A Time Projection Chamber for a future linear e^+e^- collider

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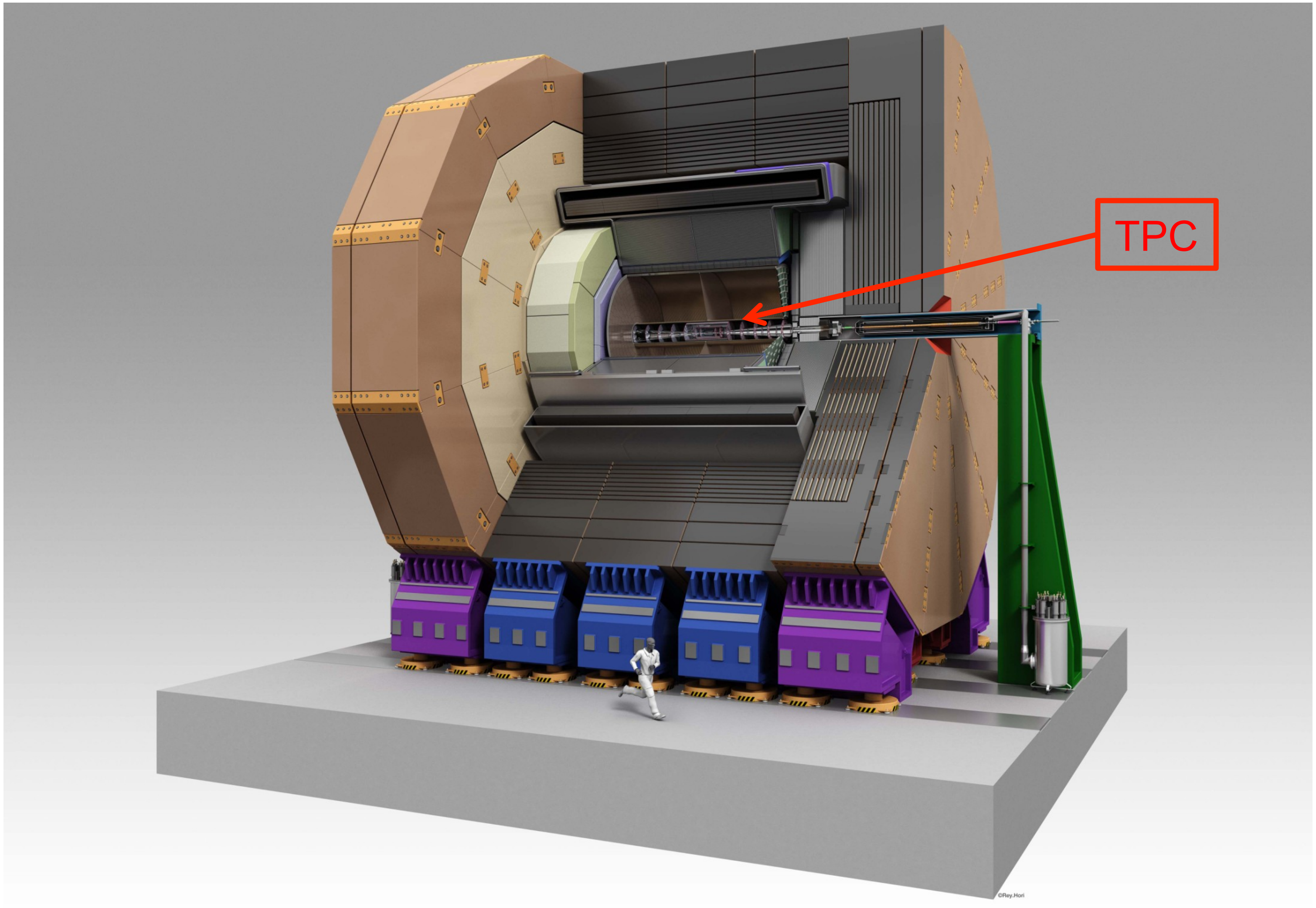
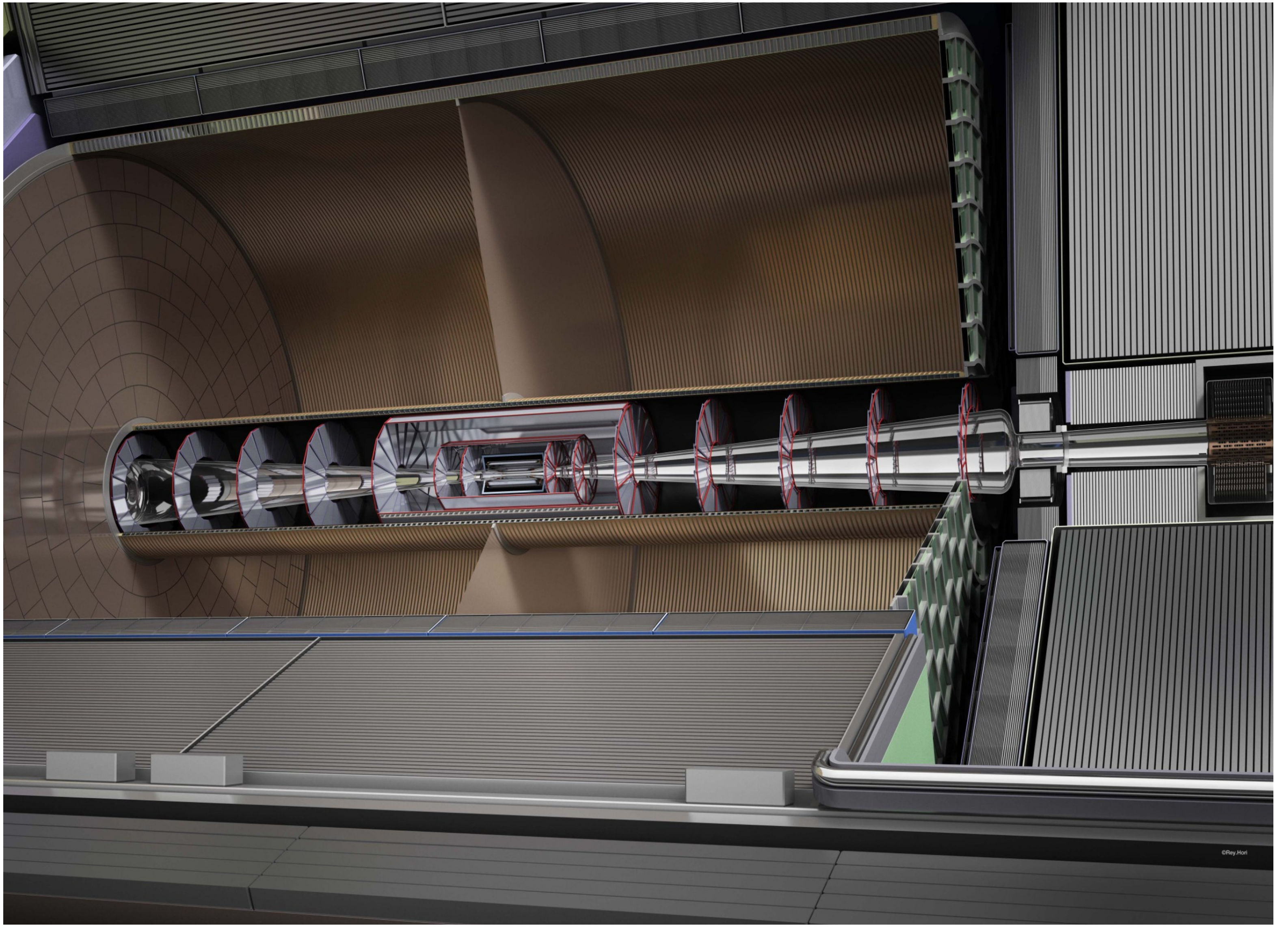
e^+e^- linear colliders

- ILC: superconducting RF (like XFEL) 31.5 MV/m accelerating gradient
  - 500 GeV cms energy; extendable to 1000 GeV (Higgs "factory" at ~ 250 GeV)
  - TDR early 2013
  - 2 detector concepts, both based on particle flow principle (high granularity tracking and calorimetry)
    - ILD: TPC as main tracker
    - SiD: all silicon tracking
- CLIC: 2-beam acceleration; high intensity, low energy drive beam to generate RF for main beam (100 MV/m)
  - Staged approach: 500 GeV, ~1.5 TeV, 3 TeV
  - ILD-like and SiD-like detectors

International Large Detector (ILD)

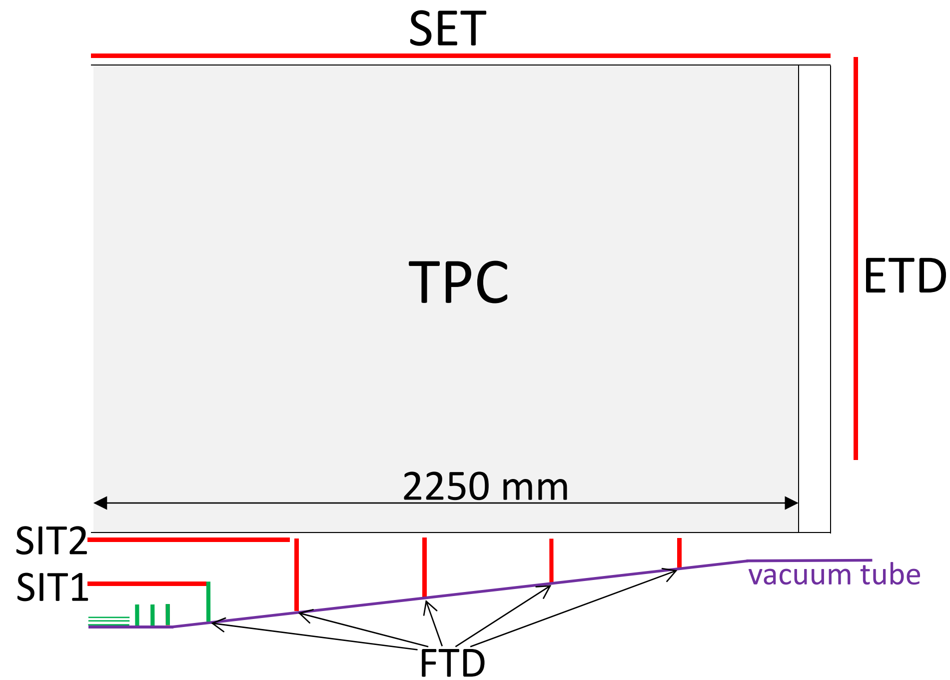


TPC in ILD



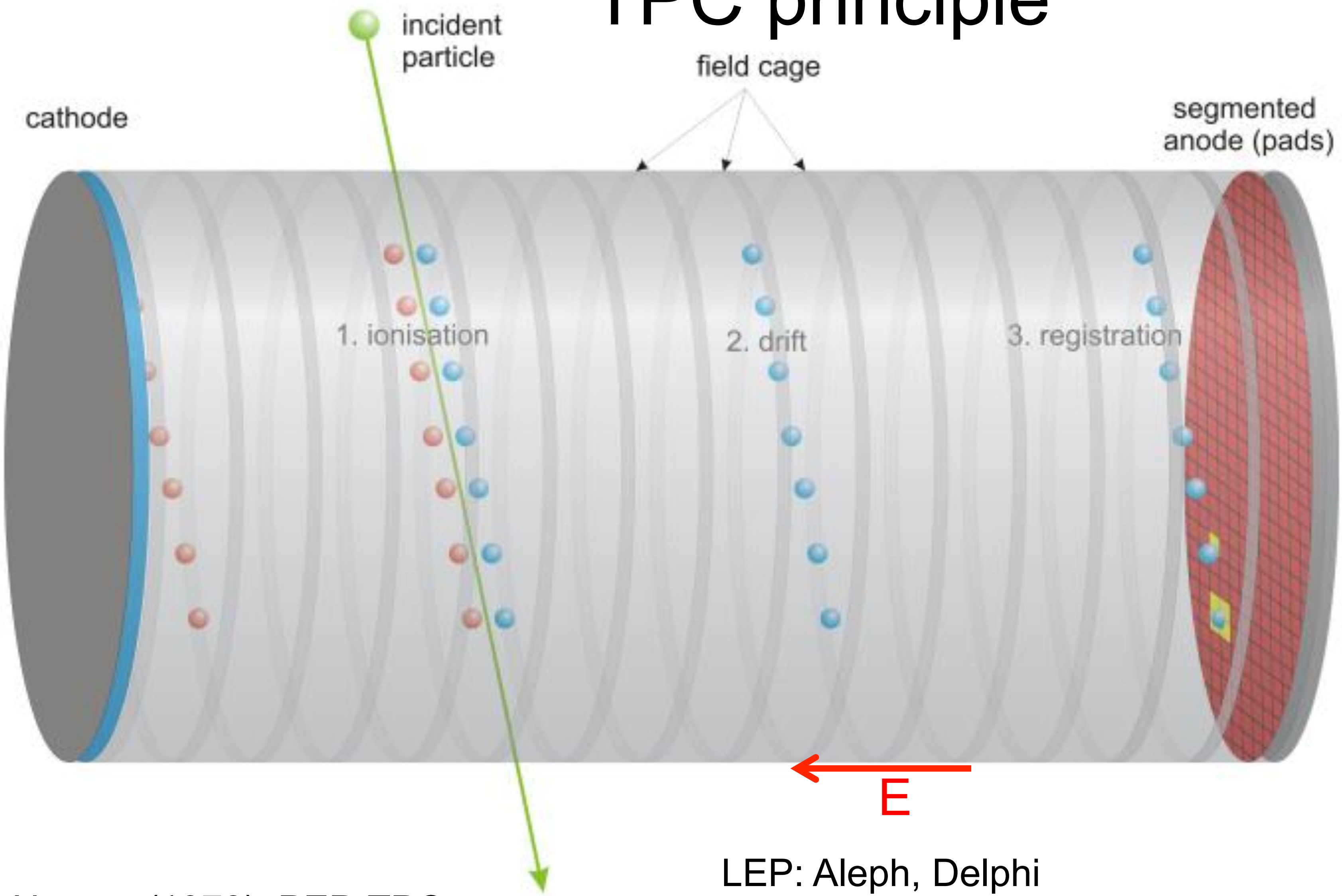
ILD tracking

- Large TPC (329 < R < 1808 mm) for highly redundant continuous tracking (~ 200 measured points)
  - Particle ID through dE/dx
  - Little material in tracking volume (5% X_0); <25% X_0 in endcap
- Complemented by silicon tracking system:
  - Independent tracking at low angles (FTD)
  - Silicon tracking layers surrounding TPC for timing and precision points (SIT, SET, ETD)



- TPC acceptance (10 measurement points) down to 12^0
- SIT acceptance down to 25^0
- FTD acceptance down to 7^0

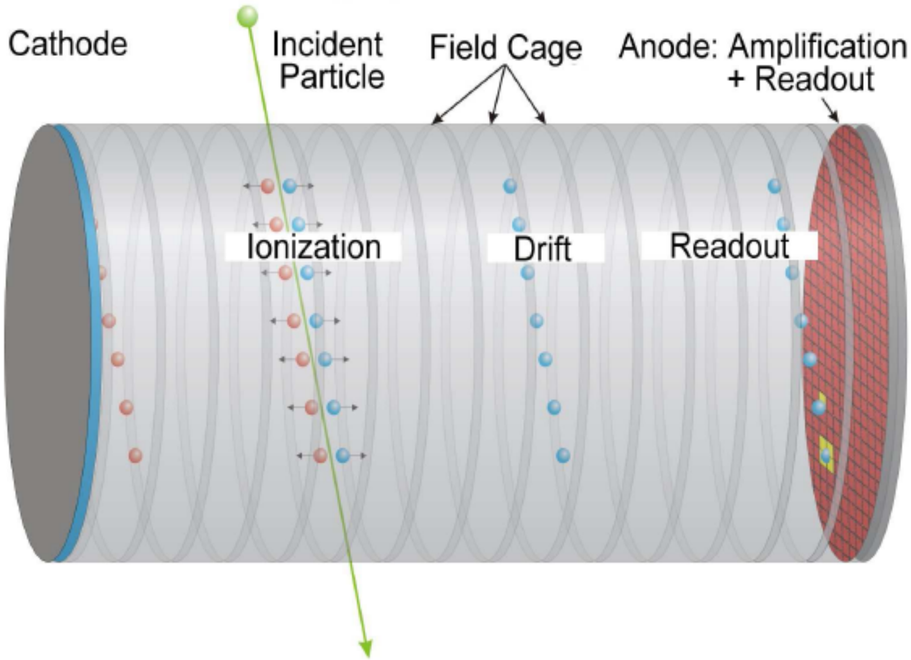
TPC principle



D.Nygren (1978): PEP-TPC

LEP: Aleph, Delphi
RHIC: Star
LHC: Alice
T2K

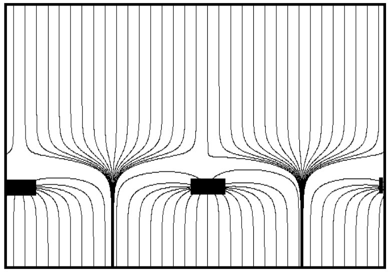
TPC with MPGD

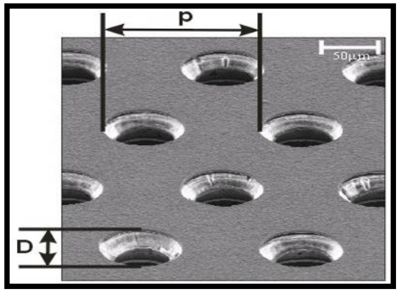


MicroPatternGasDetector
MPGD
not limited by **E** x **B** effects

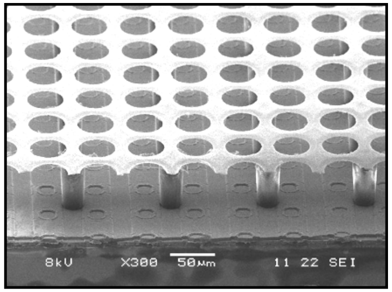
MicroMegas

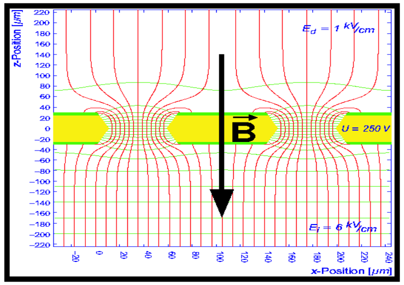
GEM



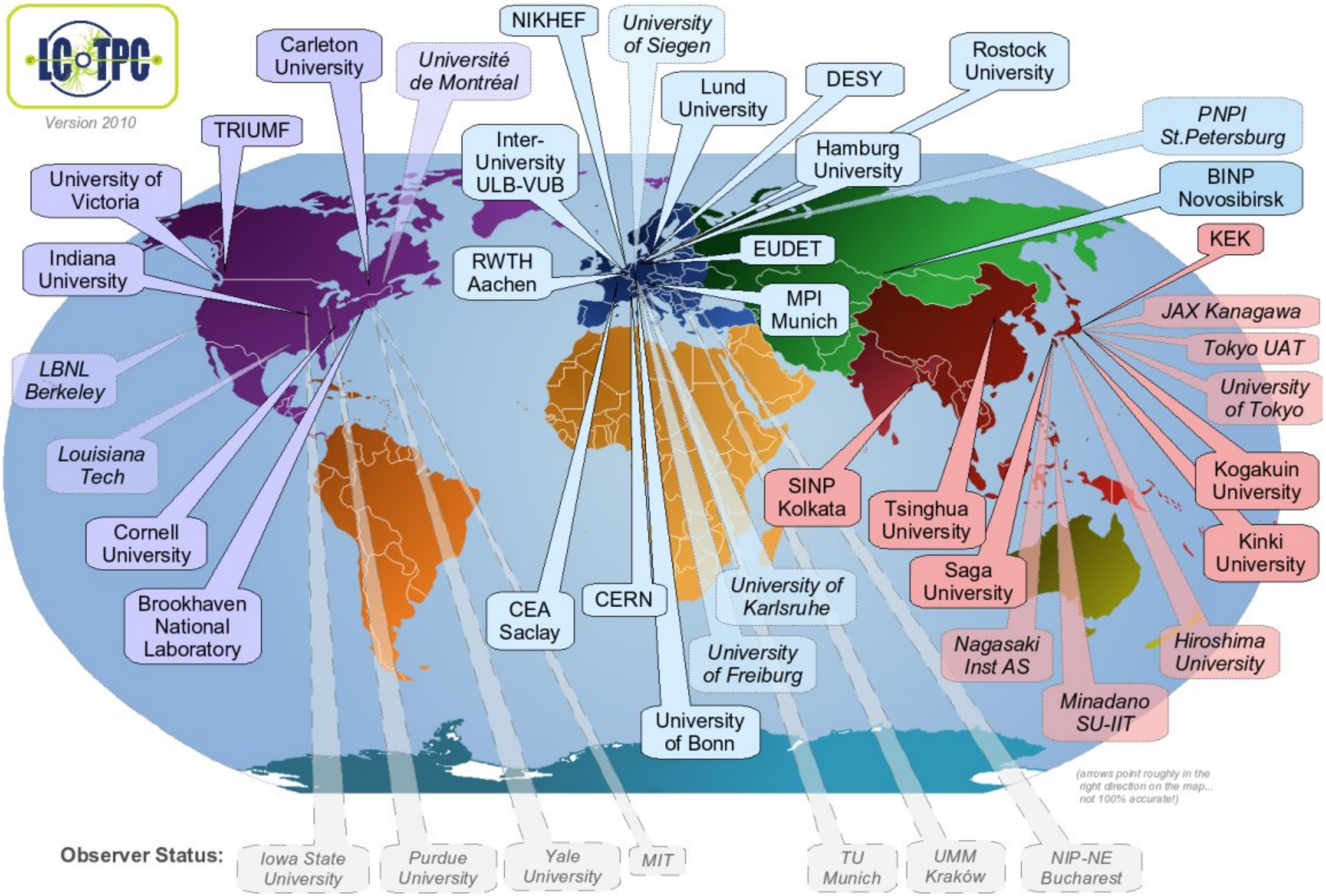


- **Two gas amplifications:**
- **Analog TPC**
  with standard pad readout
  (need signal broadening)
  Digital TPC
  with CMOS pixel readout





LCTPC Collaboration



LCTPC Workpackages

- WP1 – Mechanics
- WP2 – Electronics
- WP3 – Software
- WP4 – Calibration
- WP5 – preparations for DBD
  - Advanced endcap mechanics/alignment
  - Adv. Endcap/Saltro/Cooling/Powerpulsing
  - Gating device
  - Fieldcage
  - ILD TPC Integration/Machine-Detector-Interface
  - LCTPC Software Model
  - Test beams

TPC design parameters & performance goals

- Dimensions: R_{in} = 329 mm; R_{out} = 1808 mm; Z_{max} = 2250 mm
- Solid angle coverage: $12^o < \theta < 168^o$ (10 pad rows)
- TPC material budget: to ECAL R ~ 0.05 X_0 ; endcaps ~0.25 X_0

- Momentum resolution (B=3.5T):
  - TPC only : $\delta(1/p_T) \sim 9.\ 10^{-5}$ /GeV
  - SET+TPC+SIT+VTX: $\delta(1/p_T) \sim 2.\ 10^{-5}$ /GeV

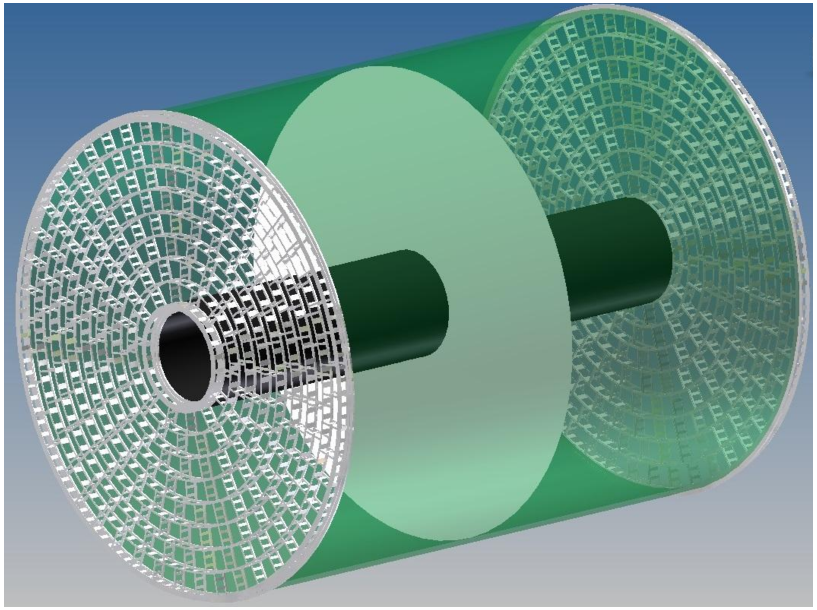
- #pads/#time buckets: ~2.10^6 / 1000 per endcap
- Pad size/#pad rows: ~1 mm x 4-6 mm / ~200 (standard readout)

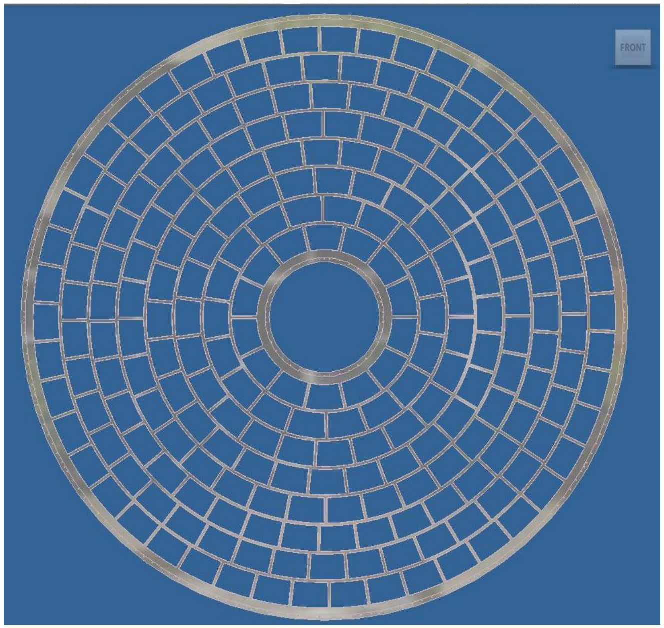
- Point resolution: in rφ: < 100 μm ; in rz: ~ 0.5 mm
- 2-hit resolution: in rφ: ~ 2 mm ; in rz: ~ 6 mm
- dE/dx resolution: ~ 5% (based on LEP TPC experience)

TPC design (1)

- Lightweight fieldcage with resistor chain for potential rings: drift field homogeneity $\Delta E/E \sim 10^{-4}$
- Central HV cathode (up to 100 kV)
- 2 endcaps each with some 240 Micropattern Gas Detector (MPGD) modules: Micromegas or GEMs
- TPC integrates charge over ~35 μs -> foresee ion gate
- Use gas mixture like (T2K gas) $Ar/CF_4/iC_4H_{10}$ (95/3/2%) for large suppression of transverse diffusion at B=3.5T
- B field has to be mapped out to relative precision of 10^{-4}
- Laser system for monitoring calibrations/distortions

TPC design (2)

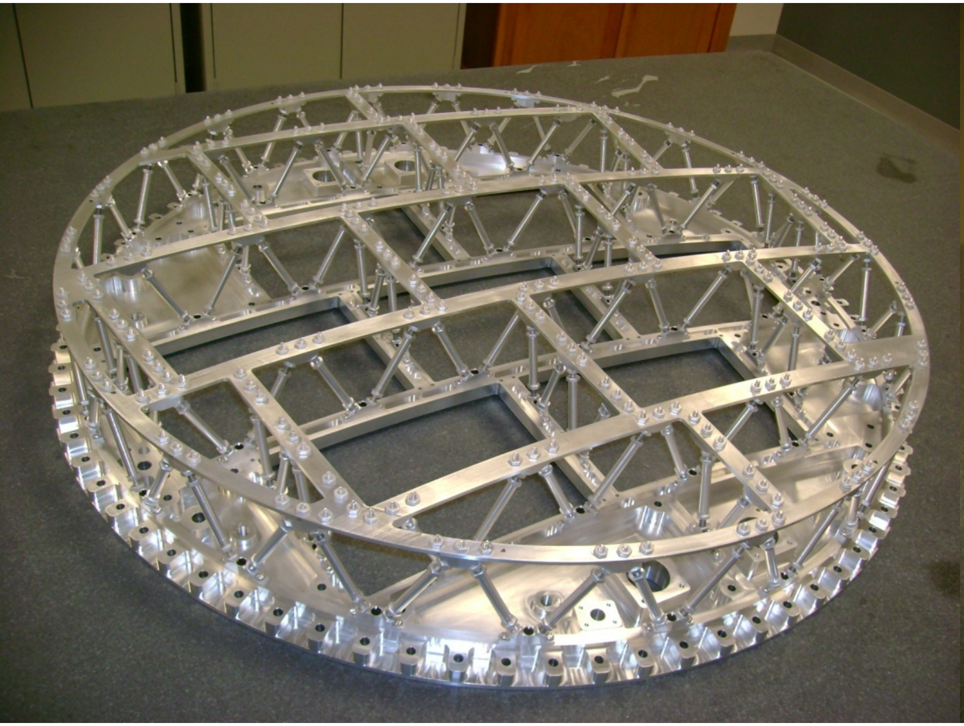


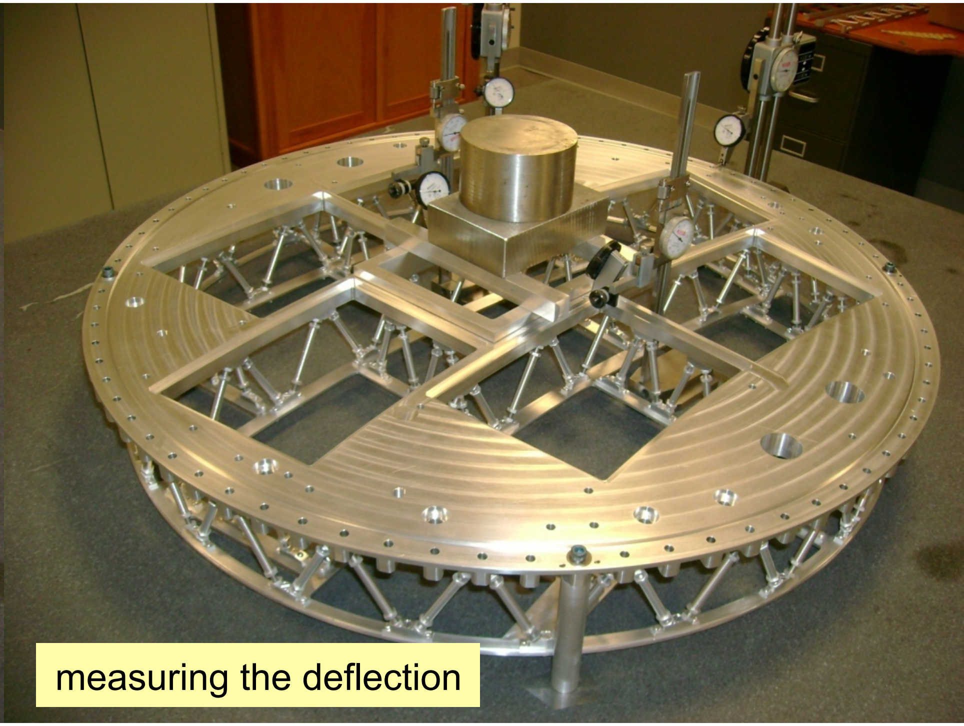


- Endcaps made with spaceframes
- Allows stable positioning of detector modules to <50 μm
- Deflection under 2.1 mbar over-pressure is 0.22 mm
- Mass is 136 kg/endplate

- 10 m^2 per endcap
- 8 rows of MPGD detector modules; module size ~ 17 x 22 cm^2
- 240 modules per endcap
- Endplate is 8% X_0
- Readout modules+electronics 7% X_0
- Power cables 10% X_0

The first of two LP2 space-frame endplates is assembled (Friday, 25-March).

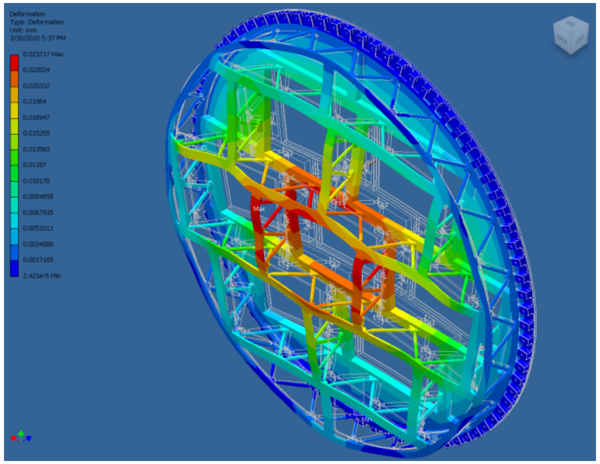




measuring the deflection

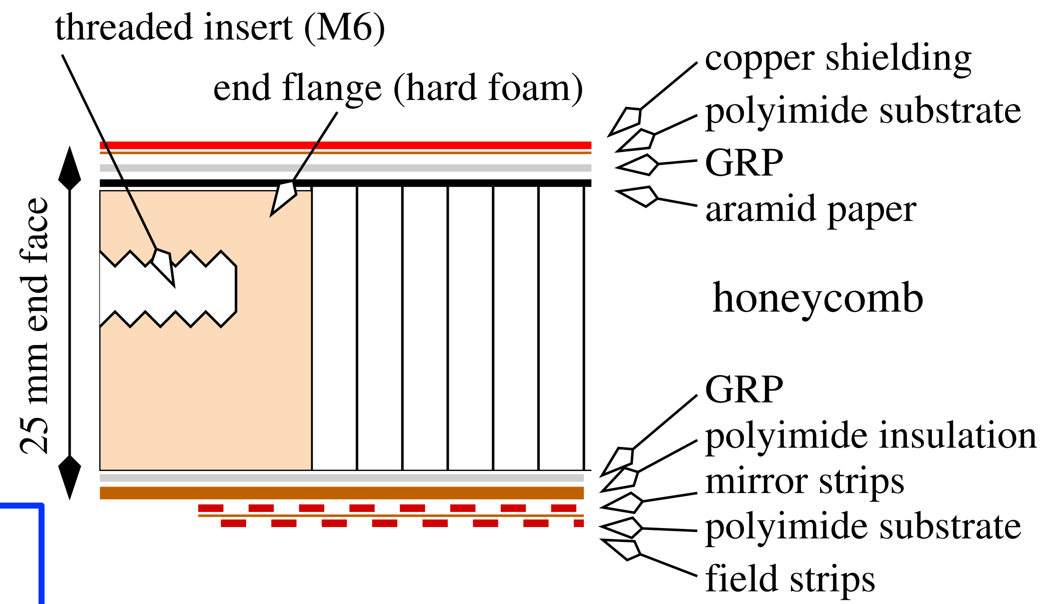
The FEA predicts a longitudinal deflection of 23 microns / 100 N load.

(with the load applied at the center module.)



TPC design (3): fieldcage wall

- Lightweight fieldcage
  - 1% X_0 inner wall
  - 3% X_0 outer wall
  - 1% X_0 gas

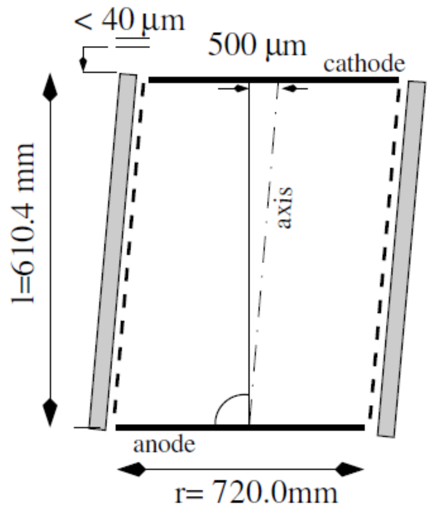


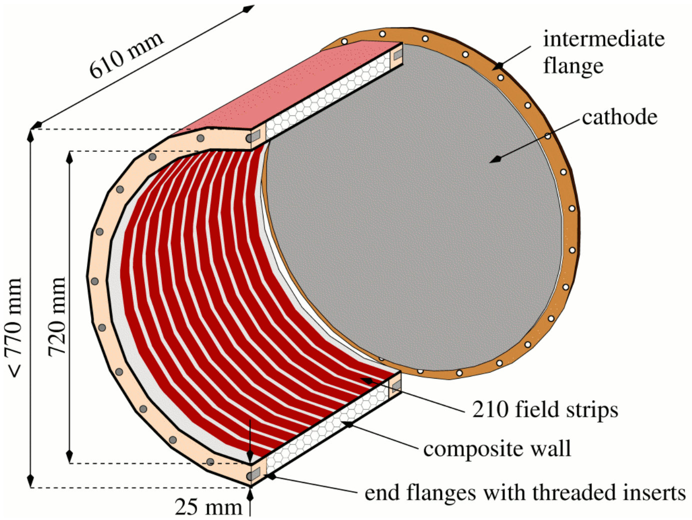
Large Prototype (LPTPC):

- Radius ≈ inner radius CLIC TPC
- 1.21% X_0
- Material samples tested up to 30 kV
- (simple) extrapolation would allow 70 kV

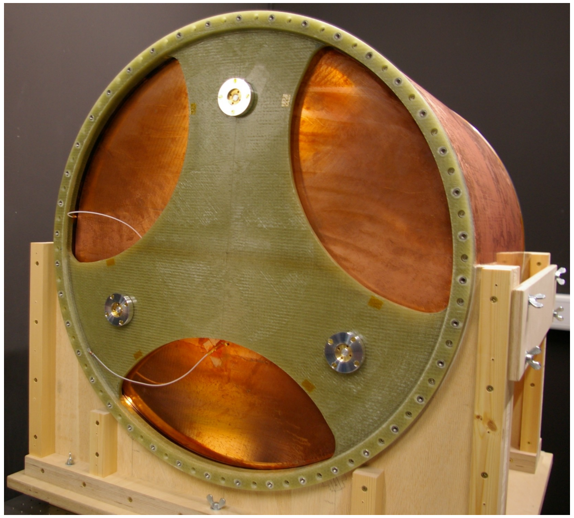
Large Prototype – Field Cage

LP Field Cage Parameter:
Length = 61 cm
Inner diameter = 72 cm
Up to 25 kV at the cathode
=> Drift field: E ≈ 350 V/cm
Made of composite materials
=> Material budget: 1.24 % X_0





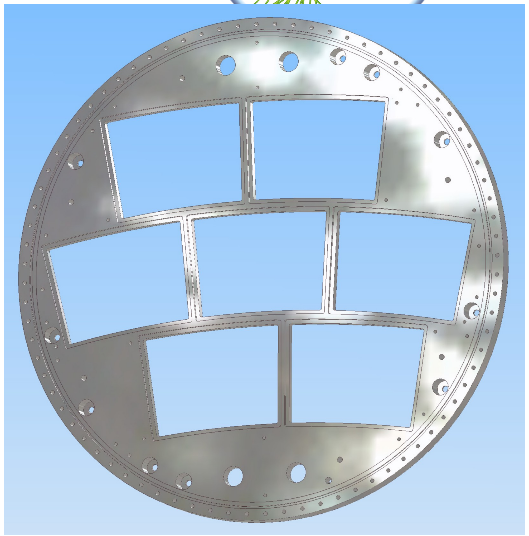
Mechanical accuracy
- Alignment of the end faces: δ < 40 µm
- Alignment of the field cage axis: offset at cathode ~500 µm

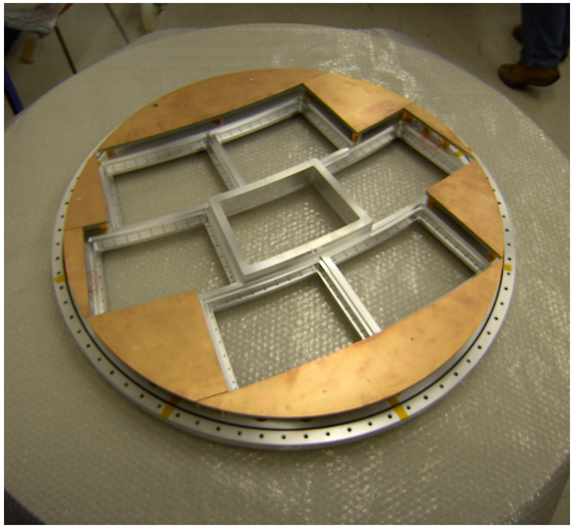


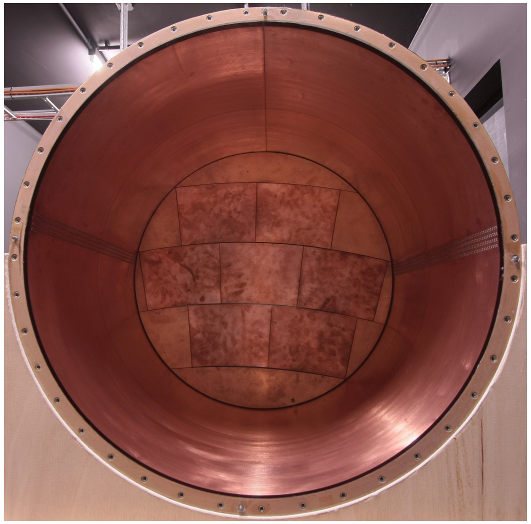
Large Prototype – End Plate

<u>Modular End Plate</u>

- First end plate for the LP made from solid Al
- During production the end plate was two times 'cold shocked' (cooled with liquid Nitrogen) to reduce stress.
- 7 module windows of size ≈ 22 × 17 cm^2
- Accuracy on the level of 30 μm
- Not designed to meet material budget requirements (weighs 18.87 kg → 16.9 % X_0)







TPC design (4): modules + electronics

- Double and triple GEM stack modules
- Bulk Micromegas with resistive anode modules
- Extensively tested at LPTPC, with similar resolution (at zero drift distance) of ~60 μm
- Resolution at larger drift distance (up to 60 cm) follows expected diffusion
- Smaller prototypes in B=5T field show ≤ 100 μm resolution when extrapolated to 2.25 m drift

- Deep-submicron electronics integration of 16-channels of full Alice chain under test; 64-ch ASIC under investigation
- Power-pulsing will be needed (gain factor 25-50)

- New concept of combined gas-amplification + pixelised readout (Ingrid) under further development; needed(?) in high-occupancy regions

TPC R&D Phases by LCTPC Collaboration

I. Demonstration Phase
(Small MPGD TPC Prototypes)

Basic evaluation of the properties of MPGD TPC by using small prototypes.

Demonstrate that the point resolution requirement can be achieved.

DONE

II. Consolidation Phase
(Large Prototype (LP) Tests)
(2008~)

Design, build and operate a "TPC Large Prototype" using the EUDET electron beam test facility at DESY.

Comparison of MPGD technologies.

Demonstration of the ILD momentum resolution.

Current phase

III. Design Phase

Design real ILD TPC

Positive ion feedback study and gating device development

Thin endplate design

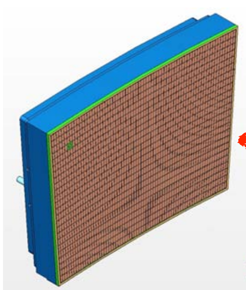
Power delivery, power pulsing and cooling

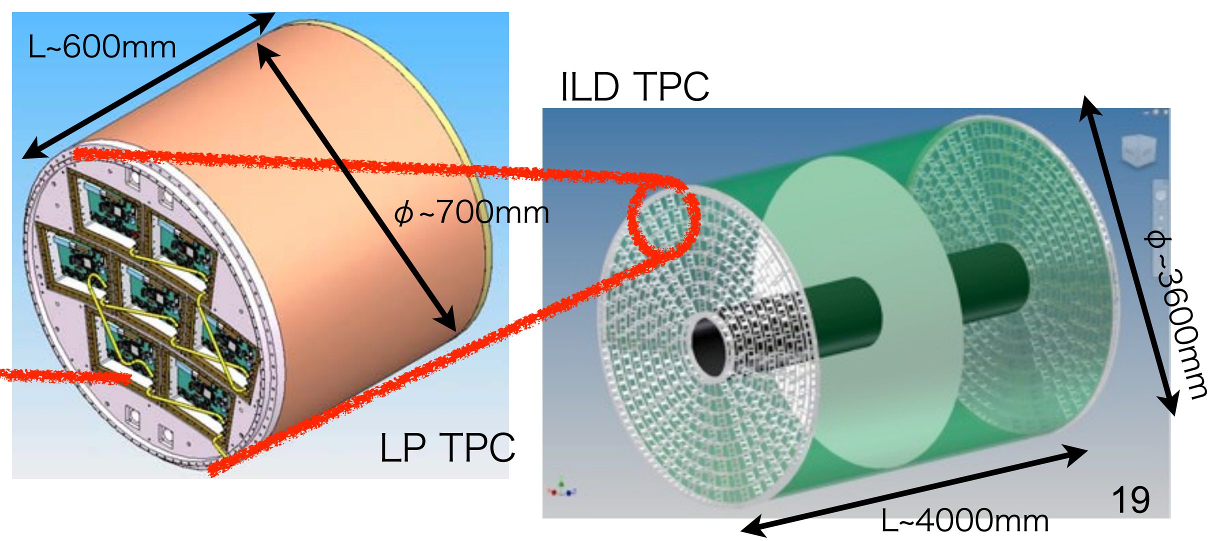
Next step
but gradually starting

Beam Tests of the Large Prototype TPC

- Large Prototype (LP) TPC is setup in DESY test beam, area T24/1. e^+/e^- from 1 to 6 GeV/c.
- PCMAG magnet: 1T magnet. This year modified to run with cryo coolers and closed cooling cycle.
- Mounted on 3-axis movable table.

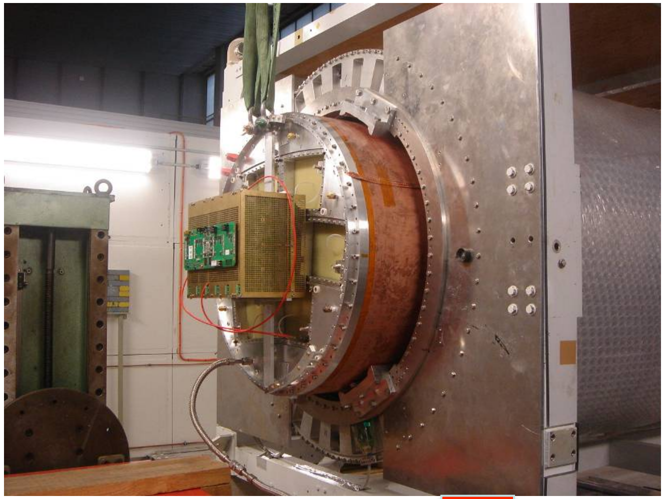
7 readout modules
with the size of ~230 x 170mm^2
can be installed.



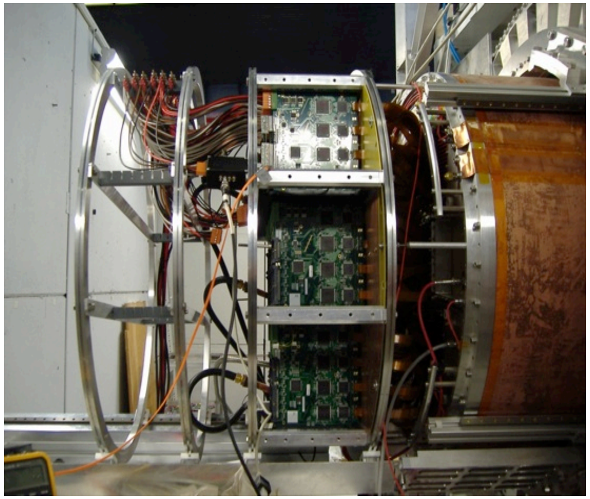


Several beam tests at DESY with LP (2008-2012) by LCTPC collaboration

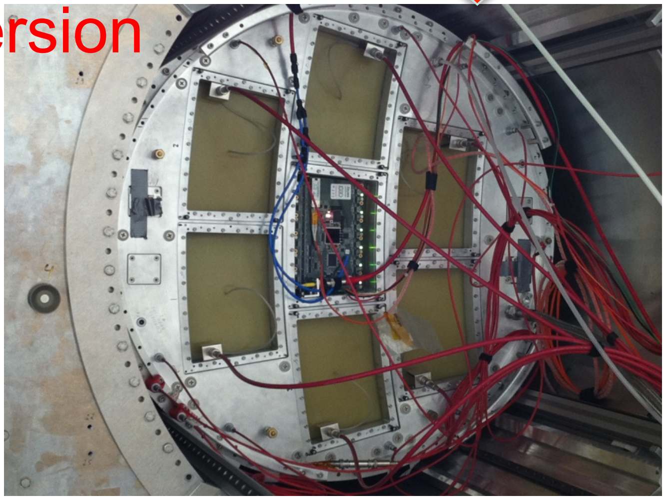
Micromegas (T2K readout)



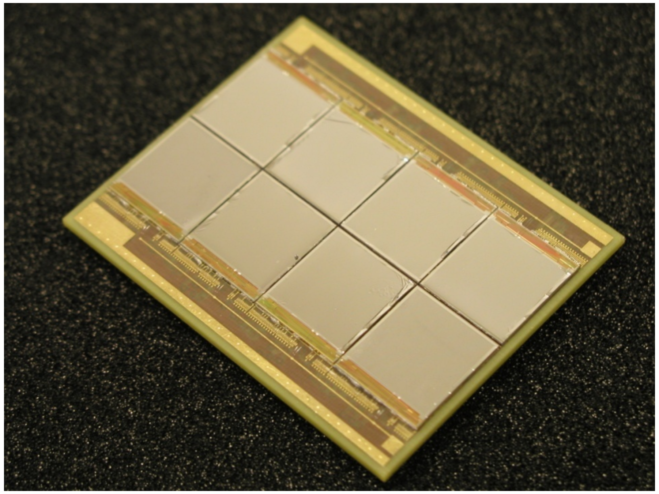
GEMs (Altro readout)



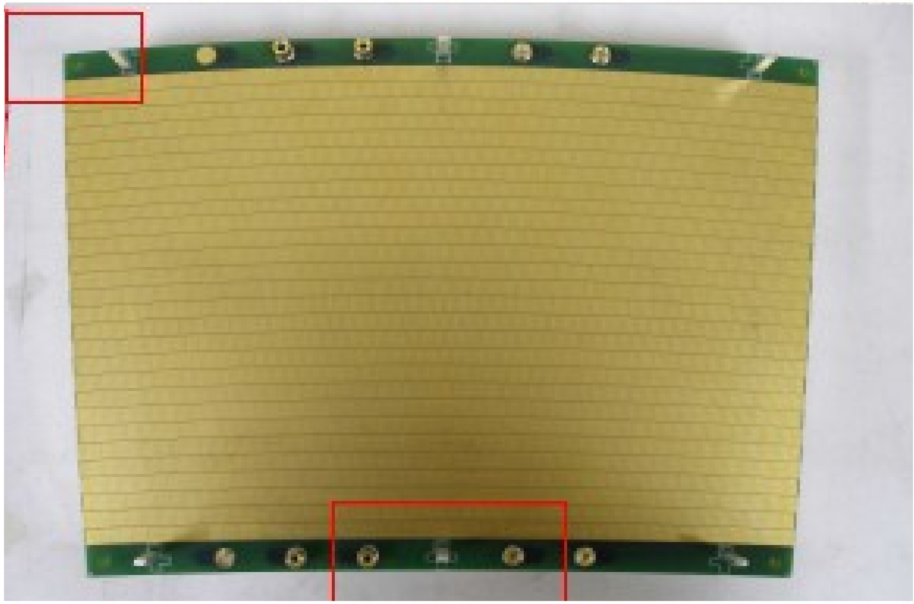
Integrated version



8-chip Ingrid module



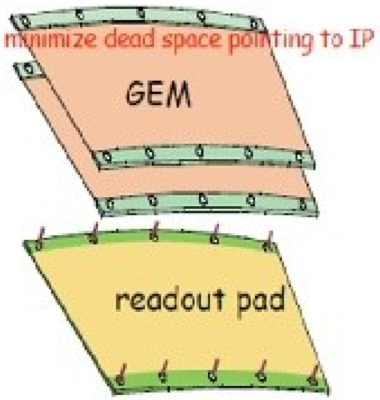
Double GEM Modules

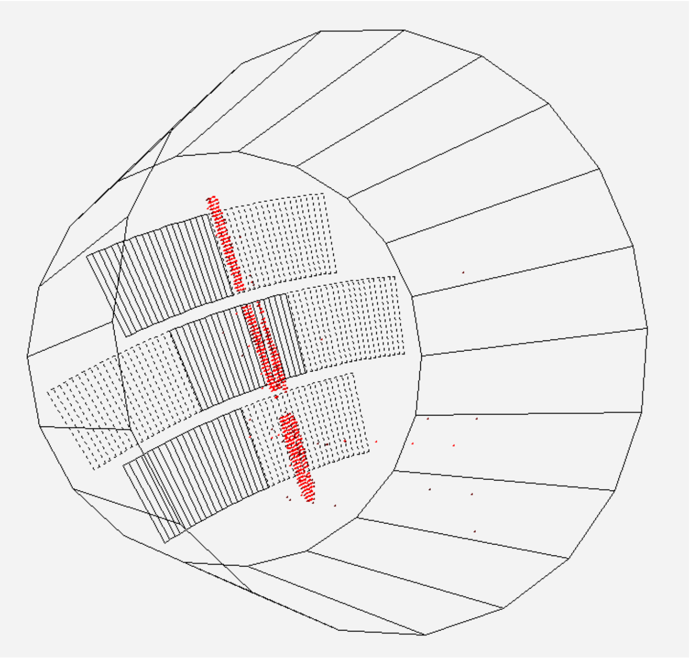


GEM Module

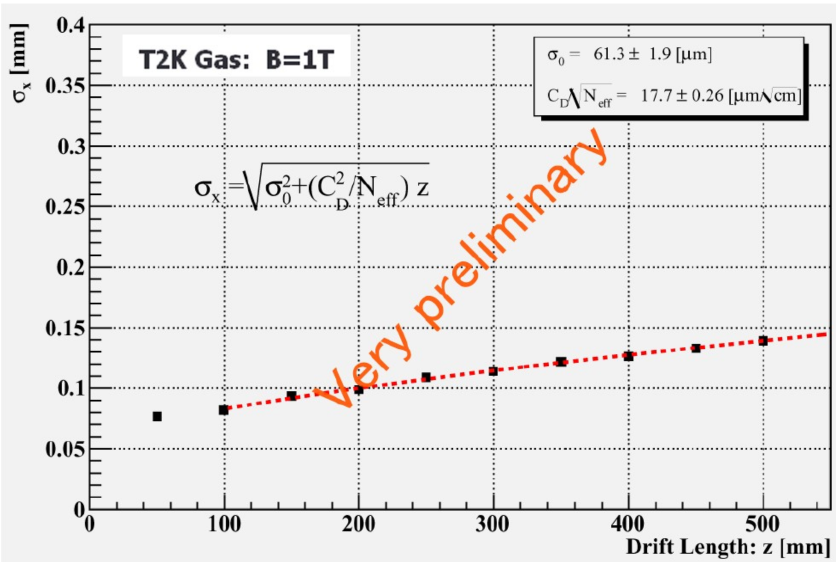
1.2×5.4 mm^2 pads - staggered
28 pad rows (176-192 pads/row)
5152 pads per module

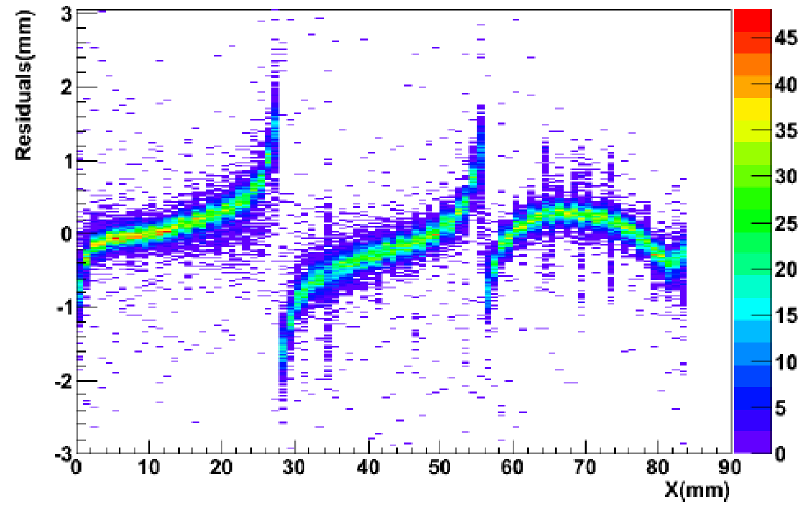
2 LCP-GEMs, 100 μm thick

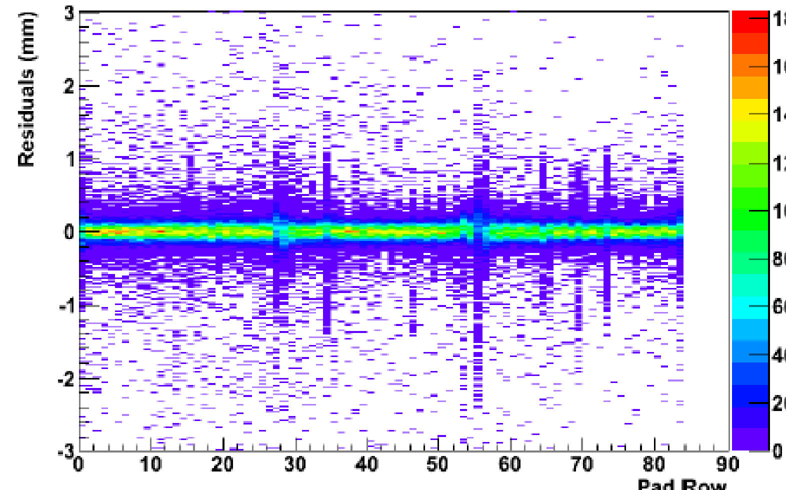




Performance of Double GEMs







Resolution parametrized as $\sigma = \sqrt{\sigma_0^2 + D_t^2/N_{eff} \cdot z}$

$\rightarrow \sigma_0 = 61.3 \pm 1.9\ \mu m$

Field distortions due to frame observed.

Effect corrected in analysis.

New modules are designed.

Triple GEM Module

3 standard CERN GEMs mounted on thin ceramic structure (bar size ~1 mm) to reduce dead space.

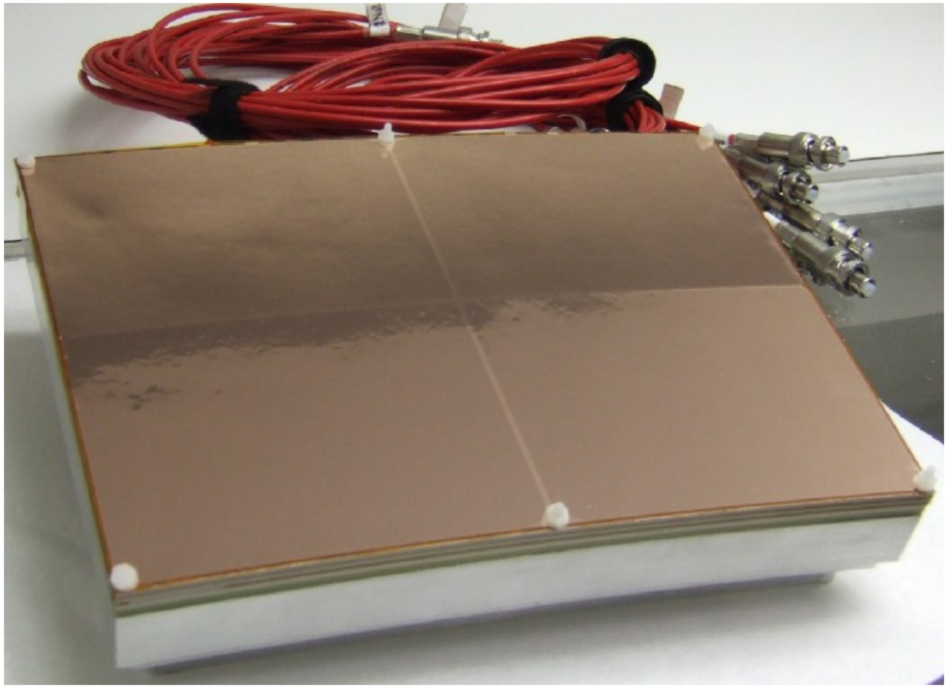
GEM is segmented into 4 parts to reduce energy stored in one sector.

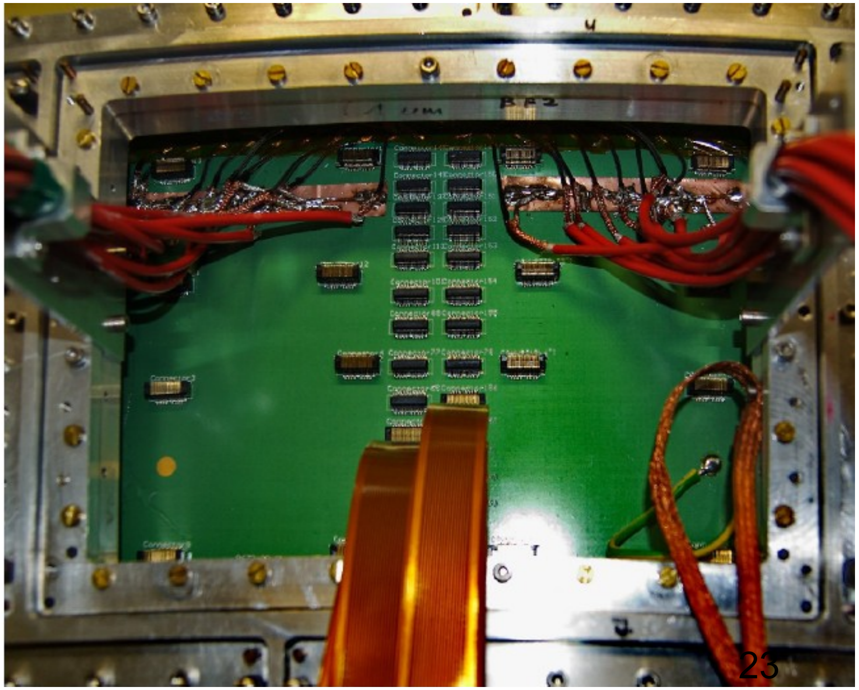
1000 small pads (1.26 × 5.85 mm^2)

First version tested last year: Detector could be operated in test beam, but a few shortcomings were identified.

Second version is being built with ~5000 pads.

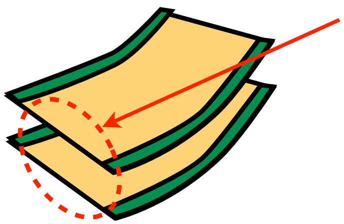
Under test NOW



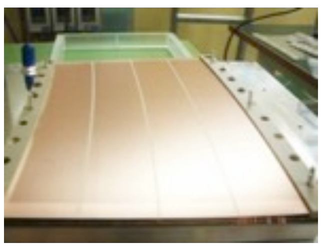


GEM + Pad Readout

Double GEMs



- 100μm-thick GEMs by SciEnergy.
- Stretch structure w/o side frames.
- Segmentation in r to reduce the energy of sparks.

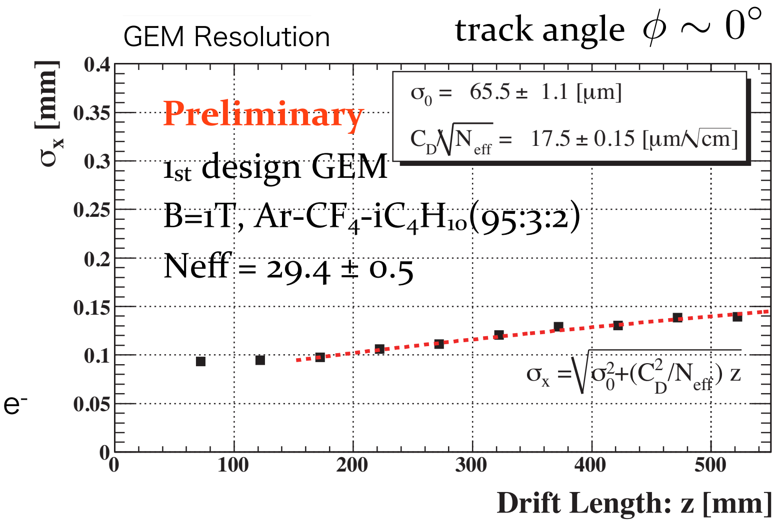


Preliminary

- N_{eff} = 29.4 ± 0.5 (pad: 1 x 5.2mm²)

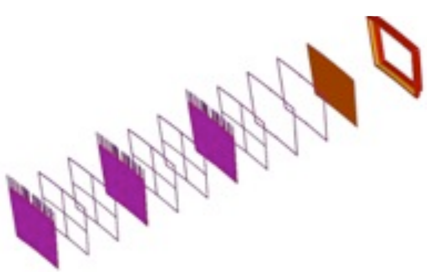
$$\sigma = \sqrt{\sigma_0^2 + \frac{C_d^2 \cdot z}{N_{eff}}}$$

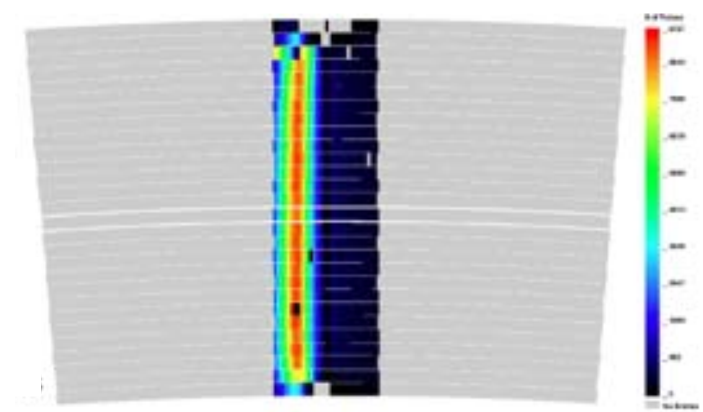
σ: resolution at z=0
N_{eff} : effective number of e⁻
C_d : diffusion constant



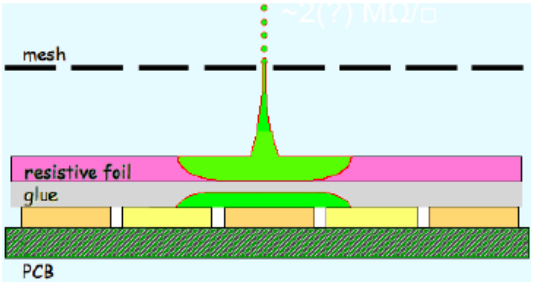
Triple GEMs

- 50μm-thick GEM by CERN.
- Full framing, but minimized dead area and material budget.
- Data analysis of first beam test ongoing.

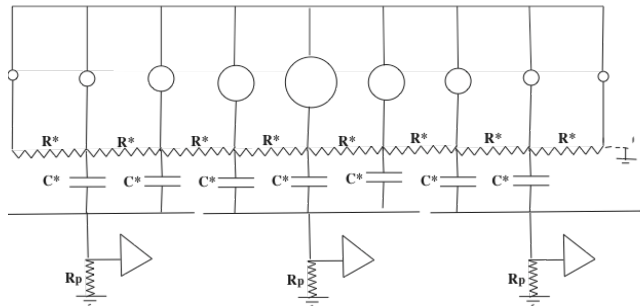




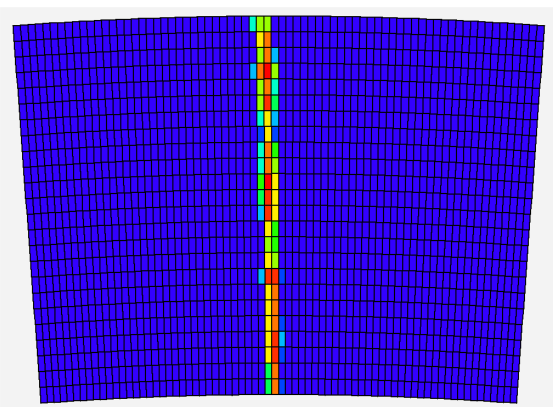
Micromegas + Resistive Pad Readout

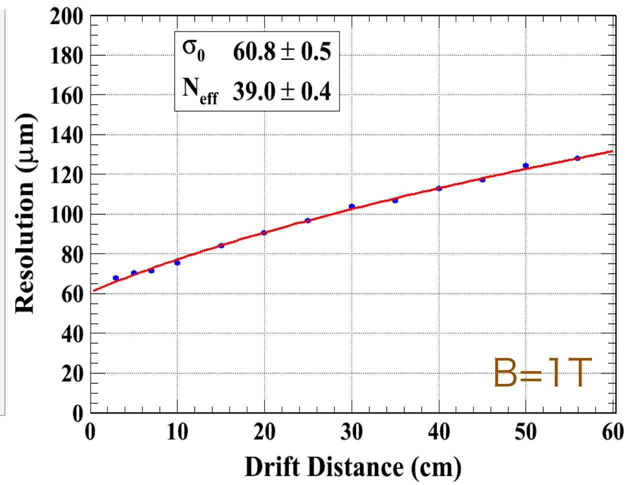


M. Dixit, A. Rankin, NIM A 566 (2006) 28

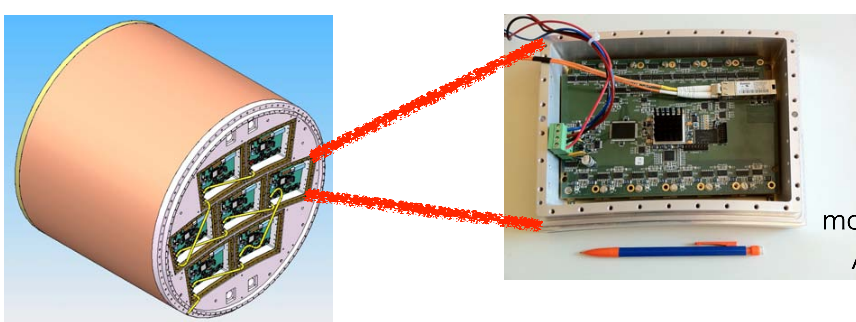


Resistive coating on top of an insulator: Continuous RC network which spreads the charge: good point resolution ~60μm with 3mm wide pads



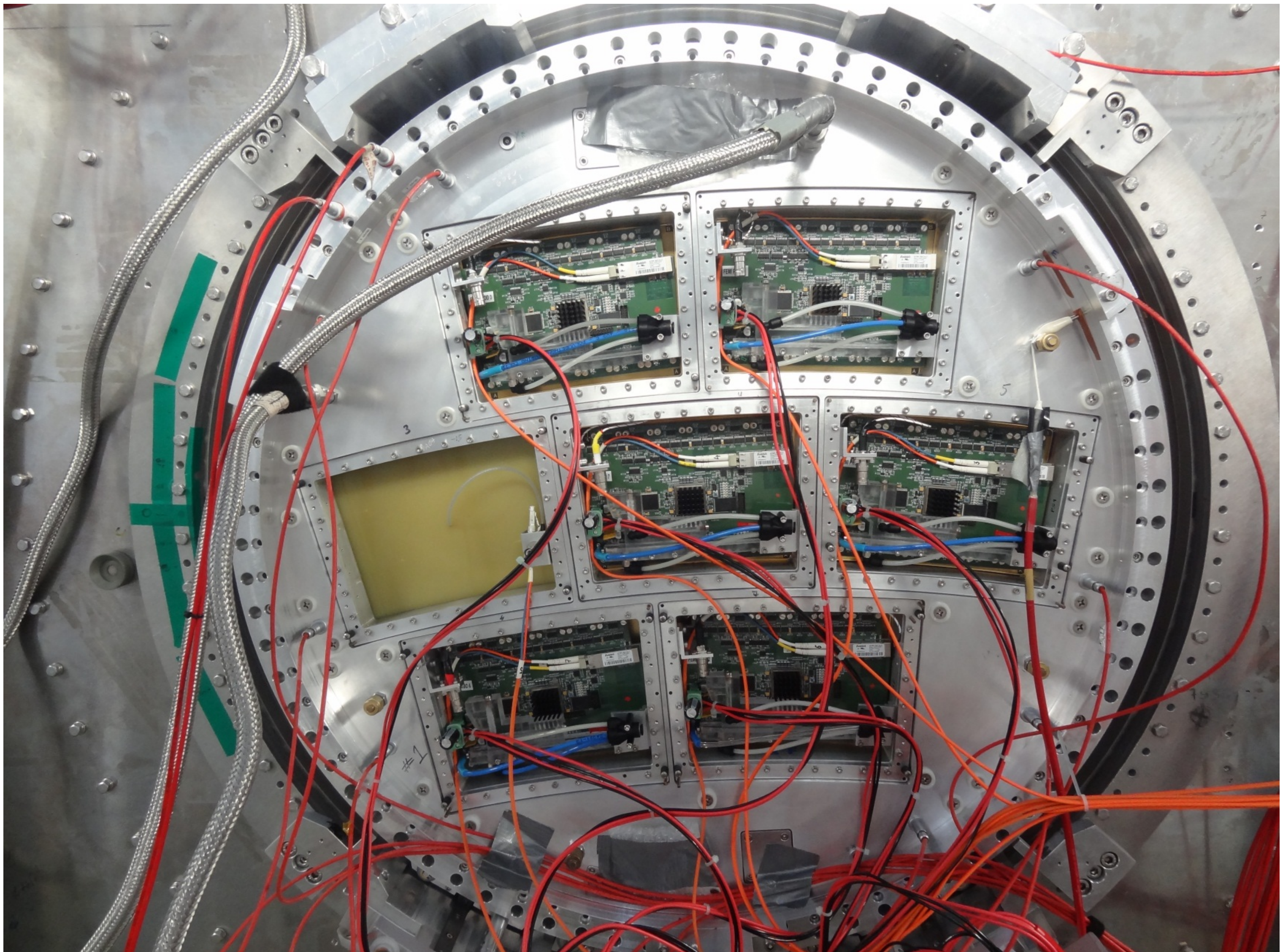


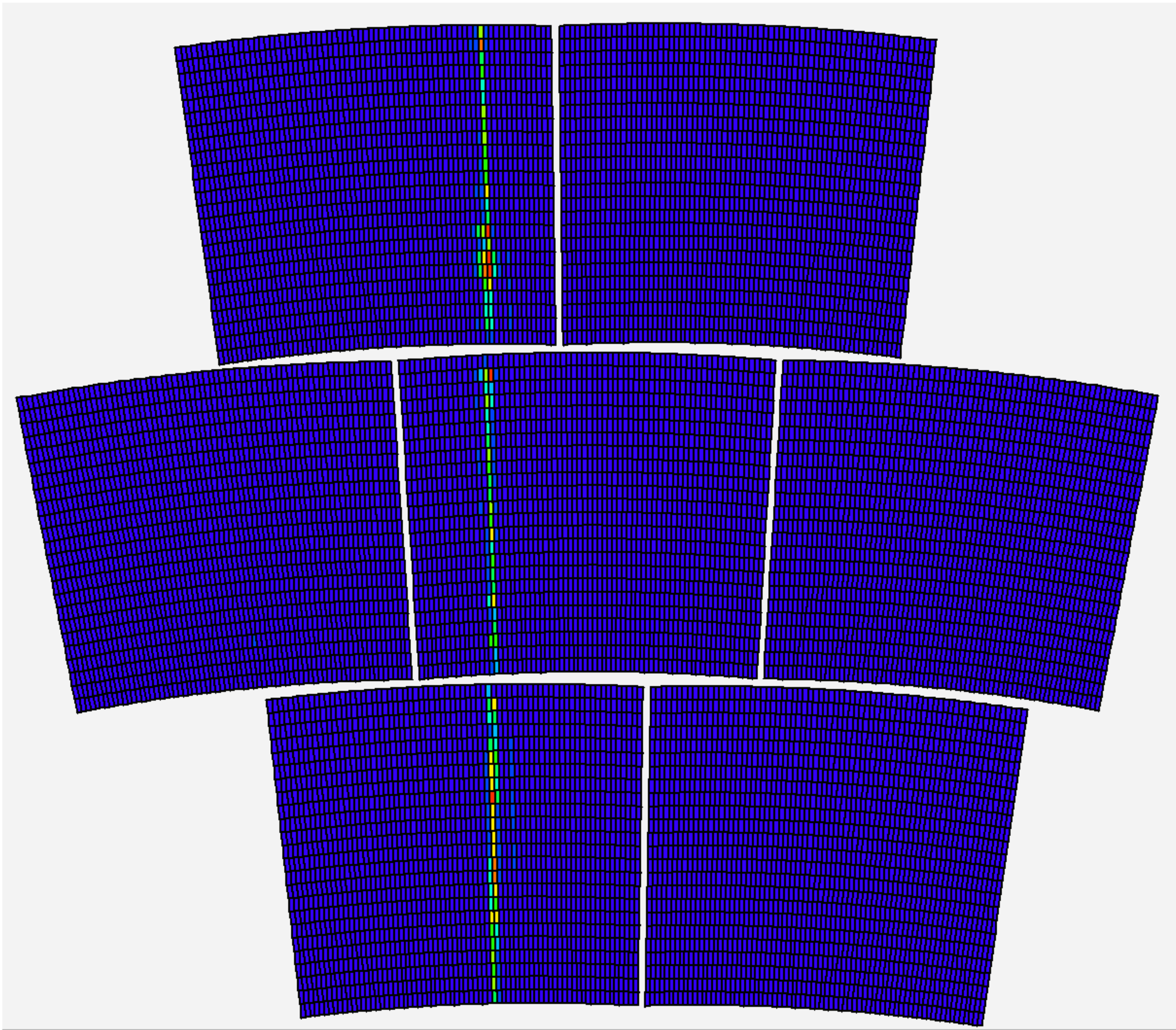
- Various resistive coatings have been tried: Carbon-loaded Kapton (CLK) of 3 and 5 MΩ/square, resistive ink.
  → CLK is chosen (good uniformity)
- Test at CERN (π beam) showed no charging up and stable operation.
- N_{eff} = 38.0 ±0.2(stat) ±0.8(C_d syst) is obtained as average of results from B=0T and 1T, with pad size of 3x7mm^2.
- New compact frontend is developed with AFTER chips. Will be tested with 7 modules integrated.

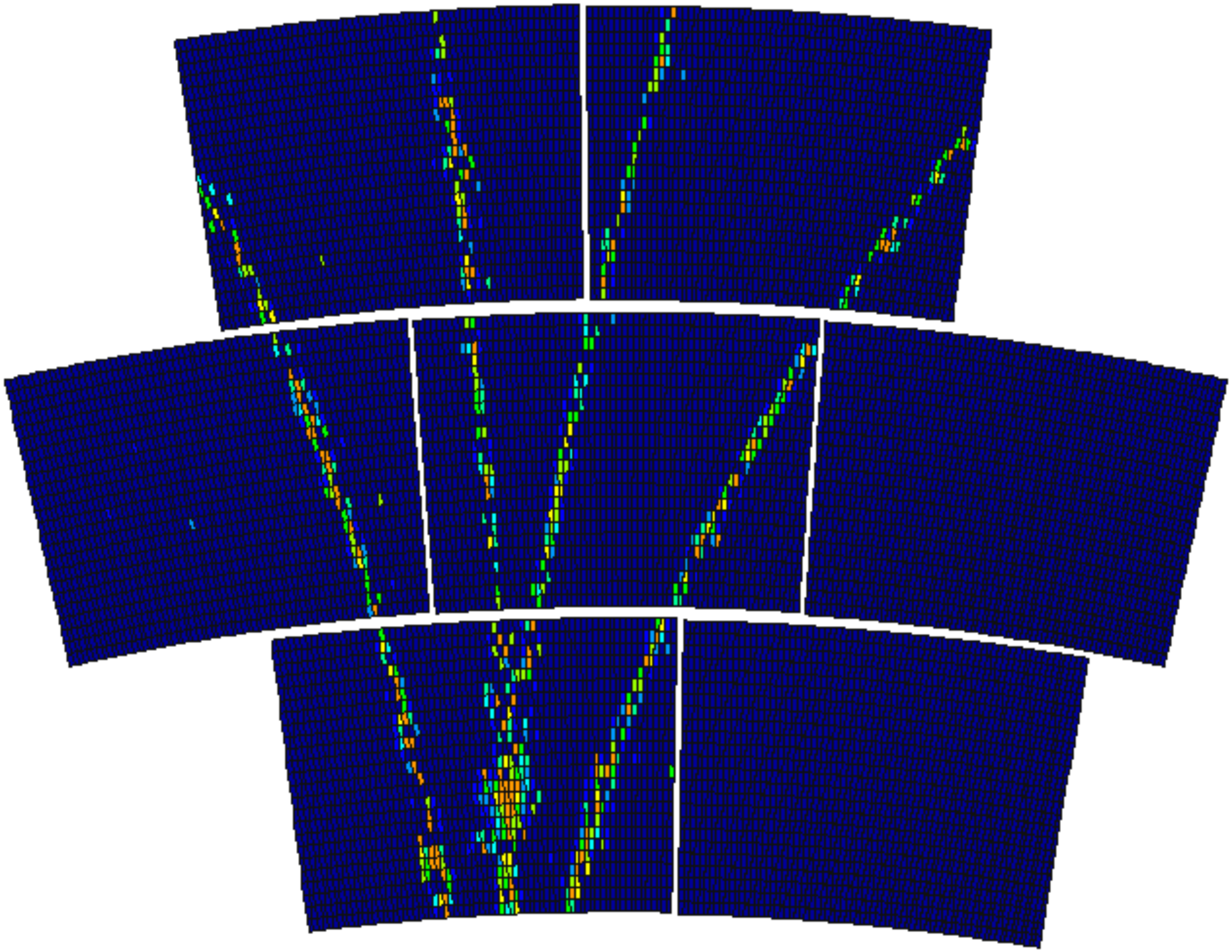


Compact module based on AFTER chips

‘’7’’–module Micromegas test (July 2012)



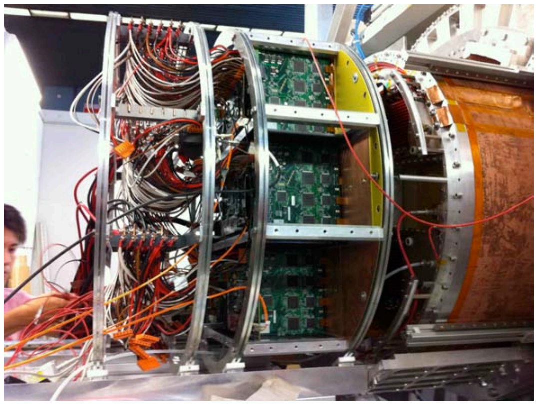




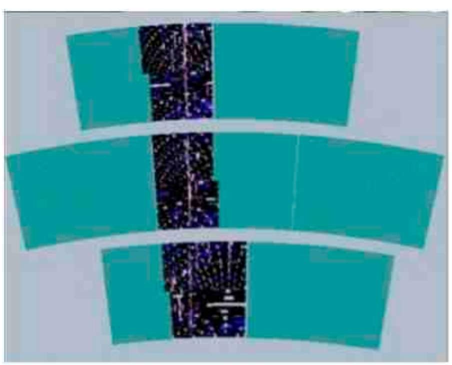
Readout Electronics Development

Phase 2 (consolidation)
Large Prototype

Readout cards perpendicular to the pad plane.
4PCA + 4ALTRO chips/Bd.

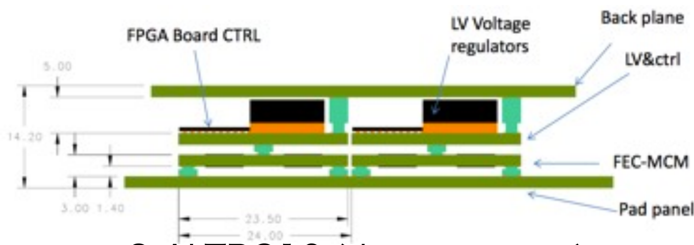


For GEM/Micromegas pad readout

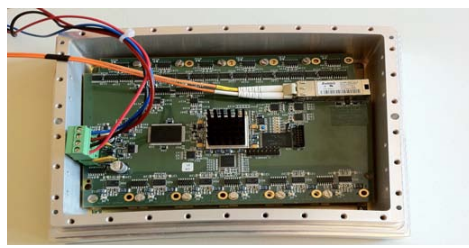


Pre-Advanced Endplate

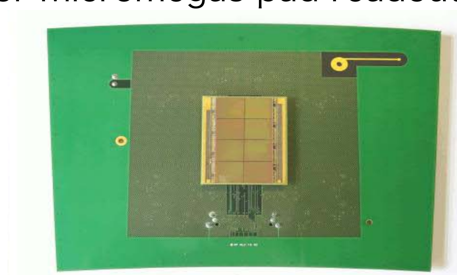
Multi-PCB flat endplate.



S-ALTRO16 (demonstrator)
for GEM/Micromegas pad readout



AFTER (T2K) electronics
for Micromegas pad readout

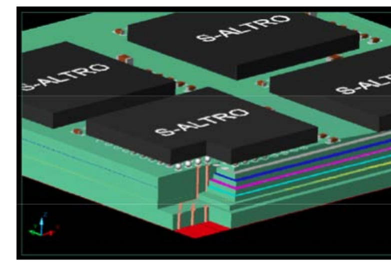


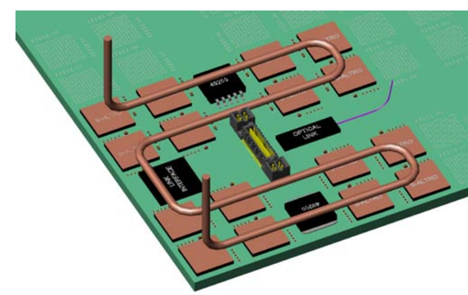
TimePix (pixel readout)

Phase 3 (design)
Advanced Endplate

Final target:
thin endplate with single-PCB
(low material budget)

Candidate: S-ALTRO64
for pad reading

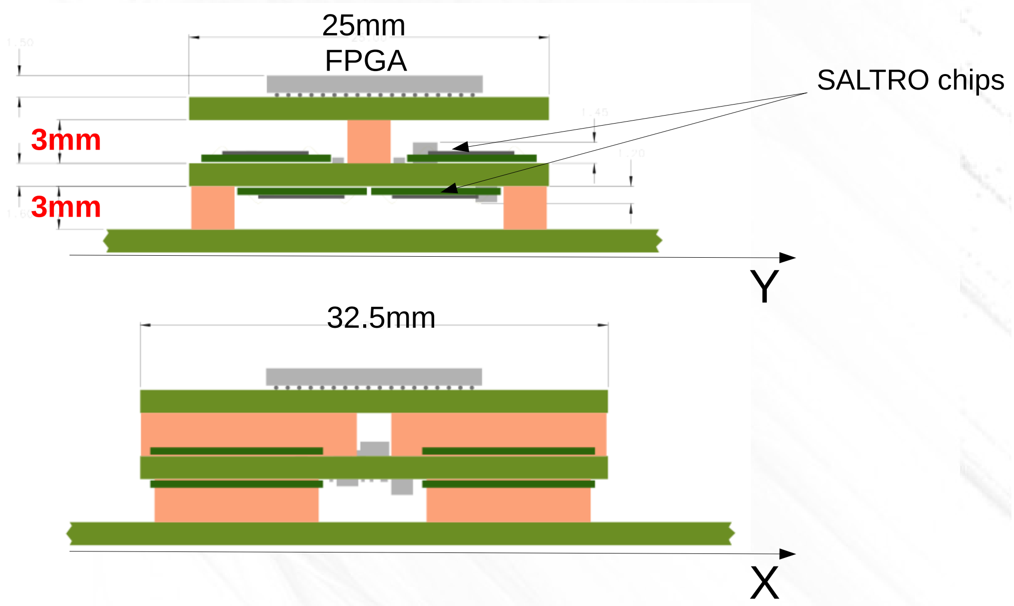


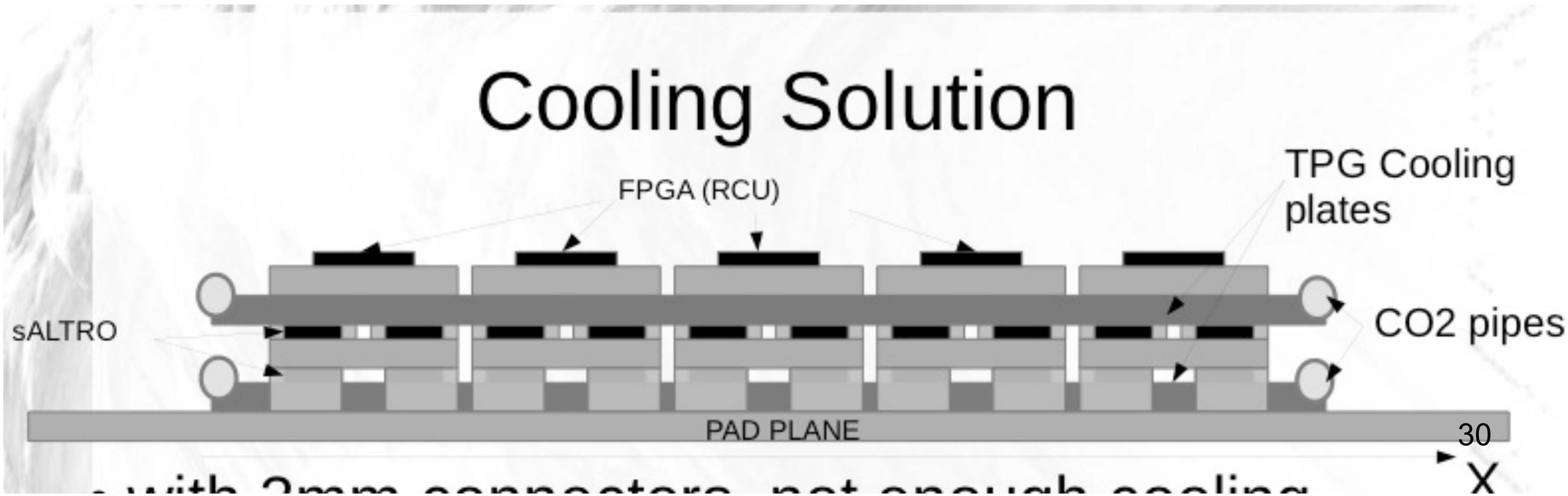


Candidate: Pixel readout option

Electronics layout proposal: MCM

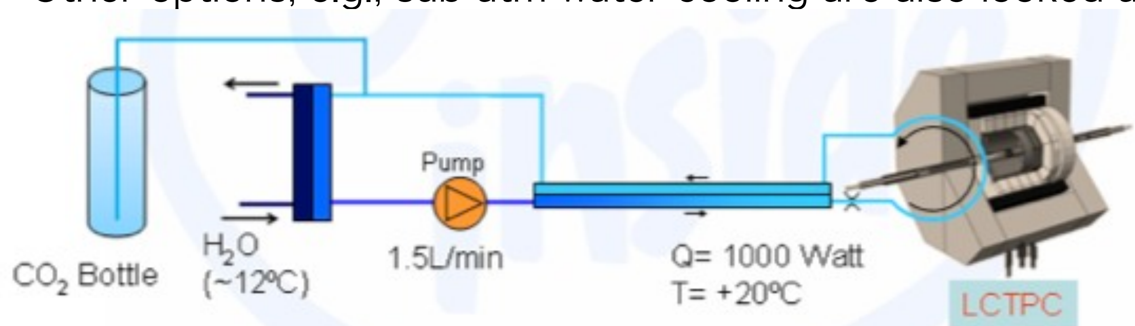
SALTRO-16



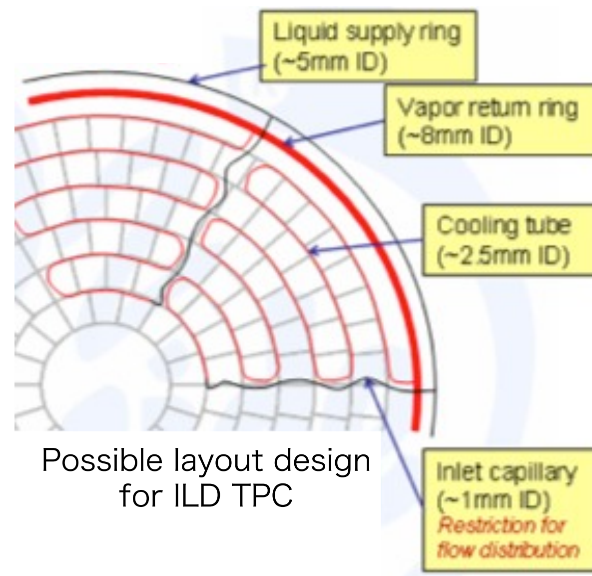


Thermal Issues: 2-Phase CO_2 Cooling

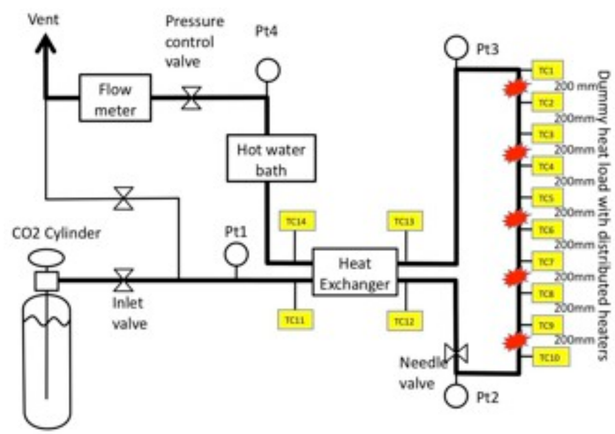
- Power density of ALTRO-based advanced endplate with 1.5% power cycle: ~210W/m^2
- 2-Phase CO_2 Cooling gives thinner cooling pipe than water cooling → low material budget.
- Small temperature gradient keeps detector temperature uniform.
- Other options, e.g., sub-atm water cooling are also looked at.



Example of 2-Phase CO_2 cooling system for LCTPC



Possible layout design for ILD TPC



Simple "blow system" test bench was established in KEK (2011).
→ Planning circulation-system test bench in DESY (2012)

A test module as heat load with dummy heat-load FPGAs in place of S-ALTRO64.
Power pulsing test is also the aim of the test module.

Pad readout vs. Pixel readout

- Pad size ~1x5 mm^2 or ~3x7 mm^2
- Timepix pixel size 55x55 $(\mu m)^2$

- Pad TPC ~ 10^6 pads; several 10^9 3D-voxels
- CMOS pixel readout ~ 2.10^9 'pads' (but 'only' ~ 4.10^4 chips); ~ 10^{12} 3D voxels

pads/pixels might be problem for software, but occupancy rather low

Full post-processing of a TimePix

· Timepix chip + SiProt + Ingrid:

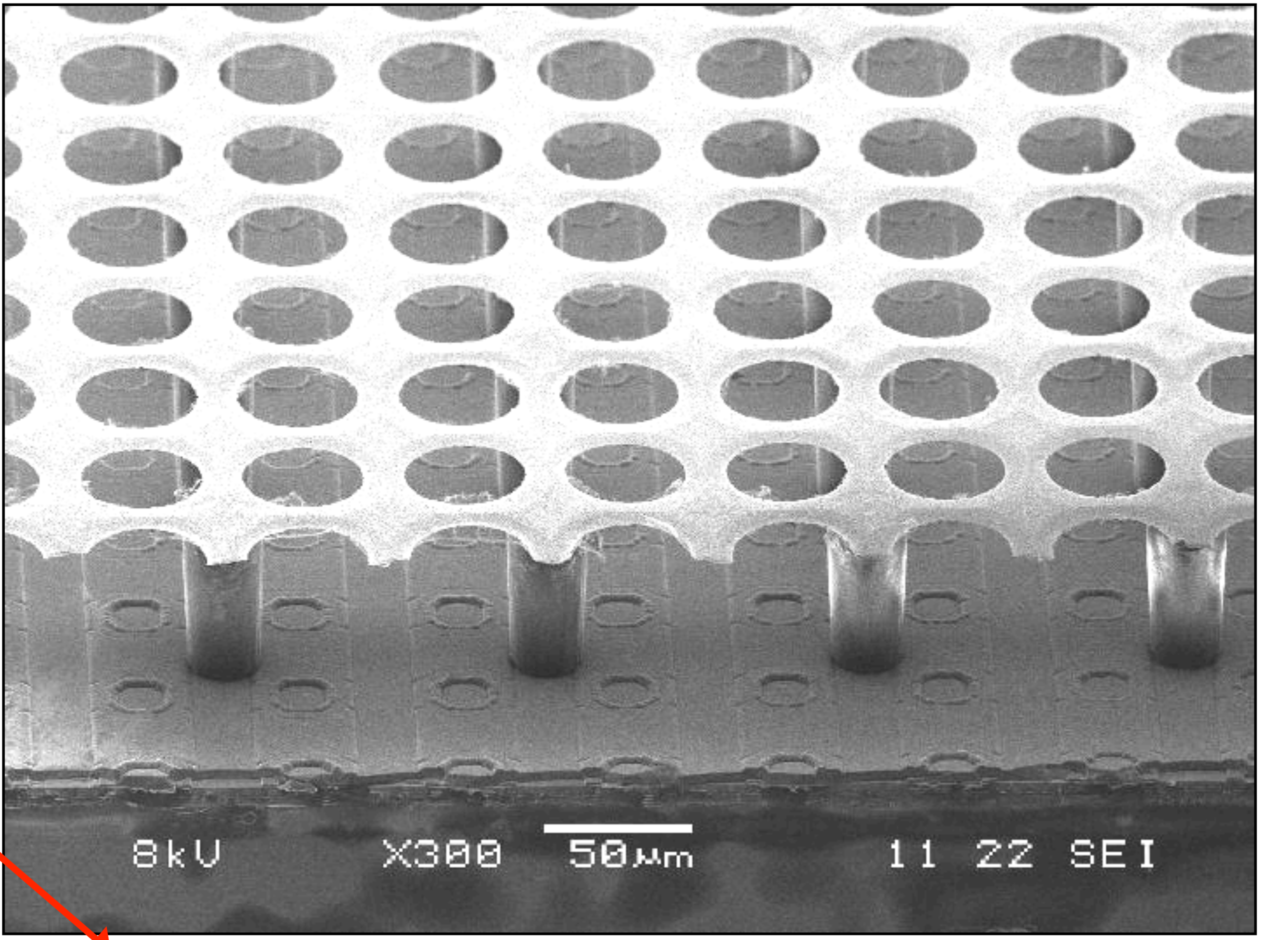
Timepix chip:

- 256x256 pixels
- pixel: 55x55 μm^2
- active surface: 14x14 mm^2

MESA+: Ingrid

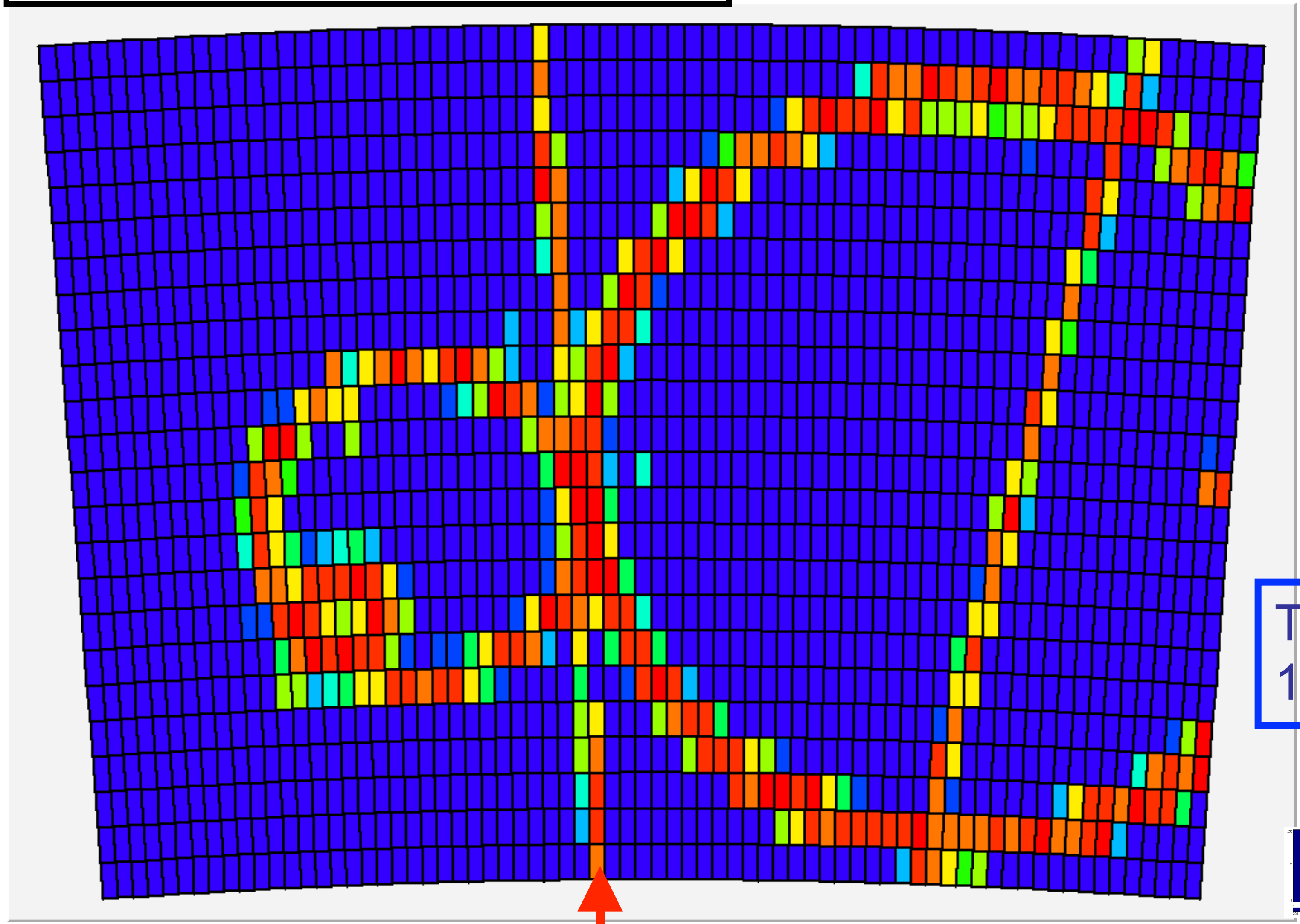
IMT Neuchatel:

15 or 20 μm highly resistive aSi:H protection layer



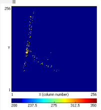
Now also Si_3N_4 protection layers (7 μm)

72x24 pads of ~3x7 mm²

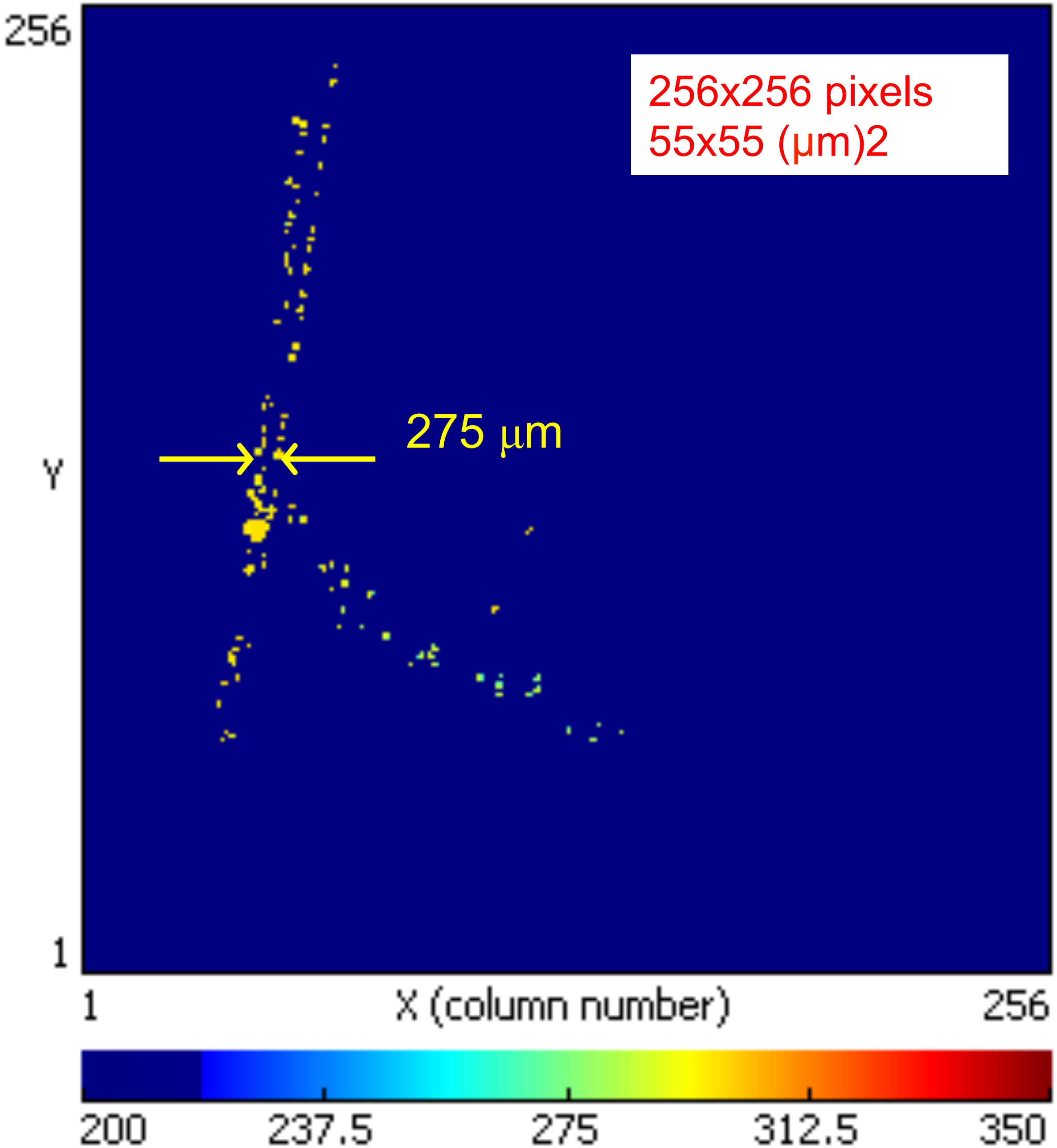


B = 1 T

TimePix chip
14x14 mm²



5 GeV e⁻ beam



Two-track separation:

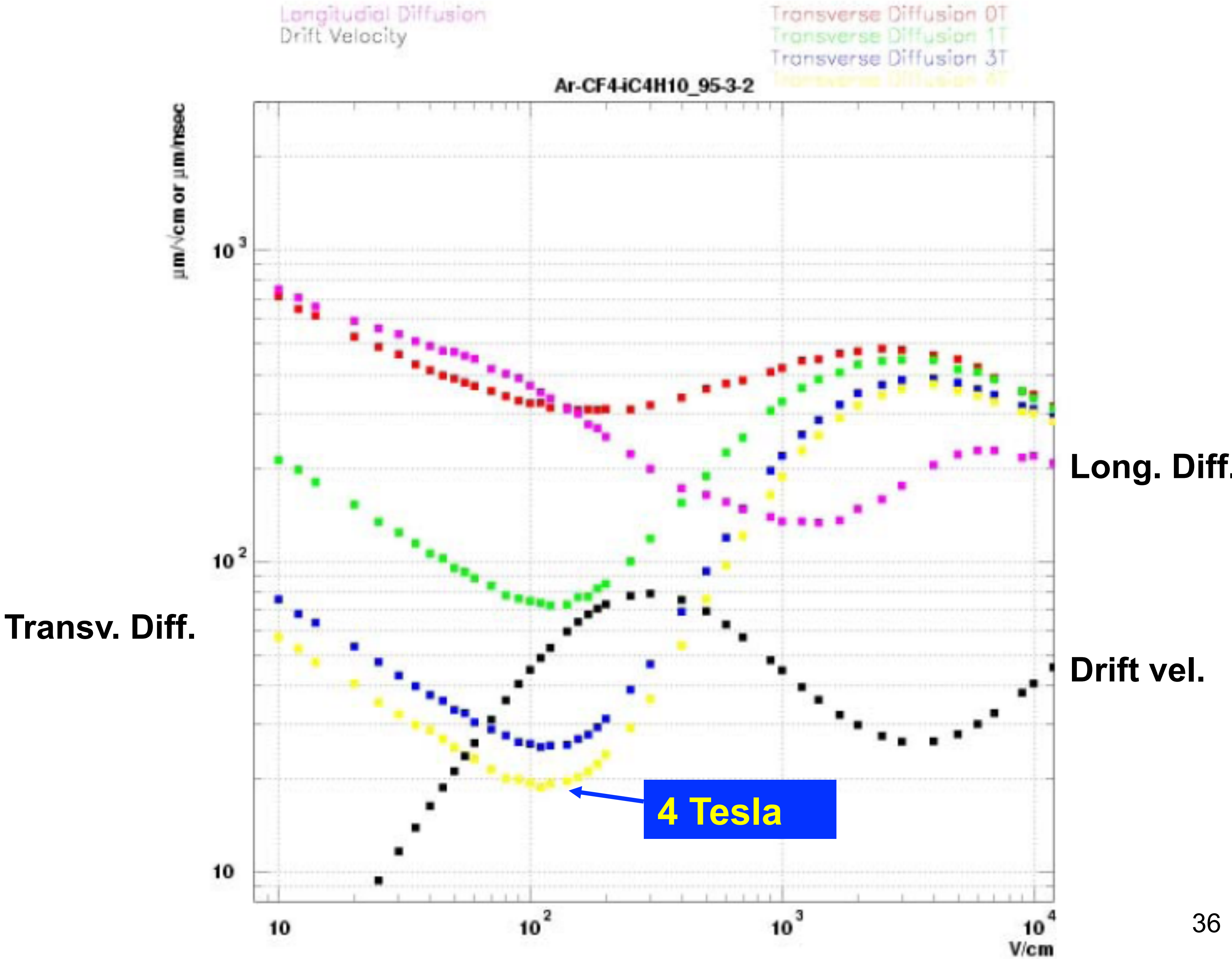
- Will be diffusion limited
- In this example:

5 pixels = 275 μm

Diffusion at 4T in

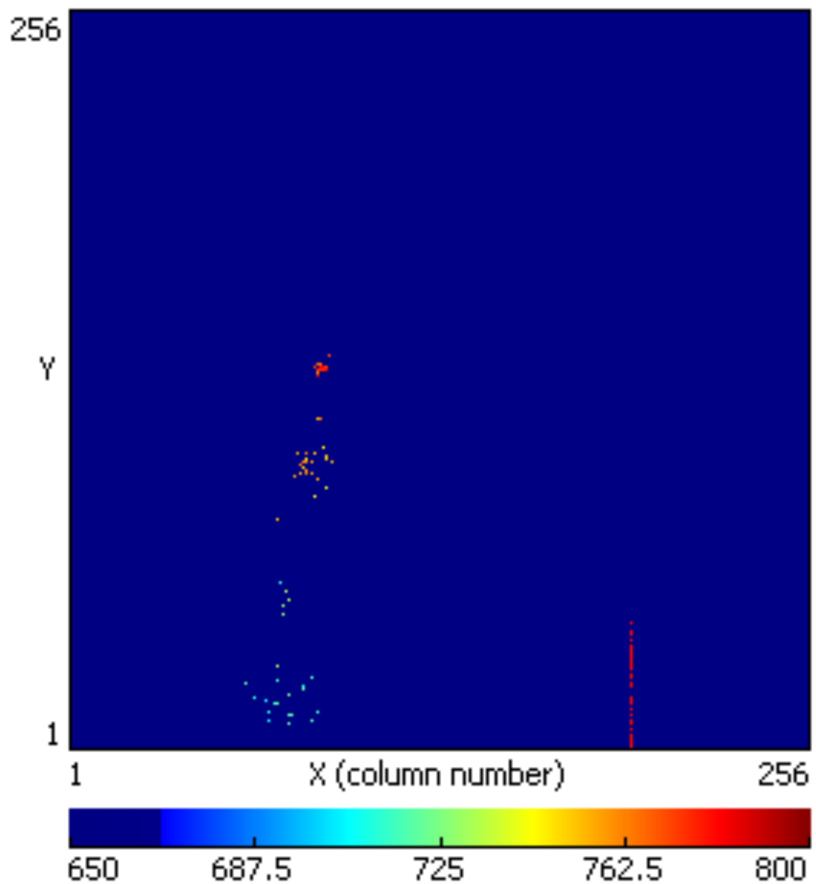
Ar/CF4/iC_4H_{10} is

~ 20√200 = 300 μm

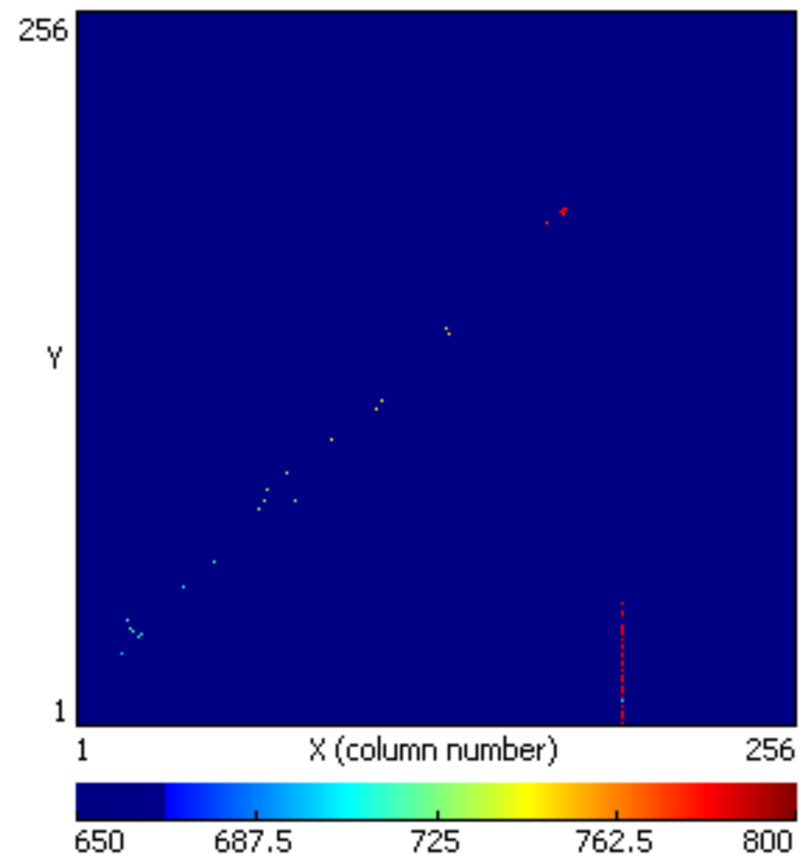

Longitudial Diffusion
Drift Velocity
Transverse Diffusion 0T
Transverse Diffusion 1T
Transverse Diffusion 3T
Transverse Diffusion 4T
Ar-CF4-iC4H10_95-3-2
µm/√cm or µm/nsec
10^3
10^2
10
10
10^2
10^3
10^4
V/cm
Long. Diff.
Transv. Diff.
Drift vel.
4 Tesla

Cosmic tracks traversing ~ 30 mm drift space
Ingrid and Ar-CF4-iC4H10 (95/3/2%)

0 T



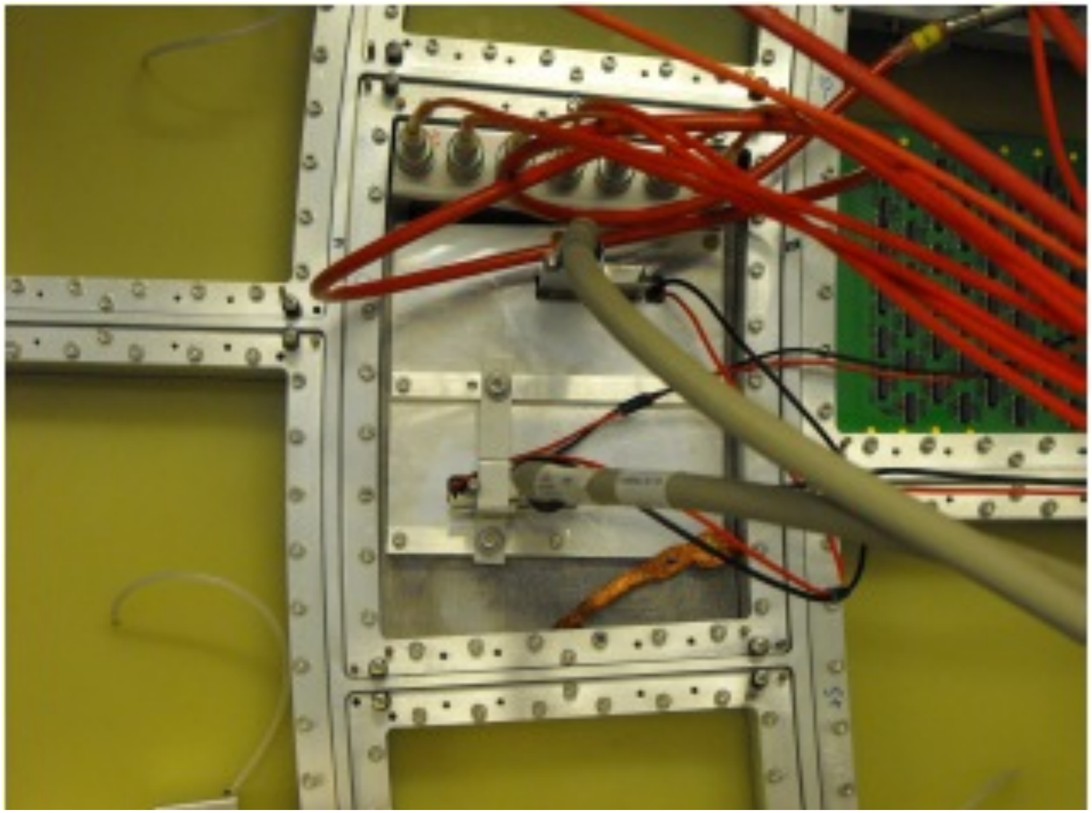
1 T



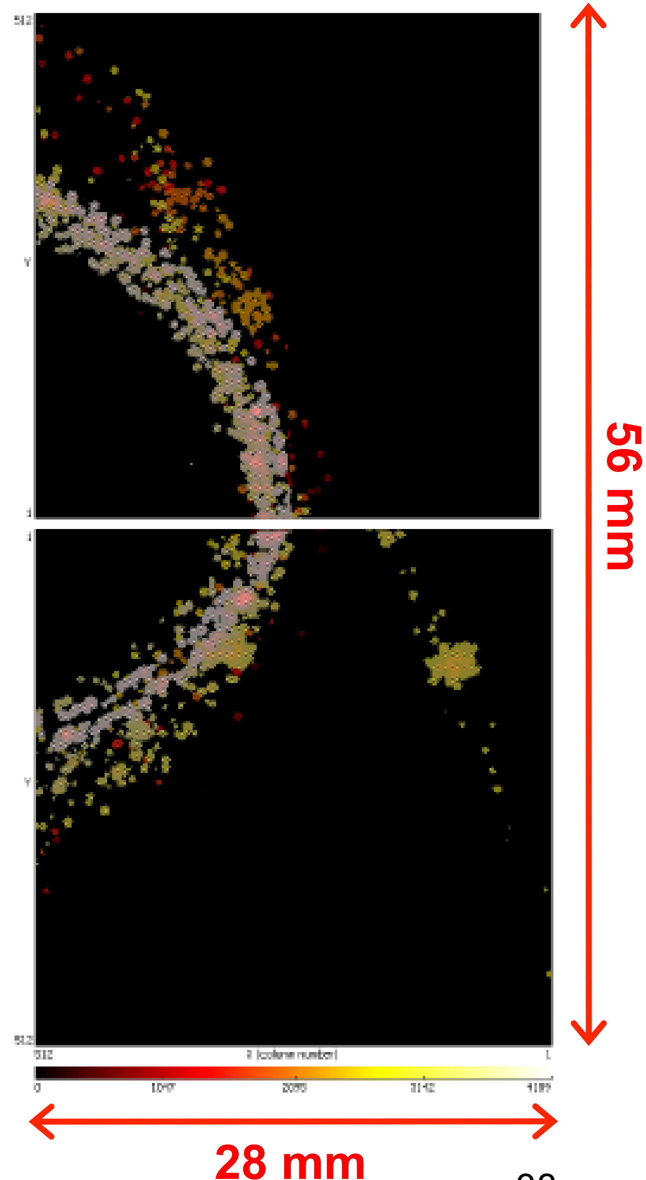
“large” diffusion

“little” diffusion

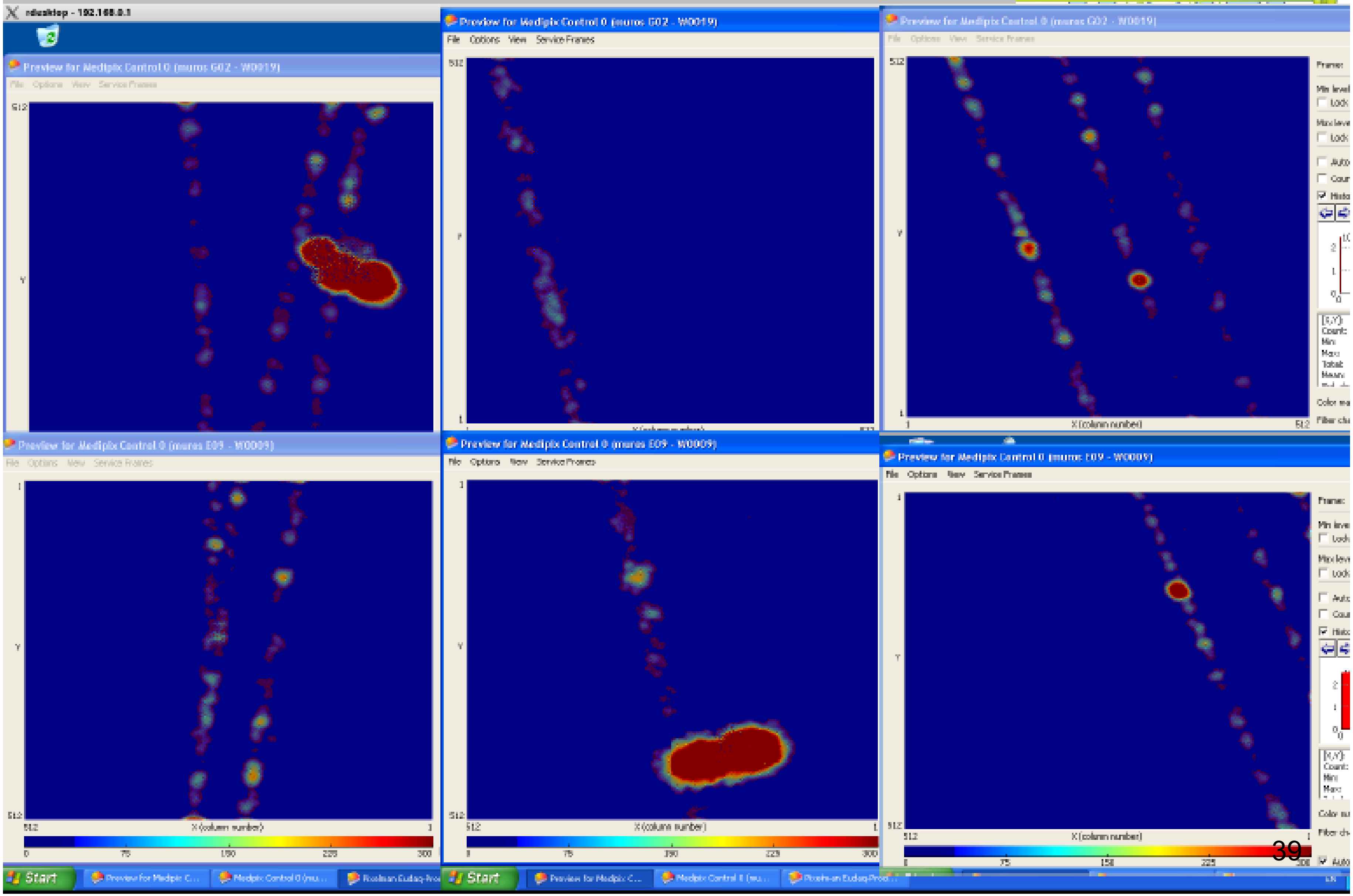
Triple-GEM module with readout by 8 Timepix chips: 16 cm2 active area, 0.5M channels



Bonn/Freiburg

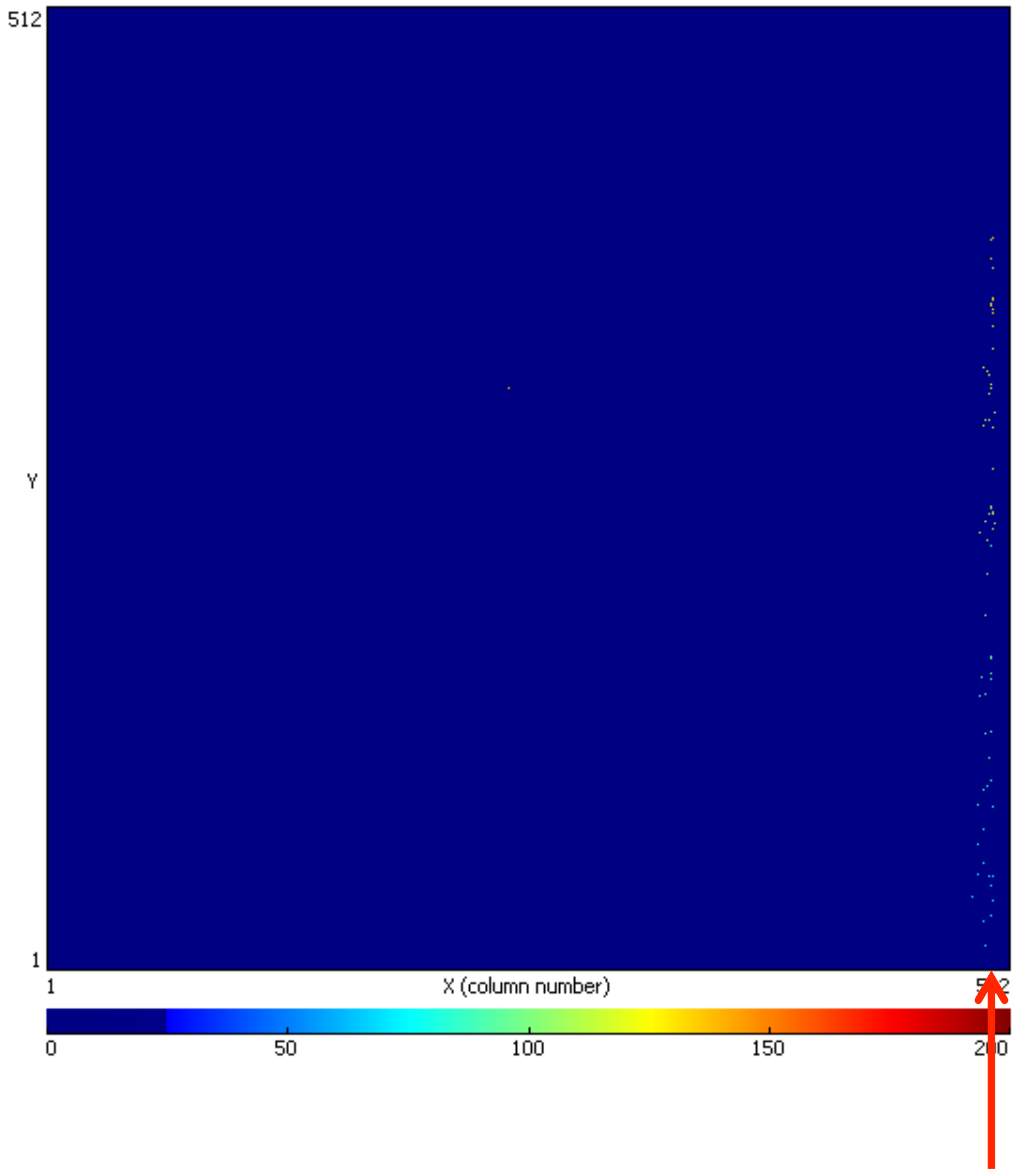


Some Pictures (III)



Track very close to border; there is 0.5mm 'dyke'

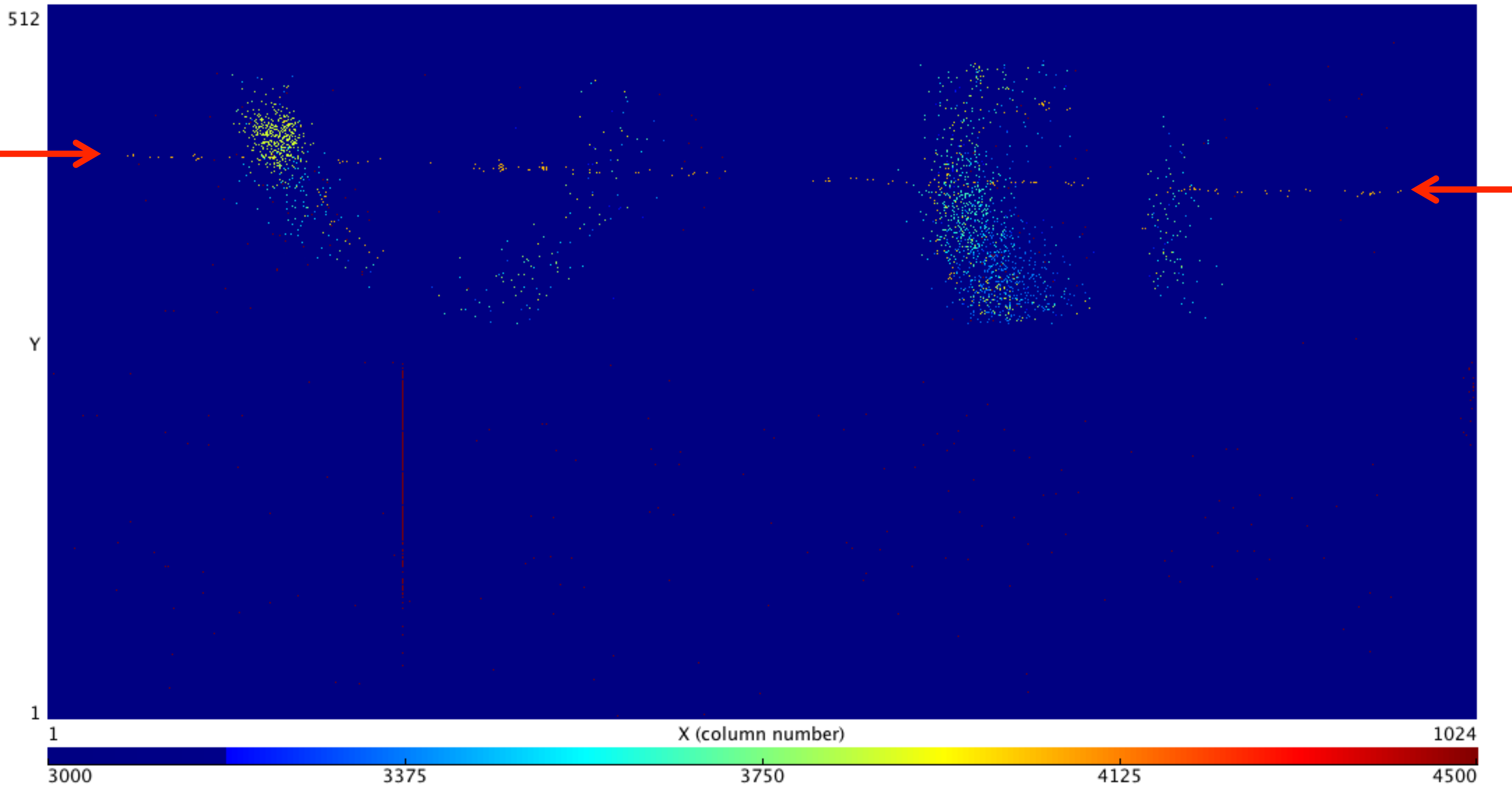
QUAD Ingrid



DESY testbeam
5 GeV e^-

OCTOPUCE: The last trigger taken: 4 Dec 2010, 11:06

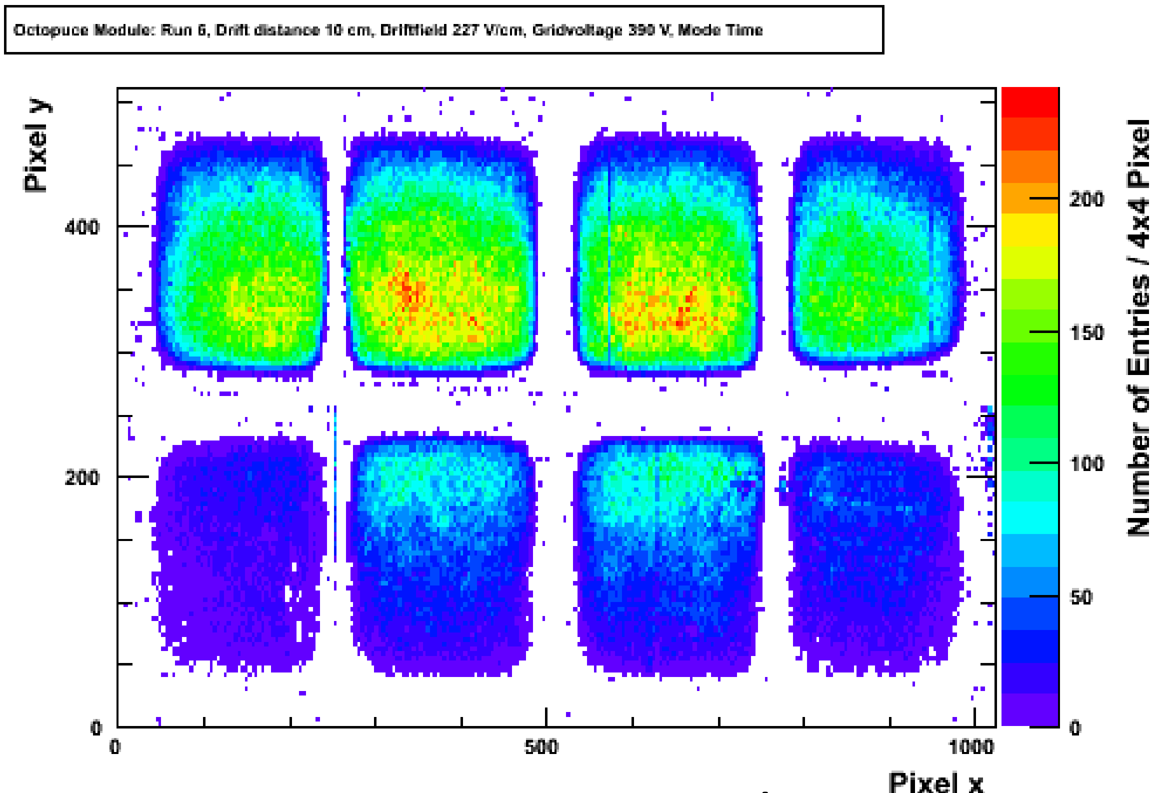
He/iC_4H_{10} 80/20 V_{grid} = -400 V B = 1 T



Occupancy Plots

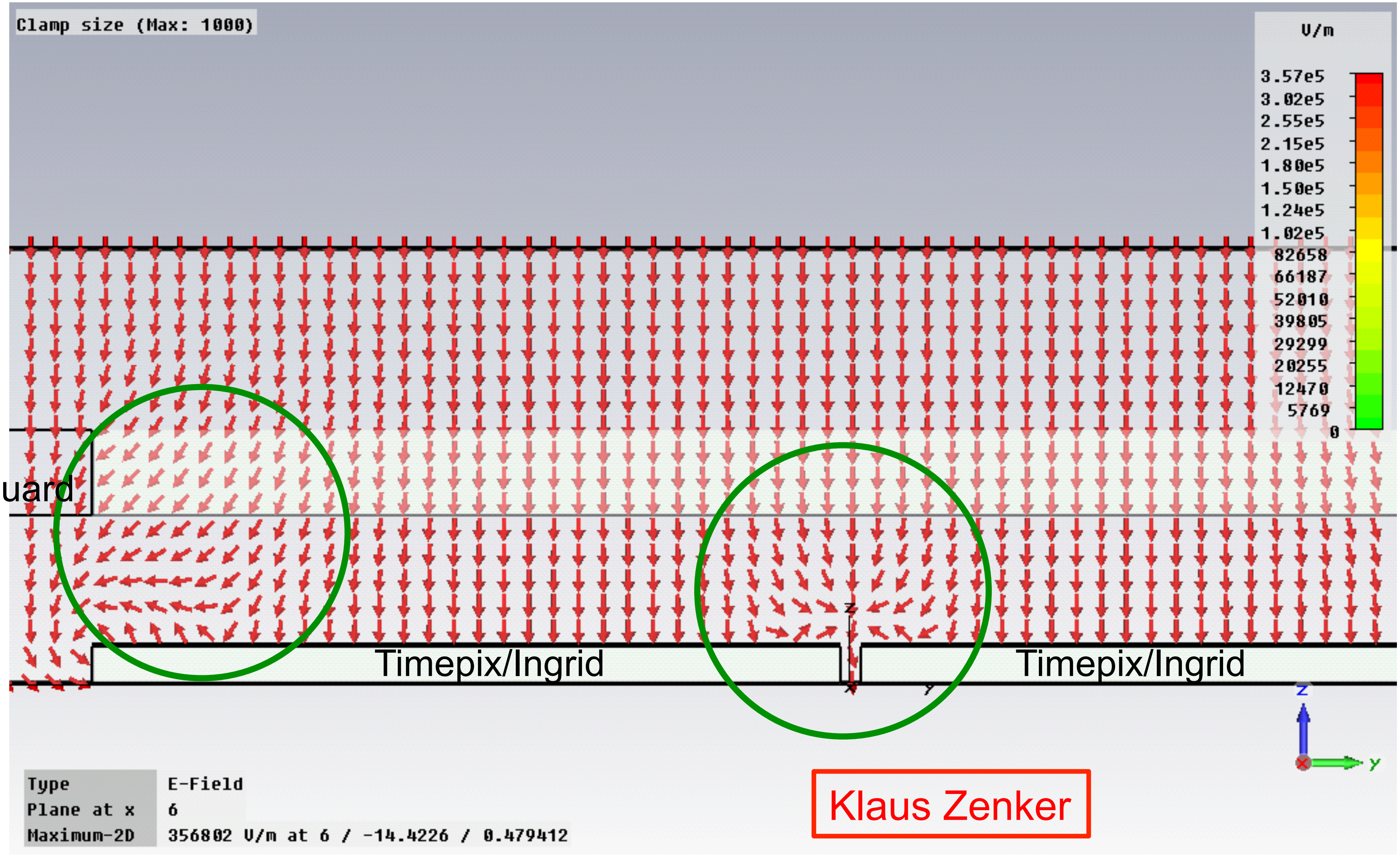
- counting hits per Pixel per Run (0/1 Entry per Event)
  -> status of pixels, distortions, comparison chip activity

-> big gaps which are not expected



Run06: Drift-Field **227 V/cm**

(current) OCTOPUCE field distortions



Future

- Wafer-scale production of Ingrids/GEMgrids at IZM Berlin:
  December 2011: delivery of first batch (48 pcs) of good looking Ingrid's; had still problems with discharge protection
  September 2012: new delivery (IZM-3): first detectors still working after more than one week of continuous operation

- Construct 2nd Octopuce and test at LP with T2K gas

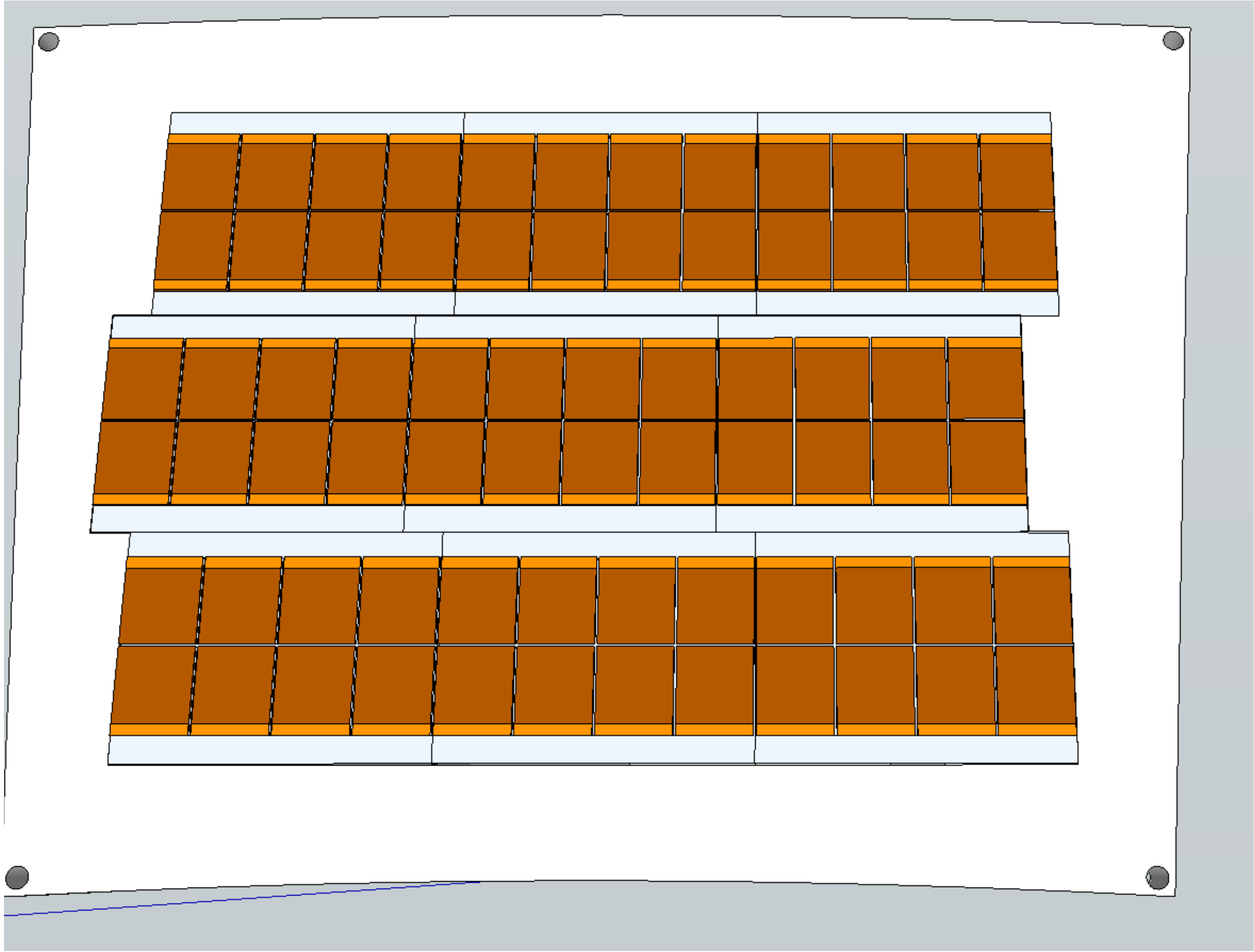
- Move to new (faster) readout: e.g. Muros/Pixelman → "Relaxed"

- Longer term (1-2(?) years): development of "full" scale LP module with >~64 Ingrids; integrated design Ingrid, cooling, FPGA readout and data transfer

- Timepix3 with better time resolution

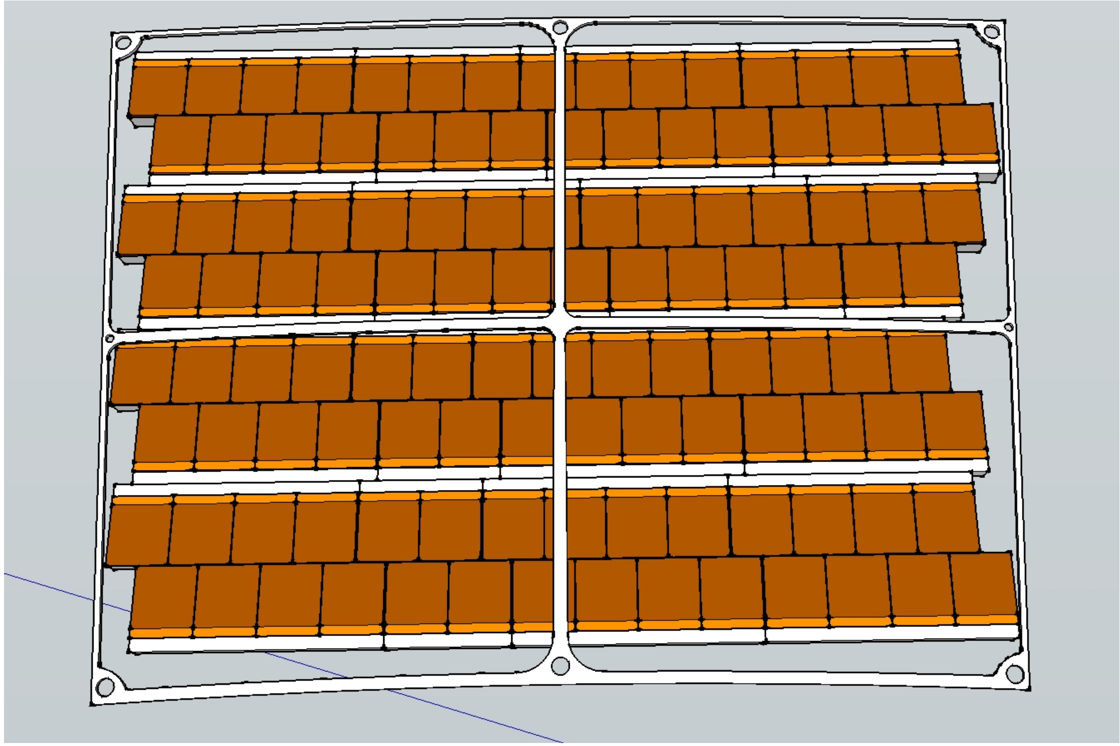
Next steps

- Near goal: LCTPC module with 3x3 submodules, each octoboards, staggered boards



Outlook

- Far goal 1: LCTPC module with InGrids
  - Maybe later...
- Far goal 2: LCTPC module with DESY GEM and as many Timepix chips as possible (115 chips, staggerd chips), consisting of 16 submodules (different sizes, most of them octoboards)
  - Still to many problems to solve for a first try...



LCTPC (LP) concluding slides

- Present: LP1
- Developments -> LP2
- How to proceed from here

Present: LP1

- Fieldcage, cathode, infrastructure (DESY)
- Endplate (Cornell)
- Modules:
  - A-GEM (double stack)
  - Micromegas (w. Resistive anode) (Saclay/Carleton)
  - D-GEM (triple stack); also with Timepix R/O (DESY, Bonn)
  - Octopuce (Saclay/NIKHEF)
- Electronics:
  - Altro
  - AFTER
  - Timepix
- Laser system

But still a lot to do before “final” conclusions

Present: LP1

- Issues:
  - Mechanics modules
  - Stability HV connections/discharges
  - E/B field distortions
  - Gating grid
  - Coping with B-field distortions

Developments,Advanced endplate / LP2

- new thinner endplate (Cornell; well advanced)
- New fieldcage (DESY)
- New cathode?
- Studying full ILD-size cathode
- How to supply drift HV?
- New modules in 2012
- S-Altro-16 electronics
- Gating studies/devices
- 2PCO2 cooling; integration with module mechanics

How to proceed from here

- Define/describe ILD baseline design for TPC in DBD (end 2012)
- Can and will continue R&D on different technologies. At some moment: choices? Will depend on timescale of “green light” for ILC

R&D by LCTPC collaboration

- Construction of advanced endplate for LP (2012)
- Improved 2nd fieldcage for LP (2012?)
- Further development of endplate modules with (integrated) electronics for GEMs and Micromegas (2012) and for Ingrids (late 2012-2013)
- Testbeams at 5 GeV electrons at DESY (2012)
- Gating device studies
- CO2 cooling studies
- Power distribution and power pulsing
- High-energy hadron testbeams (2013(?) -   )

Conclusions

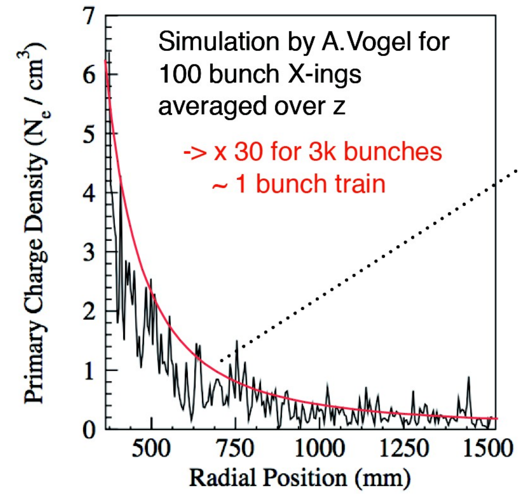
- ILD tracking (both ILC and CLIC)
  - Highly redundant, continuous tracking and dE/dx
  - Allows easy and precise reconstruction of non-pointing tracks
  - CLIC: Time stamping ~ 2ns + TPC-Si tracking
- But: CLIC (too?) high occupancy at small radius
- Space charge effects under study
- Very active R&D program

Backup slides

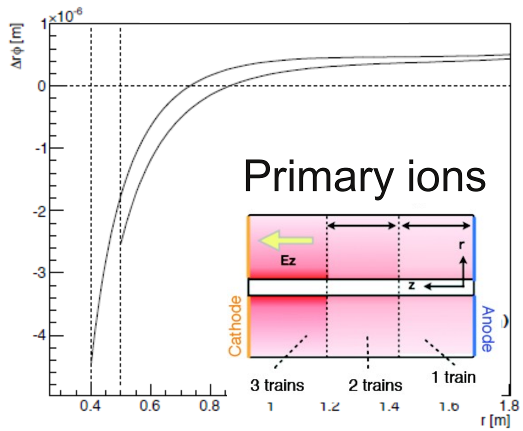
Effect of Positive Ions on e⁻

- Charge density due to beam background was approximated based on simulations.
- Complicated equations were solved to get E-field:

$$E_r(r,z) = -8\pi \sum_{n=1}^{\infty} \frac{\sin(\beta_n z)}{I_0(\beta_n a)K_0(\beta_n b) - I_0(\beta_n b)K_0(\beta_n a)} \int_0^L \frac{dz'}{L} \sin(\beta_n z')\hat{\rho}_z(z') \Bigg[[K_0(\beta_n b)I_1(\beta r) + I_0(\beta_n b)K_1(\beta_n r)] \int_a^r dr' \frac{K_0(\beta_n a)I_0(\beta r') - I_0(\beta_n a)K_0(\beta_n r')}{K_0(\beta_n r')I_1(\beta_n r') + K_1(\beta_n r')I_0(\beta_n r')} \bar{\rho}_r(r') + [K_0(\beta_n a)I_1(\beta r) + I_0(\beta_n a)K_1(\beta_n r)] \int_r^b dr' \frac{K_0(\beta_n b)I_0(\beta r') - I_0(\beta_n b)K_0(\beta_n r')}{K_0(\beta_n r')I_1(\beta_n r') + K_1(\beta_n r')I_0(\beta_n r')} \bar{\rho}_r(r') \Bigg]$$

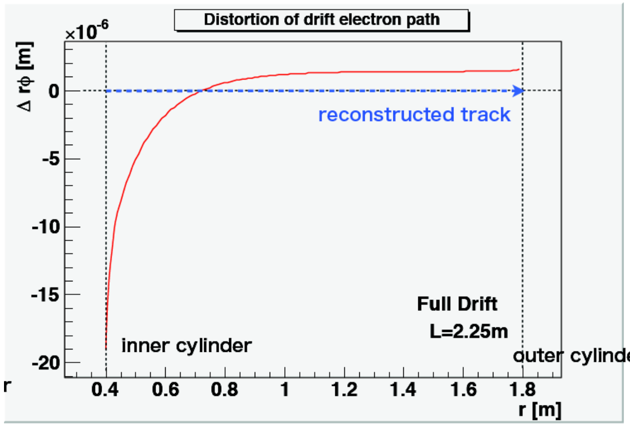


- Influence of E-field distortions on drifting electrons is evaluated for three different sources of ions:

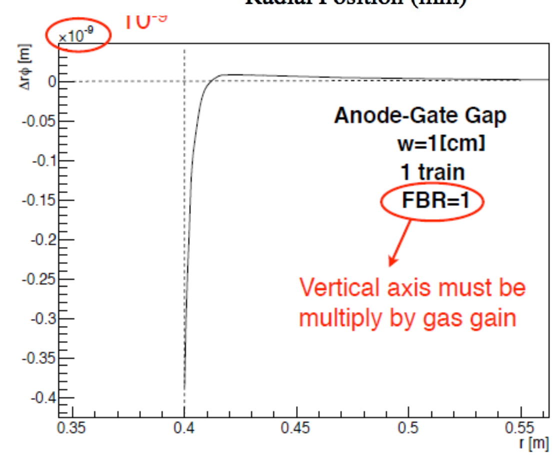


1 bunch train δ_{max} ~4.5 μm

3 bunch trains δ_{max} ~8.5 μm

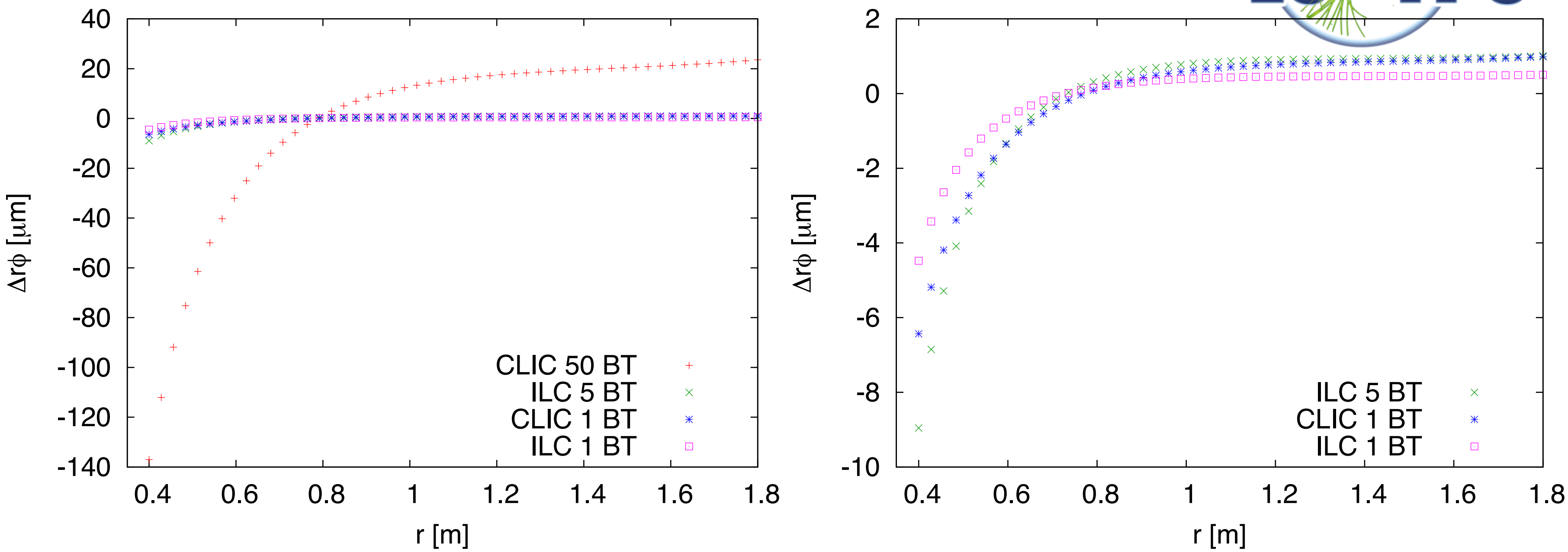


Ions from MPGD stage form 3 discs, if no gating devices is used → δ_{max} ~60 μm



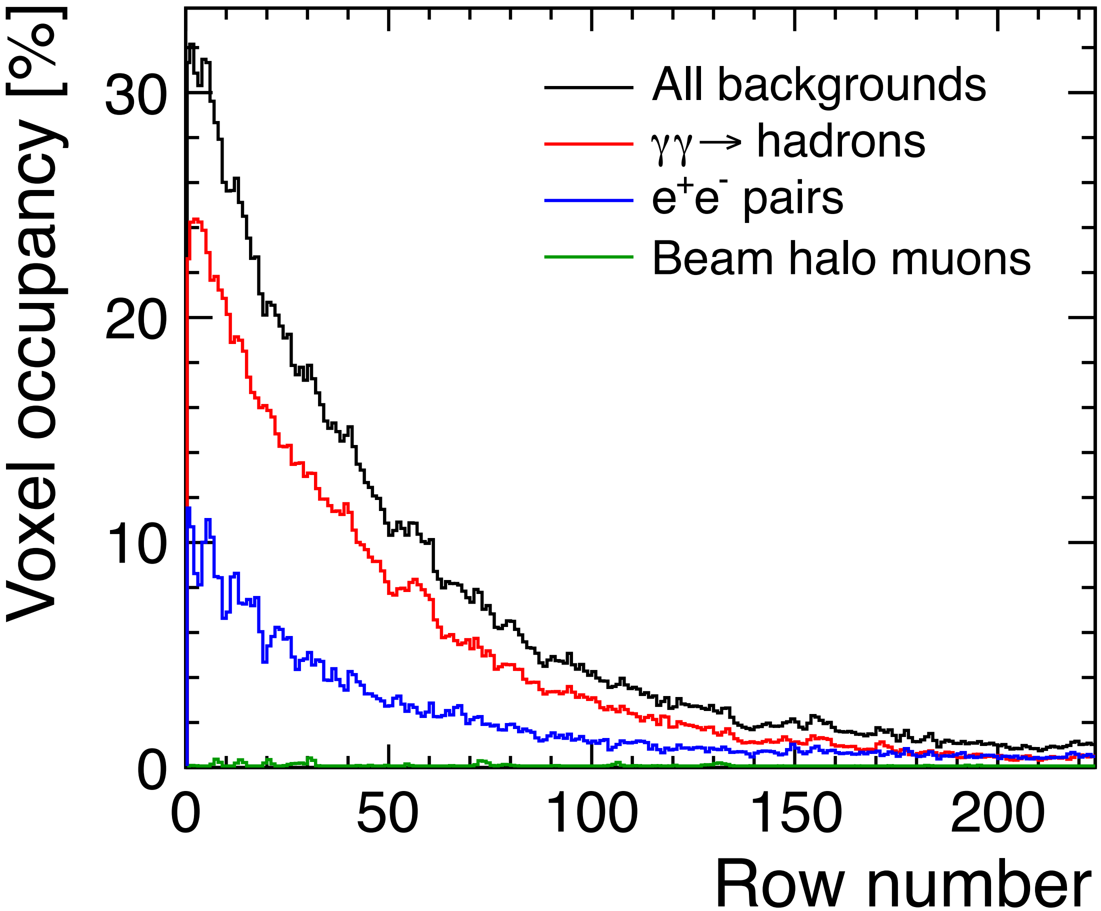
Distortions because of disk between MPGD – gating device are negligible.

Drift Distortions Near the Inner Field Cage



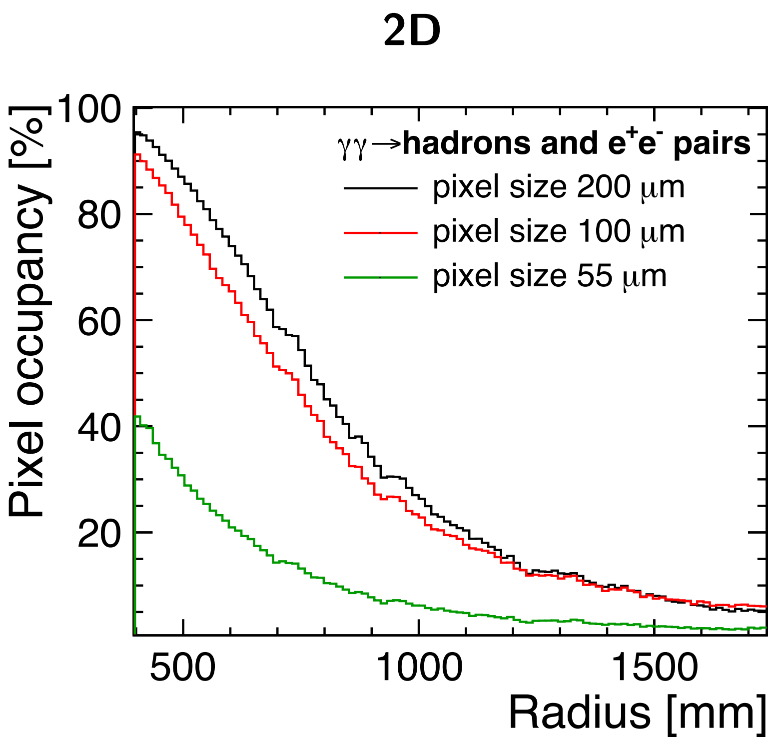
- Distortions for ILC are small
  - 5 μm for 1 BT
  - 9 μm for 5 BT
- Distortions for 1 BT CLIC are OK (7 μm)
- Distortions for 50 BT CLIC not negligible: 137 μm need to be corrected for
- Local distortions from large charge depositions not included yet

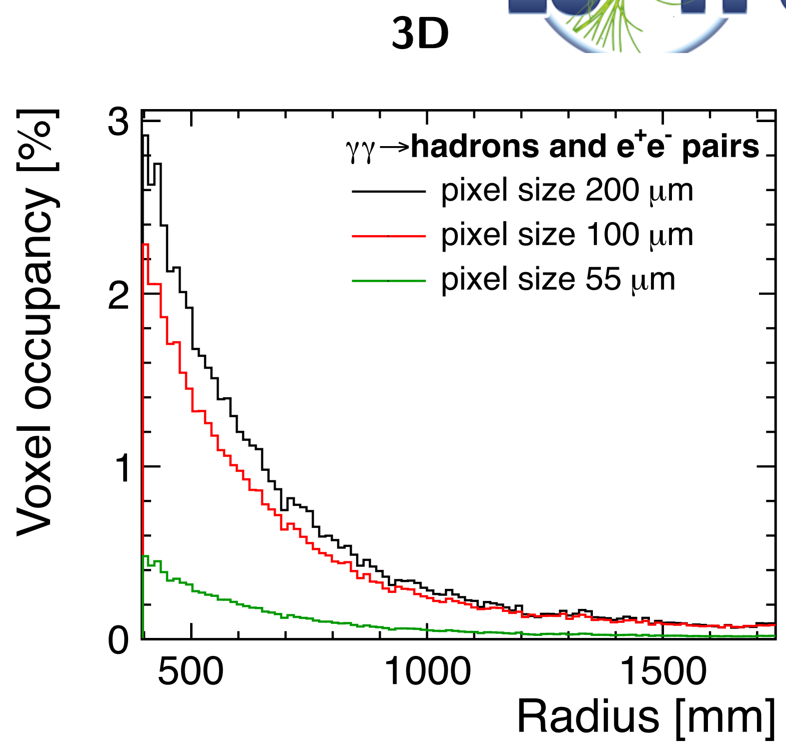
Occupancies pad readout at CLIC



Occupancy in the Pixel TPC

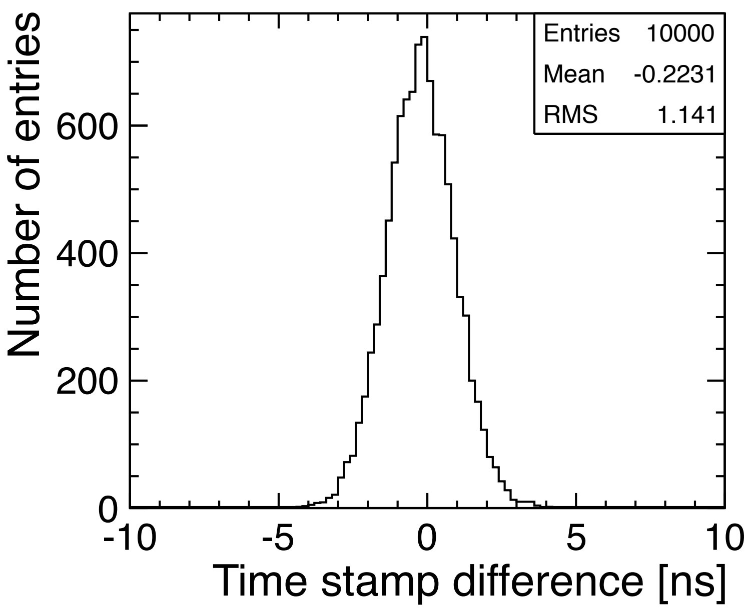
CLIC

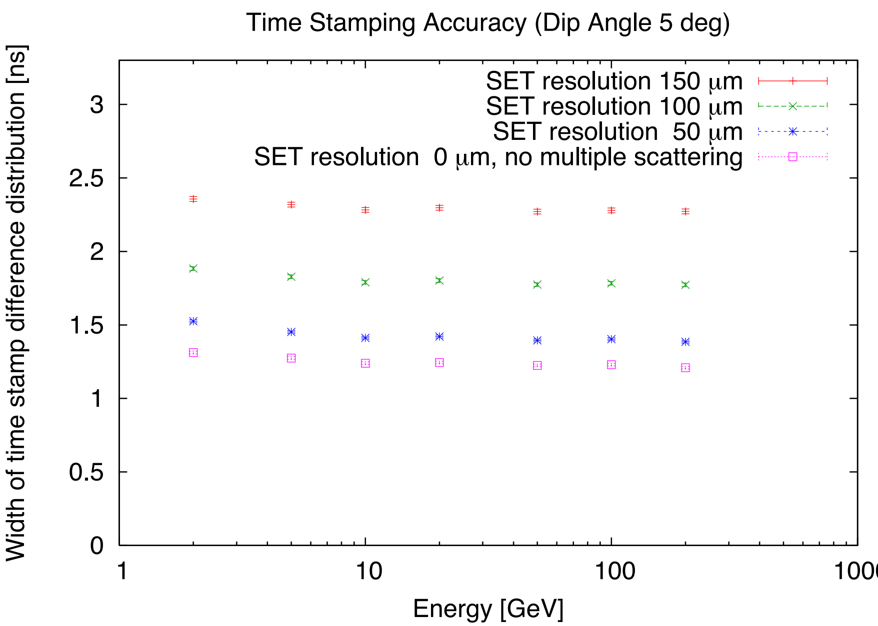




- Factor 4 in voxel occupancy between 55 μm and 100 μm pixels
- 55 μm and 100 μm pixels can resolve individual electrons
- Several hits per cluster for 200 μm pixels

Time stamping for TPC + comparison with SET





Θ = 40 degrees

θ = 85 degrees