A TPC with Micromegas-based Readout as the Central Tracker for Future Colliders

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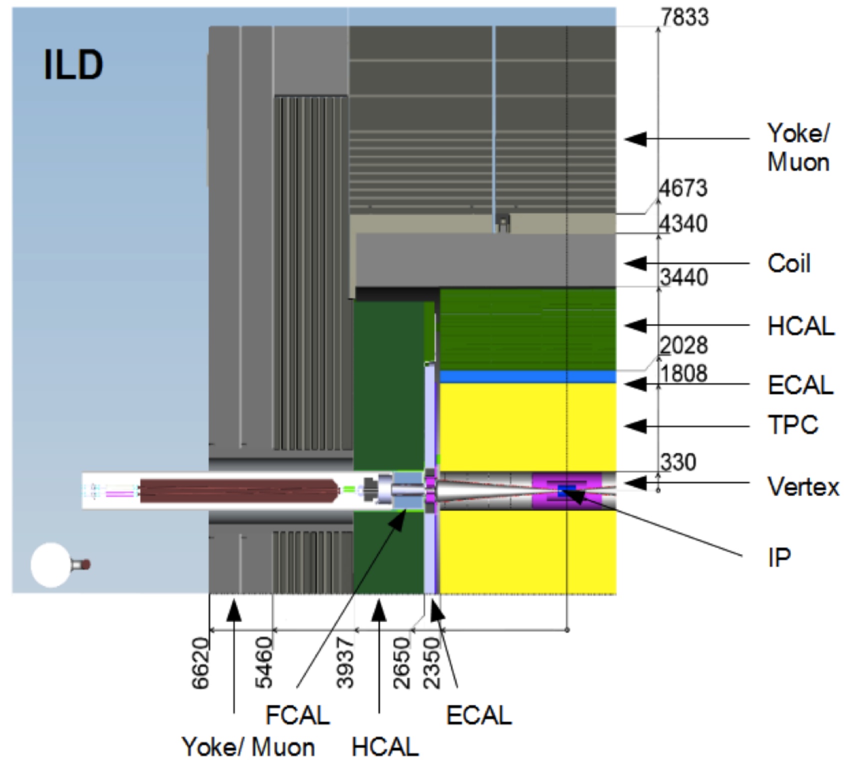
On behalf of LCTPC Collaboration



☞ International Linear Collider (ILC) project in Japan:

- energy range (baseline design): staged project starting at 250 GeV
- ILC is planned with two experiments
- TPC is the central tracker for International Large Detector (ILD)

☞ ILD components:

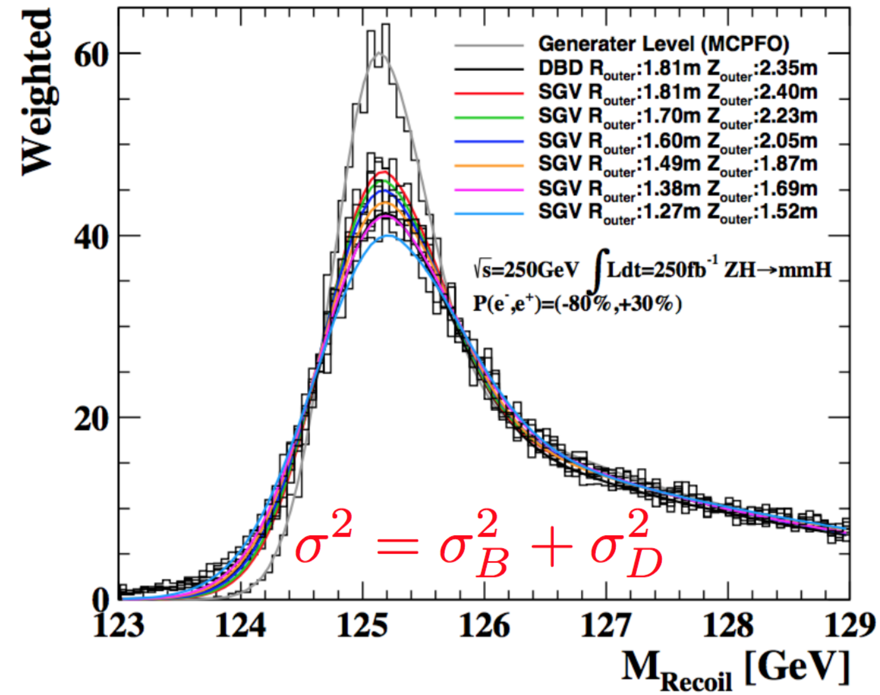
- vertex detector
- few layers of silicon tracker
- **gaseous TPC**
- ECAL/HCAL/FCAL
- superconducting coil (3.5 T)
- muon chambers in iron yoke

☞ ILD requirements:

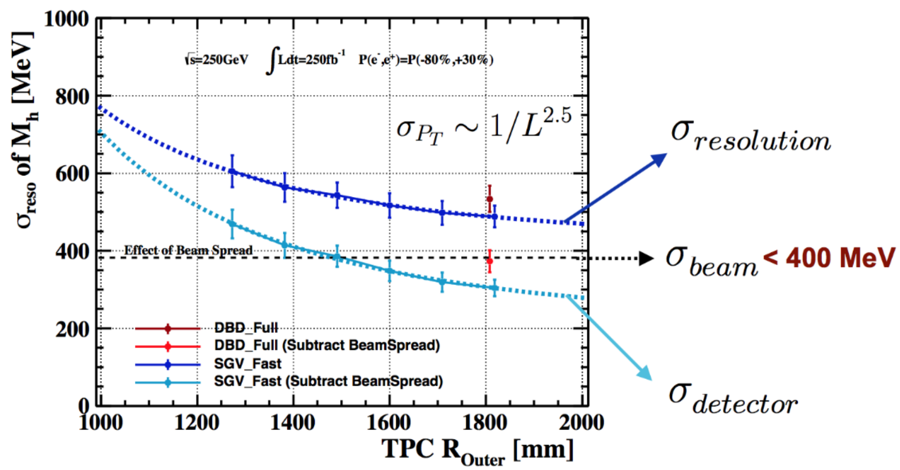
- momentum resolution: $\boldsymbol{\delta(1/p_T) \leq 2 \times 10^{-5} GeV^{-1}}$
- impact parameters: $\sigma(r\phi) \leq 5\mu m$
- jet energy resolution: $\sigma_E/E \sim 3 - 4\%$

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{720}{N+4}}\left(\frac{\sigma_x p_T}{0.3BL^2}\right)$$

- TPC point resolution is x10 worse than Si
  - would need x100 more points
  - not always practical
  - larger tracking volume
  - include 2 inner Si layers (SIT) and 1 outer Si layer (SET)



- **ILC flagship measurement**
  - recoil mass $e^+e^- \to \mathbf{Z(ll)X}$
  - driven by both **beam spread** ($\boldsymbol{\sigma}_{\mathrm{B}}$) and **momentum resolution**($\boldsymbol{\sigma}_{\mathrm{D}}$)
  - → $\boldsymbol{\sigma}_{\mathbf{B}}$ = **400 MeV** from TDR
  - → $\boldsymbol{\sigma}_{\mathbf{D}}$ = **300 MeV** at $R_{out} = 1.8$ m
  - → $\boldsymbol{\sigma}_{\mathbf{D}}$ = **400 MeV** at $R_{out} = 1.4$ m



TPC is the central tracker for International Large Detector (ILD)

- Large number of 3D points ($\sim$ 200)
  - **continuous tracking**
- Particle identification
  - **dE/dx measurement**
- Low material budget in front of the calorimeters (Particle Flow Algorithm)
  - barrel: $\sim 5\% X_0$
  - endplates: $\sim 25\% X_0$
- **Two gas amplification options:**
  - **Gas Electron Multiplier (GEM)**
  - **MicroMegas (MM)**
    - → pad-based charge dispersion readout
    - → direct readout by the TimePix chip

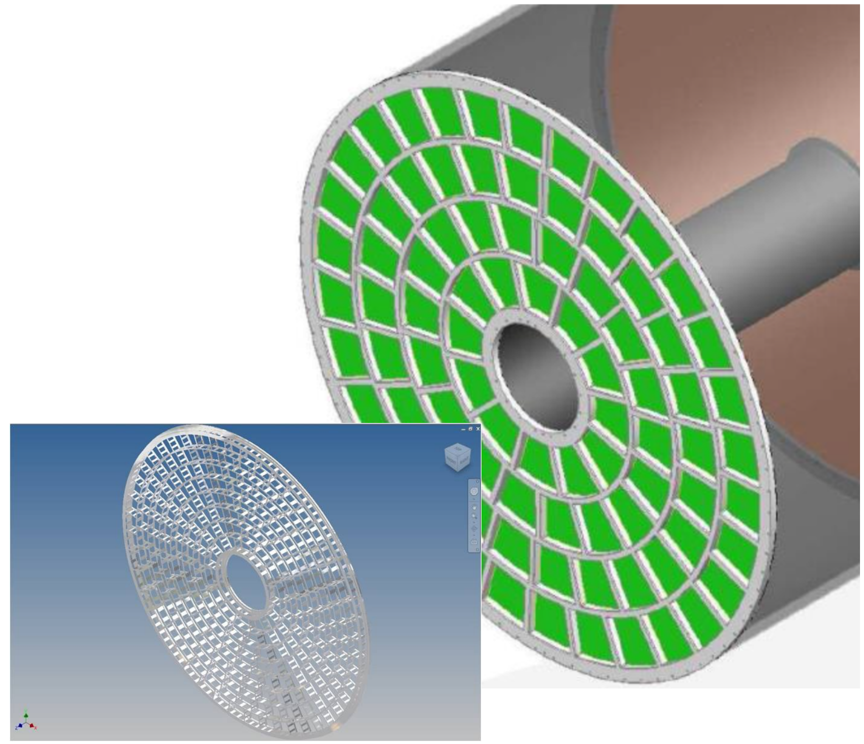
- **TPC Requirements in 3.5 T**
  - **Momentum resolution:**
    - → $\delta(1/p_T) \leq 9 \times 10^{-5} \mathrm{GeV}^{-1}$
  - **Single hit resolution:**
    - → $\sigma(r\phi) \leq 100\mu\mathrm{m}$ (overall)
    - → $\sigma(Z) \simeq 400\mu\mathrm{m}$ at z=0
  - **Tracking efficiency:**
    - → 97% for $p_T \geq 1\mathrm{GeV}$
  - **dE/dx resolution:** 5%

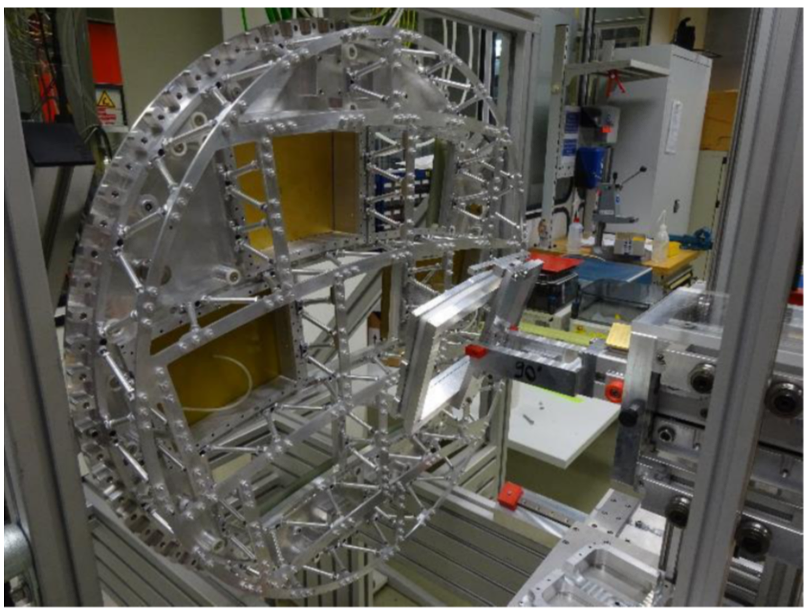
Large Prototype and TPC Mechanics

☞ **Gravitational loads:**

- self-weight of structure: 895 kg
- weight of modules: 1176 kg
  - → 84 modules
  - → 7 kg/super-module (4-ring)
  - → endplate
- total weight 2000 kg

8-ring: 4 modules combined in 1 super-module

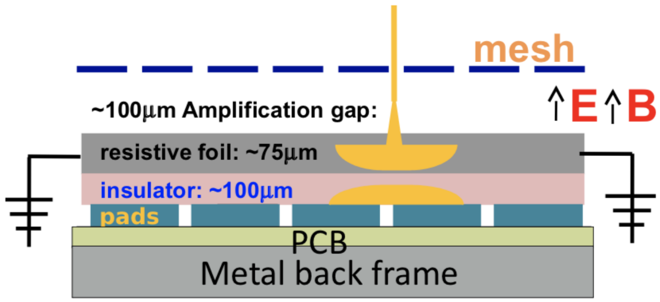




LP endplate with 7 windows to receive up to 7 fully equipped identical modules

ILD TPC is 3.5x size/B field of the Large Prototype (LP) operating in B=1 T

- Pad size limits transverse resolution
  - use resistive anode to spread charge

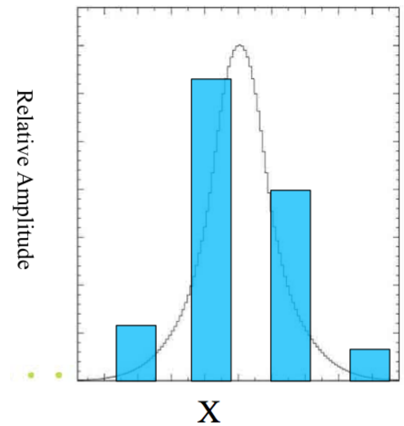


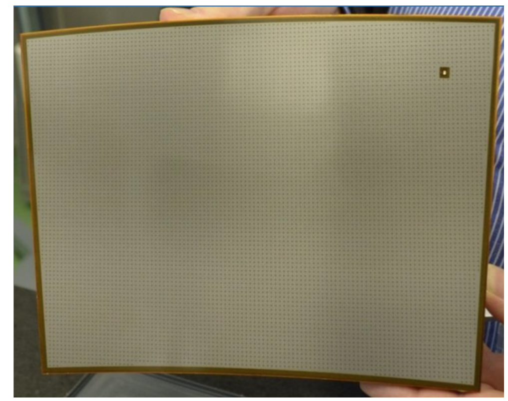
- Charge density function of time dependent charge dispersion on 2D continuous RC network:

$$\rho(r,t) = \frac{RC}{2t}\exp\left[-\frac{-r^2RC}{4t}\right]$$

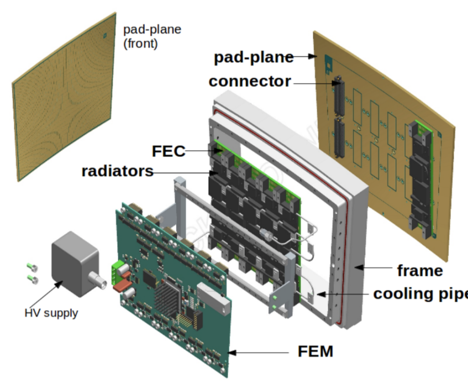
R- surface resistivity
C- capacitance/unit area

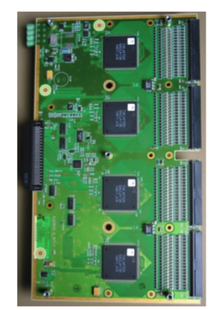
Relative fraction of charge seen by pads fitted by Pad Response Function (PRF)





- **Module**
  - Module size: 22 cm × 17 cm
  - 24 rows × 72 columns **(1726 Pads)**
  - **Pad size: 3 mm × 7 mm**

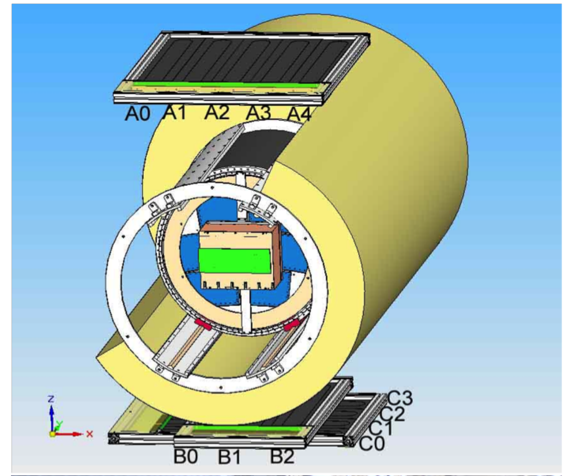




Module readout with 6 FE cards bearing 4 AFTER ASICs chips (12-bit ADC)

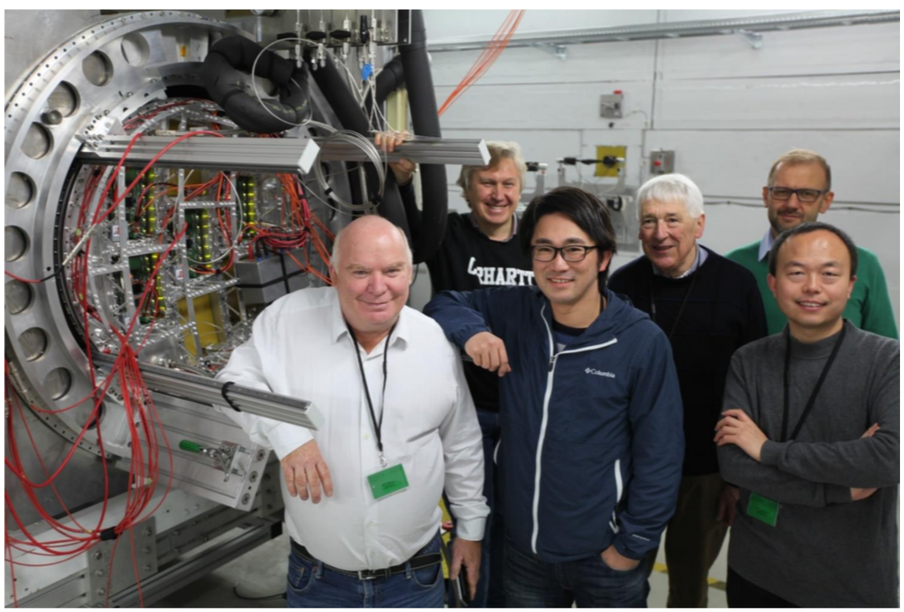
The test beam facility at DESY provides a 6 GeV electron beam

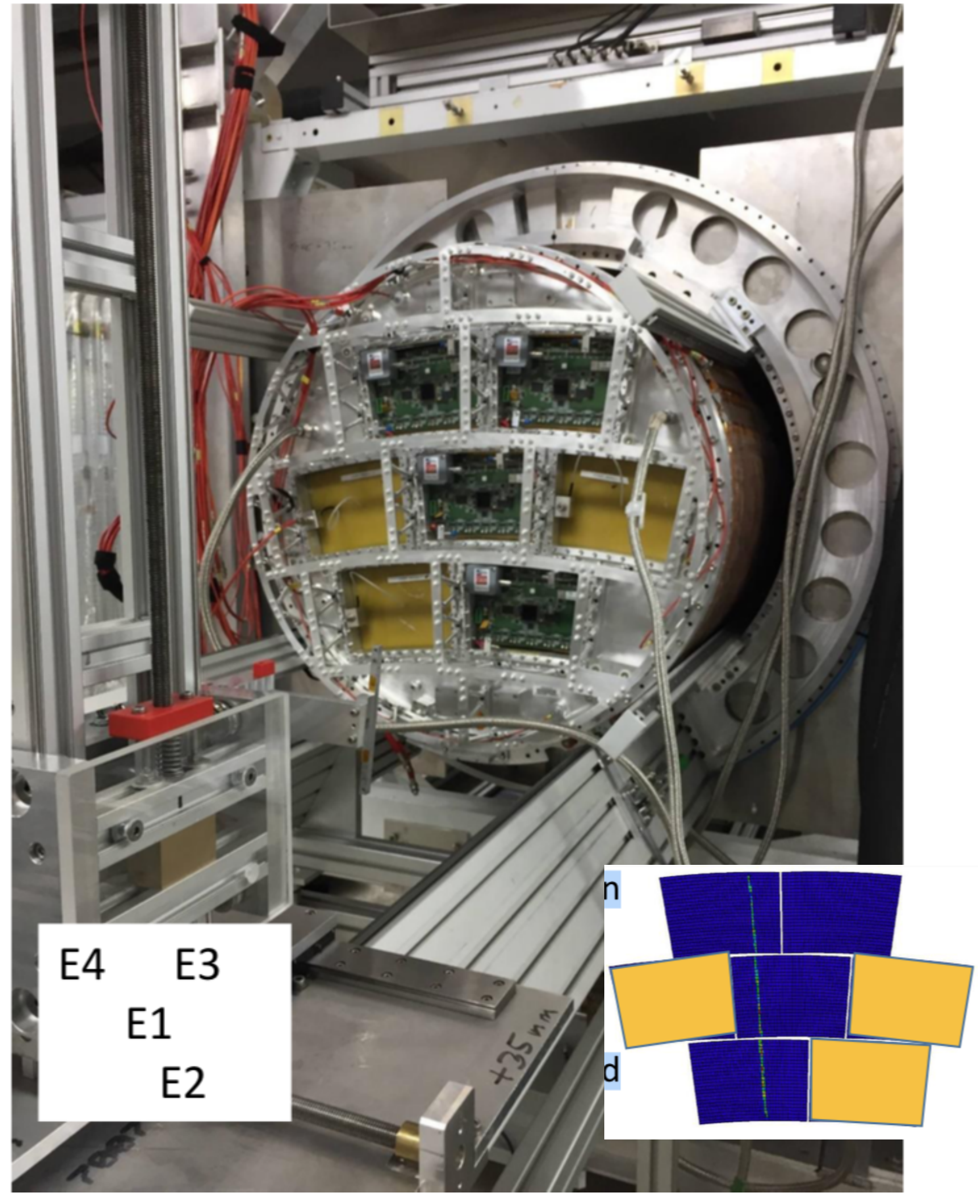
- **Beam, Laser, and Cosmic** triggers are deployed
  - **A cosmic trigger based on**
    - 12 scintillator plates
    - readout by silicon PMs
    - SiPM signal discrimination and coincidence logic with NIM modules
- **Readout system and DAQ**
  - *120 Hz maximum event taking rate*
    - 6 ASICs chips are digitized in parallel by 12-channel ADC
    - 4 sequential iterations are needed to readout a whole module
    - irreducible dead-time of **8 ms**



☞ **4 new Micromegas modules tested in November 2018 at DESY facility (NIM paper)**

- new endplate LP2
- 1-loop 2-Phase CO_2 cooling
- improved mechanics: 99.9% good connections
- **new grounding scheme:** encapsulated resistive anode

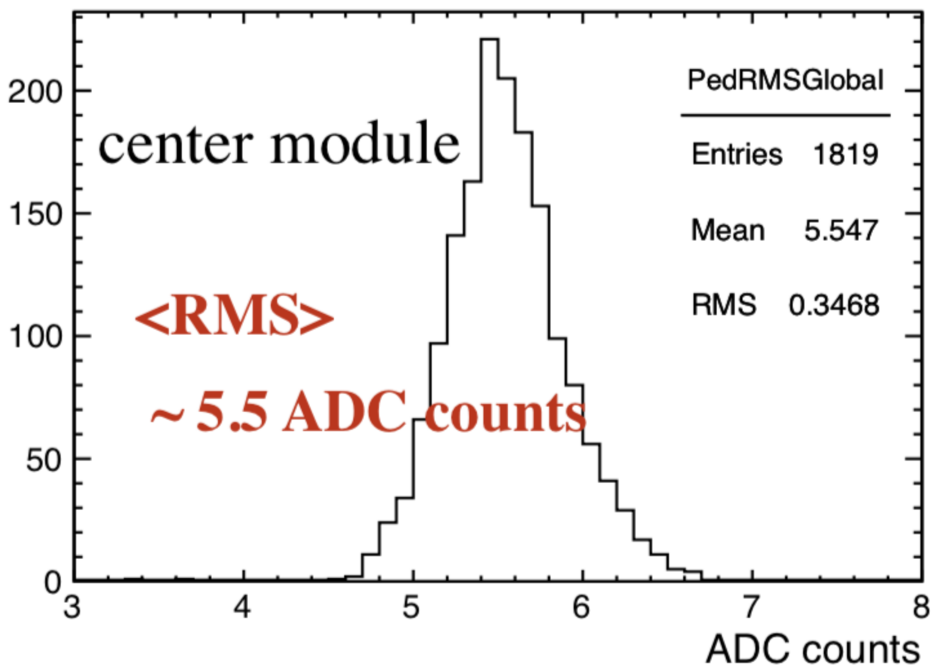




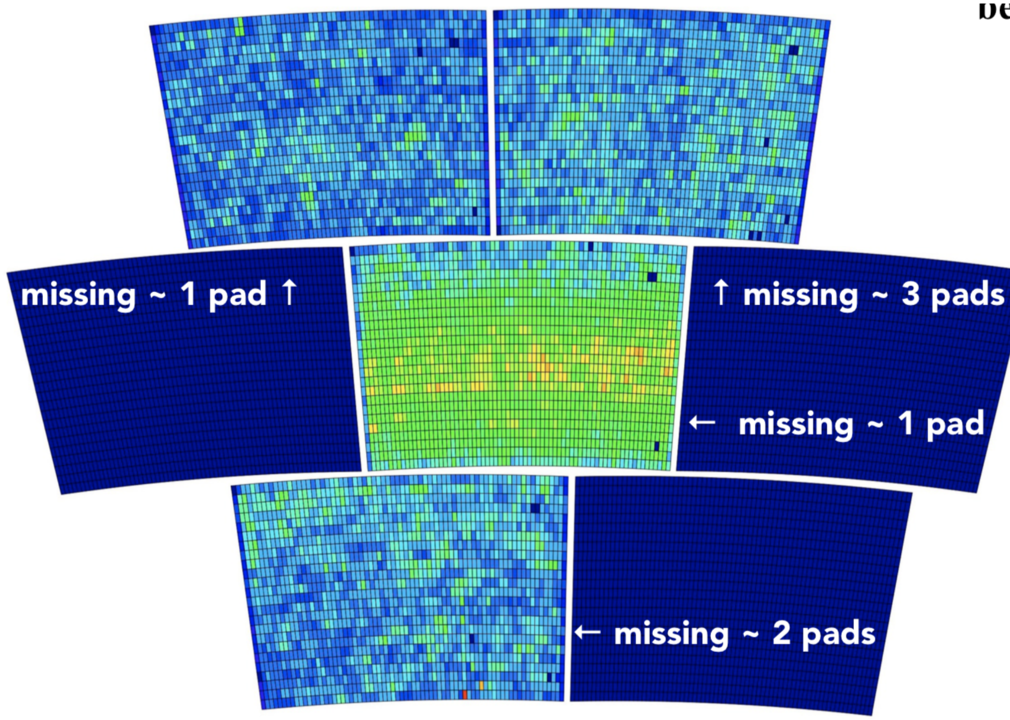
Measure the quality of connection from pedestal rms and occupancy

- ☞ Due to error in electric circuit **2 pads** in each module are missing
  - ➠ can be fixed in next production
- ☞ **1-4 missing pads** in each module due to bad pins in connector

Pedestal measured in B=1 T

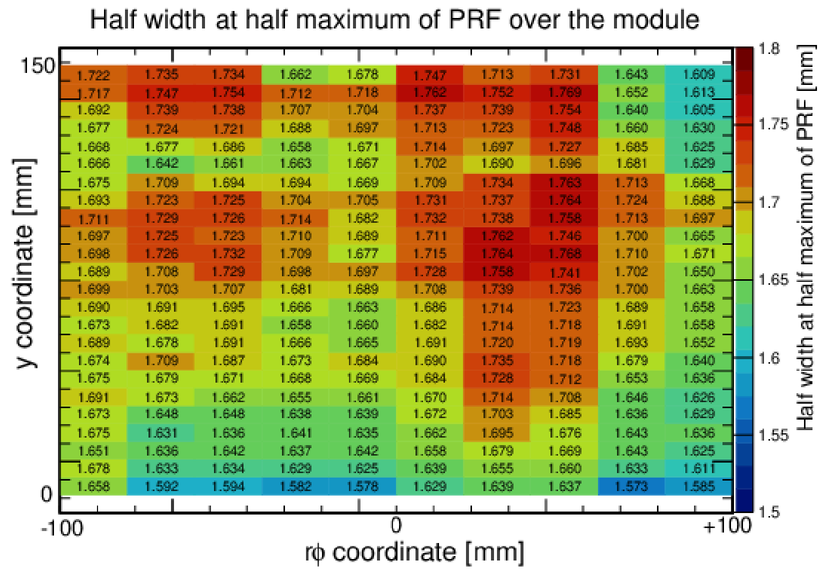


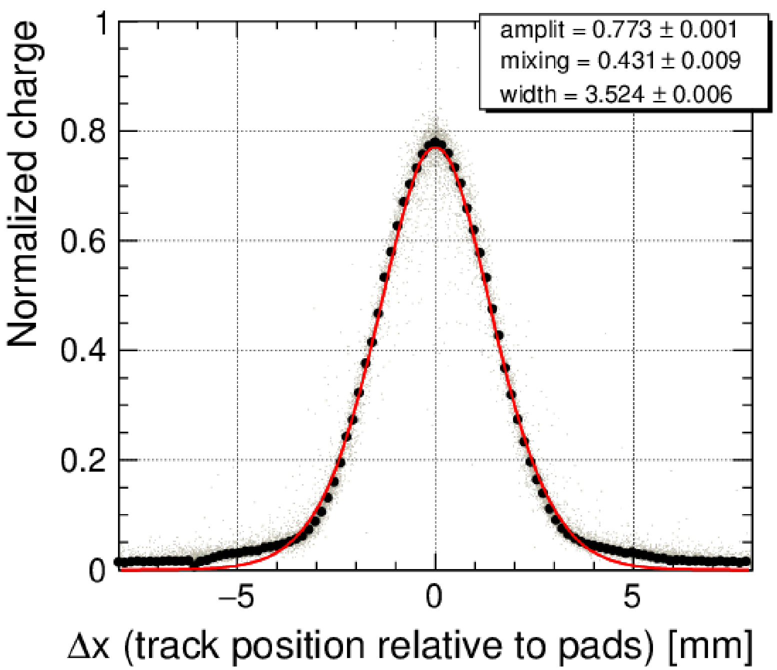
Measured occupancy from accumulated cosmic ray events



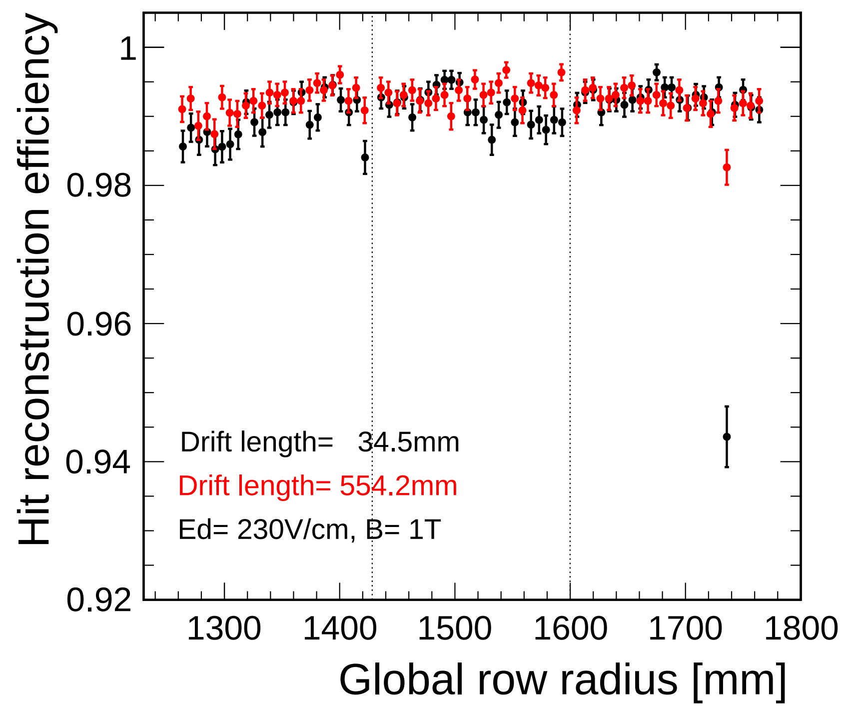
Very good electrical connection between pads (PCB) and FEC (99.9%)

- ☞ Calibration of the **Pad Responce Function (PRF)** is done for each z position
  - ➠ $\sigma \sim \mathbf{1.4mm}$ is expected for
    - ➔ R=2.5 $\mathrm{M}\Omega/\Box$
    - ➔ 200 ns shaping time
    - ➔ 200+50μm kapton





50 mm drift distance



The resolution is determined from the same statistical sample utilized for the track fit

☞ The geometric mean of inclusive and exclusive residuals in the entire 3D track fit provides unbiased resolution estimator [R.Carnegie, et.al., NIM **A538** 372 (2005)]

$$\boldsymbol{\sigma}_{\mathrm{i}} = \sqrt{\boldsymbol{\sigma}_{\mathrm{in}} \cdot \boldsymbol{\sigma}^{\mathrm{i}}_{\mathrm{ex}}}$$

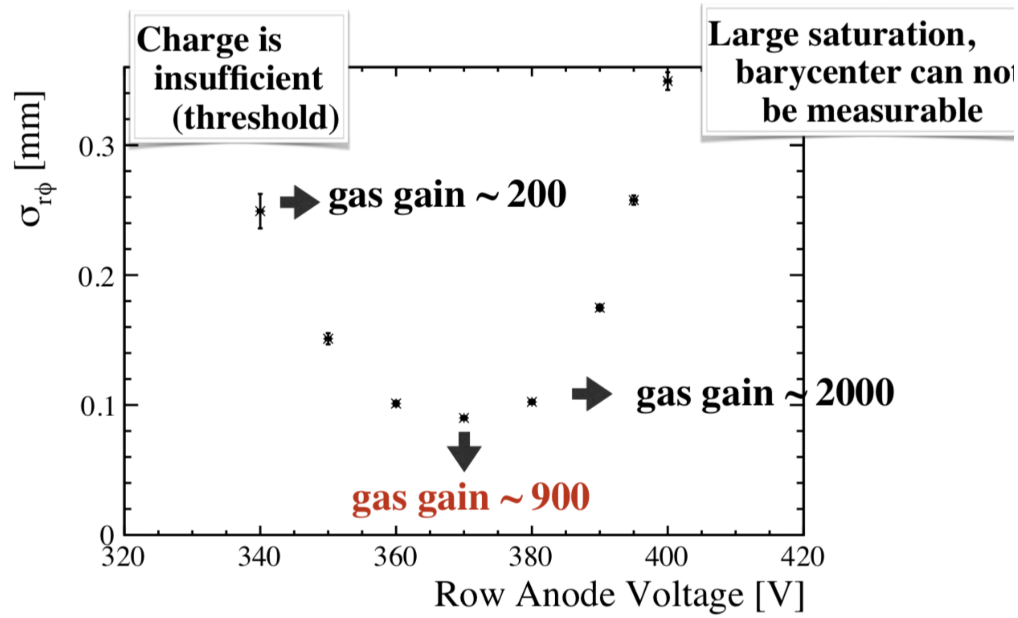
$$\sigma = \mathbf{x}_{\mathrm{track}} - \mathbf{x}_{\mathrm{hit}}$$

☞ Important requirements for σ_{i}:

- **gaussian-like**
  - ➔ low fraction of outliers
- **zero off-set**
  - ➔ systematic error

$\sigma_{r\phi}$ as a function of anode voltage (amplification):

find $\mathrm{V}_{\mathrm{mesh}} = 370\mathrm{V}$ to be optimal



☞ **Corrections to be applied**

- **bias:** determined by local RC properties
- **distortions:** driven by ExB effects
- **alignment:** measure with B=0 T data

The readout modules of the prototype operate in a 1 T magnetic field

☞ The performance is estimated solely using the **central module**

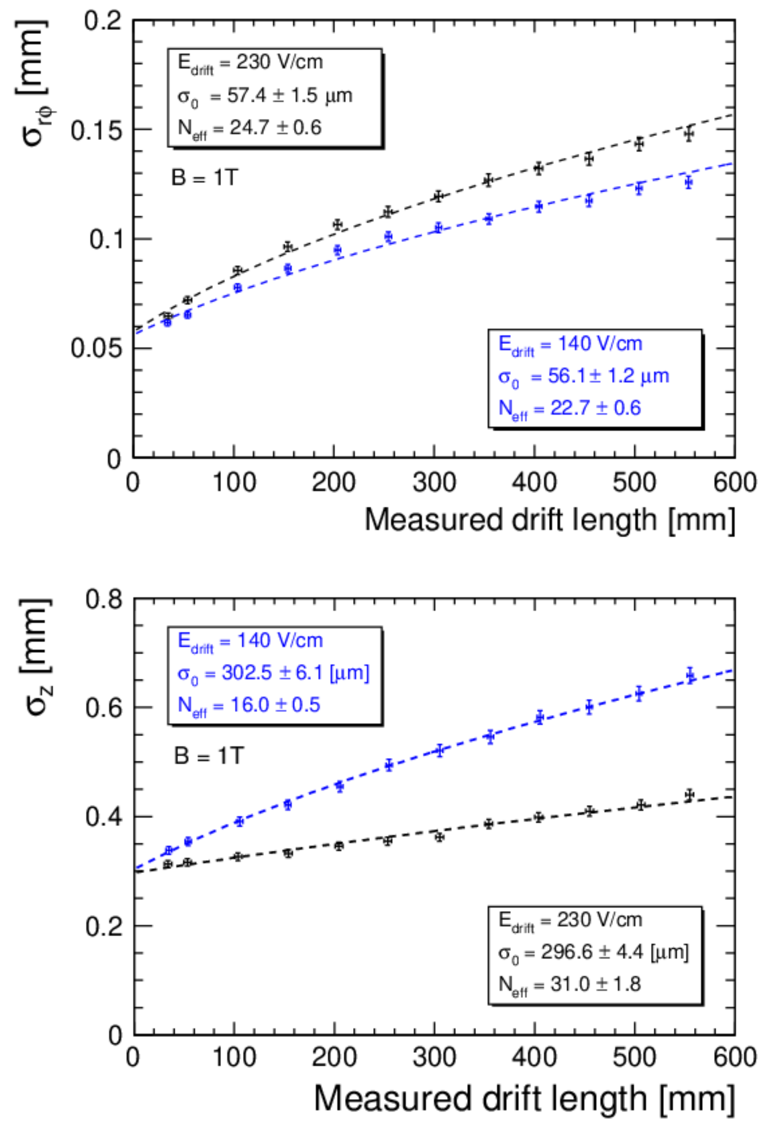
➠ a few pad rows on lower and upper modules exhibit degradation due to misalignment of electrods inside the field cage and the inhomogeneity of the resistive anode

☞ **Fit data with:**

$$\boldsymbol{\sigma^2_{r\phi/z}(z) = \sigma^2_{r\phi 0/z0} + \frac{D^2_{\perp/\parallel}}{N_{eff}} z}$$

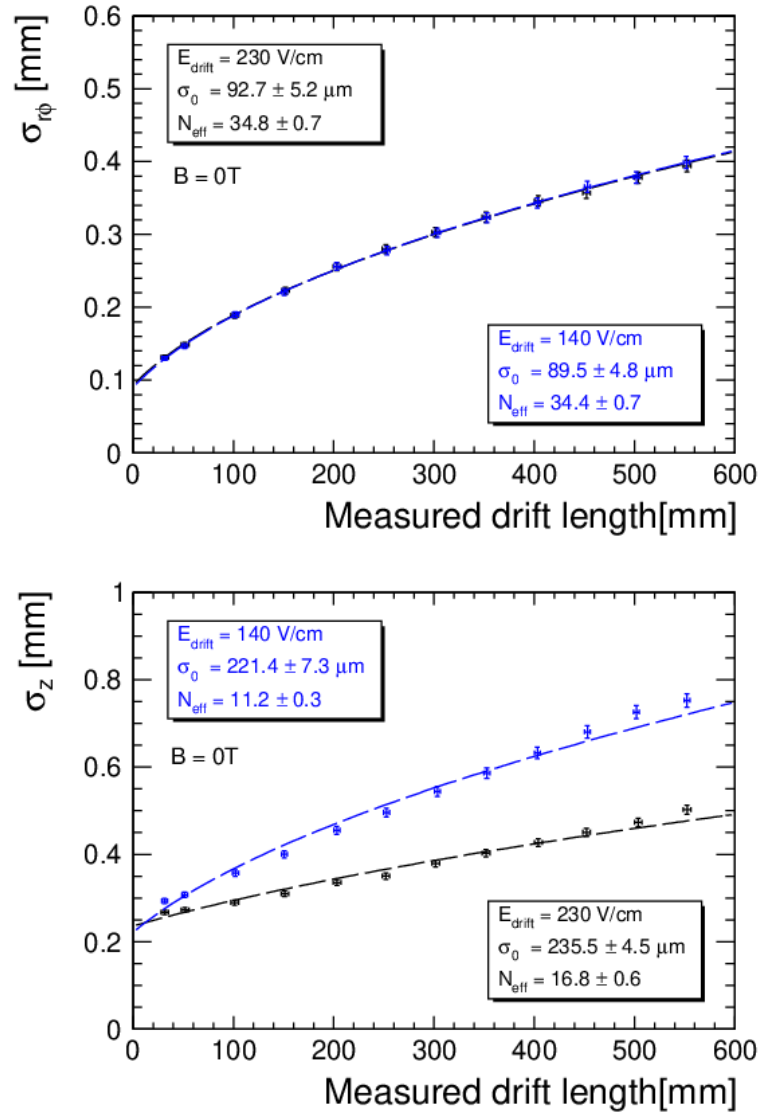
➠ σ_0 - the resolution at $z = 0$,
N_{eff} - the effective number of electrons

➠ Magboltz calculations yield $D_{\perp/\parallel}$ with approximately 3% precision



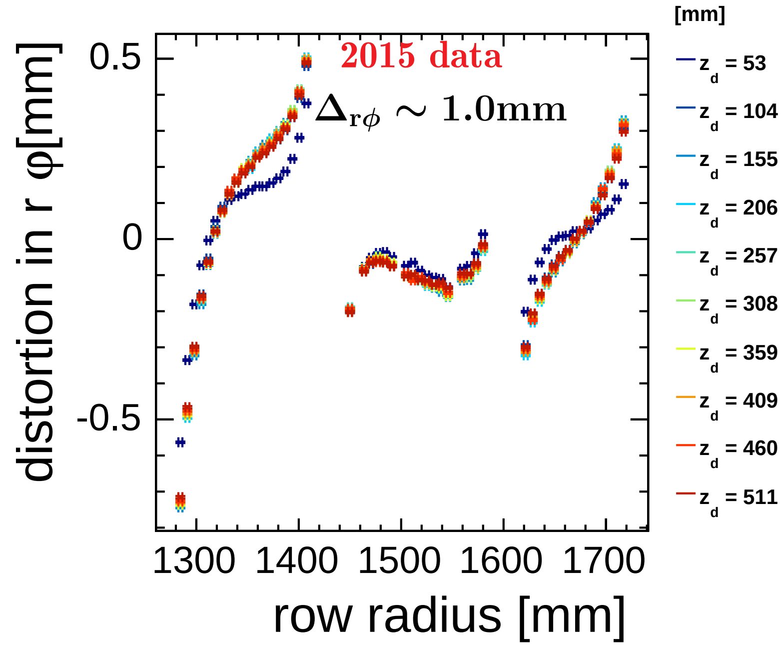
Data recorded at a 0 T magnetic field are essential for computing the alignment parameters of the modules

- A straight line is used as the track model
- Alignment primarily relies on data satisfying stringent track quality criteria at B=0 T
  - iteratively minimize the χ^2 addressing **rotations and translations** of the modules, with the central module serving as a reference
  - iterative procedure continues until the parameters fall withing their uncertainties
  - achieve convergence of all alignment parameters after **four iterations**

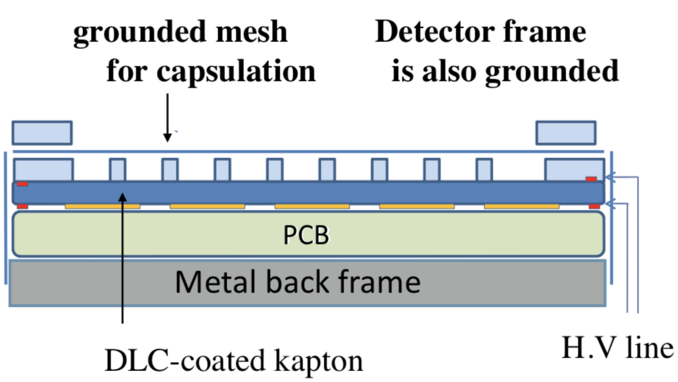


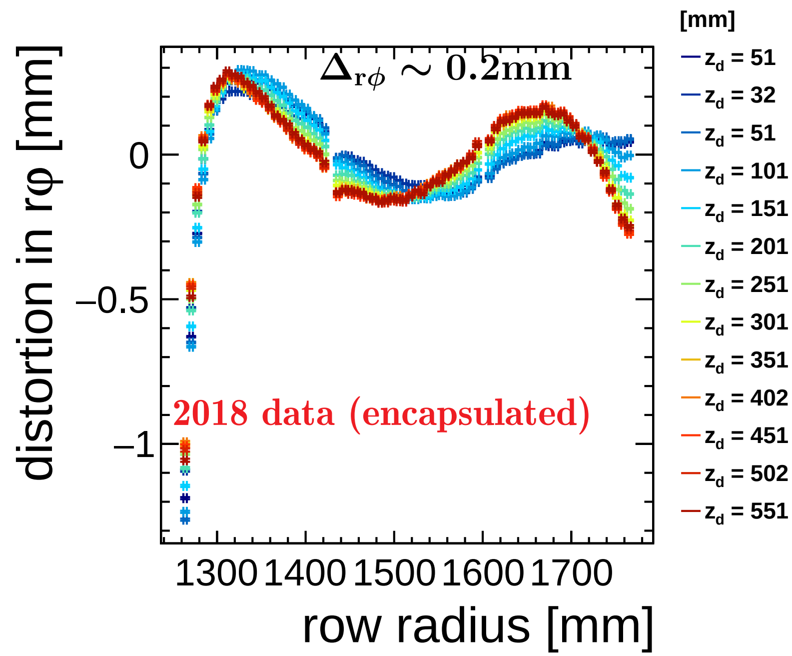
Non-uniform E-field near module boundaries induces ExB effects

- Track distortions in standard scheme
  - reach about 0.5 mm at boundaries
  - worth to minimize at design level
  - accounted as systematic error

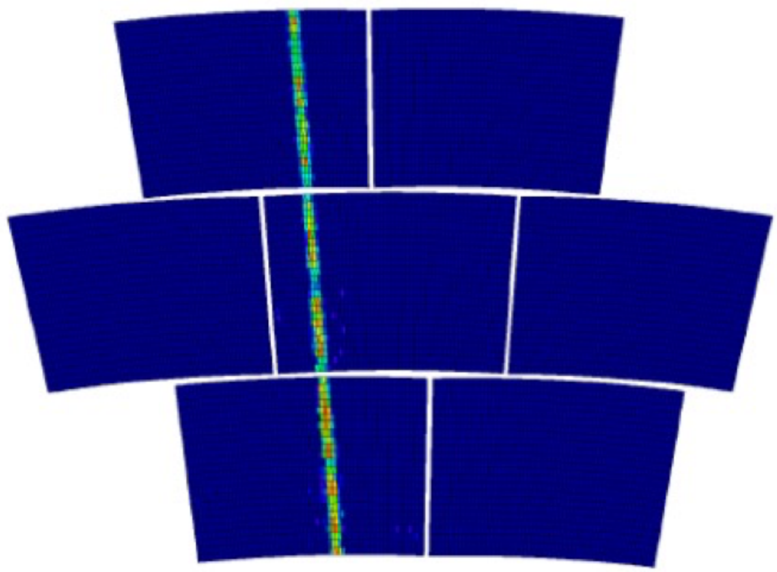


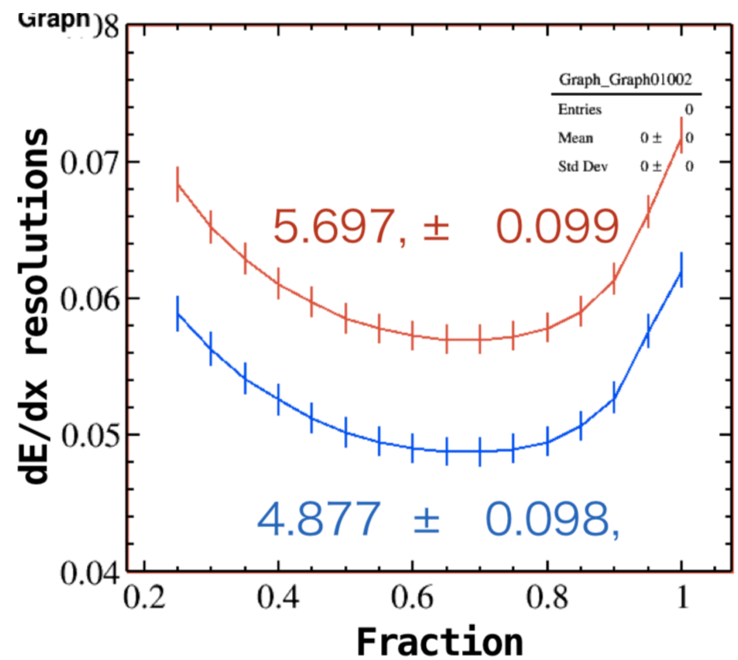
- **Encapsulated scheme (2018)** to reduce distortions at the edges of modules
  - mesh at ground (same as the frame)
  - resistive anode at the +ve HV





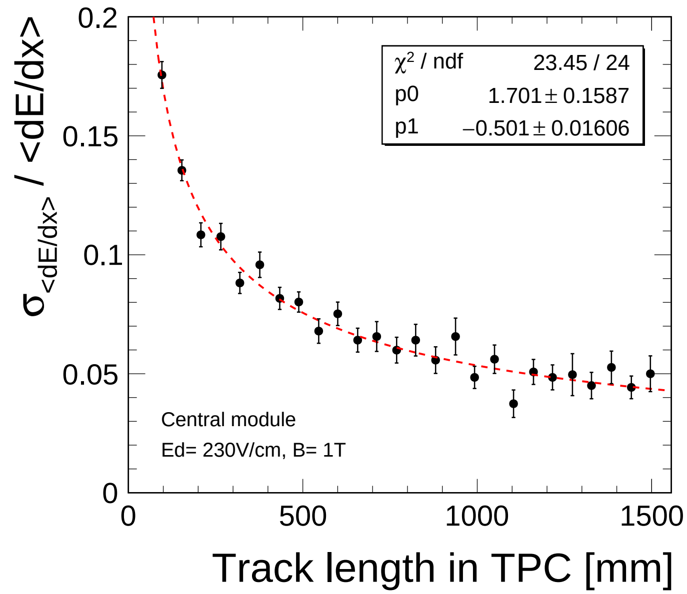
ExB effect between modules is effectively suppressed in the new scheme





Measuring dE/dx resolution with LP and extrapolating to ILD TPC

- Test arbitrary track lengths by randomly combining hits from several real tracks to create a pseudo track in the TB setup
- Estimated dE/dx resolution using a **70% truncated mean** for the ILD TPC
  - $\sigma_{\mathrm{dE/dx}} = 4.9\%$ for 192 hits (large ILD)
  - $\sigma_{\mathrm{dE/dx}} = 5.7\%$ for 144 hits (small ILD)



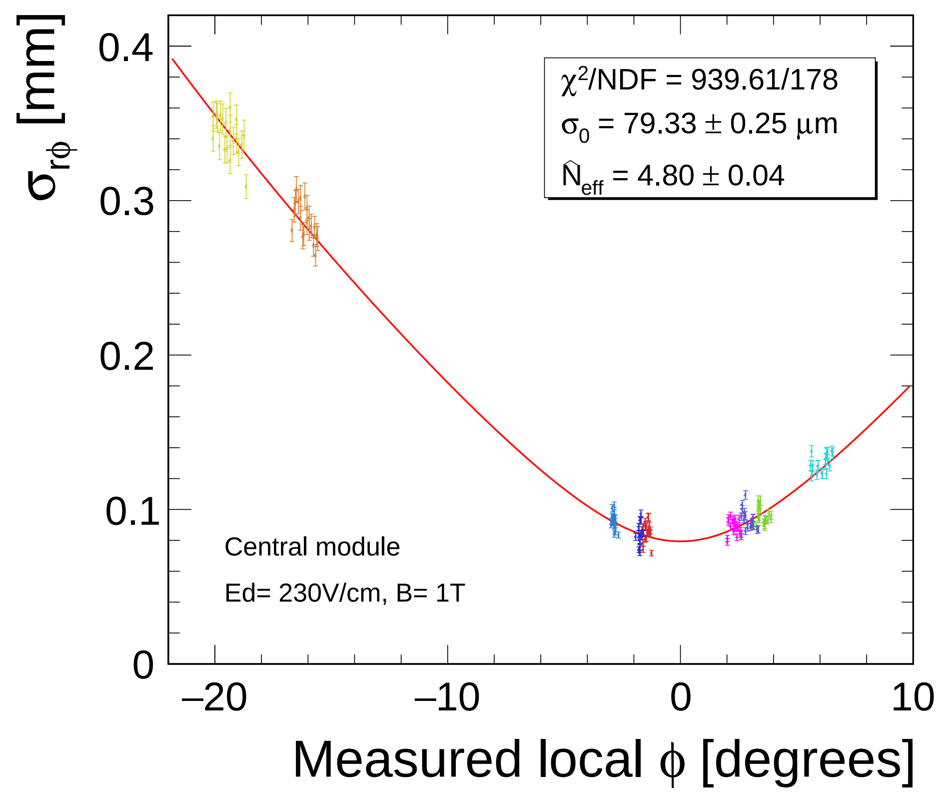
The primary goal is to achieve the utmost point resolution for radial high-momentum tracks emenating from the Interaction Point (IP)

- Resolution degrades with deviation from 0 of the local angle between pad axis and track (ϕ), due to fluctuations in cluster size during ionization
- Conducted the experiment with the TPC azimuthally rotated $[-20°, +10°]$
- Contribution from track angle effect:

$$\sigma^2_{r\phi} = \sigma^2_{r\phi 0} + \frac{h^2 \tan^2\phi}{12} \cdot \frac{\cos\phi}{\hat{N}_{\text{eff}}}$$

$\hat{N}_{\text{eff}} \simeq 5.1$ is expected for h=7 mm

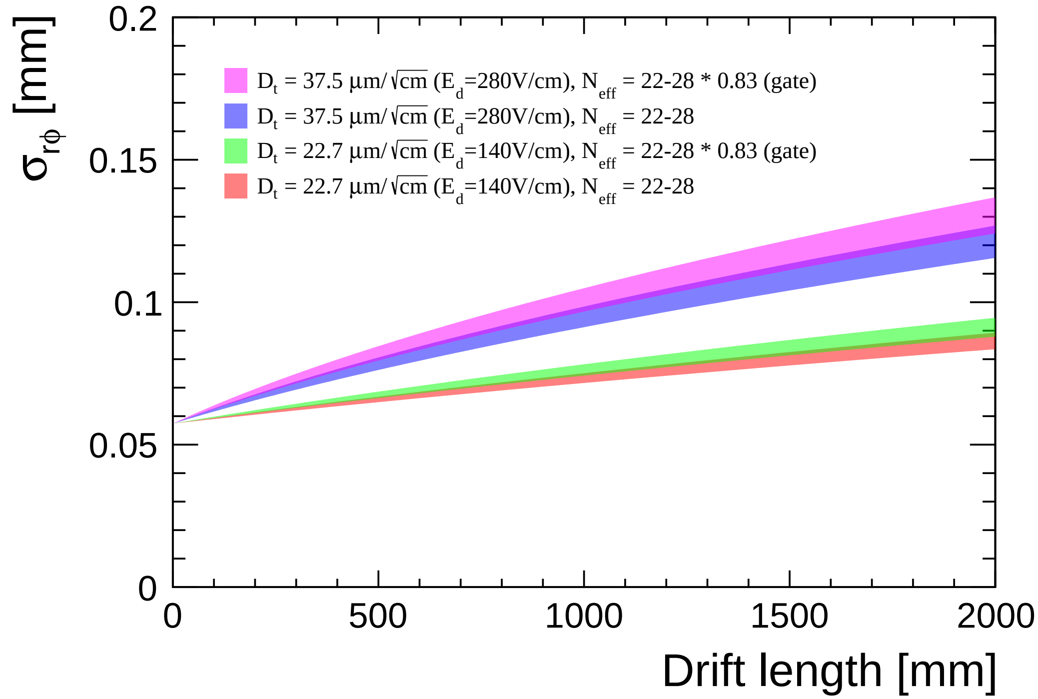
[*M. Kobayashi, et al.*, **NIM A (764), 394**]



Each data point corresponds to a distinct pad row, with a fixed drift distance of 50 mm

Extrapolation of resolution for a magnetic field of 3.5 T and 2.35 m drift length (ILD design) relies on a simple empirical function

- **Transverse diffusion $D_{\perp}$** is determined using a Magboltz simulation
- Values for $\boldsymbol{\sigma_{r\phi 0}}$ **and** $\boldsymbol{N_{\rm eff}}$ are derived from the fit to the measured resolution
- Impact of the dynamic gate using a large apperture GEM is demonstrated with an electron transmission of 83% [*M. Kobayashi, et al.,* **NIM A (918), 41-53**]
  - ➠ insights into the perspectives for **TPC at circular colliders** will be presented in **P. Colas talk**



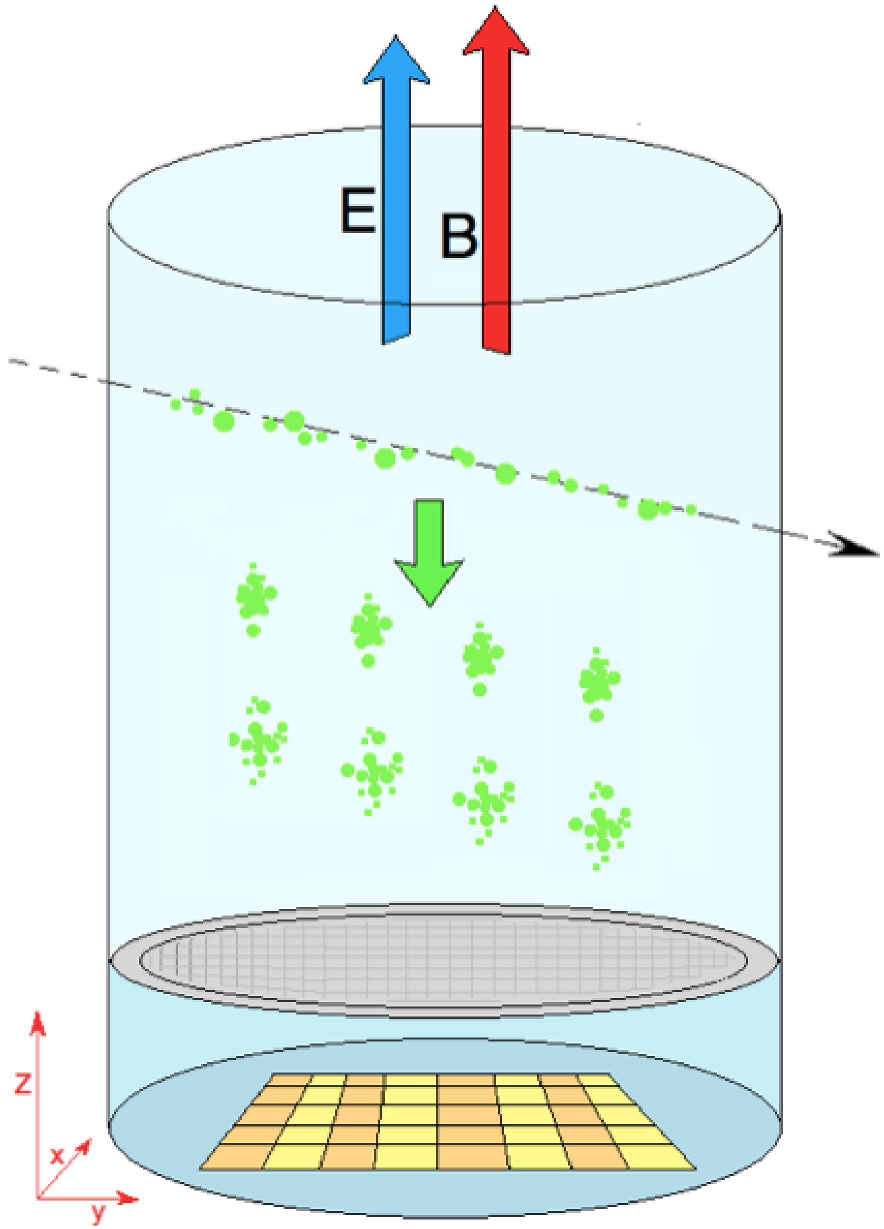
Resolution of about 100μm across the entier drift length in the ILD TPC is feasible when stringent control is maintained over gas quality, and impurities are minimized.

- **Extensive R&D work has been undertaken for the Micromegas-based readout prototype modules, marking a crucial phase in engineering toward the final design of a TPC for ILD**
- Comprehensive test of the Encapsulated Resistive-Anode with the grounded mesh scheme of the Micromegas detector performed with a 5 GeV electron beam, demonstrates excellent performance
  - $\sigma_{r\phi}$ at $z = 0 \simeq 60\mu m$ and $\sigma_{r\phi} \leq 100\mu m$
    σ_z at $z = 0 \simeq 200\mu m$ and $\sigma_z \leq 400\mu m$
  - field distortions near the edges, resulting from the ExB effect showed a notable reduction compared to the standard scheme.
- **The Encapsulated Resistive-Anode Micromegas detector meets the performance requirements for the central tracker of ILD**
  - NIM paper summarizing comprehensive results from the beam test for the Micromegas prototypes is imminient

Backup

A Time Projection Chamber (TPC) is a detector consisting of a cylindrical gas chamber and a position sensitive readout endcaps

- **The TPC acts as a 3D camera taking a snapshot of the passing particle**
- **Transverse and Longitudinal** resolutions are major characteristics of the TPC
  - **XY position:** charged particles ionize the gas, a longitudinal electric field causes ionization e^- to drift towards endcap where they are detected (transverse resolution)
  - **Z position:** measure time between ionization and detection multiply by drift velocity (longitudinal resolution)



☞ Technology choise for TPC readout: **Micro Pattern Gas Detector (MPGD)**

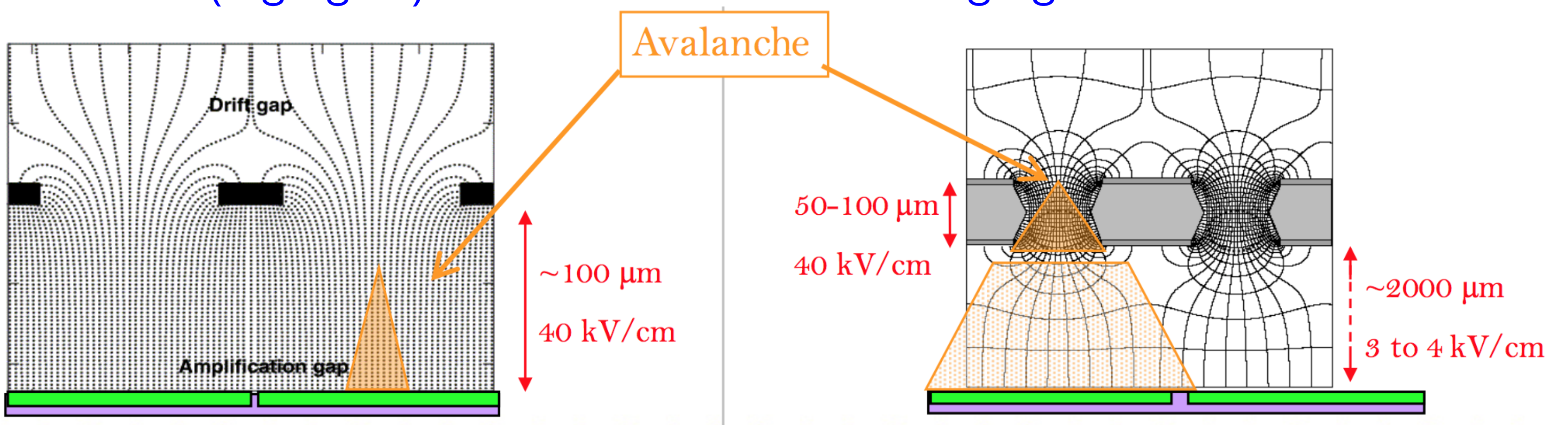
- **no ExB effect, better ageing, low ionback drift**
- easy to manufacture, MPGD more robust mechanically than wires

☞ **Resistive Micromegas (MM)**

- MICROMEsh GAseous Structure
- metalic micromesh (pitch ∼50 μm)
- supported by 50 μm pillars
- multiplication between anode and mesh (high gain)

☞ **GEM**

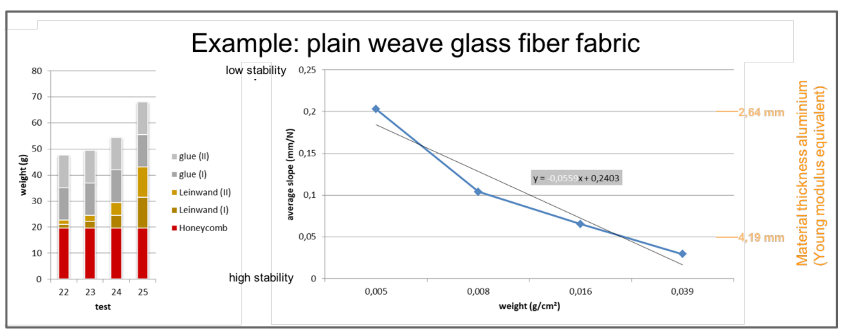
- Gas Electron Multiplier
- doublesided copper clad Kapton
- multiplication takes place in holes,
- 2-3 layers are needed to obtain high gain



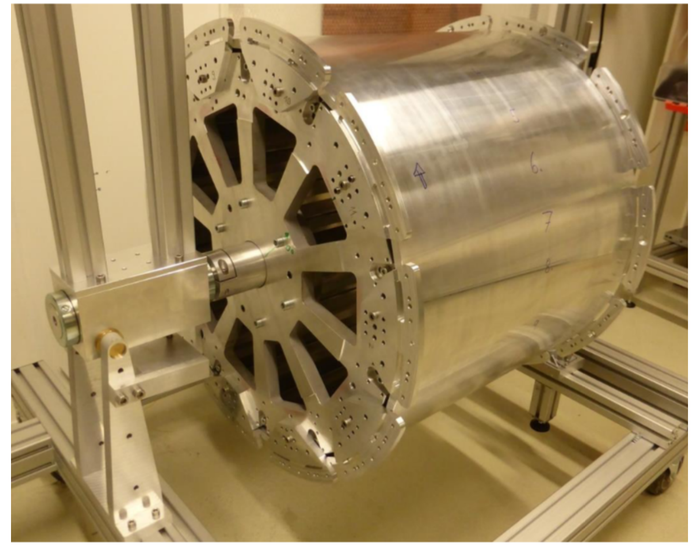
Discharge probability can be mastered (use of resistive coatings, several step amplification, segmentation)

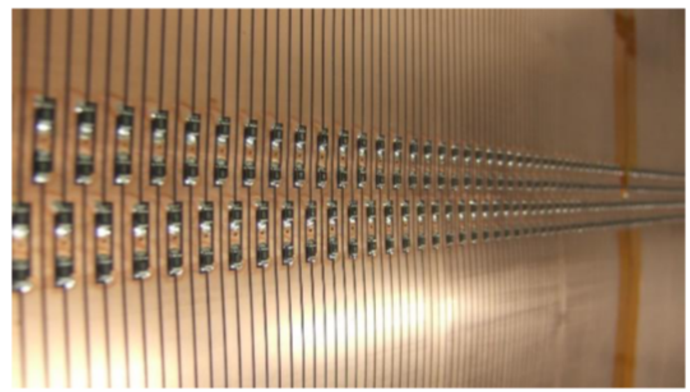
TPC Field Cage

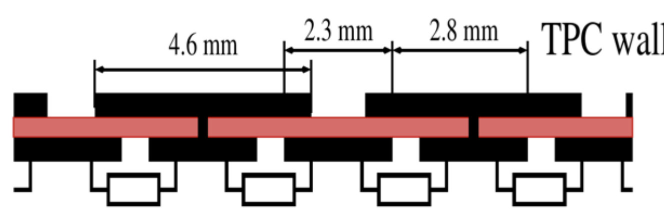
- ☞ **Overpressure 3 mbar**
  - ➠ pressure applied on the cage
  - ➠ forces applied on each endplate with the pressure on modules
- ☞ **Requires a mandrel**
  - ➠ to shape the composite material (Kapton with copper strips)
  - ➠ to install flanges
- ☞ **Field cage V2** of LP under development
  - ➠ studies different wall structures ongoing
    - ➔ glass fibers, glue, honeycomb



V2 TPC Large Prototype (LP)







TPC Mechanical Precision/Alignment

Required resolution

- electric field homogeneity: $\Delta E/E \leq 10^{-4}$
- mapping of B field to 10^{-4}
- high precision/stability of TPC field cage

Large prototype (B=1 T):

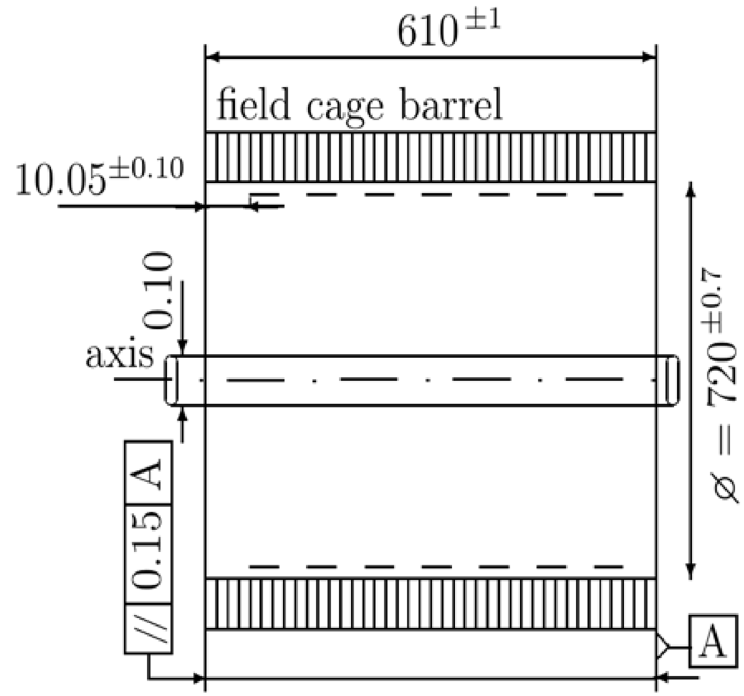
- axis alignment $\leq 0.1\text{mm}$
- cathode/anode $\| \leq 0.15\text{mm}$
- max. bending $\perp$ to Z (middle): $\sim 0.02\text{mm}$
- less critical: length to 1mm and $\varnothing$ to 0.7 mm

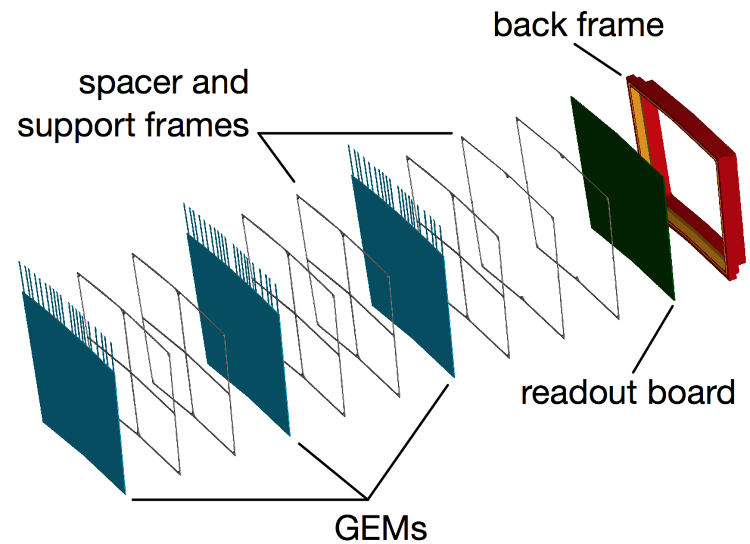
ILD TPC (3.5x size/B field):

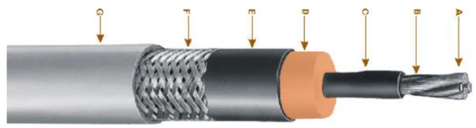
- axis alignment $\leq 0.3\text{mm}$
- cathode/anode $\| \leq 0.45\text{mm}$

Precise alignment of readout structures

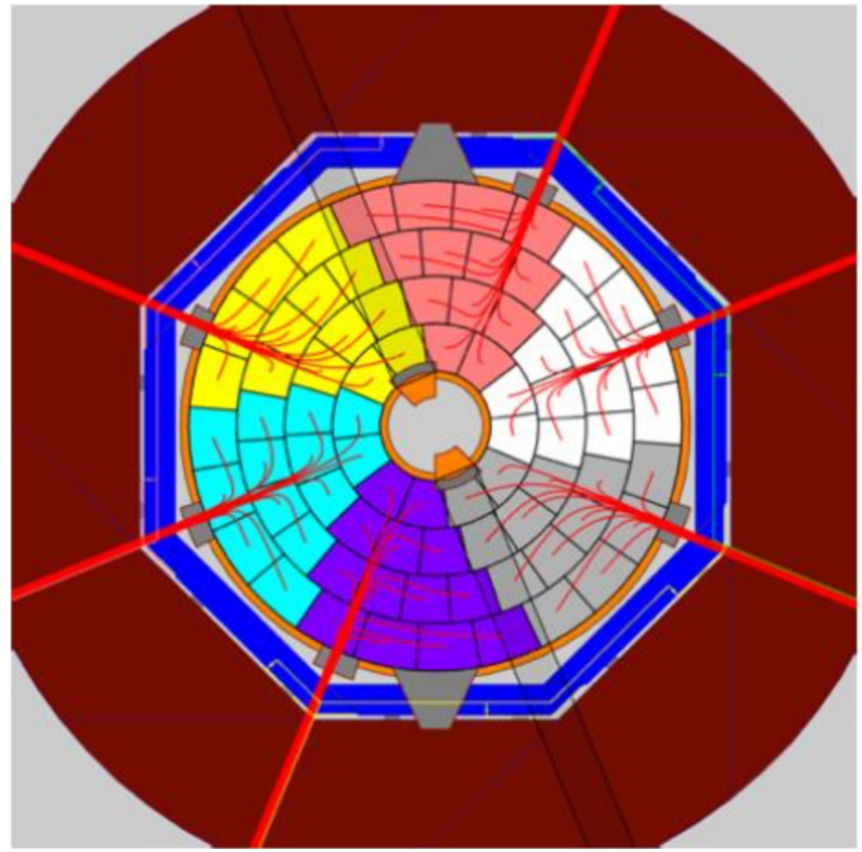
- all parts produced to a precision $\mathcal{O}$(0.05 mm)
- stable aluminum backframe
- well established with Millepede II (test beam)







Patch panels on each sector to allow disconnecting the TPC



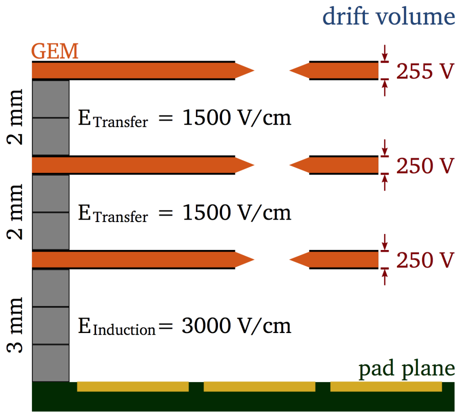
- **Very High Voltage for the central cathode:**
  - very big cable (insulation)
  - curvature radii 70mm to 280mm
- **Low-voltage power:**
  - bundles of 10 copper cables
  - 6mm^2 section (32 A)
  - 6 sectors per end-plate:
  - 120 cables, 12kW(100 W per cable)
  - 20 m cables (R=0.06 Ω) $\rightarrow$60 W loss (60% of the useful power)

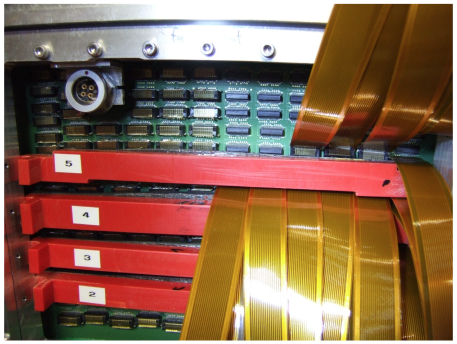
    ➔ cable cooling? DC-DC converters?

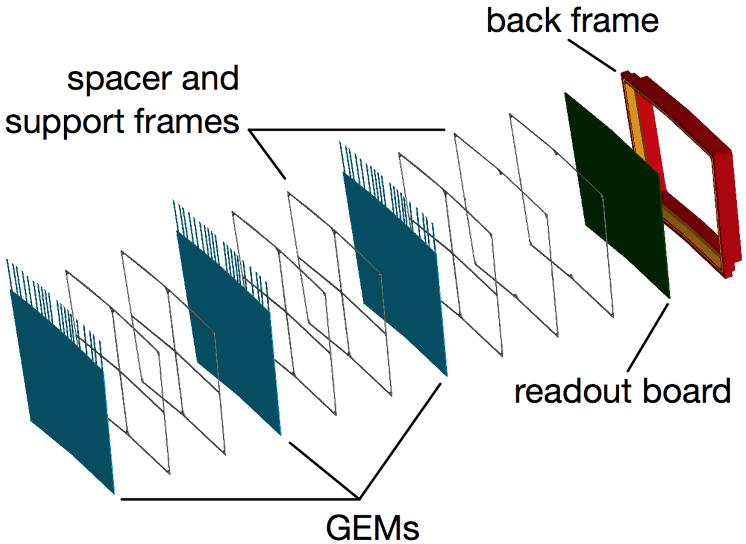
Detector HV and fibres for readout are less demanding

Possibly need a jacket against heat from the ECAL

Triple GEM Modules



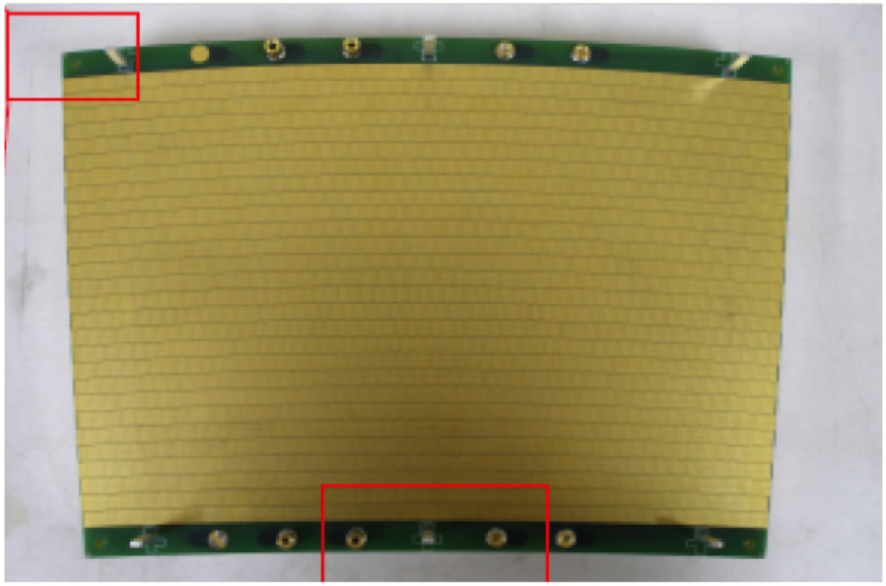


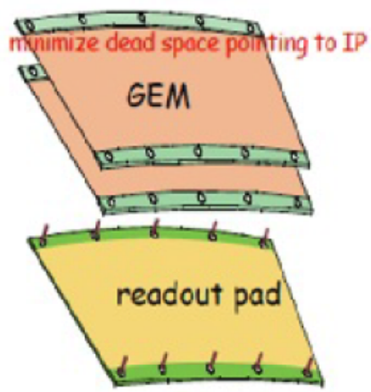


☞ **GEM: modified ALTRO readout**

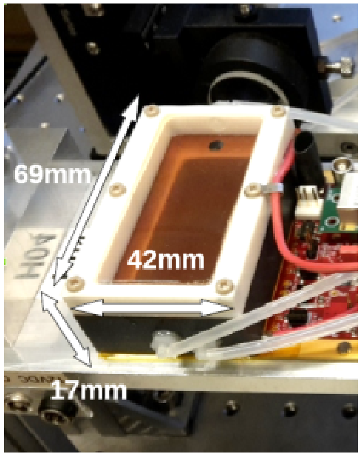
➠ 16-channel ALTRO chip (10-bit)

Double GEM Modules

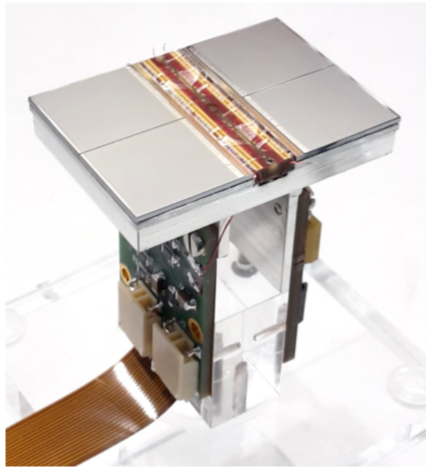




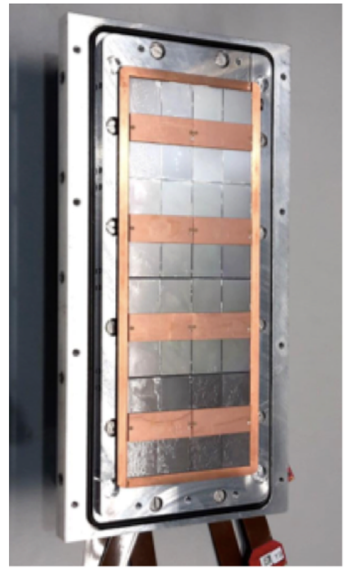
Single chip (2017)



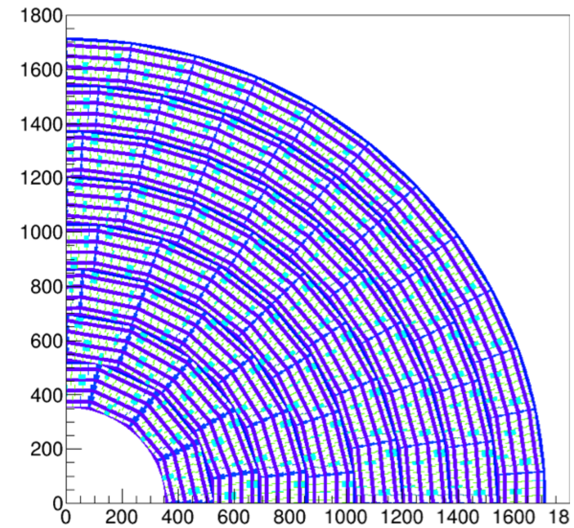
QUAD (2018)



Module (2019)

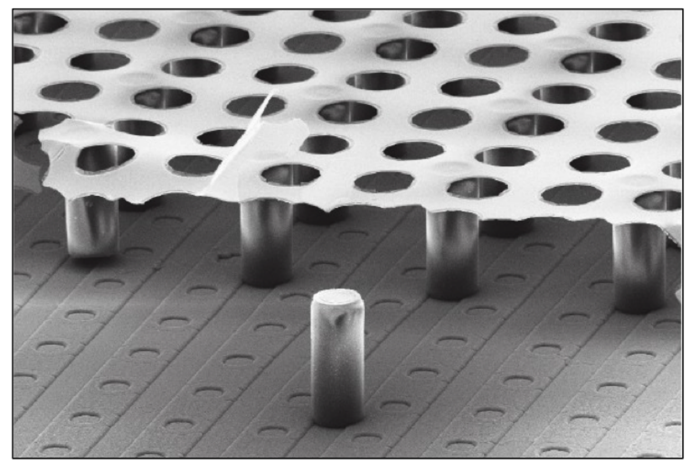


TPC Plane



☞ Micromegas on a pixelchip

- insulating pillars between grid & pixelchip
- one hole above each pixel
- amplification directly above the pixelchip
- very high single point resolution

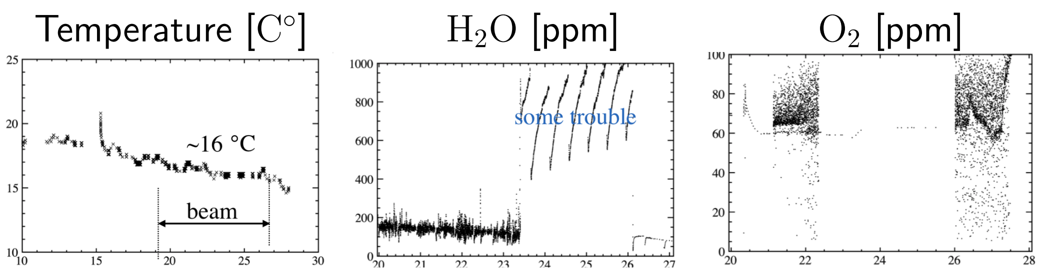


☞ New QUAD design: Four-TimePix3

- tested in a beam in Bonn (2.5 GeV e^-)
- improved chip protection against sparks

☞ Prototype operates with T2K gas

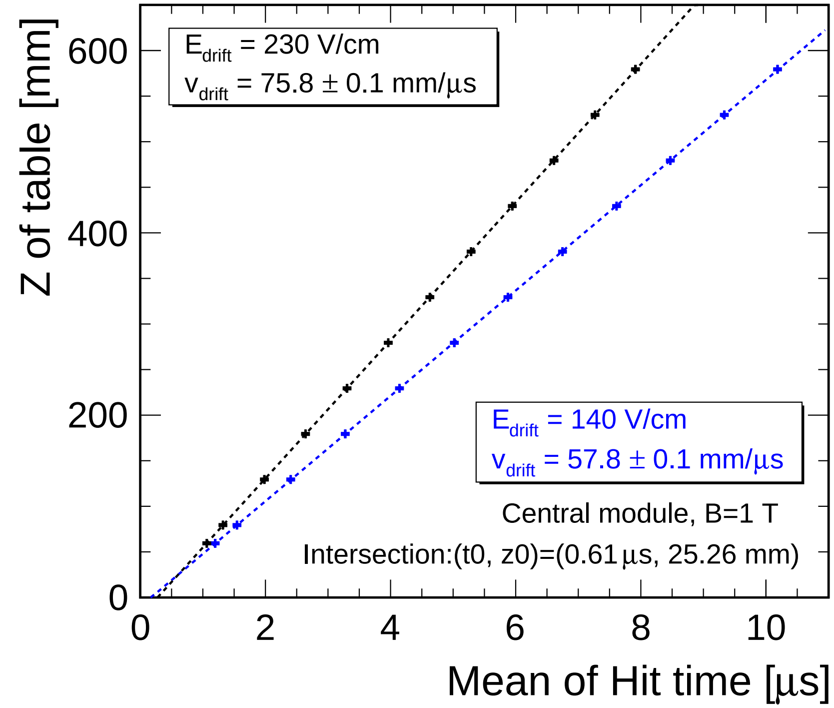
- ➠ Ar(95%), CF_4(3%), iC_4H_{10}(2%)
- ➠ gas purity: 100 ppm H_2O, 60 ppm O_2
- ➠ deploy `Magboltz` calculations

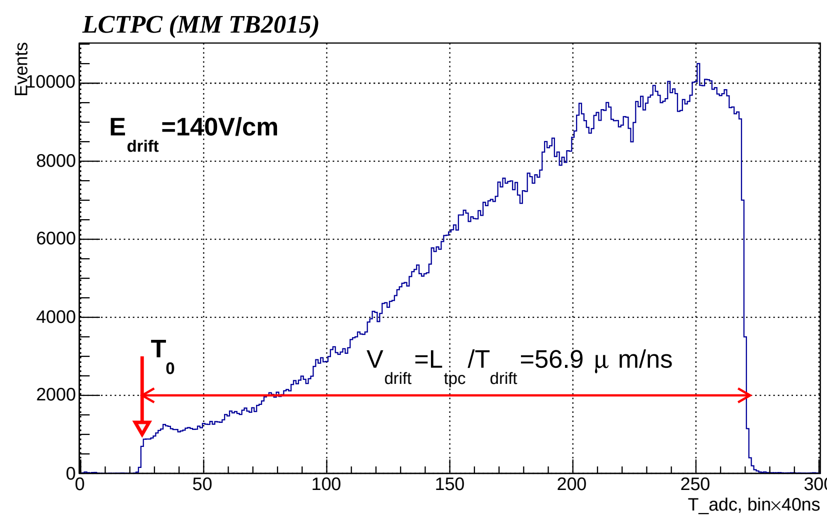


☞ **Absolute T_0 calibration:**

- ➠ **beam trigger:** dedicated z-scan at $V_{drift} = 140, 230$ V
- ➠ **cosmic trigger:** accumulate a whole LP volume data events

	E=140 V/cm	E=230 V/cm
V_d `Data`	$56.7 \pm 0.1 \mu m/ns$	$74.1 \pm 0.2\ \mu m/ns$
V_d `Magboltz`	$57.9 \pm 1.0 \mu m/ns$	$75.5 \pm 1.0 \mu m/ns$
$D_\perp$ `Magboltz`	$74.5 \pm 2.5 \mu m/\sqrt{cm}$	$94.8 \pm 3.1 \mu m/\sqrt{cm}$

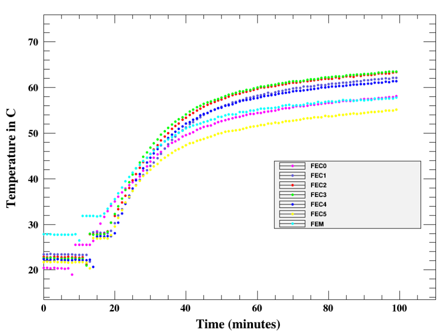


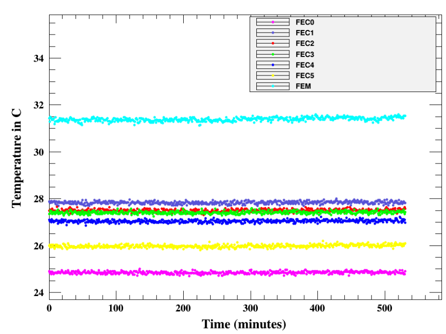


2-Phase CO_2 Cooling

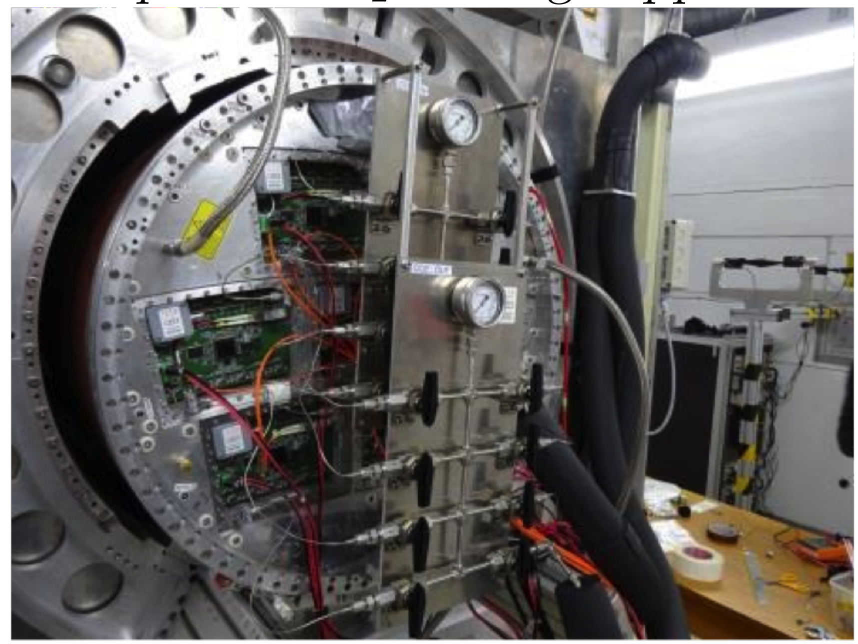
Cooling of the electronic circuit is required due to power consumption

- Temperature of the circuit rises up to 60°C
  - causes a potential damage of electronics
  - convects gas in TPC due to pad heating
- A 2-Phase CO_2 cooling with the KEK **cooling plant TRACI** was provided to 7 MM modules during 2014/15 beam tests at DESY
- **2018** tested with 4 modules in **one loop**
  - **10°C at P=50 bar** system operation
  - about 30°C on the FECs was achieved during 11 days of continuous operation





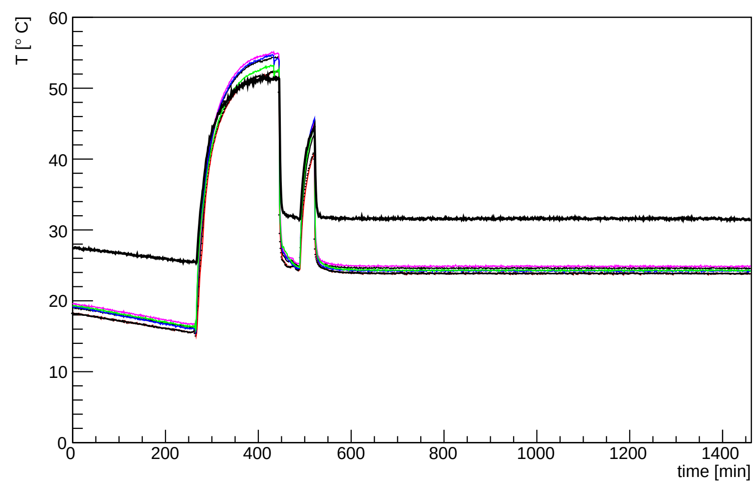
2-phase CO_2 cooling support



- Thermal behavior and effect of cooling have been simulated
  - *D.S. Bhattacharya et al.,* **JINST 10 P08001, 2015**

- **ILD TPC Requirements**
  - **about 1kW heat transfer** (half cilinder)
    - ➔ power pulsing at room T
  - $\Delta T \simeq 1°C$ over the gas volume
    - ➔ uniform pad plane temperature
  - **less material** comparing to existing experiments
- **The development of a micro-channel cooling plate using 3D printing technology is currently in progress**
  - the primary dedicated test at DESY was conducted in 2021

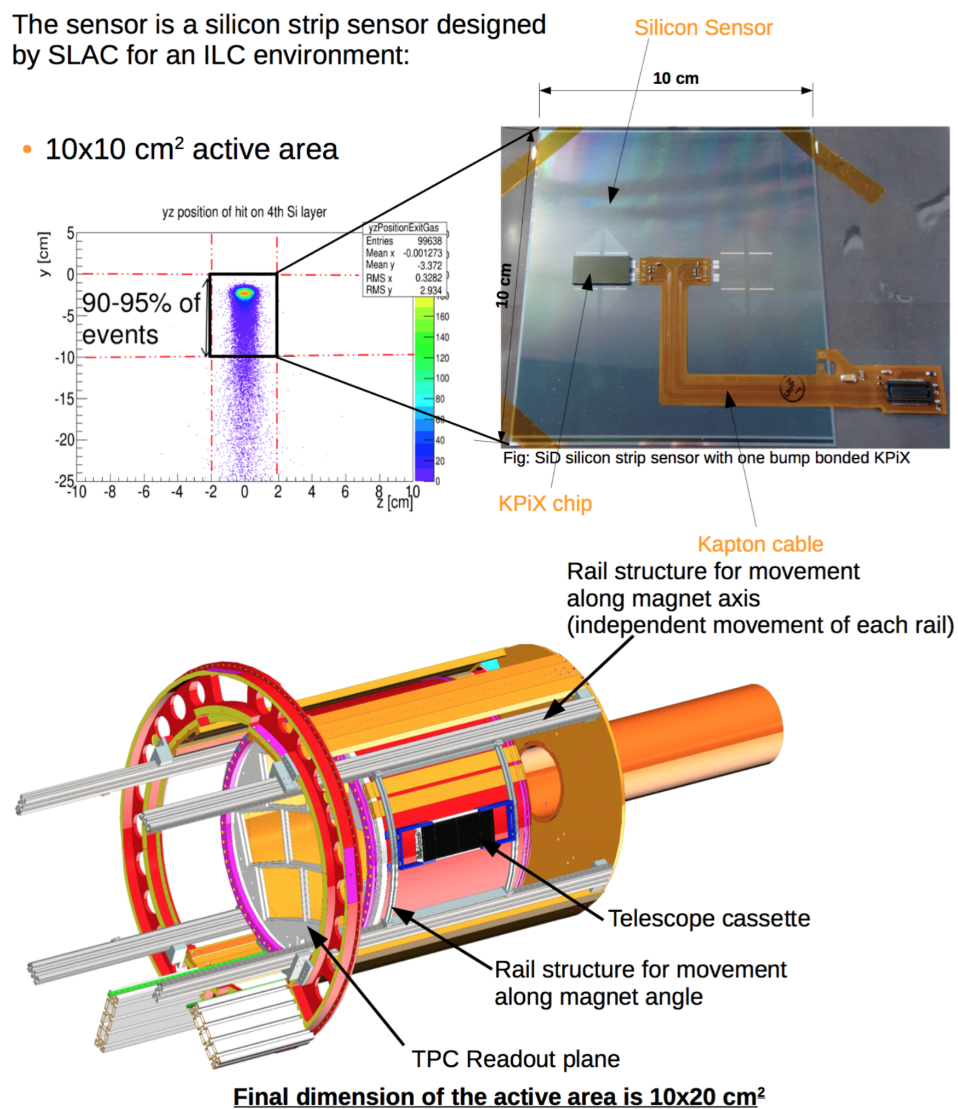
Temperature History 14-15.10.2021



☞ **Further studies toward the technology choice will be carried out with upgraded LP2**

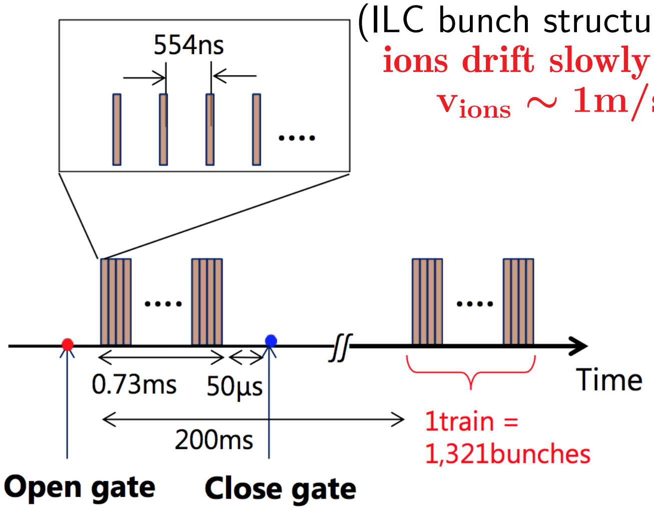
- new mechanical design of **endplate:** no space between modules
- new large area strip telescope within solenoid with **Si sensor:** (project LYCORIS)
  - → $10\text{x}10\ \text{cm}^2$ active area
  - → $320\ \mu\text{m}$ thickness
  - → $0.3\%X_0$ material budget
  - → $25\ \mu\text{m}$ strip pitch to meet momentum resolution
  - → integrated pitch adapter and digital readout (KPiX)

System is under final review before send off to production and funded by EU AIDA2020

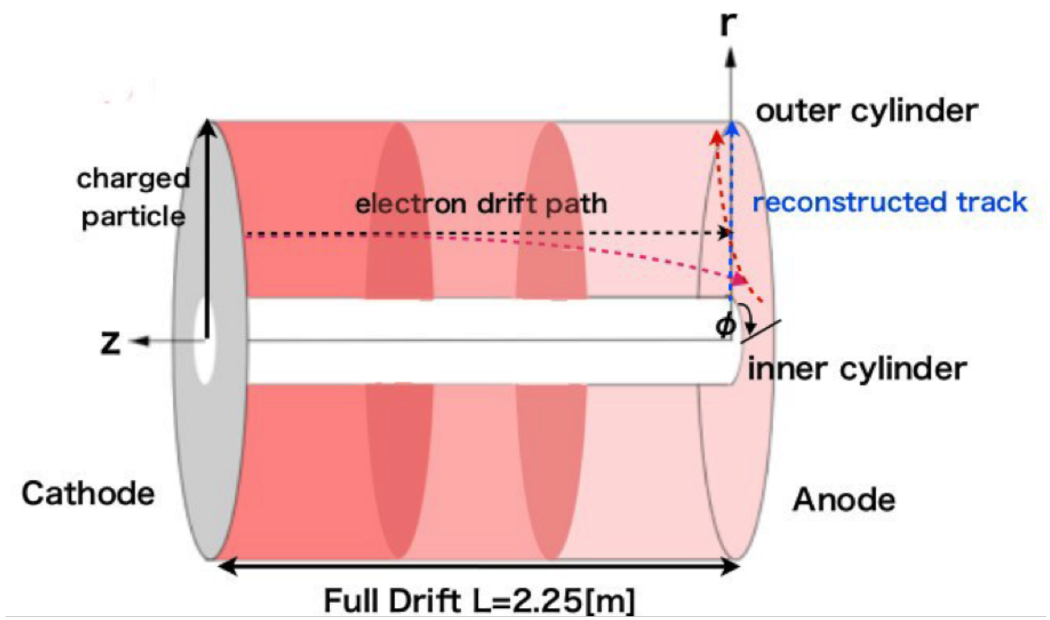


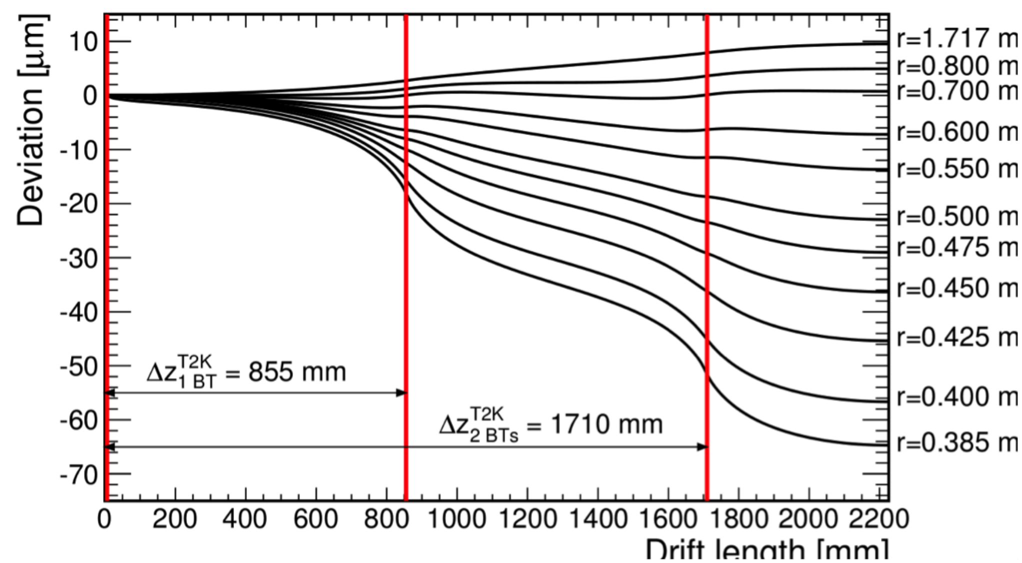
Ion Space Charge can deteriorate the position resolution of TPC

- **Primary ions** yield distortions in the E-field which result to O($\leq 1\mu$m) track distortions
- **Secondary ions** yield distortions from backflowing ions generated in the gas-amplification region:
  - 60 μm for **IBFxGain=3** for the case of 2 ion disks



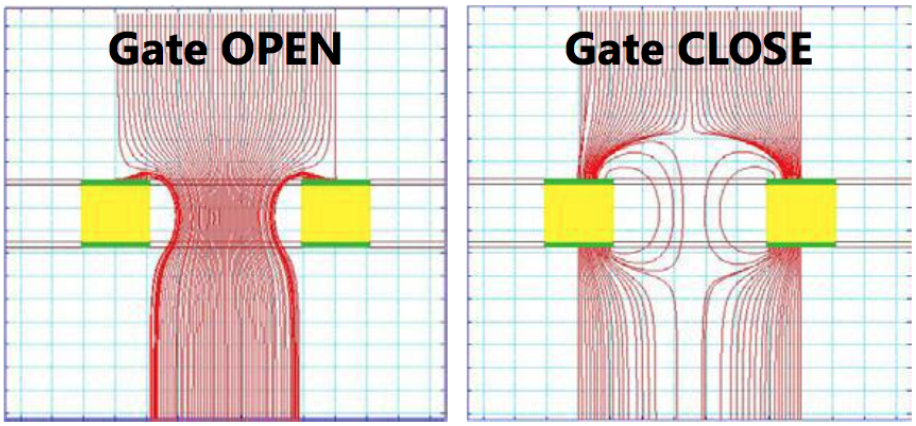
(ILC bunch structure)
ions drift slowly
$v_{\text{ions}} \sim 1\text{m/s}$

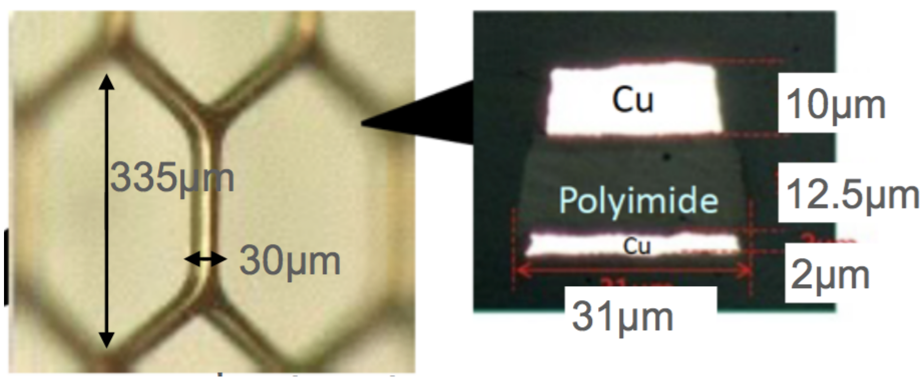




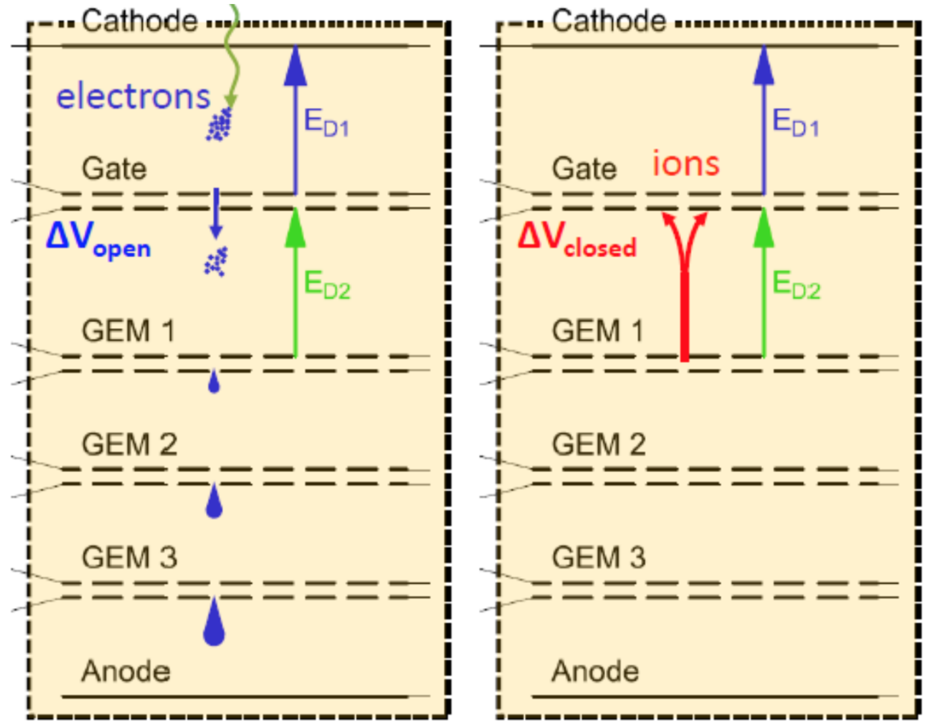
Gate is needed!

Gating: open GEM to stop ions while keeping transparency for electrons





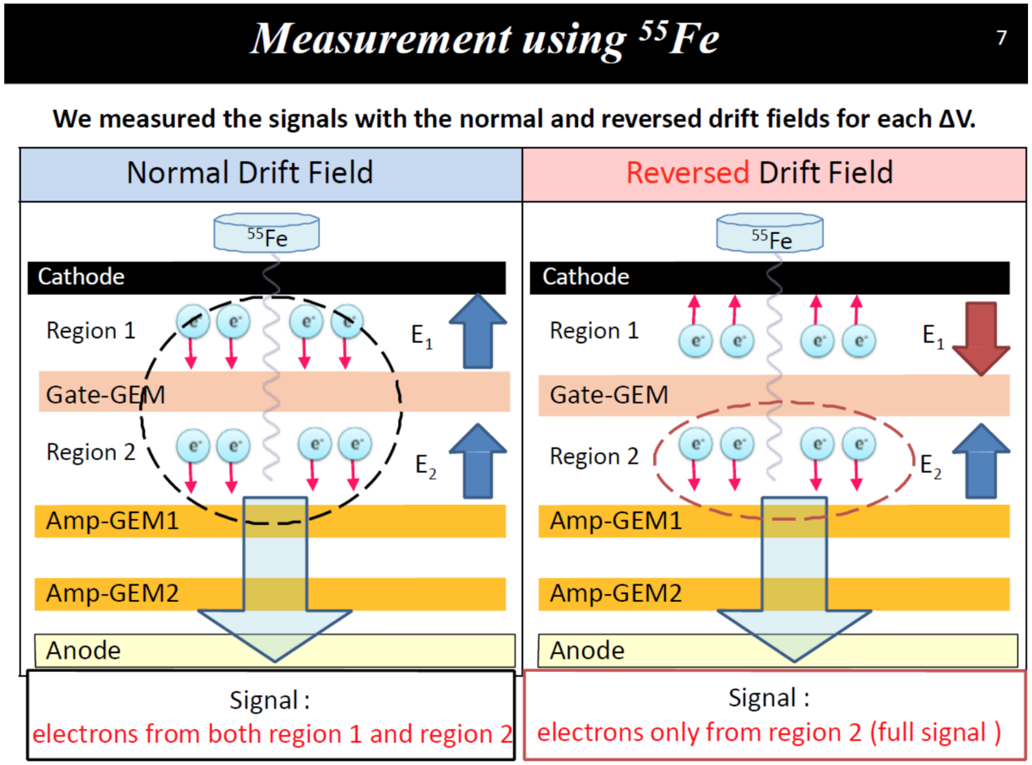
☞ A large-aperture gate-GEM with **honeycomb-shaped holes**

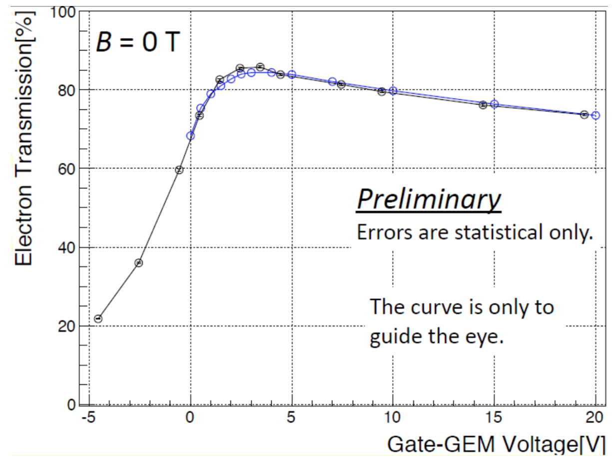


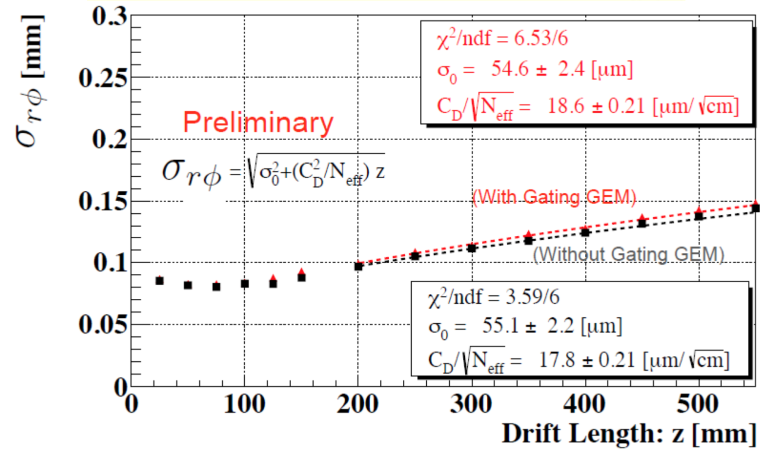
The ions must be stopped before penetrating too much the drift region

The device to stop them must be transparent to electrons

Electron transmission rate as a function of GEM voltage measured with Fe^{55}







Extrapolation to 3.5 T shows acceptable transmission for electrons (80%)

Simulation shows that ion stopping power better than 10^{-4} at 10 V reversed biases

☞ The results are consistent with no more degradation than expected (10%)

➠ *M. Kobayashi, et al.,* **NIM A (918), 41-53**