The Tipsy single soft photon detector

A pixelized detector for single free electrons in vacuum with ps time resolution

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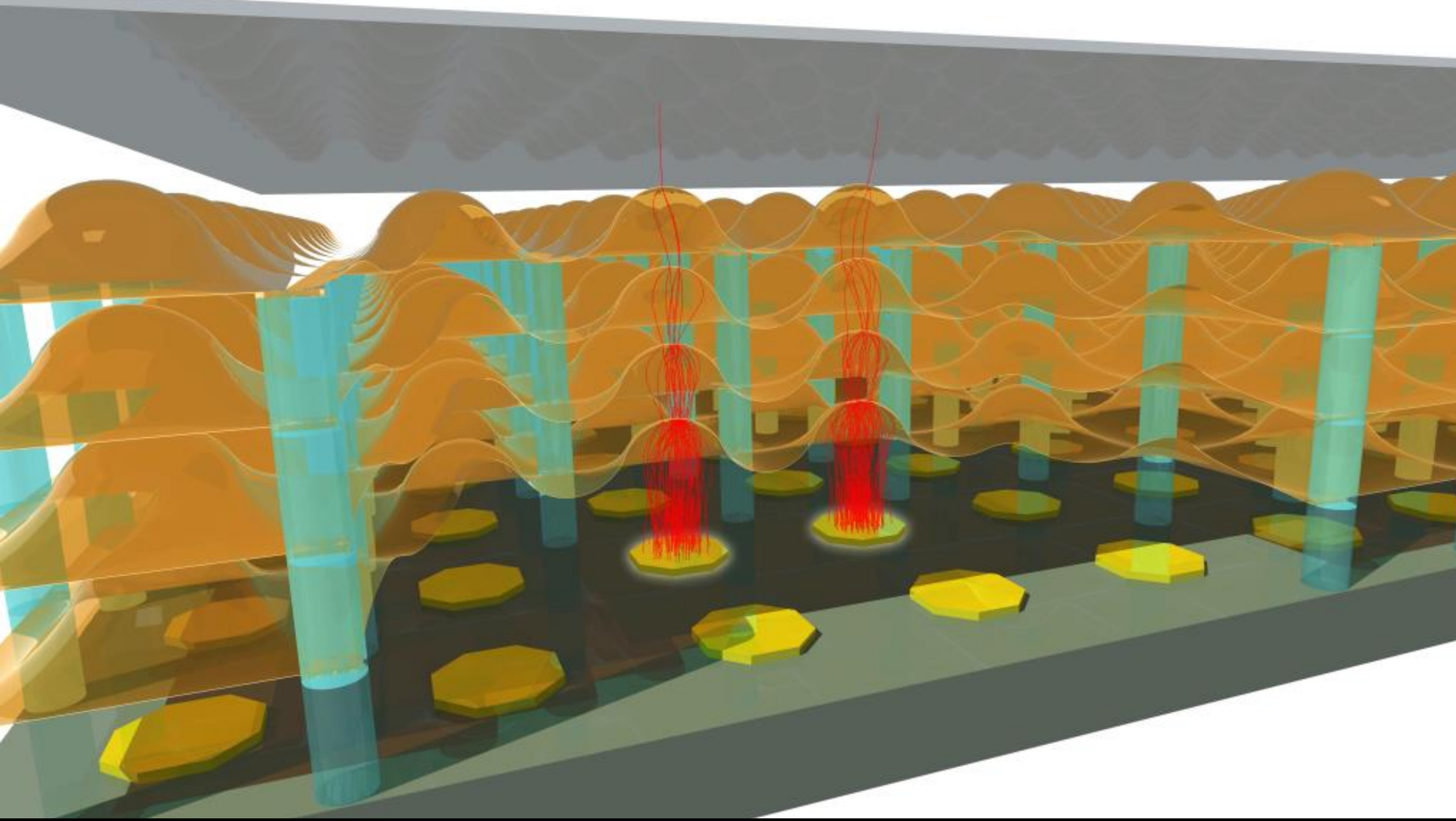


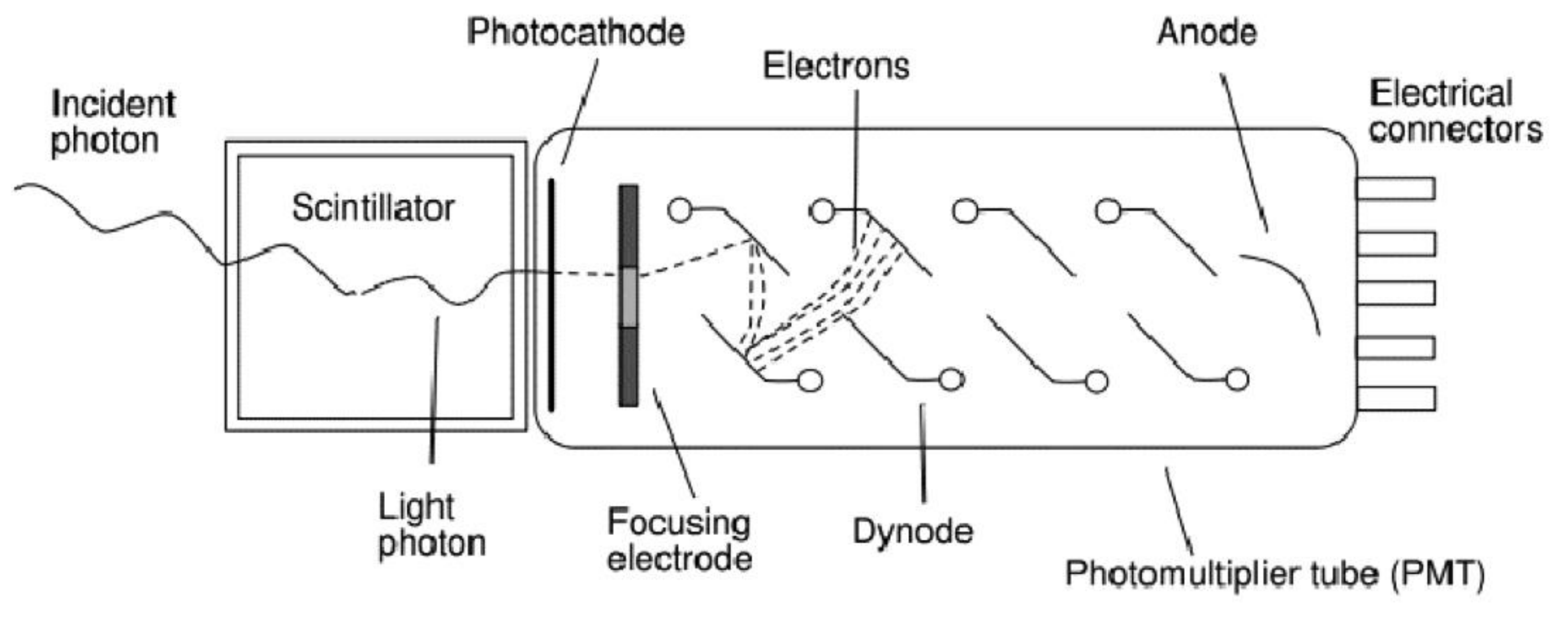
Tipsy principle

use pixel chip as 2D sensitive anode

dynode stack above individual pixel

set of closely spaced *transmission* dynodes

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!

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

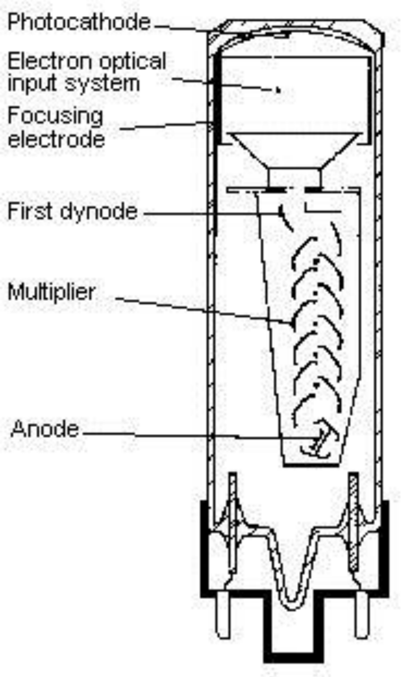
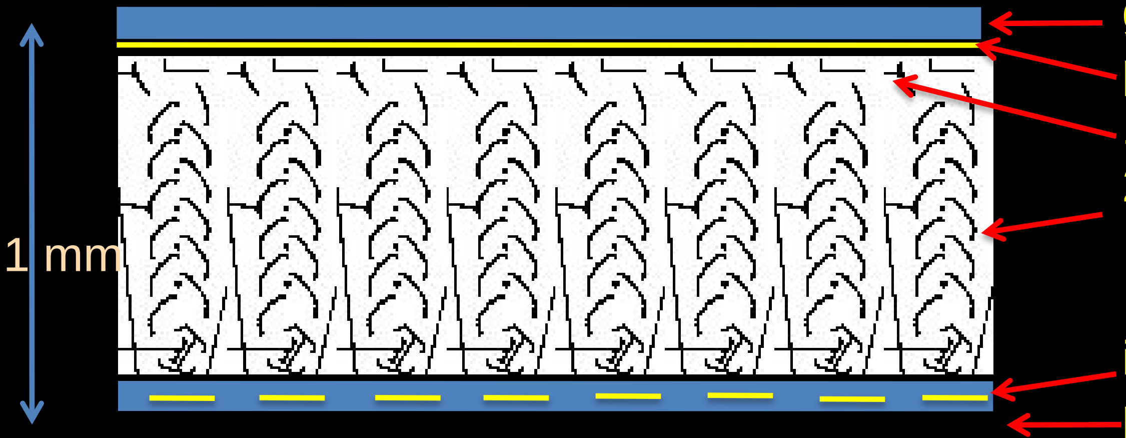


Fig. 8.1. Schematic diagram of a photo-multiplier tube (from *Schonkeren* [9.1])

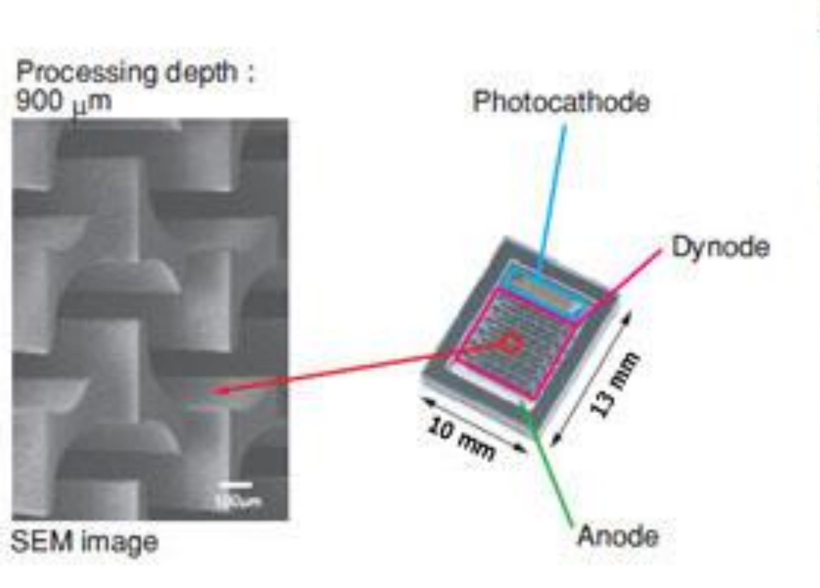
Apply MEMS Technology:

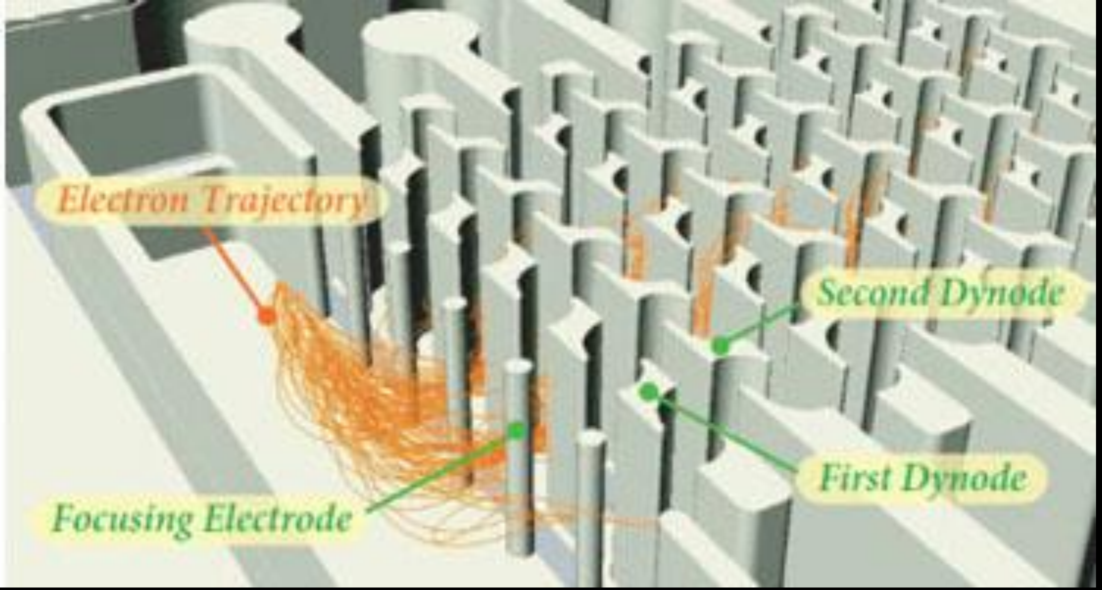


glass window
photo cathode
1st dynode
2nd – 5th dynode

input pads
pixel chip

VACUUM!
No ‘gas amplification’

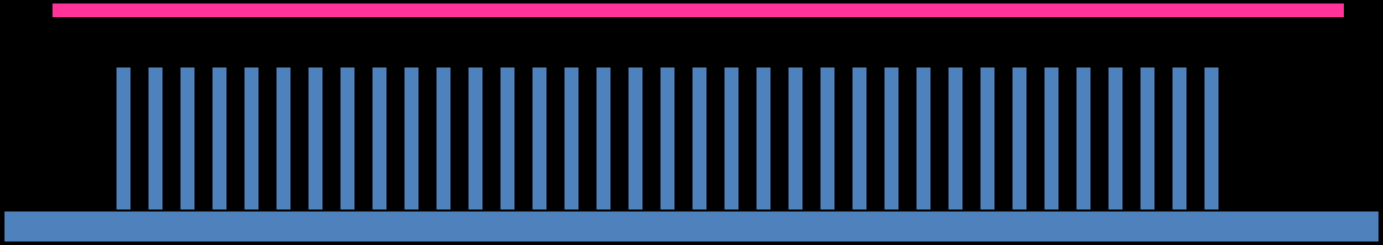




Hamamatsu: the first MEMS made μPMT

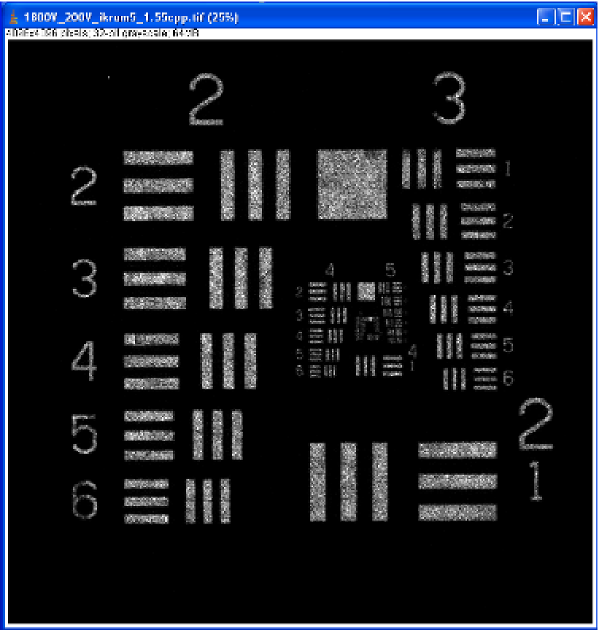
- Small dynode geometry as in Tipsy

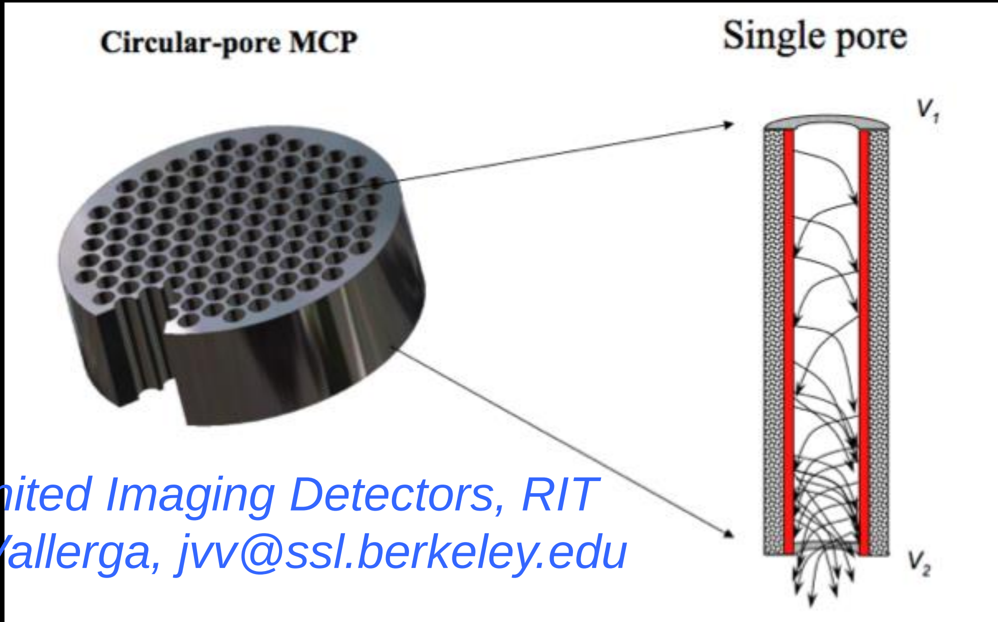
Use a MicroChannelPlate MCP?



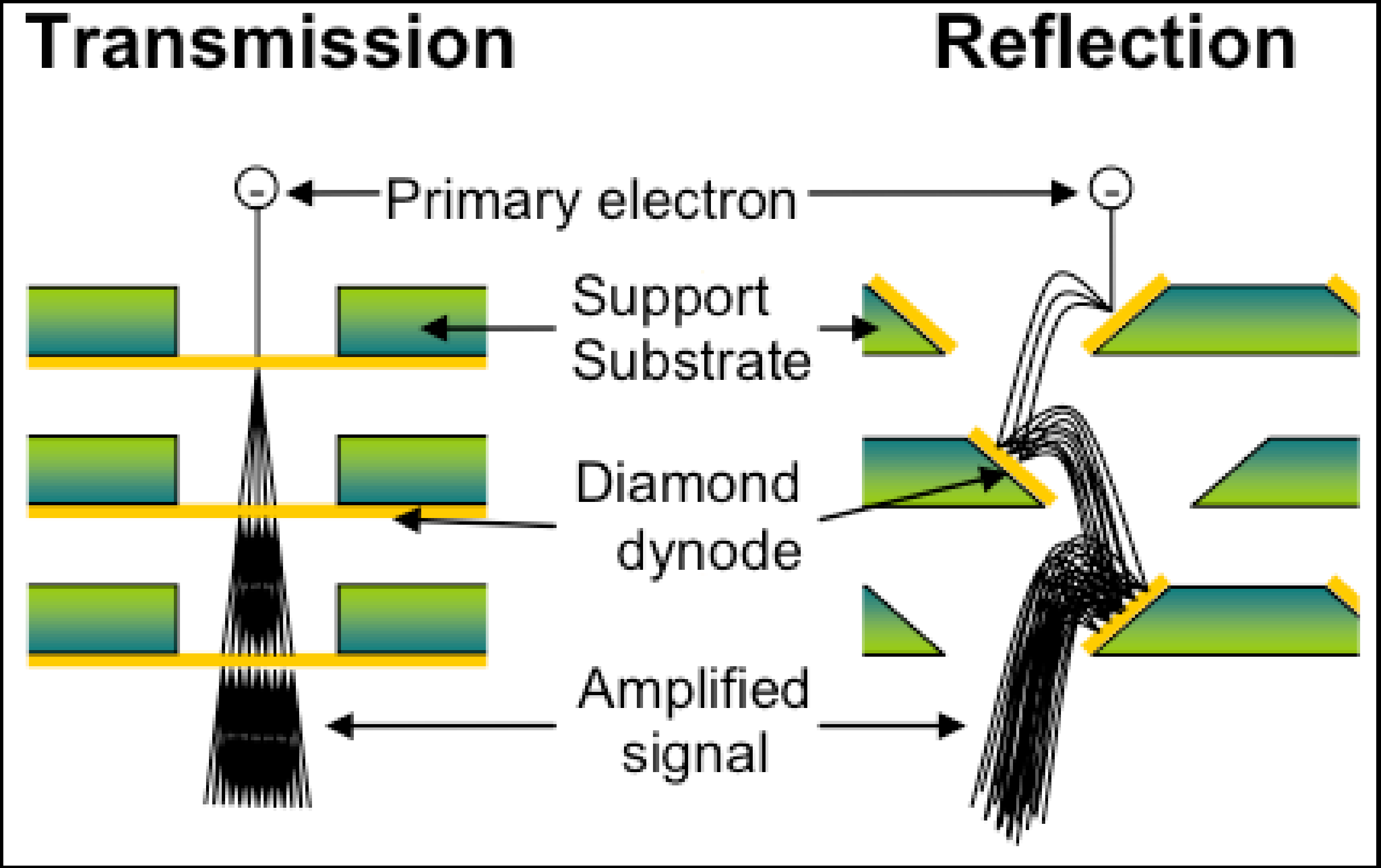
John Vallerga: TimePix + MCPs

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

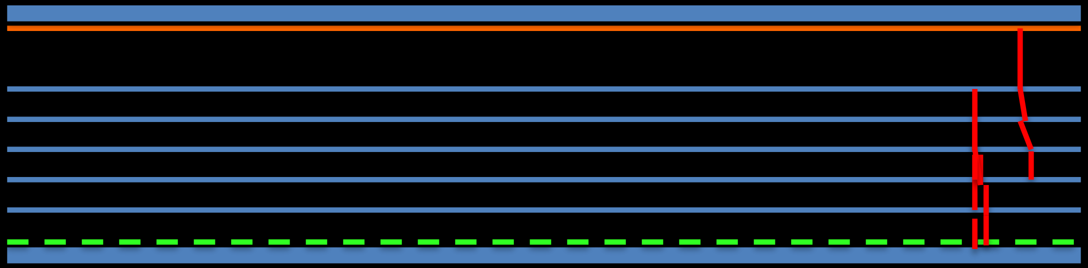




Quantum Limited Imaging Detectors, RIT 2009, John Vallerga, jvv@ssl.berkeley.edu



New: the Transmission Dynode



window + photo cathode

Ultra thin planar dynode membranes

vacuum

CMOS pixel chip

- 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

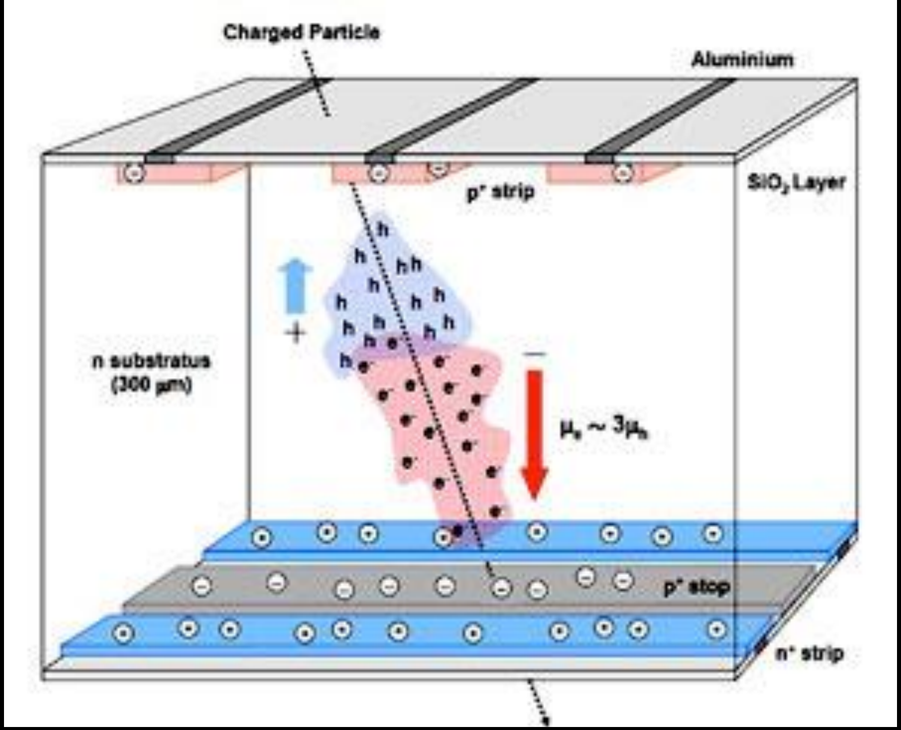
“the best electron is a free electron”

Competitor:

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

Competition: Silicon Photomultipliers

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



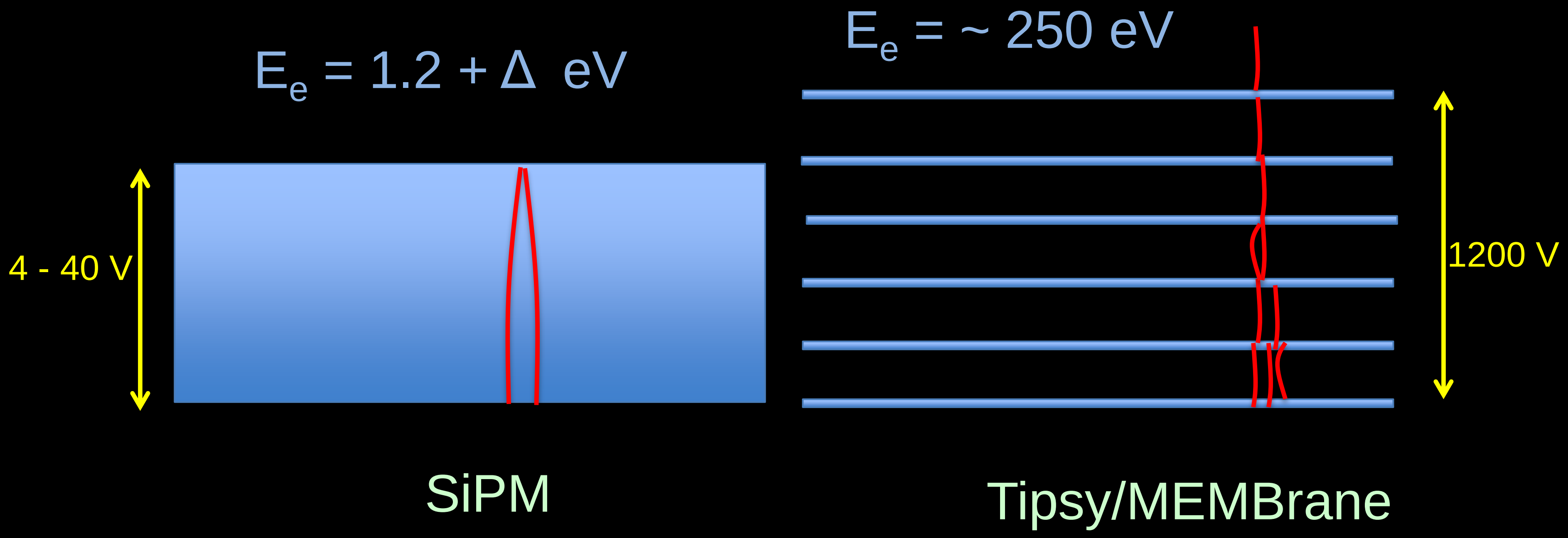
Very popular:

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

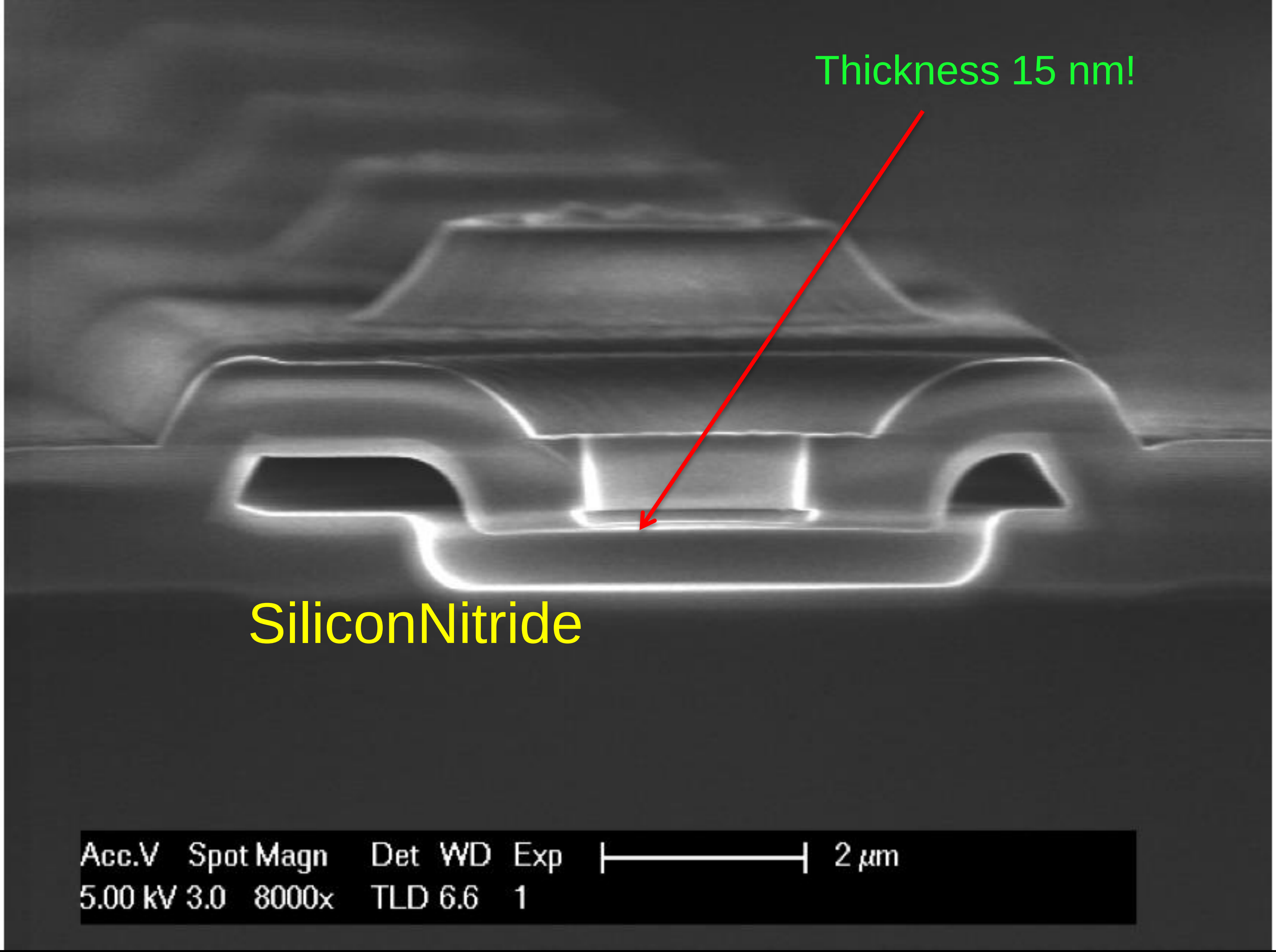
But they are:

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

Essential difference between SiPMs and Tipsy


$E_e = 1.2 + \Delta\ \text{eV}$

$E_e = \sim 250\ \text{eV}$

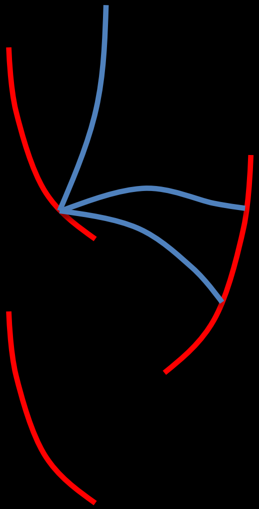


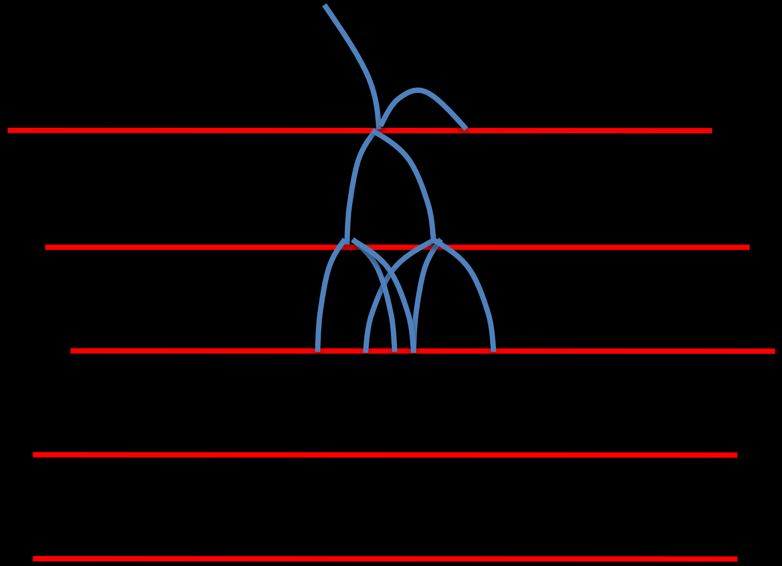
Ultra thin membranes

Delft University of Technology: DIMES

The transmission dynode: ultra thin (20 - 100 nm) layers

diamond
SiNitride (Si_3N_4) Si doped (SiRichNitride, SRN)
CsI
doped SiO_2





- ultra fast (single electron) detector: t_{cross} = 2 - 10 ps
- E-force much larger than Lorenz force: operates in B-field
- radiation hard
- low mass
- low volume (planar detector)

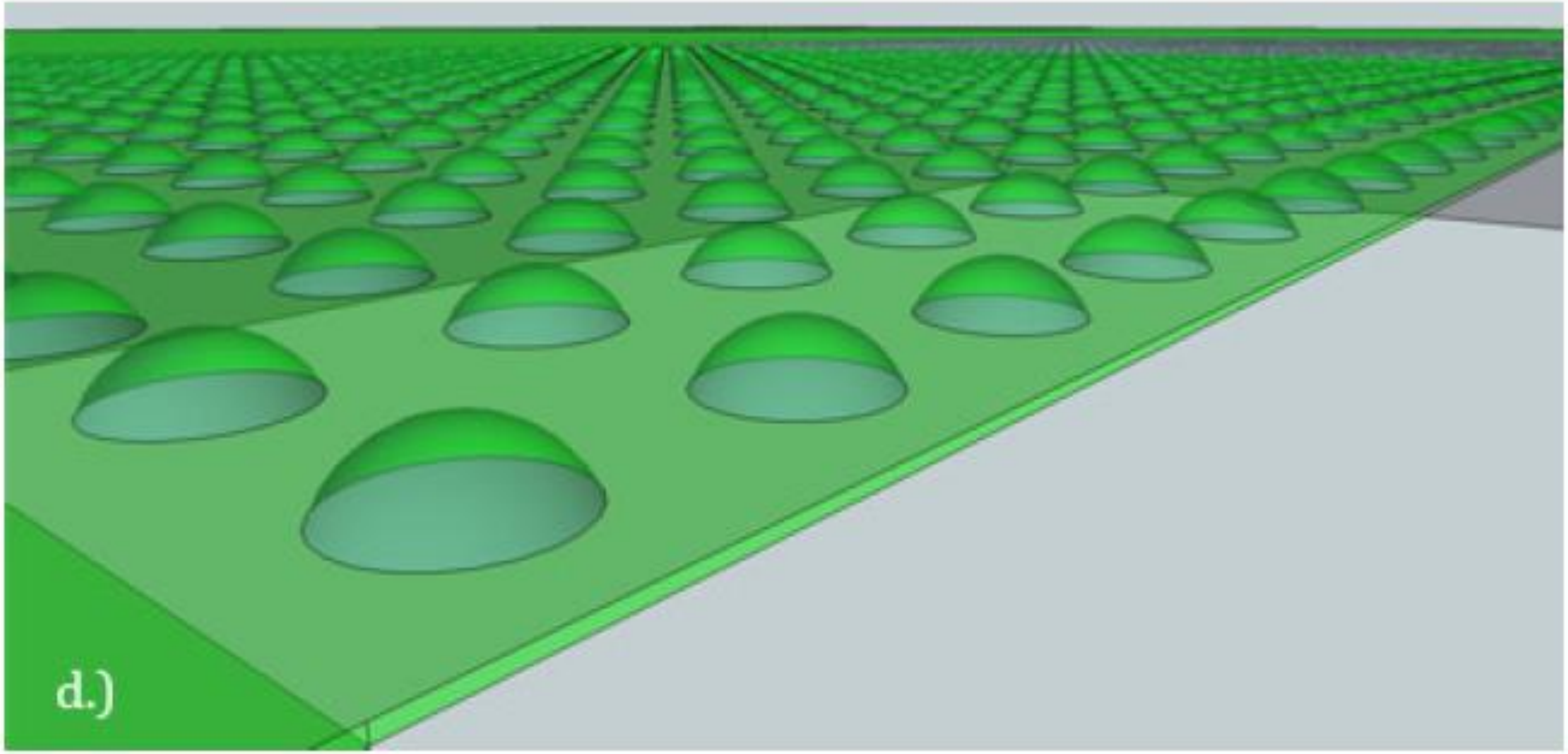
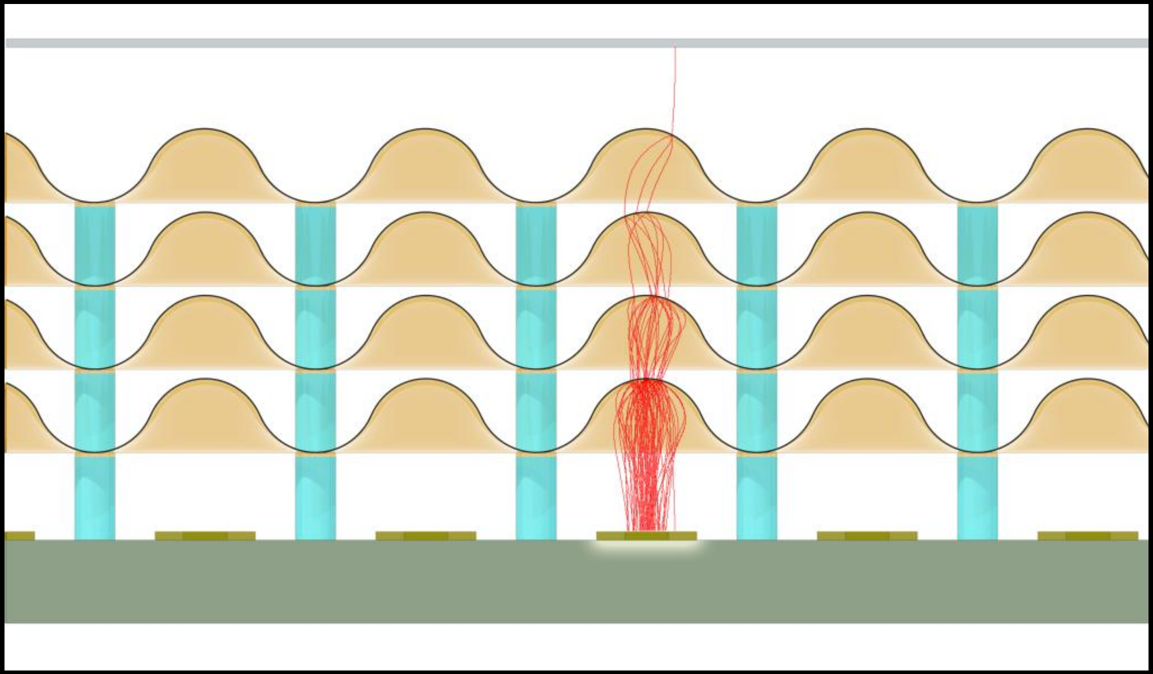


Figure 6-2 Design of a transmission dynode D1. a.) Top view. The yellow corner is a gold pad which is in contact with the doped silicon layer. b.) Bottom view. The hole is opened by KOH etching. c.) Cross section. The structural membrane is 1-2 µm thick. d.) Close up of the cross section. The cones are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

Array of ultra thin domes

A new single, free electron detector in vacuum



transmission dynodes

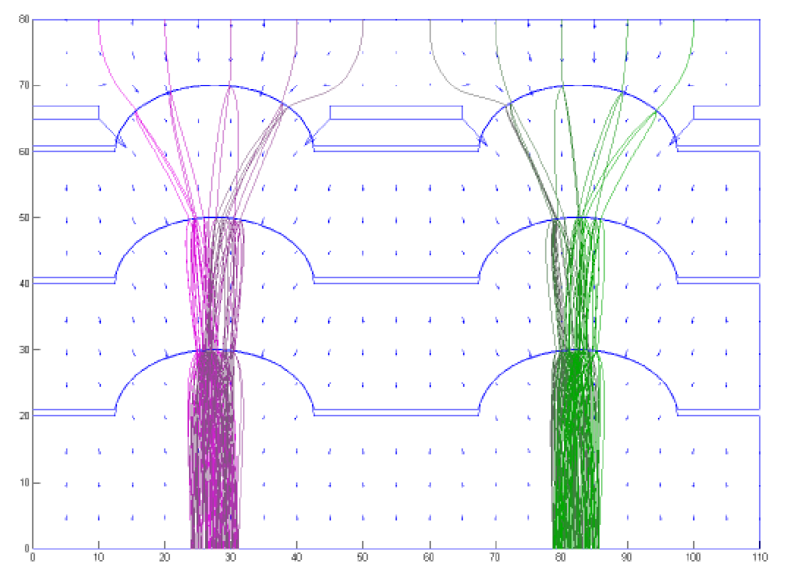
+

pixel chip

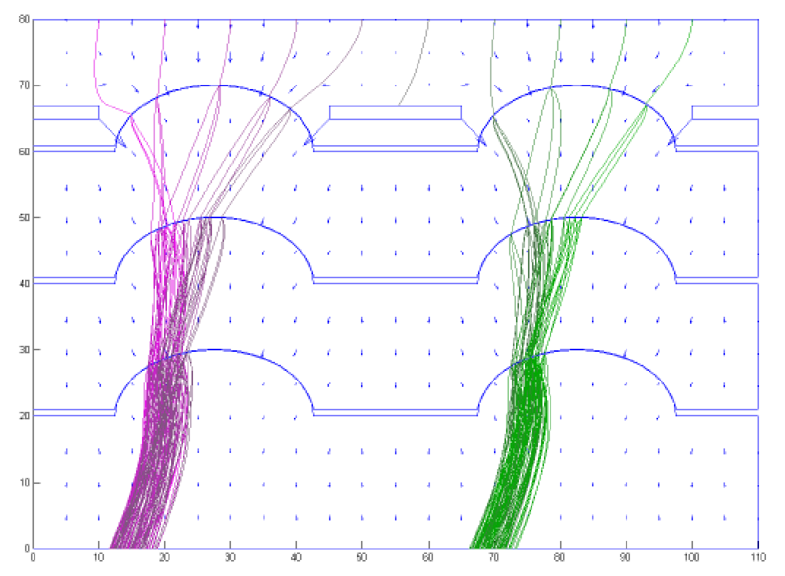
MicroElectronicMechanicalSystems ‘MEMS’ Technology
- ultra thin membranes
- Cone shape dynode section:

1. focusing electron from above
2. focusing emitted electrons
3. mechanically robust: larger diameter cones feasible

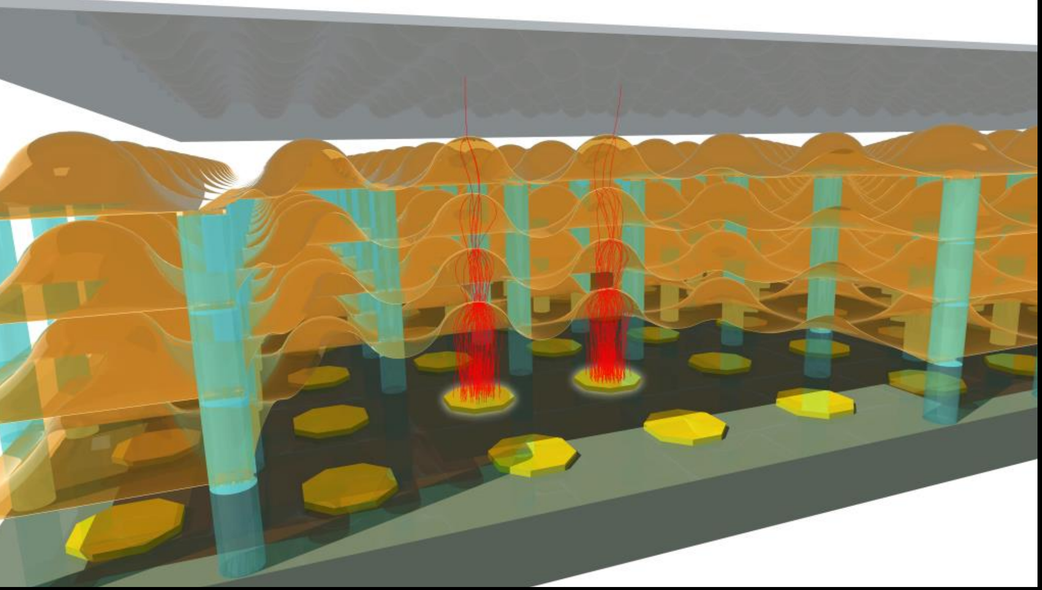
First (2D) simulations: influence magnetic field



0 Tesla



1 Tesla



Timed Photon Counter
TiPC, Tipsy

Fast: electron mobility is highest for free electrons in vacuum

Low noise: no bias current

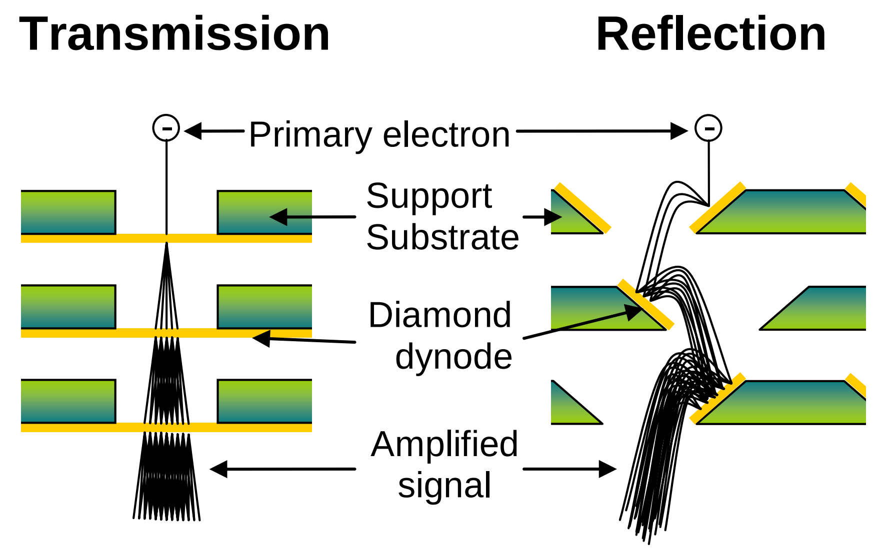
- Thin, planar, light single soft photon detector
- Electron crossing time $t_c = D \sqrt{(2 m/qV)}$ = 5 ps for V = 150 V, D = 20 μm
- Electron path: quite straight line towards next dynode
- 30 k e- enough for digital signal on pixel input pads: 7 dynodes adequate
- Signal response after 7 x 5 ps = 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
- 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

468 *J.J. Fijol et al. / Secondary electron yield of SiO_2 and Si_3N_4 thin films*

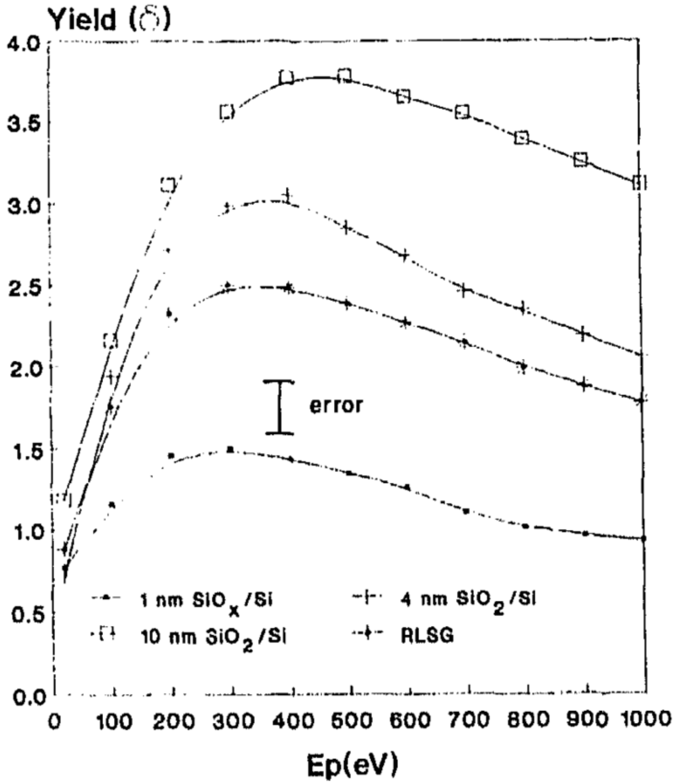


Fig. 5. Secondary electron yield δ versus primary electron energy E_p for SiO_x/Si, SiO_2/Si, and RLSG test structures at $\Theta = 0°$.

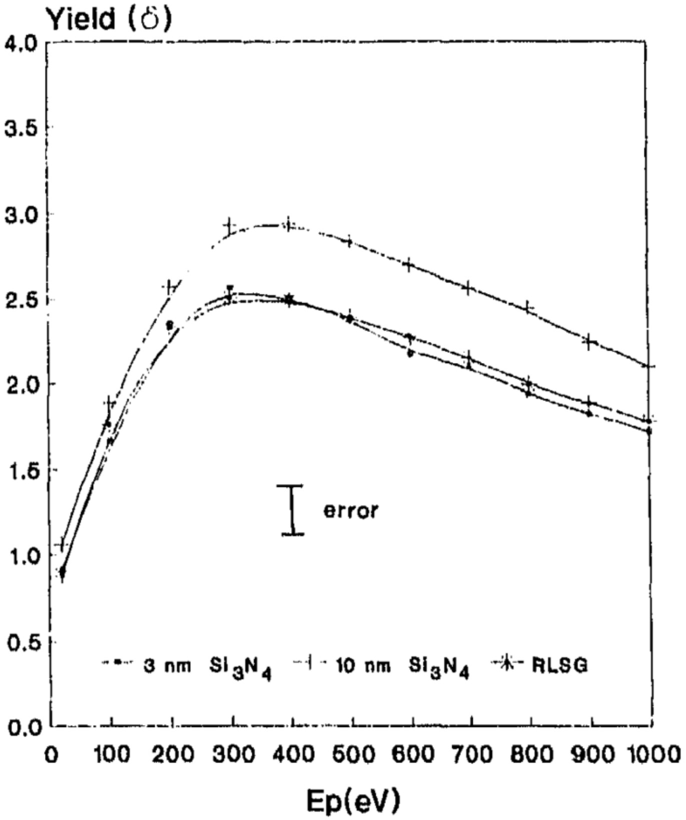


Fig. 6. Secondary electron yield δ versus primary electron energy E_p for Si_3N_4/Si and RLSG test structures at $\Theta = 0°$.

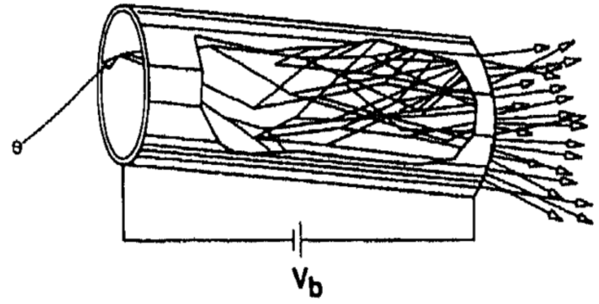


Fig. 1. Schematic of geometric electron multiplication in a straight-channel electron multiplier under bias voltage V_b.

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

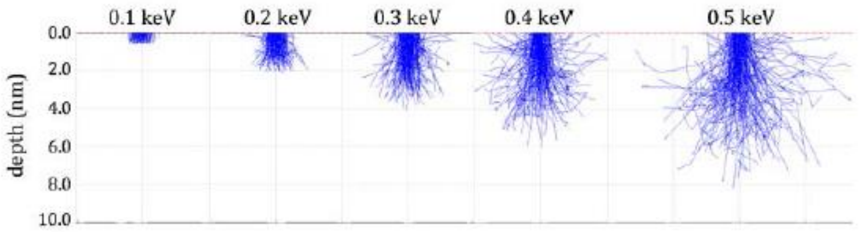


Figure 5-2 The primary electron tracks of electron beams with increasing energy. For each beam, 200 electron tracks are simulated. The sample consists of low stress silicon nitride (Si_3N_4) with a density of 3.2 g/cm^3 .

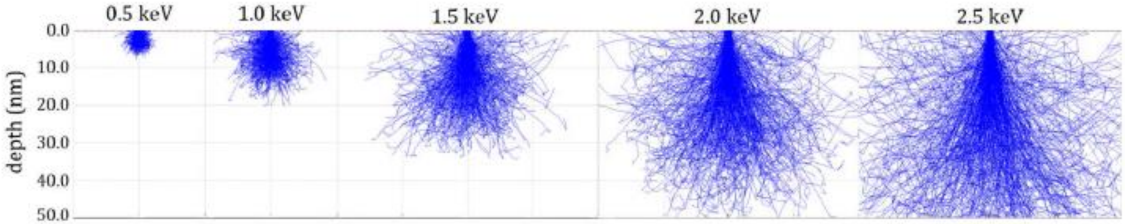


Figure 5-3 The primary electron tracks of electron beams with increasing energies. For each beam, 200 electron tracks are simulated. The sample consists of low stress silicon nitride (Si_3N_4) with a density of 3.2 g/cm^3 .

Expected for transmission dynodes:

- SEY same order as for reflective dynodes
- SEY above about equal to SEY below

Transmission Dynode construction

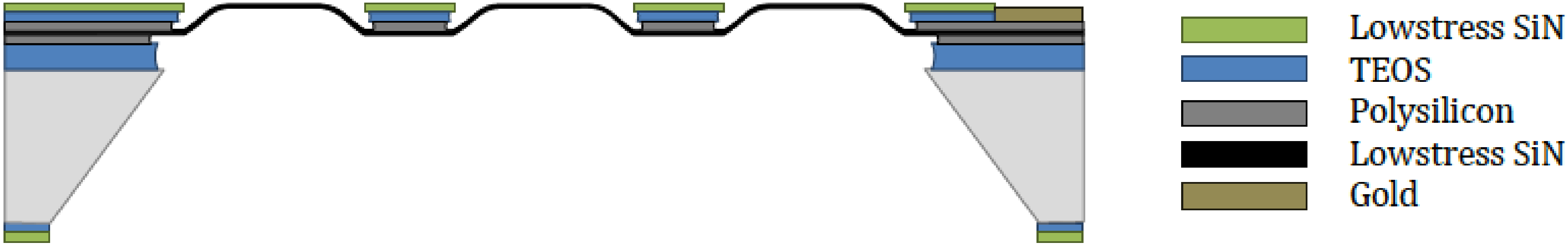
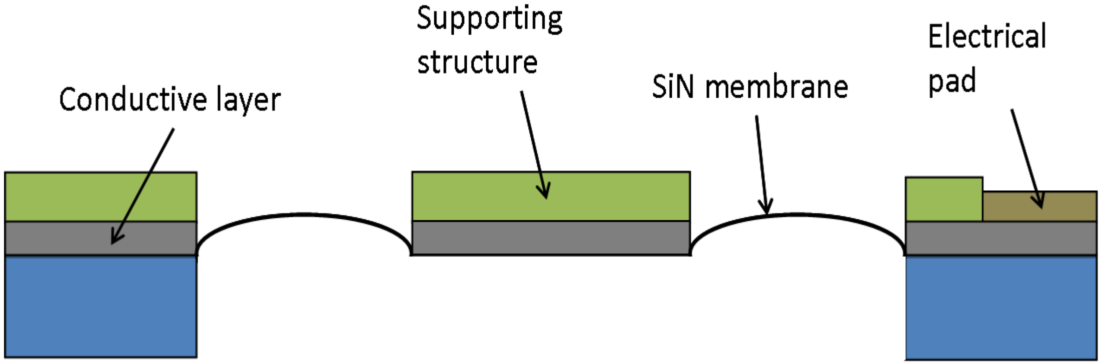
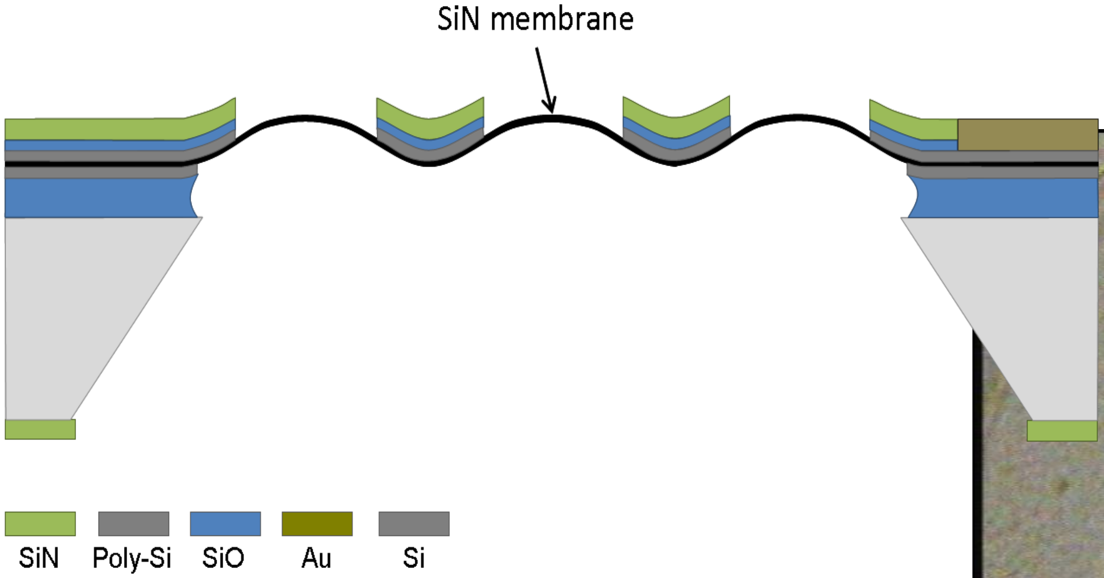


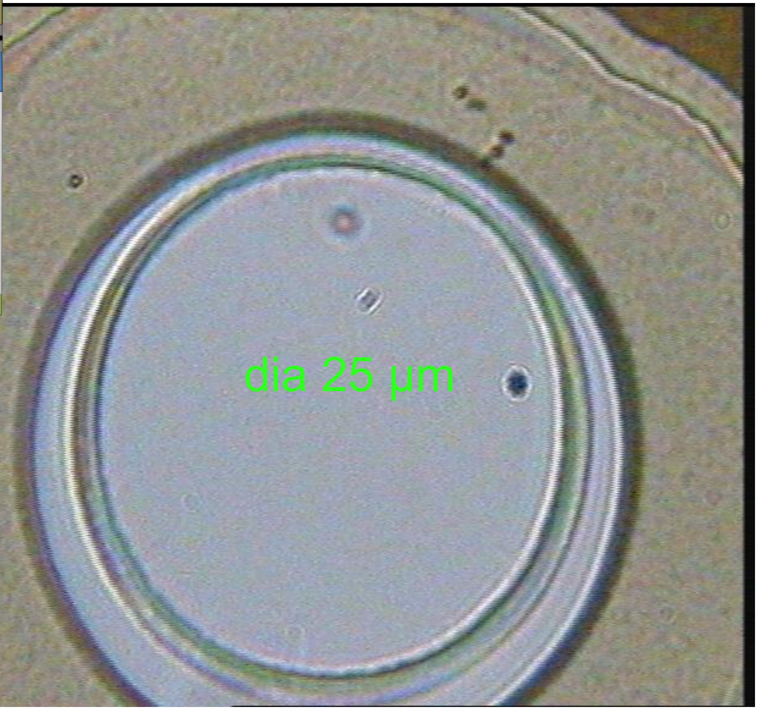
Figure 6-1 Composition of a dynode D1



Fabio Santagata
Lina Sarro
Hong Wah Chan
Violeta Prodanović

DIMES, TU-Delft

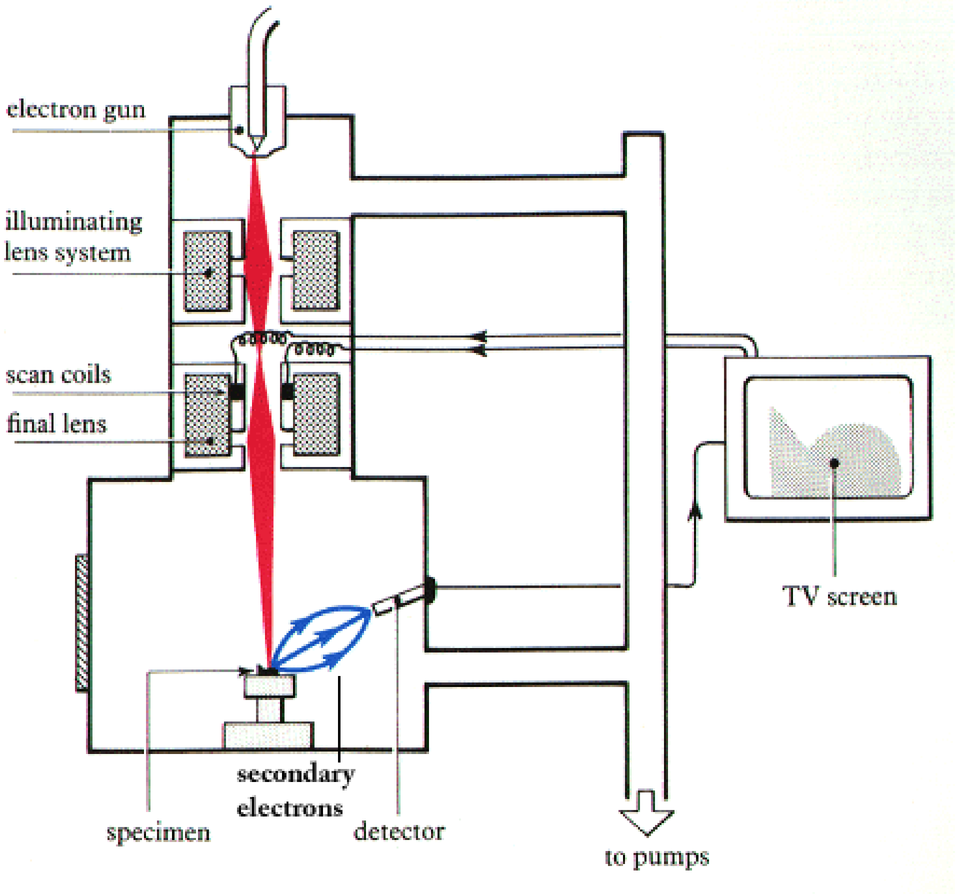




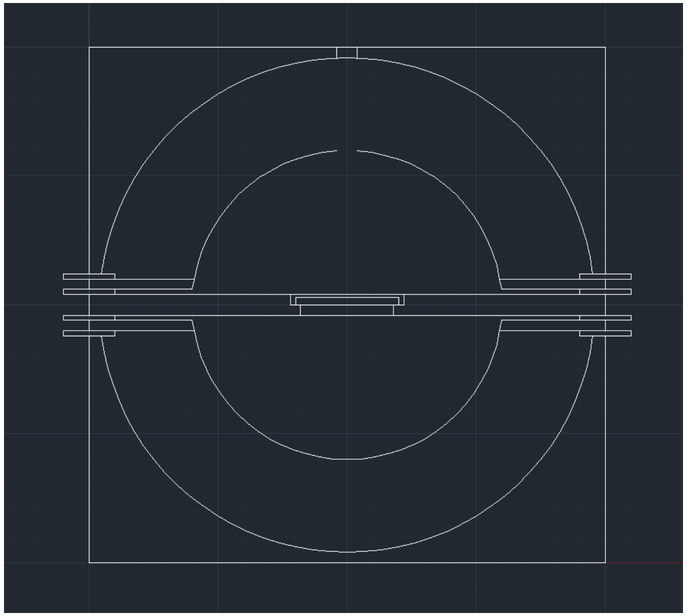
15 nm thin dynode material
Si Rich SiNitride (SRN)

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

Secondary Electron Yield
SEY Measurement 1 in SEM

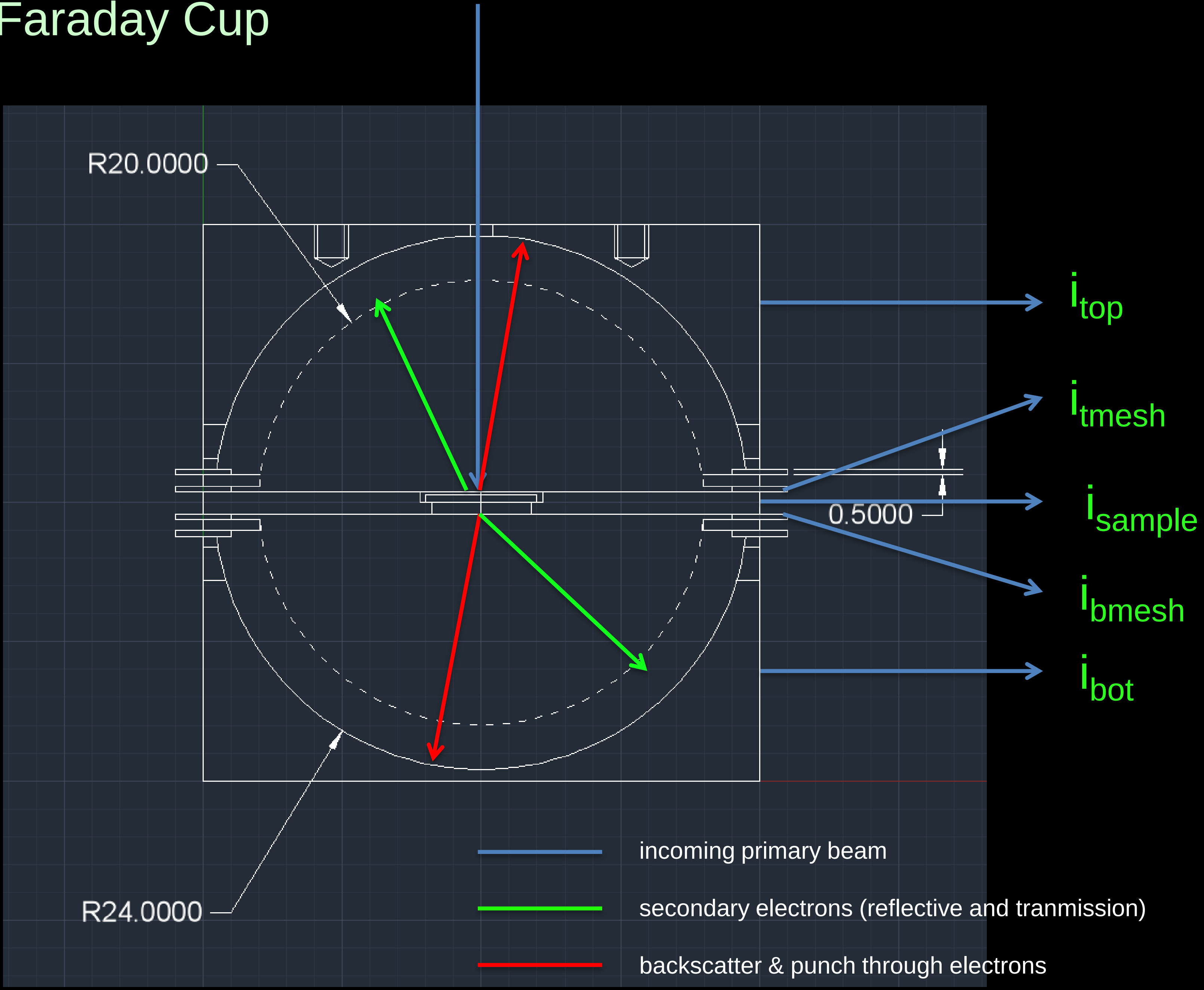


SEM/TEM to measure reflection/transmission SEY@ Particle Optics Group TU Delft



Dual Faraday Cup in SEM made at Nikhef

Dual Faraday Cup

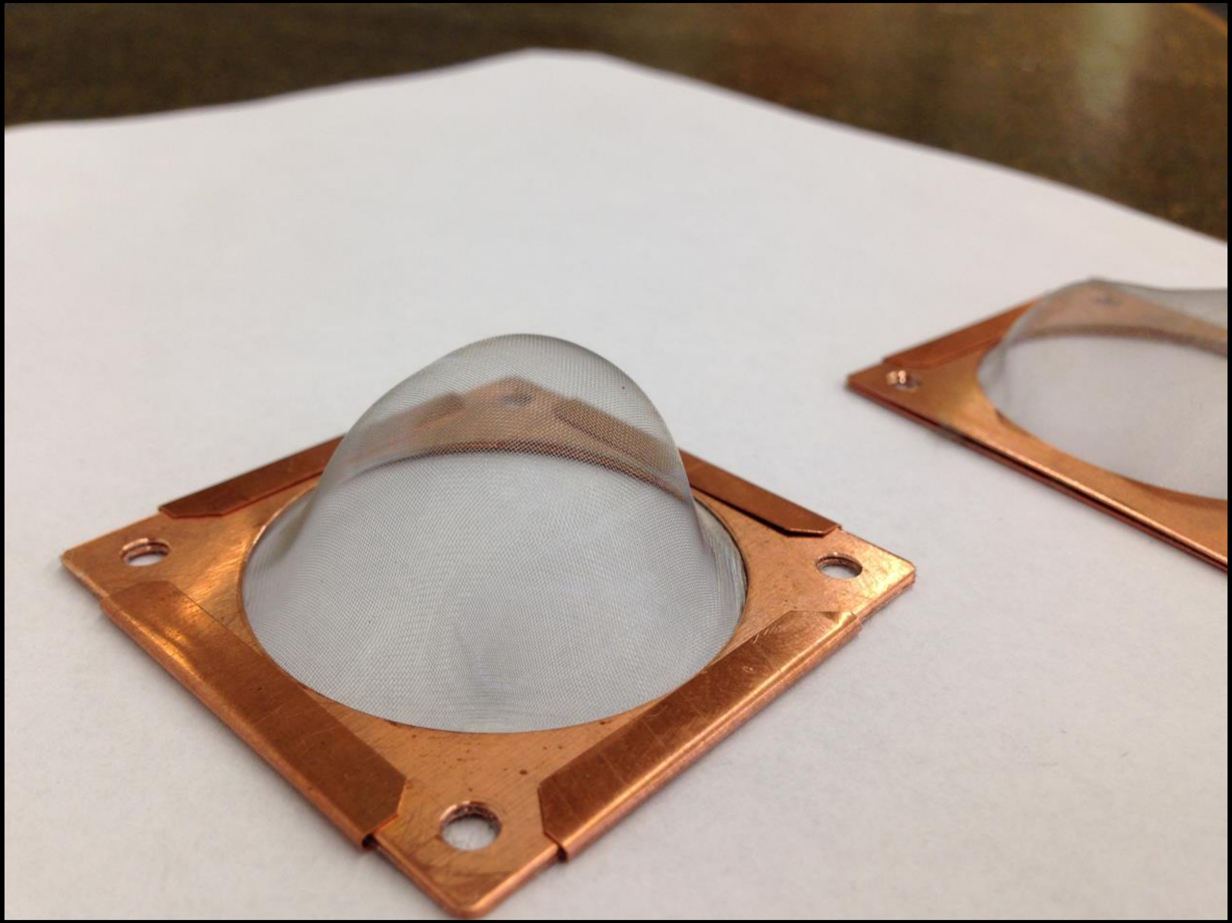


🟦 incoming primary beam

🟩 secondary electrons (reflective and tranmission)

🟥 backscatter & punch through electrons

Dual Faraday Cup

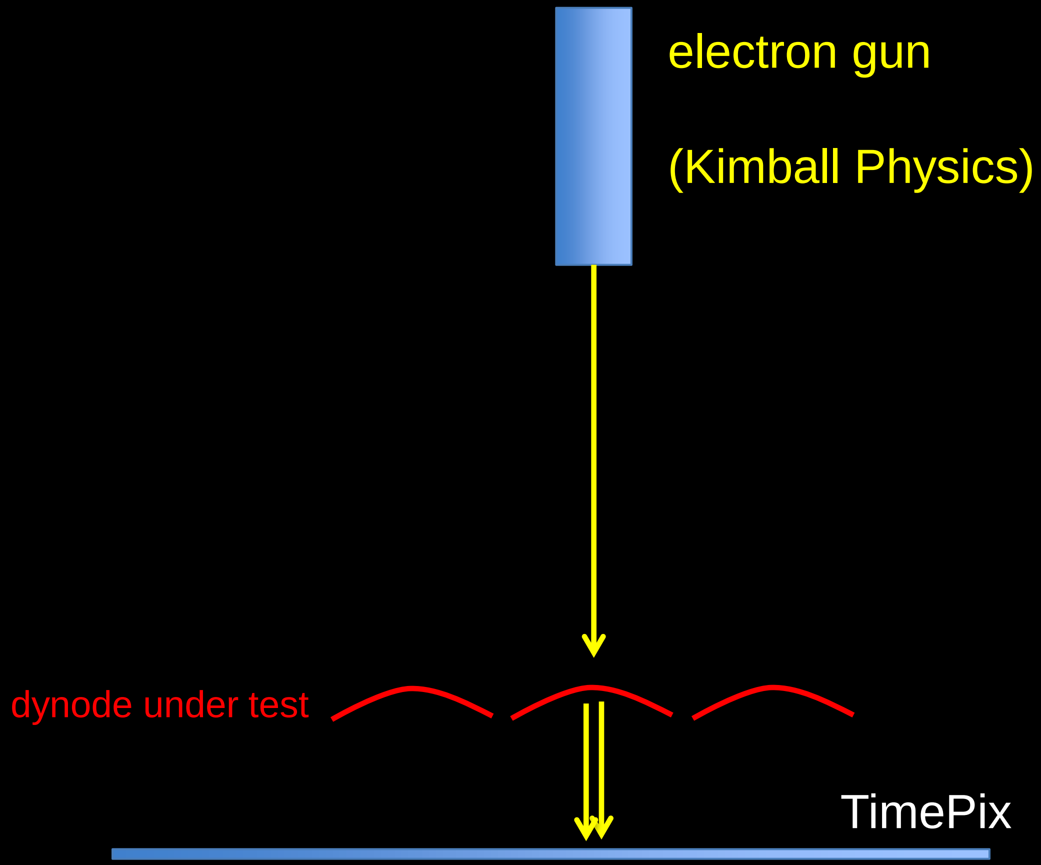


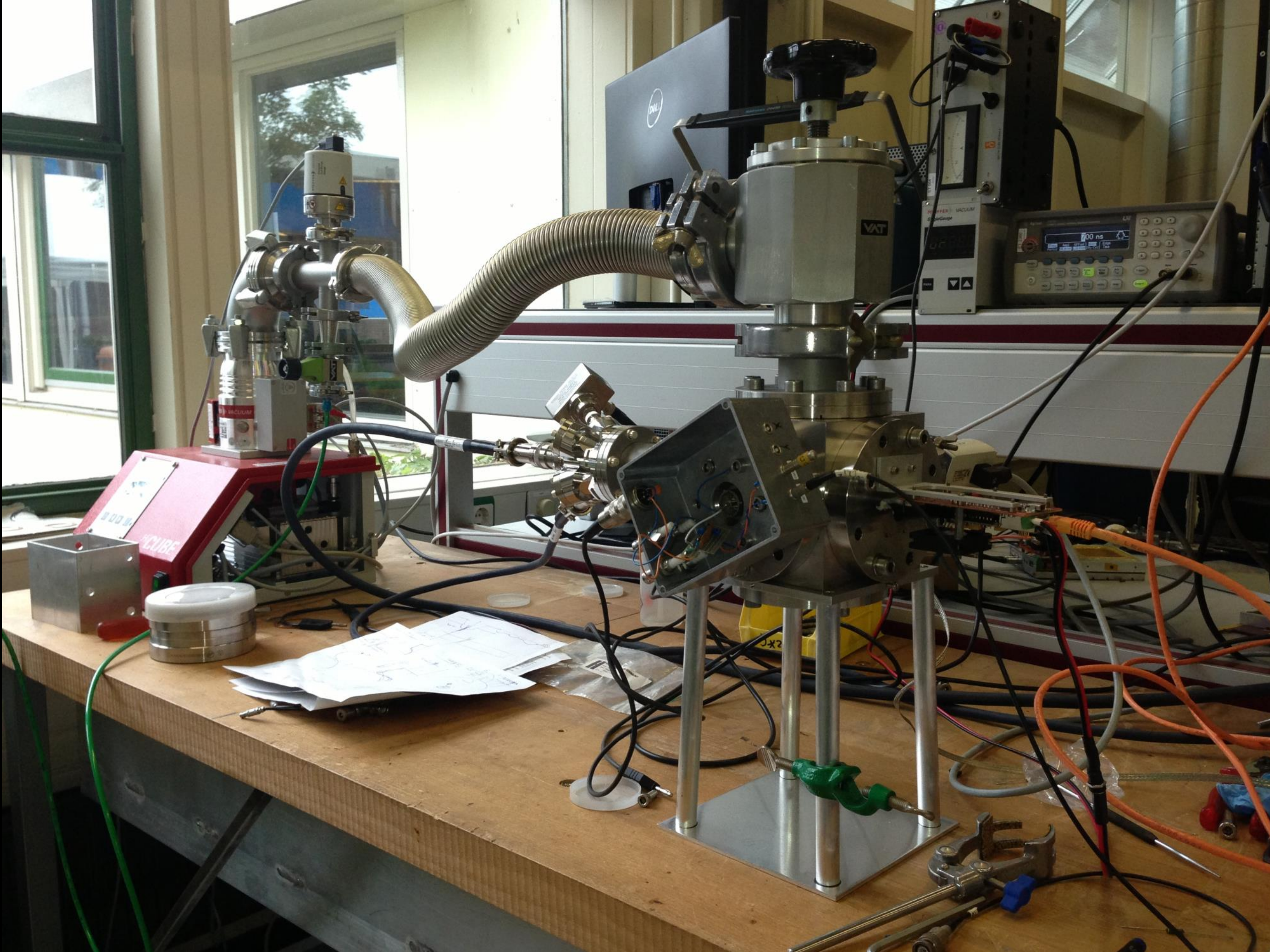
First preliminary result: SEY (transmission) = 1.3

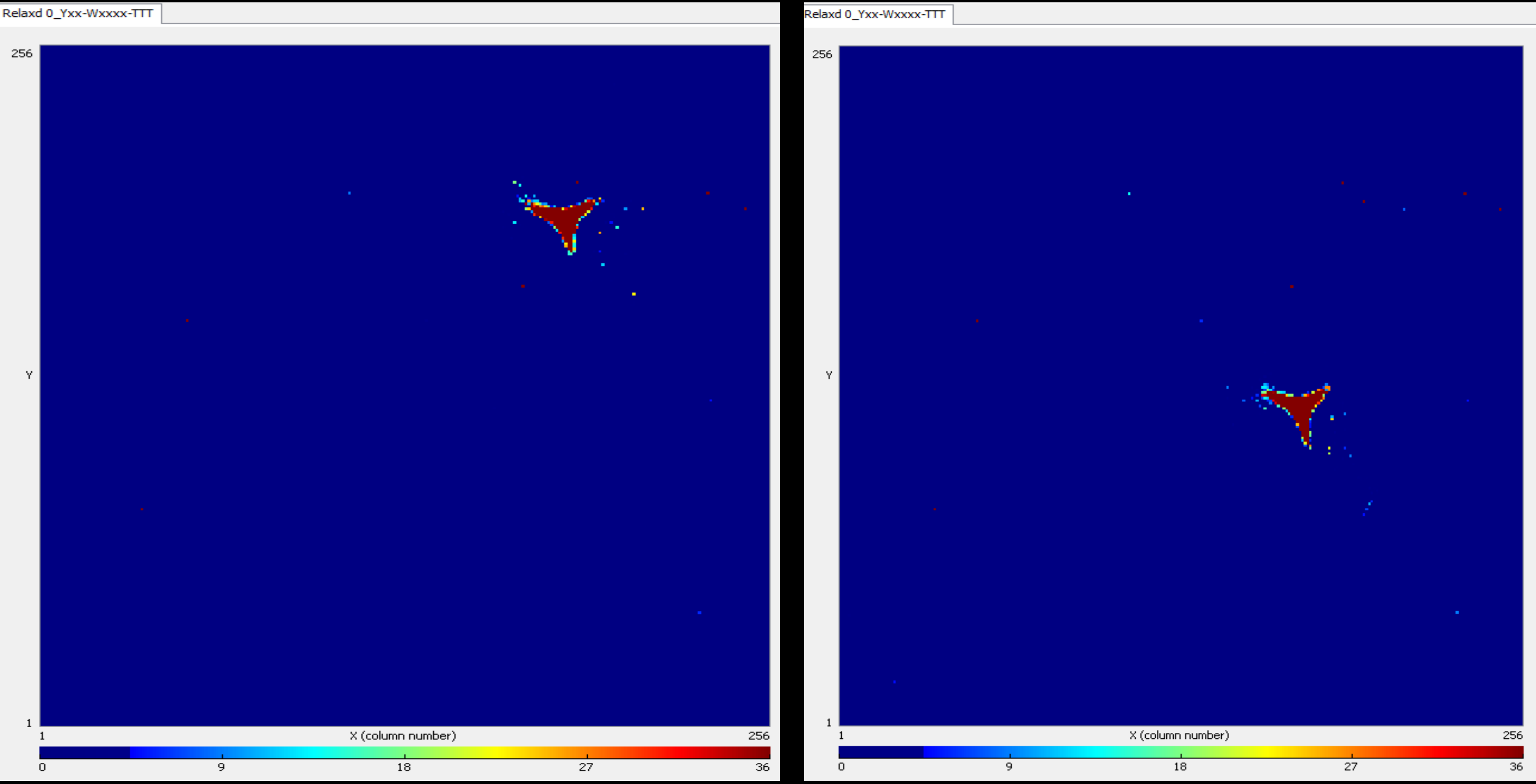
suffer charge up effects

SEY measurement 2

Set-up at Nikhef




VAT
700 ns
VACUUM
CUBE



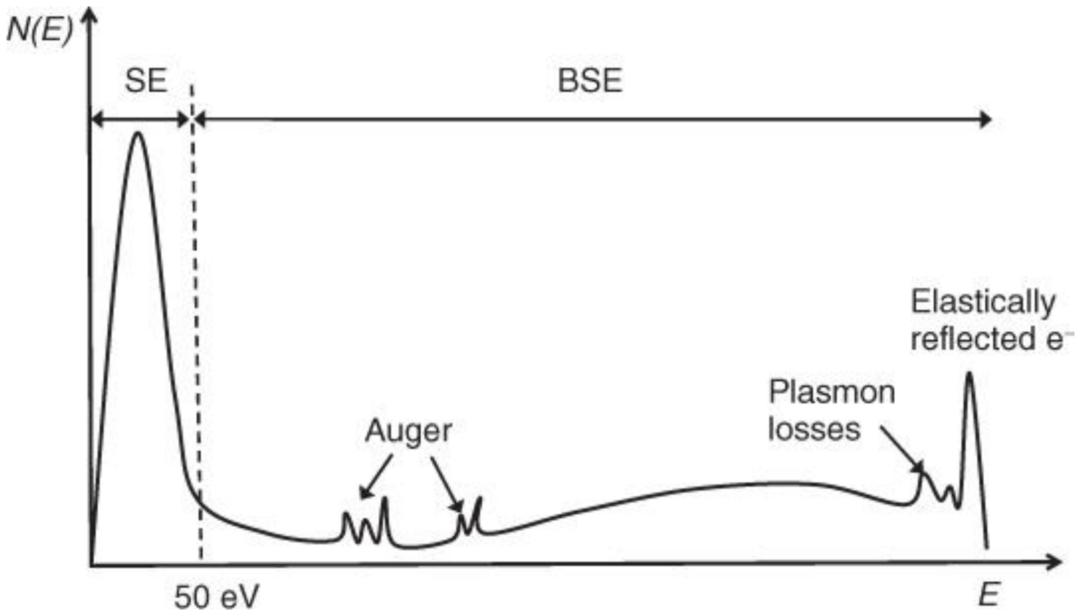
60 eV electrons on TimePix (without dynode)

….with a permanent magnet placed 1 m away…..

SEY Measurement 3

Photo emission spectrum (PES) - a new way of measuring SEY in Si_3N_4 proposed by **John Smedley**

Photon(about 400eV) ➔ Auger electron(400 eV) ➔Secondary electron



obtain energy distribution
by varying inverse bias voltage

First round measurements April 2014
@synchrotron rad. beam line NSLS Brookhaven National Laboratory;

Second round proposals @BESSY Berlin & ALS LBNL

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fist preliminary result:

The membrane project has embarked on a novel method of utilizing x-ray photoemission spectroscopy (XPS) to understand the secondary electron emission of Si doped SiN films. A recent XPS experiment at BNL evaluated several SiN samples of various doping levels with hydrogen and oxygen surface termination.
The Oxygen termination was achieved via Ozone exposure, a process commonly used for diamond, but in the case of SiN this process causes significant reduction of the strength of the Nitrogen Auger peak, suggesting damage to the SiN layer.
The Hydrogen terminated samples behaved identically to the "as grown" samples, suggesting that the SiN growth process likely leaves the samples H-terminated.
Most importantly, the relative secondary electron yield was 50% higher for the highly doped SiN as compared to the more low doped material.
The low doping material also exhibited significant charging,
even at 100 pA emitted current. The valence band structure of the SiN was also directly measured, and can be used in ongoing theoretical analysis of the emission.
Future work will include the investigation of other termination methods (both for oxygen and other materials, such as LiO) and calibration of the emission yield with materials of known secondary yield.

August: SEY calibration measurements.

Theoretical support

Solid State Physics (no high energy physics!)

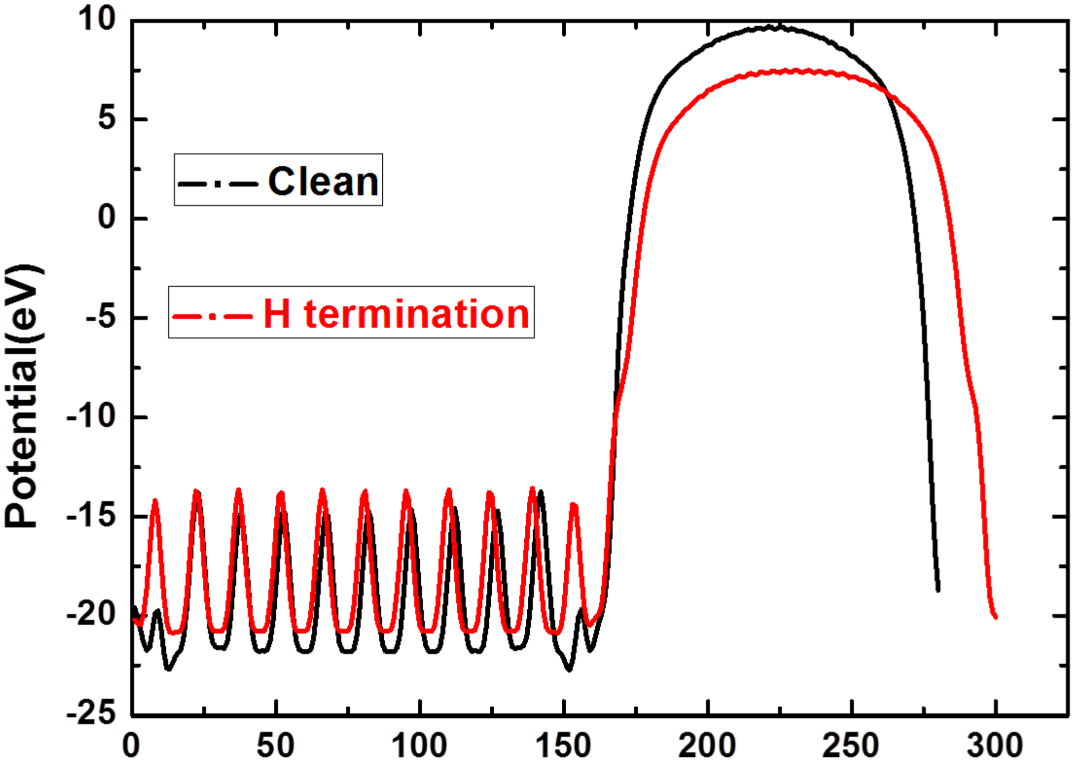
1. Inpact of ~500 eV e^- in matter:
   - energy transfer to electrons
   - scattering

   result: distribution of energetic electrons in volume dV

2. Propagation (diffusion) of energetic electrons to surface (cross sections, phonon losses)

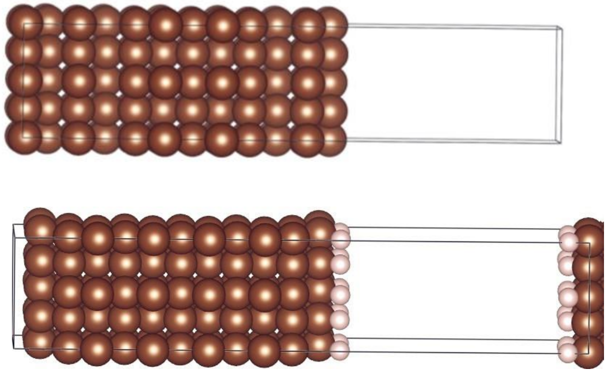
2. Electron emission in vacuum: electron affinity

Density Functional Theory DFT Simulations



Vienna Ab-Initio Simulation Program

VASP



H termination on diamond
- Negative Electron Affinity
- Enhanced SEY

- Important results on H termination and alkli metal and metal oxide

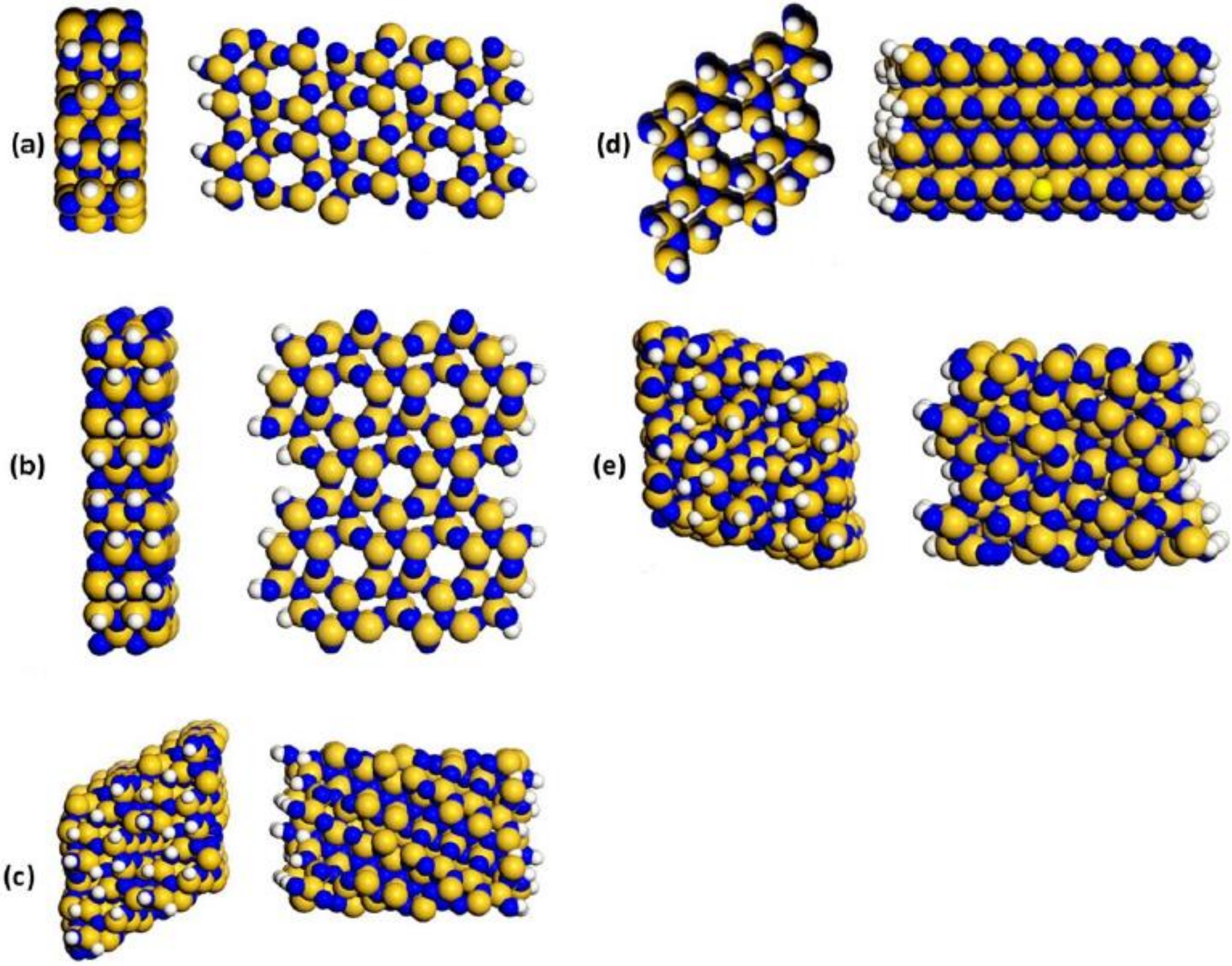
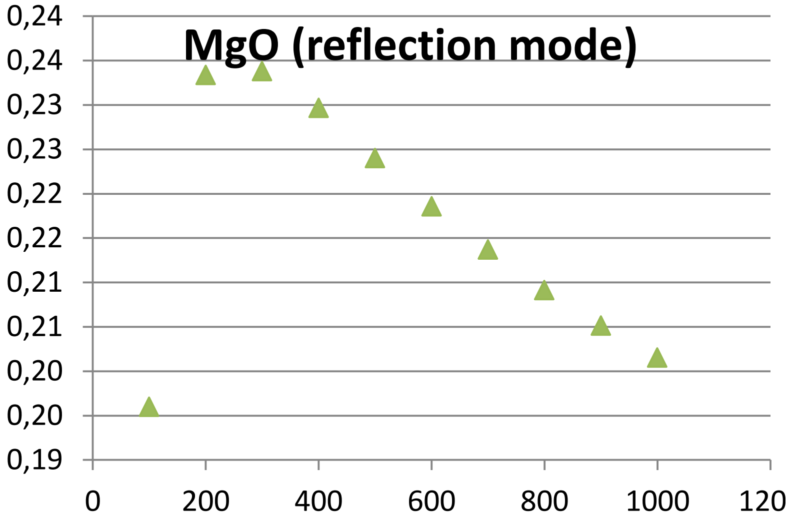
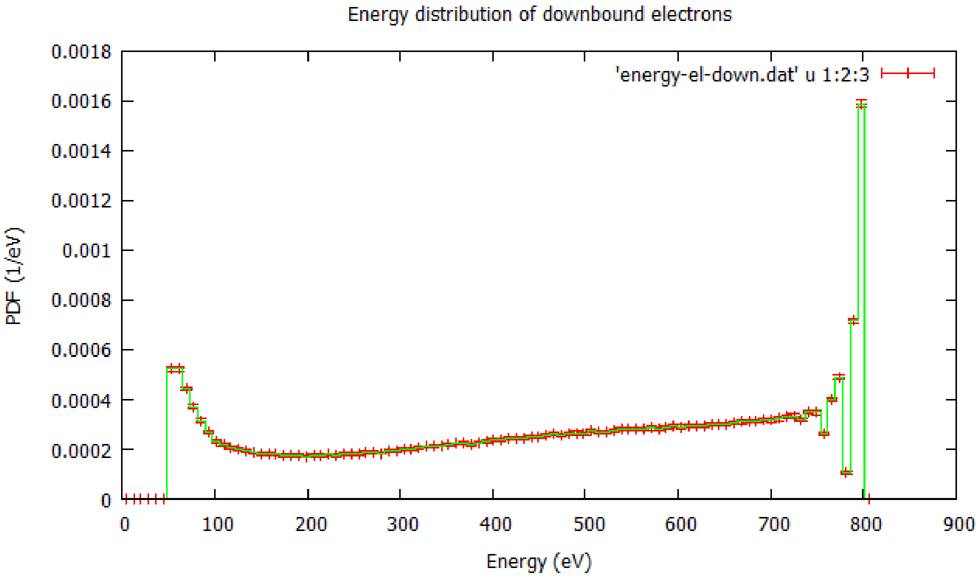


Fig. 1 Side and top views of β-Si_3N_4 surfaces with H termination: from (a) to (e) are in the order of (1010), (1120), (1011), (0001), (1121). Blue spheres denote N atoms; yellow spheres denote Si atoms; and white spheres denote H atoms.

Monte Carlo Simulations



Extremely low SEY due to the 50 eV cut-off

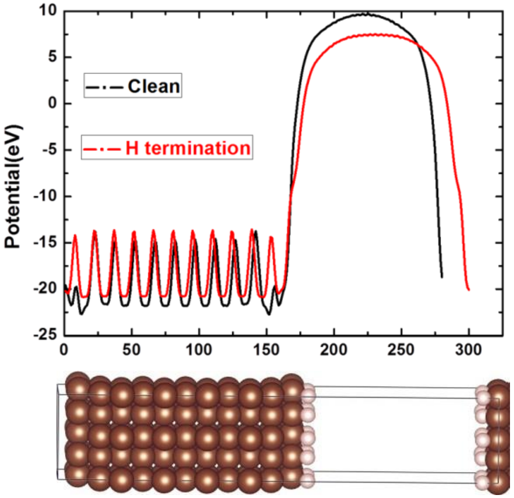


Transmission electron spectrum with 50 eV cut-off

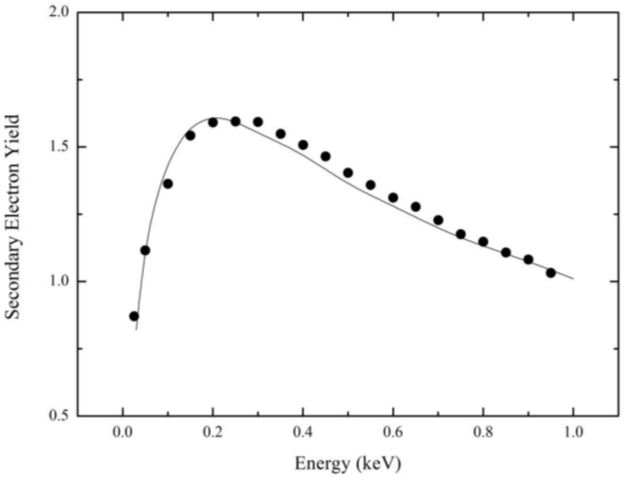
- ➢ Penelope and Geant 4 studies
- ➢ use low energy extension of GEANT4

Density Functional Theory simulations

Monte Carlo simulation



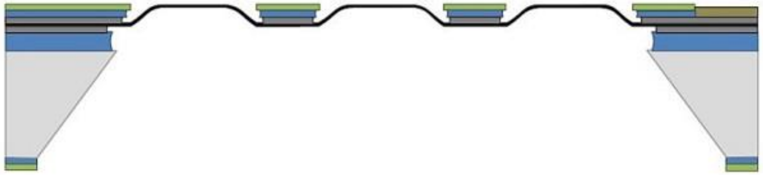
Electronic structure, work function, optical data



Model validation

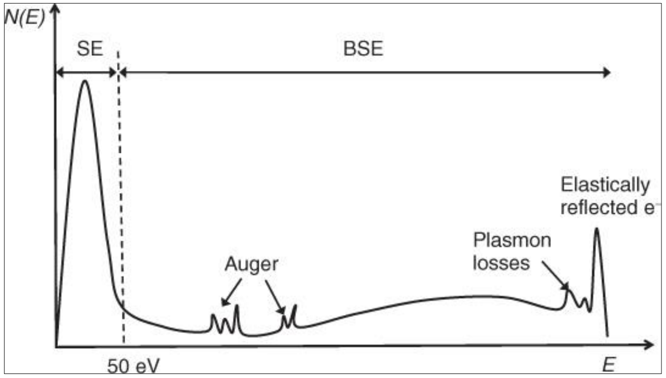
SEY
Energy spectrum

Select doping/ coating candidates



Fabrication

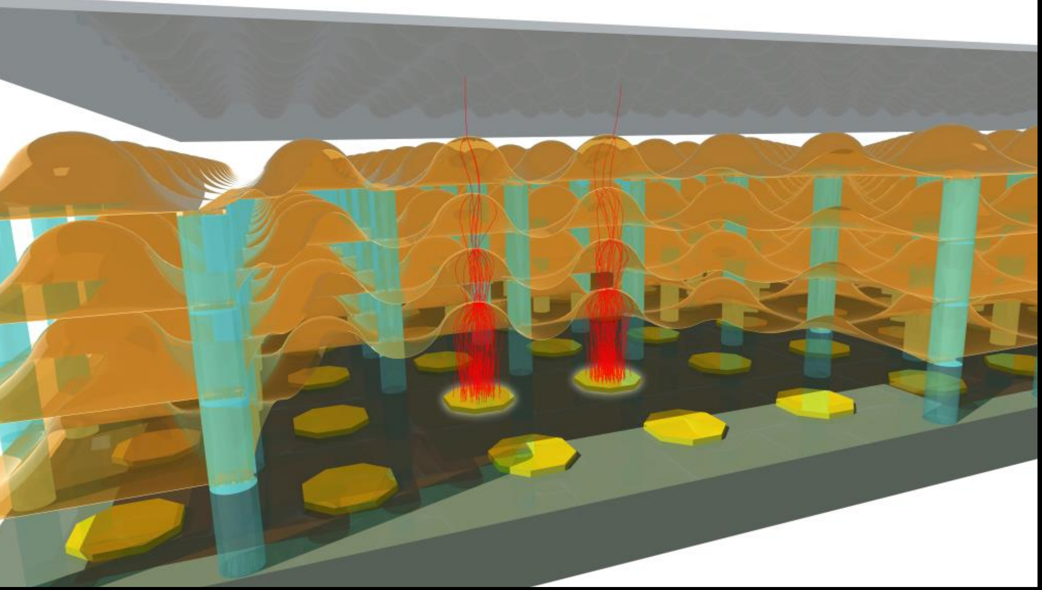
Material Property



Dynode fabrication

SEY measurements

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

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 %)!*

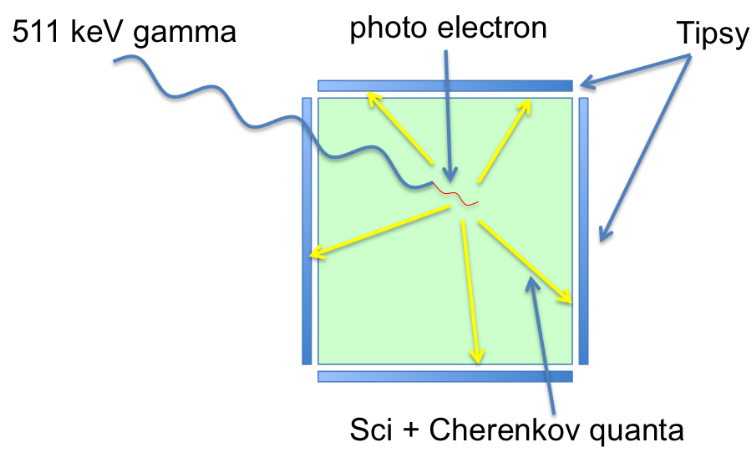
Applications of new generic soft photon detector

PET scanner

Cherenkov radiation becomes more relevant

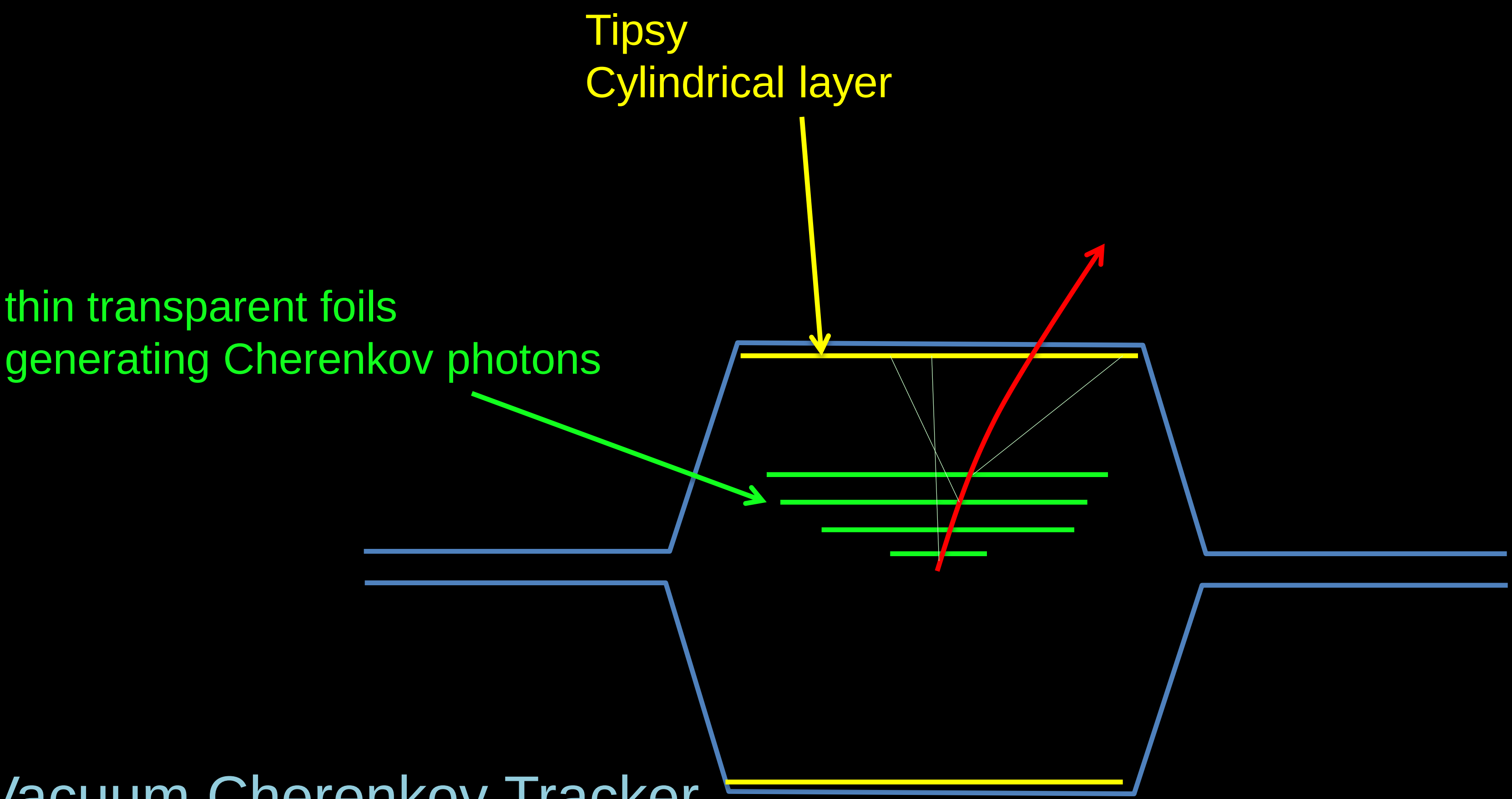
with Pb glass:
only prompt Ch soft photons
With NaI: Ch + Sci soft photons

- use Ch photons for timing
- use all photons for energy
- granularity: multi single soft photon detection within event
- low noise



Future HEP collider experiment: inner (central) tracker

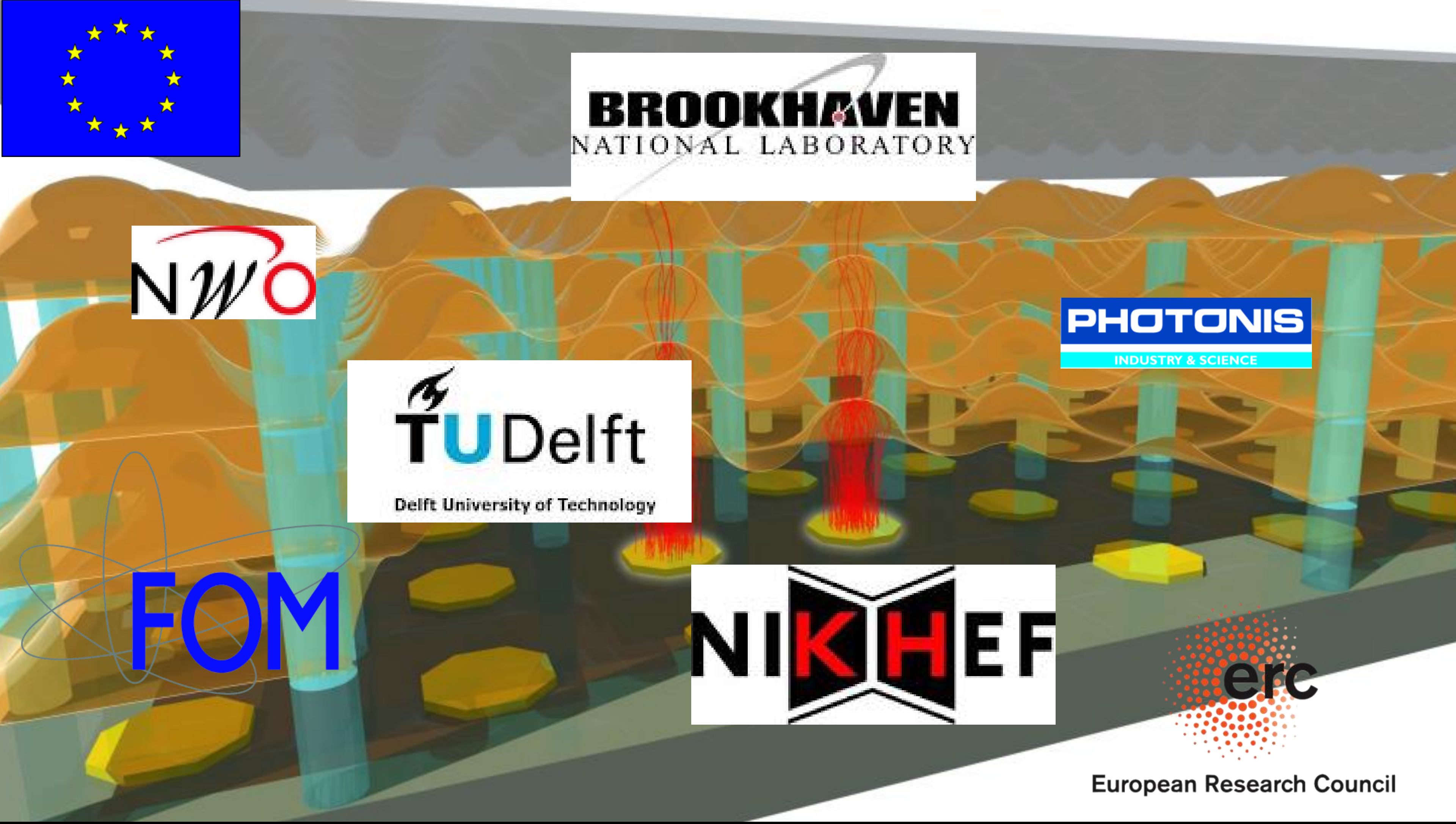
- very low detector mass
- Tipsy layer at safe distance from IP
- spatial resolution: no extrapolation



Only one crucial milestone/deliverable:

a MEMS made transmission dynode with a secondary electron yield (SEY) > 3

for an incoming e- with energy lower than 500 eV



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