Central Tracker Based on TPC for the Future Machines

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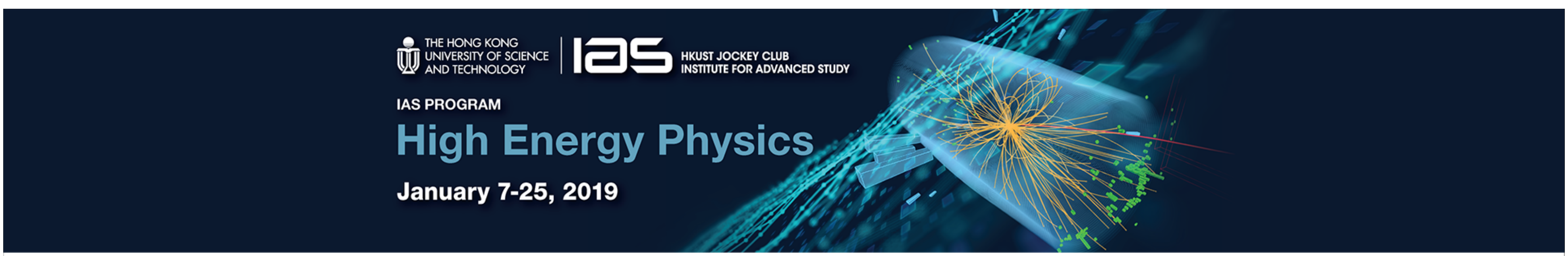


Future Large Scale Accelerators

Possible High Energy Frontier Machines

☞ Next generation linear collider in **Japan**

- ➠ **International Linear Collider-ILC:**
  e^+e^- collisions up to 1 TeV

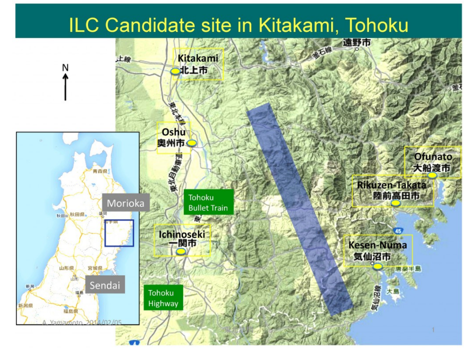
☞ Post-LHC accelerator projects at **CERN**

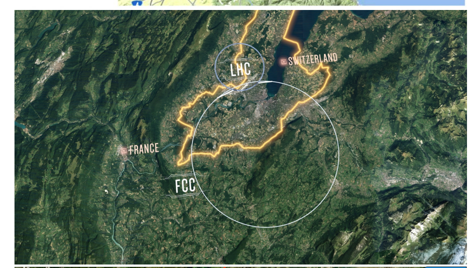
- ➠ **Future Circular Collider-FCC:**
  FCC-hh (100 TeV), FCC-e^+e^- (350 GeV), possibly ep
- ➠ **Compact LInear Collider-CLIC:**
  e^+e^- collisions up to 3 TeV

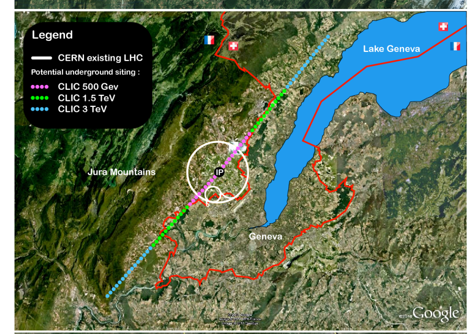
☞ Circular Collider project in **China**

- ➠ **Circular Electron Positron Collider-CEPC:**
  CEPC e^+e^- (250 GeV), SppC pp collider (100 TeV)

Extensive R&D program for TPC (LCTPC) is advanced for ILC aimed to demonstrate its feasibility

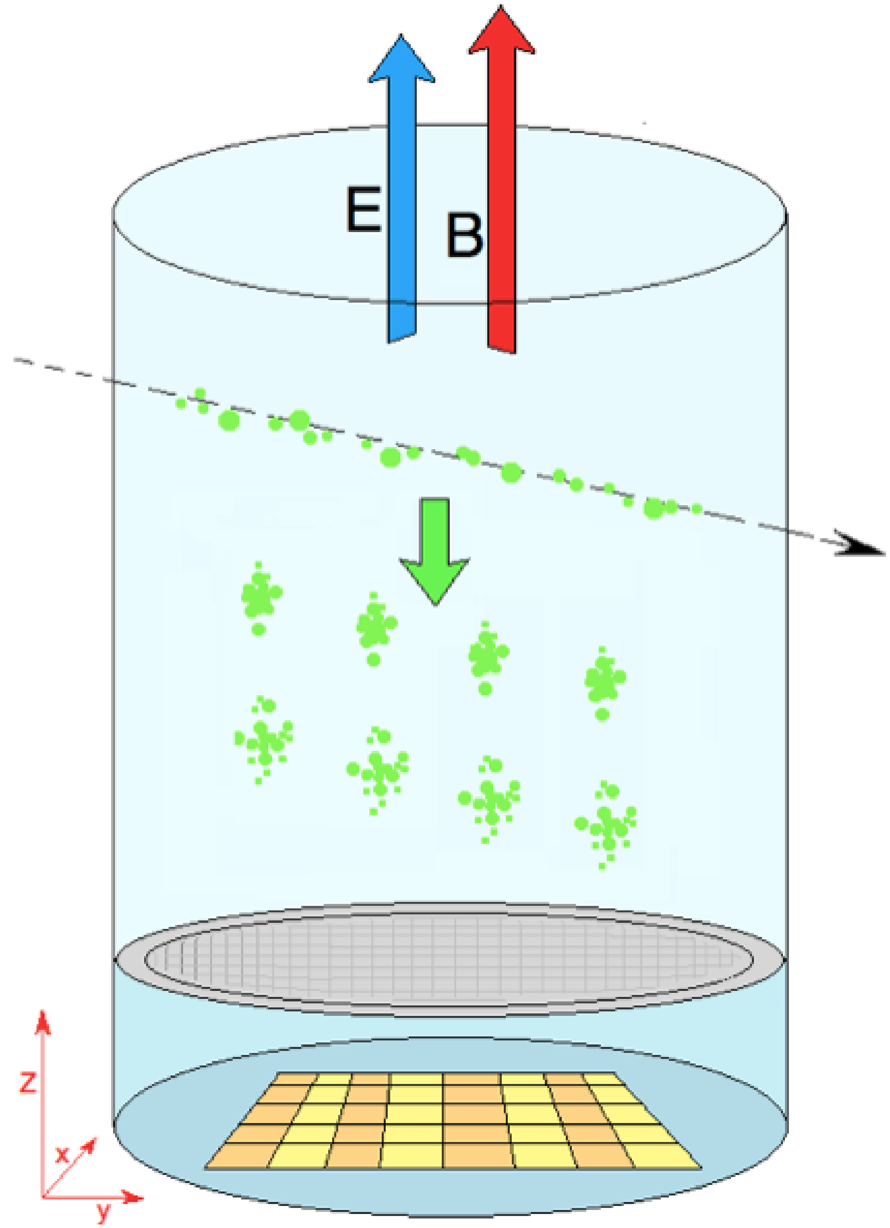




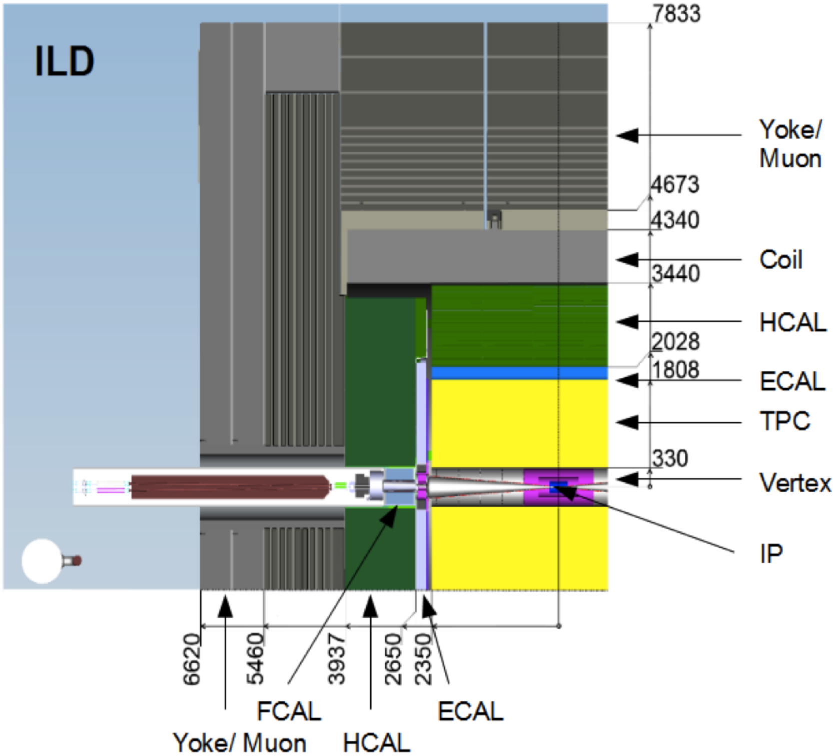


A Time Projection Chamber (TPC) is a detector consisting of a cylindrical gas chamber and a position sensitive readout endcaps

- ☞ **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)



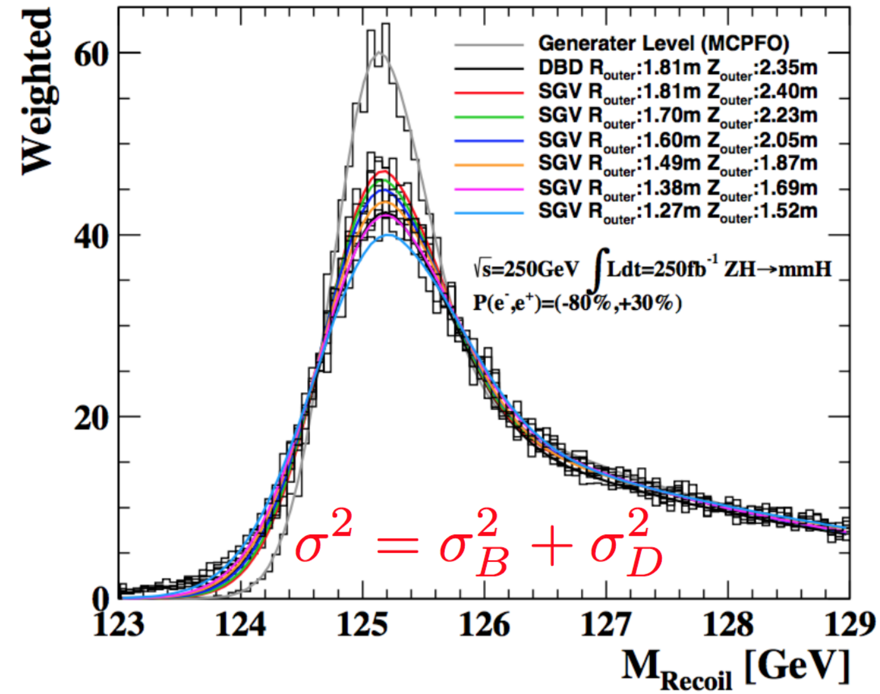
- **International Linear Collider (ILC) project in Japan:**
  - energy range (baseline design): 250-500 GeV (upgradeable to 1 TeV)
  - ILC is planned with two experiments
  - TPC is the central tracker for International Large Detector (ILD)
- **ILD components:**
  - vertex detector
  - few layers of silicon tracker
  - **gaseous TPC**
  - ECAL/HCAL/FCAL
  - superconducting coil (3.5 T)
  - muon chambers in iron yoke

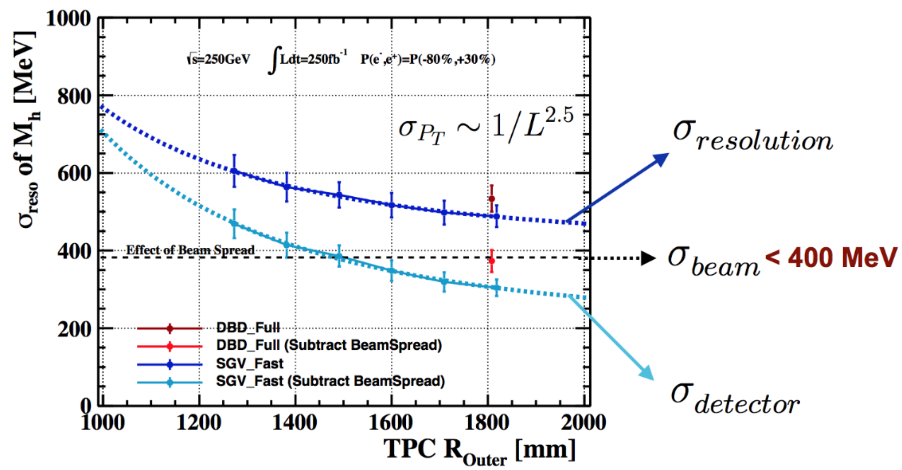


- **ILD requirements:**
  - momentum resolution: $\boldsymbol{\delta(1/p_T) \leq 2 \times 10^{-5} GeV^{-1}}$
  - impact parameters: $\sigma(r\phi) \leq 5\mu m$
  - jet energy resolution: $\sigma_E/E \sim 3-4\%$

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

- 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, ETD)
- **ILC flagship measurement**
  - recoil mass $e^+e^- \to Z(ll)X$
  - 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





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: $\sim \mathbf{25\%X_0}$

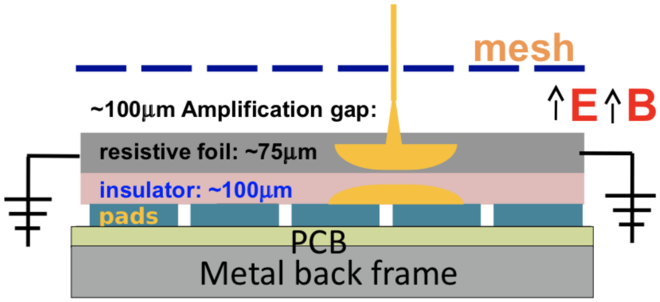
Two gas amplification options:

- **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%

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

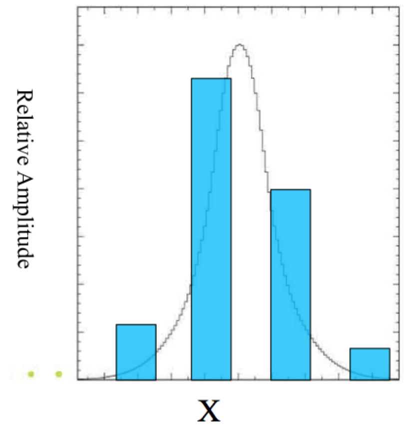


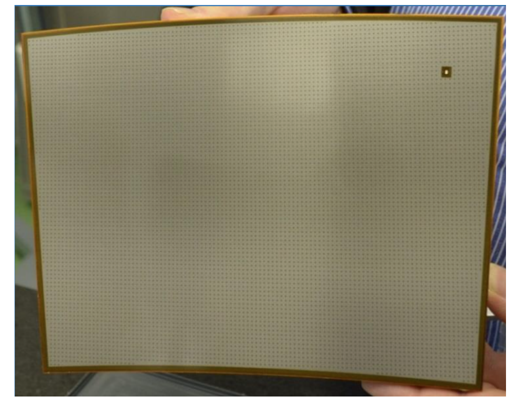
- Charge density function of time dependent charge dispersion on 2D continuous RC network:

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

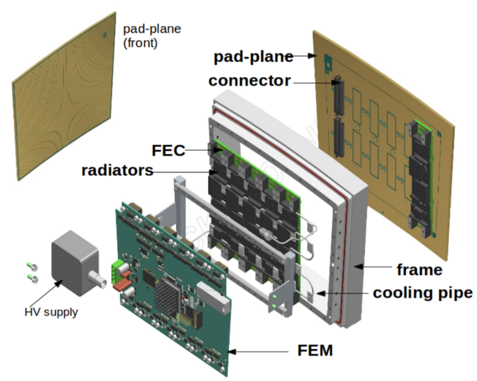
R- surface resistivity
C- capacitance/unit area

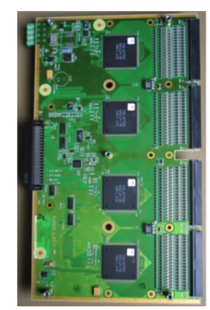
Relative fraction of charge seen by pads fitted by Pad Response Function (PRF)





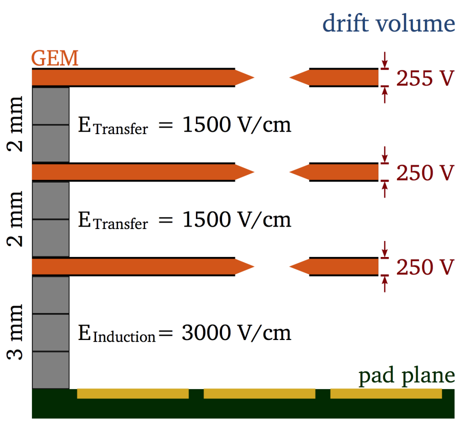
- **Module**
  - Module size: 22 cm × 17 cm
  - 24 rows × 72 columns **(1726 Pads)**
  - **Pad size: 3 mm × 7 mm**

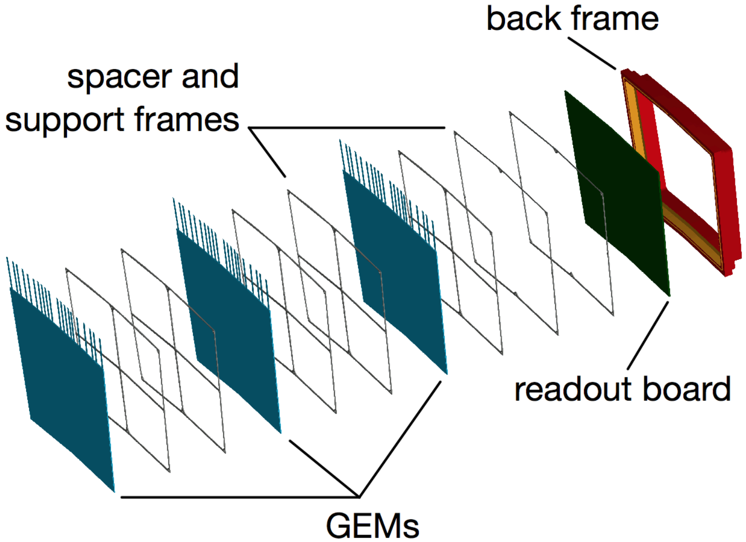




MM: T2K readout concept: *72-channel AFTER chip (12-bit)*

Triple GEM Modules

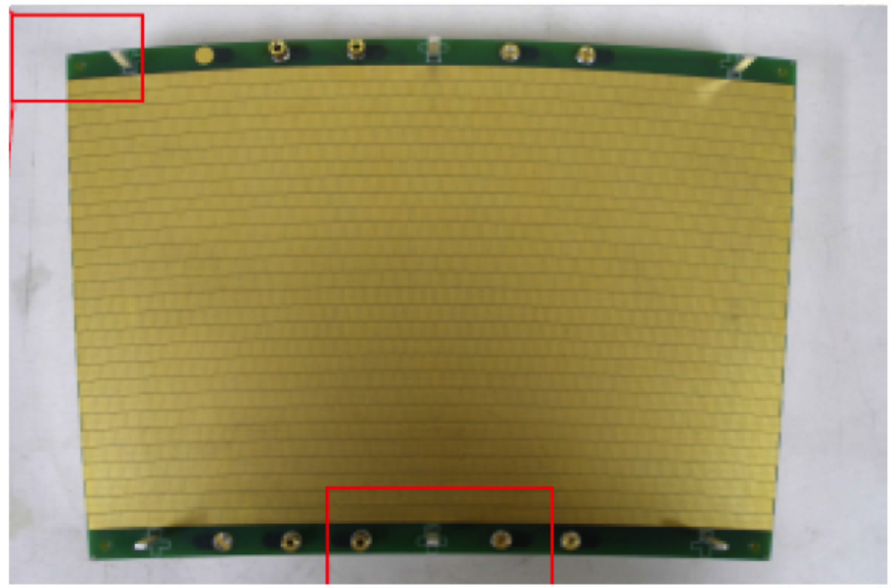


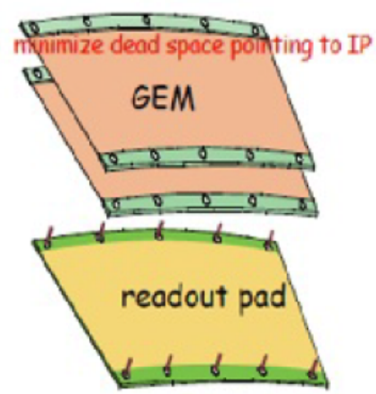


☞ **GEM: modified ALTRO readout**

➠ 16-channel ALTRO chip (10-bit)

Double GEM Modules





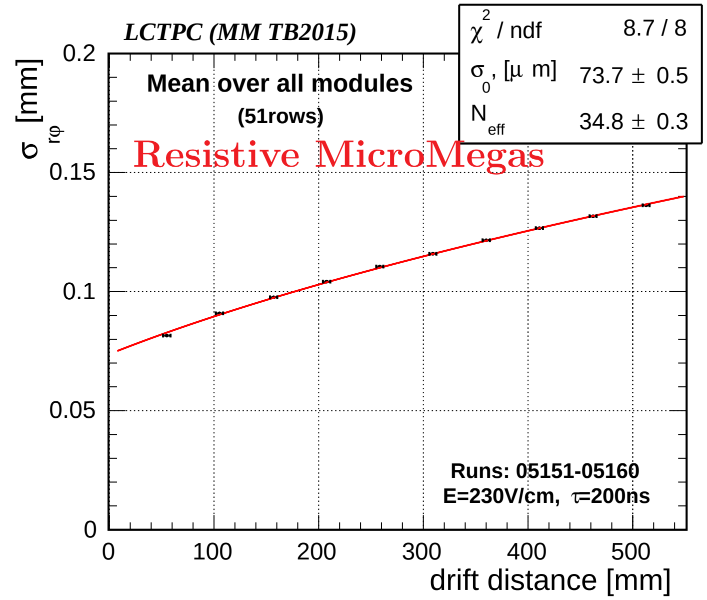
Prototype readout modules operate in a 1 T magnetic field

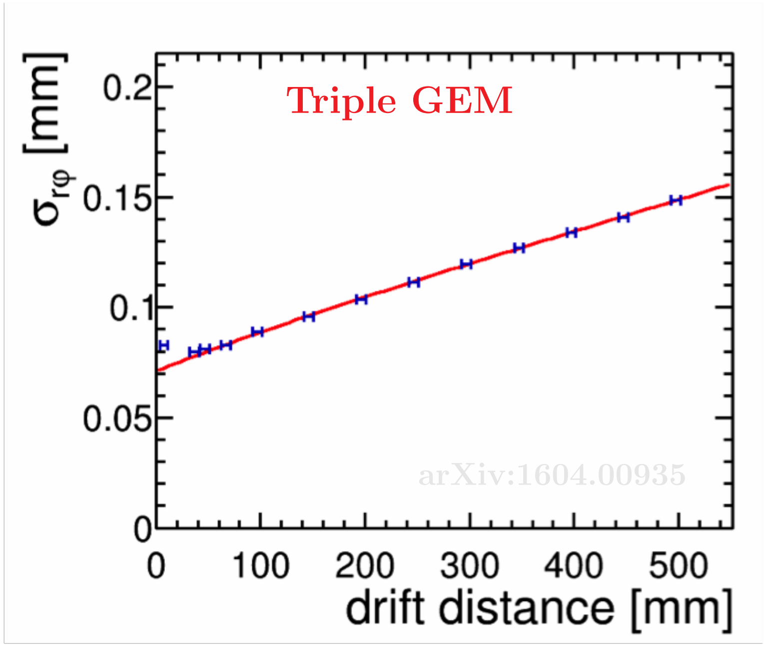
☞ **Fit data with:**

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

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

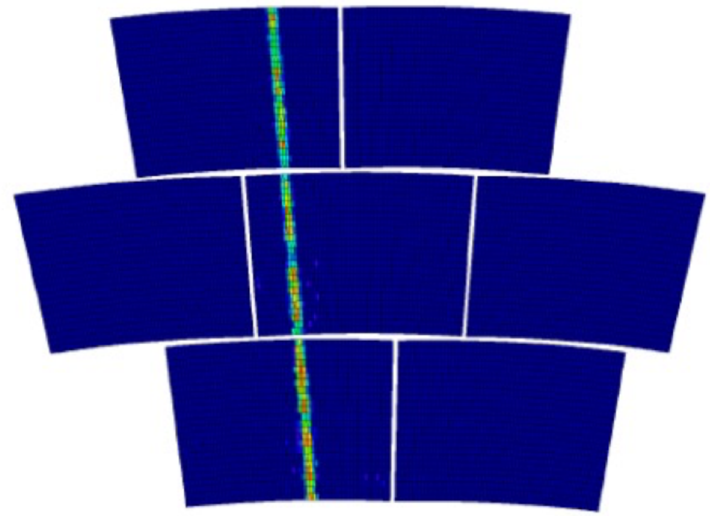
Extrapolation to a magnetic field of 3.5 T and 2.35 m drift length yield to a maximum 100 μm over the full drift length (tightly controlled gas quality and minimal impurities)

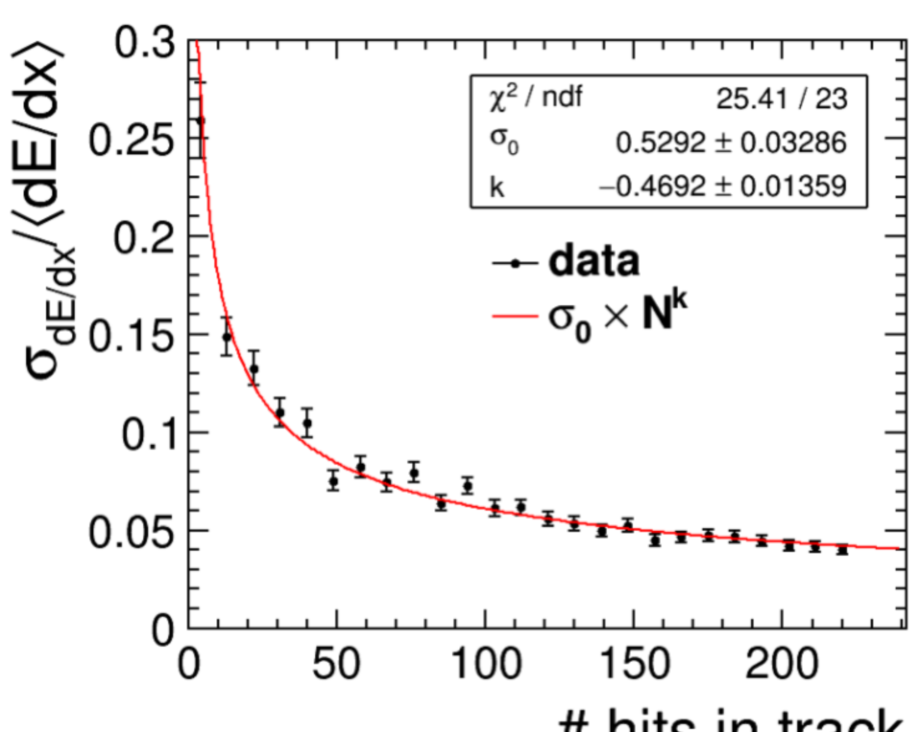




Measuring dE/dx resulution with LP test beam data and extrapolating to ILD TPC

- Test arbitrary track lengths by randomly combining hits from several real tracks to a pseudo track in test beam setup
  - allows extrapolating dE/dx resolution to the ILD TPC tracks of 130 cm
- 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 significant degradation due to resistive foil

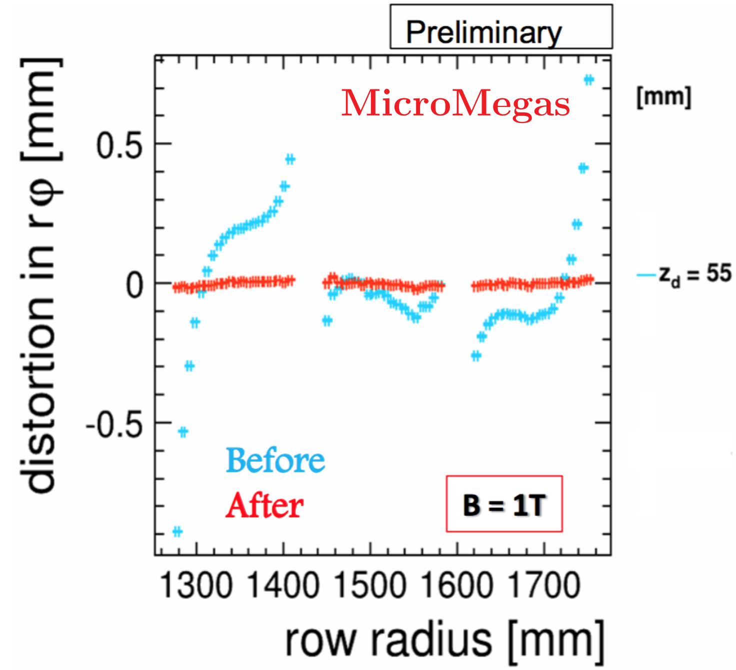


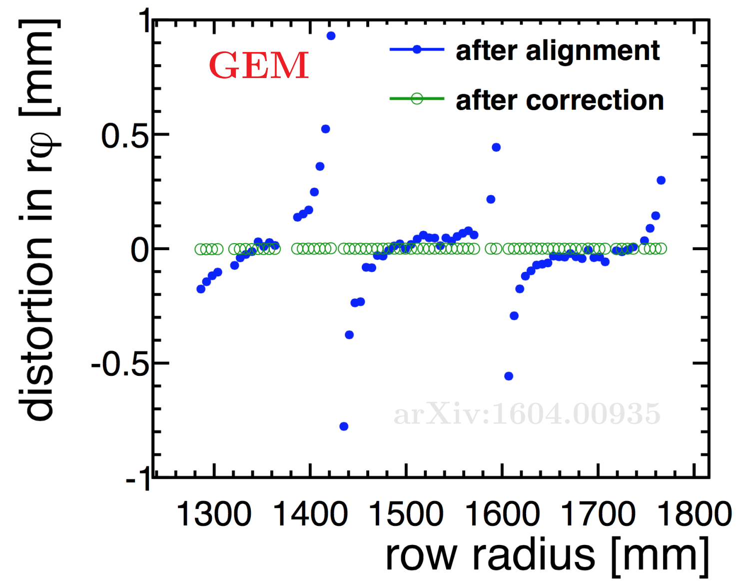


Non-uniform E-field near module boundaries induces ExB effects

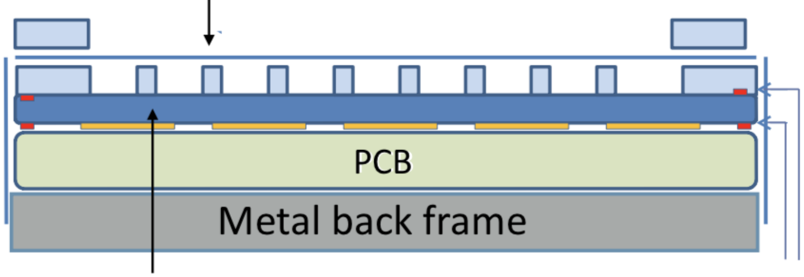
- ☞ Track distortions in standard scheme
  - ➠ reach **about 0.5 mm** at boundaries
    - **➔ worth to minimize at design level**
  - ➠ accounted as systematic residual offsets
  - ➠ determined on a row-by-row basis
  - ➠ correct residuals to zero at **about 20μm**
- ☞ Good agreement with simulations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

Refine the simulations and work on possible countermeasures are ongoing



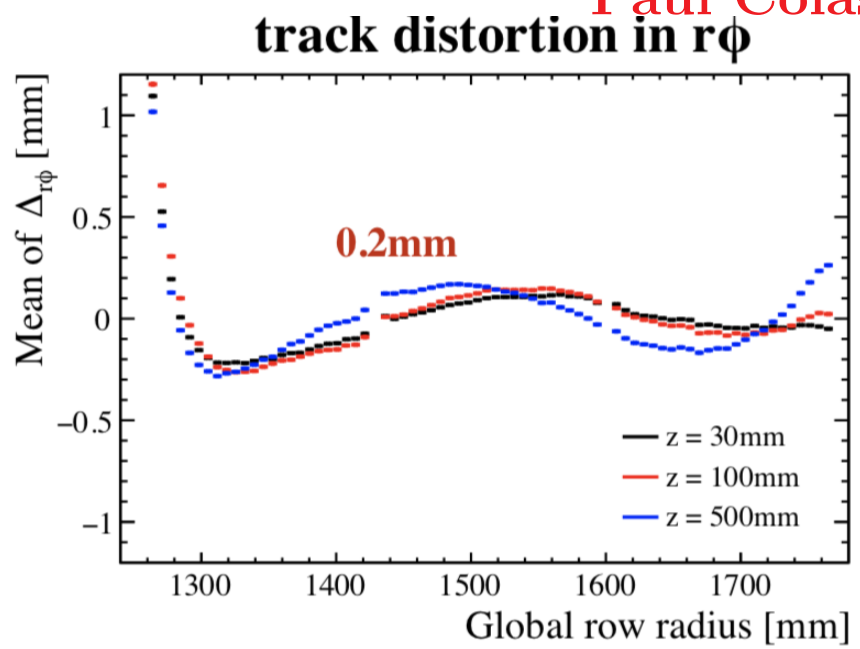


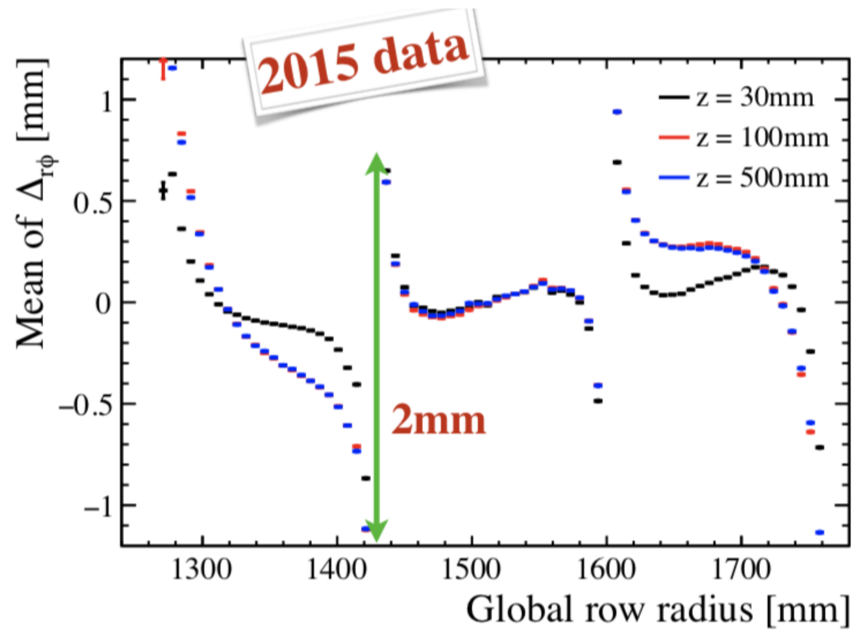
- **New scheme to reduce distortions at the edges of modules**
  - mesh at ground
    - ➔ same potential as the frame
  - resistive anode at the +ve HV
  - the amplification field can be tuned independently of the drift field
  - the gains can be equalized while keeping the drift field very uniform



ExB effect between modules is fully suppressed in the new scheme

Paul Colas



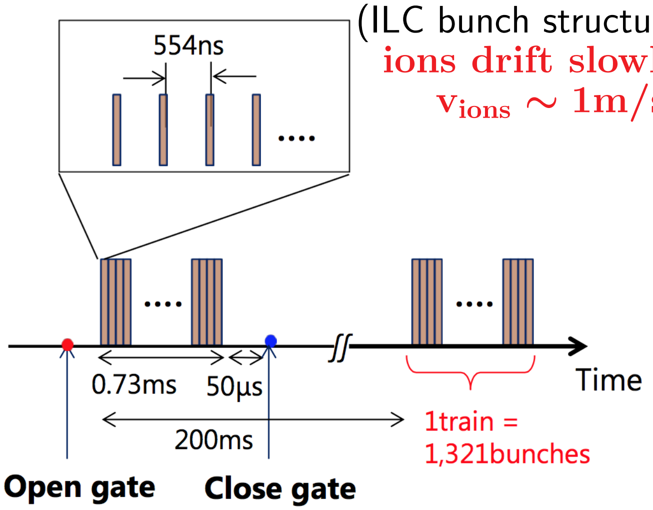


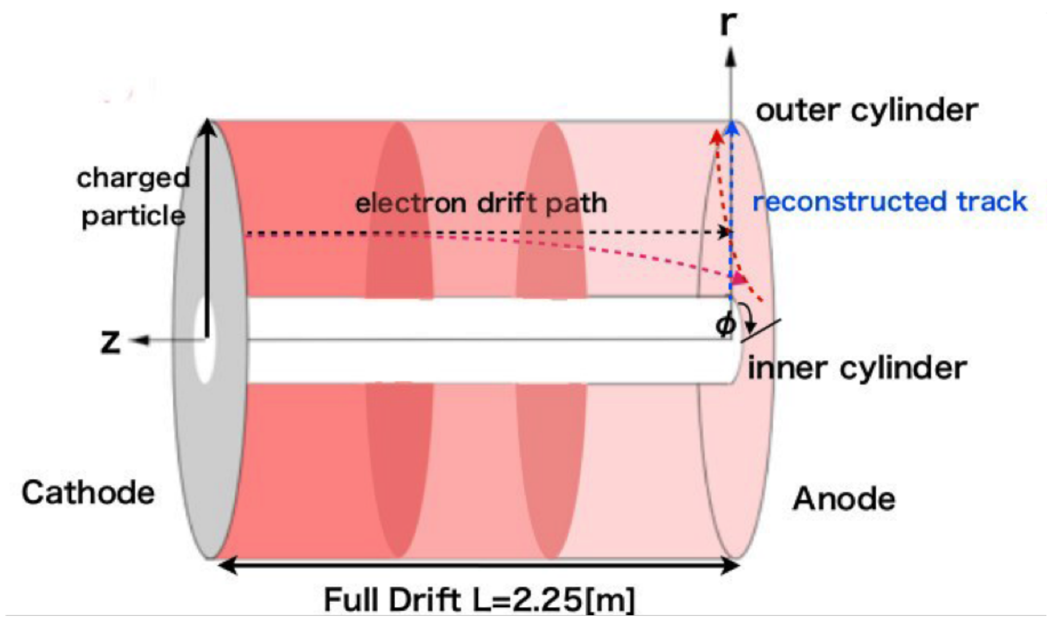
Ion Space Charge can deteriorate the position resolution of TPC

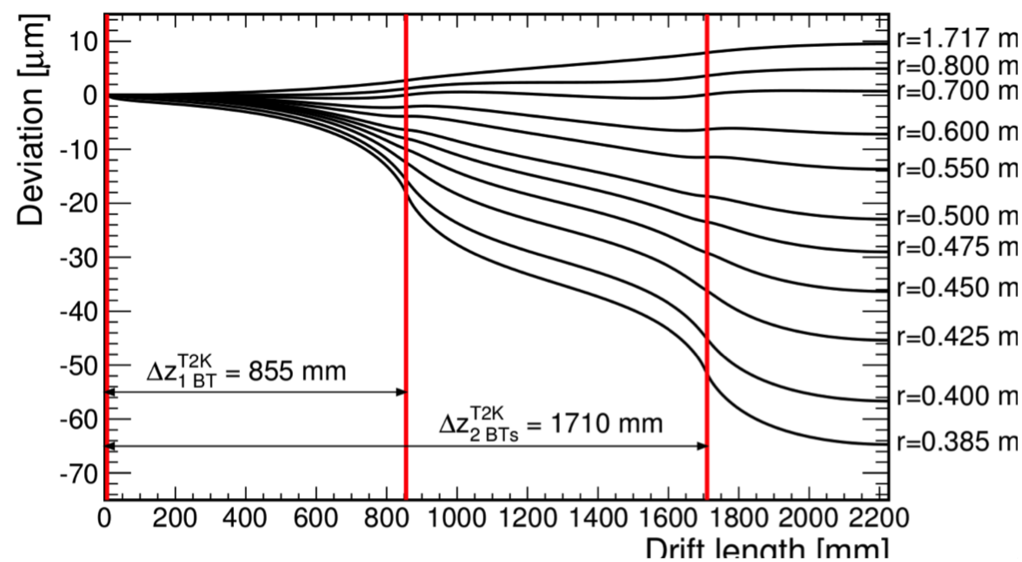
☞ **Primary ions** yield distortions in the E-field which result to O($\leq 1\mu$m) track distortions

☞ **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

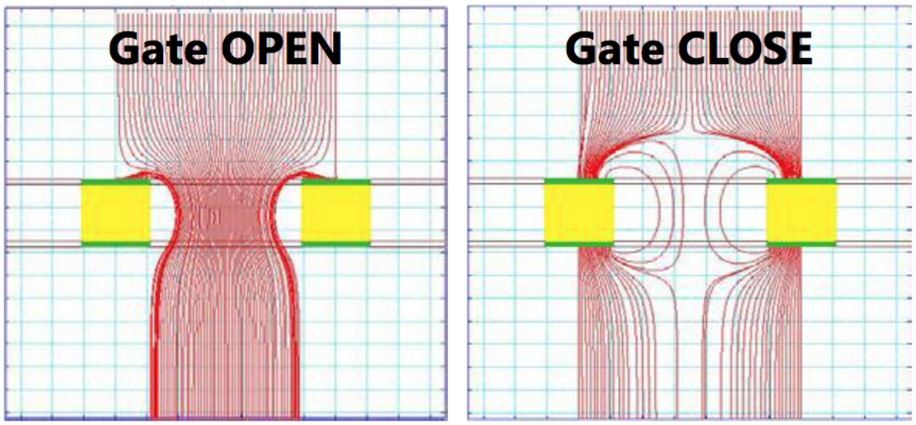


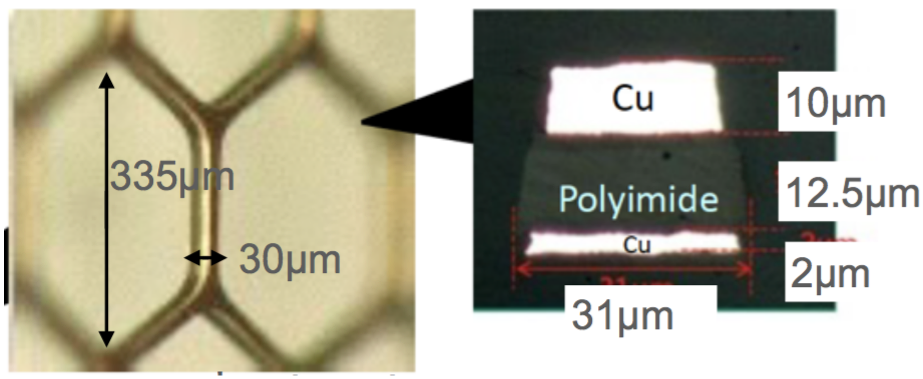




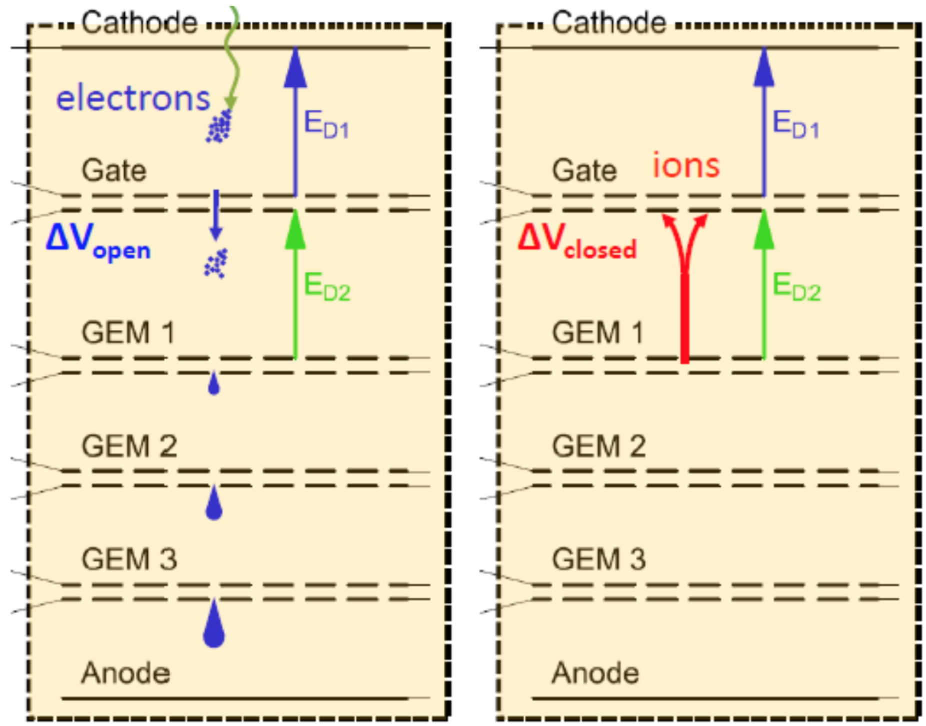
Gate is needed!

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



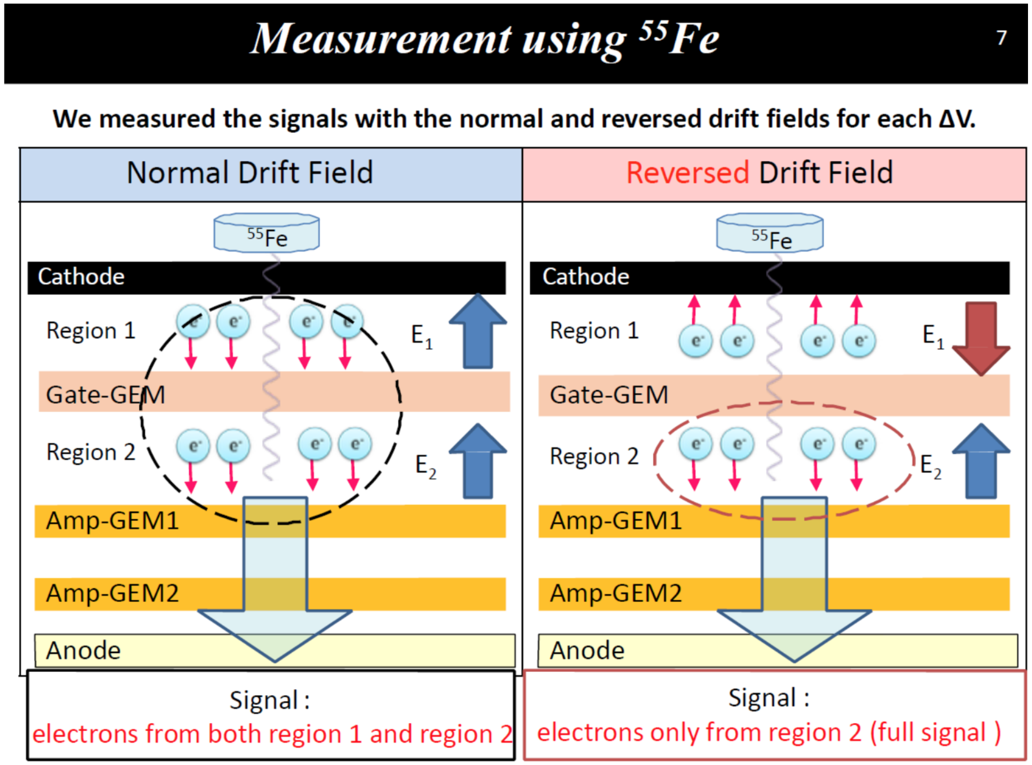


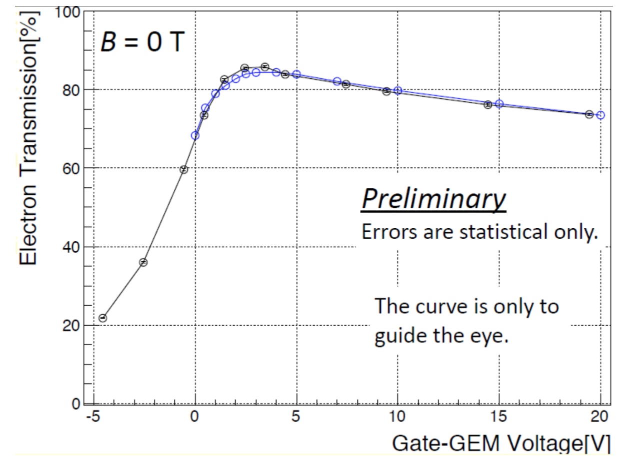
☞ A large-aperture gate-GEM with **honeycomb-shaped holes**

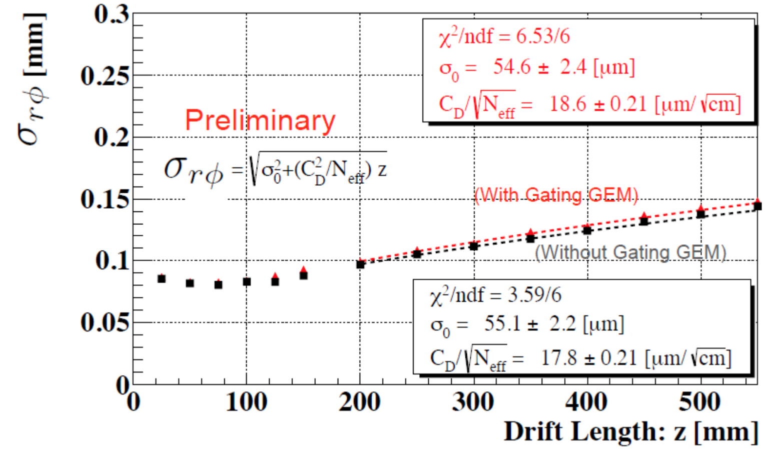


The ions must be stopped before penetrating too much the drift region
The device to stop them must be transparent to electrons

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%)

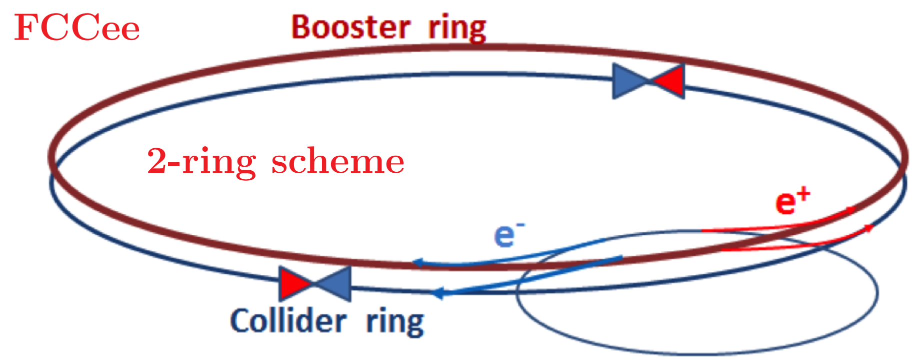
Gate-GEM seems to be a solution for the gating at ILC

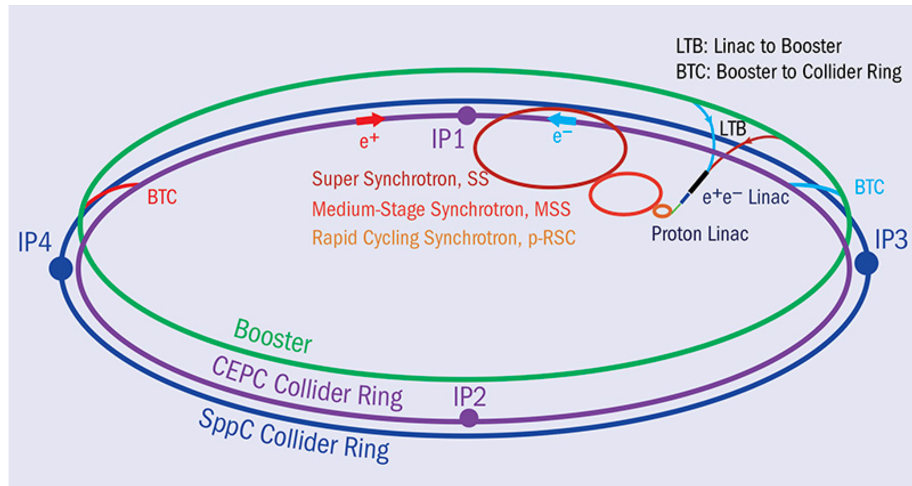
☞ **Main features:**

- E-range : **90-350 GeV**
- maximum SR power drives the machine design
- lumi increases at low E
- continious bunch structure
- **2-rings** concept allows multi-bunch operation at Z-pole

☞ **High Luminosity at Z-pole is critical for the TPC performance**

- not applicable for FCCee
- baseline option for CEPC

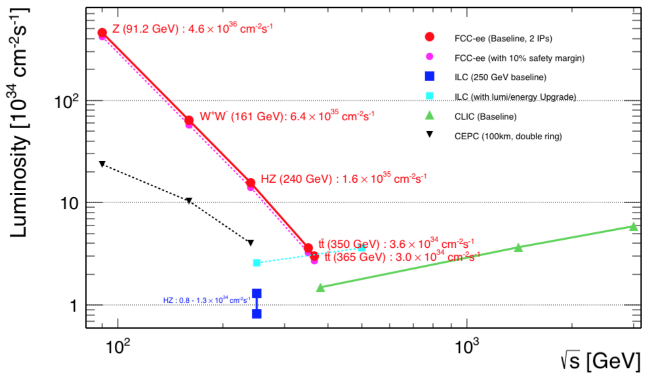




	FCCee-Z	FCCee-W	FCCee-H	CEPC-Z	CEPC-H
$\sqrt{s}$ (GeV)	90	160	240	90	240
L (10^{34}cm^{-2}s^{-1})	**230**	**32**	**8**	**17(32)**	**2.0**
# bunches	16640	2000	393	10900	286
Total RF voltage (GV)	0.1	0.44	2.0	0.05	2.14
Bunch intensity (10^{11})	1.7	1.5	1.5	0.16	1.3
Lumi lifetime (min)	70	50	42		
SR Power (MW)	50	50	50	30	30

Ion back flow is crucial since gating is not possible at circular colliders

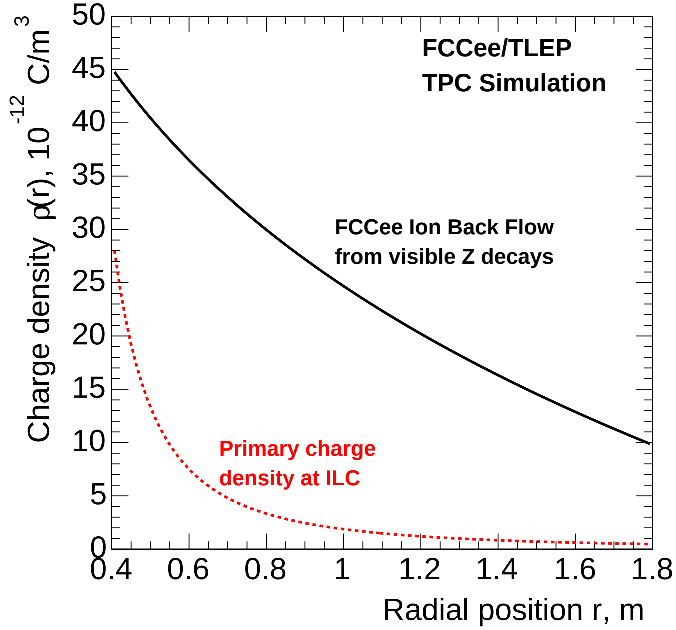
- **Charge rate is driven by** **Z $\rightarrow$ hadrons events** at low energy
  - **19.2** visible charged tracks
  - **16.8 kHz** at $L = 3 \cdot 10^{35} s^{-1} \, cm^{-2}$
  - $\gamma\gamma \rightarrow$ hadrons and machine background are possibly negligible (in contrast to ILC)

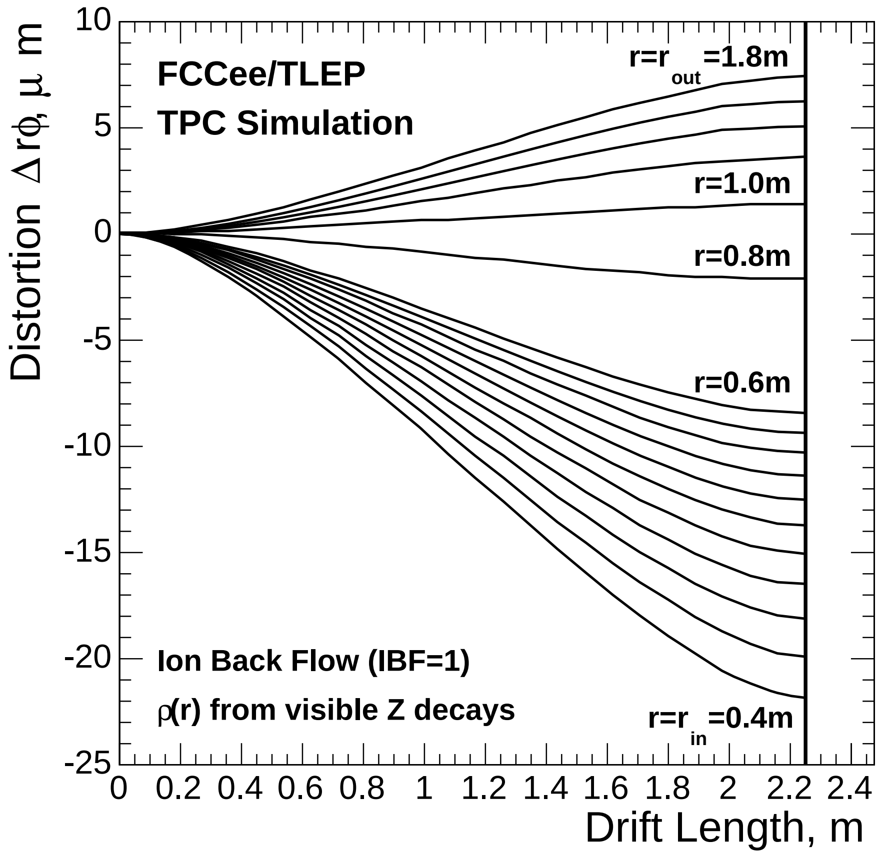


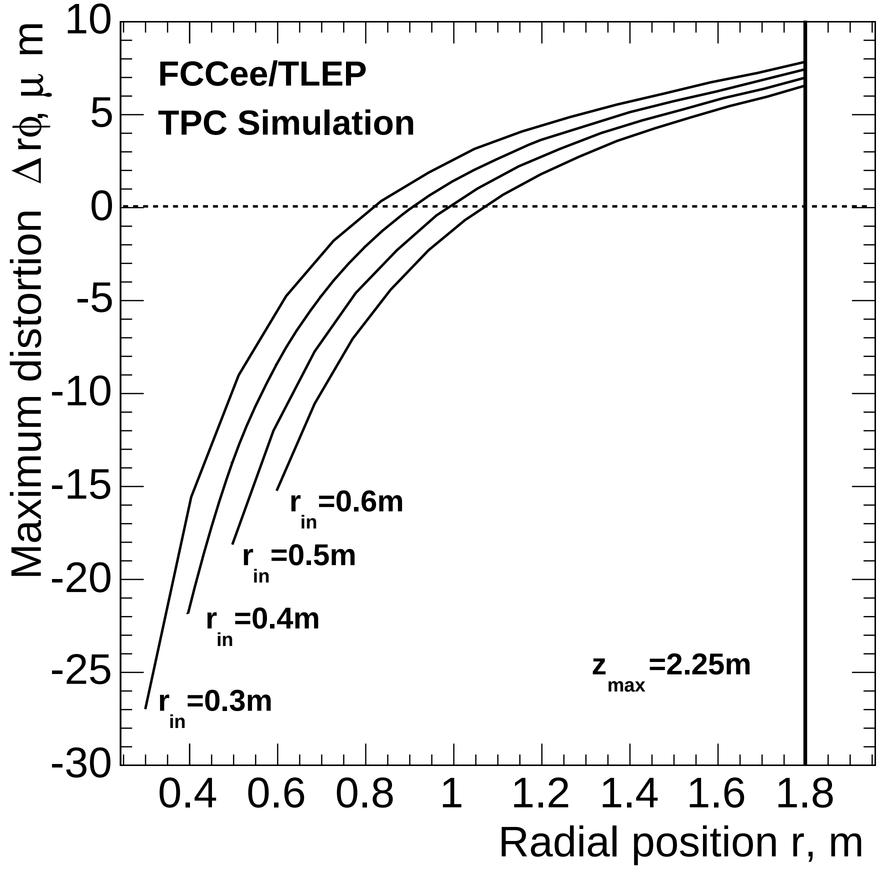
- Design **B=3.5 T** to meet spatial resolution
  - $R_{min} = 40\,cm,\ R_{max} = 190\,cm,\ Z_{max} = 225\,cm$
- Simulate $Z \rightarrow$ hadrons with `PHYTHIA`
  - factorized approach for $r \geq 0.4m$:

$$\rho(r,z) = \rho'(r)\rho''(z)$$

  - charge ionization is **40 ions/cm**
- Determine charged density due to secondary backflowing ions



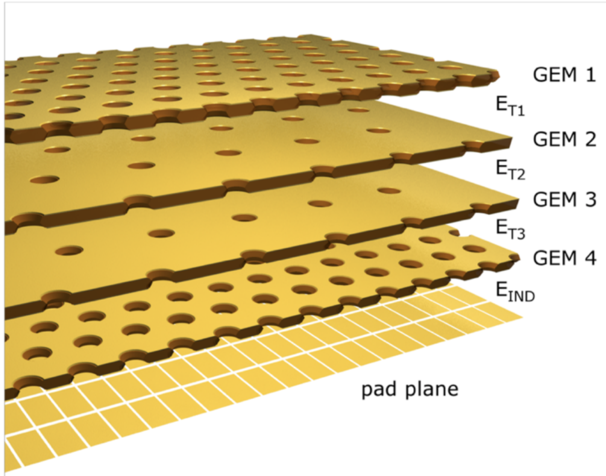


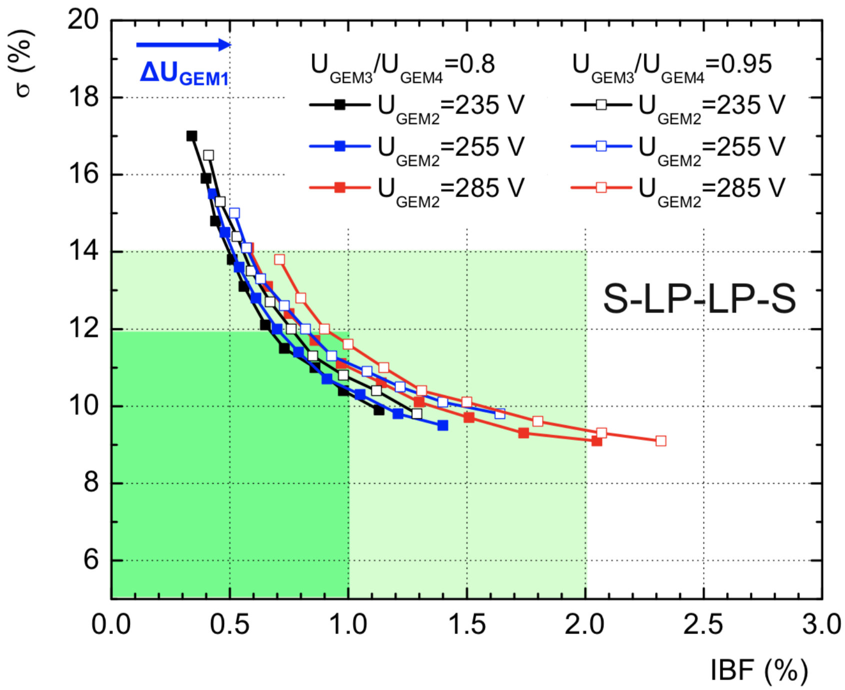


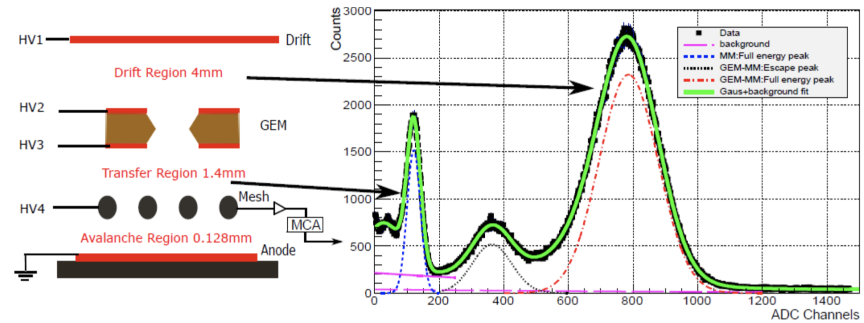
Secondary ions *yield distortions of about 20* μm *for* **IBFxGain=1** *for the case of continious charge density along z axis and corresponds to* $\mathrm{L} = 3 \cdot 10^{35}\mathrm{s}^{-2}\mathrm{cm}^{-1}$ *at 3.5 T magnetic field*

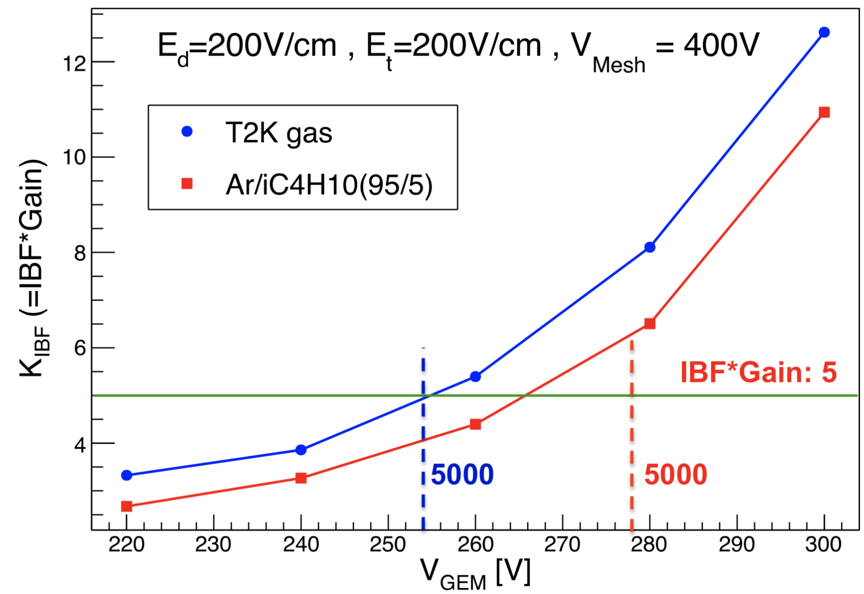
Possible Suppression of IBF

Piotr Gasik | **Huirong Qi**









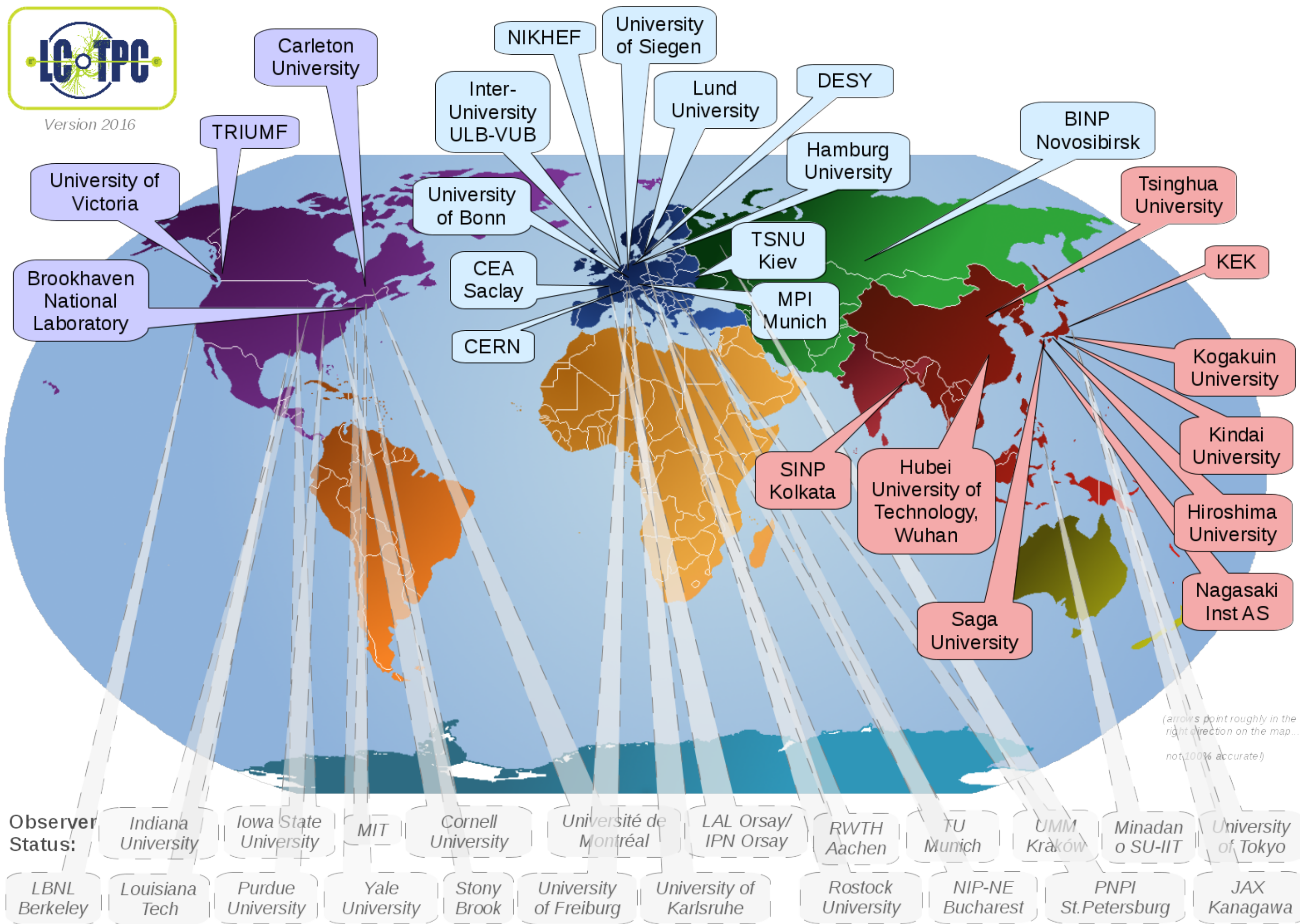
Combined MM+GEM module at IHEP

Currently IBF$\sim 10^{-3}$ is feasible, needs more R&D to go beyond

- 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
- Ion back flow is the most critical issue for the TPC at circular colliders
  - rate is driven by Z $\rightarrow$ hadrons at low energy
  - gating is not possible due to continuous bunch structure
- Possible distortions due to space charge effects are large enough
  - extremely demanding on **luminosity and magnetic field**
  - ion suppression of about 10^{-4} is required
  - dedicated calibration scheme with laser is possibly needed

Backup

Extensive R&D for ILC TPC is active research area of the LCTPC Collaboration



Total of 12 countries from 25 institutions members + several observer institutes

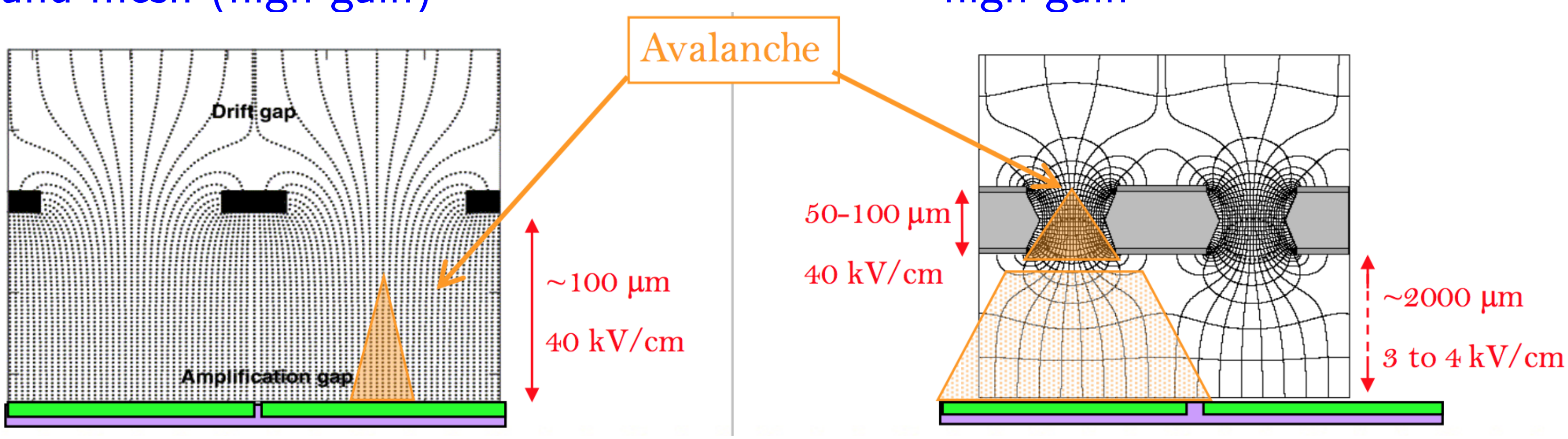
- Technology choise for TPC readout: **Micro Pattern Gas Detector (MPGD)**
  - **no ExB effect, better ageing, low ionback drift**
  - easy to manufacture, MPGD more robust mechanically than wires

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

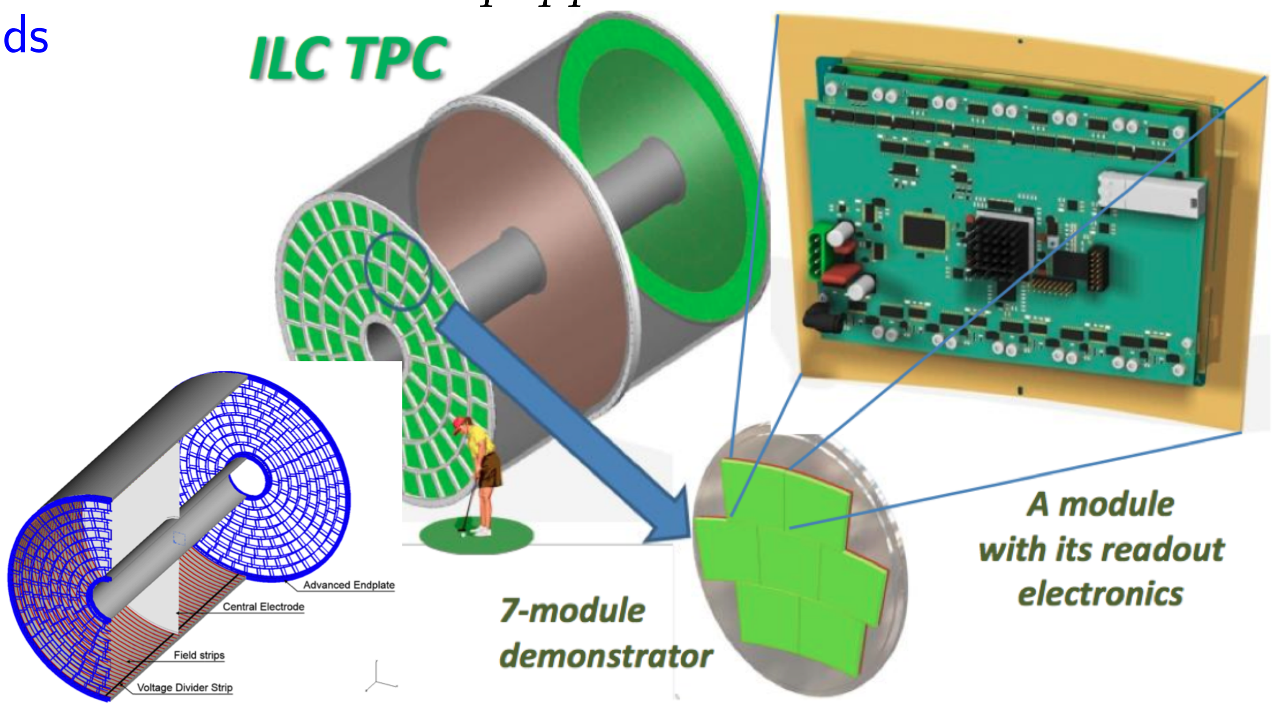


Discharge probability can be mastered (use of resistive coatings, several step amplification, segmentation)

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

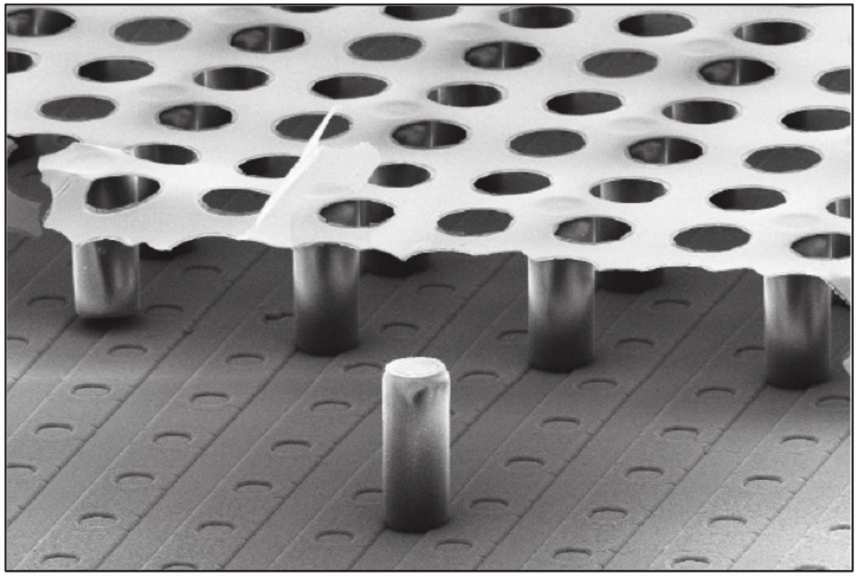
- **Two options for endplate readout with pads:**
  - GEM: 1.2x5.8 mm^2 pads
  - MM: 3x7 mm^2 pads
- **Alternative:** pixel readout with pixel size ~55x55 $\mu\mathrm{m}^2$ (newest)

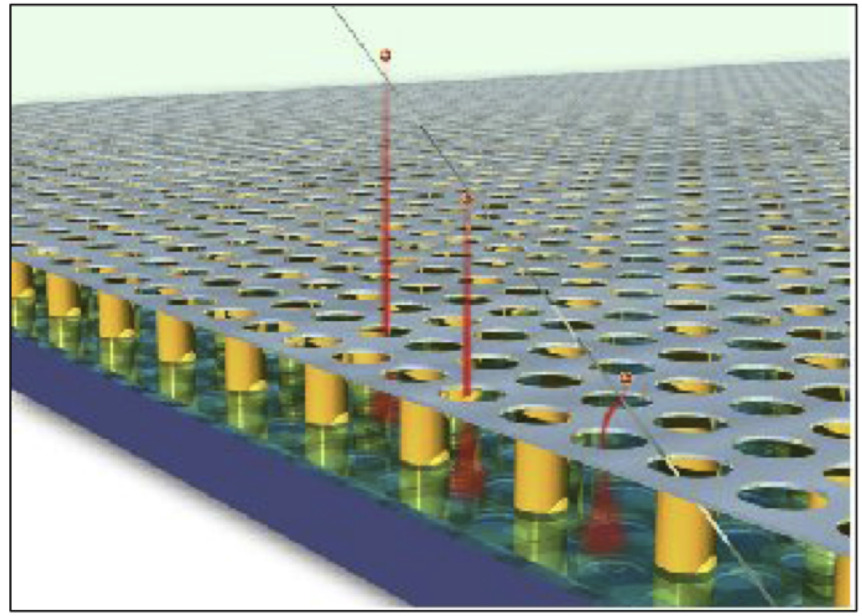
Consists of a field cage equipped with an endplate with 7 windows to receive up to 7 fully equipped identical modules



LP readout modules operate in a 1 T magnetic field

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

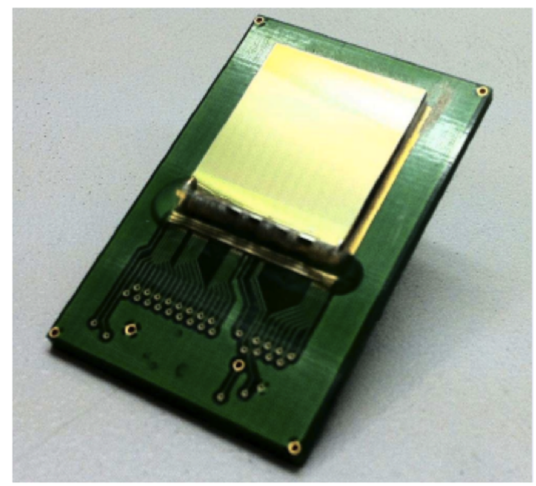




☞ **Micromegas on a pixelchip**

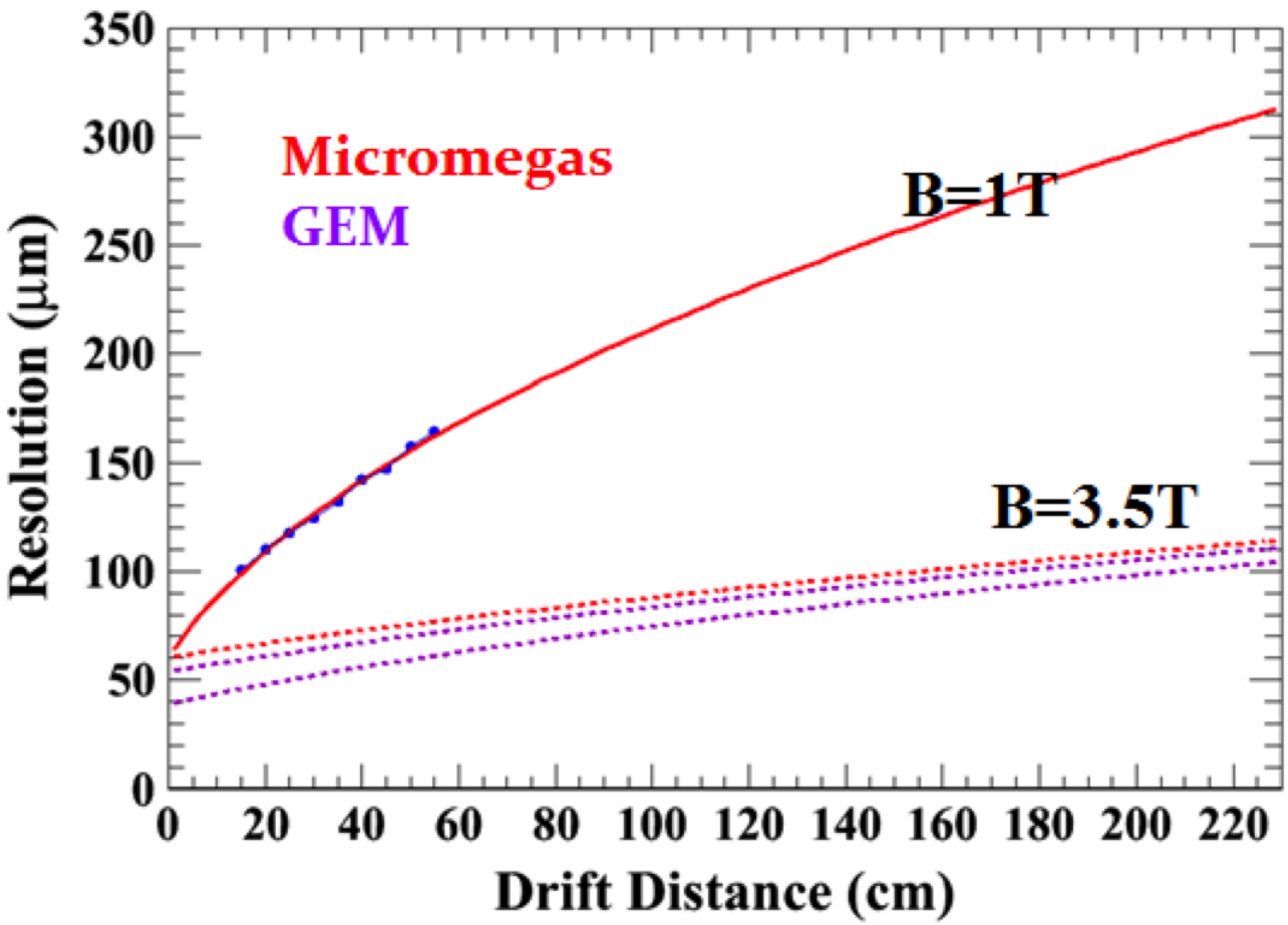
- resistive protection layer (4-8 μm) on top of chip
- insulating pillars between grid & pixelchip
- one hole above each pixel
- amplification directly above the pixelchip
- very high single point resolution

Low threshold level $\sim$500 e^- (90 e^- ENC)



Timepix: 256 x 256 pixels of size $55 \times 55 \mu m^2$

Extrapolate to B=3.5T



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