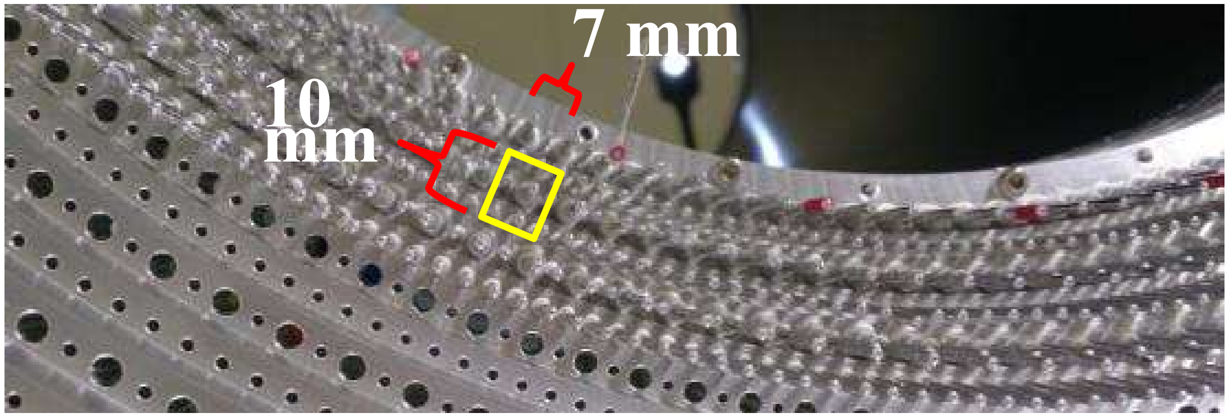
Belle-I CDC small cell chamber



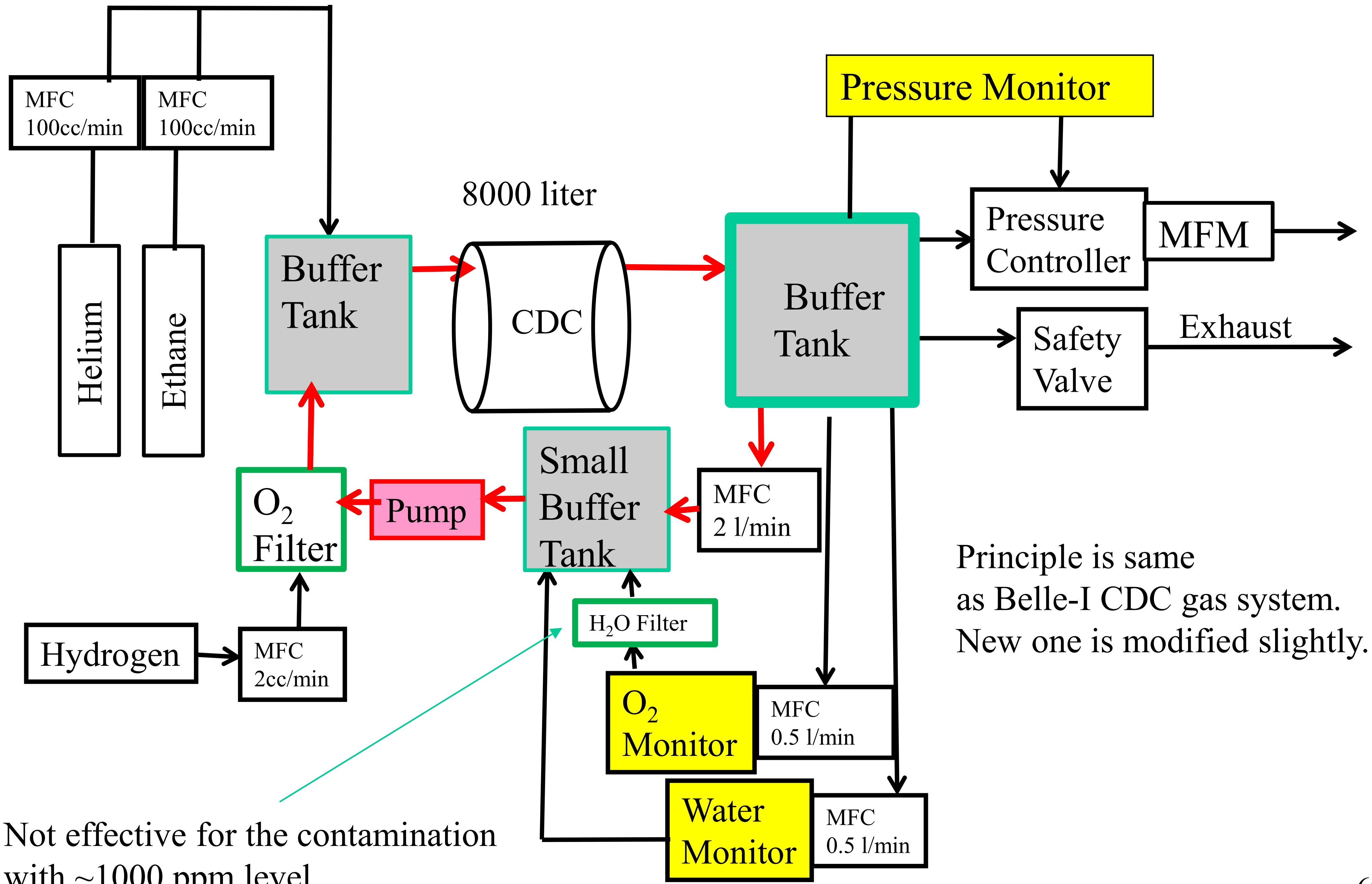


Belle-II CDC small cell chamber





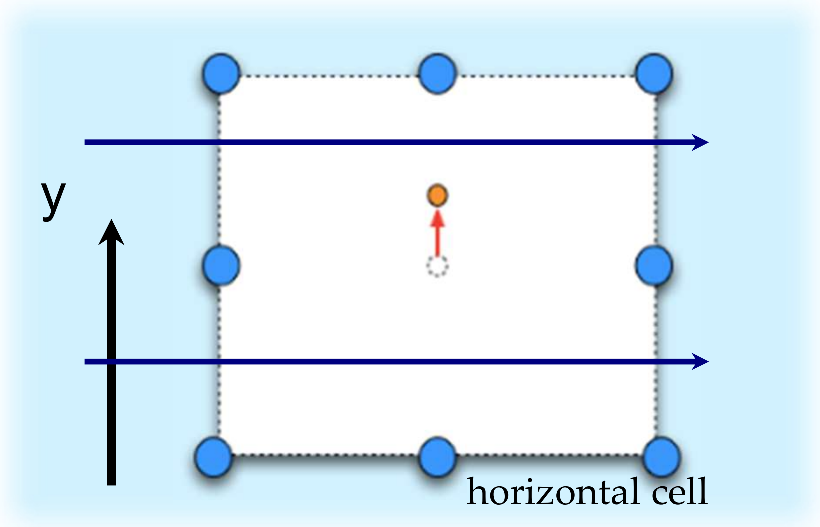
New CDC Gas System



Not effective for the contamination with ~1000 ppm level

Principle is same as Belle-I CDC gas system. New one is modified slightly.

sag calculation

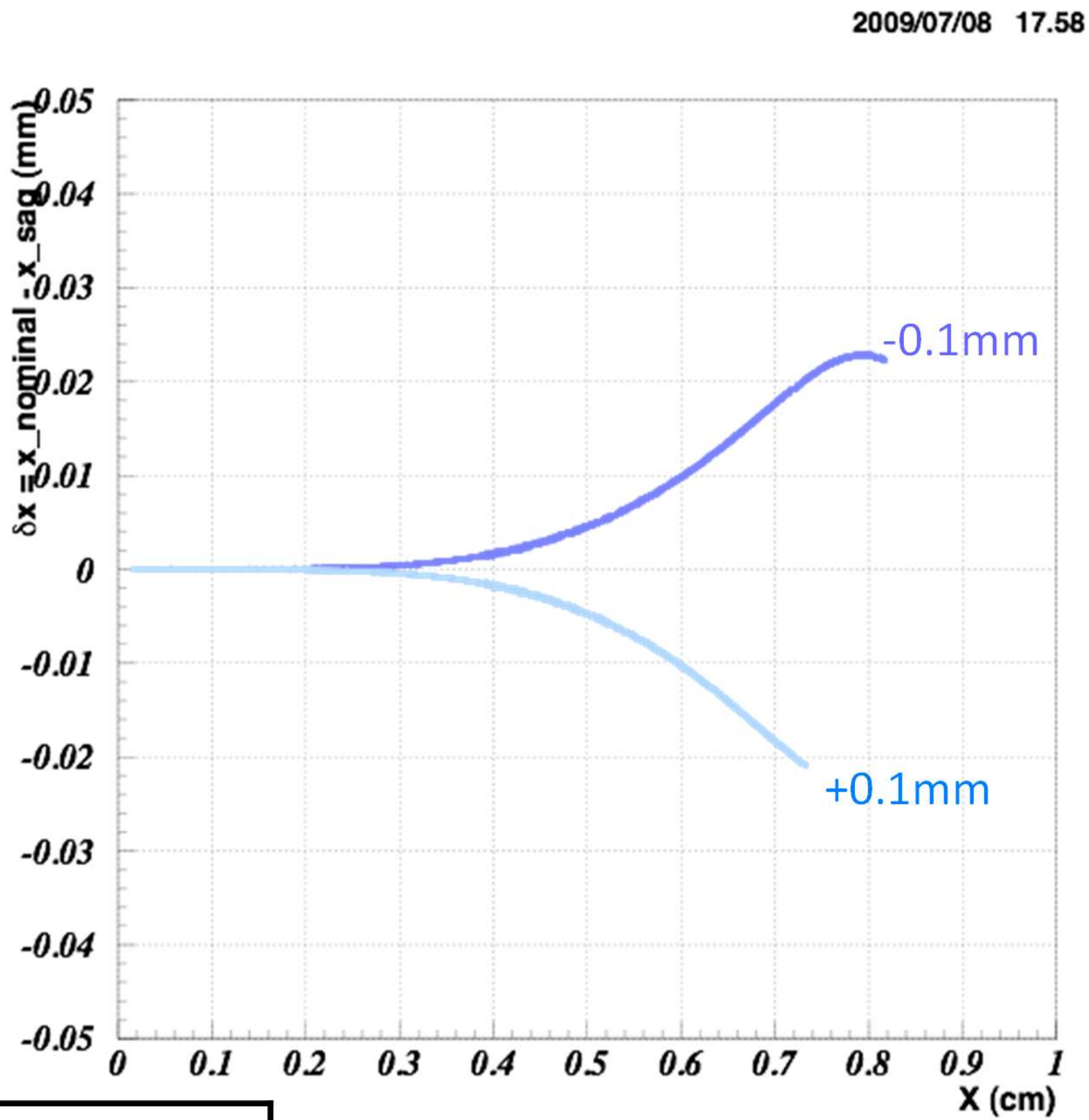


sense wire : 30μm, 50gw

tension (total tension)	80g (4.4 ton)	100g (5.2 ton)	120g (6.2 ton)
sag(field) - sag(sense)	84.8μm	28.4μm	-9.2μm

wire length : 2.4 m

current Belle position resolution
~ 100µm



(x: distance from sense wire at nominal case)

sense wire : 30µm, 50gw

tension (total tension)	80g (4.4 ton)
sag(field) - sag(sense)	84.8µm

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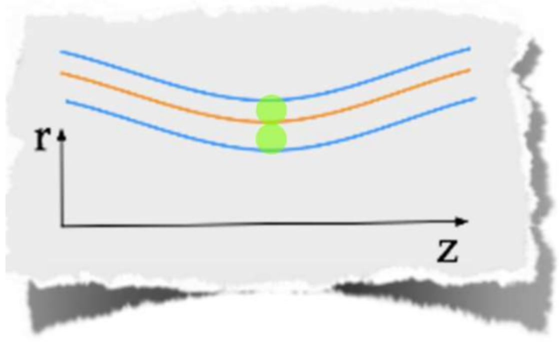
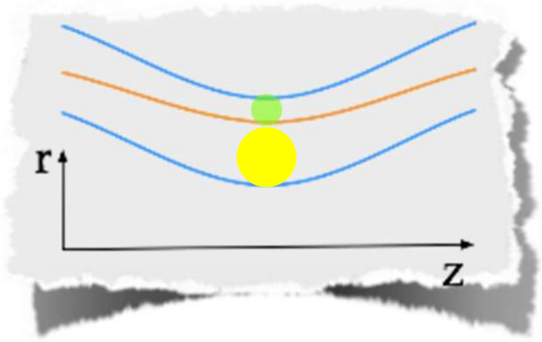
Acceptable

wire tension and gravity sag



- Current Belle CDC
  - wire tension is determined to keep the gravity sag of sense and field wire same
  - 50gw for sense wire and 120gw for field wire
  - total tension = (50gw x 8400) + (120gw x 8400 x 3) = 3.4 ton
- Belle-II
  - number of sense wire: 8400 →14336
  - total tension = (50gw x 14336) + (120gw x 14336 x 3) = 6.2 ton @ same weight
  - reduce total tension : 120gw → 80gw (base line design) , 6.2 ton → 4.4 ton
  - however difference of gravity sag is larger



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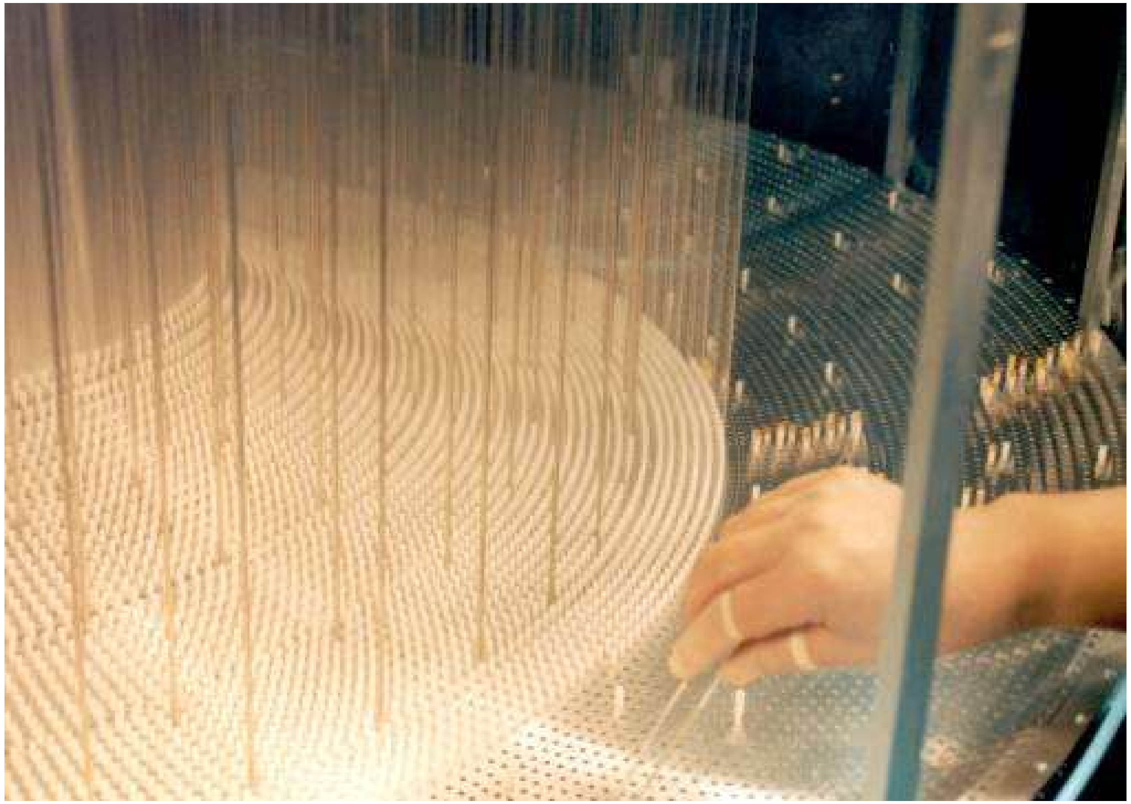
Belle I CDC

Wire chamber (Belle-CDC)



Inside of chamber
During wire stringing

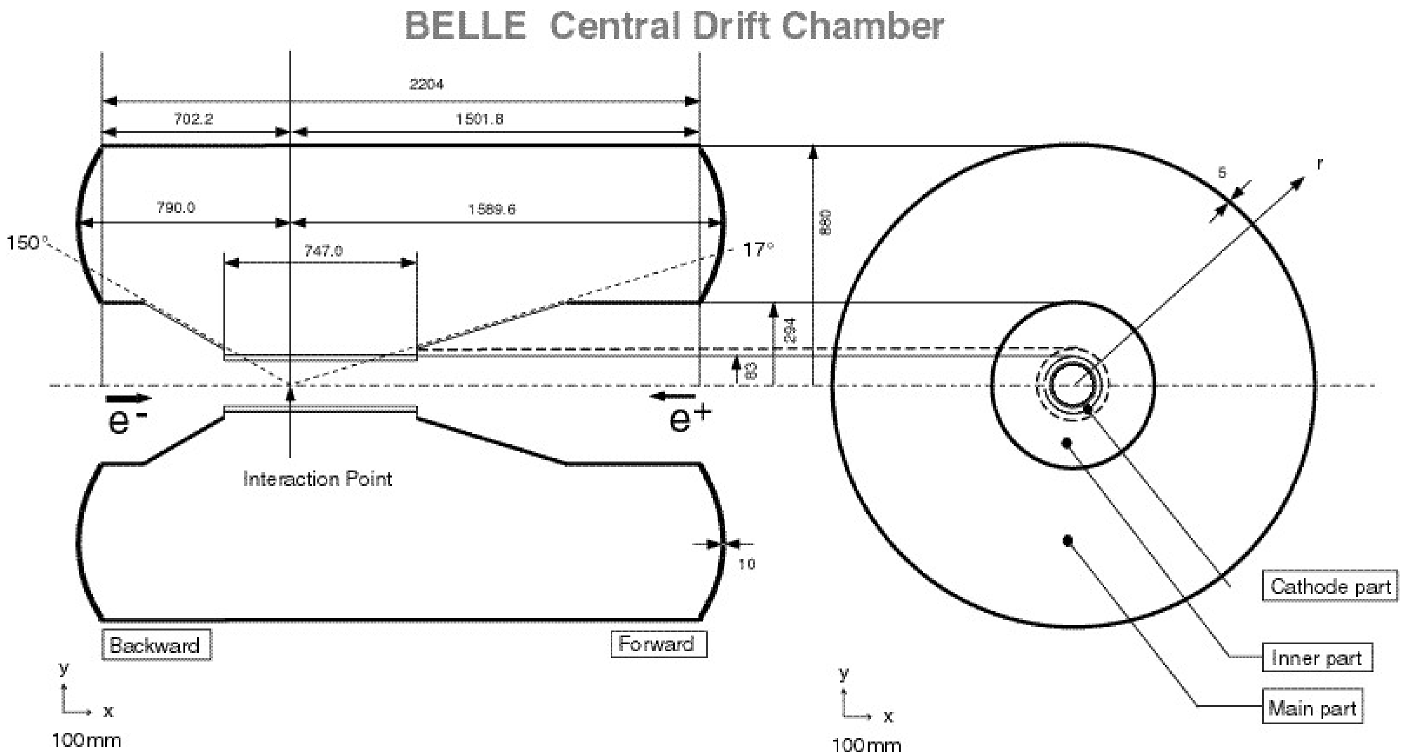
Outside view during electric checking

Structure

- Belle CDC consists of three parts(Main, Inner and Cathode).
- Curved Aluminum endplates for the main part.
  - Thickness : 10mm^t
- Conical endplates for the inner part to give a space for accelerator components.

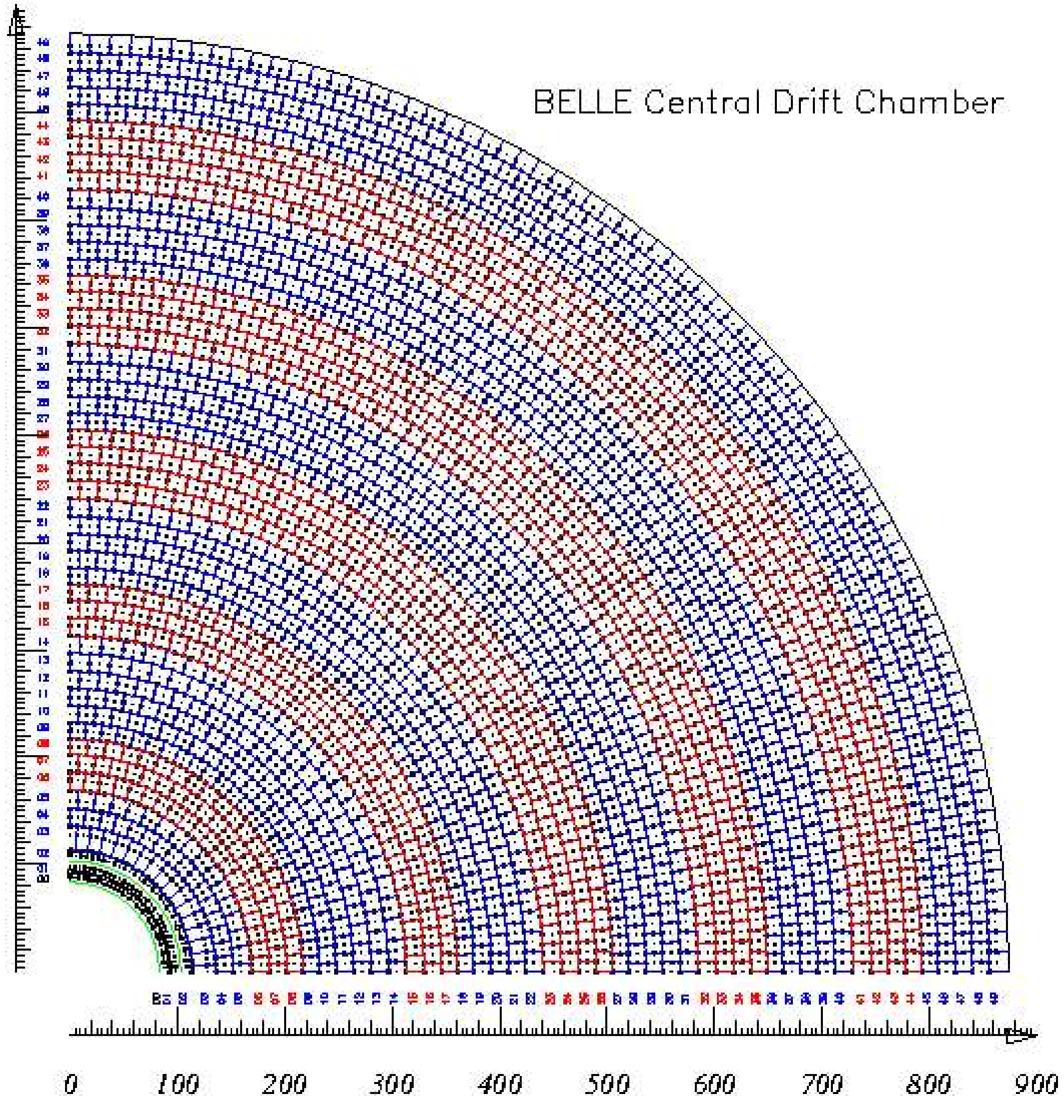
■ 5mm^t CRFP outer cylinder to support whole tension.

■ Two thin CFRP cylinder for cathode readout.
0.4mm^t x 2



Wire Configuration

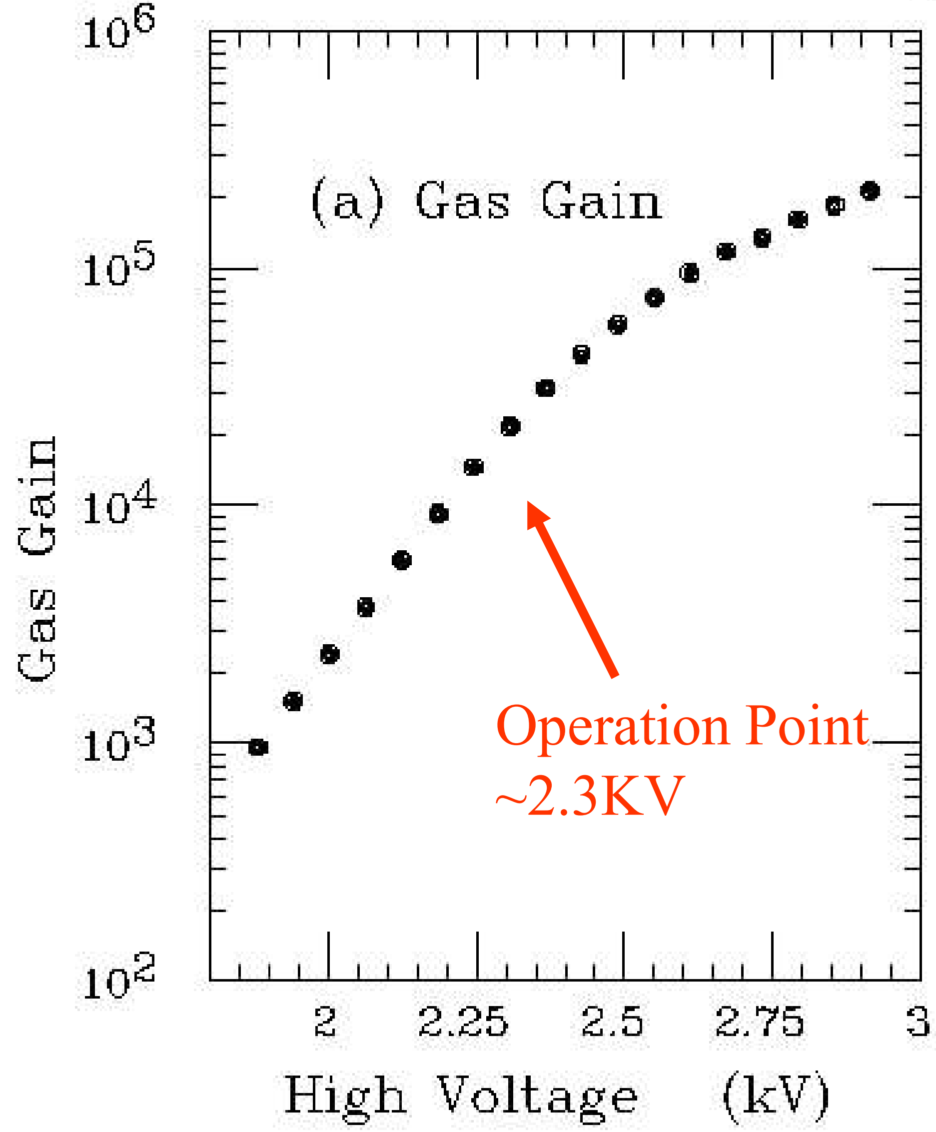
- Active region
  - R= 88mm : inner most sense wire
  - R=863mm : outer most sense wire
- Wires
  - 30μm$^{\phi}$ Au-W for sense wire
  - 126μm$^{\phi}$ Al for field wire
- Square cells
  - 16mm(r)X~18mm(rϕ)
- 6(axial)+5(stereo) super layers
  - 50 layers in total
- Readout channels
  - 8400 for sense wires
  - 1792 for cathode strips

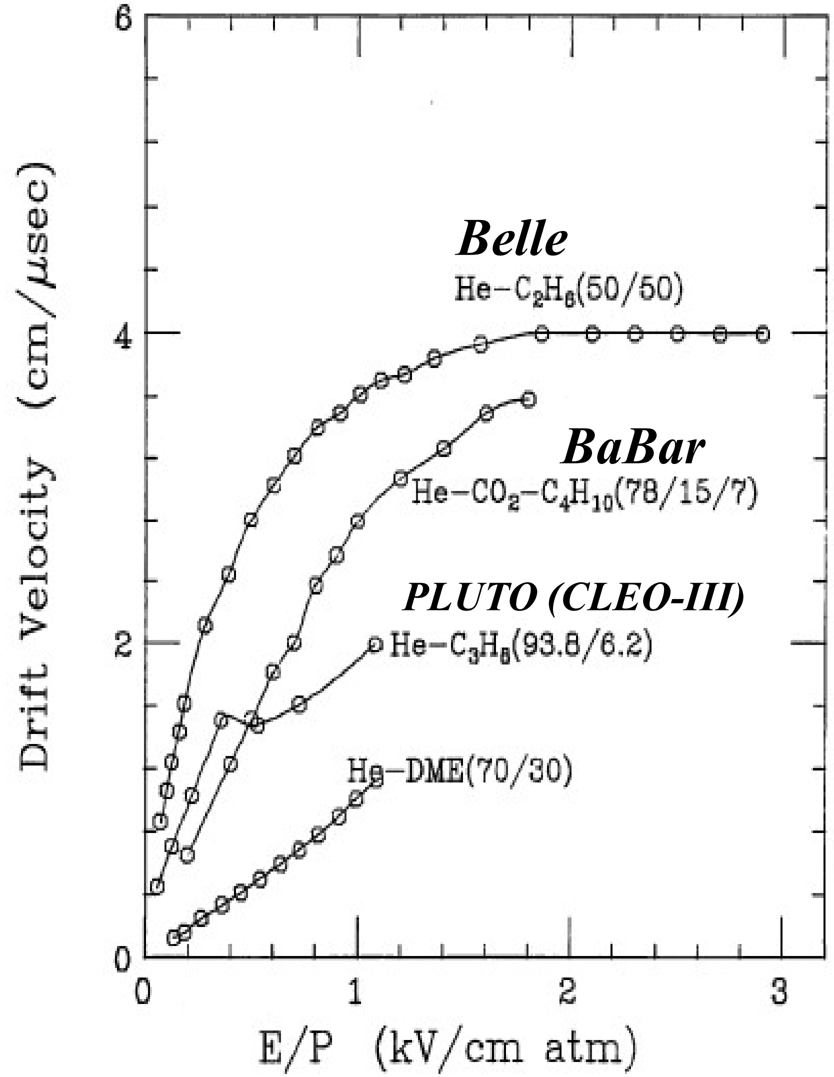


3+3, 3, 5, 3, 5, 4, 5, 4, 5, 4, 5

Gas Gain and Drift Velocity

He-C_2H_6(50/50)

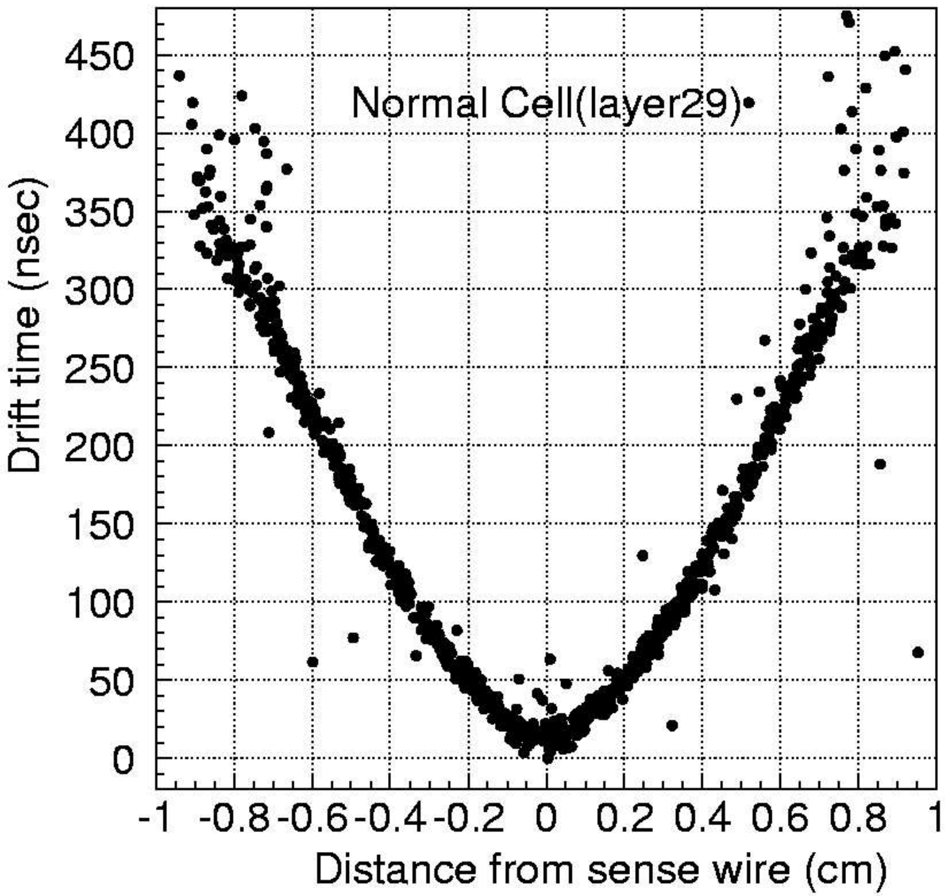




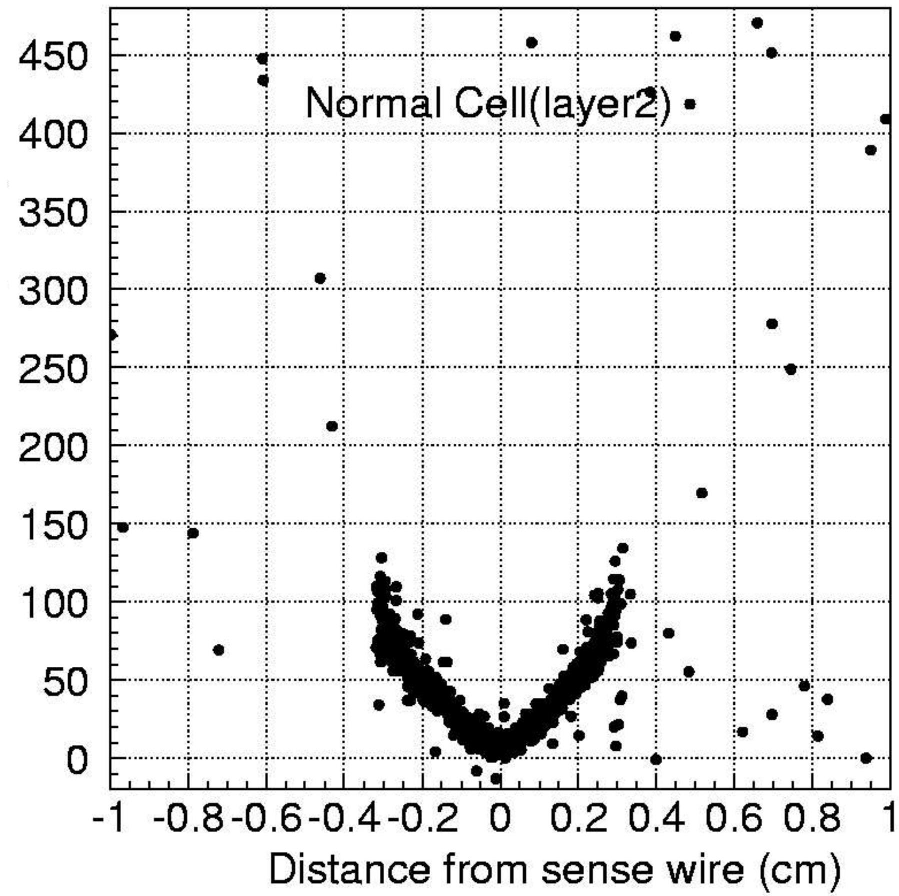
Drift velocity tends to saturate in higher electric field .

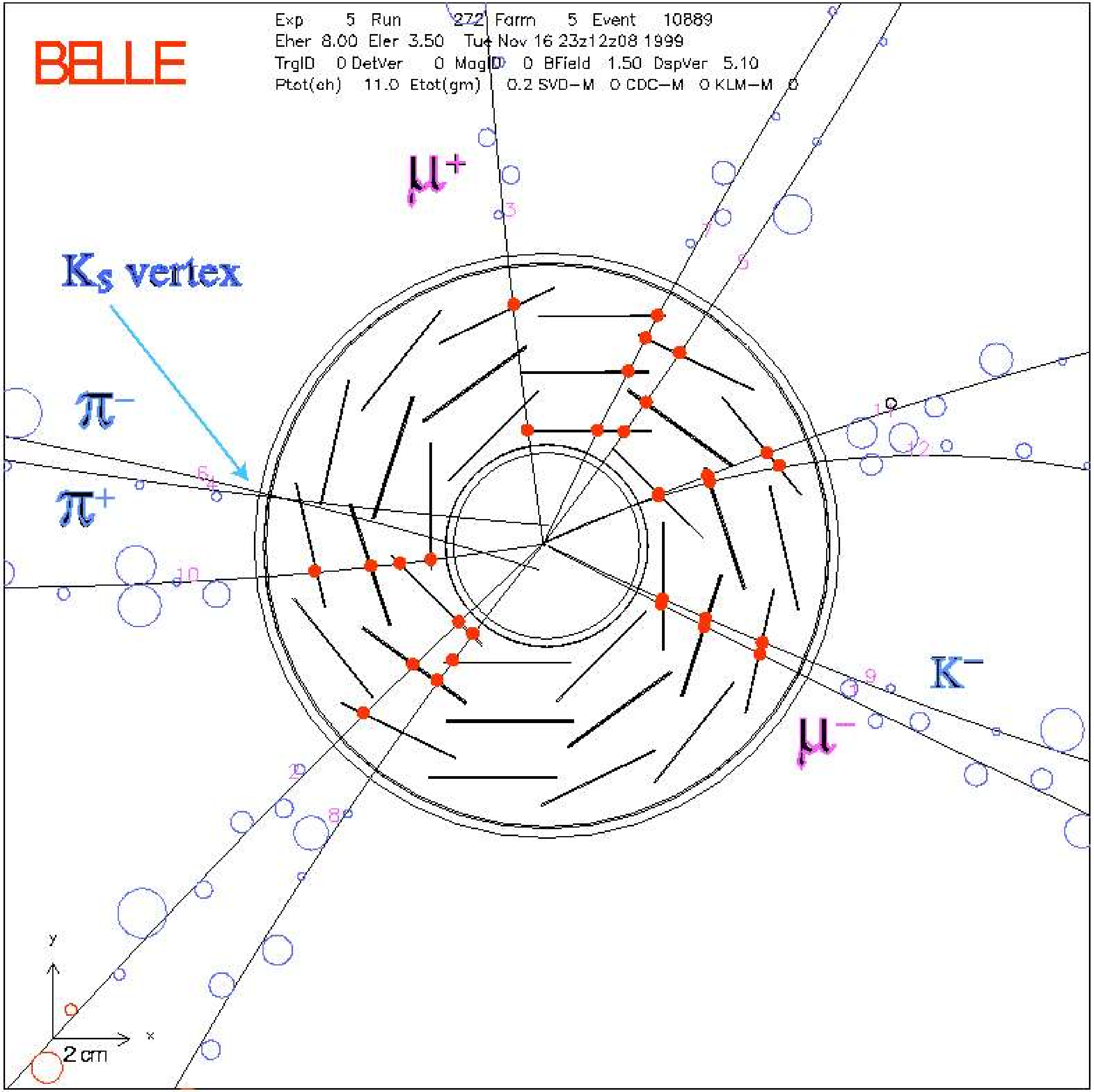
XT Curve & Max. Drift Time

Normal cell(17.3mm)



Small cell(5.4mm)





BELLE
Exp 5 Run 272 Farm 5 Event 10889
Eher 8.00 Eler 3.50 Tue Nov 16 23z12z08 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.0 Etot(gm) 0.2 SVD-M 0 CDC-M 0 KLM-M 0
μ^+
K_S vertex
π^-
π^+
K^-
μ^-
2 cm