Simulation of MCP-PMT

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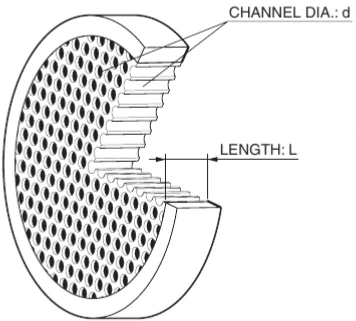
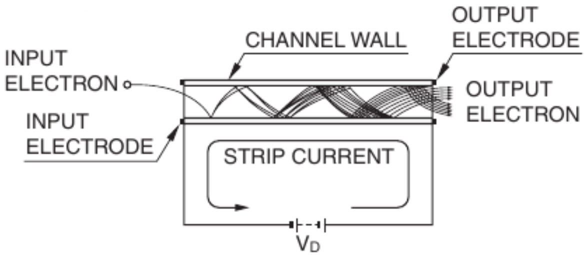
Microchannel plates





- Thin glass plate with an array of microscopic channels
- Usually made from lead glass with high electric resistance
- The faces of the plate are coated with conducting layer - electrodes for bias voltage

Images from: Hamamatsu Photonics, K. K. "Photomultiplier tubes: Basics and applications." Fourth Edition (2017).

Applications

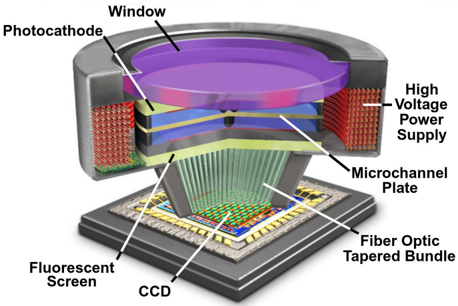


Figure: Image intensifier[1]

Used for example in microscopy or night vision

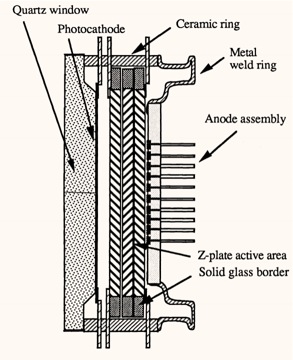


Figure: Photomultiplier[2]

Used for example for particle detection, plasma diagnostics, ...

[1] From: Nikon MicroscopyU, Fundamentals of Digital Imaging, (http://www.microscopyu.com/articles/digitalimaging/digitalintro.html)

[2] From: Giudicotti, L., et al. "Simple analytical model of gain saturation in microchannel plate devices." Review of scientific instruments 65.1 (1994): 247-258

Gain of MCP

- Key characteristic of a multiplier
- Ratio of output signal to input signal: $G = \frac{Q_o}{Q_i}$

Gain in 2D channel[3]

$$G = \delta^n; \delta = KV_c$$

$$\Downarrow$$

$$G = \left(\frac{KV_0^2}{4V\alpha^2} \right)^{\frac{4V\alpha^2}{V_0}}$$

δ - Number of electron release after collision

n - Number of collisions

V_c - Collision energy

K - Constant

V_0 - Bias voltage

V - Initial energy of an electron normally released from the wall

$\alpha =$ L/d - Length to diameter ratio

3

[3] Adams, J., and B. W. Manley. "The mechanism of channel electron multiplication." IEEE transactions on nuclear science 13.3 (1966): 88-99.

Pros and cons of MCP-PMT

Pros

- Great time resolution: $\sim 10\,\text{ps}$ to $100\,\text{ps}$
- Great spatial resolution (depends on construction)
- Stable operation in a magnetic field
- Sensitive to photons (from visible light to gamma), charged particles and neutrons. Depends on the window.

Cons

- Relatively small life span due to ion damage: improved with ALD coating
- Gain saturation (next slide)

Gain saturation

Space charge saturation

- Decrease of the electric field due to charge distribution of electron avalanche.
- Significant for single channel PMTs, not so much for MCP

Wall charge saturation

- A positive charge is generated in the wall of an MCP due to secondary emission.
- This positive charge neutralizes the electric field inside the channel.

Current saturation

- When the rate of pulses is too high, an MCP has no time to recover.
- MCPs are made out of material with high resistance so they are highly influenced by this effect.

Gain saturation

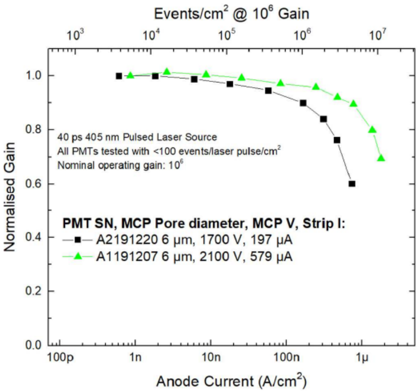


Figure: Gain saturation due to high rate[4]

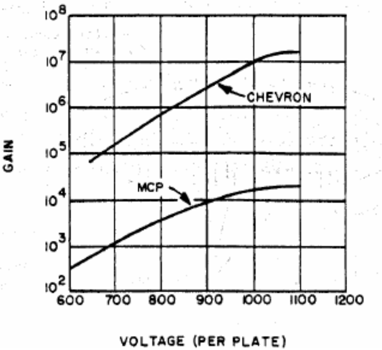


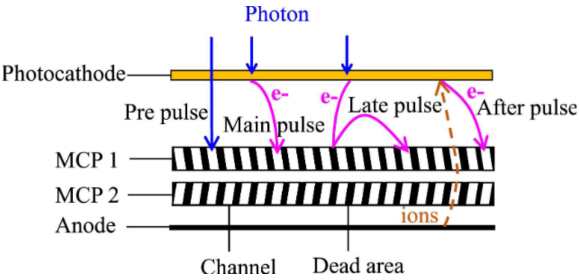
Figure: Gain saturation due to high voltage[5]

[4] Milnes, James, et al. "Analysis of the performance of square photomultiplier tubes with 6 μm pore microchannel plates." 2020 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC). IEEE, 2020

[5] Wiza, Joseph Ladislas. "Microchannel plate detectors." Nucl. Instrum. Methods 162.1-3 (1979): 587-601

Pulse generation

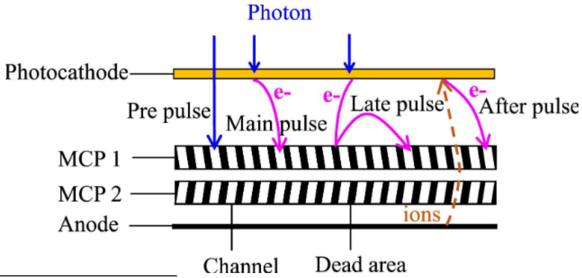
- Pre pulse - Photon pases throug the photocathode and hits the MCP
- Main pulse - Generated photoelectron enters inside MCP
- Late pulse - Photoelectron enters MCP after backscattering
- After pulse - Positive ion generates aditional electrons



[6] T. Gys - Micro-channel plate photon detectors; Micro-channel plate photon detectors – Basic principle of operation CERN Detector Seminar - 28 Apr. '23 (https://indico.cern.ch/event/1268982/)

Ion damage

- The residual gas inside the channel is ionized by the output signal
- These positive ions travel towards the photocathode
- They can hit the wall and produce new electrons - new pulse
- They can hit the photocathode and damage it - reduction of QE
- Can be mitigated with curved channels
  - Ions hit the walls with smaller energies
  - Hard to manufacture



[6] Image from: T. Gys - Micro-channel plate photon detectors; Micro-channel plate photon detectors – Basic principle of operation CERN Detector Seminar - 28 Apr. '23 (https://indico.cern.ch/event/1268982/)

Atomic Layer Deposition

- Inside of a channel is coated with atomic mono-layer - MgO or Al_2O_3
- Improvement of SEY
  - Significant gain improvement
  - Same gain at lower electron energies
  - Lower probability of ion creation

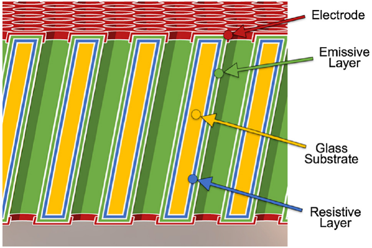


Figure: Structure of ALD MCP[7]

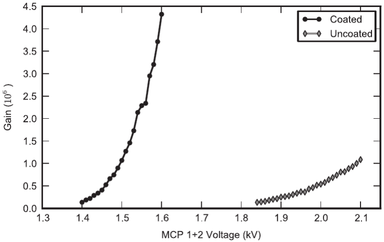


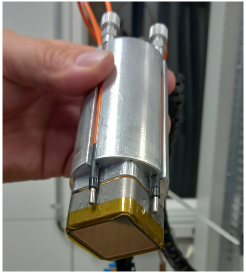
Figure: Gain comparision of coated and uncoated MCP[8]

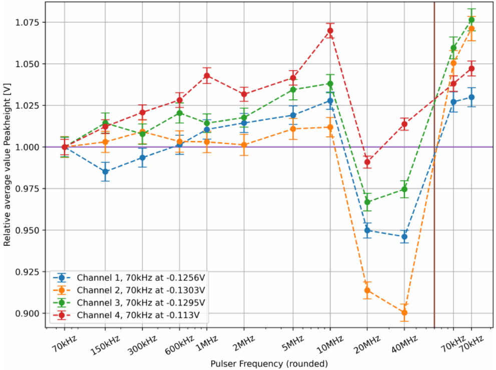
[7] C. Ertley et al. / Nuclear Inst. and Methods in Physics Research, A 912 (2018) 75–77

[8] T.M. Conneely et al. / Nuclear Instruments and Methods, The principal advantage of a higher SEY is the ability to achieve

AFP MCP-PMT

- AFP uses Photonis MCP-PMT with R2D2 ALD coating
- Radiation and ions resistant
- Strange behaviour of pulse heights





[9] Markus Österle. "Studies with the TOF detector using the pulser module and simulation of the light distribution". ARP General Meeting - Performance and Simulation, September 27, 2022

Simulations

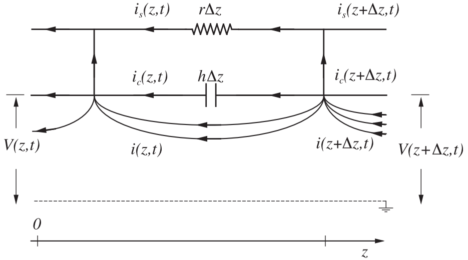
Why do we need a simulation

- The gain equation is not precise
  - Neglects lots of important effects like space charge or emission angles
  - Provides only upper limit for gain
- We want to know the response of the MCP-PMT to an arbitrary input signal

- Two approaches:
  1. Transmission line modeling
  2. Monte-Carlo

Transmission line model

- We consider TLM by L. Giudicotti
- In this model a channel is divided into parts represented by lumped component
- Kirshoff's laws are then used to derive the model equations
- Assumption: input pulse is shorter than typical charge recovery time RC, but longer than the average transit time



Original paper: Giudicotti L. Nucl. Instrum. Methods Phys. Res. A, 659 (1) (2011), pp. 336-347

- We recalculated the derivation of the model equations
- Typo in (37): wrong sign in front of $(Q(x,t)/Qs)_n$

$$g(x,t) = \exp\left\{Gx + \int_0^x \ln\left(1 + e^{\frac{-t}{RC}} \frac{Q_{W0}(t) + Q_0(t) - Q(x',t)}{Q_s}\right) dx'\right\}$$

Recreation of results

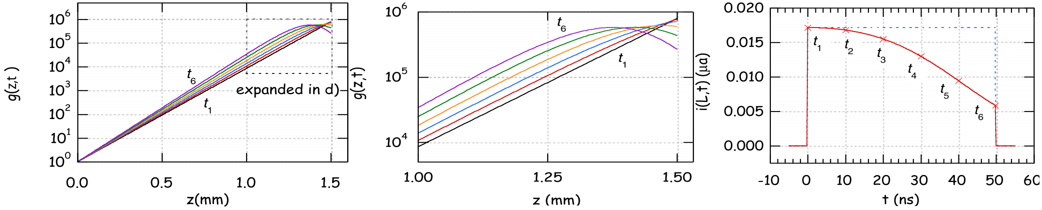


Figure: Original results

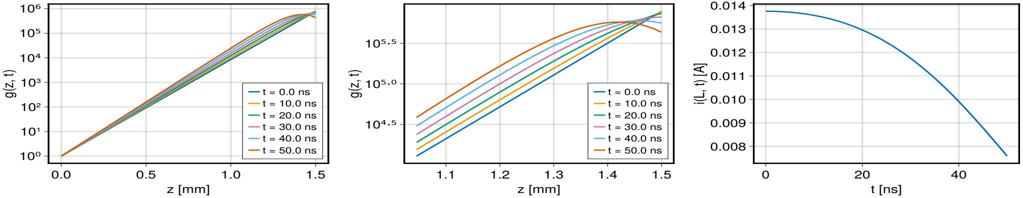


Figure: Recreation

Problem with the assumption

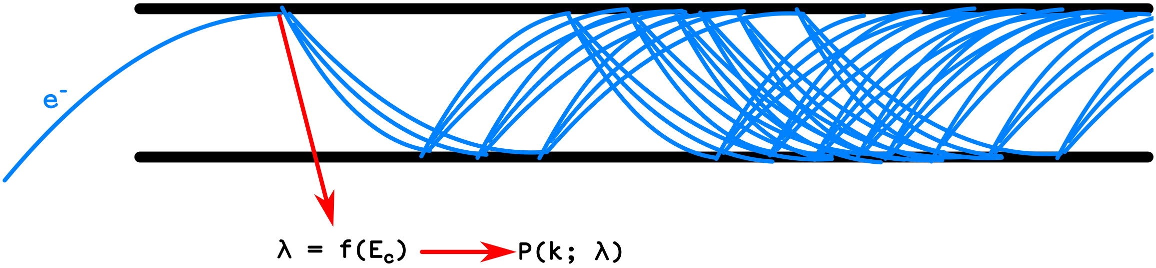
- The average number of photoelectrons arriving to MCP-PMT is between 15 and 45
- Typical number of microchannels is $10^6 - 10^7$
- This means that there is less than one photoelectron per channel and we can expect one photoelectron in a microchannel at maximum
- This corresponds to $i_0(t) = \delta(t) \Rightarrow$ signal length is shorter than transition time

Monte-Carlo simulation

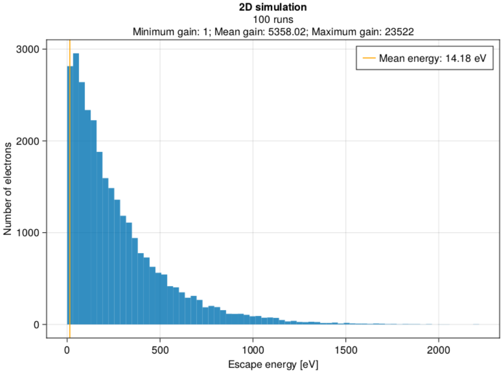
- Microscopic approach: tracking movement of (mostly) all particles
- After each collision, the energies, angles and number of secondary electrons are drawn from probability distributions
- Two variants:
  1. With analytical solution of trajectories
  2. Time-gridded, "brute force", Particle-in-cell (PIC) simulation

Simulation with analytical trajectories

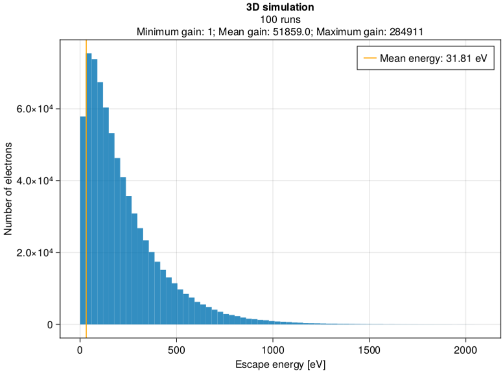
1. Calculate trajectory and collision energy of an initial electron
2. From the collision energy, calculate the number of secondary electrons using some secondary emission function
3. We use this value as the mean value of Poisson distribution $P(k; \lambda)$ and generate the random number of secondary electrons
4. Assign random initial angles and energies to secondary electrons
5. Repeat for every secondary electron



2D vs 3D



(a) 2D simulation



(b) 3D simulation

Figure: Energy distribution of electrons at the end of a channel

PIC simulation

- Simulation of motion of each particle
- Done using discrete time steps
- Macro quantities like fields and densities are calculated on mesh points
- Mover - set of equations for velocities and positions written in such a way that the calculation is highly efficient

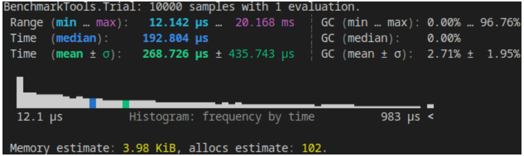
Mover (Boris method)[6]

$$\vec{v}_{k+1/2} = \vec{v}_{k-1/2} + 2q\vec{E}_k \qquad q = \frac{e}{2m}dt$$

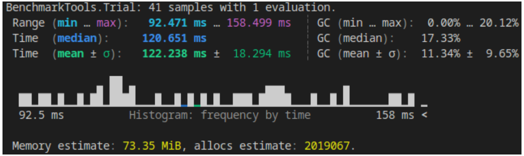
$$\vec{x}_{k+1} = \vec{x}_k + \vec{v}_{k+1/2}dt$$

[6] Based on: Tskhakaya, David, et al. "The Particle-In-Cell Method." Contributions to Plasma Physics 47.8-9 (2007): 563-594

Analytical vs PIC

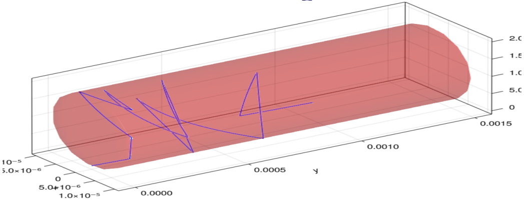


(a) Analytical

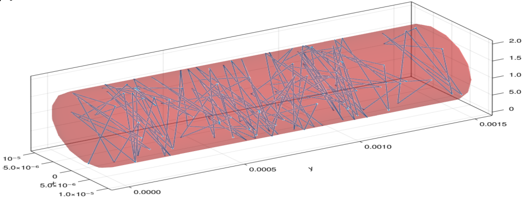


(b) PIC

Figure: Benchmark of the two types with one electron



(a) Analytical



(b) PIC

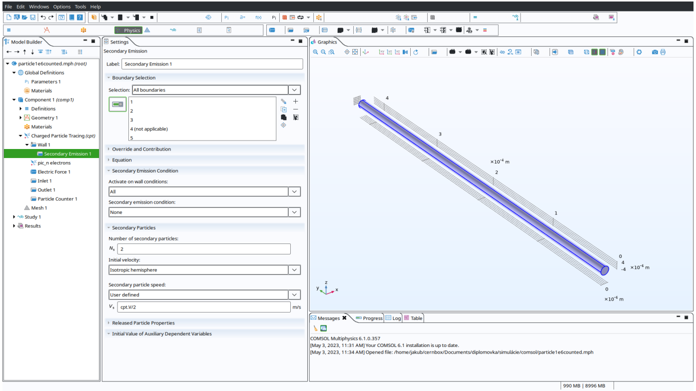
Figure: Path of an electron

Analytical vs PIC

1. Analytical
   - Better performance
   - Does not allow us to include the effect of space charge
   - Implementing the effects of fringe fields will be difficult
2. PIC
   - Adding space charge and fringe fields effects should be relatively easy
   - Requires more computations

COMSOL Multiphysics

- Comercial simulation software
- Capable of simulating various physical phenomena. We can use it for Monte-Carlo simulations.
- Easy to use GUI



COMSOL Multiphysics

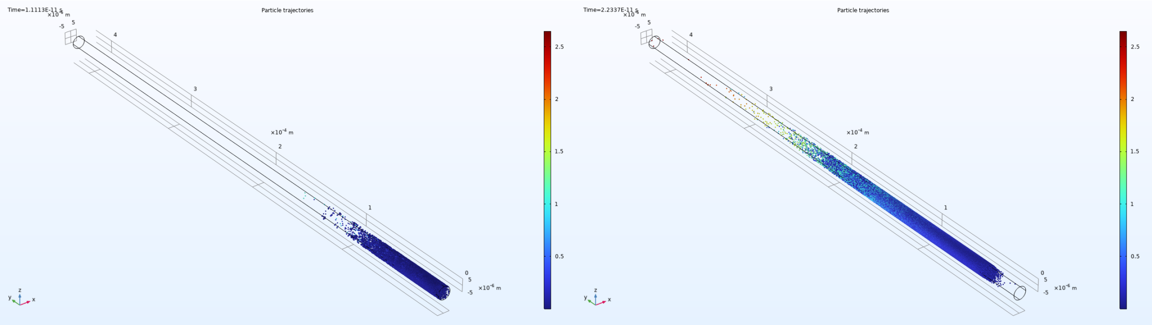
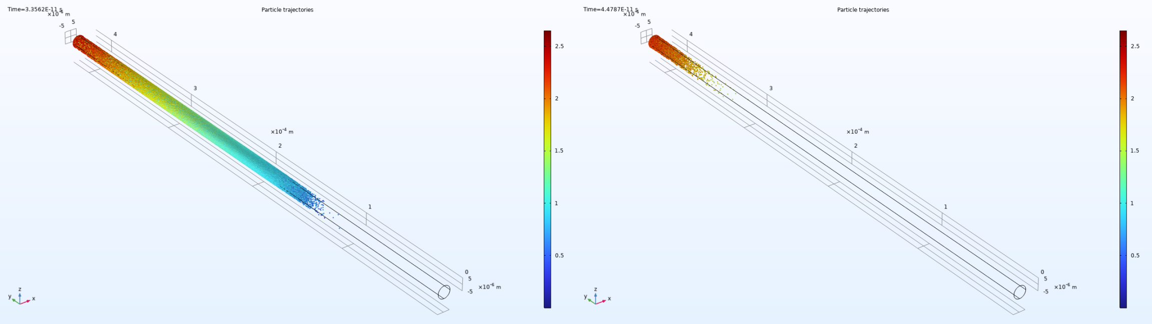


Figure: Propagation of an electron cloud inside a channel. The color represents electron kinetic energy in keV. The time between the images is around 10 ps. The propagation of the cloau took around 40 ps. The channel length (L) is 0.42 mm, the diameter (d) is 10 μm

COMSOL Multiphysics



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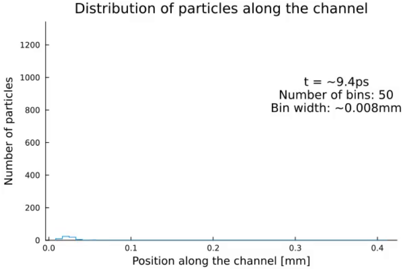
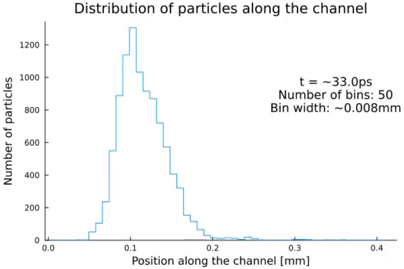
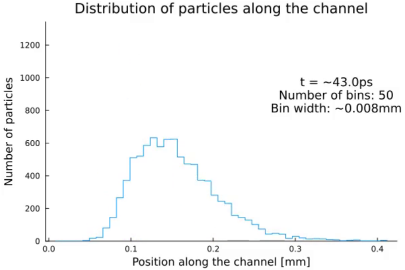
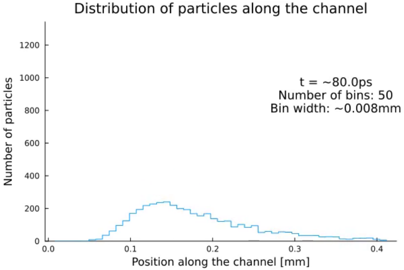
COMSOL Multiphysics





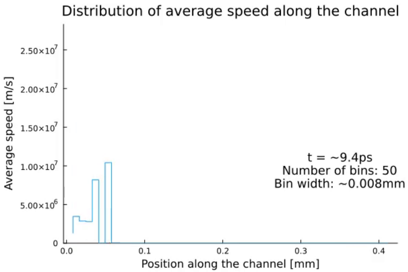


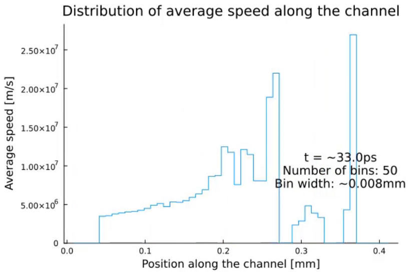


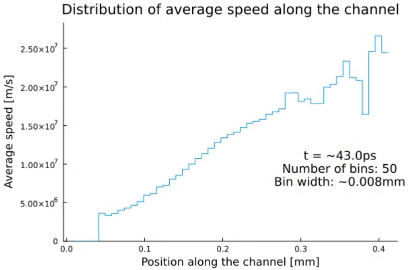
COMSOL Multiphysics

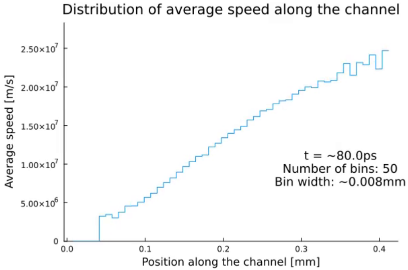
- Strange behaviour of the electron cloud
- The cloud does not propagate, but spreads out
- Indication of an error in the model
- The distribution of the average speed looks as expected
- The speed increses with the distance

COMSOL Multiphysics

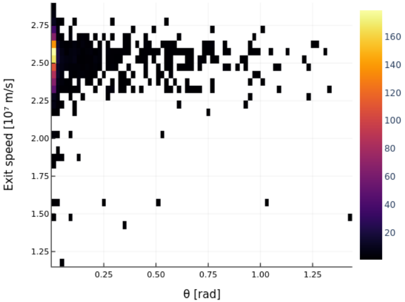




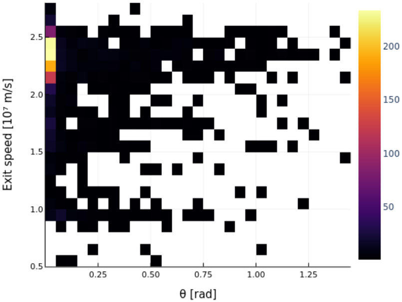




Exit speed vs. exit angle



(a) For parallel electric field



(b) For electric field under 15°

Figure: Exit speed vs. exit angle

Wall charge saturation in COMSOL

- Attempt to include wall charge saturation into COMSOL simulation
- Giudicotti's model allows calculating wall charge from simulated output
- We can get a numerical solution for Qw, which was fitted and put into COMSOL
- The result of this simulation is not analyzed yet

$$Q_w(x,t) = Q_{w0}(t) + Q_0(t) - Q(x,t)$$

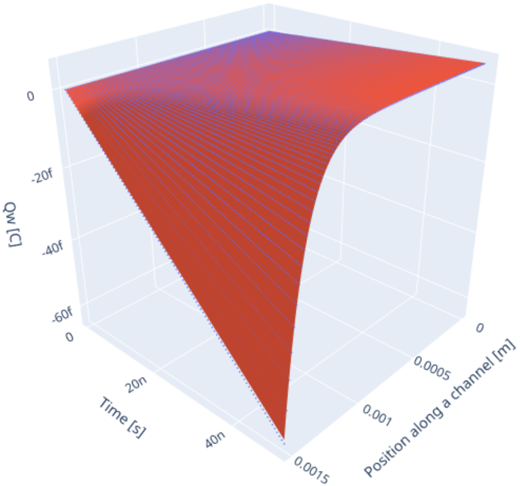
$$\frac{Q(x,t)}{Qs} = \frac{1}{Q_s}\int_0^t i_0(t')g(x,t')dt$$

$$\frac{Q_{w0}(t)}{Q_s} = \frac{1}{L}\int_0^L \frac{Q(x',t)}{Qs}dx' - \frac{Q_0(t)}{Q_s}$$

$$Q_0(t) = \int_0^t i_0(t')dt$$

$$Q_w(x,t) = (a - b\exp(cx+d))t$$

Wall charge saturation in COMSOL



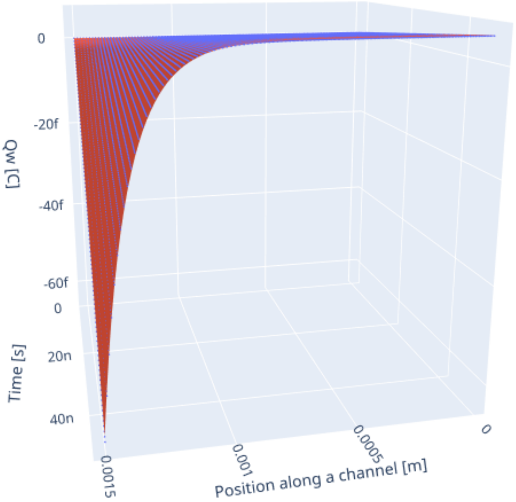


Figure: The calculated Q_w (blue dots) with fitted surface (in red)

Wall charge saturation in COMSOL

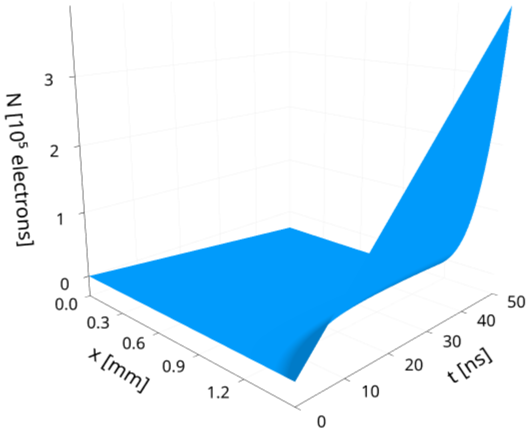


Figure: The number of electrons calculated from the fitted surface. The value at time and position zero is also 0. At some points the value is negative. The value is high near the end of the channel. This contradicts with the expected result. It was expected for the value to be high at the beginning of the channel and diminish near the end.

Summary

- A TLM model was tested, unfortunately the assumption of the model is unphysical
- There was an attempt to develop a Monte-Carlo simulation
- COMSOL Multiphysics, a comercial simulation softwere was used to develop a primitive Monte-Carlo model of MCP channel
- The model still has some problems that needs to be addressed
- More phenomena could be added into the COMSOL model

The end

Thank you for your attention!