MPGDs for TPCs at future lepton colliders

TPC - technology requirements and opportunities at ILC and CEPC

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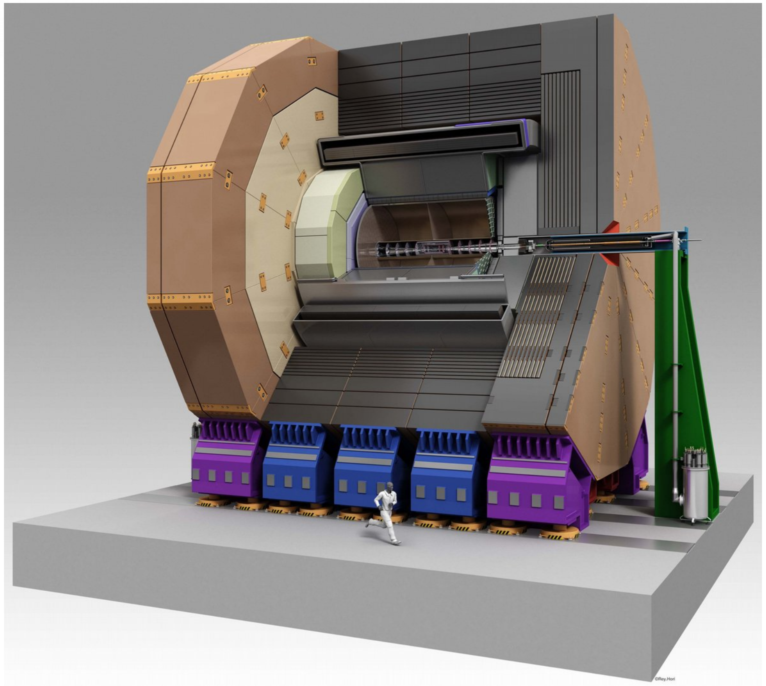
A TPC for ILD at ILC (or CEPC)



International Large Detector
- Standard HEP detector
- TPC as main tracker
- Interchanged with SiD by push and pull principle

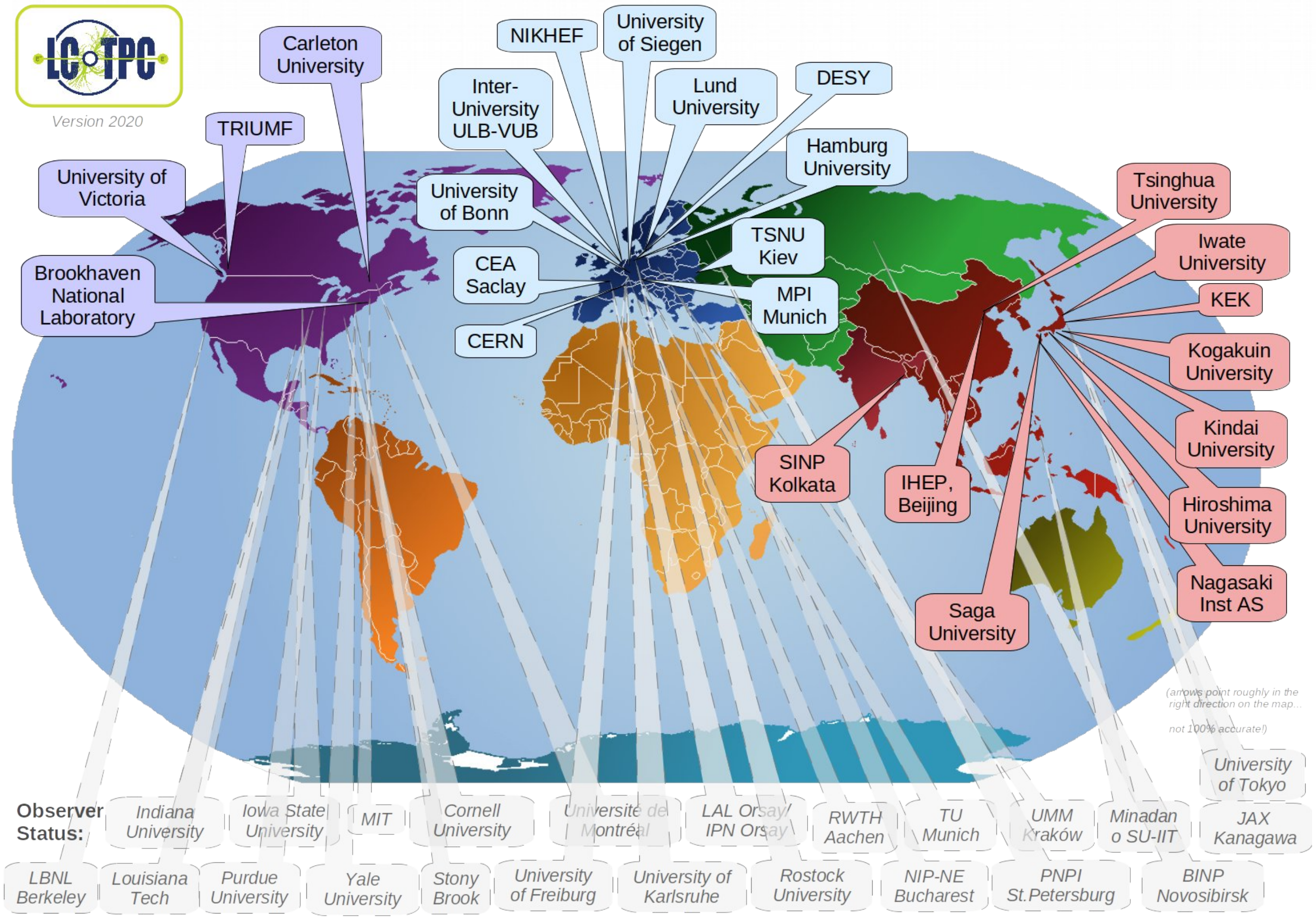
Requirements of TPC from ILC TDR vol. 4

Parameter			
Geometrical parameters	r_{in}	r_{out}	z
	329 mm	1808 mm	$\pm$ 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq 0.05\ \mathrm{X}_0$ including outer fieldcage in r		
	$< 0.25\ \mathrm{X}_0$ for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times\ 10^6$/1000 per endcap		
Pad pitch/ no.padrows	$\simeq 1\times 6\ \mathrm{mm}^2$ for 220 padrows		
σ_{point} in $r\phi$	$\simeq 60\ \mu$m for zero drift, $< 100\ \mu$m overall		
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)		
2-hit resolution in $r\phi$	$\simeq 2$ mm		
2-hit resolution in rz	$\simeq 6$ mm		
dE/dx resolution	$\simeq 5$ %		
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)		

In addition: very high efficiency for particle of more than 1 GeV.

These requirements can not be fulfilled by conventional wire-based read out. New Micropattern-based readouts have to be applied.

LCTPC Collaboration



LCTPC-collaboration studies MPGD detectors for the ILD-TPC:
25 Institutes from
12 countries
+ 23 institutes with observer status

Various gas amplification stages are studied: GEMs, Micromegas, GEMs with double thickness and GridPixes.

MPGDs in TPCs

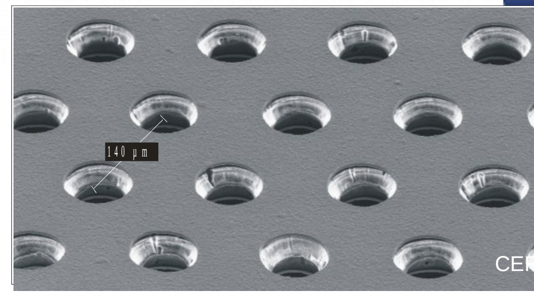
- Ion backflow can be reduced significantly
- Small pitch of gas amplification regions => strong reduction of E×B-effects
- No preference in direction => all 2 dim. readout geometries possible

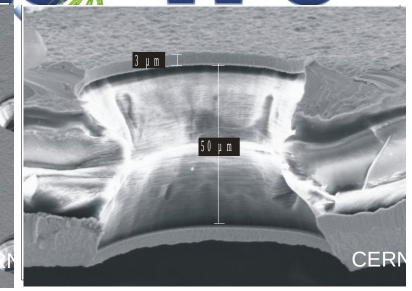
GEM

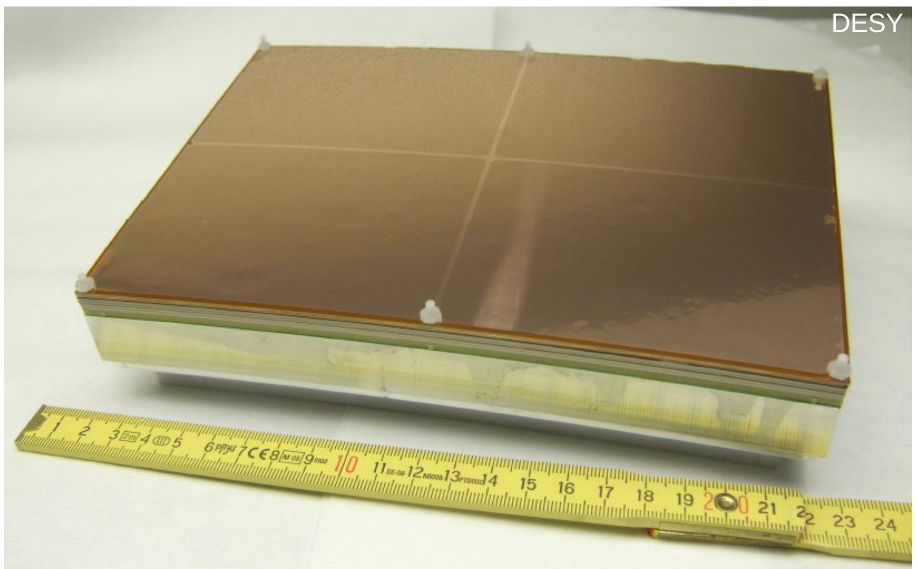
<u>GEMs:</u> copper-insulator- copper sandwich, with holes

2 configurations are being tested:

- triple GEMs with ‘standard CERN GEMs’
- double GEMs with 100µm LCP insulator

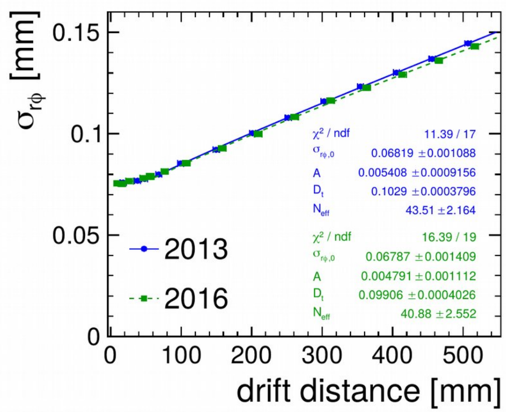


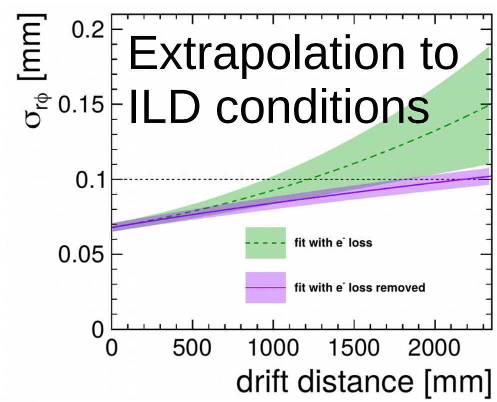


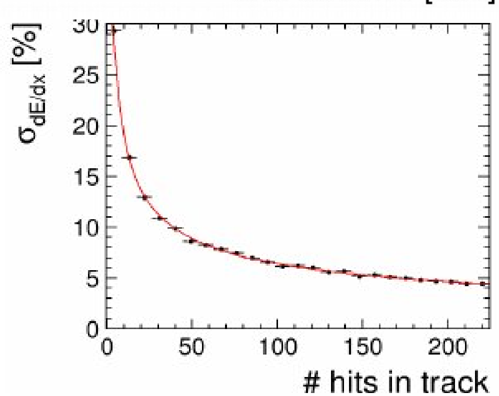


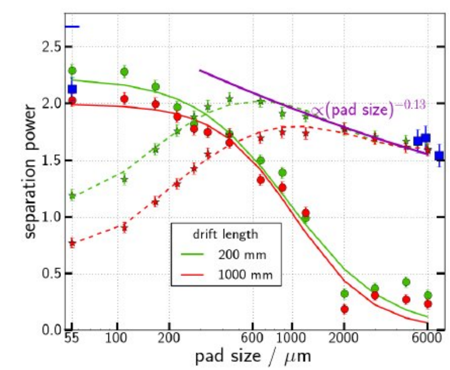
dE/dx performance is scrutinized. Also, in dependence on the pad sizes.

New publication in preparation:





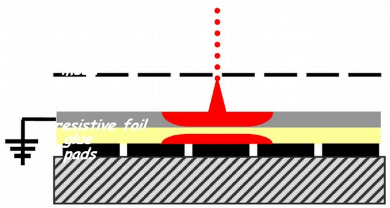




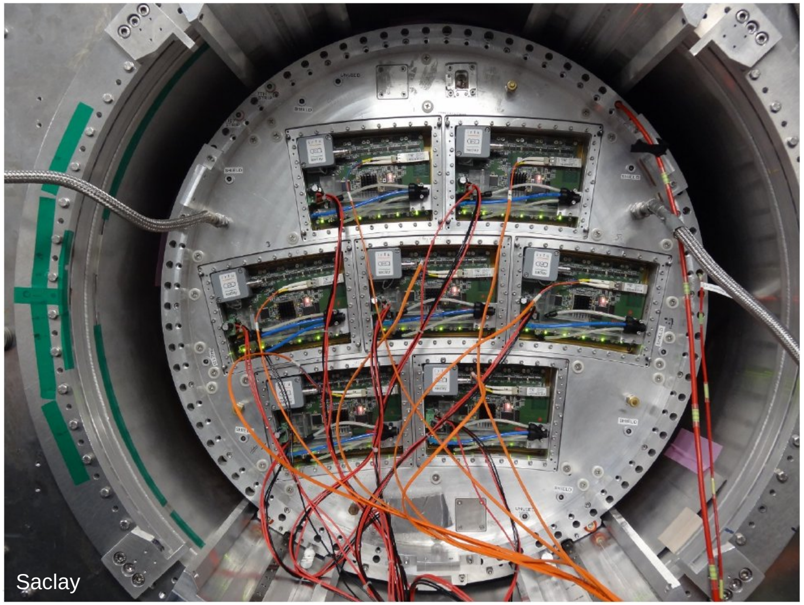
New publication (2022): arXiv:2205.12160

Resistive Micromegas

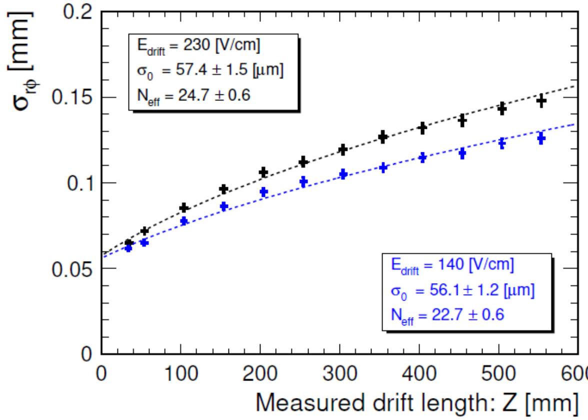
Resistive Micromegas: Bulk-Micromegas with 128 µm gap size between mesh and resistive layer

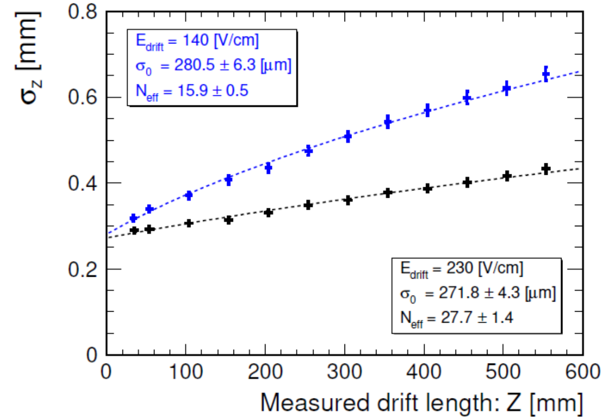


NIM A581(2007) 254



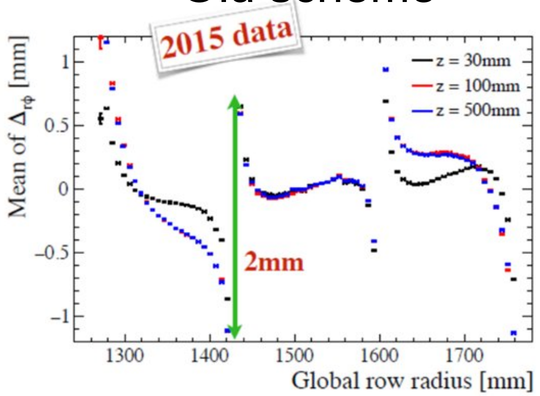
New publication in preparation:



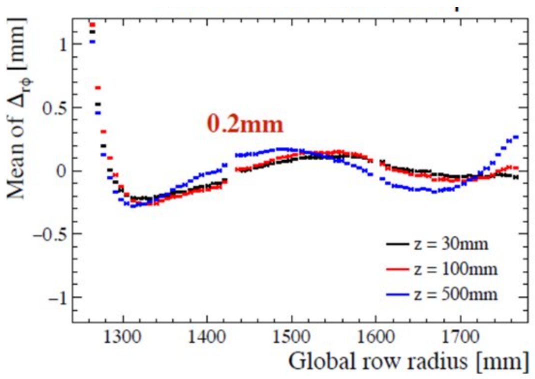


A new HV scheme of the module places grid on ground potential and reduces field distortions significantly.

Old scheme



New scheme



Detector Modules

GEM and Micromegas groups have finished analysis of test beam data with previous set of detector modules. Both groups want to implement improvements in a new generation of modules. They are discussing new common modules with

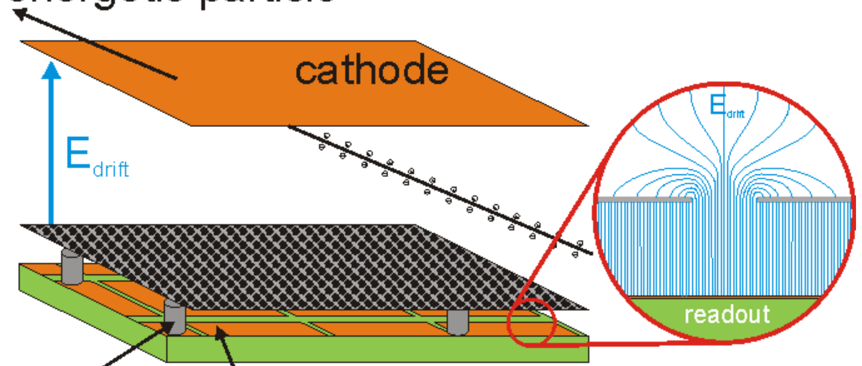
- a more final design and
- a more comparable design.

These common modules should have a

- common readout electronics (sALTRO),
- an identical gating device (gating GEM) and
- possibly a common pad plane

→ Only the gas amplification stage differs => better comparison of performance for a technology decision.

Improving Micromegas: GridPix



Could the spatial resolution of single electrons be improved?

Ar:CH_4 90:10 → $D_t = 208\ \mu m/\sqrt{cm}$

→ $\sigma = 24\ \mu m$

Ar:iButan 95:5 → $D_t = 211\ \mu m/\sqrt{cm}$

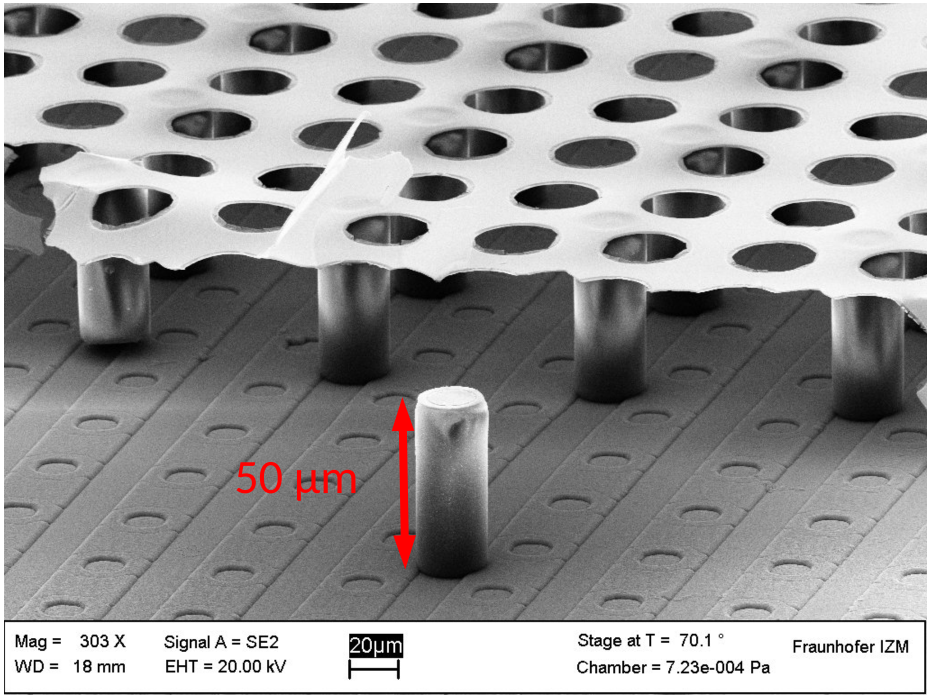
→ $\sigma = 24\ \mu m$

Smaller pads/pixels could result in better resolution!

At NIKHEF the GridPix was invented.

Standard charge collection:
Pads / long strips

Instead: Bump bond pads are used as charge collection pads.

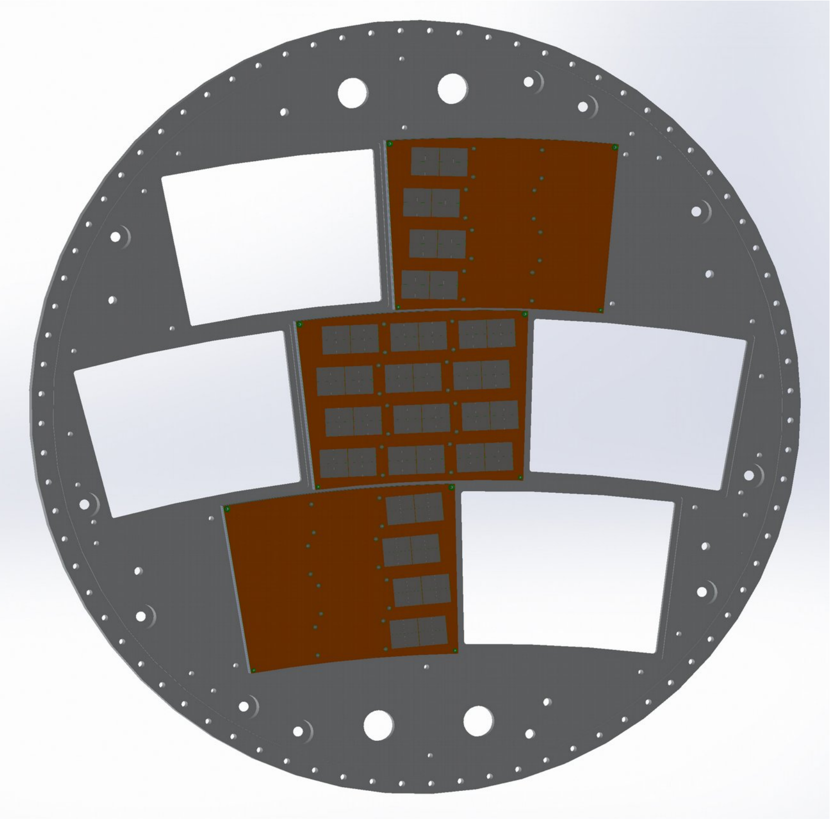


- Lower occupancy → easier track reco
- Removal of δ-rays and kink removal
- Improved dE/dx (4% seems possible)

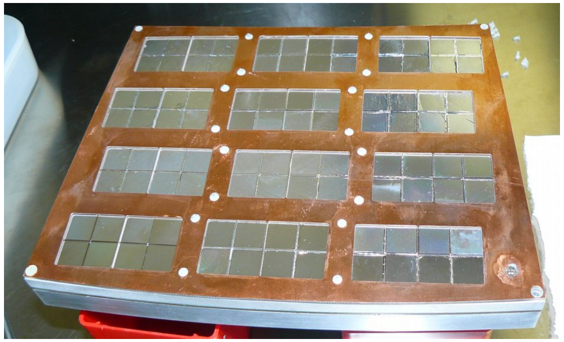
=> No angular pad effect
=> Ultimate TPC

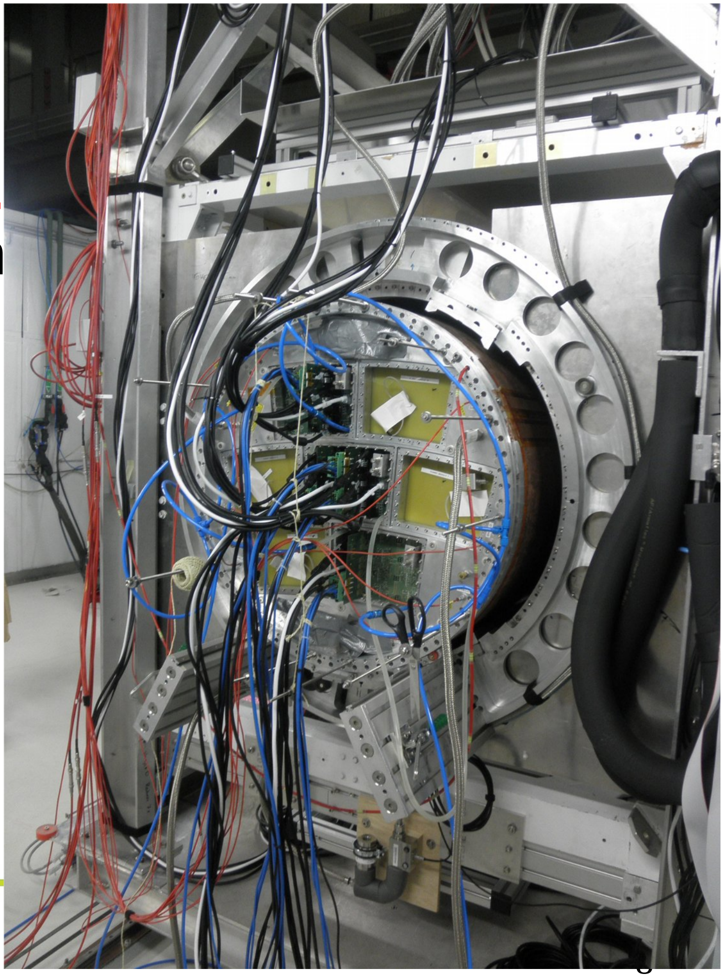
Large Scale Readout

To readout the TPC with GridPixes:
~100-120 chips/module 240 module/endcap (10 m²) → 50000-60000 GridPixes
Demonstration of mass production: One LP-module covered completely with GridPixes (96 → coverage 50%) and two partially covered modules.
In total 160 GridPixes covered an active area of 320 cm².



The test beam was a huge success: A pixel TPC is realistic. During the test beam we collected ~10^6 frames at a rate of 4.3-5.1 Hz.

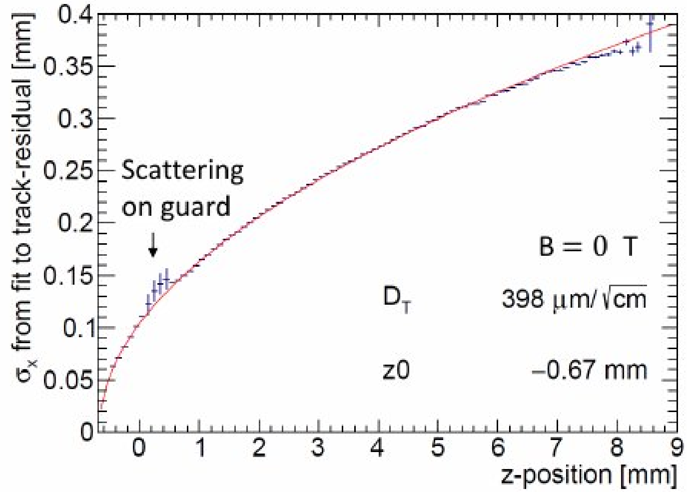


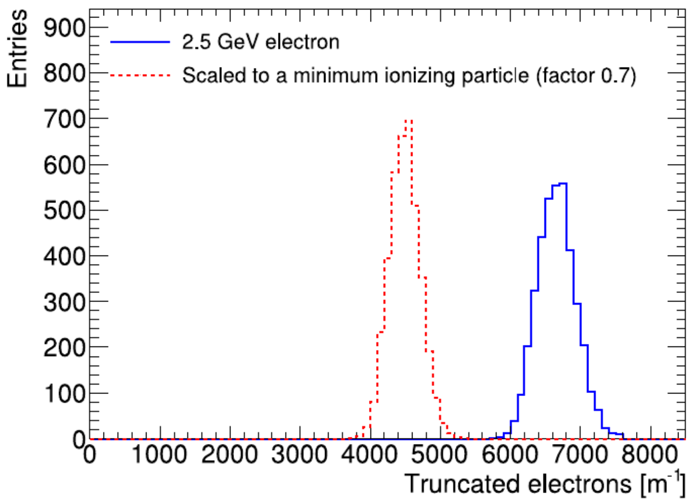


IEEE TNS 64 (2017) 1150

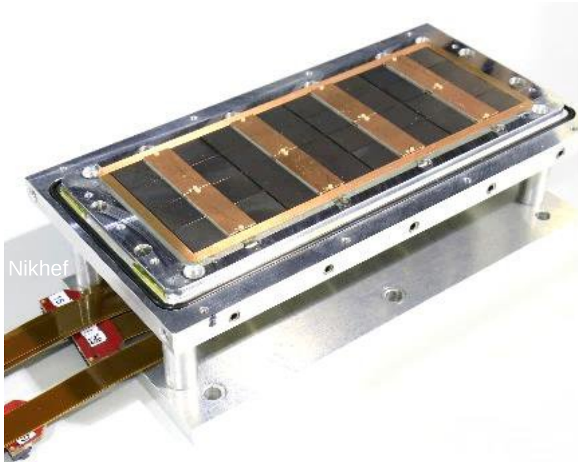
Timepix-based GridPix

GridPix detector have moved from Timepix to Timepix3 ASICs. Tests with single and quad devices have been successfully done and published.





A first module with 32 GridPixes has been constructed and will be tested in a planned test beam at DESY - including a test in a magnetic field. A complete LCTPC module would consist of about 100 GridPixes. Timepix4 ASIC next!

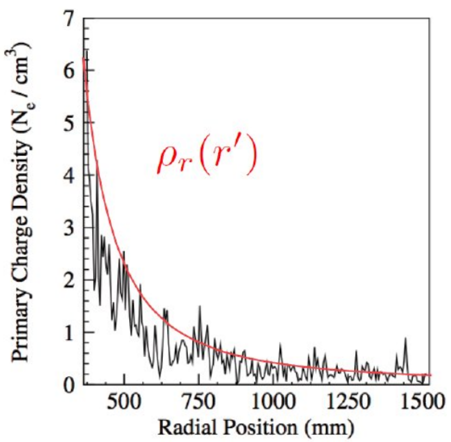


The ion back flow of the module has been measured and can be further reduced by applying a double grid. Also the resistivity of the protection layer will have to be reduced.

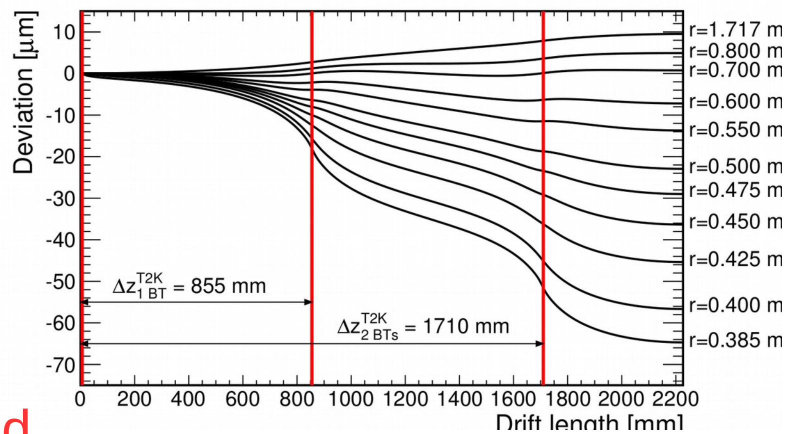
NIM A908 (2018) 18-23
NIM A956 (2020) 163331

Ion Feedback and Gating

Primary ions create distortions in the electric field which result in O(<1μm) track distortions including a safety margin of estimated BG.

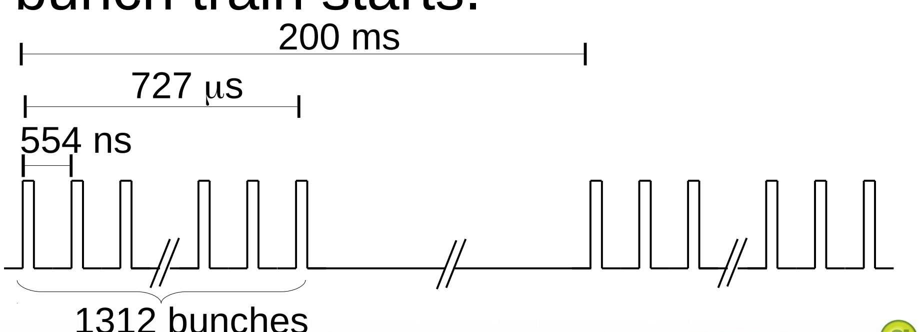


- Machine induced background has 1/r shape
- Ions from gas amplification stage build up discs
- Track distortions are 20 μm per disc without gating device, if IBF is 1/gain
- Total: 60 μm => Gating is needed



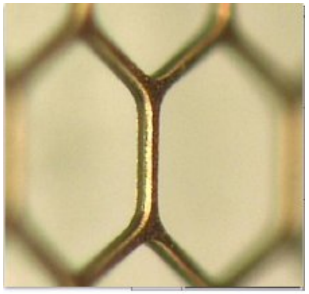
- Wire gate is an option
- Alternatively: GEM-gate
- Simulation show:
  Maximum electron transparency is close to optical transparency
- Fujikura Gate-GEM Type 3
  Hexagonal holes: 335 μm pitch, 27/31 μm rim
  Insulator thickness 12.5 μm

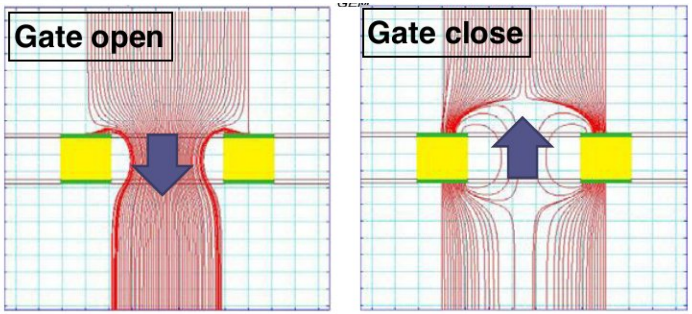
<u>Bunch structure at ILC:</u>
Damping takes 0.2 s, once all the particles are damped, extraction of bunch train starts.



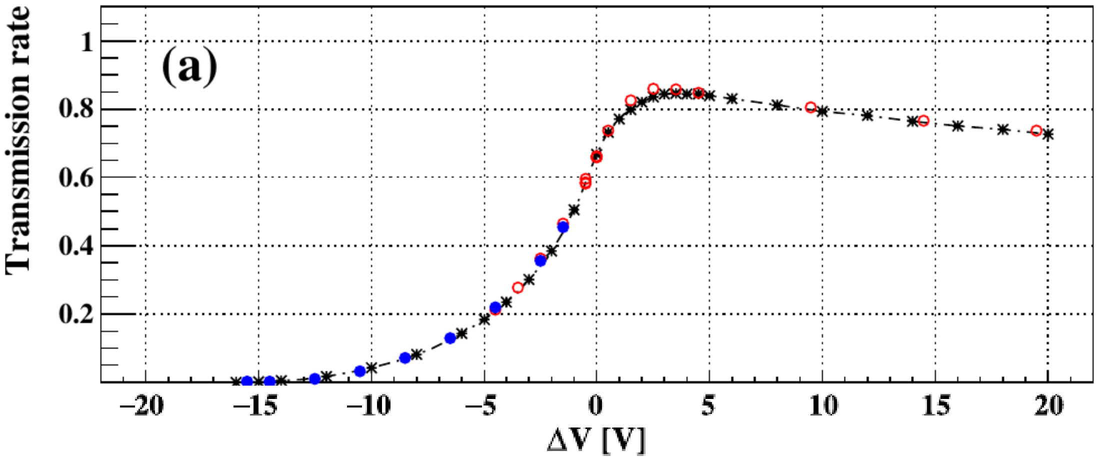
Gating GEM

The gating GEM is a favorite, which has large holes (Ø 300 µm) and thin strips inbetween (30 µm).





The electron transparency has been determined with different measurements and corresponds to 82 % as expected from simulations.

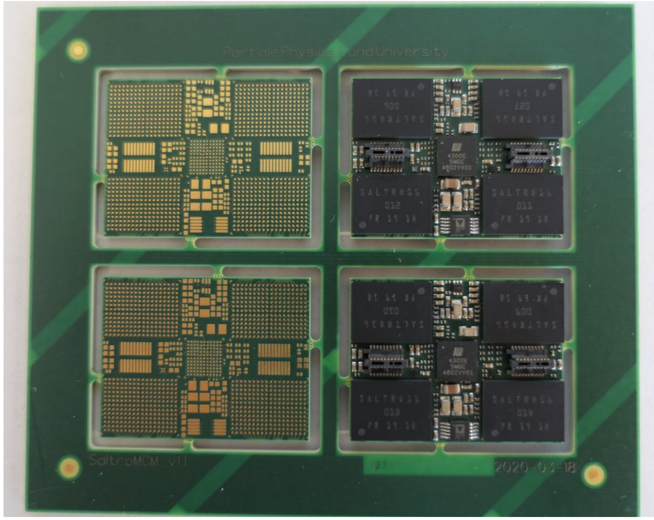


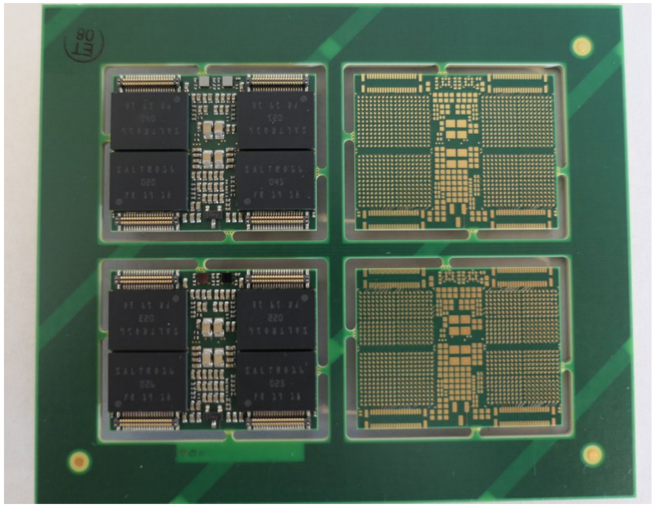
The ion blocking power still has to be determined and quantified.
First measurements have been initiated for this.
Also a fast HV switching circuit has to be developed.
The gate should also be tested in B = 3.5-4 T.

Electronics

A new electronics for R&D purposes is being developed.
It is based on the sALTRO ASICs.

- All ASICs are packaged and are being tested now.
- Additional boards have been designed and first (test) boards have been assembled. Tests show a full functionality
- The final layout is being designed.
- Still looking for an FPGA programmer to finalize the firmware.



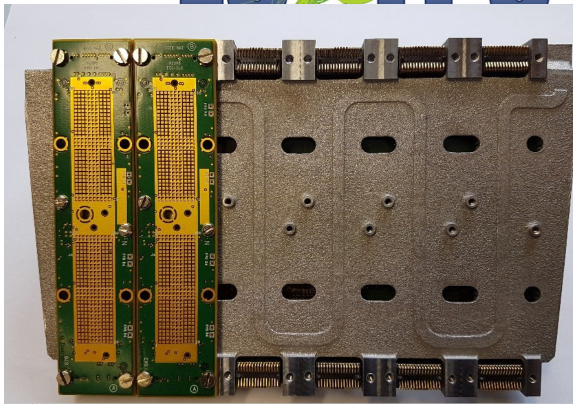


Top and bottom of a panel with 4 MCM-boards out of which 2 MCM-boards are fully mounted.

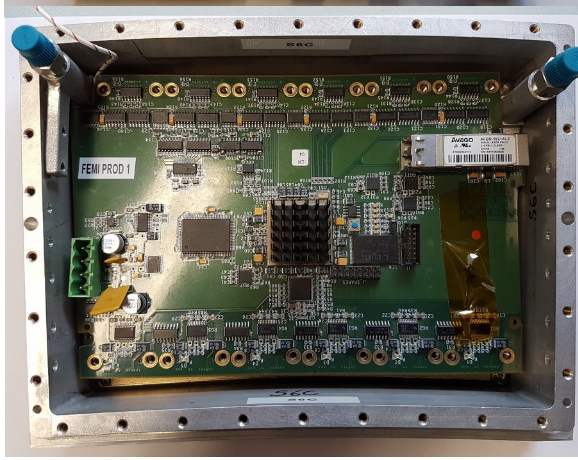
Determine design parameters for final ASIC. Possible synergy R&D.

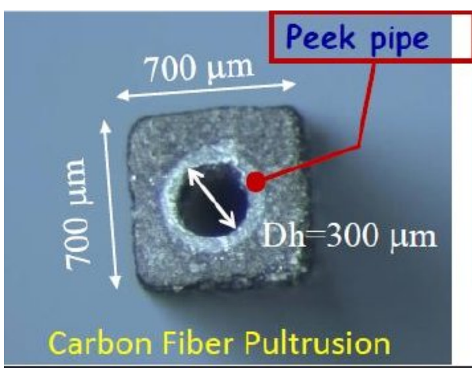
Cooling

Despite the power pulsing, the readout electronics will require a cooling system. 2-phase CO2-cooling is a very interesting candidate. A fully integrated AFTER-based solution has been tested on 7 Micromegas modules during a test beam.

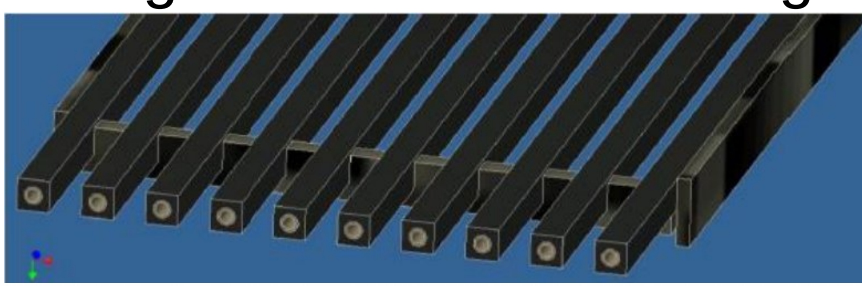


To optimize the cooling performance and the material budget, 3D-printing is an attractive possibility for producing the complex structures required. A prototype for a full module is available now at CEA, Saclay. It will be increased to 4 modules until 2021.



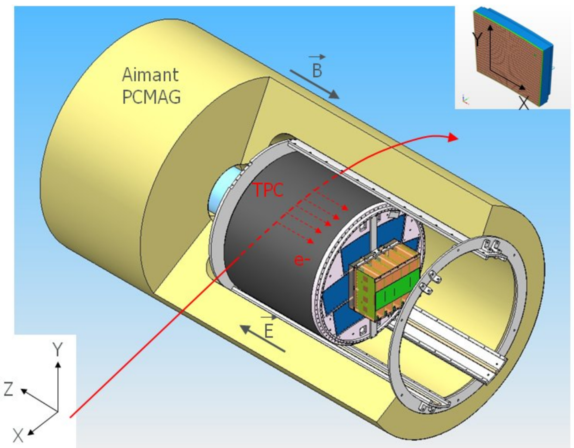


Alternatively, Lund is exploring micro channel cooling together with Pisa. These consists of pipes with Ø 300 µm in carbon fiber tubes.

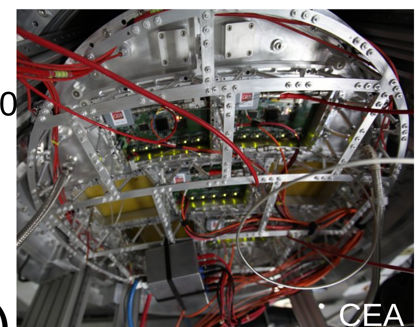


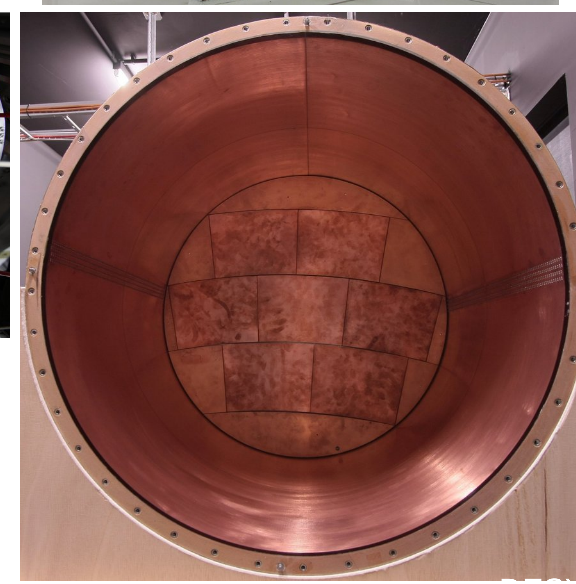
Test setup at DESY

PCMAG: B < 1.2 T, bore diameter: 85 cm
Electron test beam: E = 1- 6 GeV
LP support structure
Beam and cosmic trigger



<u>LP Field Cage Parameter:</u>
length = 61 cm
inner diameter = 72 cm
up to 25 kV at the cathode
  => drift field: E ≈ 350 V/cm
made of composite materials: 1.24 % X_0





<u>Modular End Plate</u>
two end plates for the LP made from Al
7 module windows (one is space frame)
→ size ≈ 22 × 17 cm^2 (ILD: 240 modules/endcap)

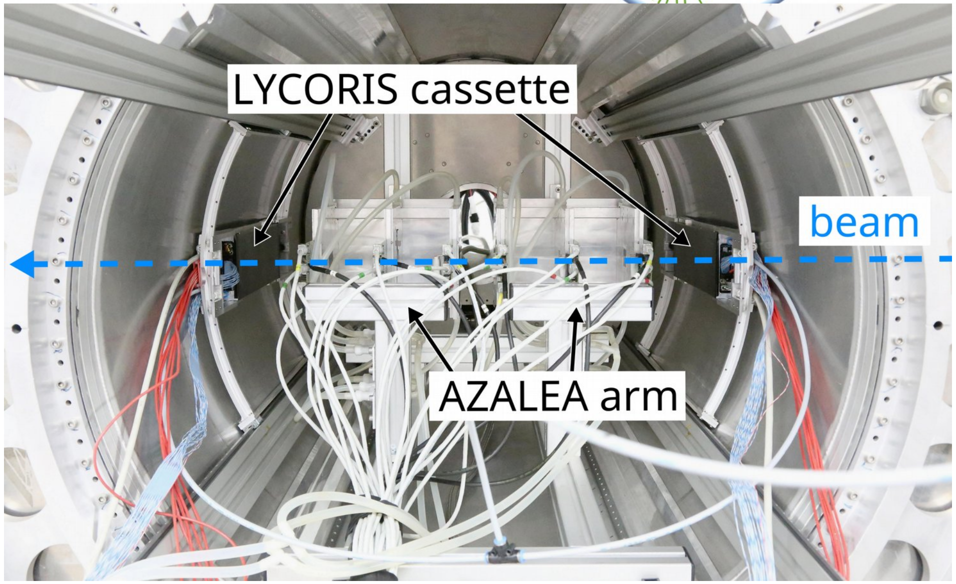
Large Prototype has been built to compare different detector readouts under identical conditions and to address integration issues.

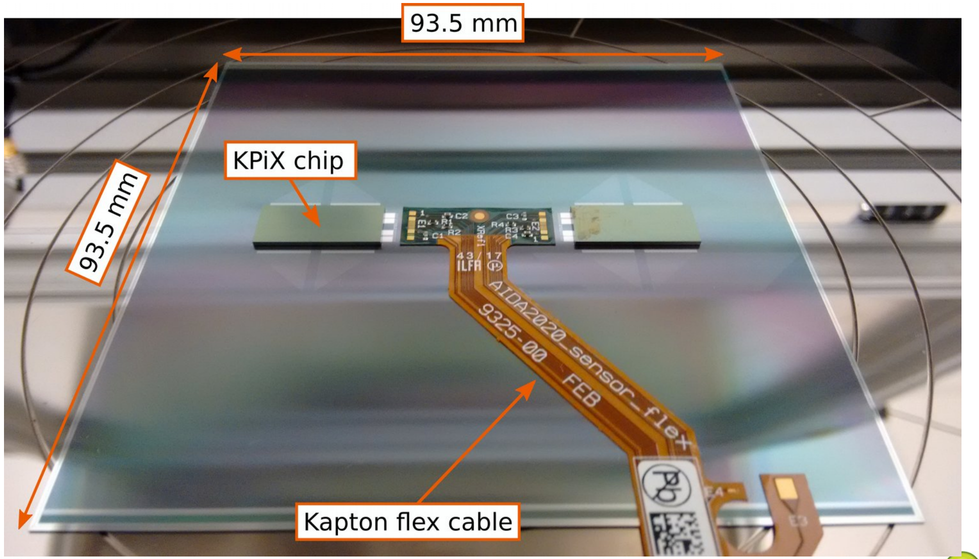
Setup at DESY

Further improvements of the test beam setup at DESY are in progress or planned:

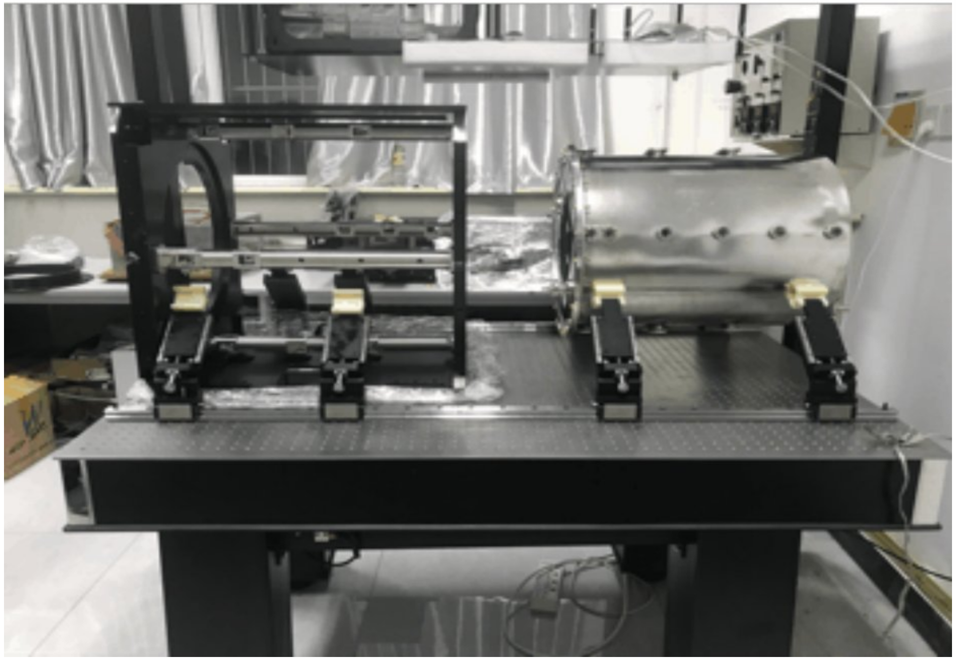
- External silicon tracker (LYCORIS) for the Large Prototype (LP) is advanced and first test beams have been performed. Integration mostly complete and ready for testbeams. All groups will redo measurements with newest module types to study distortions and resolution.

- Current field cage shows misalignments of the axis to the endcaps.
  → Construction of an improved field cage for the LP.
  → Also important for learning to build the final detector.

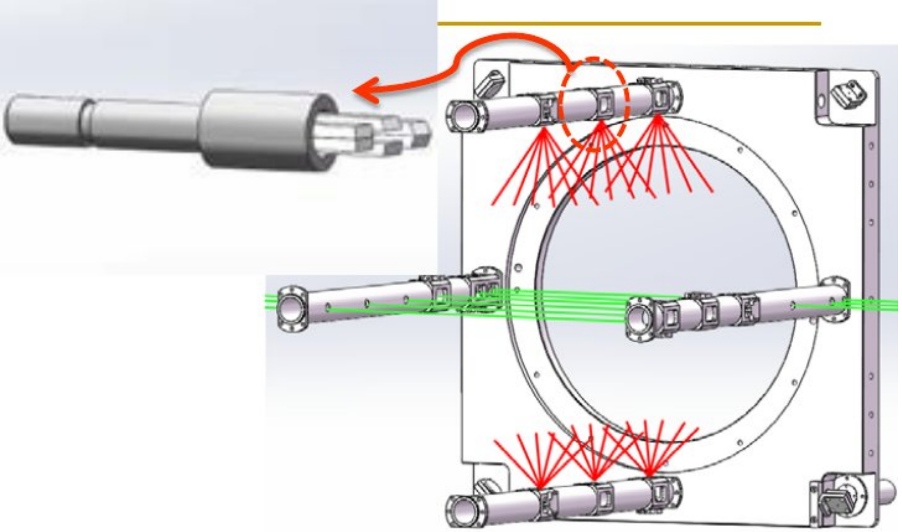


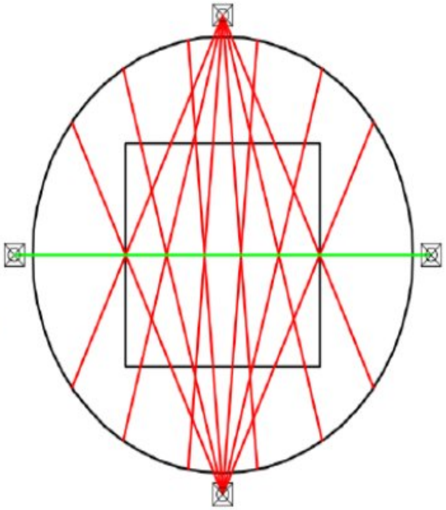


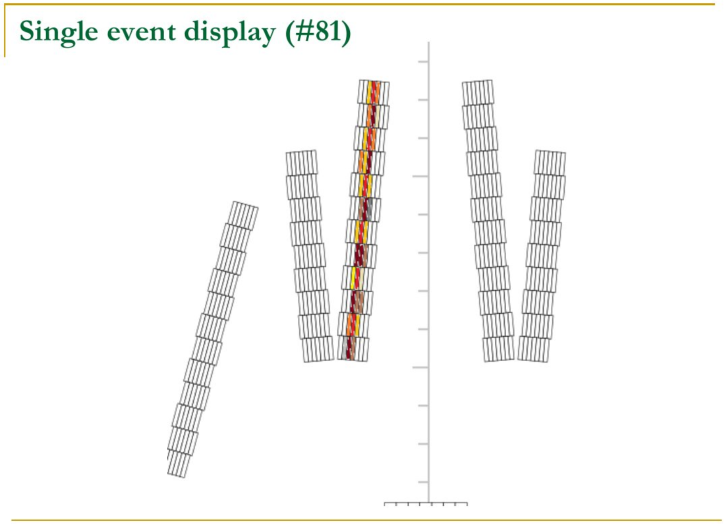
Test Setup with Laser Tracks



- Setup in IHEP, Beijing
- Smaller prototype with 50cm drift length
- Tracks at 42 positions can be
  generated by 266nm UV laser
- Only 1280 readout channels
  → pads are aligned to laser tracks
- Ionization studied using laser beam of $0.85mm^2$ in T2K, P10 and Ar/CO2(90/10)







Open Issues

There is still a long list of open issues, which is very difficult to address, because a lot of manpower is missing. Most of the issues are connected to simulating the TPC in detail:

Example: simulation

(a1) Implementation of the response of the resistive anode in our simulation, and, test of one module with a resistive anode in the ILC events with beam backgrounds conditions.

(a2) Test of our current dE/dX code for the LP events, and provide it to the physics simulation.

(a3) Study of the pad size/length in the two hit separation, the occupancy, and the spatial resolutions (in the comparison to the current condition used in the physics analysis)

(b1) Studies of the dependencies of TPC and ILD tracker performances on TPC size and configurations in cooperation with the optimization group.

(b2) Pinpoint performance requirements based on various physics analysis for the technology choice, i.e. looking at different physics channels and charting distributions and requirements (single point, double track resolution, momentum and dE/dx resolution, reliability in performance), which allow the CB later to define the technology choice. Also, suggestions for the test procedure need to be studied.

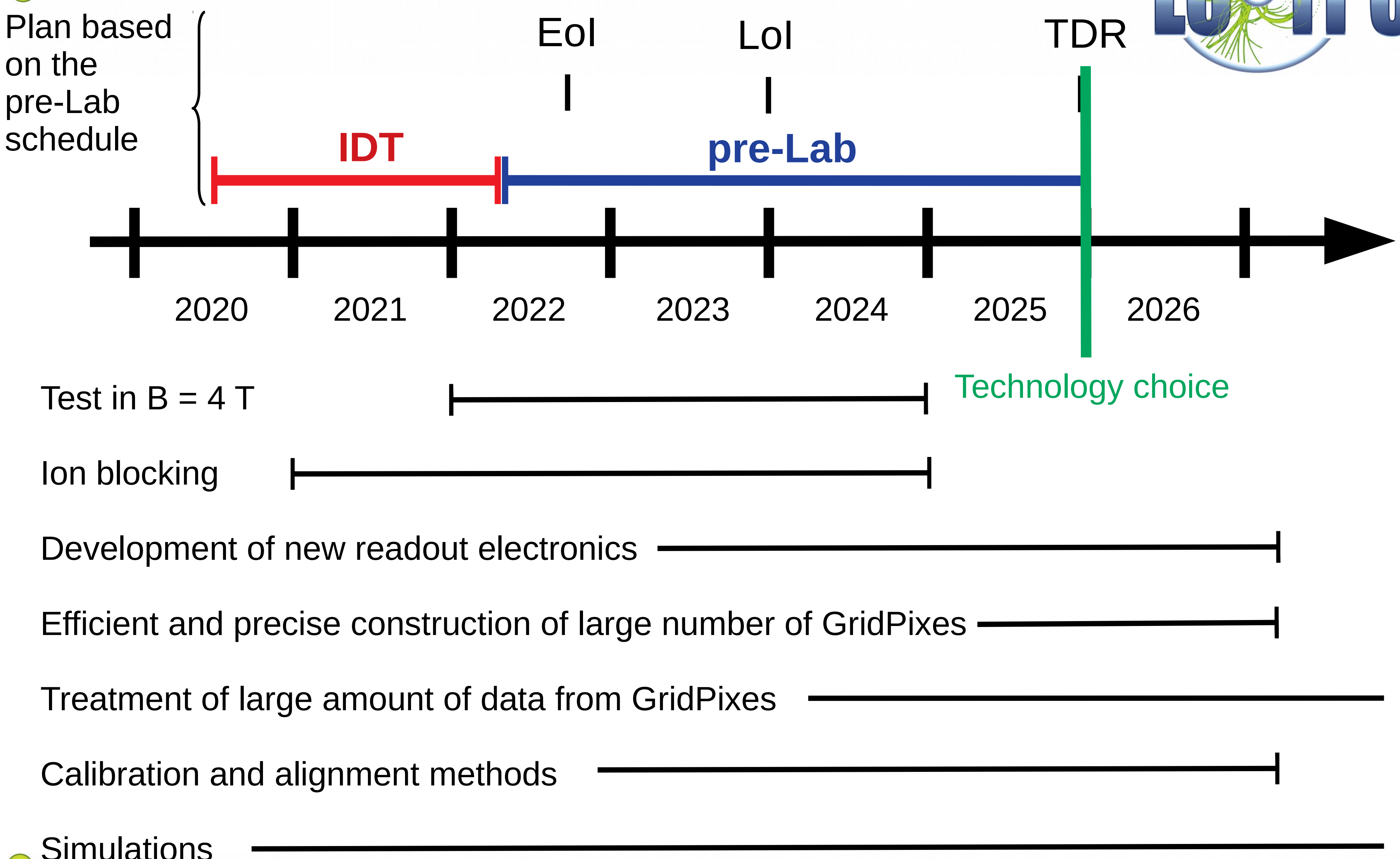
(b3) Physics simulation to study the benefit of a TPC (vs. Si detectors): dE/dx, continuous tracking, non-pointing tracks. Find appropriate channels and show what a TPC can do better.
→ mostly done by ILD optimization group, but need input and some work from LCTPC

(c1) Study of benefit of pad/pixel readout: This may be partially included in the (b2). For the pixel readout optimized reconstruction algorithms are needed.

(c2) Simulation of physics events to understand requirements on two track/hits separation: This may be studied partially in (a3) for the pad readout.

Also open issues for hardware projects require more man power to fulfill the time line on the next slide. Room for new collaborators from the USA.

Timeline


Plan based on the pre-Lab schedule
EoI
LoI
TDR
IDT
pre-Lab
2020
2021
2022
2023
2024
2025
2026
Technology choice
Test in B = 4 T
Ion blocking
Development of new readout electronics
Efficient and precise construction of large number of GridPixes
Treatment of large amount of data from GridPixes
Calibration and alignment methods
Simulations

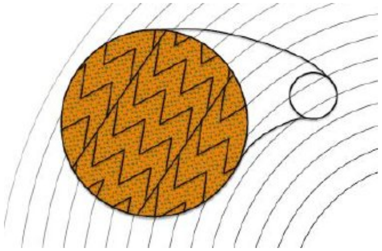
Looking beyond….

We need still a lot of support for finishing the research program!
But in case of a green light soon and a larger number groups joining LCTPC, there are more ideas, which could be looked at. Some examples were presented at the Workshop: 'New horizons in time projection chambers' (https://indico.cern.ch/event/889369/) and are listed here:

1.) new ideas of ion backflow reduction (e.g. new double-MM, COBRA, ...)

2.) new ideas of reducing discharge probabilities
– e.g. double resistive MPGDs

3.) Modules with 2 GEMs and MM



4.) Chevron type pads as suggested for sPhenix

5.) Do we gain anything with an (additional) optical readout?

6.) GridPix is a pathfinder for generic and blue-sky R&D

Summary

- Continue GEM, Micromegas and GridPix tests at the LP in preparation for the design of a TPC for a future e+e- collider! Ready.

- An ion gate should be included in the next-generation GEM, Micromegas and pixel modules.

- Synergies with ILC / T2K / ALICE / ATLAS / CMS / CEPC allow us to continue R&D and of course we learn from their experiences and R&D.

- Continue electronics, cooling and power-pulsing development.

- Many simulations are still necessary to understand the detailed requirements of the final detector (e.g. number of ADC bits, pad sizes, geometry, etc... Build the ultimate TPC for a future Higgs Factory.

- Fits with the ECFA detector R&D implementation process in Europe.

Q & A session

MPGDs for TPCs at future lepton collider

How to maintain and expand U.S. expertise on MPGDs?

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Q & A session

MPGDs is at the intersection between gas and solid state detectors for tracking. I recommend a U.S. based facility.

Gas detectors: Low material budget (< 1% X_0) critical for applications in medical physics, as well as in many HEP and nuclear physics potential future experiments

MPGDs: Technology for a TPC with the required resolutions for detector at ILC and CEPC (Belle2 upgrade)

TPC: Continuous tracking advantage (200-220 points on track with resolution reaching the diffusion limit)

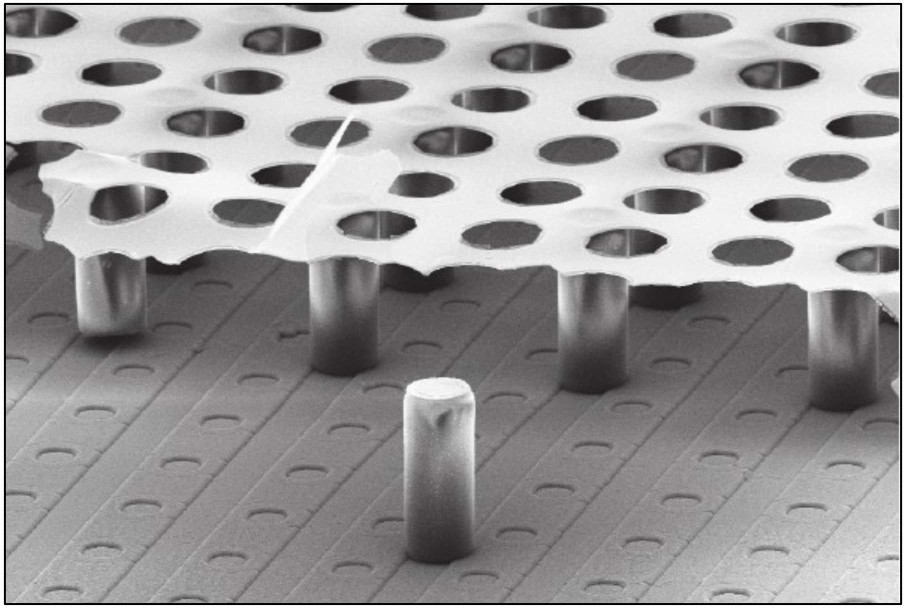
Overall: Mature detector research and LCTPC achievement allow for participation from the USA

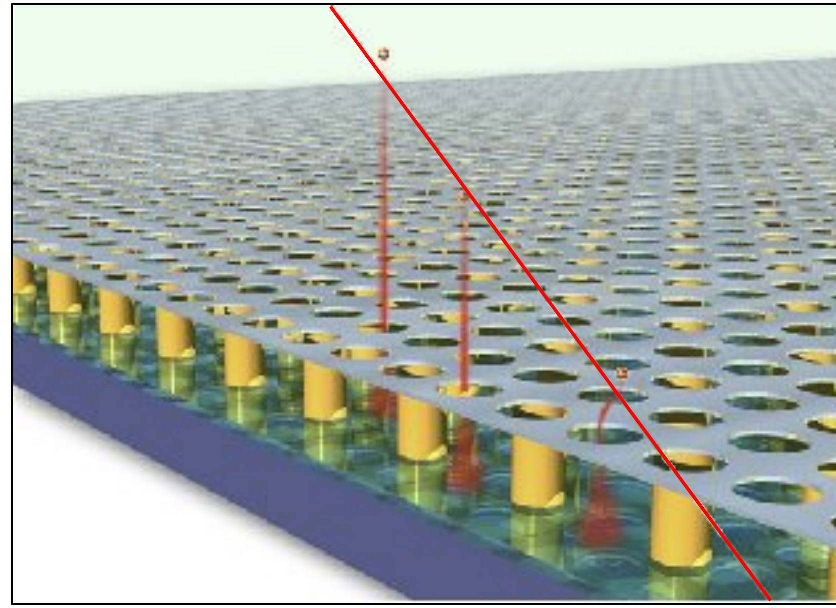
Pathway to the ultimate TPC for a future lepton collider advocates for GridPix, and further R&D for GEM and Micromegas - Establish collaborative networks.

MPGDs for TPCs at future lepton colliders

Technology choice for TPC readout: Micro Pattern Gas Detector

- no preference in track direction
- no E×B effect
- fast signal & high gain
- low ion backdrift
- better ageing properties
- easier to manufacture





- **Ability to build the <u>ULTIMATE</u> TPC for ILD at ILC, CEPC detector, and Belle2**
- MPGD on a pixelchip (Timepix+Micromegas = **GridPix)** – see pictures above
- Resistive protection layer (4-8 μm) on top of chip
- Insulating pillars between grid & pixelchip – Synergy in electronics R&D
- One hole above each pixel - Amplification directly above the pixelchip
- **Very high single point resolution! Can we achieve 2% dE/dx resolution?**

Timepix: 256 x 256 pixels of size 55 x 55 μm^2 Low threshold level ~500 e- (90 e- ENC)

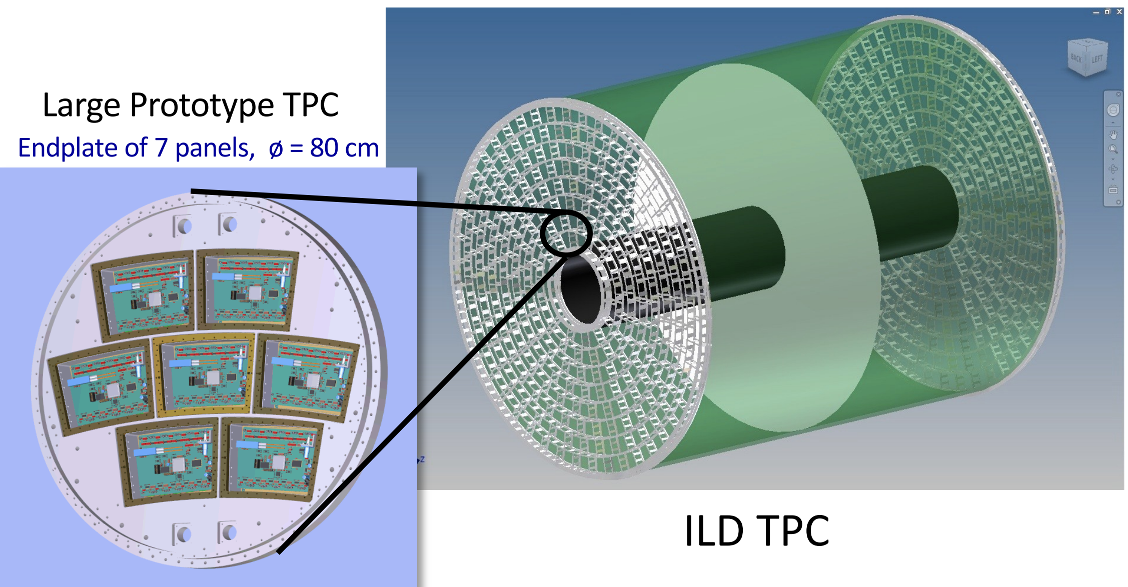
Time Projection Chamber (TPC) for Future e^+e^- Colliders

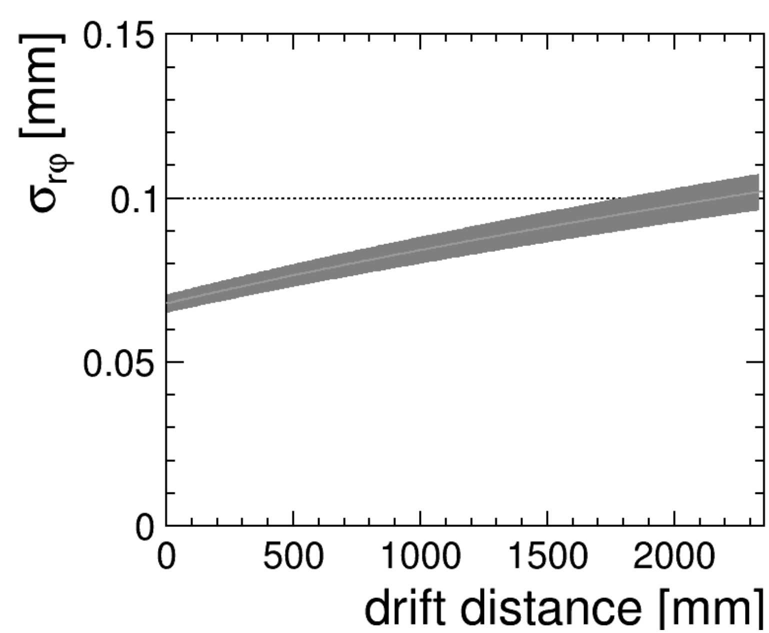
Main activities on micropattern gas detector (MPGD & RD51)

- Two options with similar resolution for endplate readout with **pads**:
  - **GEM:** 1.2×5.8 mm^2 pads (smaller pad – more electronics)
  - **Resistive Micromegas:** 3×7 mm^2 pads (larger pads – less electronics)
- Alternative: **pixel** readout with pixel size ~55×55 μm^2 (ultimate TPC)

LCTPC Collaboration on calorimetry R&D:

3 regions (America, Asia, Europe), 25 member institutions, 22 observer institutions





LCTPC = actual design meet the goal of <100 microns transverse resolution over ~2m of drift

Opportunity for the USA to engaged in pathfinder development for GridPix (timepix4)

Synergy with IF2, IF3 and IF7 for high timing & spatial resolution pixel detectors and ASCI