The new Transmission Dynode “Tynode” and its applications in the Tipsy ultra fast soft photon detector

Hassan Akhtar, Yevgen Bilevych, Neil Budko, Hong Wah Chan, Edoardo Charbon,
Alexander Cronheim, Harry van der Graaf, Conny Hansson, Kees Hagen, Gert Nützel,
Serge D. Pinto, Violeta Prodanović, Behrouz Raftari, Lina Sarro,
Dennis R. Schaart, John Sinsheimer, John Smedley, Shuxia Tao, Annemarie Theulings, Kees Vuik

Workshop on ps timing detectors for physics and medical applications

Kansas City
Sept 15, 2016

erc
European Research Council

BROOKHAVEN
NATIONAL LABORATORY

PHOTONIS
INDUSTRY & SCIENCE

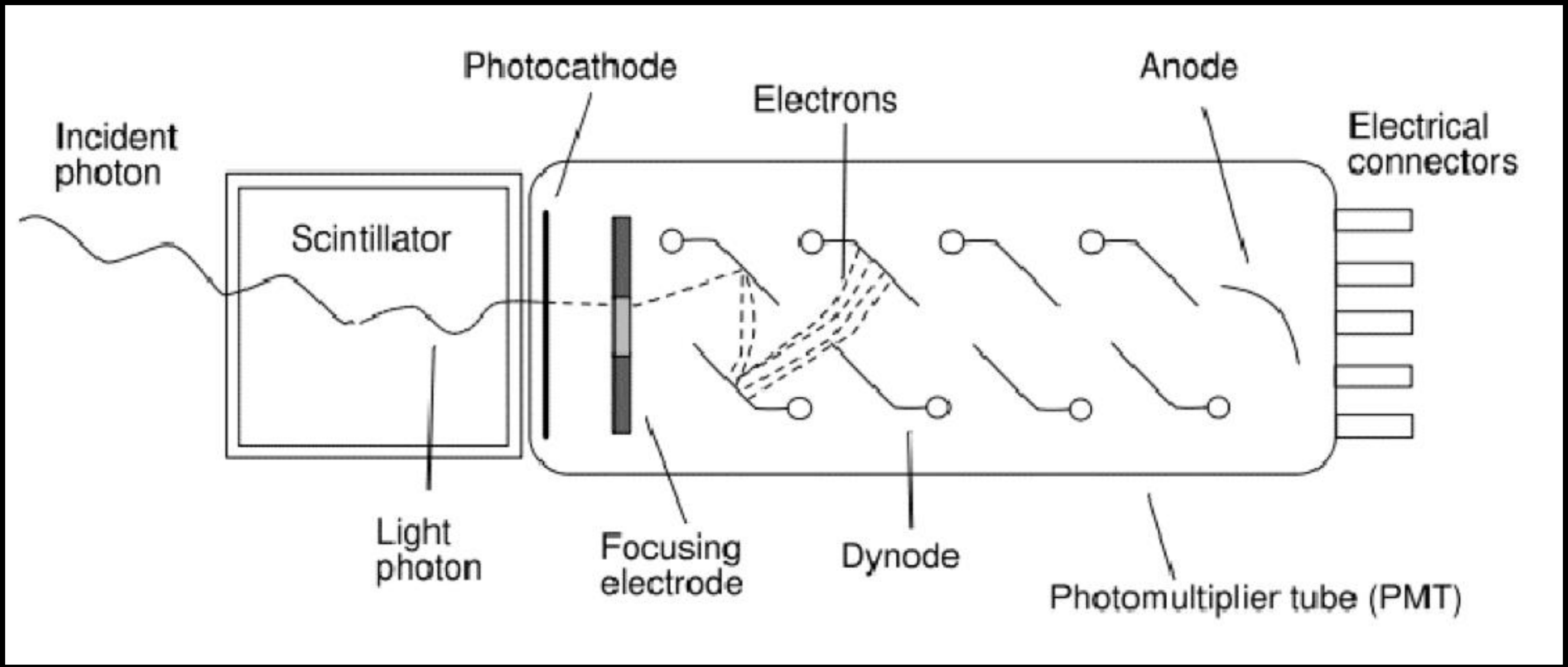
FOM

NWO

TU Delft
Delft University of Technology

NIKHEF

A very successful 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!

__Amplification by multiplication__ by means of dynodes in vacuum:

“controlled” avalanche: NO noise added in amplifier

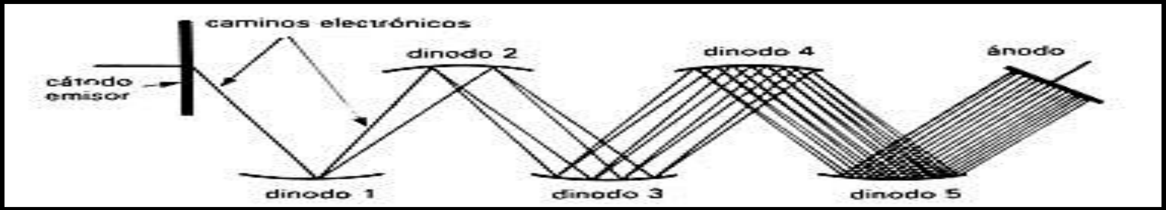
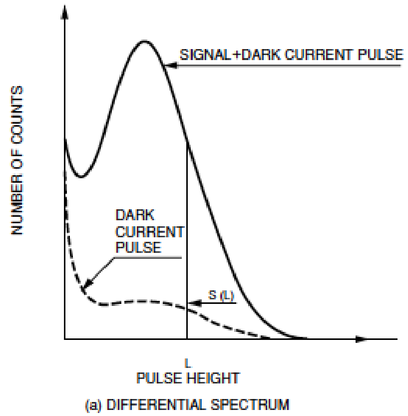


Figure 6-4 (a) shows examples of the pulse height distribution obtained with a photomultiplier tube. There are output pulses present even if no light falls on the photomultiplier tube, and these are called dark current pulses or noise pulses. The broken line indicates the distribution of the dark current pulses, with a tendency to build up somewhat in the lower pulse height region (left side). These dark pulses mainly originate from the thermal electron emission at the photocathode and also at the dynodes. The thermal electrons from the dynodes are multiplied less than those from the photocathode and are therefore distributed in the lower pulse height region.

Figure 6-4 (b) indicates the distribution of the total number of counted pulses S(L) with amplitudes greater than a threshold level L shown in (a). (a) and (b) have differential and integral relations to each other. Item (b) is a typical integral curve taken with a photon counting system using a photomultiplier tube.



(a) DIFFERENTIAL SPECTRUM

Dark current response:

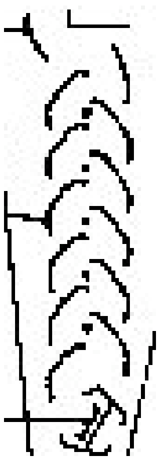
single (thermal) emitted electrons from photocathode

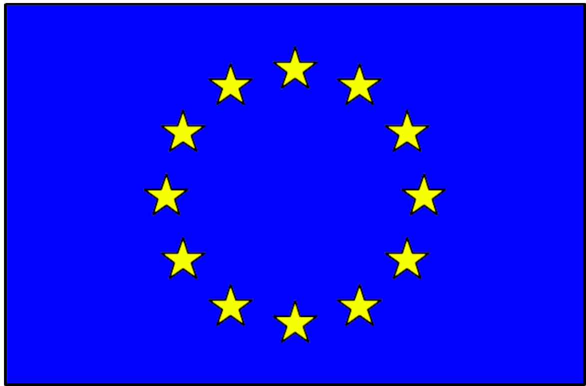
~ exponential amplitude distribution

European Research Council

ERC-Advanced ‘MEMBrane’ 2012

2.4 M€





Reduce size of dynodes (volume downscaling), and place set of dynodes on top of pixels of CMOS chip

- keep potentials as they were (V_{step} ~ 200 V)
- (non relativistic) electron trajectories same form, but smaller (volume)
- multiplication yield: assume SEY ~ 4, typical for PMs
- pixel input source capacity: only ~ 10 fF
- required gain ~1000 = $2.5^{4} =$: 5 dynodes sufficient

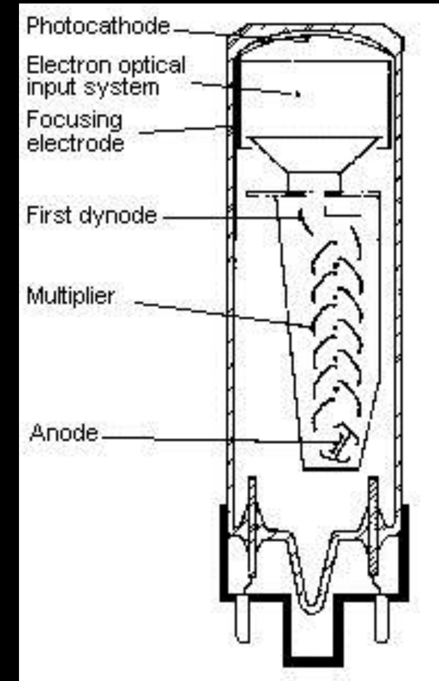
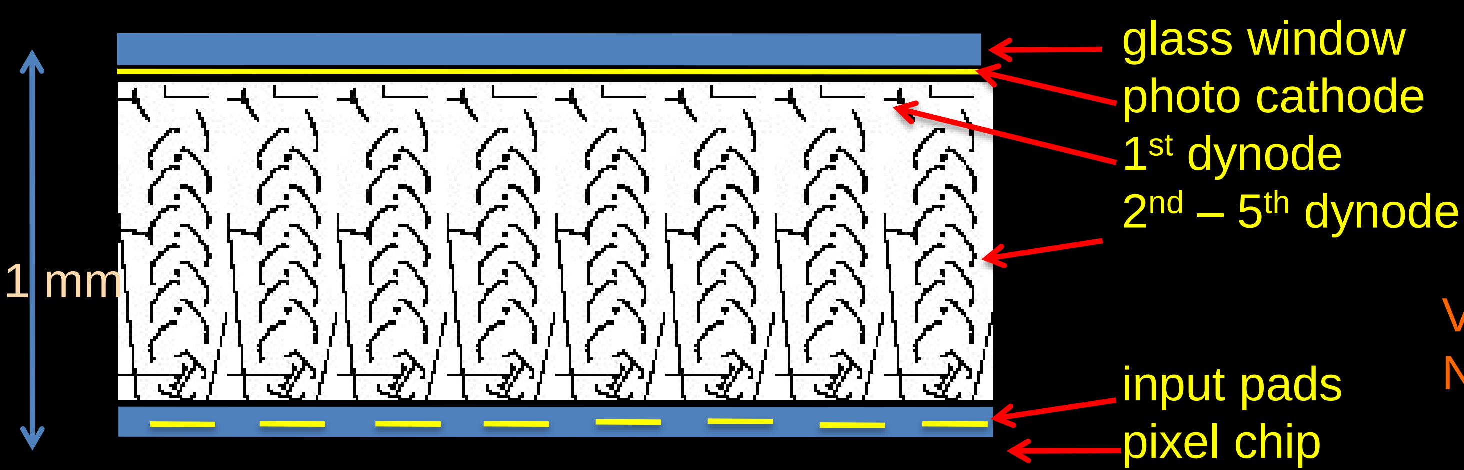
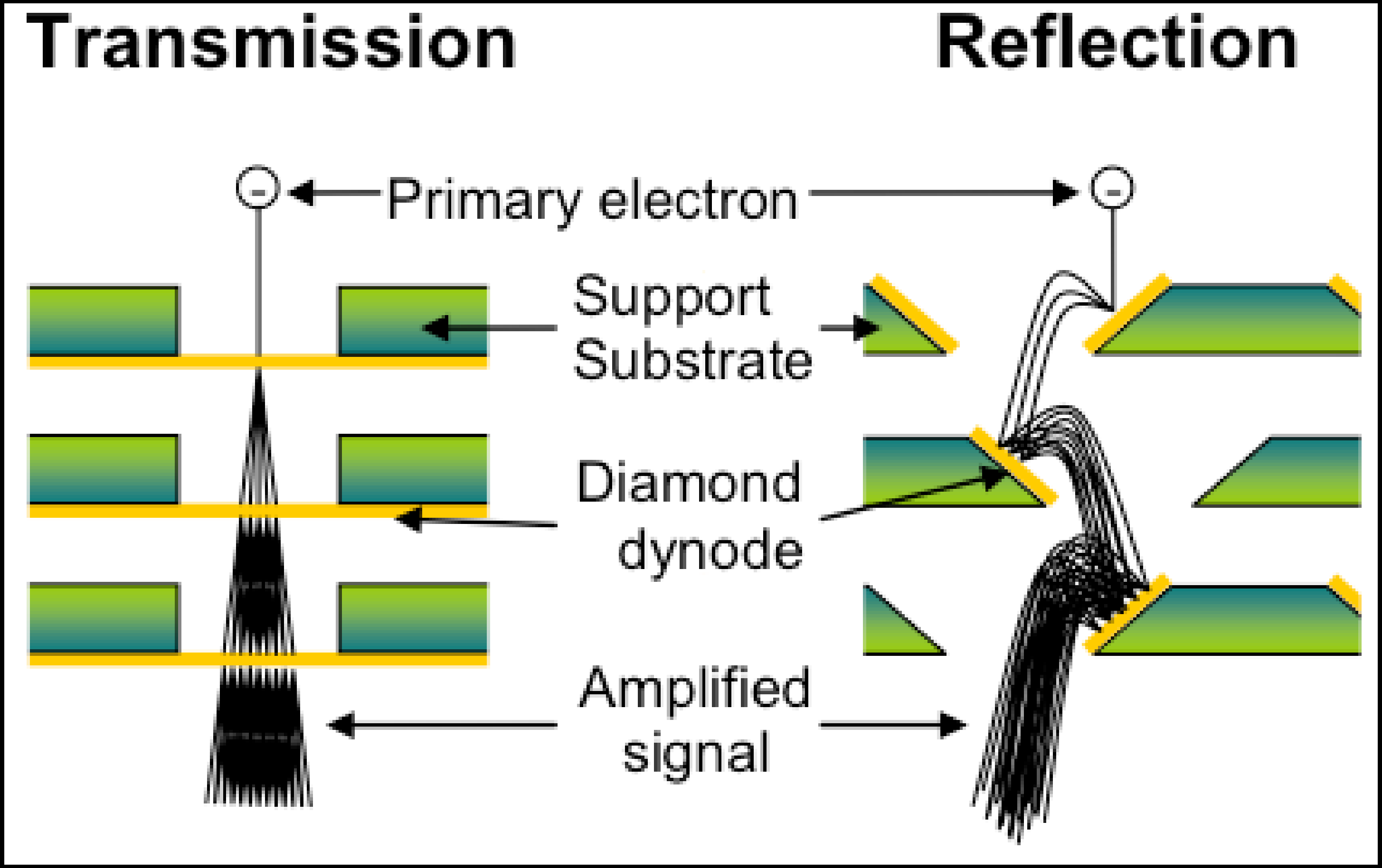


Fig. 8.1. Schematic diagram of a photomultiplier tube (from *Schonkeren* [9.1])

Apply MEMS Technology:



VACUUM!
No ‘gas amplification’



New: the Transmission Dynode “Tynode”

- Thin (~10 nm), planar dynodes, spaced ~ 30 μm
- CMOS pixel chip, square pitch ~ 55 μm
- Electron crossing time ~ 5 ps: straight short path due to homogeneous E-field
- With gain of ~ 30 k: digital (1 V) signal on pixel input pad (small source cap)
- Very strong electric field between dynodes, but far away from Fowler-Nordheim limit
- B-field has little influence since Lorentz force is small wrt. electrostatic force
- Signal development on pixel chip defined by crossing of the last gap (~ 2 ps)
- No ion feedback (not even a little bit)
- Noise-free electron multiplier
- No bias current: no bias current noise or bias current dissipation
- radiation hard

"the best electron is a free electron"

Competitors:

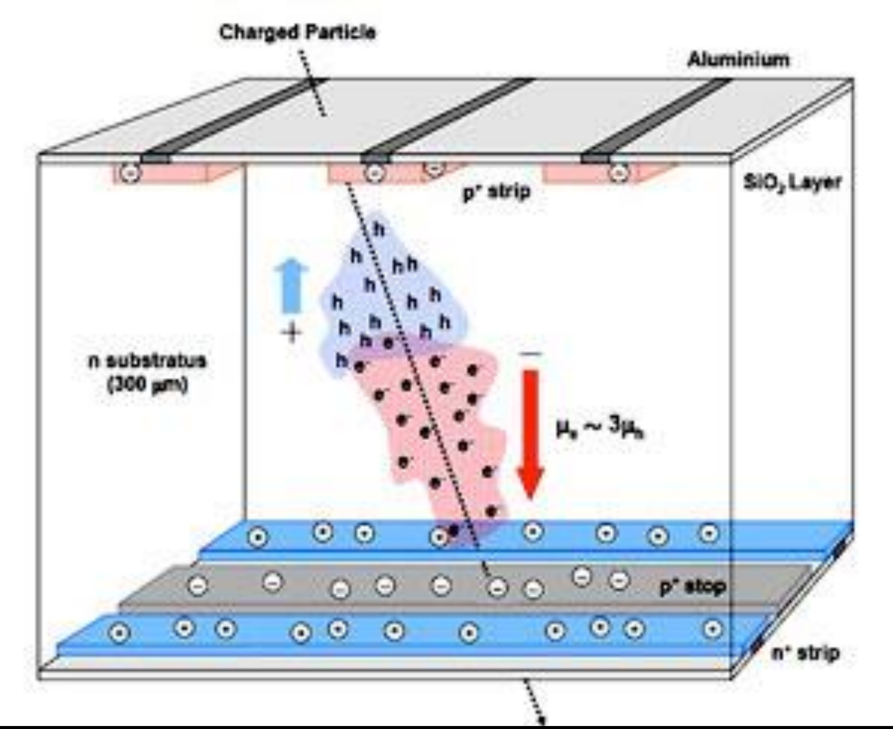
Si-Photomultipliers (APDs, SPADs, D-APDs)

Micro Channel Plates

Large Area Pico Second Photo Detectors

Competition: Silicon Photomultipliers

Photo Diodes
Avalanche Photo Diodes APD
Single Photon APD SPAD
Digital SPAD



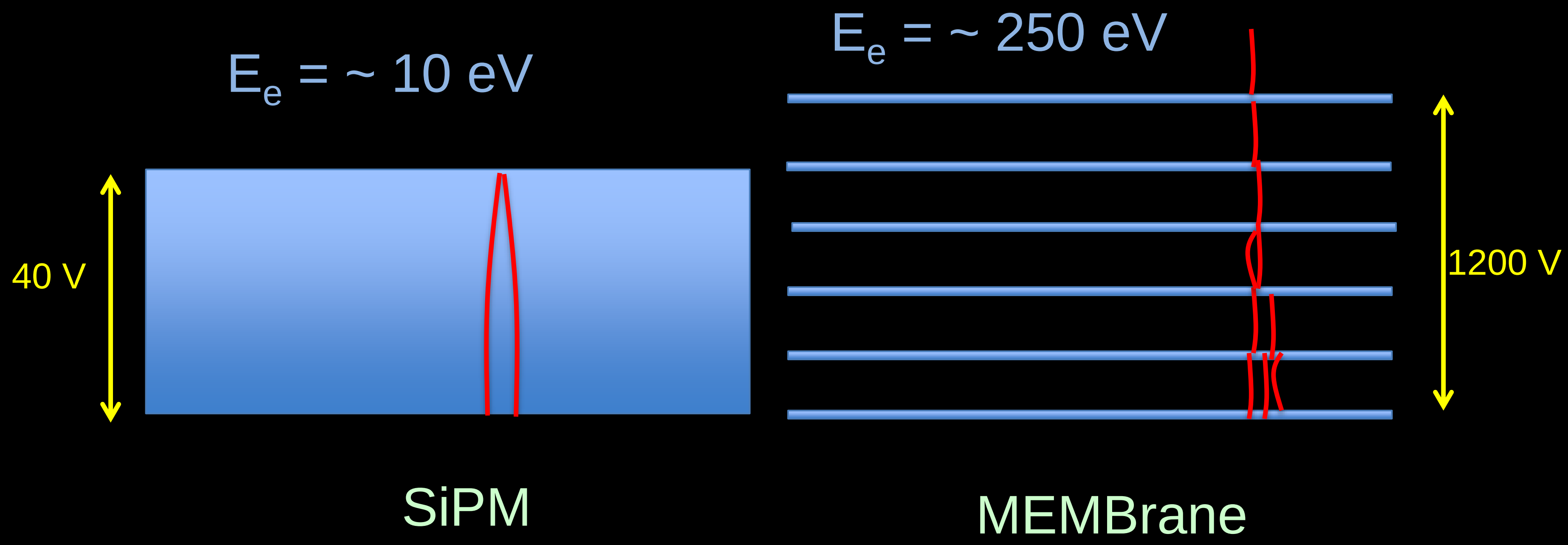
Very popular:

- Planar, thin, light
- Cheap
- Operate in B-field
- Potentially QE = 1
- faster than PMTs

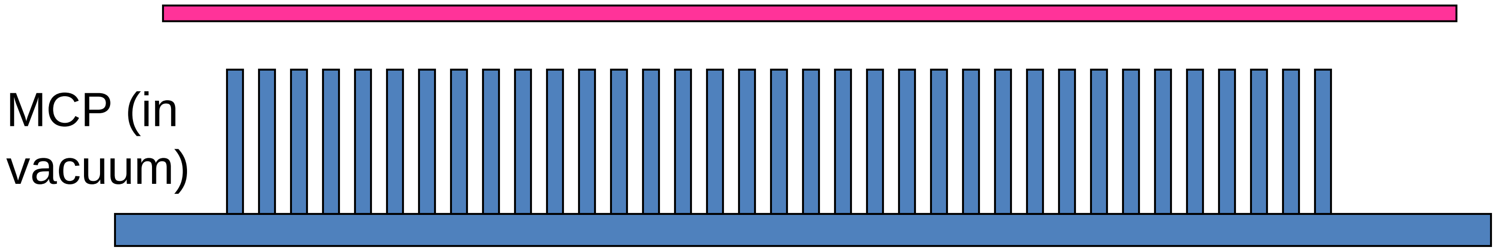
But they are:

- noisy
- have bias current
- suffer afterpulsing
- hard to pixelize
- limited to ~ 40 ps (?)
- not so radhard

Essential difference between SiPMs and Tynode Stack

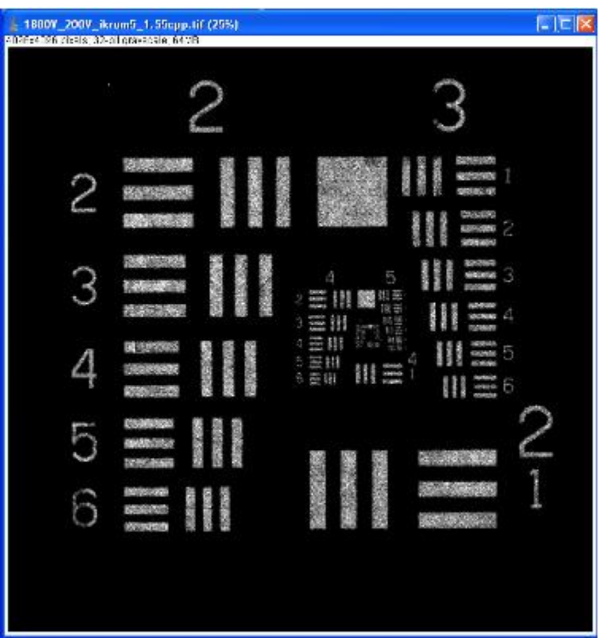


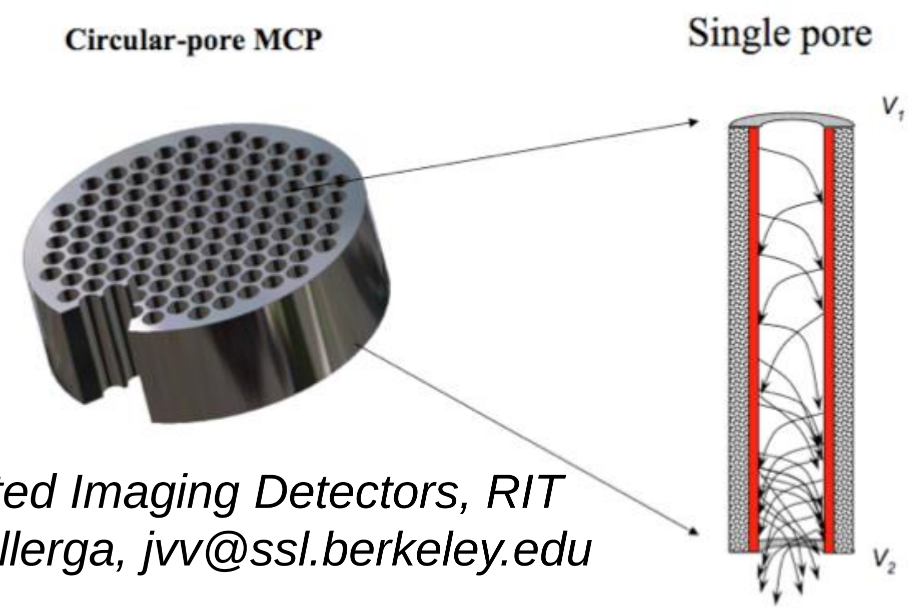
Use a MicroChannelPlate MCP?



John Vallerga: TimePix + MCPs

We do not know how to make MEMS made MCP.
Problem: aspect ratio of holes

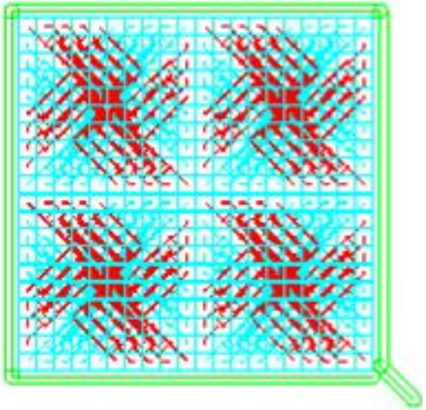




Quantum Limited Imaging Detectors, RIT 2009, John Vallerga, jvv@ssl.berkeley.edu

Large-Area Picosecond Photo-Detectors Project

Home | People | Library | Data/Analysis | Blogs | Databases | Psec Links

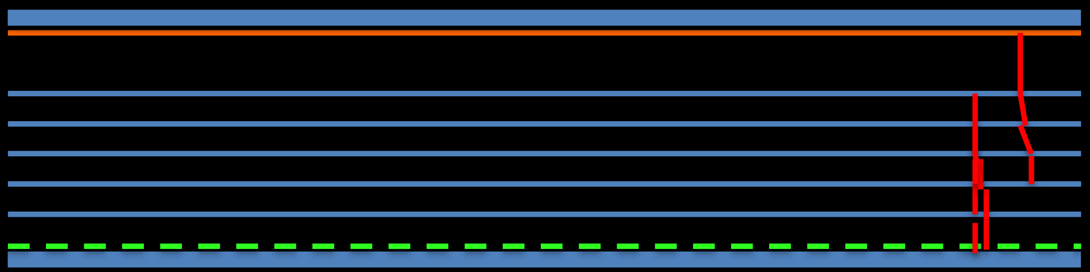


A group of us from The University of Chicago, Argonne, Fermilab and Berkeley are interested in the development of large-area systems to measure the time-of-arrival of relativistic particles with (ultimately) 1 pico-second resolution, and for signals typical of Positron-Emission Tomography (PET), a resolution of 30 pico-seconds (sigma on one channel). These are respectively a factor of 100 and 20 better than the present state-of-the-art. This would involve development in a number of intellectually challenging areas: three-dimensional modeling of photo-optical devices, the design and construction of fast, economical, low-power electronics, the `end-to-end' (i.e. complete) simulation of large systems, real-time image processing and reconstruction, and the optimization of large detector and analysis systems for medical imaging. In each of these areas there is immense room for creative and innovative thinking, as the underlying technologies have moved faster than the applications. We collectively are an interdisciplinary (High Energy Physics, Radiology, and Electrical Engineering) group working on these problems, and it's interesting and rewarding to cross the knowledge bases of different intellectual disciplines. We welcome inquiries and, even better, help.

Henry Frisch et al.

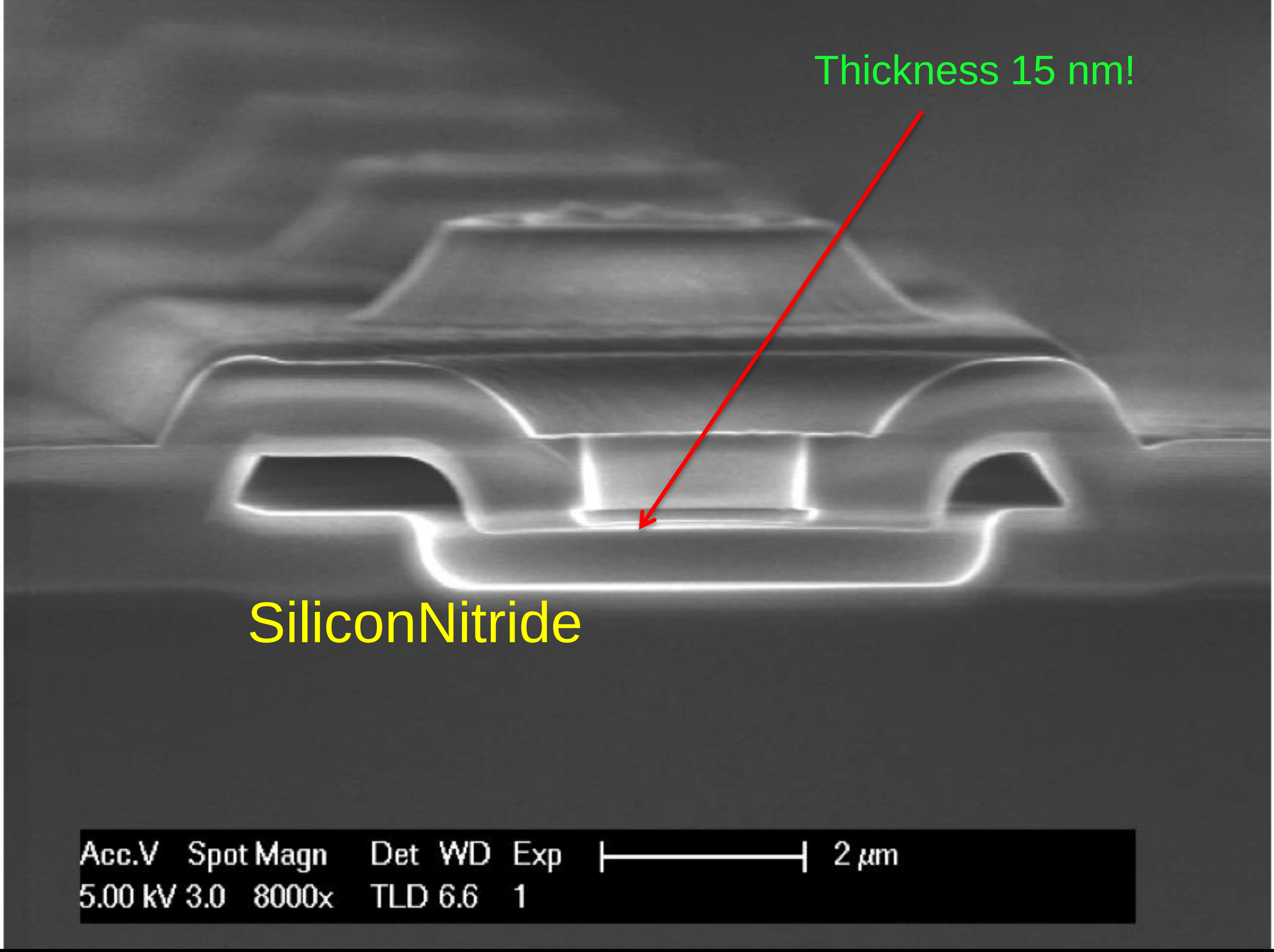
MCPs

- limited electron entrance acceptance
- ion feedback
- large fluctuations in single electron response
- time resolution not better than 10 ps (?)
- how to make them in MEMS technology? (Univ Neuchatel: Nicolas Wyrsch)



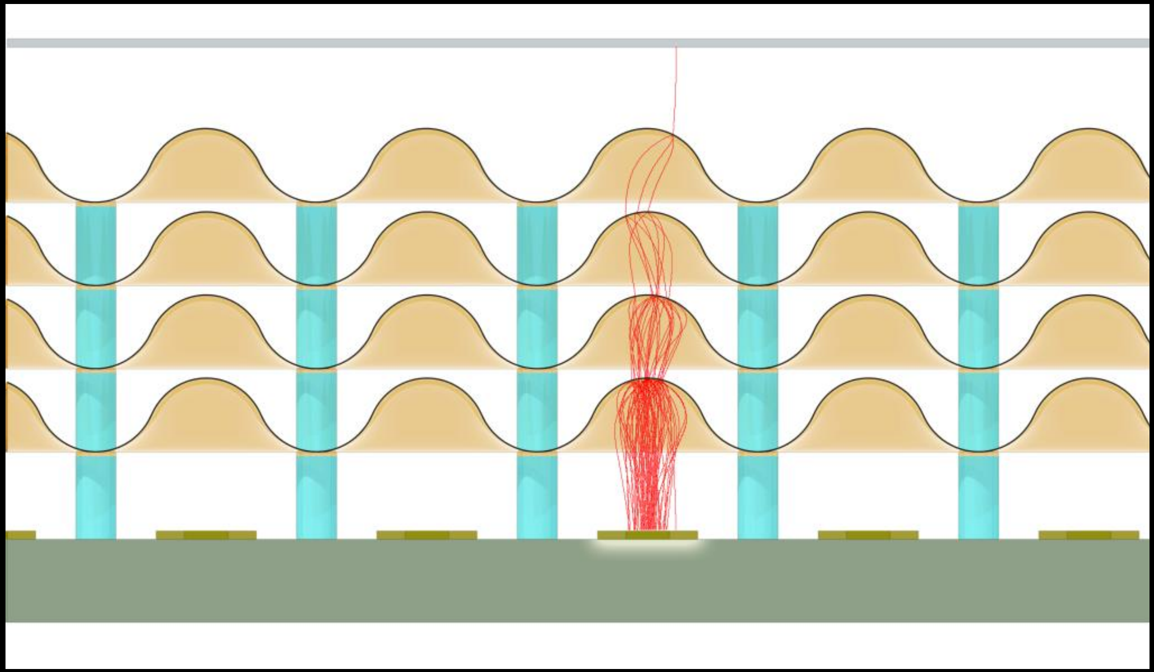
- Thin (~10 nm), planar dynodes, spaced ~ 20 μm
- CMOS pixel chip, square pitch 55 μm
- Electron crossing time ~ 5 ps: straight short path due to homogeneous E-field
- With gain of ~ 30 k: digital (1 V) signal on pixel input pad (small source cap)
- Very strong electric field between dynodes, but far away from Fowler-Nordheim limit
- B-field has little influence since Lorentz force is small wrt. electrostatic force
- Signal development on pixel chip set by crossing of the last gap (~ 2 ps)
- No ion feedback (not even a little bit)
- Noise-free electron multiplier
- No bias current, no bias current noise or bias current dissipation
- radiation hard

"the best electron is a free electron"



Delft University of Technology: DIMES

A new single & free electron detector in vacuum



transmission dynodes
"tynodes"

+

pixel chip

MicroElectronicMechanicalSystems 'MEMS' Technology
- ultra thin membranes
- Cone shape dynode section
  1. focusing electron from above
  2. focusing emitted electrons
  3. mechanically robust: larger diameter cones feasible

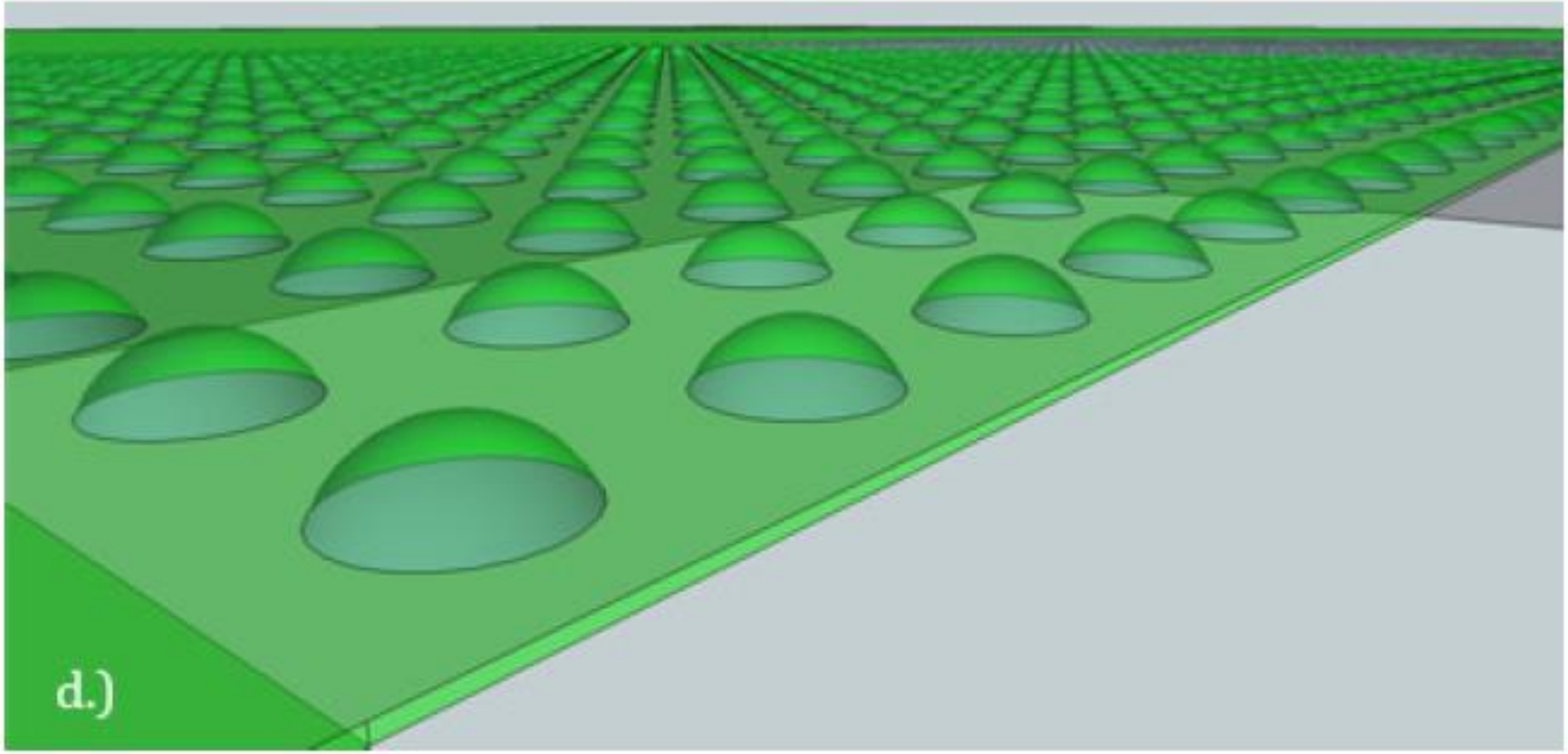
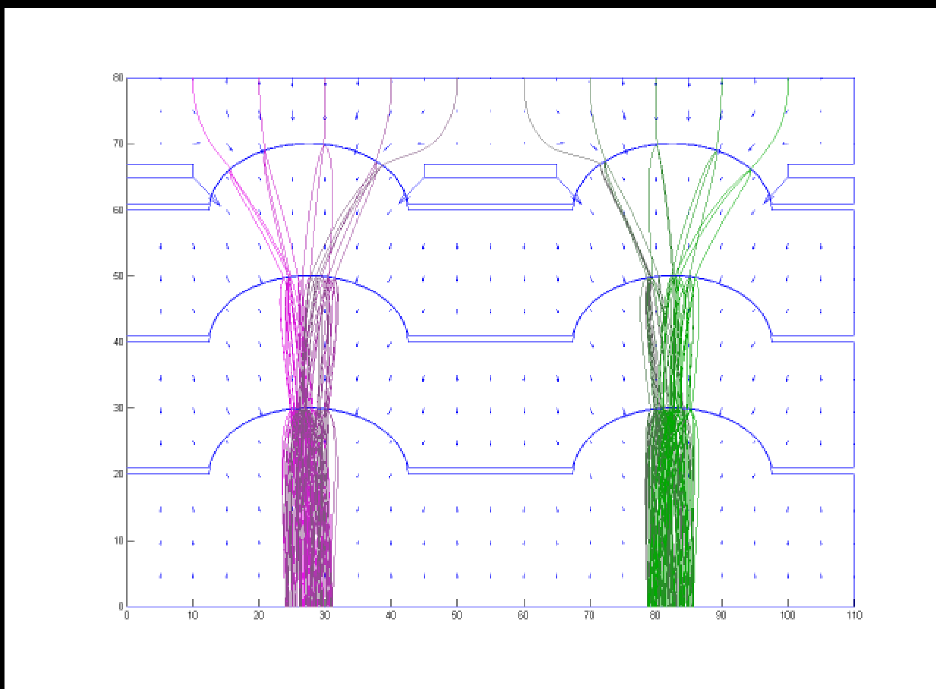


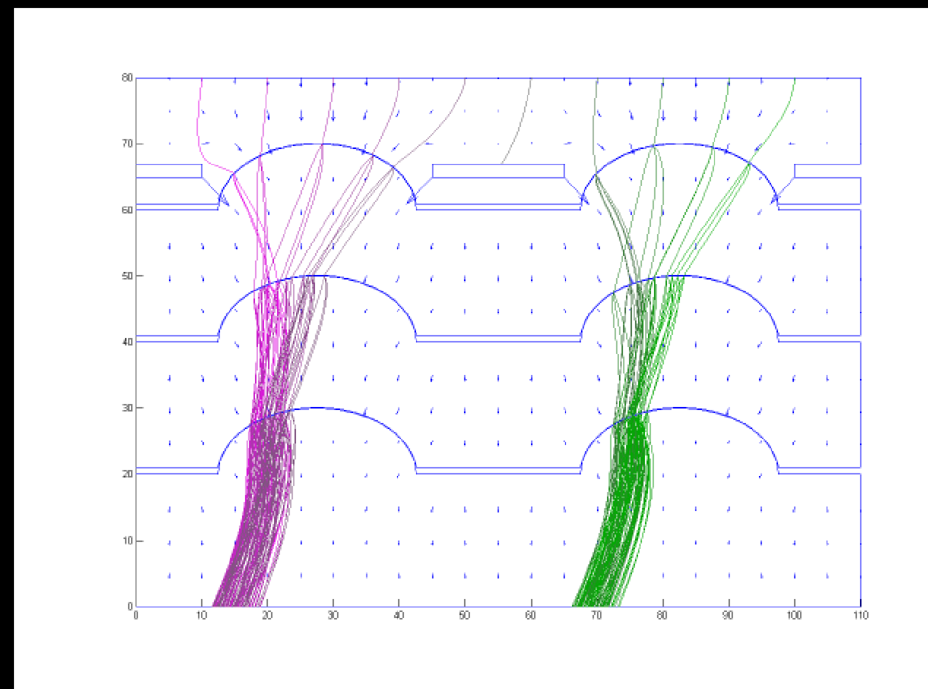
Figure 6-2 Design of a transmission dynode D1. a.) Top view. The yellow corner is a gold pad which is in contact with the doped silicon layer. b.) Bottom view. The hole is opened by KOH etching. c.) Cross section. The structural membrane is 1-2 µm thick. d.) Close up of the cross section. The cones are suspended in the structural membrane.

Array of ultra thin domes

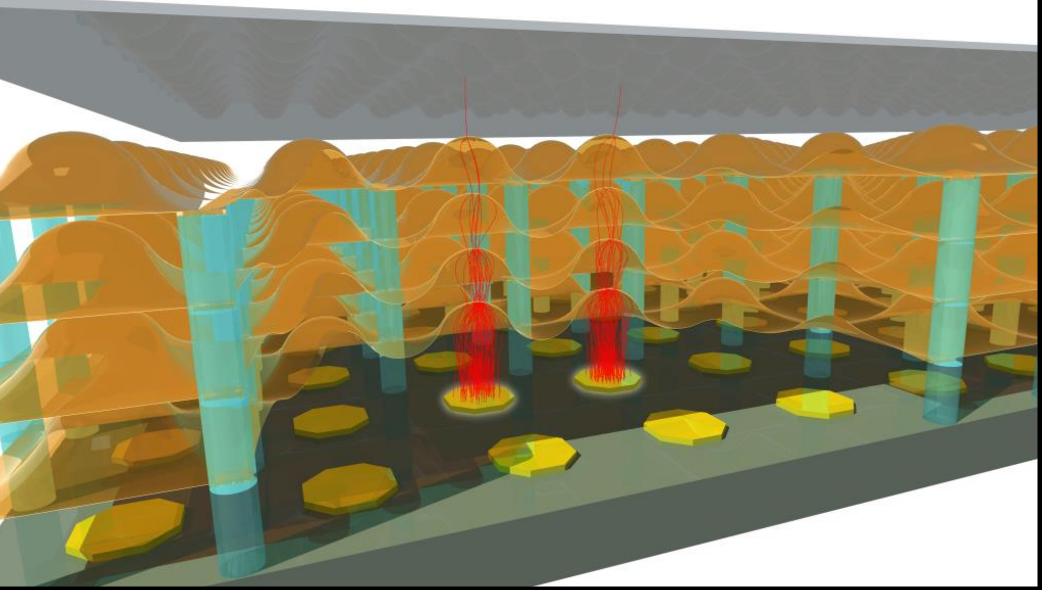
First (2D) simulations: influence magnetic field



0 Tesla



1 Tesla



Timed Photon Counter
TiPC, Tipsy

Fast: electron mobility is highest for free electrons in vacuum

Low noise: no bias current

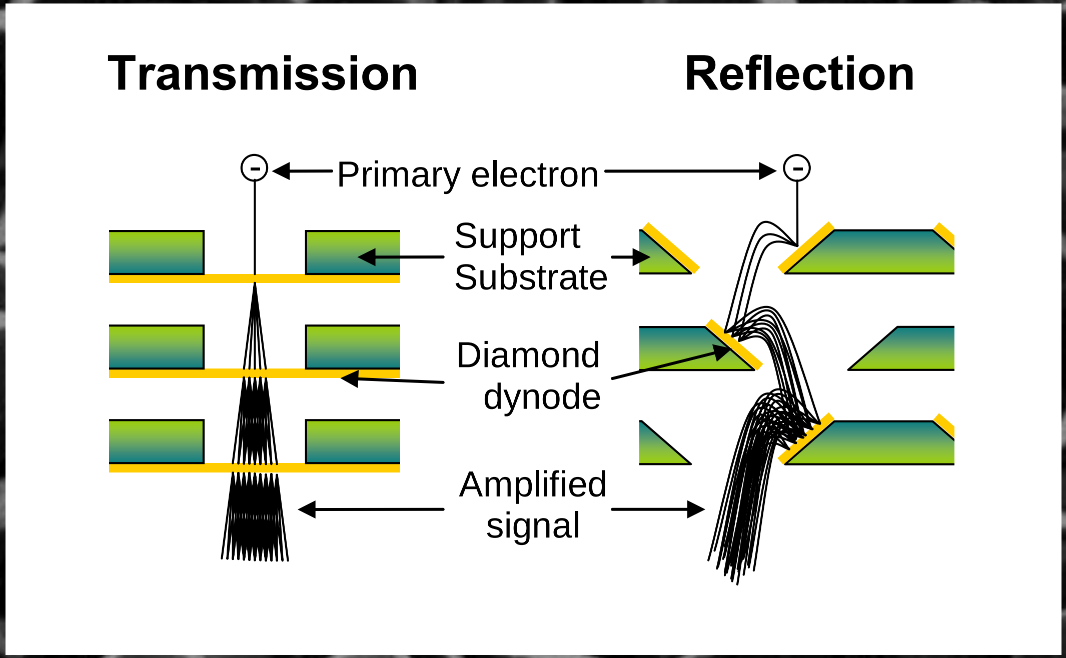
- Thin, planar, light single soft photon detector
- Electron crossing time $t_c = D \sqrt{(2 m/qV)} = 5$ ps for V = 150 V, D = 20 μm
- Electron path: quite straight line towards next dynode
- 30 k e- enough for digital signal on pixel input pads: 7 dynodes adequate
- Signal response after 7 x 5 ps = 35 ps
- Time resolution determined by last electron crossing time: ~ 2 ps
- Spatial resolution determined by pixel granularity (55 μm x 55 μm)
- No noise from electron multiplier, no bias current from electron multiplier
- No ion feedback
- Radiation hard
- Operates in magnetic field

But:

- Secondary electron emission yield not known
- Very strong electric field between dynodes: Fowler-Nordheim limit (10^9 V/m)
- *QE limited by QE of classical photo cathode (20 – 40 %)!*

Secondary Electron Yield (SEY)

Diamond detector configurations being investigated



Jon Lapington, University of Leicester

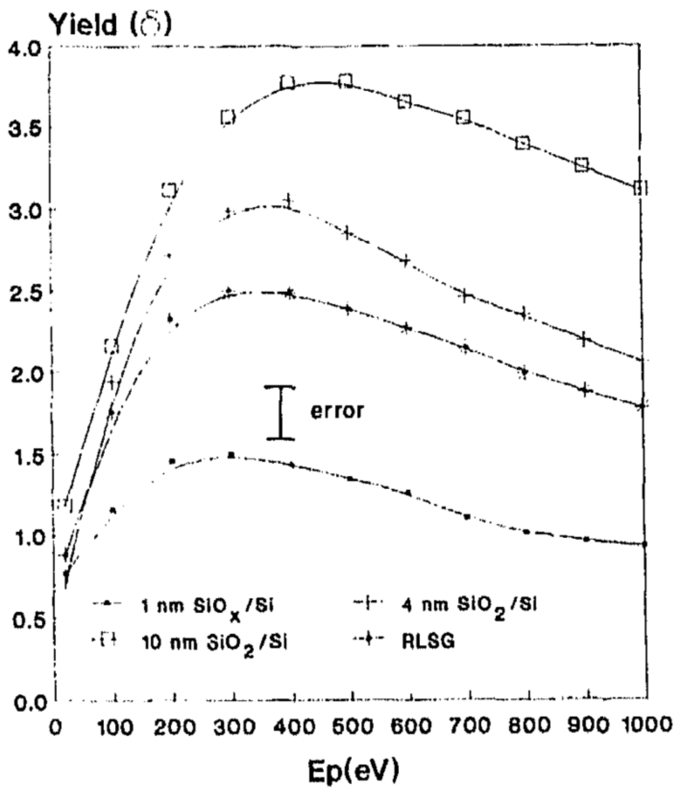


Fig. 5. Secondary electron yield δ versus primary electron energy E_p for SiO_x/Si, SiO_2/Si, and RLSG test structures at $\Theta = 0°$.

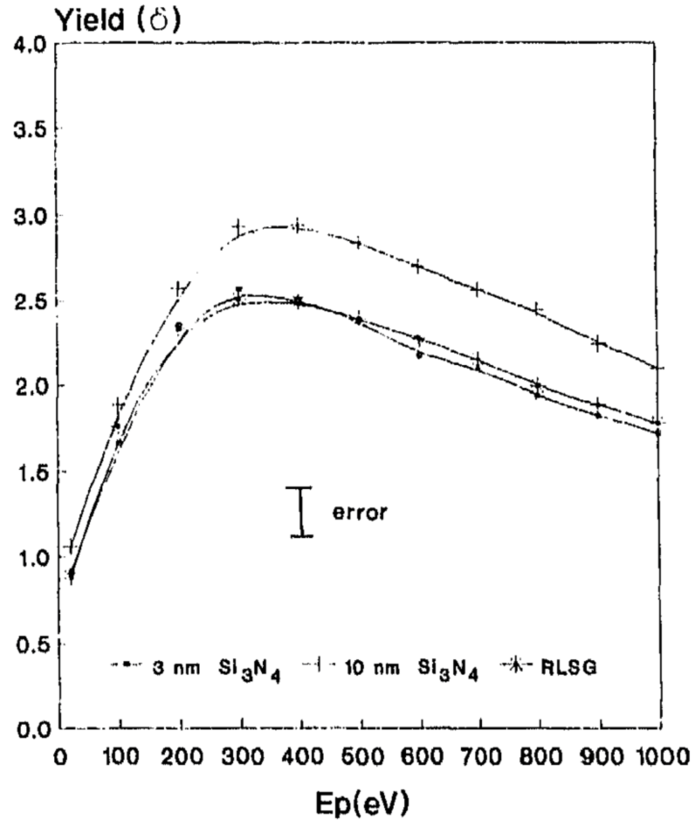


Fig. 6. Secondary electron yield δ versus primary electron energy E_p for Si_3N_4/Si and RLSG test structures at $\Theta = 0°$.

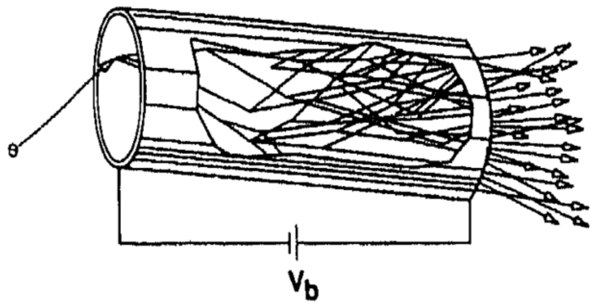


Fig. 1. Schematic of geometric electron multiplication in a straight-channel electron multiplier under bias voltage V_b.

Reflective Secondary electron emission yields of SiNitride: Fijol et al.

Depth-of-penetration of 300 eV electron in dynode material: ~ 5 nm

- from simulations
- from SEY of reflective dynodes with different active layer thickness

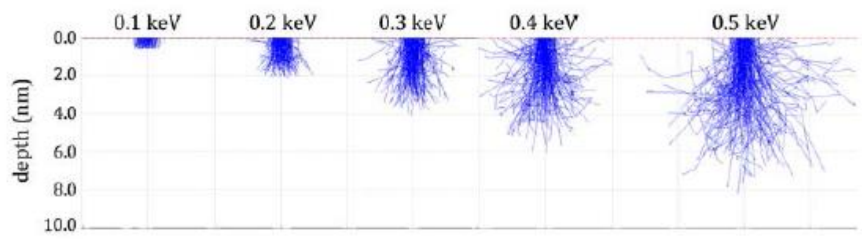


Figure 5-2 The primary electron tracks of electron beams with increasing energy. For each beam, 200 electron tracks are simulated. The sample consists of low stress silicon nitride (Si_3N_4) with a density of 3.2 g/cm^3 .

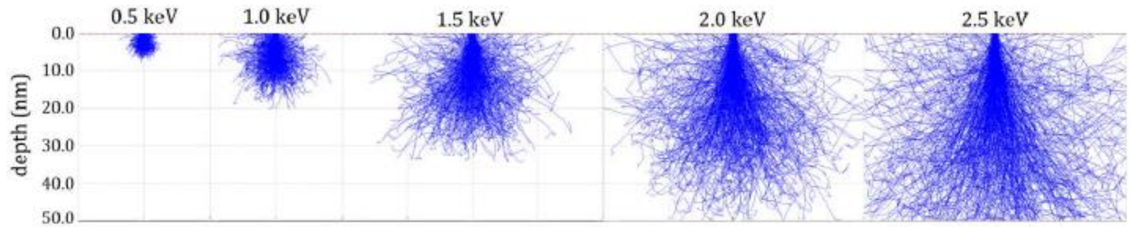
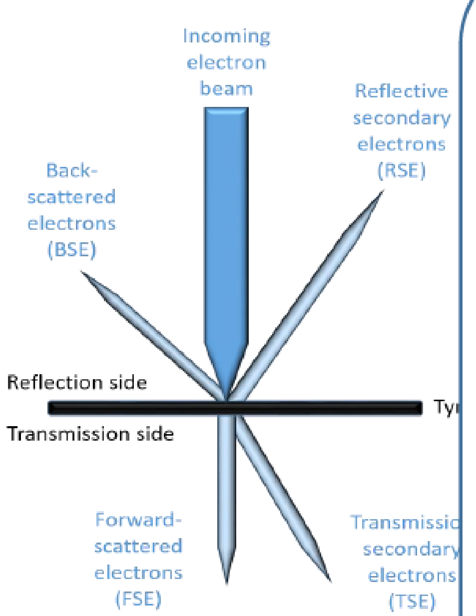


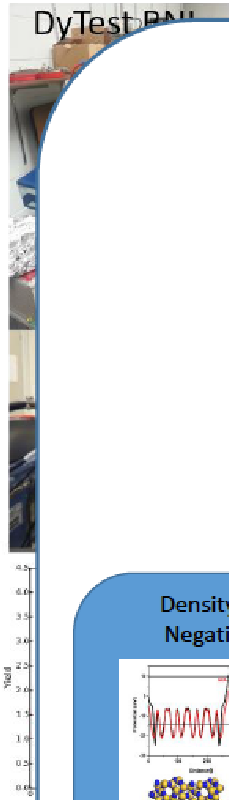
Figure 5-3 The primary electron tracks of electron beams with increasing energies. For each beam, 200 electron tracks are simulated. The sample consists of low stress silicon nitride (Si_3N_4) with a density of 3.2 g/cm^3 .

Understanding the microphysics of Tynodes

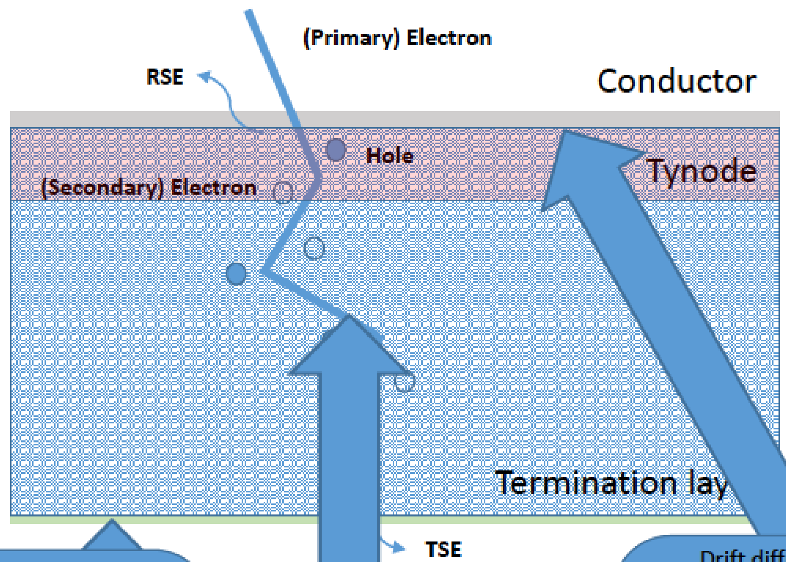


Basic measurement: compa
electron beam before and
after the sample

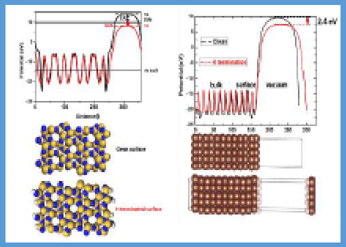
DyTest BNL DEC



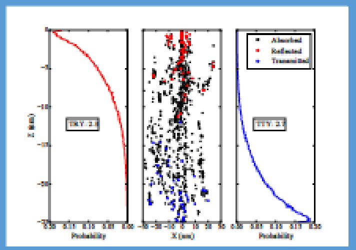
-
- R



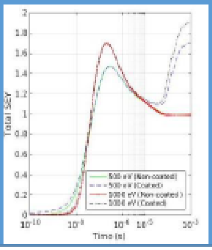
Density Functional Theory
Negative electron affinity



Geant-4 low energy extension
Charge generation – transport - SEY



Drift diffusion reaction modeling
charging effects - SEY



Transmission Secondary Electron Yield

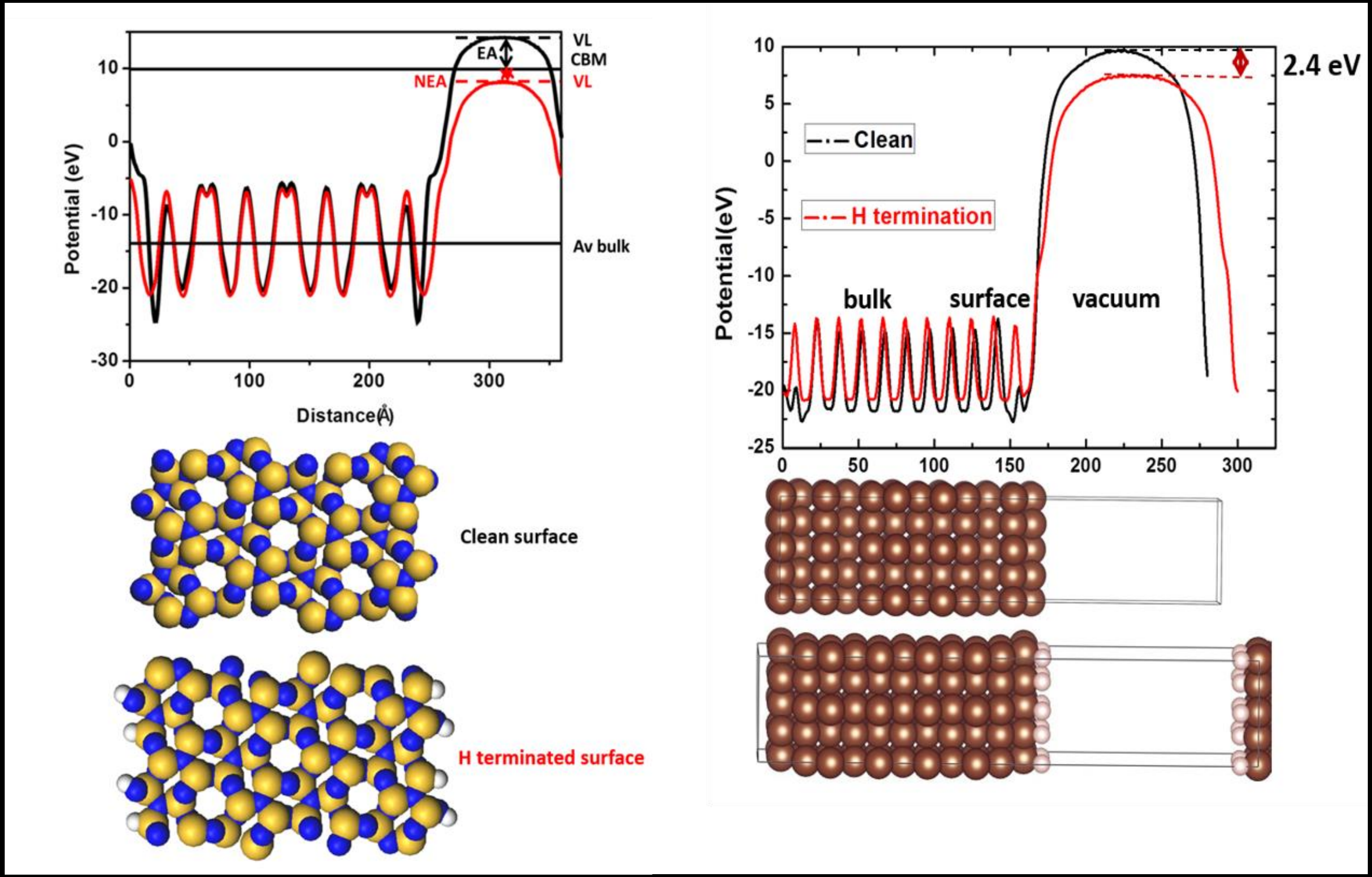
relevant processes:

1) energy transfer of incoming electron to electrons and nuclei

2) creation of electron & holes in conduction band and their transport (diffusion)

    new low-energy simulations: GEANT-4 extensions of Kieft & Bosch

2) exciting of the surface into vacuum



Potentials across a clean and H-terminated β-Si_3N_4 slab containing bulk, surface and vacuum regions and scheme of positive electron affinity (PEA of 2.0 eV) and negative electron affinity (NEA of -1.2 eV). The black curve is for the clean surface and the red curve is for the H terminated surface.

Electron Affinity of surface or Work Function

Vienna Ab initio Simulation Package VASP

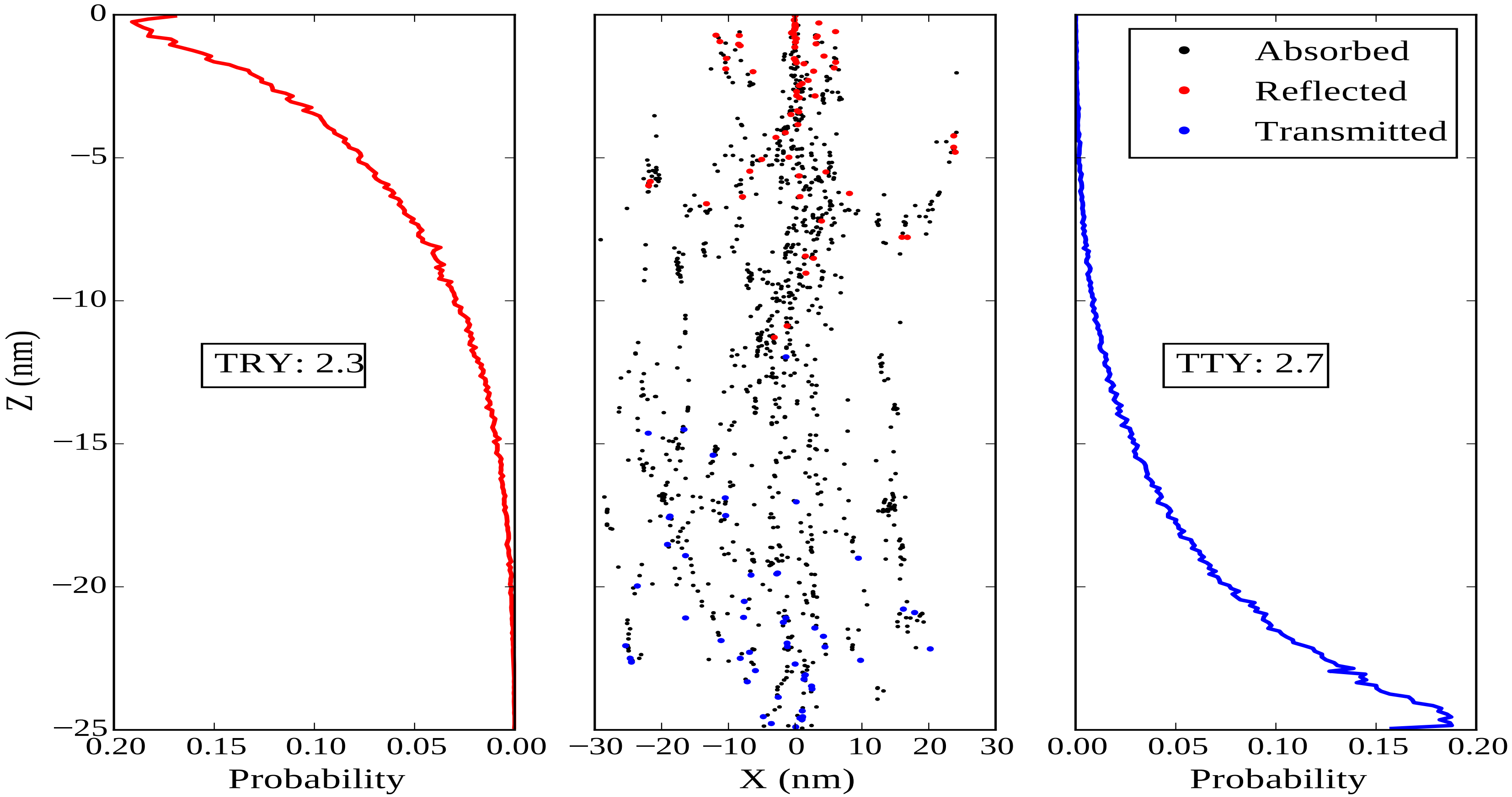


Fig. 4. Simulation of an Alumina membrane (thickness 25 nm), bombarded with 2300 eV electrons. At this energy, the total transmission yield reaches its maximum of 2.7, and the total reflection yield at this energy is 2.3, although these absolute figures have no meaning. In the centre plot all points where electrons are created during a simulation with 30 PE's are shown. The red (blue) points denote creation points of electrons that were able to escape on the reflection (transmission) side of the sample. The black points, which are plotted slightly smaller for clarity, denote creation points of absorbed electrons. The left plot shows the probability density function of the creation depth for electrons that leave the membrane on the top side. The right plot shows the same but now for electrons that leave the bottom side of the membrane.

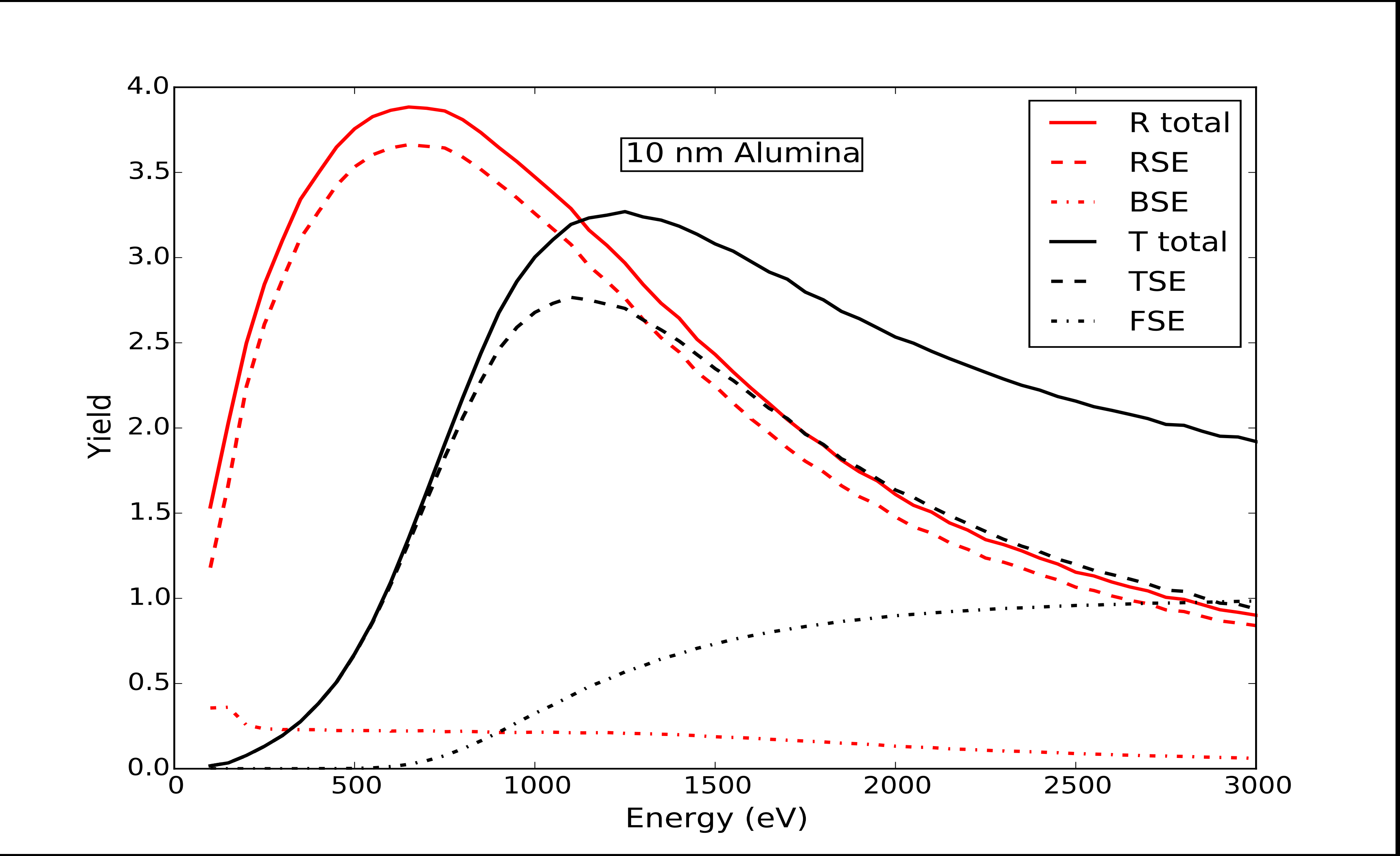


Fig. 6: The simulated yield curves for a 10 nm Alumina membrane. The maximum total reflection yield is 3.9 and is reached at 650 eV. The maximum total transmission yield is 3.3 at 1250 eV.

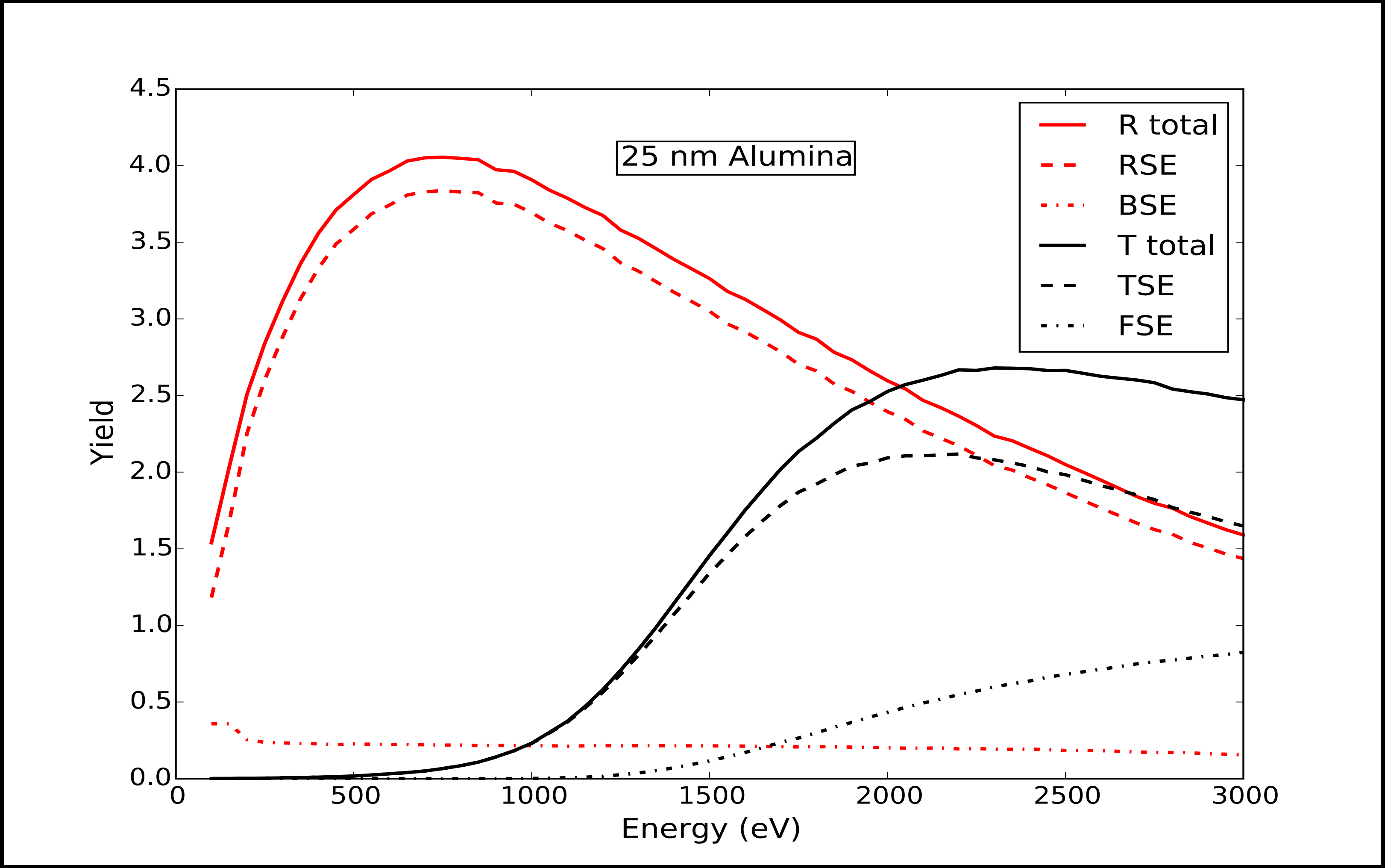


Fig. 7. The simulated yield curves for a 25 nm Alumina membrane. The maximum total reflection yield is 4.1 and is reached at 750 eV. The maximum total transmission yield is 2.7 at 2300 eV.

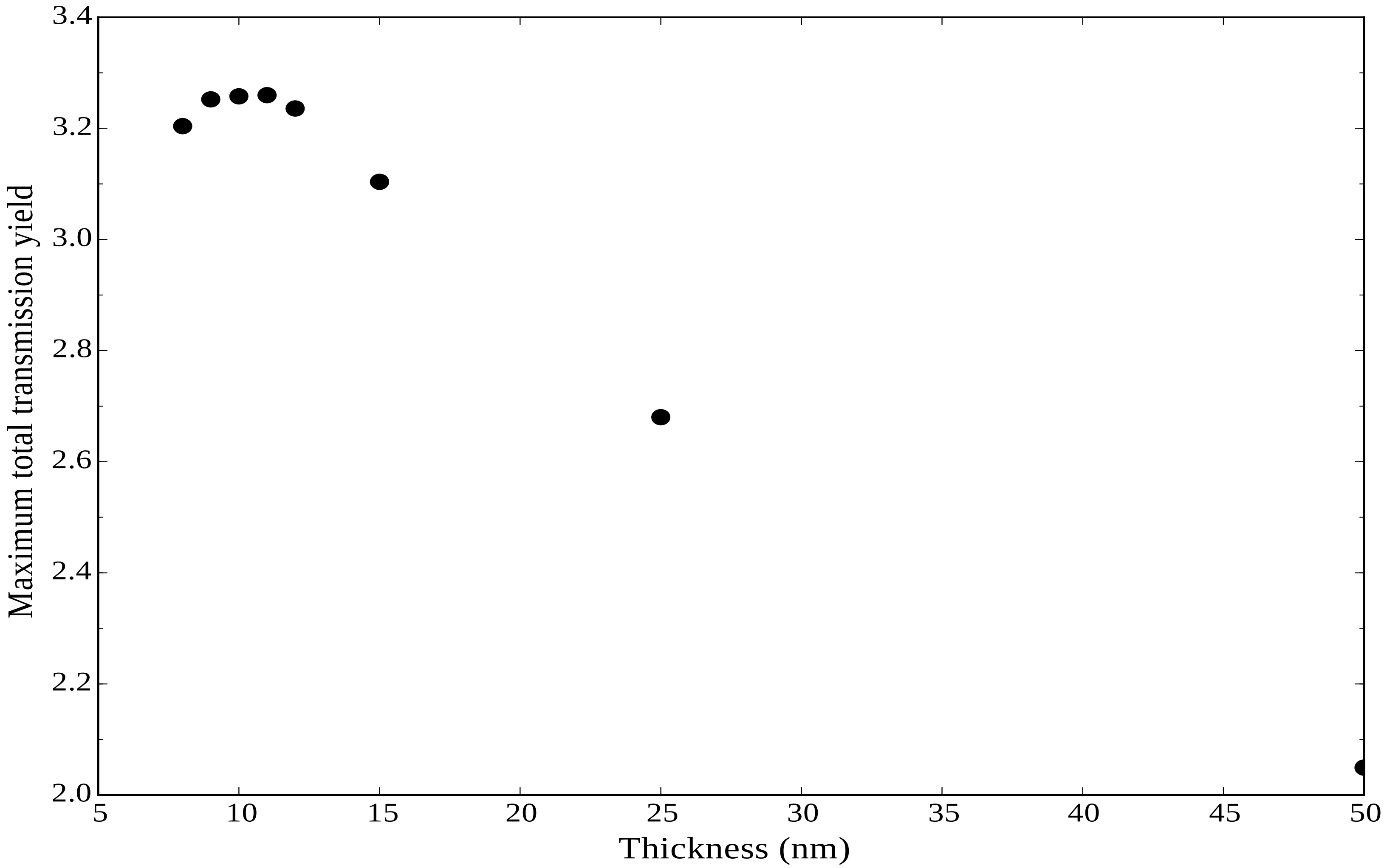


Fig. 8. The simulated maximum total transmission yield as function of membrane thickness for Alumina. The maximum total transmission yield is highest for thicknesses around 10 nm. If the thickness increases above 10 nm, the electrons created inside the membrane have a bigger probability to be absorbed before they reach the bottom surface. For thicknesses smaller than 10 nm, the primary electrons shoot through the membrane without creating so much secondary electrons. Hence in both cases, the maximum total transmission yield decreases.

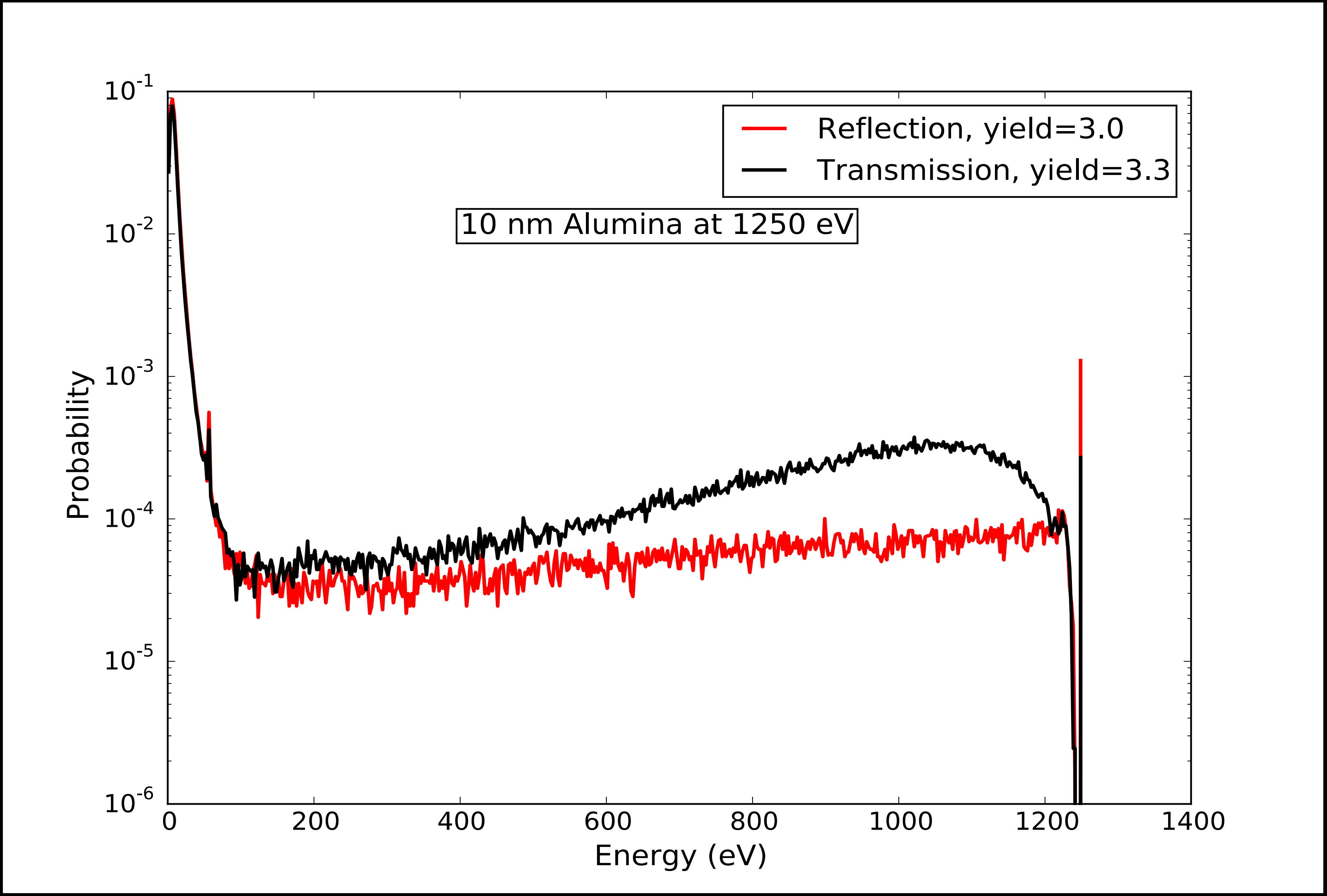


Fig. 9. The simulated energy distribution of electrons emitted by a 10 nm Alumina membrane for the transmission (black) and reflection (red) side of the membrane. The primary energy is 1250 eV. At this energy, the total transmission yield is 3.3, the total reflection yield is 3.0.

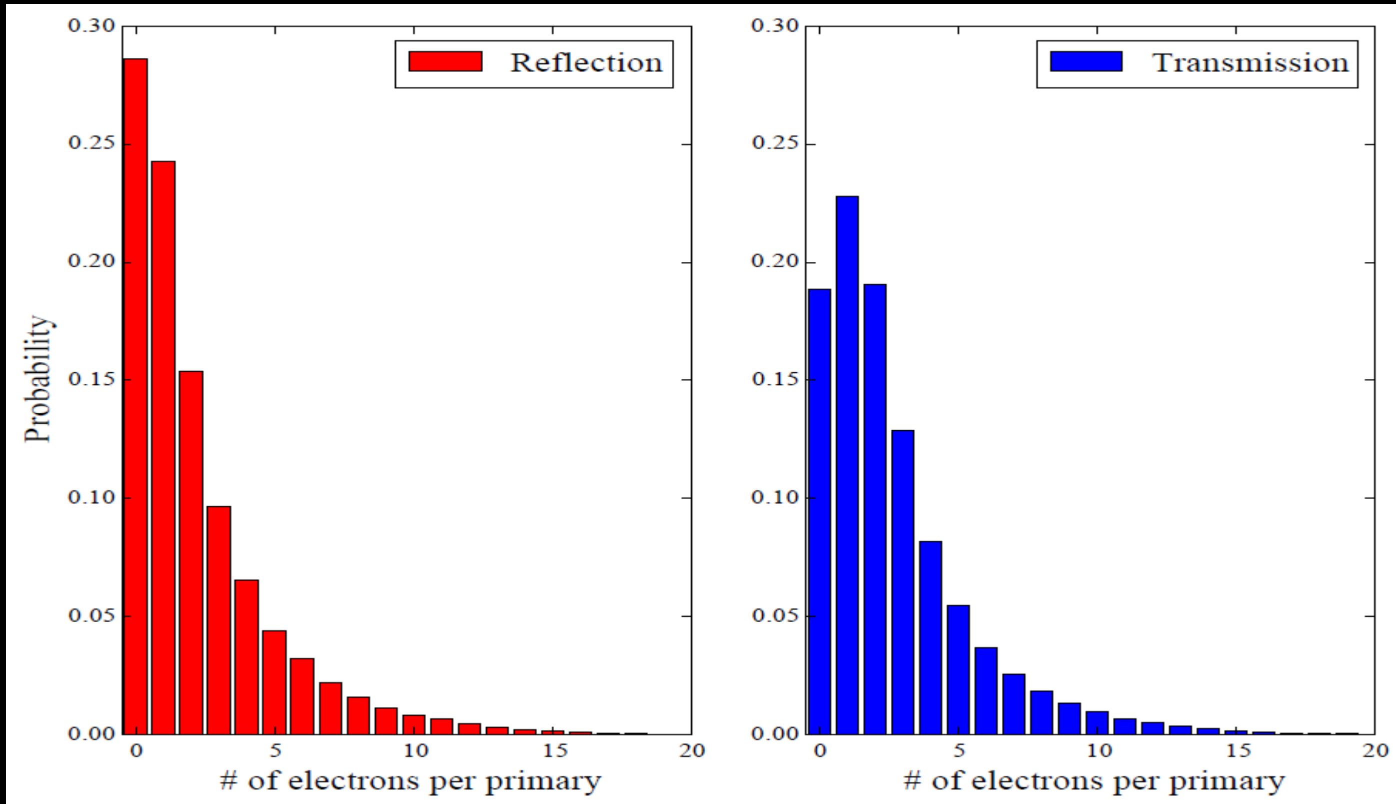
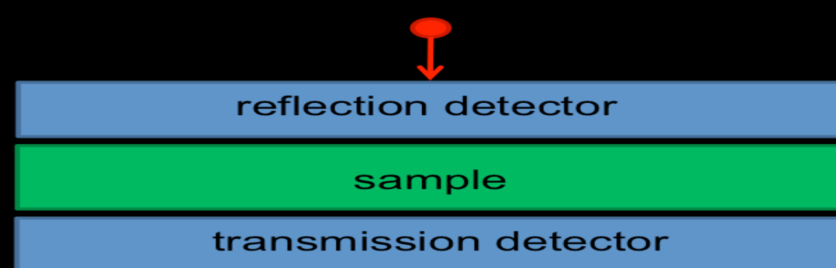


Fig. 10. Simulated distribution of number of electrons leaving the membrane per primary electron for a 25 nm Alumina membrane at a primary energy of 2300 eV (maximum transmission yield) in reflection (red) and transmission (blue) mode (normally the yield is determined by averaging over many primaries).



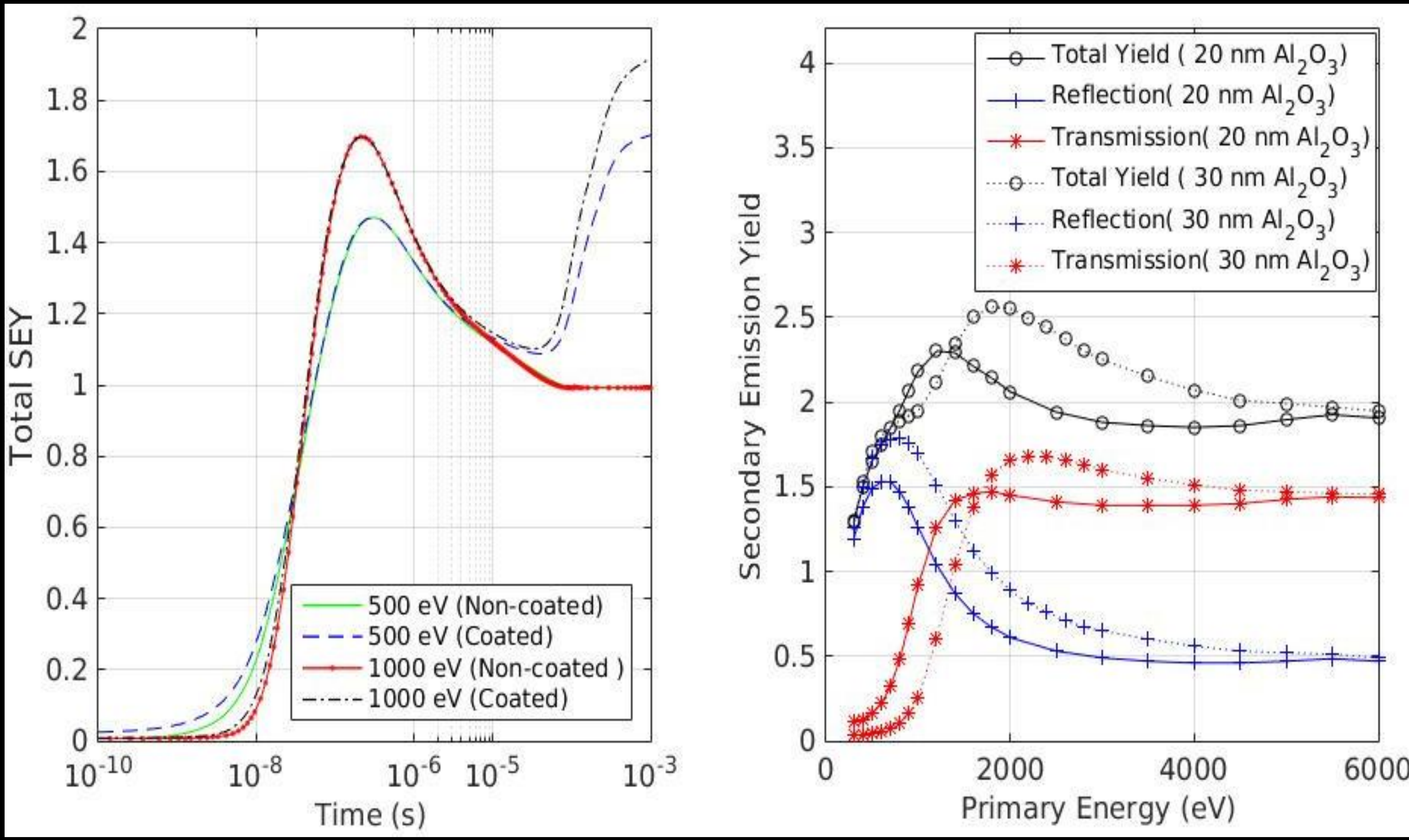


Fig. 11. Self-consistent simulation of SEY for ALD membranes. Left: time evolution of the total yield for TiN coated and uncoated membranes at two PE energies. Right: reflection, transmission, and total SEY for coated membranes as a function of PE energy.

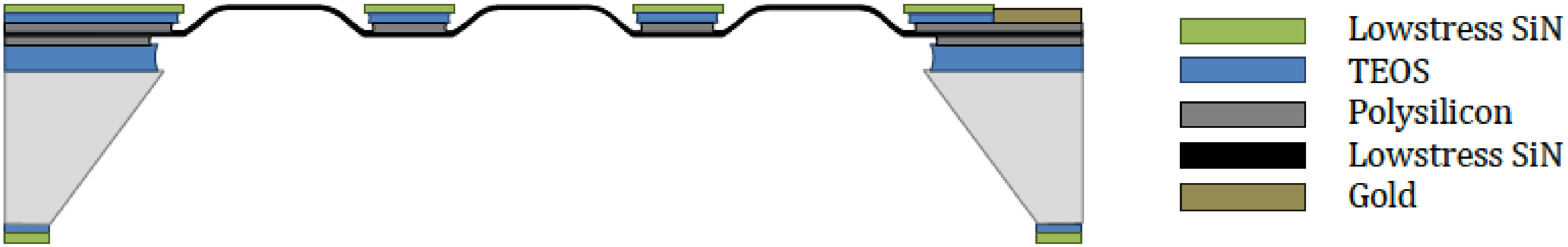
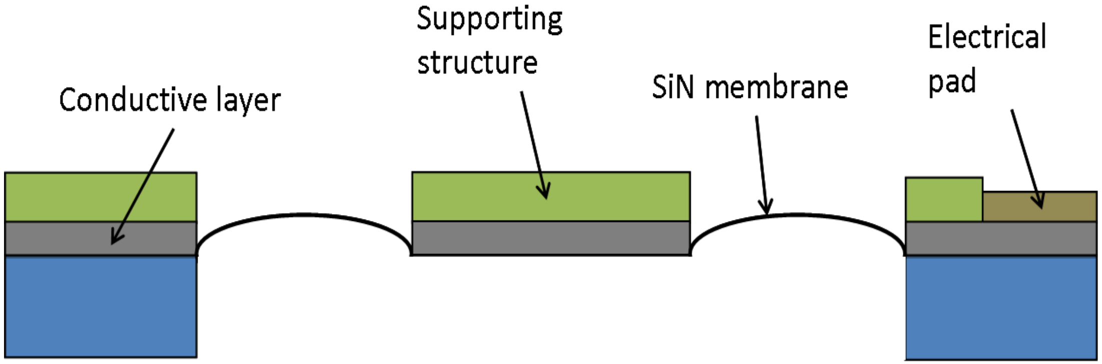
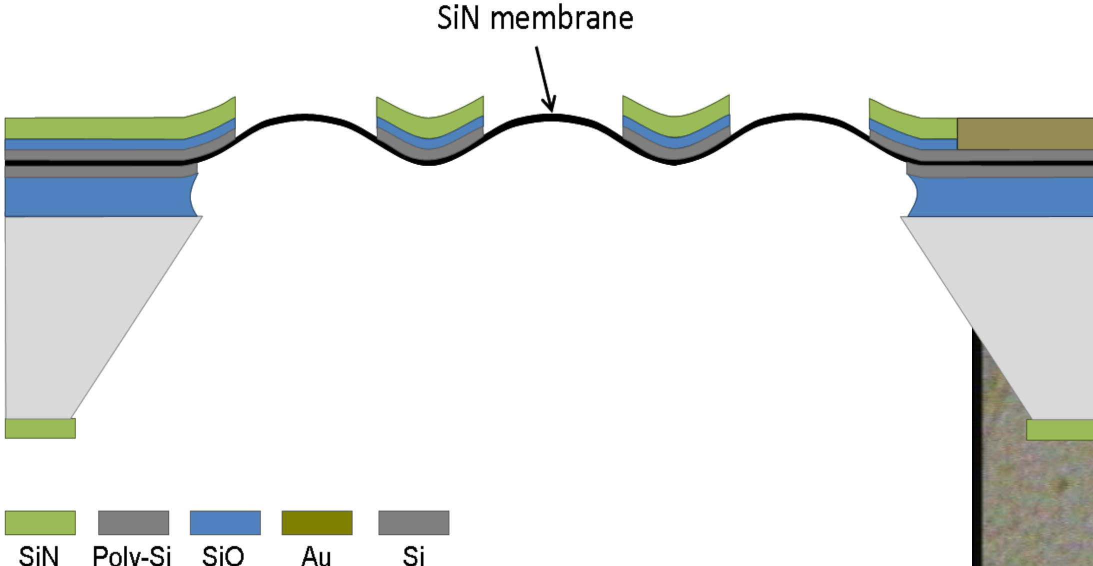


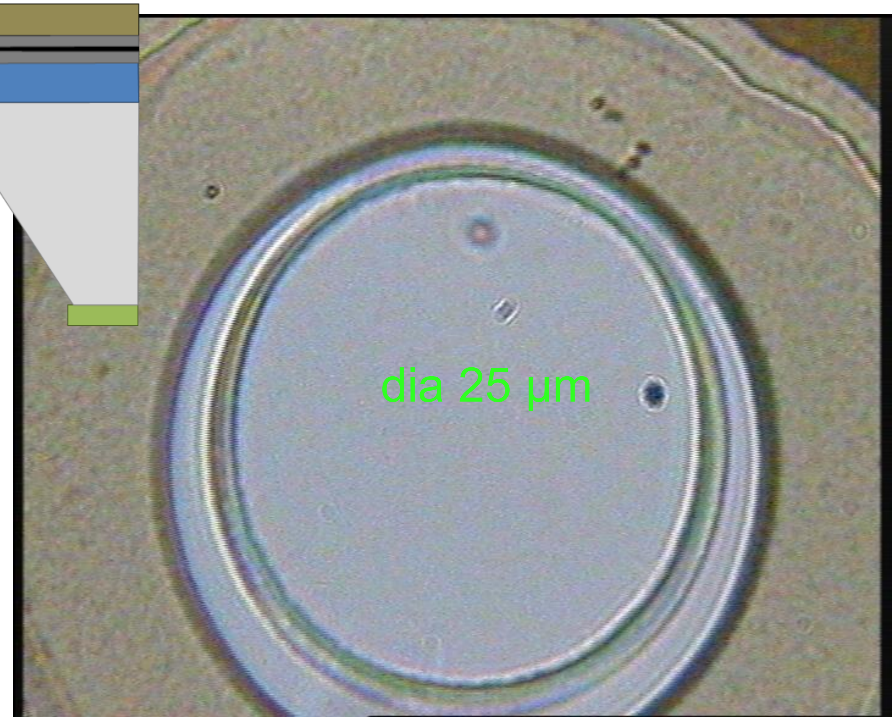
Figure 6-1 Composition of a dynode D1



Fabio Santagata
Lina Sarro
Hong Wah Chan
Violeta Prodanović

DIMES, TU-Delft





15 nm thin dynode material
Si Rich SiNitride (SRN)

First realistation of transmission dynode @ DIMES, Delft University of Technology

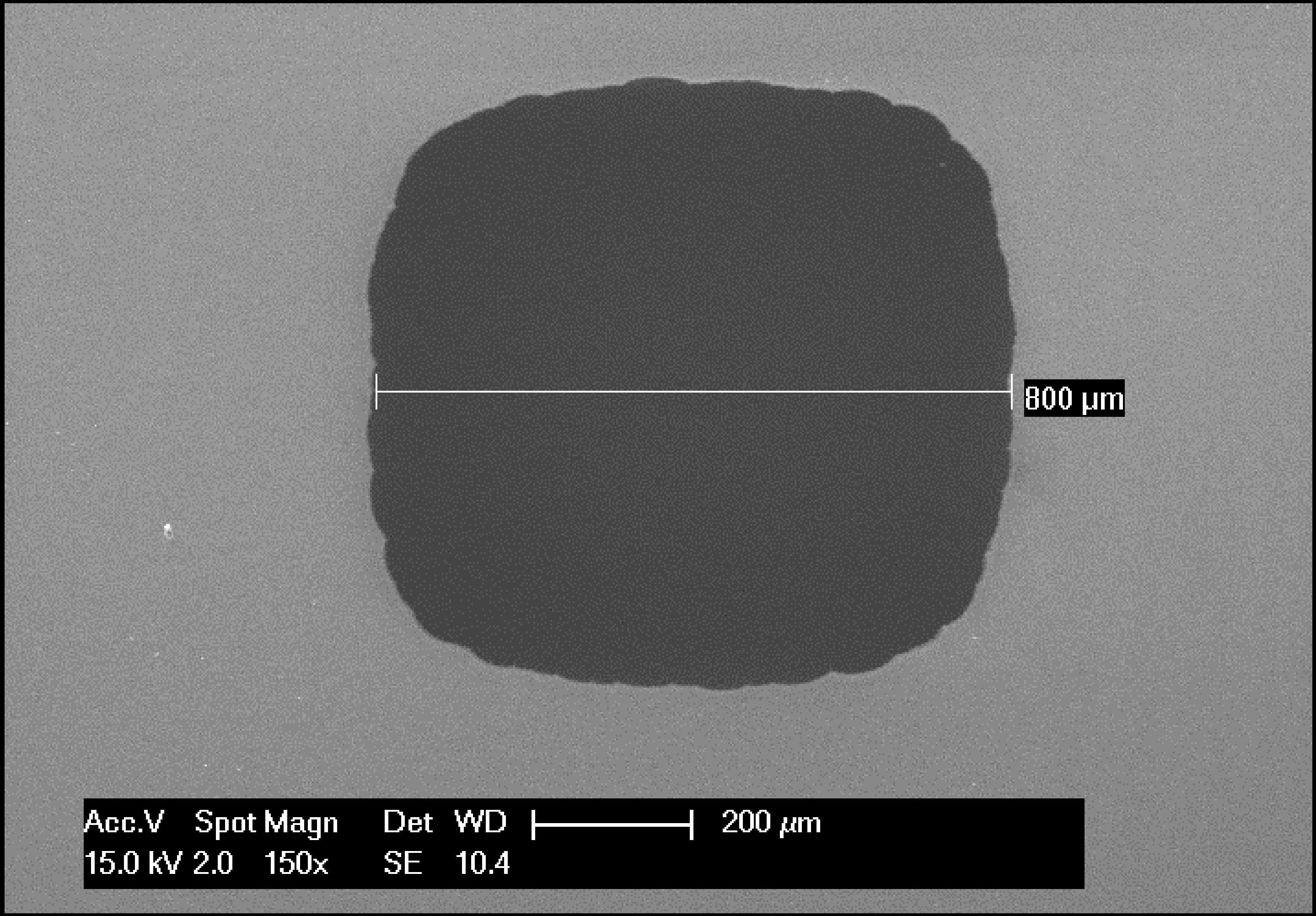


Fig. 13. SEM image of suspended 25 nm thin alumina membrane. This ALD layer looks smooth and no surface irregularity such as wrinkling due to a high stress is observed.

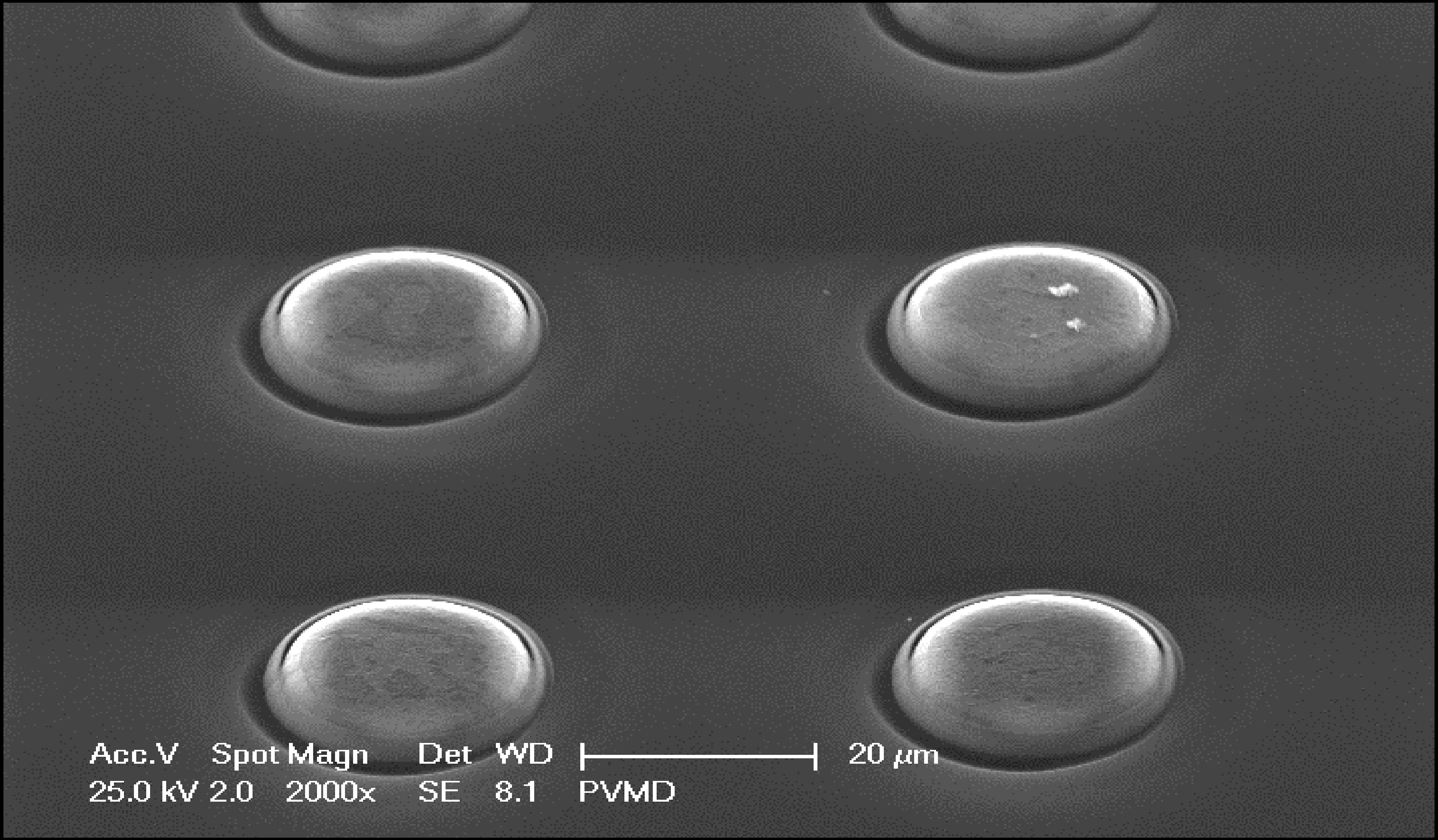
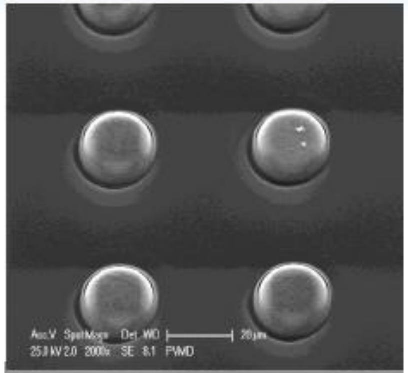
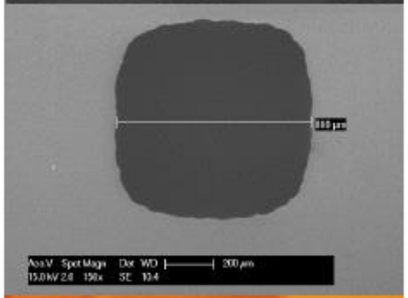
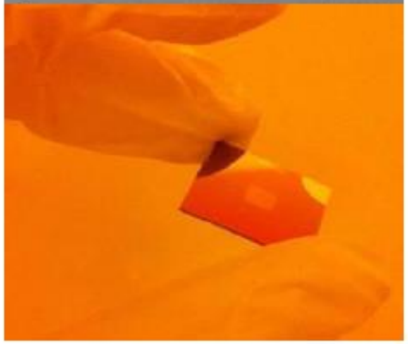


Fig. 14. SEM image of a section of 64 x 64 dome-shaped 25 nm thin SiN membranes forming a pixelized tynode. Capture is taken before final backside etching.

Transmission Secondary Electron emission membrane – TIPSY enabling technology





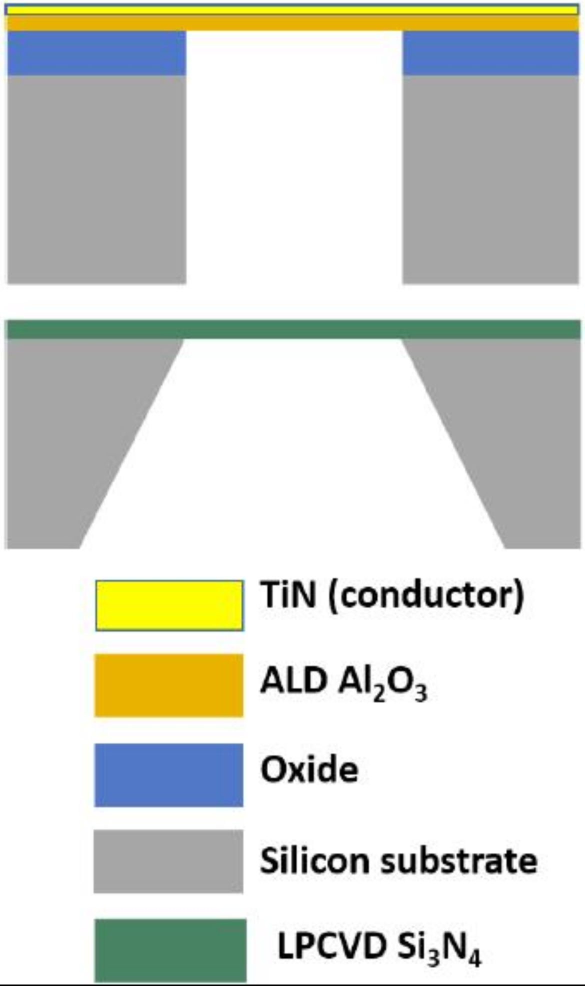


Sample 1: *Array of dynodes*

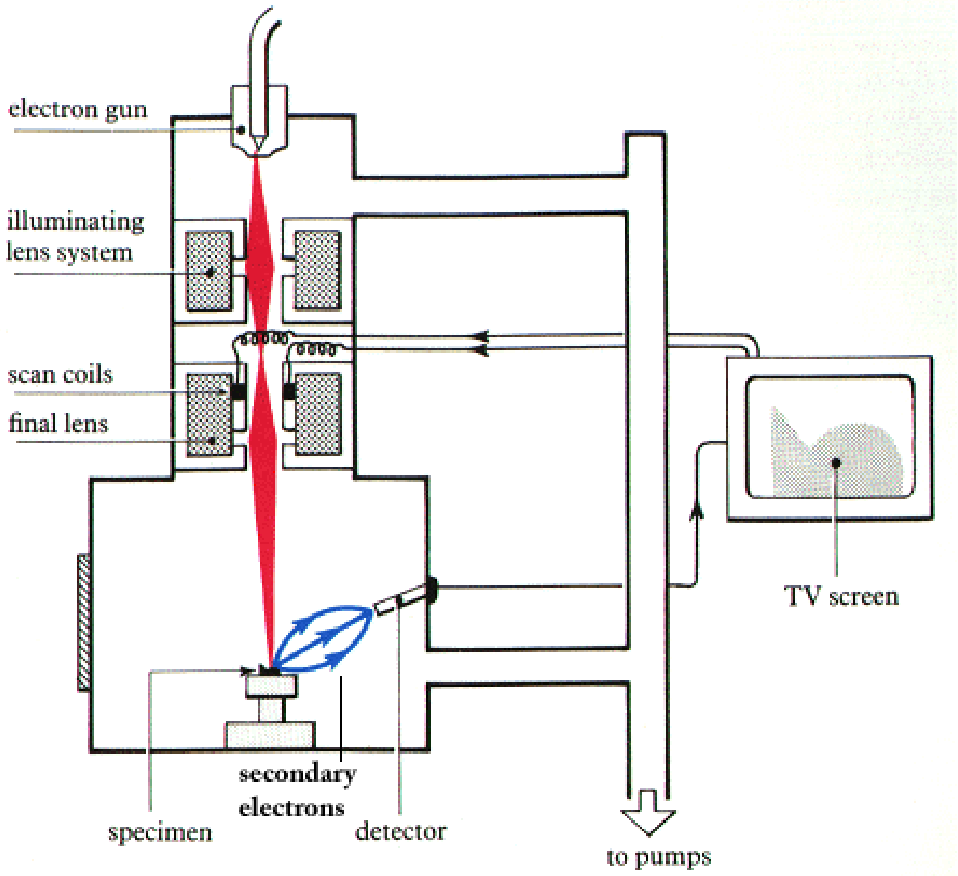
- Materials: Silicon-rich Silicon Nitride
- Thickness: 25, 40 nm
- Diameter: 10, 20, 30 µm
- Arraysize: 256 by 256

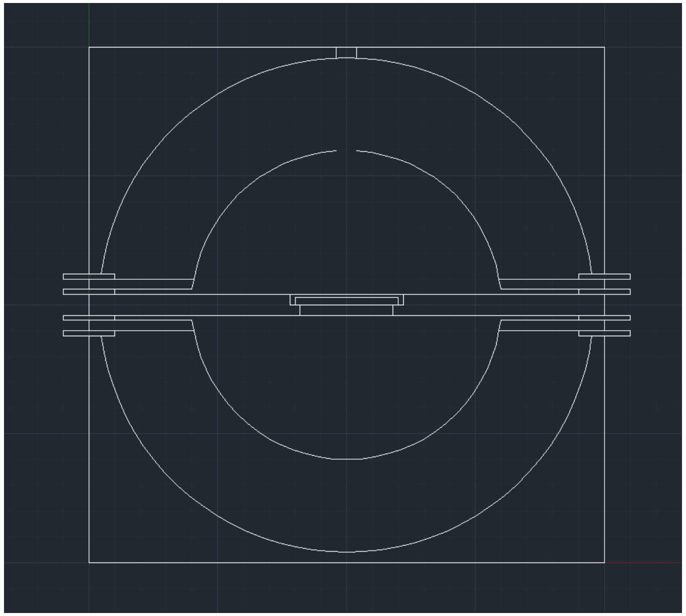
Sample 2: *Large membranes*

- Materials: Si-rich SiN, SiC, AL_2O_3
- Thickness: 40 & 180 nm
- width: 50, 100, 300, 1000 µm



SEY Measurement 1 in SEM





Dual Faraday Cup in SEM
made at Nikhef

SEM/TEM to measure reflection/transmission SEY@
Particle Optics Group TU Delft

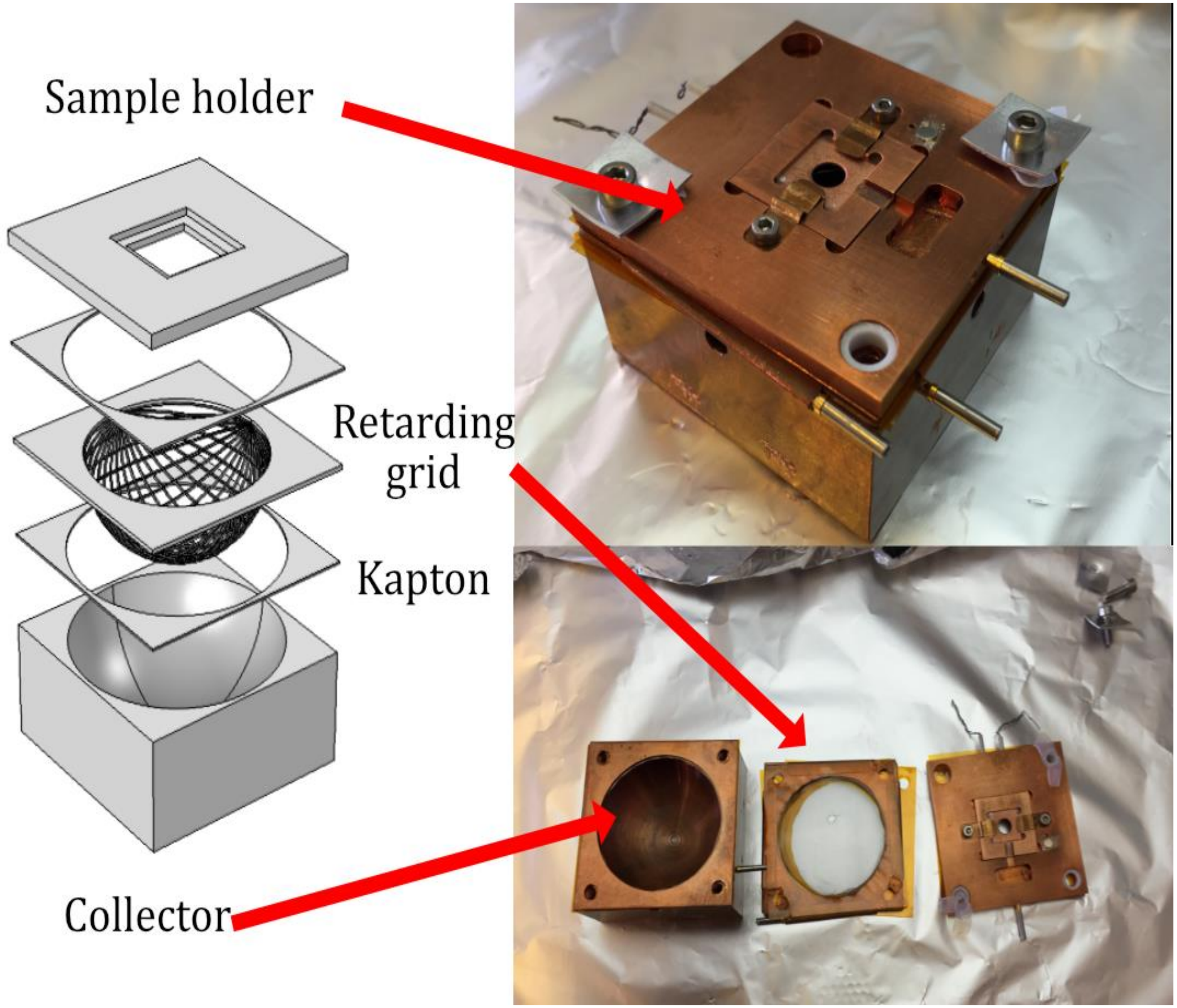
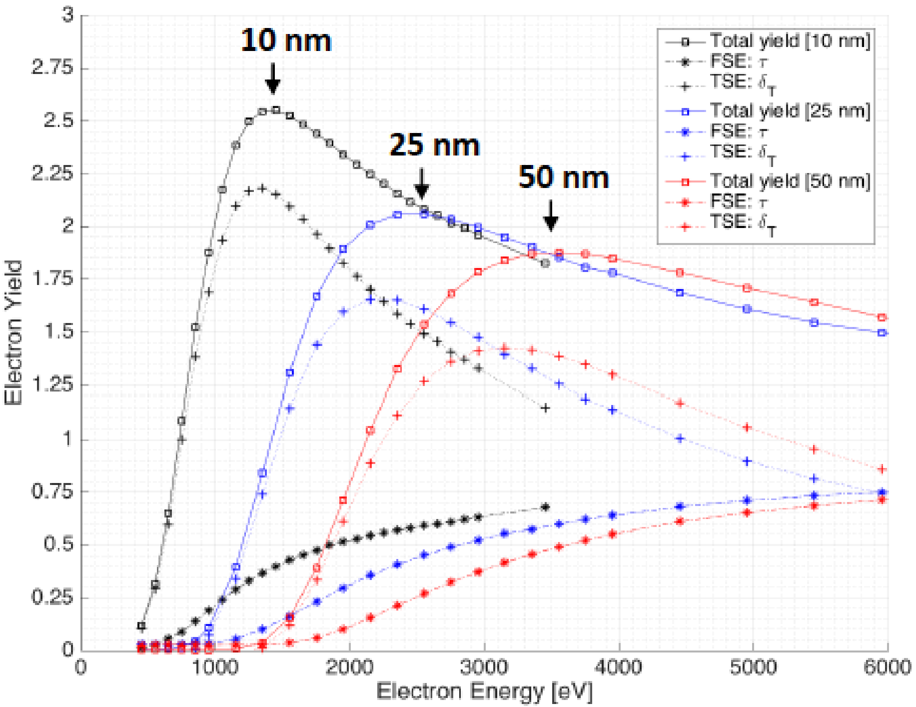
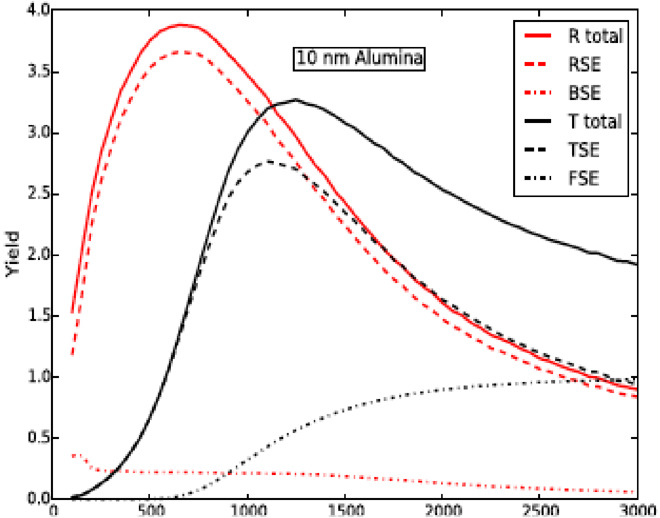


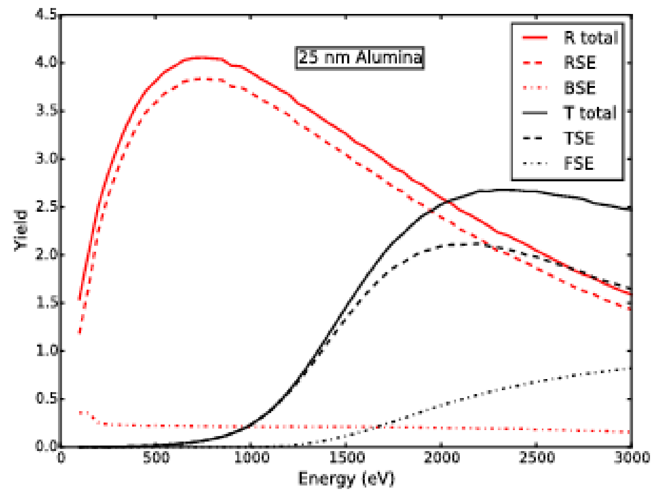
Fig. 15. The Dual Faraday Cup (DFC).

measurement



simulations

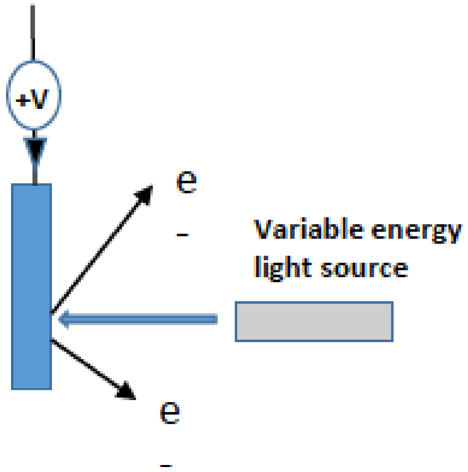


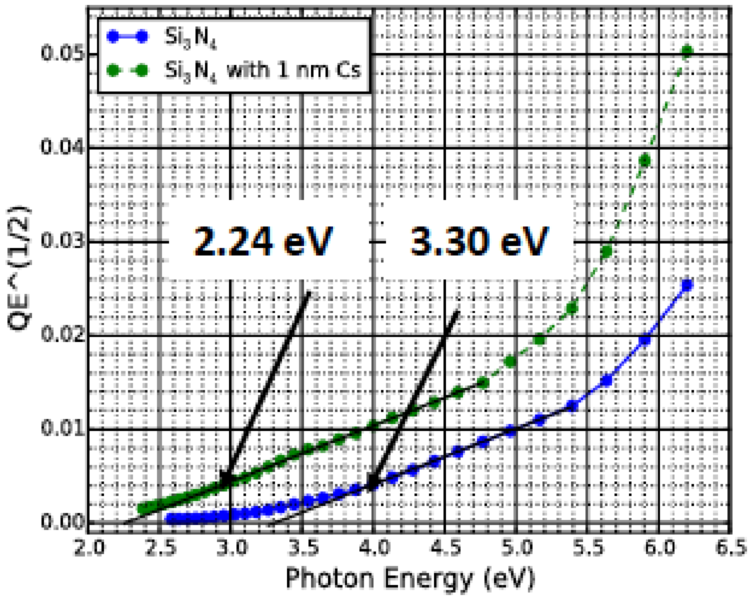


- A decrease in yield, combined with increase in optimum primary electron energy is observed as a function of sample thickness;
- Good correlation to measurements seen for the simulations.

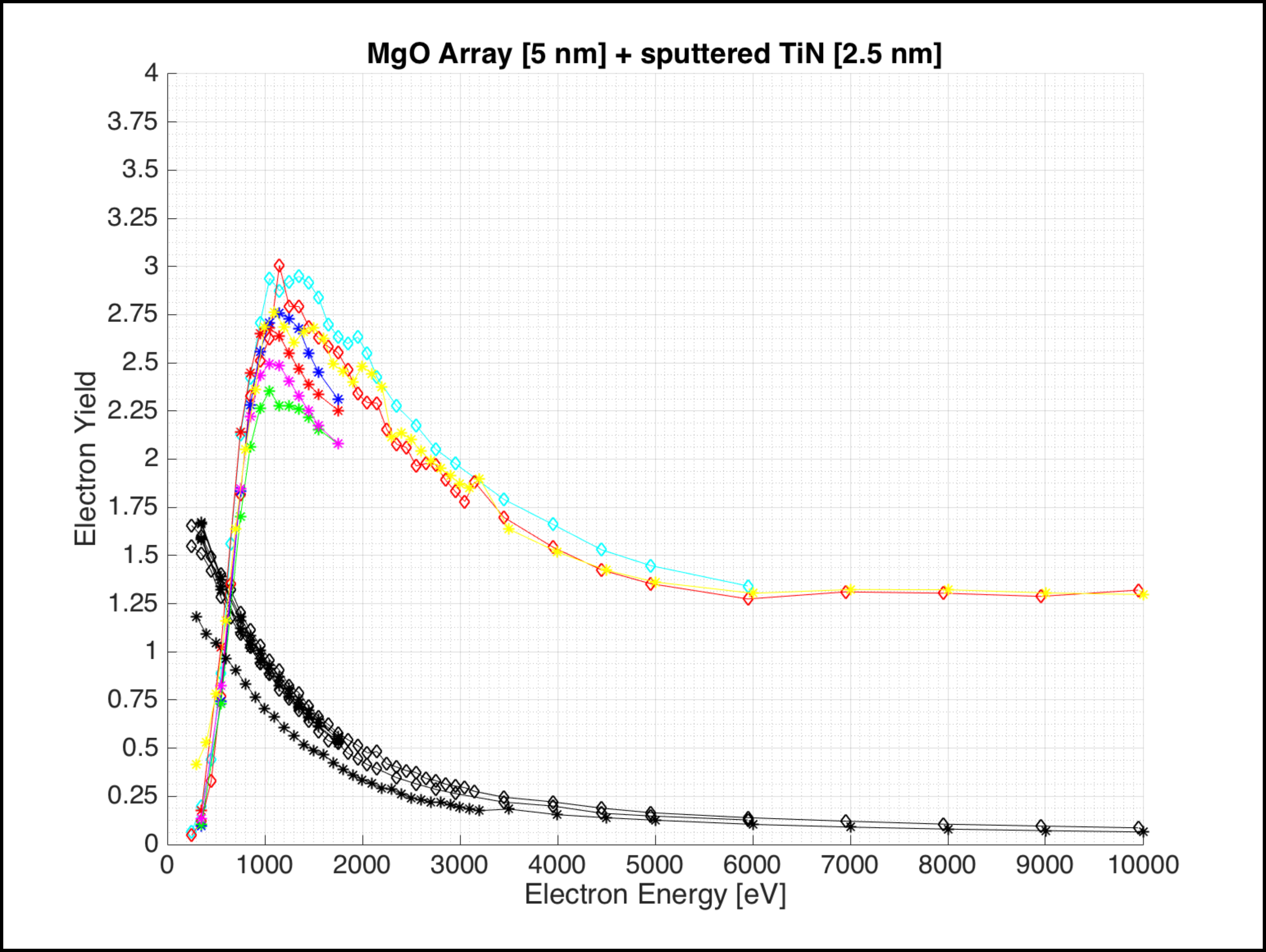
ALD Alumnia as membrane material

Fowler plot of Si_3N_4, with and without Cs termination.

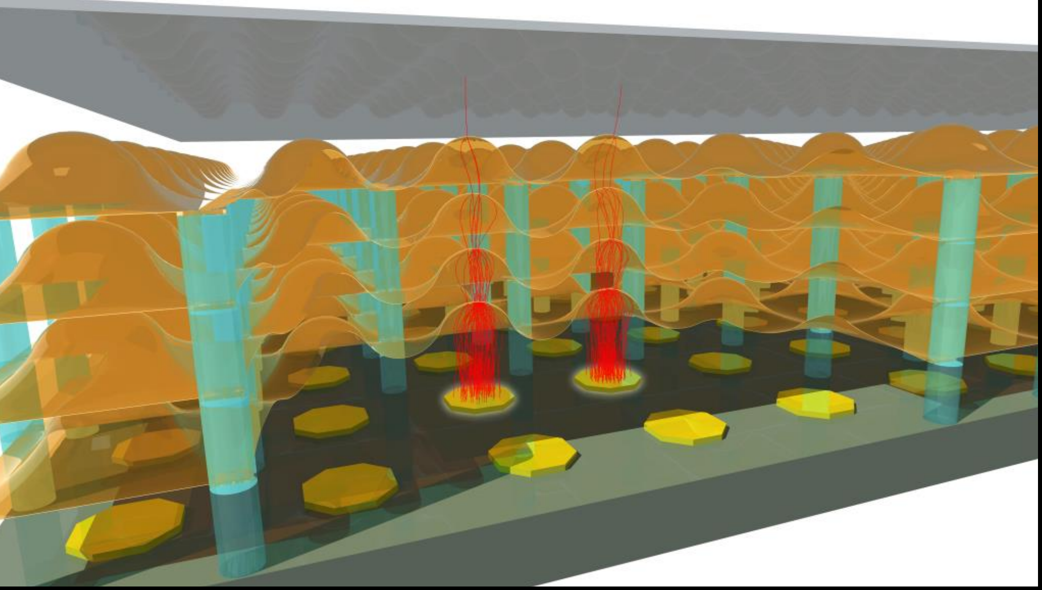




- First measurements of electron work functions for terminated vs. non-terminated samples suggest a reduction in EA.
- the increase in the square root of quantum efficiency is proportional to the increase in photon energy above the work function



Last Monday Sept 12, 2016: Latest result 5 nm ALD MgO…..collaboration with Argonne NL



Timed Photon Counter
TiPC, Tipsy

Fast: electron mobility is highest for free electrons in vacuum

Low noise: no bias current

- Thin, planar, light single soft photon detector
- Electron crossing time $t_c = D \sqrt{(2 m/qV)}$ = 5 ps for V = 150 V, D = 20 μm
- Electron path: quite straight line towards next dynode
- 30 k e- enough for digital signal on pixel input pads: 7 dynodes adequate
- Signal response after 7 x 5 ps = 35 ps
- Time resolution determined by last electron crossing time: ~ 2 ps
- Spatial resolution determined by pixel granularity (55 μm x 55 μm)
- No noise from electron multiplier, no bias current from electron multiplier
- Radiation hard
- Operates in magnetic field
- No ion feedback: no photocathode degradation

But:

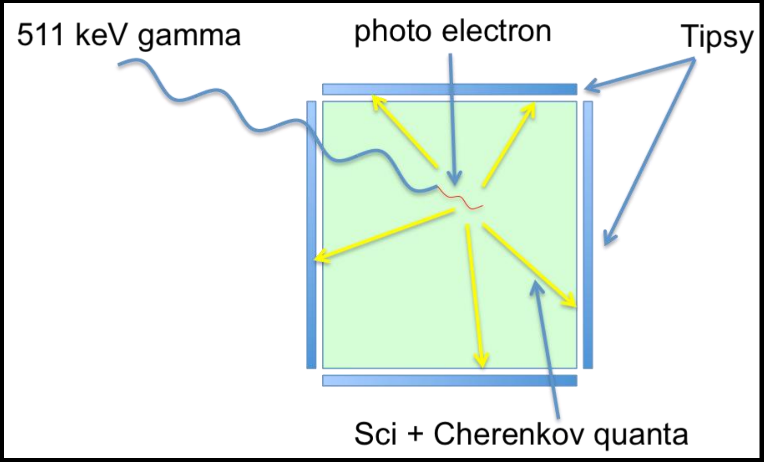
- Secondary electron emission yield not known
- Very strong electric field between dynodes: Fowler-Nordheim limit (10^9 V/m)
- *QE limited by QE of classical photo cathode (20 – 40 %)!*

Applications of new generic electron detector

With Ultra Fast Single Soft Photon Detectors (UPDs):
Cherenkov radiation becomes more relevant

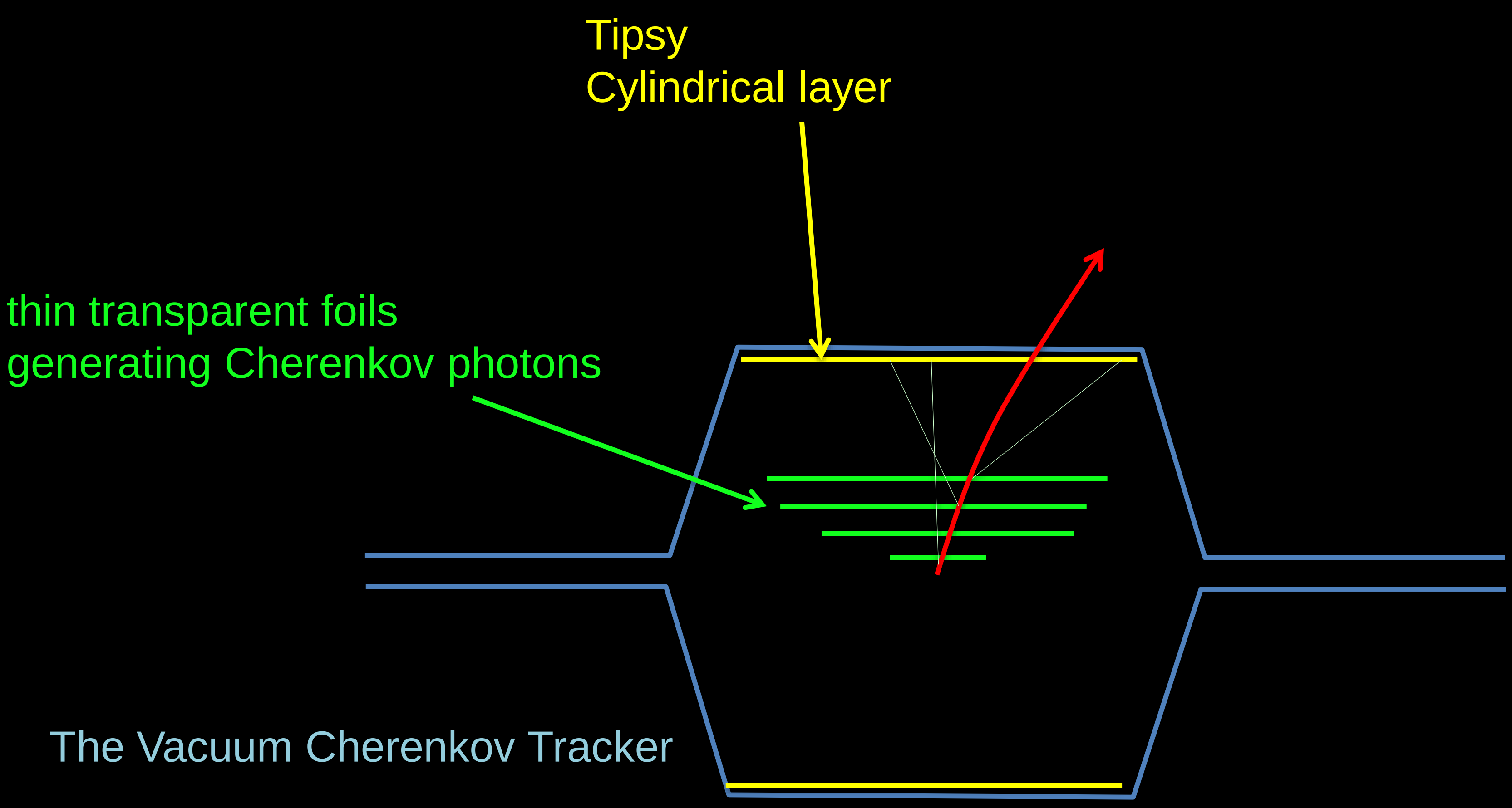
with Pb glass:
only prompt Ch soft photons
With NaI: Ch + Sci soft photons

- use Ch photons for timing (GPS analysis!)
- use all photons for energy
- granularity: multi single soft photon detection within event
- low noise



Future collider experiment: inner (central) tracker

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



Only one crucial deliverable:
a MEMS made transmission dynode with a
secondary electron yield TSEY > 3
has been realised

Short term plans:

- improve transmission yield of MgO tynodes by
  - surface termination by *ceseation*
  - proper surface conditioning (bake out, ion cleaning)
  - explore *extracting field enhancement* of yield

- use nano-grained diamond as membrane material

- manual construction of tynode stack

- realisation prototypes by inserting tynode stack in Photonis' Planacon

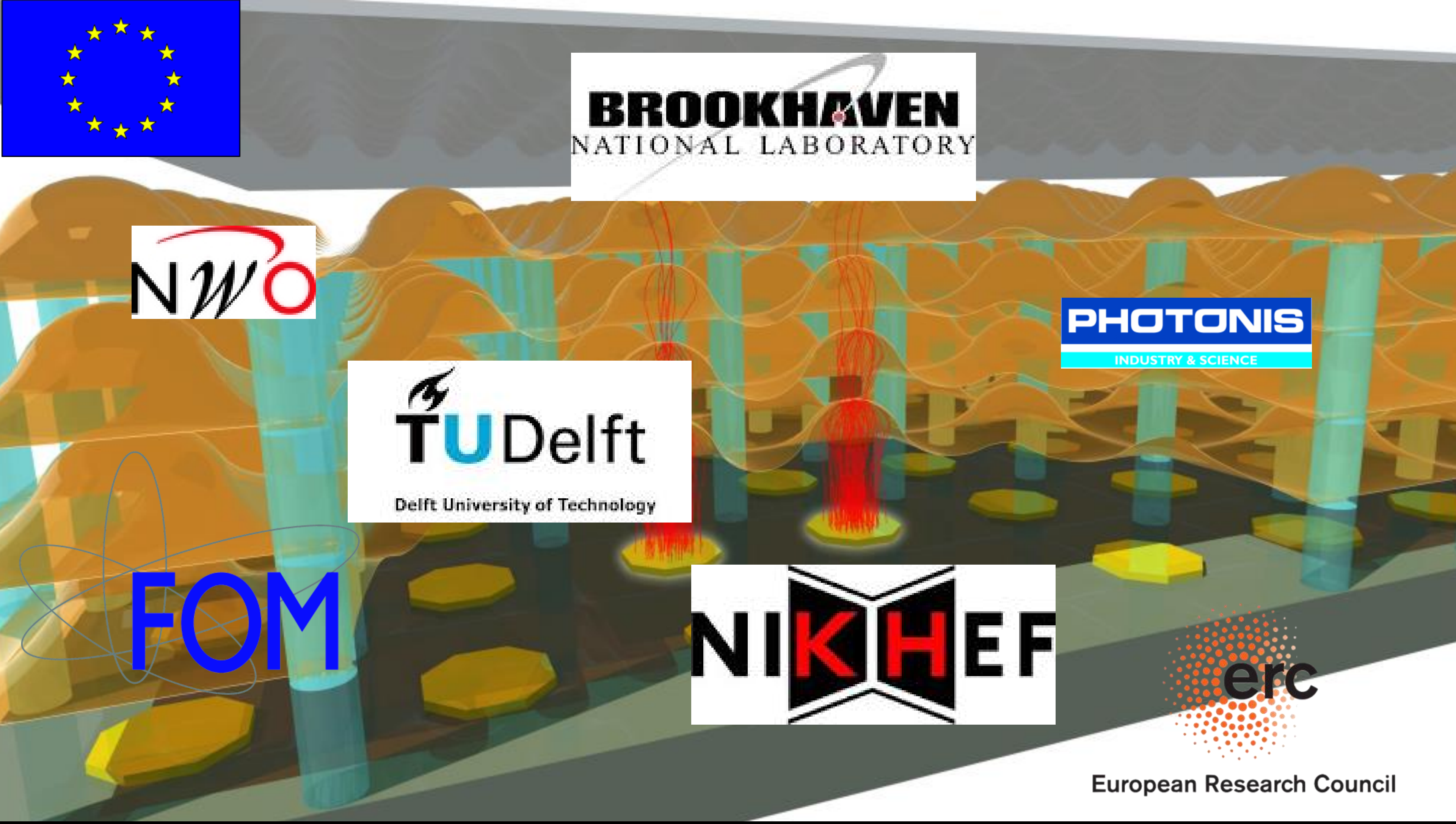
Conclusions

- the transmission yield of Tynodes depends strongly on the electron affinity of the escape surface, as is the case for the reflective yield of Dynodes.

- The transmission yield is limited by the escape depth of electrons and is therefore smaller than the reflective yield, also because of the slanted angle of incident electrons in a dynode (or MCP).

- Membranes with a transmission yield larger than 3 have been realized, albeit that the required electron landing energy is high. This enables the realization of a Tipsy prototype.

- There are good prospects for higher transmission yields, reducing the required number of tynodes in the stack, and reducing the required HV per tynode



Hassan Akhtar, Yevgen Bilevych, Neil Budko, Hong Wah Chan, Edoardo Charbon,
Alexander Cronheim, Harry van der Graaf, Conny C.T. Hansson, Kees Hagen, Gert Nützel,
Serge D. Pinto, Violeta Prodanović, Behrouz Raftari, Lina Sarro,
Dennis R. Schaart, John Sinsheimer, John Smedley, Shuxia Tao, Annemarie Theulings, Kees Vuik

Thanks to Arjen van Rijn, Michiel Jaspers, Oscar van Petten, Gerrit Brouwer, Johan Hidding
Wim Gotink, Joop Rövekamp, Bas van der Heijden, Berend Munneke, Henk Peek