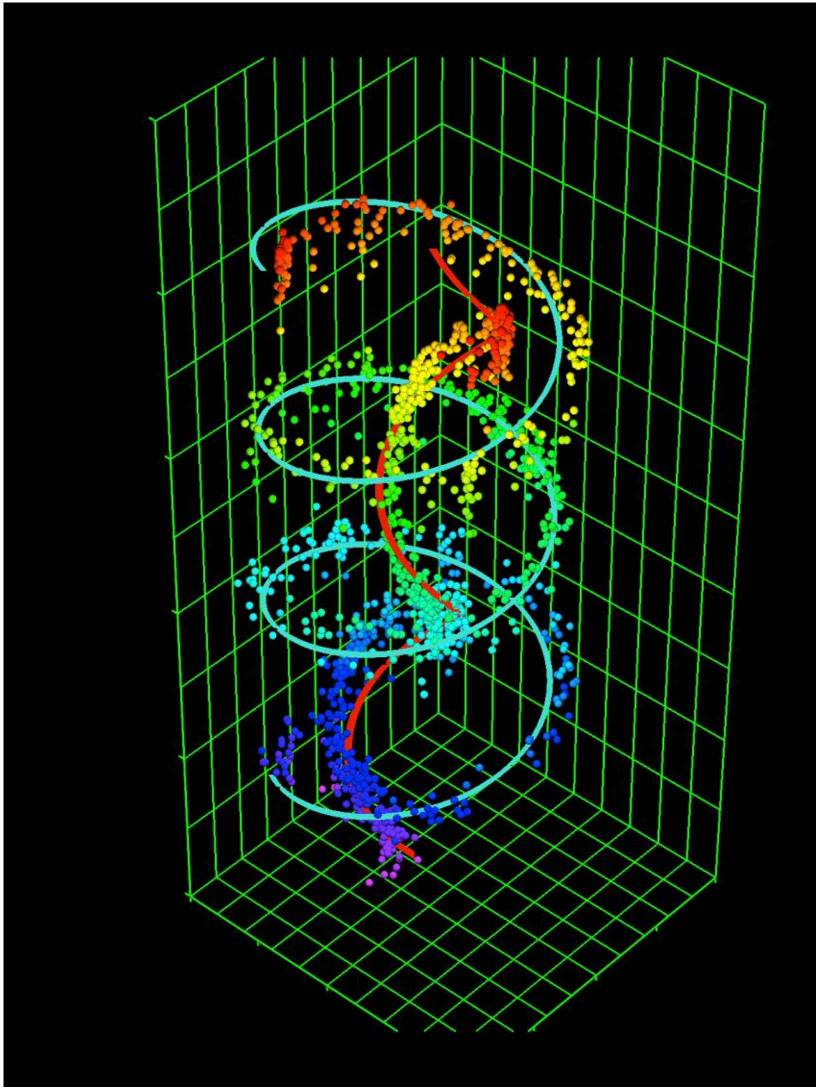
A general-purpose and GridPix-based 'Quad' modular readout system for TPCs

Test beam results of a quad GridPix TPC with focused electric drift field

+ reaching transmission secondary electron yield TSEY = 5.2

Harry van der Graaf
Nikhef & TU Delft

RD51 MiniWeek
Dec 14, 2016



2007: GridPix with functioning protection layer the ultimate TPC detector:

- single electron sensitive
- extract ALL info of primary electrons in gas
- only gas diffusion limits TPC performance
- (and pixelsize)

2007 – 2016:

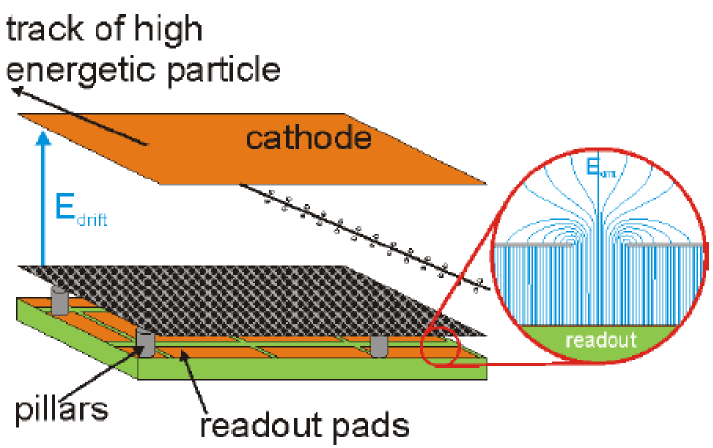
1. attempt GridPix mass production on wafers: wafer post processing (InGrid)
2. Improve protection layer: no faults permitted

GridPix & InGrid *stalled* for the last 6 years

From Micromegas to GridPix Detectors

universitätbonn

Micromegas



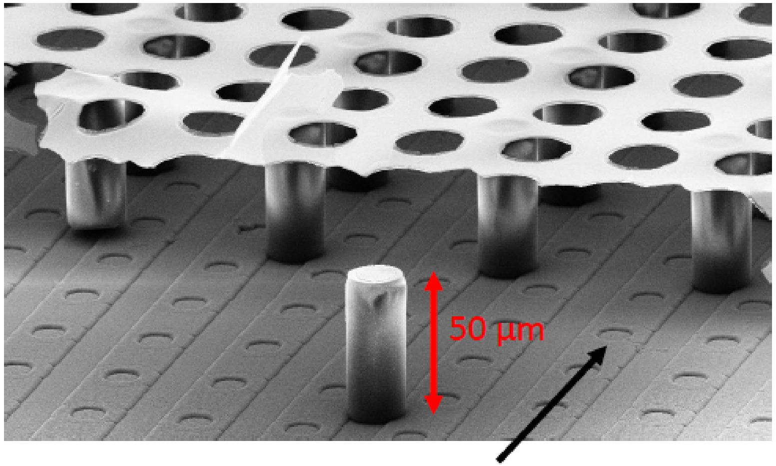
Standard charge collection:

- Pads of several mm²
- Long strips (~10 cm length, ~200 µm pitch)

Diffusion within gas amplification region:

- $Ar:CH_4$ 90:10 → σ ≈ 25 µm
- $Ar:iC_4H_{10}$ 95:5 → σ ≈ 25 µm

GridPix



Smaller pads/pixels should improve spatial resolution

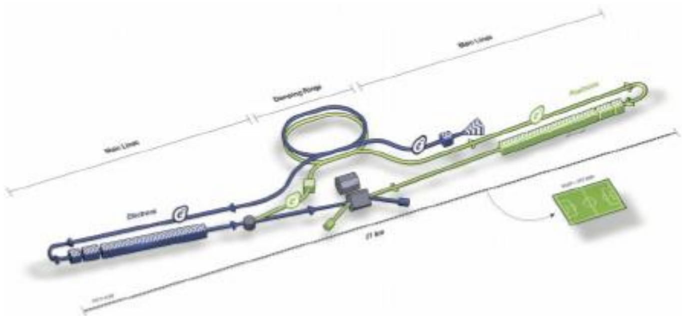
Invention of the GridPix in 2006 at Nikhef

Nikhef

Use **bump bond pads** of a readout ASIC as charge collecting anodes

Production of Micromegas structure directly on top of pixelized readout ASIC through photolithographic postprocessing

Applications III – Large Area GridPix Detector

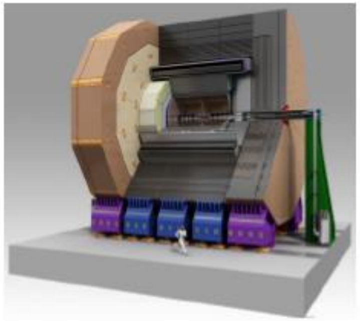


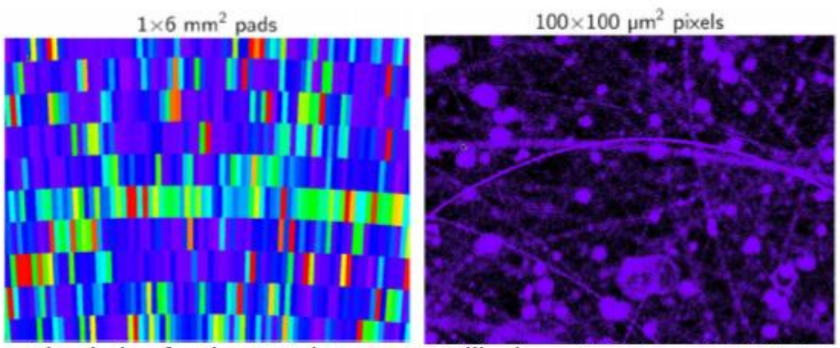
International Linear Collider:

- Linear e^+e^- collider with $\sqrt{s}$ = 500 GeV – 1 TeV

International Large Detector:

- One of two ILC general purpose detectors
- Foresees a central TPC as main tracker

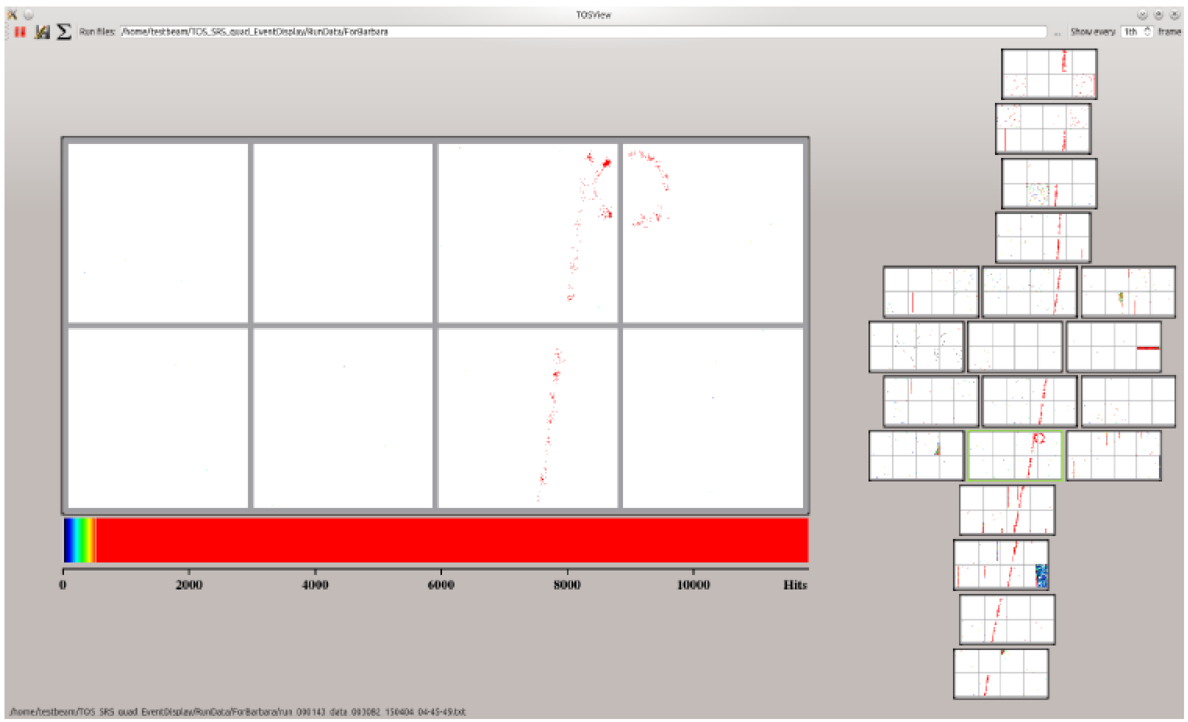




Simulation for the CLIC detector, M. Killenberg, LCD-Note-2013-005

- High occupancy through background processes ($\gamma\gamma$ → hadrons, e^+e^- → pairs/beam halo)
- Use of GridPixes would minimize the occupancy
  → better track finding, δ-ray removal
  → improved dE/dx by primary e^- counting
  →pad plane and readout electronics fully integrated
- For full readout of ILD-TPC about 50,000 to 60,000 GridPixes are needed (2 endcaps with 10 m² each)
  → need to prove large area coverage and scalability

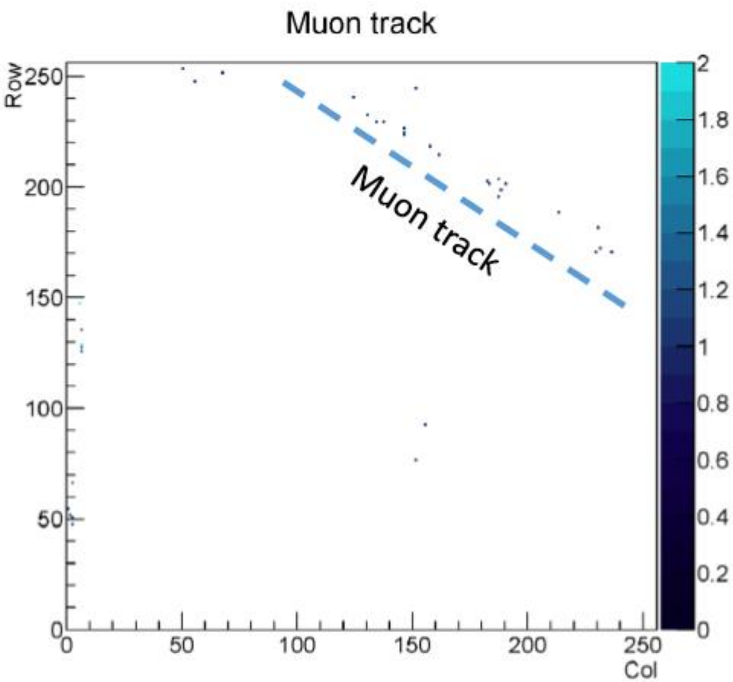
Applications III –
Large Area GridPix Detector

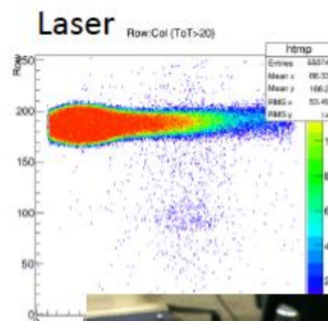


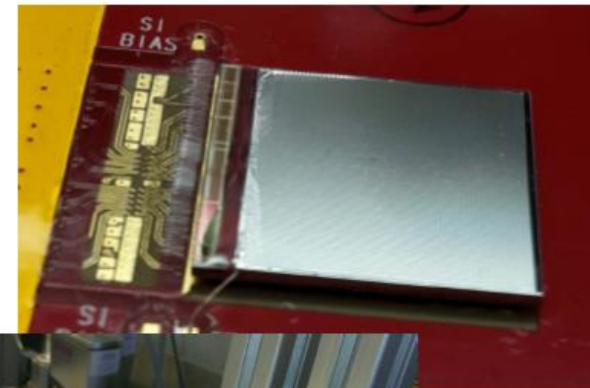
First Timepix3 GridPix

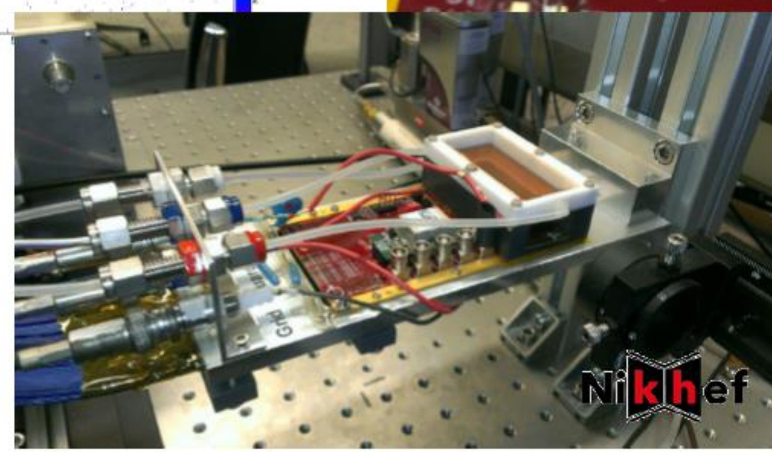
In collaboration with Nikhef LEPCOL group:
F. Hartjes, K. Heijhof, P. Kluit, G. Raven,
J. Timmermans, S. Tsigaridas, H. van der Graaf

- First Timepix3 wafer has been successfully processed at IZM Berlin
- First tests with Timepix3 GridPix were performed at Nikhef some days ago









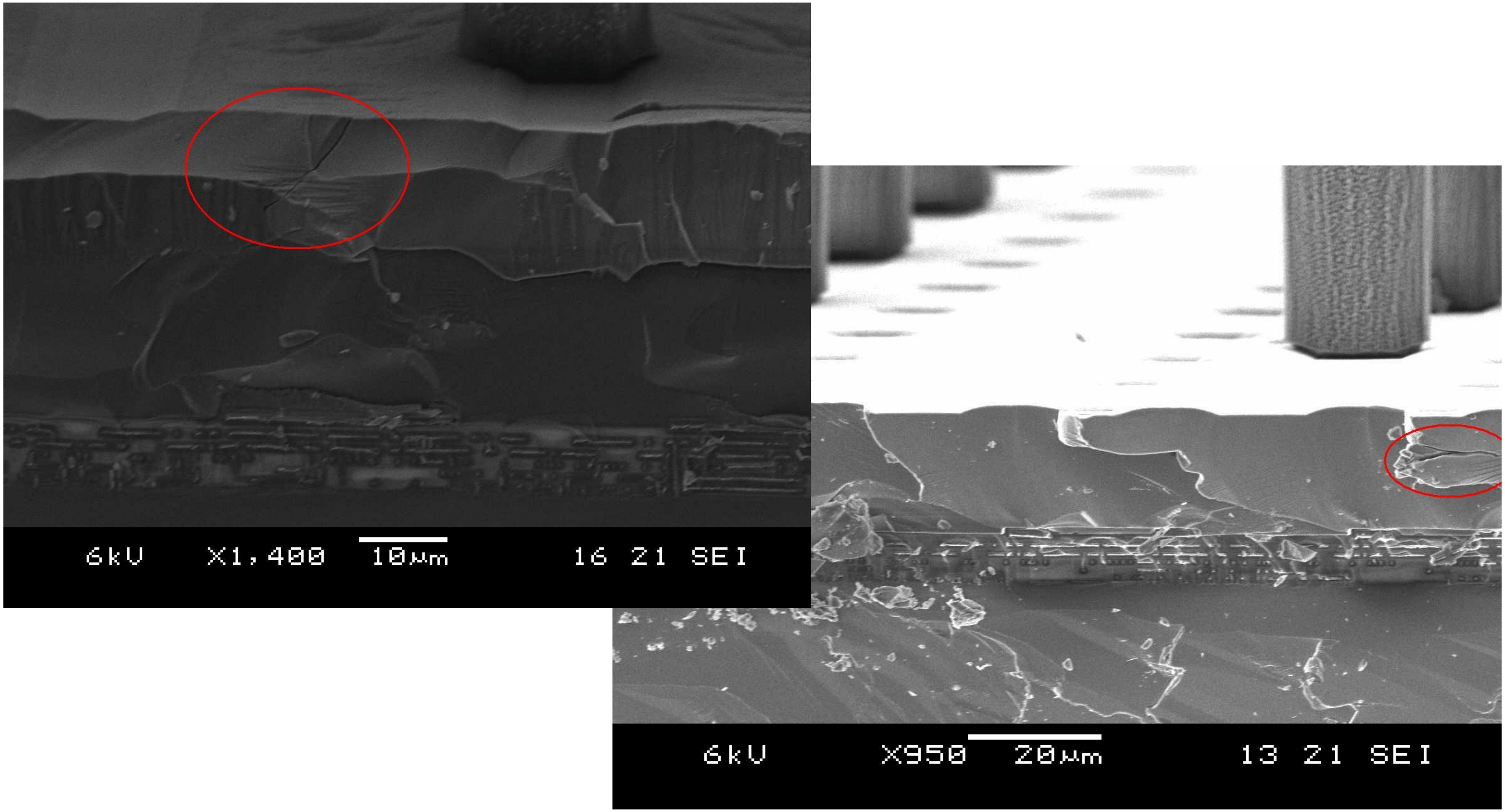


Fig 6. SEM images of a cut-open GridPix chips, clearly showing the SiNitride protection layer on top of the chip, of which its metal layers are well visible. A fault in the form of a cavity is identified and indicated.

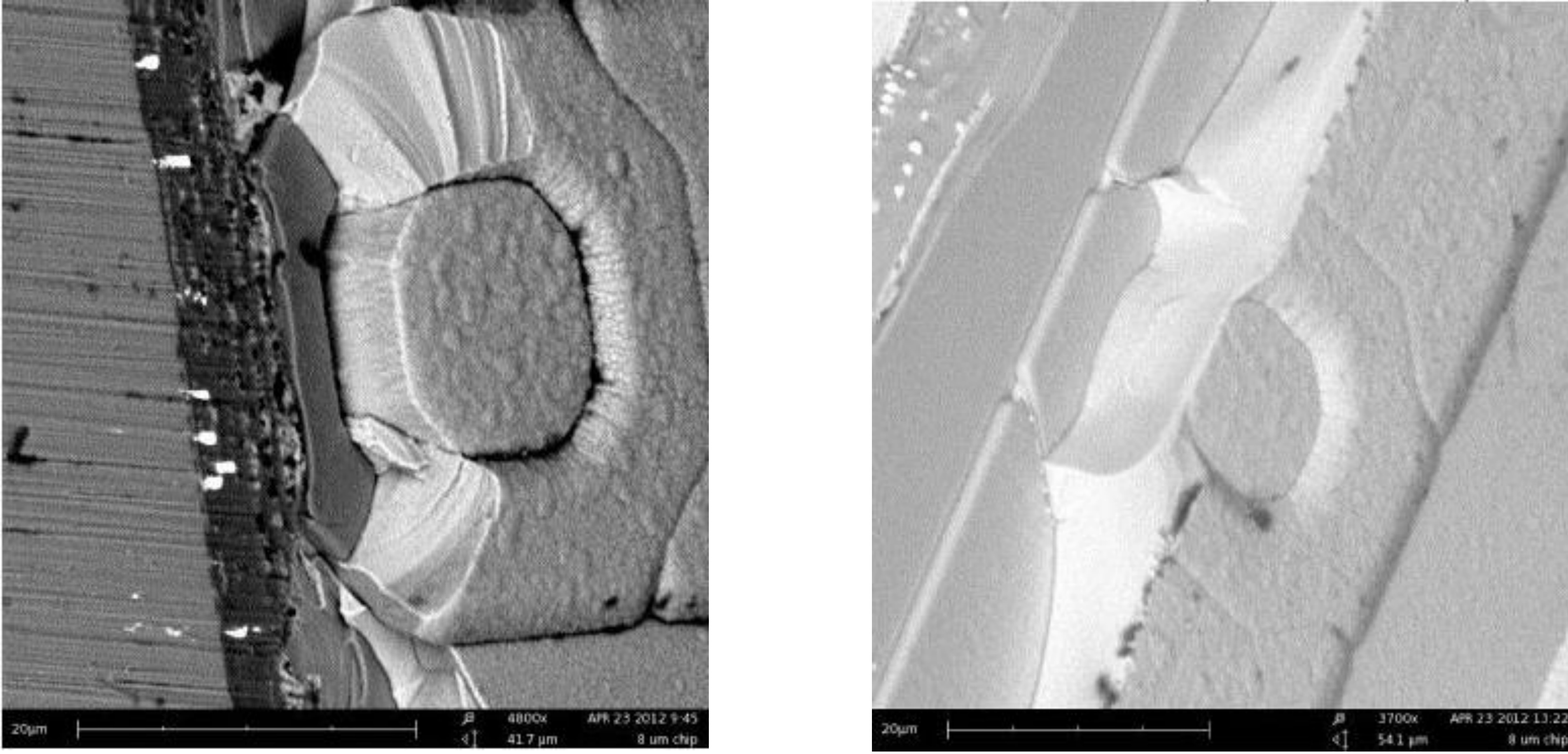


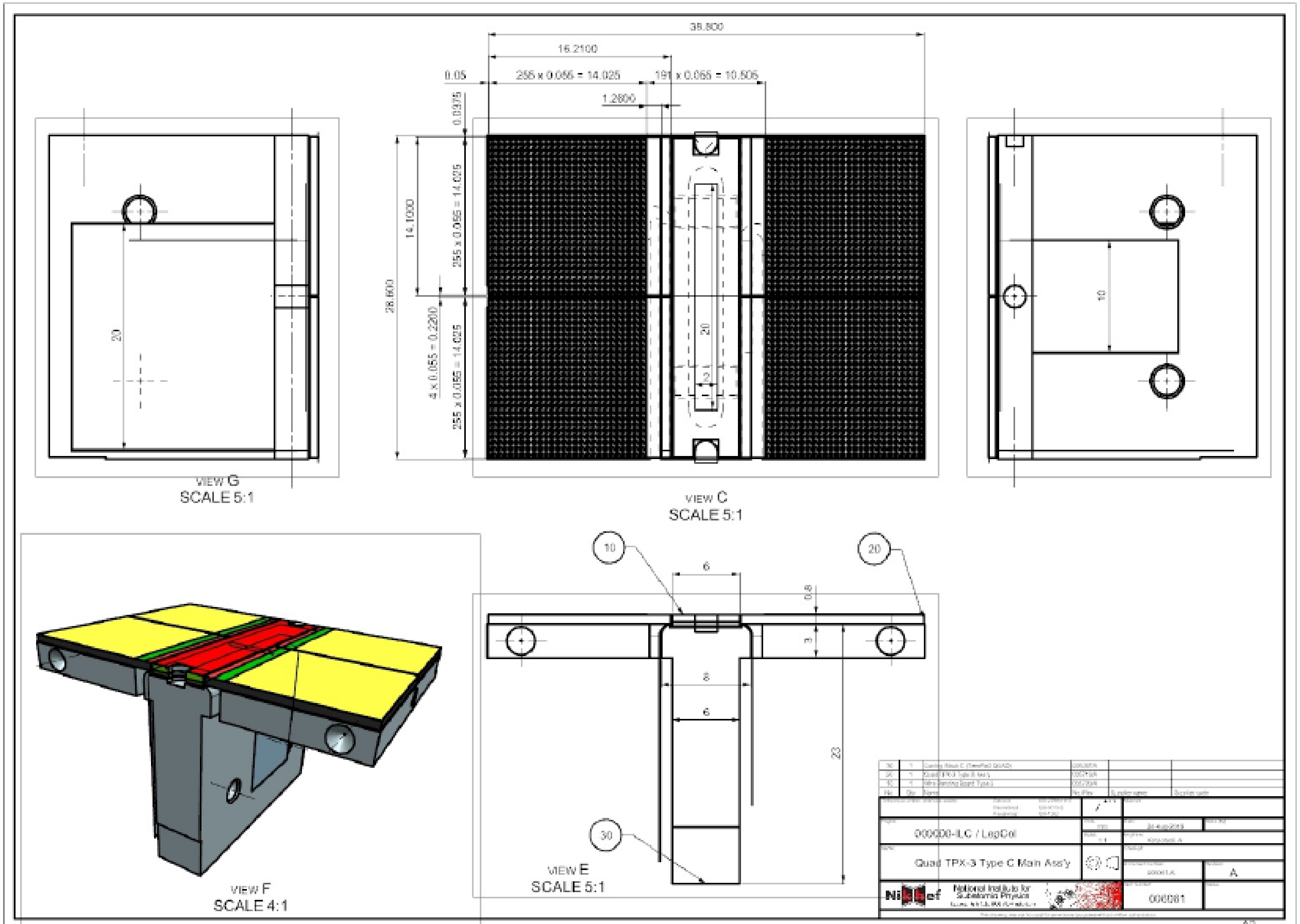
Fig 7. The pixel input pads of the TimePix 1 chip cause a well-known irrigularity acting as seed for a cavity (defect) in a protection layer to be deposit. Left: edge variation seeds cavity, right: no problem

New opportunity:

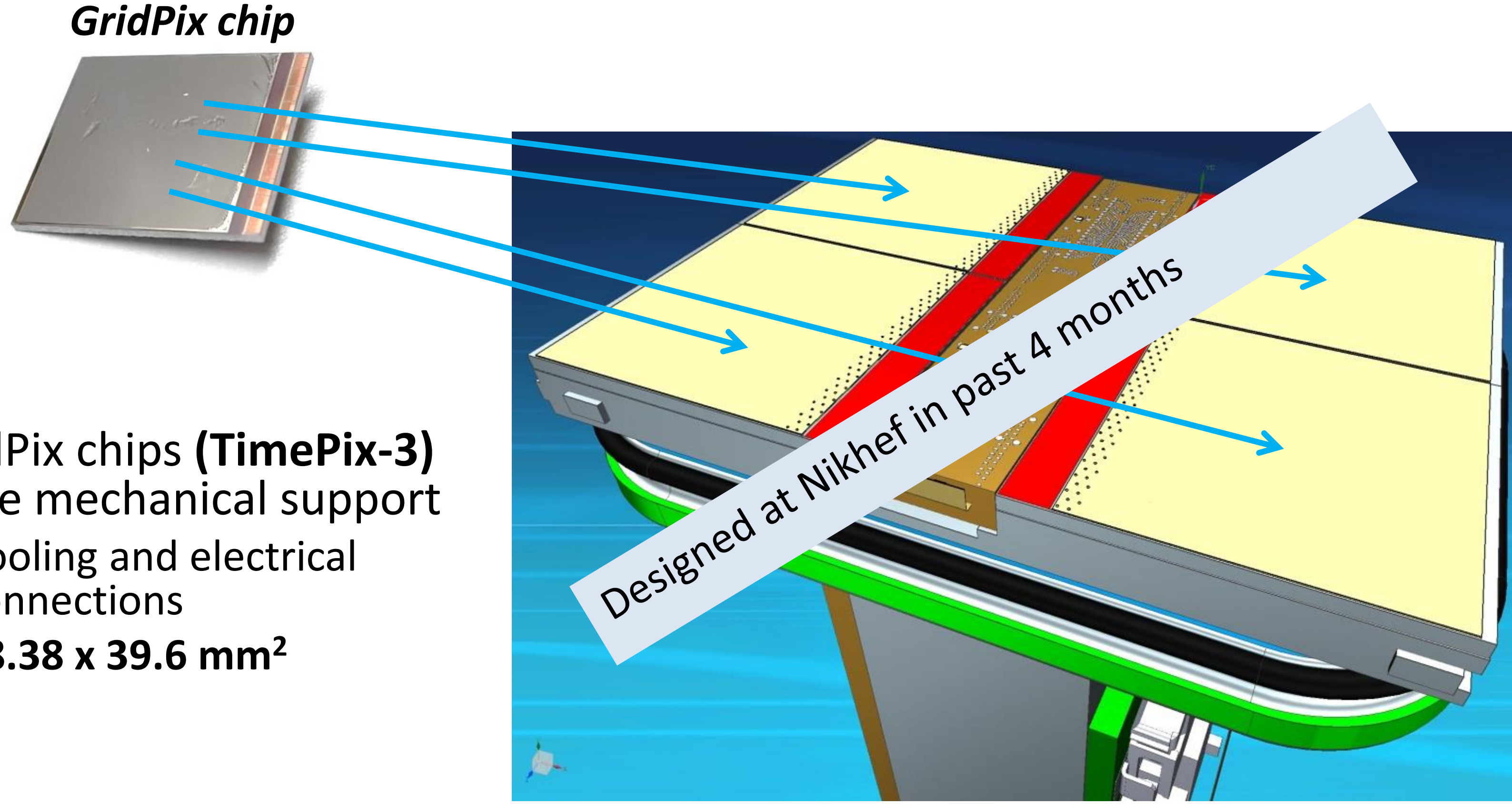
- IZM-Berlin can now (2016) make much better (fault free) SiNitride protection layer
- A series of Timepix-3 based GridPixes has been made, better discharge proof
- Bonn and Nikhef have started the LepCol project: GridPix for the TPC for ILC

- Modular system: small basic surface modules, exchangeable, repairable
- Large number of feedthrough’s (50/GridPix chip)
- cooling required
- Readout with SPIDRE system; each Quad connected with multichannel Concentrator

Quad TPX-3 Type C Main Ass’y (006081_A1 & 006057_A1)



Realisation GridPix technology



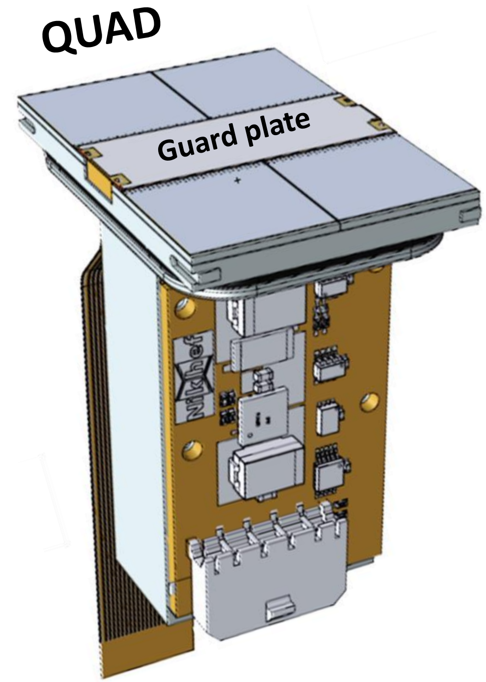
QUAD building block

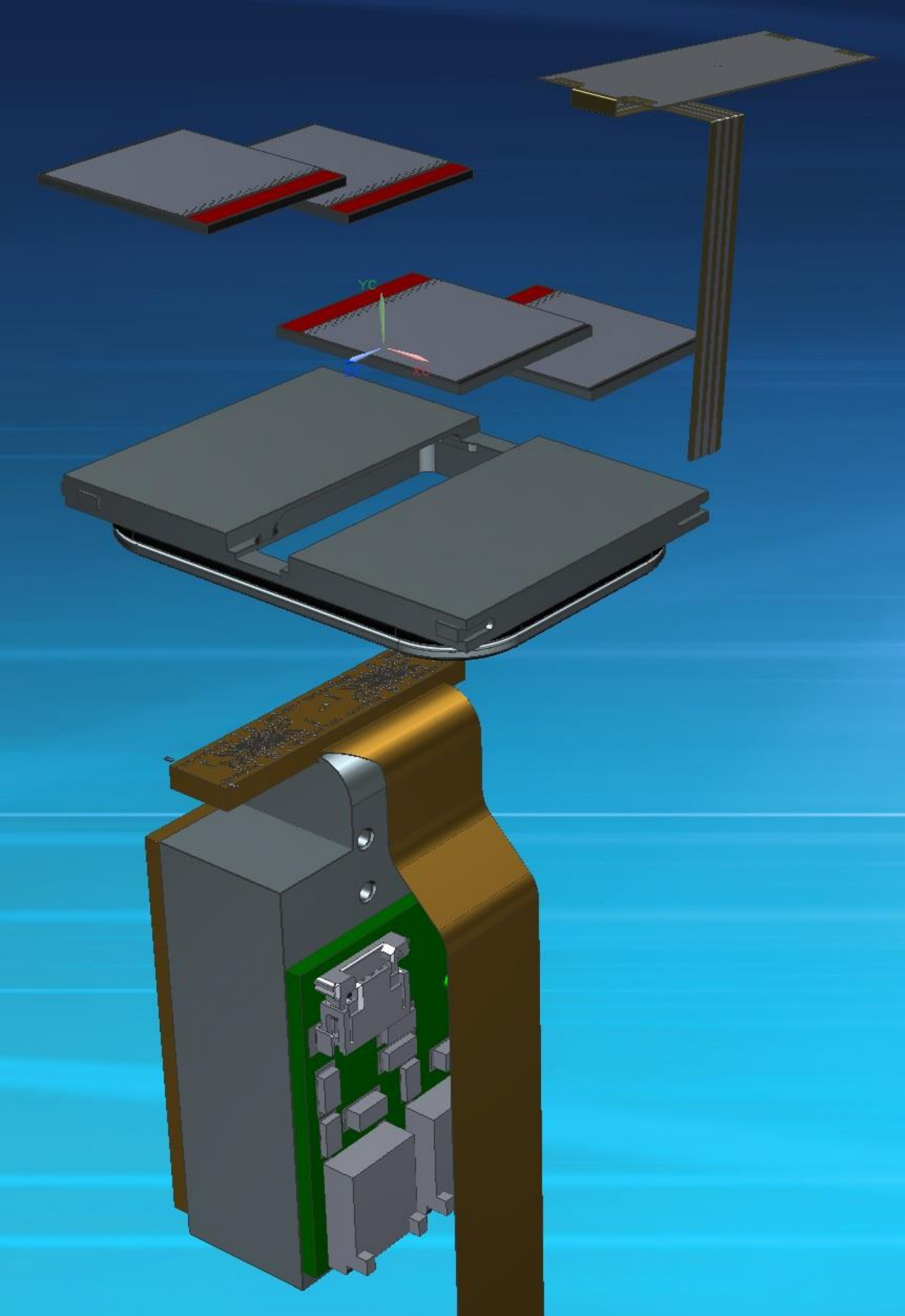
- 4 GridPix chips **(TimePix-3)** on one mechanical support
  - Cooling and electrical connections
  - **28.38 x 39.6 mm^2**

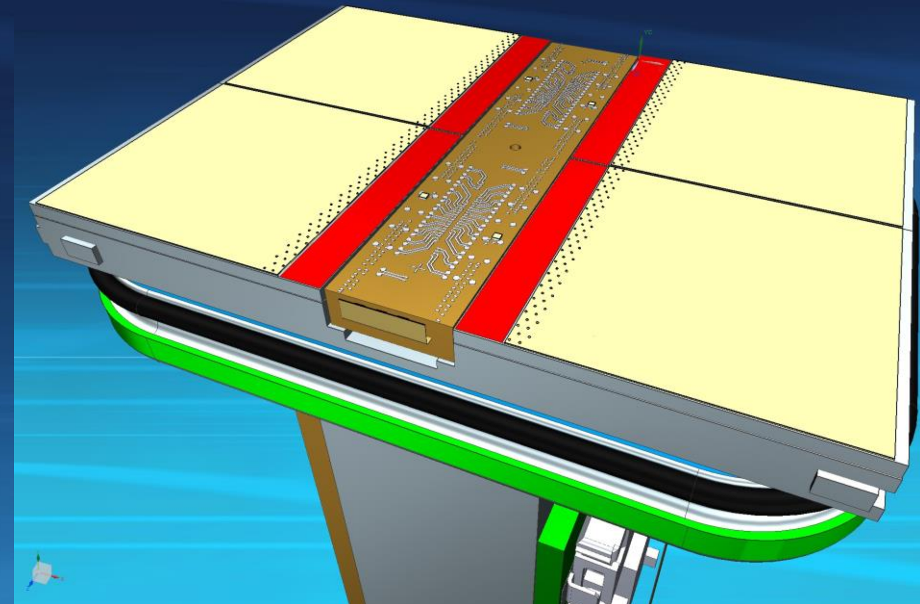
- All chips wire bonded to central interface board

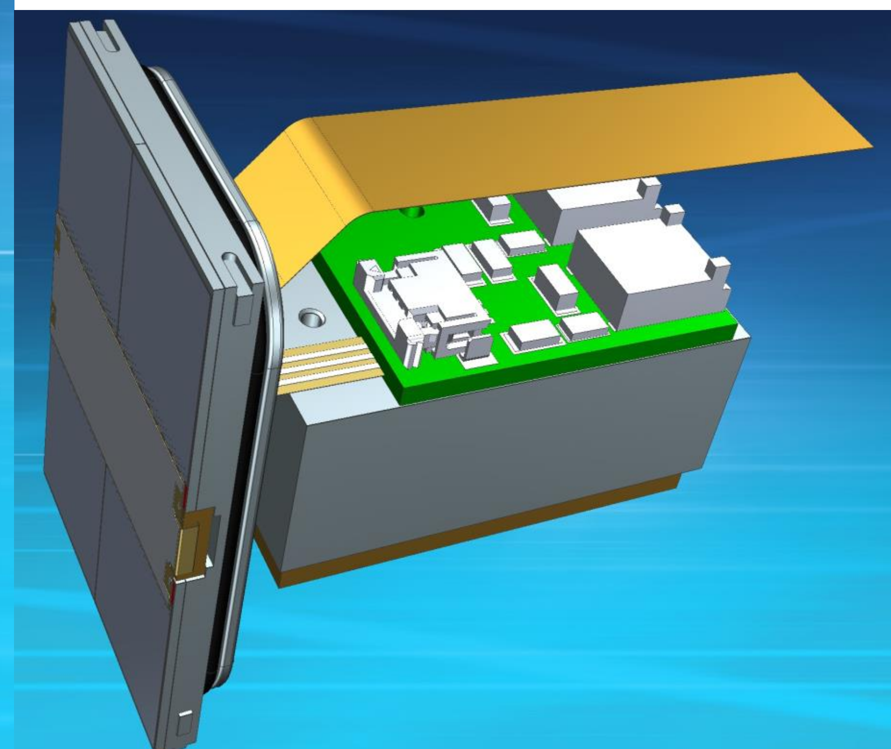
Building block

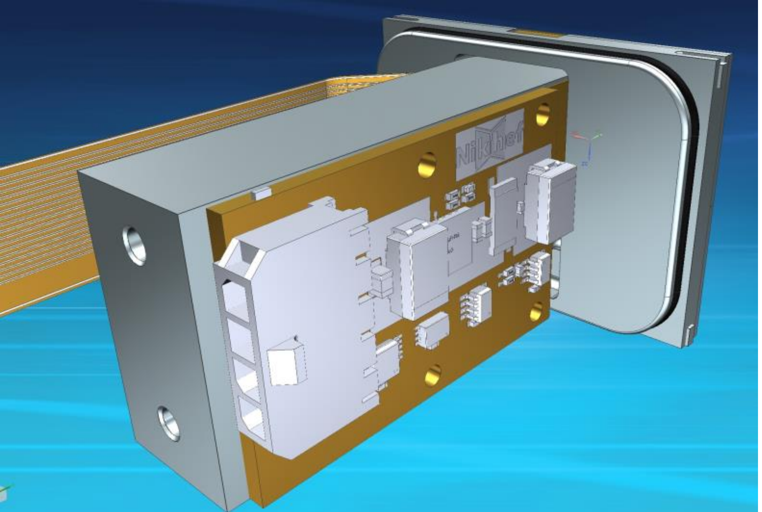
Unlimited surface may be covered

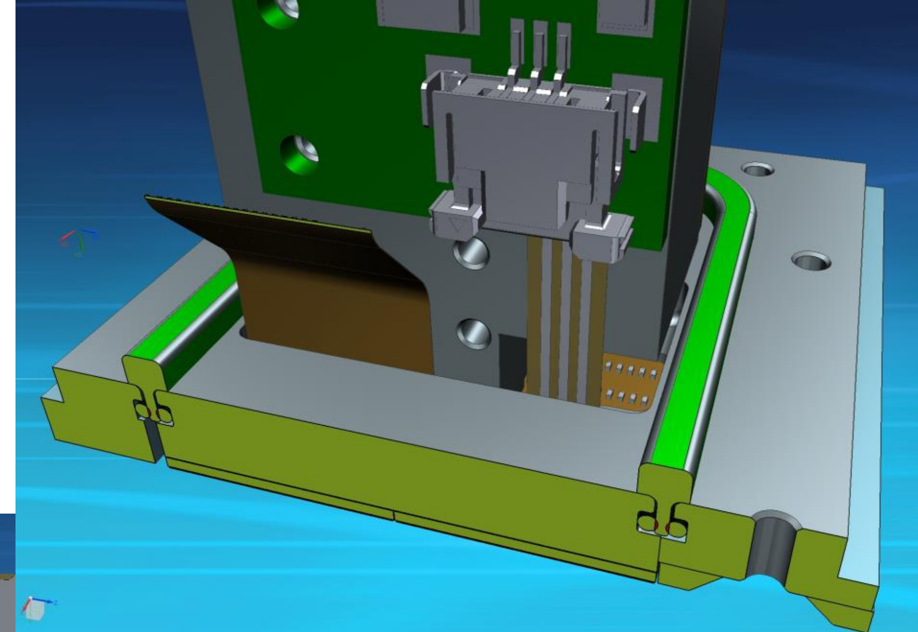


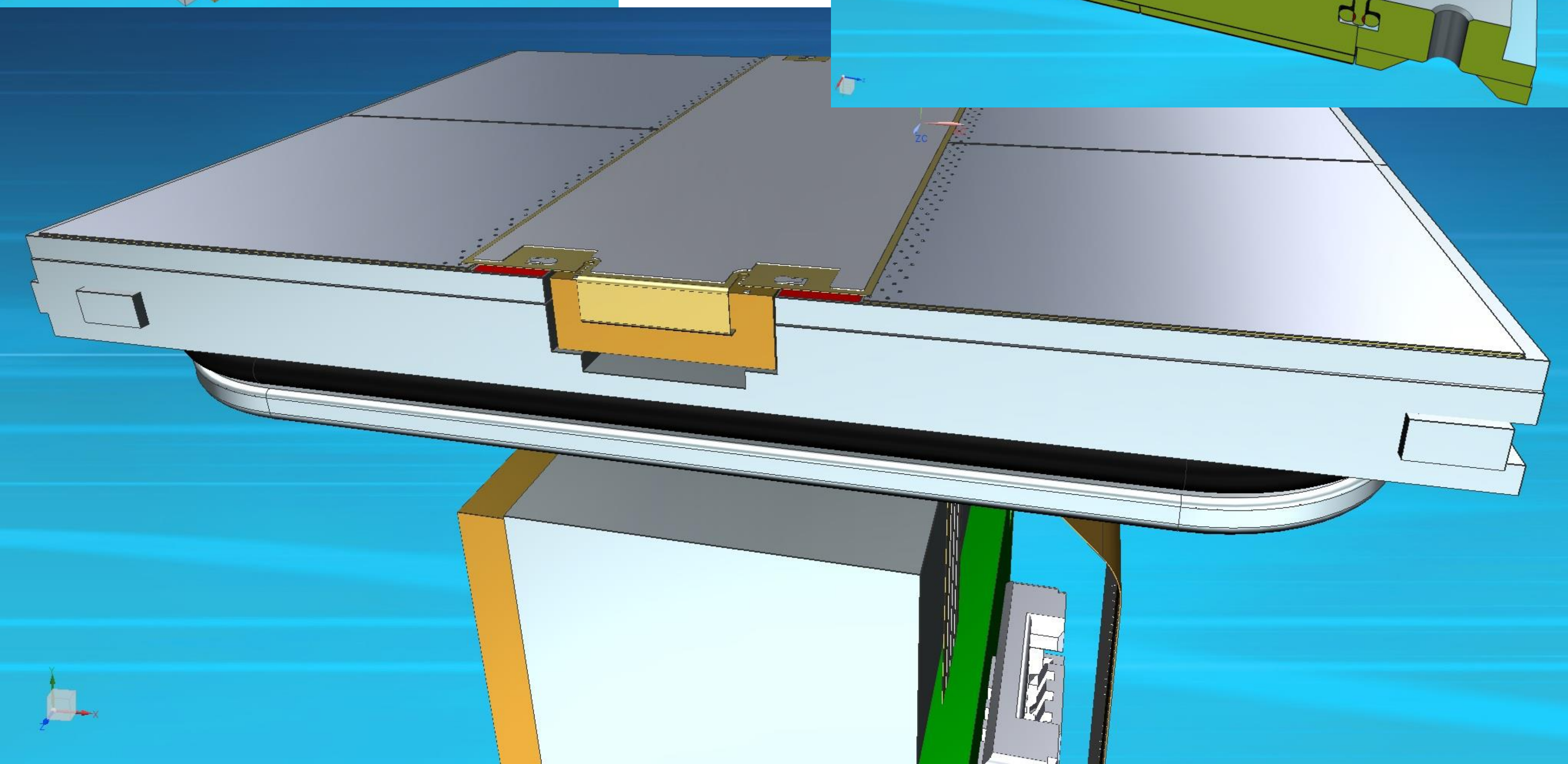












The heart of the QUAD

- **Two PCBs connected by flex**
- Fabricated as one item
- No connectors

Quad Building Block

- single primary electron sensitive
- Time resolution 1 ns, 2D spatial resolution 20 um
- electron detection efficiency > 90 %
- data driven hit-pixel output @ 2.2 Gb/s (SPIDRE)
- modular system: basic unit includes 4 TPX-3 GridPix (28 mm x 40 mm)
- fiducial surface: 60 % of total (peripheral electronics & wire bonds (TSV!)

- Should become available for third users
- Future new versions:
  - larger basic units
  - better surface efficiency: Through Silicon Via's (TSVs), reduced peripheral area
  - reduction of effective radiation length X0: replace aluminium by C-foam

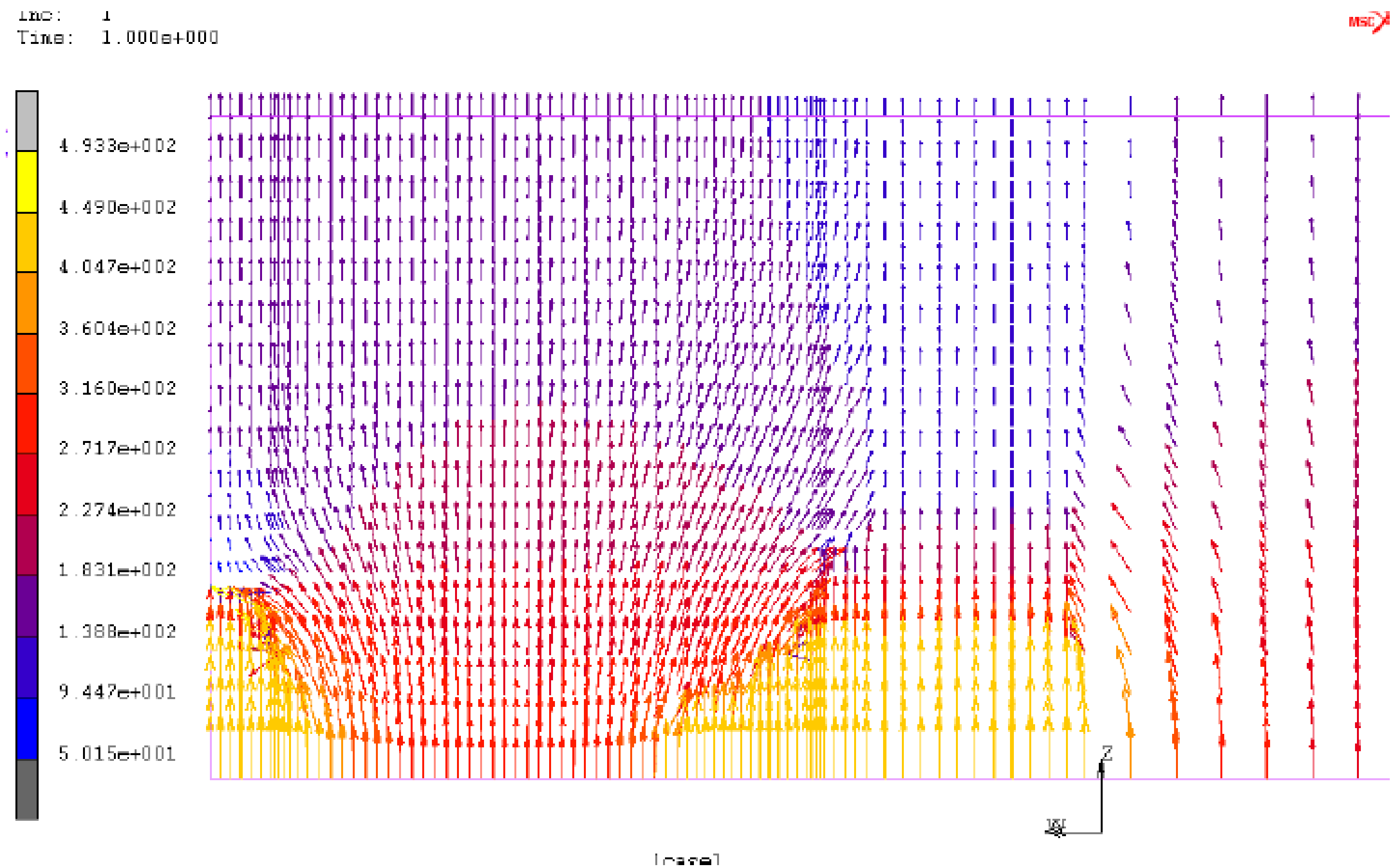
Drift Field Focusing

‘dead’ area between GridPix fiducial areas:
distortion of electric drift field

What about a controlled drift field distortion?
Focusing may reduce dead area

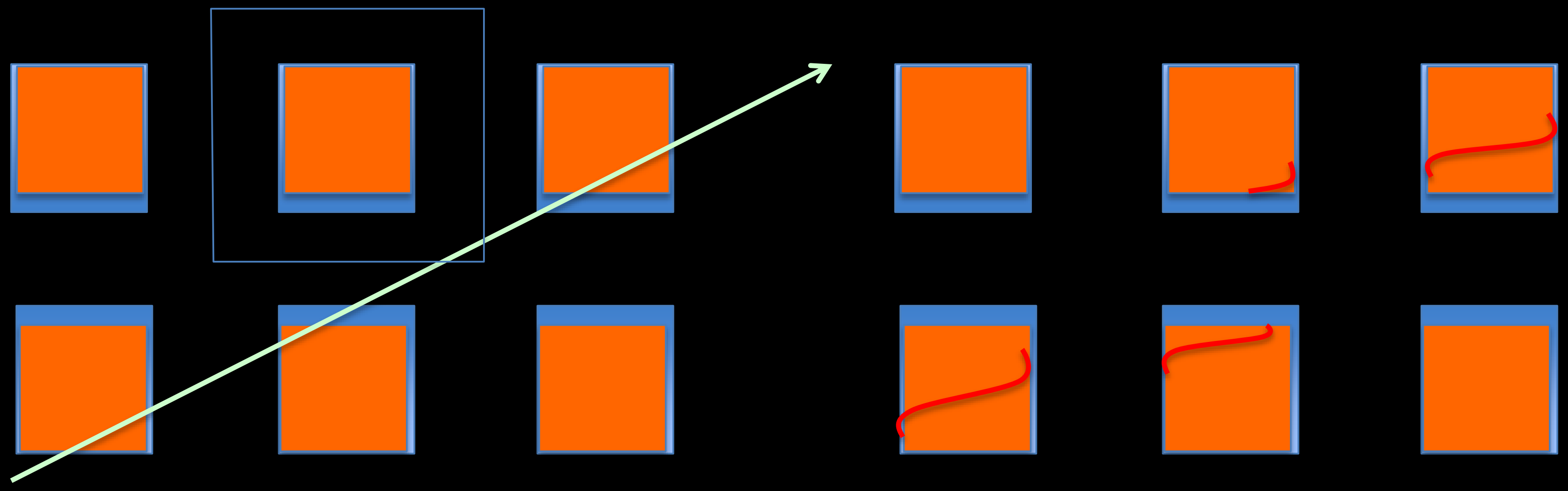
QuadFocus

- 3D simulation
- Upper part homogeneous E-field
- Lower part controlled focused E-field



work:

- pcb
- focusing electrode
- cooling (ReLaXd)

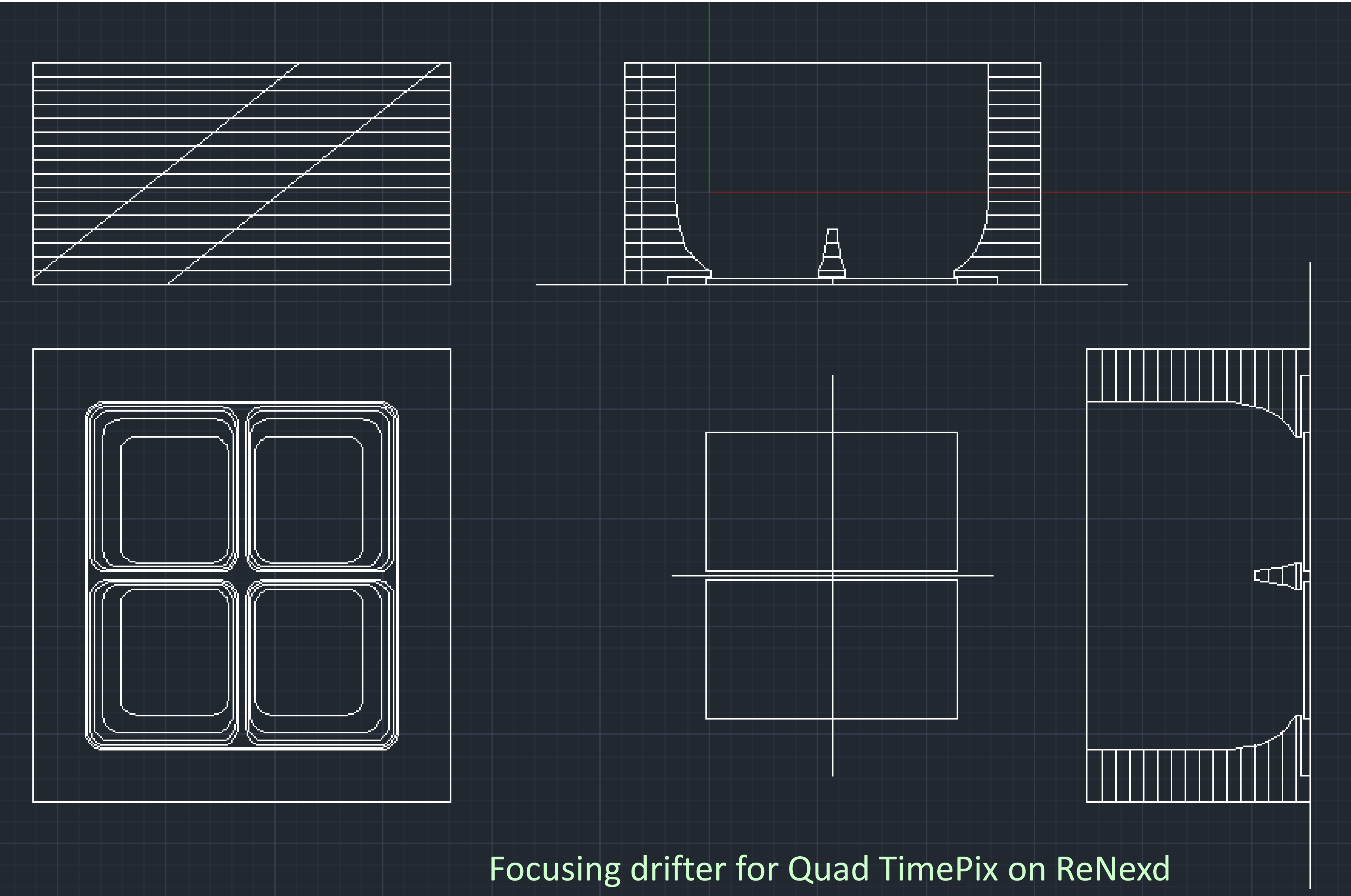


Autocalibration

- get initial f(X,Y)➔ (X’,Y’) from 3D e-field
- make scatter plots of residials
- modify f(X,Y) until residuals are minimized

Basic correction: X’ = C X, Y’ = C Y

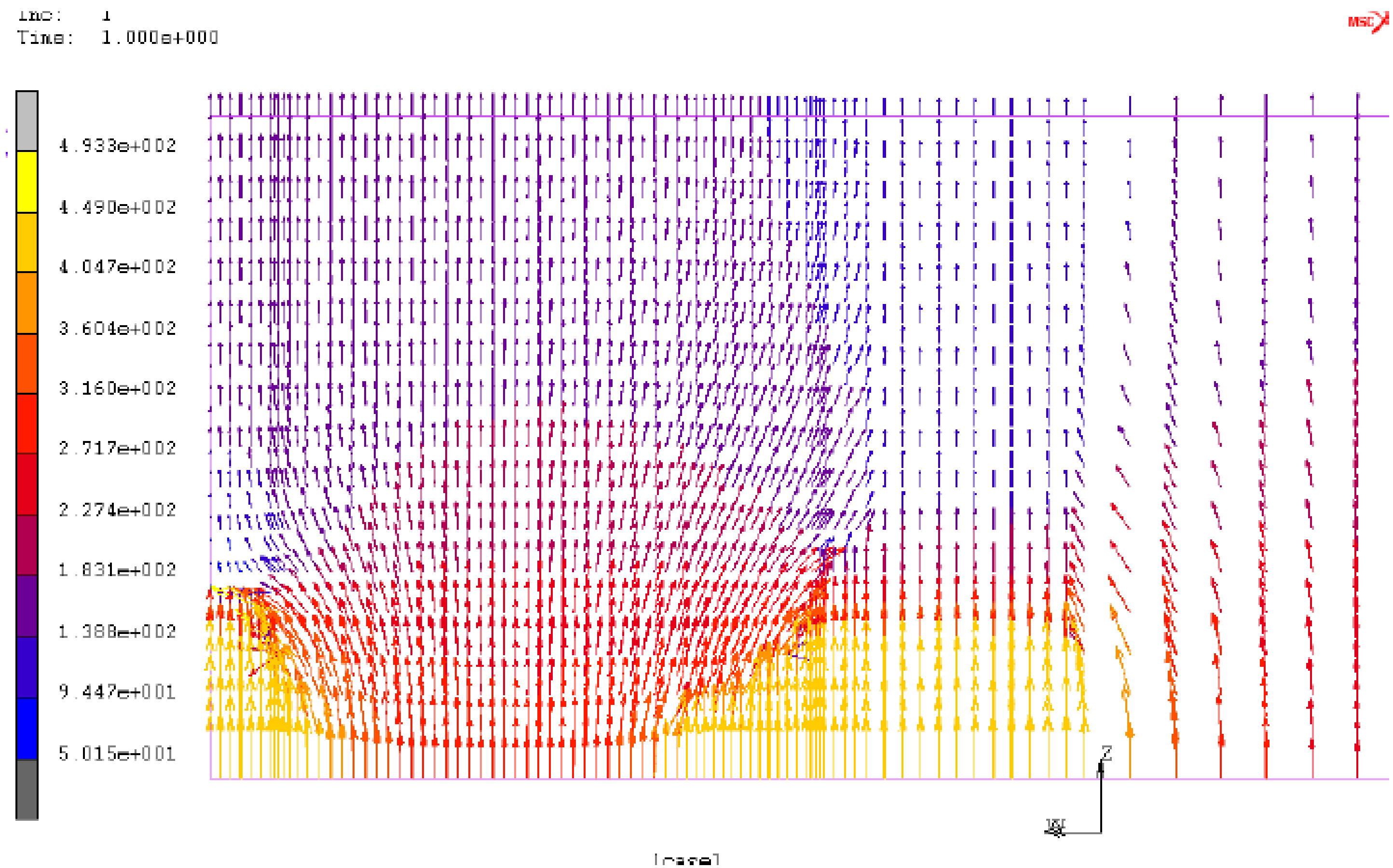
+ E x B effect



Focusing drifter for Quad TimePix on ReNexd

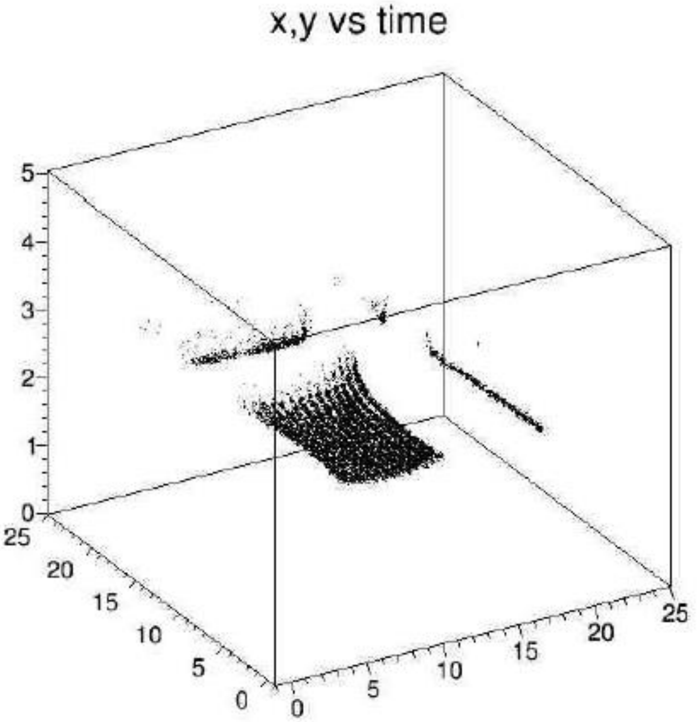
QuadFocus

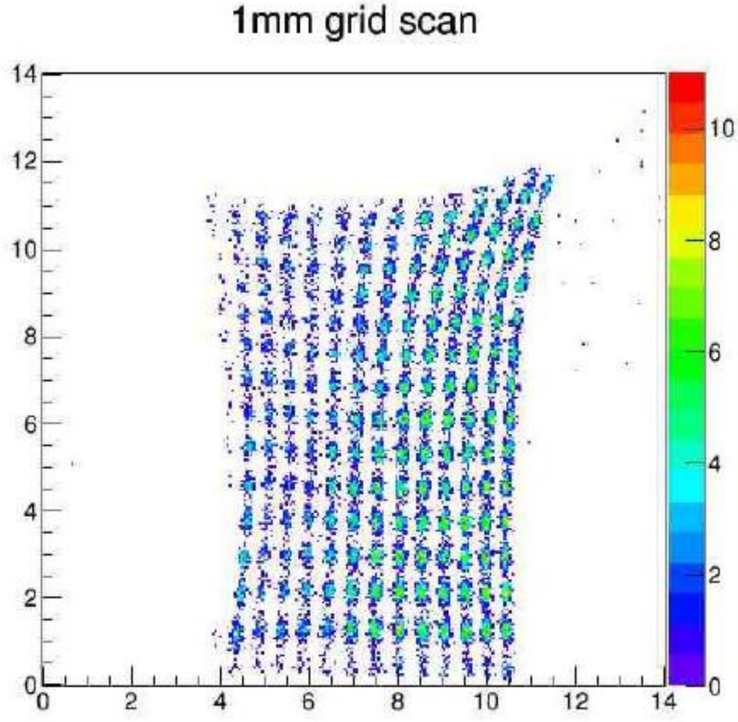
- 3D simulation
- Upper part homogeneous E-field
- Lower part controlled focused E-field



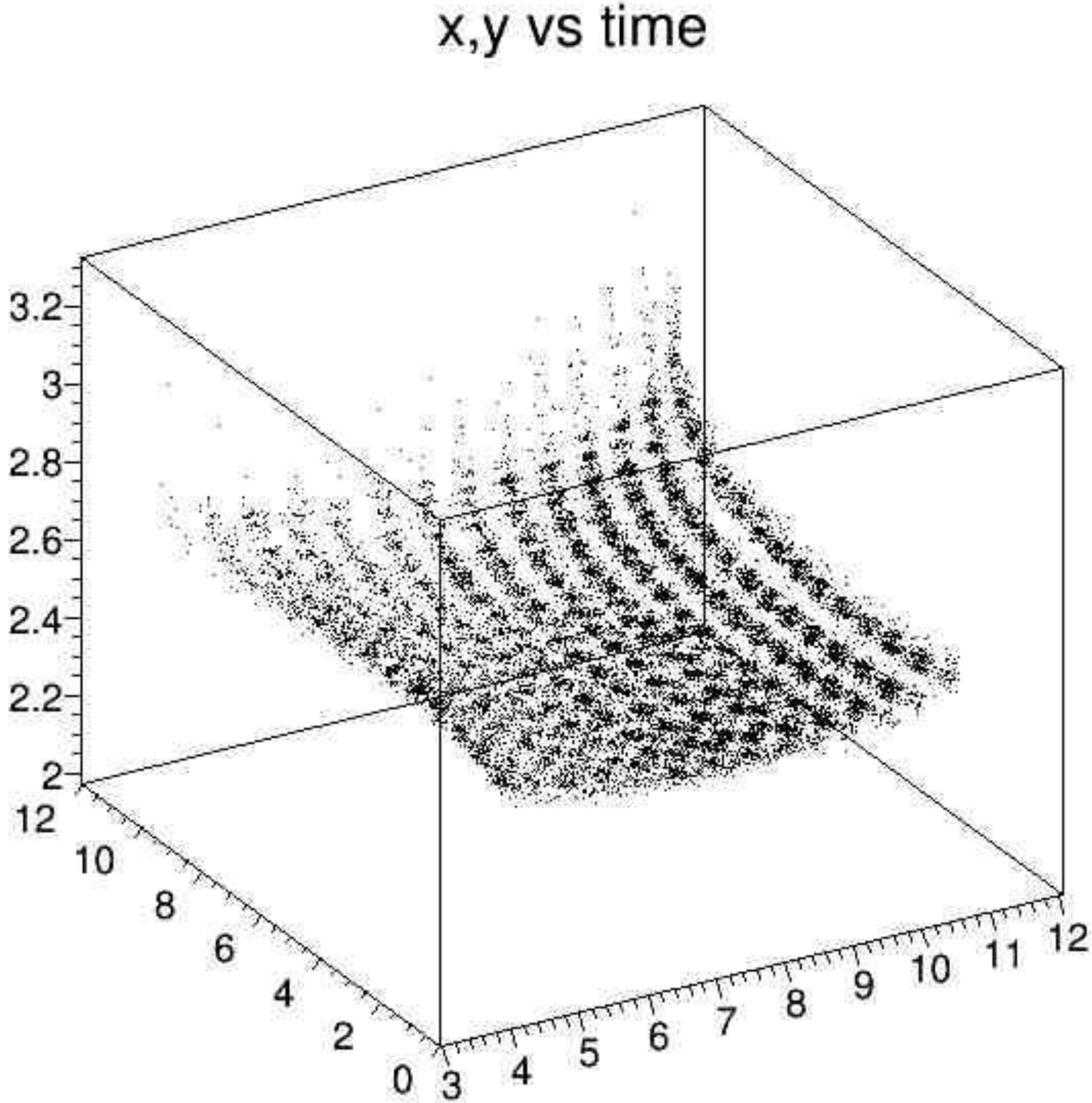
E-field deformations

- Single chip electron depositions in 1[mm] grid
- Height drift due to longer path
- No dead spot between chips



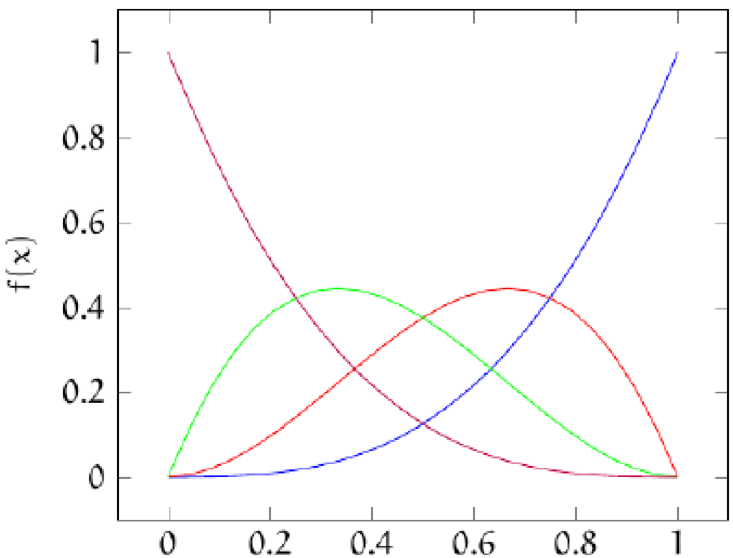


measured with focused UV N_2 laser with 3D adjustable focal point

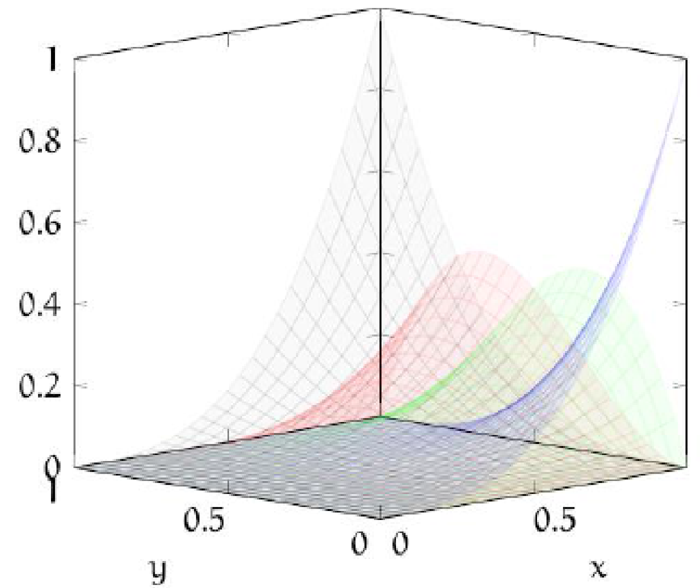

x,y vs time
3.2
3
2.8
2.6
2.4
2.2
2
12
10
8
6
4
2
0
3
4
5
6
7
8
9
10
11
12

BiCubic interpolation

- Cubic interpolation in 2 dimensions
- 2 functions: F(x,y)->x' and G(x,y)->y'



4 1D base functions



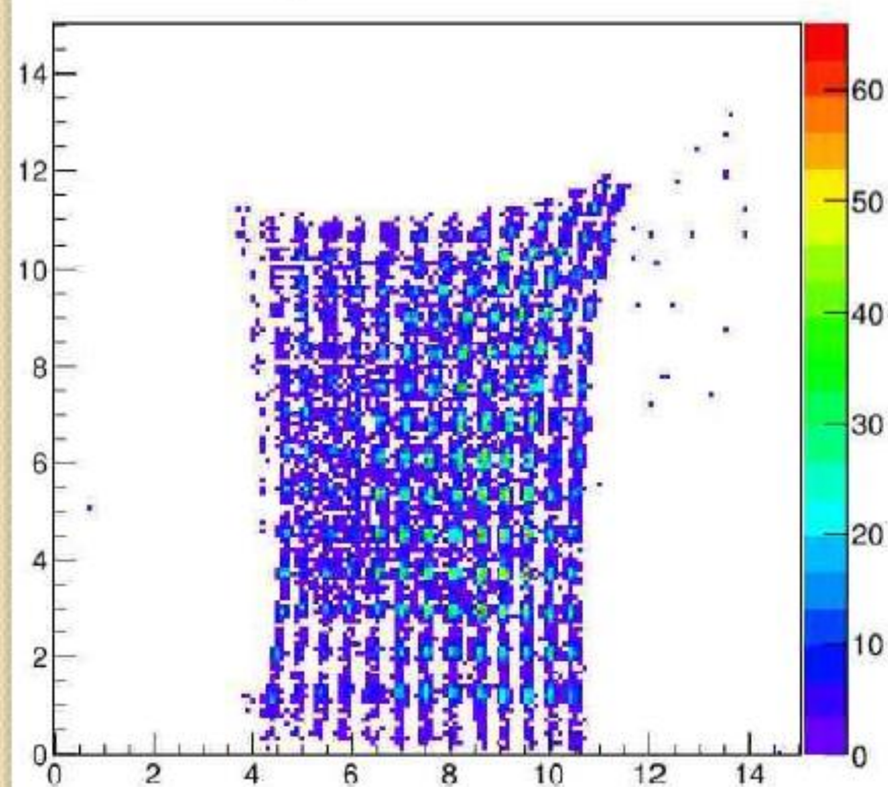
4 of the 16 2D base functions

- Weighted addition of 16 base functions gives smooth surface
- Datapoints and smoothness provide conditions

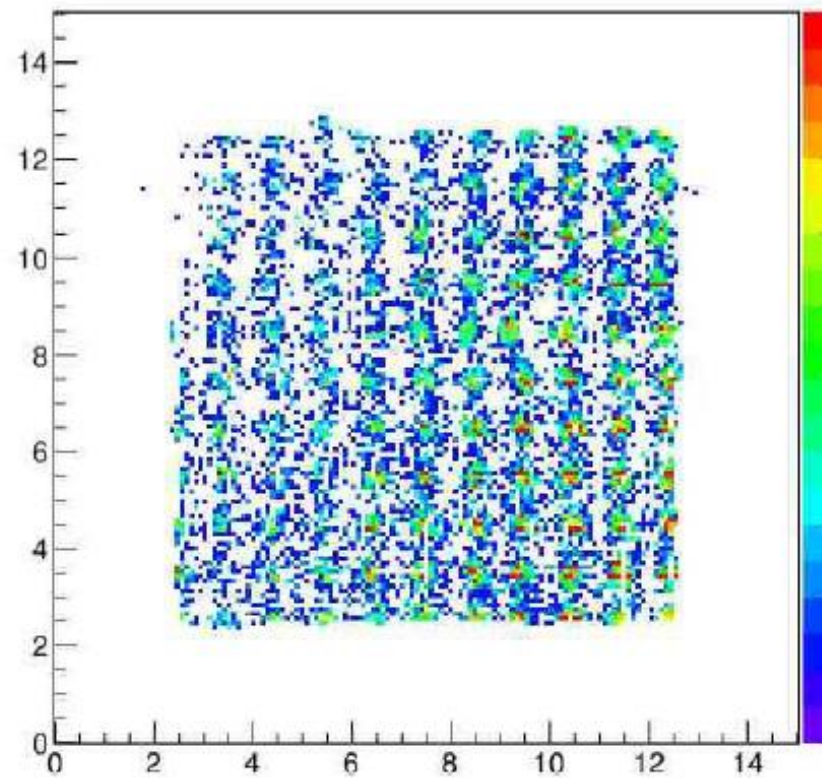
E-field deformations

- 1mm grid scan
- Transforming deformed grid gives uniform grid
- Improvement for spots near the edge

Original Grid

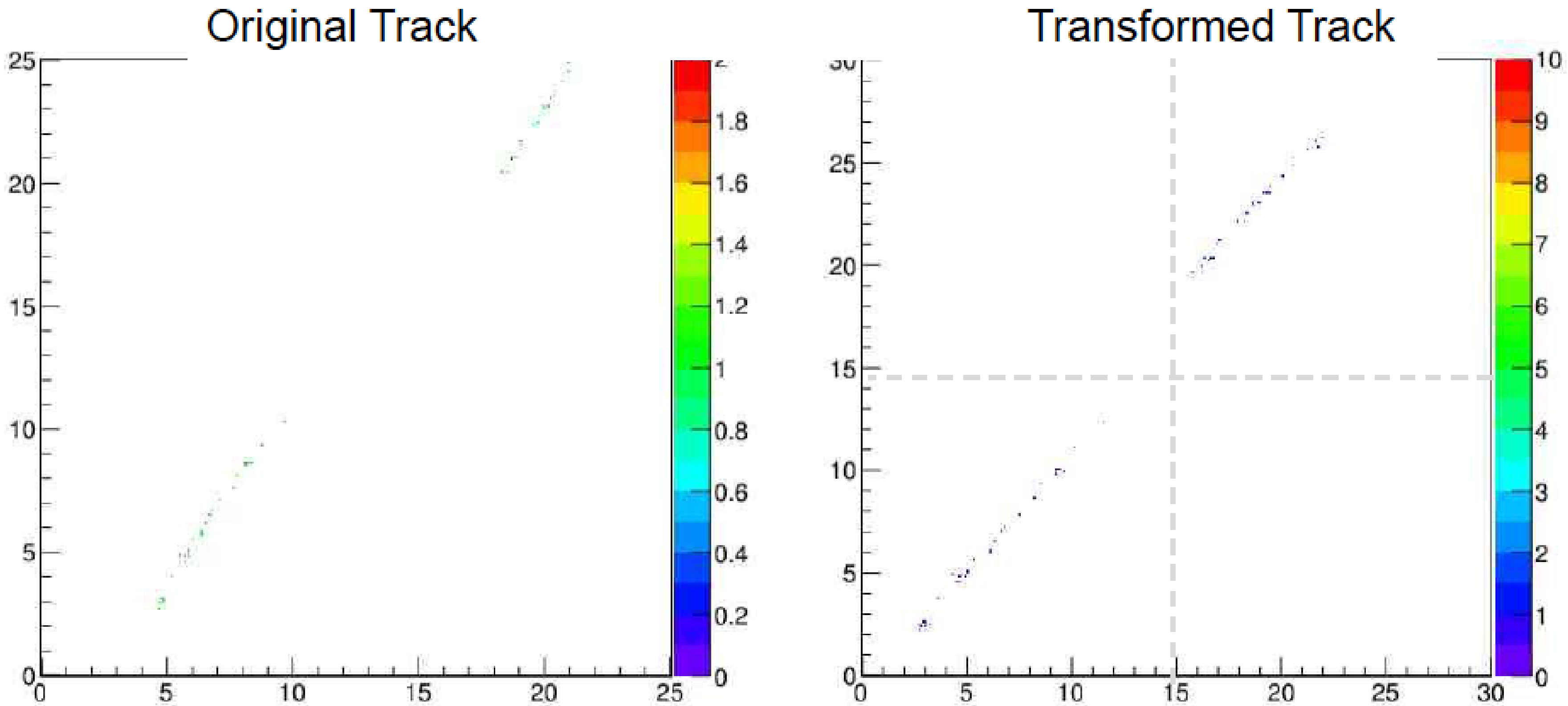


Transformed Grid



E-field deformations

- Tracks on multiple chips are straightened
- Resulting angle 45 degrees as expected
- Needs distance between chips



Results from Testbeam T10 (CERN PS), Nov 9 – 12 2016)

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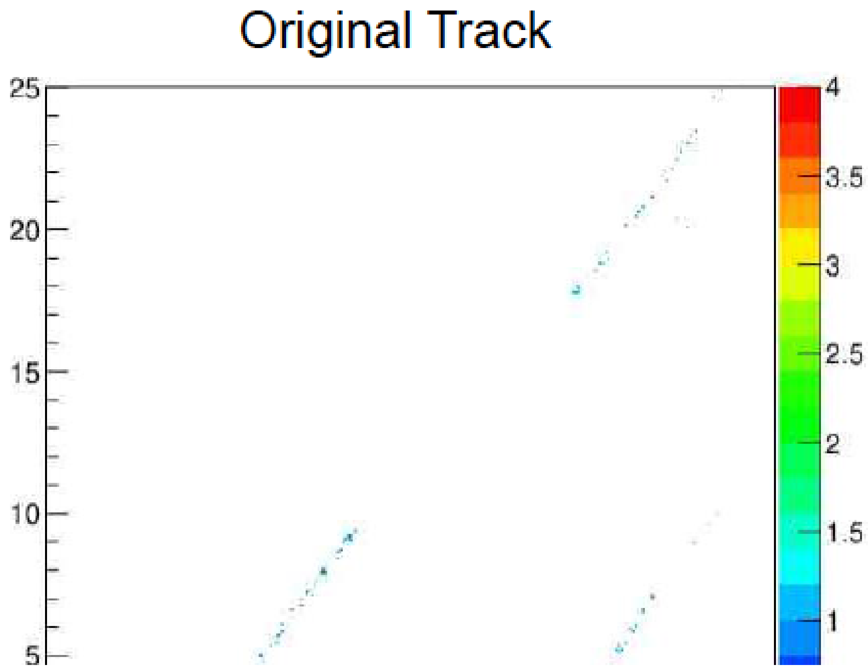

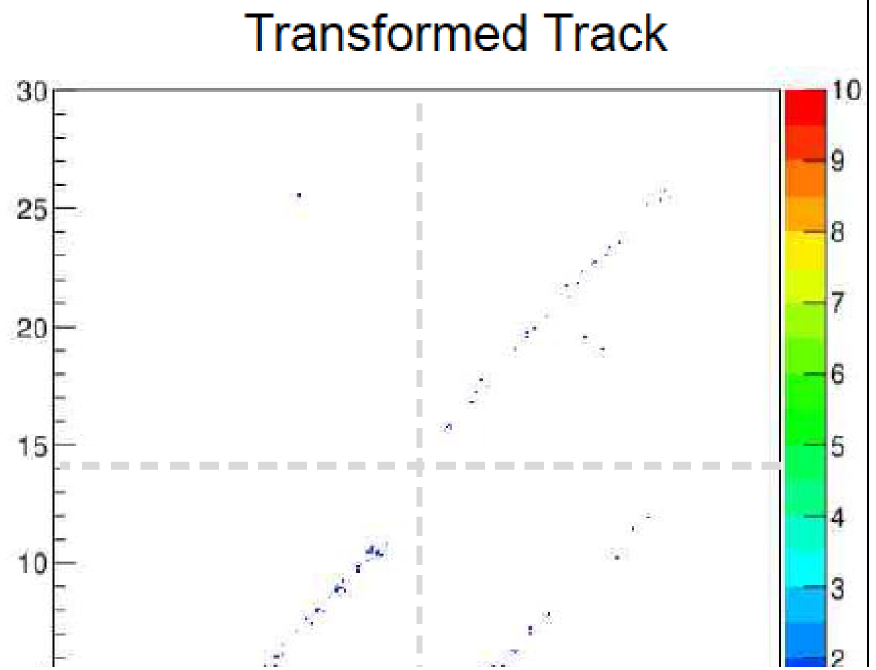

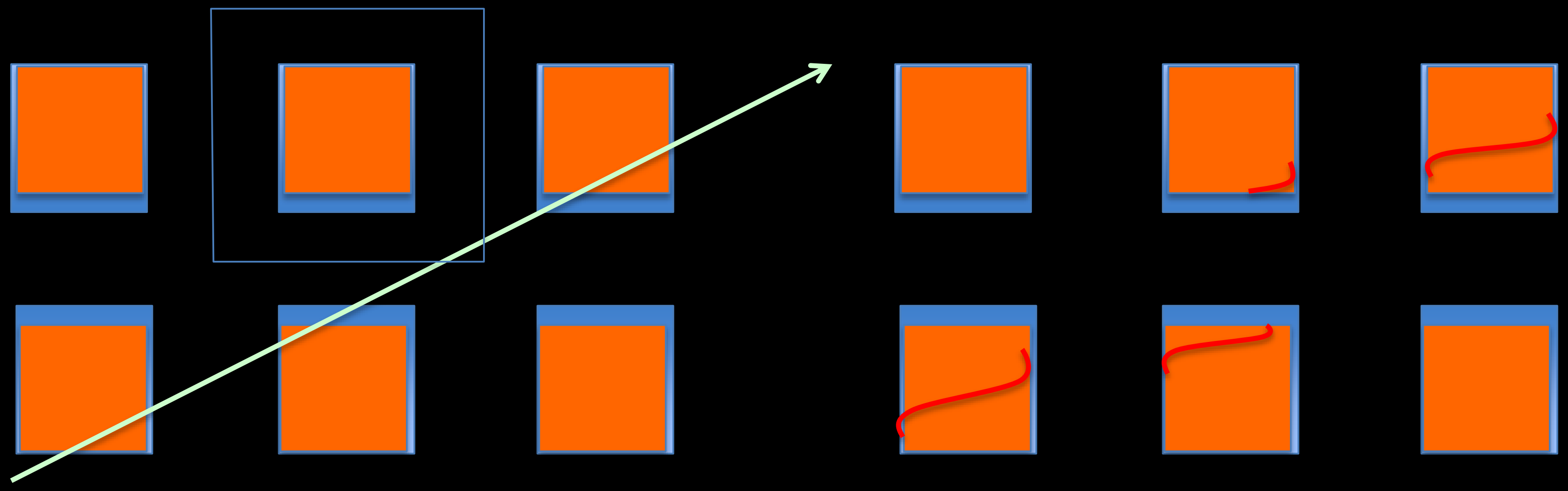

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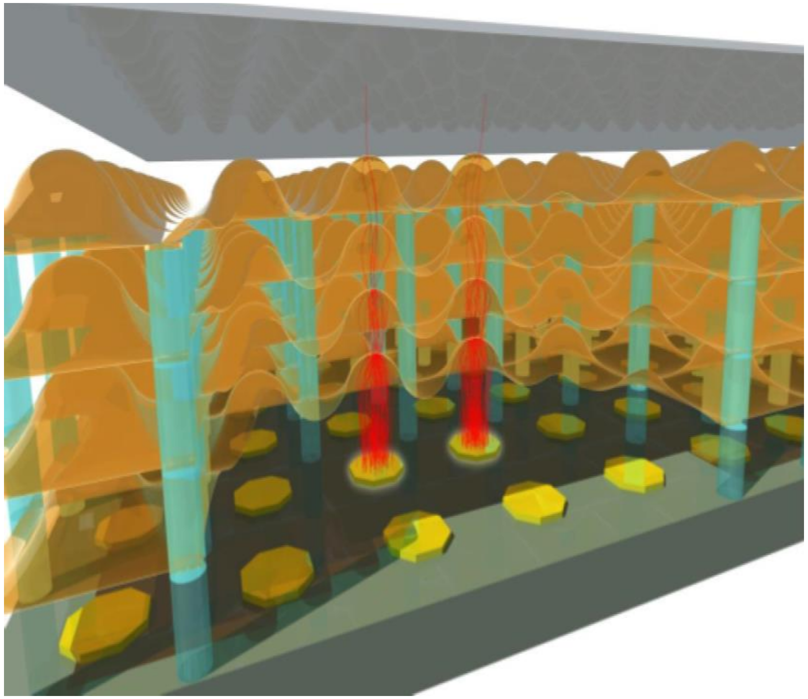
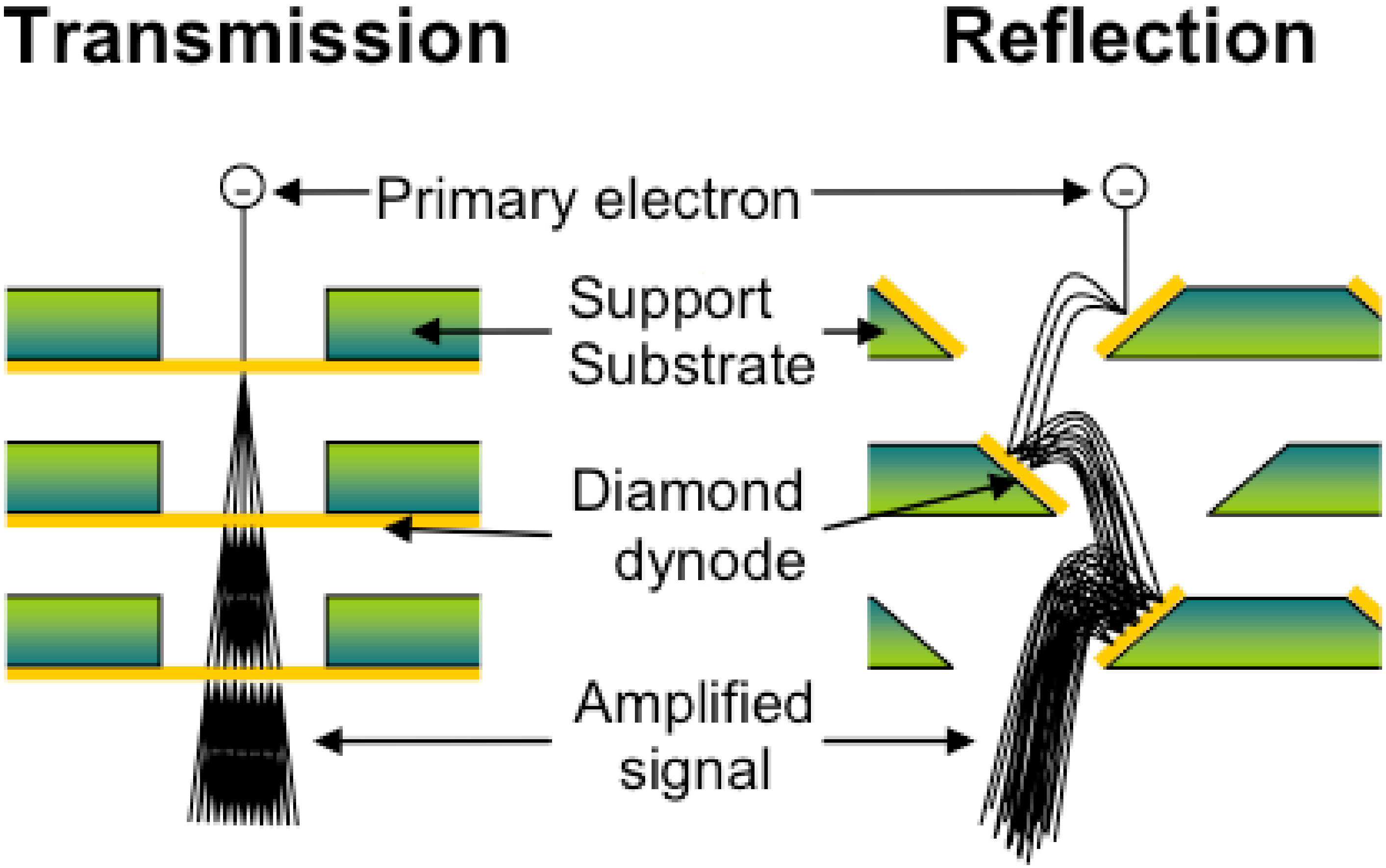


The Tynode: a Transmission Dynode with sufficient yield enabling the construction of Tipsy 0.0

On behalf of the Membrane project:

Harry van der Graaf, Conny C.T. Hansson
Hong Wah Chan, Shuxia Tao, Annemarie Theulings, Violeta Prodanović, John Smedley, Kees Hagen, Yevgen Bilevych, Lina Sarro, Gert Nützel, Serge D. Pinto, Neil Budko, Behrouz Raftari

Supported by ERC – Advanced 2012 "MEMBrane" 320764



New: the Transmission Dynode

Tynode®

Trynode®

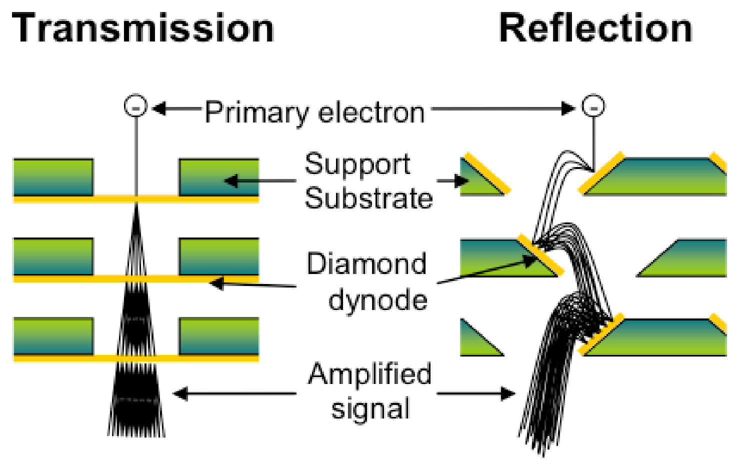
The TiPC concept - advancing PMT's

Photomultiplier tubes

- High gain
- Low noise
- Secondary Electron Yield (SEY)

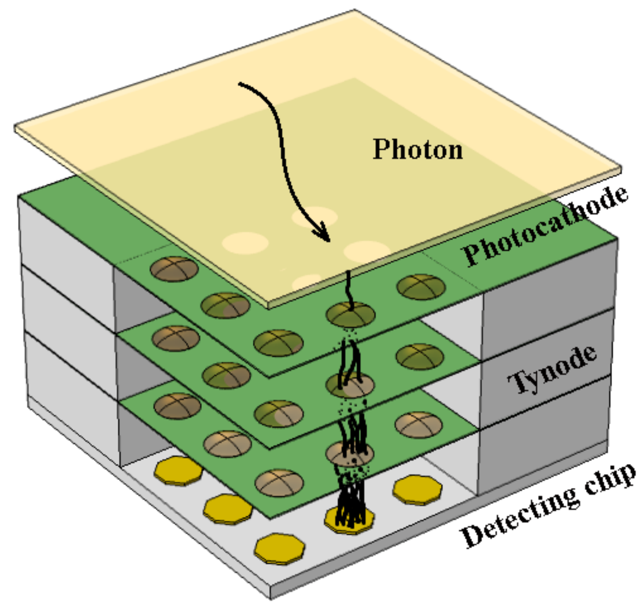
$$SEY = \delta = \frac{\#\ of\ secondary\ electrons}{\#\ of\ primary\ electrons} = \frac{I_{SE}}{I_{PE}}$$

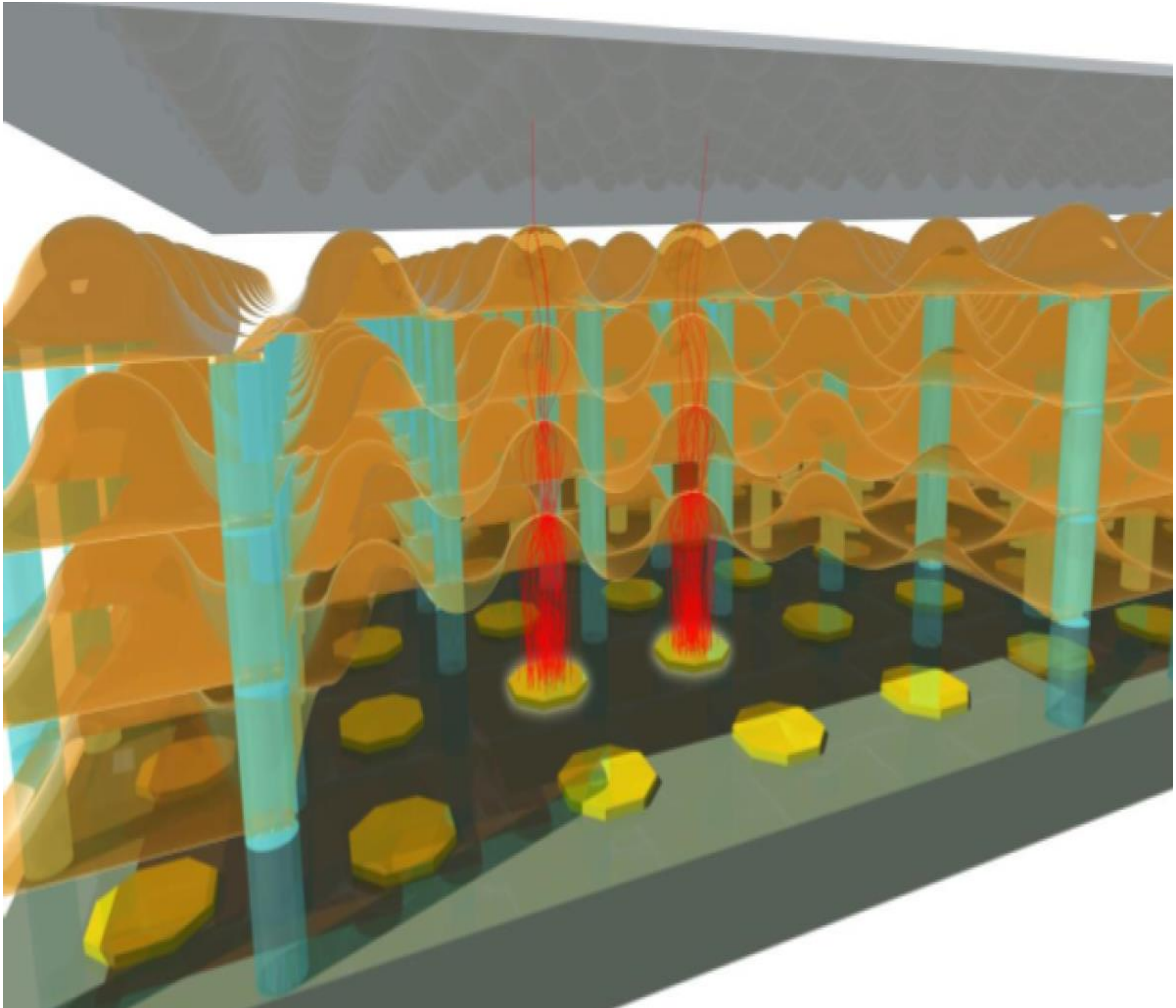
Gain = δ^N



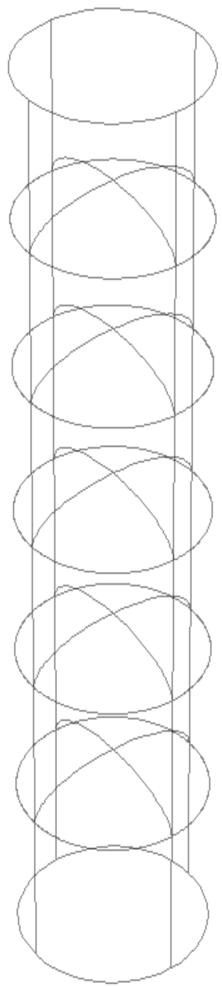
…Can we make it smaller?

- Transmission dynodes – **Tynodes**
- **Dark noise free** electron multiplication mechanism
- Stacking the photocathode, Tynodes and pixel chip → **compact device**
- Pixelated detector → **spatial resolution** (imaging)
- Operation of the detector **in high B-field.**
- Time resolution = few ps
- 2D spatial resolution = 10 µm





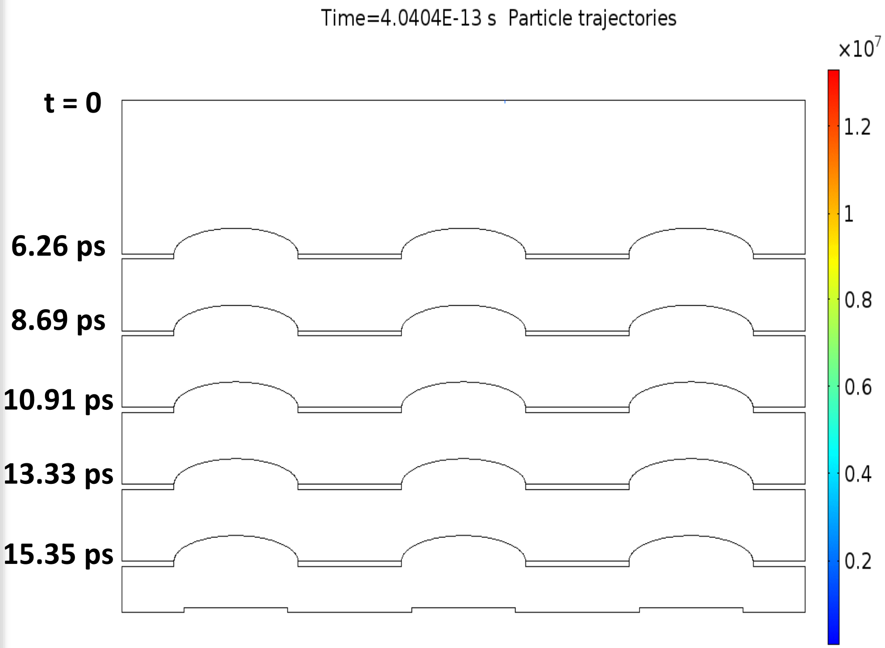
The Transmission Dynode → Tynode



- Similar to PMT dynodes, but with amplification through transmitted secondary electrons through nanoscale thickness membranes (**Tynodes**)
- The Tynodes offer effectively **dark noise free** electron multiplication
- A **compact device** (see top right) can be fabricated with a photocathode on top stacked tynodes and collector readouts on the bottom.
- The pixelated detector allows for **spatial resolution** (imaging)
- The high bias field between the membranes, and the tailored dome shape of the membranes allow for **operation in high B-field.**

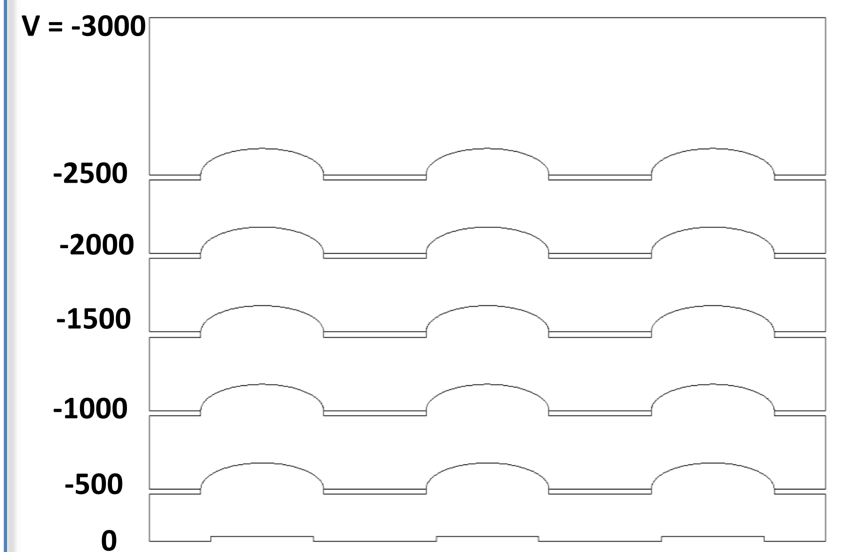
Stacked Tynodes Simulations

More compact → faster detector



- Simulated device thickness ≈ 100 microns
- Time between tynodes ≈ 5 ps
- Time spread of generated electron cloud below ps timeframe (path uniformity)

Performance in magnetic fields



- Operational in 1 T magnetic fields

The Timed Photon Counter – TiPC – "Tipsy"

Photocathode ⟶ Tynodes ⟶ TimePix chip

TimePix chip:

- 256 by 256 pixels with 55 μm pitch
- Surface = 1.4 cm by 1.4 cm

Matching Tynodes (Transmission Dynodes):

- Diameter = 30 μm
- Pitch = 55 μm
- Separation = 25 μm

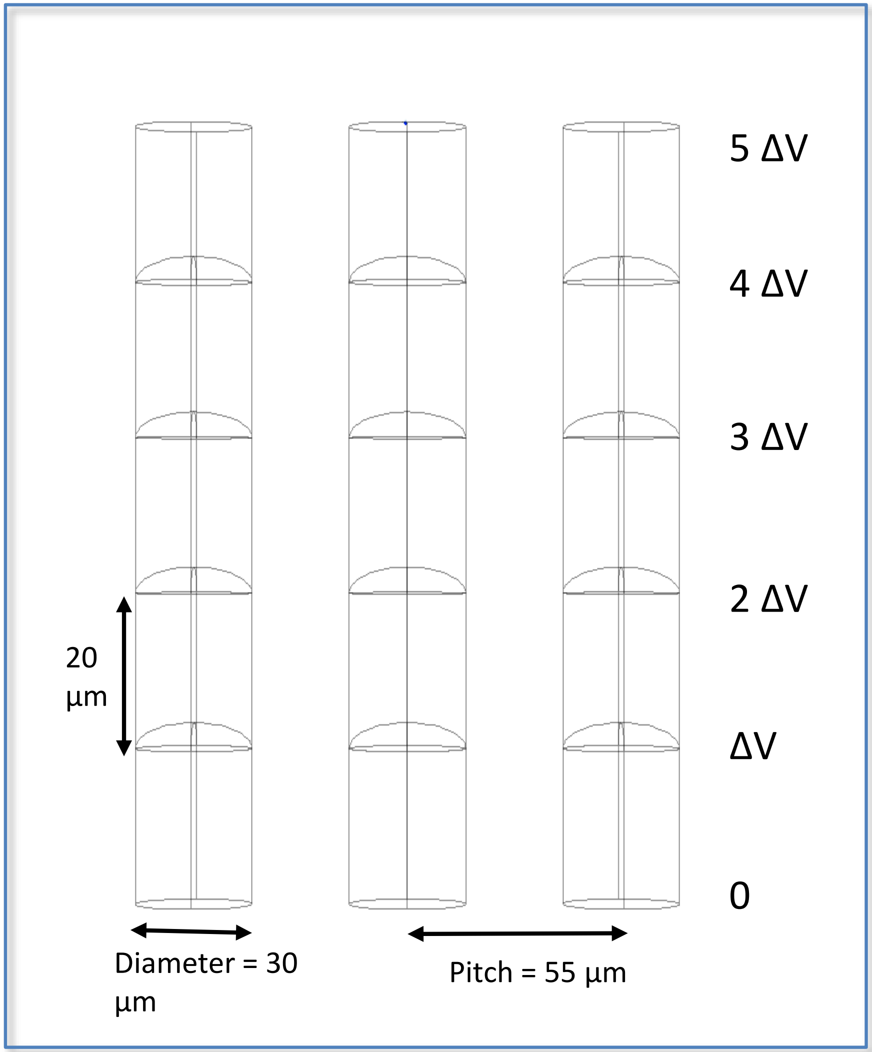
Sensor Charge Requirements:

	Timepix 1 (2006)	**Timepix 3 (2013)**	**Timepix FG**
Min. detectable charge	>750 e-	>500 e-	**>60 ke-**

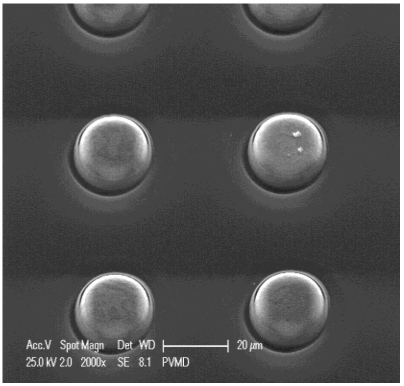
Tynode gains:

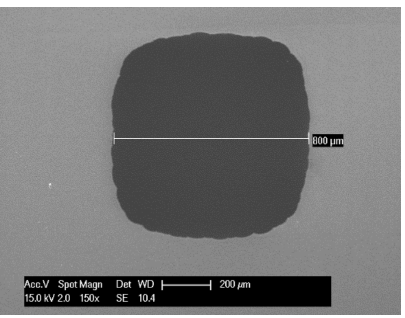
Gain = $\delta^N = 4^5$ = 1k → threshold

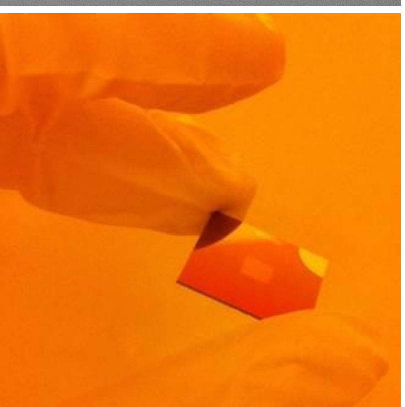
Gain = $\delta^N = 4^8$ = 60k → 1 Volt digital



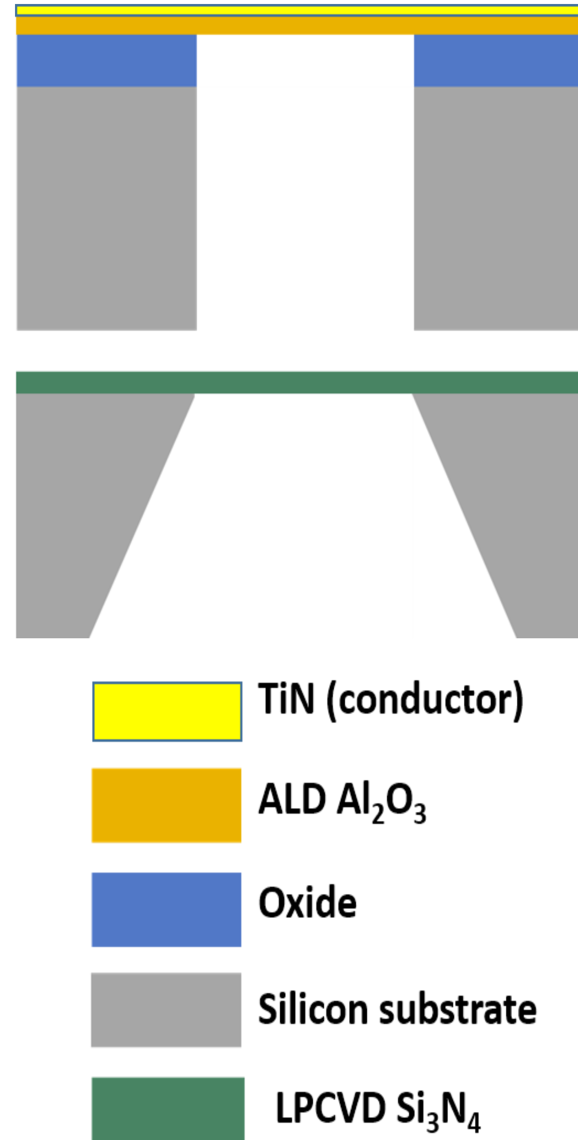
Membrane Fabrication





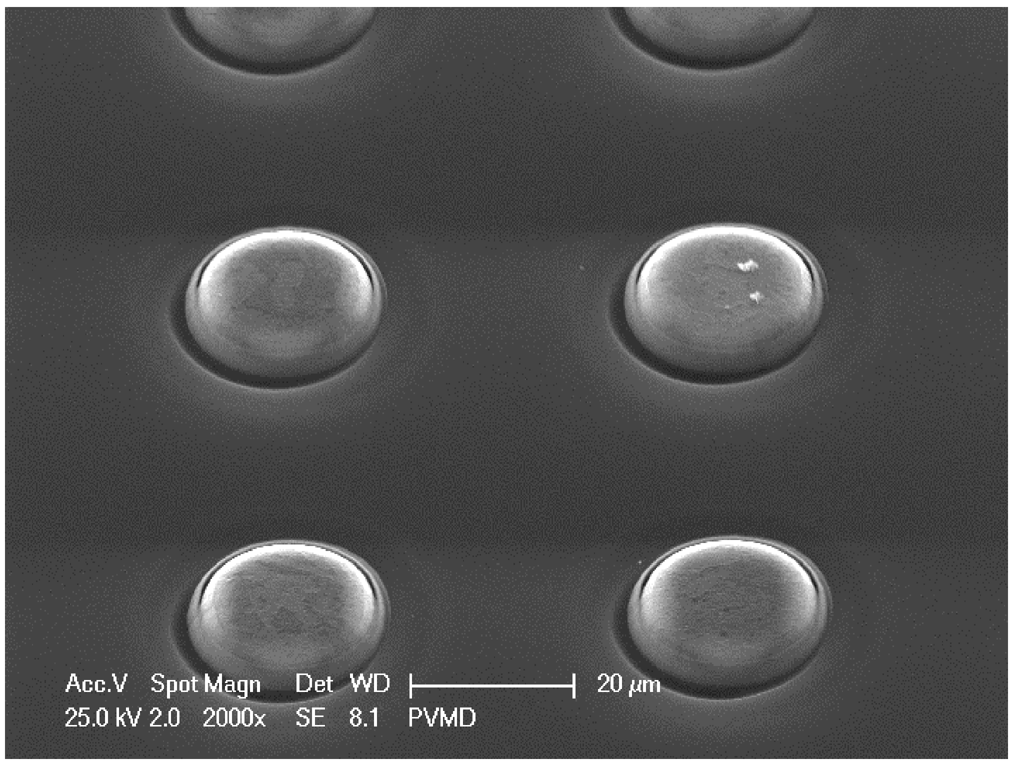


- Fabrication through combinations of lithography, etching, and atomic layer deposition
- Materials considered: Si_3N_4, Si-rich Si_3N_4, Al_2O_3, SiC, MgO
- TiN used as conductive layer to reduce charging effects with minimal effect on secondary electron yields.
- Array of tynodes
  - Thickness: 5-40 nm
  - Diameters: 10, 20, 30 µm
  - Array size: 256 by 256
- Large area tynodes for testing purposes
  - Thicknesses: 40-200 nm
  - Diameters: 50, 100, 300, 1000 µm



Path towards first prototype

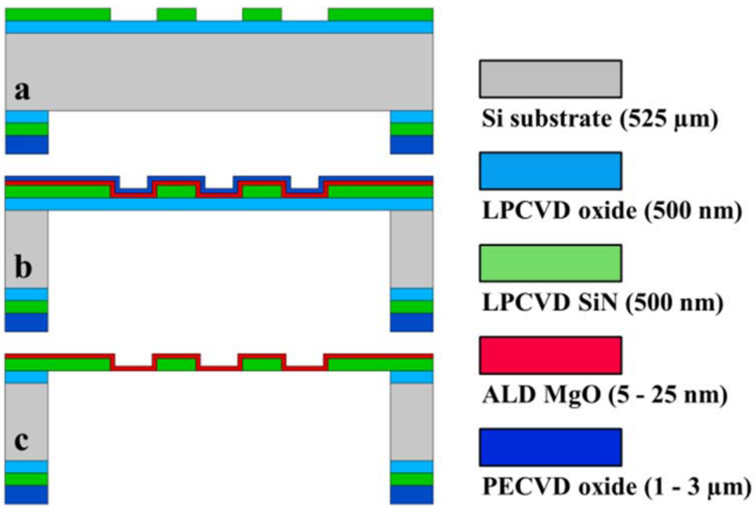
- We have created many tynodes of various sizes and materials
- Most recently, we have achieved transmission yields of >3 with 5 nm MgO membranes, coated with 2.5 nm TiN, without other special surface treatments
- Now working towards building a first prototype device

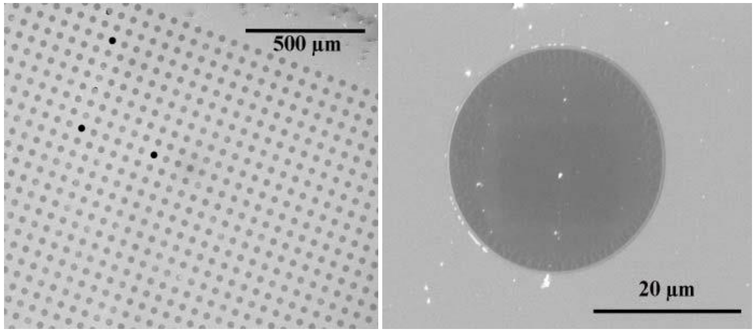


MEMS fabriaction of Tynodes: ALD MgO

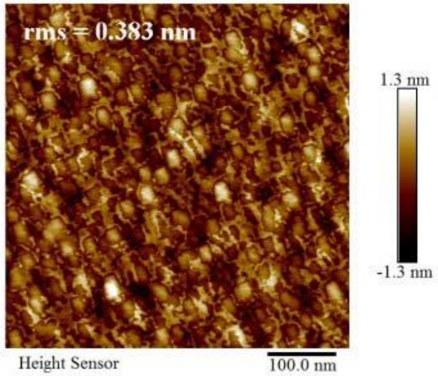
Thermal ALD reactor with ($Mg(Cp)_2$) and H_2O as precursors

- Deposition temperature: 200 °C
- Measured stress: ~ -200 MPa
- Growth rate = 0.165 nm/cycle (3 + 15 + 1 + 15 sec)





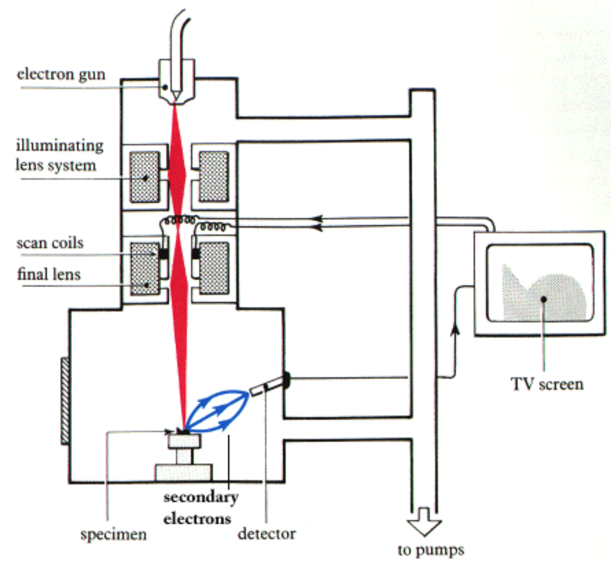
SEM captures of 5 nm thin MgO membranes in 64 x 64 array

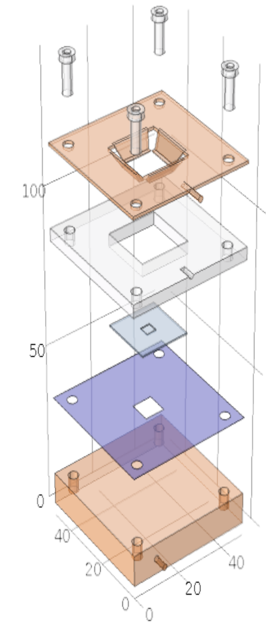


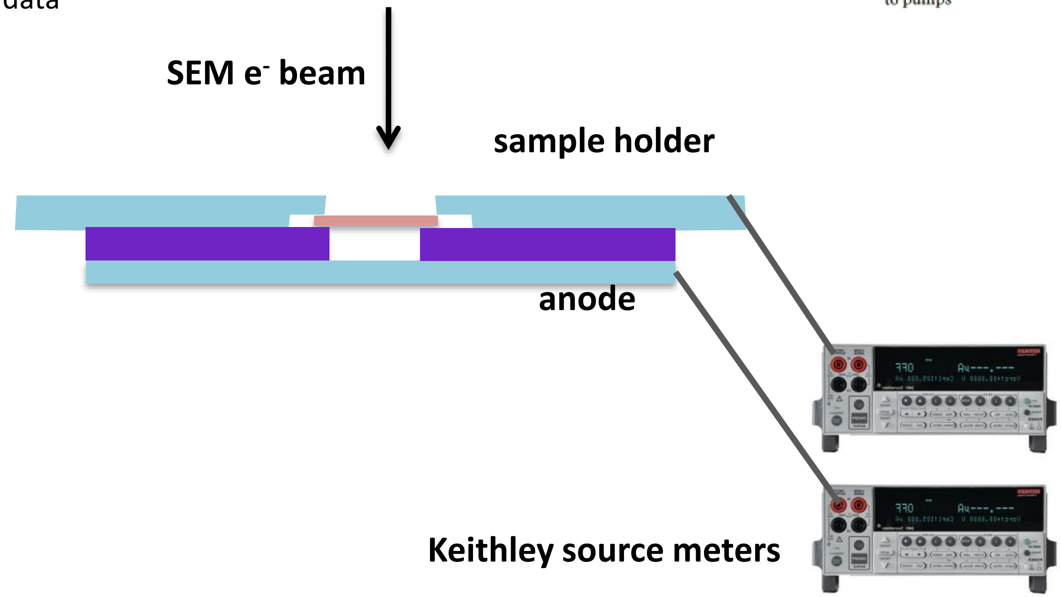
AFM image of released 25 nm thin MgO membrane

TSEY Measurement in SEM
Measurement method

- ***Scanning Electron Microscope**:*
    - Electron beam energy
    - Measure beam current
    - Acquire image (4.2 min)
- ***Keithley 2450 Sourcemeters***
    - Measure Sample Current
    - Measure Collector Current
- Repeat for different beam energies
- Process data

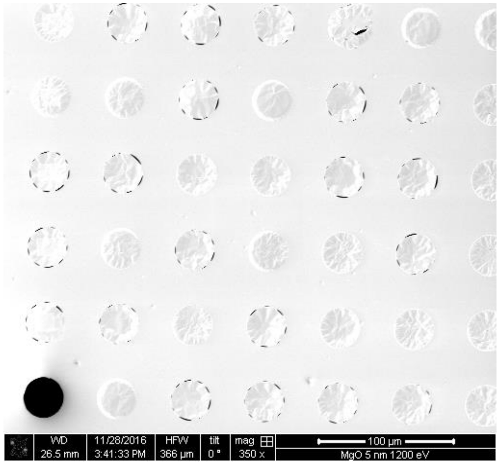


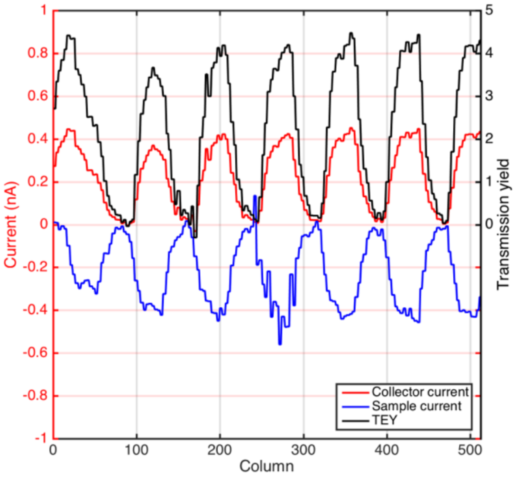


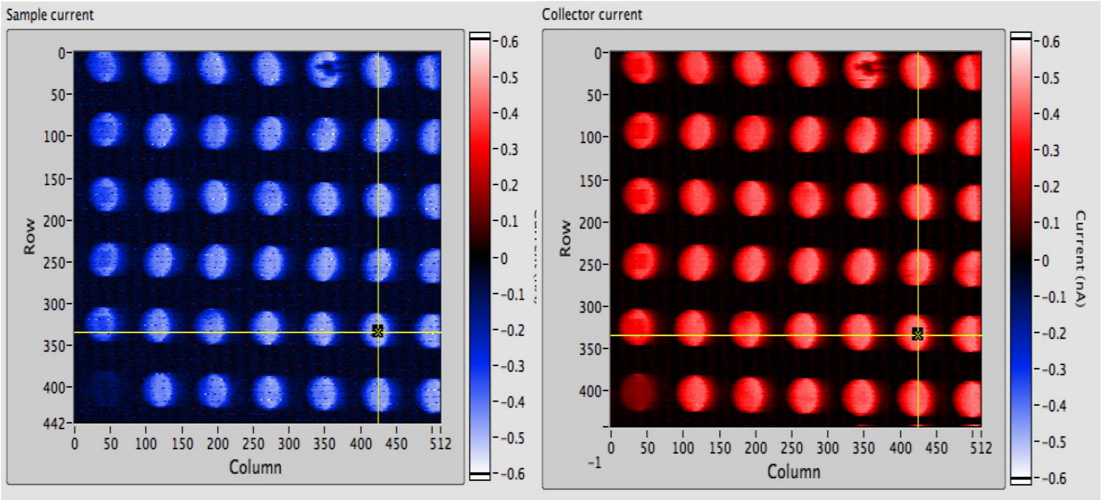


Measurement method: SEM imaging

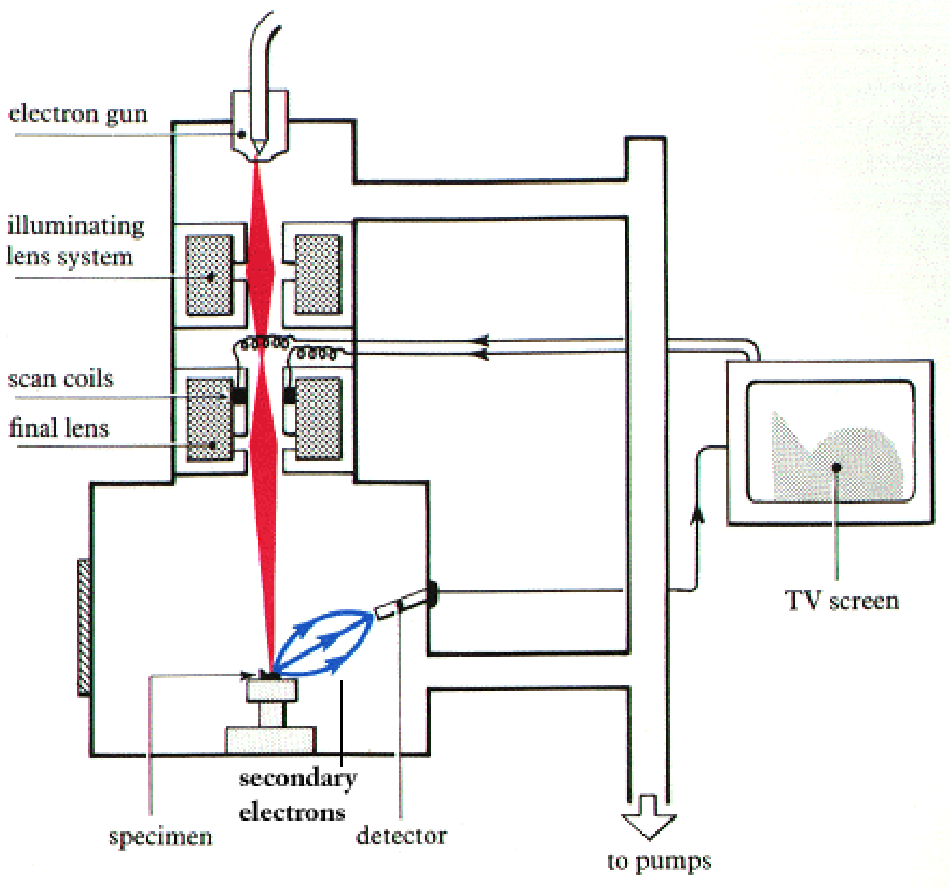
- SEM image of the sample is taken in 4.2 min while measuring the sample and collector current.
- The images are reconstructed by combining the linescans.
- The yields can be determined by selecting the right pixels (square)
- Repeating for several energies, the yield curves are obtained.
- EE = 1200 eV
- Beam current = 0.1 nA

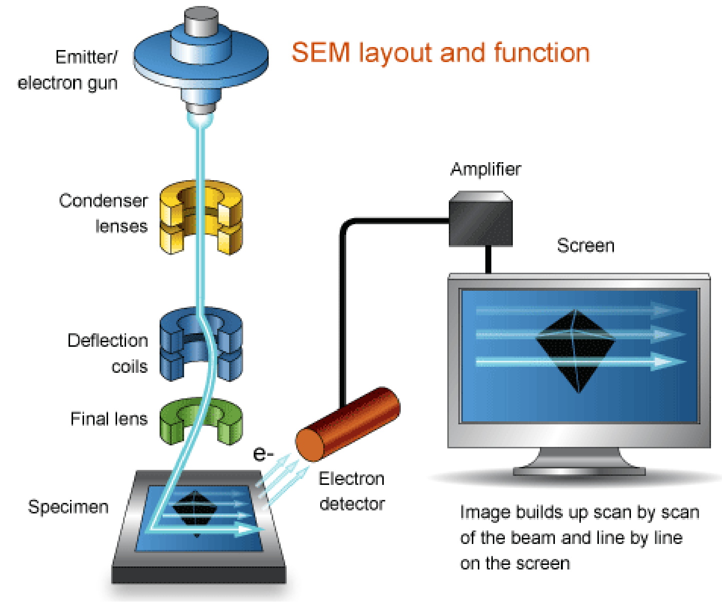




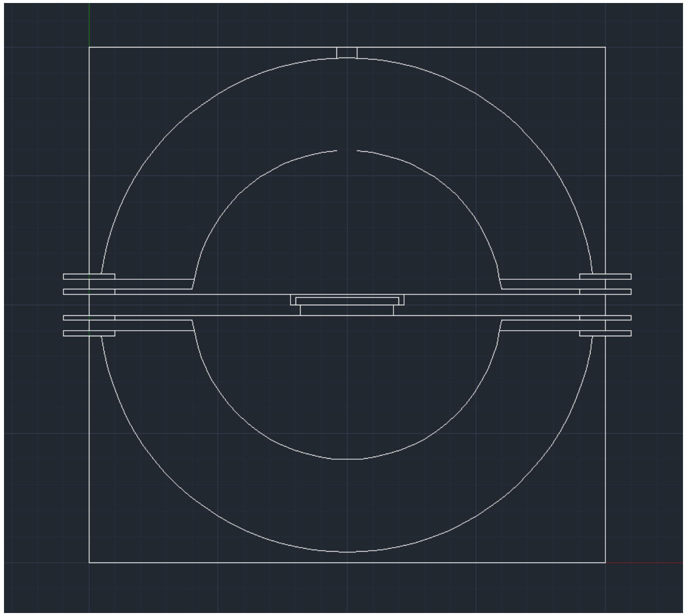


SEY Measurement in SEM





SEM/TEM to measure reflection/transmission SEY@ Particle Optics Group TU Delft by **Alexander and Kees**

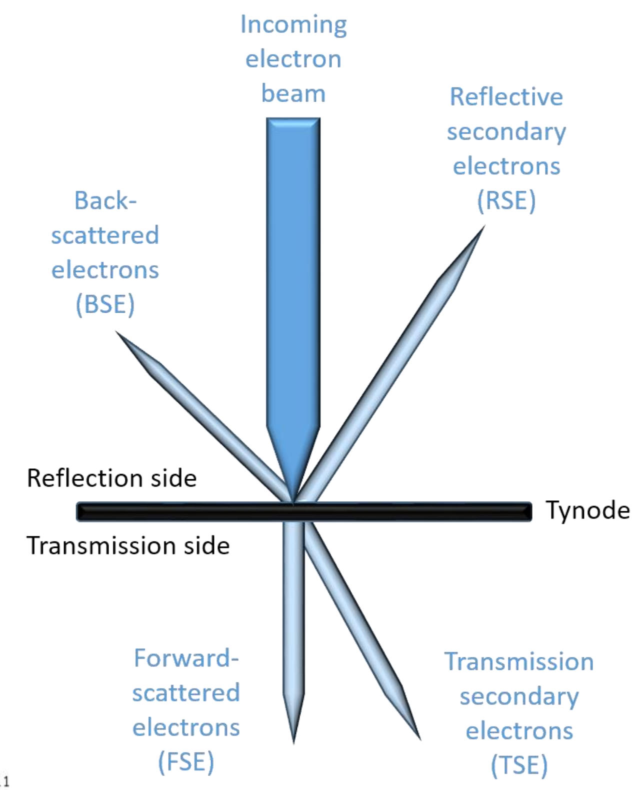


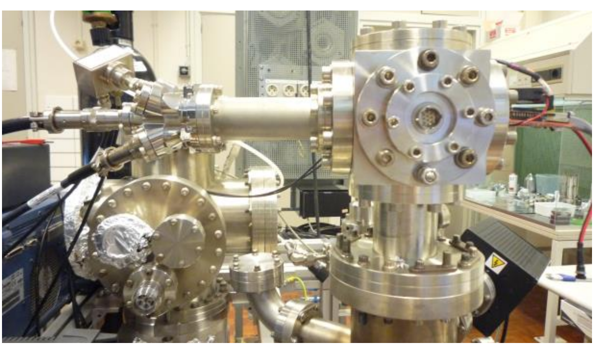
Dual Faraday Cup in SEM made at Nikhef

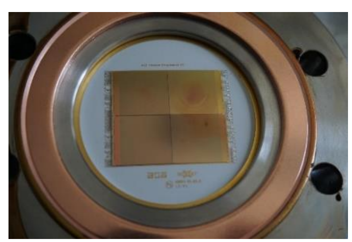
Measurement Techniques

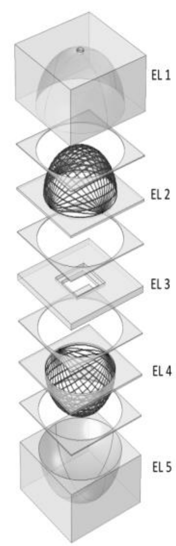
Search for material and/or surface treatment for transmission yield goal of 4.

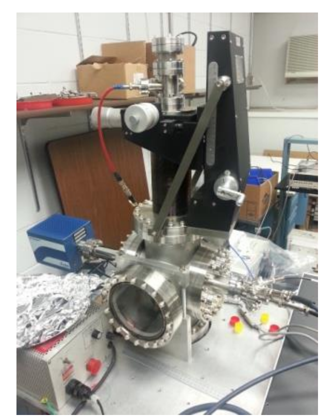
- Collaboration using four unique vacuum systems optimized for different aspects of dynode/tynode measurement
- Reflected and transmitted secondary electron yields for different membranes or thin films
- Measure under different electron beam fluxes or pulsing schemes
- Consider different surface terminations for improving electron yields





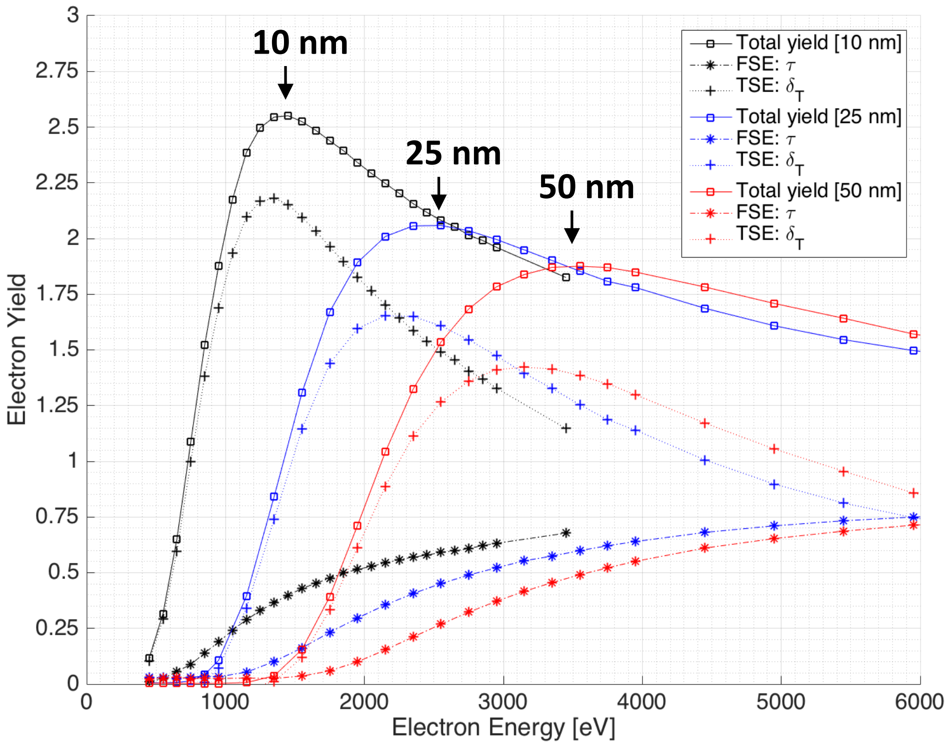




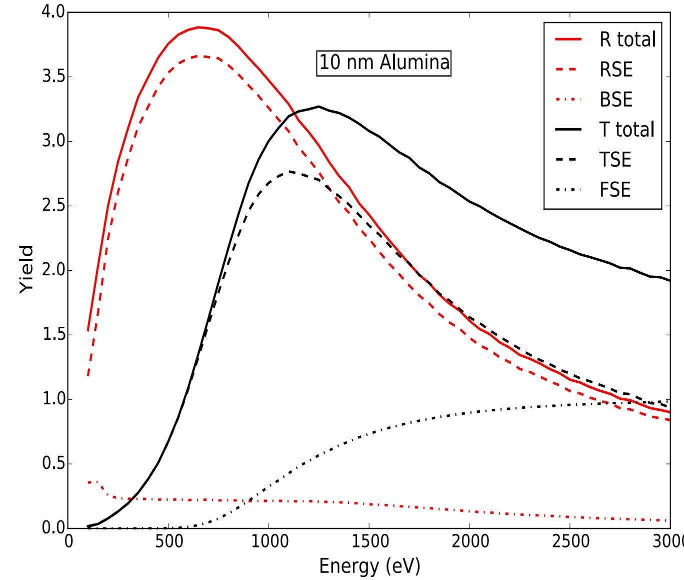


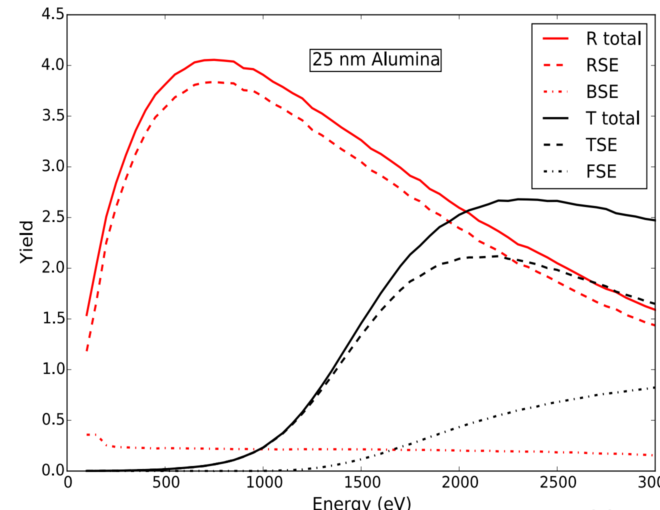
Al_2O_3 Measurements and Simulation

Measurement



Simulations





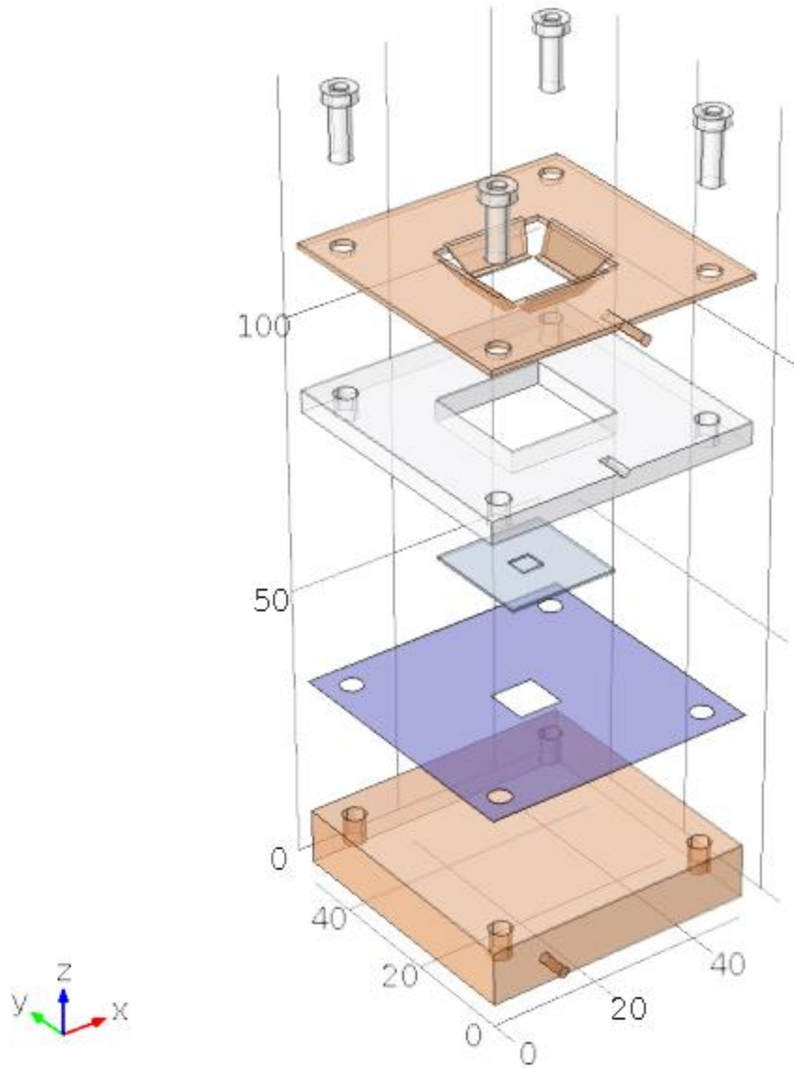
- A decrease in yield, combined with increase in optimum primary electron energy is observed as a function of sample thickness
- Good correlation to measurements seen for the simulations.

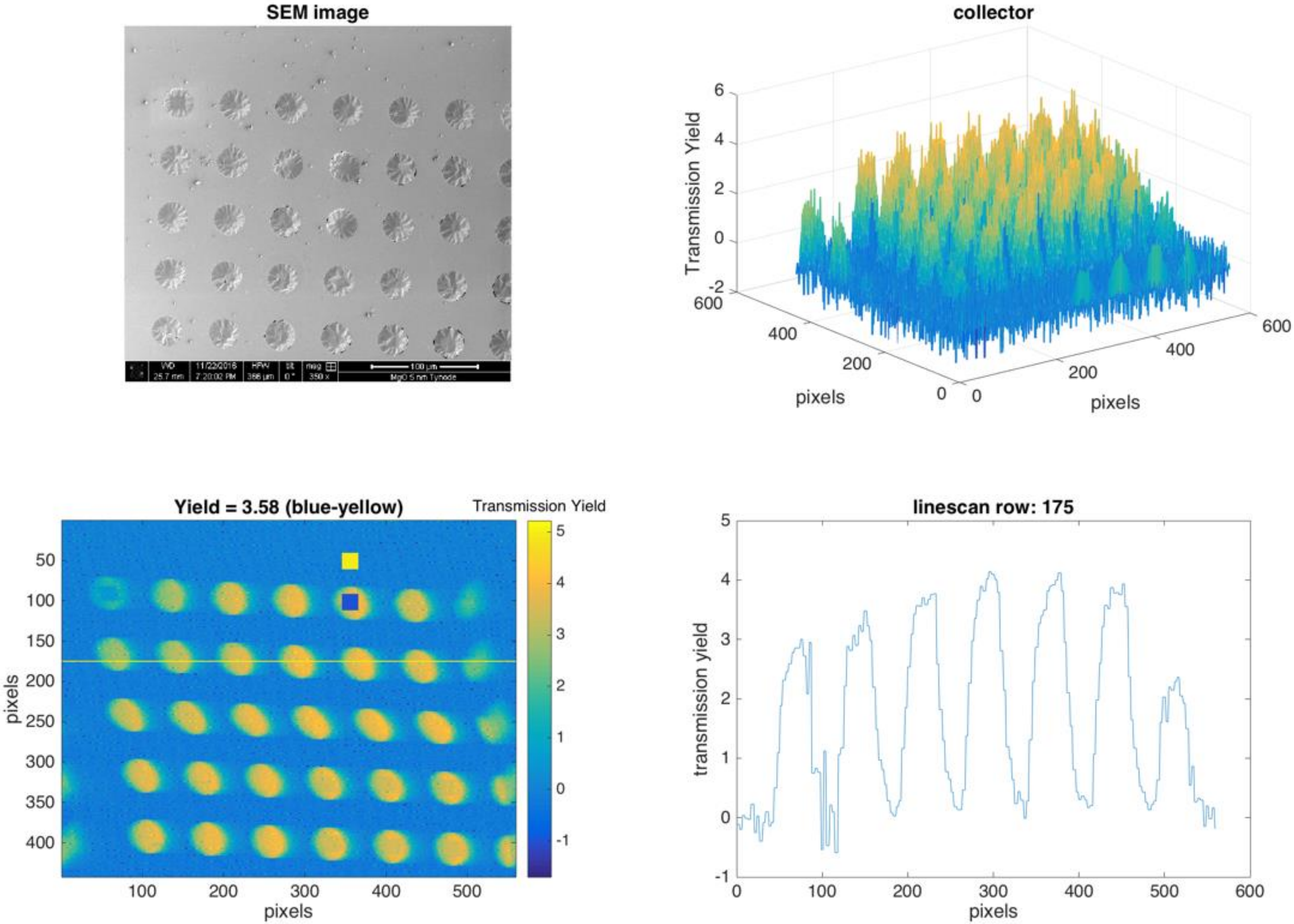
SEM measurement setup: E-field setup
Sample: MgO [5nm] + TiN [2.5 nm]. 64x64 array with 30 um diameter. (Same sample when we obtained ~ 3.2)

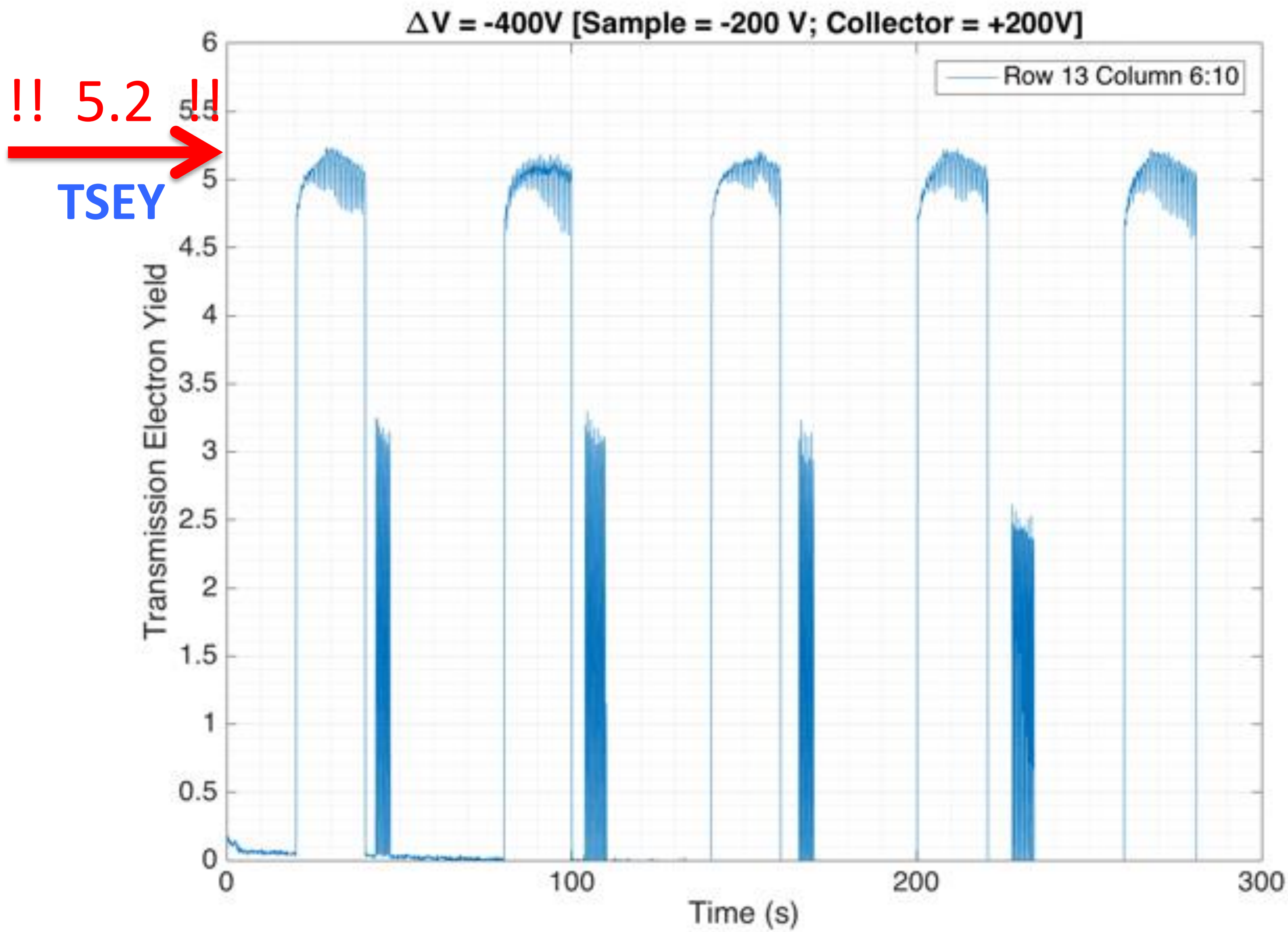
Electron beam energy: 1500 eV
Electron beam current: 0.12025 nA
HFW: 12.8 um
Magnification: 10000x
Distance between Tynode and collector: 30 um - 100 um (?)

Method:
- Apply bias
- measure background
- Irradiate a Tynode for 20 sec.
- Locate next Dynode
- repeat 5 times

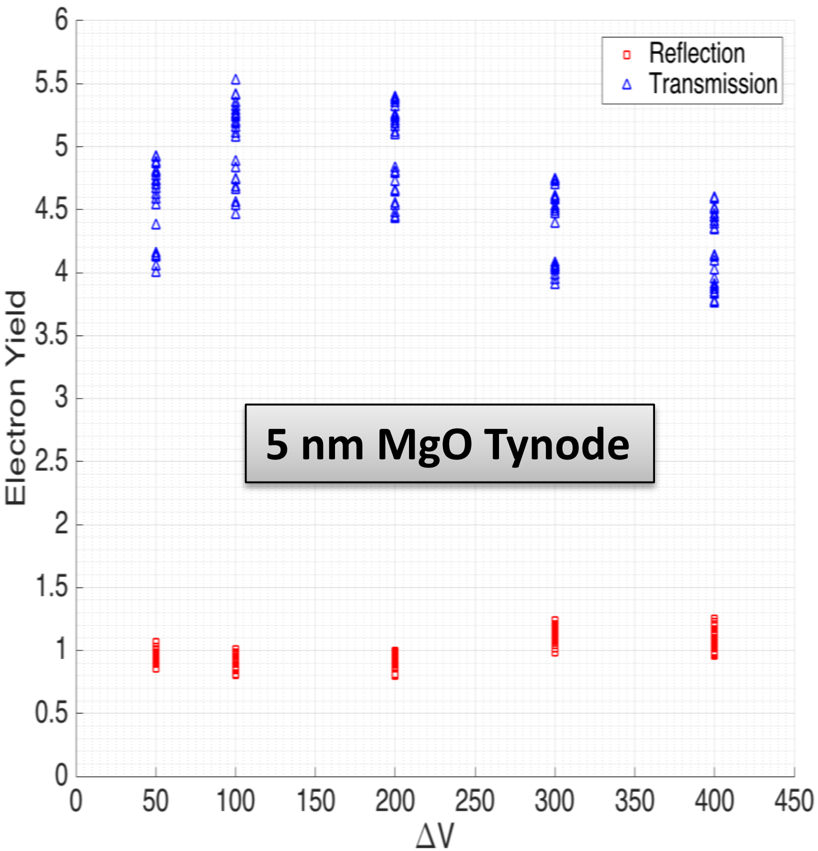
Calculation: TEY = I_collector / I_beam

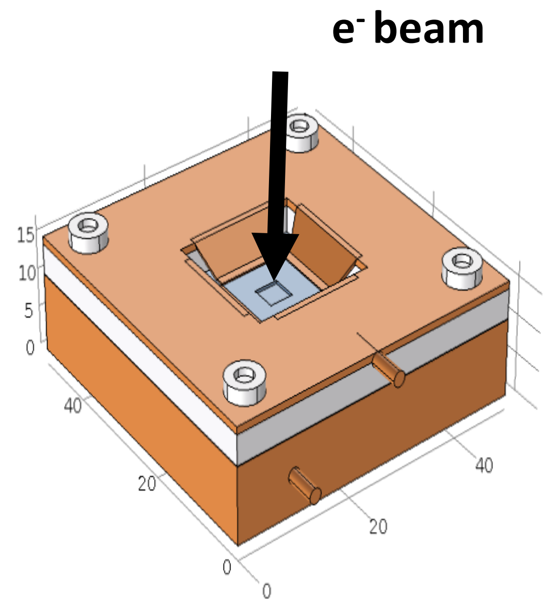



SEM image
collector
Transmission Yield
6
4
2
0
-2
600
400
200
0
pixels
0
200
400
600
pixels
Yield = 3.58 (blue-yellow)
Transmission Yield
50
100
150
200
250
300
350
400
pixels
100
200
300
400
500
pixels
5
4
3
2
1
0
-1
linescan row: 175
transmission yield
5
4
3
2
1
0
-1
0
100
200
300
400
500
600
pixels


ΔV = -400V [Sample = -200 V; Collector = +200V]
Row 13 Column 6:10
!! 5.2 !!
TSEY
Transmission Electron Yield
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
0
100
200
300

Measurement method: Extracting field

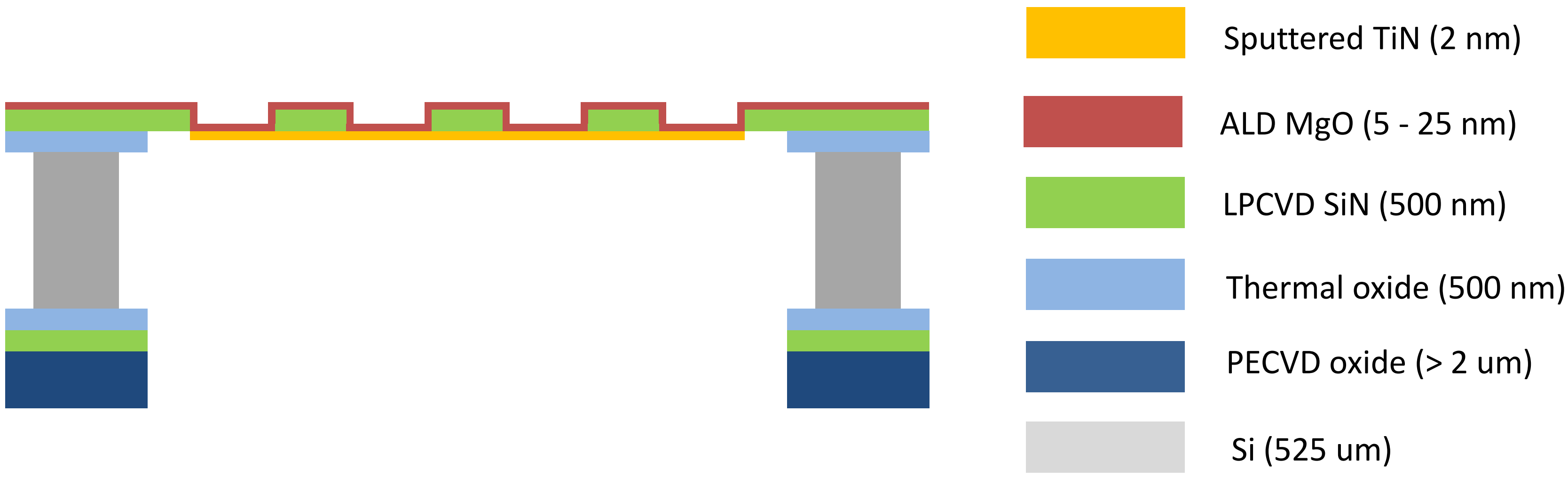




ΔV	Sample [V]	Collector [V]	Electron energy [eV]	Landing energy [eV]
50	-50	0	1200	1150
100	-50	+50	1200	1150
200	-50	+150	1200	1150
300	-200	+100	1200	1000
400	-200	+200	1200	1000

Timed Photon Counter – Tipsy 0.0 – Fabrication of First Prototype

Finalized layout of MgO domes



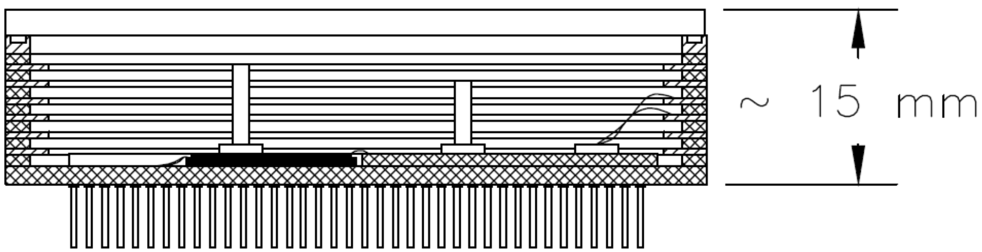
- We intend to manually stack 5 of these tynodes and place the stack above a TimePix-1 chip
- When in a close stack, we may achieve higher yields from close, extracting fields:
  There is a report[1] that, with a single Si membrane, yields of 200 has been reached due to a strong extracting field. We may have an even much higher extracting field!

1) Qin, Kim, Blick. APL **91,** 183506 (2007).

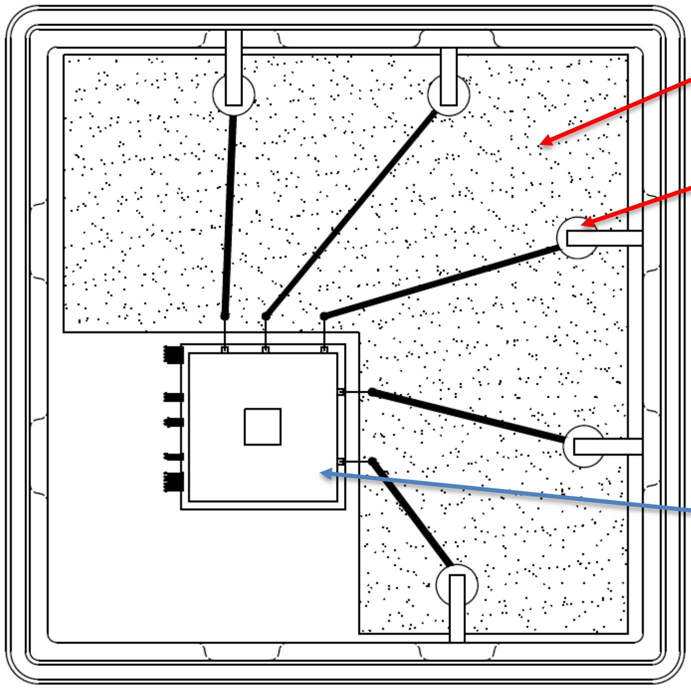
Concept - Fabrication Tipsy 0.0 into a Photonis PLANACON^{TM} Style Device

TimePix-1 pixel chip on Kyocera carrier board

- Ultra high vacuum compatible, sealing with Planacon window, photocathode compatible



Tipsy 0.0 will be limited to the 10 ns bin size of TPX-1 or 1 ns bin size of TPX-3 a new TimePix NN with 10 ps time resolution



Fan-out ceramic with metalized top-traces for HV distribution

Metal studs and weld ribbons to electrode rings

Backside metalized ASIC (TIMEPIX) with tynodes eutectic bonded into envelope + wirebonds

Conclusions and future work

- Transmission dynodes or Tynodes can be fabricated and used for effective electron amplification with TSEY > 5.2
- ALD is an ideal deposition method for TiPC application where ultrathin films are required
- **Further yield improvement**:
    - ❑ fully exploration of Extracting Field Bonus
    - ❑ Surface termination
    - ❑ Tynode annealing
    - ❑ higher vacuum
    - ❑ bake out
    - ❑ the active Tynode - **Trynode**