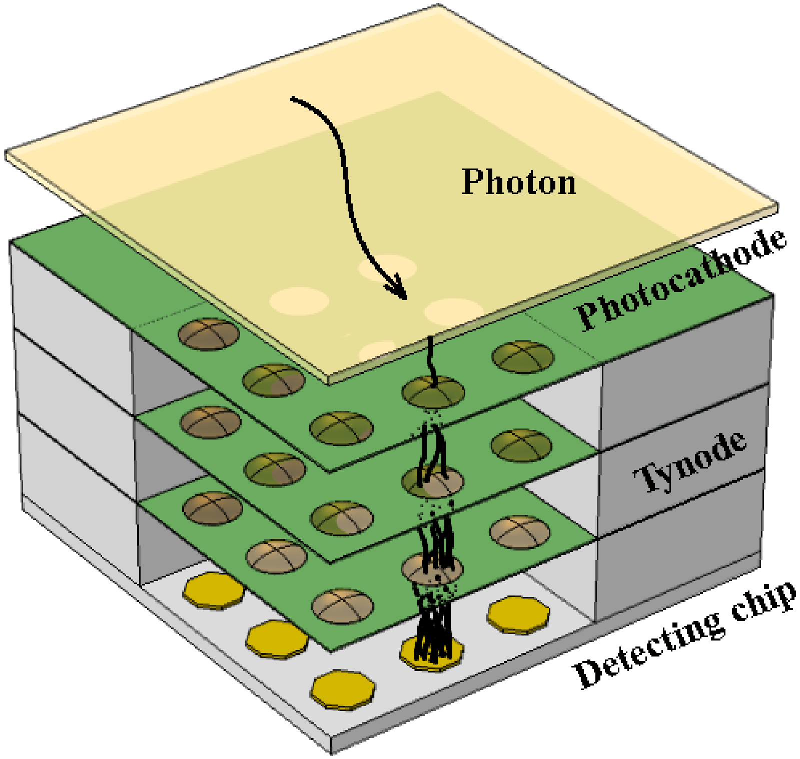


An Active High QE Photocathode

for single soft photon detection

On behalf of the MEMBrane project:

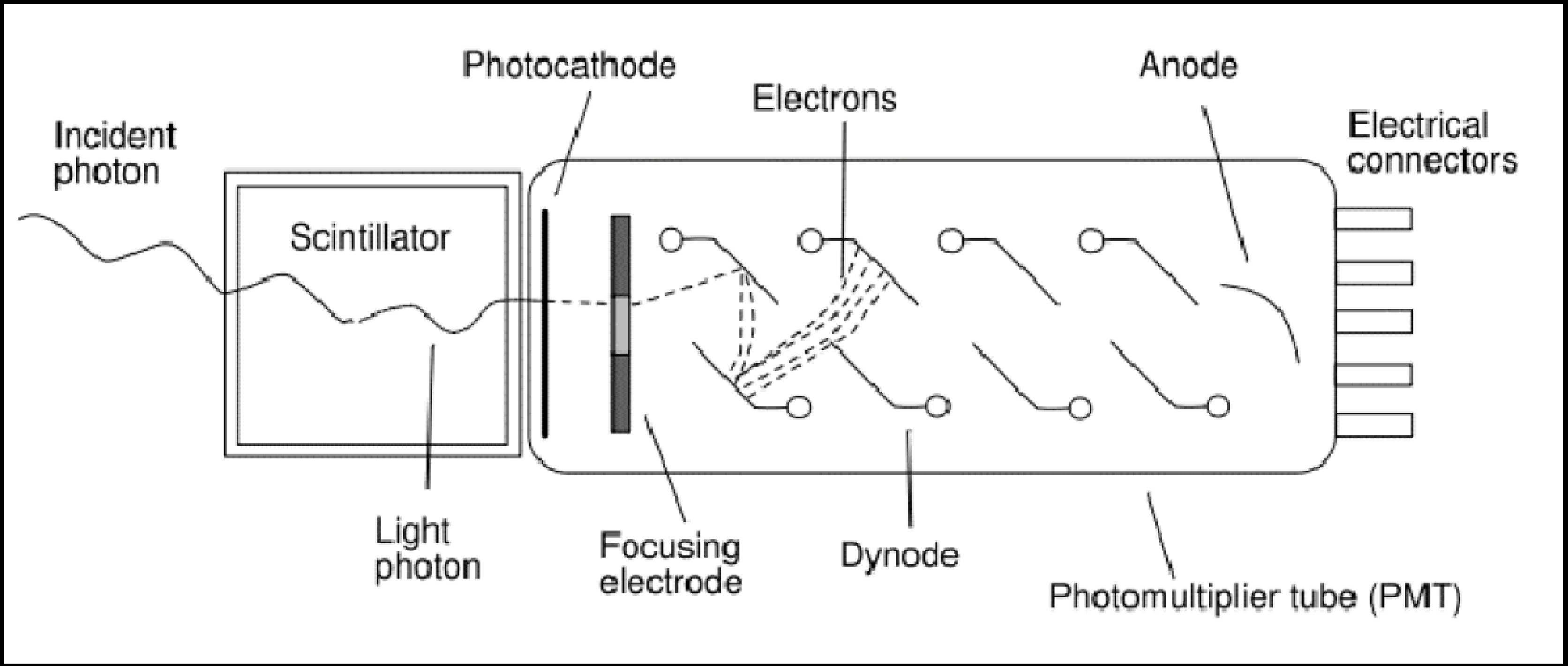
Harry van der Graaf, Jeff de Fazio, Conny C.T. Hansson Hong Wah Chan, Annemarie Theulings, Violeta Prodanović, John Smedley, John Sinsheimer, Kees Hagen, Carel Heerkens, Lina Sarro, Gert Nützel, Serge D. Pinto, Neil Budko, Behrouz Raftari, Wouter de Landgraaf, Henk van Zeijl

Supported by ERC – Advanced 2012 "MEMBrane" 320764

EWPAA 2017

Berlin, Sept 20, 2017

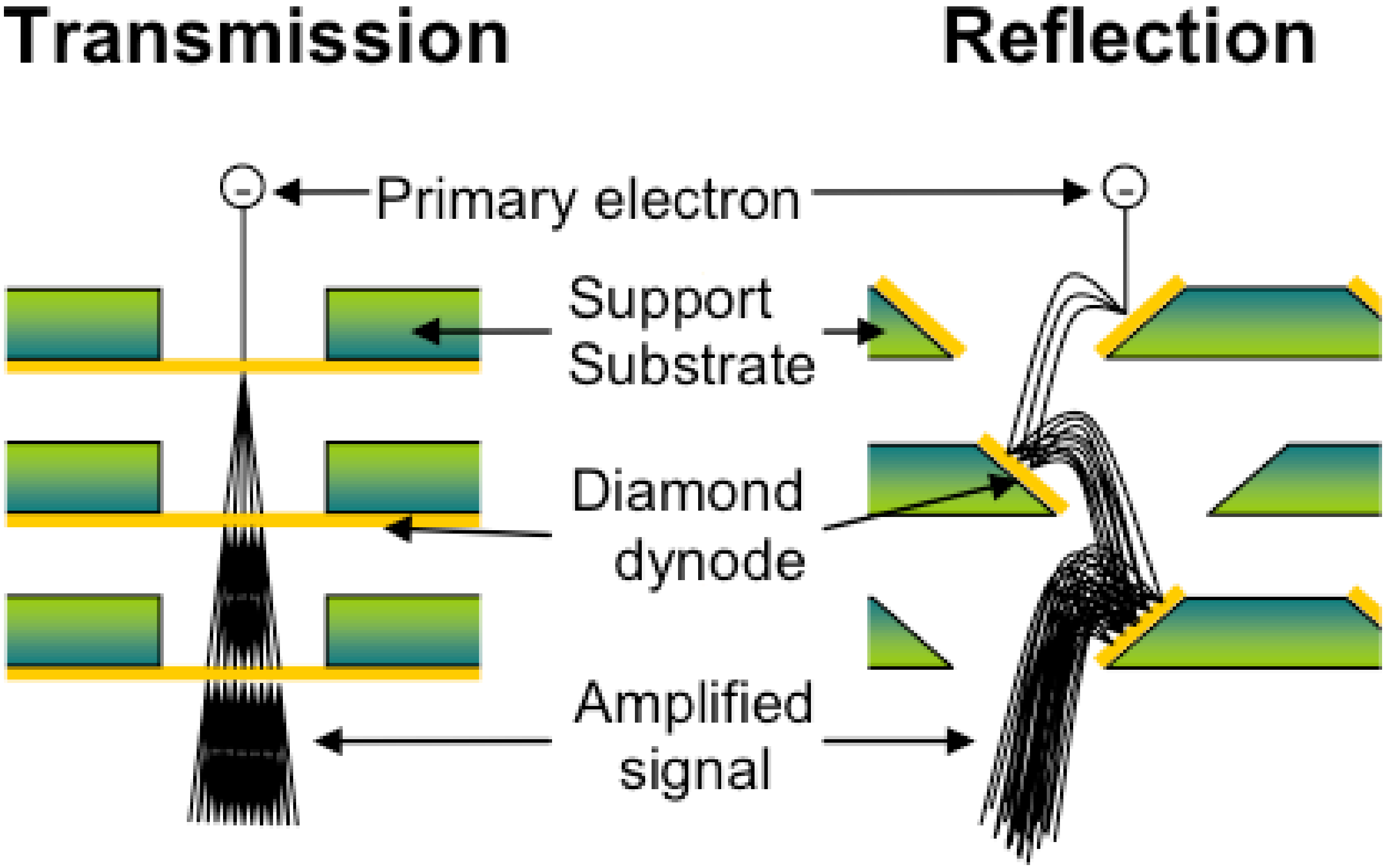
A very successful soft photon detector: the Photomultiplier (1934 -1936)



- 'good' quantum efficiency
- rather fast
- low noise @ high gain: very sensitive
- little dark current, no bias current
- radiation hard
- quite linear

- voluminous, bulky & heavy
- no spatial resolution, not even 1D
- expensive
- quite radioactive
- can't stand B fields

Amplification by multiplication: low noise!



Dynode: amplification by multiplication

New: the Transmission Dynode

Tynode®

Trynode®

The Timed Photon Counter TiPC "Tipsy"concept: advancing PMT's

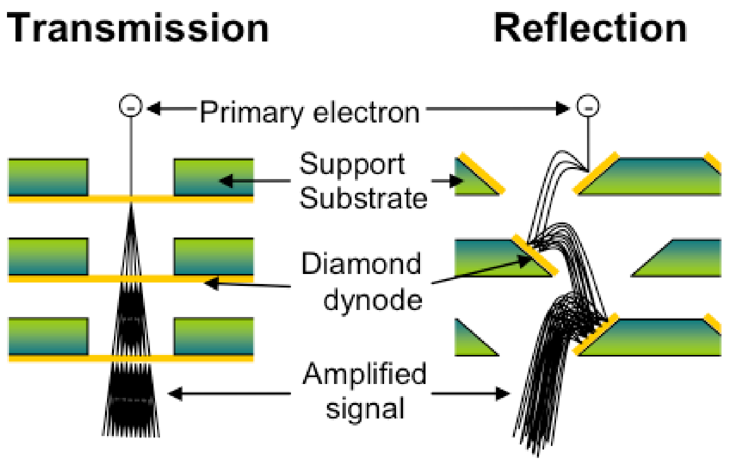
Photomultiplier tubes

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

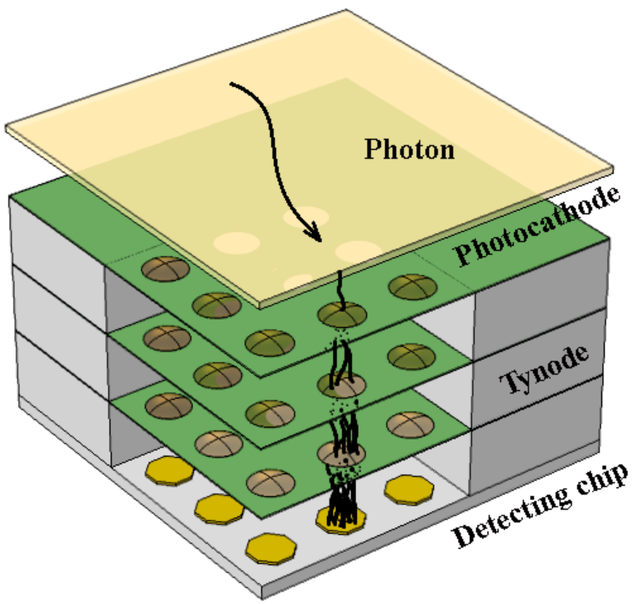
Gain = δ^N

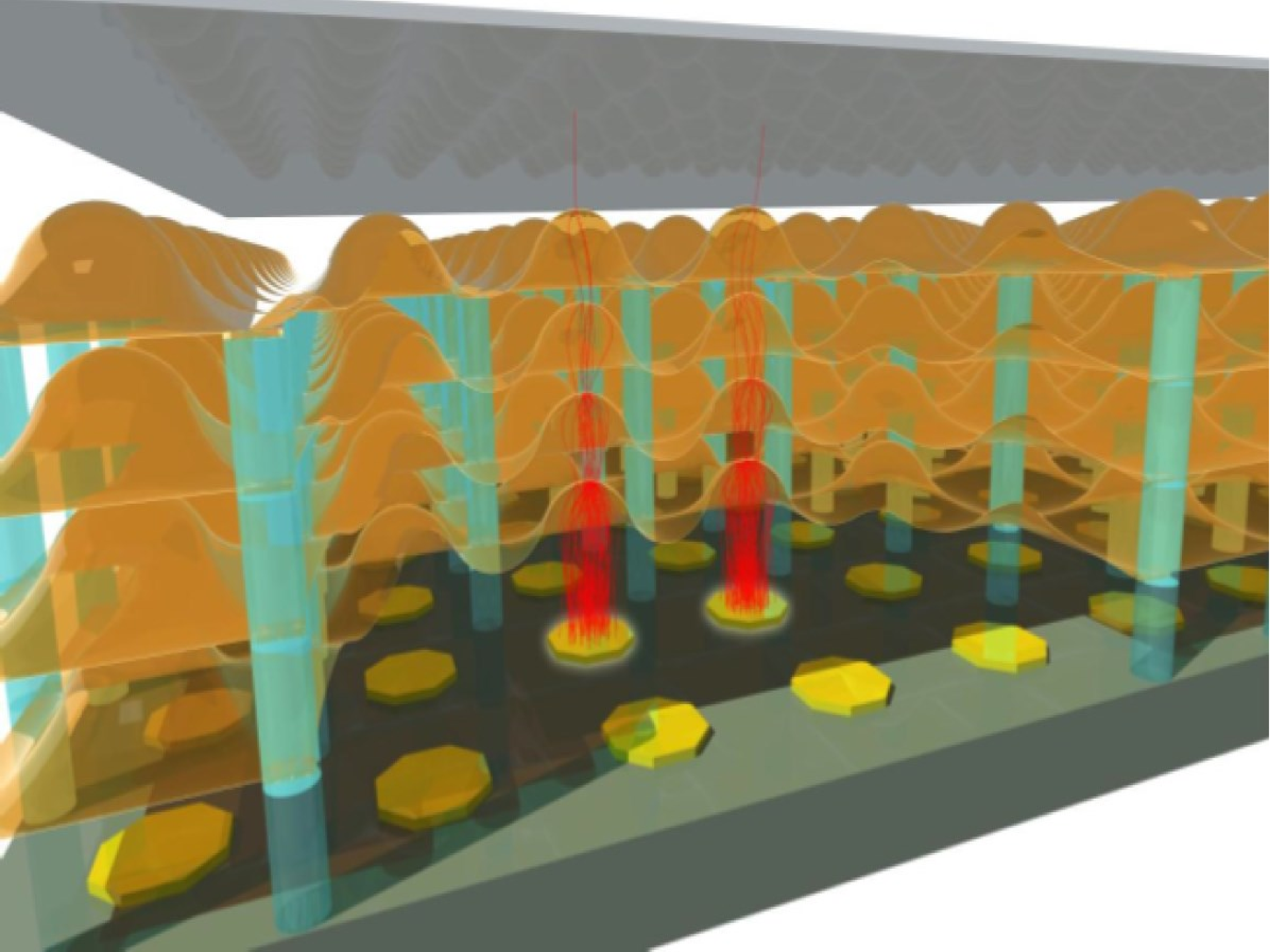
…Can we make it smaller?

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



- 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 due to form factor and straight electron path's
- 2D spatial resolution = 10 µm





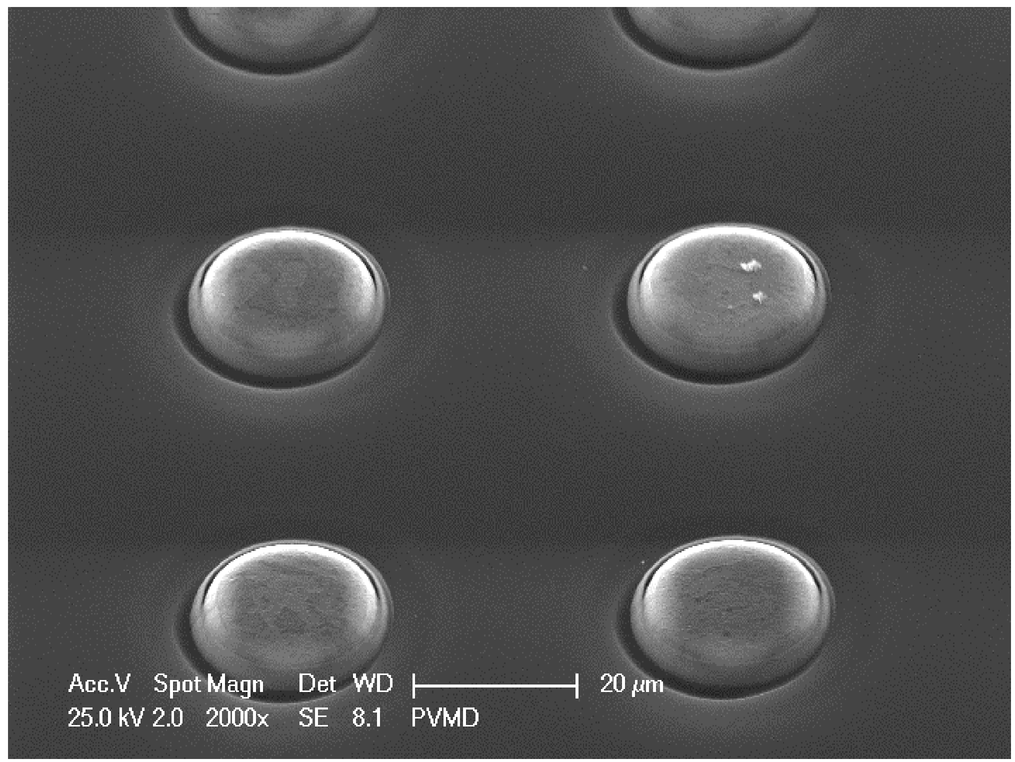
Path towards first prototype

- We have created many tynodes of various sizes and materials
- Most recently, we have achieved transmission yields of 5.5 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 technology

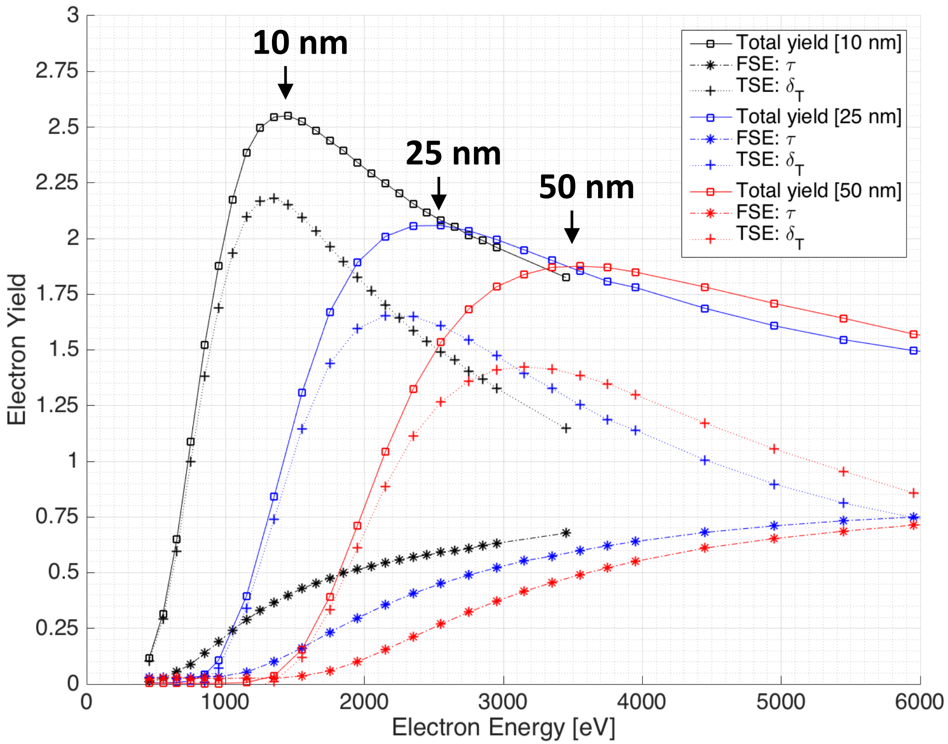
Else Kooi Laboratory

TU Delft

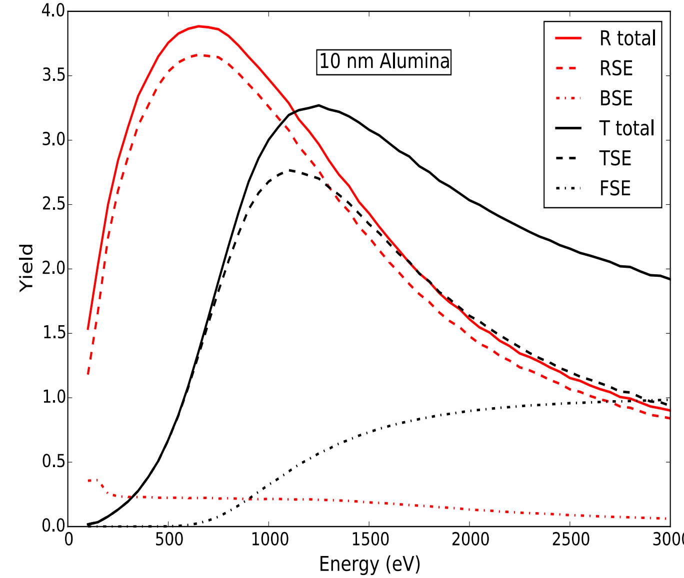


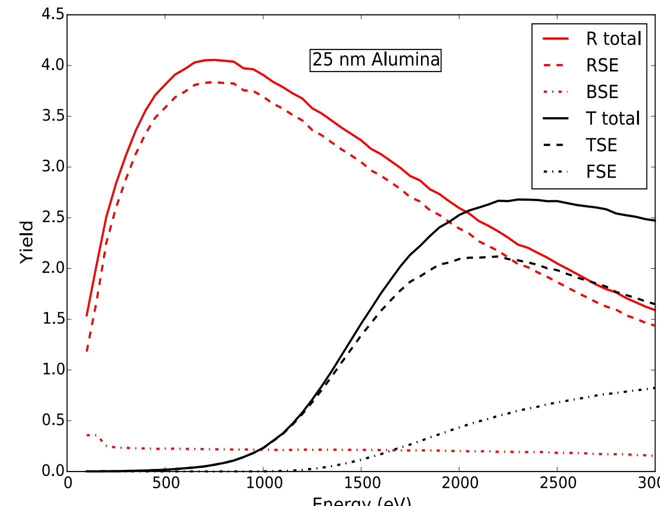
Al_2O_3 Measurements and Simulation using low-energy GEANT extensions

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.

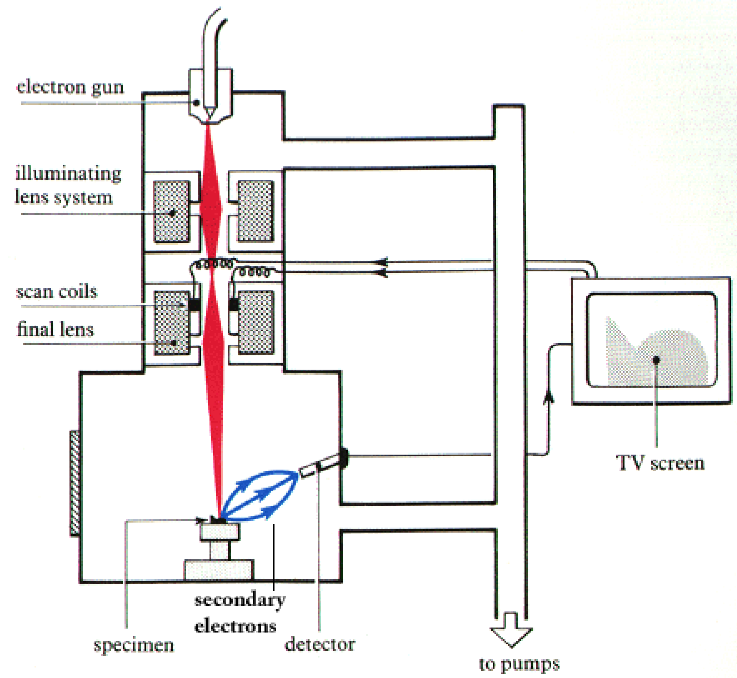
Theory: solid state physics.   Now: wide knowledge of Silicon only.

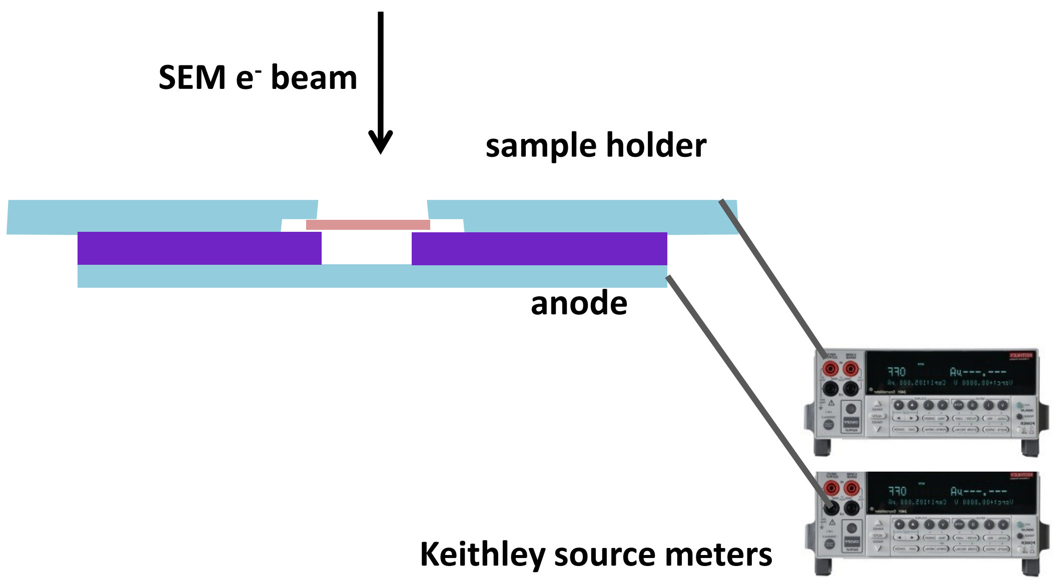
Relevant processes:

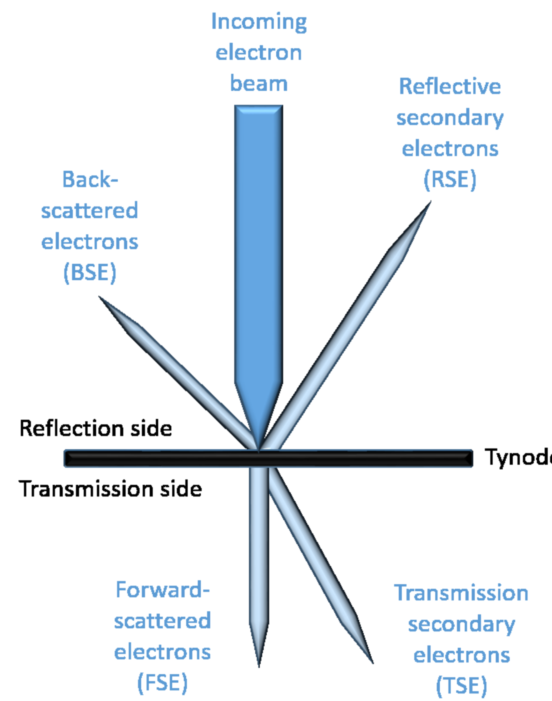
- soft photon absorption: photo-effect, electron binding energy; band gap
- (photo)electron & hole lifetime
- mobility, diffusion & scattering of photo-electrons
- energy gain and energy loss of photo-electrons when traveling through matter
- at surface: work function, electron affinity, probability of electron emission

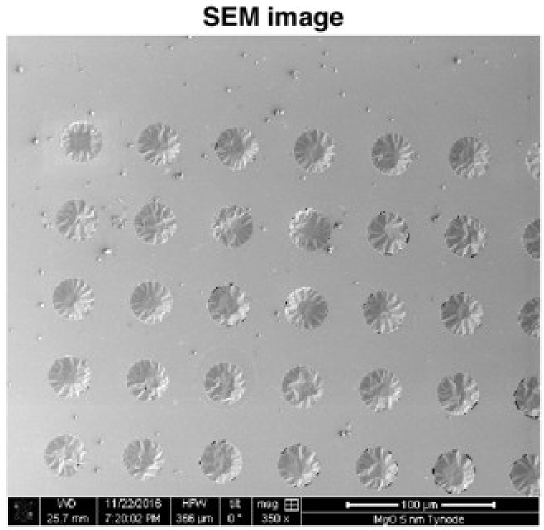
TSEY Measurement in SEM

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

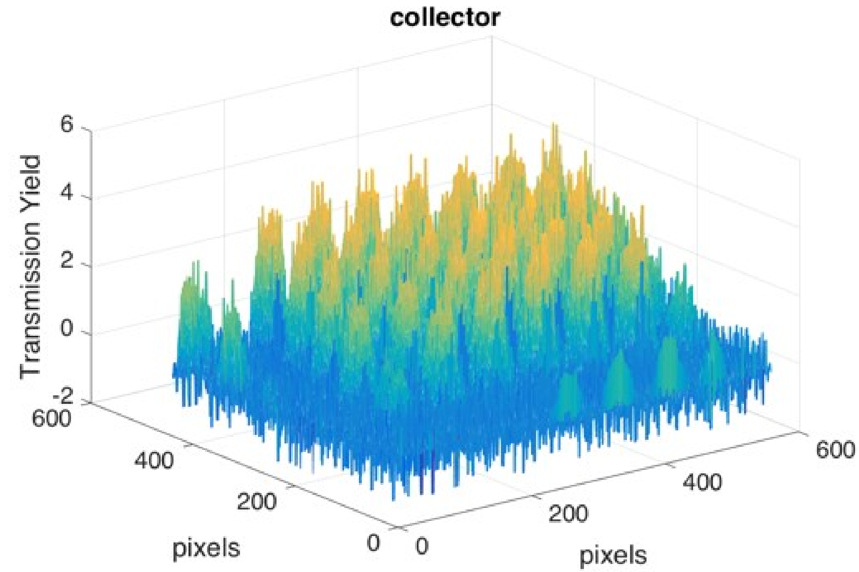




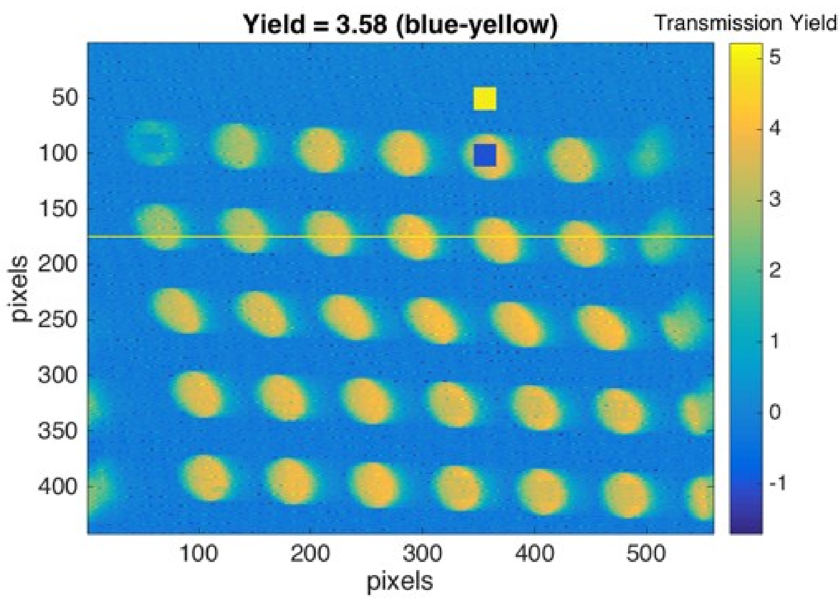




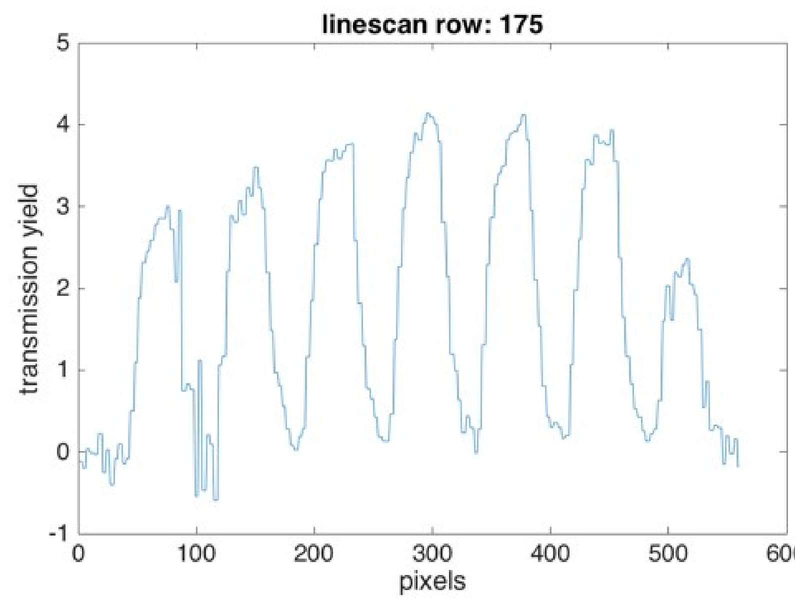
SEM image
WD
25.7 mm
11/22/2016
7:20:02 PM
HFW
366 µm
tilt
0 °
mag
350 x
100 µm
MgO 5 nm Tynode



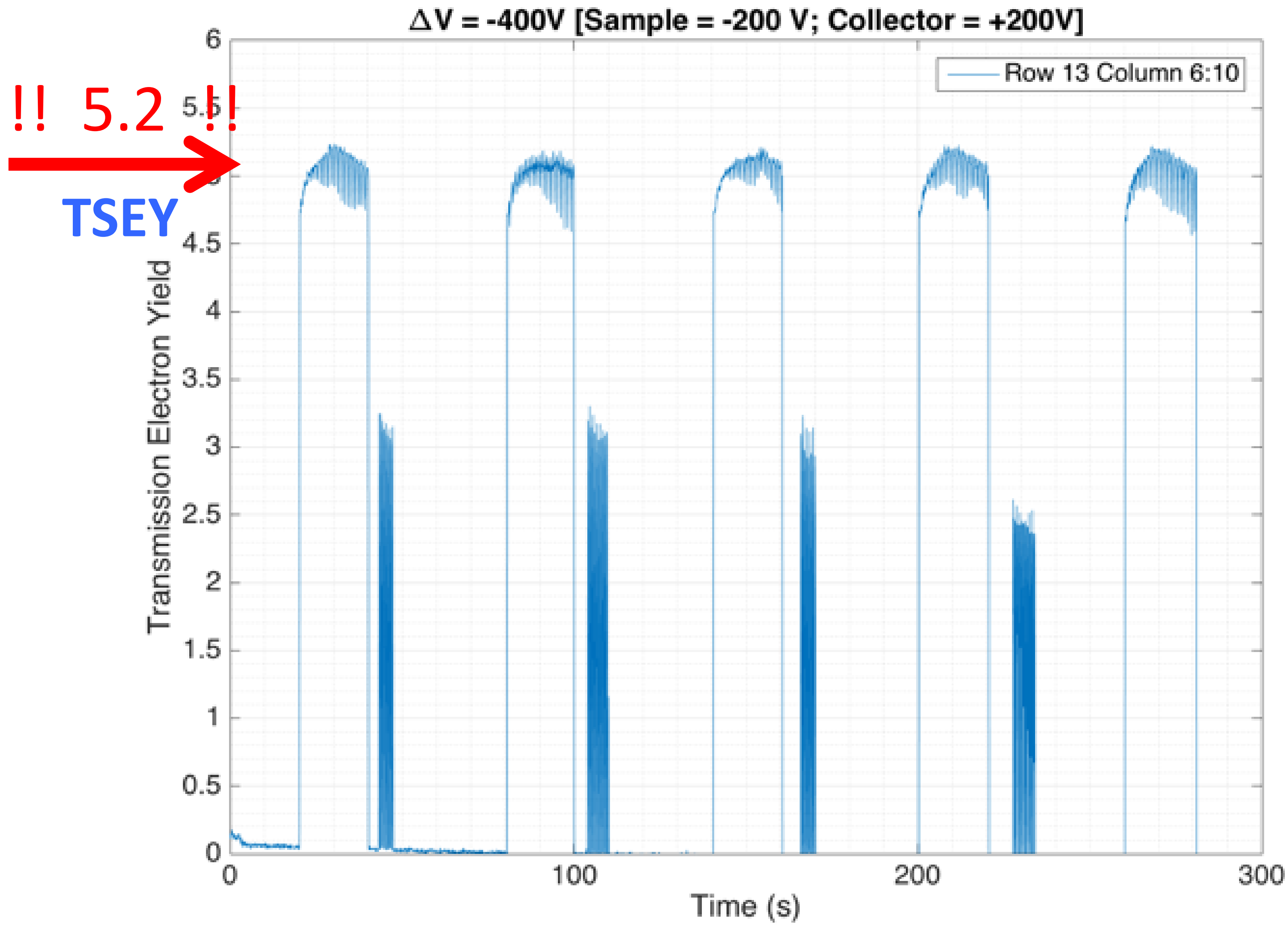
collector
Transmission Yield
6
4
2
0
-2
600
400
200
0
pixels
0
200
400
600
pixels



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

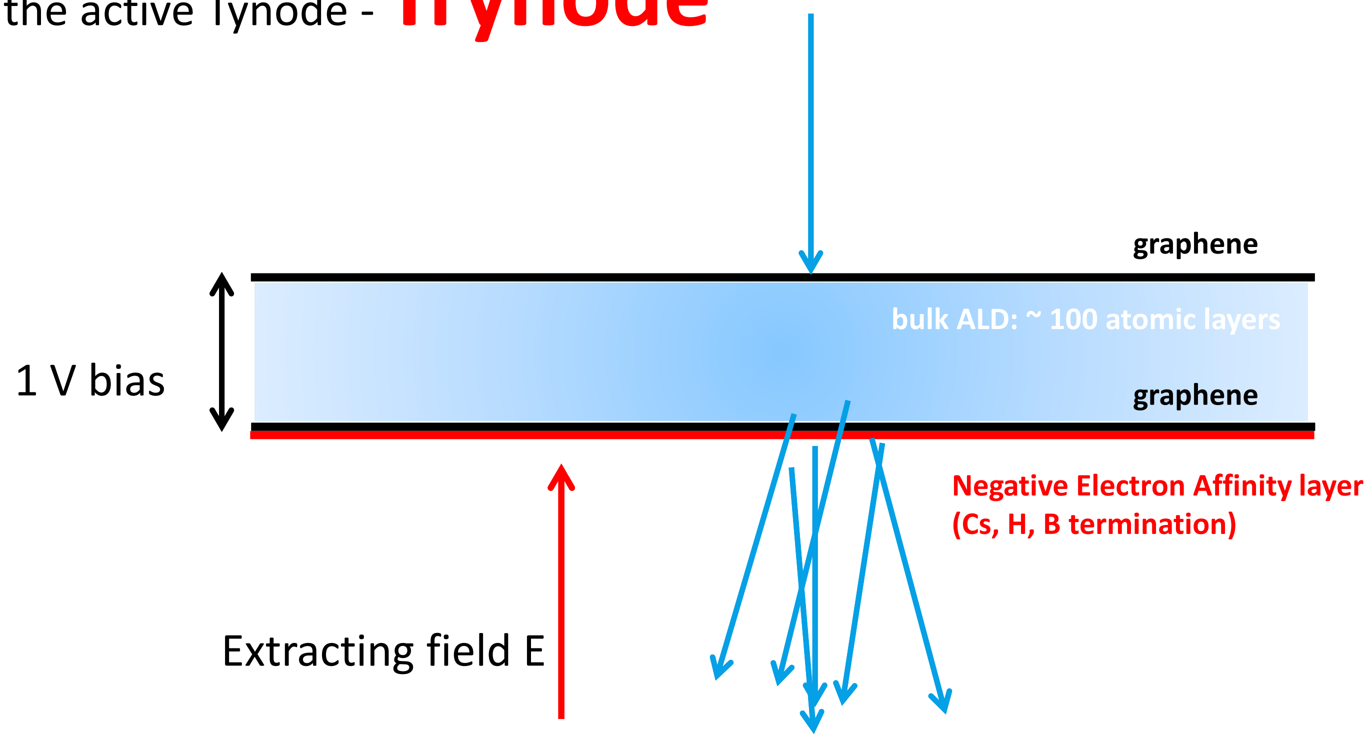


linescan row: 175
transmission yield
5
4
3
2
1
0
-1
0
100
200
300
400
500
600
pixels



November 2016: TSEYmax = 5.5

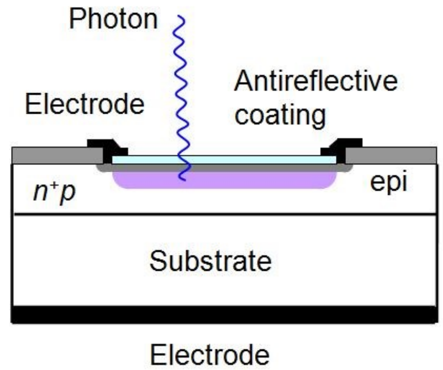
- **Further yield improvement**:
  - ❑ fully exploration of Extracting Field Bonus
  - ❑ Surface termination
  - ❑ Tynode annealing
  - ❑ better vacuum
  - ❑ bake out
  - ❑ the active Tynode - **Trynode**



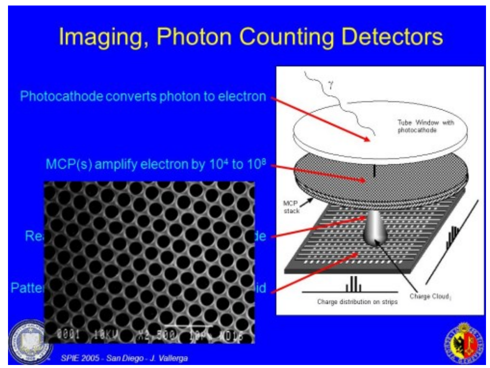
a high Quantum Efficiency photocathode

New Single Soft Photon Detectors

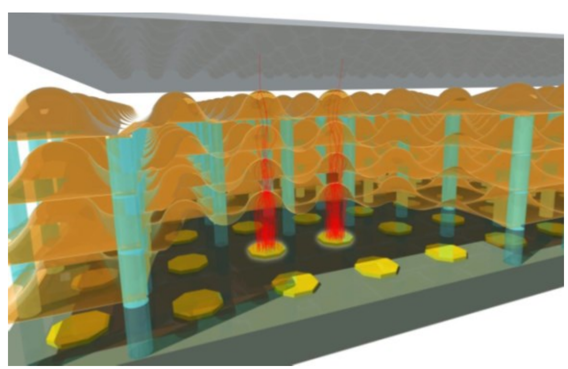
Si PMs



MCPs (+ pixel chip)
Planacon Photonis
John Vallerga
Nicolas Wyrsch

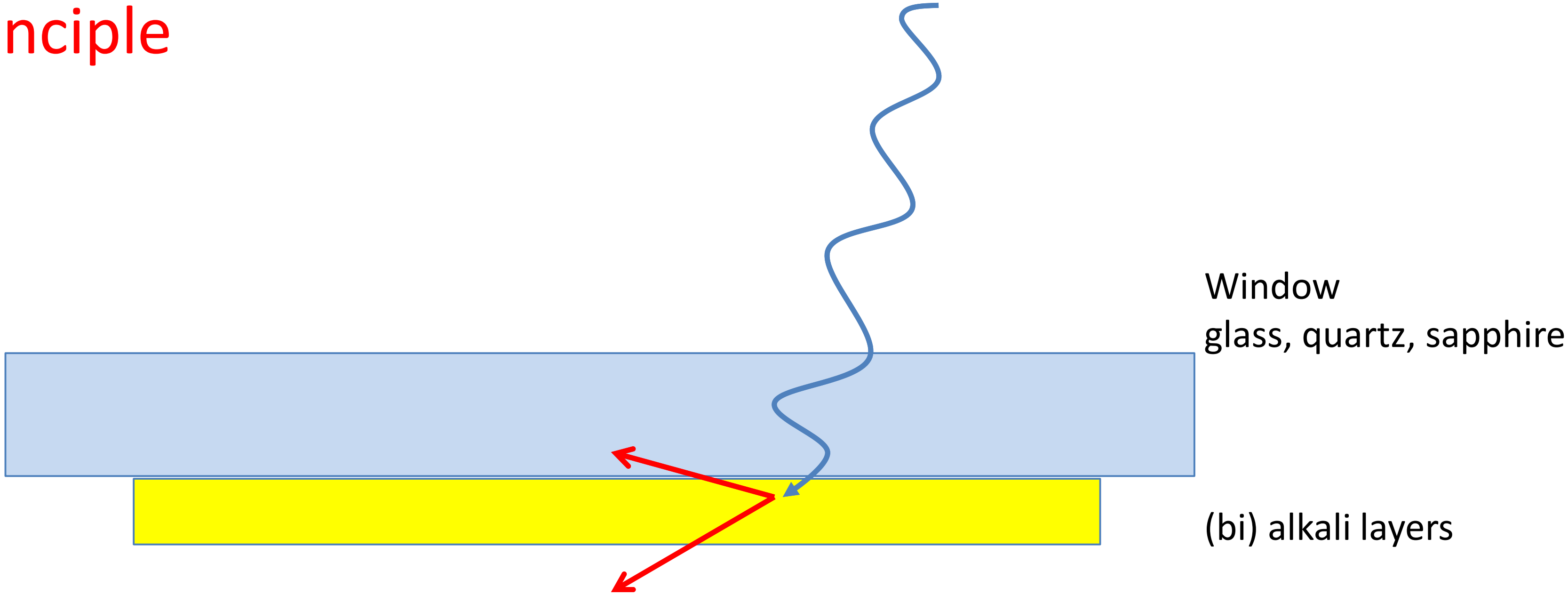


the Tynode: Tipsy
MEMBrane project



	noise	QE	ΔT
Si PMs	●	✓	●
MCPs (+ pixel chip)	✓	●	✓
the Tynode: Tipsy	✓	●	✓✓

Principle



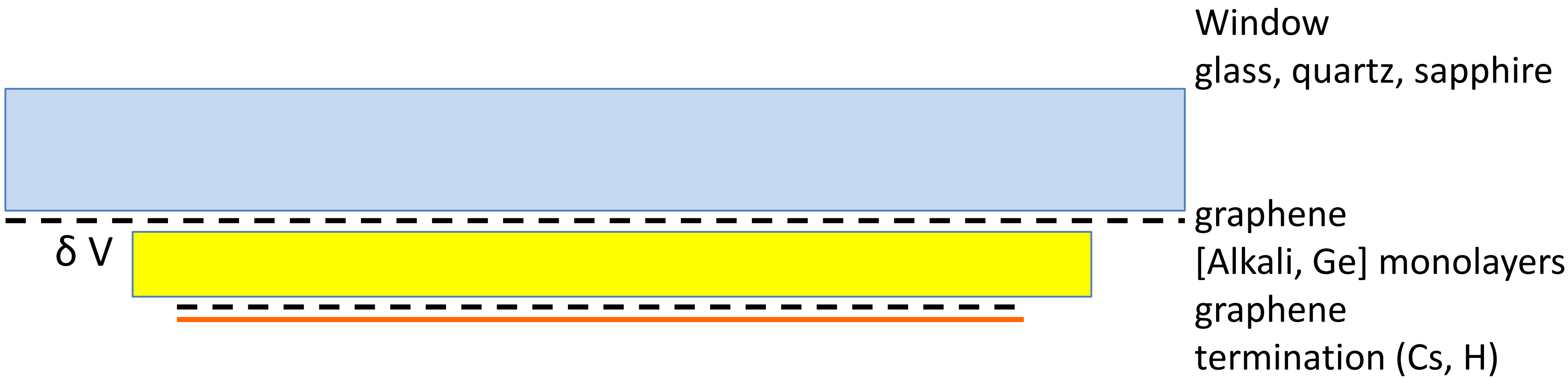
- absorption
- diffusion
- emission

QE never exceeds 0.5 *in principle*

real practical solutions (Photonis, Hamamatsu) are classified

Tipsy's only limitation: its efficiency equals the QE of photocathodes: 0.4 at best

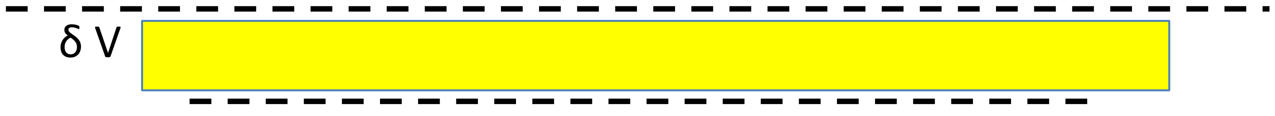
Therefore: the High Quantum-Efficiency (QE) Photocathode



- *Active* photocathode: drift field pushing electrons to emission vacuum surface
- electric field created in between by potential defining graphene planes
- all layers build up individually by *atomic layer deposition* ALD
- electron emission stimulated by negative electron affinity by *termination*
- First designed after *ab initio* simulations of 3D atomic building blocks

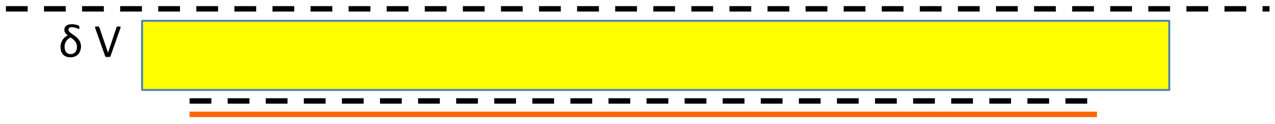
Proposal *for theoretical concept* study: let us first understand the present state-of-the-art

1 Bias field over absorption layer



- Sandwich absorption layer by means of graphene
- prevent electron/hole injection at electrode
- alternative: apply strong surface dopant: termination

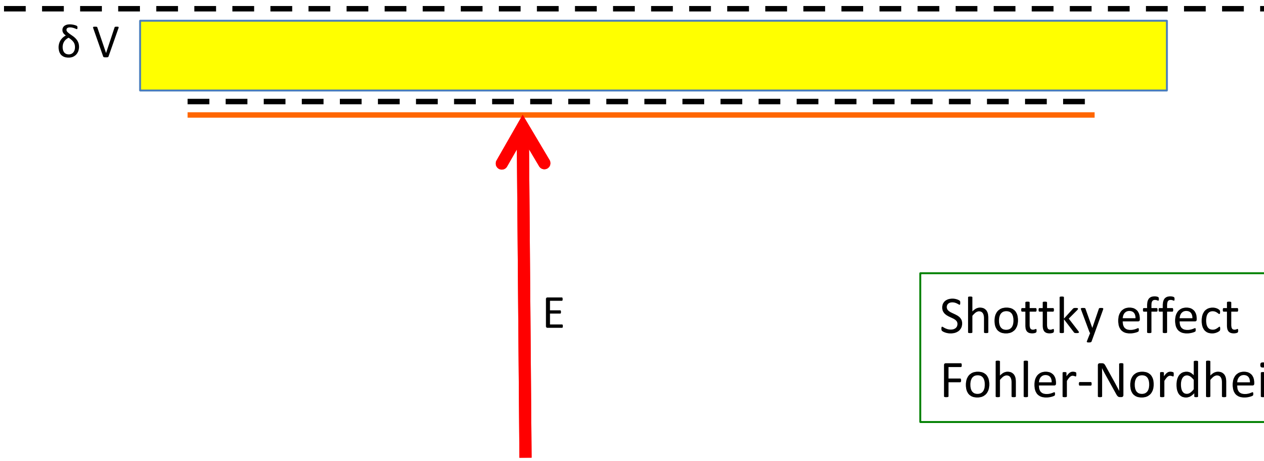
2 Negative electron affinity at emission side



Termination of emission surface, in combination with presence of electrode at emission side

These functionalities must be **optimised.**

3 Optimise positive effect of extracting field

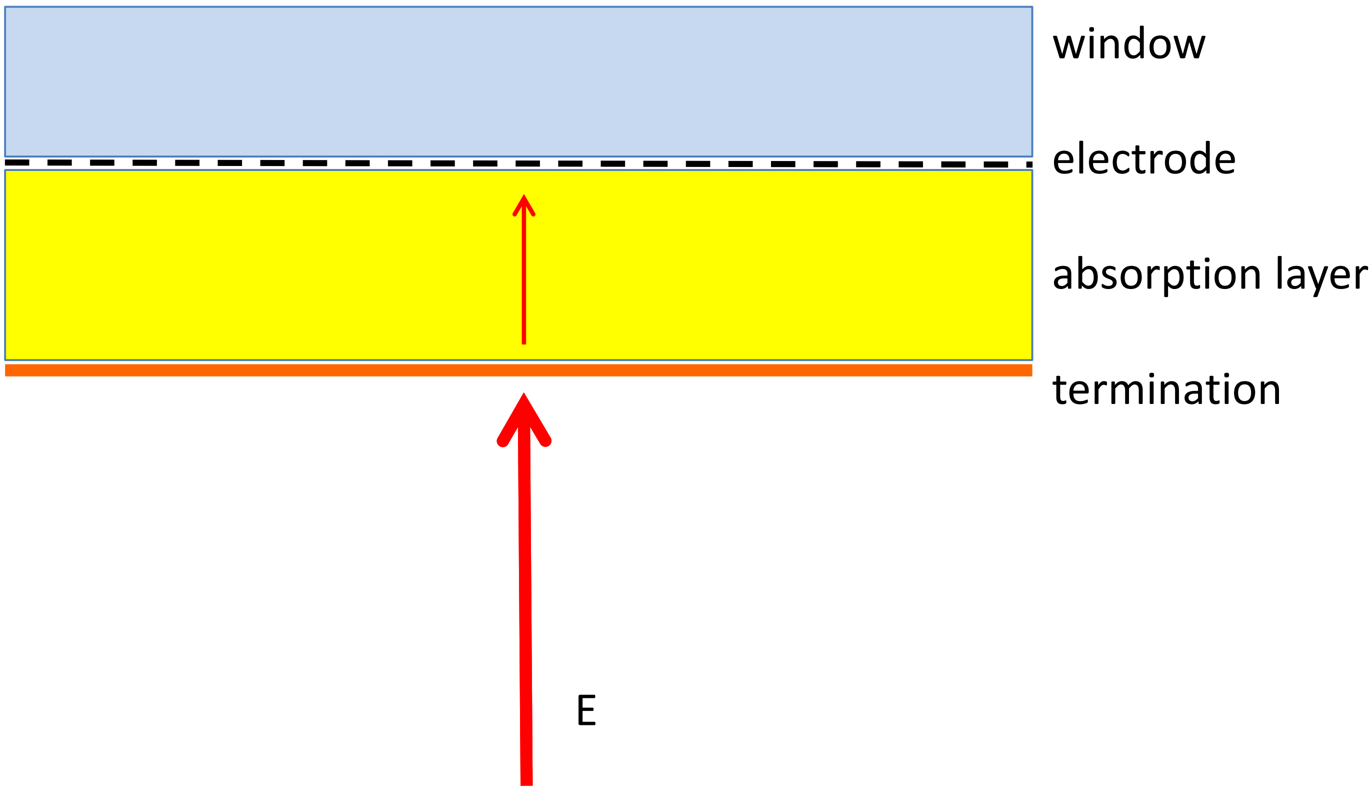


Shottky effect
Fohler-Nordheim tunneling

The required extracting field can be much stronger:

- emitted electrons must have landing energy of 200 – 1000 eV
- distance between photocathode and first tynode can be very small: 20 μm

4 Apply semiconductor layer

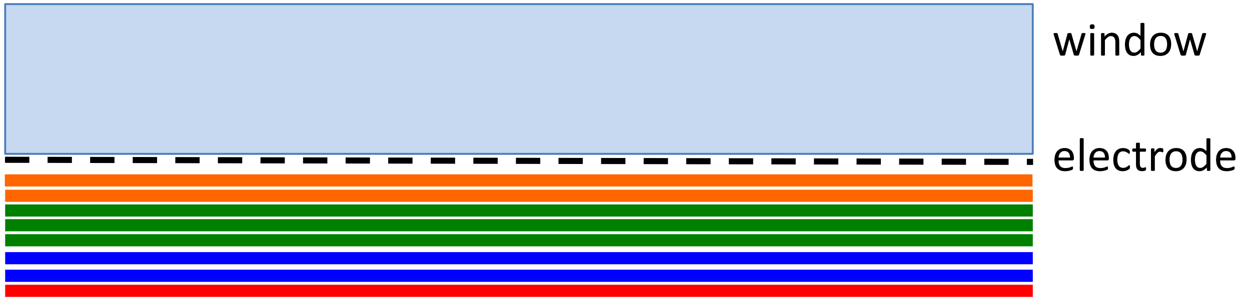


Apply semiconductor as absorber: acts as dielectric (insulating) layer when biased by external extracting field.

The extracting field propagates into the absorption layer.

Absorption layer will be polarised: a photo-electron will drift towards the emission side.

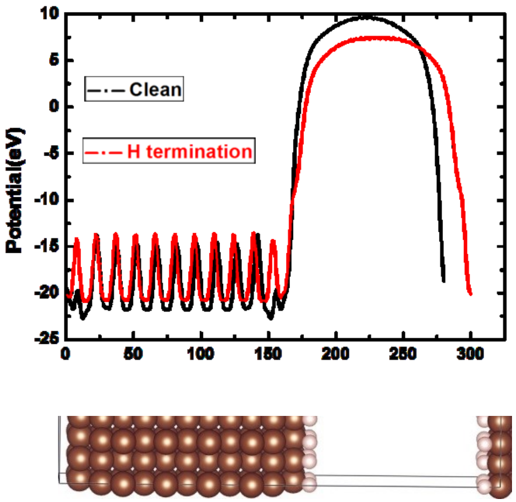
5 Apply Atomic Layer Deposition ALD



Atomic Layer Deposition: rapid development in MEMS technology

First: theoretical model: VASP simulations

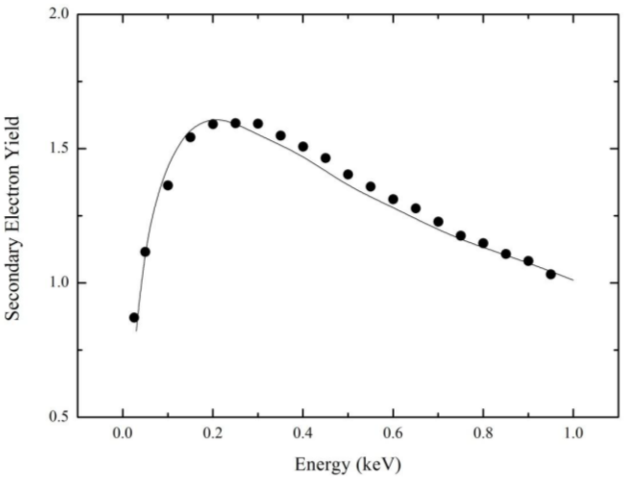
Solid State Physics
Density Functional Theory simulations



Electron density, energy distributions
density structure,
band gap
work function,
optical data

Monte Carlo simulations

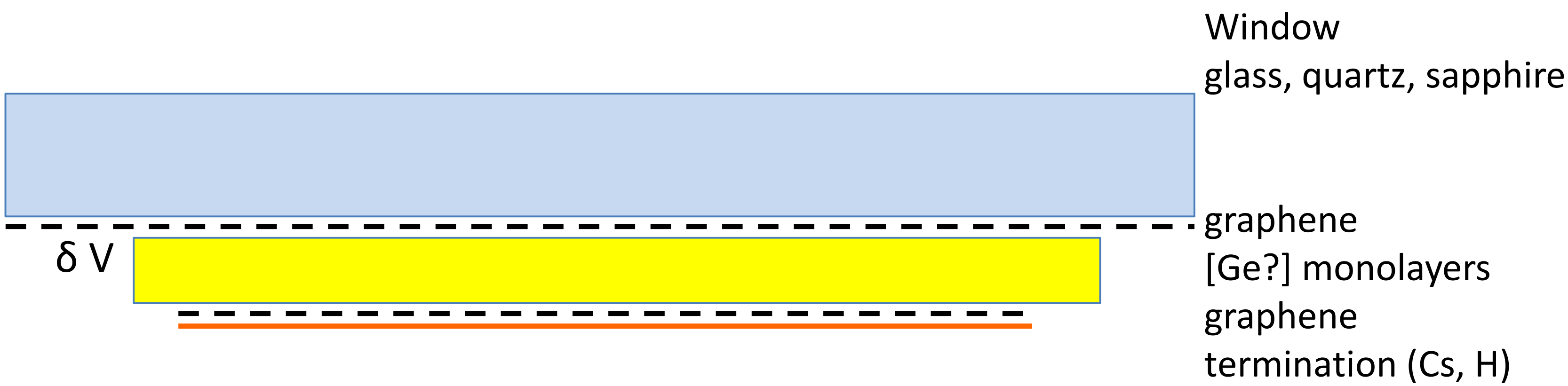
Vienna Ab-Initio Simulation Program
VASP



(T) SEY

Tipsy's only limitation: its efficiency equals the QE of photocathodes: 0.4 at best

Therefore: the High Quantum-Efficiency (QE) Photocathode



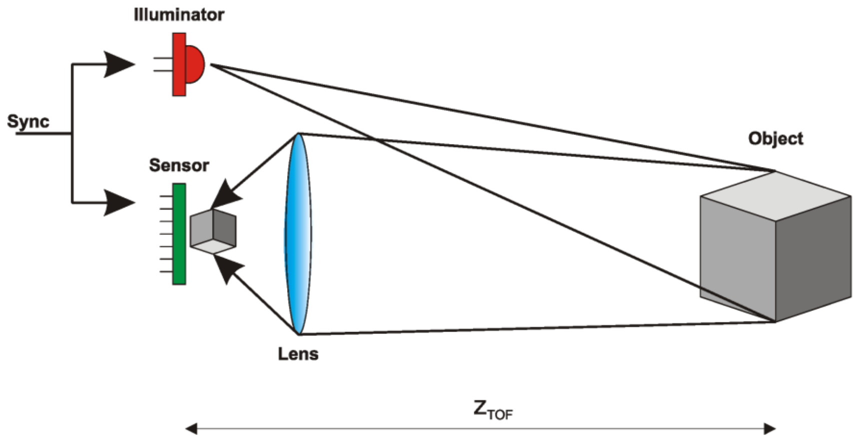
Proposal *for theoretical concept* study: let us first understand the present state-of-the-art photocathodes.

Cooling of the new photocathode is likely to be required in order to limit thermal electron emission. Note that the tynode stack is a noise-free amplifier!

The new photocathode will be non-transparent and will look **black!**

Tipsy (with high QE photocathode):

- digital single soft photon sensitive, with high efficiency
- 20 – 2 ps time resolution per photon
- (2D) spatial resolution: 10 µm
- very low shot noise (dark current)
- Data driven counting rate per pixel
- total data rate of 5 GHz/s



Applications

Consumer products

Night goggles: most sensitive light detection — Tipsy in iPhone S10 (2022)?

Prompt 3D Imaging with z-resolution of 0.5 mm — Tipsy in iPhone S10 (2022)?

3D Machine viewing: robotics

Self-driving of vehicles: situation info source: prompt 3D radar like image

Medical Imaging: The Cherenkov-ToF-PET scanner

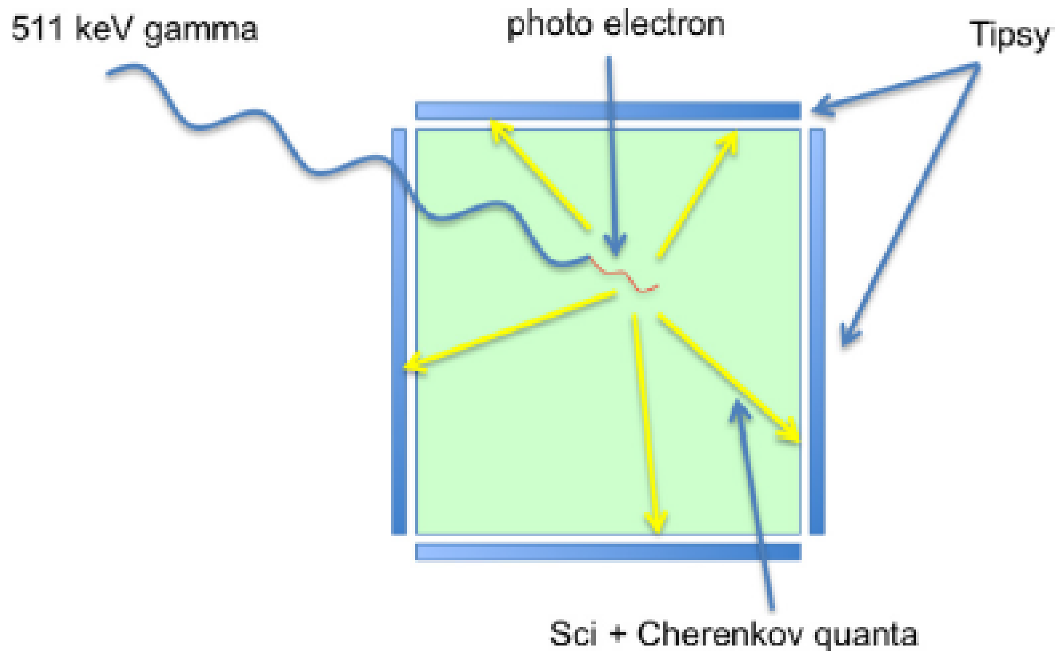
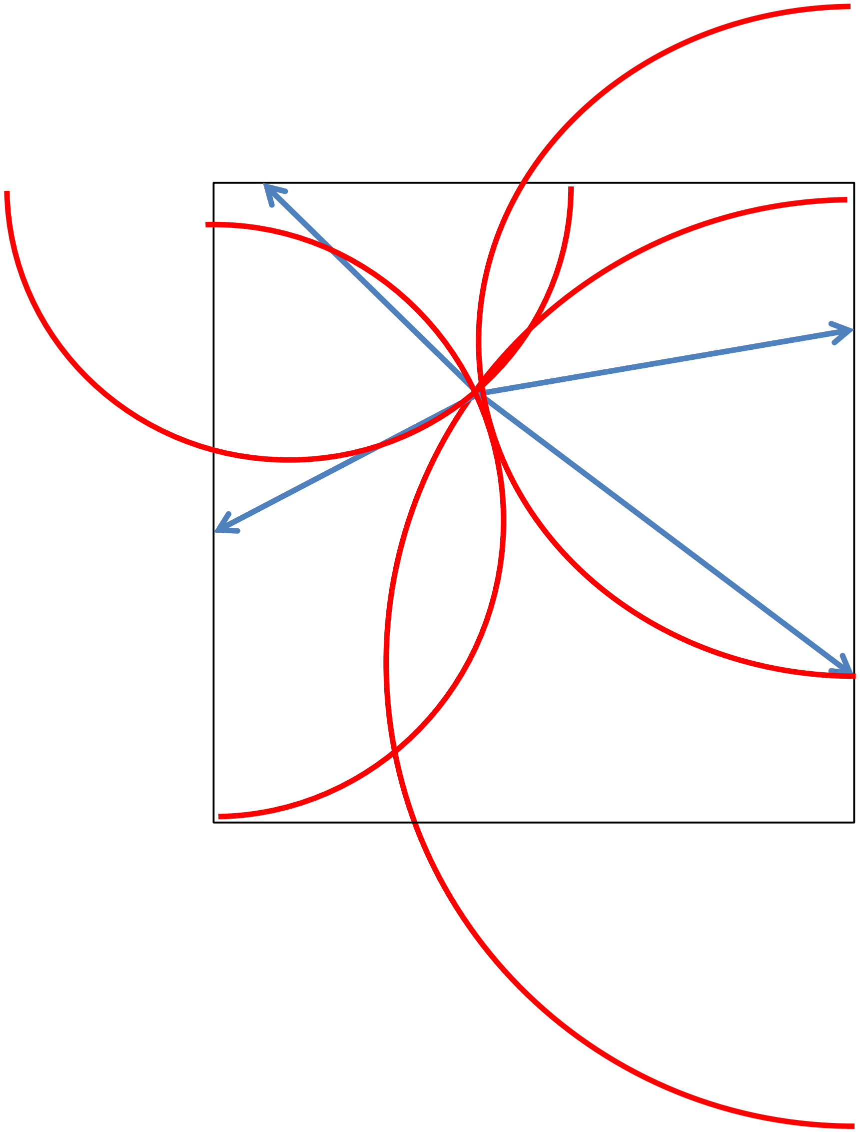


Fig. 5. A PET scanner detection element with Timed Photon Counter Tipsy soft photon detectors as readout. Cherenkov photons, created after the absorption of a 511 keV annihilation photon in a lead glass cube are read out at all six sides.

4D (X,Y,Z,t) measurement of conversion point of 511 keV quantum:
only 3 ChQs are required for 4D fix using GPS algorithm

…PET is no longer Tomography…..



with 10 ps time resolution:

Reconstruction of interaction point: origin of all prompt Cherenkov photons:

4D GPS analysis method:

Only 3 Cherenkov photons are required for fix in 3D position and time

Cherenkov photons emitted by 511 keV photo-electron in lead glass

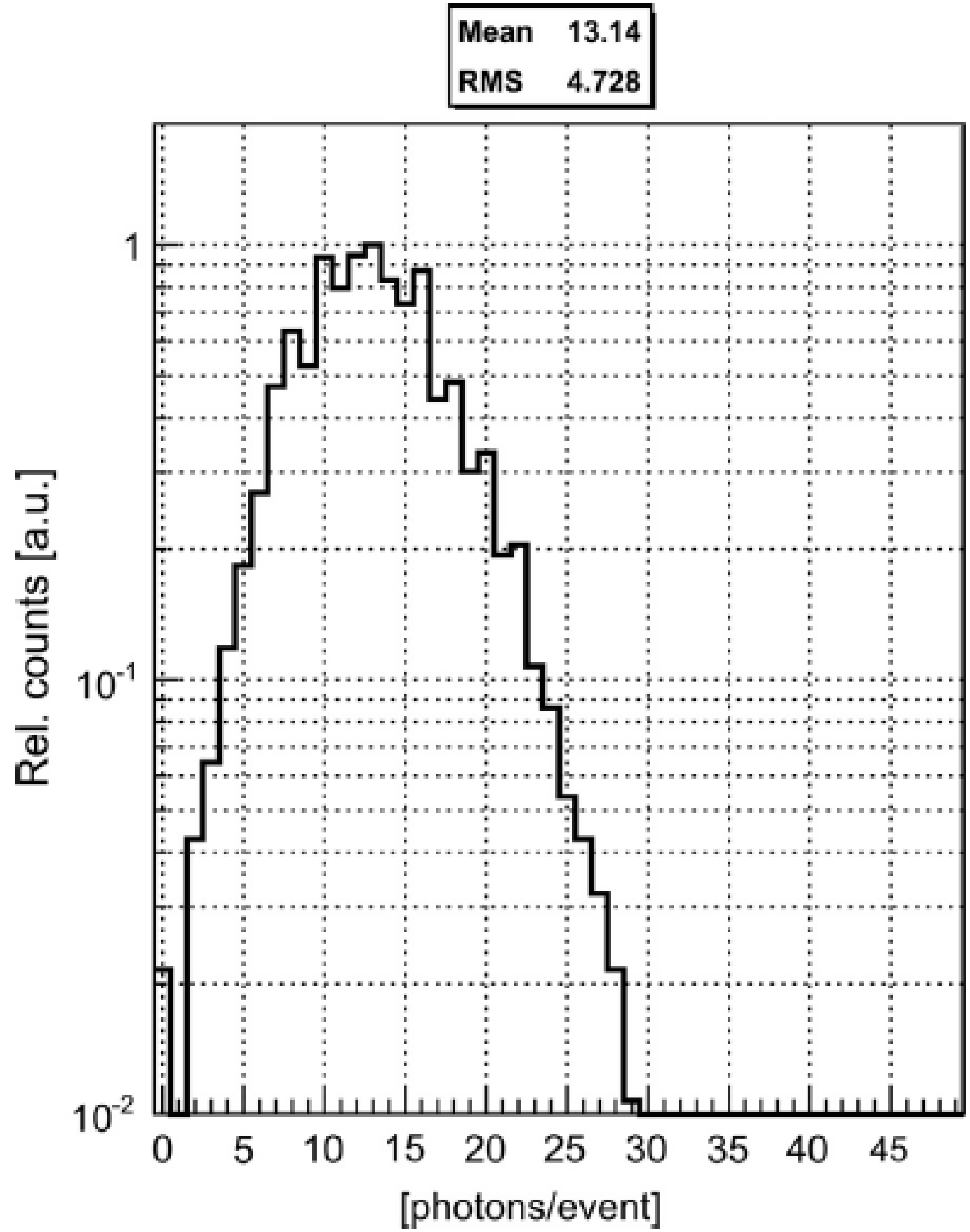
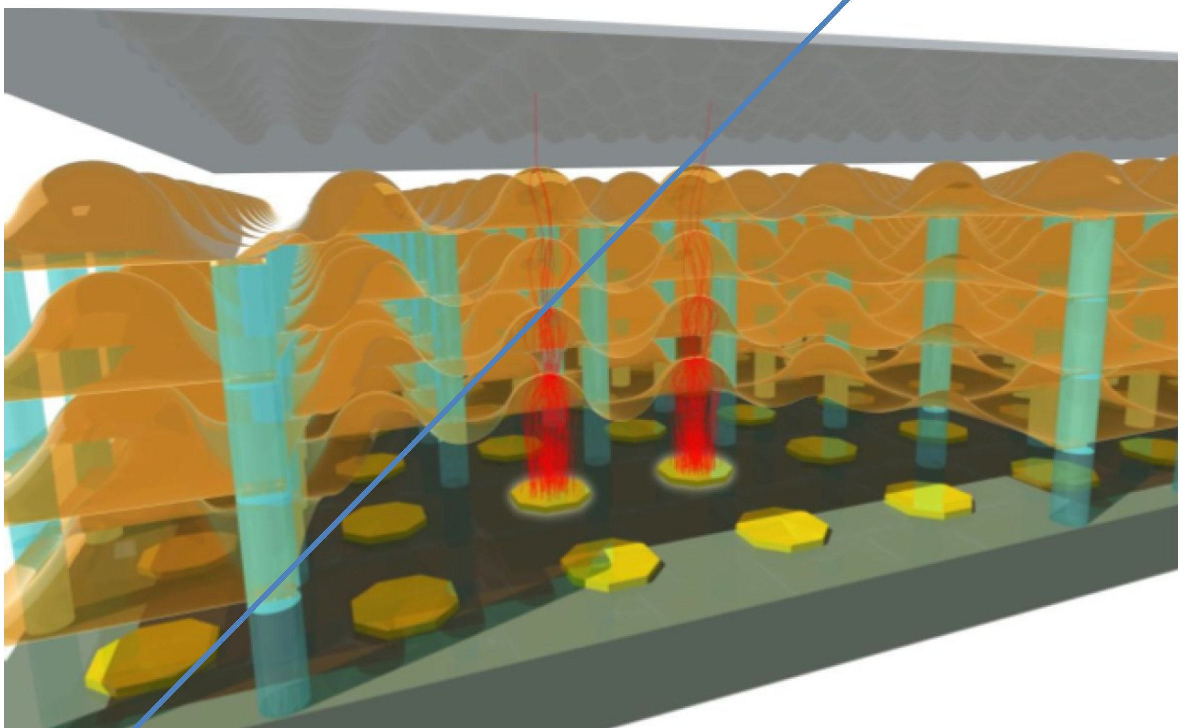


Fig. 6. The probability of the emission of a specific number of Cherenkov photons due to the absorption of a 511 keV photon in lead glass. Assuming a QE of 0.3, and no other losses, the probability to have at least four photoelectrons is about 60% [15].

MIP detection using e-Brane

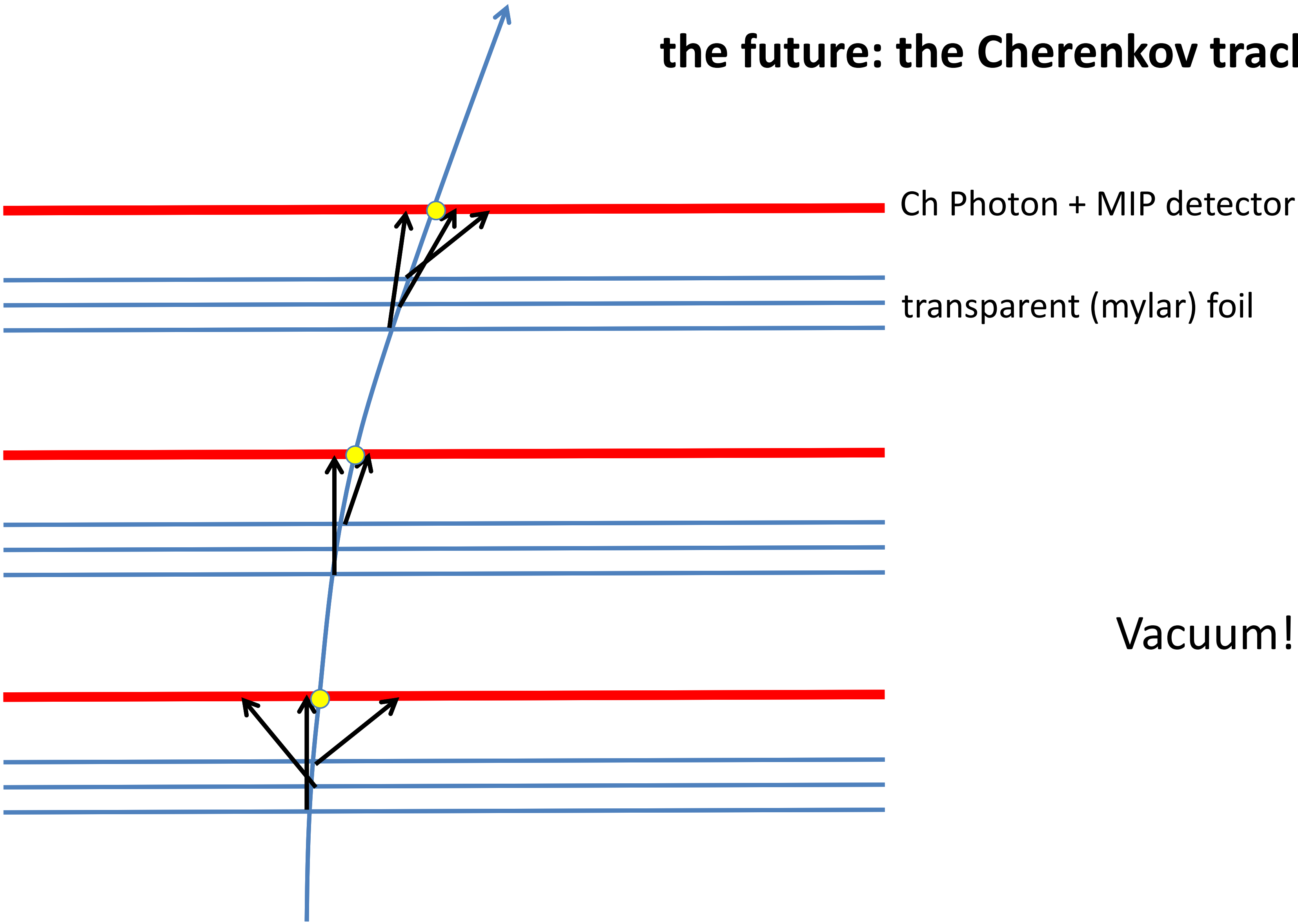


muon
MIP

e-Brane: surface with a high probability to emit at least one electron at the passage of a MIP (in position and time)

- low electron affinity of emitting surface
- 3PM experiment: naked but black shielded PMs in MIP testbeams
- glassplate thick 0.1 mm e-Brane: sufficient Cherenkov photons!

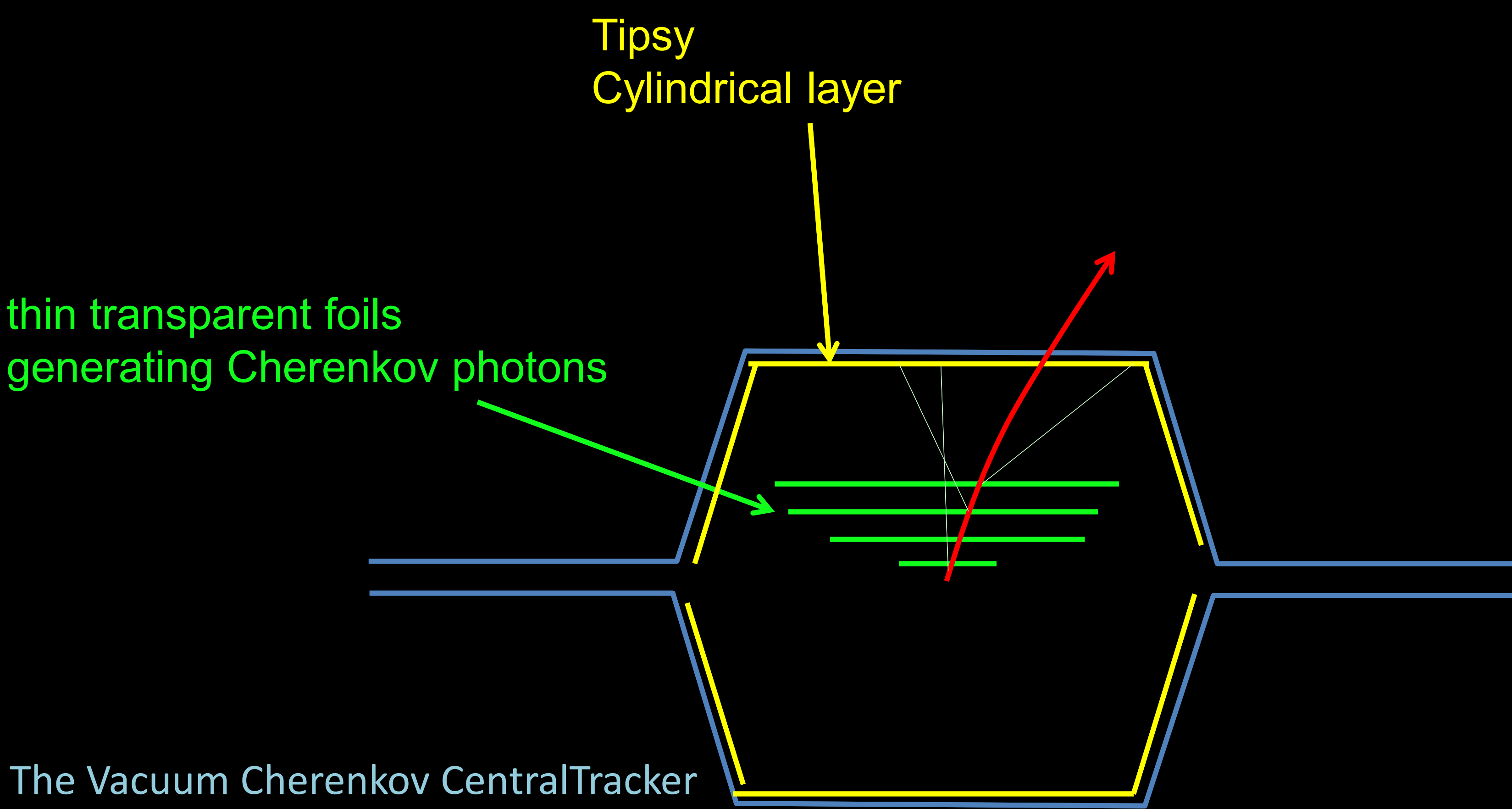
the future: the Cherenkov tracker



Cherenkov photons are emitted with given angle with track
see TORCH

Future inner (central) tracker in collider experiments: the Cherenkov tracker

- very low detector mass
- Tipsy layer at safe distance from interaction point
- no extrapolation

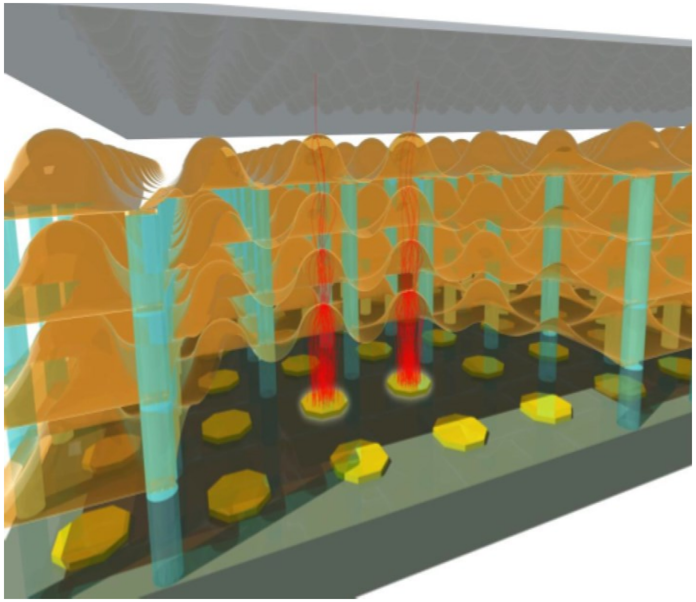


Conclusions

New MEMS technology, namely Atomic Layer Deposition ALD, may enable the development of a new generation of photocathodes

New solid state theoretical physics models are required first, leading towards the development of new ALD technology

With better soft photon detectors, Cherenkov photons are becoming more important. Scintillators are slow and may be phased out.



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H. van der Graaf et al.: The Tynode: A new vacuum electron multiplier.
Nucl. Instr. & Methods, in press. http://dx.doi.org/10.1016/j.nima.2016.11.064. T

H. van der Graaf et al.: Potential applications of electron emission membranes in medicine.
Nucl. Instr & Methods, special Medical Physics issue on "Advances in detectors and applications for Medicine". A809 (2016) 171-174. http://dx.doi.org/10.1016/j.nima.2015.10.084.