KEK-JAPAN

Toward the technology choice for the TPC of the ILD detector (D_RD_18)

CEA - Saclay

Keisuke Fujii, Serguei Ganjour

KEK, Tsukuba, Japan

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

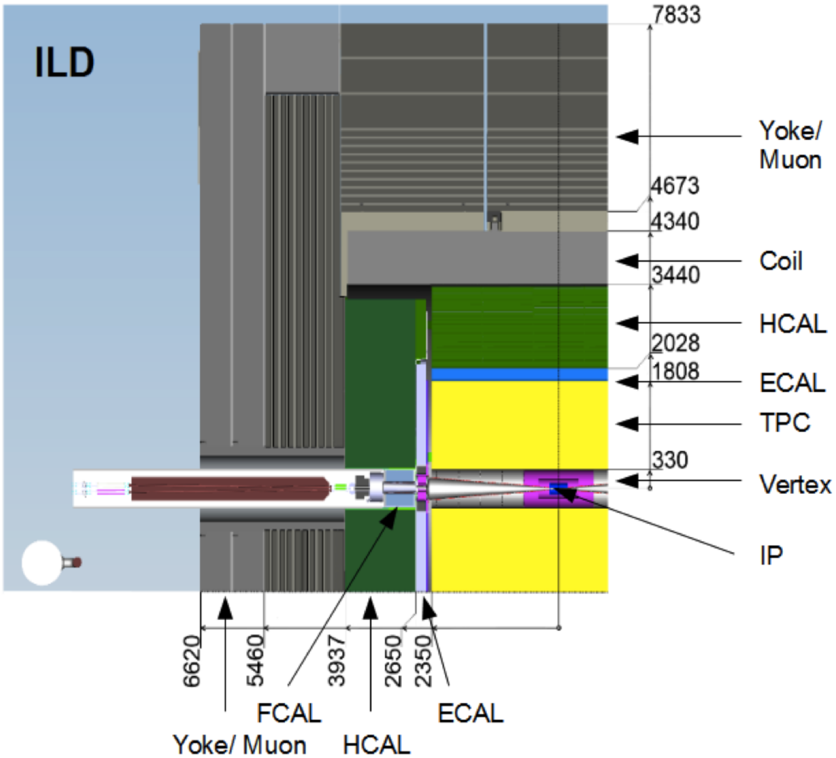
TYL-FJPPL Workshop
Jeju island, South Korea
May 8-10, 2019

☞ International Linear Collider (ILC) project in Japan:

- energy range (baseline design): staged project starting at 250 GeV
- ILC is planned with two experiments
- **Time Projection Chamber** (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 or 4 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: $\sigma_E/E \sim 3-4\%$

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

☞ Large number of 3D points

➠ **continuous tracking**

☞ Particle identification

➠ **dE/dx measurement**

☞ Low material budget inside the calorimeters (PFA)

➠ barrel: $\sim \mathbf{5\%X_0}$

➠ endplates: $\sim \mathbf{25\%X_0}$

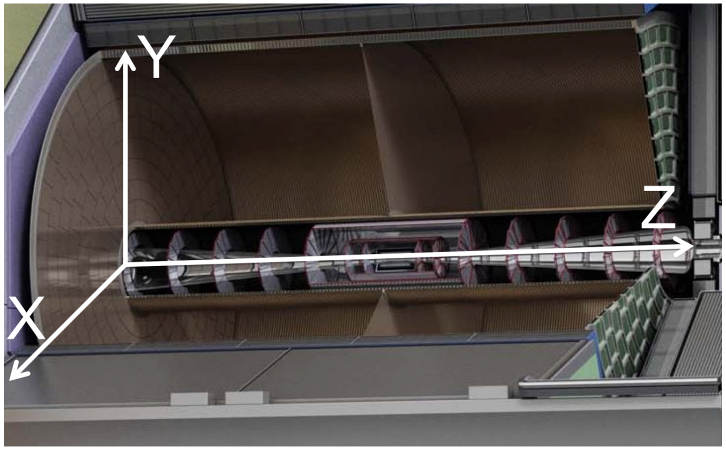
☞ Technologies for gas amplification:

➠ **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)

→ $\sigma(Z) \simeq 400\mu m$

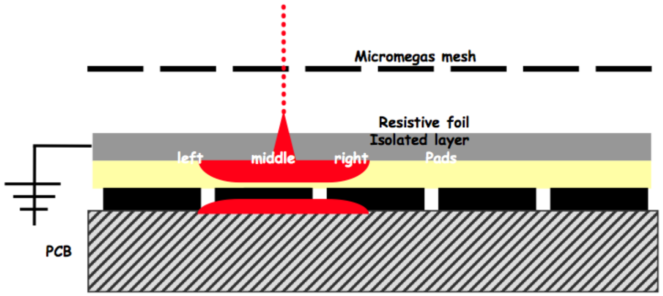
➠ **Tracking efficiency:**

→ 97% for $p_T \geq 1\mathrm{GeV}$

➠ **dE/dx resolution:** 5%

- The feasibility of a TPC for the LC was demonstrated in D_RD_2 project
  - ILD detector baseline document was completed in March 2013
- **Main issues towards final design were pushed forward with Large Prototype (LP) of the TPC within D_RD_9 project**
  - first test beam experiment of the large aperture GEM-like gating device
  - key issues of the engeneering design: CO_2 cooling, track distortions, etc
- **D_RD_18 project started in 2018 and has to resolve remaining issues towards technology choice for the ILD TPC**
  - single hit, momentum and dE/dx resolution with Large Prototype 2 (LP2)
  - mitigate ExB effects at design level (field distortions)
  - design optimization of the GEM-like gating device
  - 2-phase CO_2 cooling
  - simulation of the effect of the resistive anode layer for MM
  - minimize the GEM discharge rate and gain uniformity
  - new module design with common pad structure and electronics

France:

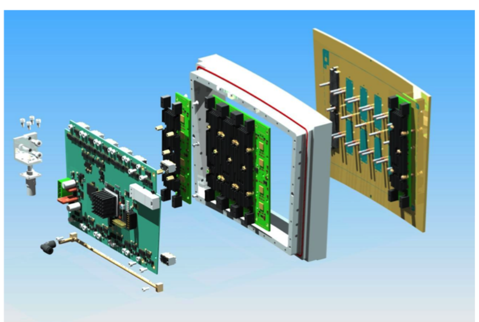


☞ **Charge density function**

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

R- surface resistivity

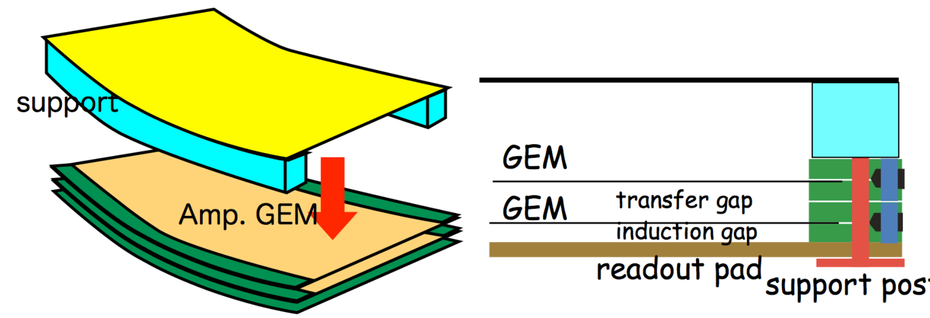
C- capacitance/unit area



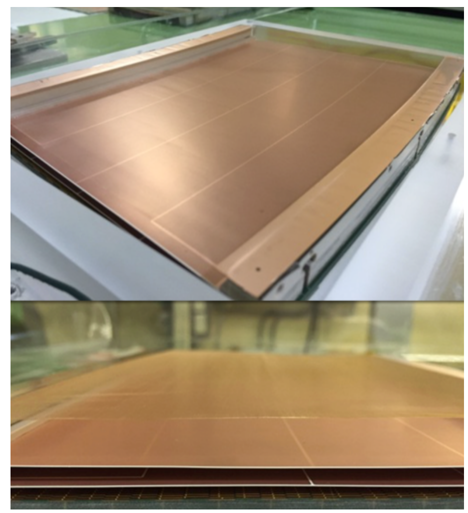
☞ **MM: T2K readout ASIC**

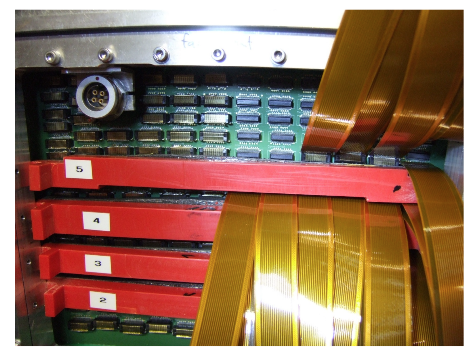
➠ 72-channel AFTER chip (12-bit)

Japan:



☞ 2-3 layers are needed to obtain high gain



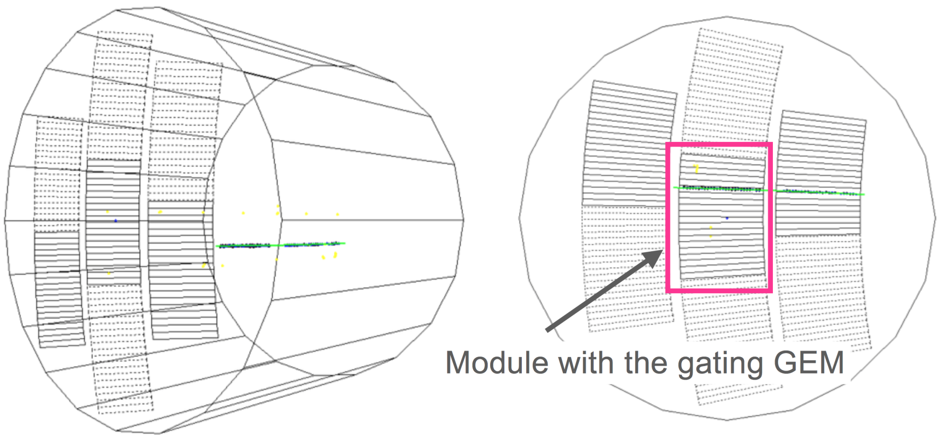


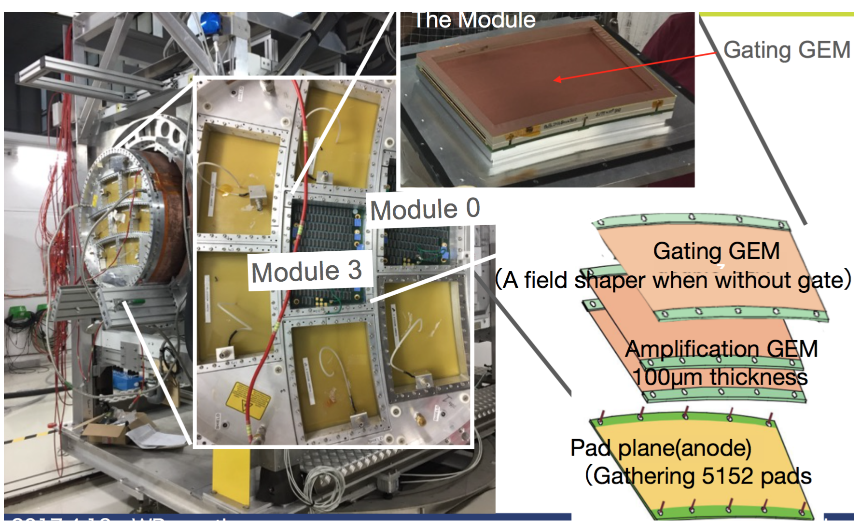
☞ **GEM: modified ALTRO readout**

➠ 16-channel ALTRO chip (10-bit)

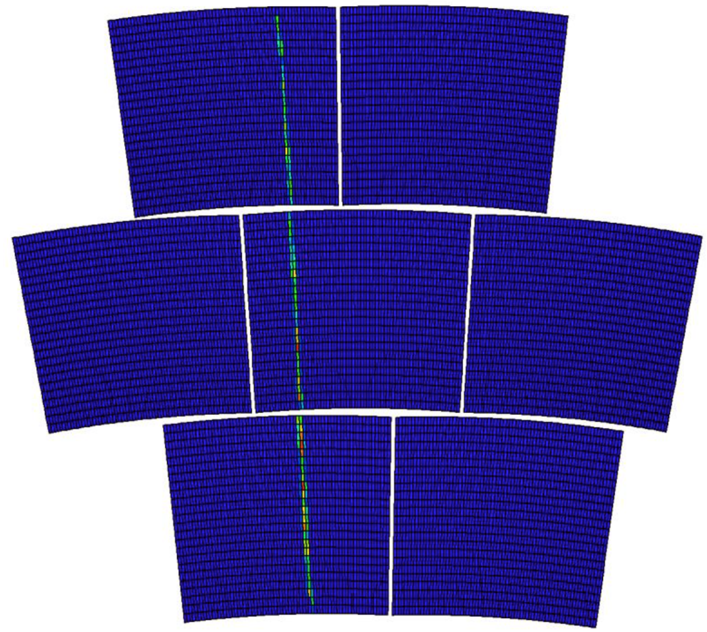
TPC Large Prototype at DESY

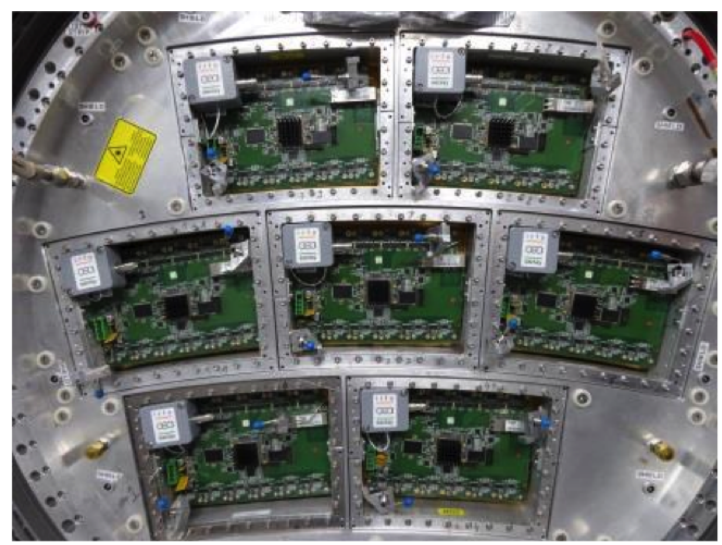
2-layers GEM (Japan)





MicroMegas (France)

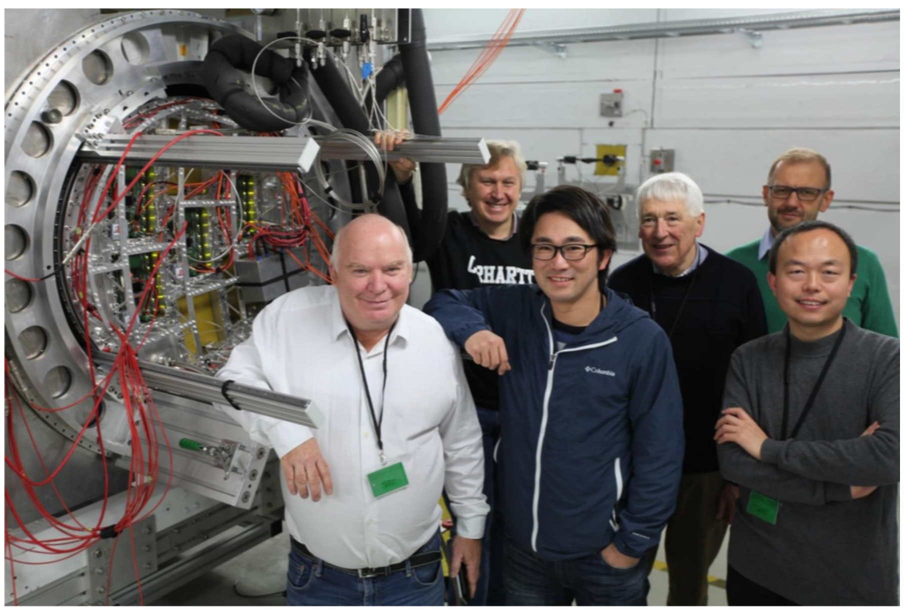


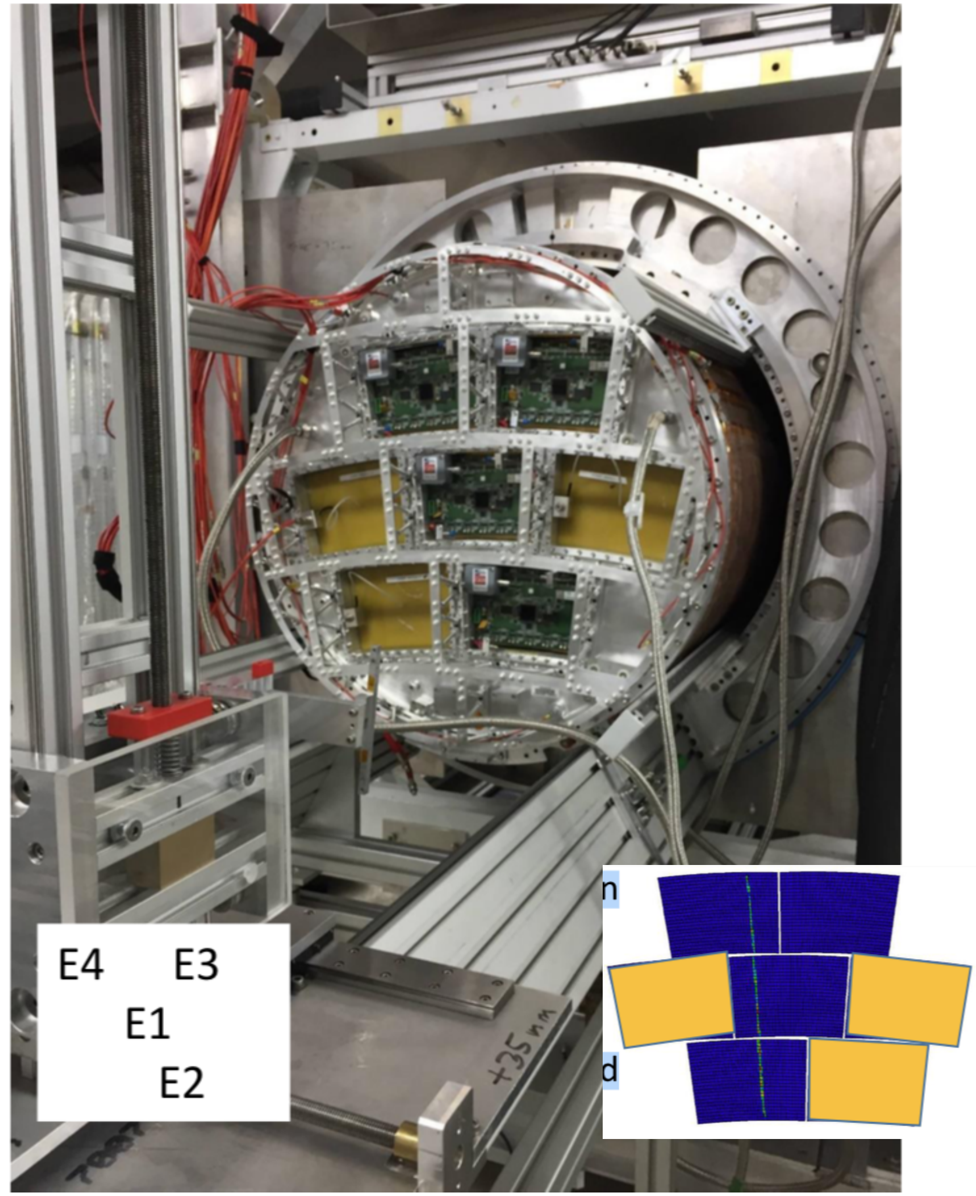


Beam Test at DESY 2018

☞ **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

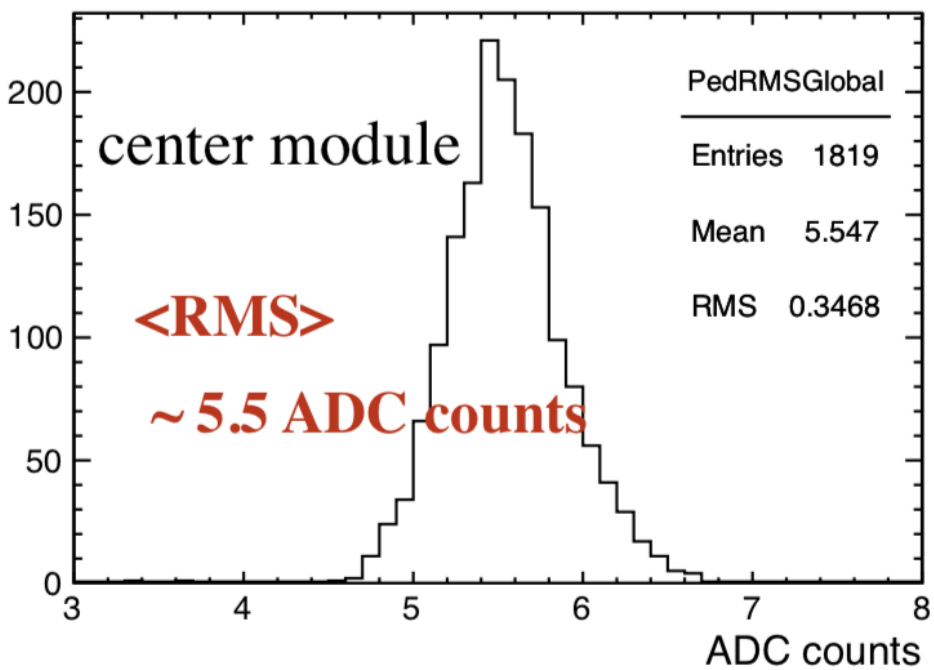




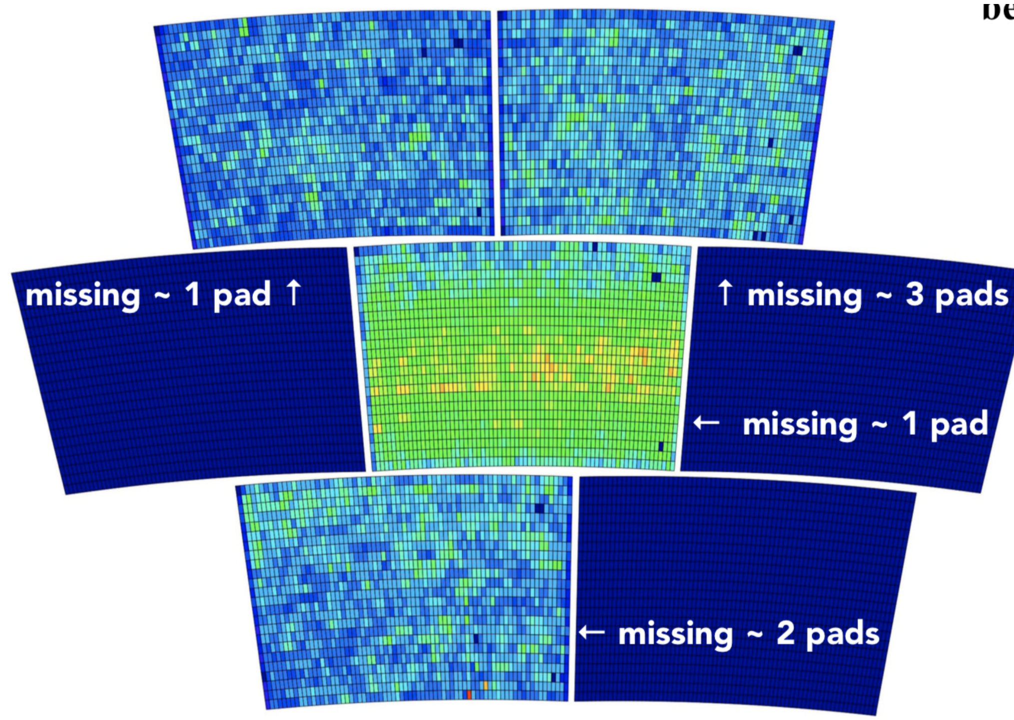
Measure the quality of connection from pedestal rms and occupancy

- ☞ 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%)

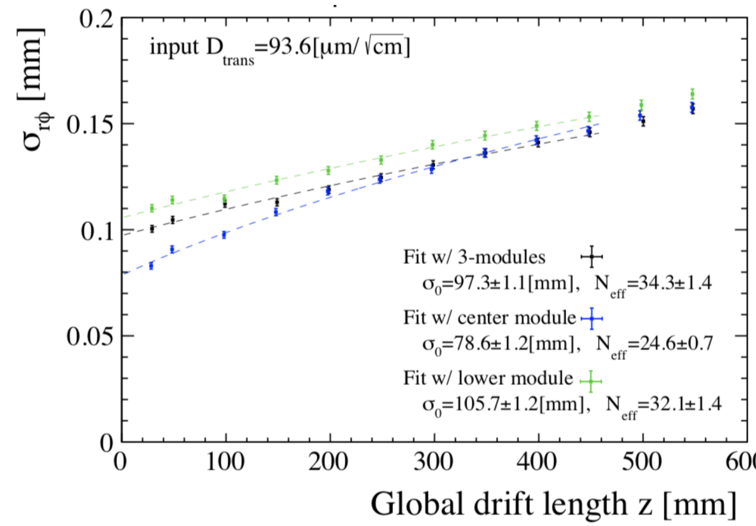
Prototype readout modules operate in a 1 T magnetic field

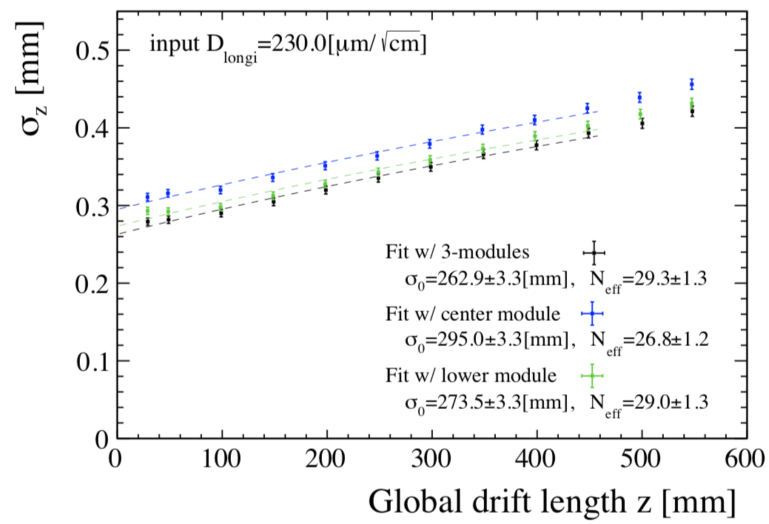
☞ **Fit data with:**

$$\boldsymbol{\sigma}(\mathbf{z}) = \sqrt{\boldsymbol{\sigma}_0^2 + \frac{\mathbf{D}_\perp^2}{\mathbf{N}_{\mathbf{eff}}}\mathbf{z}}, \ \boldsymbol{\sigma}_0^2 = \mathbf{b}^2/\mathbf{N}_{\mathbf{eff}}$$

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

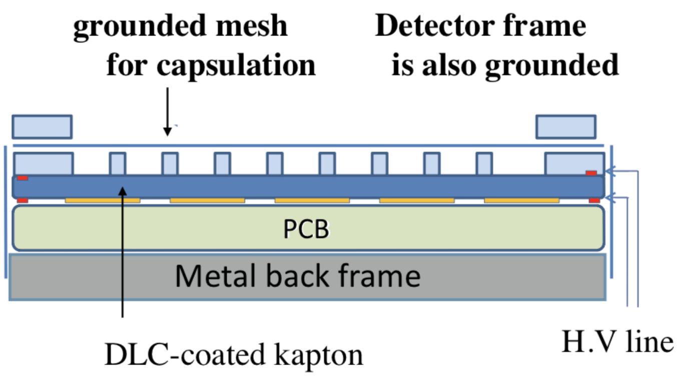
Extrapolation to a magnetic field of 3.5 T and 2.35 m drift length yield to a maximum 100 μm over the full drift length (tightly controlled gas quality and minimal impurities)

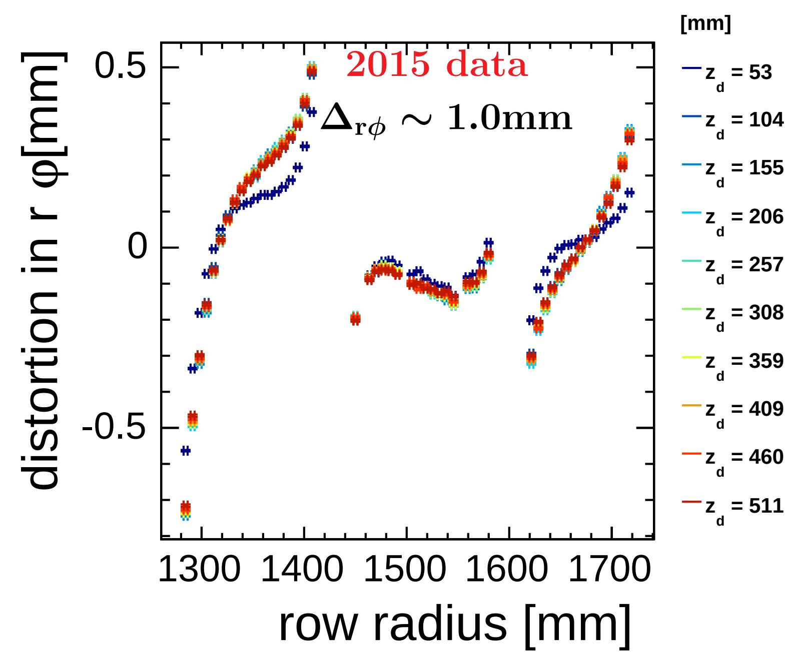


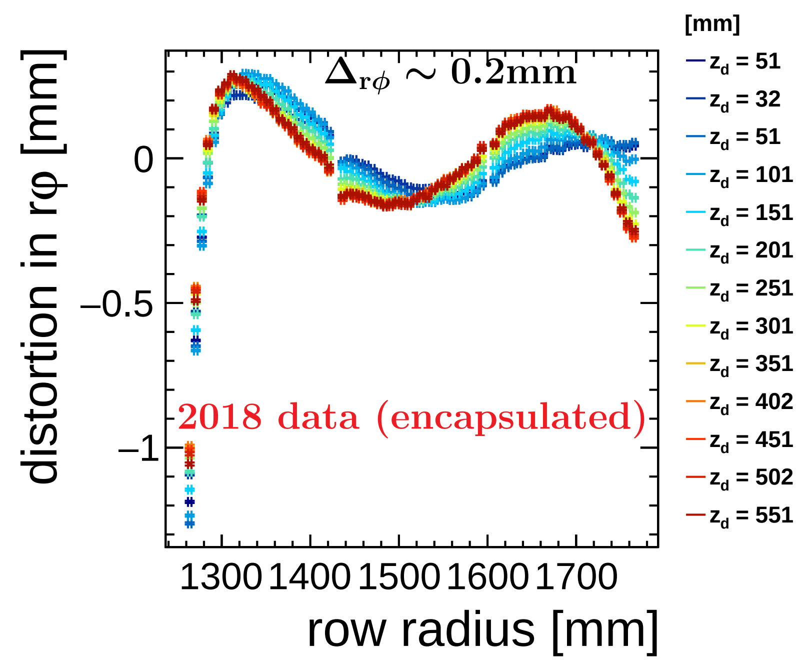


Non-uniform E-field near module boundaries induces ExB effects

- ☞ 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 MM modules
  - ➠ mesh at ground (same as the frame)
  - ➠ resistive anode at the +ve HV



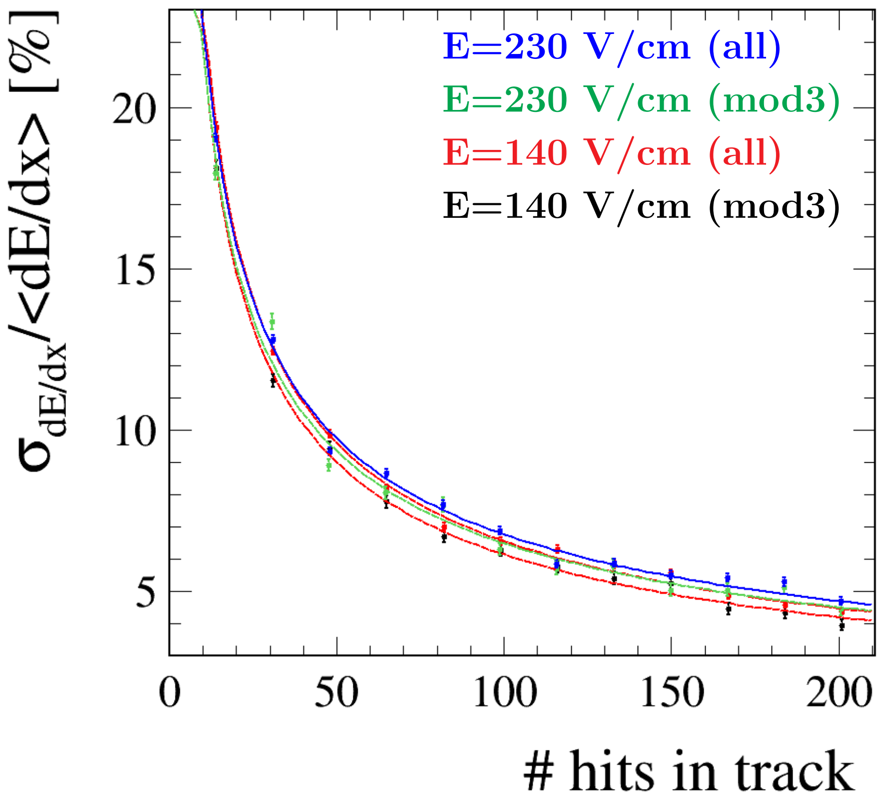




ExB effect between modules is fully suppressed in the new scheme

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
  - allows extrapolating dE/dx resolution to the ILD TPC tracks
- 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: $\sigma_{\mathrm{dE/dx}} = 4.8\%$ for 192 hits
    - ➔ no degradation due to resistive foil

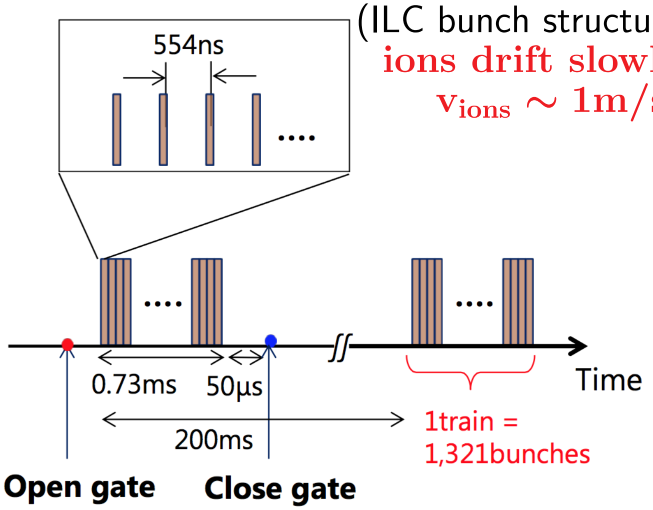


Ion Space Charge can deteriorate the position resolution of TPC

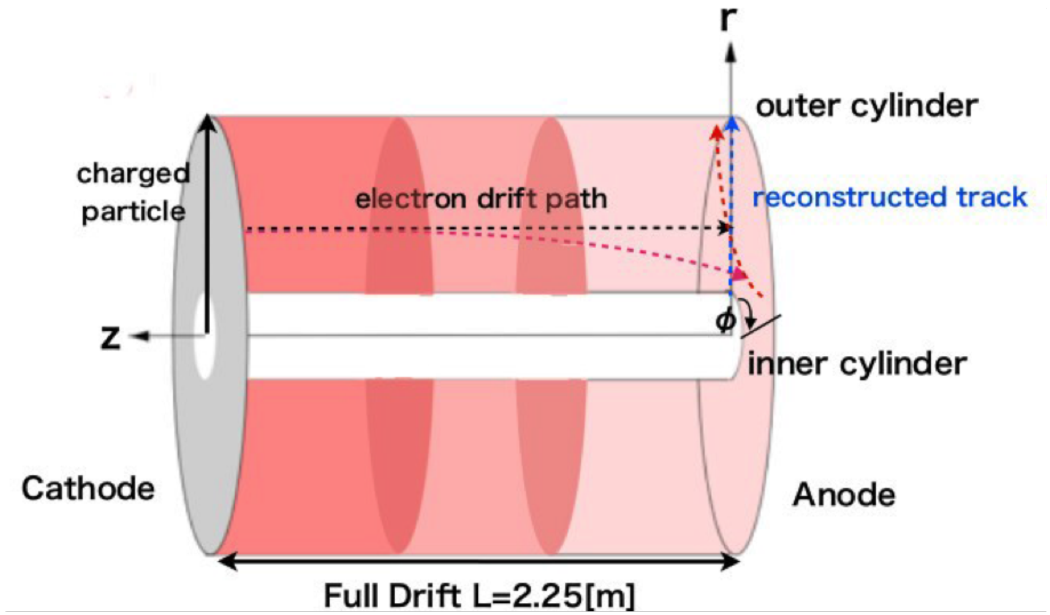
☞ **Primary ions** yield distortions in the E-field which result to O($\leq 1\mu$m) track distortions

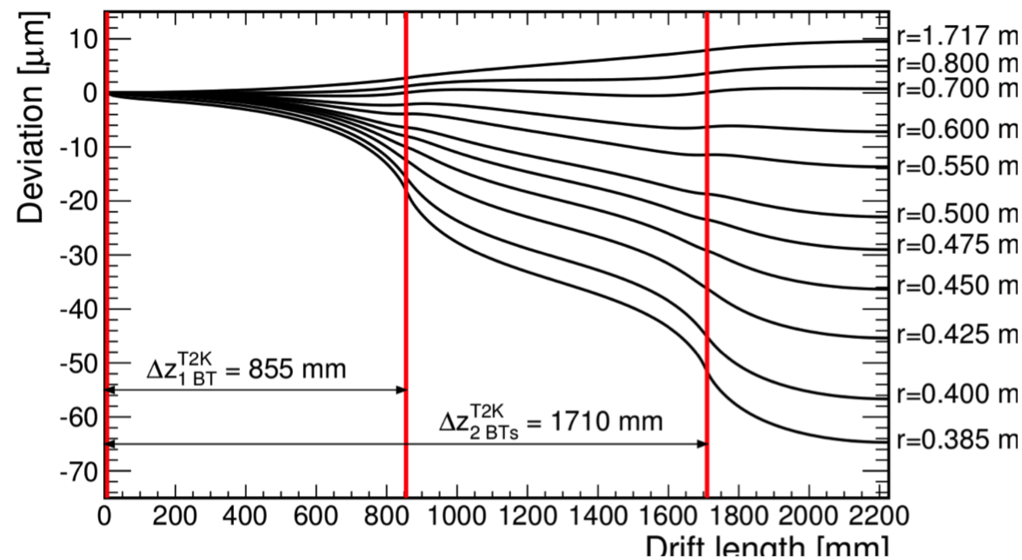
☞ **Secondary ions** yield distortions from backflowing ions generated in the gas-amplification region:

➠ 60 μm for **IBFxGain=3** for the case of 2 ion disks



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



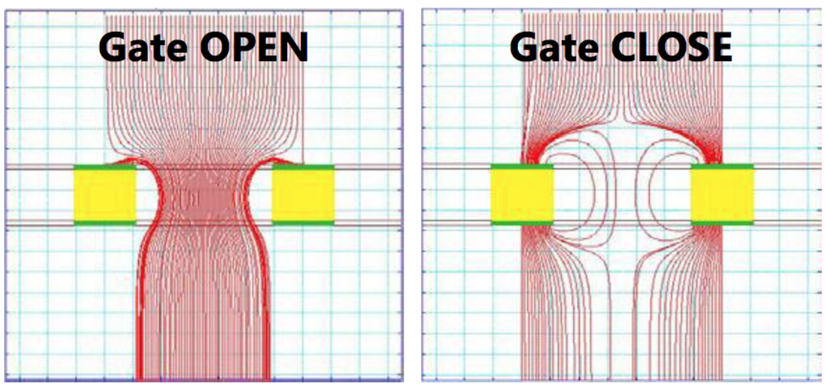


Gate is needed!

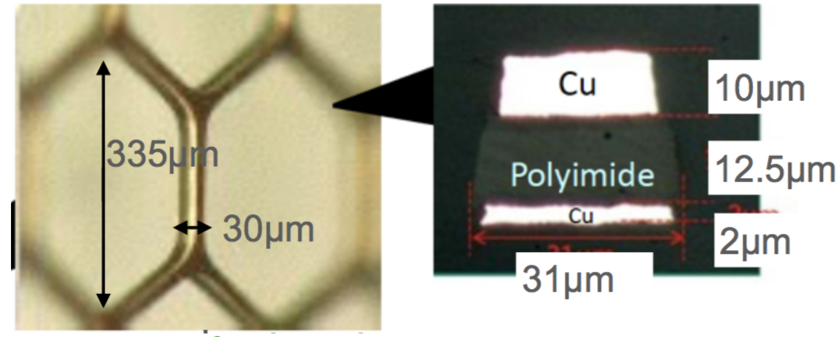
Ion Gating

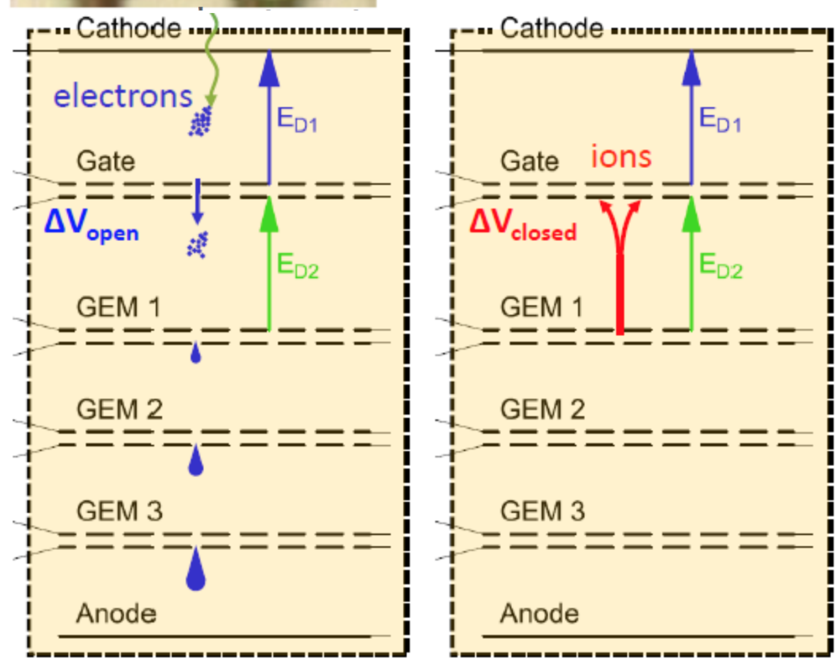
Gating: open GEM to stop ions while keeping transparency for electrons

- ☞ A large-aperture gate-GEM with **honeycomb-shaped holes**
  - ➠ **produced in Japan**
  - ➠ handed to Saclay for transparency measurements with MM
  - ➠ use test setup at CERN



- ☞ **French team:** simulating in hardware an **ion disk** with a UV lamp



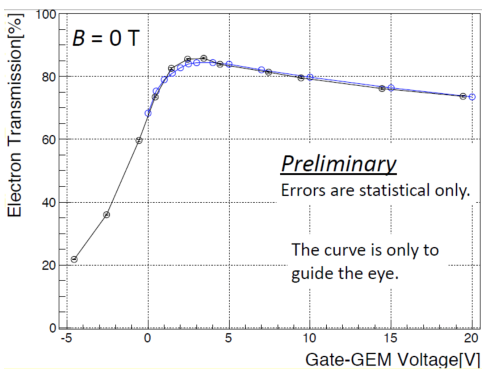


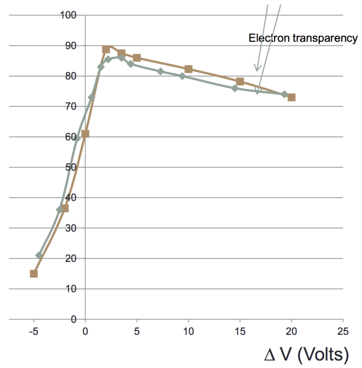
The ions must be stopped before penetrating too much the drift region

The device to stop them must be transparent to electrons

GEM Gating –Large aperture GEM transparency

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

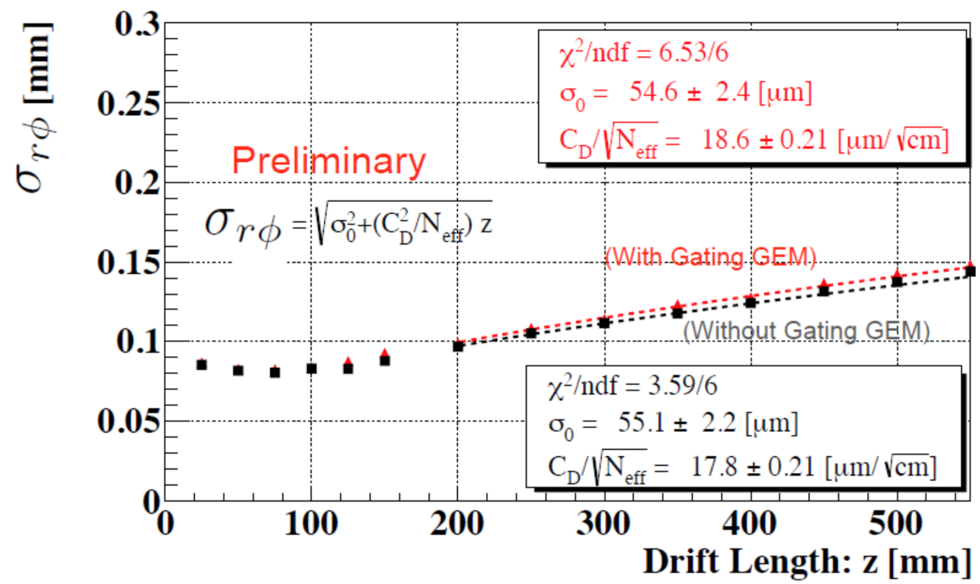




- ☞ Measurements with GEM (at KEK) and MM (at CERN) are consistent
- ☞ Extrapolation to 3.5 T shows acceptable transmission for electrons (80%)
- ☞ Estimate ion-stopping power based on electron-stopping power measured with a laser beam ⇒ better than 10^{-4}

Measurement of ion-stopping power withing this project!

A module with a gating GEM has also been tested in beam in November 2016



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

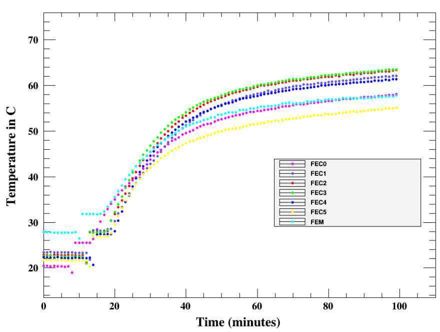
GEM gating seems to be a possible solution for the gating at ILC

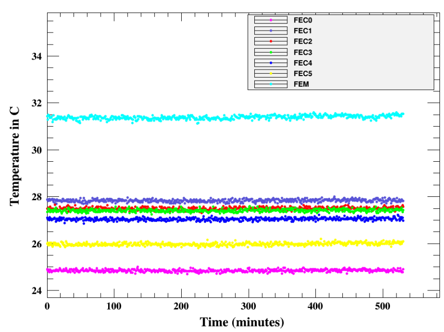
M. Kobayashi, et al.,

NIM A918 (2019), 41-53

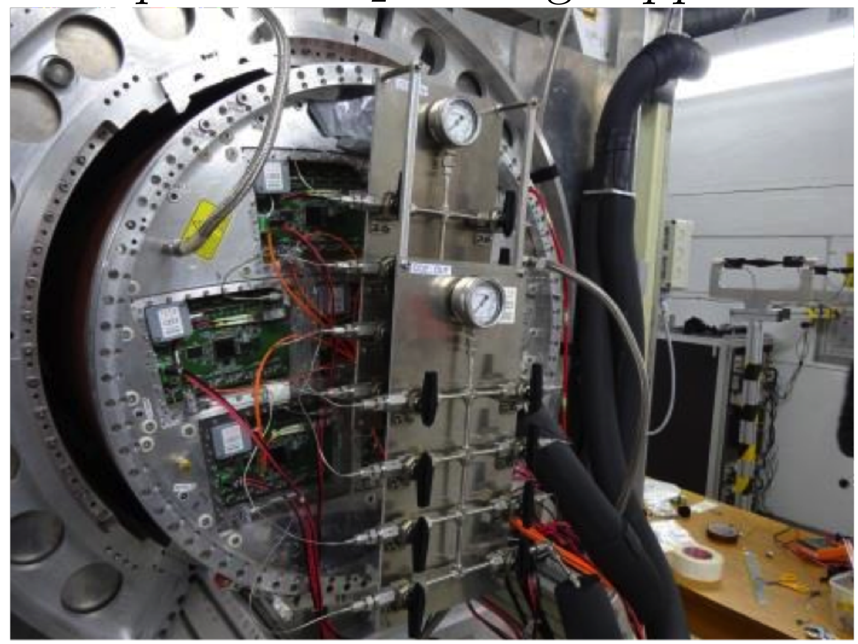
Cooling of the electronic circuit is required due to power consumption

- 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**

3D Cooling Circuit

☞ **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

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

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

☞ **Saclay project "COSTARD"**

- cooling plate by metallic additive fabrication by laser using sintered powder of Al with a 2 mm inner-diameter serpentine
  - ➔ test possibility to remove the powder residuals from the serpentine
  - ➔ test pressure up to 100 bar
  - ➔ develop connection to pipes

Members, Funding

Spending on French Funds				
Description	€/unit	Nb of units	Total (€)	Provided by:[1]
TYL WS (Nara, 8-13 May, 2018)	150/day			
S. Ganjour, P. Colas/ 5 days		2 travels	2600	CEA/IRFU
Total			2600	
Spending on KEK Fund				
Description	**k¥/Unit**	**Nb of units**	**Total (k¥)**	
Visit to France (K.Fujii, Jan. 2019)	20/day	8 days	160	KEK
Travel	260	1 travel	260	KEK
Visit to France (A.Sugiyama, Jan. 2019)	20/day	4 days	80	KEK
Travel	220	1 travel	220	KEK
Visit to France (T.Ogawa, Jan. 2019)	15/day	8 days	120	KEK
Travel	180	1 travel	180	KEK
				Shared with HEP_9
Total			1,020	

Additional spending on French funds			Additional spending on Japan funds		
Provided by:[2]	Type	€	Provided by:[3]	Type	k¥
E-JADE H2020 RISE	secondment	15000	IPNS/KEK	travel	140
CEA/IRFU	equipment	15000	Tokyo Univ	secondment	500
Total		30000	Total		640

	French Group			Japanese Group		
	Name	Title	Lab./Organis.[2]	Name	Title	Lab/Organis.[3]
Leader	S. Ganjour	Dr.	IRFU/CEA	K. Fujii	Dr.	KEK
Members	P. Colas	Dr.	IRFU/CEA	T. Fusayasu	Dr.	Saga Univ.
	D. Attie	Dr.	IRFU/CEA	K. Kato	Dr.	Kinki Univ.
	I. Giomataris	Dr.	IRFU/CEA	M. Kobayashi	Dr.	IPNS/KEK
	A. Giganon	Mr.	IRFU/CEA	T. Matsuda	Dr.	IPNS/KEK
	M. Titov	Dr.	IRFU/CEA	A. Sugiyama	Dr.	Saga Univ.
	B. Tuchming	Dr.	IRFU/CEA	T. Takahashi	Dr.	Hiroshima Univ.
				T. Watanabe	Dr.	Kogakuin Univ.
				S. Narita	Dr.	Iwate Univ.
				K. Negishi	Dr.	Iwate Univ.
				Y. Aoki	Miss	Sokendai/KEK
				A. Shoji	Miss	Iwate Univ.
				K. Yumino	Mr.	Sokendai/KEK

Funding Request from France				
Description	€/unit	Nb of units	Total (€)	Requested to[4]:
Visit to Japan	150/day	45 days	6750	IRFU/CEA
Travel	1000	3 travel	3000	IRFU/CEA
Total			9750	
Funding Request from KEK				
Description	**k¥/Unit**	**Nb of units**	**Total (k¥)**	**Requested to:**
Visit to France	20/day	28 days	560	KEK
Travel	200	4 travels	800	KEK
Total			1350	

Additional Funding from France			Additional Funding from Japan		
Provided by/Requested to[5]	Type	€	Provided by/Requested to[6]	Type	k¥
CEA/Irfu	ILC R&D	20,000	IPNS/KEK	travel	280
EU	AIDA 2020	5,000			
Total		25,000	Total		280

☞ Saclay applied to

➠ **E-JADE** fund travels to Japan

➔ for 4 years

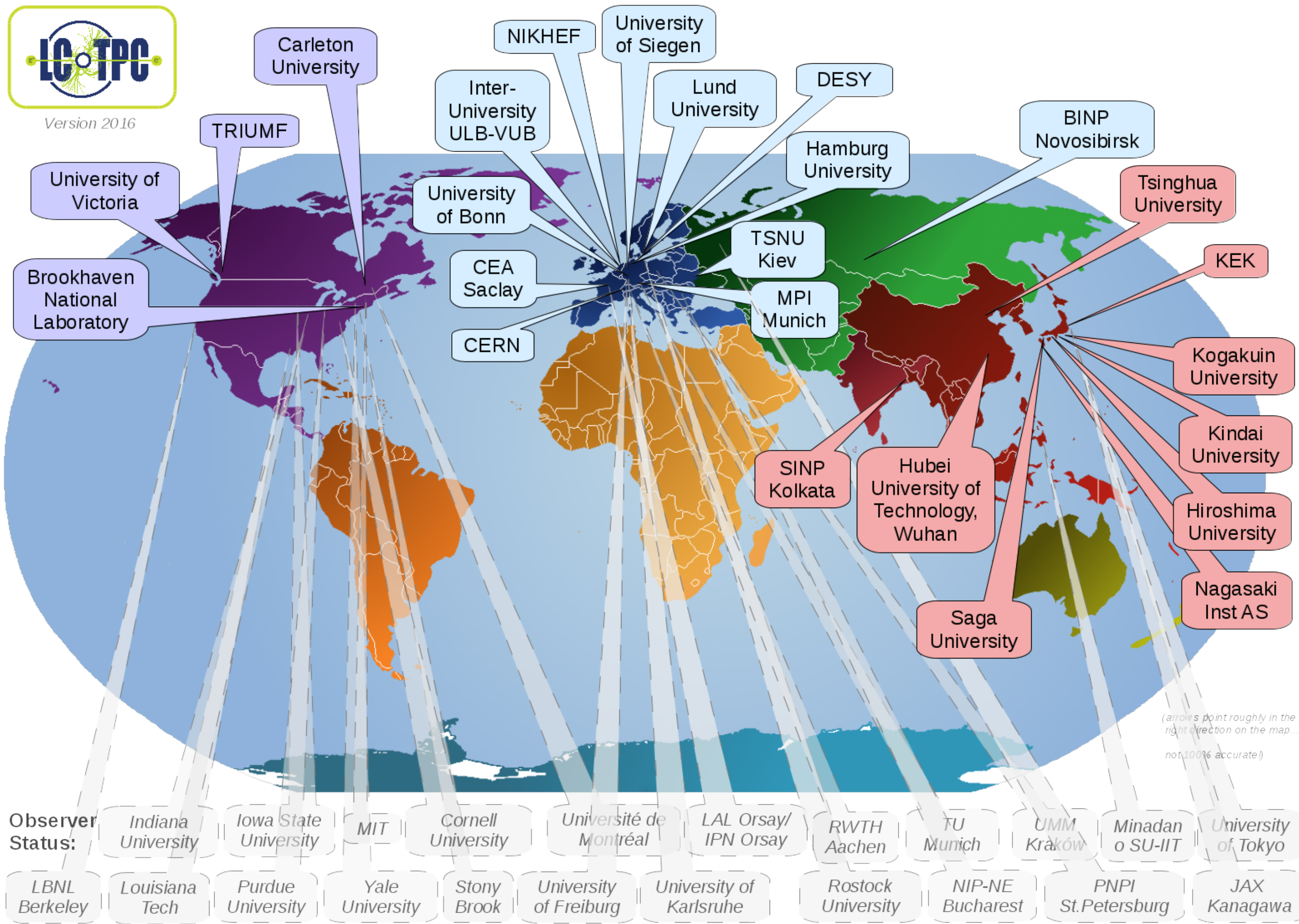
☞ A **postdoc from Japan** visited Saclay for 2.5 months

Conclusions

- **A TYL project D_RD_18 has been engaged in 2018 on the possible consequences of the "expression of interest" of the Japanese governement this year, as an input to the European Strategy Update**
- **The French-Japan R&D work is in a phase of engineering toward the technology choice of a TPC for the ILD detector**
  - **new beam test** carried out with the LP equipped with a new end-plate
    - ➔ 4 MM modules with a new grounded scheme (encapsulated) were tested
    - ➔ ExB effect between modules is fully suppressed in the new scheme
    - ➔ 2-phase CO_2 cooling operation with 1-loop circuit was confirmed
  - we identify points requiring **common active R&D** to be pursued
    - ➔ further analysis of the test beam data together with simulations
    - ➔ optimization of the GEM-like gating device and measurement of ion-stopping power
    - ➔ testing of new amplification GEM foils aiming reduction of discharge rate
    - ➔ 2-phase CO_2 with a monolitic cooling circuit using 3D printing technologies
    - ➔ engineering aspects, electronics and simulation
- **Special thanks to P. Colas and A. Sugiyama**

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

Micro Pattern Gas Detectors (MPGDs)

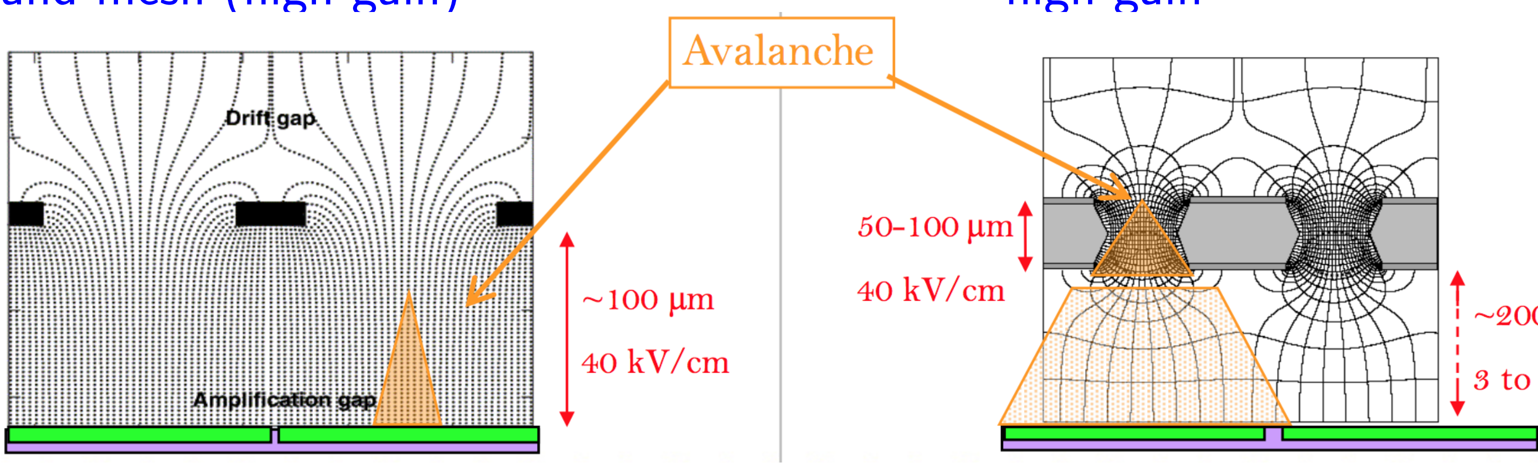
- Technology choise for TPC readout: **Micro Pattern Gas Detector (MPGD)**
  - **no ExB effect, better ageing, low ionback drift**
  - easy to manufacture, MPGD more robust mechanically than wires

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

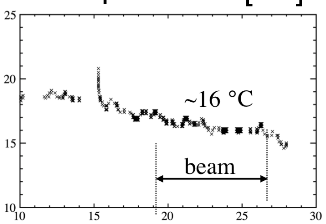


Discharge probability can be mastered (use of resistive coatings, several step amplification, segmentation)

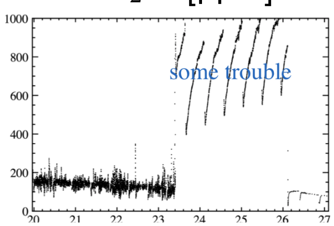
☞ Prototype operates with T2K gas

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

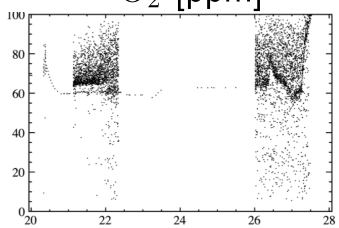
Temperature [C°]

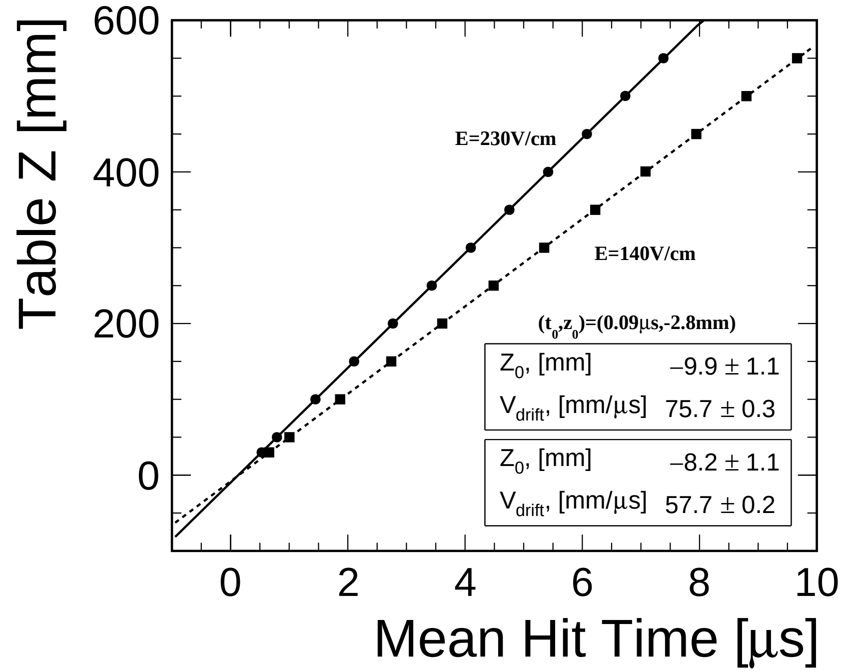


H_2O [ppm]



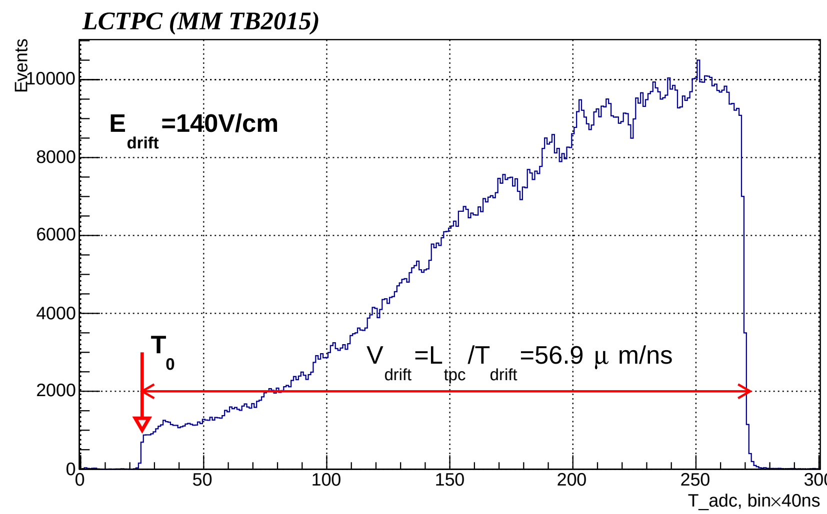
O_2 [ppm]





☞ **Absolute T_0 calibration:**

- **beam trigger:** dedicated z-scan at $V_{\rm drift} = 140, 230$ 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`	$74.5 \pm 2.5\mu m/\sqrt{cm}$	$94.8 \pm 3.1\mu m/\sqrt{cm}$

- **The beam test electronics are not those to be used in the ILD detector**
  - AFTER (T2K chip) is not extrapolable to **Switched Capacitor Array (CSA)** depths of 1 bunch train
  - ALTRO does not satisfy power consumption requirements
- **S-Altro 16 has to evolve**
  - improve packing factor (probably 65 nm)
  - lower power consumption
  - power pulsing from the beginning
- **Final design based on S-Altro 16 requires a renewed project**
  - current effort on being made at Lund University
  - this is not in the final form
  - could still use it to test cooling, power-pulsing, etc

Design of a **large GEM and MM modules** *with cooling and high channel density has been started*

☞ 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

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

- 10x10 cm² active area

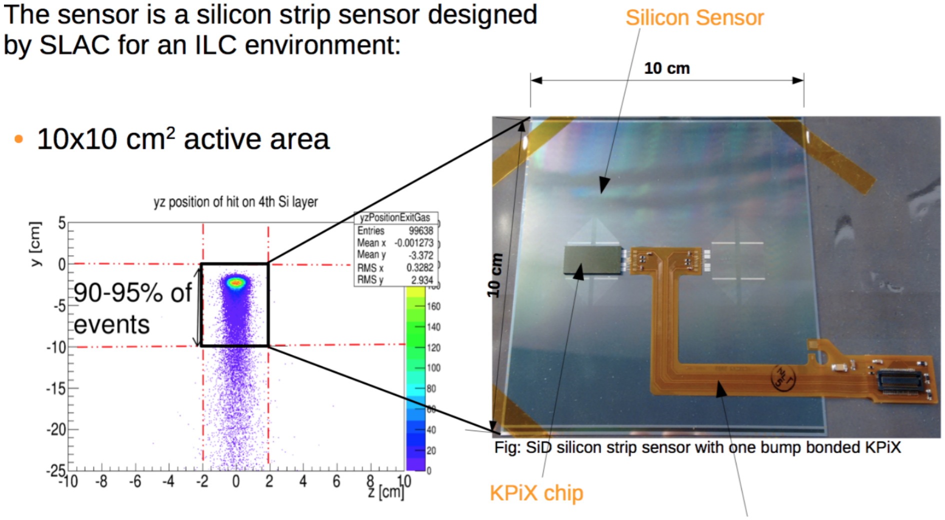
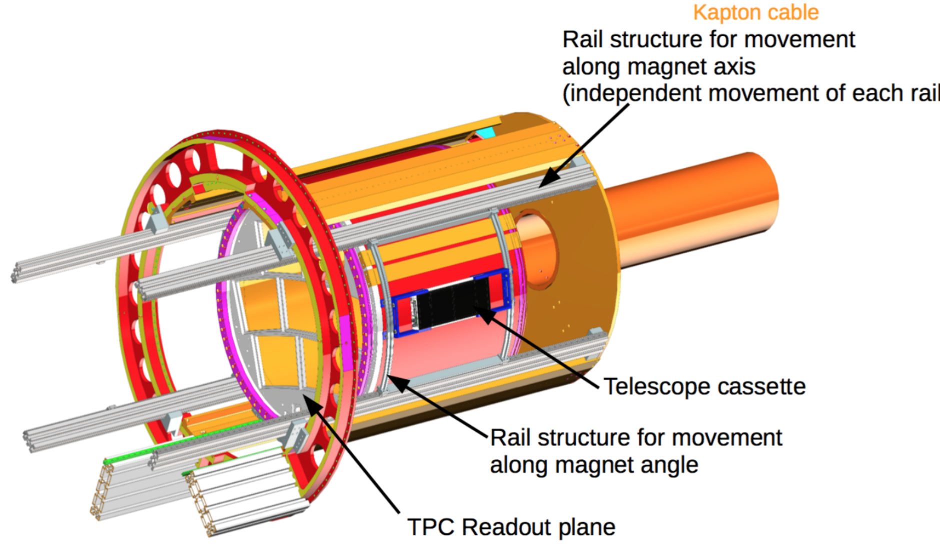


Fig: SiD silicon strip sensor with one bump bonded KPiX



Final dimension of the active area is 10x20 cm²