岩手大学
IWATE UNIVERSITY

Toward the design of the TPC at future colliders (D_RD_28)

CEA - Saclay

Shinya Narita, Serguei Ganjour

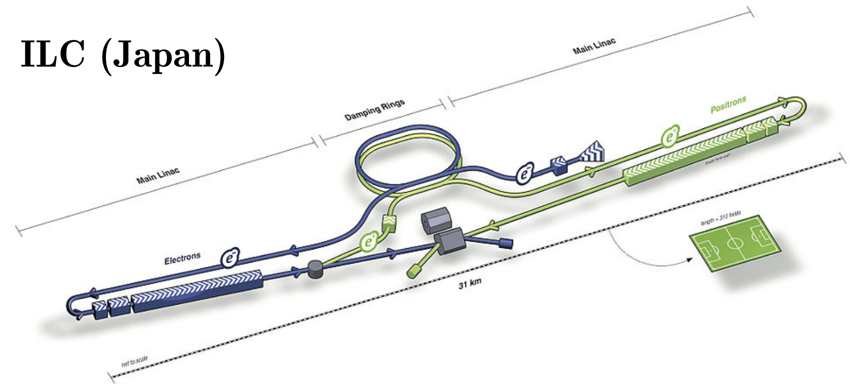
narita@iwate-u.ac.jp, Serguei.Ganjour@cea.fr

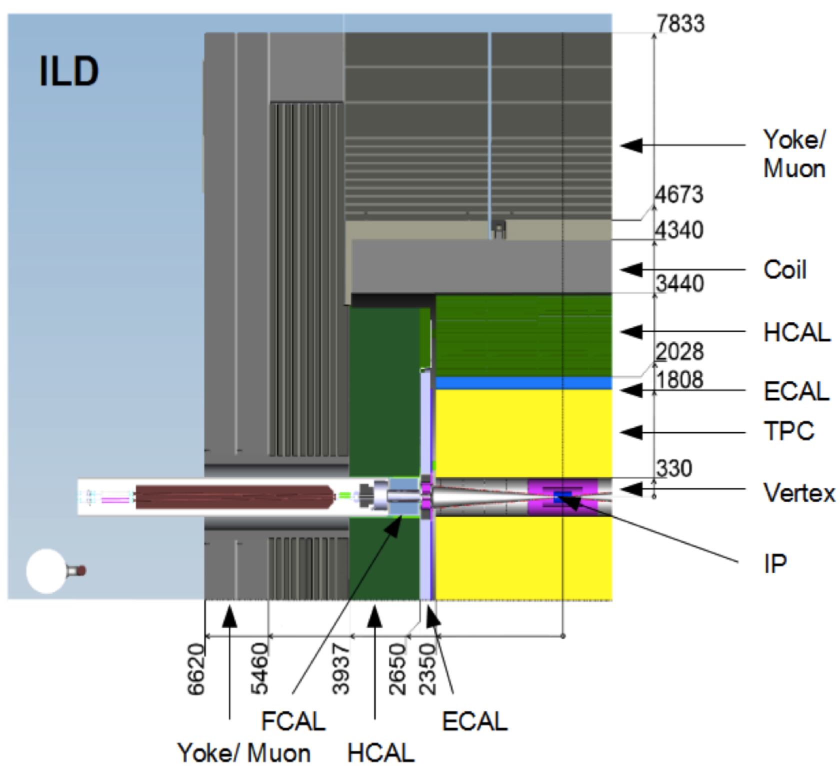
Iwate University, Morioka, Japan

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

TYL-FJPPL
May 22-24, 2024

- **International Linear Collider (ILC) continues to stand as the most advanced design among projects aimed at realizing a future Higgs Factory**
  - staged project beginning with 250 GeV center-of-mass energy
  - **Time Projection Chamber** (TPC) is the central tracker for the **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





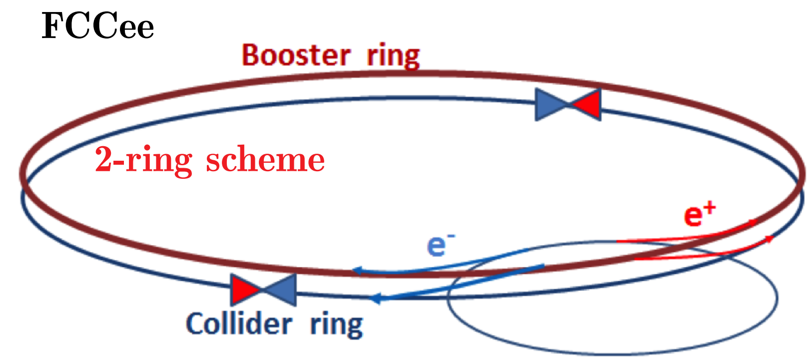
Proposals for Higgs Factories include circular colliders like FCCee and CEPC

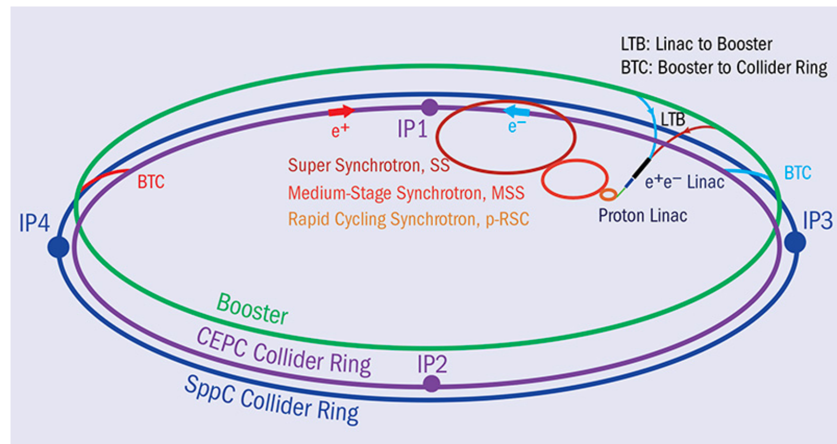
☞ Main features:

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

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

Our collective focus is on the challenge of adopting a TPC designed for the ILC to effectively operate within a circular machine





	FCCee-Z	FCCee-H	CEPC-Z	CEPC-H
$\sqrt{s}$ (GeV)	90	240	90	240
L ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	**200**	**7**	**191.7**	**8.3**
# bunches	16640	328	19918	415
Total RF voltage (GV)	0.1	2.0	0.12	2.2
Bunch intensity (10^{11})	1.7	1.8	1.4	1.4
Lumi lifetime (min)	68	38	80	20
SR Power (MW)	50	50	50	50

☞ The feasibility of a TPC for the LC was demonstrated in D_RD_2 project

☞ 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: $\mathrm{CO_2}$ cooling, track distortions, etc

☞ **D_RD_18 addressed issues related to technology choice for the ILD TPC**

- mitigate ExB effects at design level (field distortions)
- design optimization of the GEM-like gating device
- spacial and dE/dx resolution with Large Prototype 2 (LP2)

☞ **D_RD_28 started in 2023 and has to tackle the design challenges specific to the TPC at circular colliders**

- simulation of the field distortions caused by positive ions $\Rightarrow$ very advanced
- dynamic corrections of the space charge distortions $\Rightarrow$ in progress
- static gating R&D with graphene membrane $\Rightarrow$ started
- optimization of the MPGD readout structure $\Rightarrow$ in progress

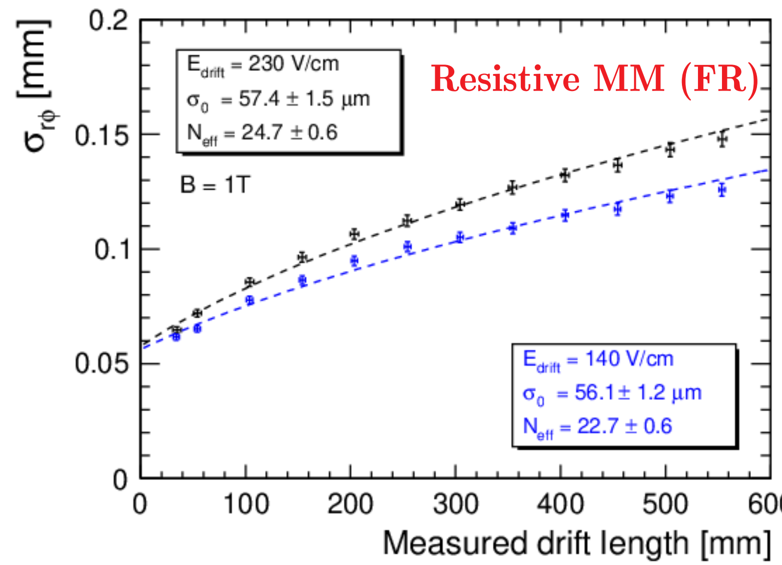
Prototype Performance

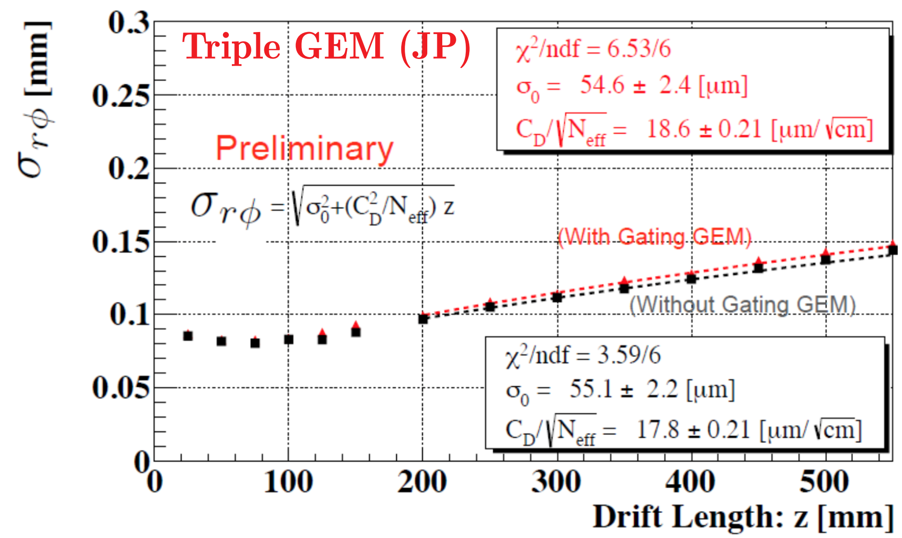
Collective effort between French and Japanese teams for conducting beam tests at DESY facility and subsequent data analysis

☞ **Key findings from the beam tests:**

- achieve the designed performance, including spatial and dE/dx resolutions
- validate the design of the gating-GEM
- evaluate the effectiveness of the new grounding scheme with encapsulated resistive anode to mitigate ExB effects

Extrapolating to a magnetic field of 3.5 T and a drift length of 2.35 m yield to a maximum uncertainty of 100 μm accross the entire drift length





The substantial difference in operating conditions between circular and linear colliders demands further technological progress in TPC design

☞ **Distortions within the drift volume is one of the most critical concern for the TPC during high-rate operation at circular colliders**

➠ they originate from primary ions generated by tracks from Z-pole events and machine background, as well as backflowing ions produced during amplification

☞ **Japaneese and French teams involved in this project are developing diverse methods to suppress ion backflow and correct for the remaining distorsions**

➠ dynamic gating structure based on high-aperture GEM foil for linear colliders

➠ revising the configuration of the MPGD readout system

➔ combined Micromegas and GEM readout module

➔ static gating with graphene membrane

➠ simulating space charge fields and implementing corrections to track distortions using physics events such as $Z \to \mu^+\mu^-$

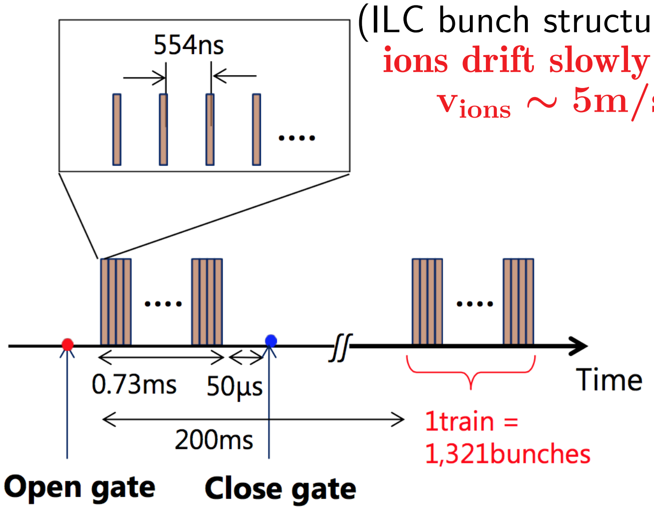
Ion Space Charge can deteriorate the position resolution of TPC

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

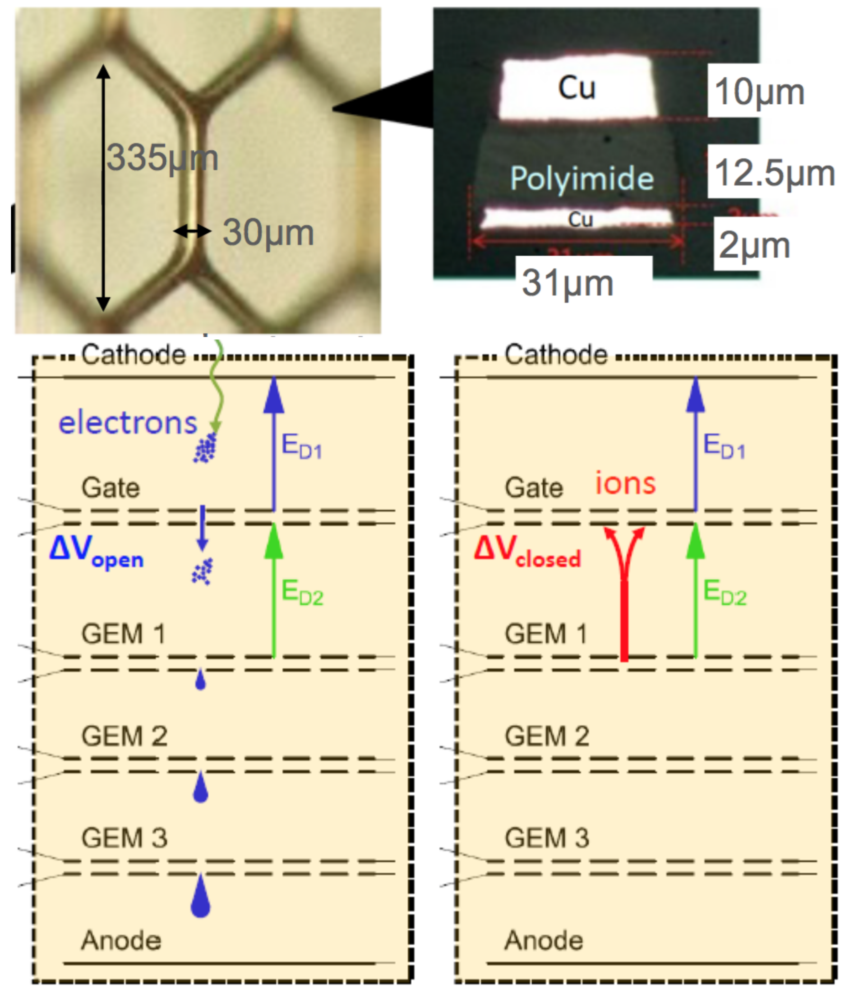
➠ 60 μm for **IBFxGain=3** for the case of 2 ion disks

(ILC bunch structure)

ions drift slowly $v_{ions} \sim 5m/s$



Dynamic gating is only feasible for a linear collider with low-rate operation

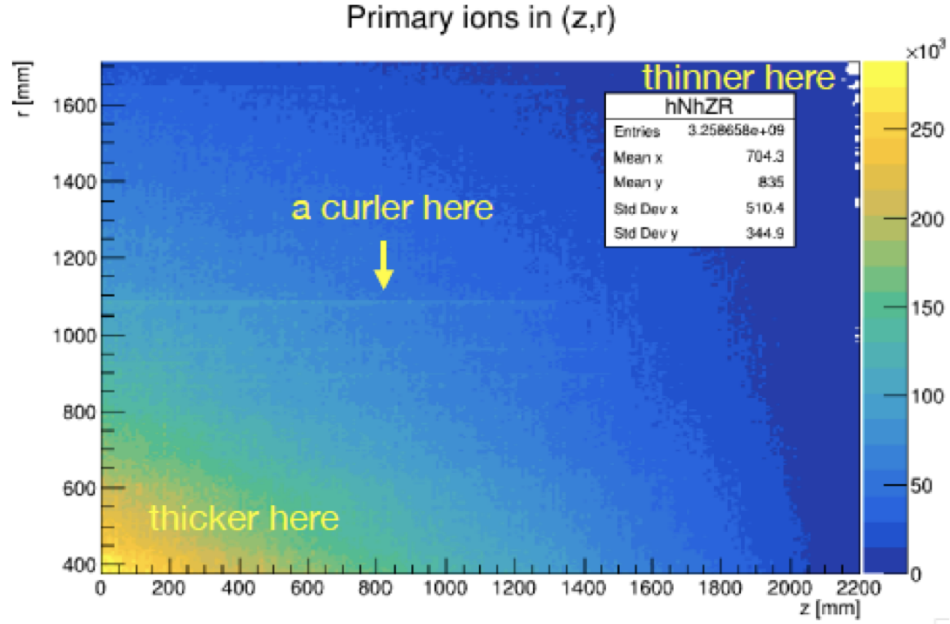


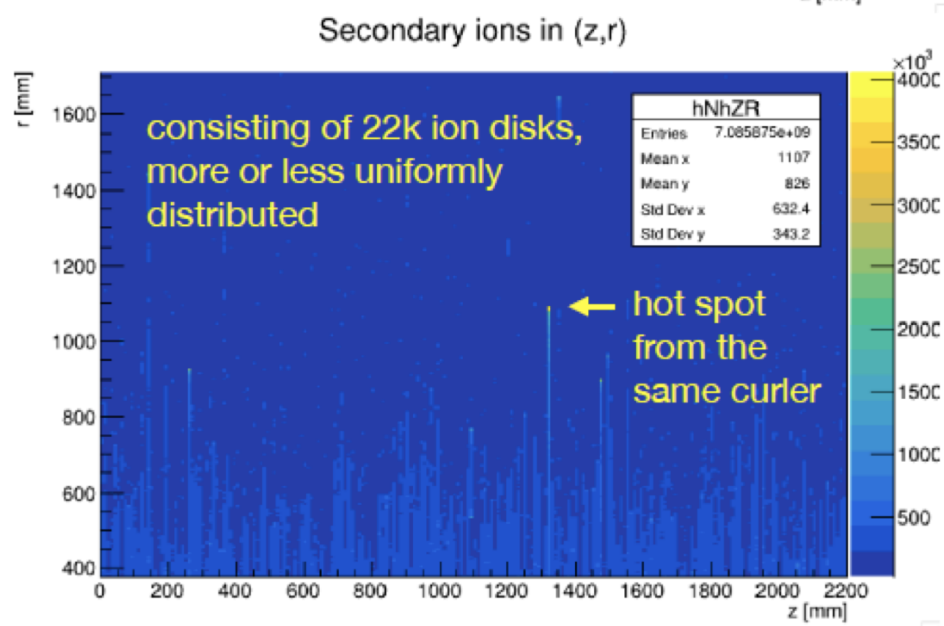
The ions must be stopped before penetrating too much the drift region

The device to stop them must be transparent to electrons

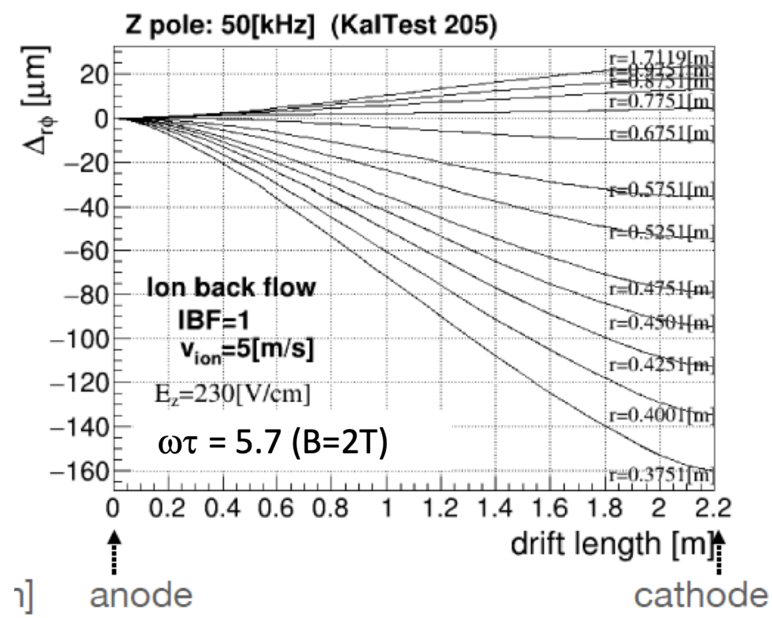
Simulation of the space charge density in the TPC volume involves the complete detector simulation

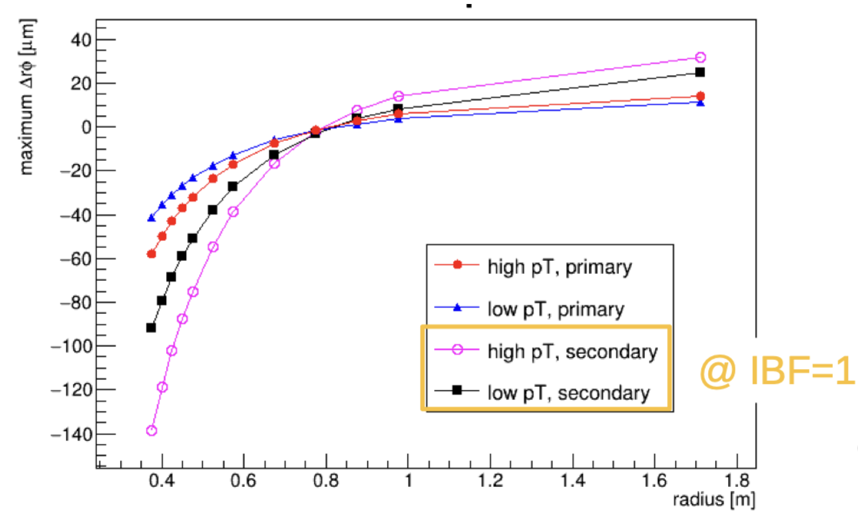
- Simulating $e^+e^- \rightarrow \text{hadrons}$ at the Z-pole with Pythia8 yields a rate of 50 kHz
- **Simulation inputs:**
  - TPC volume: $L = 2200$ mm, $r_{in} = 375$ mm, $r_{out} = 1720$ mm
  - solenoidal magnetic field B=1 T
  - ion drift velocity $v_{ions} \sim 5m/s$
- Every e^+e^- event generates 1 million **primary ions** within the TPC volume
- **Secondary ions** appear as an almost continuous set of disks, with approximately 22 000 disks created in the amplification region





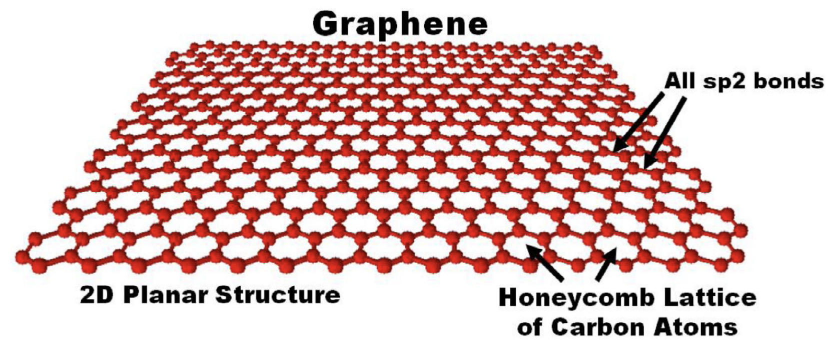
- The computation of electron trajectory distortions relies on the space charge model and employs Langevin equation (K.Fujii)
  - maximum distortions of **60 μm** attributed to **primary** ionization
  - **secondary** ions result in maximum distorsions of **140 μm** for Gain$\times$IBF=1
  - current achivement for the MPGD readout system, with a Gain$\times$IBF=5, leads in maximum distorsions of **800 μm**
- Simulating beamstrahlung induces x200 more primary ions compared to $e^+e^- \to$ hadrons, predominantly due to MDI elements
- Efforts to mitigate trajectory distortions through **dynamic corrections** are ongoing
  - stability of distortions wrt time
  - measure space charge distribution



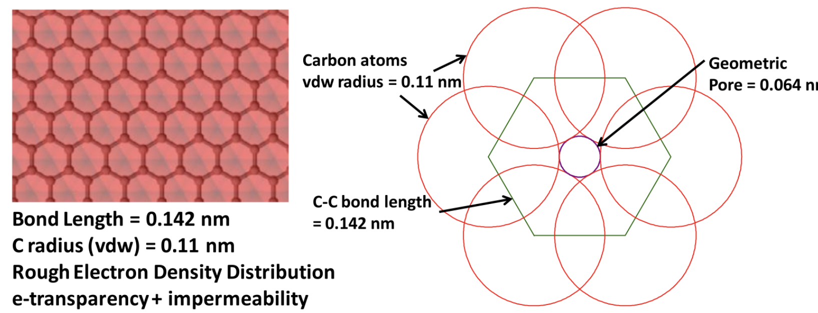


A TPC with IBF=4 at a circular collider operating at Z-pole has similar space charge as at ALICE

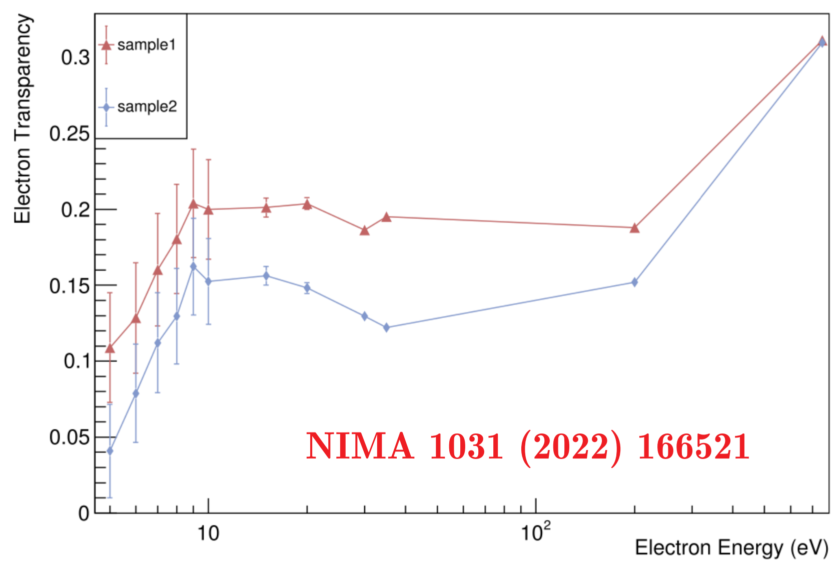
- **Graphene** holds promise as a material capable of completely eliminating ion backflow
  - impermeable to atoms, molecules and ions
  - effectively blocks ions in TPC due to their insufficient energy
  - electrons must pass through it to generate the electron avalanche



- The transmission coefficient of 5 eV electrons to **monolayer graphene is 40-50%**



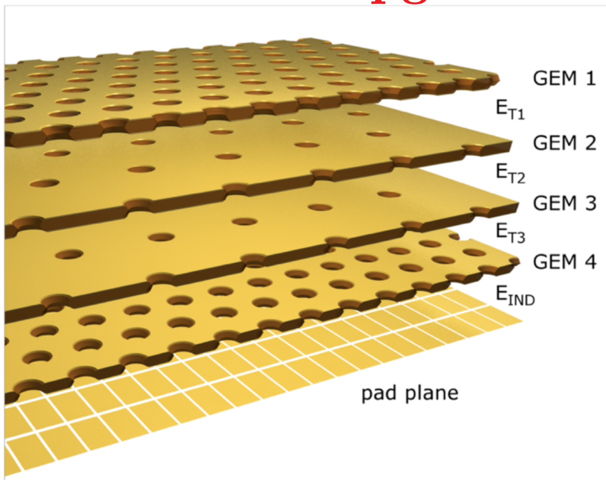
- Graphene coating technology has been tested for the first time using two MM bulk samples
  - to achieve high-quality graphene transfer, an intermediate conductive structure with smaller holes, ideally $\leq 1\mu\mathrm{m}$, may be necessary

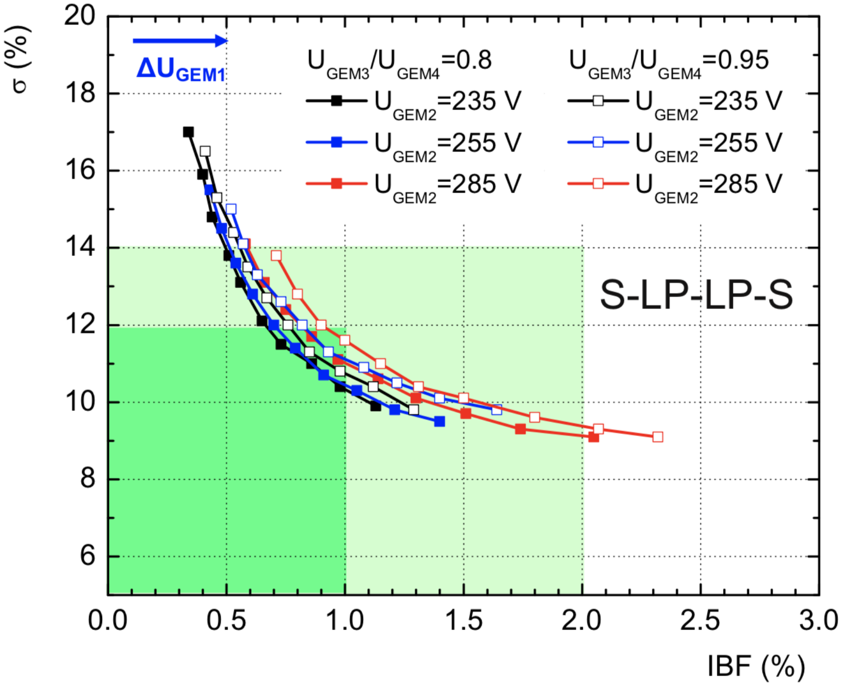


R&D involving the nano-channel plate is anticipated

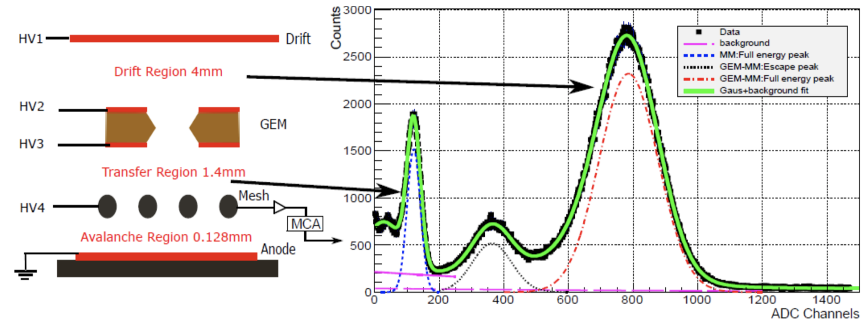
Modifications in the Readout Schema

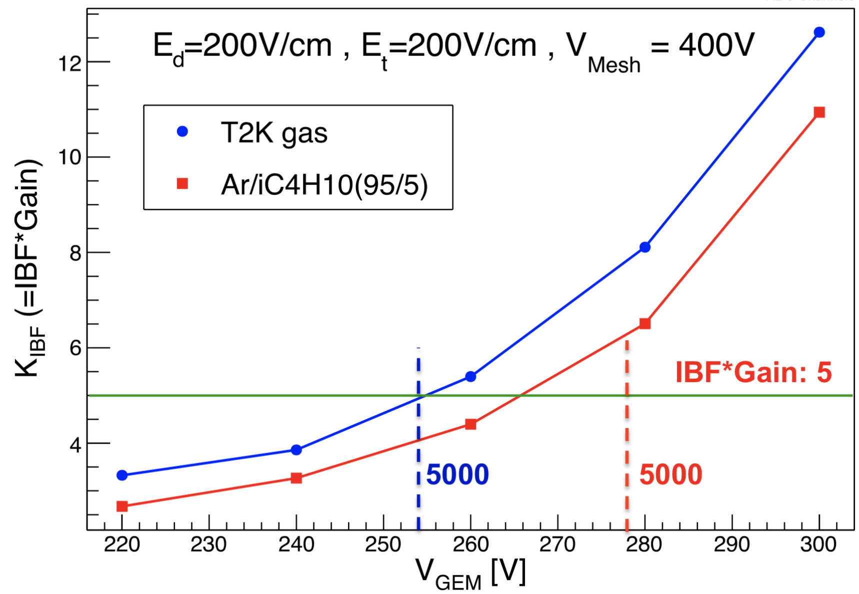
ALICE TPC Upgrade





R&D LCTPC Collaboration





Combined MM+GEM module at IHEP

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

Spending on French Funds				
Description	**€/unit**	**Nb of units**	**Total (€)**	**Provided by:[1]**
S. Ganjour				
TYL WS (Ochanomizu University, 9-11 May 2023)		10 days	2079	CEA/IRFU
Visit KEK, Iwate Univ. (12-17 May 2023)		1 travel	2136	CEA/IRFU
P. Colas				
TYL WS (Ochanomizu University, 9-11 May 2023)		10 days	1619	CEA/IRFU
Visit KEK, Iwate Univ. (12-17 May 2023)		1 travel	2078	CEA/IRFU
Total			7912	

Spending on KEK Fund				
Description	**k¥/Unit**	**Nb of units**	**Total (k¥)**	**Provided by:[1]**
Total			0	

Additional spending on French funds			Additional spending on Japan funds		
Provided by:[2]	**Type**	**€**	**Provided by:[3]**	**Type**	**k¥**
CEA/IRFU	equipment	5000	Iwate Univ.	Consumable/ Travels	463
Total		5000	Total		463

	French Group			Japanese Group		
	name (Family name, First name)	**title**	**lab.**	**name** (Family name, First name)	**title**	**lab.**
PIs:	S. Ganjour Serguei.Ganjour@cea.fr	Dr.	IRFU/CEA	S. Narita narita@iwate-u.ac.jp	Dr.	Iwate Univ.
Members:	P. Colas	Dr.	IRFU/CEA	R. Hosokawa	Dr.	Iwate Univ.
	D. Attie	Dr.	IRFU/CEA	K. Fujii	Dr.	IPNS/KEK
	I. Giomataris	Dr.	IRFU/CEA	D. Jeans	Dr.	IPNS/KEK
	M. Titov	Dr.	IRFU/CEA	T. Fusayasu	Dr.	Saga Univ.
	B. Tuchming	Dr.	IRFU/CEA	Y. Kato	Dr.	Kinki Univ.
				T. Watanabe	Dr.	Kogakuin Univ.
				K. Watanabe	Ms.	Iwate Univ.
				K. Oikawa	Mr.	Iwate Univ.
				R. Sugawara	Mr.	Iwate Univ.
				J. Nakajima	Ms.	Sokendai/KEK

Funding Request from France				
Description	**€/unit**	**nb of units**	**total (€)**	**requested to**
Visit to Japan	170/day	30 days	5100	IRFU/CEA
Travel	3000	2 travels	3000	IRFU/CEA
Total			8100	

Funding Request from Japan				
Description	**k¥/Unit**	**nb of units**	**total (k¥)**	**requested to**
Visit to France	20/day	20 days	400	KEK
Travel	250	2 travels	500	KEK
Total			900	

Additional Funding from France			Additional Funding from Japan		
provided by/requested to	**Type**	**€**	**provided by/requested to**	**Type**	**k¥**
IRFU/CEA	consumable	5000	Iwate	Consumable/ Travels	400
Total		5000	Total		400

☞ Visited student

- **J.Nakajima** (Sokendai/KEK)
- 3 months stay at Saclay

Conclusions

- In 2019-2023, under TYL D_RD_18 project, Japaneese and French teams made significant progress in addressing key issues related to technology selection for the TPC
- **In 2023, the TYL project D_RD_28 was initiated due to widespread interest in future Higgs Factories, including circular colliders, serving as an input to the European Strategy Update**
- **The French-Japan R&D efforts are currently focused on the design phase of the TPC design for future circular colliders**
- We have identified areas where **collaborative active R&D** will be pursued this year within the scope of the D_RD_28 project
  - simulating field distortions caused by positive ions leading track distortions
  - developing dynamic correction methods for track distortions
  - pursuing R&D of static gating with graphene membrane
  - optimizating the MPGD readout structure for effective IBF suppression
  - improving the 2-phase CO_2 cooling system

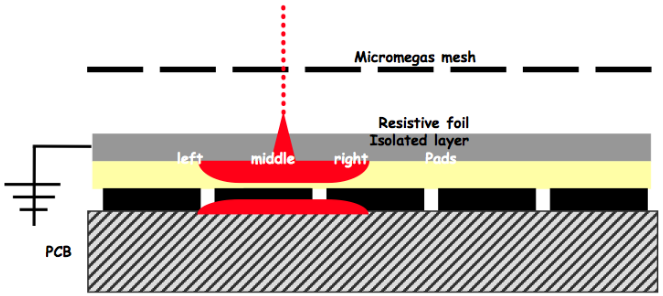
Backup

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%

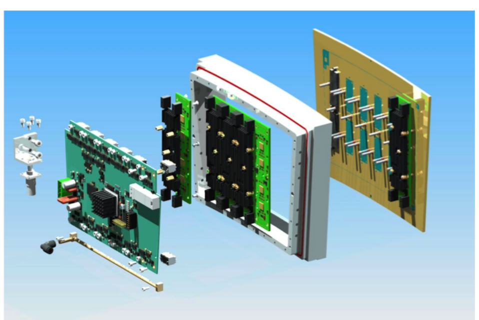
France:



☞ **Charge density function**

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

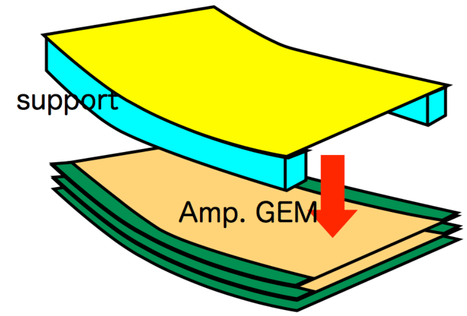
R- surface resistivity
C- capacitance/unit area

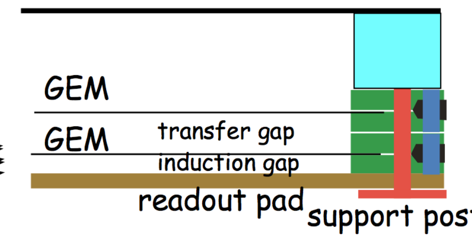


☞ **MM: T2K readout ASIC**

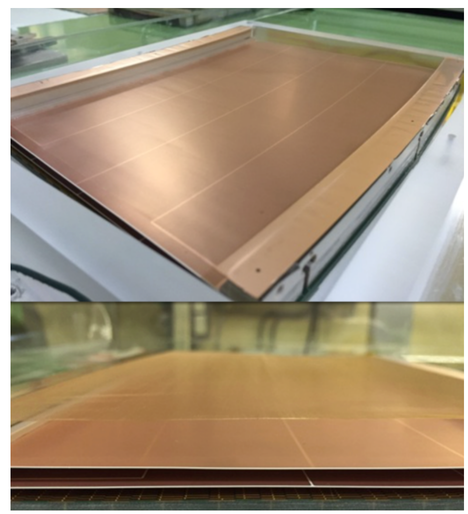
➠ 72-channel AFTER chip (12-bit)

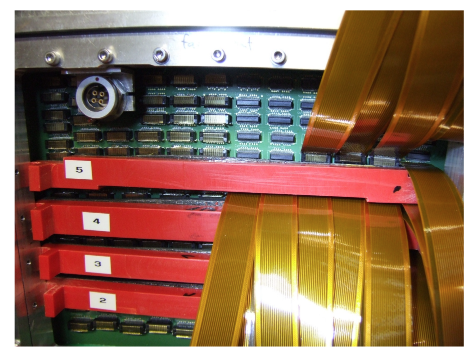
Japan:





☞ 2-3 layers are needed to obtain high gain





☞ **GEM: modified ALTRO readout**

➠ 16-channel ALTRO chip (10-bit)

3D Cooling Circuit

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