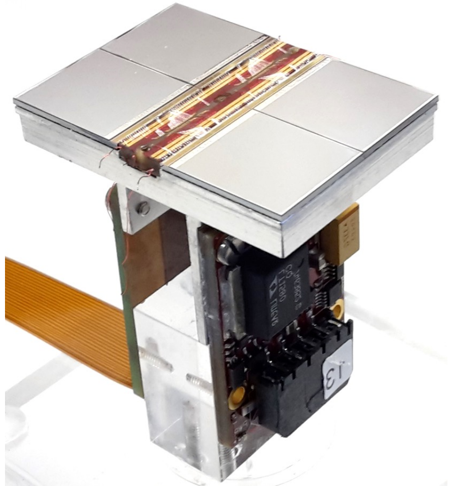
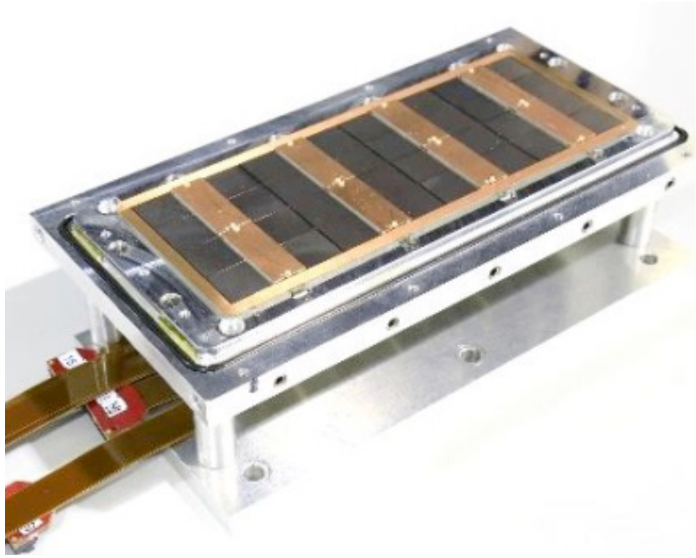
A Pixel TPC as a central tracker

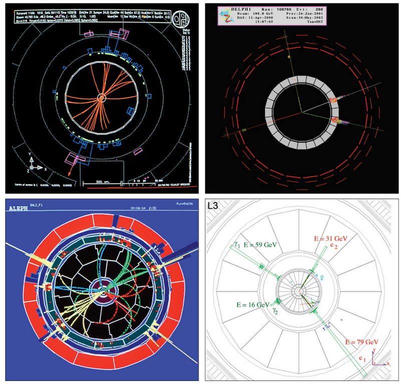
Yevgen Bilevych, Klaus Desch, Sander van Doesburg, Harry van der Graaf, Fred Hartjes, Jochen Kaminski, Peter Kluit, Naomi van der Kolk, Cornelis Ligtenberg, Gerhard Raven, and Jan Timmermans

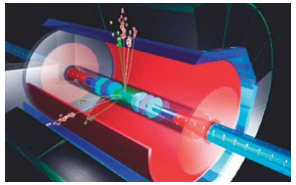




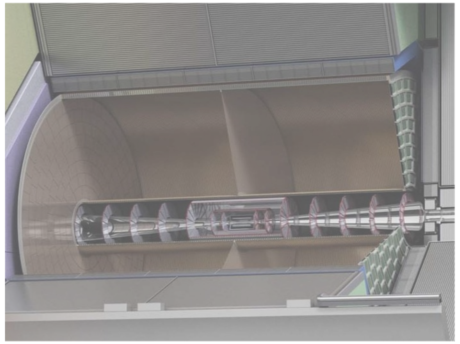
ECFA 2024 presentation
FCC tracking workshop 2025

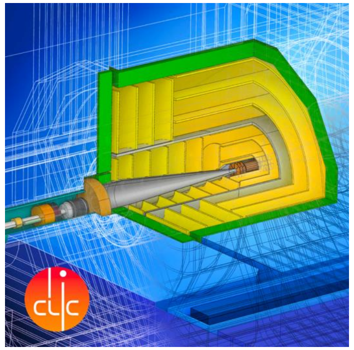
Nikhef involvement in Detector R&D for Future colliders

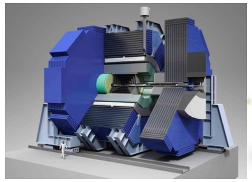




Linear







LEP experiments
1989-2000

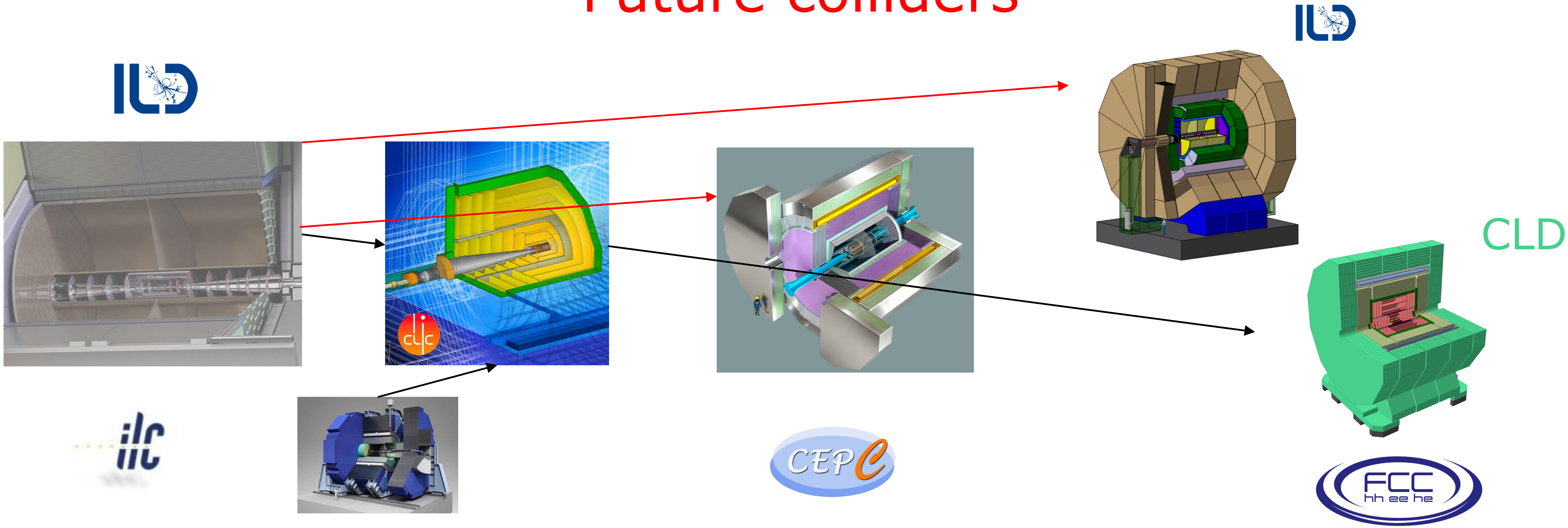
Tesla
2001

ILD/SiD
2008

ILD LOI 2010 IDR 2020

CLIC detector
2018

Nikhef involvement in Detector R&D for Future colliders



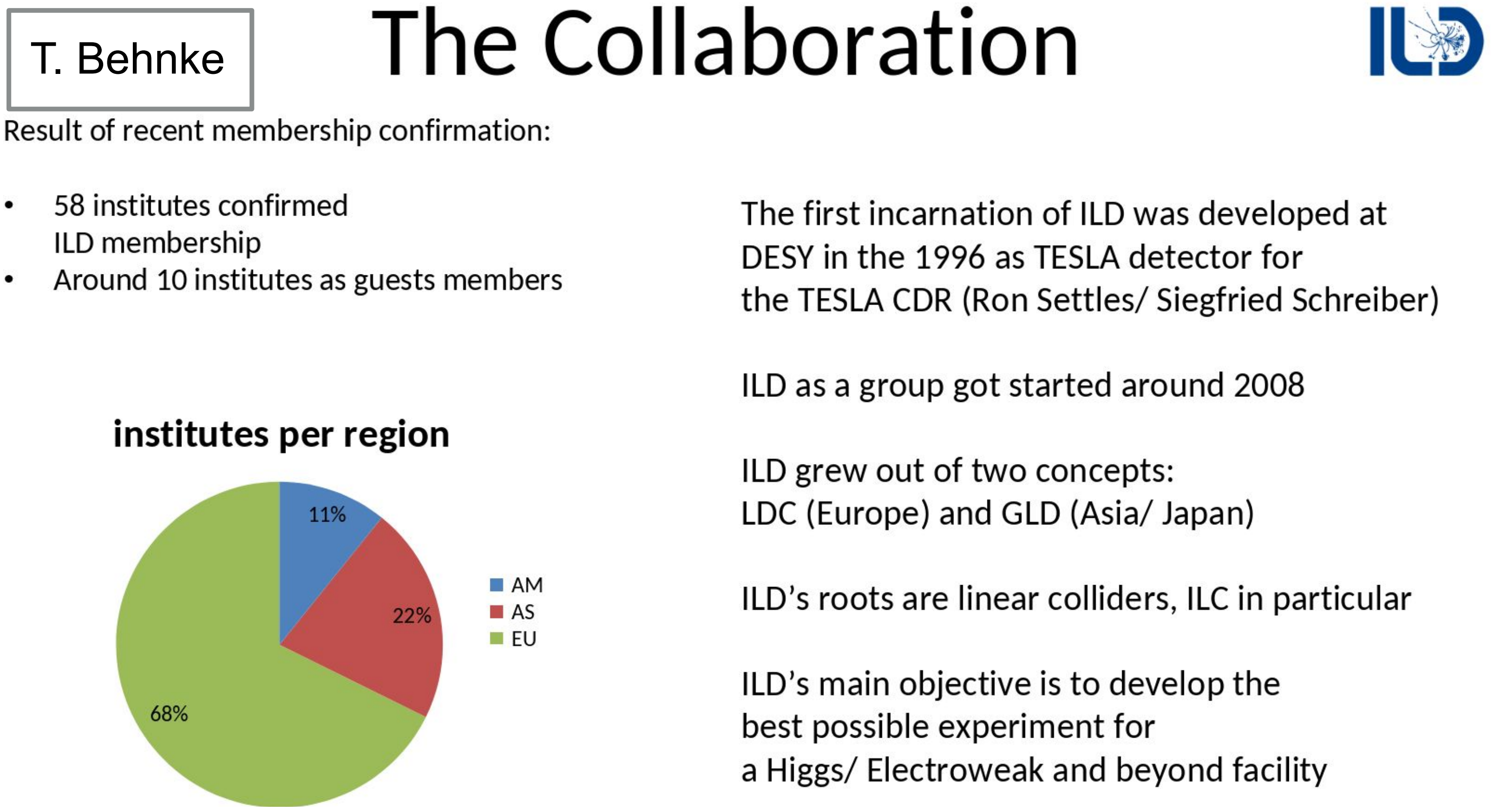
ILD/SiD
2008
TPC/Si

CLIC detector
2018
Si

CEPC detector
2018 CDR 2025 TDR
Pixel TPC

FCCee concepts

The ILD Detector concept



T. Behnke

The Collaboration

Result of recent membership confirmation:

- 58 institutes confirmed ILD membership
- Around 10 institutes as guests members

institutes per region

The first incarnation of ILD was developed at DESY in the 1996 as TESLA detector for the TESLA CDR (Ron Settles/ Siegfried Schreiber)

ILD as a group got started around 2008

ILD grew out of two concepts:
LDC (Europe) and GLD (Asia/ Japan)

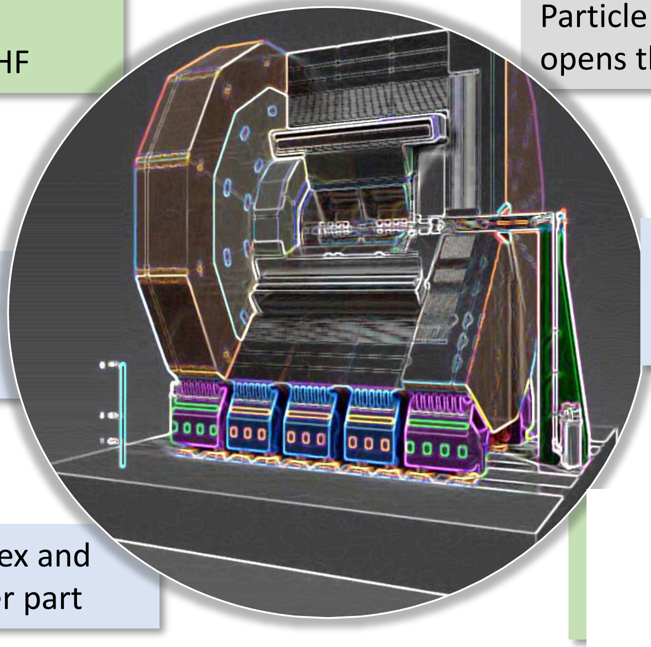
ILD's roots are linear colliders, ILC in particular

ILD's main objective is to develop the best possible experiment for a Higgs/ Electroweak and beyond facility

ILD LOI 2010 IDR 2020. Nikhef member of ILD since 2008

The ILD Detector concept

ILD fundamental choices
similar to other FCC/ILC concepts



Particle flow is the central paradigm to optimally reconstruct events at a HF

Particle ID in particular at the lower energies opens the route to an excellent flavor program

Marcel Demarteau plea 2025 for a TPC

A gaseous central tracker ensures high efficiency high resolution tracking

A highly granular sampling calorimeter inside the coil ensures excellent particle flow performance

A high precision low mass vertex and tracking system forms the inner part

ILD will run without trigger and with minimum external cooling

Adapted from Ties Behnke

9

Nikhef detector R&D for future e^+e^- colliders

2001 Involved in the Tesla electron-positron collider project at DESY and the symposium

2002 Start of R&D on GridPix detectors since the first working prototype detector made by Harry van de Graaf, Jan Timmermans et al. GridPix = Gaseous detector with grid and silicon readout chip.

2002-2024 Gradual development of the GridPix detector for a Pixel TPC with 6 theses and an EUDET grant (2004-2008) by Alessandro Forniani (2005), Max Chefdeville (2009), Martin Fransen (2012), Spiros Tsigaridas (2017), Cornelis Ligtenberg (2021)

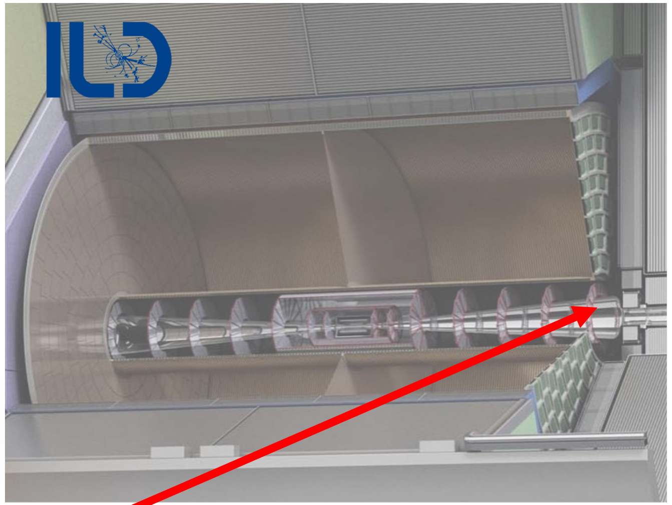
2007 LCTPC collaboration since 2007: R&D collaboration for a TPC at a (linear) collider

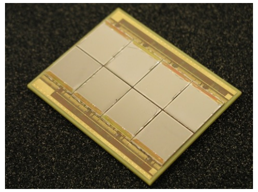
2007 Participation in the ILD experiment: Nikhef expressed interest in the TPC, silicon tracking and the forward calorimeter. ILD developed a detector concept with a (Pixel) TPC for a linear electron-positron collider (thesis Ligtenberg)

2021 ILD develops a detector concept at a circular electron-positron collider. Nikhef contributes actively to a Pixel TPC for the CEPC/FCCee.

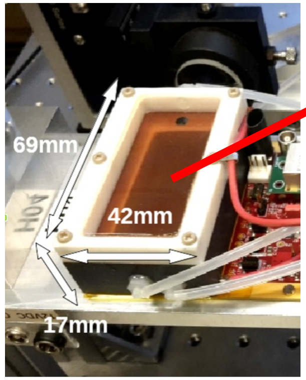
[*]2012-2015 CLIC accelerator: the Rasnik alignment method to the beam adjustment system and thesis Glenn Vanbavinckhove (2012) on Optics for colliders (LHC,CLIC)

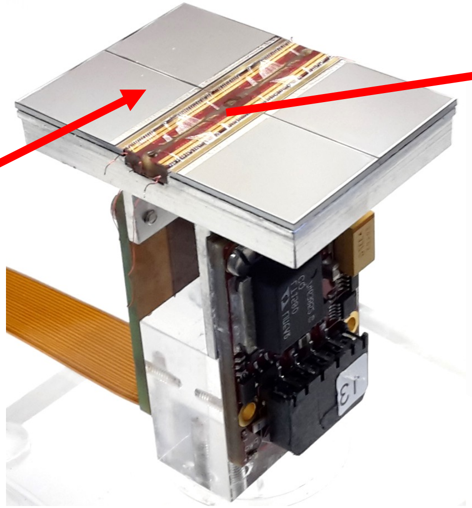
Pixel TPC

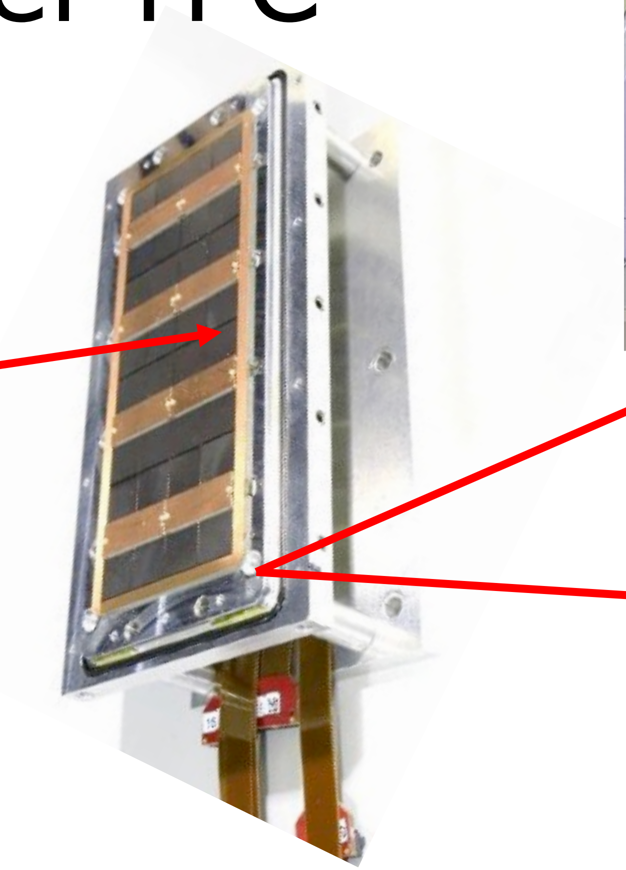


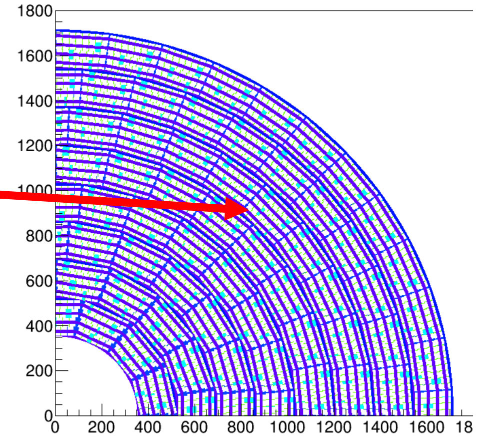


(Octopuce)









(TimePix1)

(2007-14)

TPX3 chip

2017

Quad

2018

Module

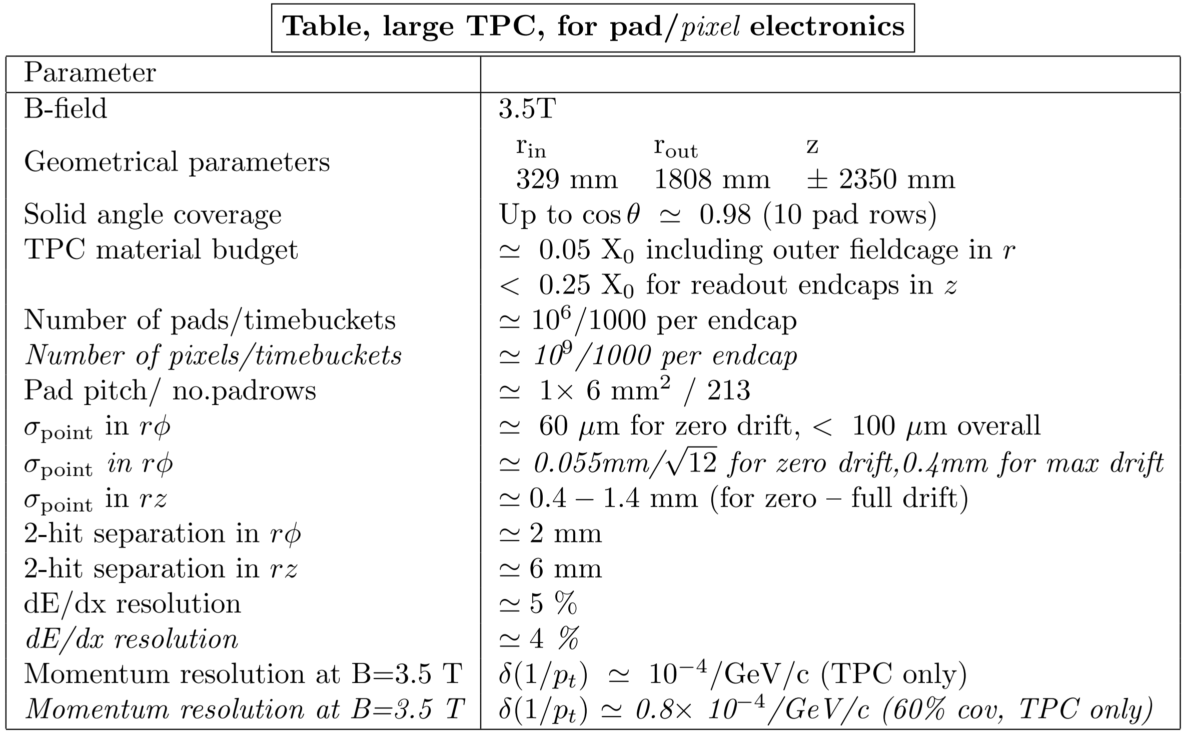
2019

TPC plane

TPC requirements

The R&D on a TPC for a e.g. Linear Collider is done in the LCTPC collaboration

Requirements for a TPC from the ILC TDR

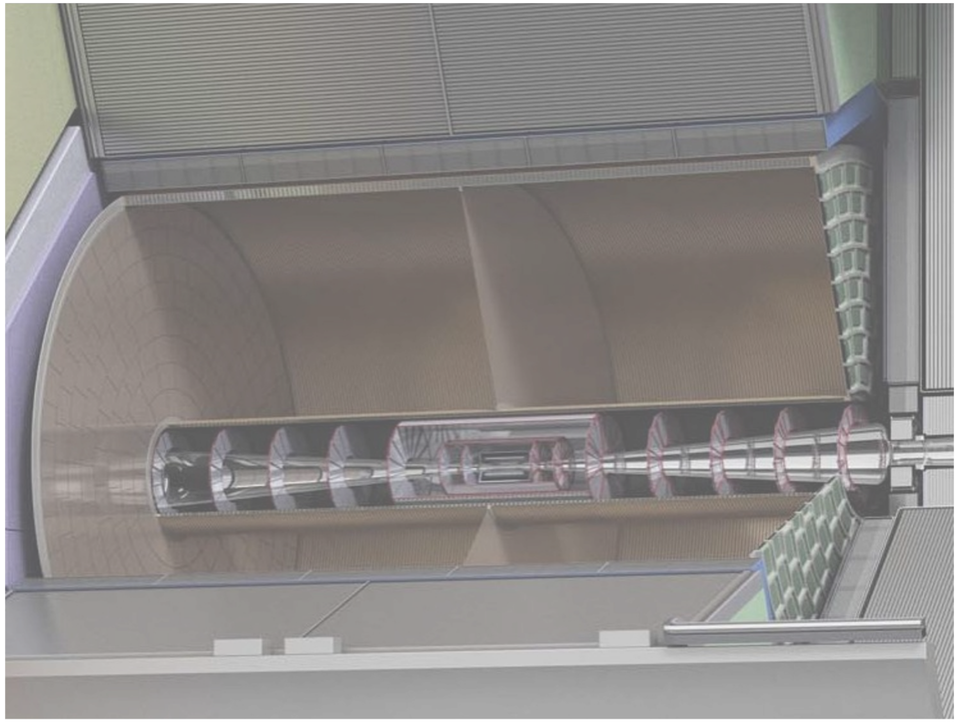


Table, large TPC, for pad/*pixel* electronics

Parameter	
B-field	3.5T
Geometrical parameters	r_{in} r_{out} z 329 mm 1808 mm ± 2350 mm
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq$ 0.05 X_0 including outer fieldcage in r $<$ 0.25 X_0 for readout endcaps in z
Number of pads/timebuckets	$\simeq 10^6/1000$ per endcap
Number of pixels/timebuckets	*$\simeq 10^9/1000$ per endcap*
Pad pitch/ no.padrows	$\simeq 1\times 6\ \mathrm{mm}^2$ / 213
σ_{point} in $r\phi$	$\simeq$ 60 μm for zero drift, $<$ 100 μm overall
σ_{point} in $r\phi$	*$\simeq 0.055\mathrm{mm}/\sqrt{12}$ for zero drift,0.4mm for max drift*
σ_{point} in rz	$\simeq$ 0.4 – 1.4 mm (for zero – full drift)
2-hit separation in $r\phi$	$\simeq$ 2 mm
2-hit separation in rz	$\simeq$ 6 mm
dE/dx resolution	$\simeq$ 5 %
dE/dx resolution	*$\simeq$ 4 %*
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)
Momentum resolution at B=3.5 T	*$\delta(1/p_t) \simeq 0.8\times 10^{-4}$/GeV/c (60% cov, TPC only)*

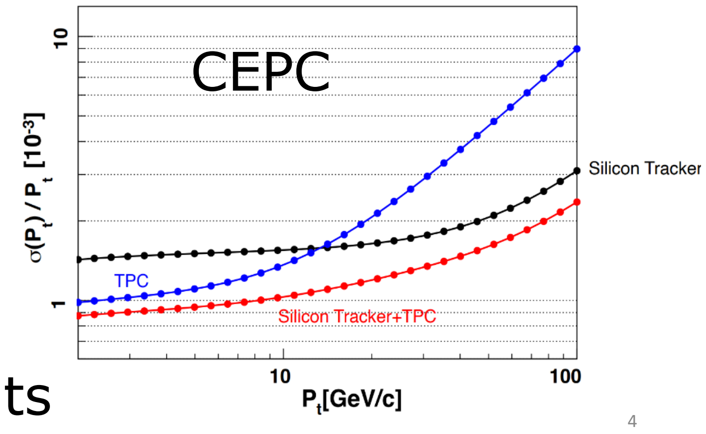
- ILD like detector concept with a TPC central tracker can be used for FCC
- Challenging tracking precision
  - driven by (Z) Higgs running
- For Z running the requirement on $\delta(1/p_t)$ can IMO be loosened by e.g. a factor 10 (LEP like)

ILD TPC layout



- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between silicon detectors VTX, SIT and SET
- pixel readout is a serious option for the TPC readout plane @ ILC/FFC-ee/CLIC/CEPC colliders

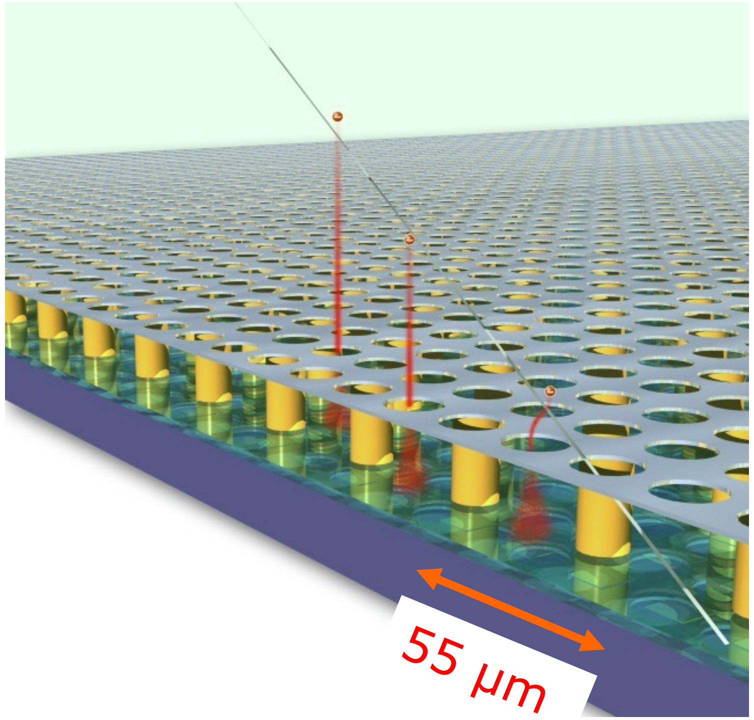
Why a (pixel) TPC as a central tracker

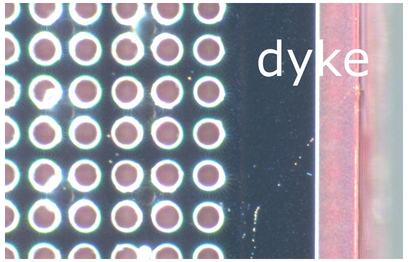


- Low material budget that allows high precision tracking
- Continuous 3D tracking (x,y, t) and track following
  - Excellent v0 reconstruction
  - Ideal for particle flow and combined calorimetry
- TPC is sliced between silicon detectors
  - provides required momentum resolution and constraints
- Very powerful particle identification based on dEdx
  - for electrons (suppress pions)
  - for kaons (H->ss) and protons
- TPC excellent option for FCCee WW, ZH, tt etc running
- Running at the Z is challenging due to beam and synchrotron backgrounds
- A pixel TPC combines a large drift volume with a silicon read out plane
  - tracking with high granularity and low systematic uncertainties due to “silicon” precision (1-10 μm) in the production process
  - the best (see slides) PID performance dEdx and cluster counting

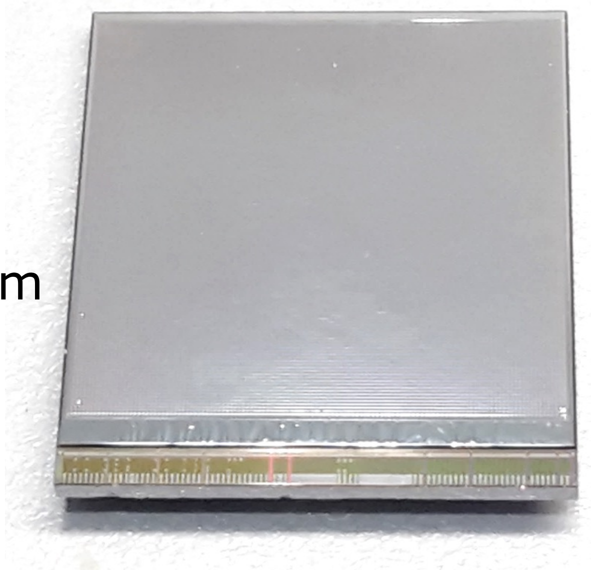
GridPix technology

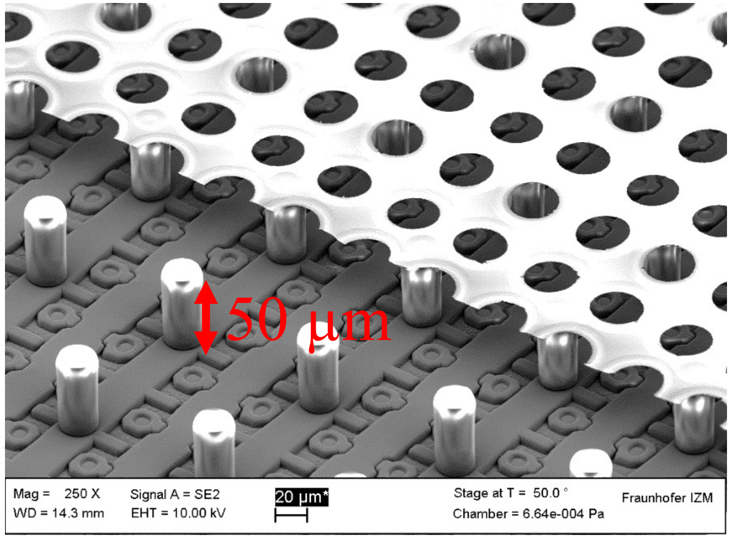
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM (in 2025 @ Bonn)
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 µm)
- detecting individual electrons





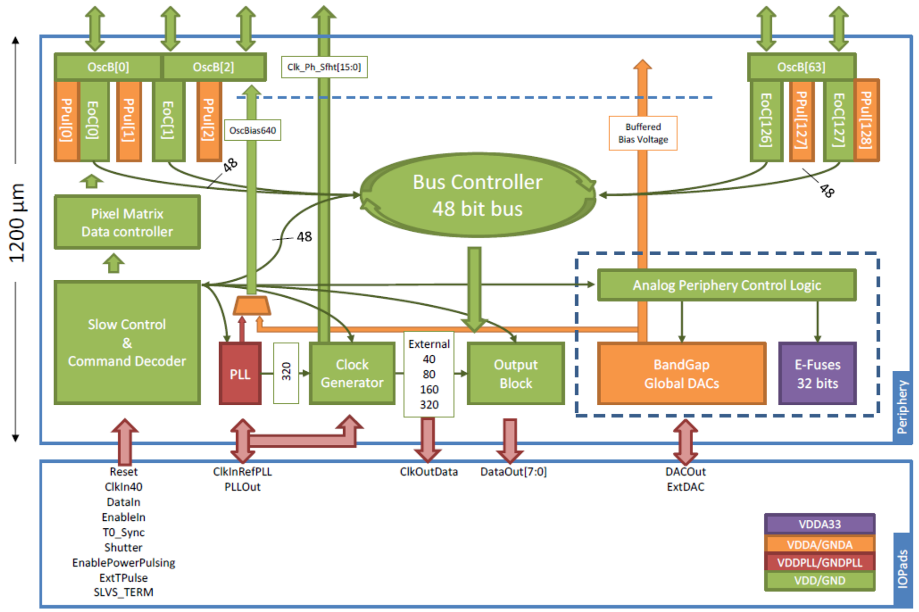
- Aluminium grid (1 µm thick)
- 35 µm wide holes, 55 µm pitch
- Supported by SU8 pillars 50 µm high
- Grid surrounded by SU8 dyke (150 µm wide solid strip) for mechanical and HV stability

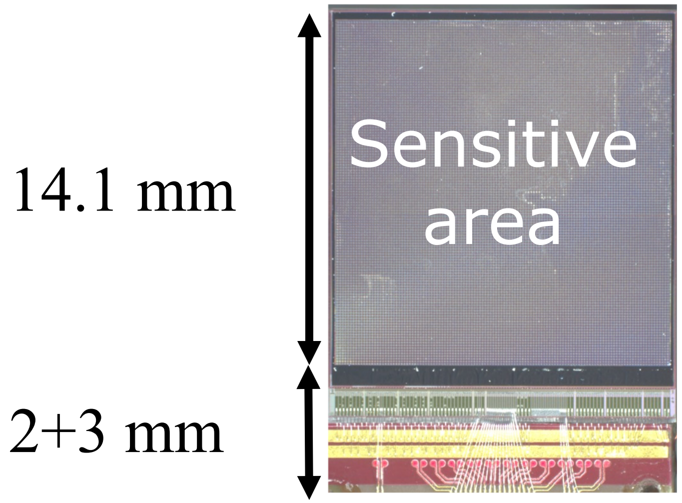




Pixel chip: TimePix3

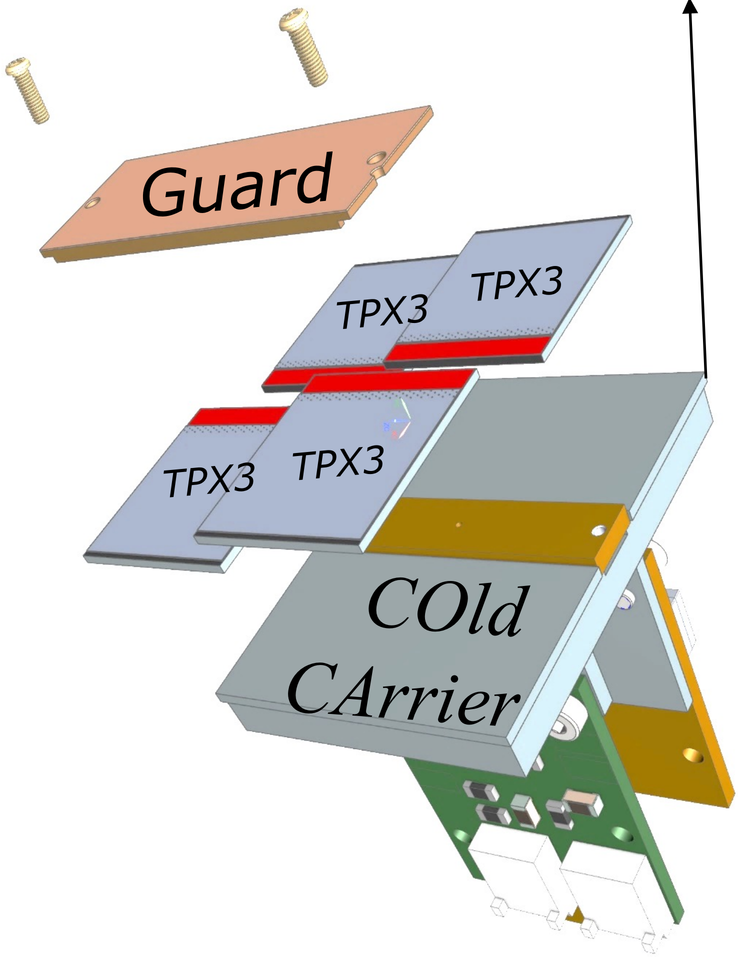
- 256 x 256 pixels
- 55 x 55 µm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - compensation for time walk
  - **Trigger** (for t_0) added to the data stream as an additional time stamp
- Power consumption
  - ~1 A @ 2 V (2W) depending on hit rate
  - good cooling is important





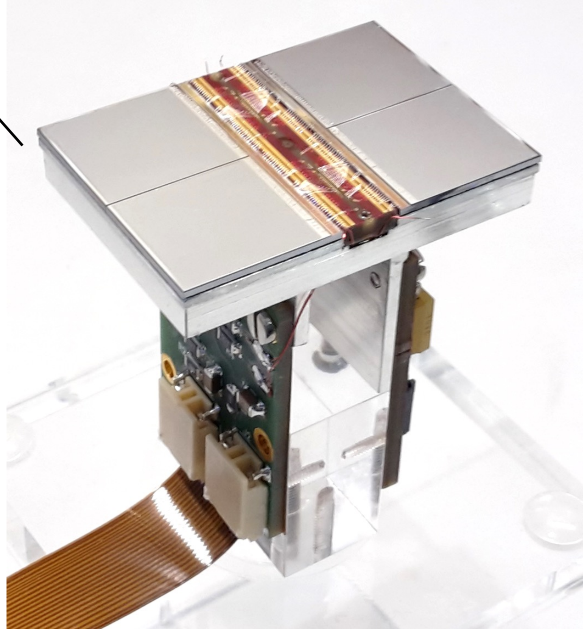
QUAD design and realization

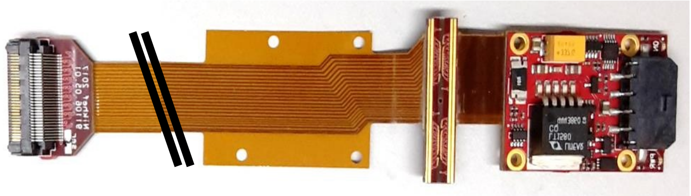
- Four-TimePix3 chips
- All services (signal IO, LV power) are located under the detection surface
- The area for connections was squeezed to the minimum
- Very high precision 10 μm mounting of the chips and guard
- QUAD has a sensitive area of 68.9%
- DAQ by SPIDR board



39.6 x 28.38 mm

series of QUADs



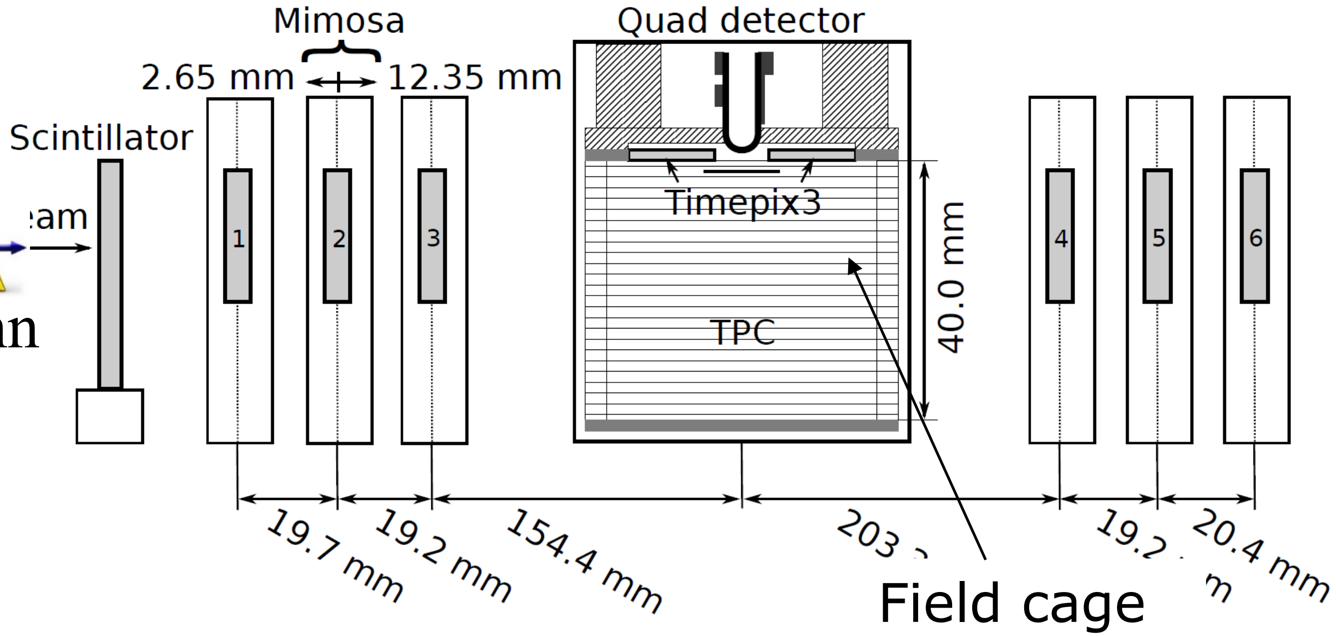


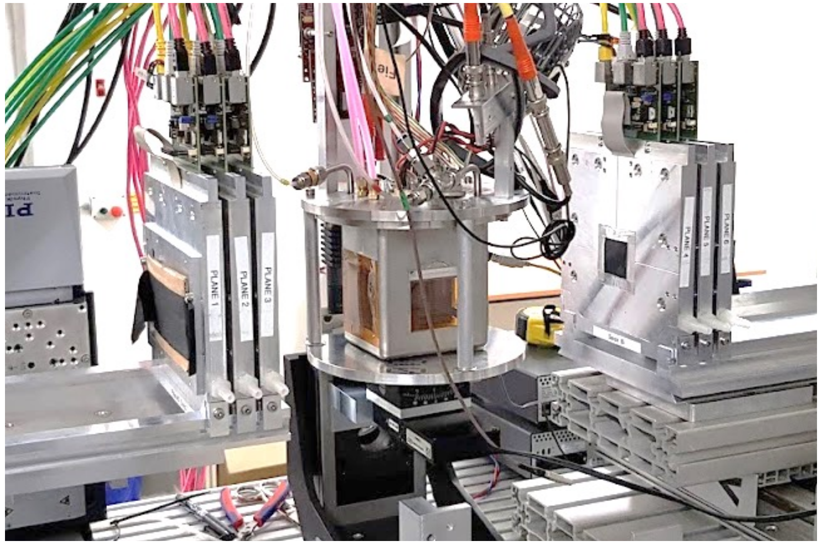
QUAD test beam in Bonn (October 2018)

- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
  - 6 planes with 18.4 μm × 18.4 μm sized pixels
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 400 V/cm, V_{grid} = -330 V
- Typical beam height above the chip: ~1 cm

Published NIMA
https://doi.org/10.1016/j.nima.2019.163331

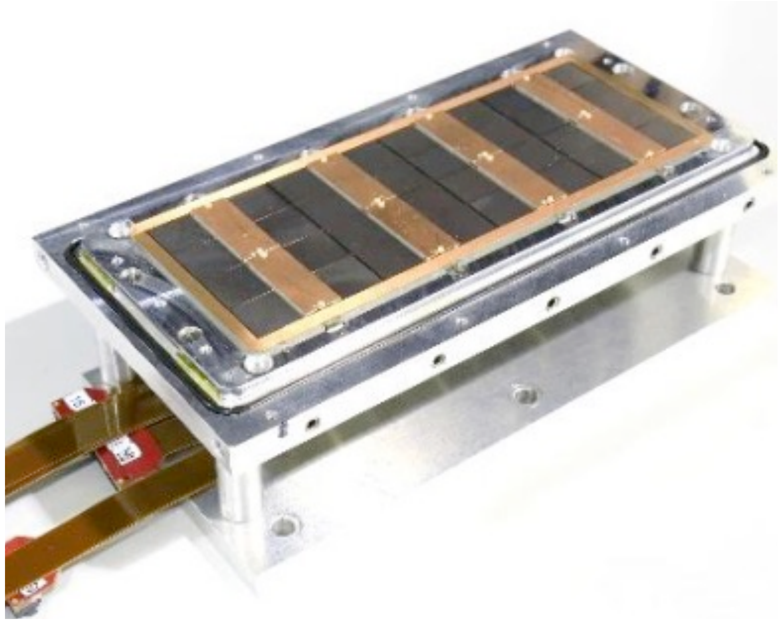
@Bonn

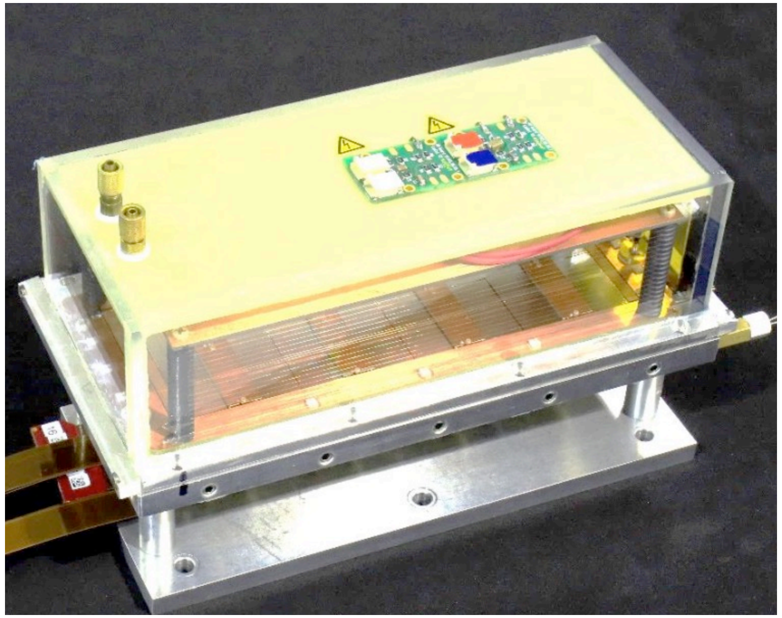


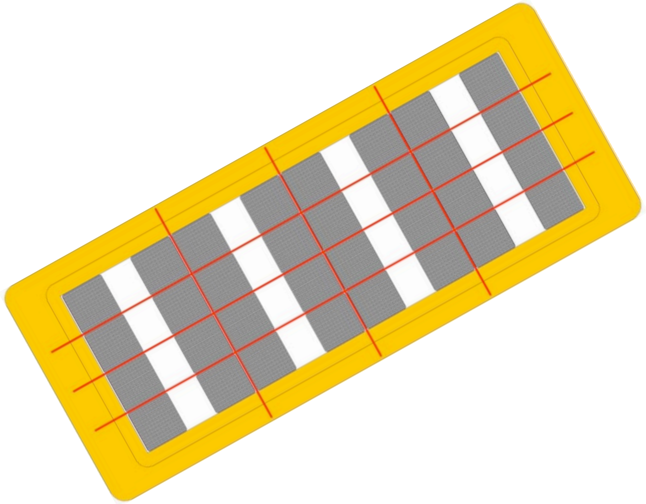


QUAD as a building block

8-QUAD module (2x4 quads) with field cage

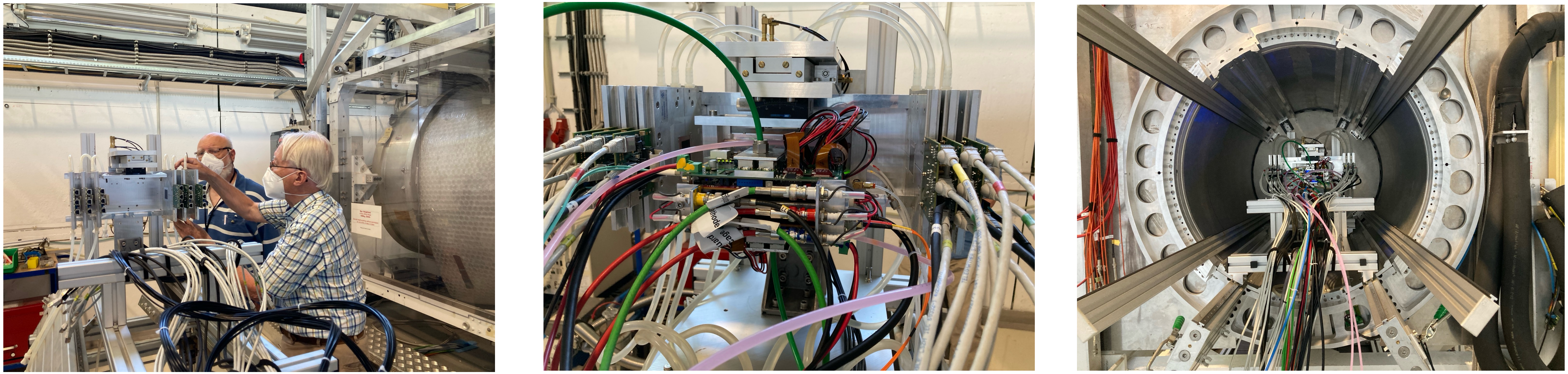






in red guard wires

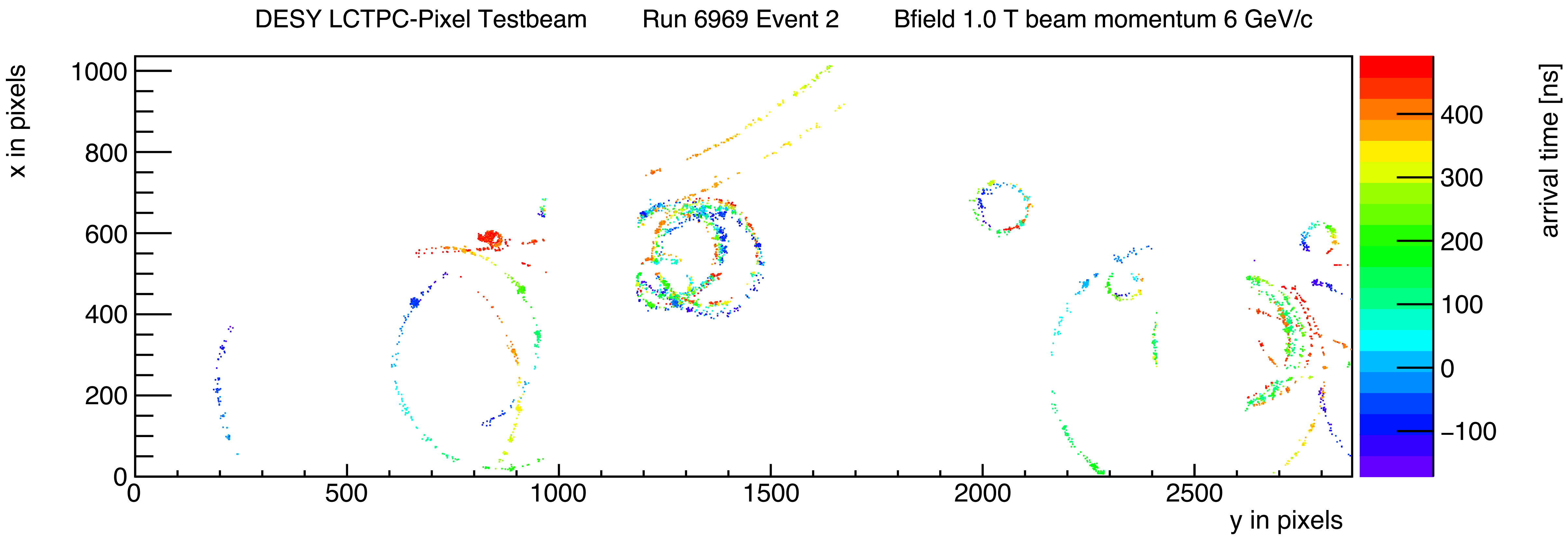
DESY testbeam June 2021



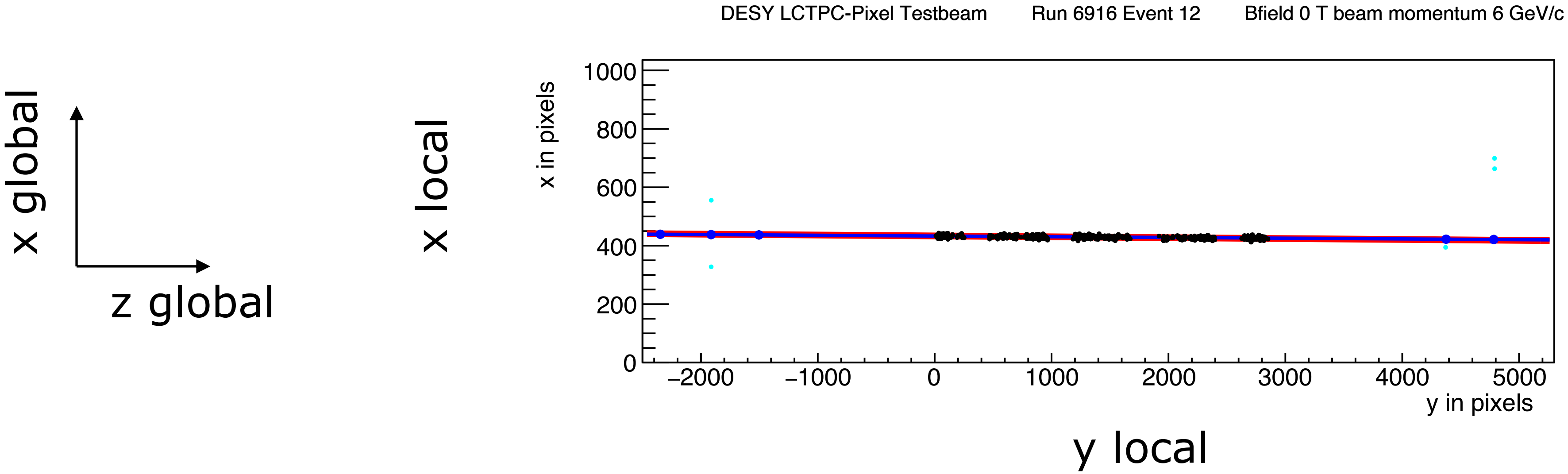
Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

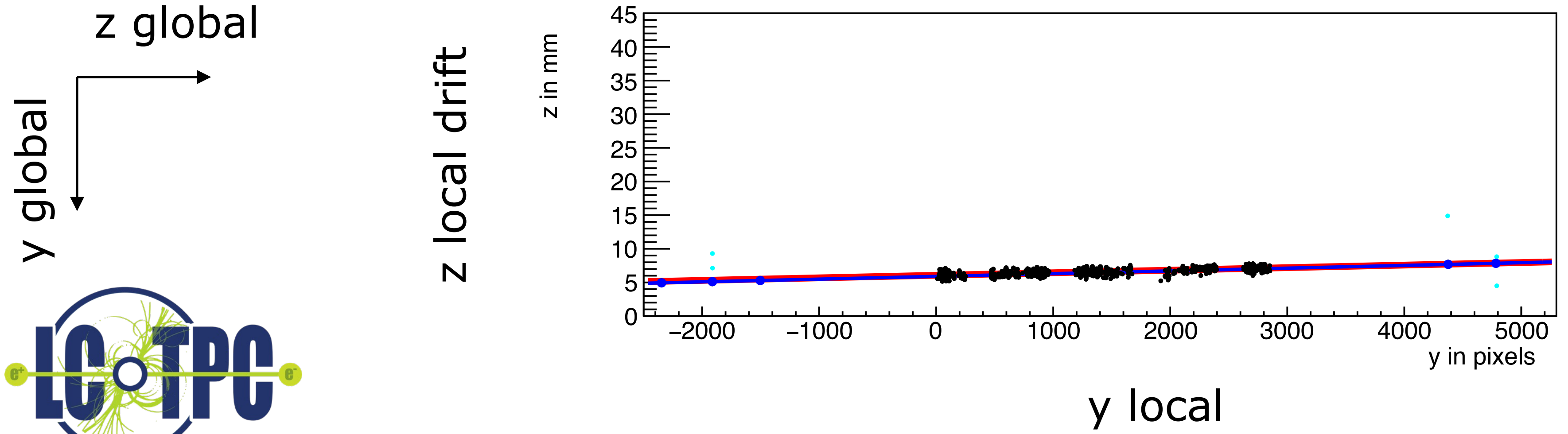
Towards a Pixel TPC part I: construction and test of a 32-chip GridPix detector, Nucl. Instrum. Meth. A 1075 (2025) 345

DESY testbeam June 2021



DESY testbeam Module Analysis





Event display with module and telescope

TPX3 track 1130 hits

χ^2_{xy} = 677.5/1128

χ^2_{z} = 775.9/1069

Asymmetric tail outlier removal applied 1071 hits in z kept.

TPX3 track hits

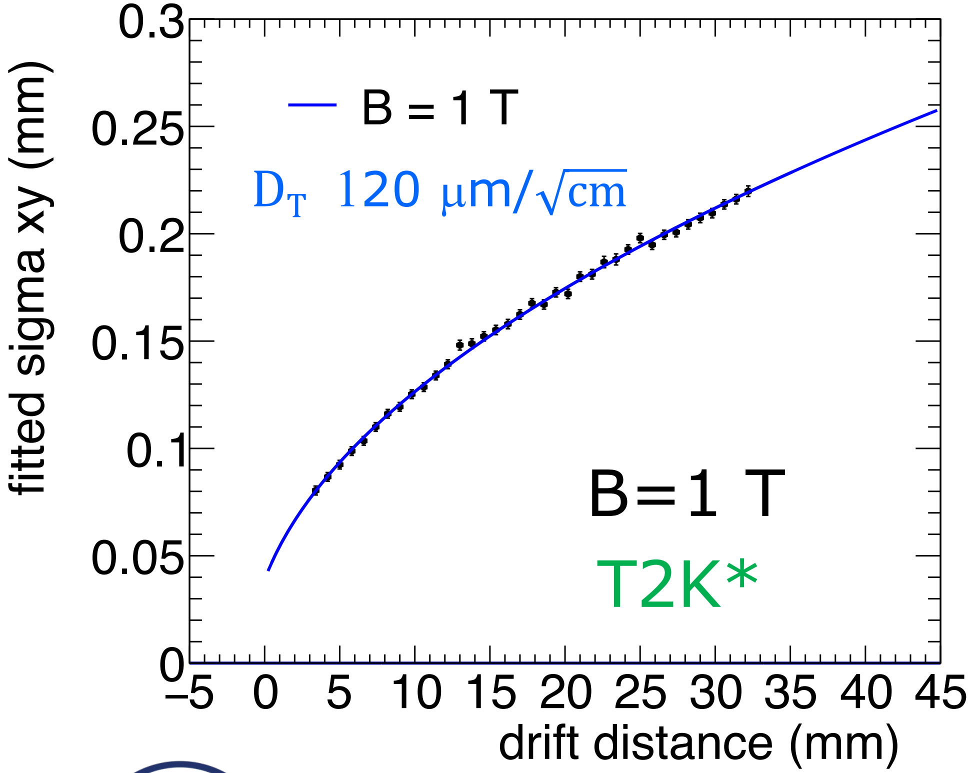
Telescope track hits (off track green)

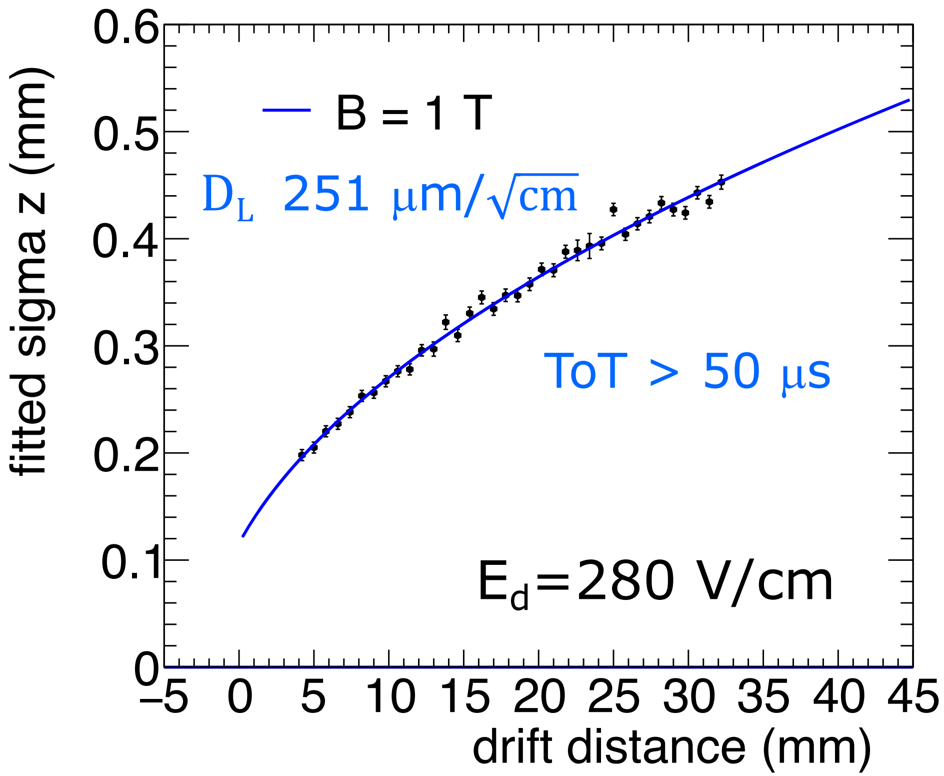
DESY testbeam Module Analysis

B=1 T p=5 and 6 GeV

Fitted resolution

$$\sigma_{xy,\,z}^{2} = \sigma^{2}_{xy_{0},\,z_{0}} + D^{2}_{xy,\,z}\,(z - z_{0})$$





$\sigma^2_{xy0} = \sigma^2_{pixel} + \sigma^2_{xy\ tele}$
$\sigma^2_{pixel} = 55^2/12\ \mu m^2$
$\sigma_{xy\ tele} = 42\ \mu m$

Magboltz gives for D_T =121 µm/$\sqrt{\text{cm}}$

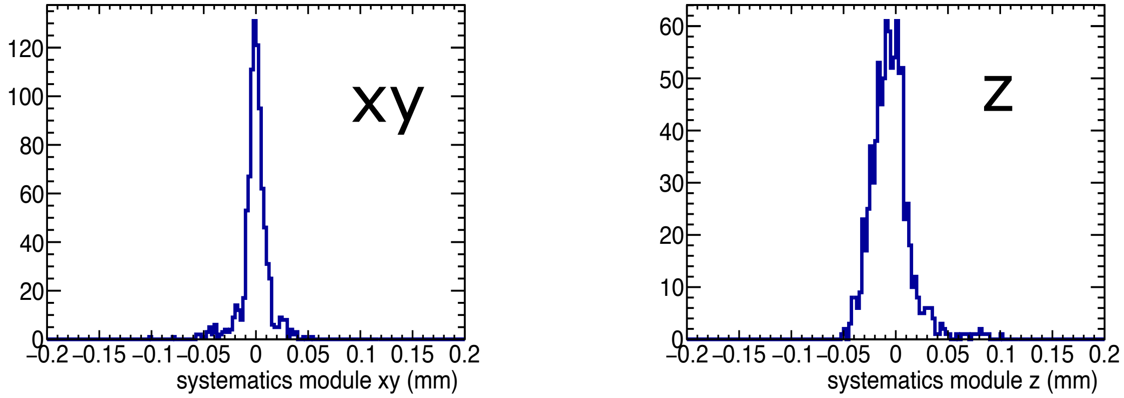
T2K* = T2K gas with O_2 and H_2O

DESY testbeam Module Analysis

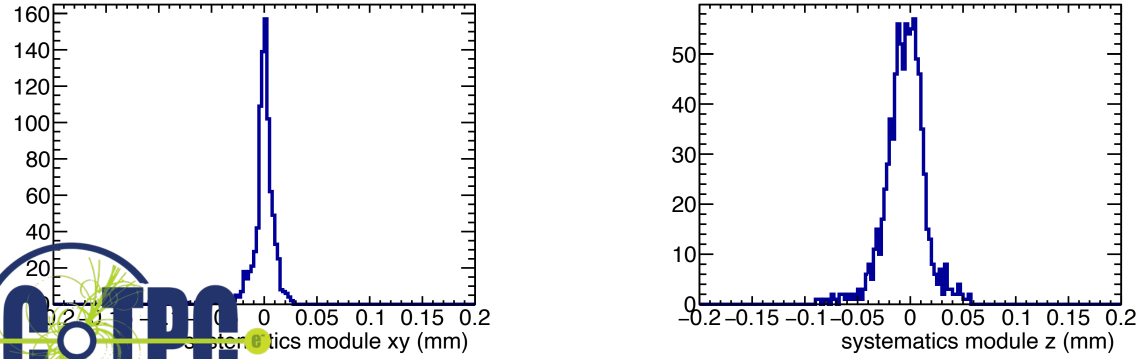
B=1T p=5 GeV

Distribution of mean residuals in the module plane

Method row



Method column



B=1 T data set

method	**rms (stat) xy**	**bins xy**	**rms (stat) z**	**bins z**
row	13 (2) μm	896	19 (5) μm	896
column	11 (2) μm	880	20 (5) μm	880

* We did not include the 4 corner chips and (11), 14, 8, 13 and 19.
These are affected by the field cage and the short in chip 11.

Tracking resolution and precision

- The results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- One chip (nr 11) out of 32 was disconnected due to a short*

- In run 6916 e.g. 964 tracks were selected with 1009 hits on track
- The tracking precision: position 9 (xy) 13 μm (z) in angle 0.19 (dx/dy) 0.25 (dzdy) mrad for a module or tracklength is 157.96 mm
- The diffusion coefficients at B=0 T $D_{xy} = 287\ \mu m/\sqrt{cm}$ $D_z = 273\ \mu m/\sqrt{cm}$
- The diffusion coefficients at B=1 T is $D_{xy} = 120\ \mu m/\sqrt{cm}$ $D_z = 251\ \mu m/\sqrt{cm}$
  - In agreement with Magboltz $D_{xy} = 121\ \mu m/\sqrt{cm}$

*the chip was successfully repaired in 2023 Bonn

Tracking resolution and precision

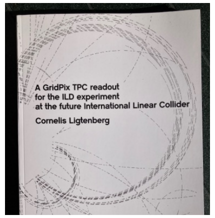
- Results for the module showed that:
  - the HV of the guard wires was well tuned
  - B=0 T rms residuals in the module plane xy 13 μm and z 15 μm
  - The results are compatible with (very) high stats quad measurement
  - B= 1 T rms residuals in the plane xy 13 μm and z 20 μm;
- High tracking precision is demonstrated with small systematics
  - deformations xy stay below 13 μm

- Published in Nucl. Instrum. Meth. A 1075 (2025) 345

Towards a Pixel TPC part I: construction and test of a 32-chip GridPix detector

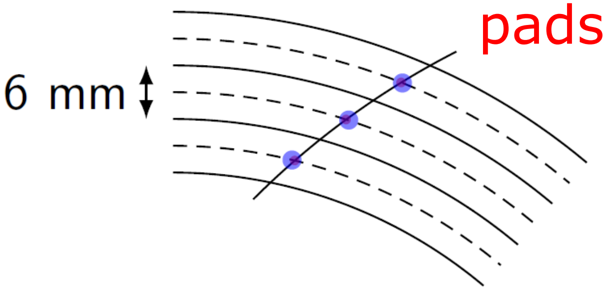
Simulation of ILD TPC with pixel readout

- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels

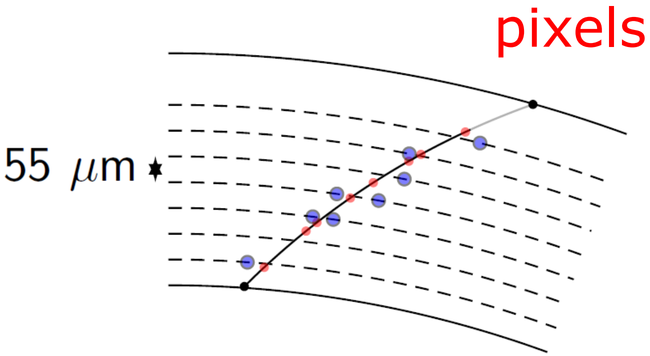


A GridPix TPC readout
for the ILD experiment
at the future International Linear Collider
Cornelis Ligtenberg

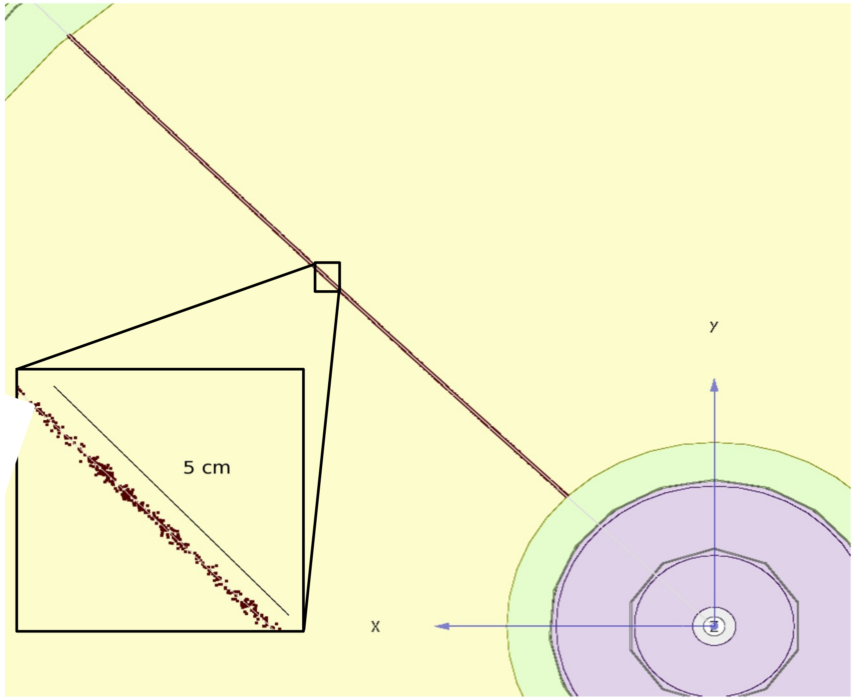
details: PhD thesis
Kees Ligtenberg 2022



22 electrons / hit
~ 200 hits / track



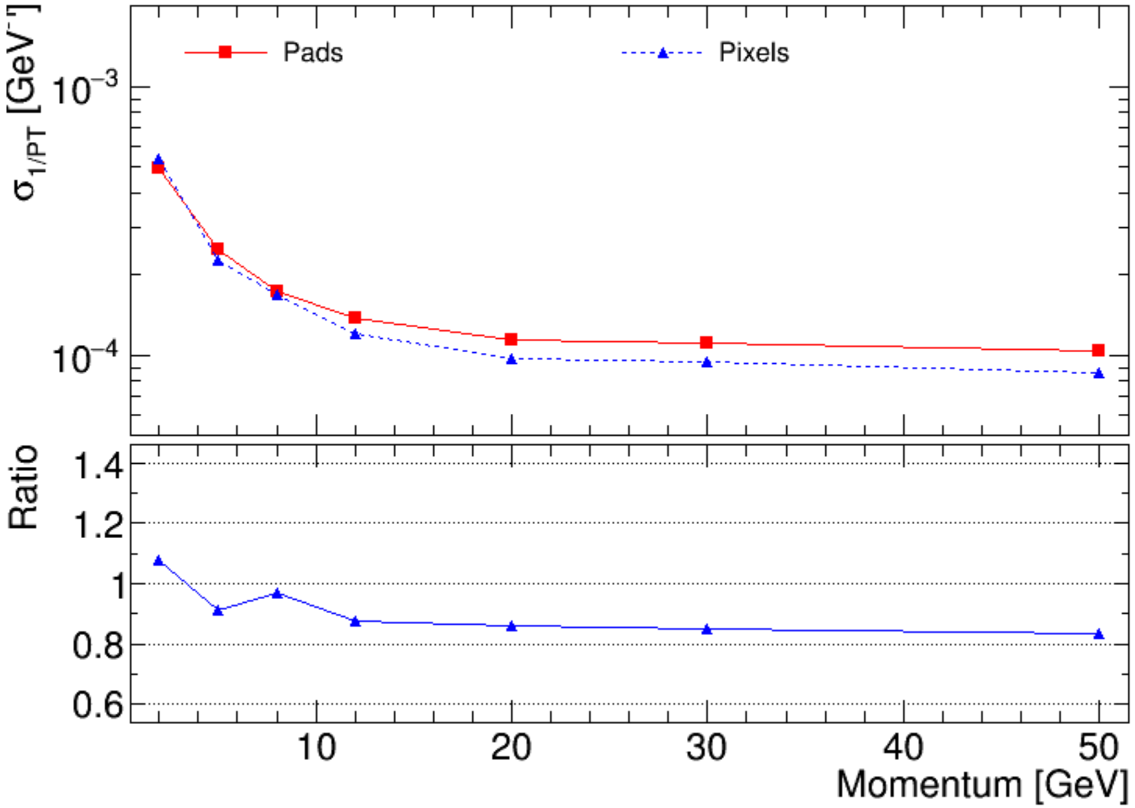
1 electron / hit
~ 10 000 hits / track

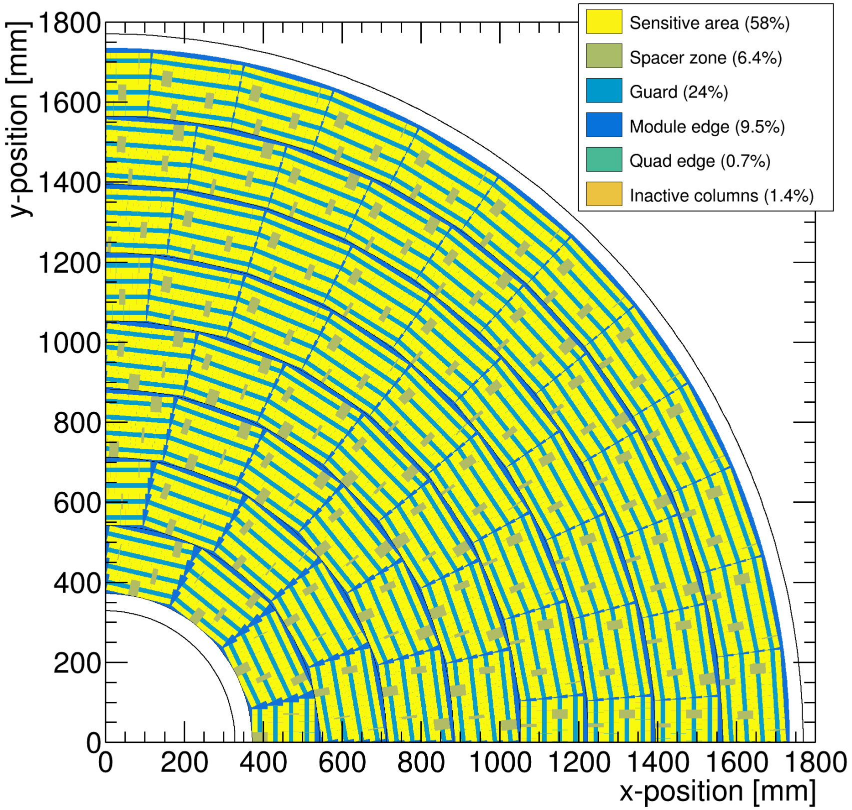


50 GeV muon track with pixel readout

Performance of a GridPix TPC at ILC

- From full simulation the momentum resolution can be determined
- Momentum resolution is about 15% better for the pixels with realistic coverage (with the quads arranged in modules coverage 59%) and deltas.





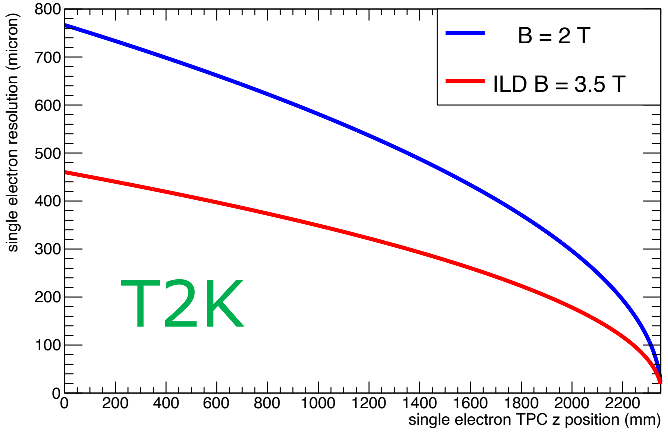
Pixel TPC tracking studies

ILD tracking Performance for a Pixel TPC based on test beam

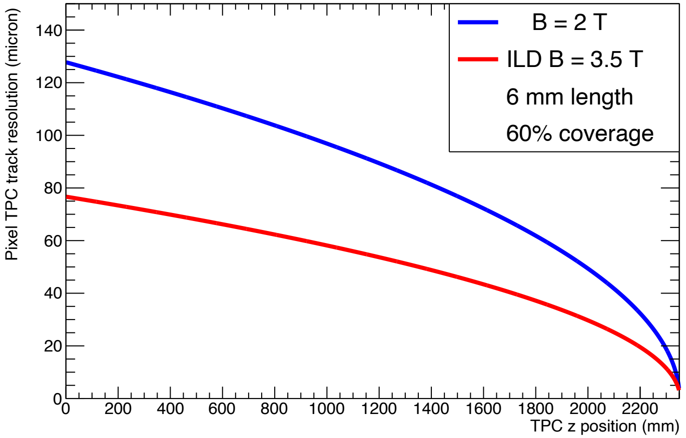
Running at B=3.5 T improves the resolution

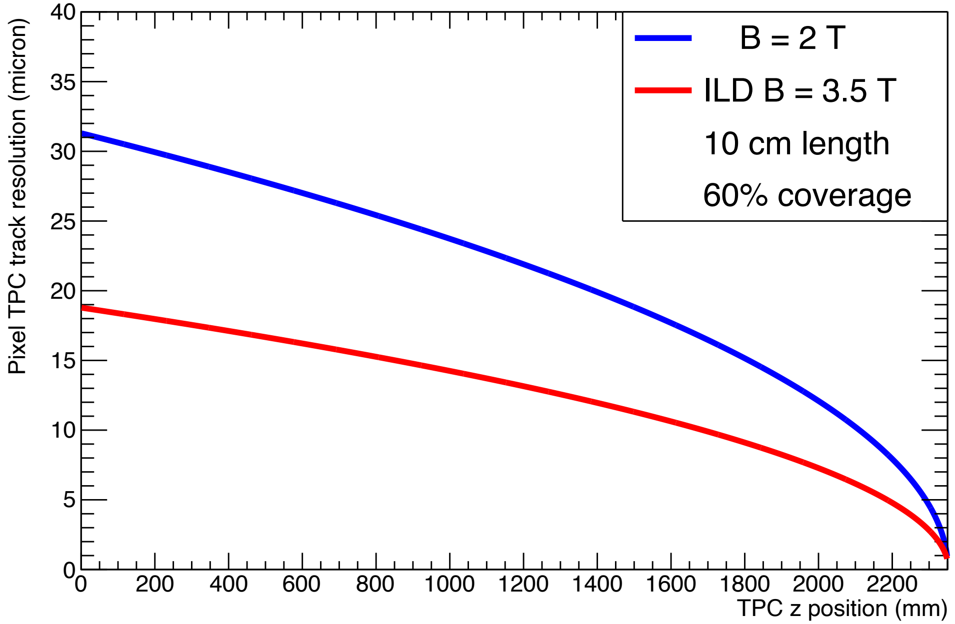
10 cm track resolution

Single electron resolution



6 mm track("pad") resolution





Each 10 cm we have a point with a resolution of < 18 (31) μm on the track
Comparable to performance of a silicon detector (but TPC gas material).

DESY testbeam Module Analysis

Particle identification (PID) performance

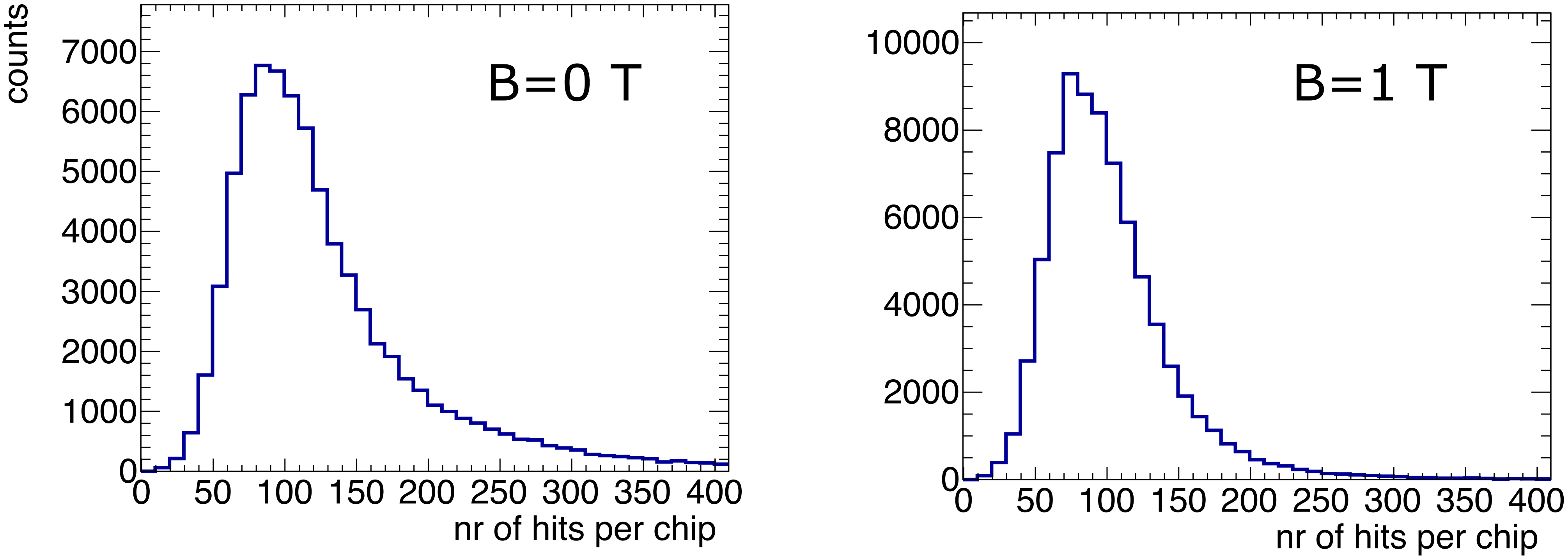
- It is possible to study in test beam data the dE/dx or dN/dx of electrons
- The Pixel TPC has measurements with 55 μm pixel size
- It detects single electrons with an efficiency > 85%
- This allows to measure the number of clusters (hits) as a function of the distance along the track dN/dx (dE/dx) with high granularity

- The advantage of hit counting in a Pixel TPC is – due to the digital read out - that one is not including the fluctuations from the multiplication process in the charge measurement
- Using e.g. a pad readout, the charge is used as a measure of dEdx
    - This readout has a larger granularity and includes avalanche fluctuations
    - One has to go to very small pads ('pixels') to measure the clusters

DESY testbeam Module Analysis

Testbeam PID performance

NIM A 1075 (2025) 345



- B=0 T has a large Landau tail
- B=1 T smaller Landau tail and a more gaussian distribution
- An electron crossing 8 chips in the module has about 1000 hits

DESY testbeam Module Analysis

Analysis of PID performance

Combine chips to form a 1 m long track with 60 % coverage for electrons

❑ Method 1 ”dEdx truncation”: reject large clusters and then run dEdx @ 90% using slices of 20 pixels along track (xy) (gives nr of selected hits). A large cluster has more than 6 hits in 5 consecutive pixels.

❑ Method 2 “Template fit”: fit the slope of the N_{scaled} minimum distance (d) in xy distribution with an exponential function ($N_{scale}(d)$=defines the inverse weights):

$N(d)_{scaled} = N_{scale}(d)\, N_{observed}(d)$

$N(d)_{scaled}$ is then fitted for each track with N_0 exp(-slope d)

✓ Calculate the PID observable for electrons and MIP (==70% of hits)

- method 1 = nr of selected hits, method 2 = fitted slope
- Resolution is $\sigma = \sigma(PID)/PID$ (for σ we use the rms)

Published as “Towards a Pixel TPC part II: particle identification with a 32-chip GridPix detector”, Nucl. Instrum. Meth. A 1081 (2026) 170849

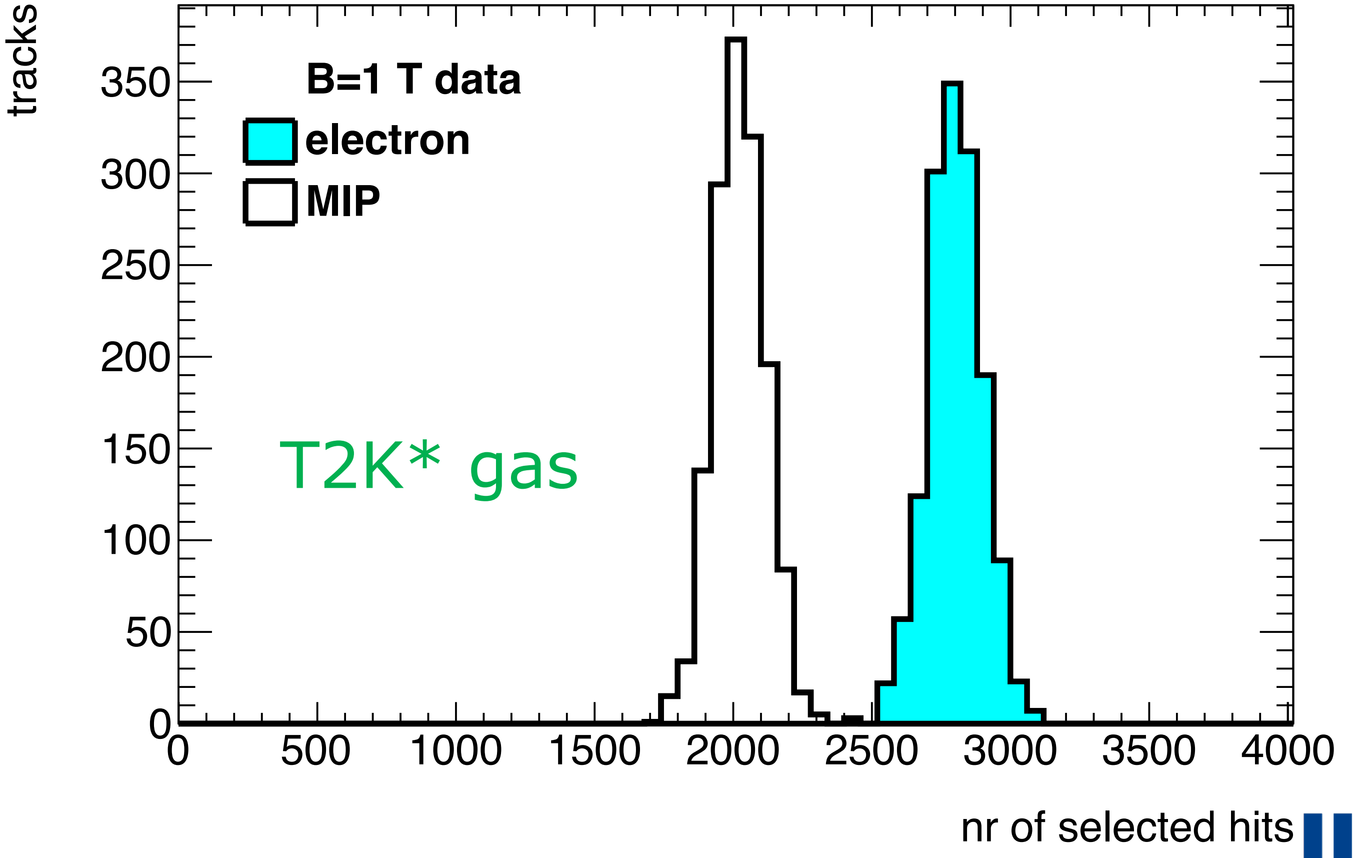
DESY testbeam Module Analysis

PID performance method “dEdx truncation”

Electron resolution
3.6%
1 m track 60% and
coverage

Linearity MIP-e = 1.03
z drift=5-15 mm (flat)

MIP distribution is obtained
by dropping 30% of the hits



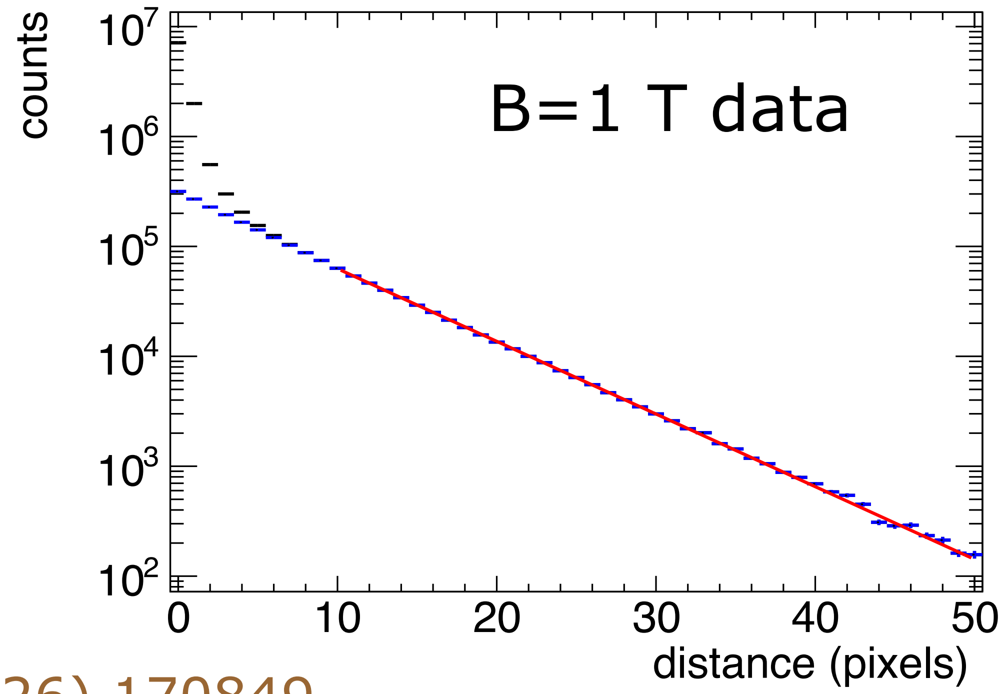
DESY testbeam Module Analysis

PID performance method "Template fit"

Calculate minimum distance between the hits. The slope of the distribution is related to the number of primary clusters /cm

The diffused peak at d<10 (black) comes from clusters with more than 1 hit. Weights are applied at d < 10 to the follow the exponential cluster distance distribution (blue). In red the exponential function.

Per 1 m track the slope is fitted to the full distance distance distribution using a ML fit.



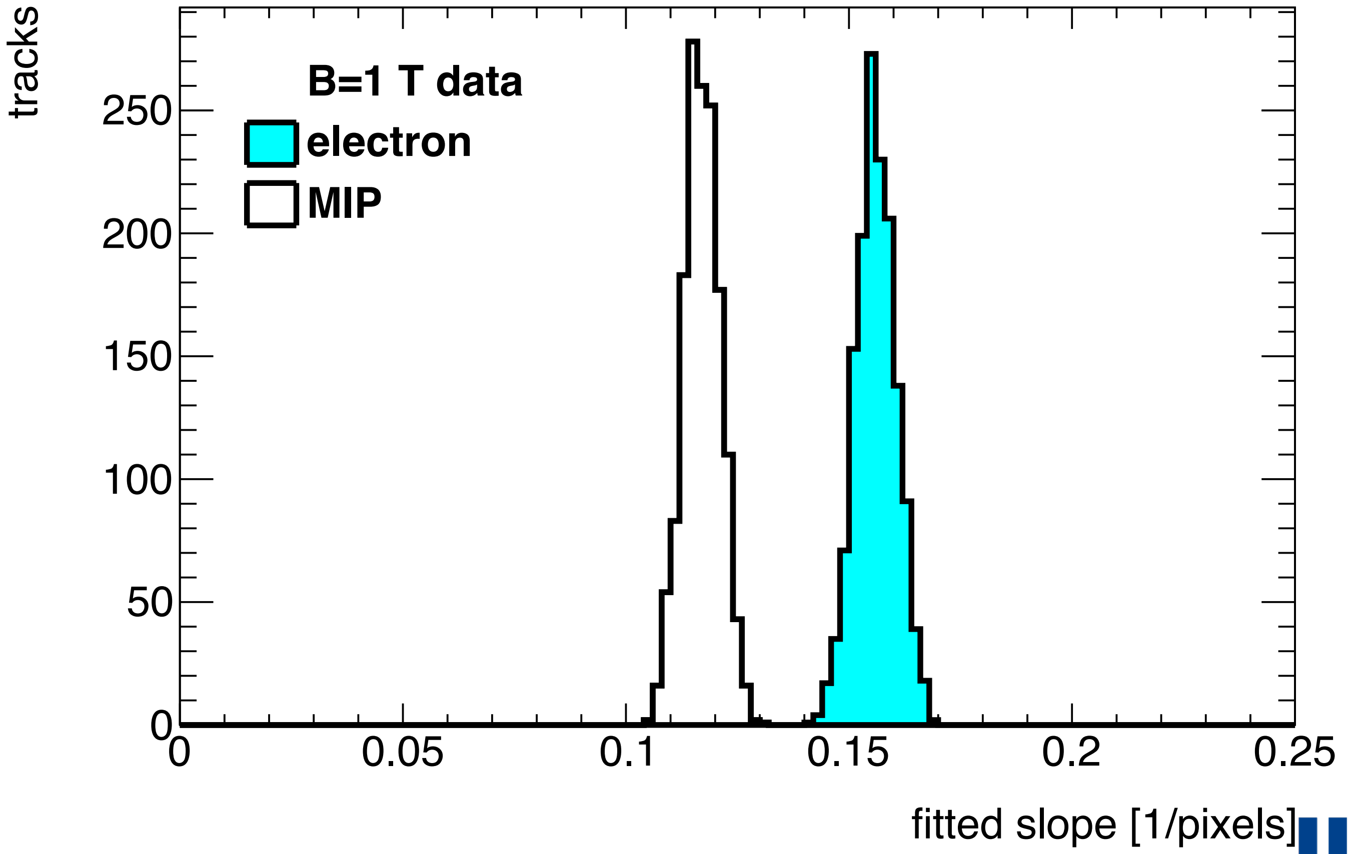
Nucl. Instrum. Meth. A 1081 (2026) 170849

DESY testbeam Module Analysis

PID performance method “Template fit”

Electron resolution
2.9%
1 m track 60% and
coverage
Linearity MIP-e = 1.07

Ideally this is 1. A number
larger than 1 means that
the resolution is +7% larger



DESY testbeam Module Analysis

Summary of PID performance

The PID resolution for electrons from data by combining tracks to form a 1 m long track with realistic coverage ~60% coverage.

Method	B=0 Resolution (%)	B= 1 T Resolution (%)
(1) dEdx truncation	6.0	3.6
(2) Template fit	5.4	2.9

The resolution for B=0 is worse than of the B=1 T data because of the larger fluctuations, that were already observed at the chip level.

Published as "Towards a Pixel TPC part II: particle identification with a 32-chip GridPix detector", Nucl. Instrum. Meth. A 1081 (2026) 170849

DESY testbeam Module Analysis

dEdx Performance extrapolated to the ILD detector

Test beam B = 1 T
p=5,6 GeV/c

electron resolution 2.9(3.6)%
for method 2 (1)

1 m track 60% and coverage

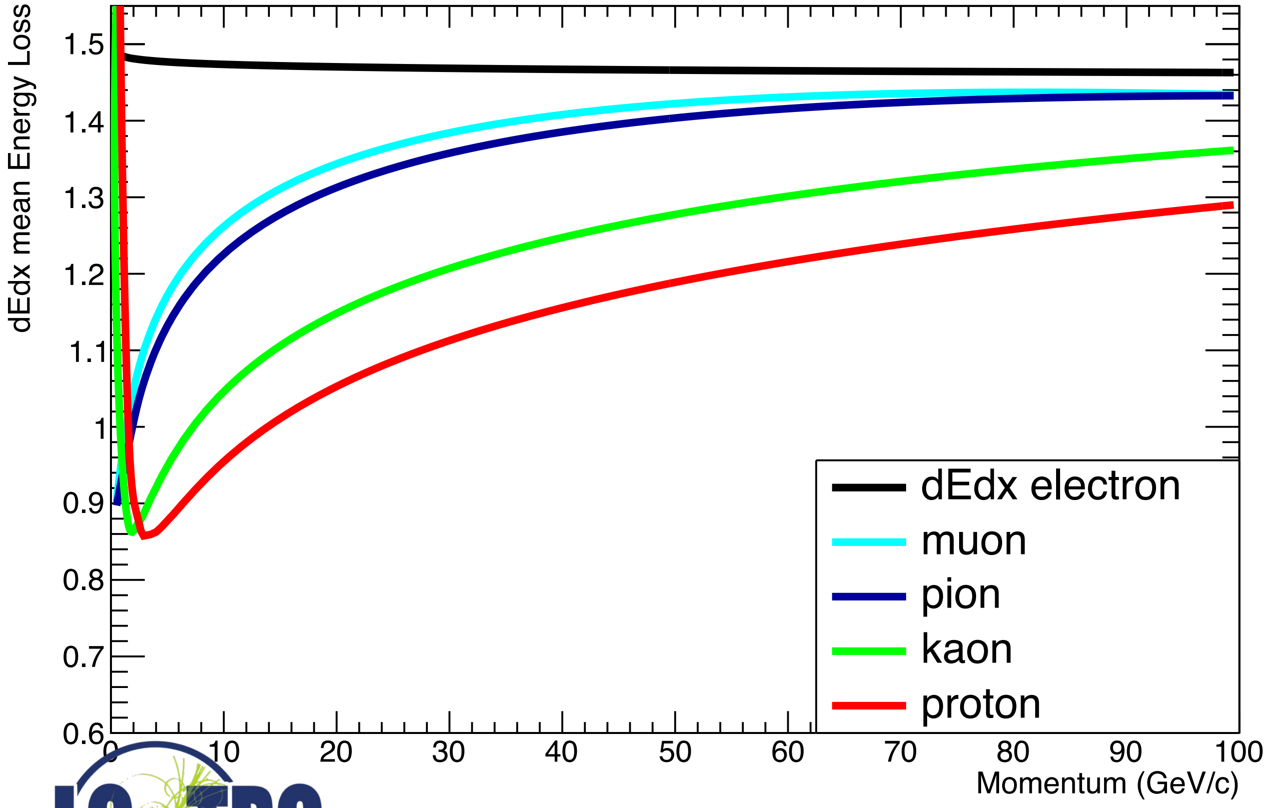
ILD detector

rInner = 329 rOuter = 1770 mm
halflength (z) = 2350 mm
electron resolution = 2.5(3.0)%
at $\theta=\pi/2$ for method 2 (1)

Assume Pixel TPC performance at
B = 1 T at p = 5,6 GeV/c

DESY testbeam Module Analysis

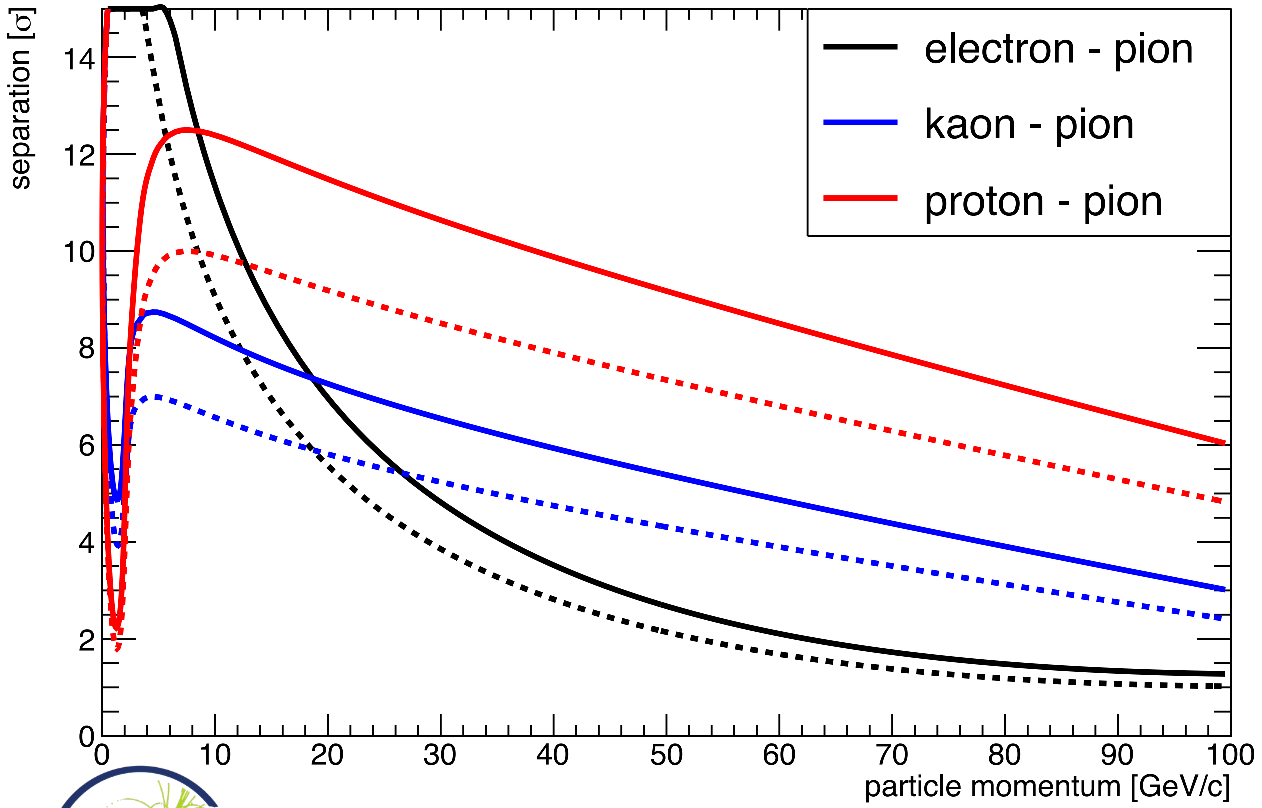
ILD dEdx performance for T2K gas



- Ullrich Einhaus performed dEdx studies in ILD and extracted the ILC soft parametrisations for energy loss based on G4 and full simulation of the ILD TPC with T2K gas
- Link to the software. Samples were generated in 2020 with ILC soft v02-02 and v02-02-01

DESY testbeam Module Analysis

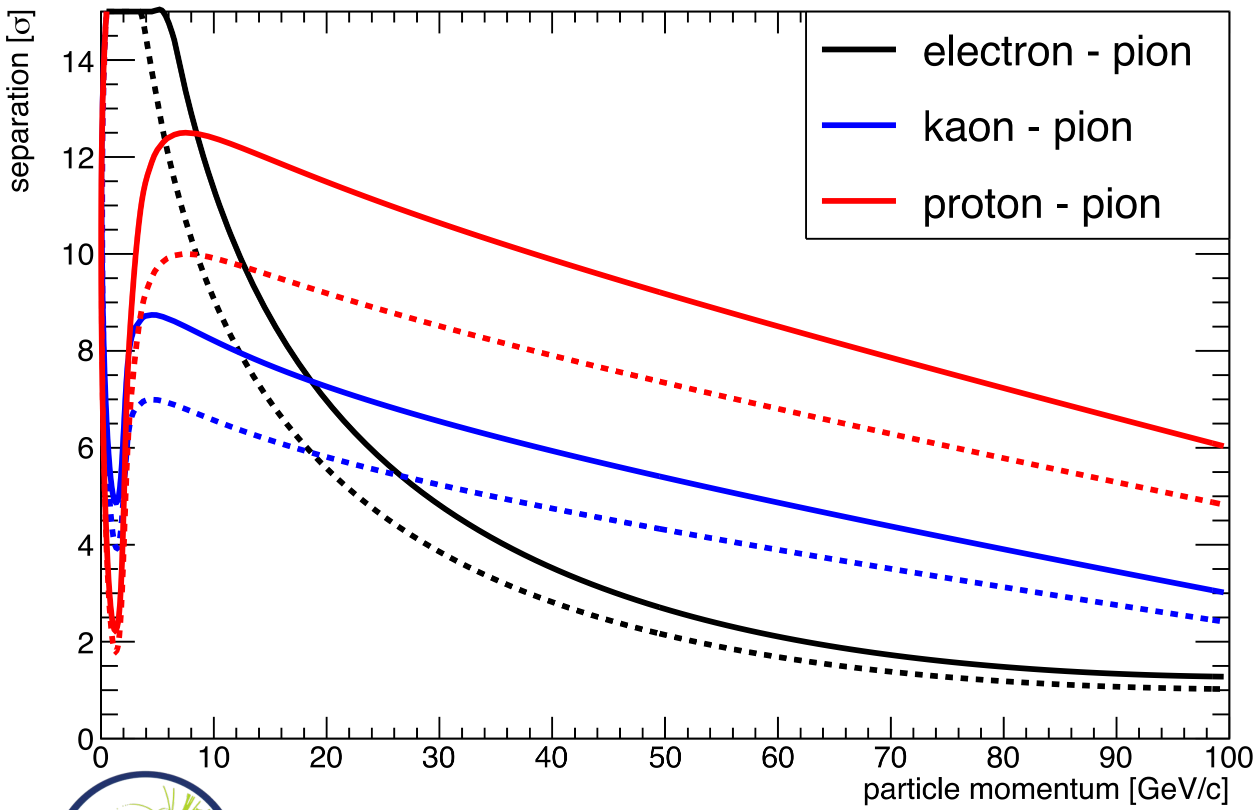
Pixel TPC PID performance



- ILD Performance with specified detector dimensions for particles at cos $\theta = 0$
- Pixel TPC resolution from electron p = 5 (6) GeV test beam (for B = 1 T) of 2.5% and 3% (--- = method 1) at cos $\theta = 0$
- Separation electron pion defined as:
  $|\langle \text{Eloss } e \rangle - \langle \text{Eloss } \pi \rangle| \,/\, \sigma_\pi$
- Separation pion kaon as:
  $|\langle \text{Eloss } \pi \rangle - \langle \text{Eloss } K \rangle| \,/\, \sigma_\pi$

DESY testbeam Module Analysis

Pixel TPC PID performance



- The expected pion-kaon separation for momenta in the range of 2.5-45 GeV/c at cos θ = 0 is more than 5.5(4.5)σ for the two resolution scenarios.
- At a momentum of 100 GeV/c the separation is still 3.0(2.0)σ.

- Protons can be separated from pions for momenta in the range of 2.5-100 GeV/c with more than 6.0(4.8)σ.

Nucl. Instrum. Meth. A 1081 (2026) 170849

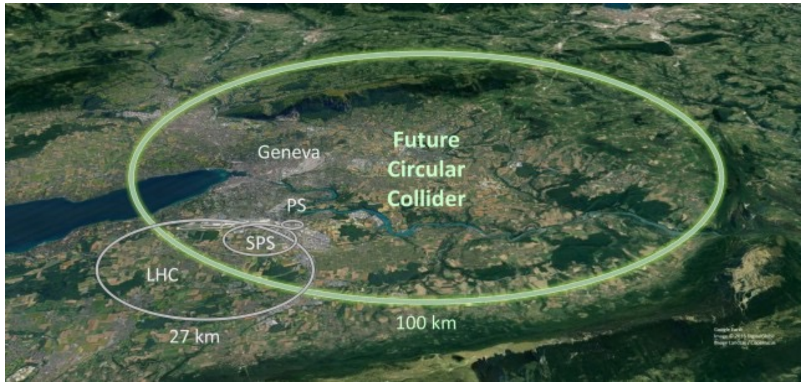
Pixel TPC PID performance

- The PID resolution for an electron with p=5,6 GeV/c of 1 m track length with 60% coverage is measured to be 2.9(3.6)% at B = 1 Tesla.
- The extrapolated PID resolution for an ILD detector is 2.4% (3%)
- This allows for particle identification and separation of kaons from pions up to momenta of 45 GeV with more than 5.5σ (4.5σ) for cos θ = 0. The separation increases up to cos θ = 0.85 (see back up slide).
- As demonstrated, the digital read out of a pixel TPC with a small pixel size allows to perform hit and cluster counting

- Currently a coverage of ~60% is realized with the TPX3 chip. Using the next generation TPX4 chip with Through Silicon Via‵s will allow to enlarge the coverage and increase the PID and tracking performance. The R&D is part of the DRD1 program

A Pixel TPC at a circular collider

At the FCCee a pixel TPC as a central tracker – sliced between silicon detectors as in the ILD concept detector - is well suited to carry out the WW, ZH and tt physics program.



At the CEPC a pixel TPC is selected as one of the baseline CDR/TDR detectors

A more challenging situation for a TPC is running at the Z and in particular the FCCee Tera Z program with L = 140 10^{34} $cm^{-2}s^{-1}$ and Z bosons produced at a rate of ~40 kHz and huge beam backgrounds*.
A 10 Giga-Z FCCee physics program looks realistic with a GridPix pixel TPC and an improved FCCee MDI design.

*For detailed studies/questions/answers see backup slides

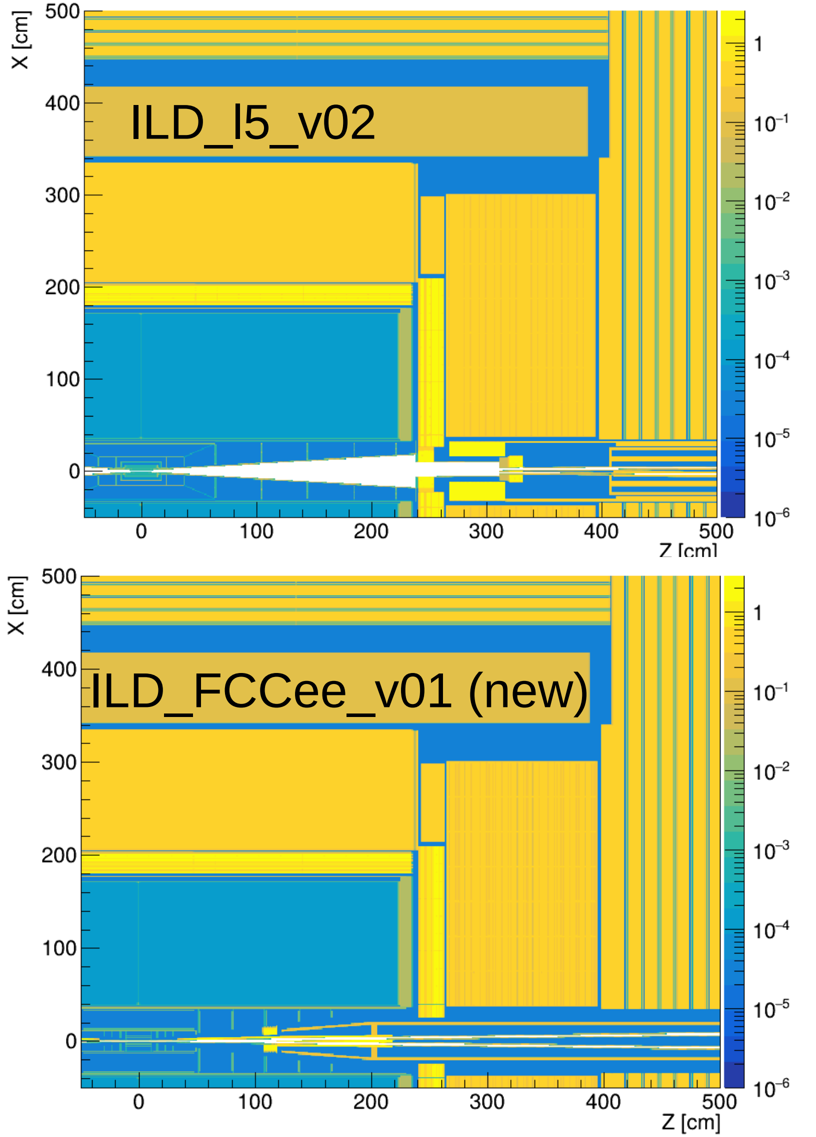
Detector MDI optimization for FCCee

This is important to reduced the machine backgrounds from beam-strahlung and synchrotron radiation.

The problem with the current FCCee Machine-Detector-Interface (MDI) - so the interaction region is that there are many machine elements near the detector, that create huge backgrounds from beamstrahlung…. 2500 – 20 times higher than in the ILC.

Recently the FCC synchrotron radiation bakcgorund turned out to be up to five orders of magnitude larger than the beam background.

It is clear that this makes it difficult to operate any type of detector…



Conclusions: Pixel TPC at a circular collider

- The performance of a pixel TPC based on GridPixes has been studied based on prototypes and test beam measurements. It provides
  - high precision continuous tracking with a low material budget
  - very powerful particle identification
- At the FCCee a pixel TPC as a central tracker – sliced between silicon detectors as in the ILD concept detector - is well suited to carry out the WW, ZH and tt physics program.
- A 10 Giga-Z FCCee physics program looks realistic with the proposed pixel TPC and an improved FCCee MDI design.
- After years of R&D, a pixel TPC has become a realistic viable option for experiments
- R&D on a Pixel TPC with GridPix devices with reduced ion back flow based on the TPX3 or TPX4 ASICs are part of the DRD1 program
- One could consider to use Ne as a TPC gas for the Tera-Z running

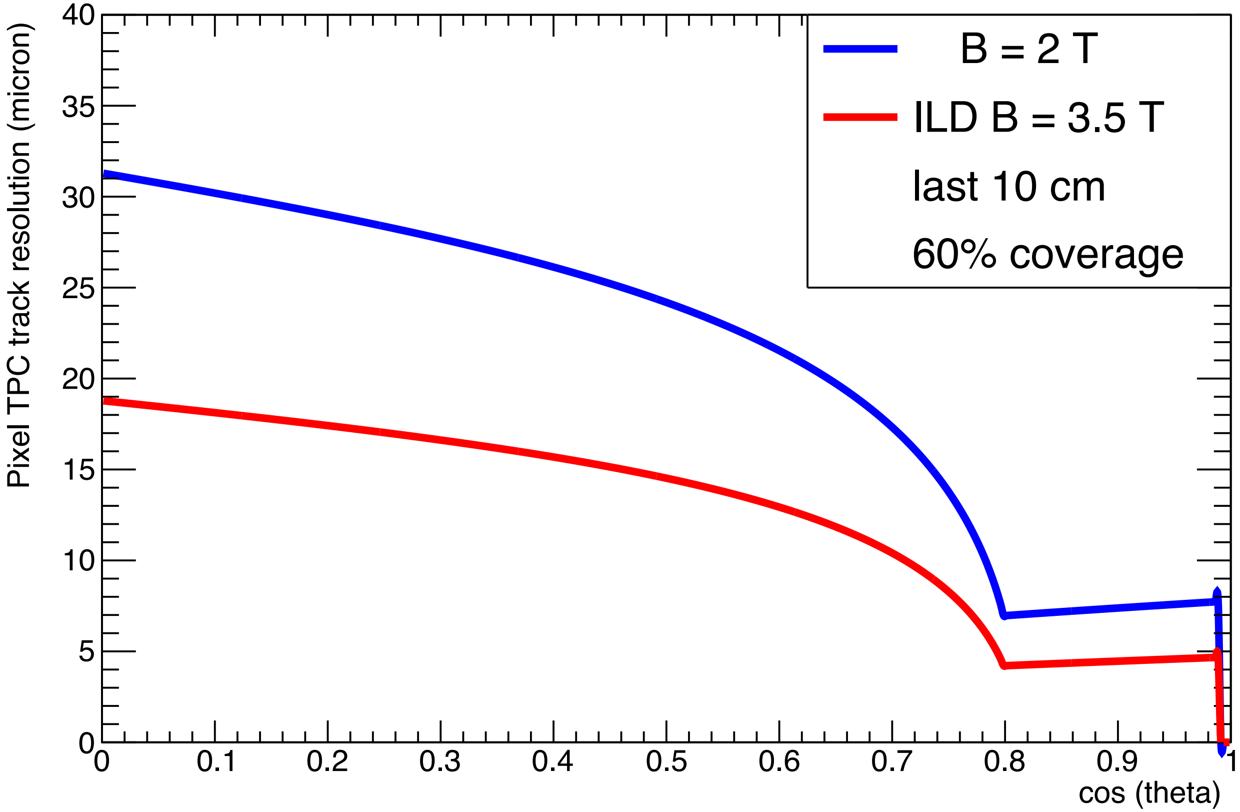
Backup plots

Pixel TPC tracking studies

ILD tracking Performance for a Pixel TPC based on test beam

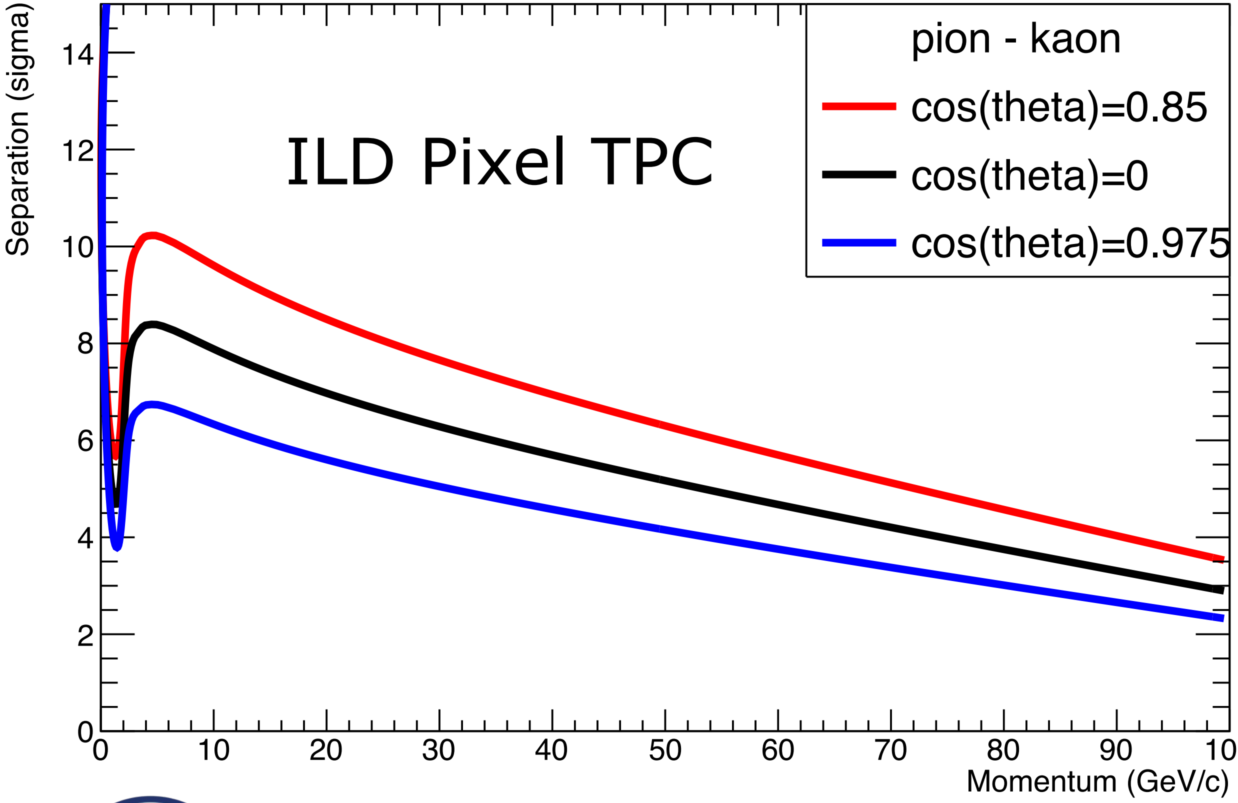
The last 10 cm track provides very high resolution 'point' in the endcap (cos θ>0.8). This is due to the short drift distance and the high resolution pixel readout.

One use the endcap 'point' to calibrate out (part of) the TPC distortions.



DESY testbeam Module Analysis

Pixel TPC PID performance acceptance



- Separation pion kaon
  |<Eloss π > - <Eloss K>| / σ_π
- Separation pion kaon for different cos(theta) values due to the track length dependence
- For cos(theta)=0 till 0.95 the separation lies between the black and red curves. Only above 0.95-0.975 the separation drops till the blue curve.
- Excellent performance over very large polar angle range

A Pixel TPC at a circular collider

- Can a pixel TPC reconstruct the Z events?
  - The TPC total drift time is about 30 μs
  - This means that there is on average 1.2 event / TPC readout cycle
  - YES: The excellent time resolution: time stamping of tracks < 1.2 ns allows to resolve and reconstruct the events
- Can the current readout deal with the Z rate?
  - Link speed of Timepix3 (in Quad): 2.6 M hits/s per 1.41 × 1.41 cm^2 In the module testbeam we tested up to rates of 5.7 kHz
  - YES: This is sufficient to deal with hits from Z's in high luminosity Z running
    - Expect about 90 kHz/cm^2 from hadronic Z decays@inner radius
- What is the current power consumption?
  - No power pulsing is possible at a circular collider (at e.g. ILC power pulsing is possible)
  - Current power consumption TPX3 chip ~2W/chip per 1.41 × 1.41 cm^2
  - So: good cooling is important but no show-stopper.
  - In LCTPC, CO2 cooling has been developed and tested for the MM read-out technology
  - To save power the TPX3/4 chips can be run in LowPowerMode: reduction factor 10.

A Pixel TPC at a circular collider

- The importance of the beam background and the optimization of the FCCee machine detector interface MDI
  - Hit rates from beam background are significant (wrt hits of Z decays)
  - The beam background study presented in the October 2024 ECFA meeting by Daniel Jeans (for a 2 T B field) would correspond to a sizeable background rate of about 300 MHz/cm^2 (@inner radius).
  - Since October 2024, the FCCee MDI has improved. A study summarizes the reduced beam background results. The results have been discussed in the FCCee workshop.
  - Recently the synchrotron background was studied that turns out to be very large for tracking detectors. Clearly it is important to reduce this background substantially.
  - The Pixel TPC – due to the high granularity – has an occupancy of < 1% for 300 MHz/cm^2 (@inner radius). The read-out speed of the current TPX3 has to be upgraded to cope with the large background rates. R&D for a fast read-out based on TPX3/4, like the VeloPix (LHCb) is needed.

A Pixel TPC at a circular collider

- What about track distortions?
  - Not an issue for running at cms energies of WW, ZH, tt
  - There are two important sources of track distortions of the TPC drift field:
    - the slowly drifting primary ions (from Zs and background)
    - the ions produced in the amplification process flowing back (IBF)
  - At the ILC gating is possible to reduce the IBF; at FCC-ee this is not realistic, for a Pixel TPC a double grid is the best solution (see below)
- Is it possible to reduce the IBF for a pixel TPC?
  - IDEA: by making chip with a double grid structure (see back up slide)
  - This idea was already realized as a 'TWINGRID' NIMA 610 (2009) 644-648
  - For GEMs for the ALICE TPC this was also the way – use several GEMs to reduce IBF
  - The IBF* can be easily modelled and with a hole size of 25 μm an IBF of $3\ 10^{-4}$ can be achieved and the value for IBF*Gain (2000) would be 0.6.
  - YES: the IBF can be reduced. It needs R&D that can be done in the detector lab in Bonn.

* Measured IBF of single grid GrixPix is 1.3% and IBF*Gain (2000) is 26.

A Pixel TPC at a circular collider

- What would be the size of the TPC distortions at a TeraZ factory?
  - Tera-Z studies by Daniel Jeans and Keisuke Fuji show that for FCC-ee this means: distortions from Z decays up to < O(100) μm.
  - The problem is that the beam and synchrotron backgrounds are by far the dominant source for the ions in the TPC volume. The beam distortions by beam backgrounds are less than 1 cm as the latest studies by Daniel Jeans shows. The synchrotron backgrounds are largest and the reduction of that background –by optimizing the MDI - is important for all detectors.
  - There is also an idea to operate the TPC with a Neon based gas that could bring the backgrounds down by a factor of 40. This needs study.
  - It can be argued that in an ILD like detector the distortions can be mapped out using the silicon VTX-SIT/SET detectors. See e.g. the backup slide on fitting out TPC distortions.

A Pixel TPC at a circular collider

- A 10 G Z FCCee physics program* could be carried out, but
  - It needs a lot of power to process the large amounts of background hits in the tracking detectors
  - It needs more study to reduce the backgrounds by an improved MDI
  - Fitting techniques should be studied to correct for the TPC distortions
  - The current TPX3 read out should be optimized to cope with the high readout rate and minimise the power consumption

* The physics case for a Tera Z physics program seems IMO rather weak

Fitting out and reducing TPC distortions

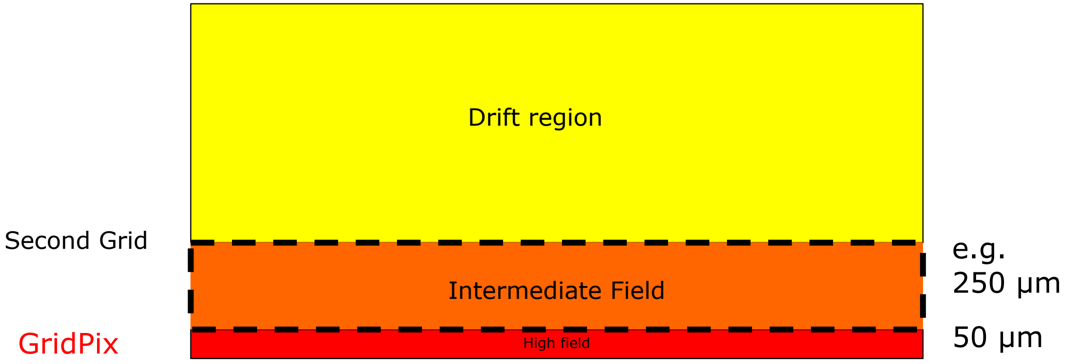
- It is possible to map out distortions using e.g. muons from Z decays
  - E.g. by fitting the 3D spatial distribution as a function of time as was done by ALEPH and more recently by ALICE. Using this distribution the hits positions are corrected and the TPC track refitted.
- However, with silicon trackers around the TPC, more elaborate methods can be used. One can use the track predictions based of the silicon trackers SIT and SET to correct on a track-by-track level the TPC track.
  - One can use as a constraint that the extrapolated positions and angles agree with the measured in the SIT and SET.
  - Practically, one can e.g. correct the TPC track parameters
- The ultimate way is a fitting technique similar to ATLAS. In the ATLAS track fit the common systematics is fitted out for sets of Muon hits. For ILD @ FCC the fit would fit free parameters in the distortion model, while using as a constraint the SIT and SET position and direction measurements.
  - The simplest case is a model where the strength (amplitude) and radial dependence would be scaled and a model is used for the 3D extrapolations.

Reducing the Ion back flow in a Pixel TPC

The Ion back flow can be reduced by adding a second grid to the device.

It is important that the holes of the grids are aligned. The Ion back flow is a function of the geometry and electric fields. Detailed simulations – validated by data - have been presented in LCTPC WP #326.

With a hole size of 25 µm an IBF of 3 10^{-4} can be achieved and the value for IBF*Gain (2000) would be 0.6.



Ion backflow	Hole 30 µm	Hole 25 µm	Hole 20 µm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	12 10^{-4}	3 10^{-4}	1 10^{-4}
transparancy	100%	99.4%	91.7%