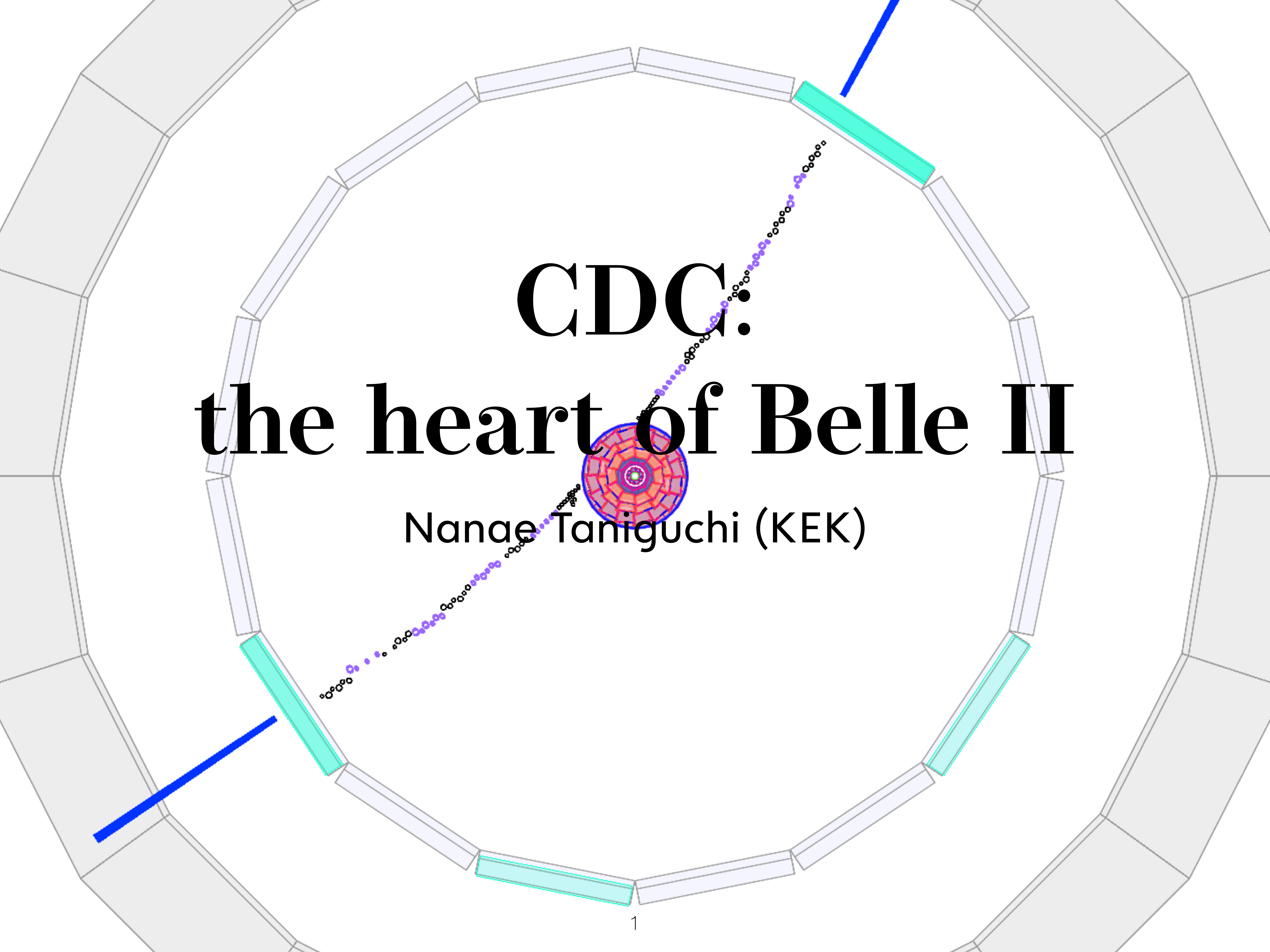
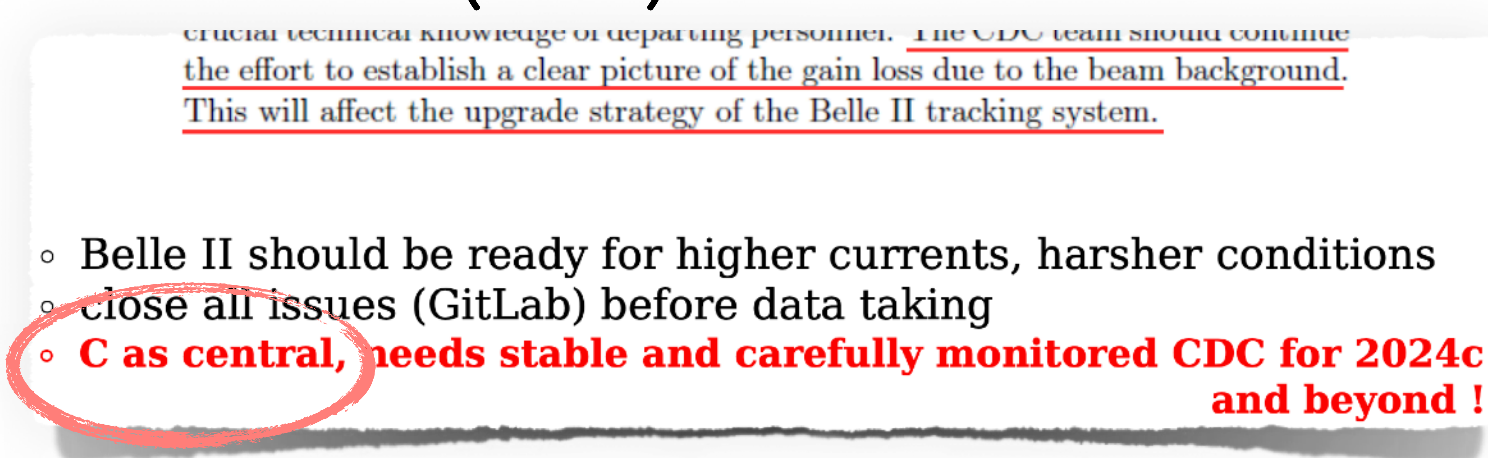


# CDC: the heart of Belle II

Nanae Taniguchi (KEK)

# Central Drift Chamber

- Belle I/II; Central Drift Chamber (CDC)
- VENUS; Central Drift Chamber (CDC)
- AMY; Central Drift Chamber (CDC)
- BaBar; Drift CHamber (DCH)
- ARGUS; Drift chamber
- KLOE; Drift chamber
- CLEO; DRift chamber (DR)
- MEG I/II; Cylindrical Drift CHamber (CDCH)
- COMET; Cylindrical Drift Chamber (CDC)



crucial technical knowledge of departing personnel. The CDC team should continue the effort to establish a clear picture of the gain loss due to the beam background. This will affect the upgrade strategy of the Belle II tracking system.

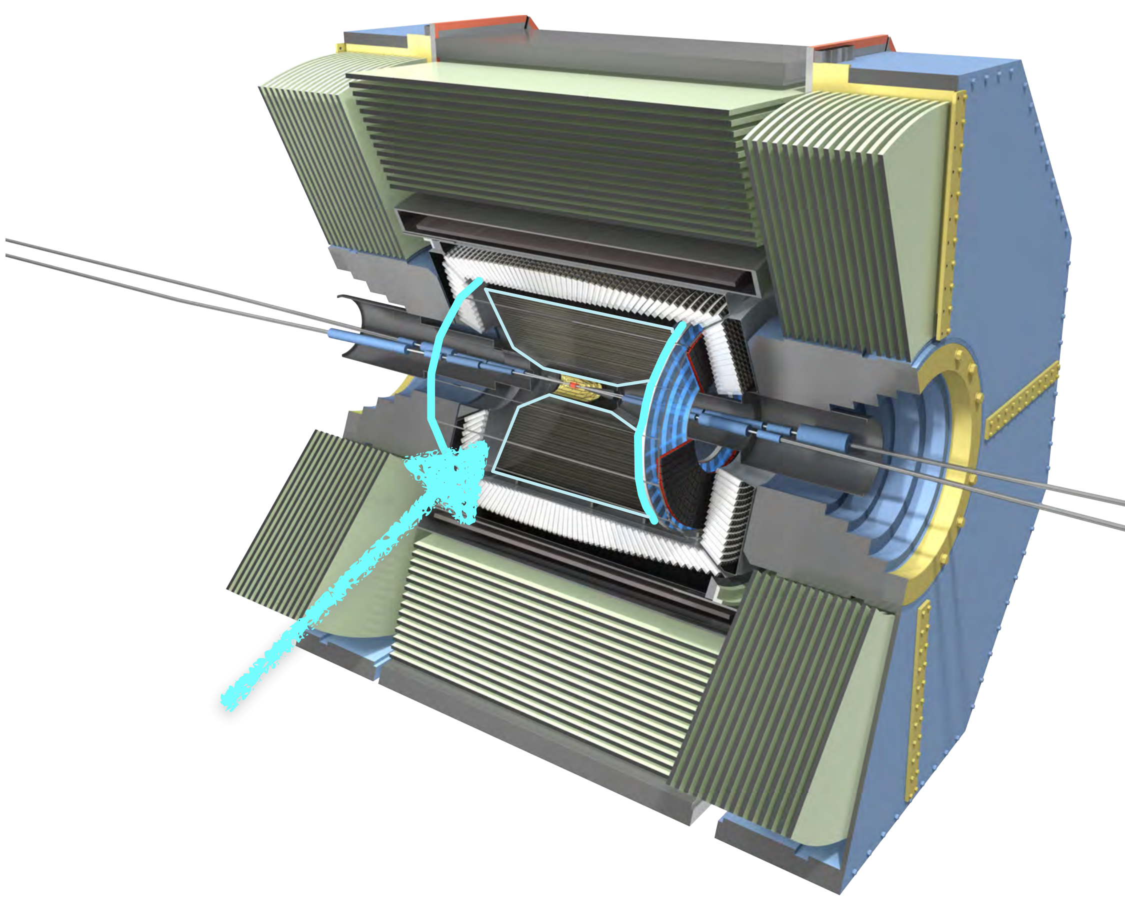
- Belle II should be ready for higher currents, harsher conditions
- close all issues (GitLab) before data taking
- **C as central, needs stable and carefully monitored CDC for 2024c and beyond !**

by Karim Trabelsi in B2GM

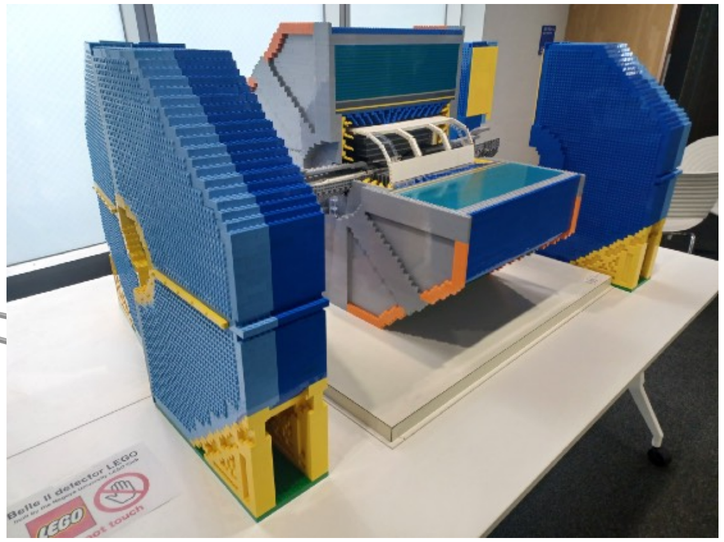
# Tracking detector

- "CDC" is main tracker of Belle II
- Roles of tracking detector in Belle II
  - measure momentum of charged particles
  - particle identification
  - provide track trigger signal
-

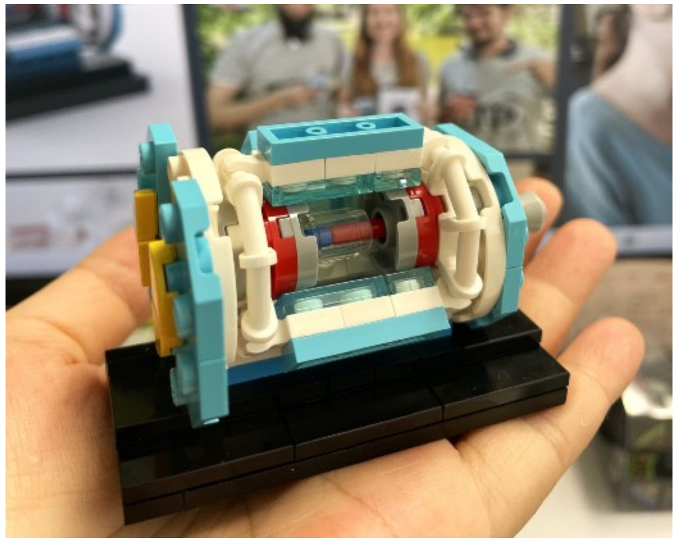
the most important !!



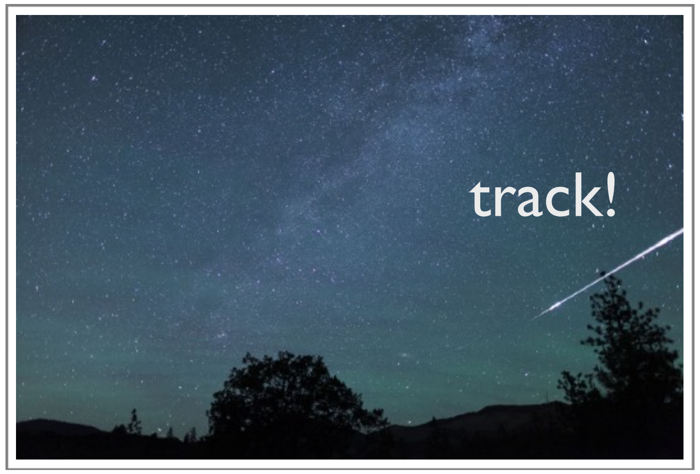
Nagoya University LEGO Club
Belle II model



Belle II micro scale model
(KIT)



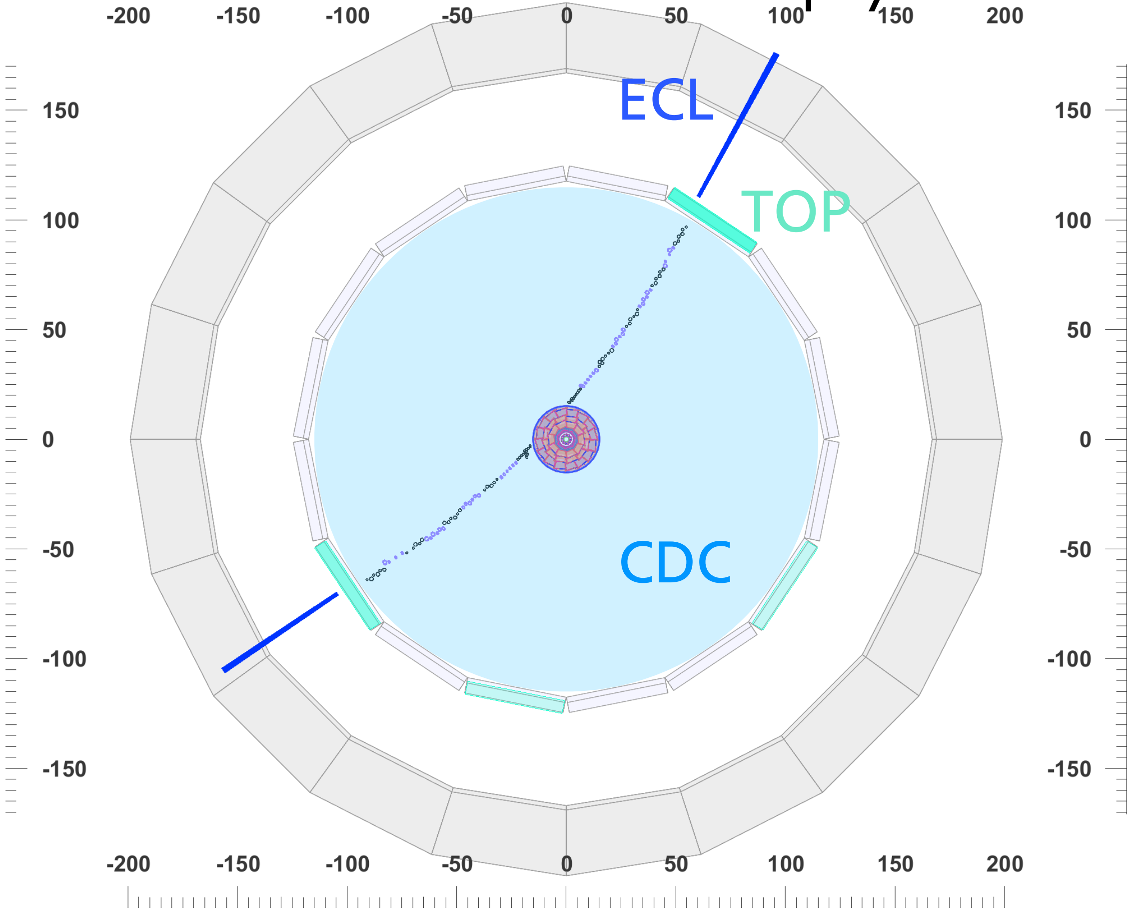
# “track”



- though we can’t see airplane far away, comet, we can see a track which is caused by interaction with surroundings
  - water vapor → cooling → cloud
  - interaction between dust and atmosphere → excited state of molecular → photon emission
- we can’t see particles (muon, pion,..) by eye, but we can detect and obtain information of “track” via interaction with materials

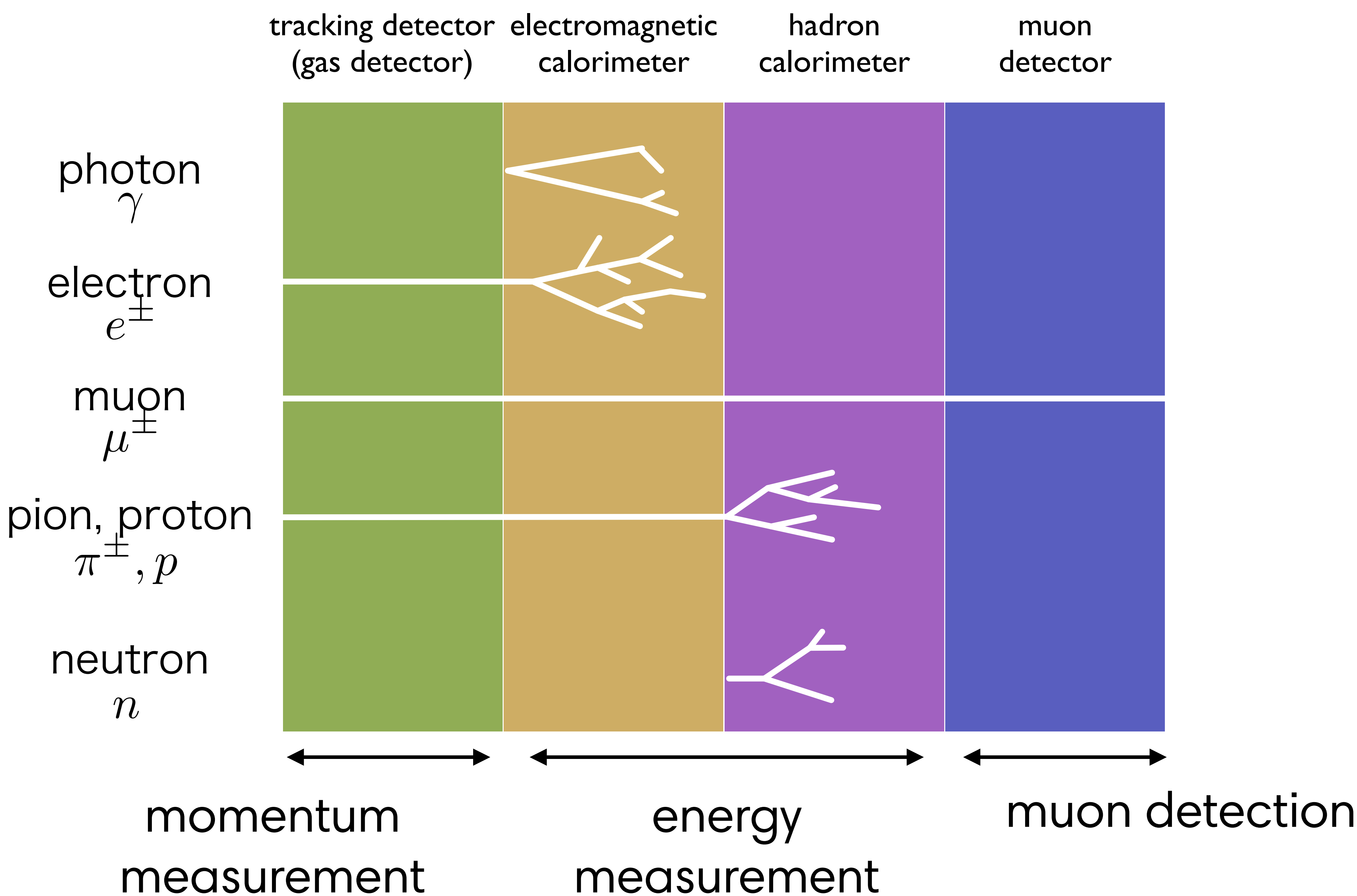
Belle II detector event display




track of cosmic ray (muon)

# interactions in the detector

interaction of each particle is different

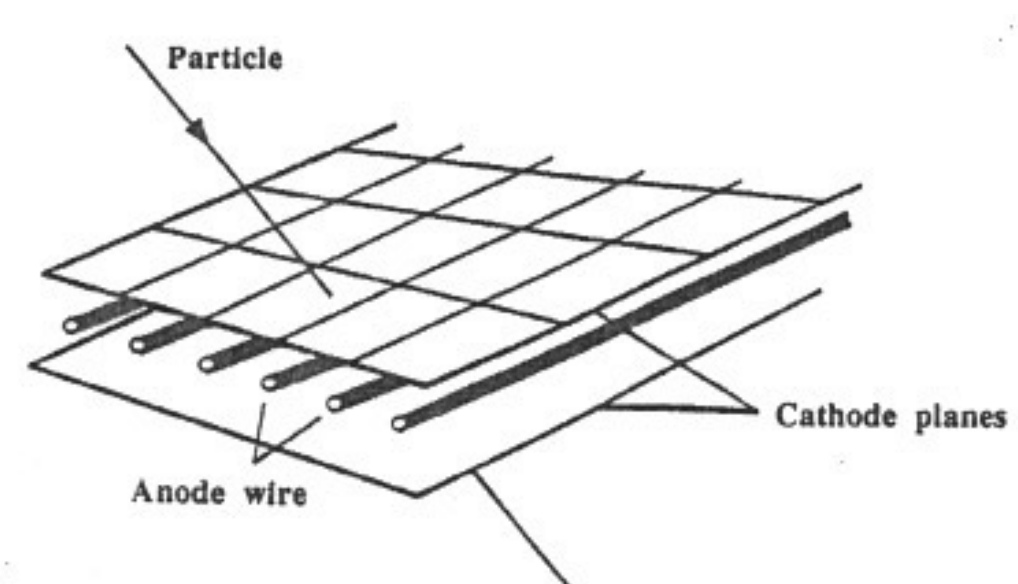


# tracking technology

- 3 major technologies
- gas detectors
  - ionization in gas (electron-ion pairs are created)
    - O(10) electrons/cm, dependent on gas element
  - gas amplification
    - gas amplification ~$10^4$ is needed to reach sufficient signal over noise
- silicon detectors
  - ionization in solid state (electron-hole pairs are created)
    - O(100) electron-hole pairs/um
  - no amplification is needed
- fiber trackers
  - scintillation fibers; scintillating light detected by photon sensor

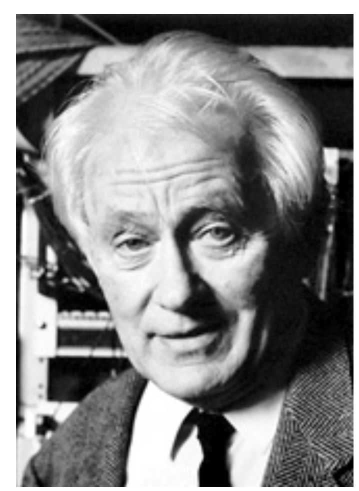
# drift chamber

- drift chamber is one of gas detector
  - wire + gas
- other gas detectors
  - multi-wire proportional chamber (MWPC)




https://www.nobelprize.org/prizes/physics/1992/press-release/

## The Nobel Prize in Physics 1992



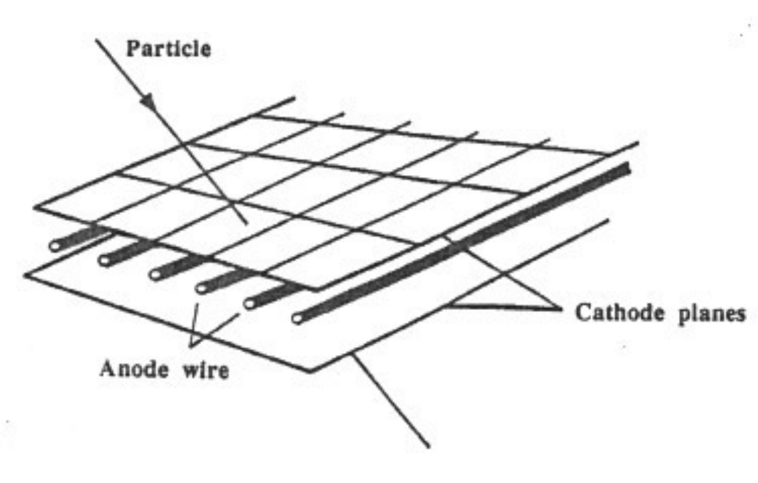
Georges Charpak
Prize share: 1/1

The Nobel Prize in Physics 1992 was awarded to Georges Charpak *"for his invention and development of particle detectors, in particular the multiwire proportional chamber"*.

# drift chamber

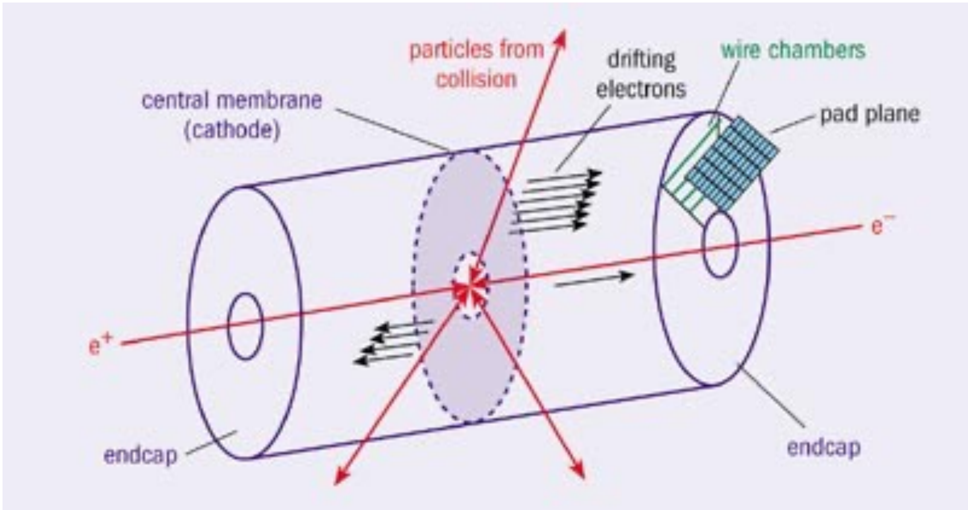
- drift chamber is one of gas detector
  - wire + gas
- other gas detectors
  - multi-wire proportional chamber (MWPC)
  - Time Projection Chamber (TPC)
  - Gas Electron Multiplier (GEM)
    - no wire !!

MWPC



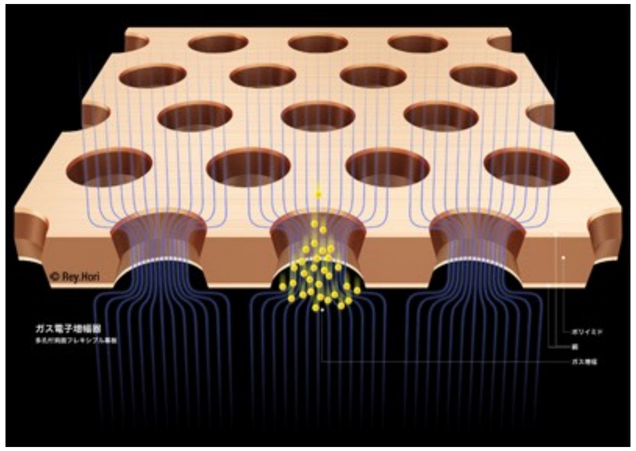

https://www.nobelprize.org/prizes/physics/1992/press-release/

TPC



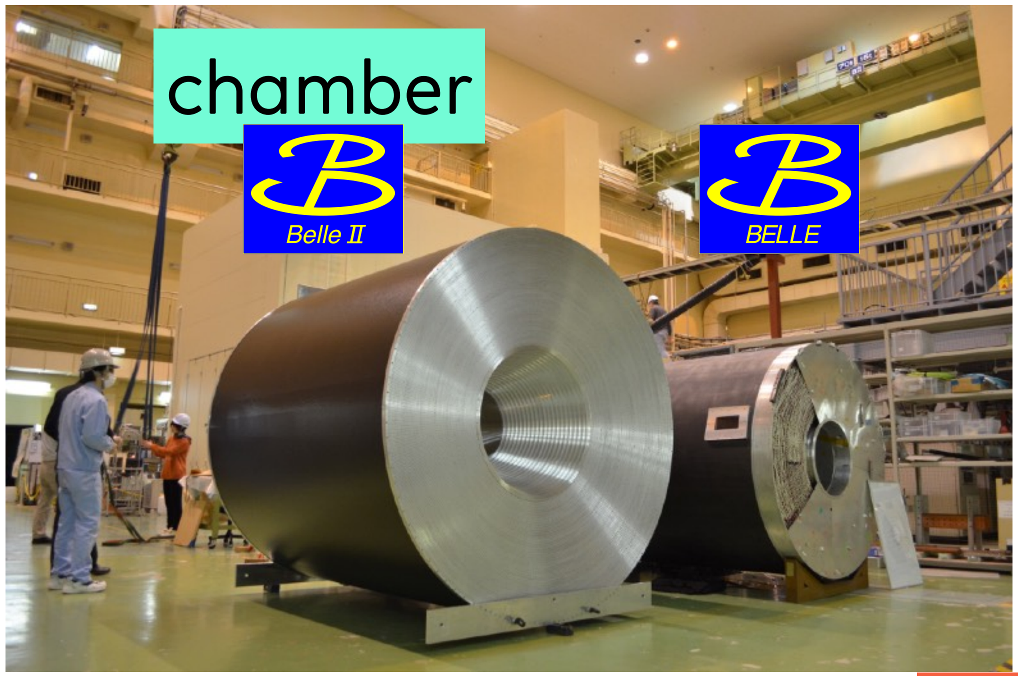

https://cerncourier.com/a/the-time-projection-chamber-turns-25/

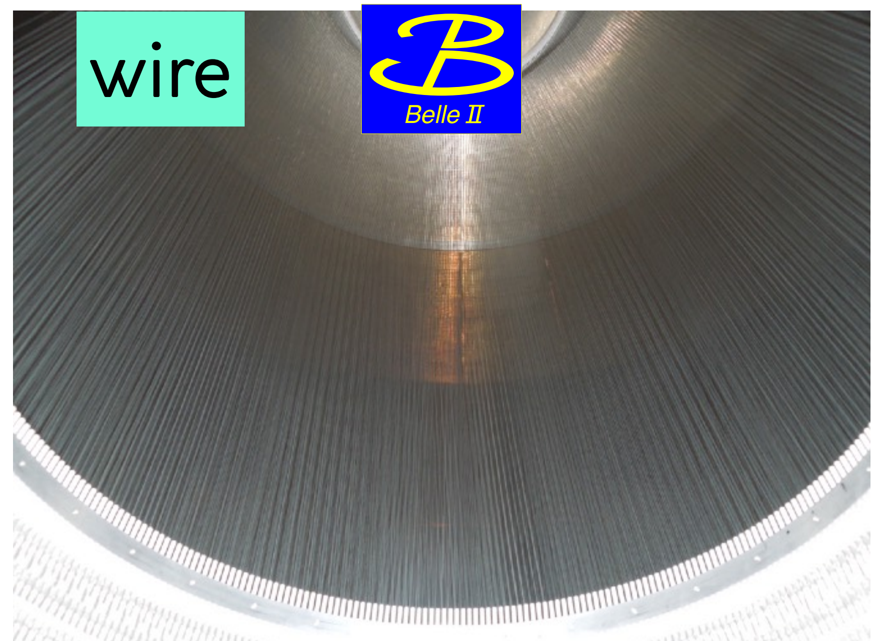
GEM

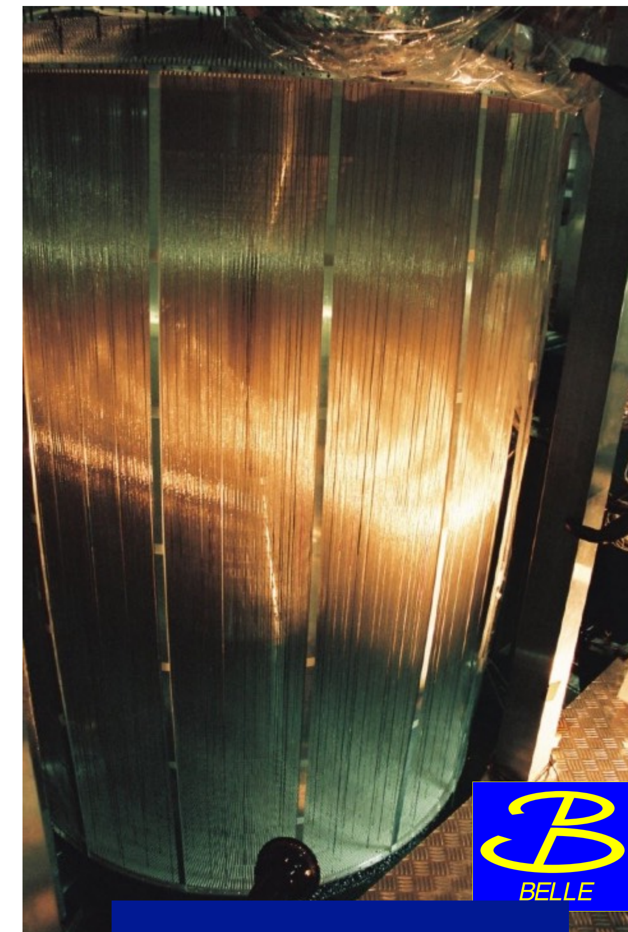


https://rd.kek.jp/lab_02_1_e.html

# drift chamber



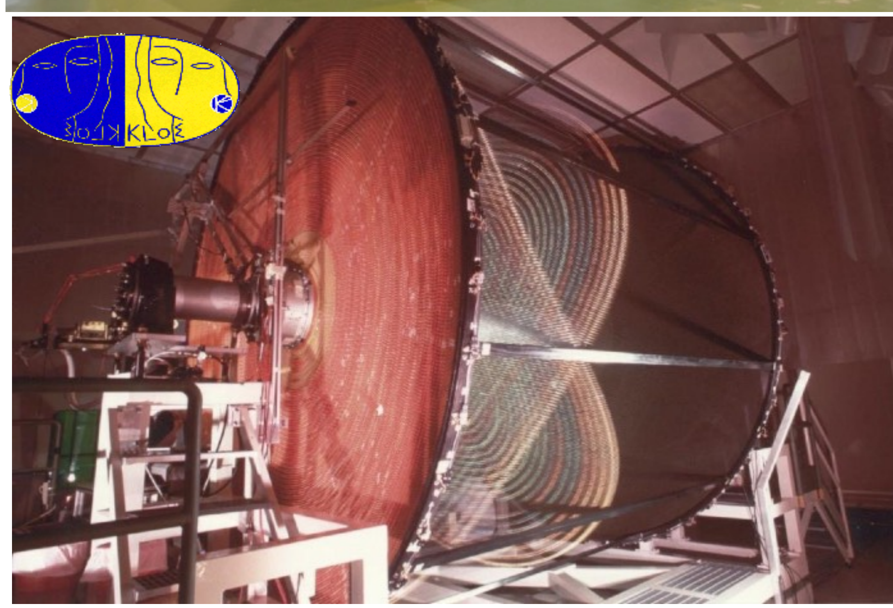



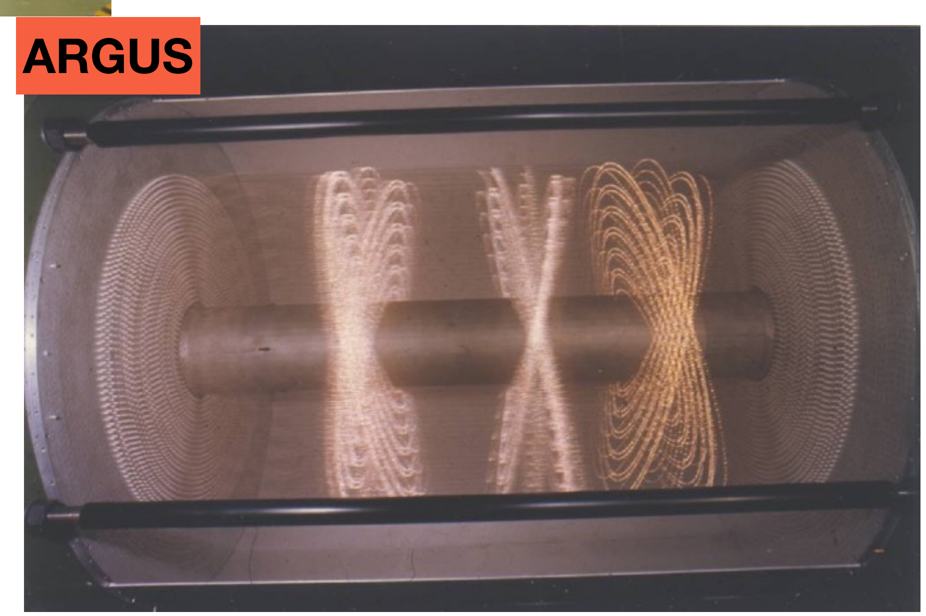




Cylinderical

drift chamber

$e^+e^-$ collider



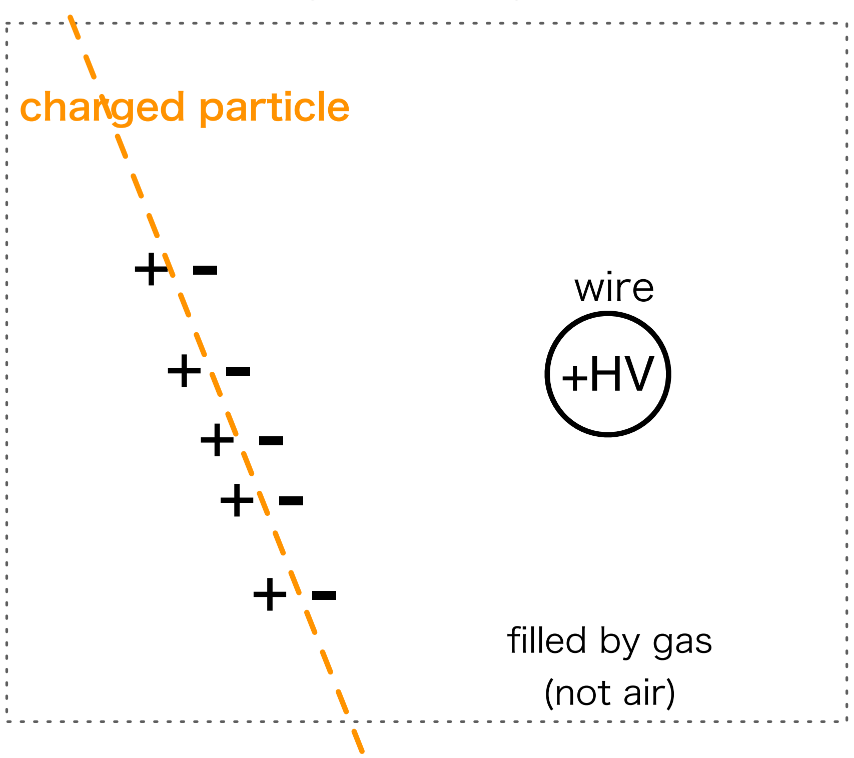

There are/were many other drift(wire) chambers in many experiments

# gas wire chamber

## How gas wire chamber works

1. charged particle ionize gas molecular inside chamber
2. electron created by ionizing move to wire
3. gas amplification (electron avalanche) near wire
4. signal is generated by electromagnetic induction

ionization




A pair of electron and positive ion is created by collision between charged particle and molecular in gas (ionization)

charged particle lose energy which is used for ionization (energy loss)

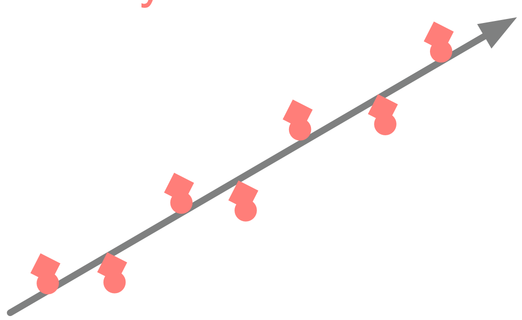
The number of created electron-ion pair is proportional to energy loss of charged particle in gas

# gas wire chamber

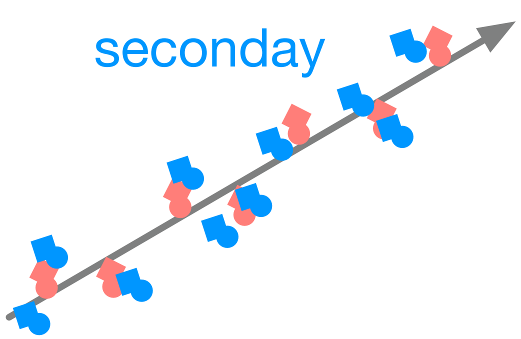
## How gas wire chamber works

1. charged particle ionize gas molecular inside chamber
2. electron created by ionizing move to wire
3. gas amplification (electron avalanche) near wire
4. signal is generated by electromagnetic induction

primary ionization



seconday



total ionization
= primary + secondary

$$N_T = \frac{\Delta E}{W_i}$$
$$\Delta E = 0.32\ \mathrm{keV/cm}$$
$$W_i = 41.3\ \mathrm{eV}$$
$$N_T \sim 8/\mathrm{cm}$$

**Table 34.5:** Properties of noble and molecular gases at normal temperature and pressure (NTP: 20° C, one atm). $E_X$, $E_I$: first excitation, ionization energy; $W_I$: average energy per ion pair; $dE/dx|_{\min}$, $N_P$, $N_T$: differential energy loss, primary and total number of electron-ion pairs per cm, for unit charge minimum ionizing particles.

| Gas | Density, mg cm$^{-3}$ | $E_x$ eV | $E_I$ eV | $W_I$ eV | $dE/dx\|_{\min}$ keV cm$^{-1}$ | $N_P$ cm$^{-1}$ | $N_T$ cm$^{-1}$ |
|---|---|---|---|---|---|---|---|
| He | 0.179 | 19.8 | 24.6 | 41.3 | 0.32 | 3.5 | 8 |
| Ne | 0.839 | 16.7 | 21.6 | 37 | 1.45 | 13 | 40 |
| Ar | 1.66 | 11.6 | 15.7 | 26 | 2.53 | 25 | 97 |
| Xe | 5.495 | 8.4 | 12.1 | 22 | 6.87 | 41 | 312 |
| $CH_4$ | 0.667 | 8.8 | 12.6 | 30 | 1.61 | 28 | 54 |
| $C_2H_6$ | 1.26 | 8.2 | 11.5 | 26 | 2.91 | 48 | 112 |
| $iC_4H_{10}$ | 2.49 | 6.5 | 10.6 | 26 | 5.67 | 90 | 220 |
| $CO_2$ | 1.84 | 7.0 | 13.8 | 34 | 3.35 | 35 | 100 |
| $CF_4$ | 3.78 | 10.0 | 16.0 | 54 | 6.38 | 63 | 120 |

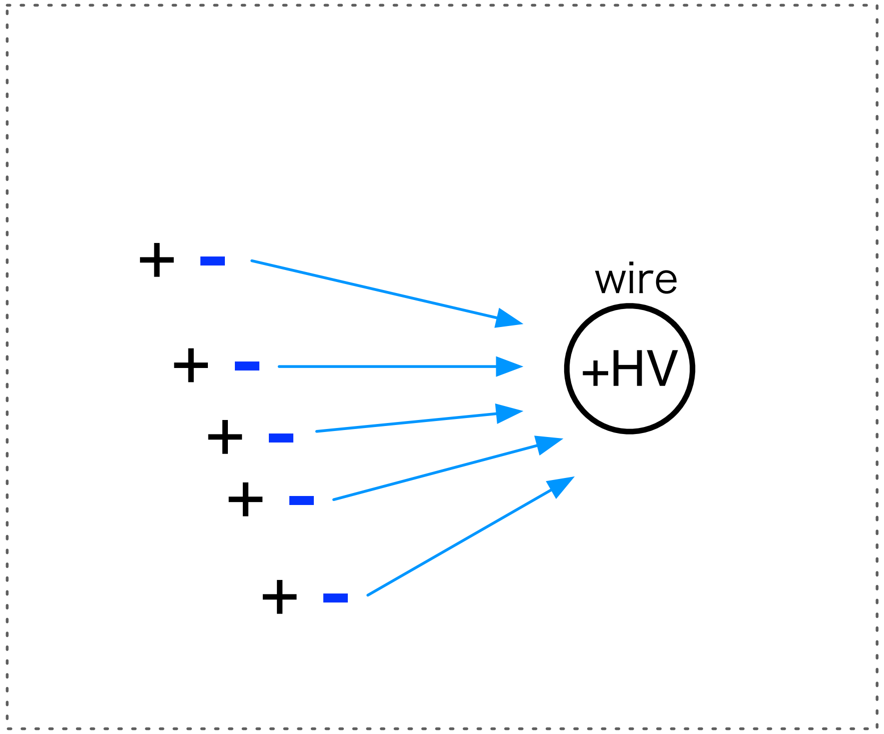
an ionizing particle passes through the gas it creates electron-ion pairs
often the ejected electrons have sufficient energy to further ionize the medium.

# gas wire chamber

## How gas wire chamber works

1. charged particle ionize gas molecular inside chamber
2. electron created by ionizing move to wire
3. gas amplification (electron avalanche) near wire
4. signal is generated by electromagnetic induction

electron drift




electric field is induced by applying high voltage to wire

electron move toward wire along electric field line
multiple-scattering is occurred during moving (drifting)

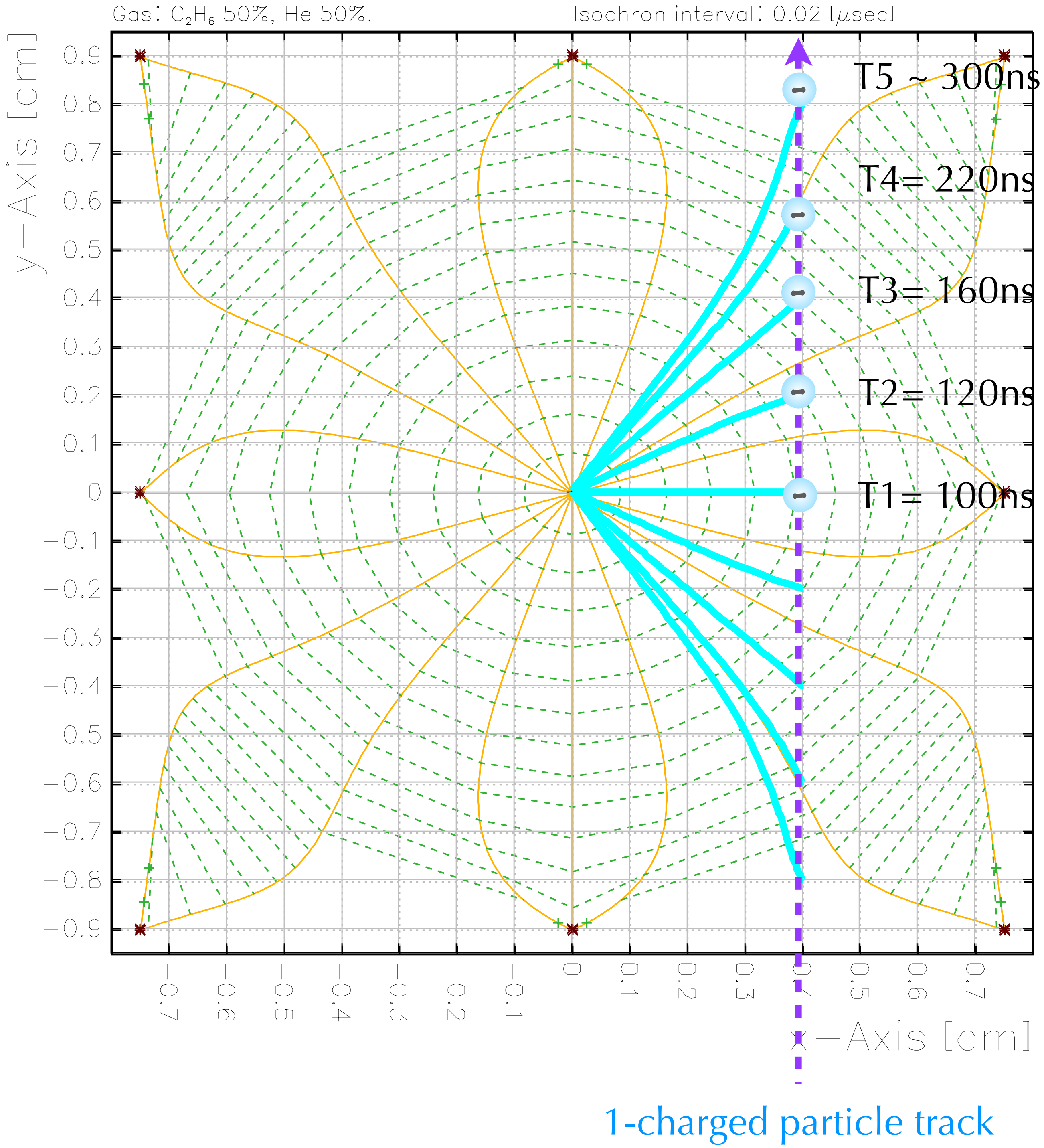
drift velocity is determined by gas mixture, pressure and electric field.
~4cm/usec (He base gas)

measurement of drift time can provide track position

➡ **"Drift Chamber"**

# drift

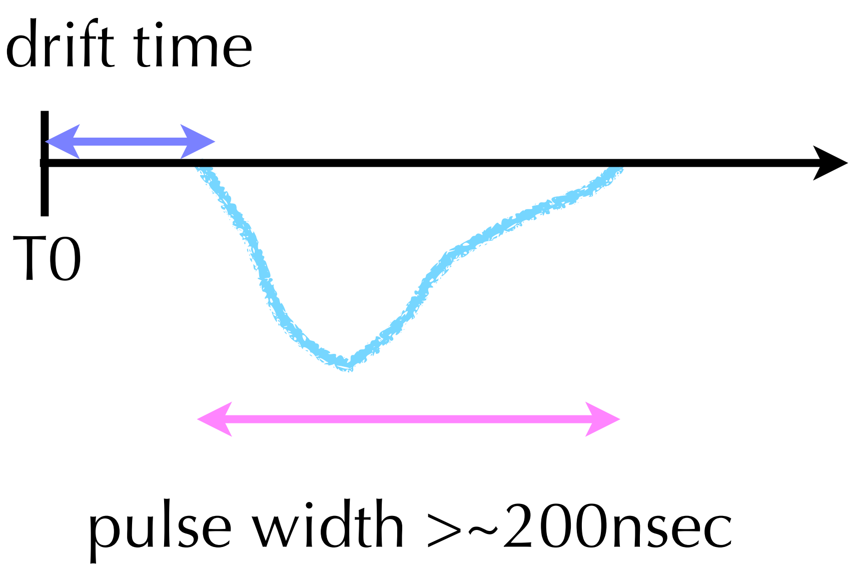
B=0T




yellow : drift line

green : equivalent drift time line

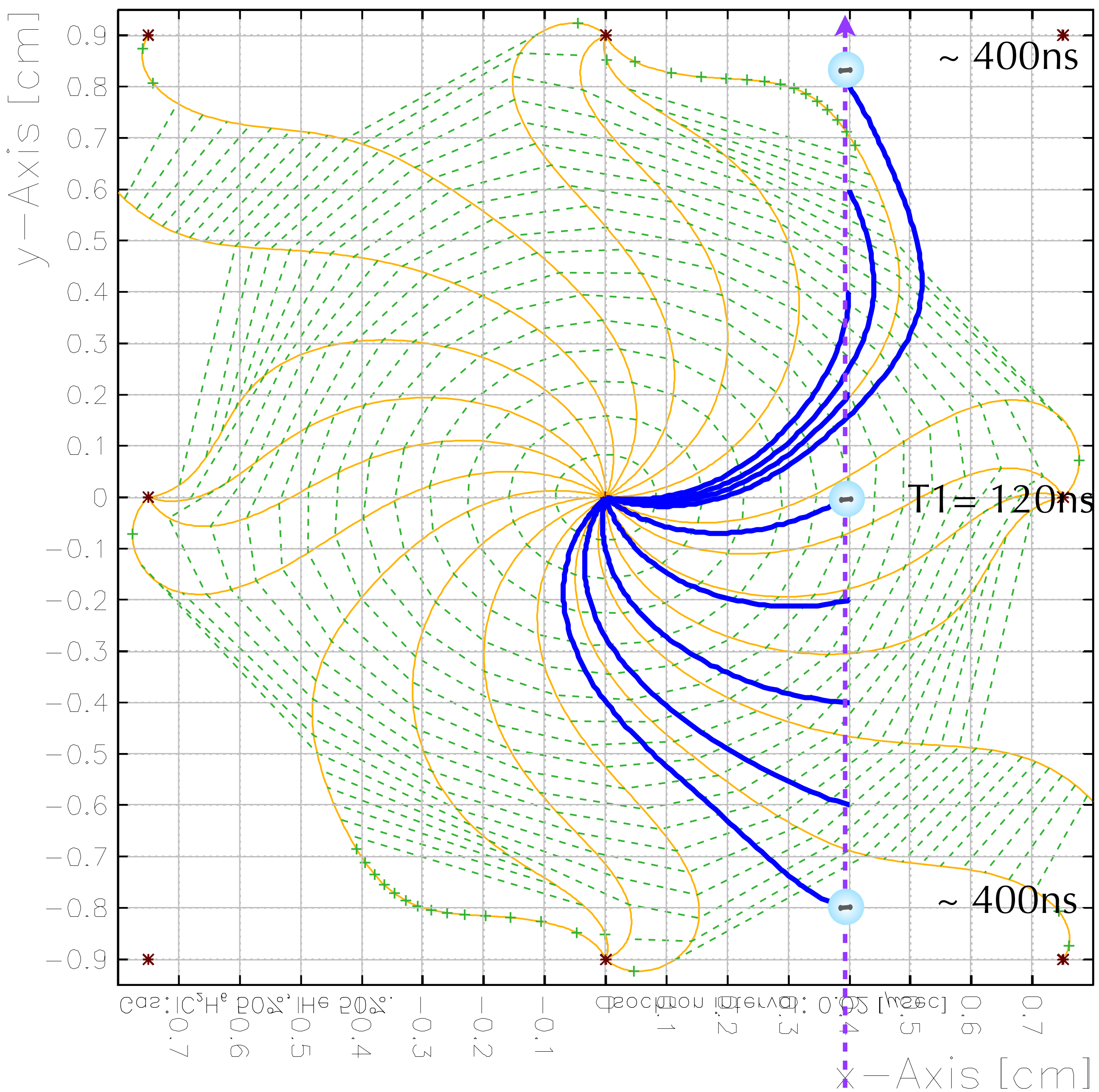
arrival time difference > 200nsec



# drift

in magnetic field

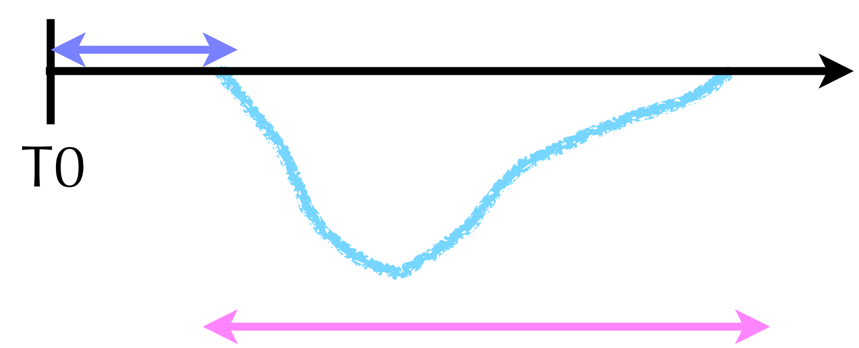
B=1.5T




1-charged particle track

arrival time difference > 300nsec

drift time




pulse width >~300nsec

duration becomes longer

# gas wire chamber

## How gas wire chamber works

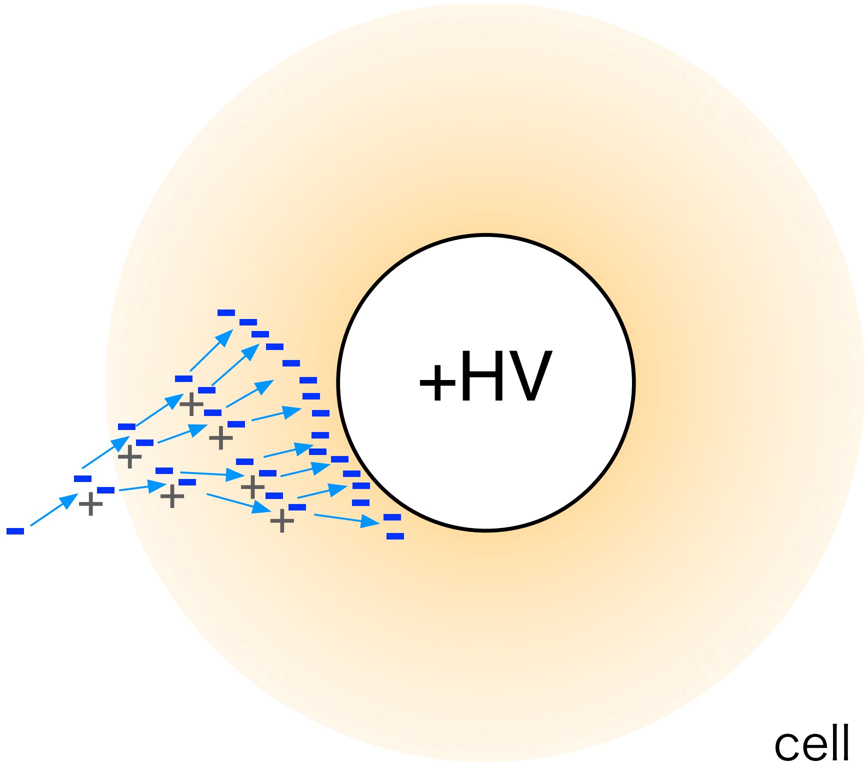
1. charged particle ionize gas molecular inside chamber
2. electron created by ionizing move to wire
3. gas amplification (electron avalanche) near wire
4. signal is generated by electromagnetic induction

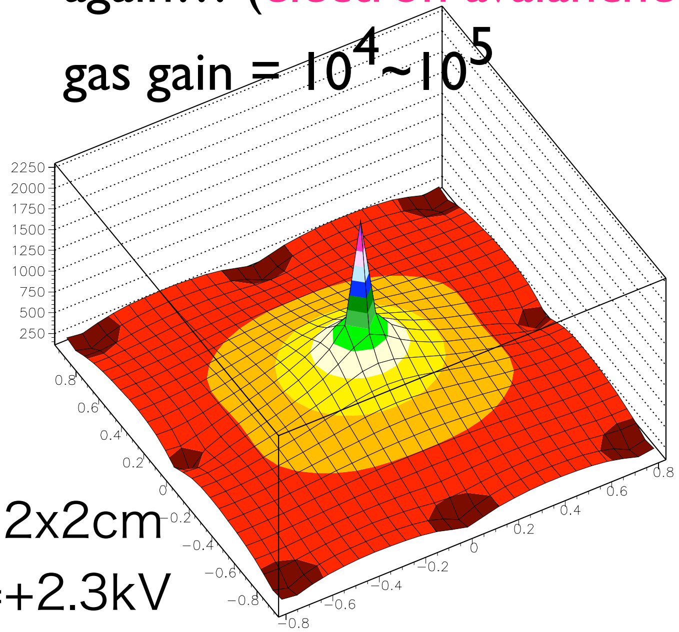
electron is accelerated by strong electric field near wire

the electron (which has higher energy) can ionize molecular of gas

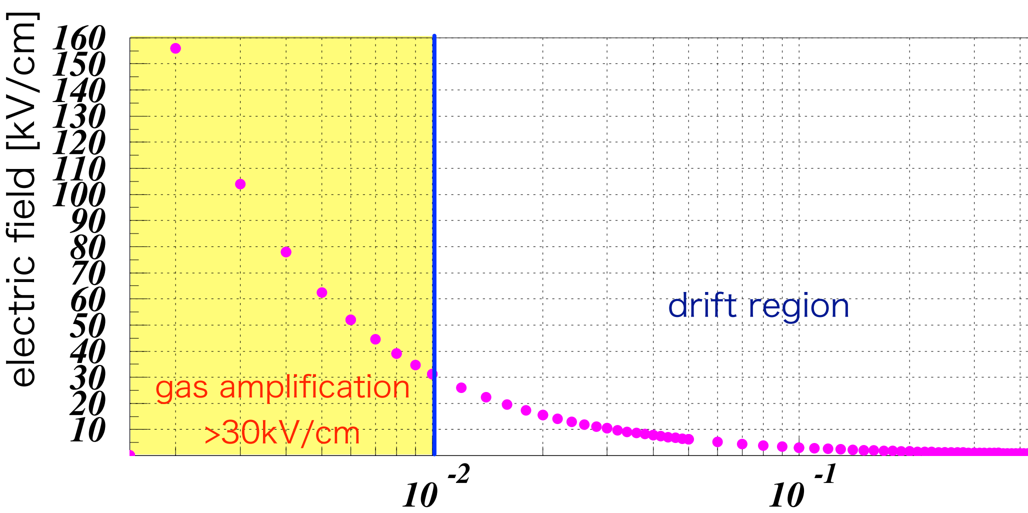
secondary electron is accelerated and ionization occur again and again… (electron avalanche, gas amplification)

gas gain = $10^4 \sim 10^5$



cell 2x2cm
HV=+2.3kV



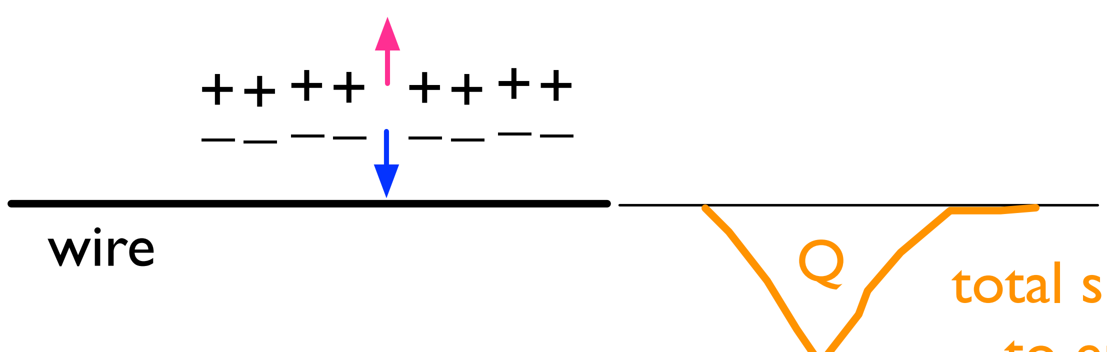
# gas wire chamber

## How gas wire chamber works

1. charged particle ionize gas molecular inside chamber
2. electron created by ionizing move to wire
3. gas amplification (electron avalanche) near wire
4. signal is generated by electromagnetic induction

signal is induced by electromagnetic induction by electron and positive ion
ion mainly contribute on generation of signal. (contribution by electron is small)

positive ion is 1000 times slower than electron → signal duration is longer
distance of positive ion moving is longer than electron since gas amplification occur near wire → generate large signal



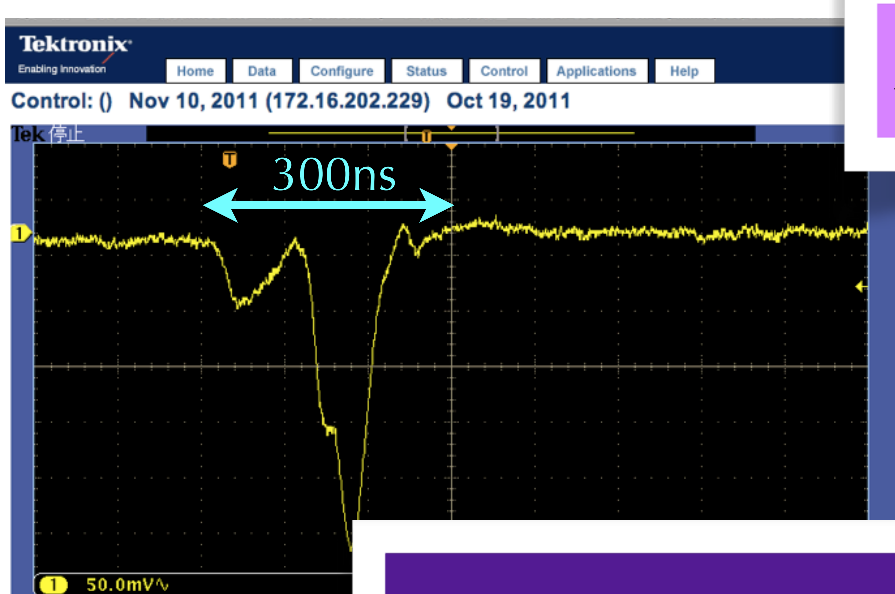

total signal charge (Q) is proportional to energy loss of charged particle

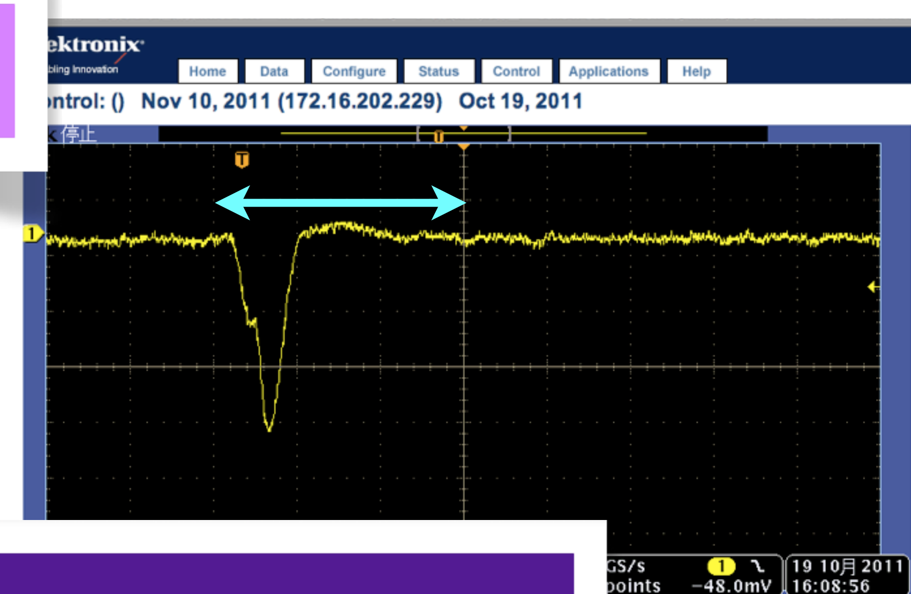
electron reach wire rapidly ($<10^{-9}$ sec)

distance of electron moving is shorter

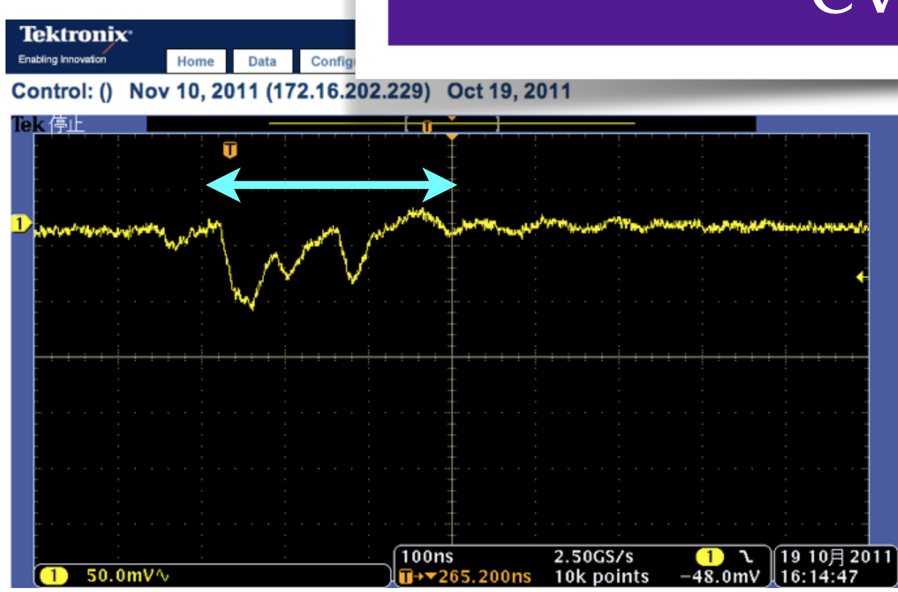
# Signal shape

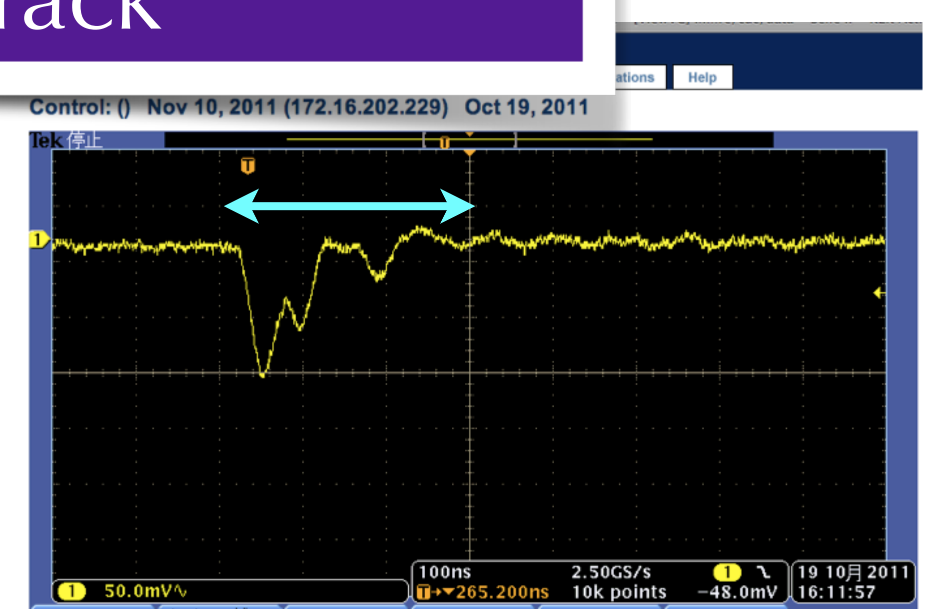
analog signal of drift chamber
1 GeV/c electron beam (beam test@2011)



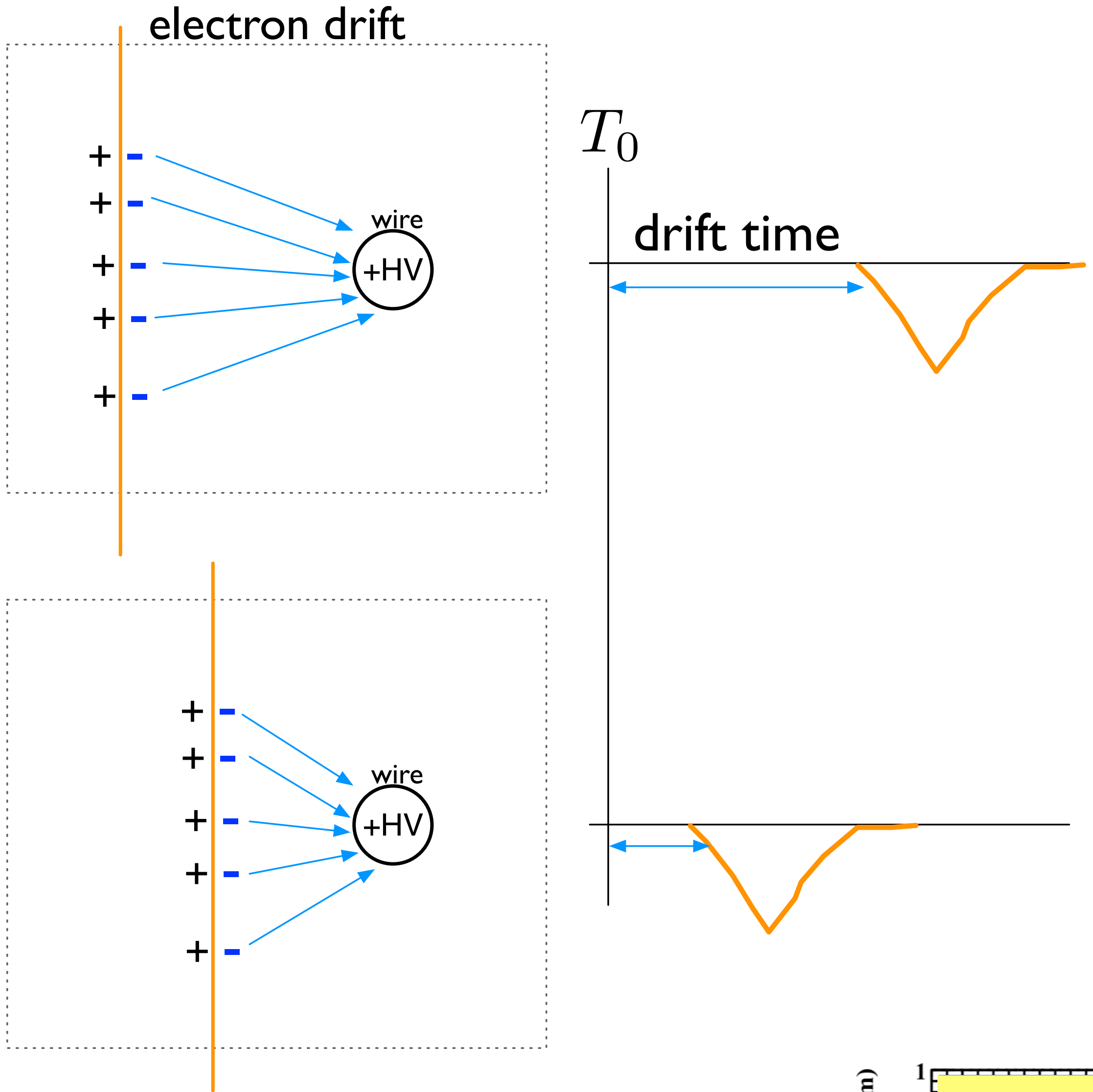




1. Long duration
2. A diversity of signal shape of gas chamber even for one charged track



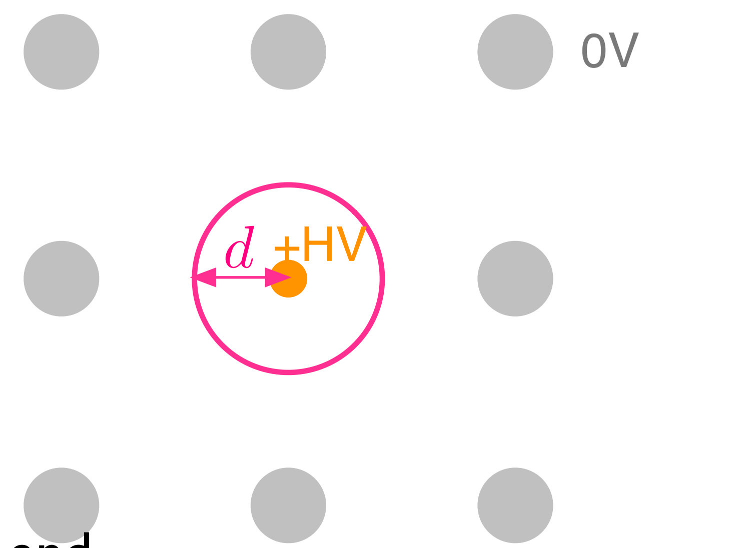
# measure position




$$d = vt$$

drift velocity (known): $v$

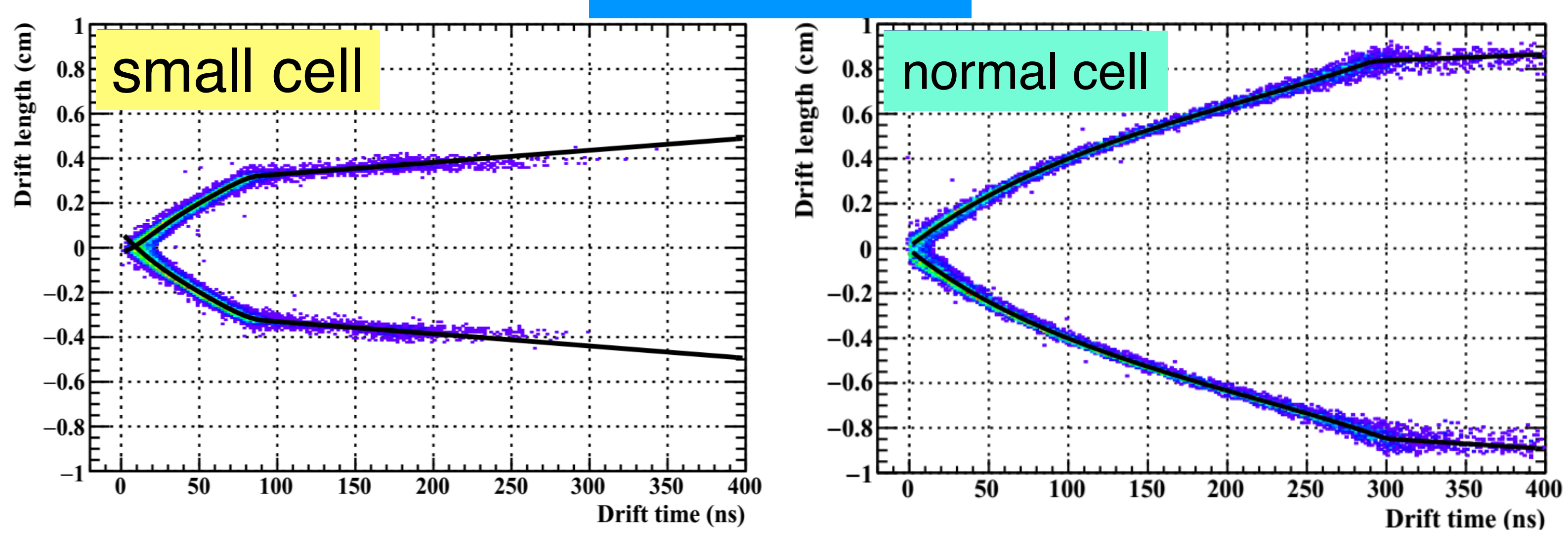
drift time (measurement): $t$



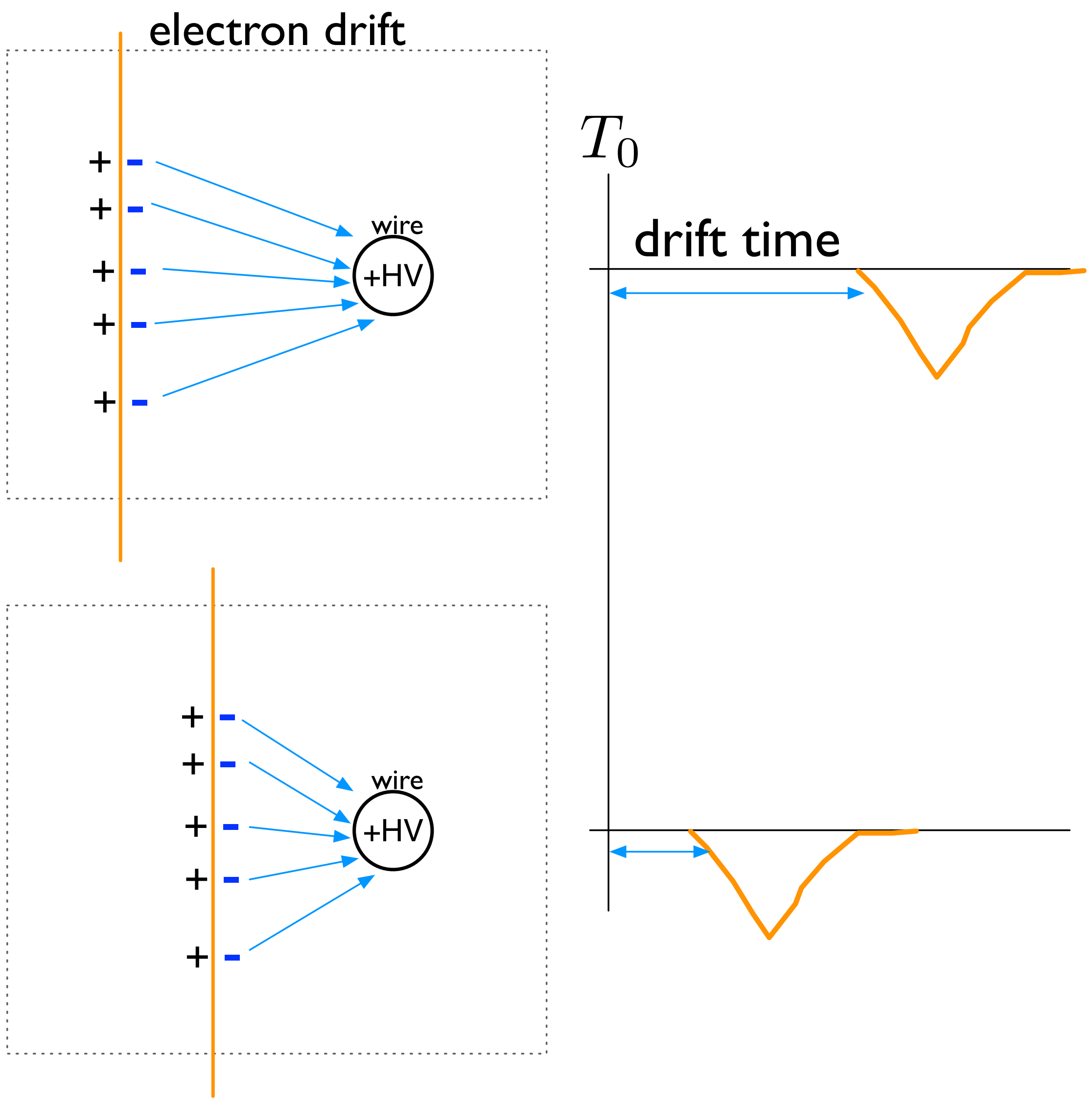

wire cell : signal wire (center) and grounding wires

drift distance (d) give information of a circle around signal wire.
up-down-left-right can not be determined by single wire

## XT relation



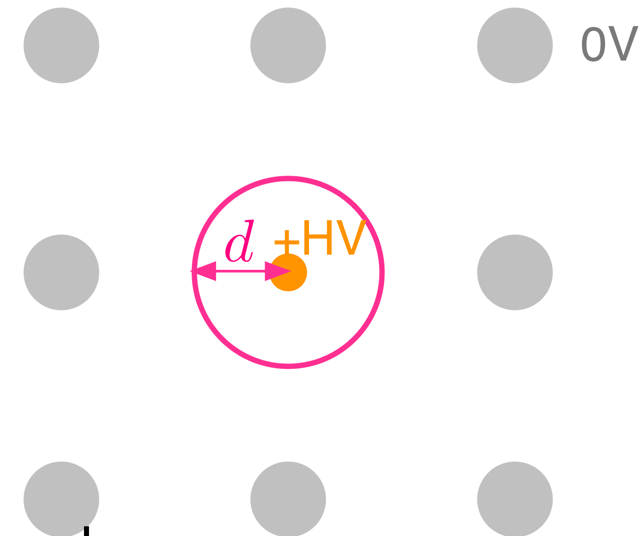
# measure position




drift velocity (known)

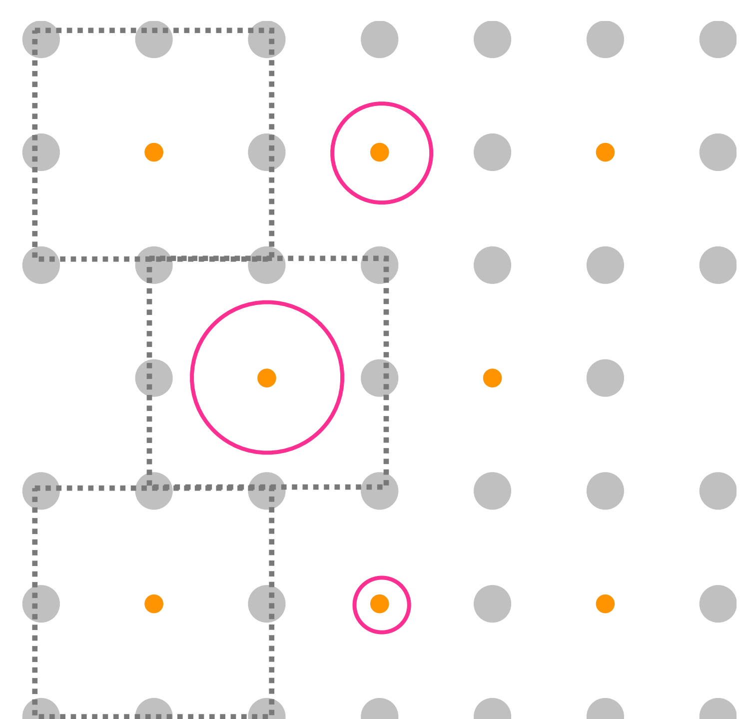
$$d = vt$$

drift time (measurement)




wire cell : signal wire (center) and grounding wires

drift distance (d) give information of a circle around signal wire.
up-down-left-right can not be determined by single wire



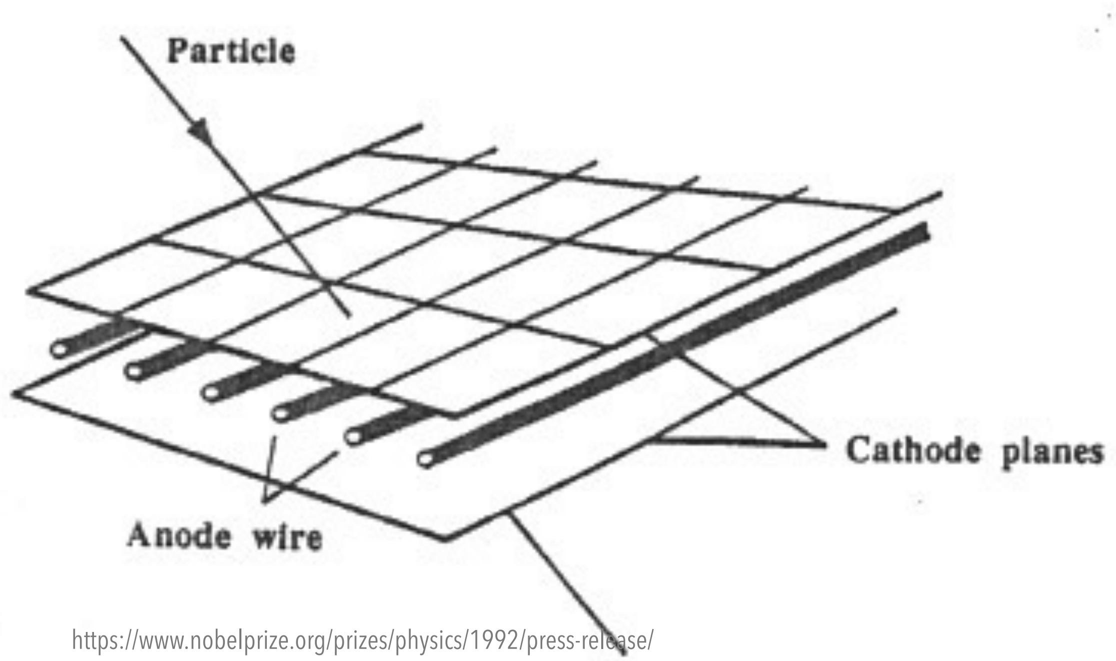
cell configuration is staggered by half cell.
it can solve "Left-Right ambiguity".

# measure position

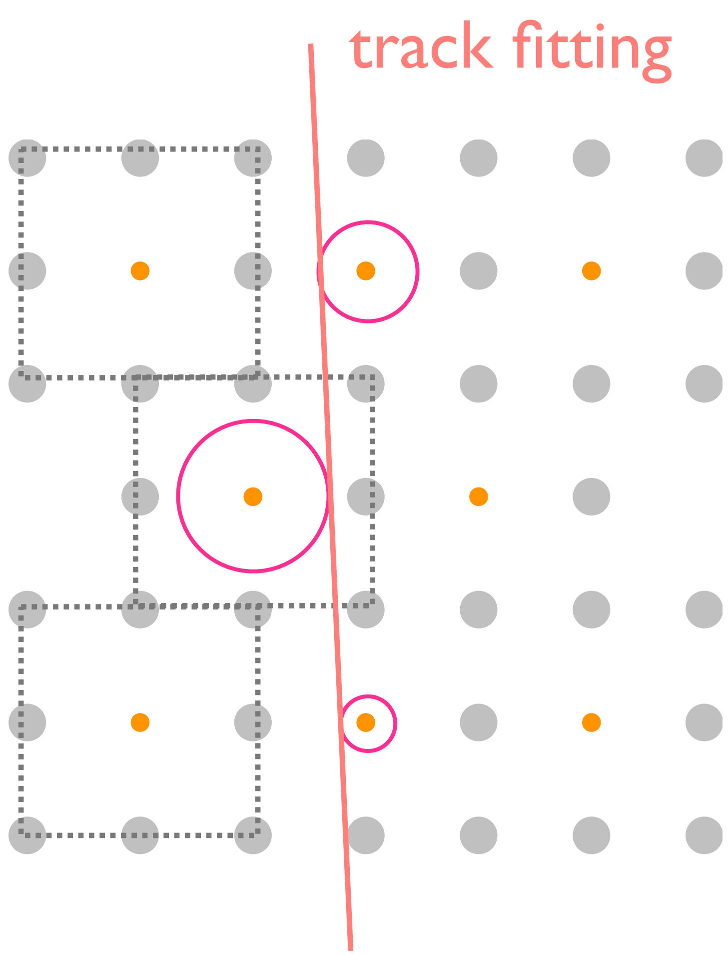
position resolution is much improved

interval of wire determine resolution in wire chamber before
1mm interval → ~300um resolution

drift chamber
10mm interval → ~100um resolution

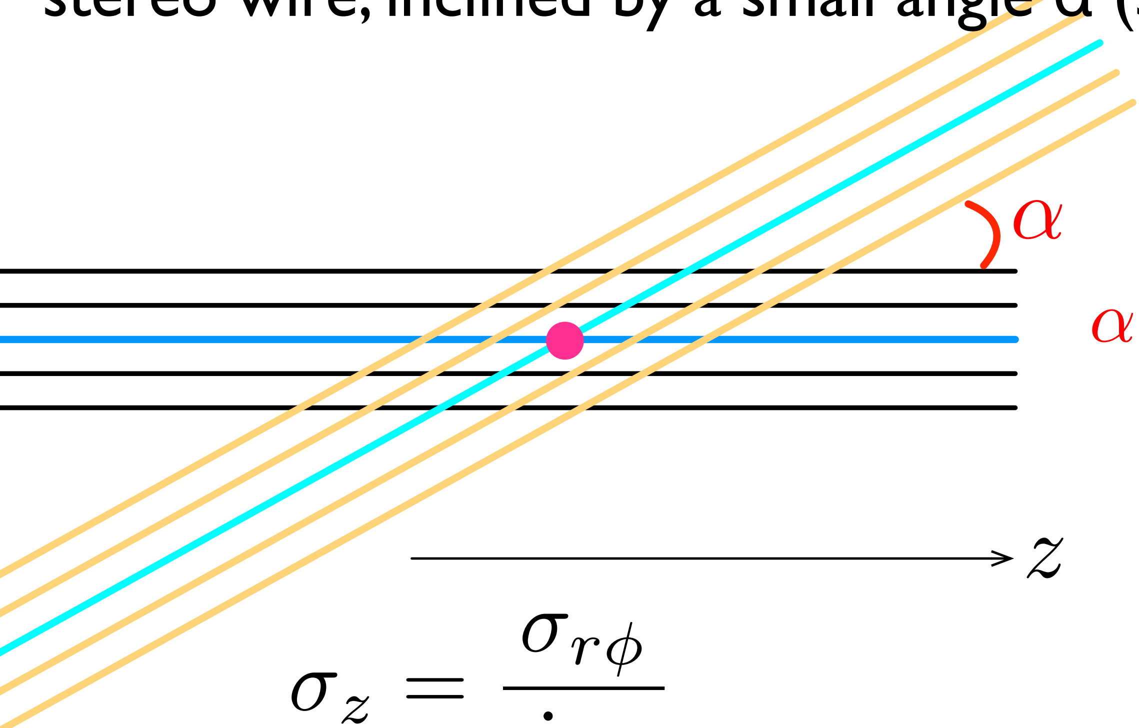



https://www.nobelprize.org/prizes/physics/1992/press-release/



# Z position

axial wire; parallel to z-direction
stereo wire; inclined by a small angle α (stereo angle)

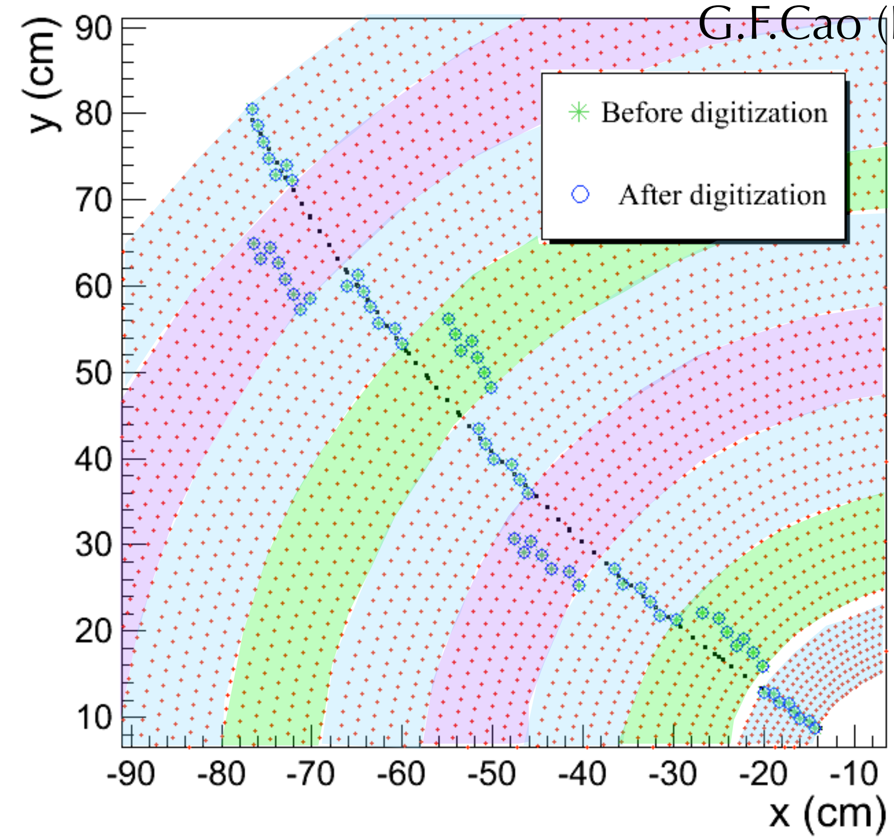


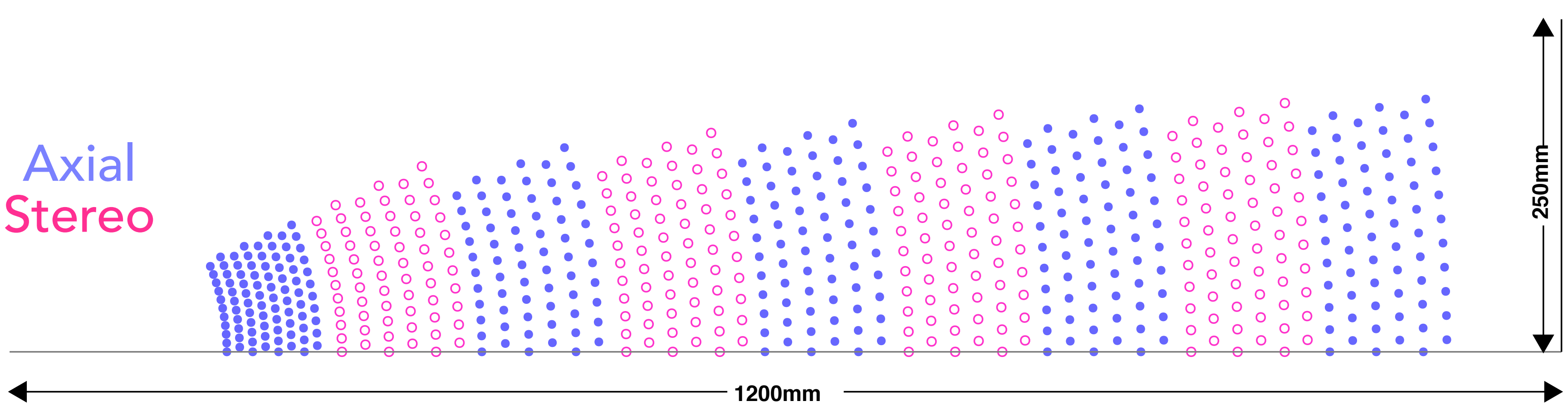

$\alpha = 60 \sim 80\text{mrad}$
(BelleII)

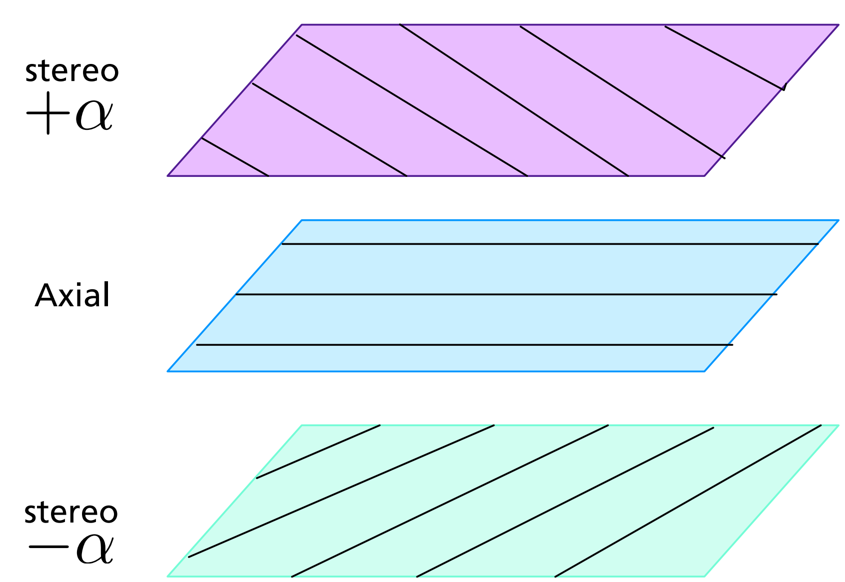
$$\sigma_z = \frac{\sigma_{r\phi}}{\sin\alpha}$$

$$\sigma_z = 1.9 \sim 2.5\text{mm}(\sigma_{r\phi} = 0.15\text{mm})$$

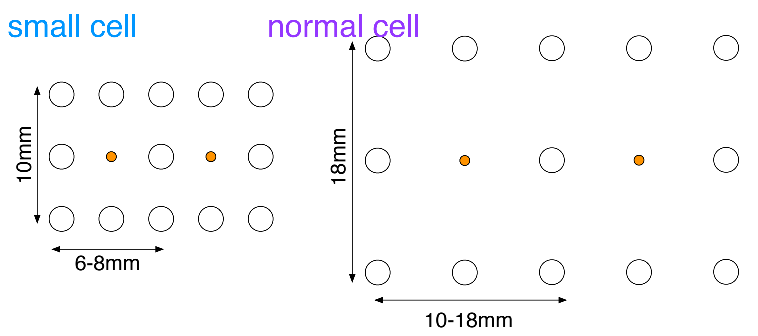
G4sim by G.F.Cao (IHEP)

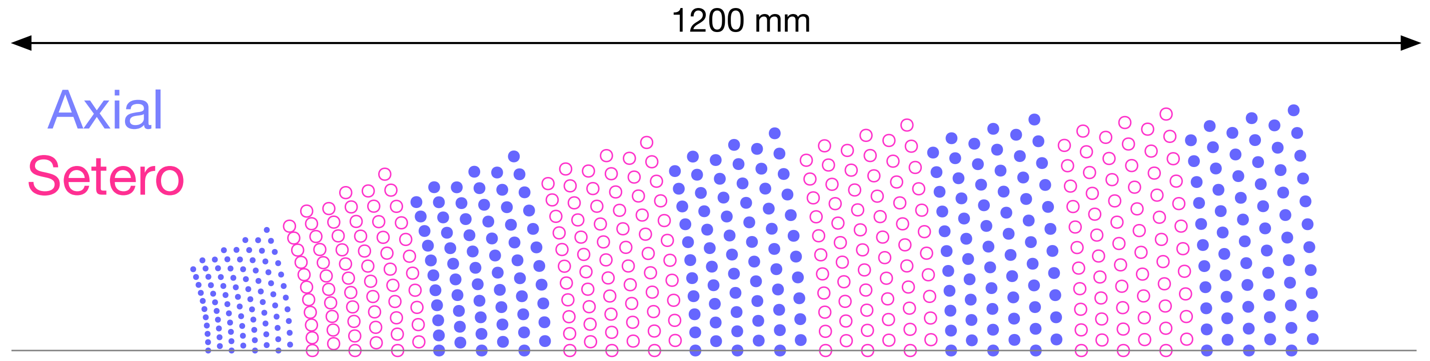


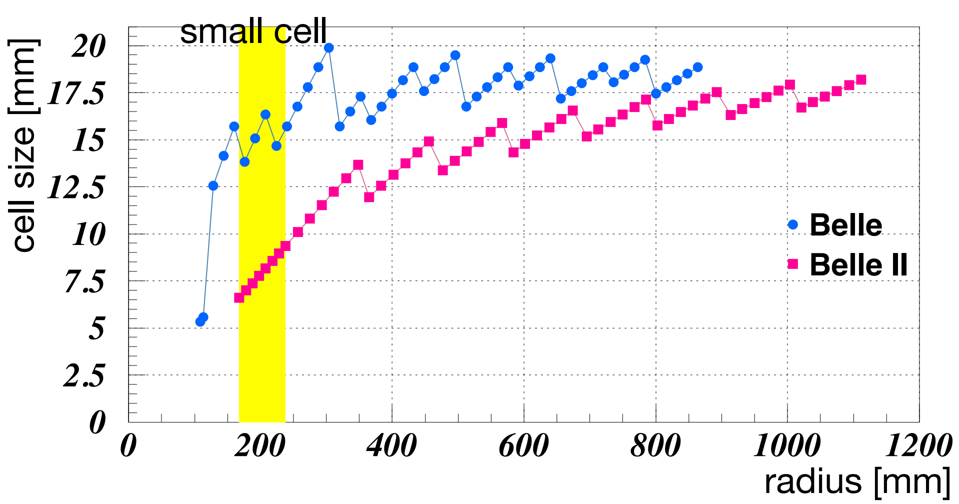



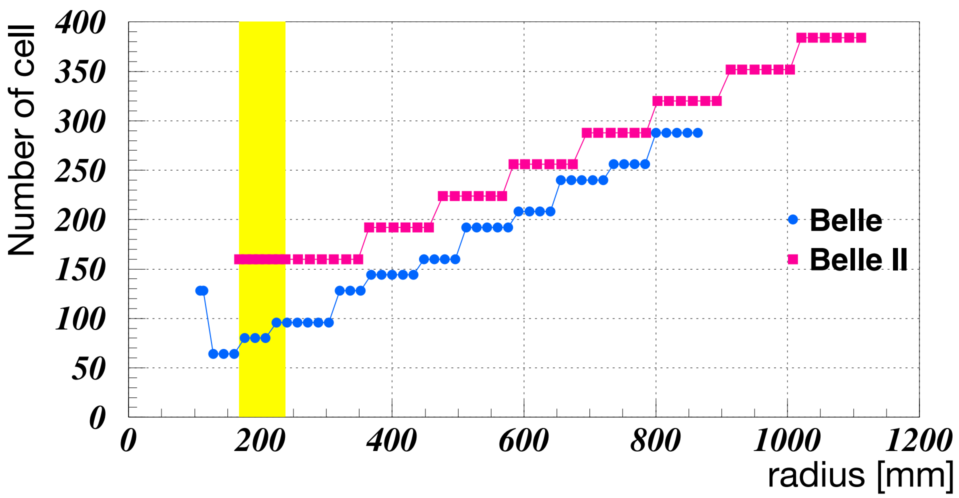



# cell configuration

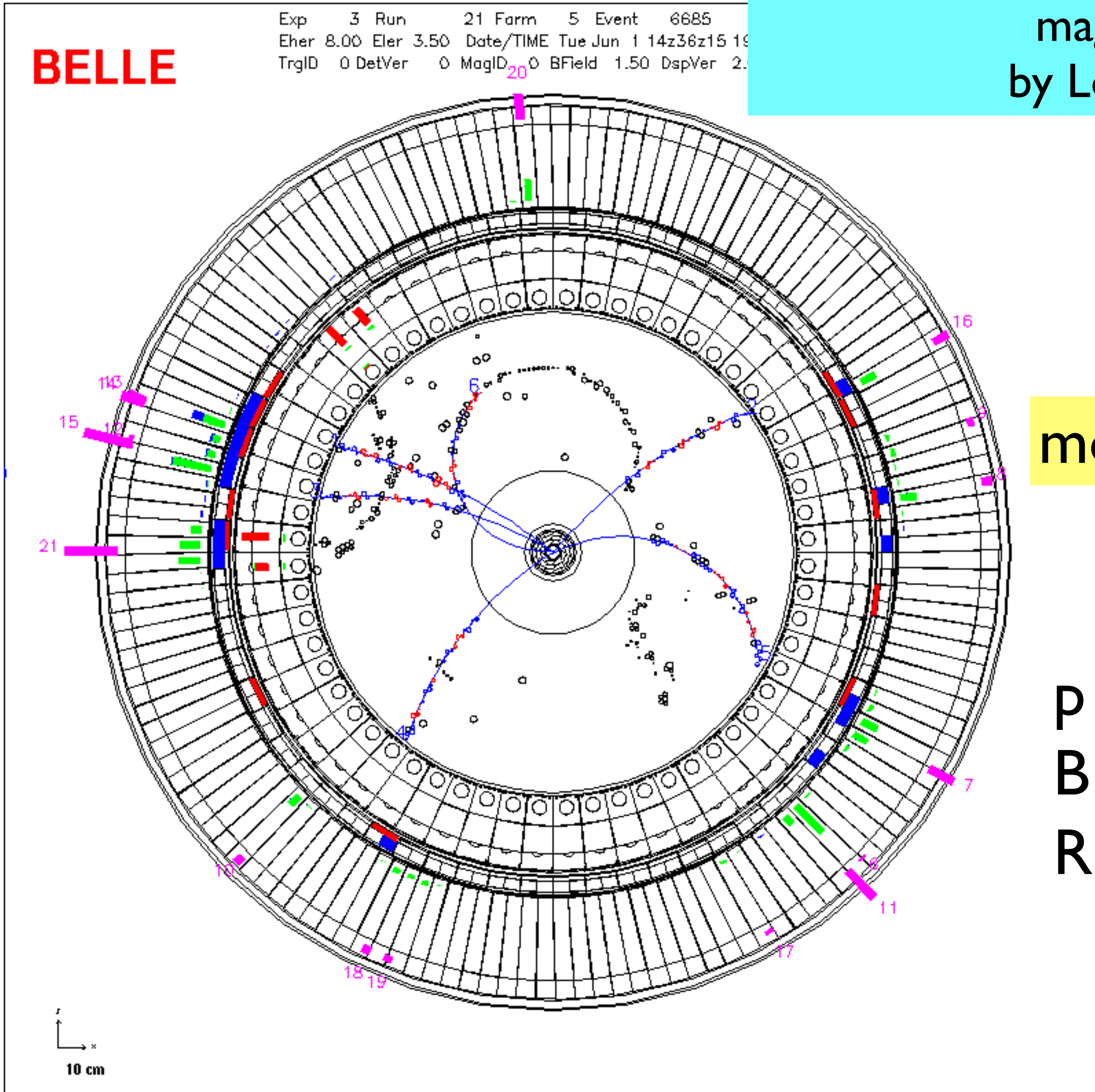



- 56 layers in total
  - radius of innermost/outermost = sense wire 168/1111.4 mm
- 'super layer' structure
  - 5-axial super layers and 4-stereo super layers
    - stereo (+/-)45 ~ 74
  - innermost super layer = small cell (2+6 layers)
- 6 layer/super-layer; it is required by CDCTRG




circular movement of charged particle in magnetic field by Lorentz force

1.5T; Belle II solenoid (z-direction)

momentum measurement

$$p = 0.3B \cdot R$$

p : momentum [GeV/c]

B : magnetic field [T]

R : curvature radius [m]

direction → charge(+-)

# momentum measurement

**why momentum information is so important**

invariant mass: **unique for a particle**

invariant mass can be calculated by using energy and momentum of daughter particles

2 body decay

$$M = \sqrt{(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2}$$

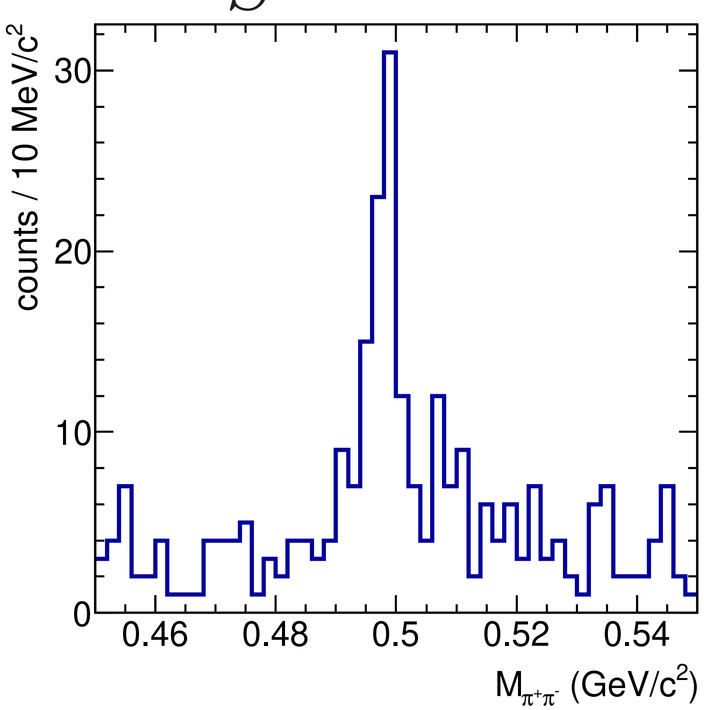
$$E_i = \sqrt{\vec{P}_i^{\,2} + m_i^2}$$

$E$ : energy of particle

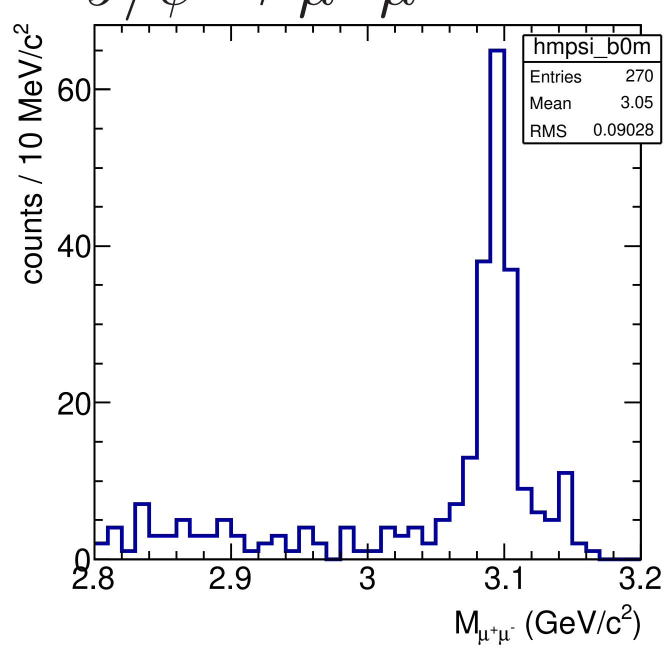
$P$ : momentum of particle

$m$ : mass of particle

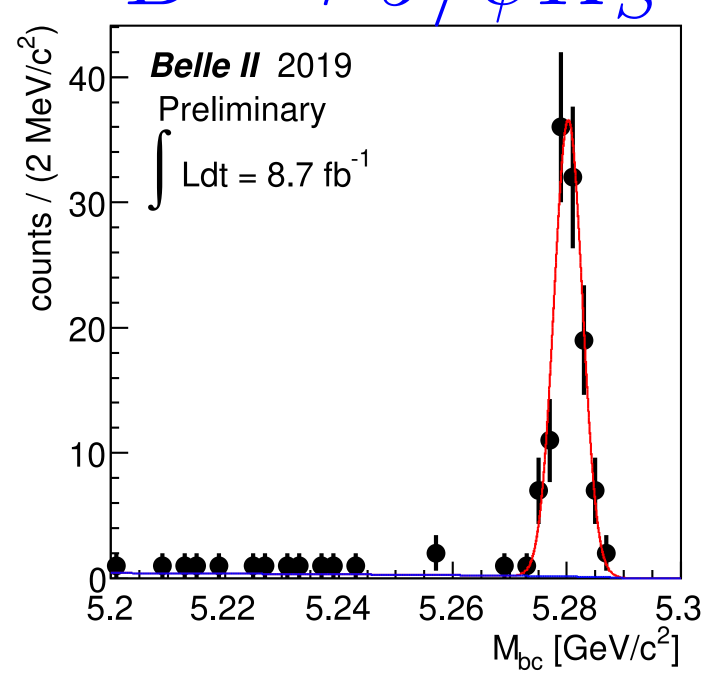
$K_S \to \pi^+\pi^-$




$J/\psi \to \mu^+\mu^-$




$B^0 \to J/\psi K_S$



# momentum resolution

**momentum resolution**

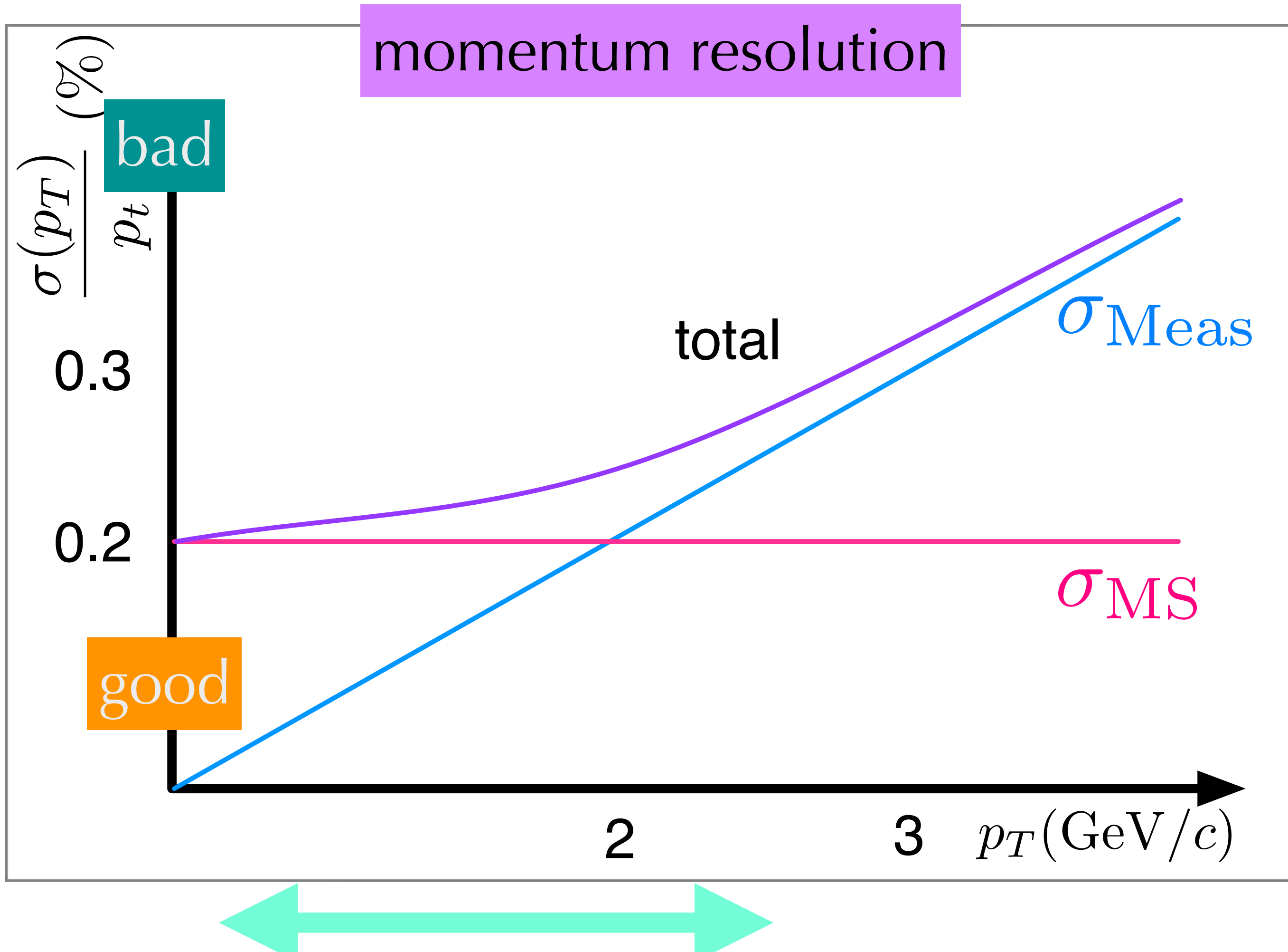
$$\left(\frac{\sigma_{P_t}}{P_T}\right)^2 = \left(\frac{\sigma_{P_t}}{P_T}\right)^2_{measu.} + \left(\frac{\sigma_{P_t}}{P_T}\right)^2_{MS}$$

error due to measurement | error due to multiple-scattering

$$\left(\frac{\sigma_{p_t}}{p_t}\right)_{mea.} \propto \frac{\epsilon p_t}{BL^2}$$

$$\left(\frac{\sigma_{pt}}{p_t}\right)_{MS} \propto \frac{1}{BL}\sqrt{\frac{L}{X_0}}\left(1 + 0.038\ \ln\frac{L}{X_0}\right)$$

ε: position resolution
X0: radiation length




momenta of charge particles
@Belle/Belle2

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

10.58 GeV

Bの質量
5.279 GeV

multiple scattering is dominant

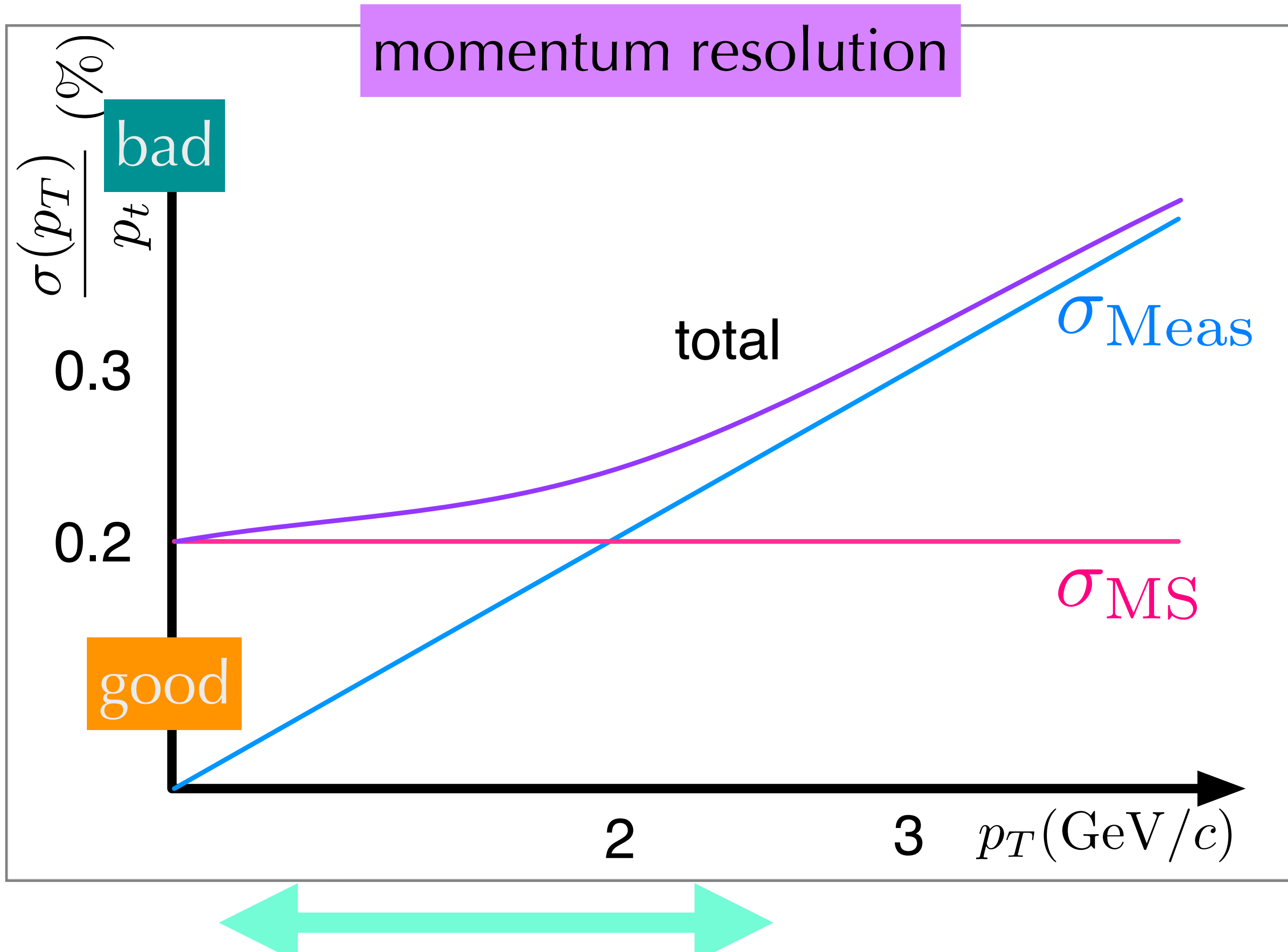
# momentum resolution

momentum resolution

$$\left(\frac{\sigma_{P_t}}{P_T}\right)^2 = \left(\frac{\sigma_{P_t}}{P_T}\right)^2_{measu.} + \left(\frac{\sigma_{P_t}}{P_T}\right)^2_{MS}$$

error due to measurement

error due to multiple-scattering




momenta of charge particles @Belle/Belle2

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

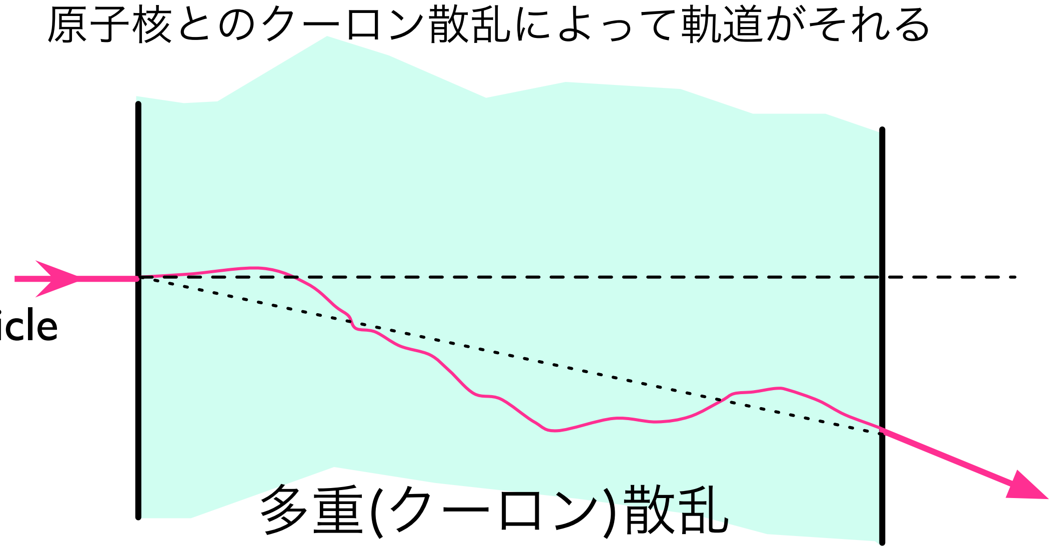
10.58 GeV

Bの質量 5.279 GeV

charged particle traveling matter is scattered by the Coulomb potentials.

物質中を進む荷電粒子は
原子核とのクーロン散乱によって軌道がそれる

荷電粒子
charged particle



多重(クーロン)散乱
multiple(coulomb) scattering

multiple scattering is dominant

# momentum resolution

momentum resolution

$$\left(\frac{\sigma_{P_t}}{P_T}\right)^2 = \left(\frac{\sigma_{P_t}}{P_T}\right)^2_{measu.} + \left(\frac{\sigma_{P_t}}{P_T}\right)^2_{MS}$$

error due to measurement

error due to multiple-scattering

$$\left(\frac{\sigma_{p_t}}{p_t}\right)_{mea.} \propto \frac{\epsilon p_t}{BL^2}$$

$$\left(\frac{\sigma_{pt}}{p_t}\right)_{MS} \propto \frac{1}{BL}\sqrt{\frac{L}{X_0}}\left(1 + 0.038 \ln\frac{L}{X_0}\right)$$

ε: position resolution

X0: radiation length

multiple scattering is dominant in Belle II

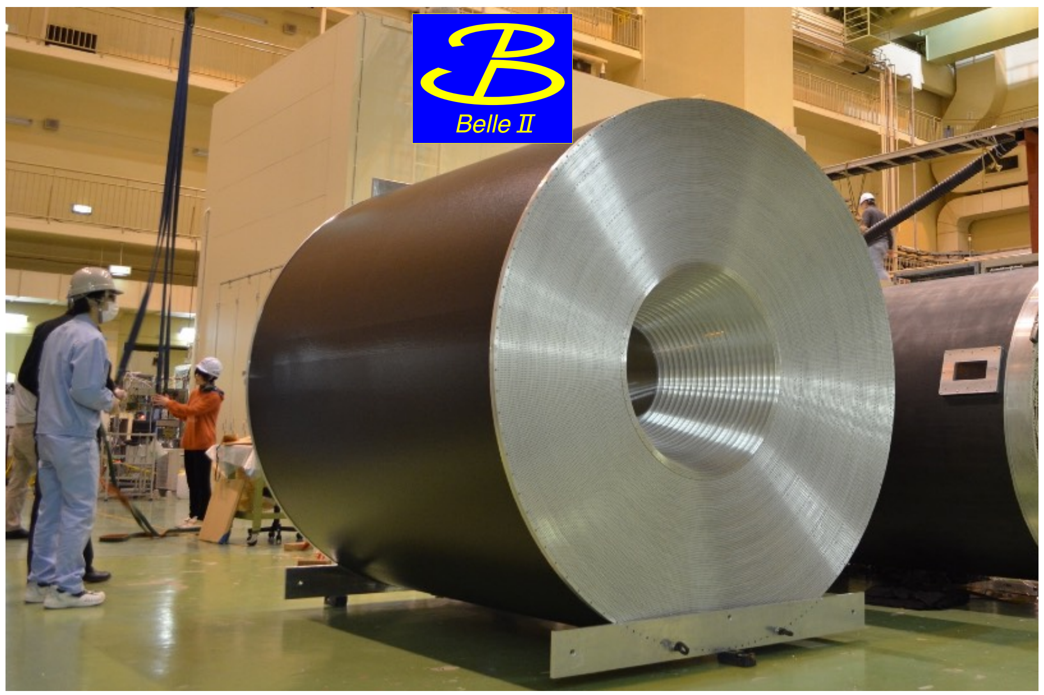
to obtain good resolution, need to mane radiation length longer

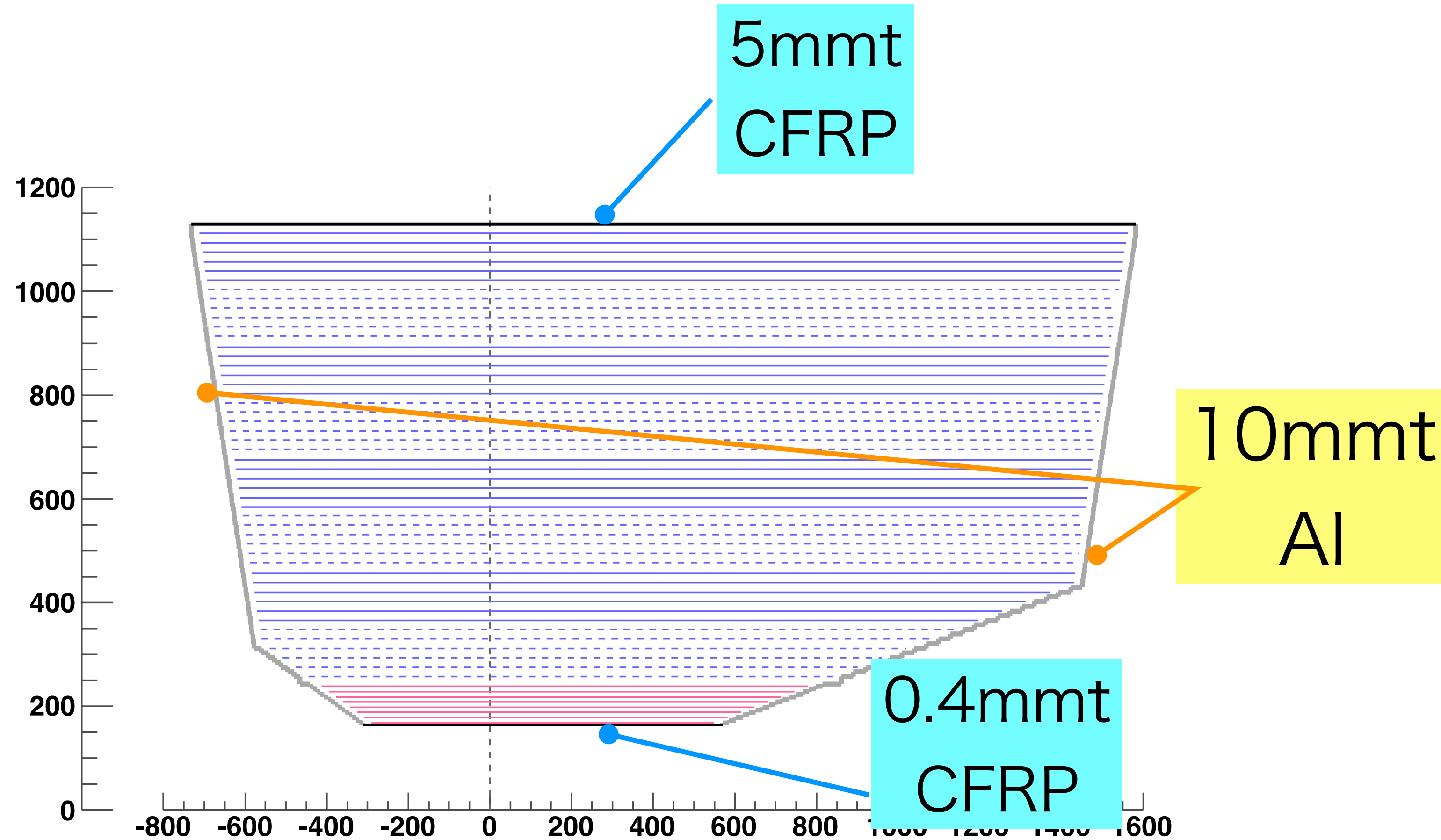
low material is necessary

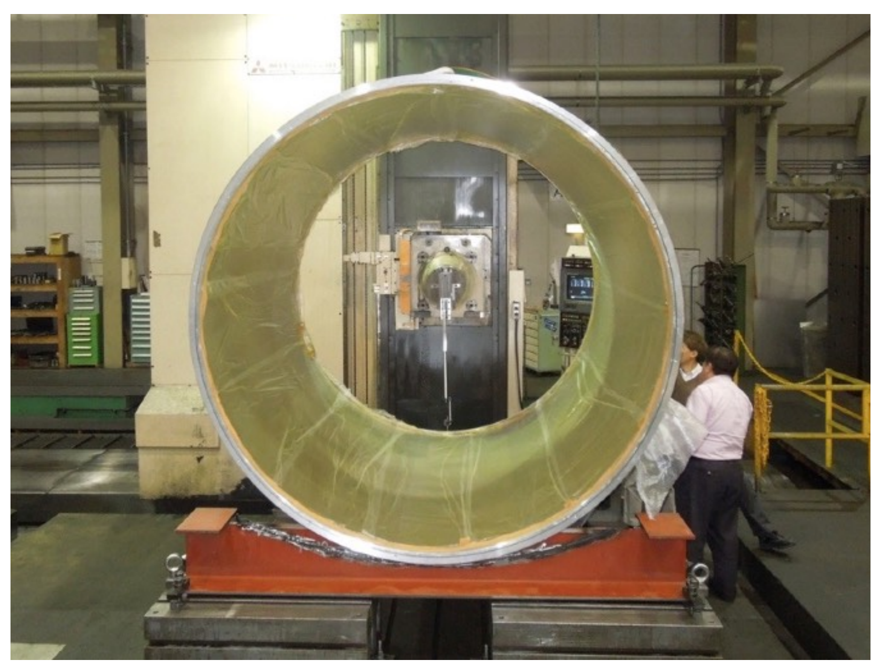
Gas + Wire

# low material

< 600kg



Au-W of $\phi$30um; x14336
Al of $\phi$126um; x 42240

Gas; He:ethane (50:50)

Aluminum endplate    Carbon Fiber Reinforced Plastics (CFRP)

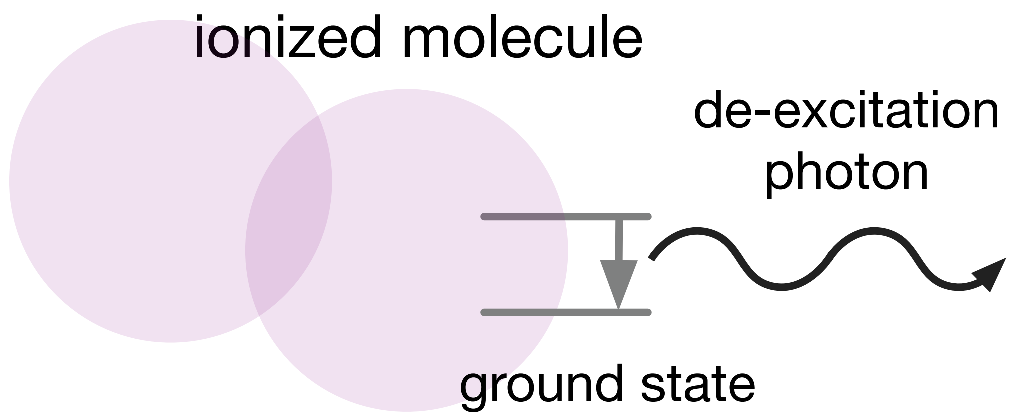
# gas

**Table 34.5:** Properties of noble and molecular gases at normal temperature and pressure (NTP: 20° C, one atm). $E_X$, $E_I$: first excitation, ionization energy; $W_I$: average energy per ion pair; $dE/dx|_{\min}$, $N_P$, $N_T$: differential energy loss, primary and total number of electron-ion pairs per cm, for unit charge minimum ionizing particles.

| Gas | Density, mg cm$^{-3}$ | $E_x$ eV | $E_I$ eV | $W_I$ eV | $dE/dx\vert_{\min}$ keV cm$^{-1}$ | $N_P$ cm$^{-1}$ | $N_T$ cm$^{-1}$ |
|---|---|---|---|---|---|---|---|
| He | 0.179 | 19.8 | 24.6 | 41.3 | 0.32 | 3.5 | 8 |
| Ne | 0.839 | 16.7 | 21.6 | 37 | 1.45 | 13 | 40 |
| Ar | 1.66 | 11.6 | 15.7 | 26 | 2.53 | 25 | 97 |
| Xe | 5.495 | 8.4 | 12.1 | 22 | 6.87 | 41 | 312 |
| $CH_4$ | 0.667 | 8.8 | 12.6 | 30 | 1.61 | 28 | 54 |
| $C_2H_6$ | 1.26 | 8.2 | 11.5 | 26 | 2.91 | 48 | 112 |
| $iC_4H_{10}$ | 2.49 | 6.5 | 10.6 | 26 | 5.67 | 90 | 220 |
| $CO_2$ | 1.84 | 7.0 | 13.8 | 34 | 3.35 | 35 | 100 |
| $CF_4$ | 3.78 | 10.0 | 16.0 | 54 | 6.38 | 63 | 120 |

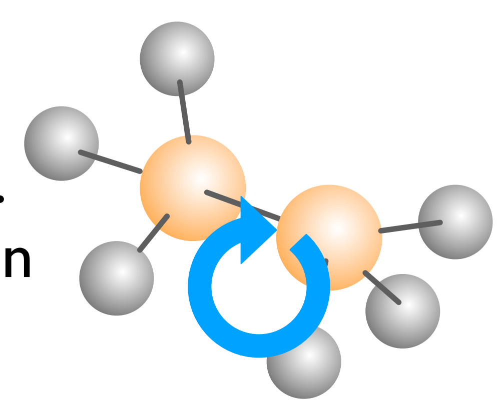
Noble gas is stable gas.
Ne and Xe are expensive!
Ar is reasonable.
He is low-Z gas. → longer radiation length and smaller multiple scattering effect

quencher gas ; to prevent discharge
complex molecules absorb de-excitation photons produced in avalanches

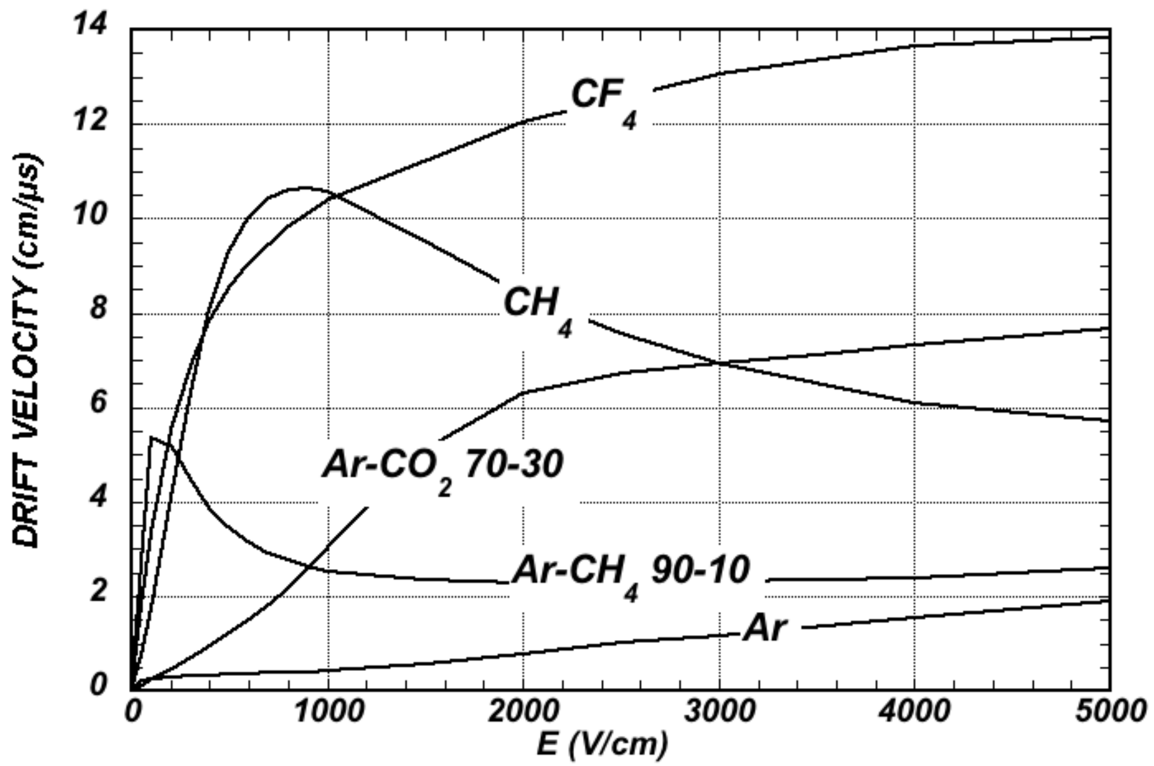



it can ionize another gas molecule.
→ avalanches don't stop
→ signal is generated persistently

poly-atomic molecules have flexibility for internal energy.
translational motion+rotation

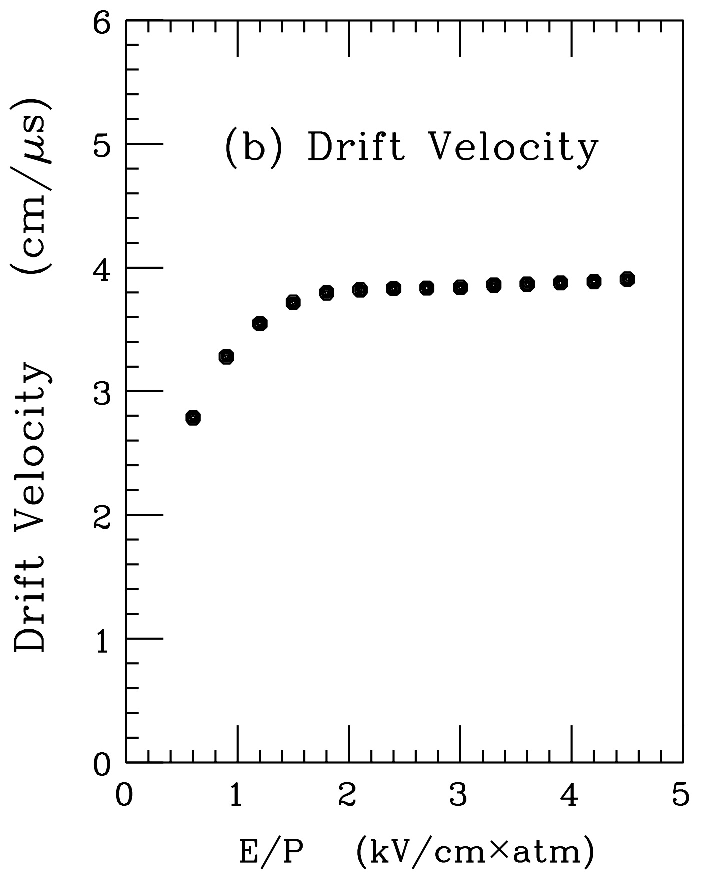


# gas




drift velocity is dependent on gas mixture

## He:ethane (50:50)
## Belle/Belle II gas




He:ethane (50:50) has plateau region.
stable against change of electric field and gas pressure → good stability of performance

# energy deposit (dEdx)

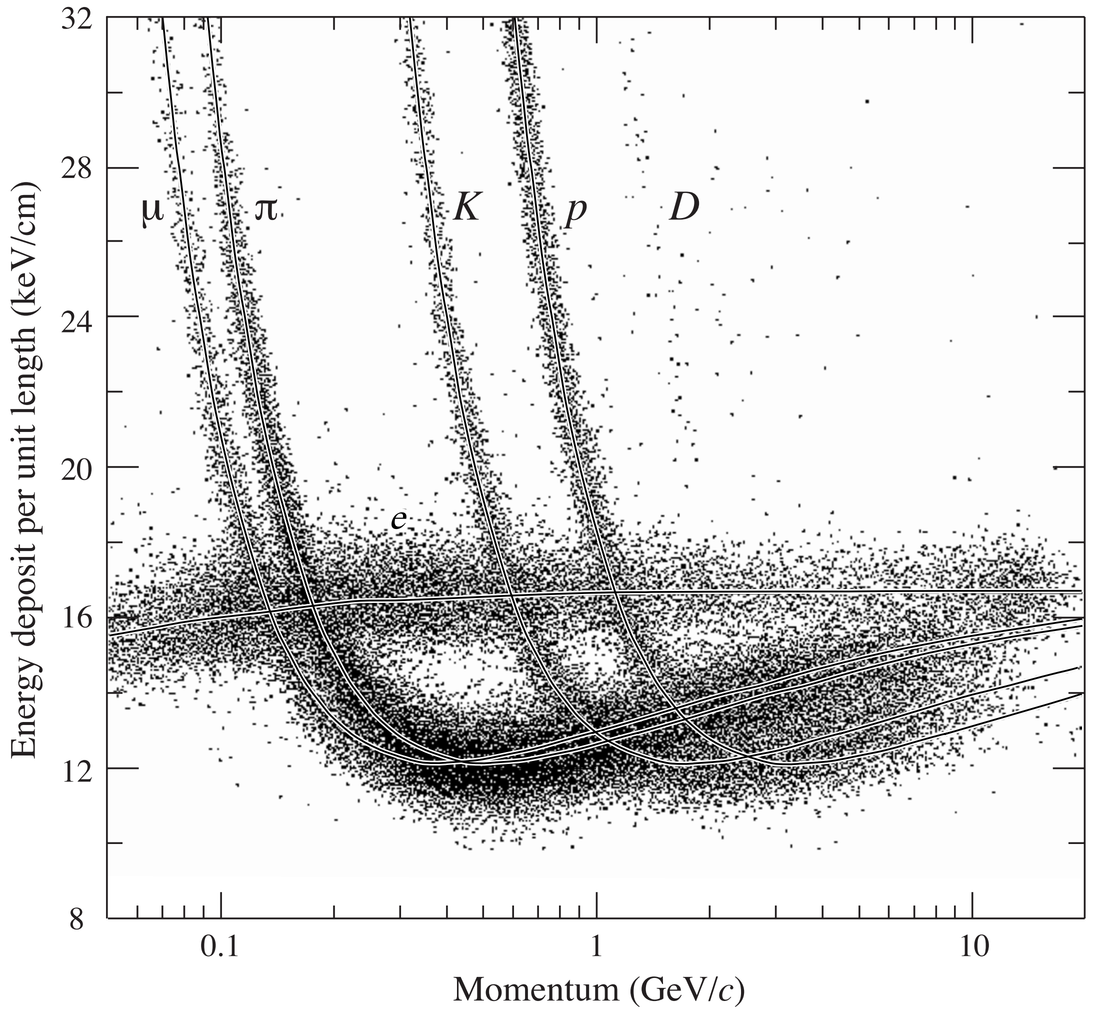


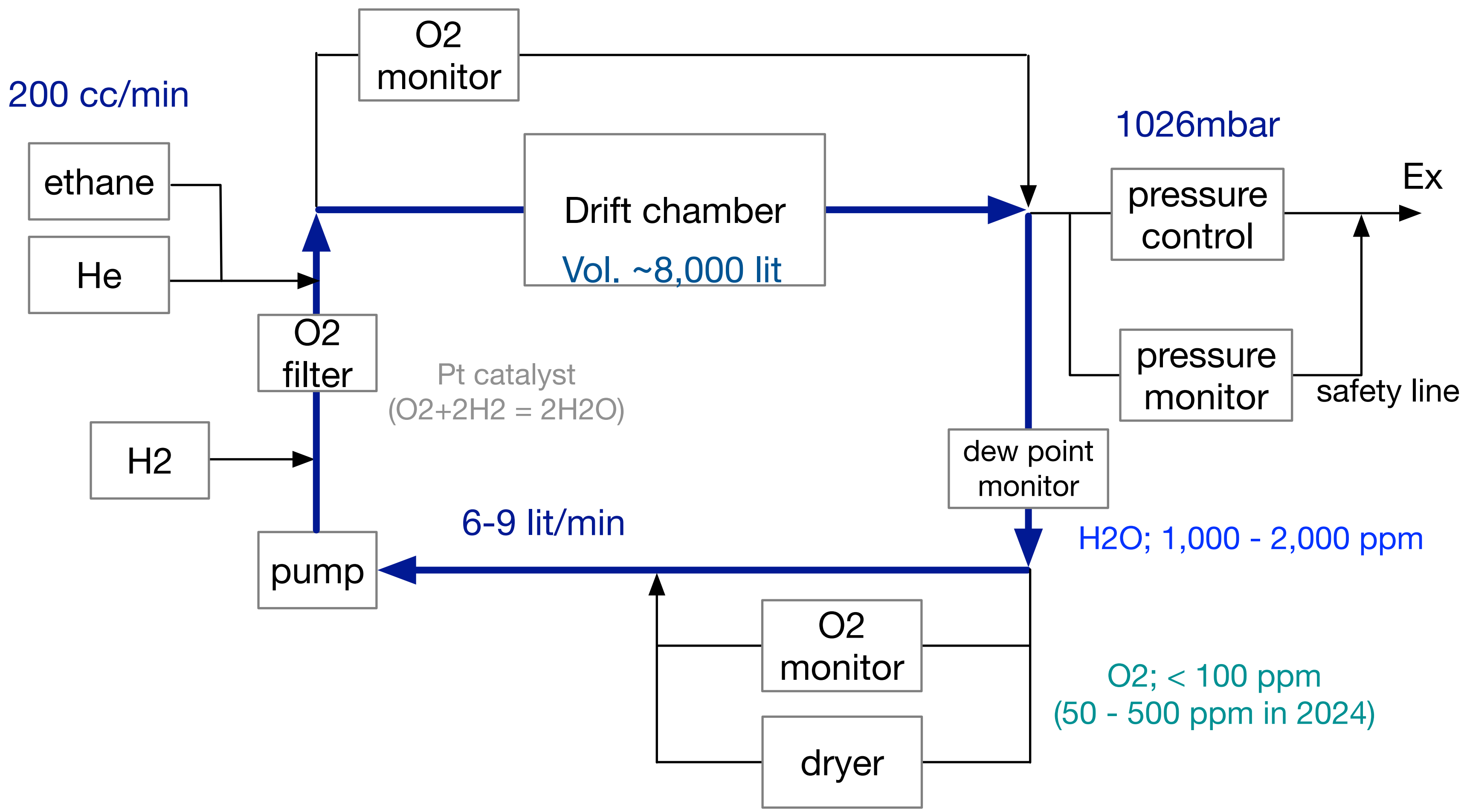

**Figure 28.8:** PEP4/9-TPC energy-deposit measurements (185 samples @8.5 atm Ar-$CH_4$ 80–20%) in multihadron events. The electrons reach a Fermi plateau value of 1.4 times the most probably energy deposit at minimum ionization. Muons from pion decays are separated from pions at low momentum; $\pi/K$ are separated over all momenta except in the cross-over region. (Low-momentum protons and deuterons originate from hadron-nucleus collisions in inner materials such as the beam pipe.)

Ionizing resolution

$$C \cdot N^{-0.14} L^{-0.32} P^{-0.32}$$

N : number of samples
L : lever arm
P : chamber gas pressure
C : constant dependent on gas

# gas system

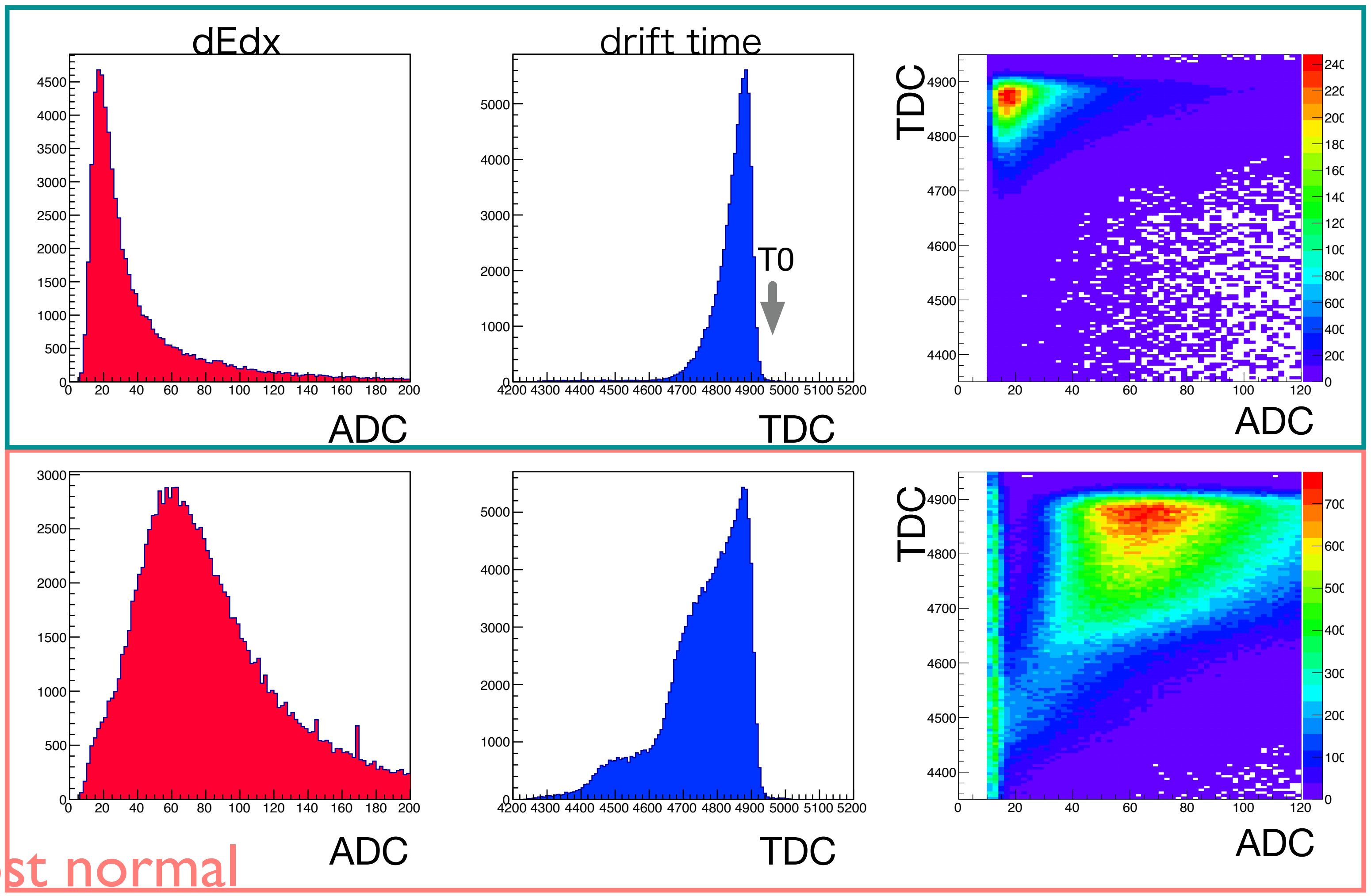


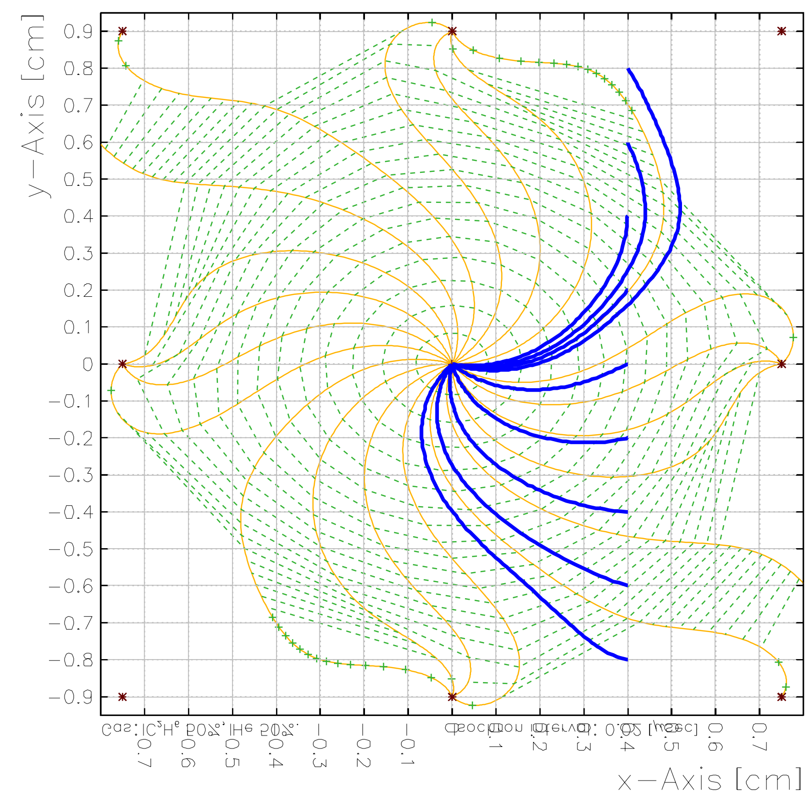

- keep absolute pressure constant ~1026 mbar to keep gas gain stable
- gas circulating (6-9 lit/min)
  - O2/H2O are removed and monitored in the circulation line
  - O2; electro-negative. capture electron created via ionization → gain degradation

# gas condition

much O2 content

due to trouble, O2 contamination became large..



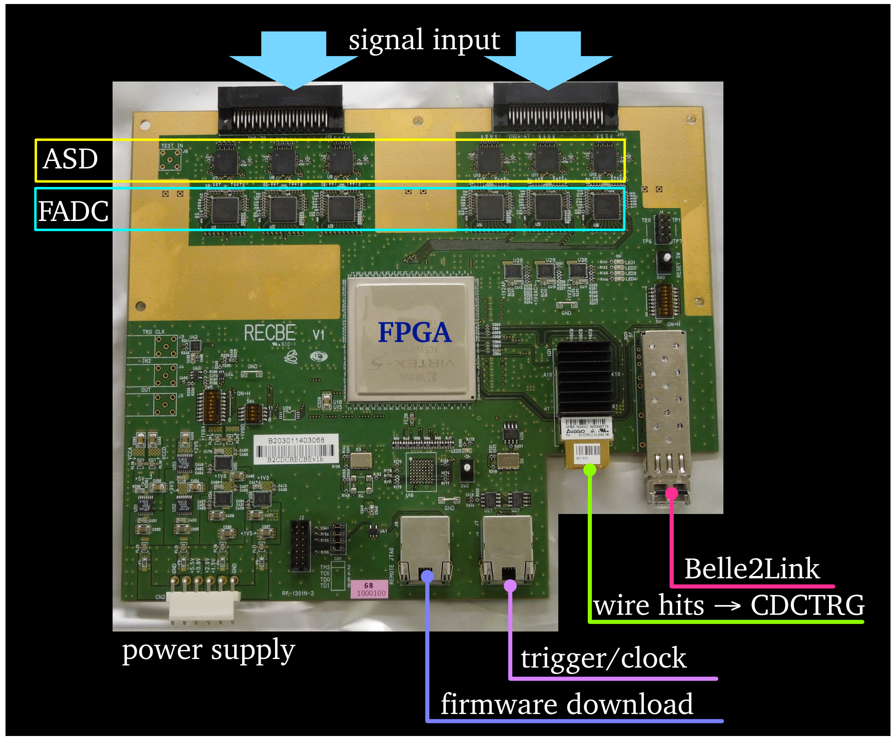



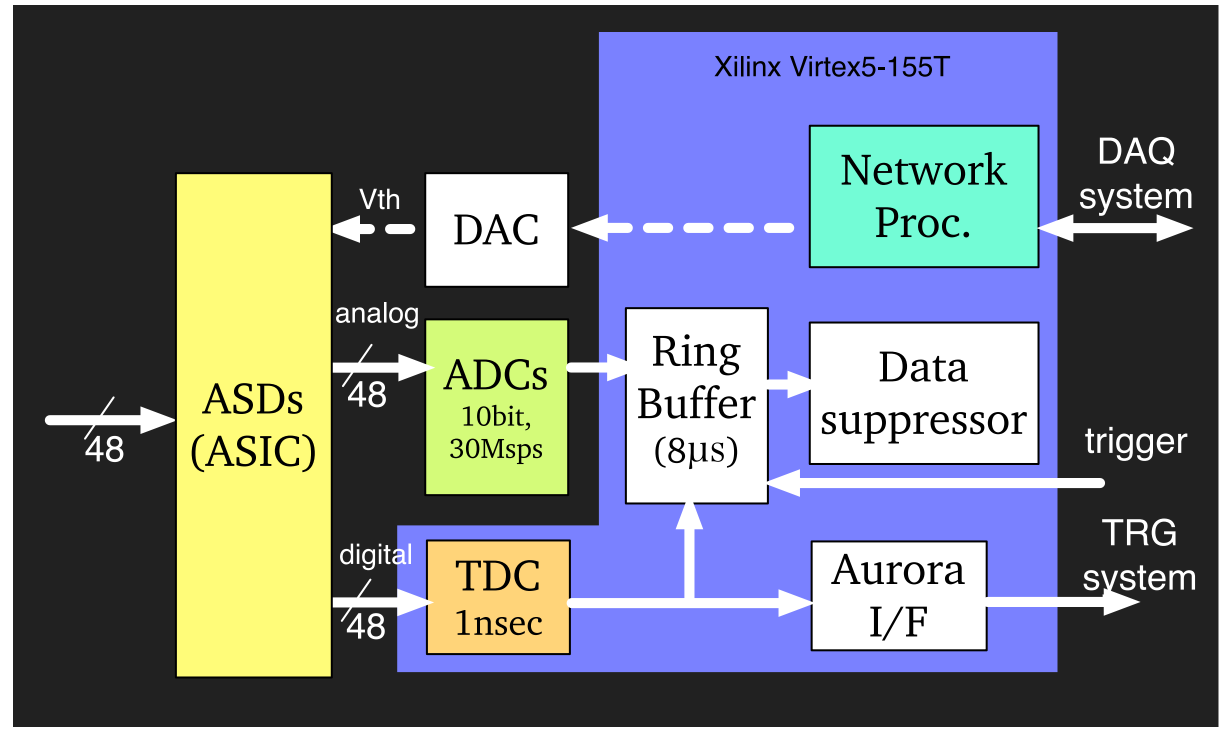

almost normal
(less O2 content)

effort for removing O2 by O2 filter

# Readout electronics

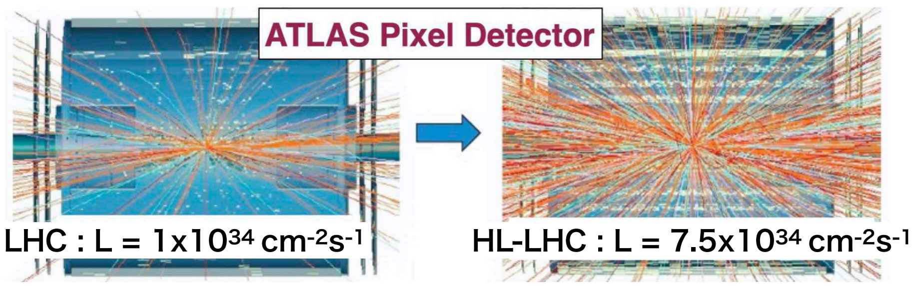
# signal readout electronics



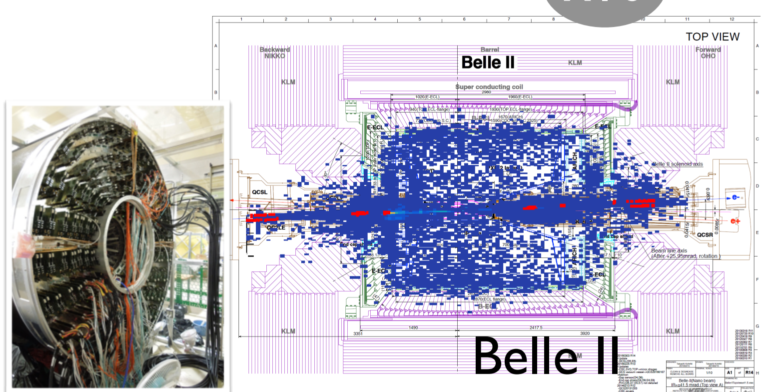

- FPGA-based front-end electronics
  - TDC with 1 nsec resolution for drift time measurement
  - ADC with 32MHz sampling for dEdx (charge) measurement
  - 48ch/board
- upgrade of readout board is ongoing
  - will install in long shutdown 2 (~2026)
  - radiation tolerance, cross talk, ..

# radiation in HEP experiments

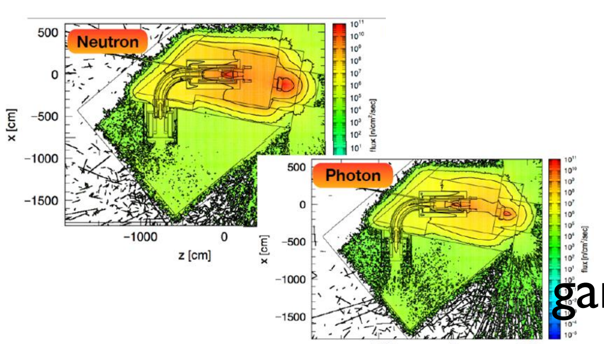



| | LHC | HL-LHC | FCC/HE-LHC |
|---|---|---|---|
| NIEL (1 MeV neq/cm2) | $10^{15}$ | $10^{16}$ | $10^{17}$ |
| TID (MGy) | ~1 | ~10 | ~100 |

x10 x10



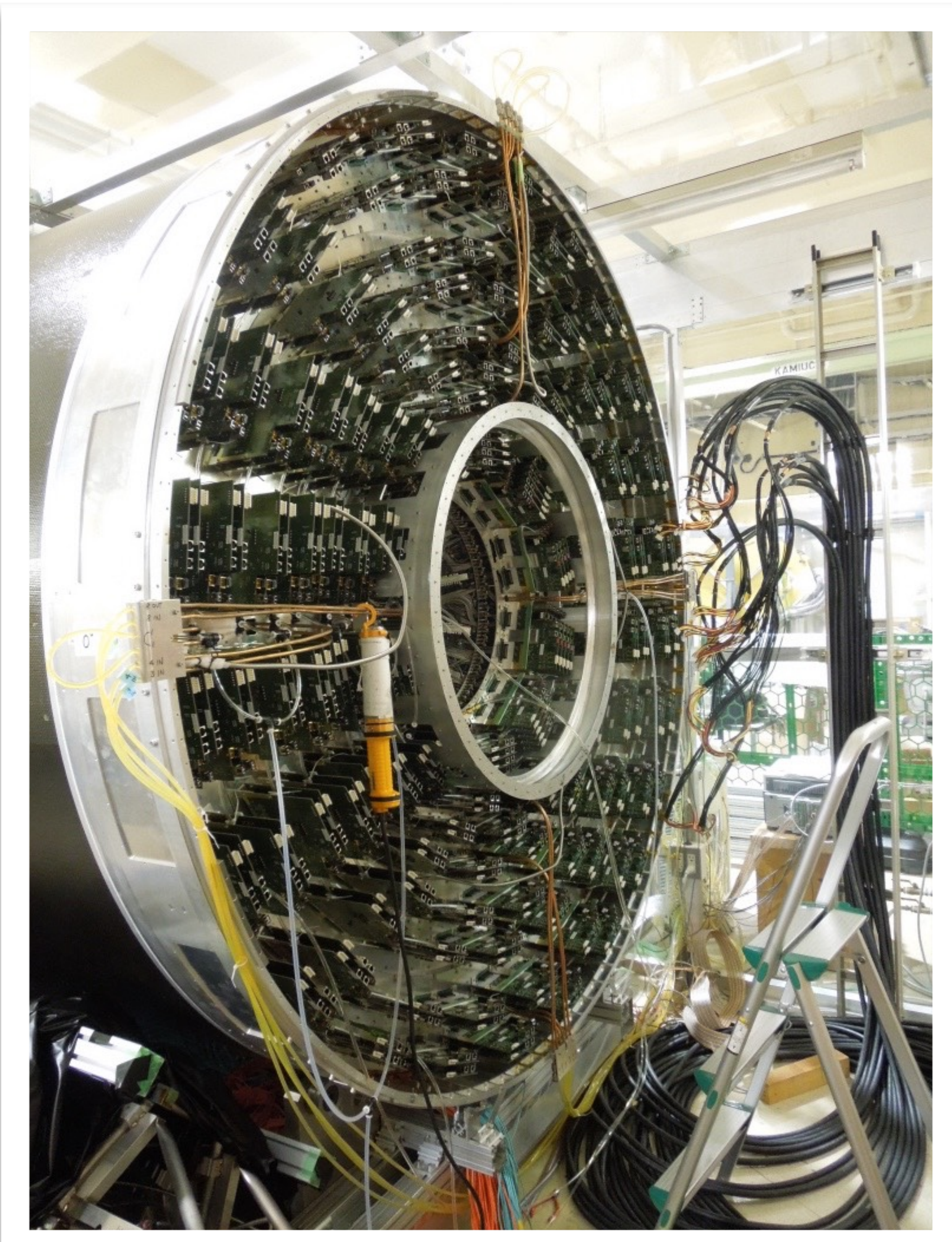

neutron >$10^{12}$/cm2
gamma ~1kGy (10 years)




COMET
neutron ~$10^{12}$/cm2
gamma ~1kGy (200days)

- Higher energy, higher luminosity and higher intensity are desired to search for new physics
- As performance of accelerator increases, radiation level become much higher
- Better performance at severe condition is needed for detector and electronics

# signal readout electronics



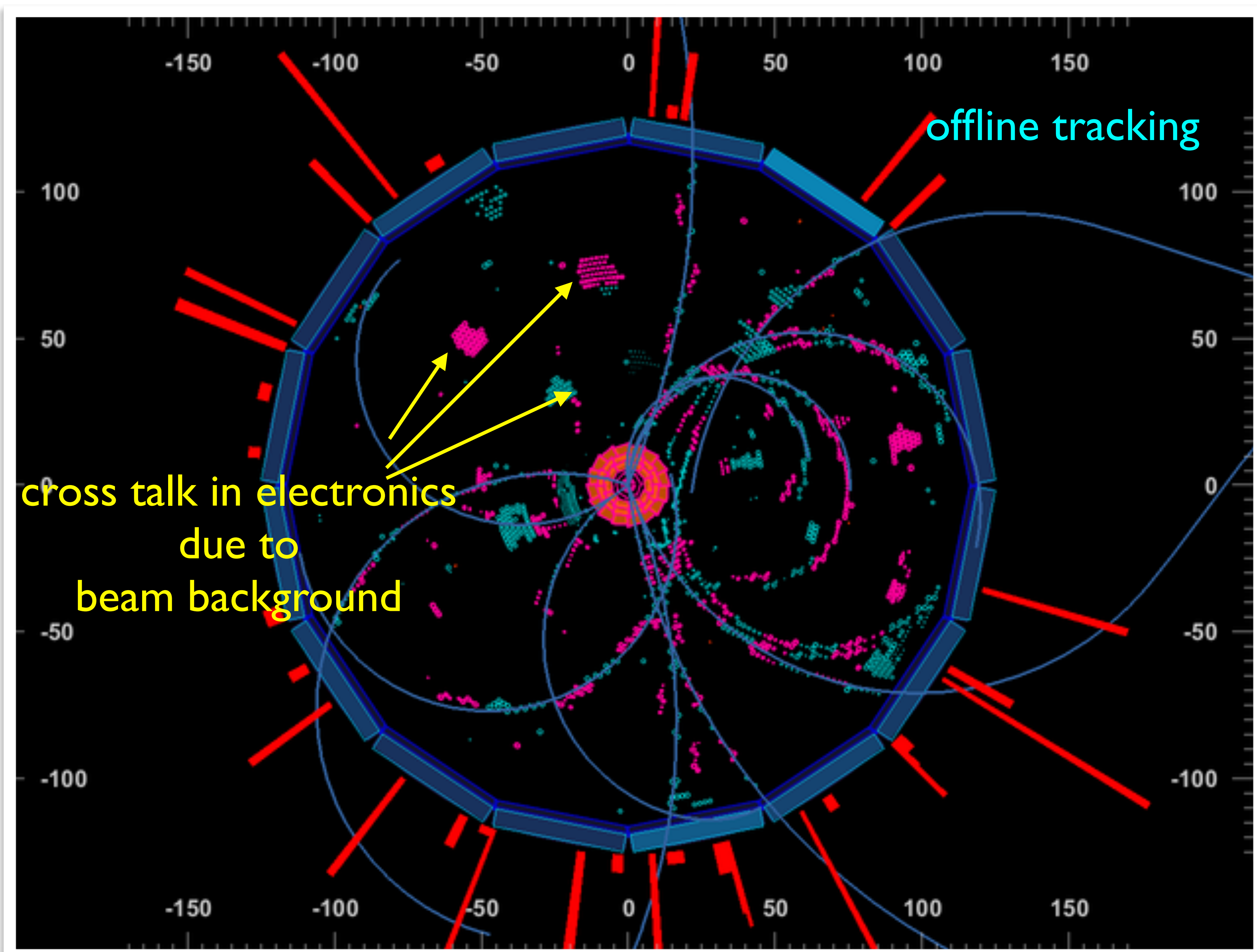
- readout board is located in detector
  - BWD side. direction of lower energy beam (positron)
- power consumption 15W x 299 ~ 4.5kW
  - water cooling
  - as firmware has been updated to implement additional functions, power consumption has become larger

← 5kW

電気ファンヒーター TEH-50

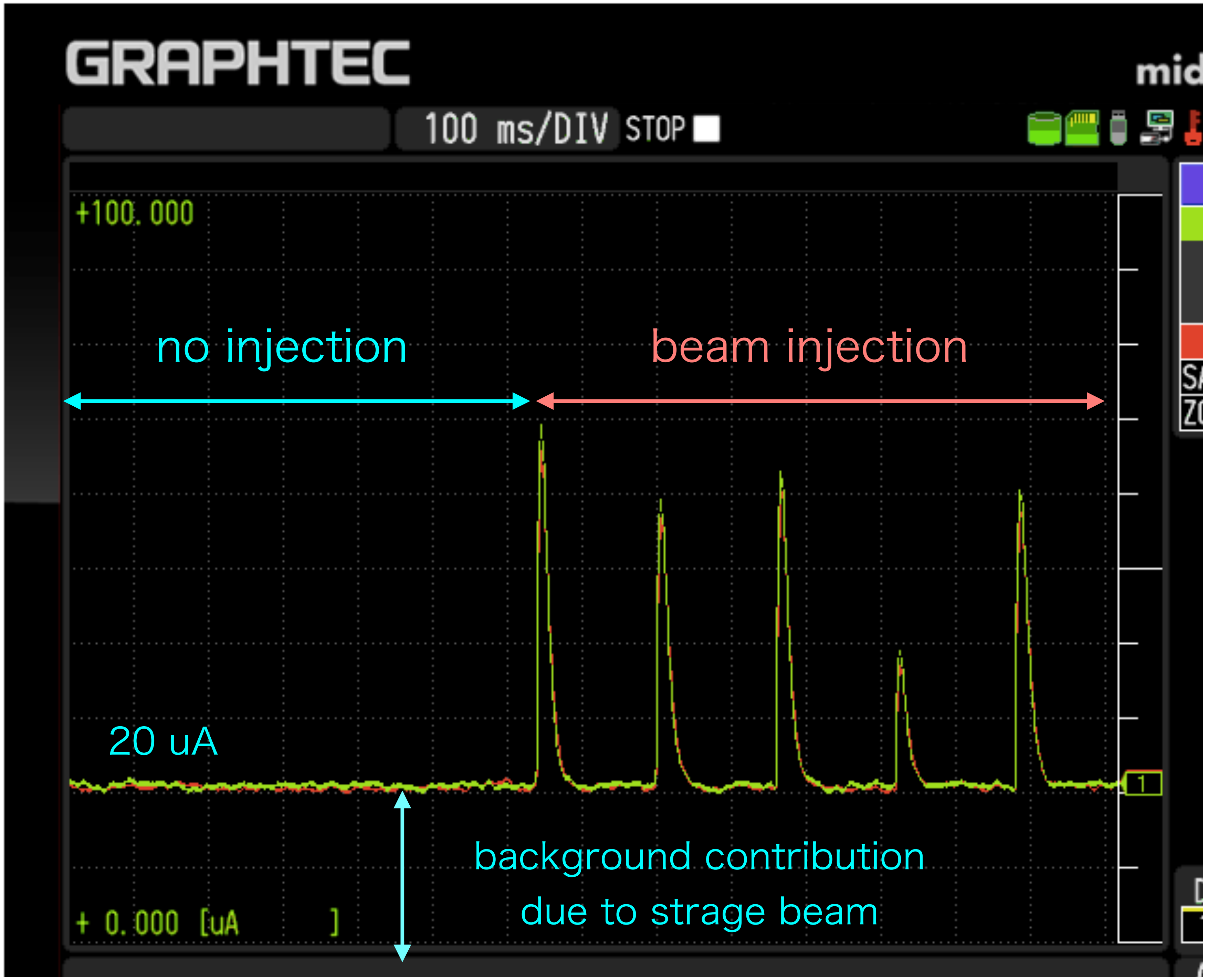
# operation in beam

B decay event

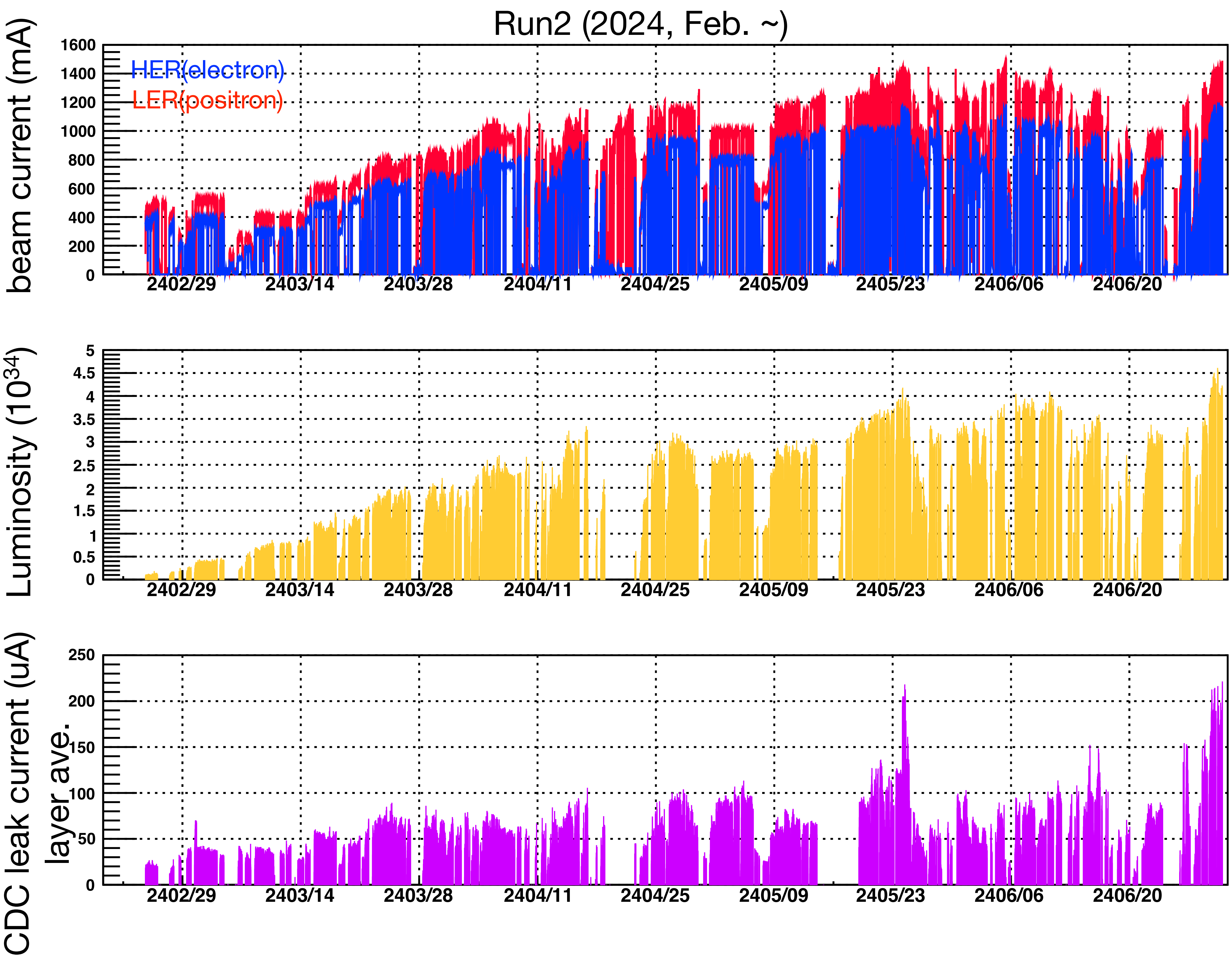


# beam operation

CDC leak current (40 wires in inner layer)

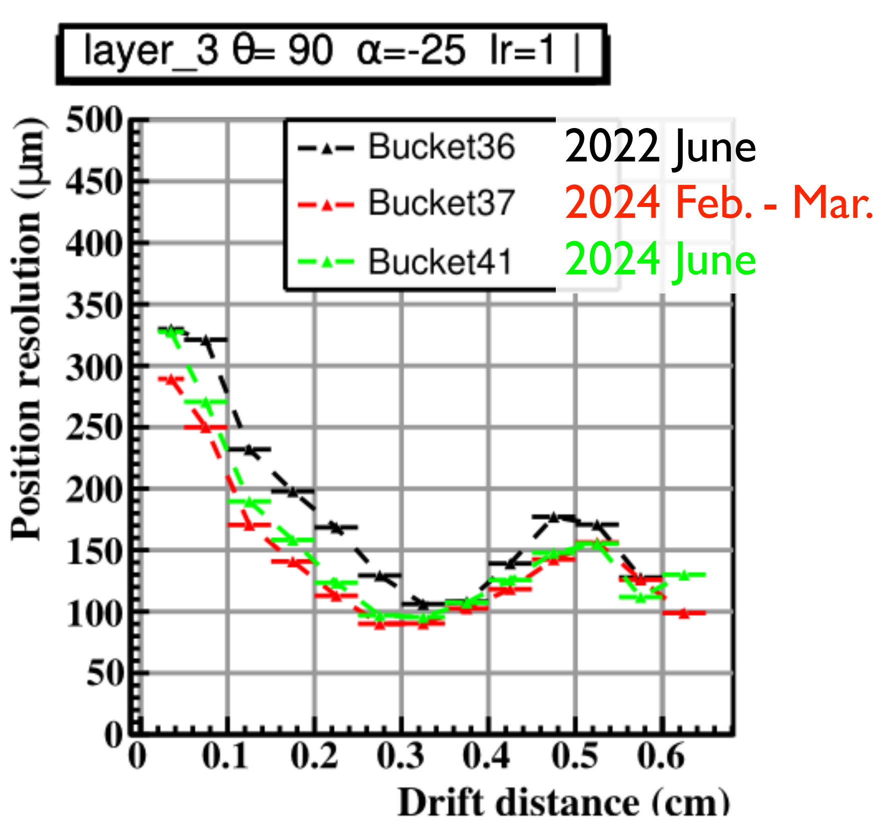


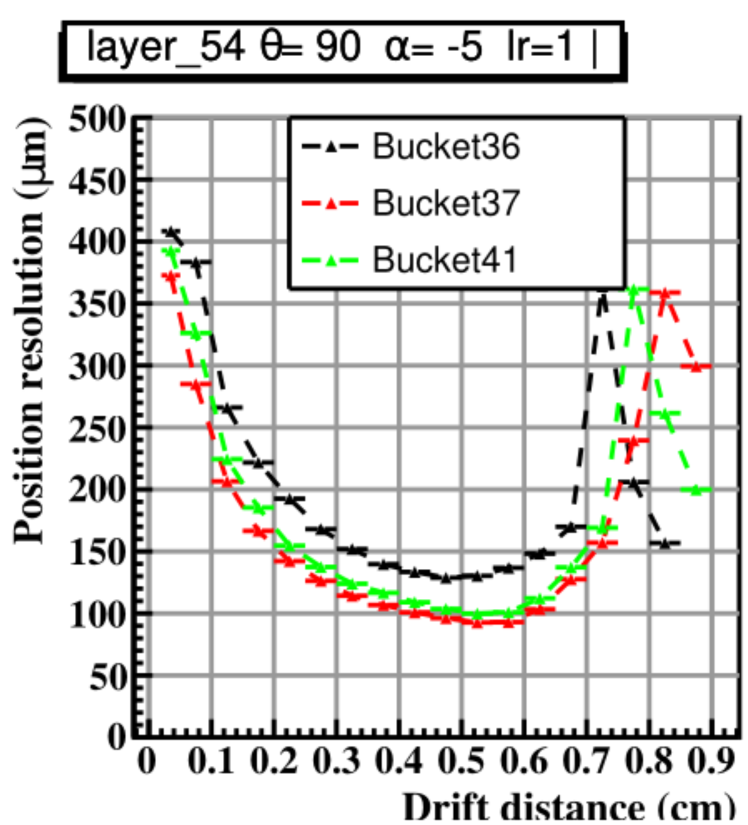
# operation in beam (2024)

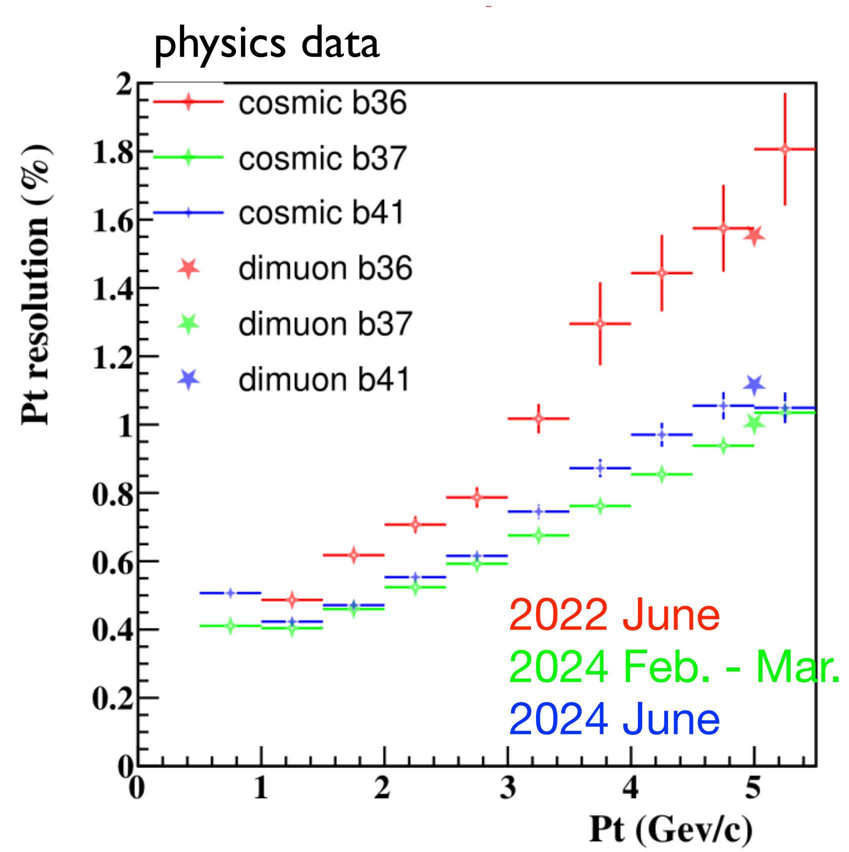


# CDC performance in 2024ab

- gas condition and operation are improved thanks to improvement of gas monitoring/operation system
- CDC performance in 2024ab is better than 2022ab
  - higher gas gain
- remark; resolution is better after tracking with PXD+SVD hits



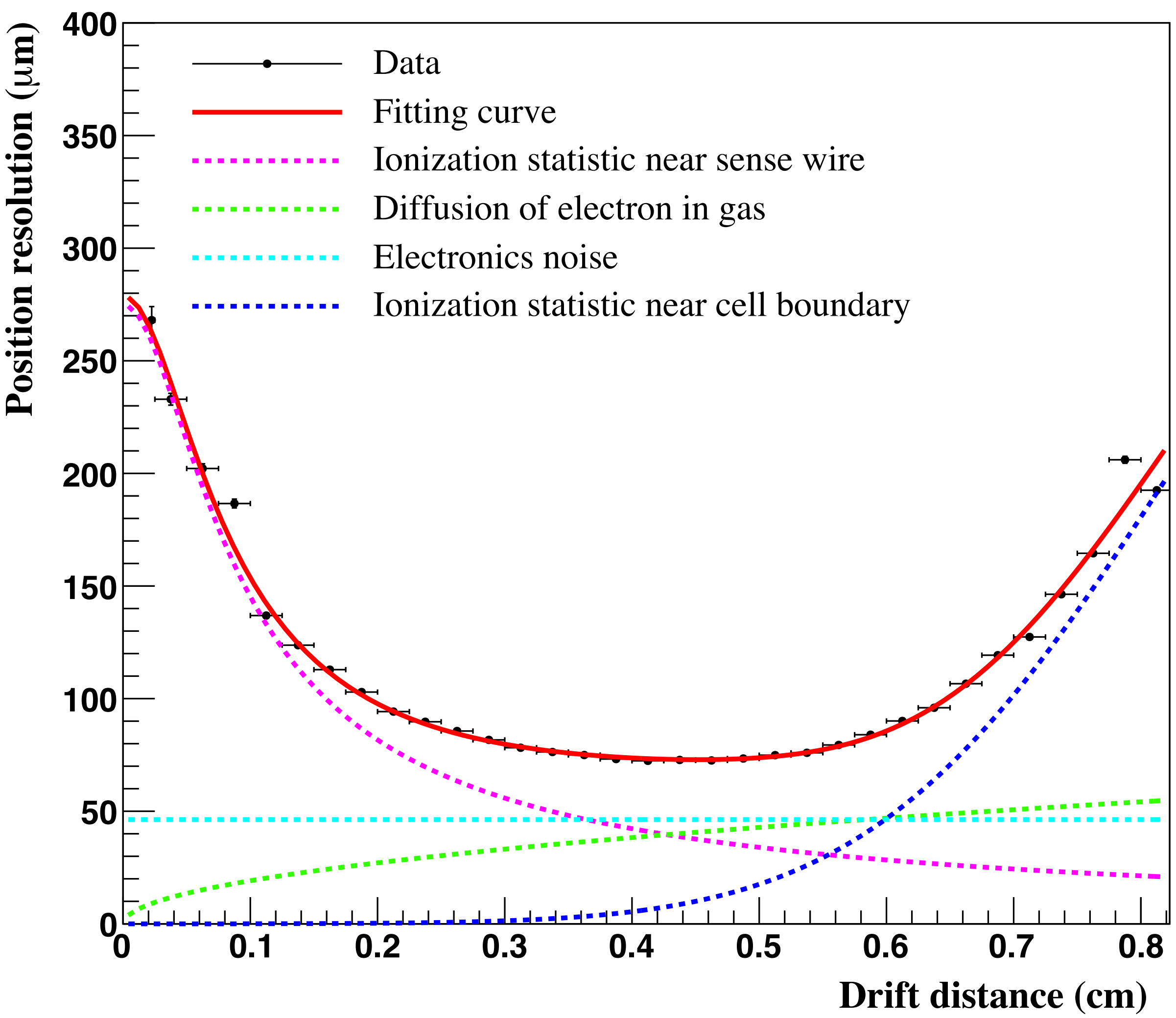



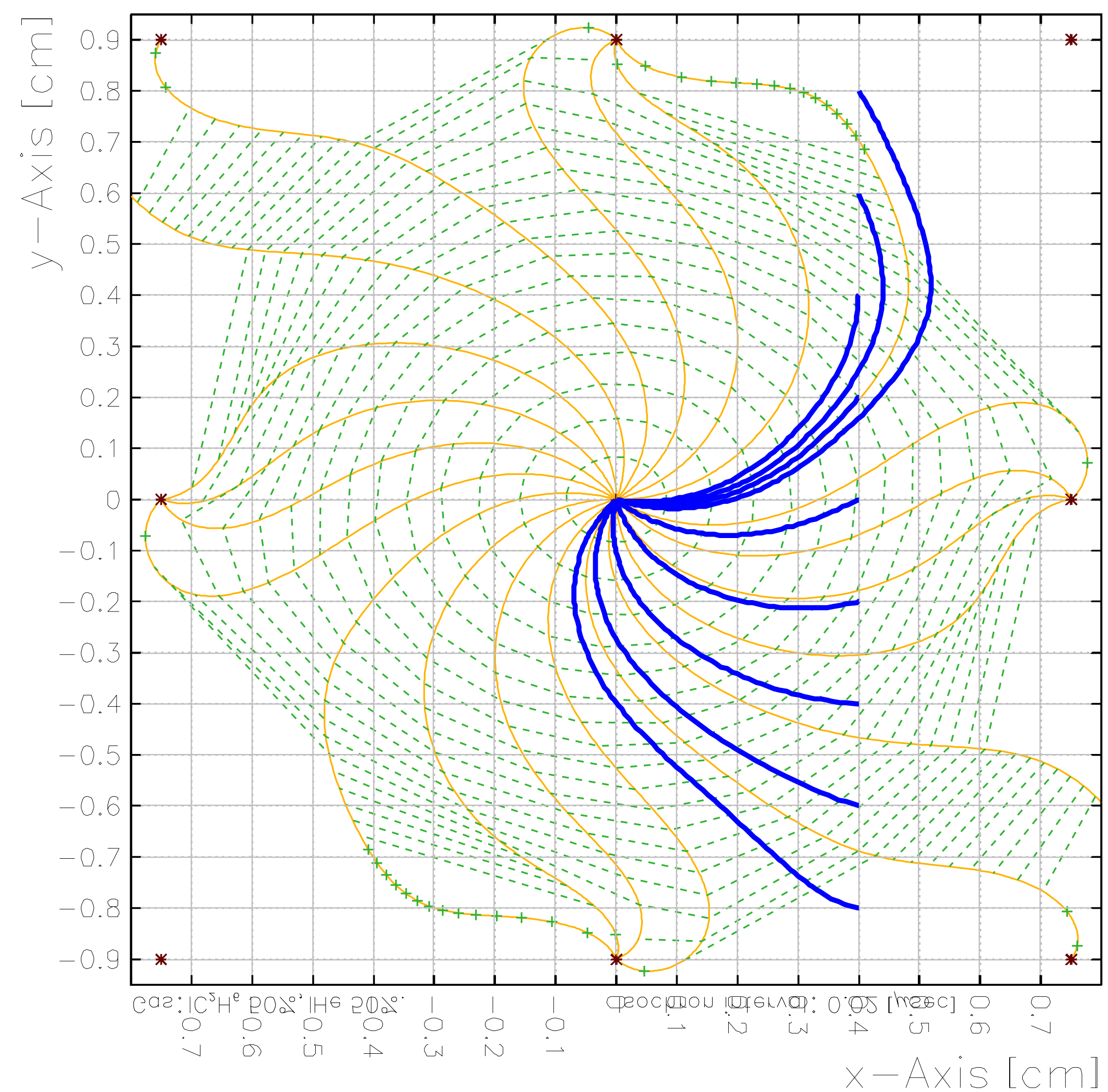

by Thanh Dong

# summary

- CDC is main tracker of Belle II
  - measure charged particle momentum
  - low mass, gas+wire, drift chamber to achieve good performance
- gas mixture and condition are effective for detector performance
- detector is required to achieve good performance at higher background condition
  - need to understand drift chamber behavior with beam for future operation
  - electronics upgrade is ongoing
- Belle II CDC is drift chamber which operates at ee collider of the highest luminosity

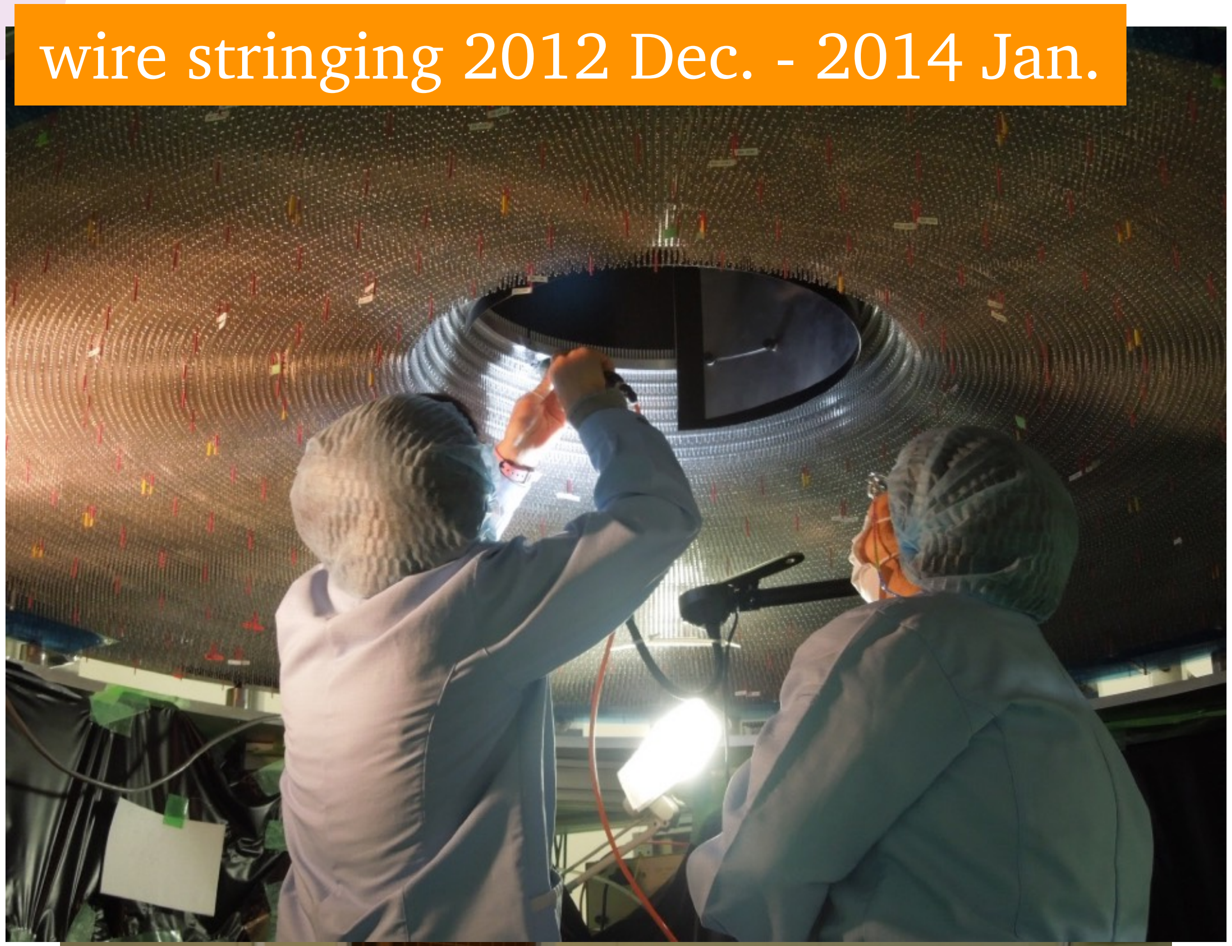
# position resolution

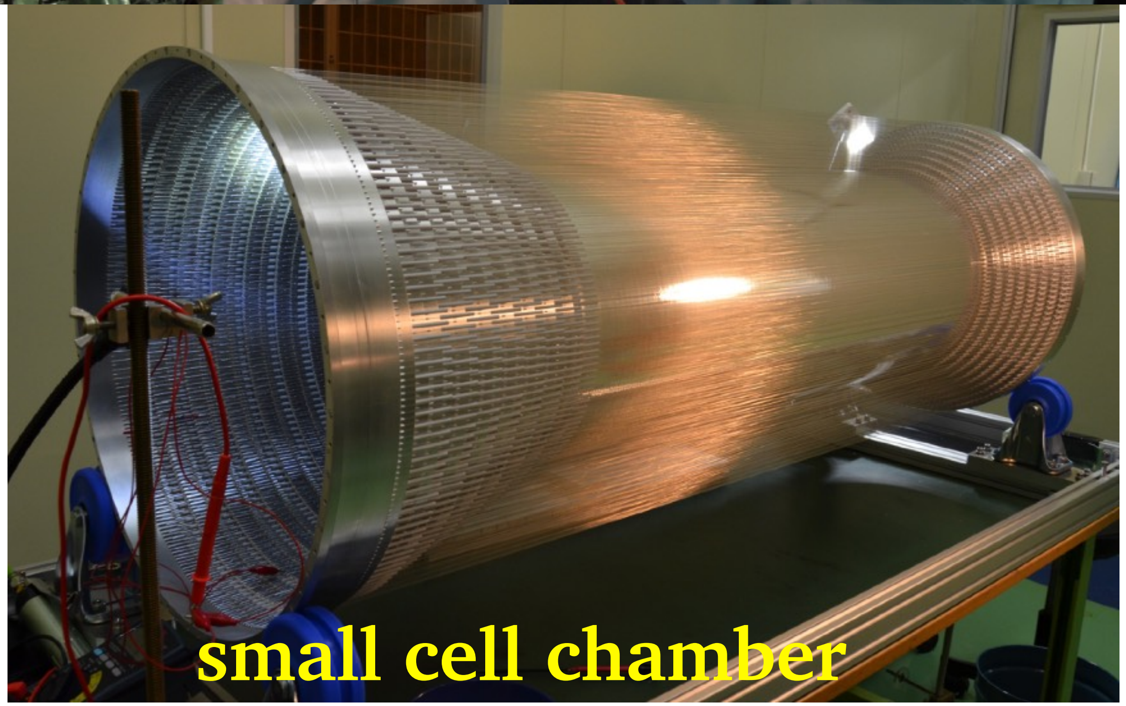


Nanae Taniguchi (KEK)

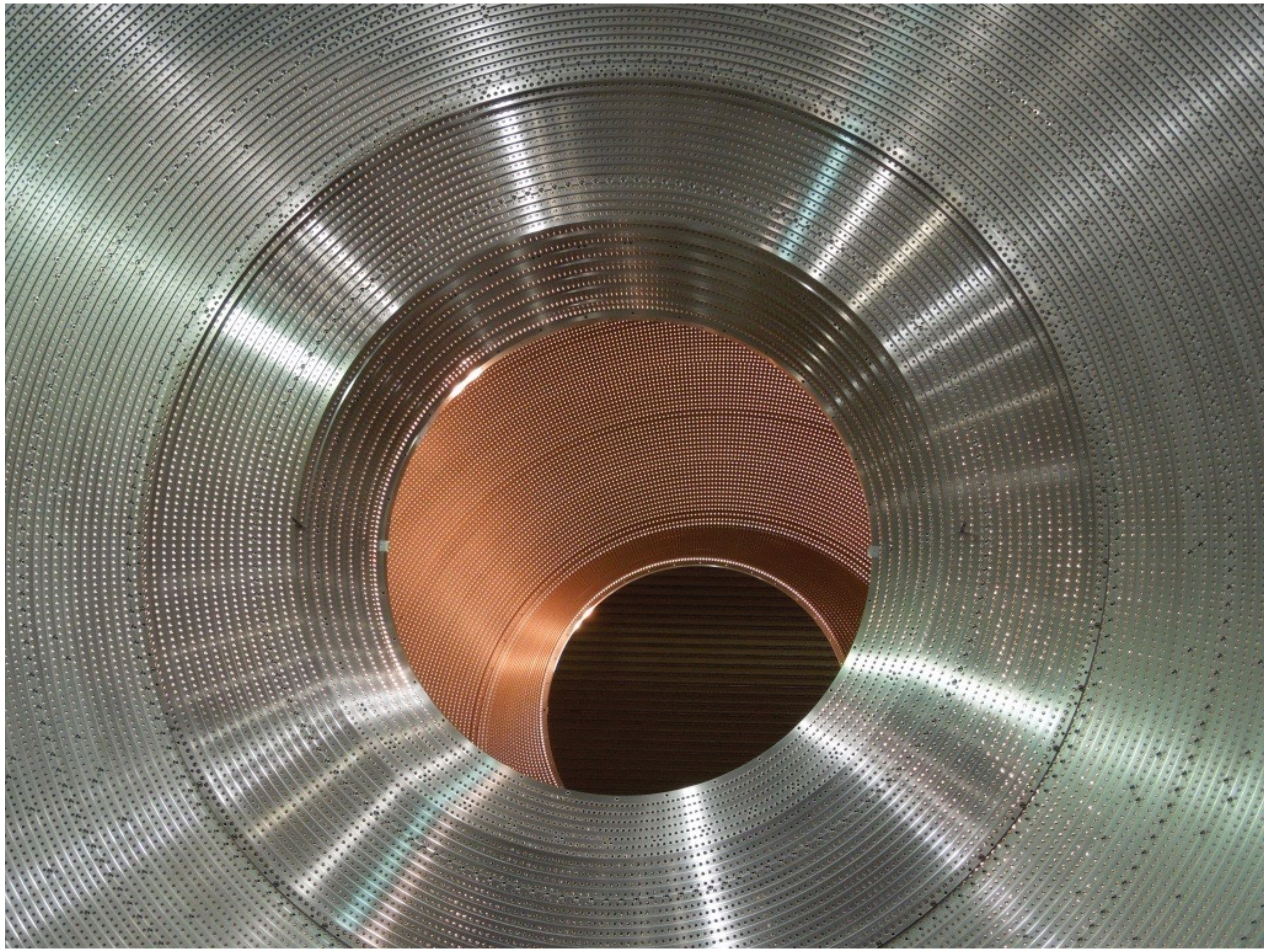
# wire stringing

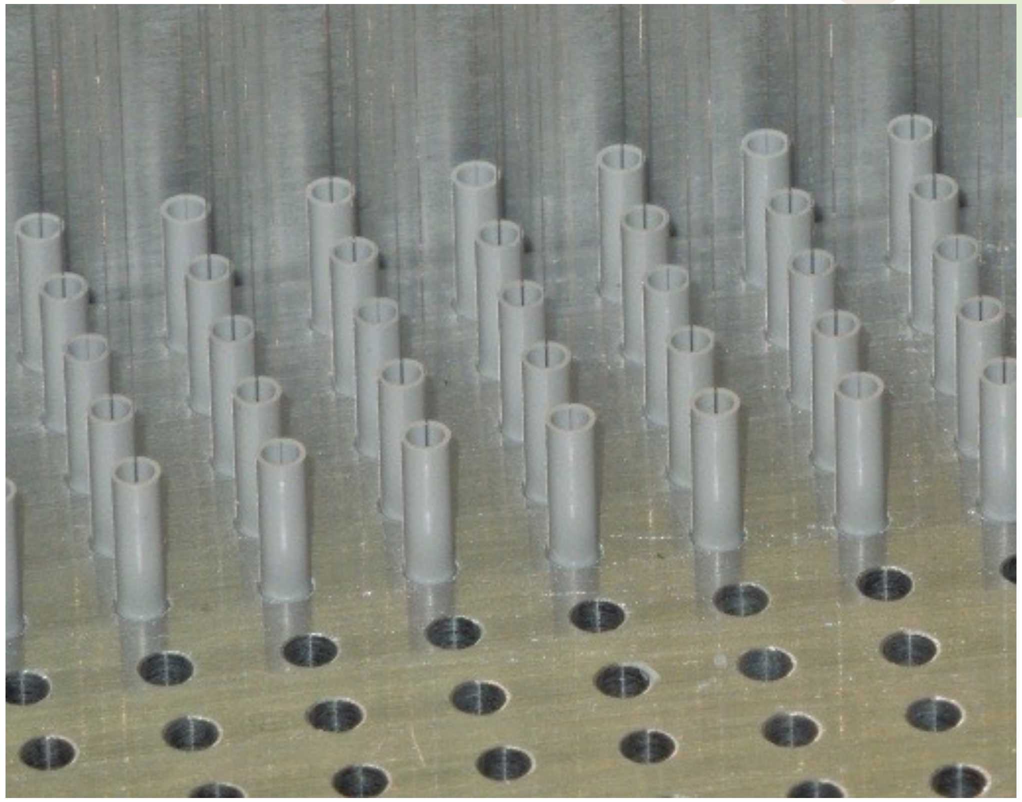



- total # of wire =56576
  - it took around 1 year
- manually stringing wire
  - daily schedule
    - wire stringing ; 8 hours (company people)
    - tension check : 2-3 hours (Belle II CDC members)
- tension is necessary
  - Au-W(ϕ30um) : 50gw
  - Al(ϕ126um) : 80gw
  - total tension : ~4.1ton (3.7+0.4)

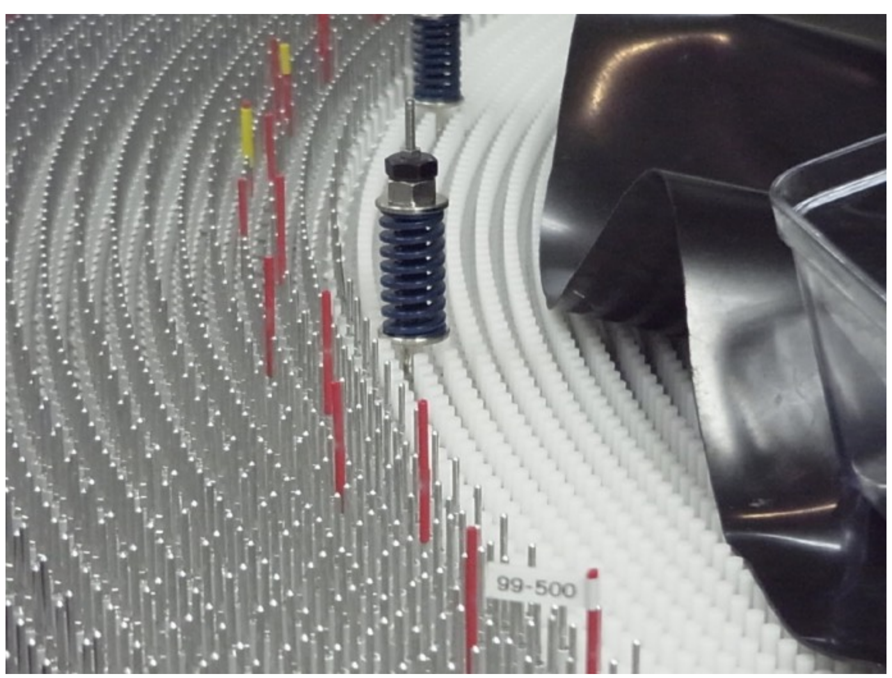
# Wire stringing

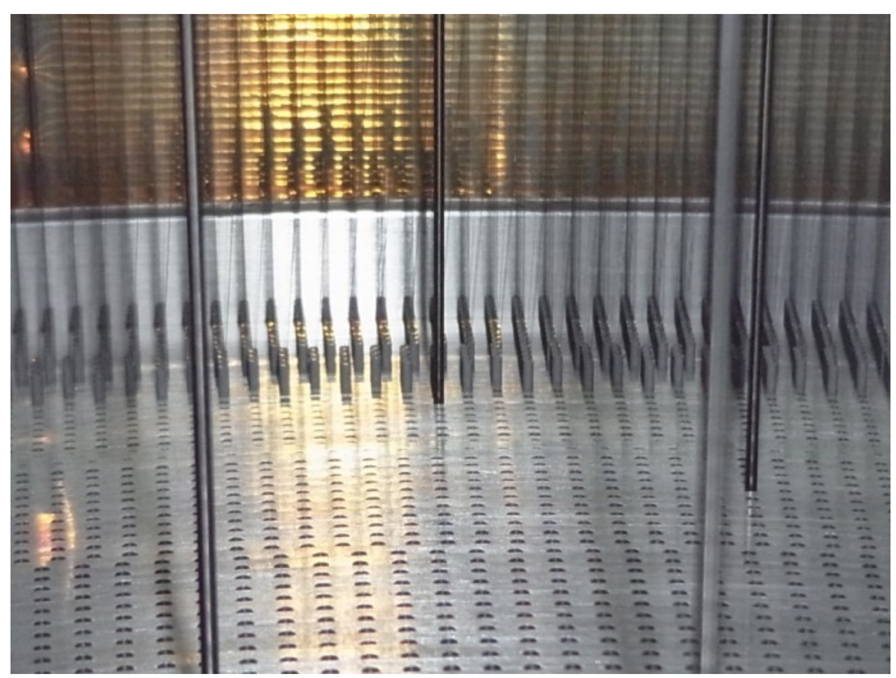




# Wire stringing

- total tension is ~4 ton → it can deform endplate by ~2mm
- endplate is deformed as total tension increase
- distance between both endplates become shorter → wire is loosen
- To avoid that, stress is applied to deform endplate in advance and release step by step
- distance between both endplate was monitored and controlled within a few m



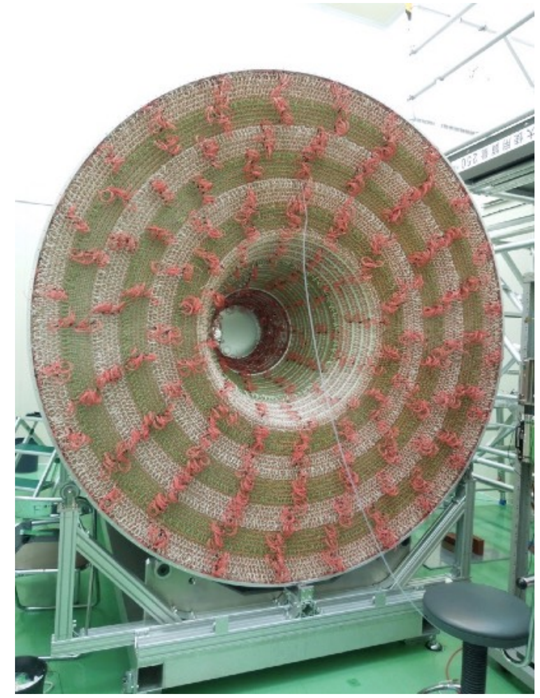
HV side (Fwd.)

Apr. 2014

gas leak check

Oct. 2014

ground cable



Dec. 2014

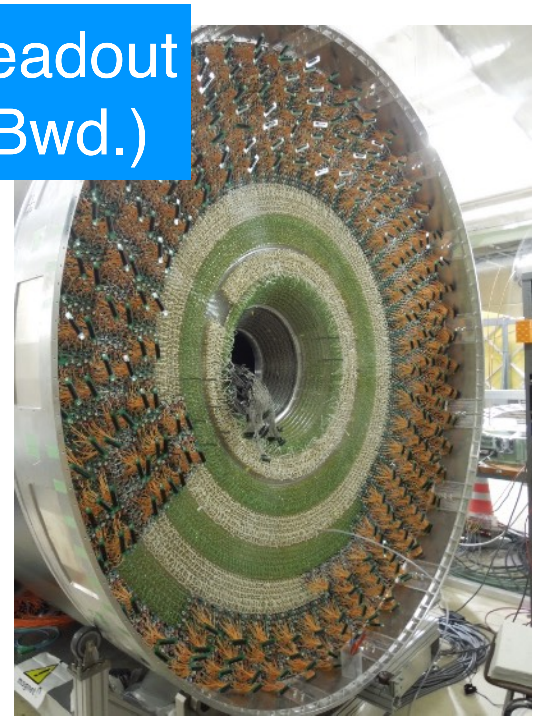
HV cable

Jan. 2015

HV test

Fuji to Tsukuba-hall

Readout (Bwd.)

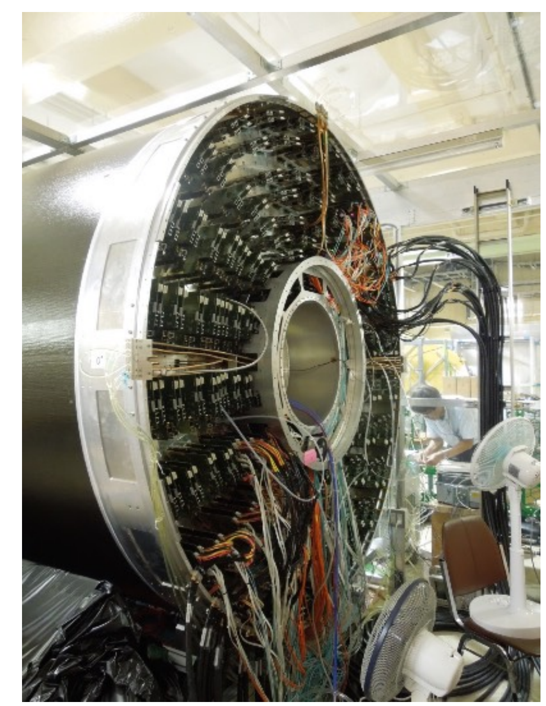


Dec. 2015

signal cable

Jan. 2016

readout electronics

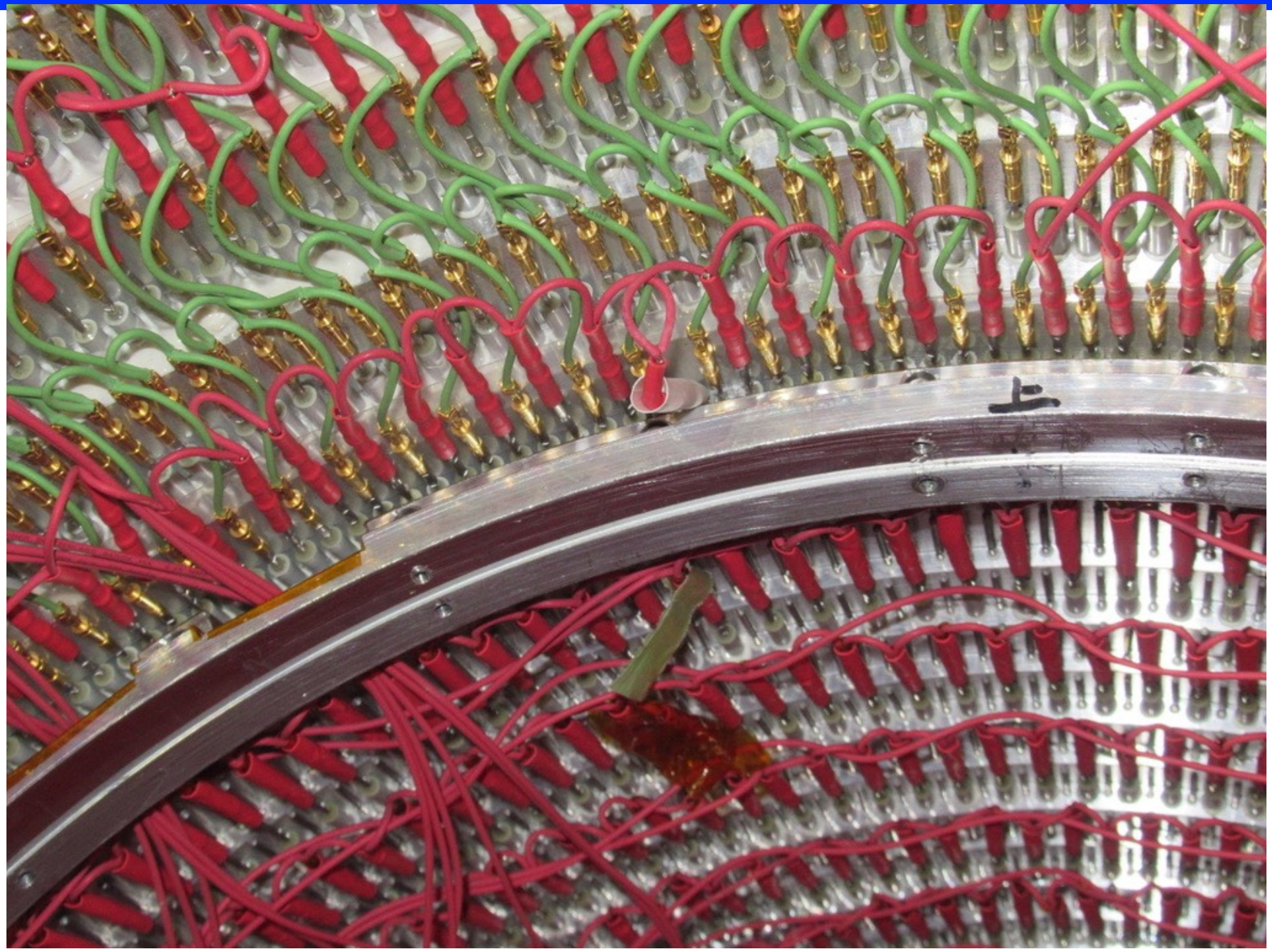


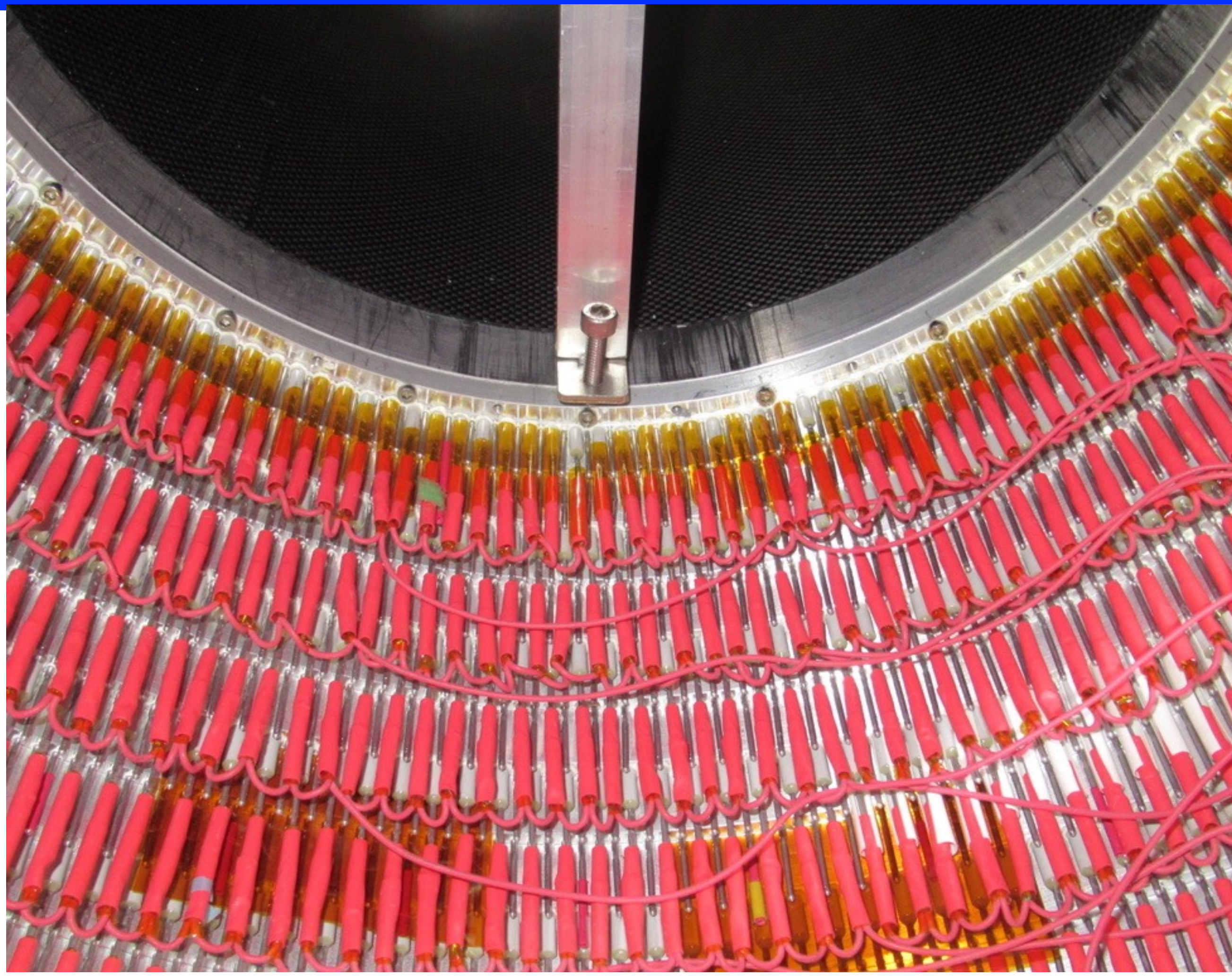
Spring - Autumn. 2016

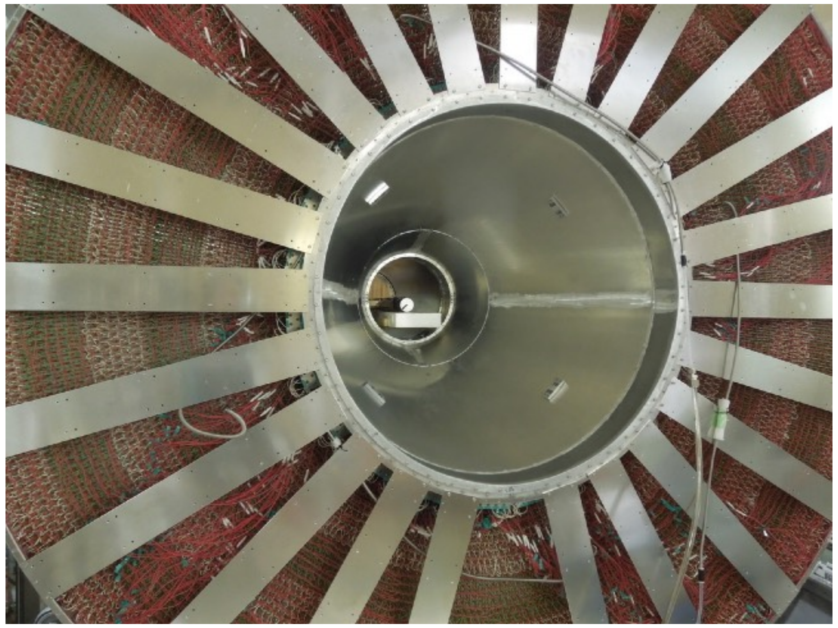
cosmic run with partial readout

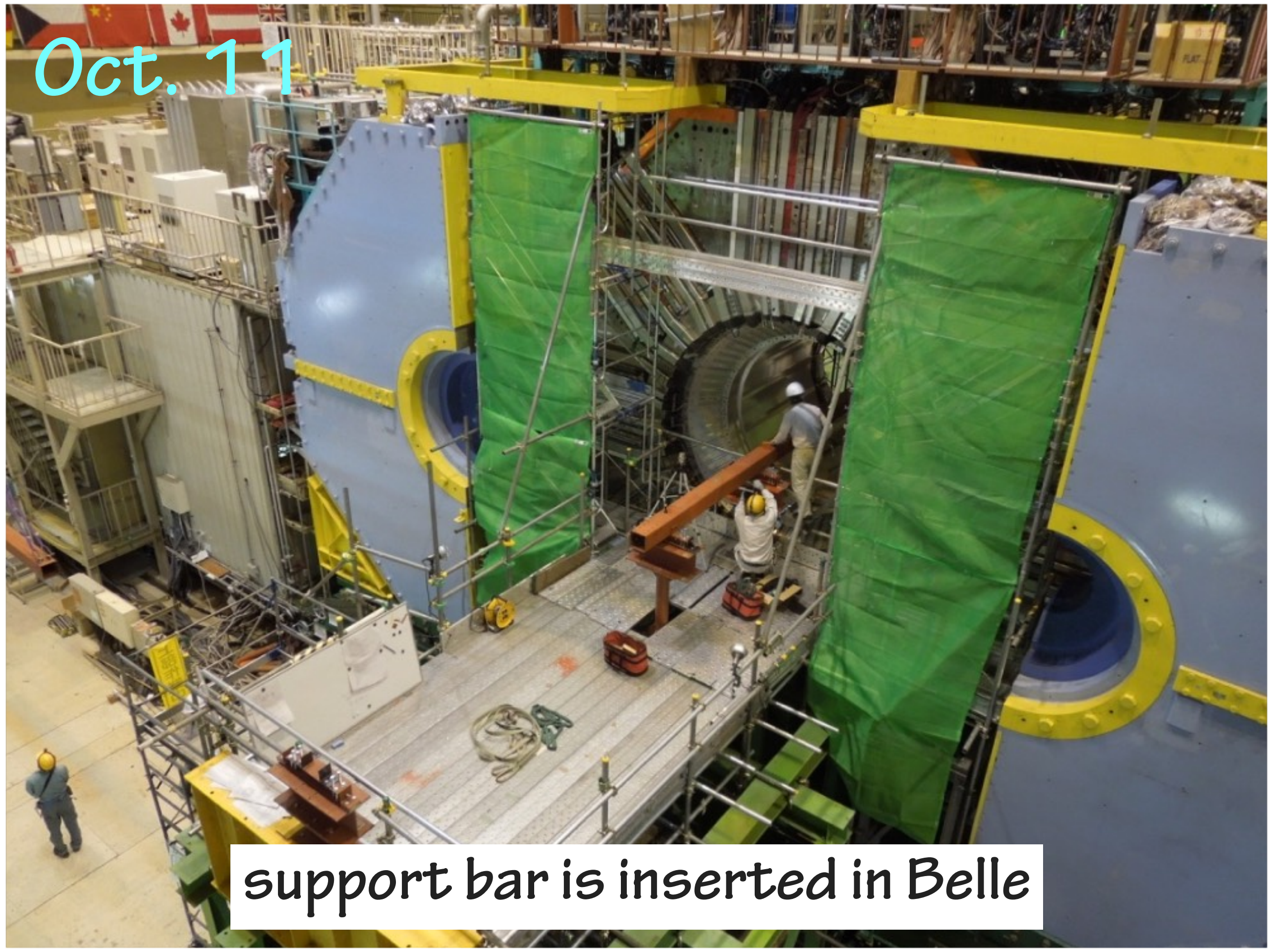
HV side (Fwd.)

# applying High Voltage

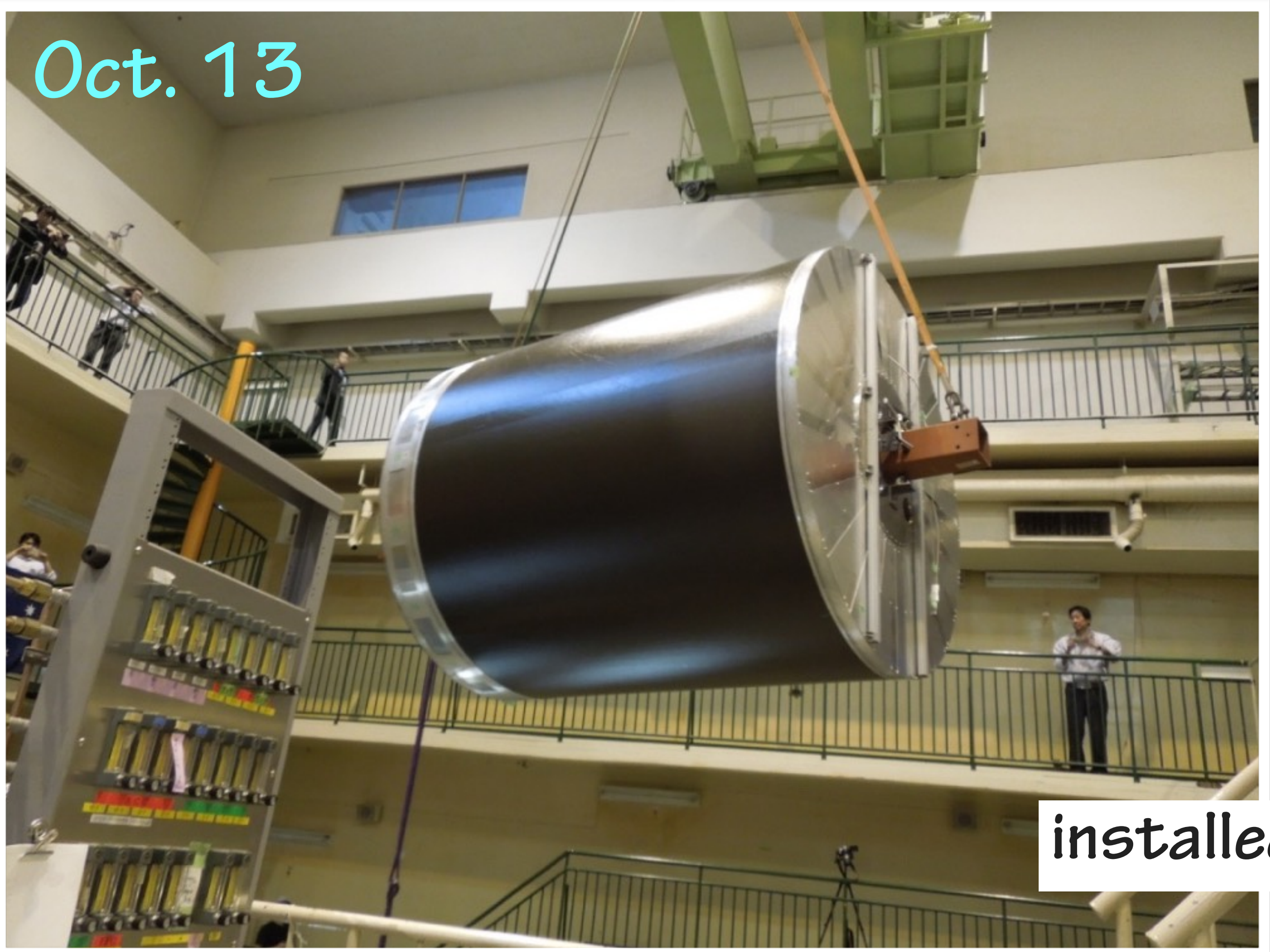


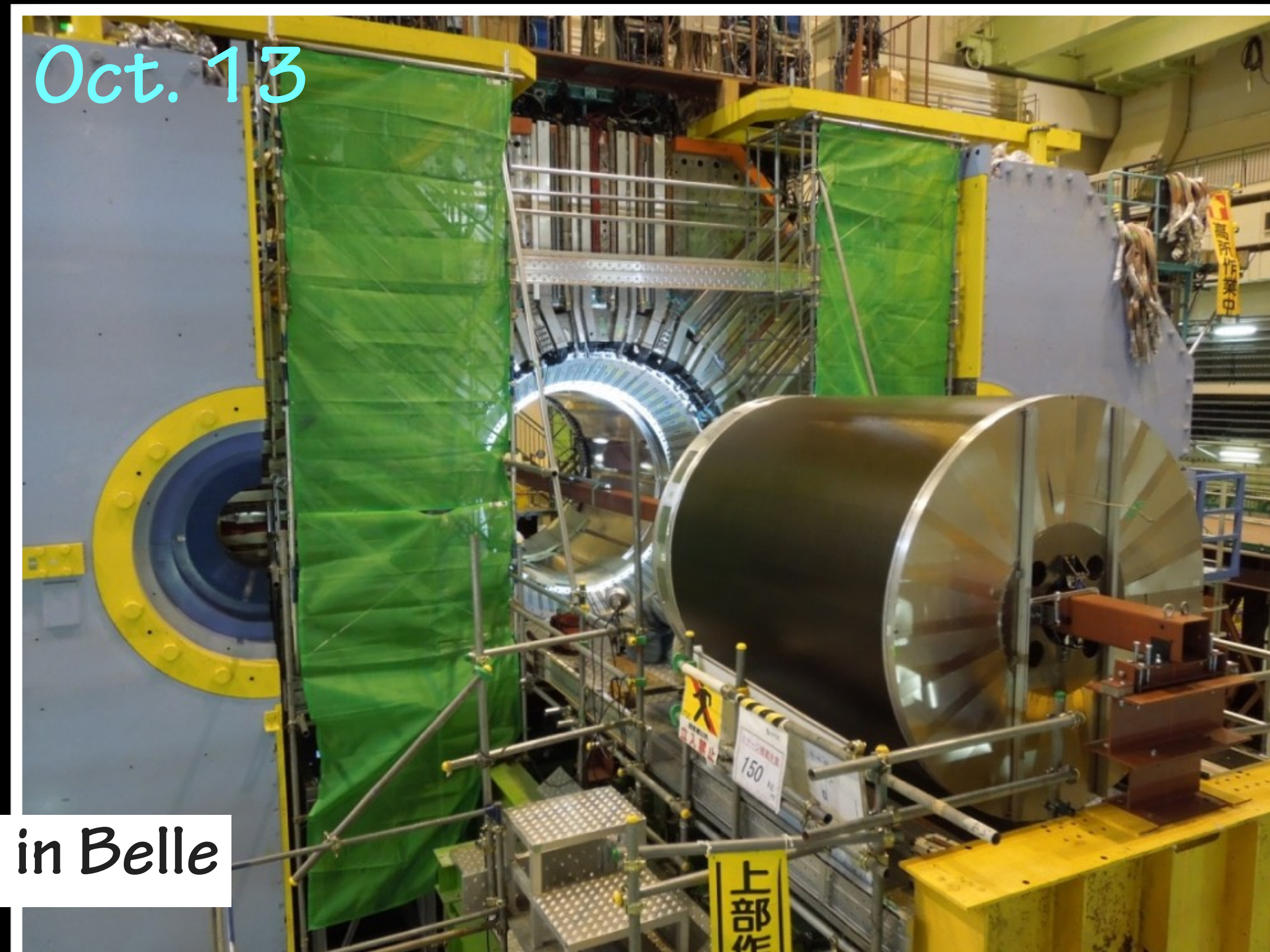




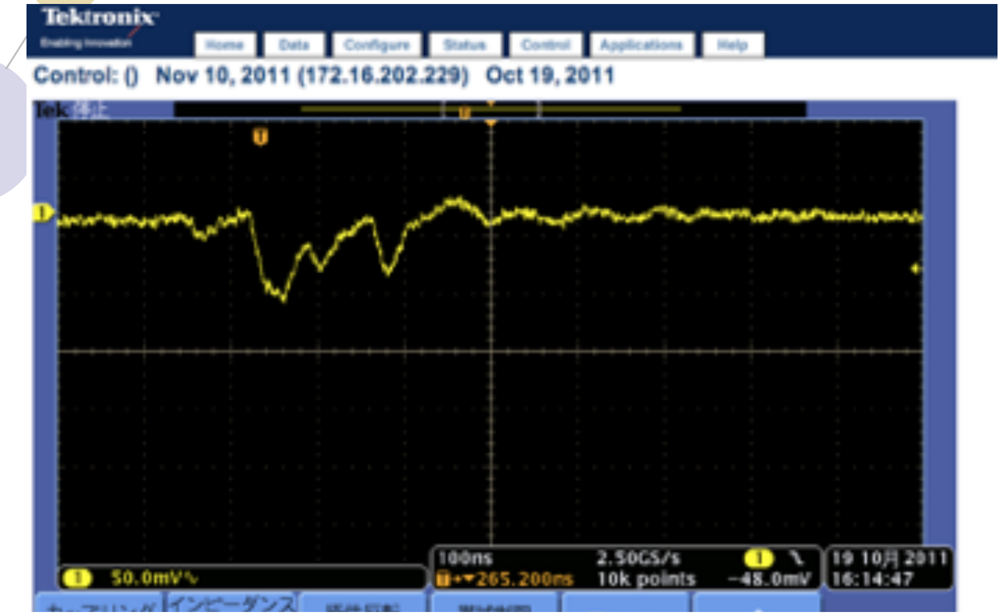




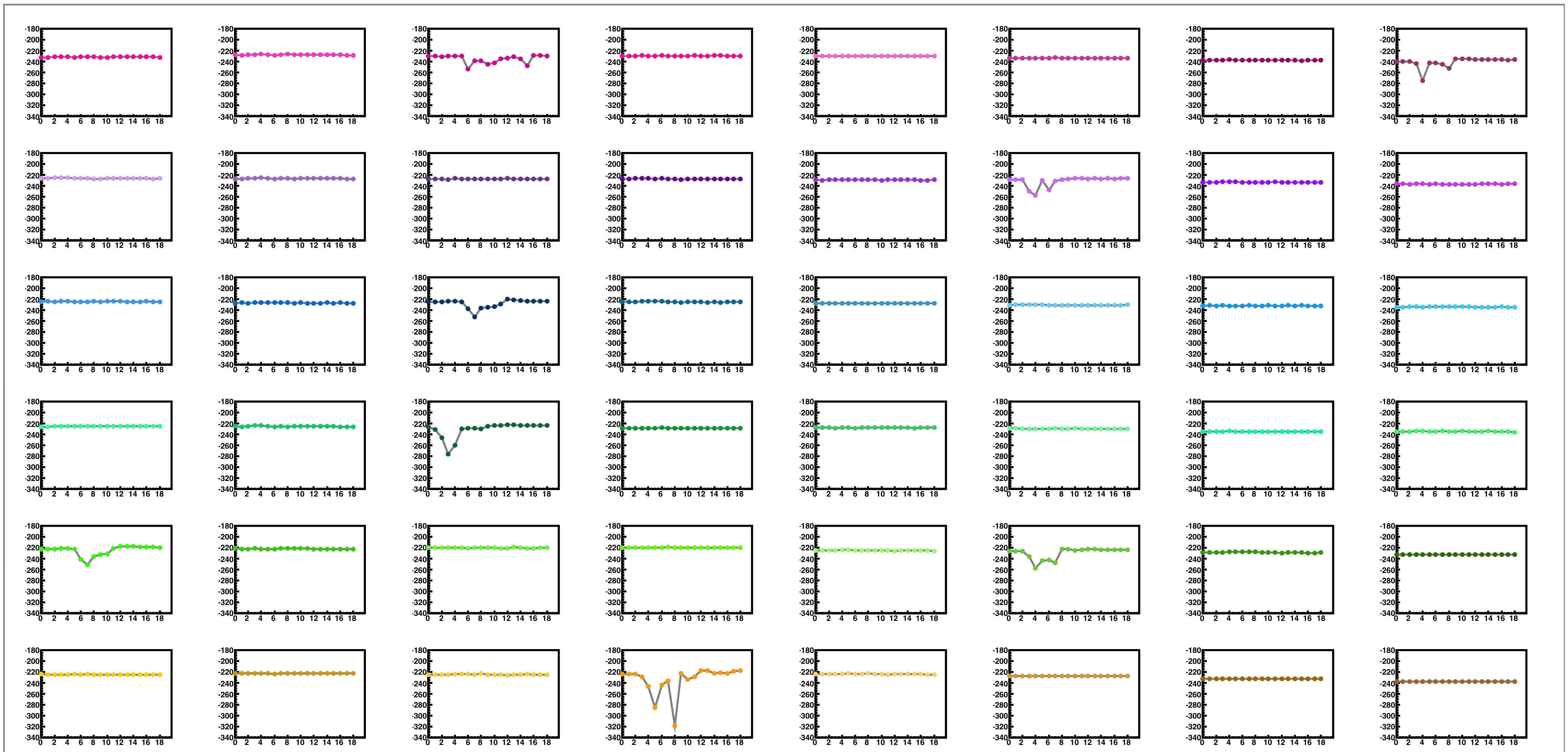


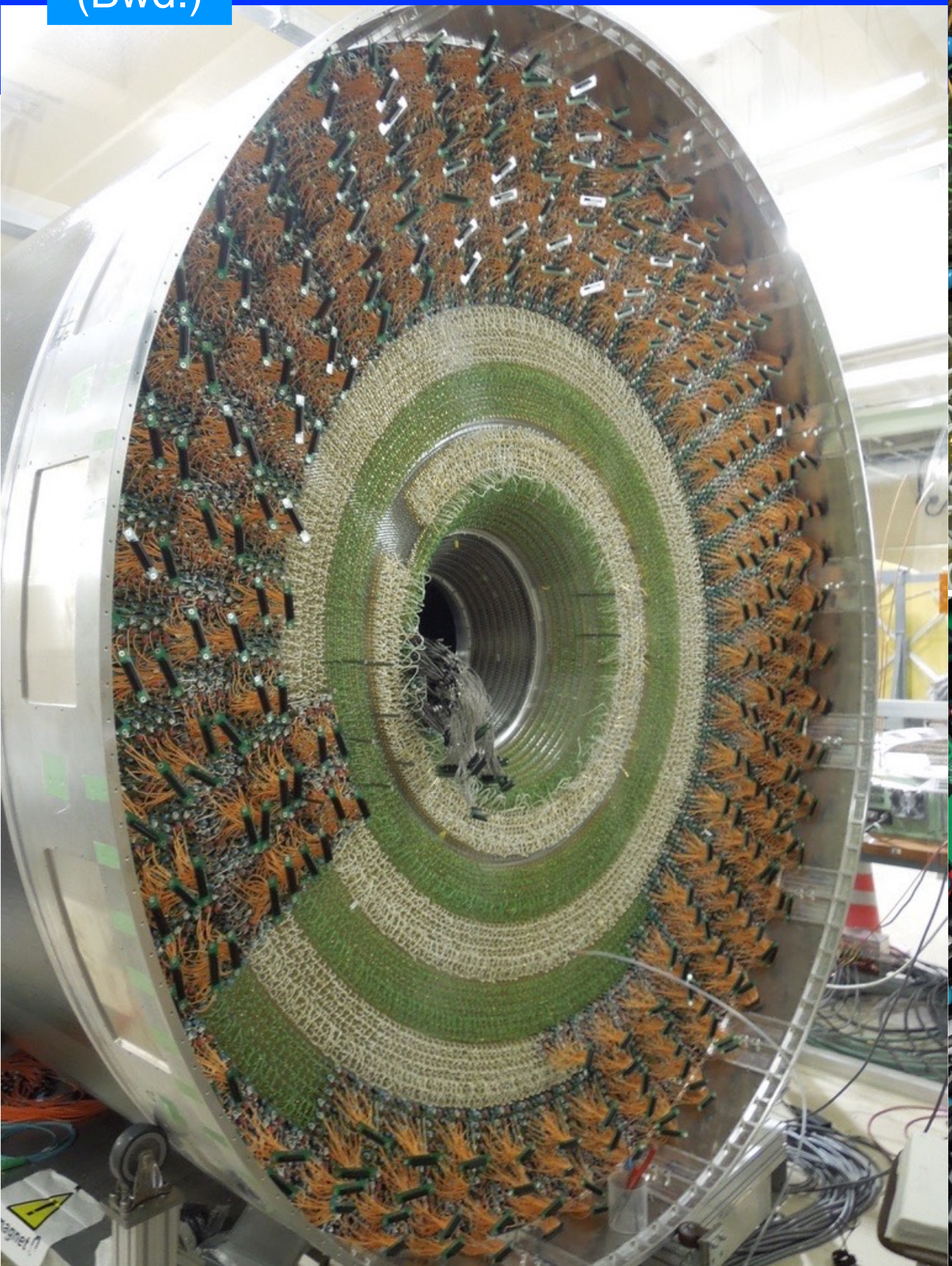

installed in Belle

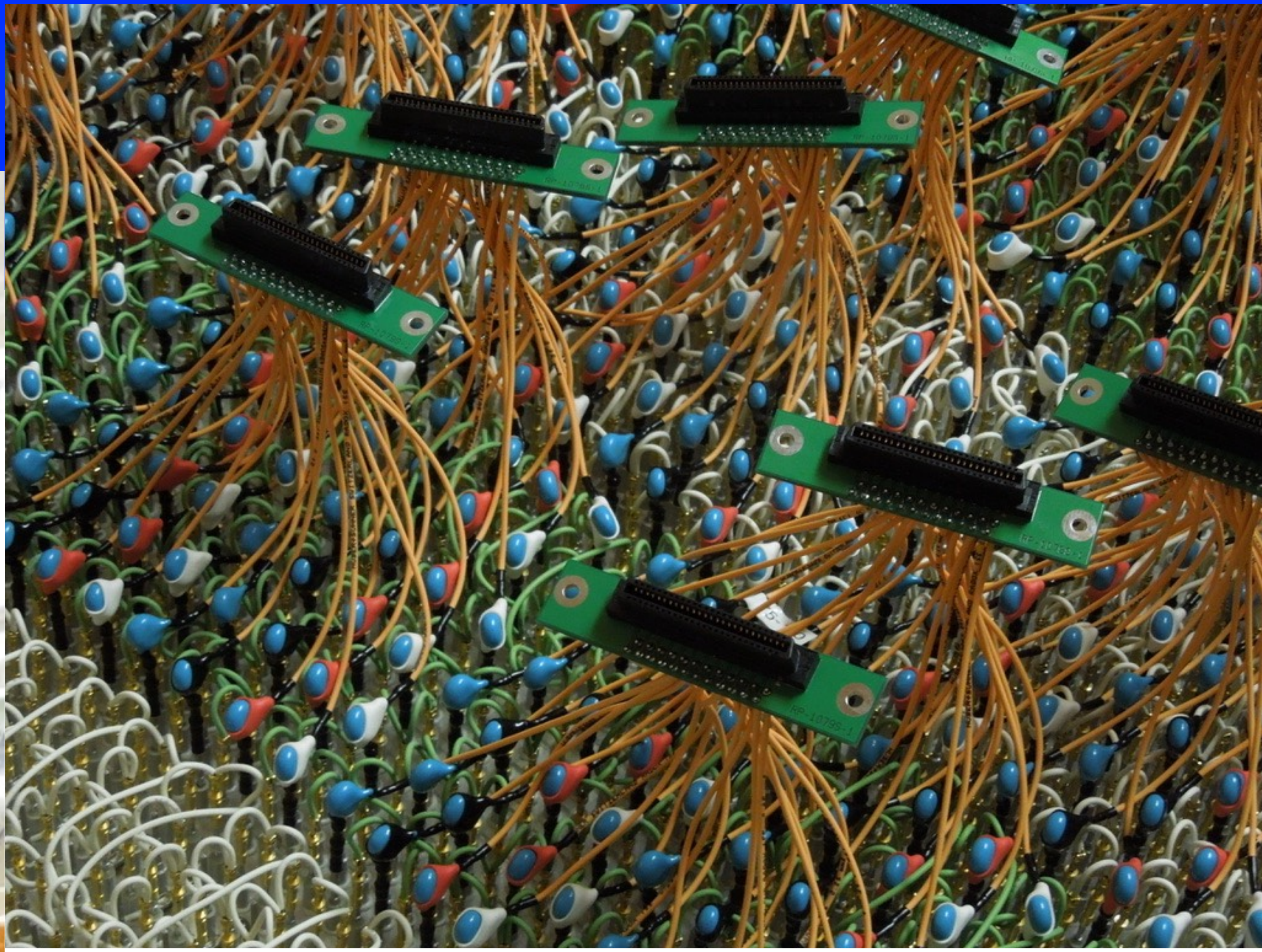

Tektronix
Control: () Nov 10, 2011 (172.16.202.229) Oct 19, 2011
50.0mV
100ns 2.50GS/s
265.200ns 10k points -48.0mV
19 10月 2011
16:14:47

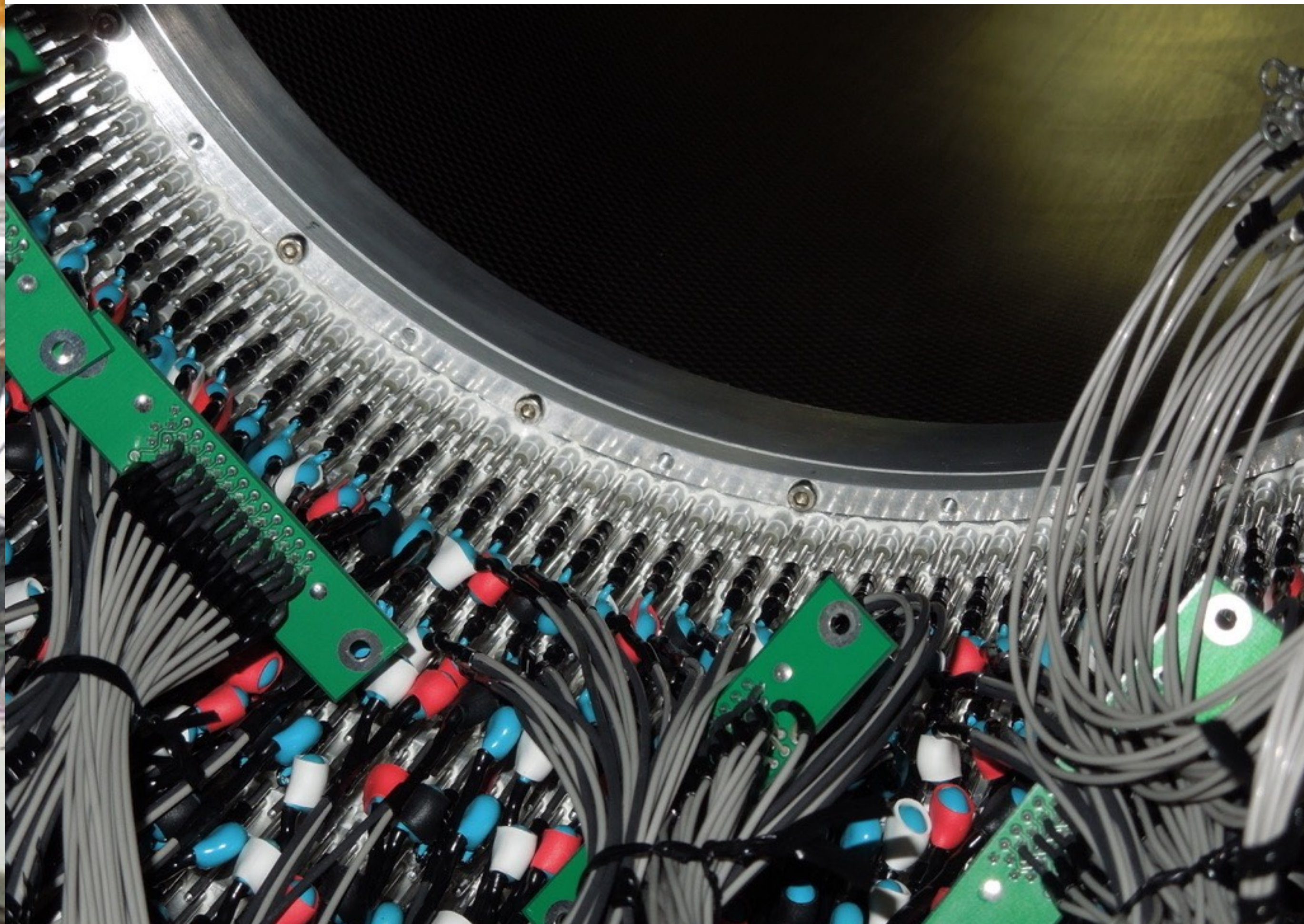

Tektronix
Control: () Nov 10, 2011 (172.16.202.229) Oct 19, 2011
50.0mV
100ns 2.50GS/s
265.200ns 10k points -48.0mV
19 10月 2011
16:08:56



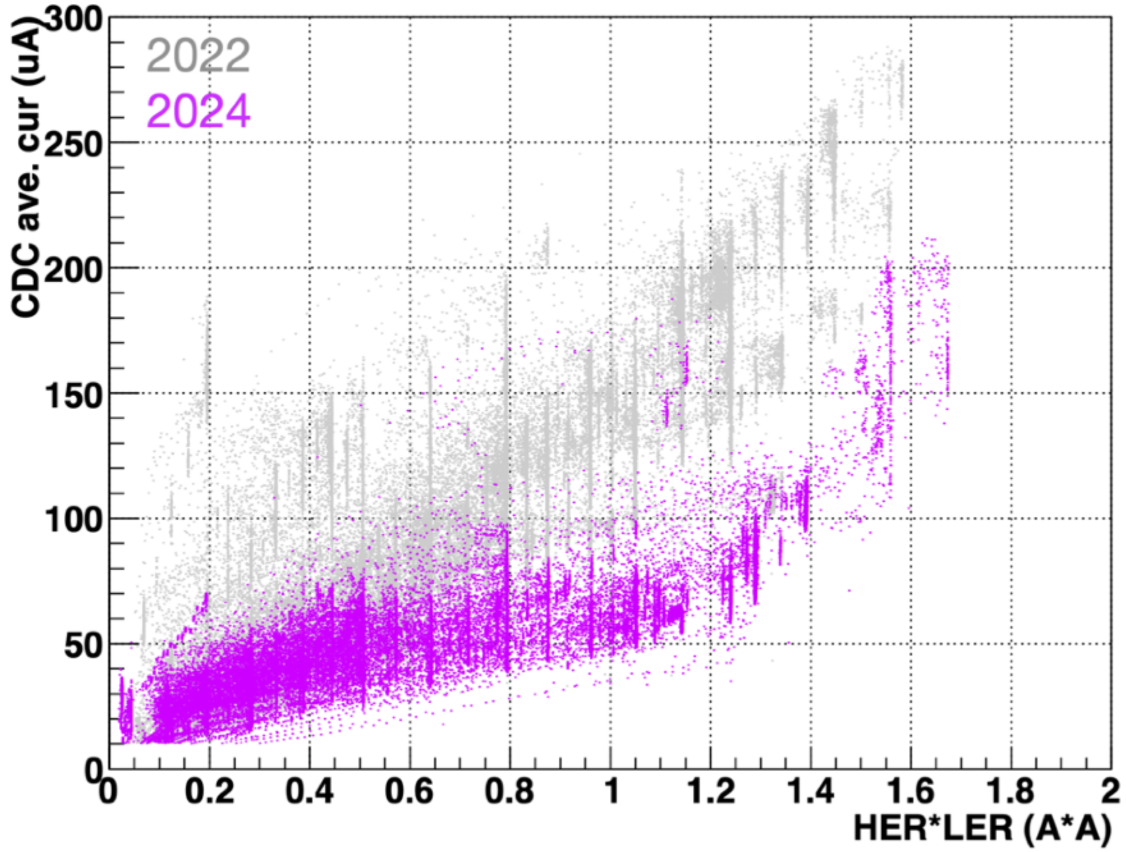
# Readout (Bwd.)

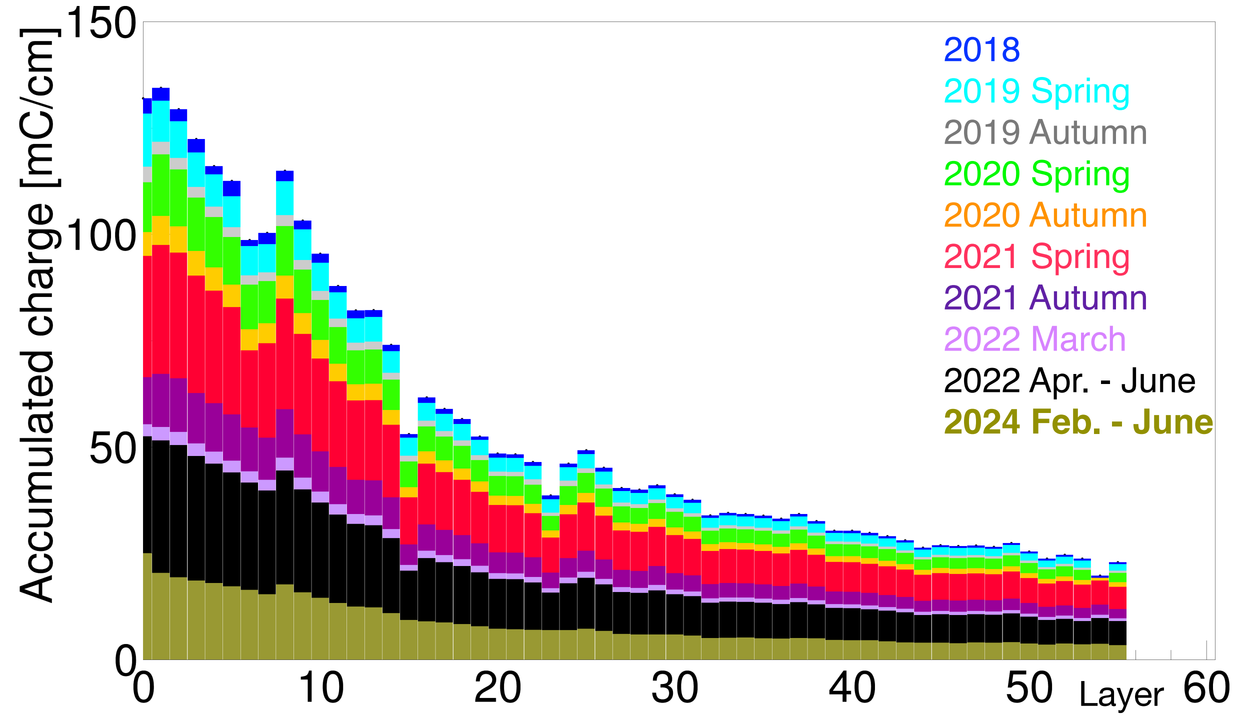






# operation in beam




- beam background in 2024 has been suppressed at the same beam condition compared with 2022
- accumulated charge is 30-130mC/cm
  - no indication of aging effect (gain drop) so far
-

### 34.6.3 *High Rate Effects*

Revised March 2010 by F. Sauli (CERN) and M. Titov (CEA Saclay, DSM/IRFU/SPP).

The production of positive ions in the avalanches and their slow drift before neutralization result in a rate-dependent accumulation of positive charge in the detector. This may result in significant field distortion, gain reduction and degradation of spatial resolution. As shown in Fig. 34.8 [111], the proportional gain drops above a charge production rate around $10^9$ electrons per second and mm of wire, independently of the avalanche size. For a proportional gain of $10^4$ and 100 electrons per track, this corresponds to a particle flux of $10^3\,\mathrm{s}^{-1}\mathrm{mm}^{-1}$ (1 kHz/mm$^2$ for 1 mm wire spacing).

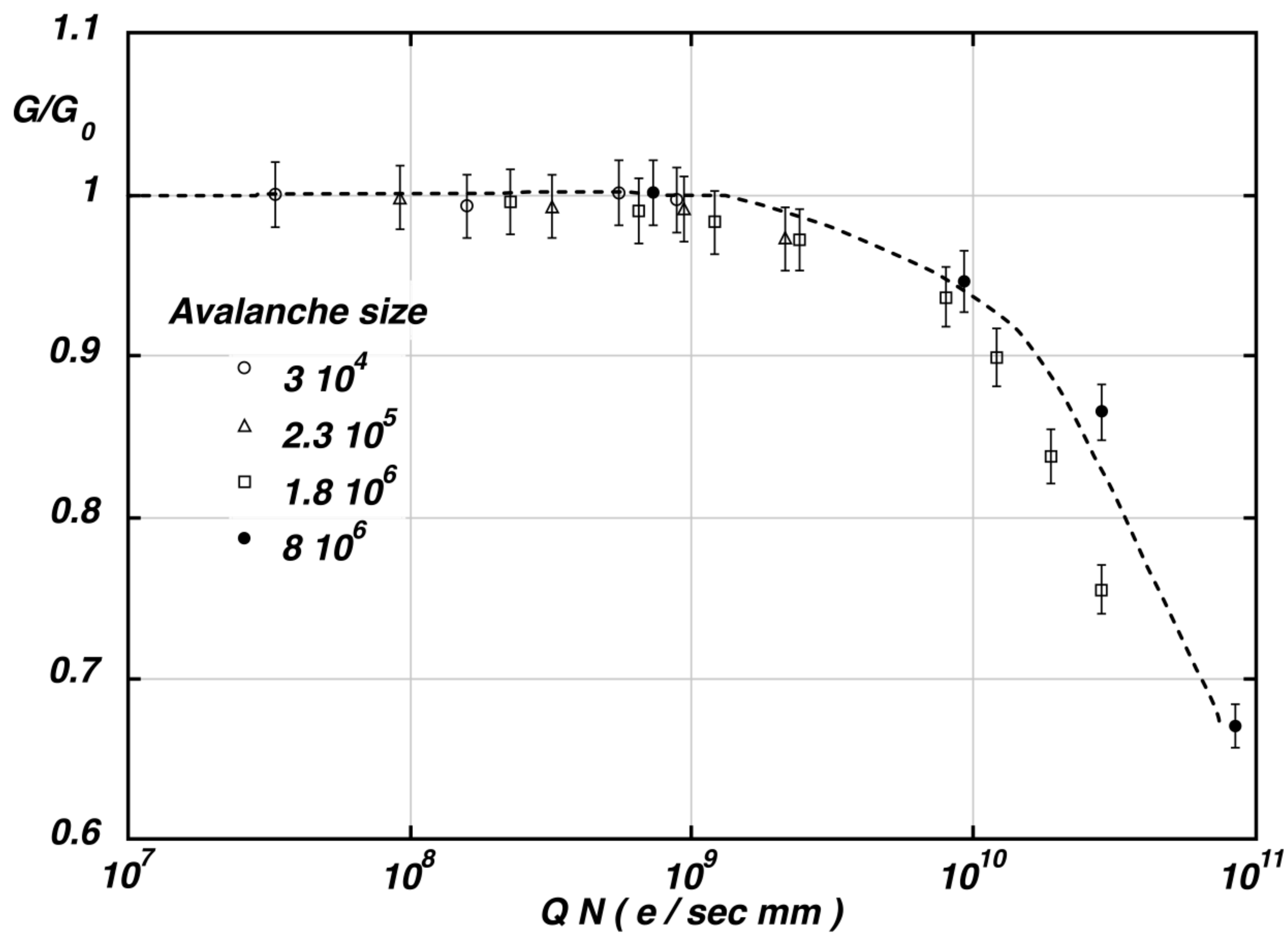



Figure 34.8: Charge rate dependence of normalized gas gain $G/G_0$ (relative to zero counting rate) in proportional thin-wire detectors [111]. $Q$ is the total charge in single avalanche; N is the particle rate per wire length.

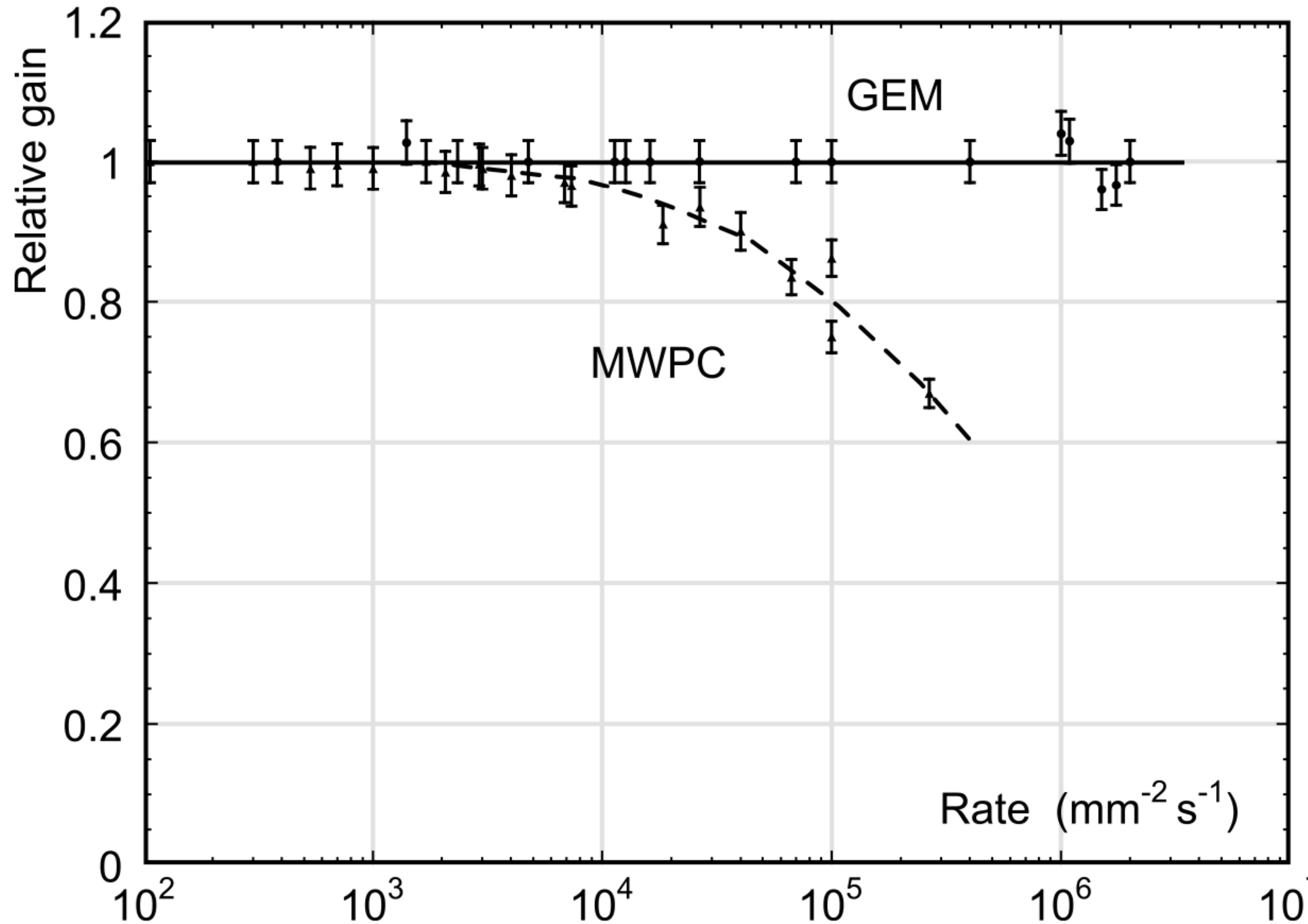



Figure 34.9: Normalized gas gain as a function of particle rate for MWPC [117] and GEM [118].