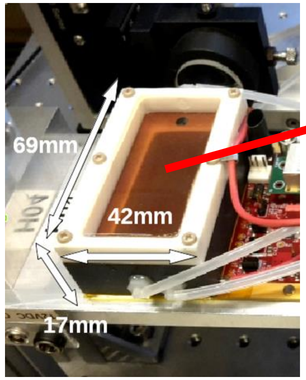
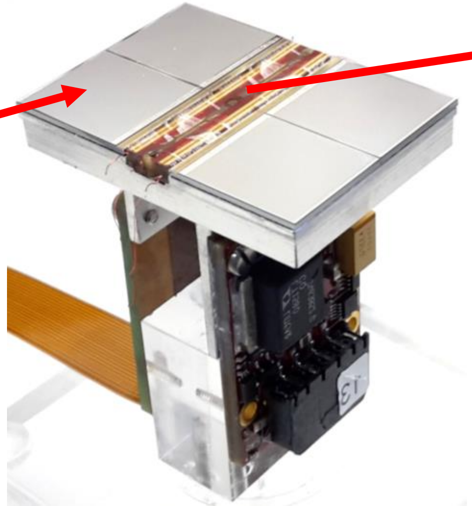
Pixel TPC status and research plans

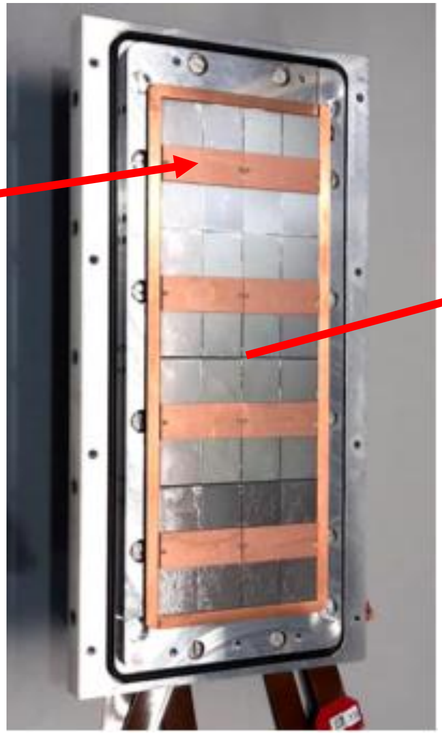
Yevgen Bilevych, Klaus Desch, Sander van Doesburg, Jean-Paul Fransen, Harry van der Graaf, Markus Gruber, Fred Hartjes, Bas van der Heijden, Kevin Heijhoff, Charles Ietswaard, Dimitri John, Jochen Kaminski, Peter Kluit, Naomi van der Kolk, Auke Korporaal, Cornelis Ligtenberg, Oscar van Petten, Gerhard Raven, Joop Rövekamp, Tobias Schiffer and Jan Timmermans

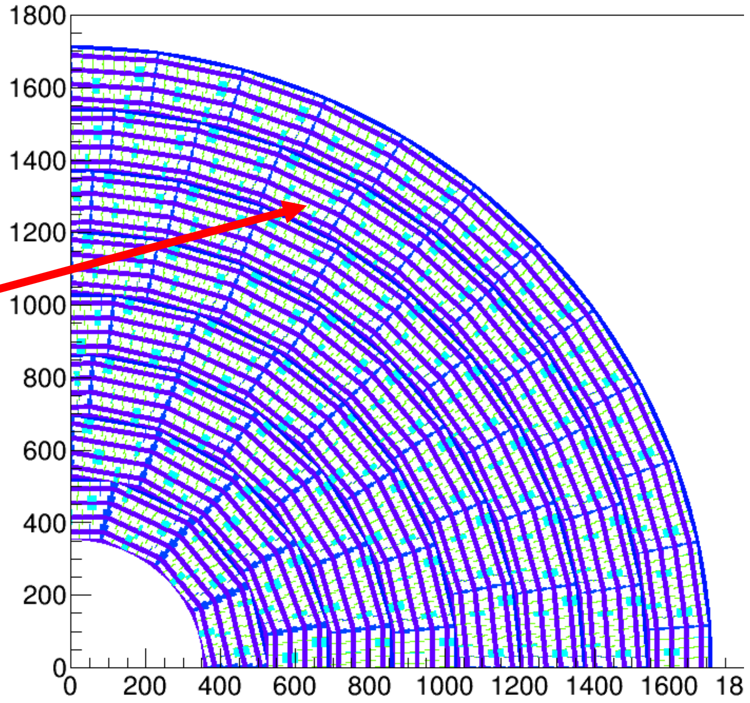
- GridPix production and improvement of resistivity TPX3 layer SiN
- Ion Back Flow measurement Quad
- Negative Ion Pixel TPC paper
- TimePix4 potential TPC applications
- Pixel TPC and Quad Module performance

Pixel TPC









Single chip 2017

Quad 2018

Module 2019

TPC plane

GridPix production and improvement of resistivity TPX3 layer SiN

- In the post-processing step a resistive layer is put on the TPX3 chip
- This protects the device from sparks
- In the quad beam tests it was found that the SiN layer charges up at very high rates (> 10 kHz)
- Yevgen is investigating how to reduce significantly the resistivity of the SiN layer; this will reduce the charge up
- Different trial samples were made in 2020; this continues in 2021
- Production of TPX3 wafers with InGrids @ IZM Berlin is foreseen 2021
- Bonn has a new Detector Lab starting in March 2021

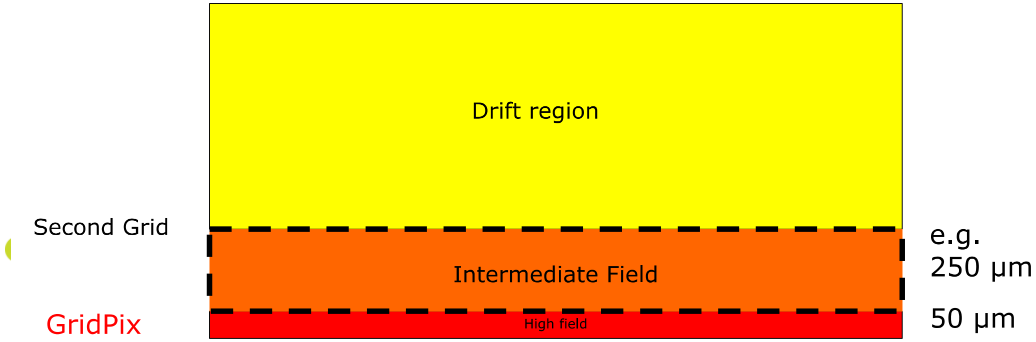
Ion Back Flow measurement

- Ion Back Flow are the ions created in the avalanche process that flow back in the TPC volume
- For TPC applications at a circular collider e.g. CEPC or FCC-ee or for heavy ion experiments it is important to reduce the IBF and to limit the distortions
- In 2020 the IBF has been measured for a quad inside the module. It is 1.3% at a gain of ~2000. For the drift field in ILD. The result is compatible with previous GridPix/InGrid and simulation results for these Voltage/E field settings and hole sizes. So IBF*Gain is ~25
- For TPC applications at a circular collider e.g. CEPC or FCC-ee or for heavy ion experiments it is interesting to reduce the IBF
- NB: At the ILC the IBF can be reduced by adding a gating device on top of the readout module

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 field ratios in the regions.
- Detailed simulations – validated by data - have been presented in LCTPC in April 2020 WP 326 and shown at the International Workshop on the High Energy Circular Electron Positron Collider Shanghai in October 2020
- With a hole size of 25 μm an IBF of $3\ 10^{-4}$ can be achieved and the value for IBF*Gain would be 0.6. Simulation is without magnetic field, and assuming equal E field ratios of 16. This is interesting to pursue further.

Plan 2021 to test a second grid and measure IBF



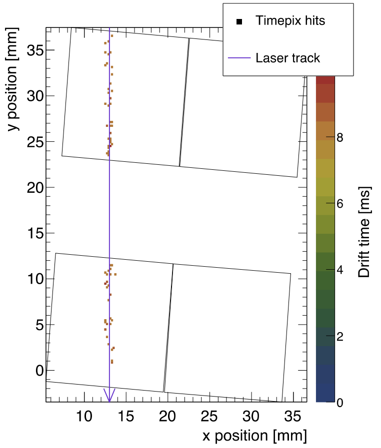
Ion backflow	Hole 30 μm	Hole 25 μm	Hole 20 μm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	$12\ 10^{-4}$	$3\ 10^{-4}$	$1\ 10^{-4}$
transparancy	100%	99.4%	91.7%

Negative Ion pixel TPC

- There is an interesting application for a pixel TPC using negative ions
  - The idea for a NITPC was presented by Martoff et al. in NIMA A 440 (2000) 355
  - Use a gas CS_2 (SF_6) here negative ions are formed. They drift slowly to the read-out plane. These gasses have a very small diffusion coefficient: high resolution - interesting for pixels
  - NITPC with GEM read-out experiment for dark matter searches Drift IIb
- We took data in 2020 with a Ar-iCH_4-CS_2 93.6/5.0/1.4 gas mixture and ran it at atmospheric pressure and room temperature.
  - Preliminary results were shown by Kees in LCTPC WP 329 June 2020

Negative Ion pixel TPC paper

Submitted NIMA December 2020



On the properties of a negative-ion TPC prototype with GridPix readout

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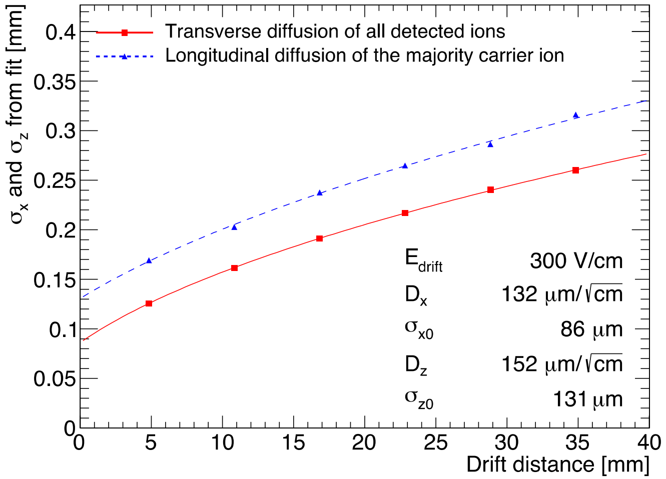
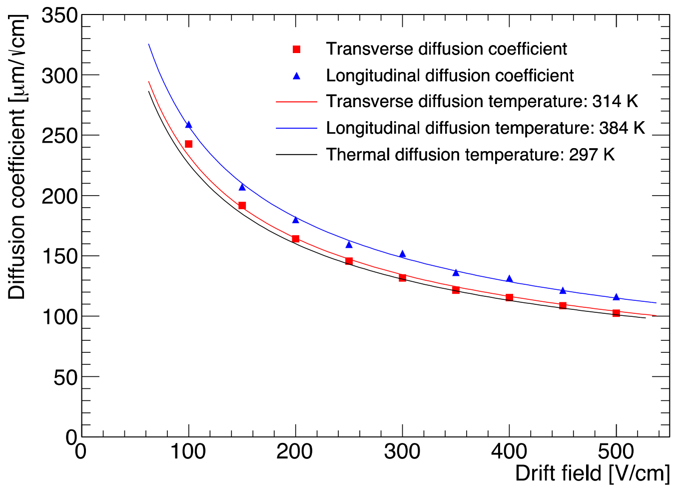
- Important conclusion is that the diffusion coefficient of a NITPC is for the chosen gas mixture pretty close to the thermal limit
- For dark matter applications: using minority and majority carriers the drift distance can be determined rather accurately





TimePix 4 potential TPC applications

In April 2020 we held a brainstorm meeting to discuss the construction of a GridPix detector based on Timepix4 (https://indico.nikhef.nl/event/2243/)

- The TPX4 has the size of a typical Quad (3.5/4)
- The layout Fred proposed will have a larger coverage than the Quad. Quad coverage is about 69%. Still there will be an area (~1+3.5 mm) where the wirebonds are connected to the PCB - with a guard on top of it. Estimated coverage is 73%.
- The layout will not need an expensive flex/PCB. That is a large improvement with respect to TPX3.
- For TPX4 a multiplexer board for a module is not needed
- Lower power consumption (0.55 W/cm^2) than TPX3

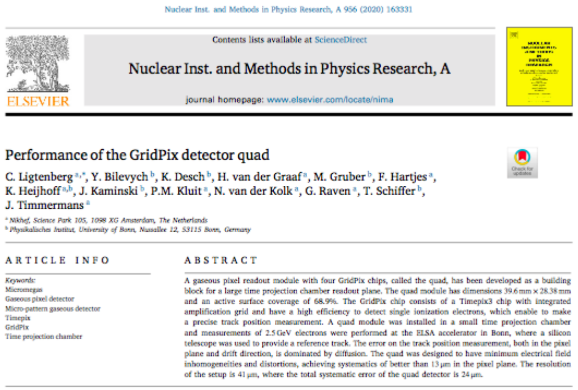
TimePix 4 potential TPC applications

  - Assembly due to the layout of the TPX4 will be much easier
  - The use of Through Silicon Via’s will alllow to improve the coverage substantially: potentially up to 96%. It is interesting to follow the TSV developments
- Several years effort
  - It all starts with post-processing of a TPX4 wafer
  - At Nikhef there is only support for TPX4 silicon tracking applications and the read out SPDR software for TPX4
  - Support will be easier with ILC approved or CEPC funding

Pixel TPC and Quad Module performance

- The details of the construction of the Quad Module were presented by Fred Hartjes in LCTPC 2020 https://agenda.linearcollider.org/event/8362/timetable/#20200114.detailed.
- The Pixel TPC simulation and the latest results are updated wrt LCTPC 2020 and written up in the thesis of Kees Ligtenberg that will be submitted before March 2021. A summary was e.g. presented by Kees in the Topical workshop on New Horizons in Time Projection Chambers, 7 October 2020
- In the following slides I will review the current status of the Quad and the status of the 8-Quad Module.

Quad paper published
https://doi.org/10.1016/j.nima.2019.163331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Performance of the GridPix detector quad

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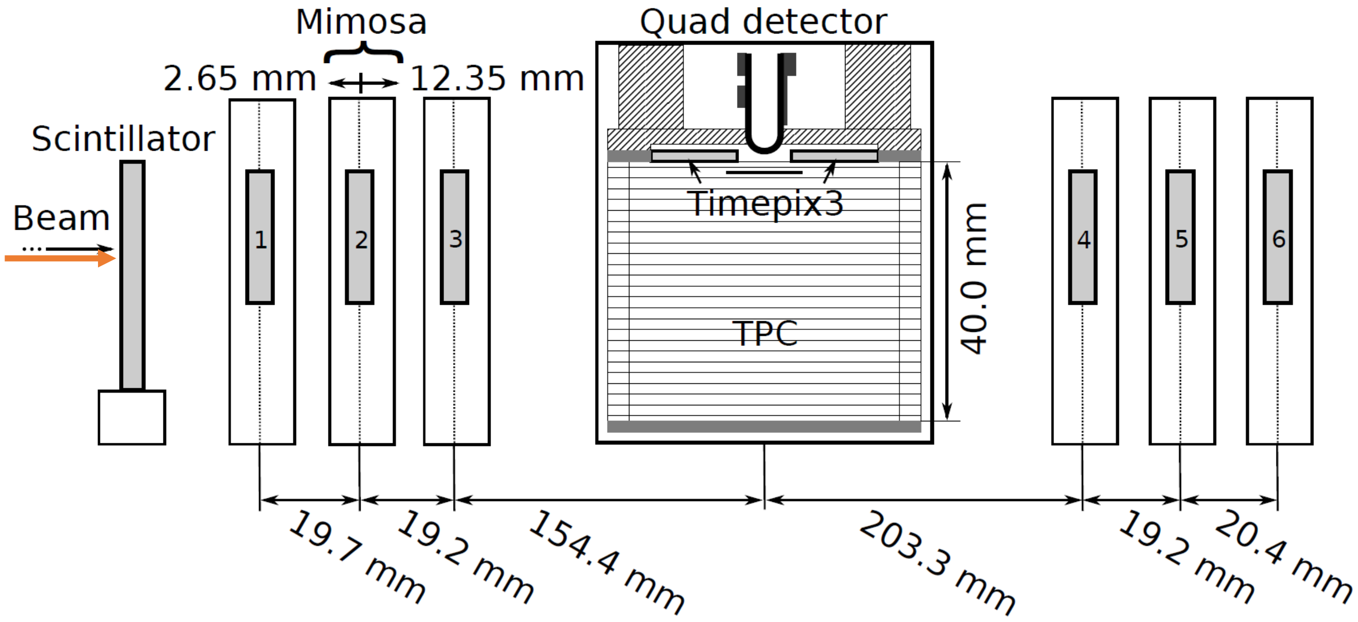
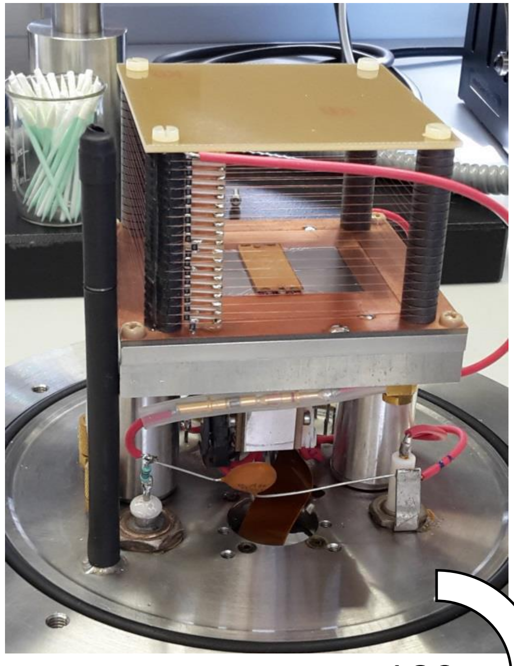
ABSTRACT

A gaseous pixel readout module with four GridPix chips, called the quad, has been developed as a building block for a large time projection chamber readout plane. The quad module has dimensions 39.6 mm × 28.38 mm and an active surface coverage of 68.9%. The GridPix chip consists of a Timepix3 chip with integrated amplification grid and have a high efficiency to detect single ionization electrons, which enable to make a precise track position measurement. A quad module was installed in a small time projection chamber and measurements of 2.5 GeV electrons were performed at the ELSA accelerator in Bonn, where a silicon telescope was used to provide a reference track. The error on the track position measurement, both in the pixel plane and drift direction, is dominated by diffusion. The quad was designed to have minimum electrical field inhomogeneities and distortions, achieving systematics of better than 13 μm in the pixel plane. The resolution of the setup is 41 μm, where the total systematic error of the quad detector is 24 μm.

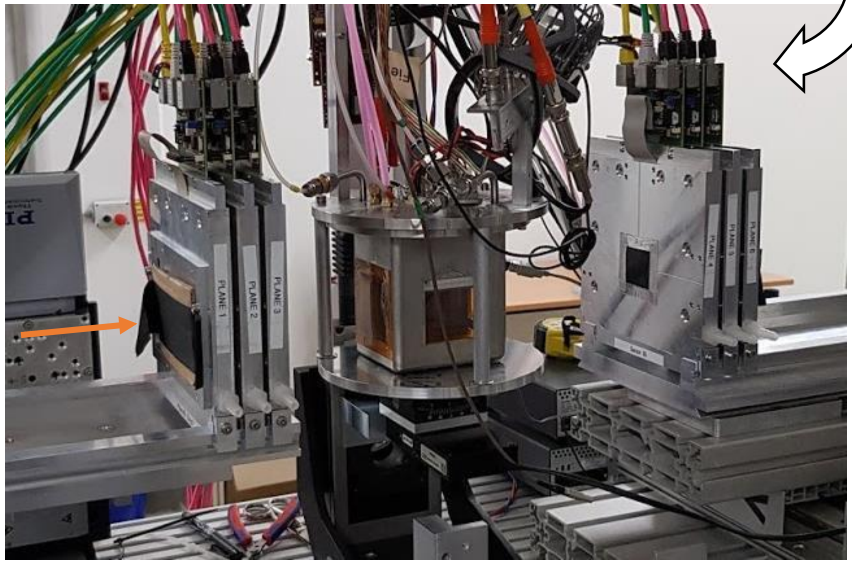
Test beam measurements (2018)

- 2.5 GeV electrons at the ELSA accelerator in Bonn, Germany
- T2K gas with E_{drift} = 400 V/cm, V_{grid} = -330 V
- Events are triggered by a scintillating plane
- 6 plane mimosa telescope with 18.4 µm × 18.4 µm sized pixels

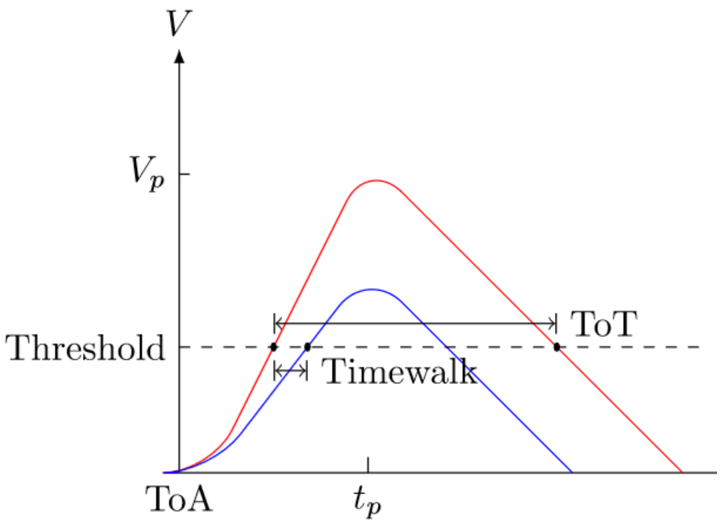




180 º

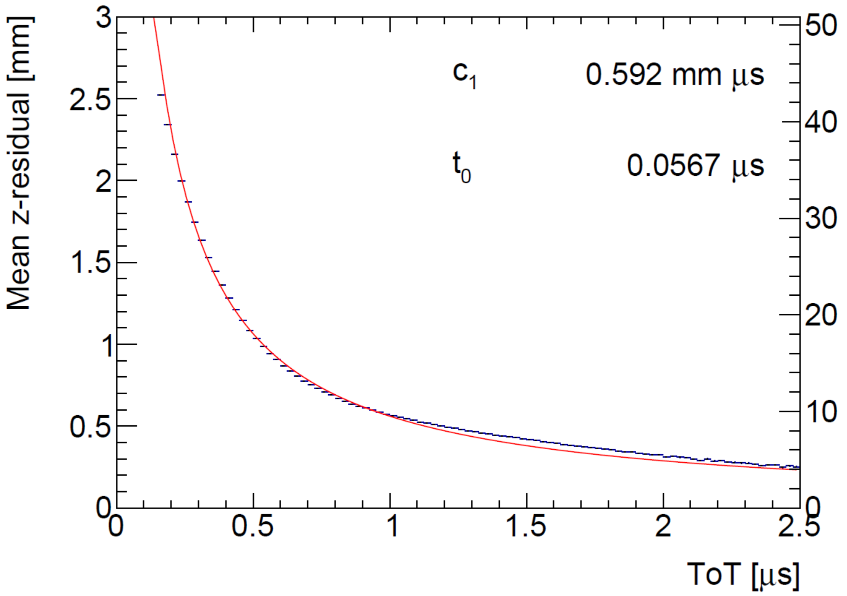


Time walk correction with the Timepix3



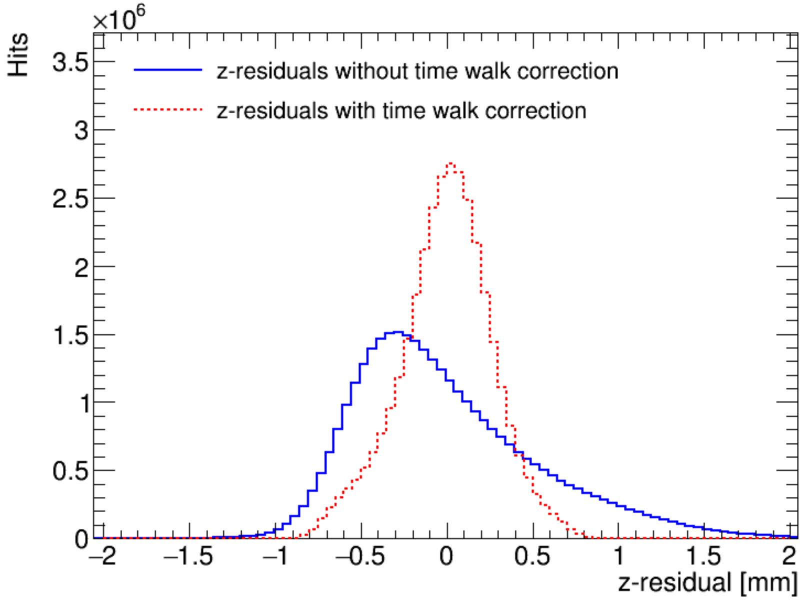
Time walk error: time of arrival depends on signal amplitude

Time walk can be corrected using Time over Threshold (ToT) as a measure for signal strength



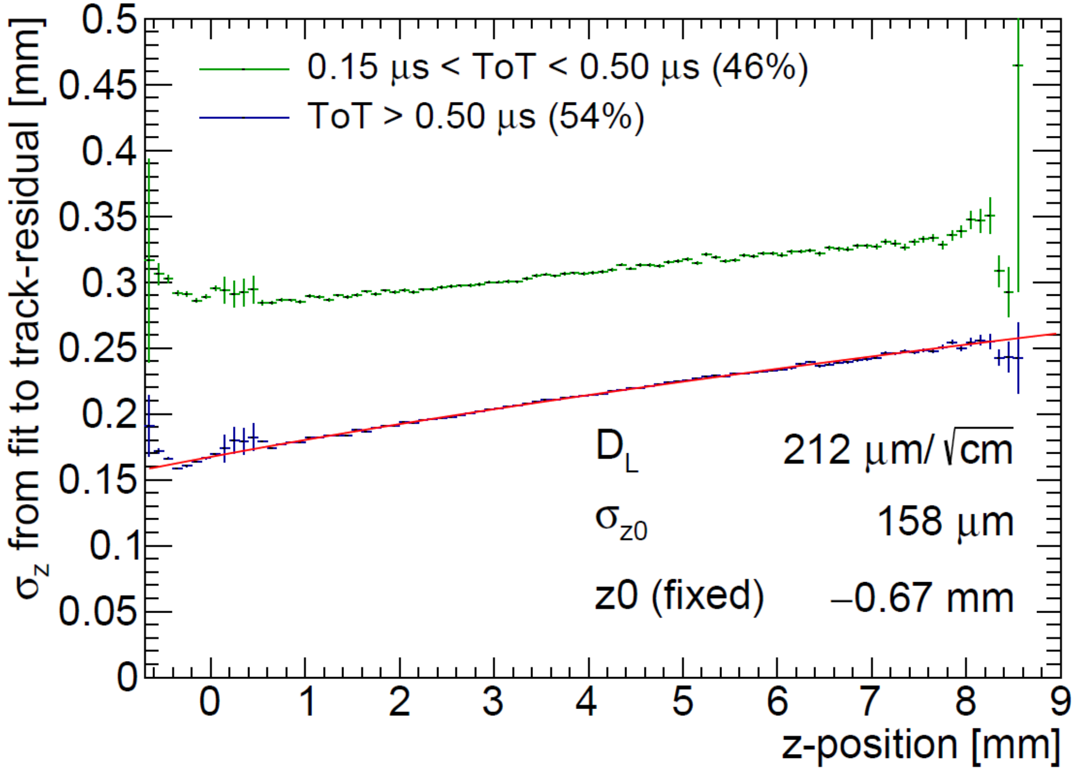
First order correction fitted and applied:

$$\delta z_{\text{timewalk}} = \frac{c_1}{t_{ToT} + t_0} + z_0$$



Distribution of residuals becomese more Gaussian after the time walk correction

Hit resolution in the drift direction



Single hit resolution in drift direction

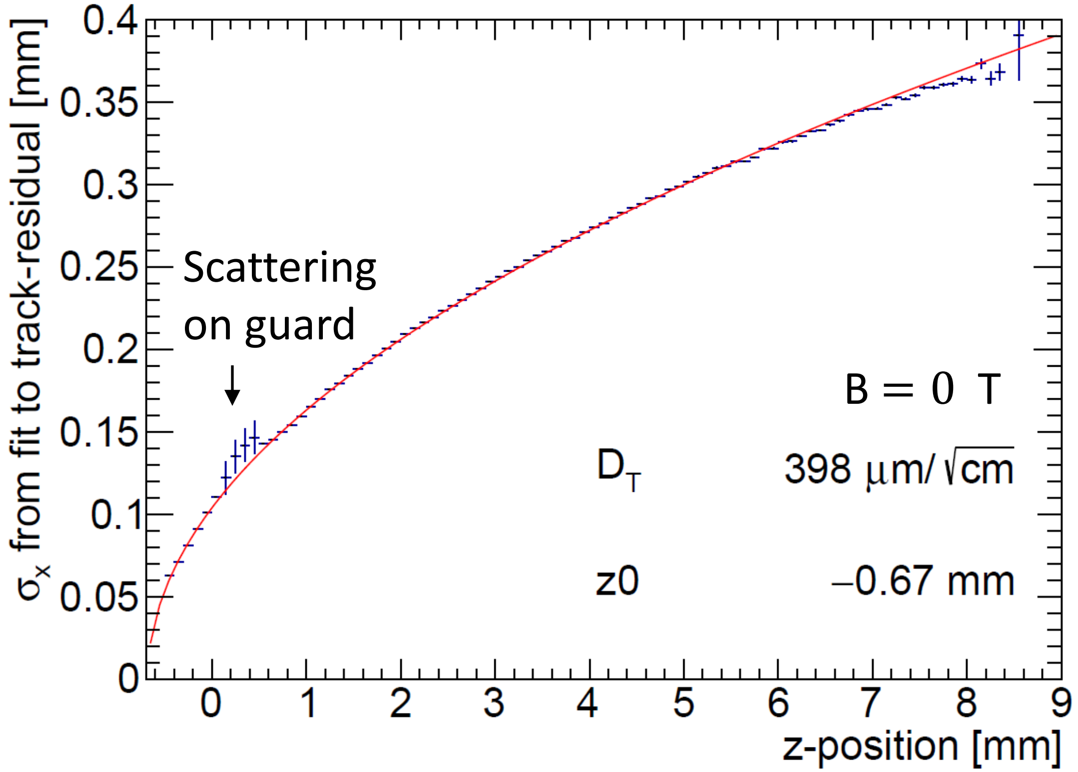
$$\sigma_z^2 = \sigma_{z0}^2 + D_L^2(z - z_0)$$

Depends on

- σ_{z0} from fit
- Diffusion D_L from fit

Because of a large time walk error in hits with a low signal strength, an additional ToT cut (> 0.50 µs) was imposed

Hit resolution in the pixel (precision) plane



Single hit resolution in pixel (precision) plane:

$$\sigma_y^2 = \sigma_{y0}^2 + D_T^2(z - z_0)$$

Depends on:

- σ_{y0} = pixel size 55 μm/$\sqrt{12}$
- Diffusion D_T from fit

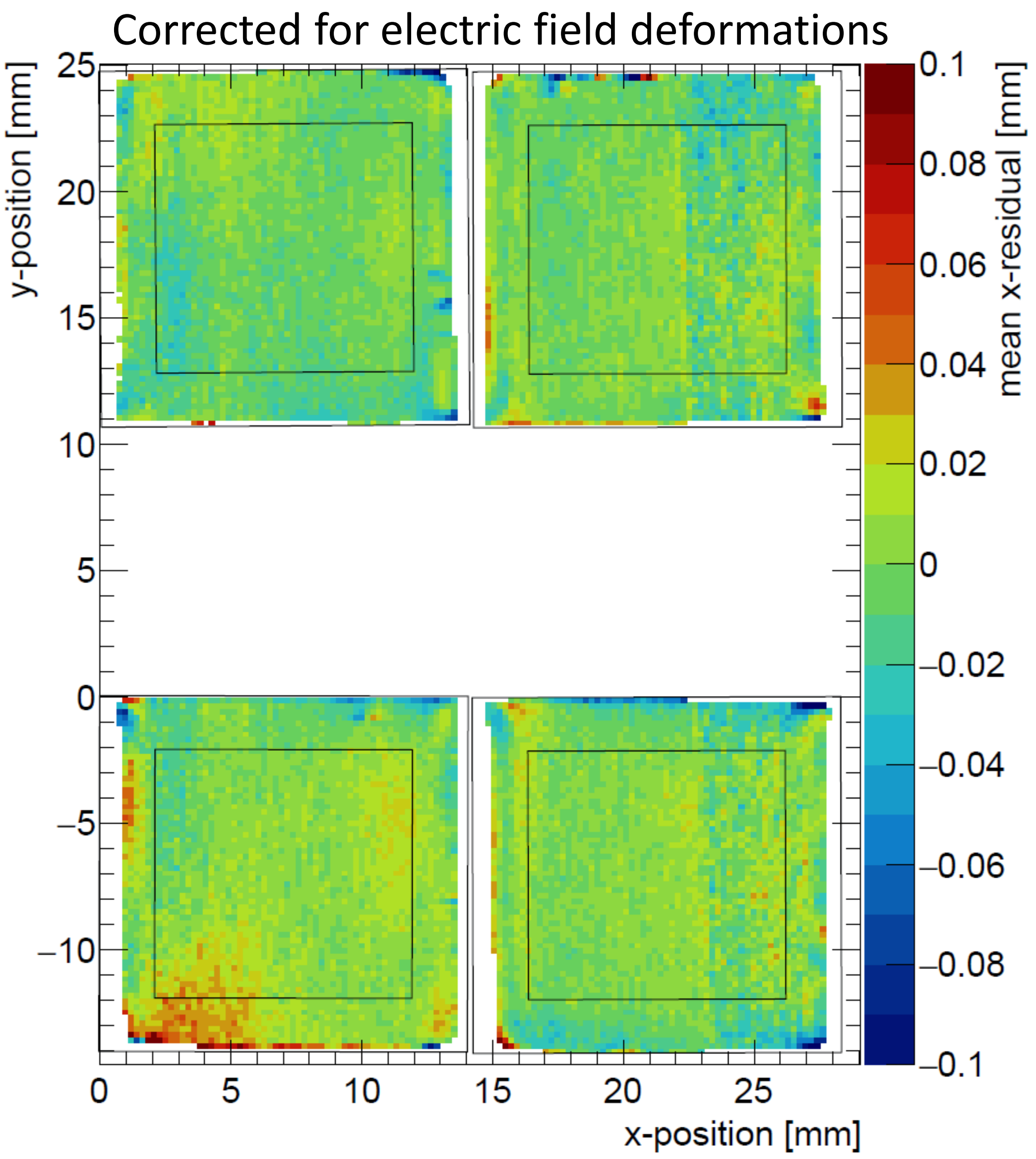
Note that:

- A hit resolution of ~250 μm is ~25 μm for a 100-hit track (~ 1 cm track length)
- At B = 4 T , expected $D_T = 25\ \mu\text{m}/\sqrt{\text{cm}}$
- At B = 2 T , expected $D_T = \sim 60\ \mu\text{m}/\sqrt{\text{cm}}$

Deformations in the pixel (precision) plane

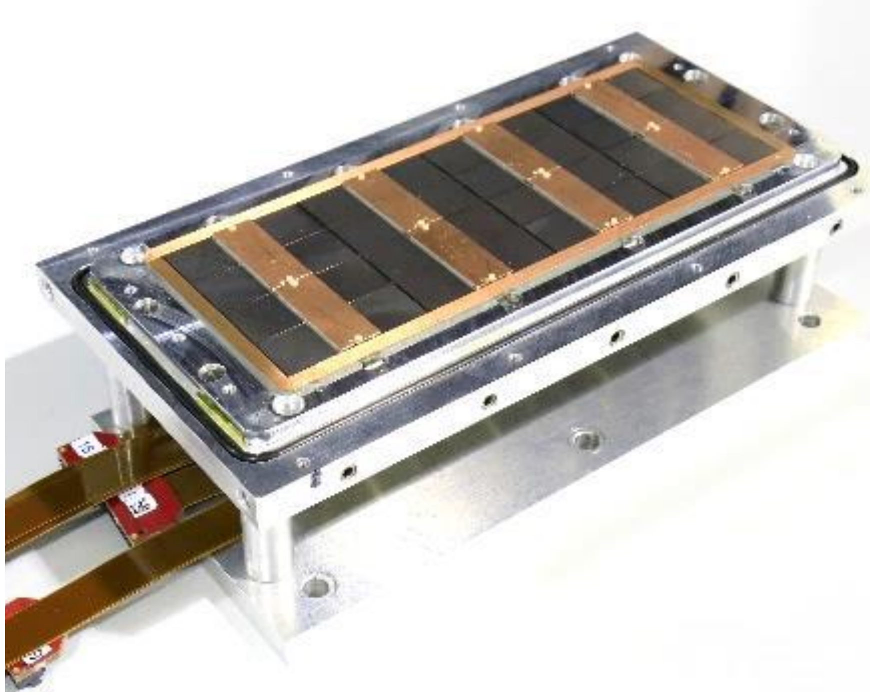
- Investigation of systematic deviations over the pixel plane
- Each bin displays mean of residuals from 4 × 4 pixels
- After correction of the residuals for the distortions from the electric field

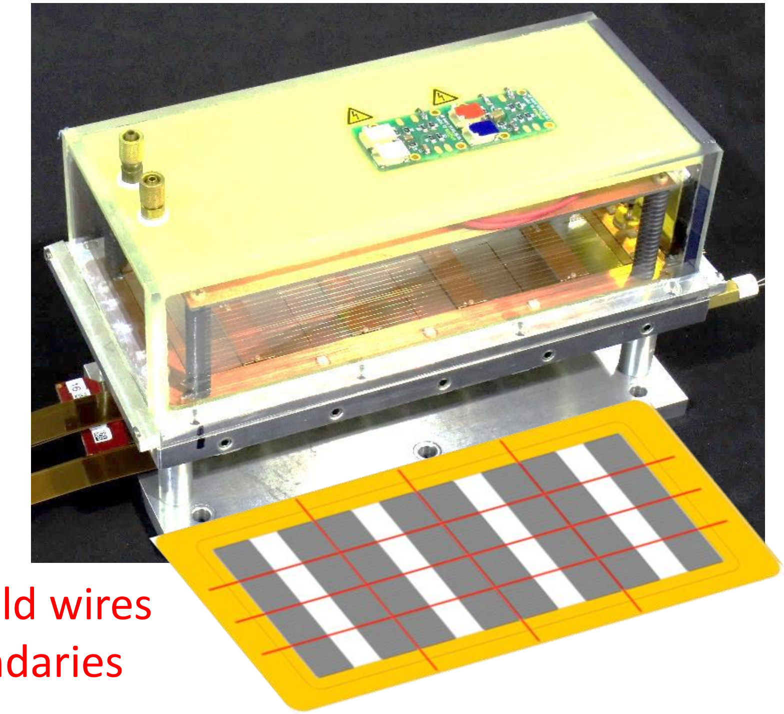
- The RMS is 13 µm over the whole chip, and 9 µm in the centre (black outline)



8 quad module development

- The 8 quad test box has 32 chips in total
- Simultaneous read out through one SPIDR board using data concentrators
- Field wires added to improve electric field, and reduce deformations

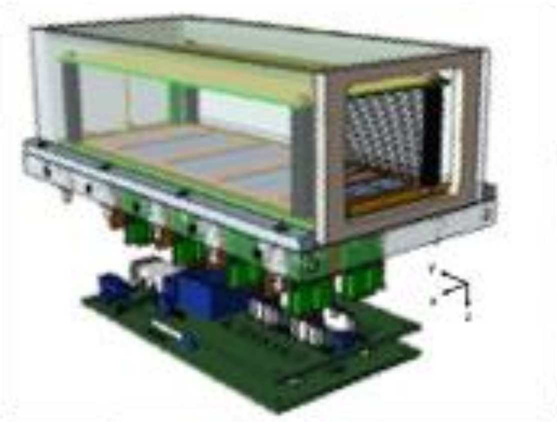


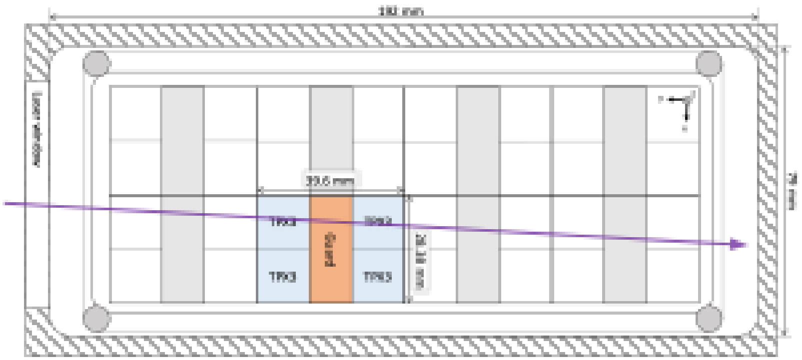


with field wires
at boundaries

8-Quad Module status

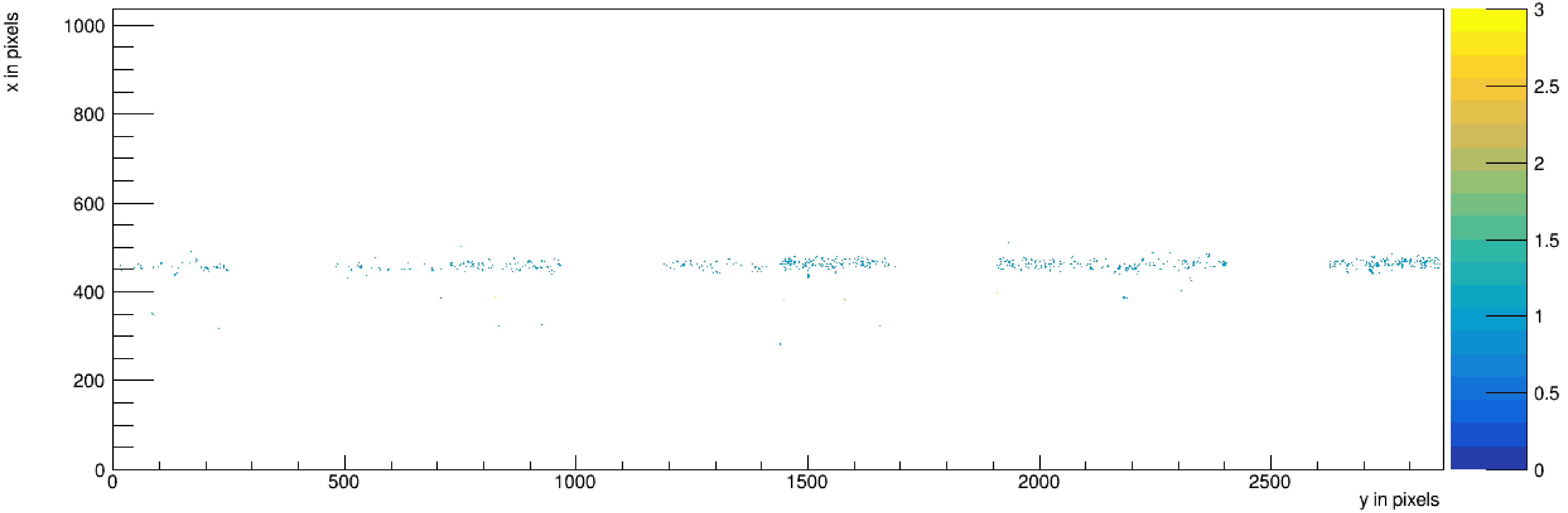
- Organisation of the DAQ: one SPIDR is connected to 2 concentrators that serve 8 quads. Another SPIDR registers a timestamp for the laser and synchronizes the 2 concentrators.
- Three data streams are made: LINK0 and LINK1 for the two concentrators and the TIMESTAMP laser trigger stream
- It took considerable effort to commission the online ‘concentrator’ and offline ‘daq’ software and to sort out the timing. Now things look quite good, as the event display demonstrates. Currently, 30 from the 32 chips can be read out.





8-Quad Module performance

Run 1298 event 14 on 22 December 2020 with laser tracks
V_{grid} = -330 V and V_{drift} = -280 V; all pixels shown for a 50 msec window



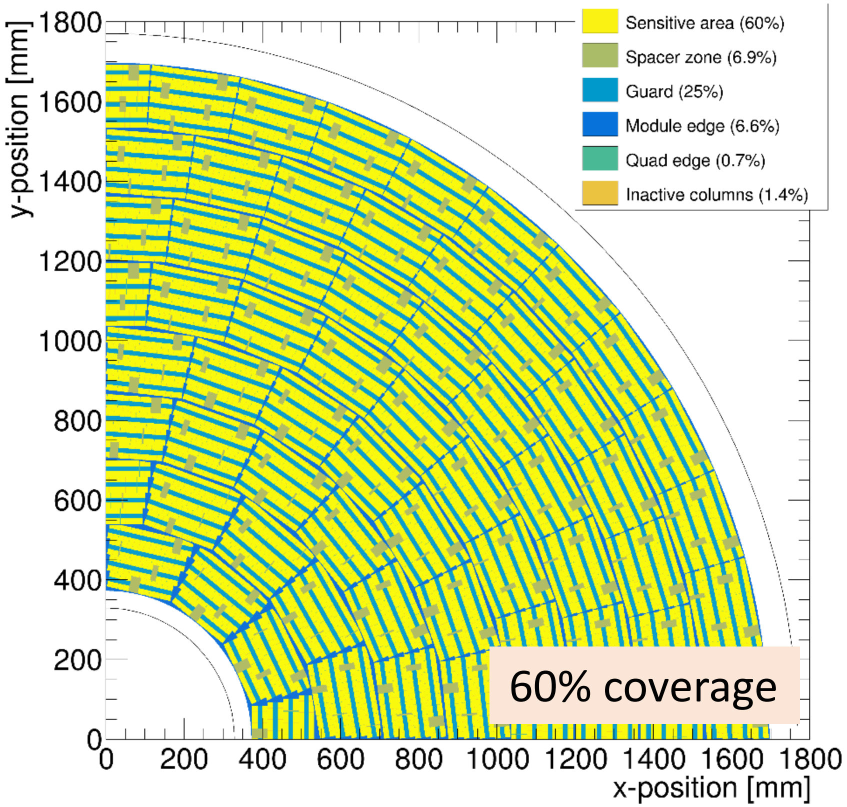
The timing has still a 50 ms spread that is understood and will be fixed next week.

Performance of a GridPix TPC at ILC

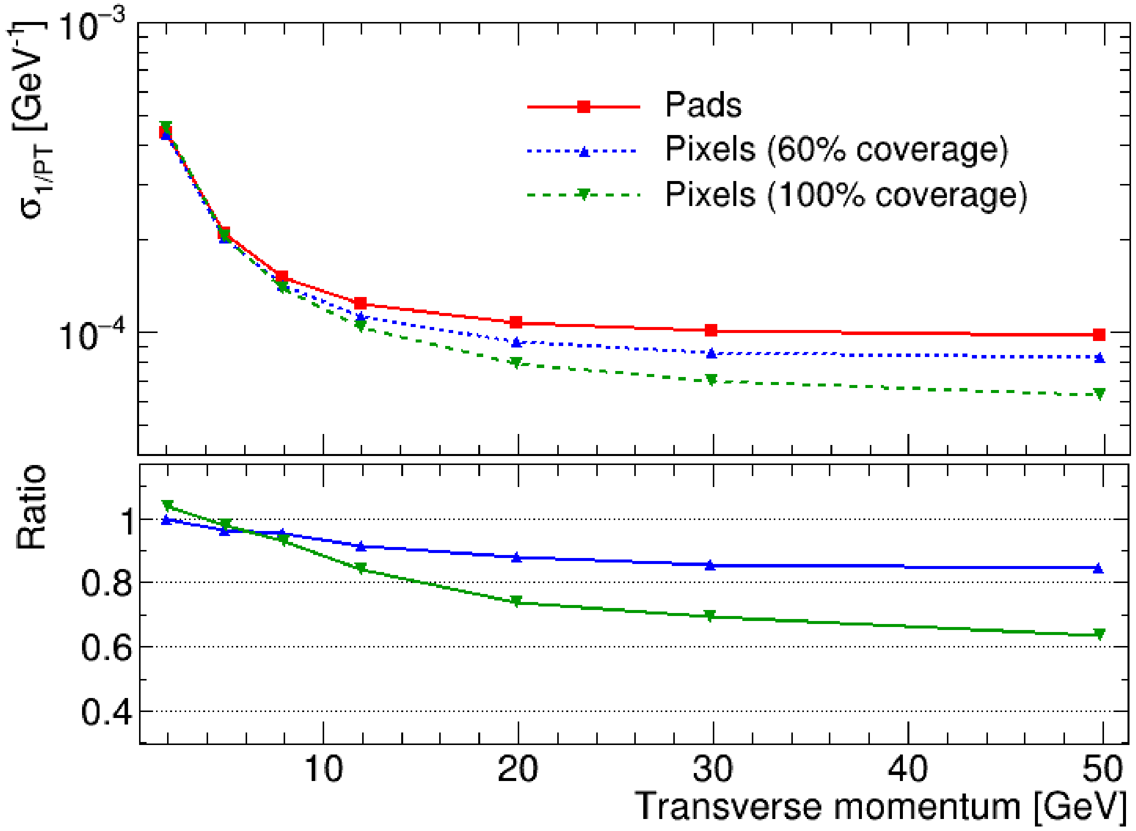
Thesis of Kees Ligtenberg

- From full simulation, momentum resolution can be determined
- Momentum resolution is ~15% better (with realistic 60% coverage)

Realistic tiling with quad module



Momentum resolution of the TPC for a simulated muon



Conclusions

- A quad module with four Timepix3 based GridPix chips has been designed and built
- The resolution is limited by diffusion
- Systematic uncertainties are small: 9 μm in the pixel plane
- A GridPix readout will allow for dE/dx measurements through cluster counting
- The status of the 8-Quad Module was presented
- The test of the Module at test beam DESY is scheduled for June 2021
  - We will take data with a silicon telescope that will allow us to measure the performance in a magnetic field as well as the deformations in a module
- A Pixel TPC is a good option at the ILC (CLIC) and circular e^+e^- colliders
- ILD Simulations show an improvement in momentum resolution of a pixel TPC read out over a pad readout of 15 – 35 %

GridPix Pixel TPC Plans

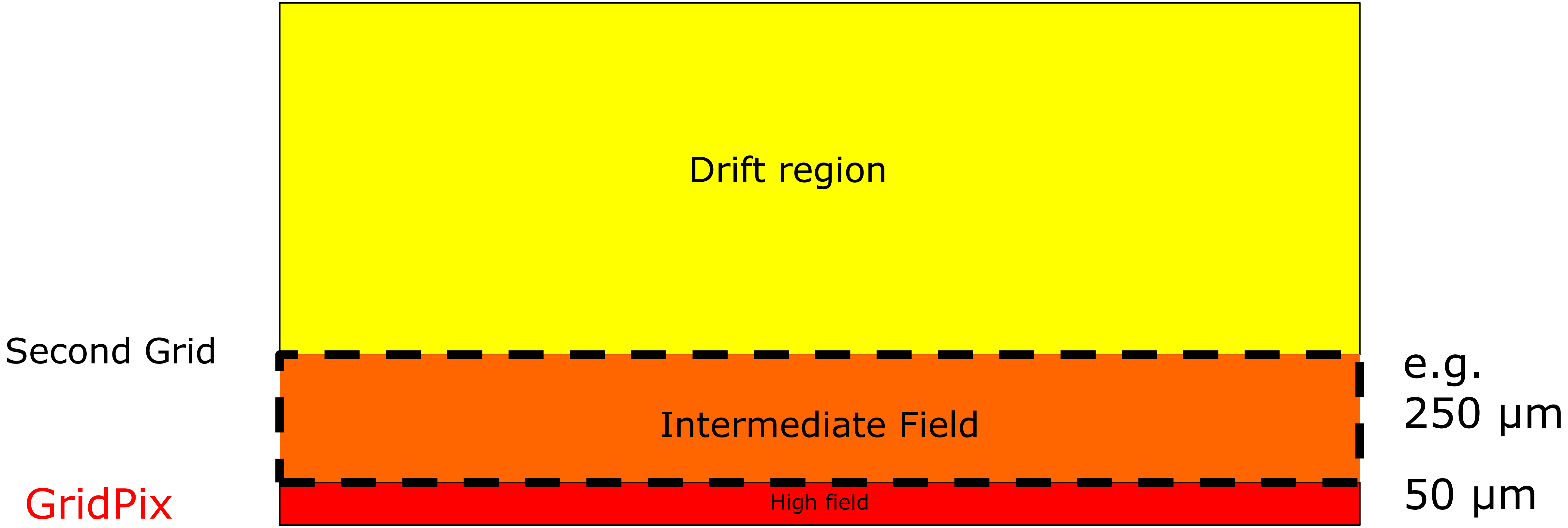
- Improvement of SiN layer and production of TPX3 GridPixes
- Ion Back Flow: Try out of a double grid structure
- TPX4: follow the ongoing development Nikhef R&D group
- 8-Quad Module Test beam in DESY is scheduled for June 2021
  - Measure the performance in a magnetic field as well as the deformations for a module
  - Analysis of the data and publication of the results
- Future manpower resources at Nikhef are rather limited
  - Post doc Naomi left and Kees will submit his thesis
  - No follow up project approved yet
  - The test beam is supported
- We are contacted by groups that show interest for: X ray polarimetry in space, TPC for Dark Matter searches or in a Heavy Ion experiment

Back up slides

Pixel TPC with double grid to reduce the ion back flow

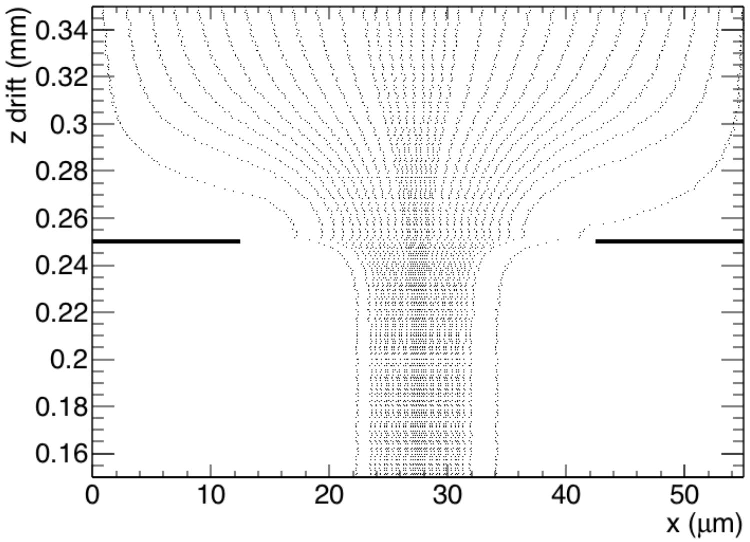
- Question: can one reduce the Ion Back Flow of a GridPix detector?
- We could design a GridPix detector using a double grid
- The idea is that by creating two field regions, one with a medium field and one with a high field (our standard Grid Pix) one could reduce the ion backflow in two stages.
  - The high field avalanche region has a measured IBF of 1.3%
  - The aim is to reduce the IBF by another factor 100
  - The second Grid replaces the Gating device and is always operational

Design of a double Grid

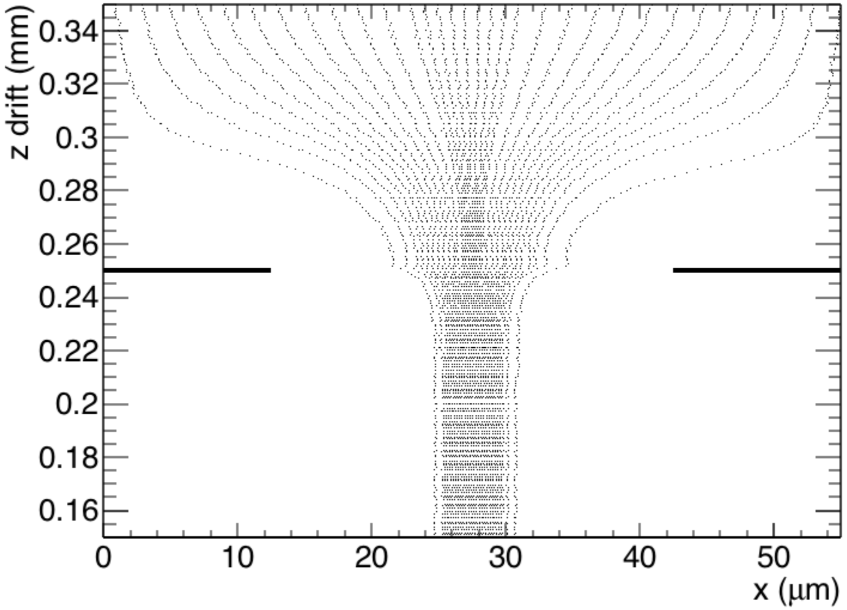


In (down) flow trajectories second Grid

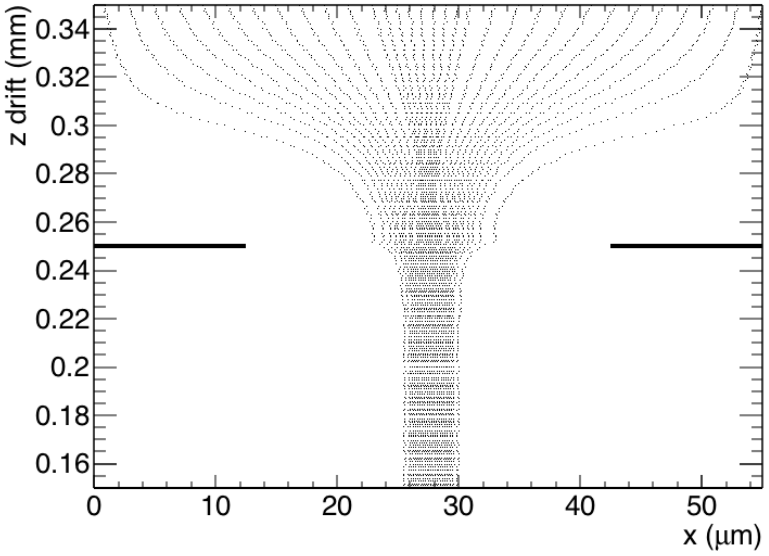
Field ratio 10



Field ratio 40



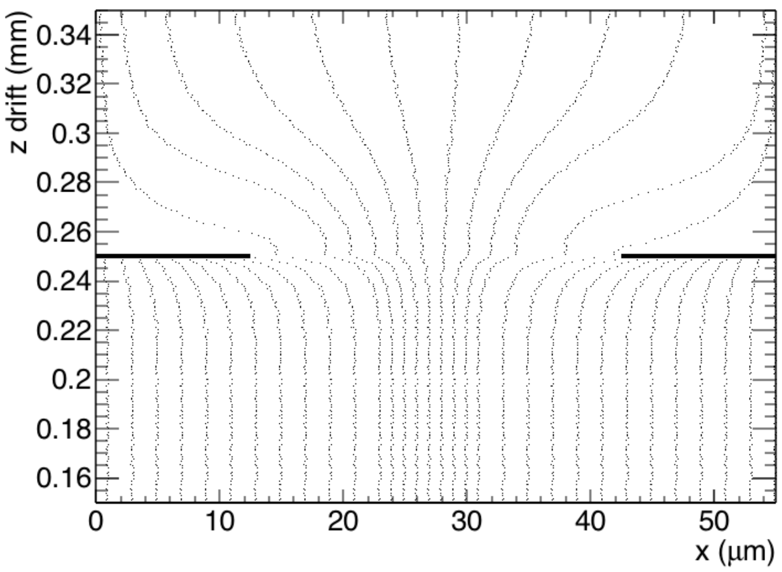
Field ratio 240



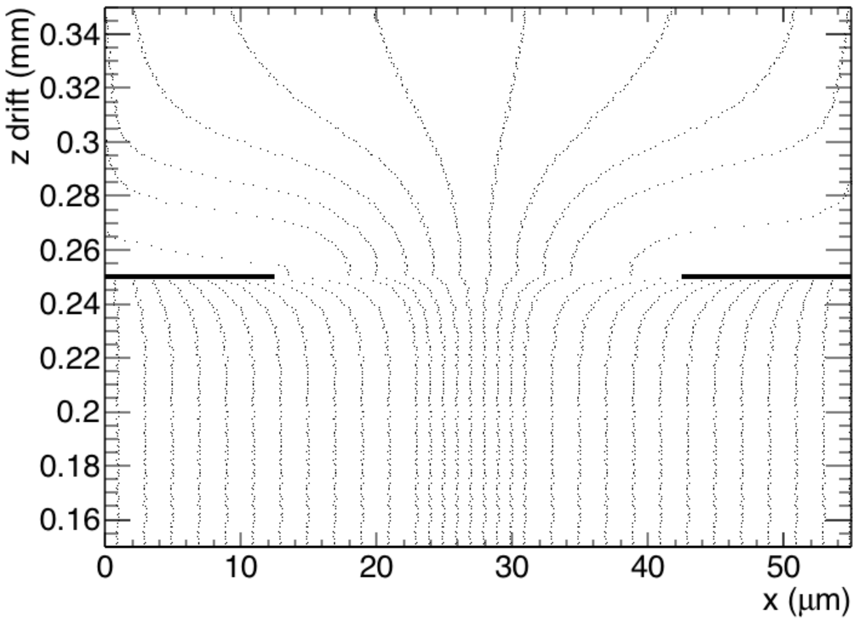
Geometry: second grid at 0.250 mm (z); Cathode at 550 mm
Standard GridPix pitch 55 μm and hole 30 μm
Field ratio = mean Field (0-0.250 mm)/ mean Field z (2-550 mm)
Electron tracking without diffusion:
σ (rms) size of funnel (focussing E field) = 2.6-1.5-1.1 (Fr 10,40,240)

Backflow (up) trajectories second Grid

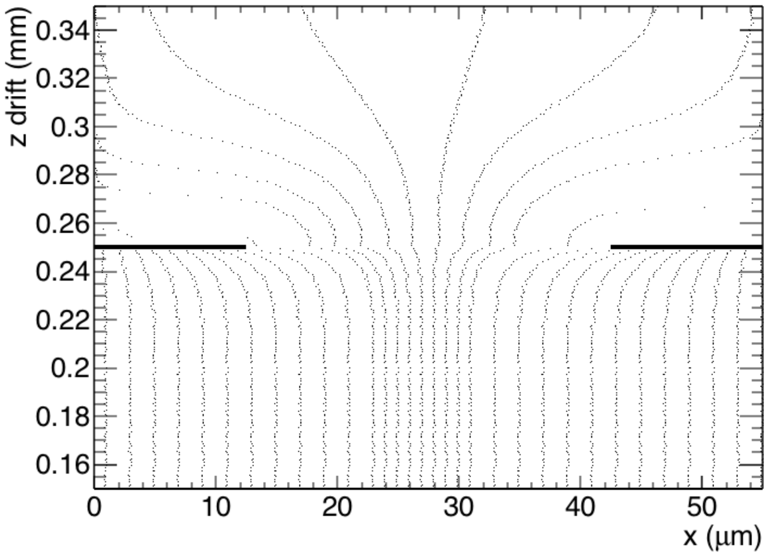
Field ratio 10



Field ratio 40



Field ratio 240



Here the trajectories of ions from the bottom upwards are shown
The differences between the different field ratios are small

Modeling of ion back flow

Modeling of the ion backflow is based on the measurements for a standard GridPix with FR 240. The ion backflow was measured to be 1.3%.

The Ion BackFlow is sensitive to the diffusion in the high field region.
The electron funnel size is 1.1 μm just from the field focussing.
For the GridPix (gap 50 μm) one expects an electron diffusion of 150-200 μm/√cm. This gives a smearing of the funnel of about 10-14 μm.
The calculated IBF corresponds to 1.3% for a smearing of 15 μm.
So this agrees reasonably well with expectations.

The performance IBF of the top grid.
What happens is that the back flowing ions that make it through the lower grid that runs at FR240 will be flat distributed if one is 60-100 μm or more above it.

IBF of the second grid

The performance IBF of the second grid.
What happens is that the back flowing ions that make it through the lower grid that runs at FR240 will be flat distributed if one is 60-100 µm or more above it.

The field ratio should not be too high to avoid gas amplification in the top grid. Therefore we leave out the FR240 point.

IBF (%) FR 40	FR 10
1.2	3.5

Transparancy of the grid

Another important aspect is the electron transparancy.
Using the simulation this can be calculated.

Transparancy (%) FR 240	FR 40	FR 10
100.	100.	99.0

It is important to choose a FR with a high (electron) transparancy so with FR of 40 or higher.

Further reflections on the gap size

Another important aspect is diffusion that takes place in the intermediate field region. For the T2K gas this can be at most 400 μm/√cm. The gap is the distance between the two grids.

Smearing σ (μm) gap 1 mm	gap 250 μm	gap 60 μm
126	63	31

So in case of a 1 mm gap there is a sizeable probability that the neigbour pixels detect the avalanche.
So a smaller gap is preferable.

Ion backflow for a double grid

Here calculations for the IBF of the two grids in case one has a total FR of about 240 – normal GridPix operation. For the simulations the FR of the top grid was put at 16. The lower Grid(Pix) was at FR 16 too. Total FR 256.

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%

In order to reach IBF*Gain ($2\ 10^{3}$) below one has to choose a slightly smaller hole size of 25 or 20 microns.

Conclusions: double grid

The Ion Back Flow can be significantly reduced by putting a grid with a identical pitch and hole size on top of the Gridpix.

A device placed e.g. at 60-250 μm above the GridPix and ran with a Field ratio of 16 (top) and 16 (lower) would do an excellent job.
The electron transparancy would be over 99 (91)% and the IBF would go down from 1.3% to 3 (1) 10^{-4} for a hole size of 25 (20) μm.

This would solve the issue of IBF at CEPC and ILC.

We could do a test at Nikhef mounting this grid on top of the Gridpix (holes 30 μm) and measure the electron transparancy and the IBF and test the prediction on the previous slide.

It would be interesting to think about a post-processing step to integrate the two grids.