Time Projection Chamber

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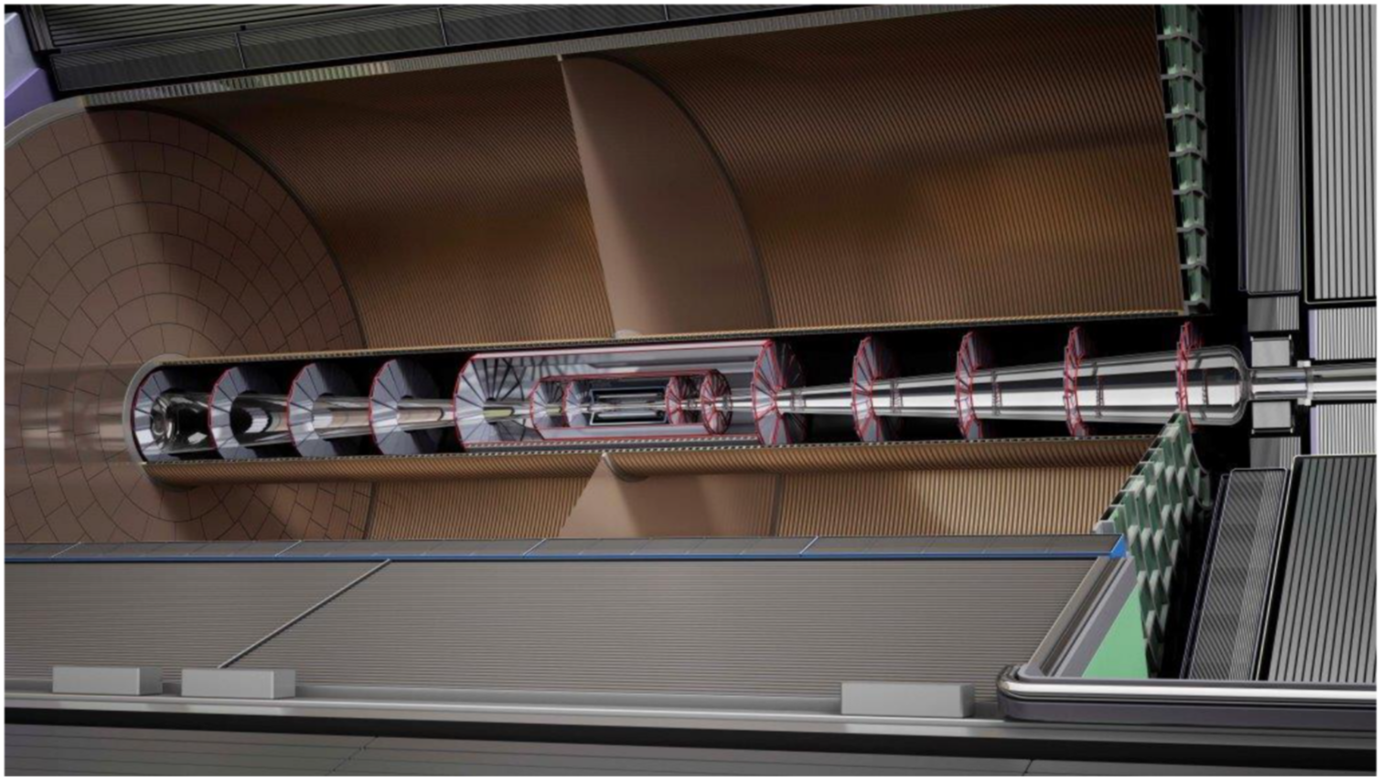
On behalf of LCTPC Collaboration



ILD Collaboration Meeting
KEK, Japan
25 - 26 February, 2019

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

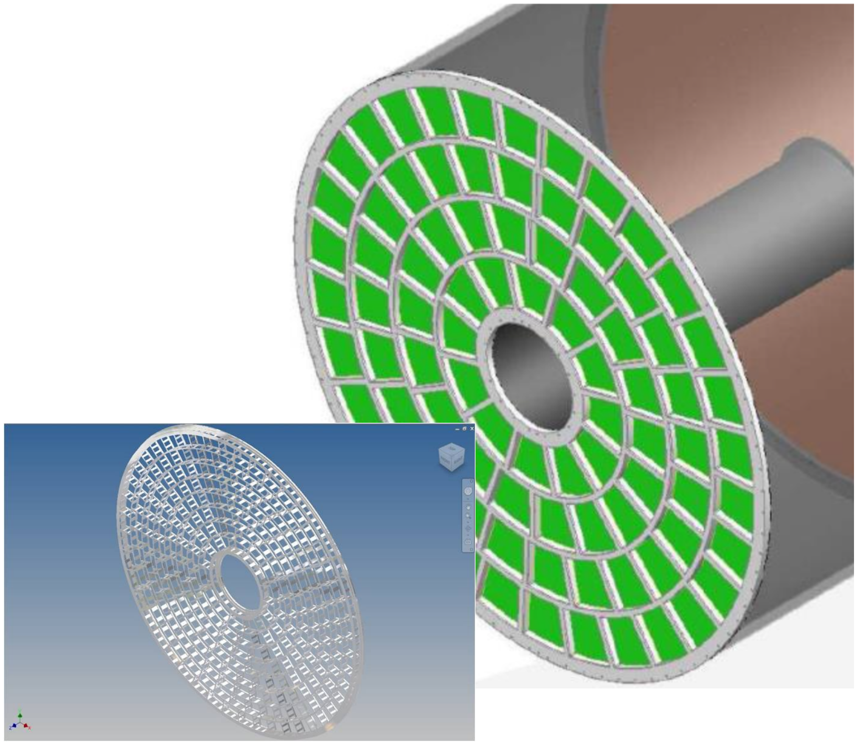
TPC Requirements in 3.5 T

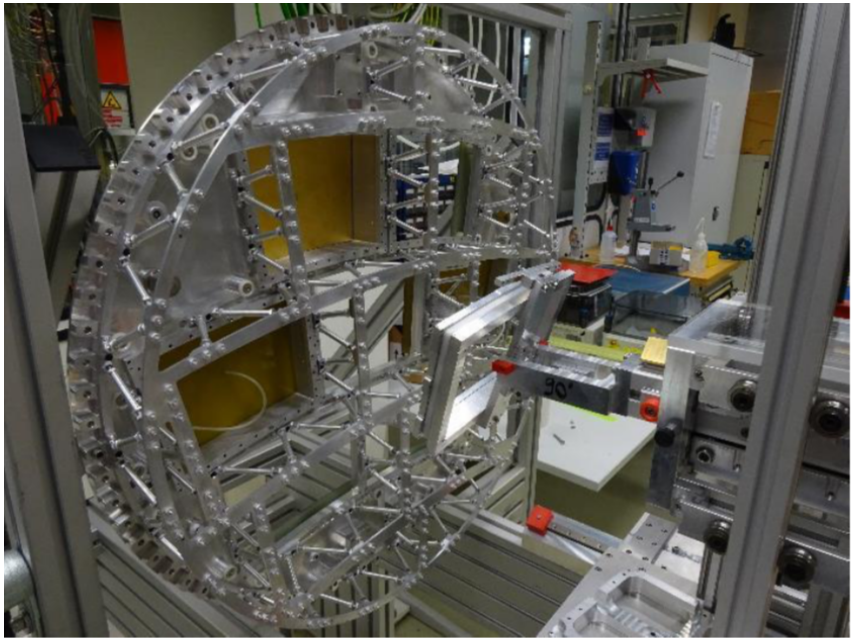
- **Momentum resolution:**
  - → $\delta(1/p_T) \leq 9 \times 10^{-5} \mathrm{GeV}^{-1}$
- **Single hit resolution:**
  - → $\sigma(r\phi) \leq 100\mu m$ (overall)
  - → $\sigma(Z) \simeq 400\mu m$ at z=0
- **Tracking efficiency:**
  - → 97% for $p_T \geq 1\mathrm{GeV}$
- **dE/dx resolution:** 5%

☞ **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

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



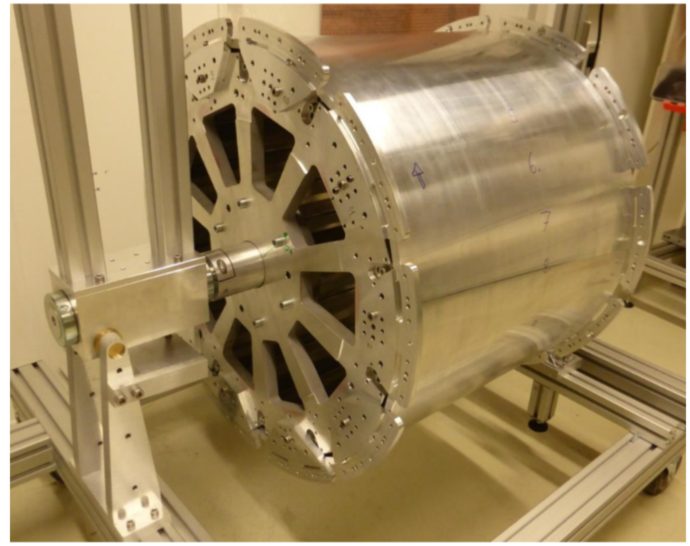


$\mathcal{O}(50\mu\text{m})$ *accuracy of the module positioning*

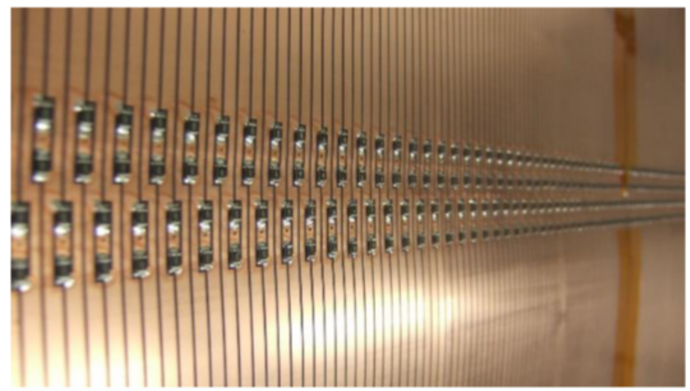
Possibly need to fill windows by dummy modules to keep the stiffness and exchange them one by one in the grey room after assembly

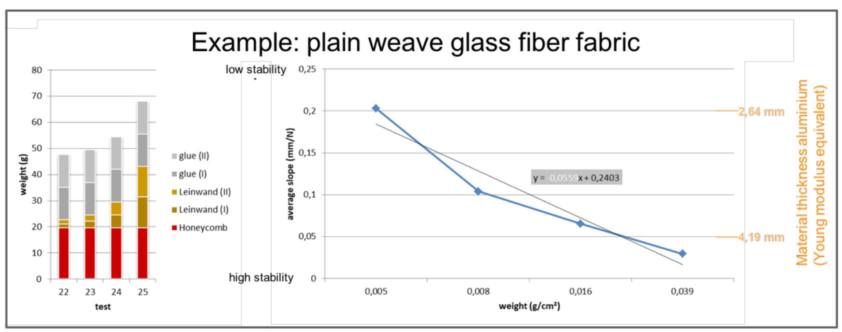
TPC Field Cage

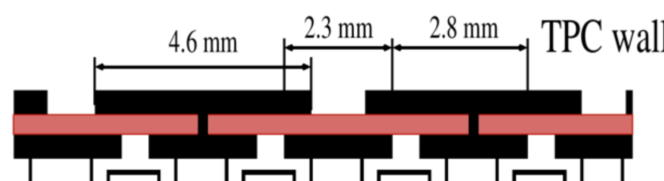
V2 TPC Large Prototype (LP)



- **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





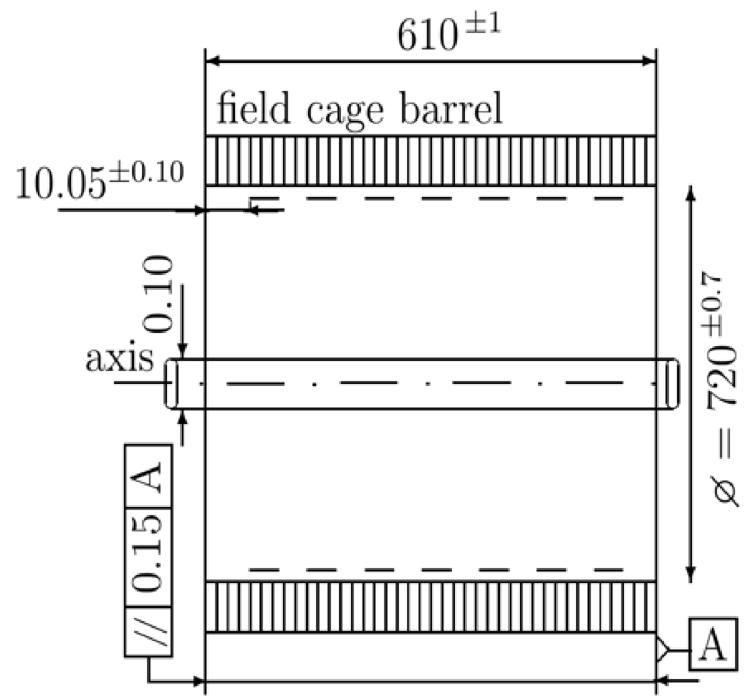


☞ Required resolution

- 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 ≤ 0.1mm
- cathode/anode $\| \leq 0.15$mm
- max. bending $\perp$ to Z (middle): ~ 0.02mm
- less critical: length to 1mm and $\varnothing$ to 0.7 mm

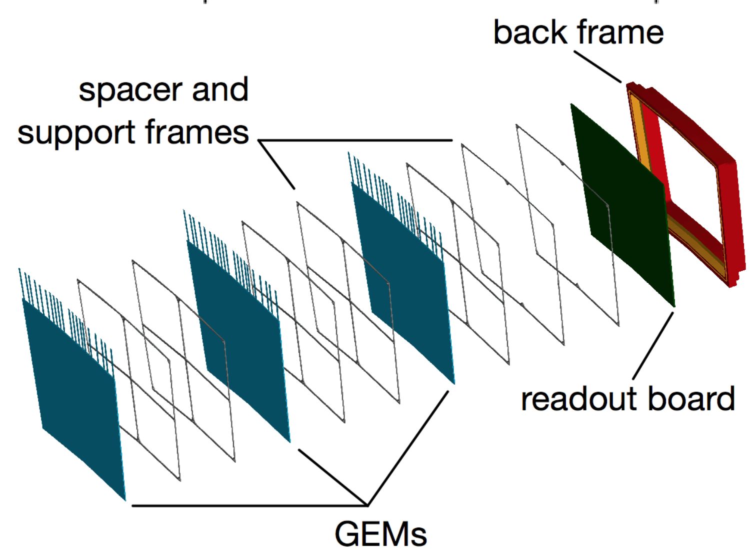


☞ ILD TPC (3.5x size/B field):

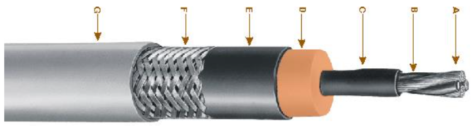
- axis alignment ≤ 0.3mm
- cathode/anode $\| \leq 0.45$mm

☞ 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)



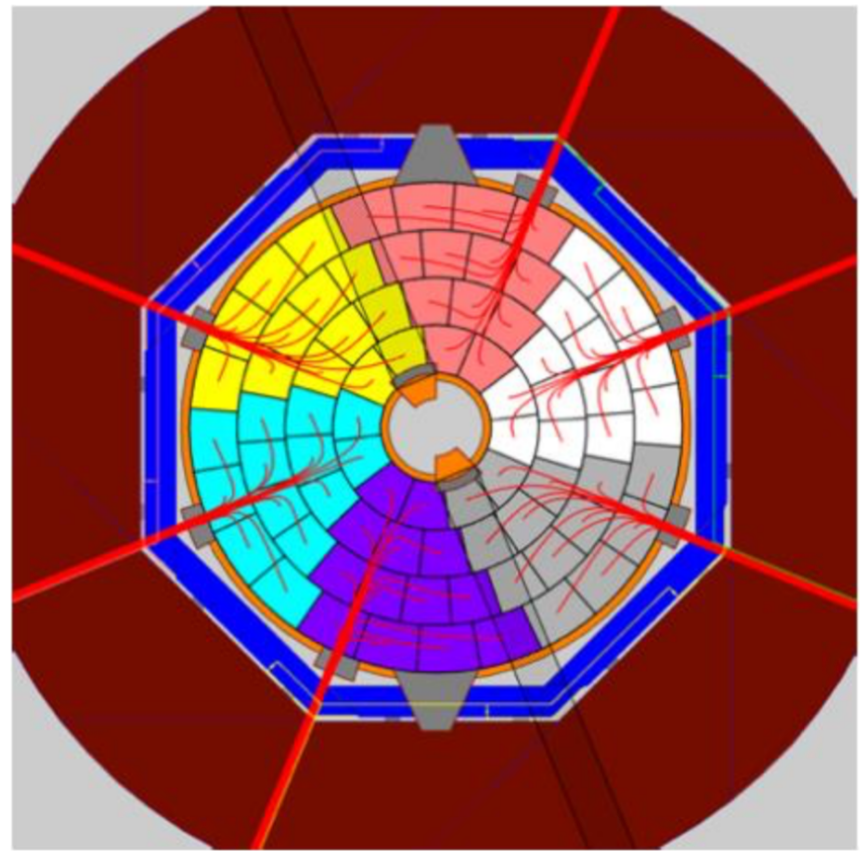
TPC Interfaces



- **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

Patch panels on each sector to allow disconnecting the TPC

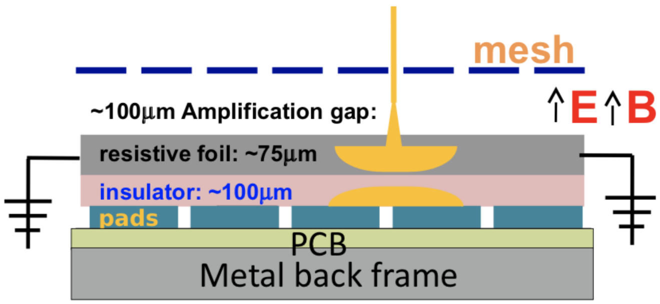


Possibly need a jacket against heat from the ECAL

Prototype Technologies (Resistive Micromegas)

☞ Pad size limits transverse resolution

➠ use resistive anode to spread charge



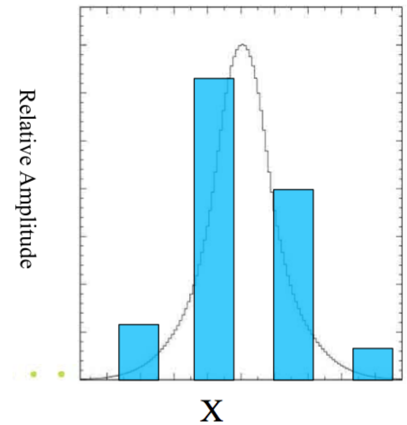
☞ Charge density function of time dependent charge dispersion on 2D continuous RC network:

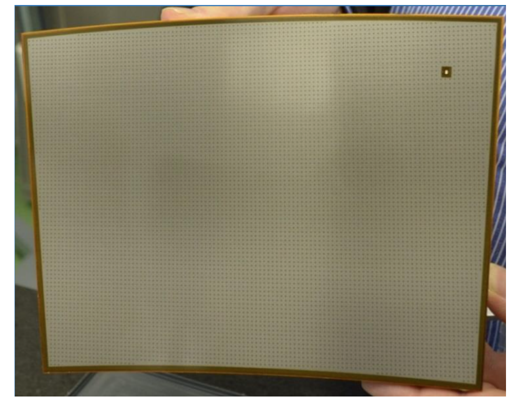
$$\rho(r,t) = \frac{RC}{2t}\exp[-\frac{-r^2RC}{4t}]$$

R- surface resistivity

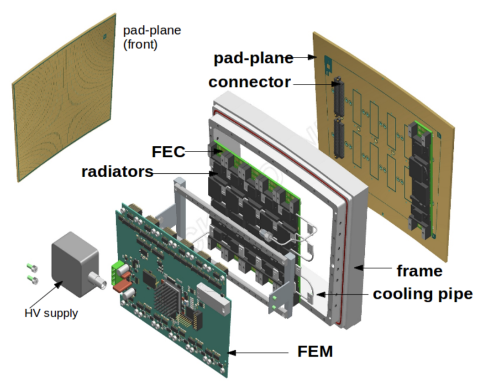
C- capacitance/unit area

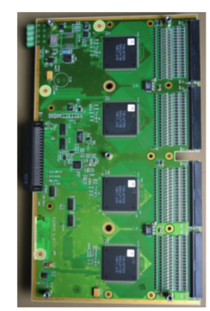
Relative fraction of charge seen by pads fitted by Pad Response Function (PRF)





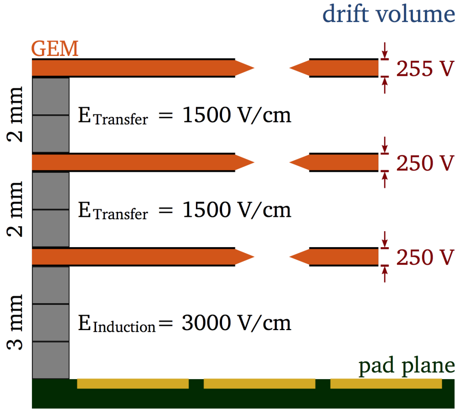
- **Module** { Module size: 22 cm × 17 cm; 24 rows × 72 columns **(1726 Pads)**; **Pad size: 3 mm × 7 mm**

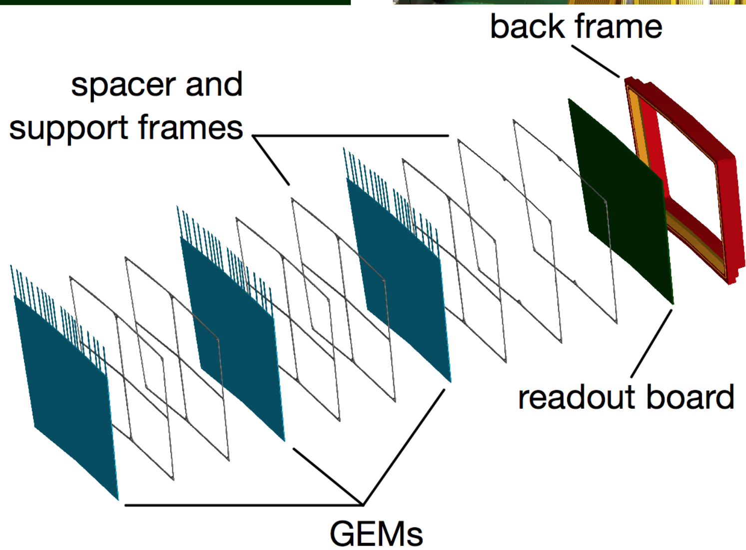




MM: T2K readout concept: *72-channel AFTER chip (12-bit)*

Triple GEM Modules

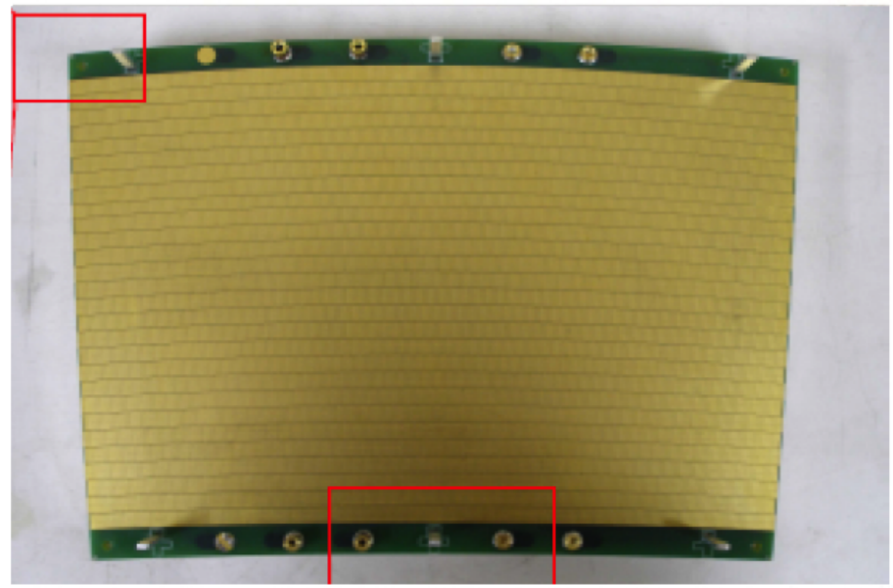


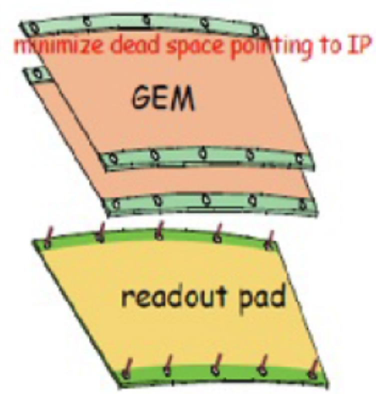


☞ **GEM: modified ALTRO readout**

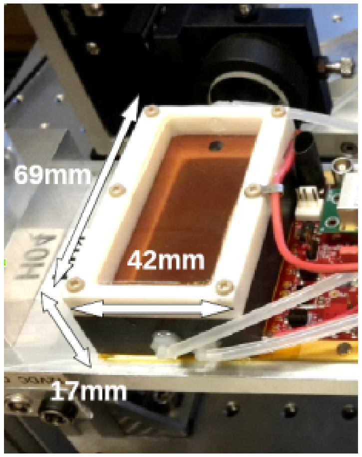
➠ 16-channel ALTRO chip (10-bit)

Double GEM Modules

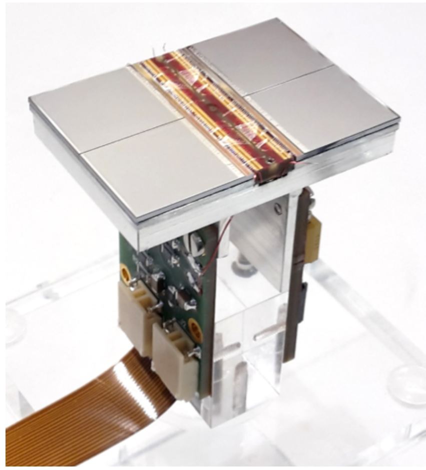




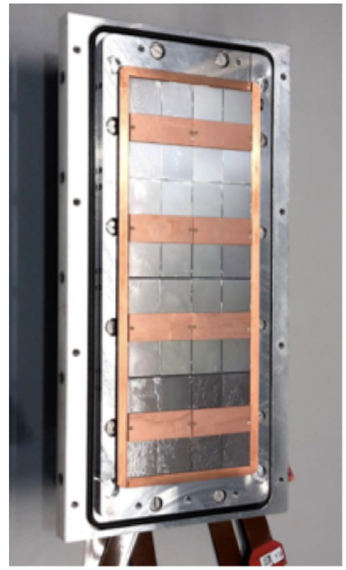
Single chip (2017)



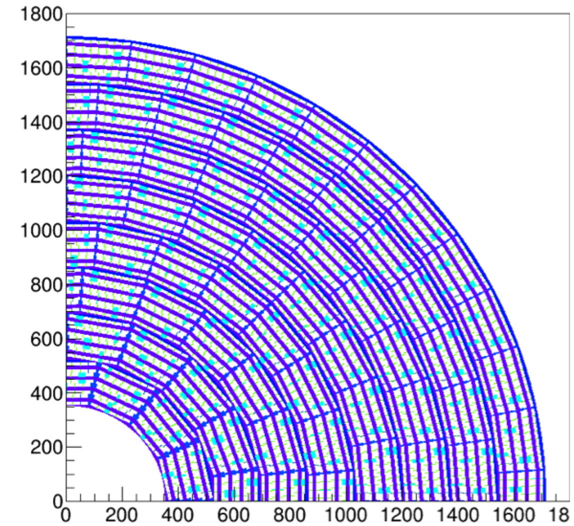
QUAD (2018)



Module (2019)

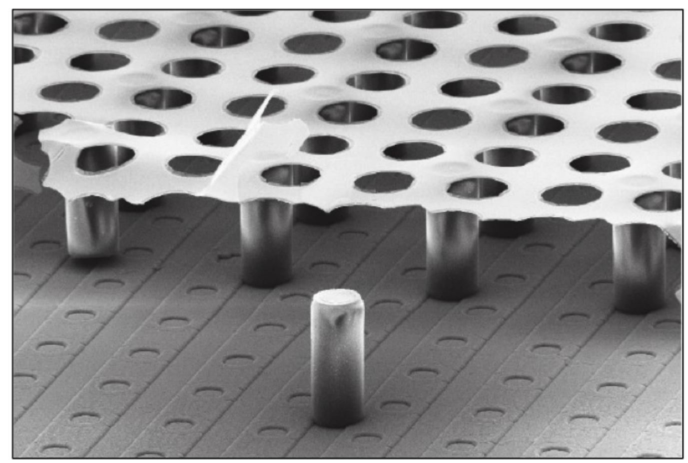


TPC Plane



☞ Micromegas on a pixelchip

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

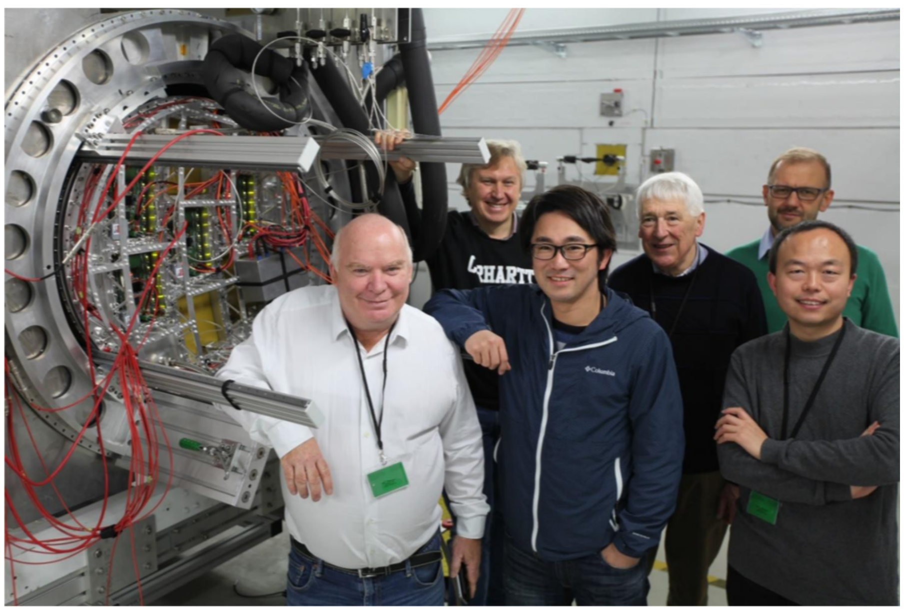


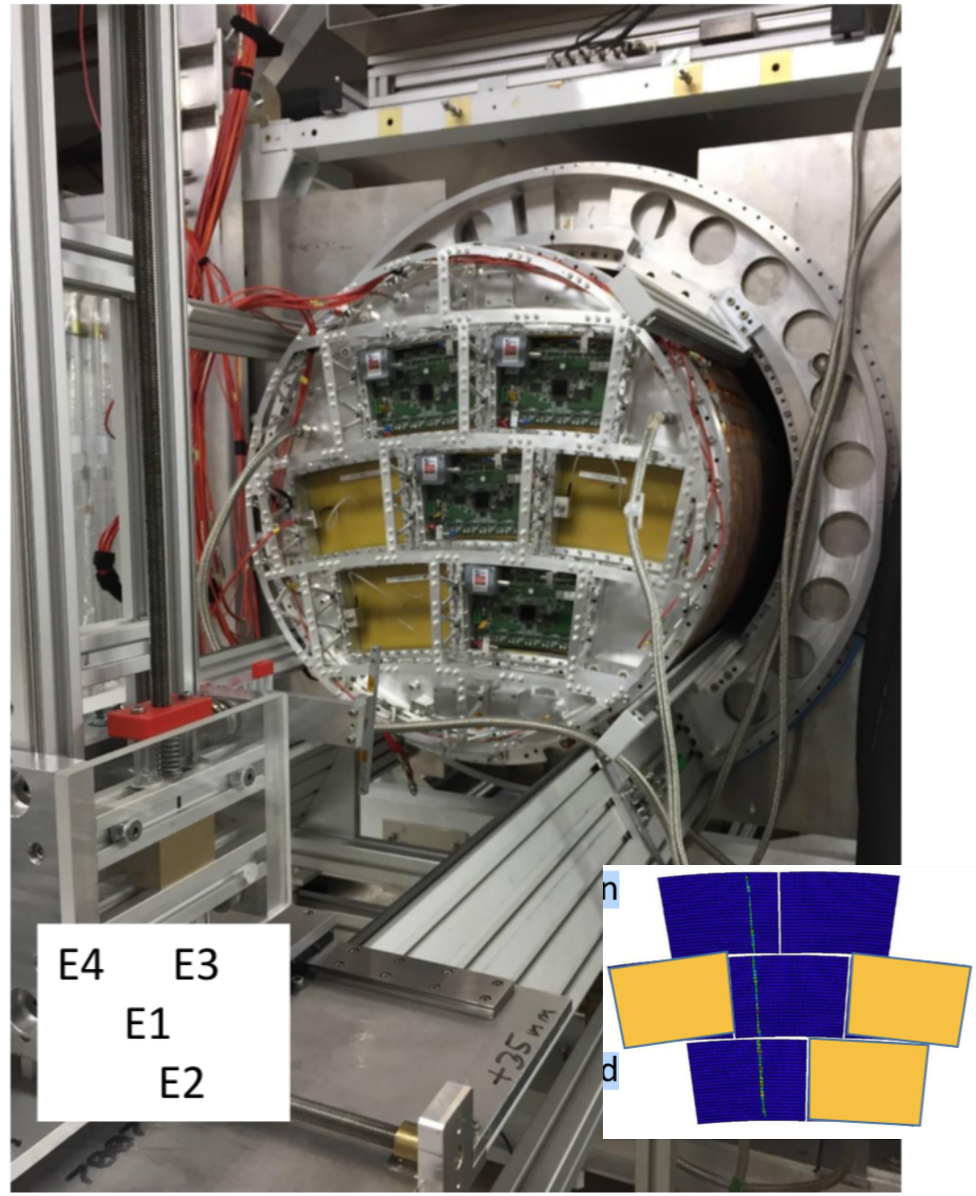
☞ New QUAD design: Four-TimePix3

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

4 new Micromegas modules tested in November 2018 at DESY facility

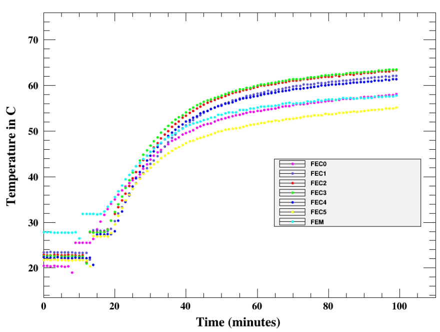
- new endplate LP2
- 1-loop 2-Phase CO_2 cooling
- improved mechanics:
  99.9% good connections
- **new grounding scheme:**
  encapsulated resistive anode

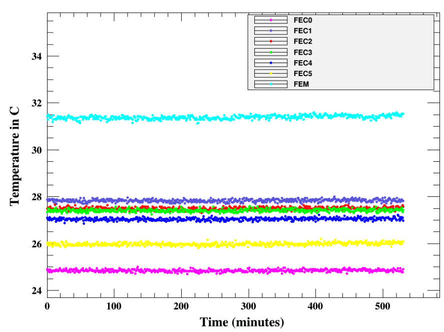




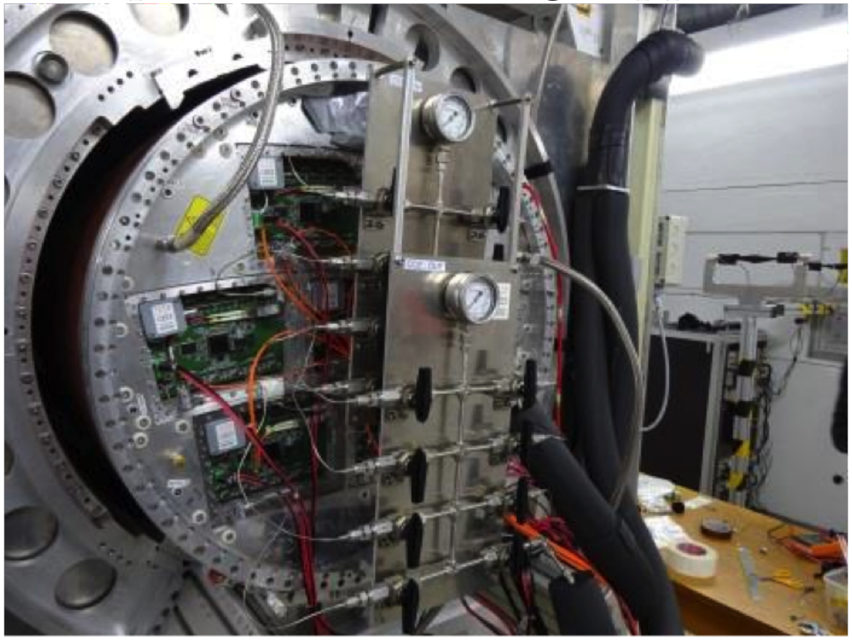
Cooling of the electronic circuit is required due to power consumption

- Temperature of the circuit rises up to 60°C
  - cause a potential damage of electronics
  - convect gas to TPC due to a 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

- **Saclay project "COSTARD"**
  - cooling plate by metallic additive fabrication by laser using sintered powder of Al with a 0.8 mm inner-diameter serpentine
    - → test possibility to remove the powder residuals from the serpentine
    - → test pressure up to 100 bar
    - → develop connection to pipes

Development of micro-channel cooling plate in PCB piping with 3D printing technology

Cooperation for industrial contacts for the ***micro-cooling circuit*** *option*

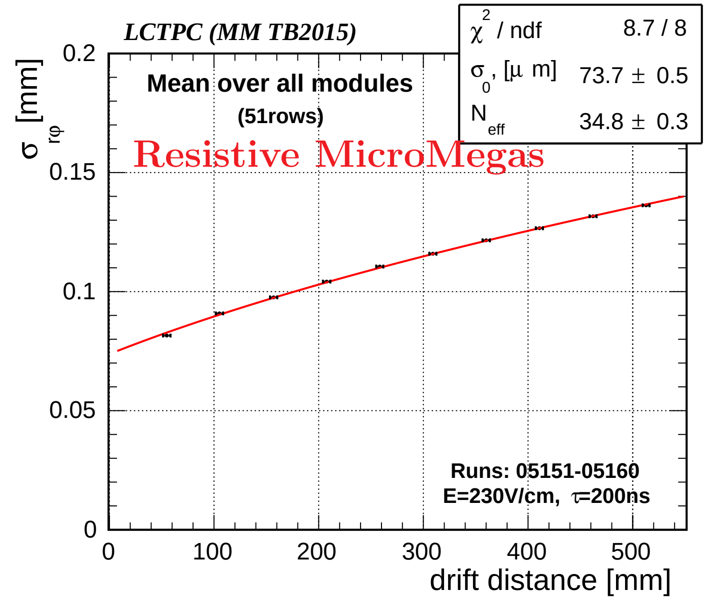
Prototype readout modules operate in a 1 T magnetic field

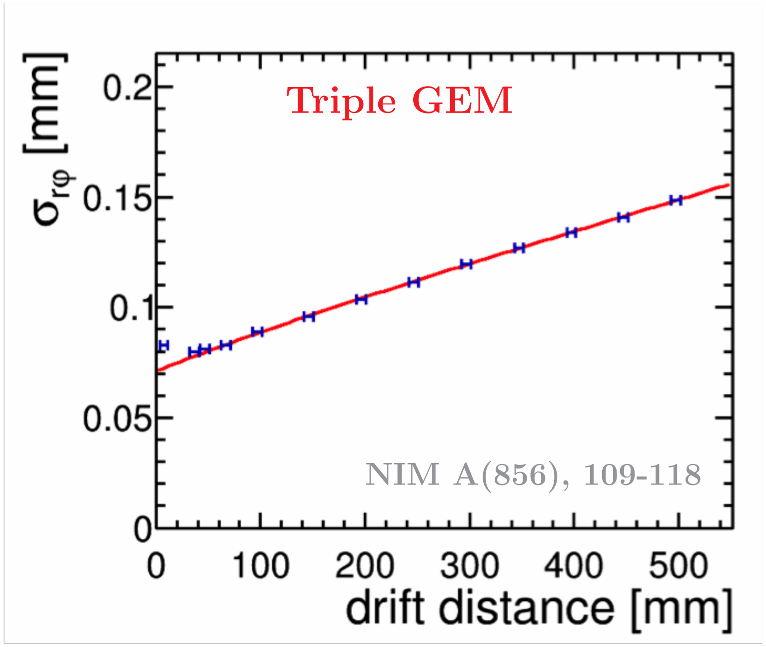
☞ **Fit data with:**

$$\sigma(z) = \sqrt{\sigma_0^2 + \frac{D_\perp^2}{N_{eff}} z}, \quad \sigma_0^2 = b^2/N_{eff}$$

- σ_0 - the resolution at $z = 0$,
  N_{eff} - the effective number of electrons
- Magboltz calculations of $D_\perp$ at about 3% precision

Extrapolation to a magnetic field of 3.5 T and 2.35 m drift length yield to a maximum 100 μm over the full drift length (tightly controlled gas quality and minimal impurities)

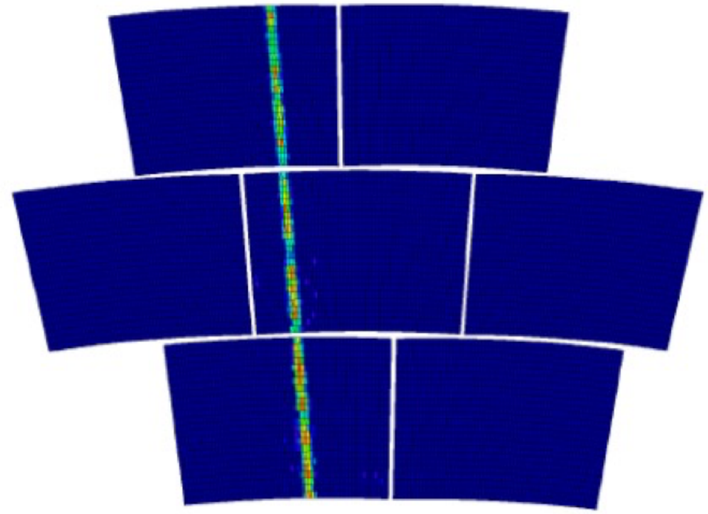


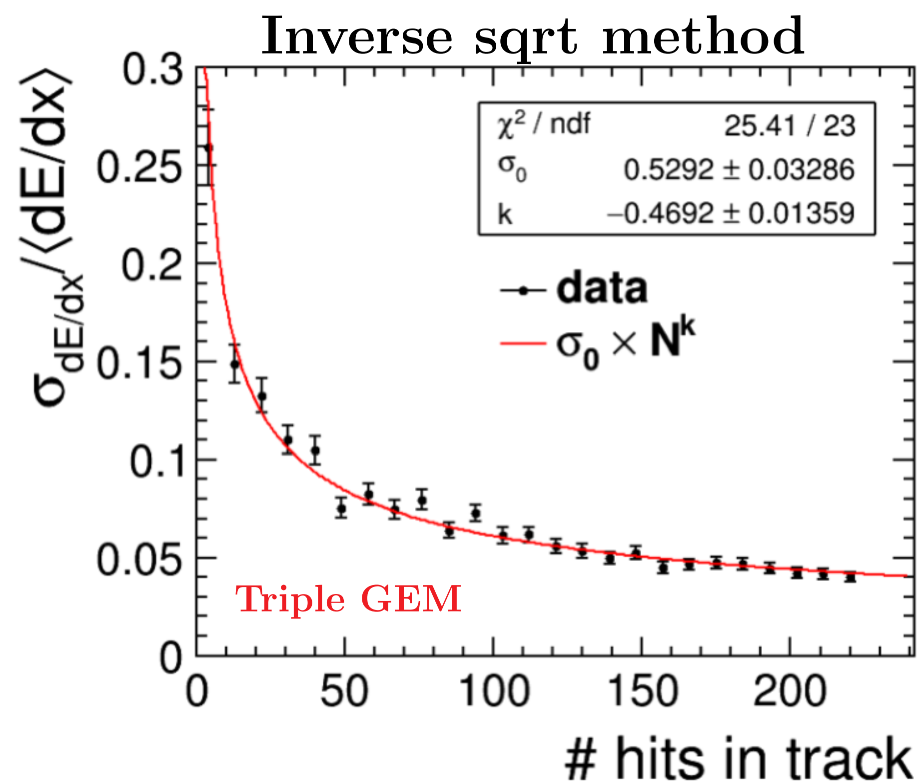


dE/dx Resolution

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

- Test arbitrary track lengths by randomly combining hits from several real tracks to a pseudo track in test beam setup
- Estimated dE/dx resolution with **70% truncated mean** for ILD TPC
  - GEM: $\sigma_{\mathrm{dE/dx}} = 4.1\%$ for 220 hits
    - ➔ no degradation due to gating GEM
    - ➔ good agreement with simulation
  - MM: $\sigma_{\mathrm{dE/dx}} = 4.5\%$ for 170 hits
    - ➔ no degradation due to resistive foil
- **Inverse sqrt** method for Triple GEM:
  - $\sigma_{\mathrm{dE/dx}} = 4.2\%$ for 220 hits (large ILD)
  - $\sigma_{\mathrm{dE/dx}} = 4.8\%$ for 165 hits (small ILD)

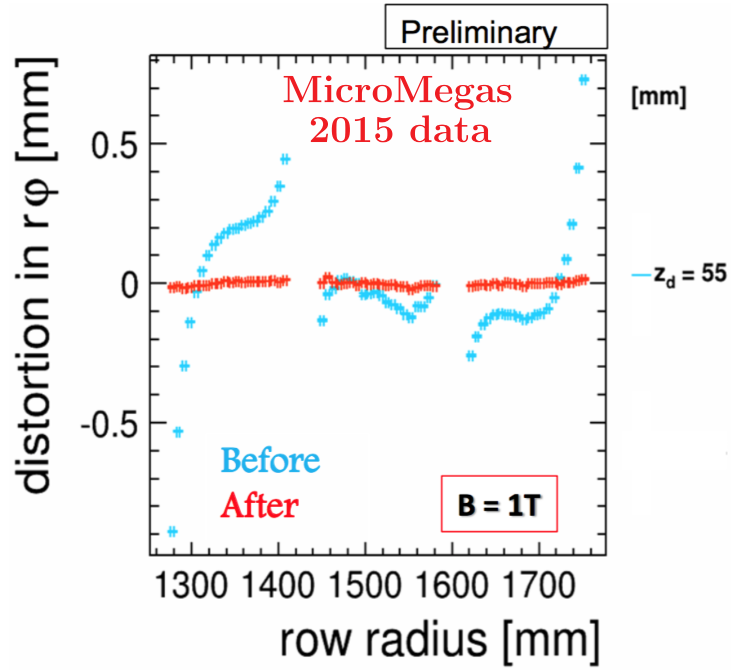


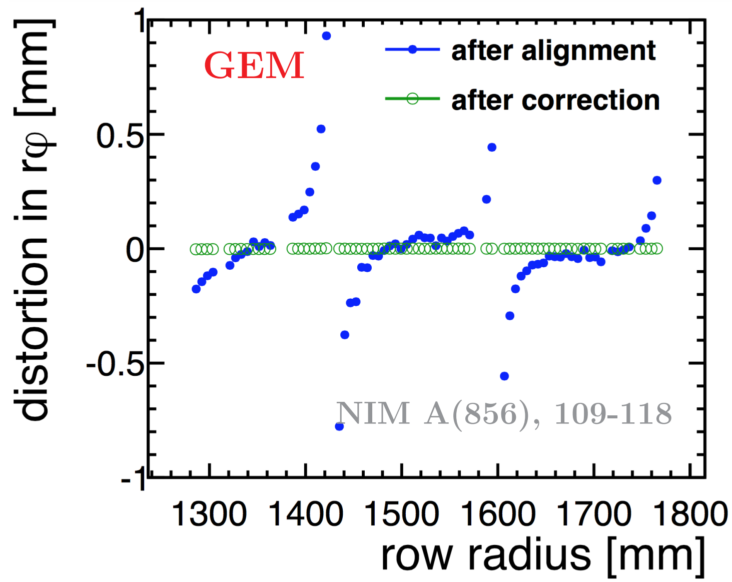


Non-uniform E-field near module boundaries induces ExB effects

- ☞ Track distortions in standard scheme
  - ➠ reach **about 0.5 mm** at boundaries
    ➔ worth to minimize at design level
  - ➠ accounted as systematic residual offsets
  - ➠ determined on a row-by-row basis
  - ➠ correct residuals to zero at **about 20μm**
- ☞ Good agreement with simulations
  - ➠ E and B field inhomogeneity at module boundaries and near the edges of the magnet
  - ➠ refine the simulation is ongoing

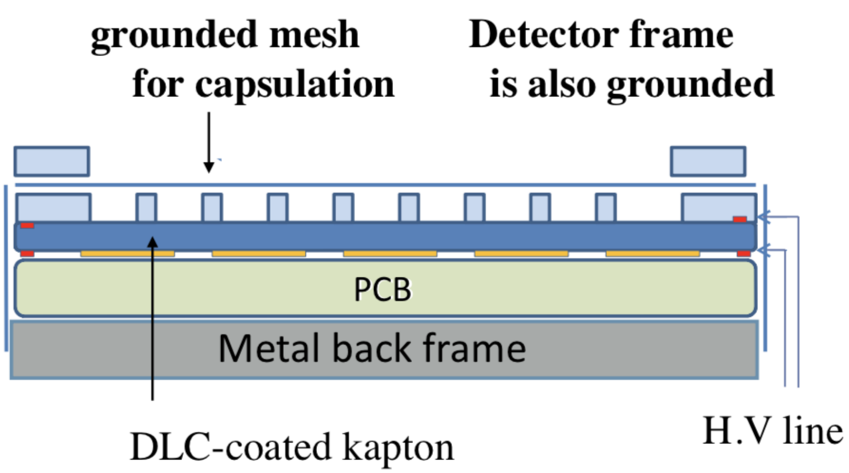
Crucial step toward possible countermeasures was done in 2018



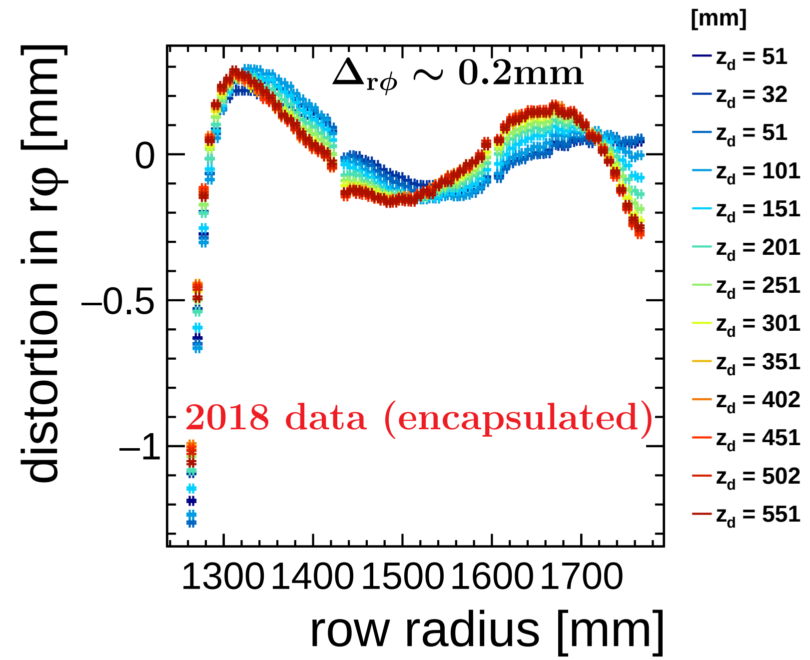


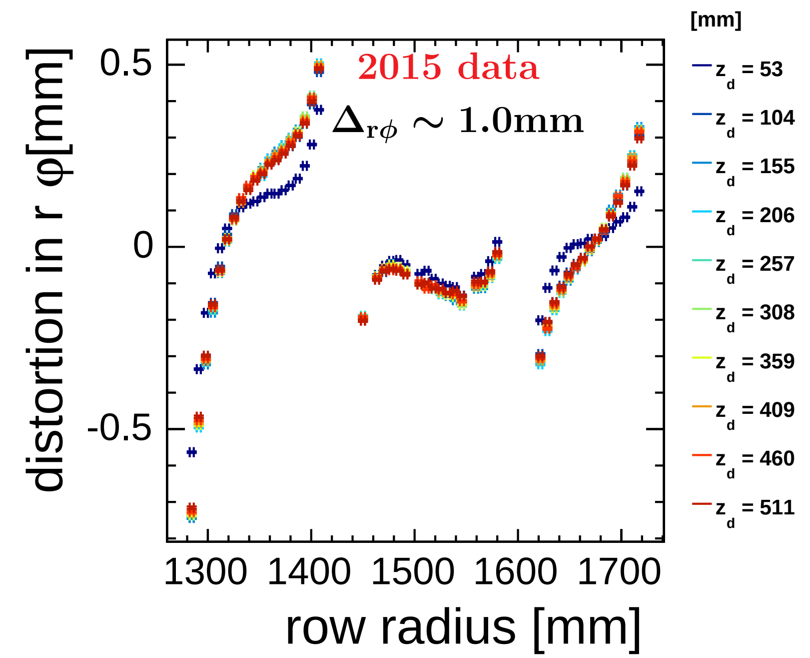
☞ New scheme to reduce distortions at the edges of modules

- mesh at ground
  - ➔ same potential as the frame
- resistive anode at the +ve HV
- the amplification field can be tuned independently of the drift field
- the gains can be equalized while keeping the drift field very uniform



ExB effect between modules is fully suppressed in the new scheme





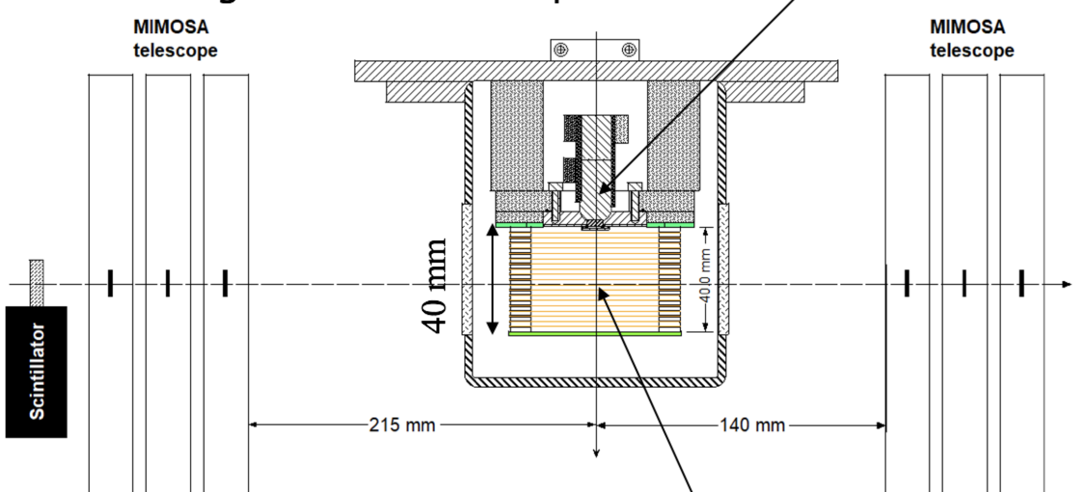
QUAD test beam in Bonn (October 2018)

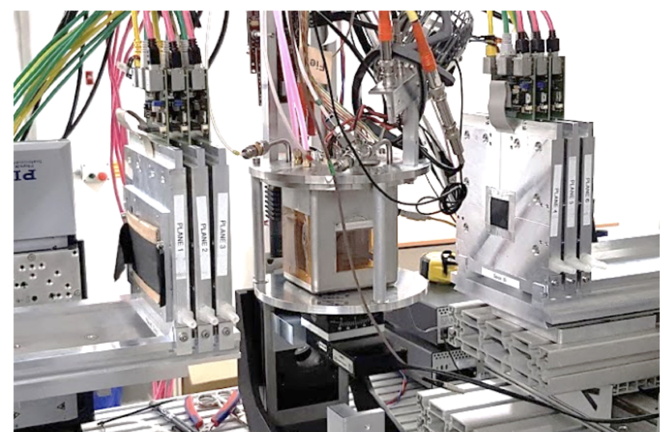
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 280 V/cm, V_{grid} = -300 V
- Typical beam height above the chip: ~1 cm

QUAD

guard

@Bonn





Field cage

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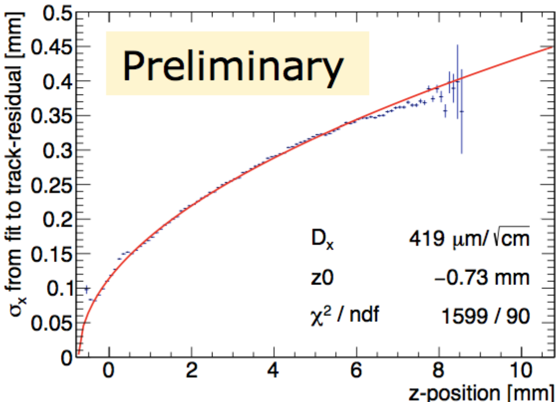
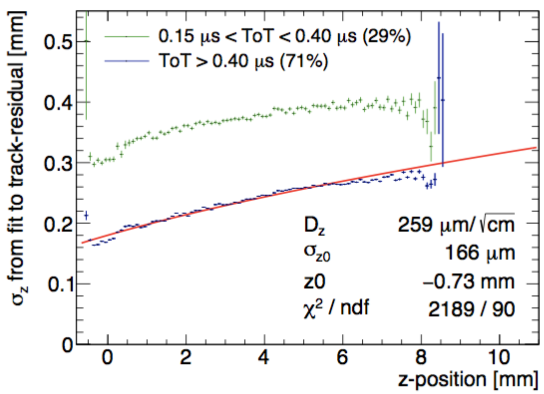
QUAD single hit resolution

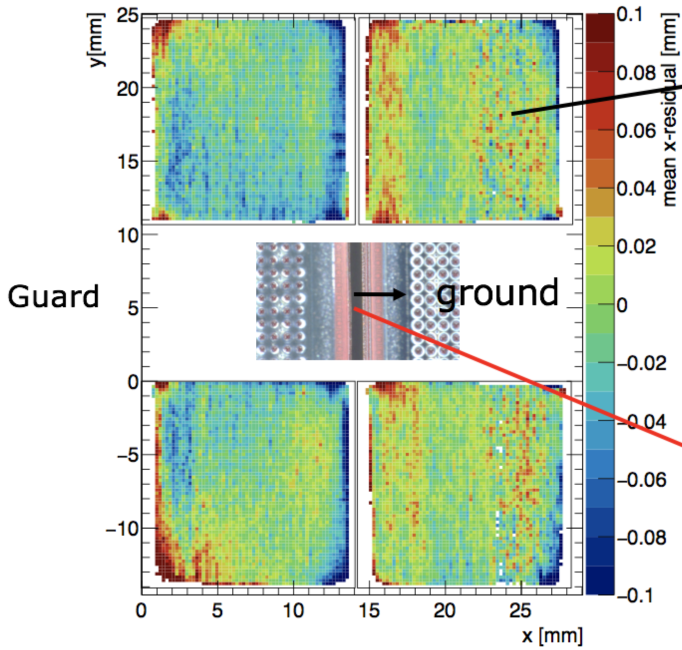
Transverse

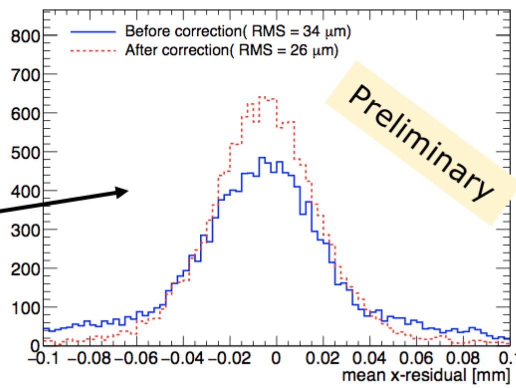


Longitudinal



Quad top view
Transverse deformations





- RMS of the mean residuals are 26 μm over the whole QUAD
- For module: add proper guard wire electrode over chip boundaries

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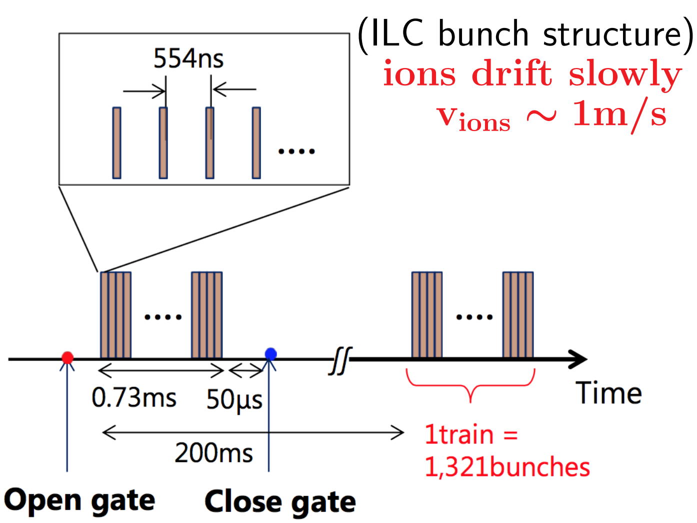
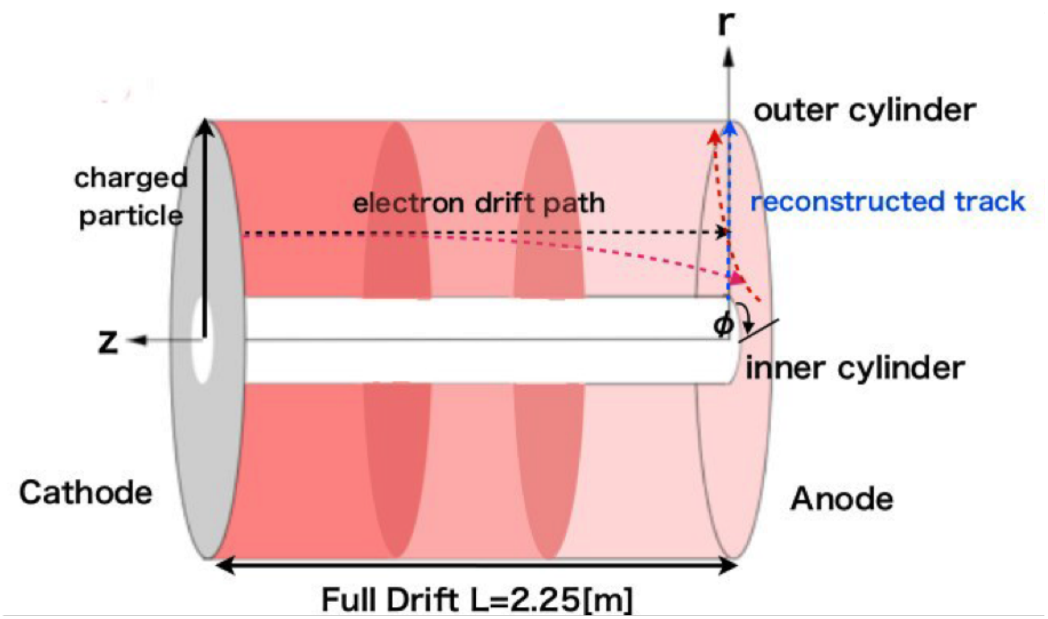
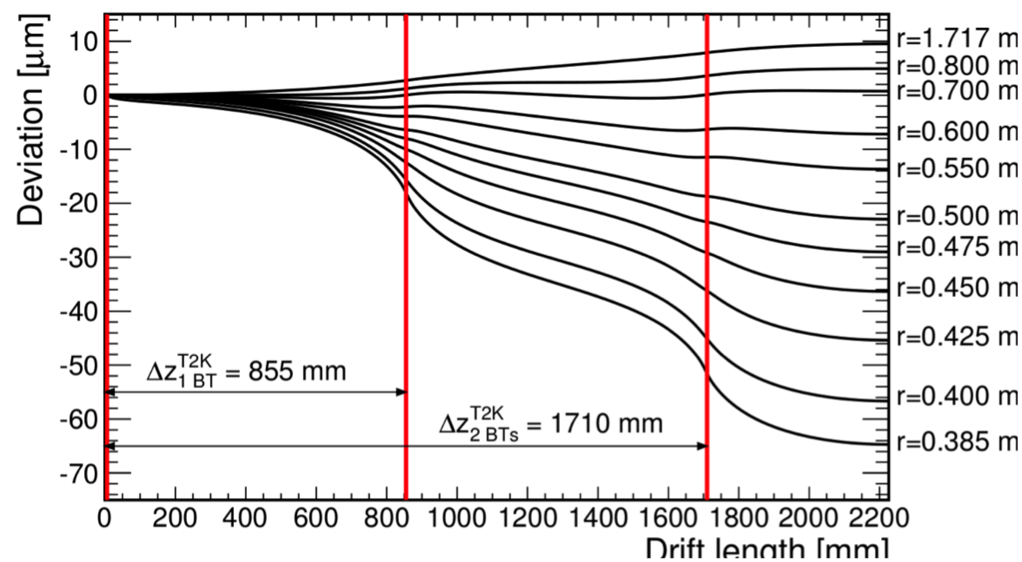
Ion Space Charge can deteriorate the position resolution of TPC

- **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



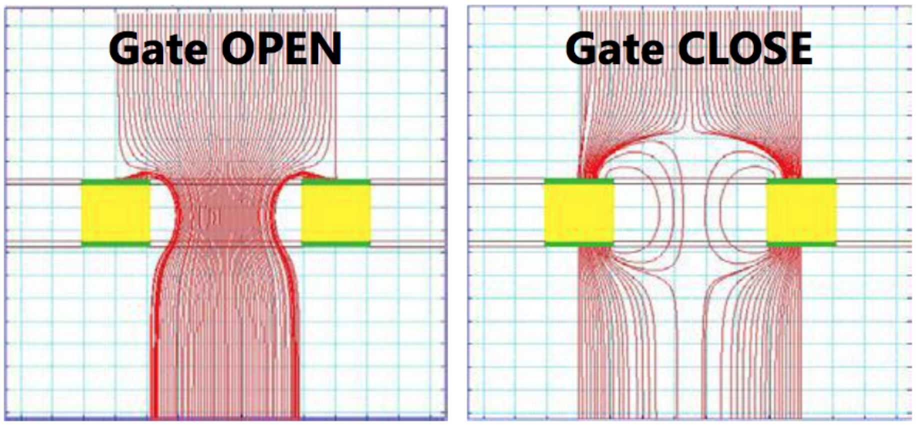


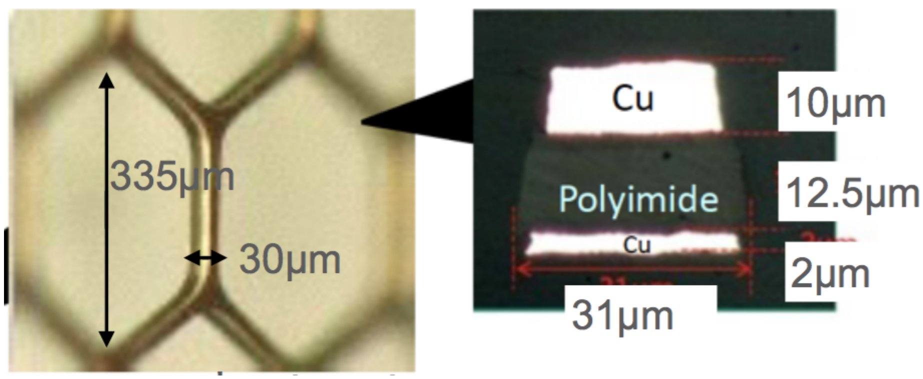


Gate is needed!

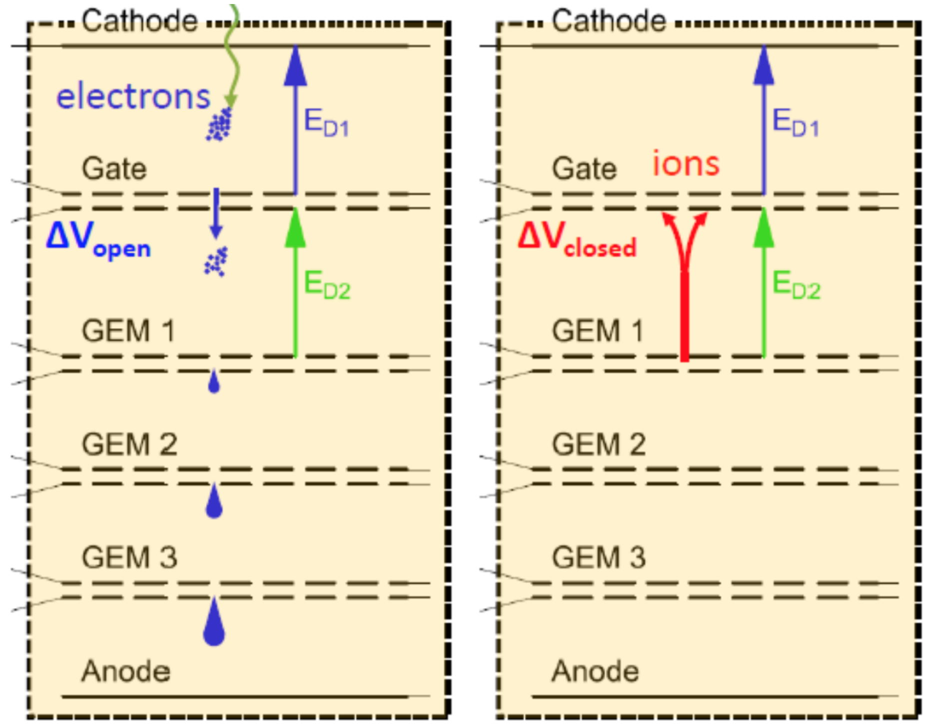
Ion Gating

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





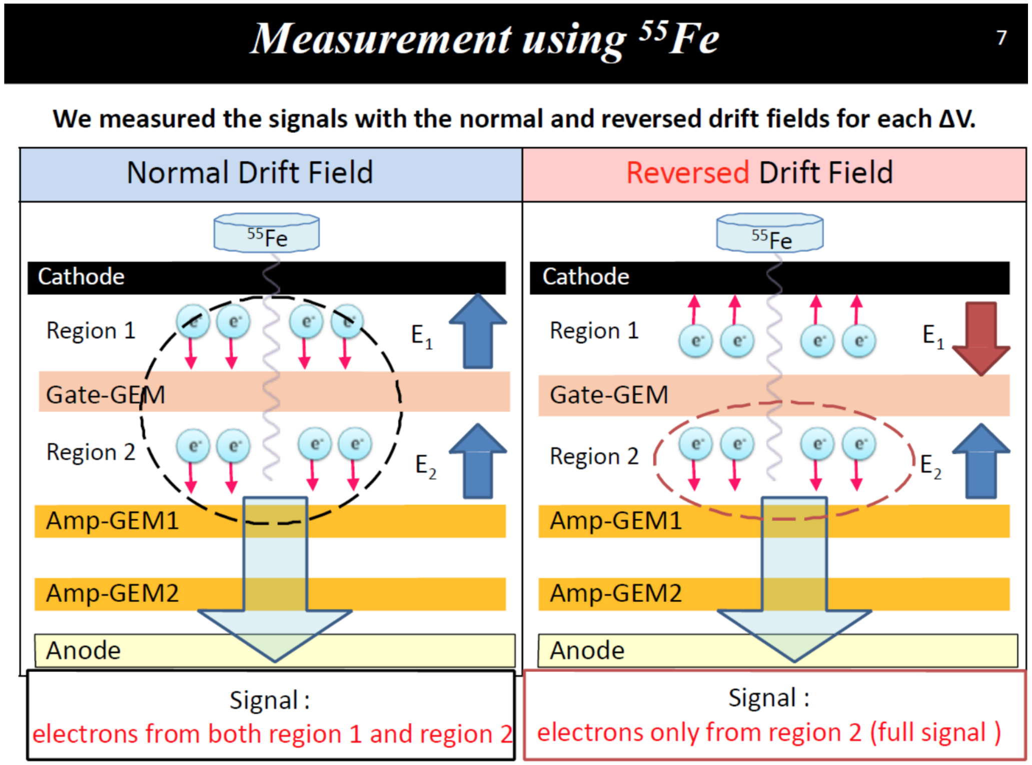
☞ A large-aperture gate-GEM with **honeycomb-shaped holes**

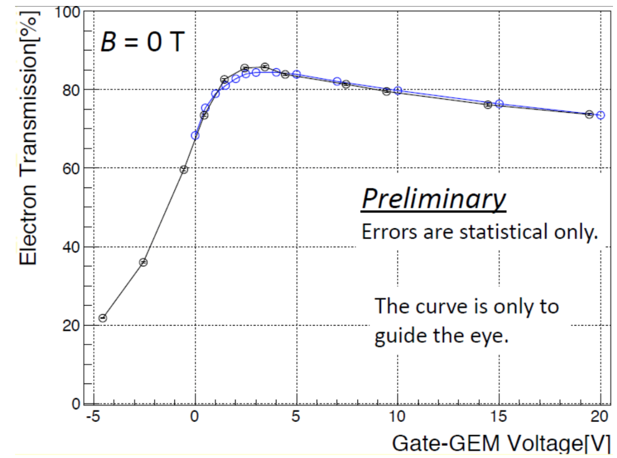


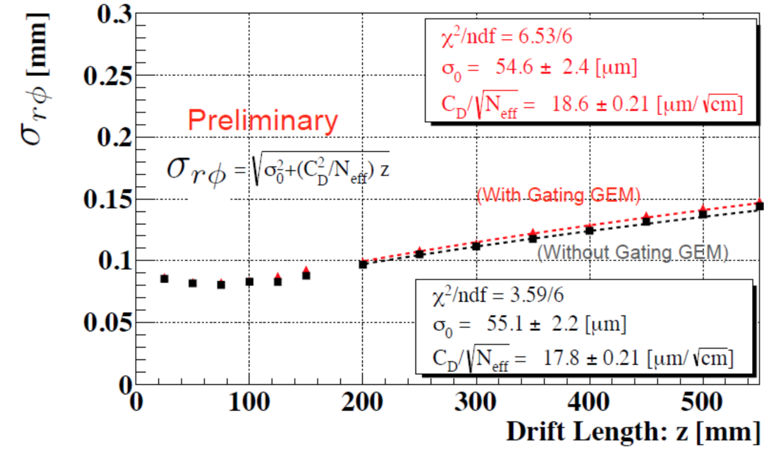
The ions must be stopped before penetrating too much the drift region

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%)

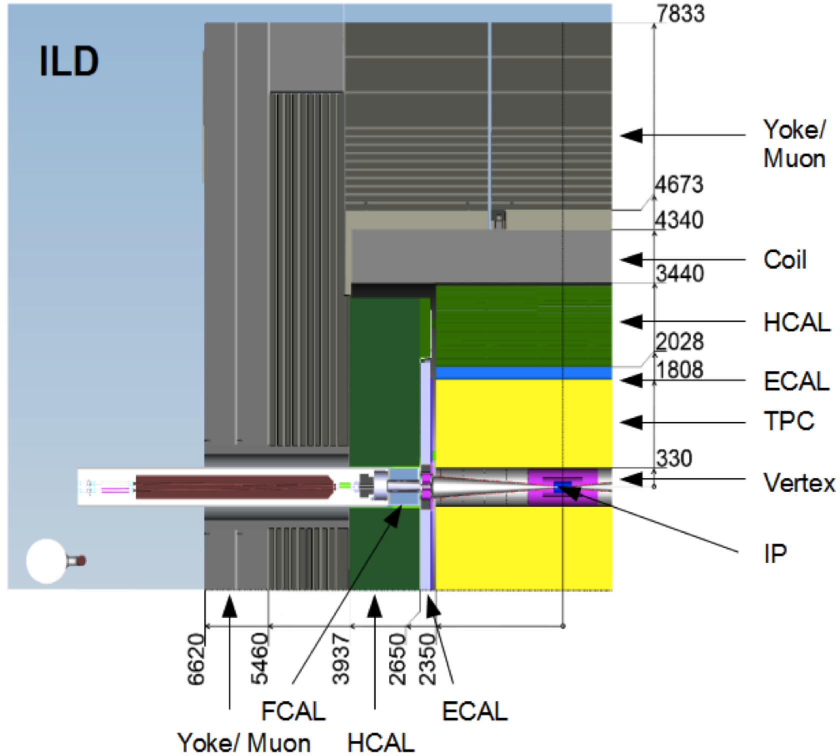
➠ *M. Kobayashi, et al.*, **NIM A (918), 41-53**

Conclusions

- A lot of experience has been gathered in building and operating MPGD TPC panels within the LCTPC collaboration
- The characteristics of the MPGD studied in detail, results indicate that it meets ILC requirements
  - The R&D work is in a phase of engineering toward the final design of a TPC for the ILD detector
- **Highlights 2018 for ILD TPC**
  - **TPC mechanics:** static deformations under weight and pressure, wall structure, new solution for TPC fastening
  - **ILD integration studies:** interfaces, scheme to assemble and test the detector in Kitakami, revision of the costing
  - **R&D and analysis:** dE/dx studies for 4 technologies, gating, new beam tests, distortion studies, 2-track separation

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)

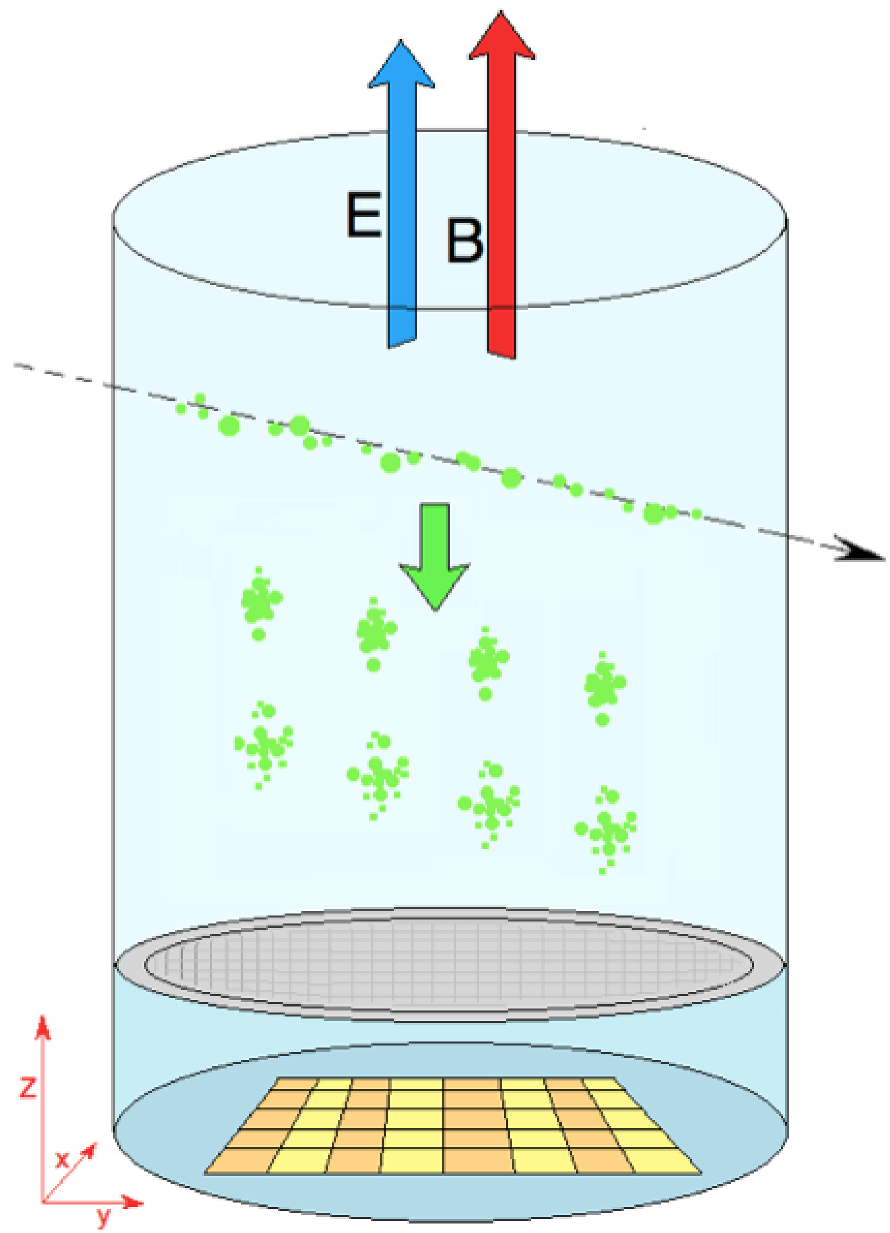


- **ILD components:**
  - vertex detector
  - few layers of silicon tracker
  - **gaseous TPC**
  - ECAL/HCAL/FCAL
  - superconducting coil (3.5 T)
  - muon chambers in iron yoke

- **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: $\sigma_E/E \sim 3-4\%$

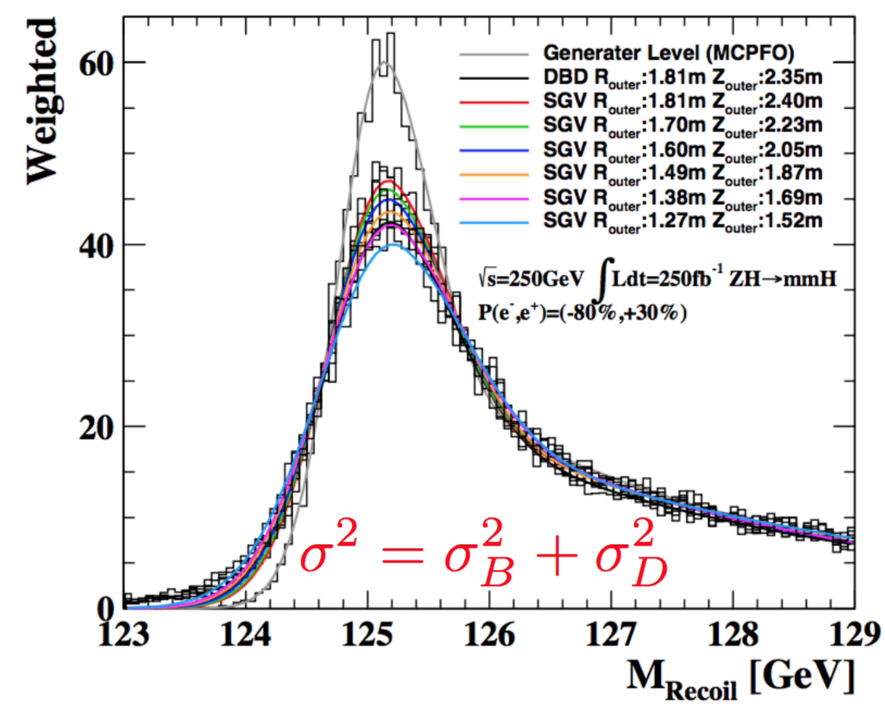
A Time Projection Chamber (TPC) is a detector consisting of a cylindrical gas chamber and a position sensitive readout endcaps

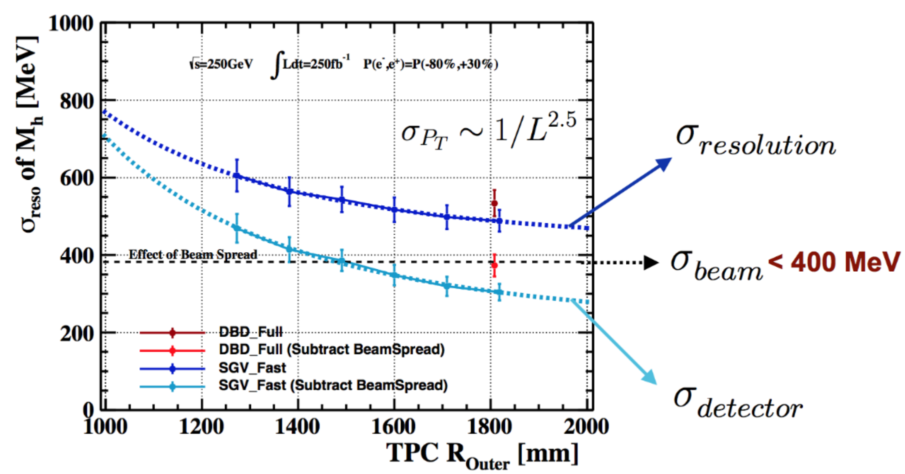
- **The TPC acts as a 3D camera taking a snapshot of the passing particle**
- **Transverse and Longitudinal** resolutions are major characteristics of the TPC
  - **XY position:** charged particles ionize the gas, a longitudinal electric field causes ionization e^- to drift towards endcap where they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



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

- 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 $e^+e^- \rightarrow Z(ll)X$
  - driven by both **beam spread** (σ_B) and **momentum resolution** (σ_D)
  - → σ_B = **400 MeV** from TDR
  - → σ_D = **300 MeV** at R_{out} = 1.8 m
  - → σ_D = **400 MeV** at R_{out} = 1.4 m





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

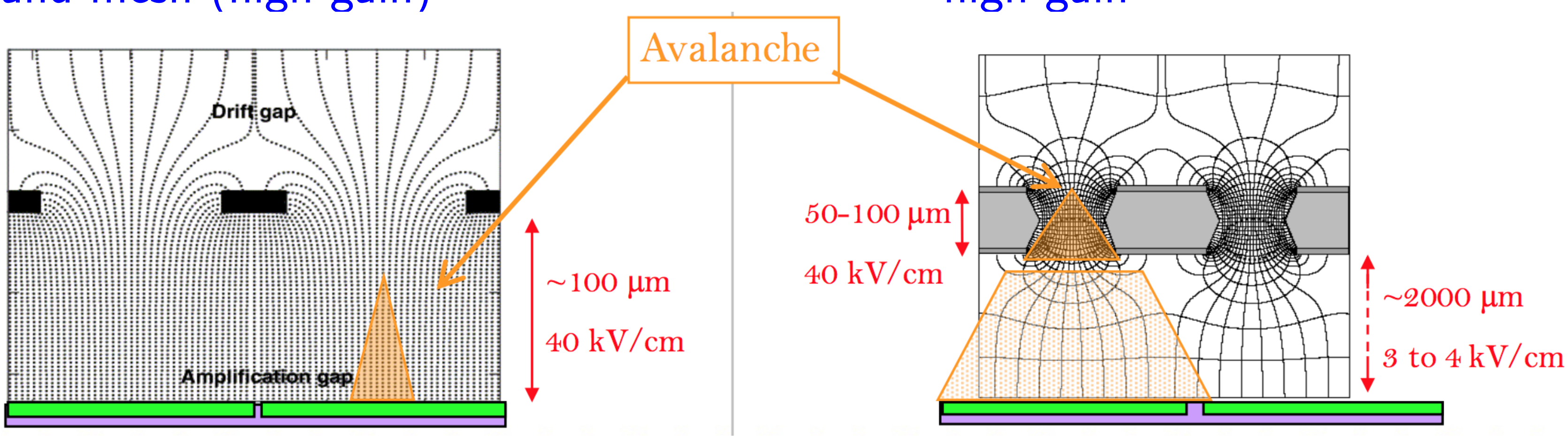
- **no ExB effect, better ageing, low ionback drift**
- easy to manufacture, MPGD more robust mechanically than wires

☞ **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



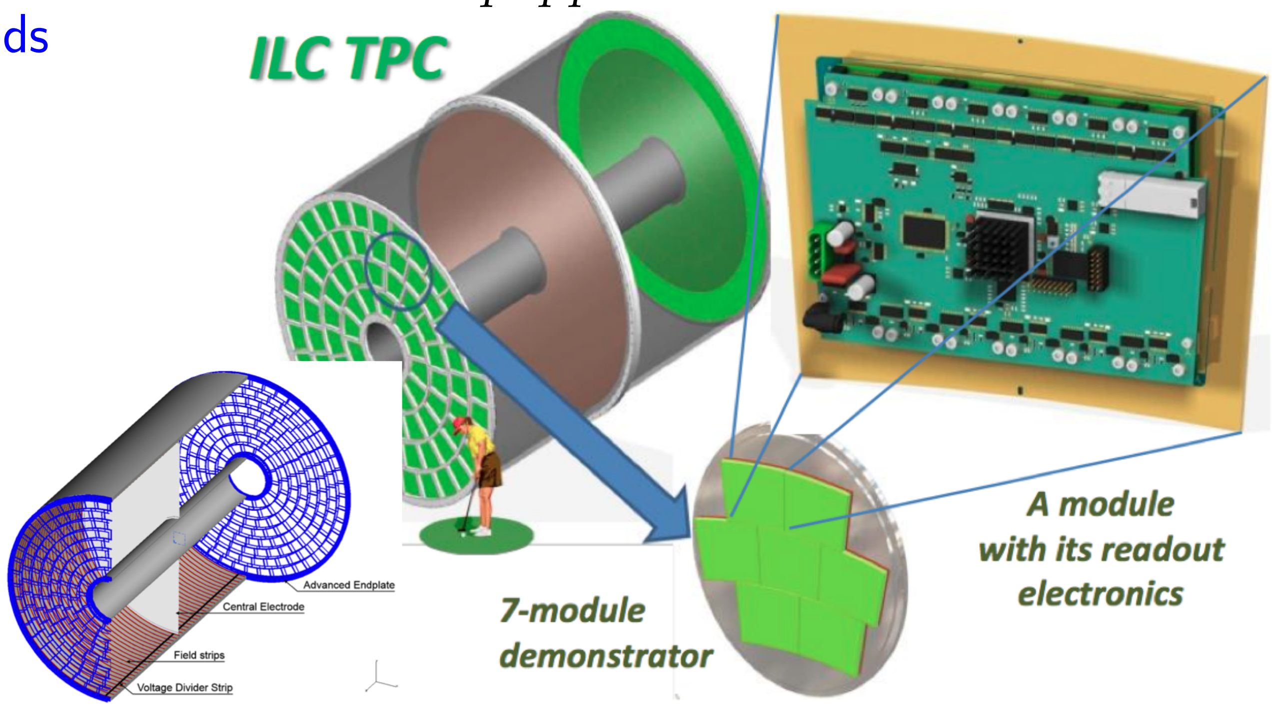
Discharge probability can be mastered (use of resistive coatings, several step amplification, segmentation)

Large Prototype at DESY

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

- **Two options for endplate readout with pads:**
  - GEM: 1.2x5.8 mm^2 pads
  - MM: 3x7 mm^2 pads
- **Alternative:**
  pixel readout with pixel size $\sim$55x55 $\mu\mathrm{m}^2$ (newest)

Consists of a field cage equipped with an endplate with 7 windows to receive up to 7 fully equipped identical modules

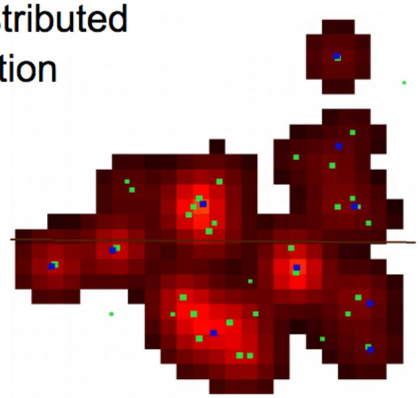


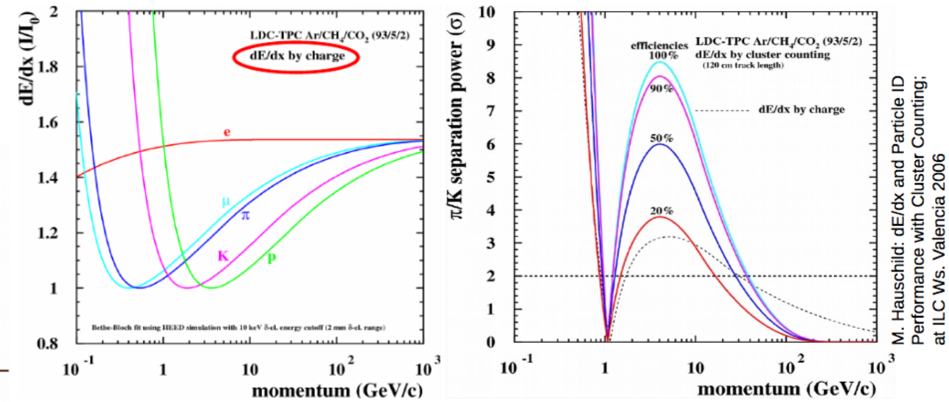
LP readout modules operate in a 1 T magnetic field

Different layouts are considered for ILD: 4-wheel and 8-wheel scheme

dE/dx - High Granularity and Cluster Counting

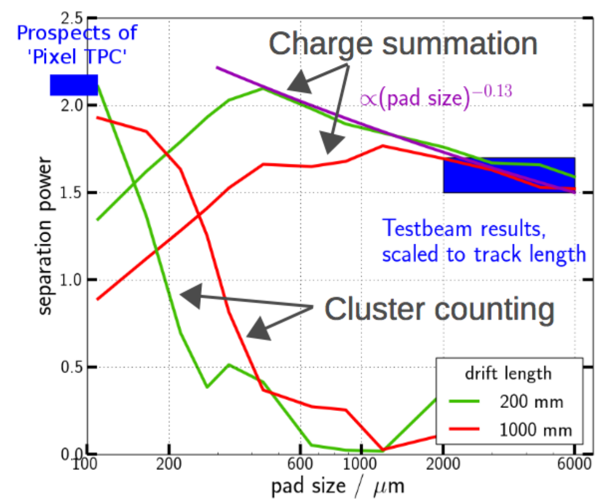
- Charge on a track distance Landau distributed, number of ionizations Poisson distributed
  → smaller RMS → better correlation
  → better particle identification
- Counting clusters allows for improved particle separation depending on cluster counting efficiency → high granularity



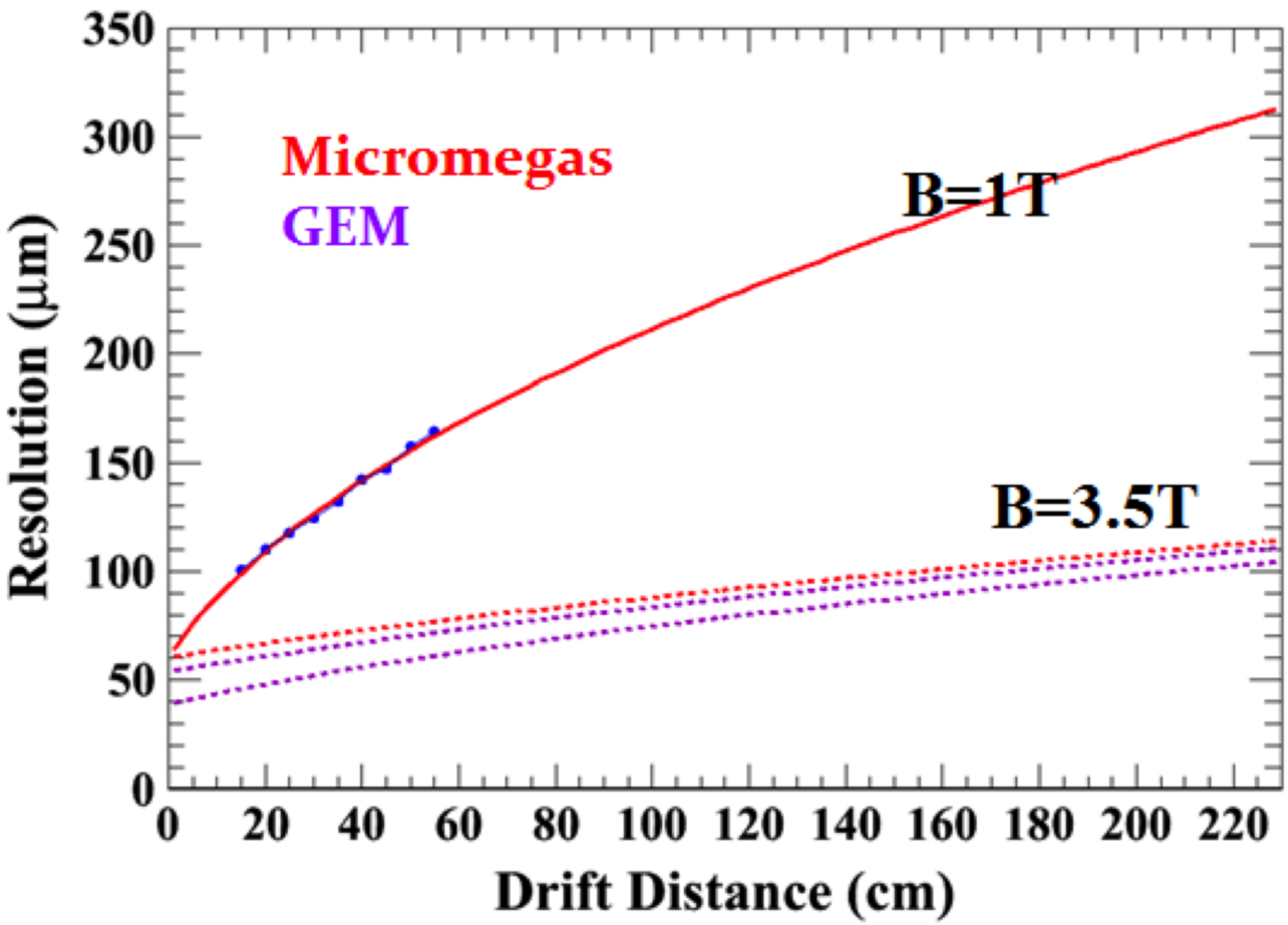


- Simulation studies (using GEM amplification)
  - Multiple (squared) pad sizes from 100 μm to 6 mm
  - Comparison of charge summation and cluster counting studying Pion-Kaon separation power

    → Cluster counting is working at high granularity (pads < 300 μm)
  - Very good agreement on both edges of the studied spectrum, for classical pad readout as well as Timepix pixel readout results



Extrapolate to B=3.5T



Micromegas 3x7mm^2 pads and GEM 1.2x5.8mm^2 pads

Facility Upgrade: Large Prototype 2 (LP2)

☞ **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
  - ➔ $0.3\%\text{X}_0$ 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

The sensor is a silicon strip sensor designed by SLAC for an ILC environment:

- 10x10 cm² active area

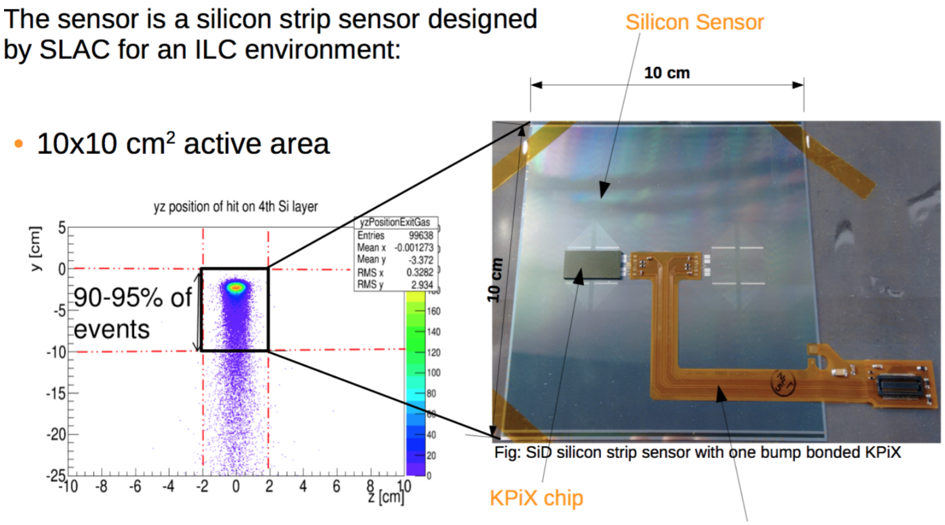
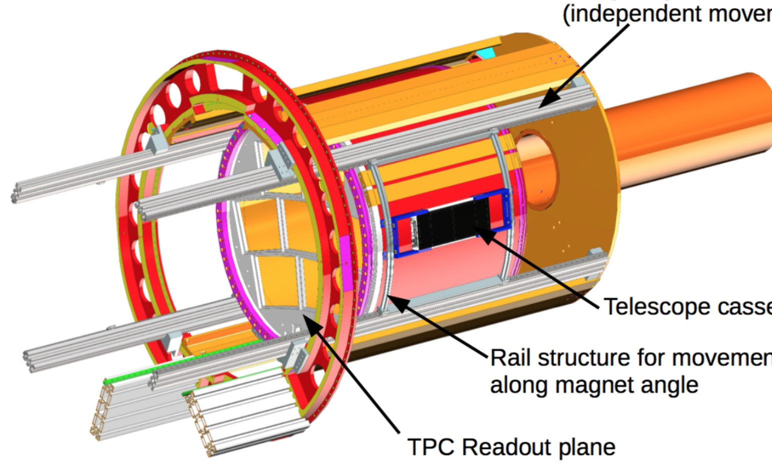


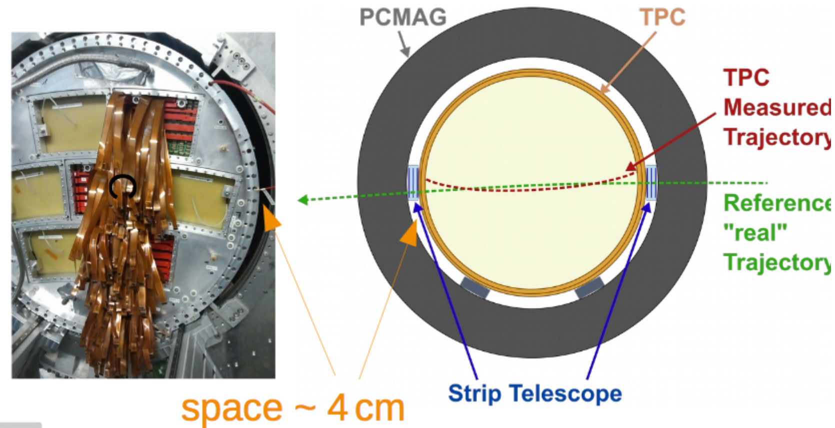
Fig: SiD silicon strip sensor with one bump bonded KPiX

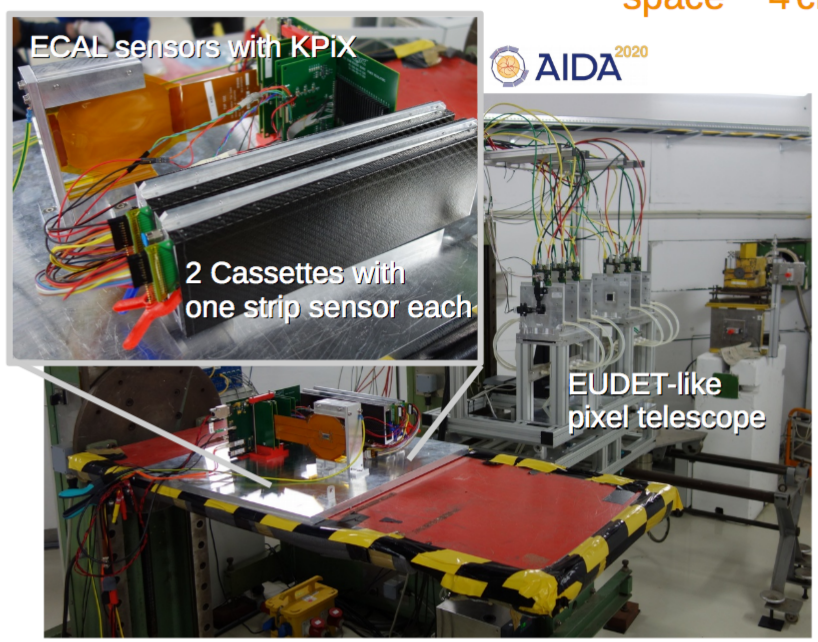


Final dimension of the active area is 10x20 cm²

Lycoris - External Silicon Tracker

- External Si-strip tracker as reference for the TPC prototype
  - Momentum and field distortion studies
  - To be installed in 1 T solenoid at the DESY II test beam
- Successful test beam with 2 sensors
  - System working
  - Efficiency currently ~ 30% → being improved
  - Software progressing: DAQ and reconstruction
  - Last pieces coming together
    - Boards / cables for mounting in final mounting cassette
    - Final DAQ boards, TLU
    - Mechanical mounting structure





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