A Time Projection Chamber with Micromegas-based Readout (NIM Paper Status Report)

CEA - Saclay

P. Colas, S. Ganjour, M. Titov

CEA-Saclay/IRFU, Gif-sur-Yvette, France

LCTPC Collaboration Meeting

DESY

March 12, 2024

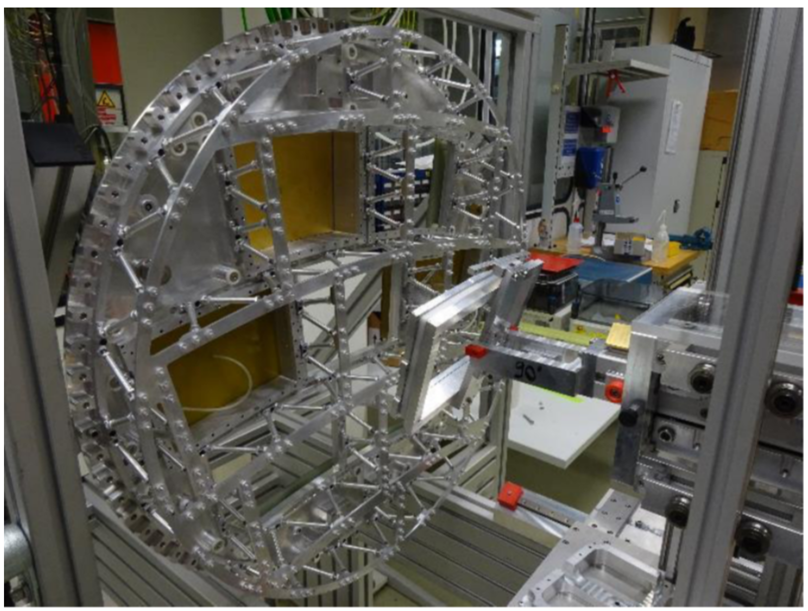
TPC is the central tracker for International Large Detector (ILD)

- 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: $\sim \mathbf{5\%X_0}$
  - endplates: $\sim \mathbf{25\%X_0}$
- **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:**
    - → $\sigma(r\phi) \leq 100\mu m$ (overall)
    - → $\sigma(Z) \simeq 400\mu m$ at z=0
  - **Tracking efficiency:**
    - → 97% for $p_T \geq 1\mathrm{GeV}$
  - **dE/dx resolution:** 5%

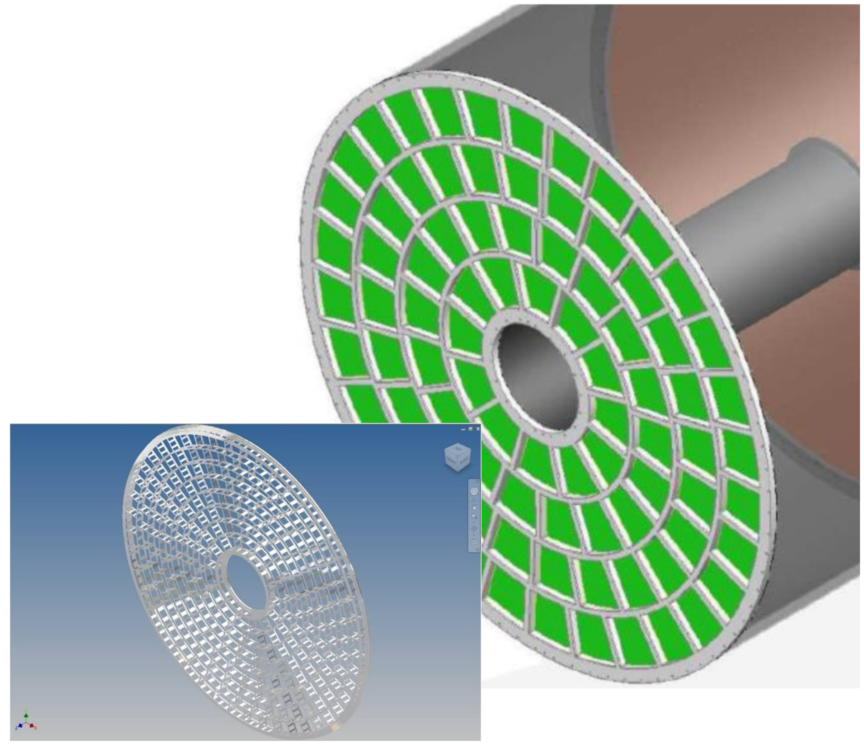
☞ **Gravitational loads:**

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



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

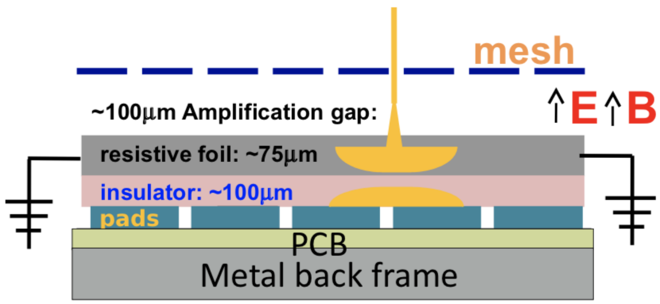
8-ring: 4 modules combined in 1 super-module



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



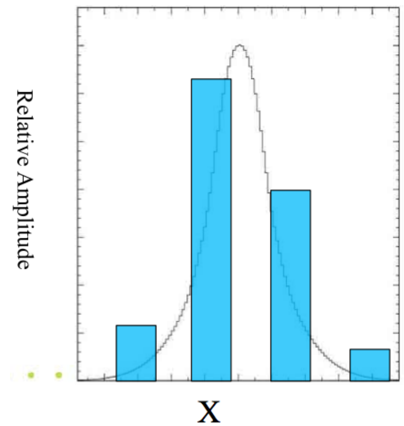
☞ Charge density function of time dependent charge dispersion on 2D continuous RC network:

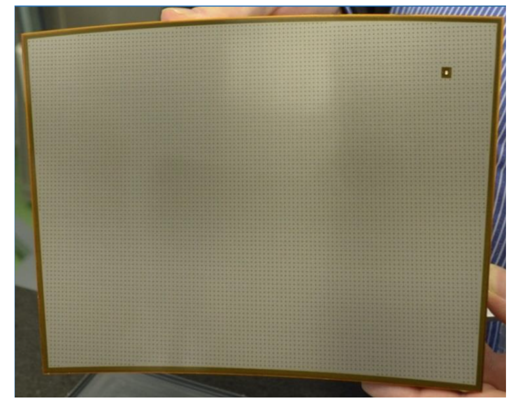
$$\rho(r,t) = \frac{RC}{2t}\exp[-\frac{-r^2RC}{4t}]$$

R- surface resistivity

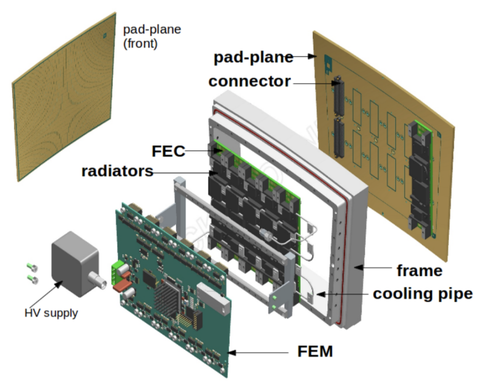
C- capacitance/unit area

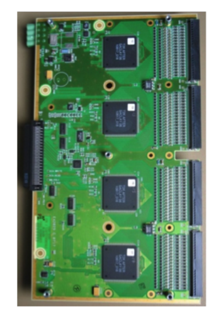
Relative fraction of charge seen by pads fitted by Pad Response Function (PRF)





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

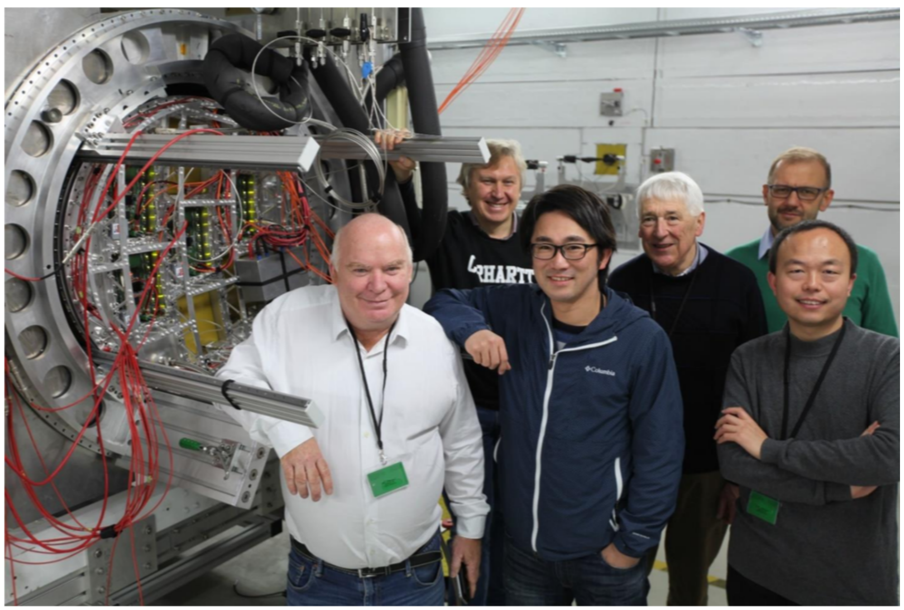


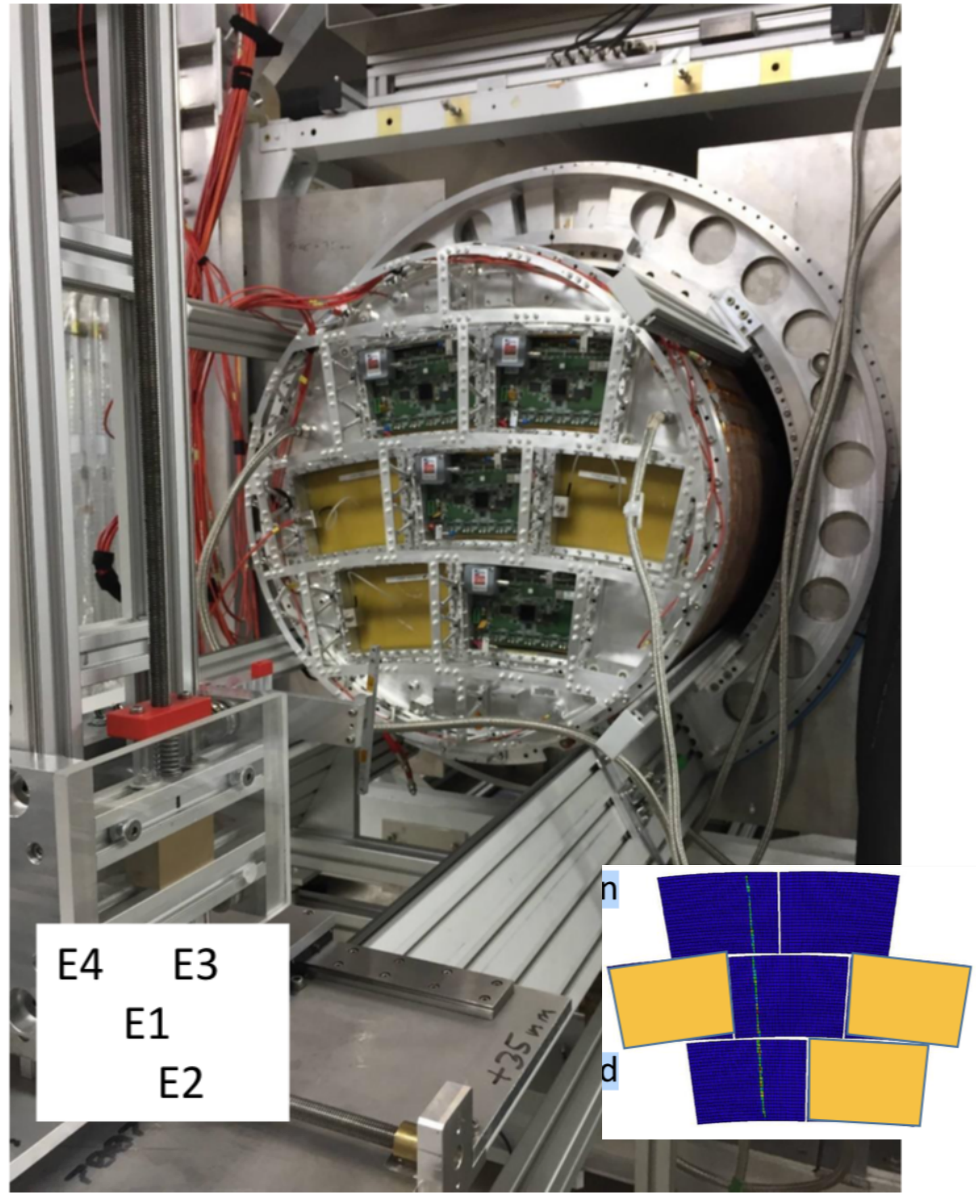


Module readout with 6 FE cards bearing 4 AFTER ASICs chips (12-bit ADC)

☞ **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

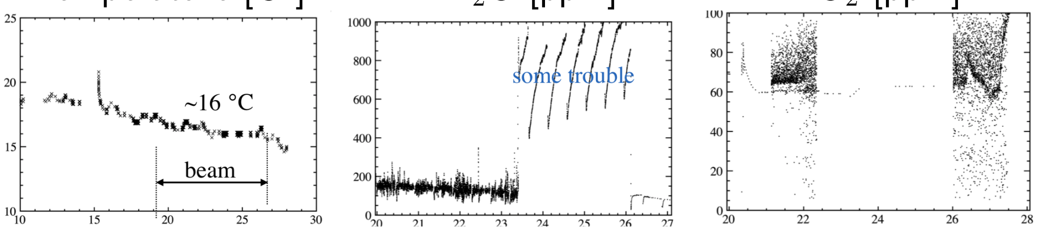




☞ Prototype operates with T2K gas

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

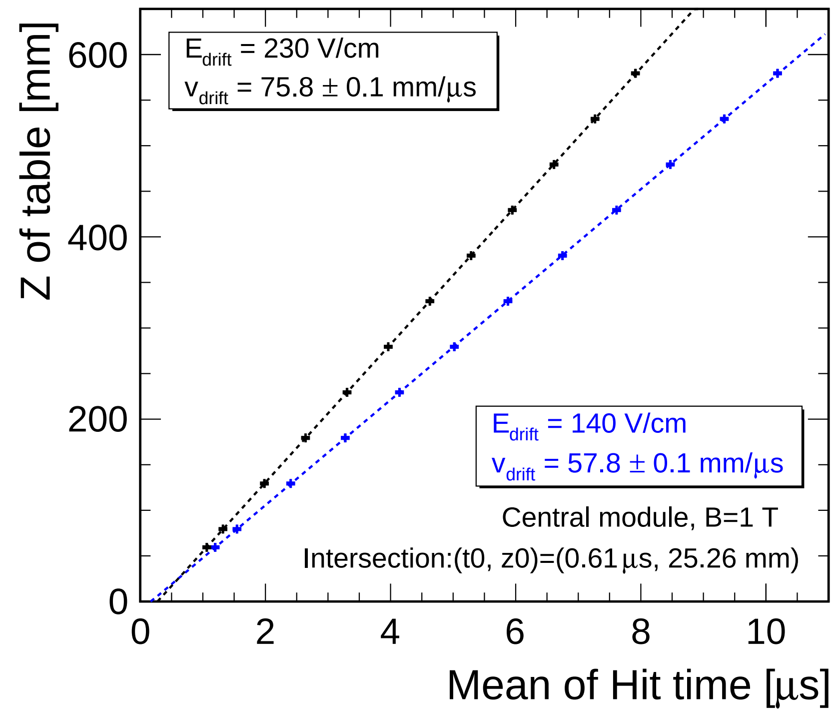
Temperature [C°] | H_2O [ppm] | O_2 [ppm]

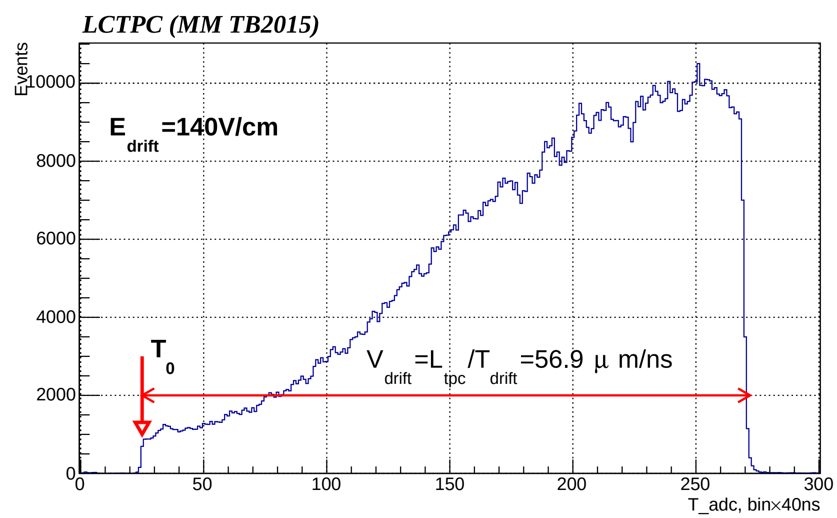


☞ **Absolute T_0 calibration:**

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

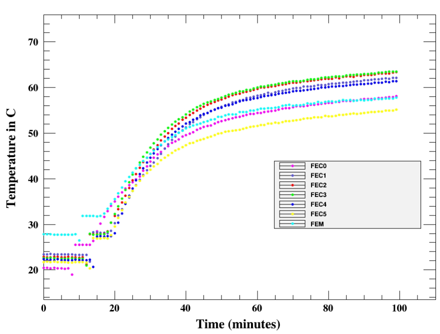
	E=140 V/cm	E=230 V/cm
V_d `Data`	$56.7 \pm 0.1 \mu m/ns$	$74.1 \pm 0.2\ \mu m/ns$
V_d `Magboltz`	$57.9 \pm 1.0 \mu m/ns$	$75.5 \pm 1.0 \mu m/ns$
$D_\perp$ `Magboltz`	$74.5 \pm 2.5 \mu m/\sqrt{cm}$	$94.8 \pm 3.1 \mu m/\sqrt{cm}$

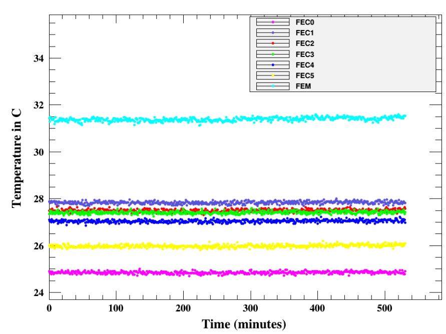




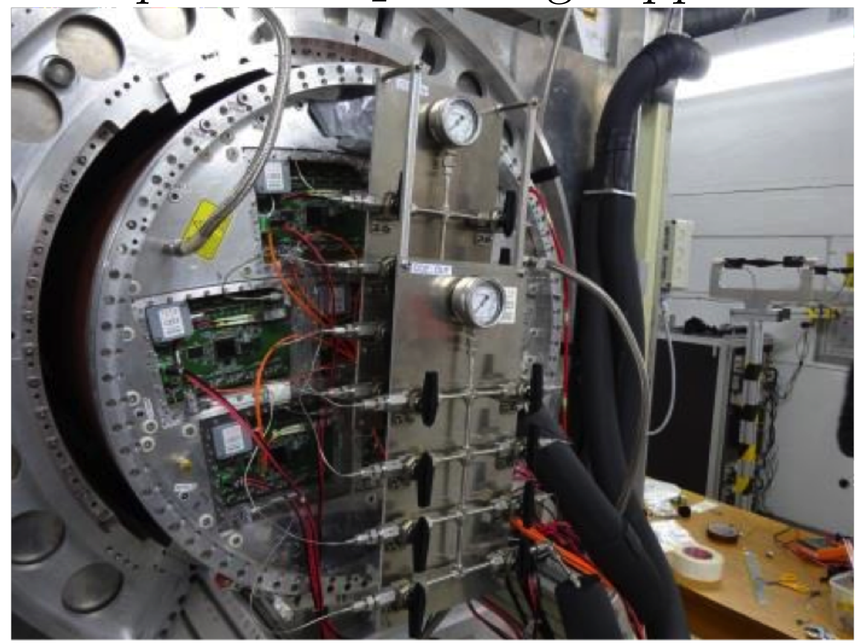
Cooling of the electronic circuit is required due to power consumption

- 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



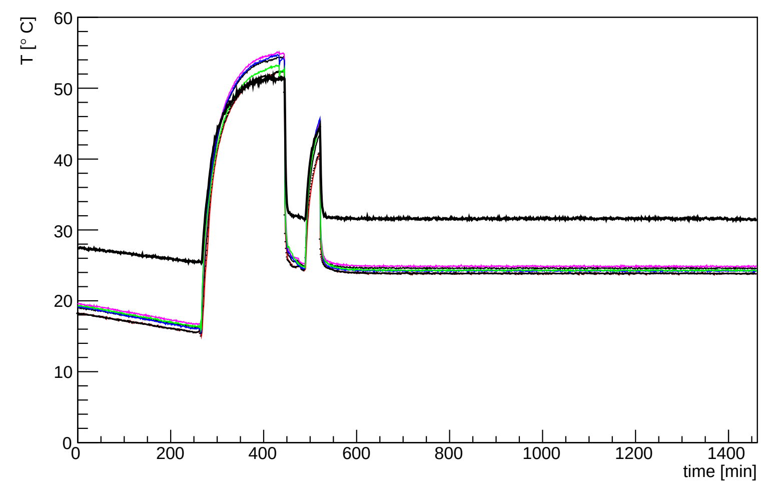
- Thermal behavior and effect of cooling have been simulated
  - *D.S. Bhattacharya et al.,* **JINST 10 P08001, 2015**

☞ **ILD TPC Requirements**

- **about 1kW heat transfer** (half cilinder)
  - ➔ power pulsing at room T
- $\Delta T \simeq 1^\circ C$ 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**

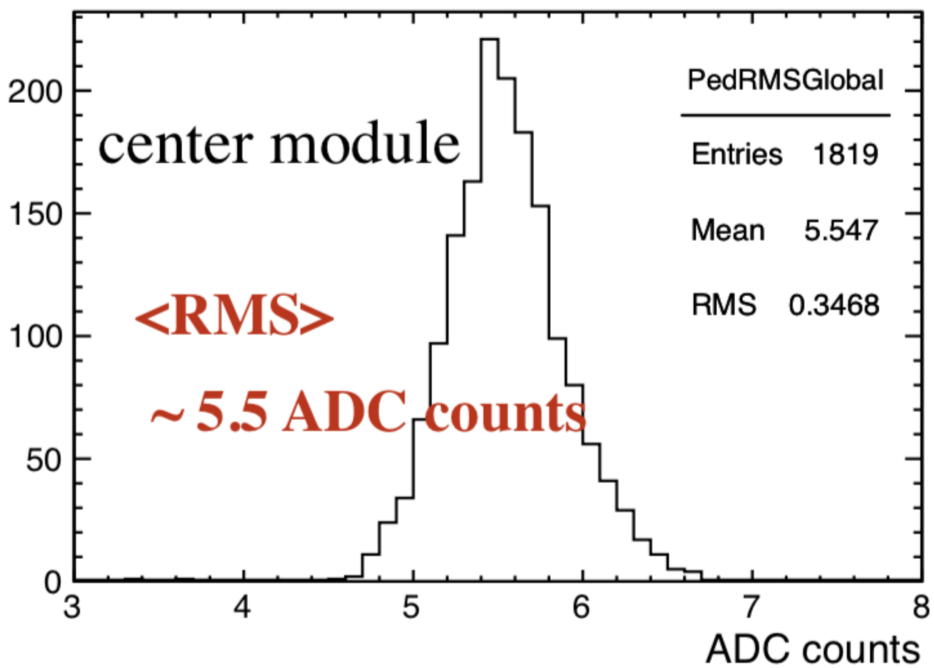
- the primary dedicated test at DESY was conducted in 2021



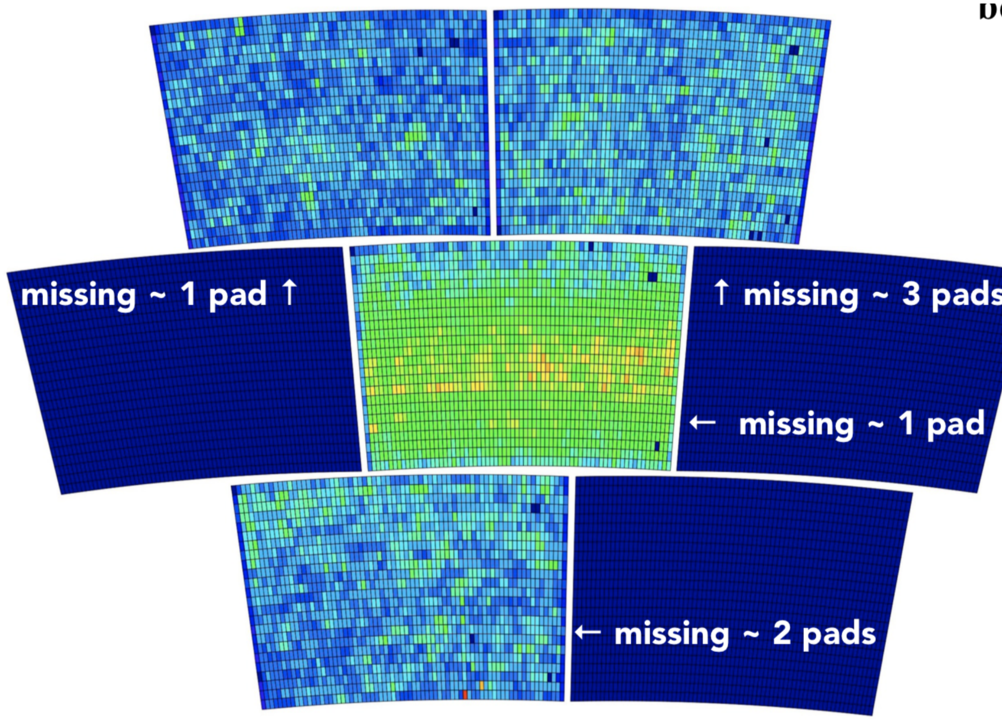
Measure the quality of connection from pedestal rms and occupancy

- 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



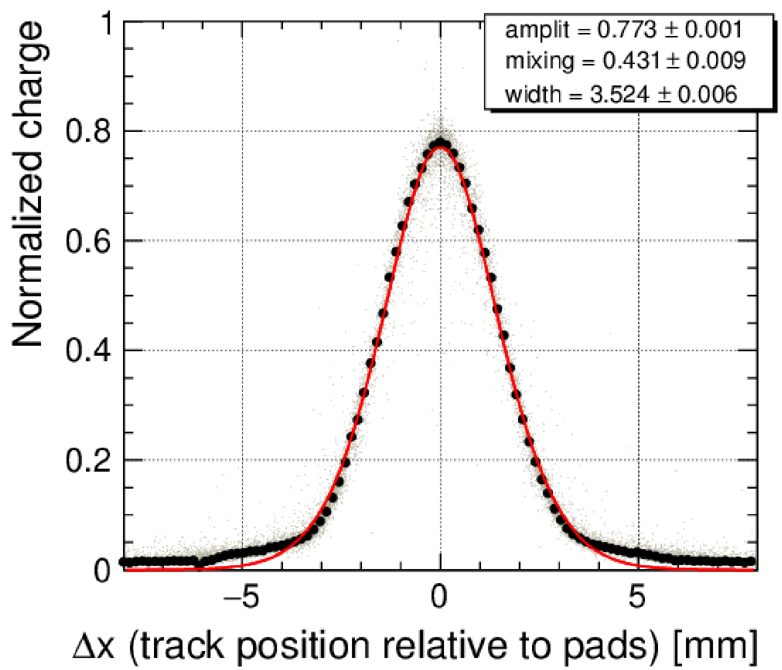
Measured occupancy from accumulated cosmic ray events



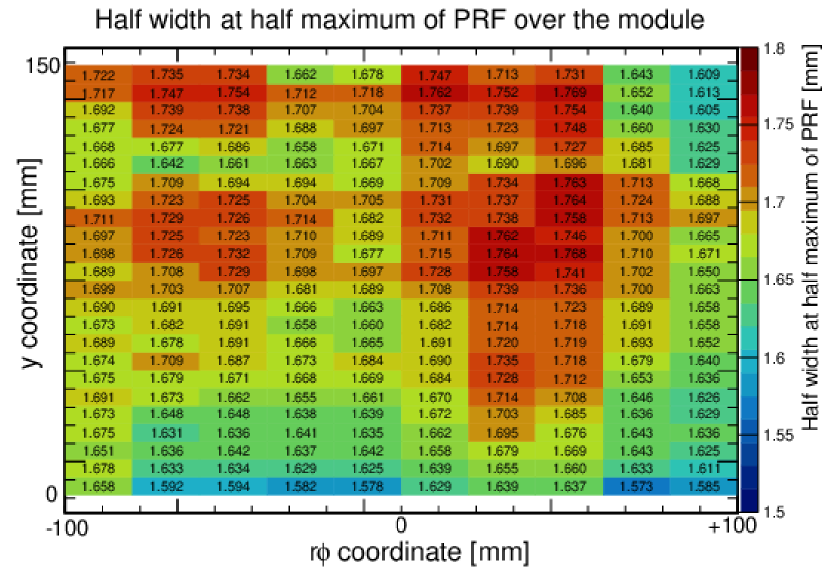
Very good electrical connection between pads (PCB) and FEC (99.9%)

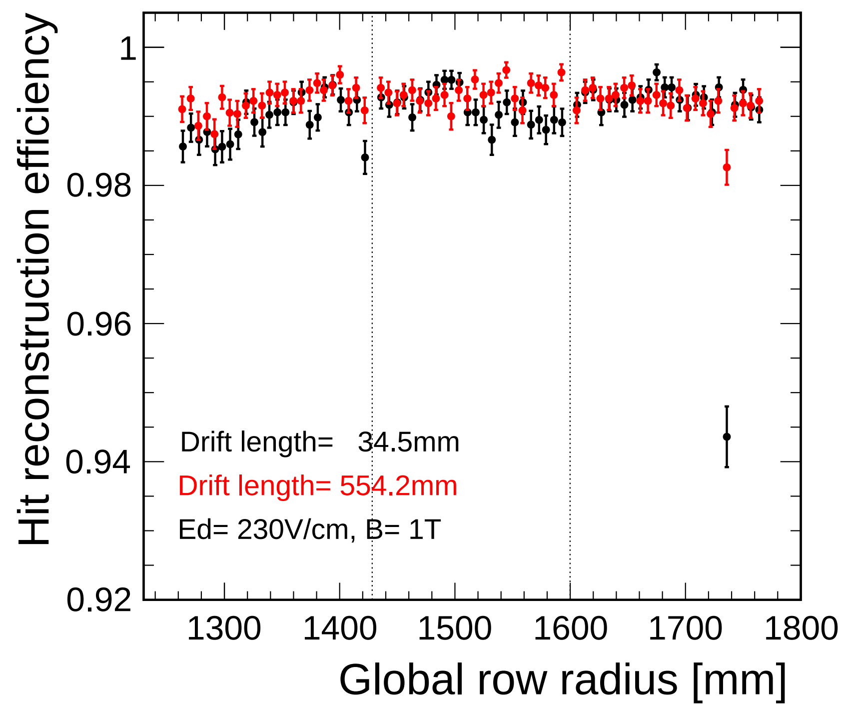
☞ Calibration of the **Pad Responce Function (PRF)** is done for each z position

- $\sigma \sim$ **1.4mm** is expected for
  - ➔ R=2.5 $\mathrm{M}\Omega/\square$
  - ➔ 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)]

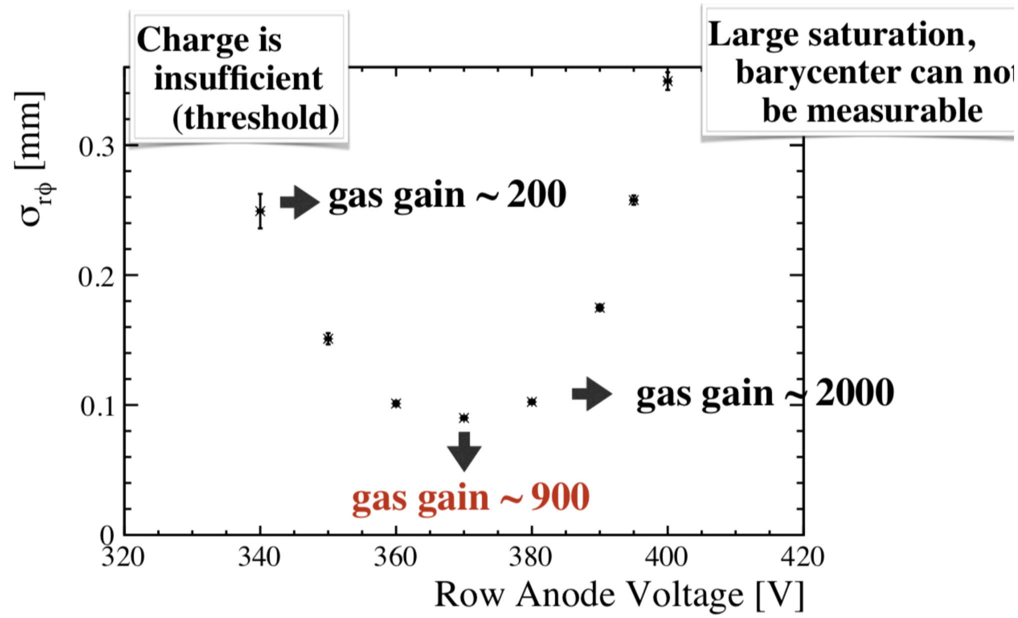
$$\boldsymbol{\sigma}_{\mathrm{i}} = \sqrt{\boldsymbol{\sigma}_{\mathrm{in}} \cdot \boldsymbol{\sigma}^{\mathrm{i}}_{\mathrm{ex}}}$$

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

- 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 $\mathrm{V_{mesh}} = 370\mathrm{V}$ 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**

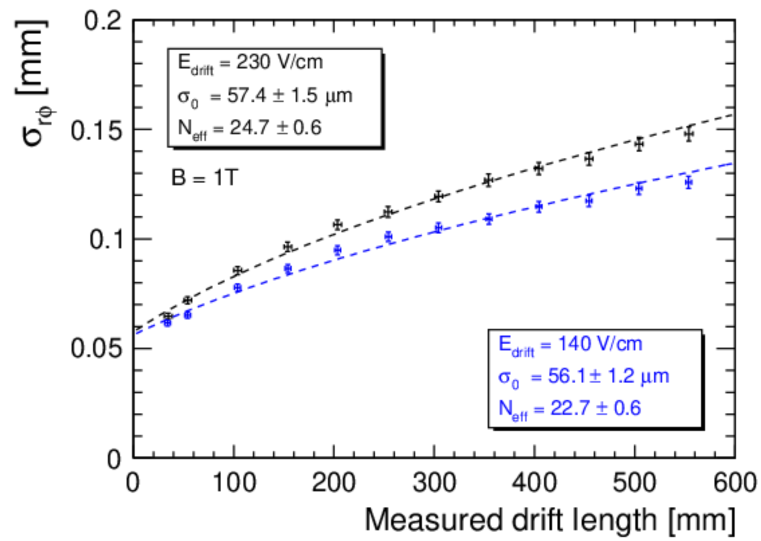
➠ a few pad rows on lower and upper modules exhibit degradation due to misalignment of electrods inside the field cage and the inhomogeneity of the resistive anode

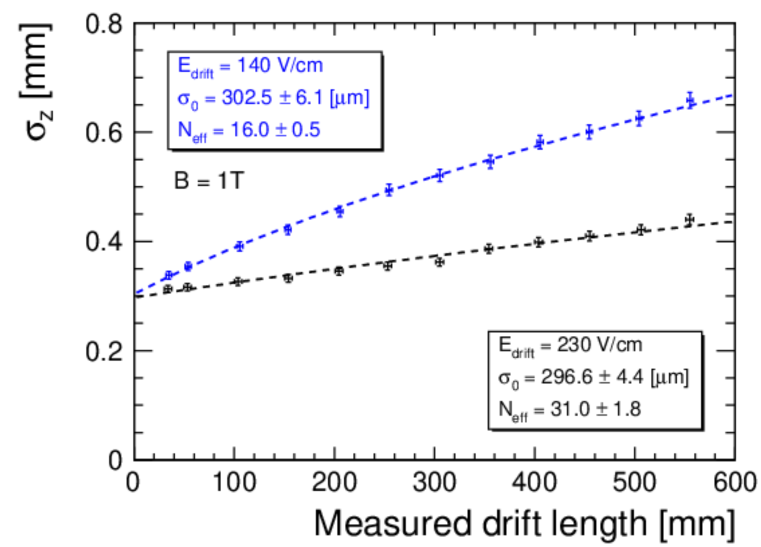
☞ **Fit data with:**

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

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

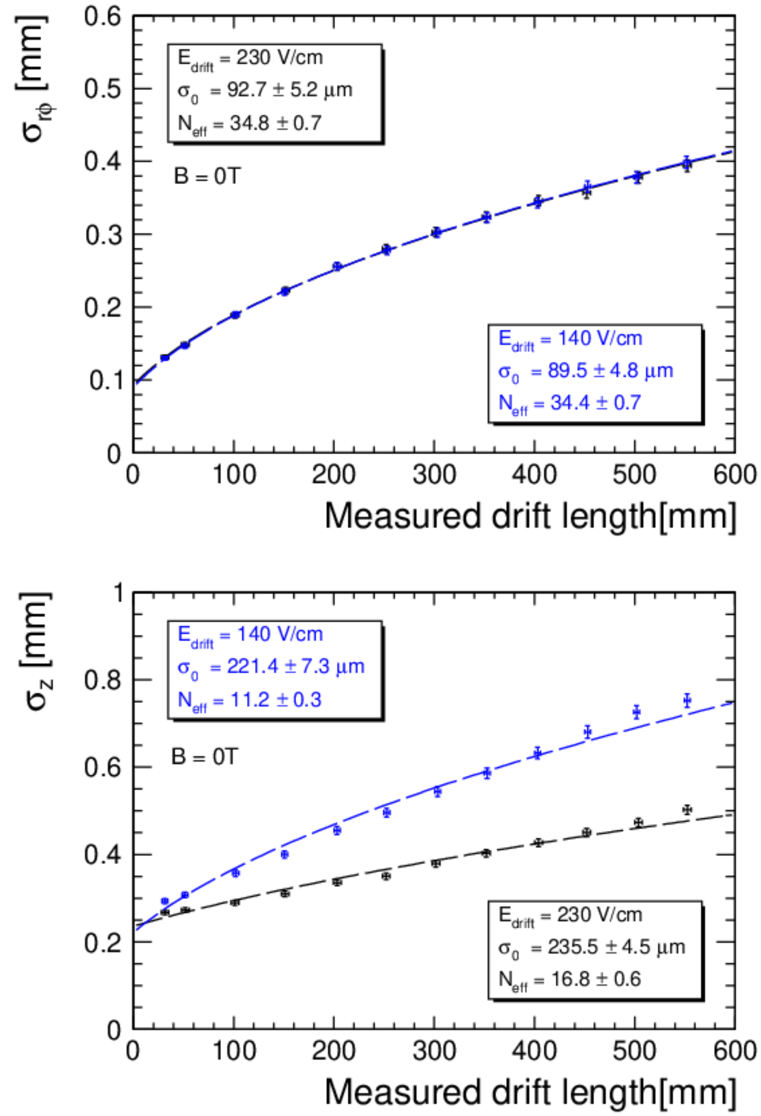
➠ Magboltz calculations yield $D_{\perp/\parallel}$ with approximately 3% precision





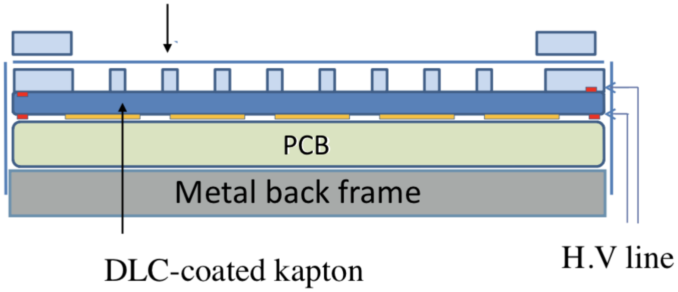
Data recorded at a 0 T magnetic field are essential for computing the alignment parameters of the modules

- 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**

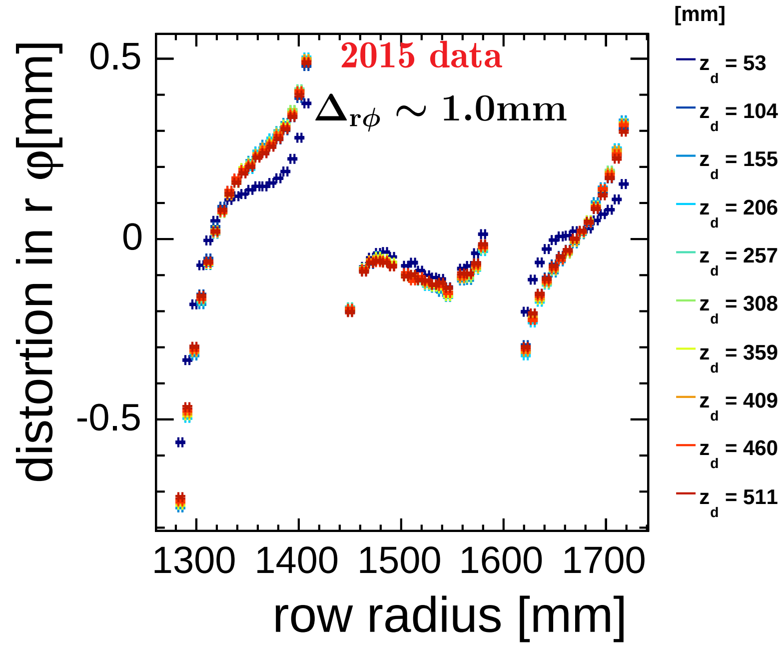


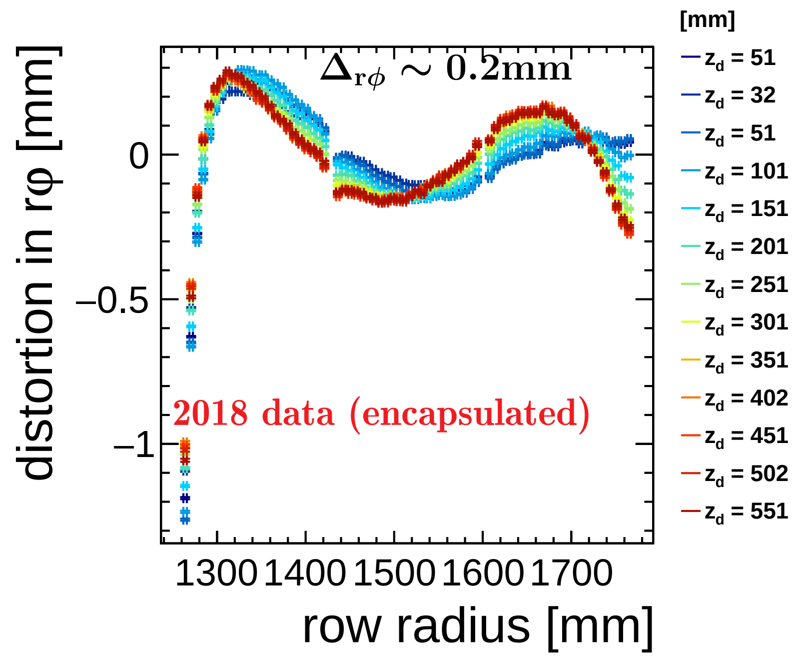
Non-uniform E-field near module boundaries induces ExB effects

- 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

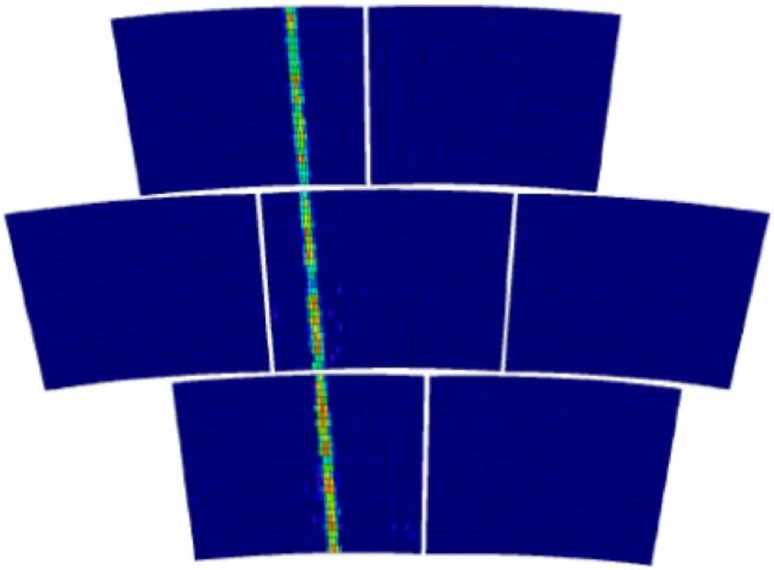


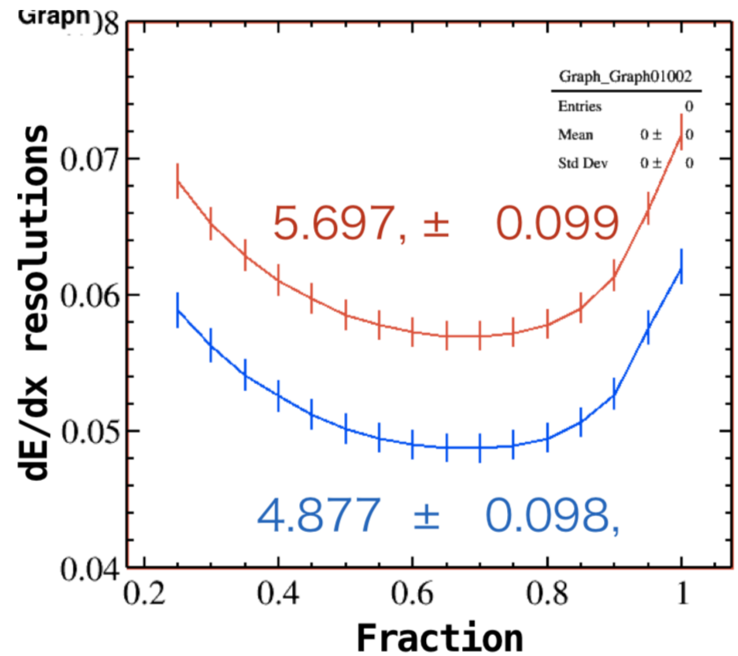
ExB effect between modules is effectively suppressed in the new scheme

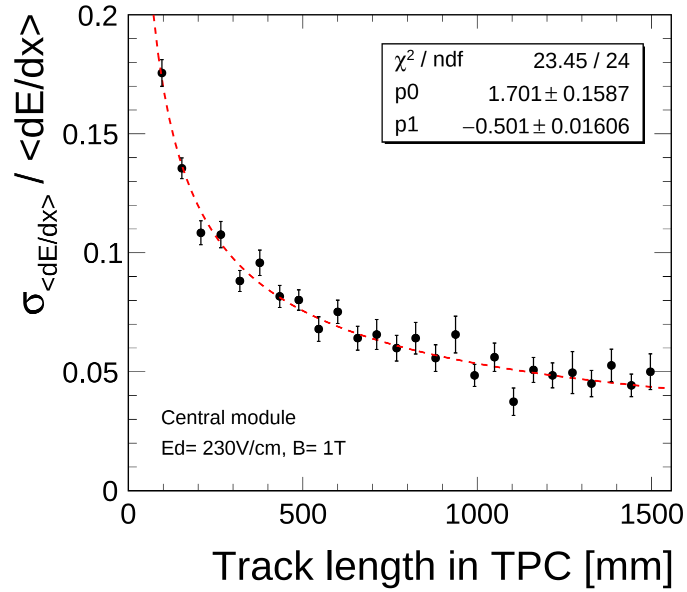




dE/dx Resolution







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

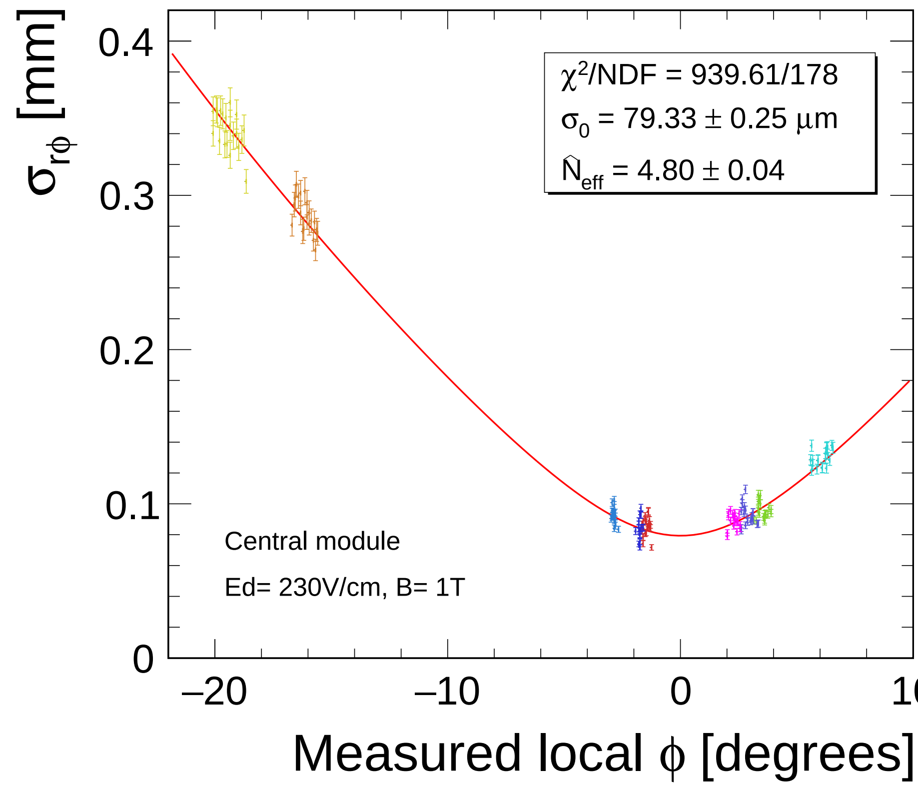
- Test arbitrary track lengths by randomly combining hits from several real tracks to create a pseudo track in the TB setup
- Estimated dE/dx resolution using a **70% truncated mean** for the ILD TPC
  - $\sigma_{\mathrm{dE/dx}} = 4.9\%$ for 192 hits (large ILD)
  - $\sigma_{\mathrm{dE/dx}} = 5.7\%$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

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

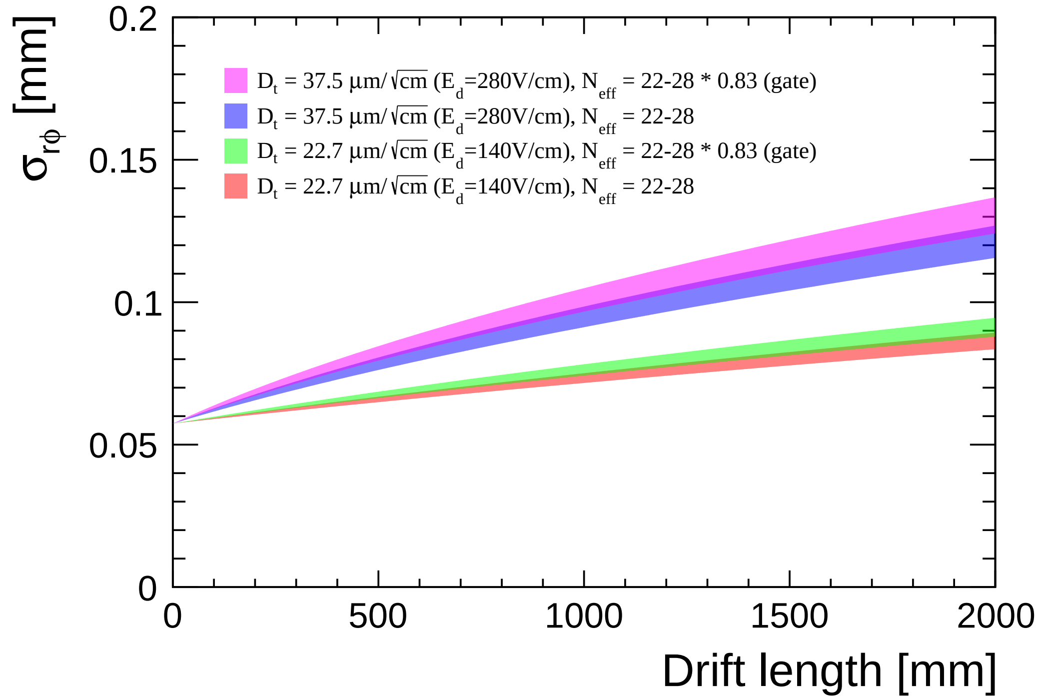
$\hat{N}_{\text{eff}} \simeq 5.1$ is expected for h=7 mm
[*M. Kobayashi, et al.*, **NIM A (764), 394**]



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 $\boldsymbol{\sigma_{r\phi0}}$ **and** $\boldsymbol{N_{\mathrm{eff}}}$ 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 **IBF rejection** will be presented in **S. Narita 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
  - $\sigma_{\mathrm{r}\phi}$ at $\mathrm{z} = 0 \simeq 60\mu\mathrm{m}$ and $\sigma_{\mathrm{r}\phi} \leq 100\mu\mathrm{m}$
    σ_{z} at $\mathrm{z} = 0 \simeq 200\mu\mathrm{m}$ and $\sigma_{\mathrm{z}} \leq 400\mu\mathrm{m}$
  - 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

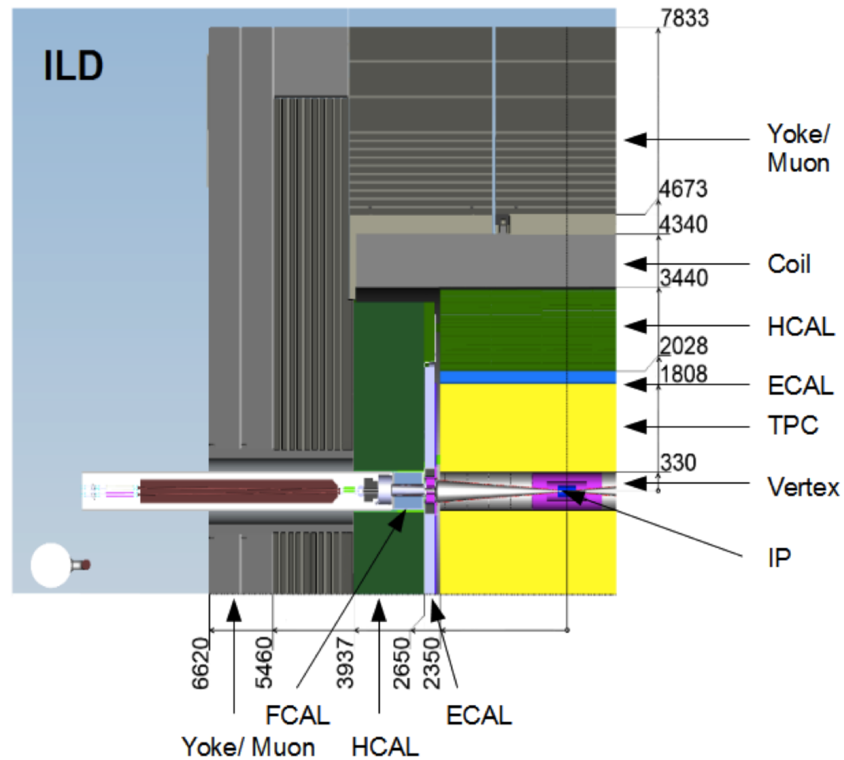
Backup

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

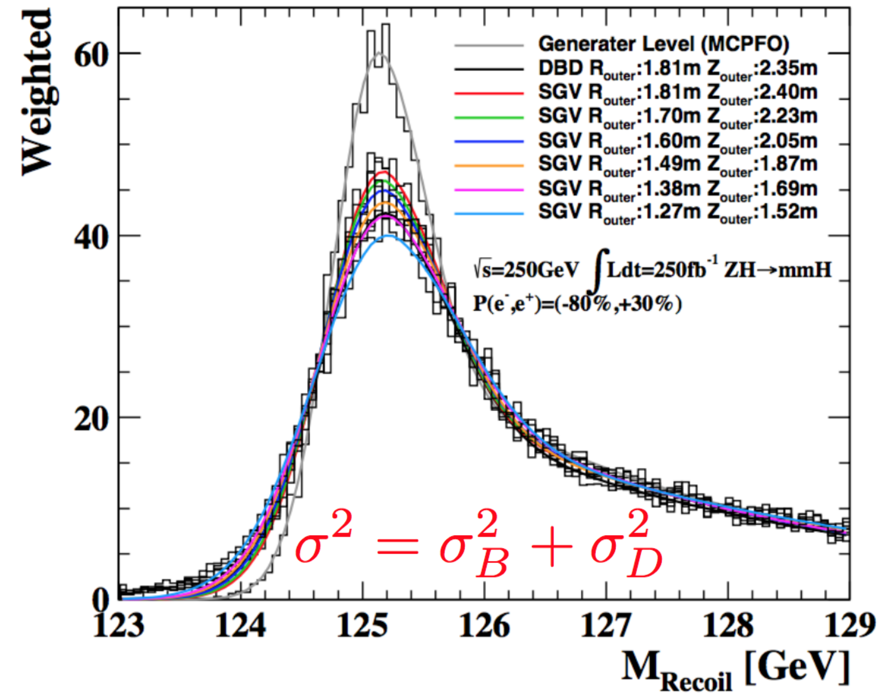


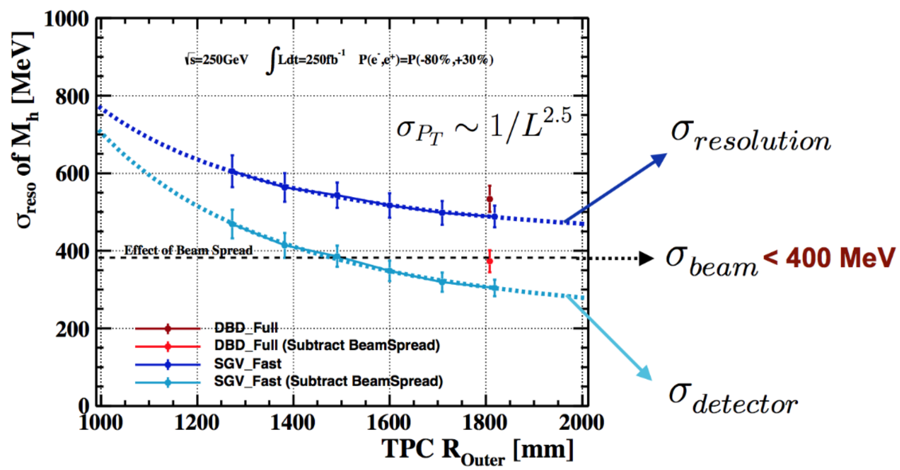
ILD requirements:

- 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($\boldsymbol{\sigma}_\mathrm{D}$)**
  - → $\sigma_B = $ **400 MeV** from TDR
  - → $\sigma_D = $ **300 MeV** at $R_{out} = 1.8$ m
  - → $\sigma_D = $ **400 MeV** at $R_{out} = 1.4$ m





Trigger and DAQ

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**