Interns' seminar

Laboratoire Leprince-Ringuet

Université Paris Cité

Application of Shockley-Ramo theorem to understand the PEPITES signal and estimate the time resolution for a ToF monitor

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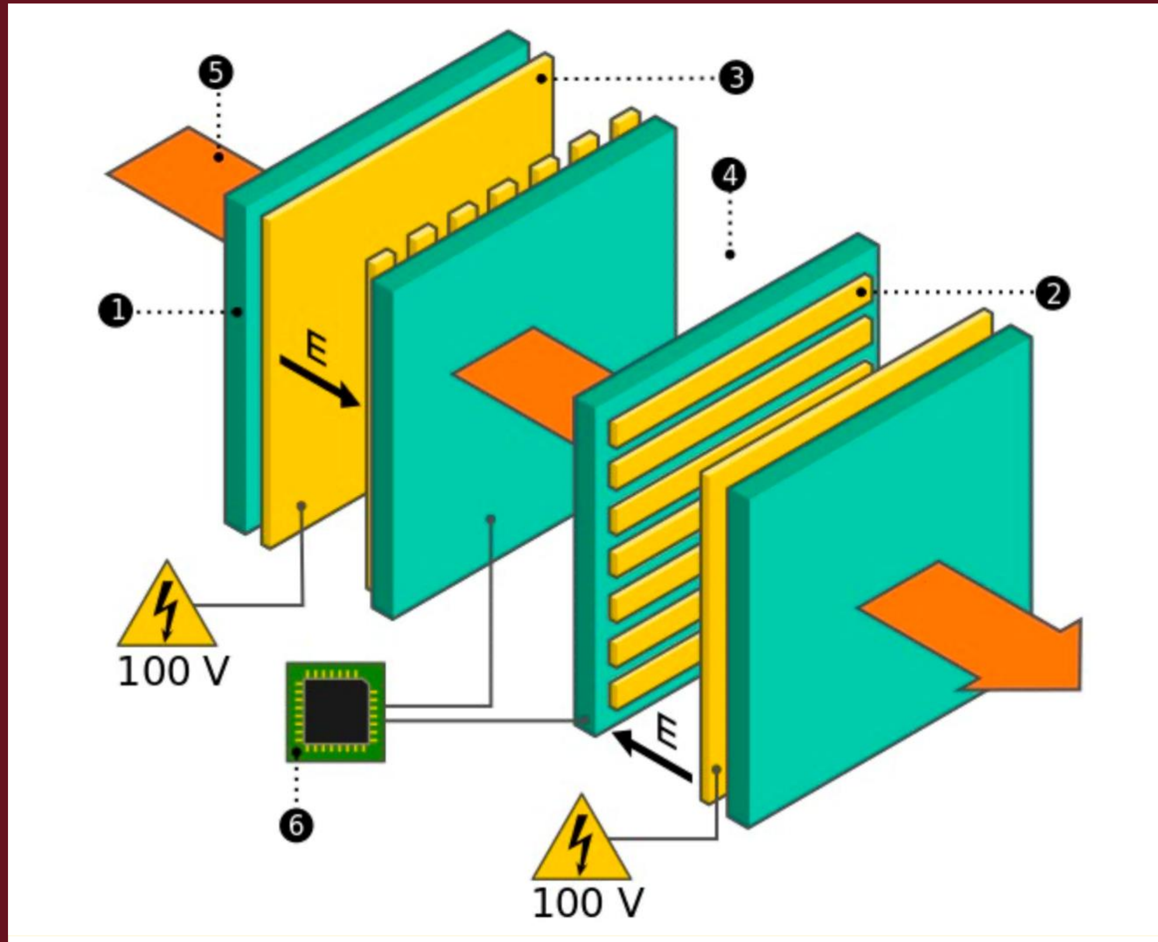
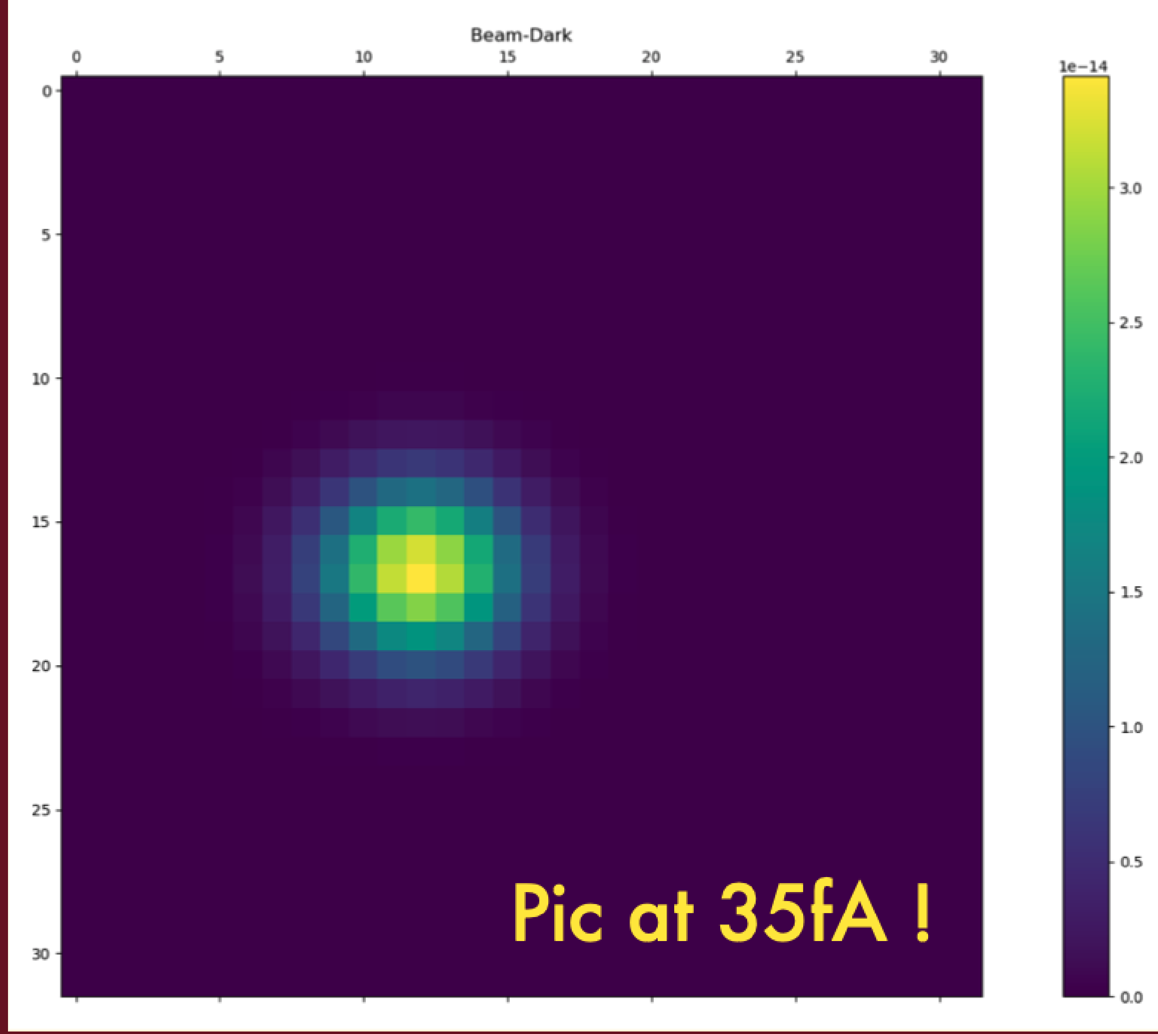
Summary

- PEPITES detector
- Internship: objectives
- Shockley-Ramo theorem in brief
  - Introductory example
  - Application in PEPITES
    - Simulation of the different fields
    - Simulation of the different currents
- Preliminary results and future work:
  - Time resolution
  - Study of the signal form to trigger the measurement

PEPITES detector

- PEPITES is a beam monitor developed at LLR, using Secondary Electron Emission (SEE) as its detection principle
- SEE occurs when ionization electrons, created near a material’s surface, escape into the vacuum
- SEE requires only a material thickness of O(10 nm), allowing for the creation of ultra-thin, non-perturbing beam monitors
- These monitors provide real-time (online) measurements of the beam as it strikes the target
- SEE is highly linear, making it ideal for use with high-intensity beams
- This makes PEPITES particularly suited for emerging techniques like FLASH radiotherapy





Internship: objectives

- Explore a new application of SEE using PEPITES as a Time-of-Flight (ToF) monitor
- Simulate the signal shape (from electron generation to their collection, to assess the feasibility of precise triggering)
- Use the Shockley-Ramo theorem to calculate the signal induced by moving charges
- Gain insights into the PEPITES signal to understand its behaviour

Shockley Ramo theorem in brief

- Consider a set of electrodes raised to potentials V_i
- Let there be a particle with charge q, whose motion $\vec{M}(t)$ is known. Then its velocity is $\vec{v}(t)$.
- Electrode *k* receives a current *I(t)* induced due to the particle's motion.

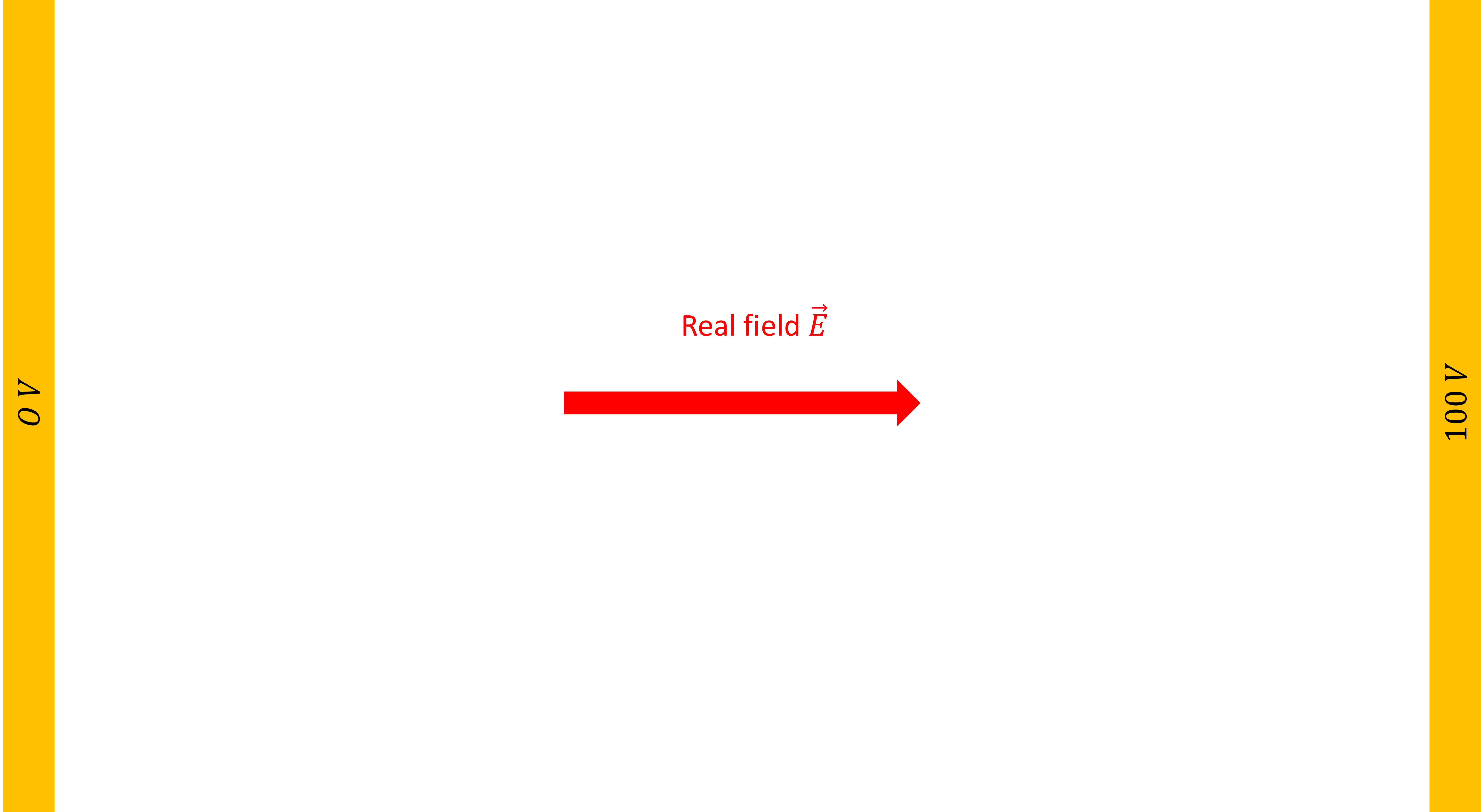
$$\boxed{I(t) = -q \cdot \vec{v}(t) \cdot \frac{\overrightarrow{E^*}}{1V}}$$

derived from Maxwell's equations

where $\overrightarrow{E^*}$ is the virtual electric field that would exist if:

- electrode k were placed at potential $1V$
- all other electrodes being grounded $(0V)$
- all charges present in the detector were removed

Application: 2 infinite planes 1/4



Application: 2 infinite planes 2/4

$1\,V$

Ramo field $\overrightarrow{E_1^*}$

$0\,V$

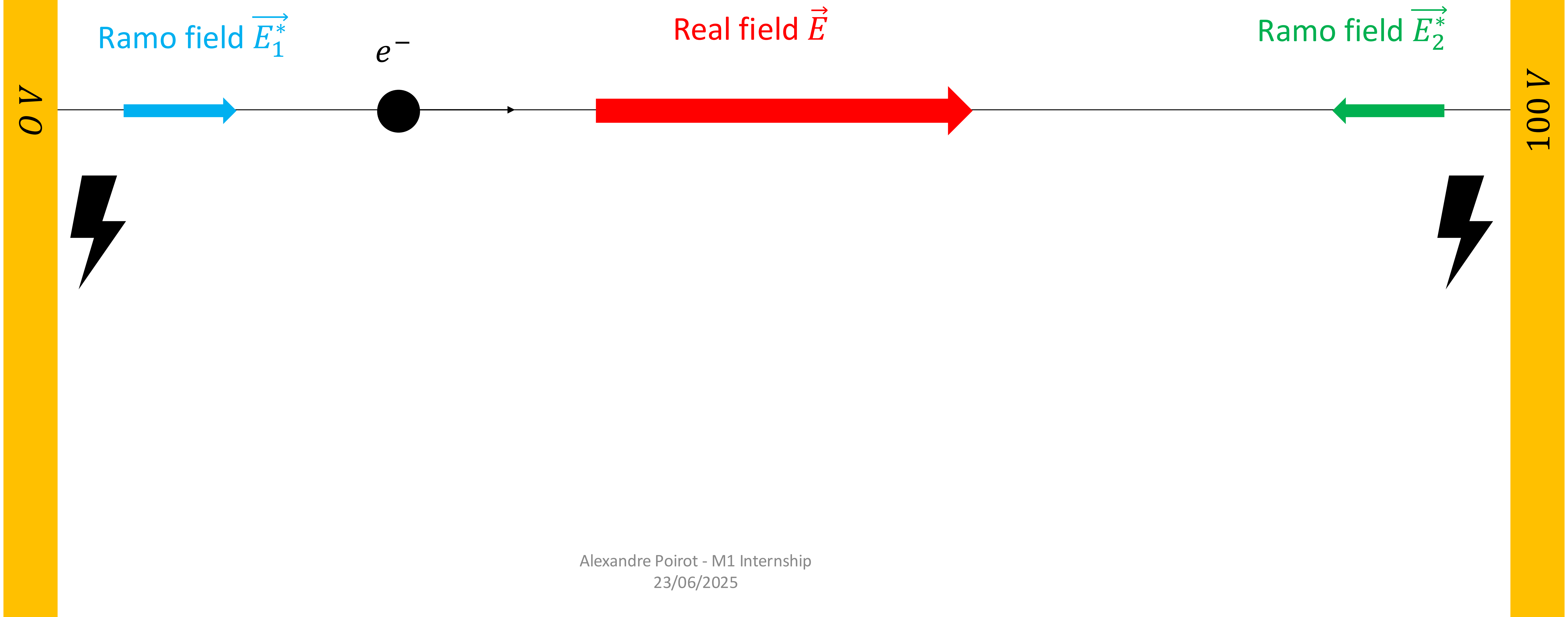
Application: 2 infinite planes 3/4

$0\,V$

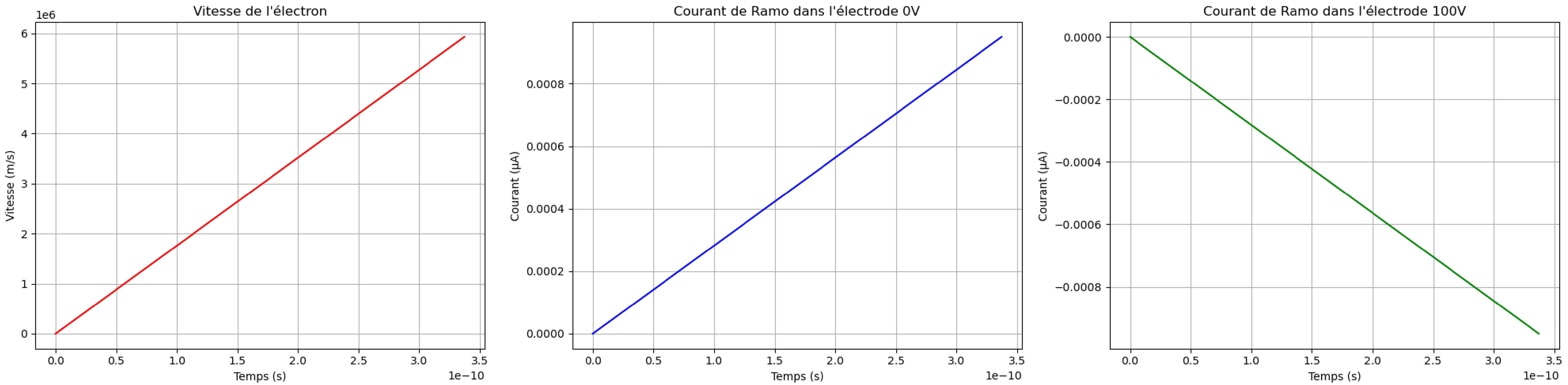
Ramo field $\overrightarrow{E_2^*}$

$1\,V$

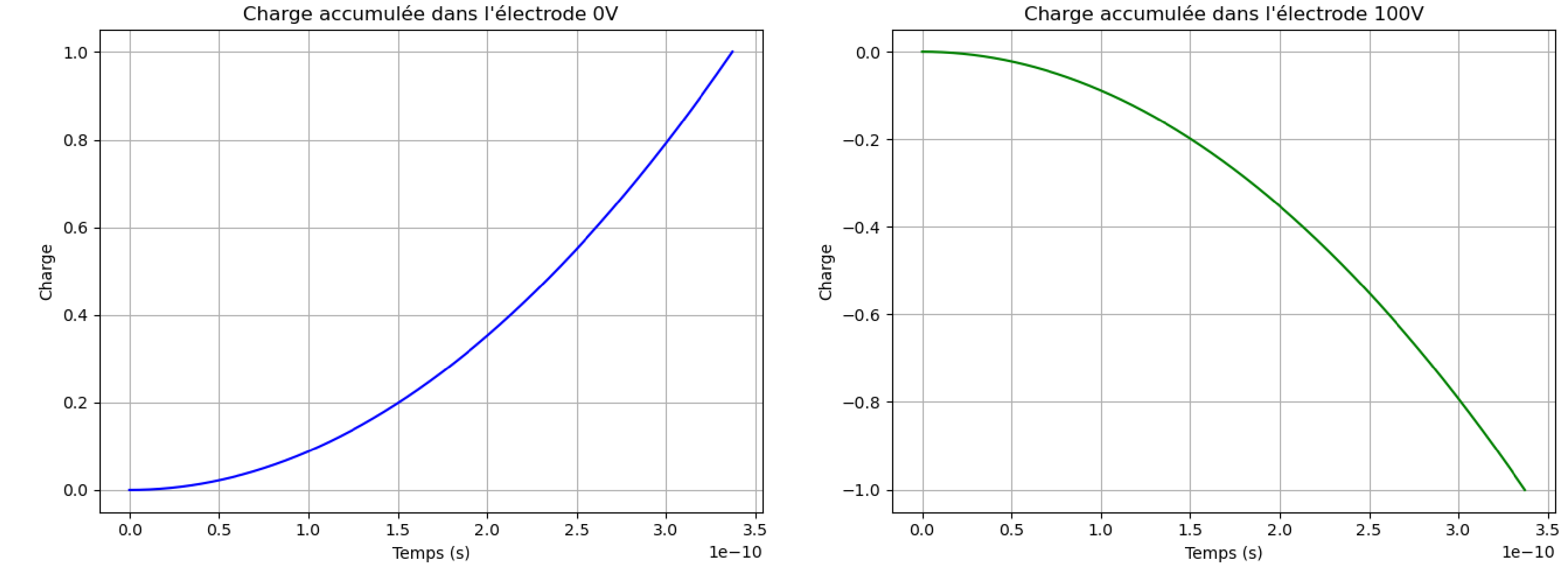
Application: 2 infinite planes 4/4



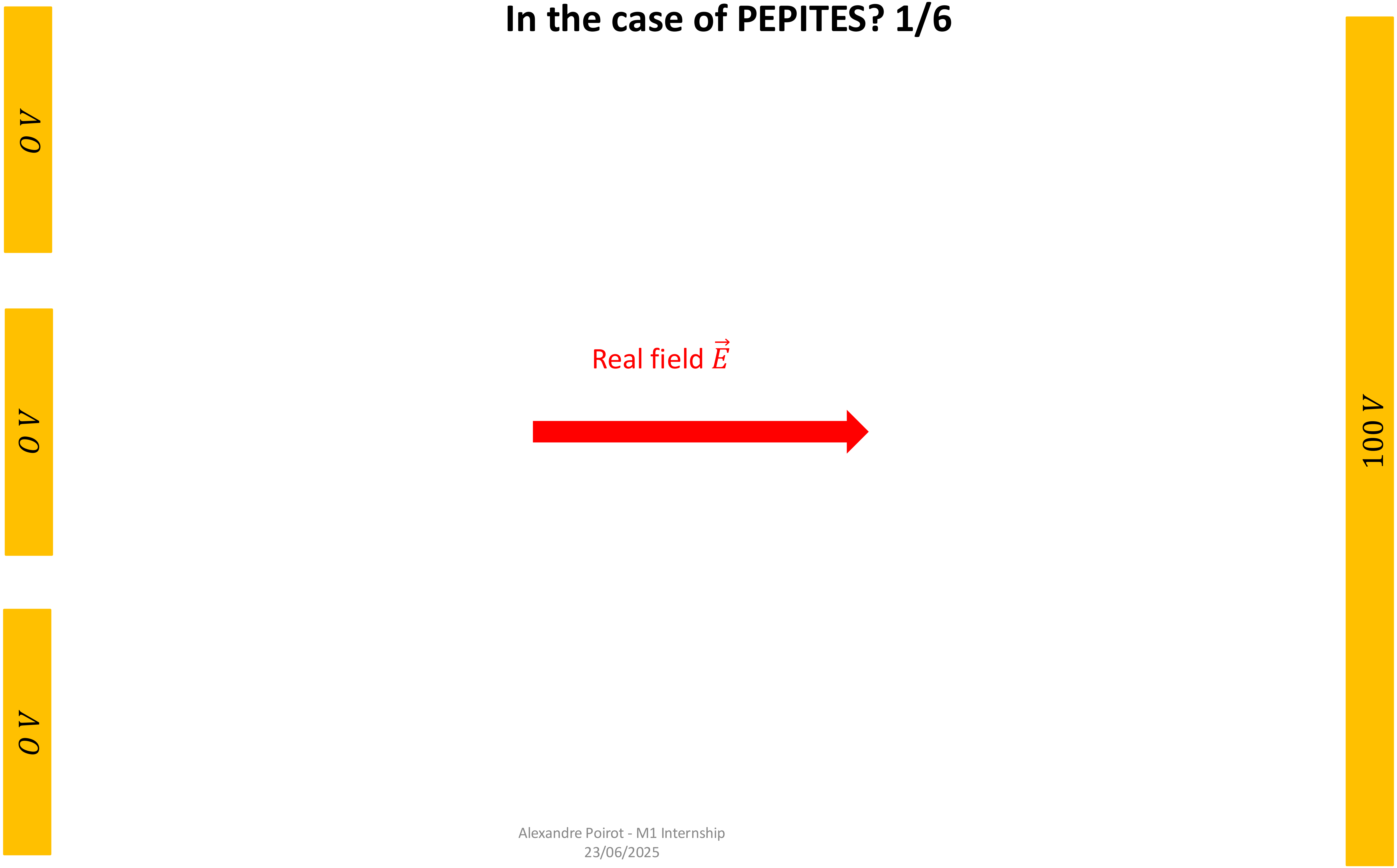
Analytical resolution (1mm plane)



Electric charge conservation



In the case of PEPITES? 1/6



In the case of PEPITES? 2/6

Ramo field $\overrightarrow{E_1^*}$

$1\,V$

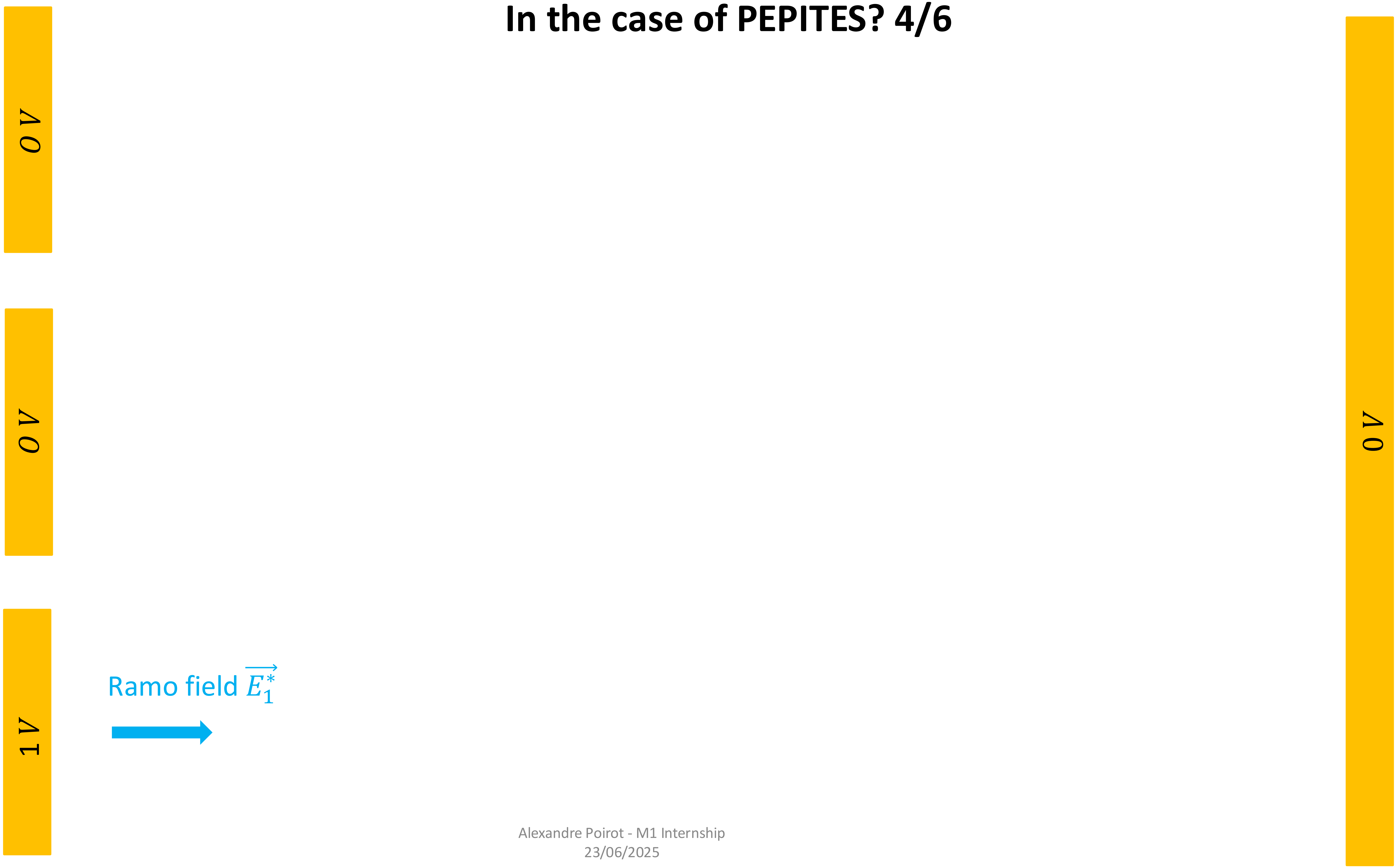
$0\,V$

$0\,V$

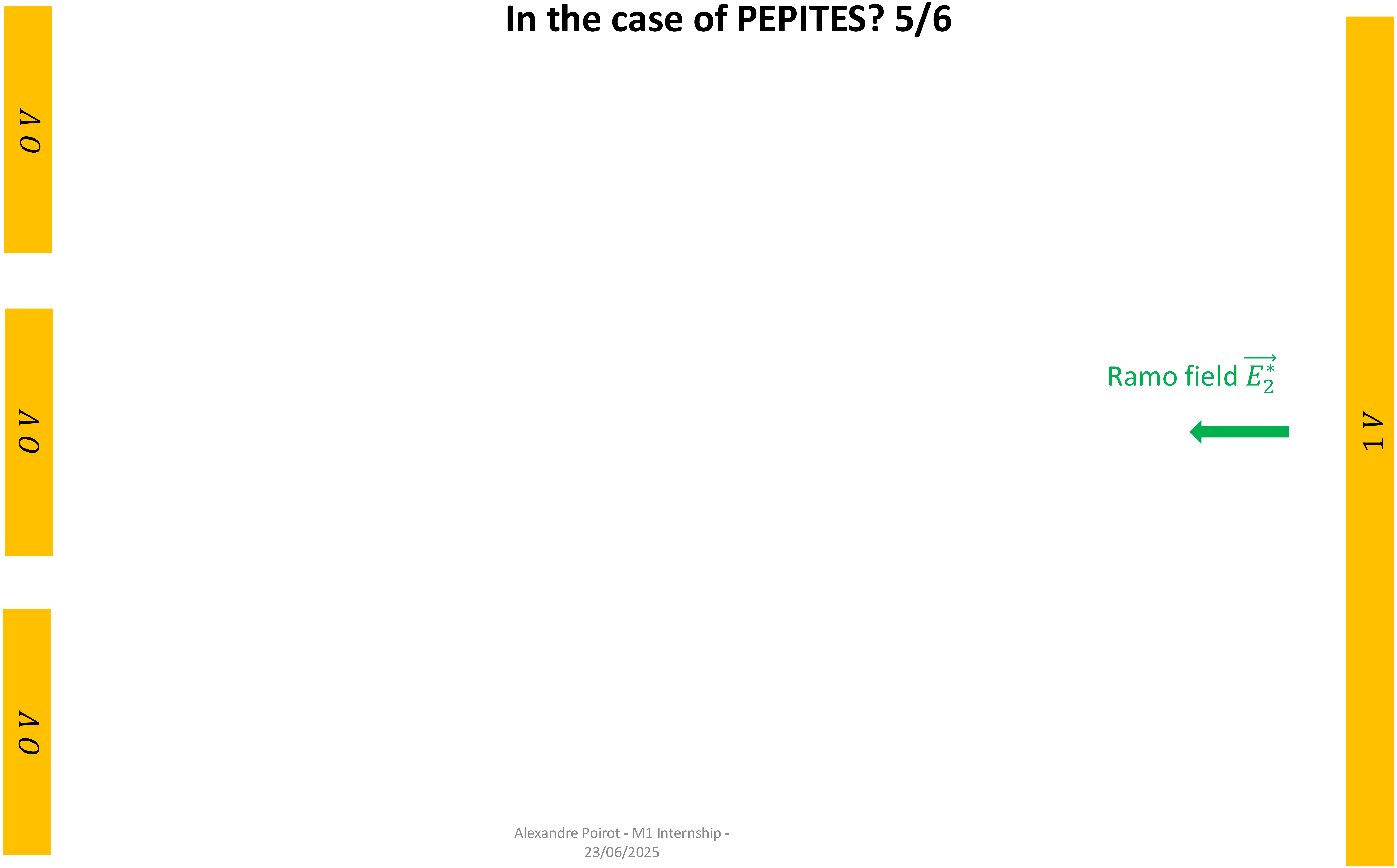
$0\,V$

In the case of PEPITES? 3/6

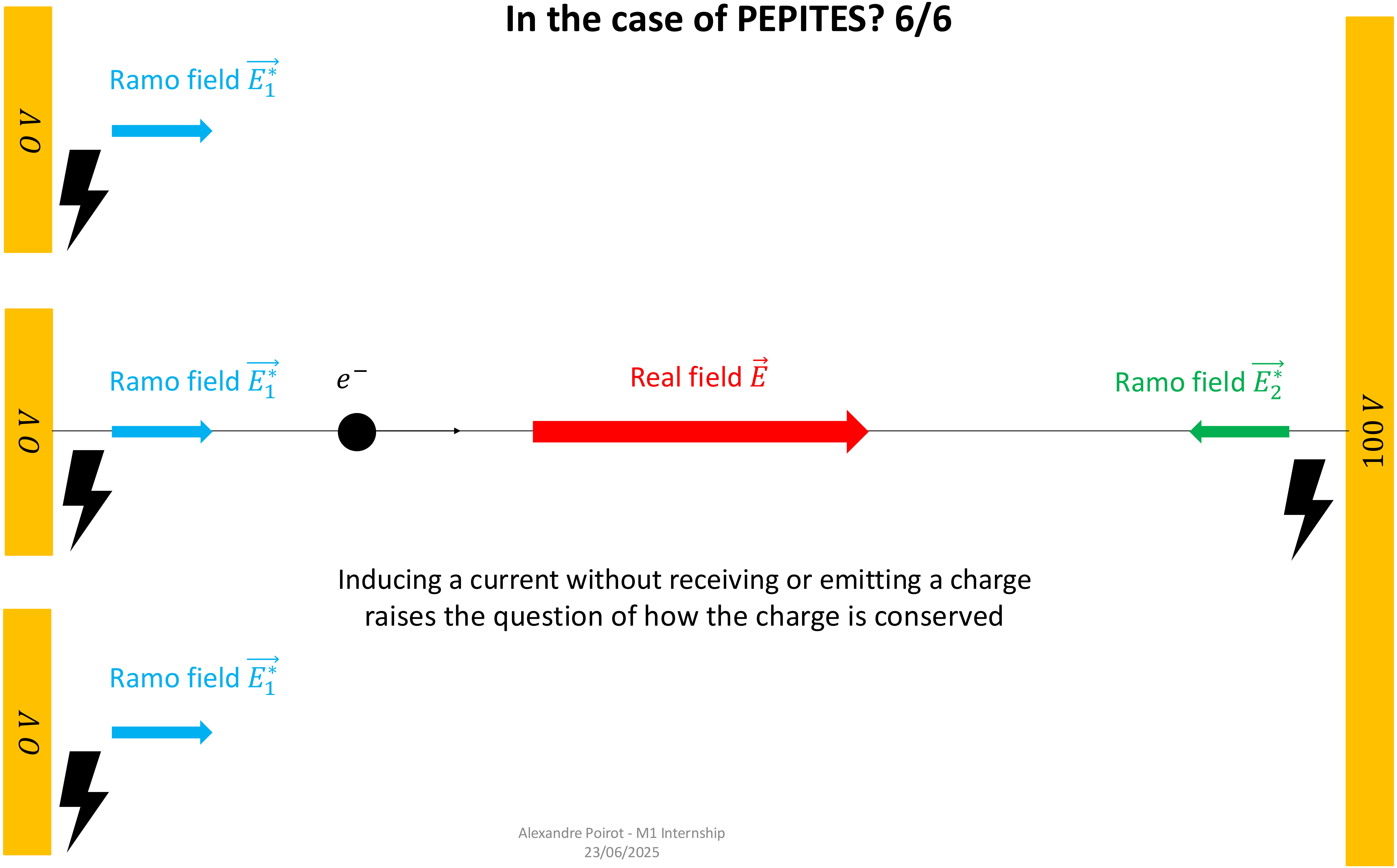
In the case of PEPITES? 4/6



In the case of PEPITES? 5/6

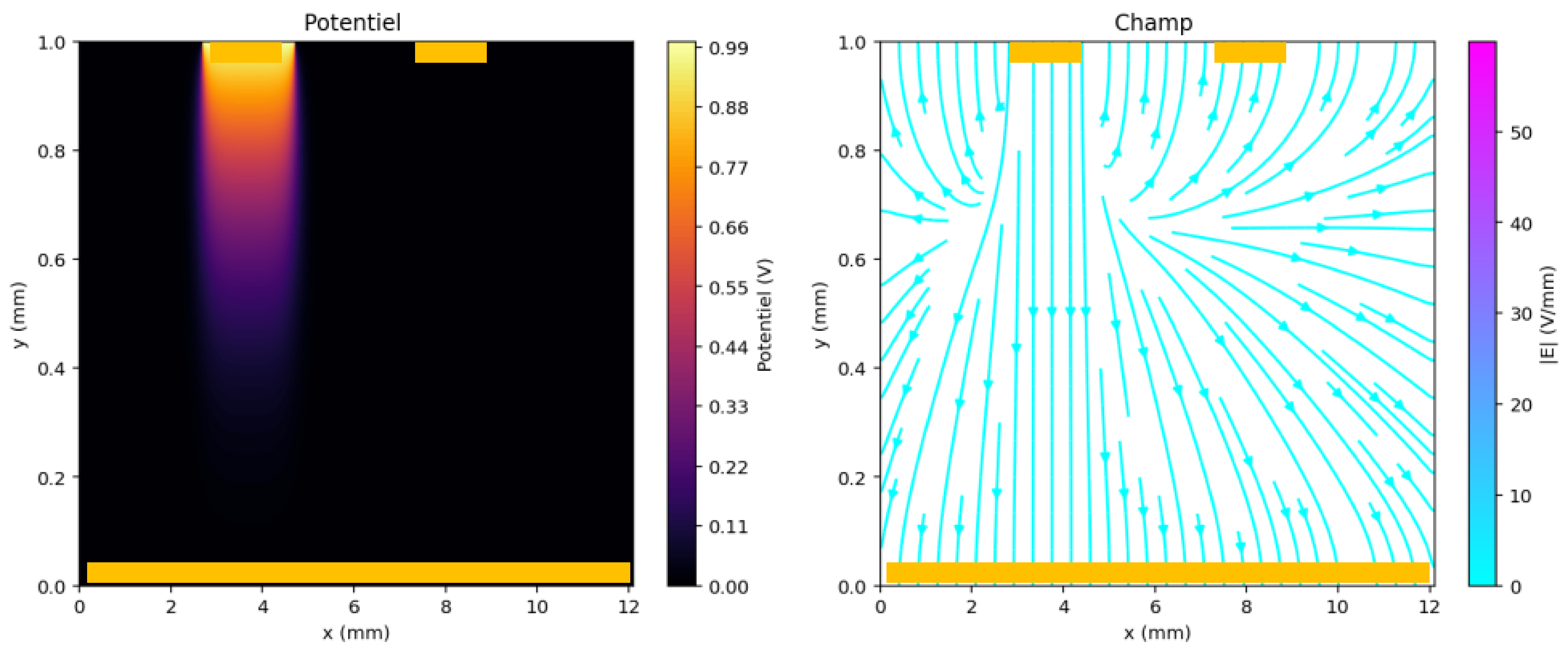


In the case of PEPITES? 6/6



Inducing a current without receiving or emitting a charge raises the question of how the charge is conserved

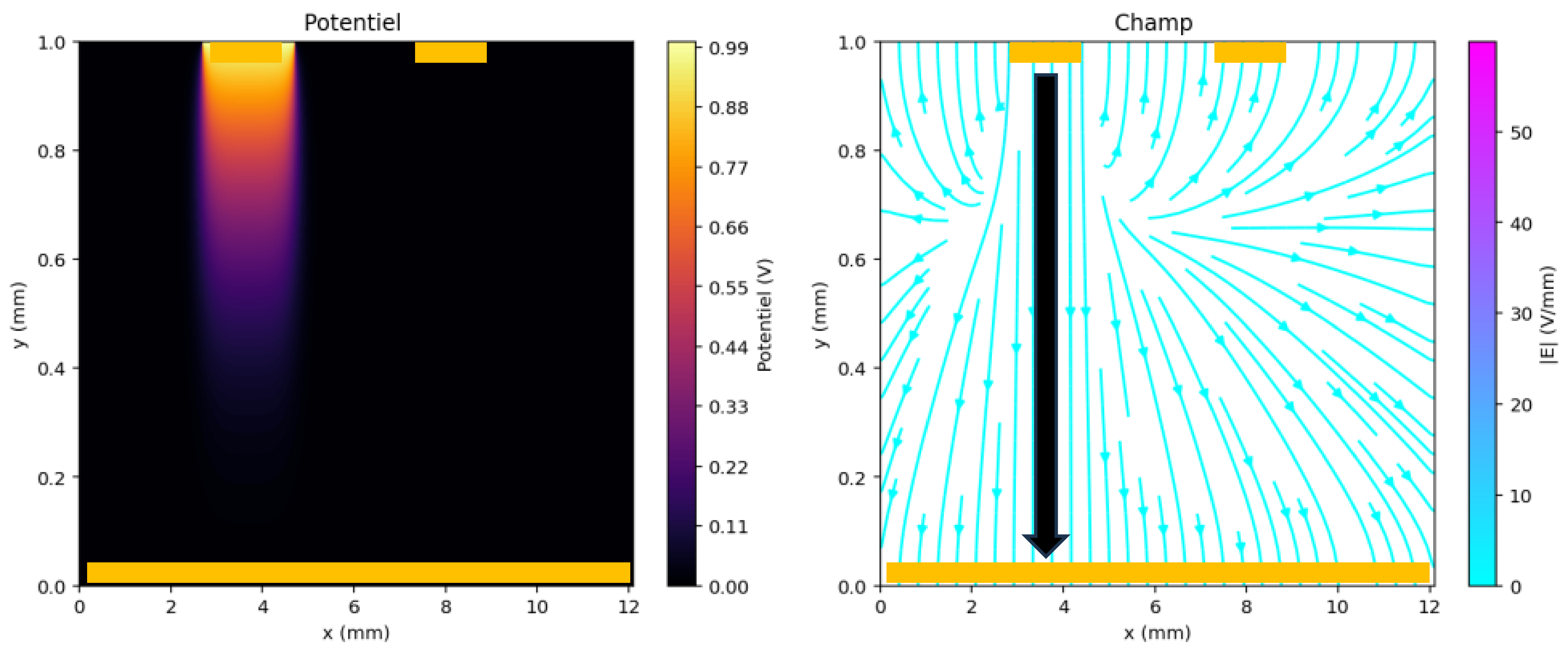
What really happens 1/3



The motion of the electron induces a transient current in the adjacent electrodes, starting positive and then becoming negative

The two currents cancel each other out, so the integral is zero and no charge is transmitted to the neighboring electrodes

What really happens 2/3



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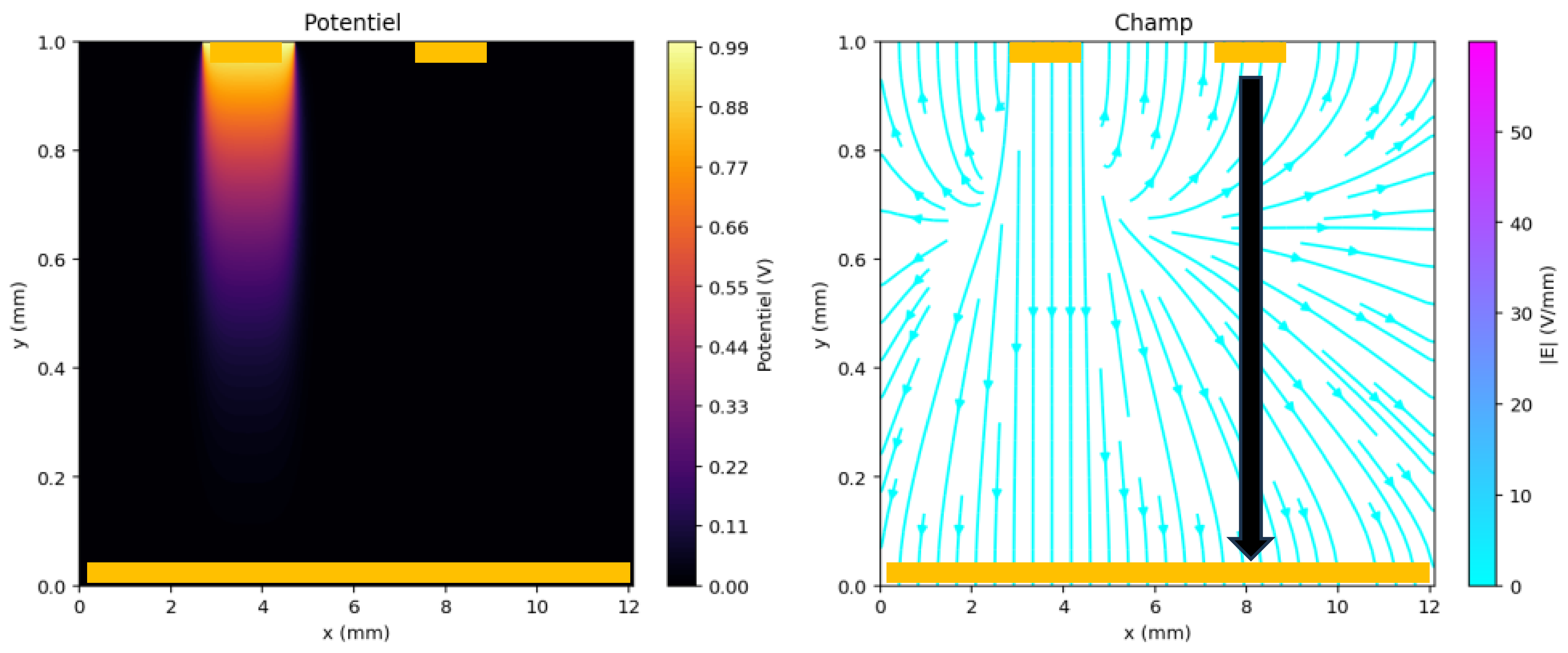
What really happens 3/3



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Calculation of the different fields: working principles

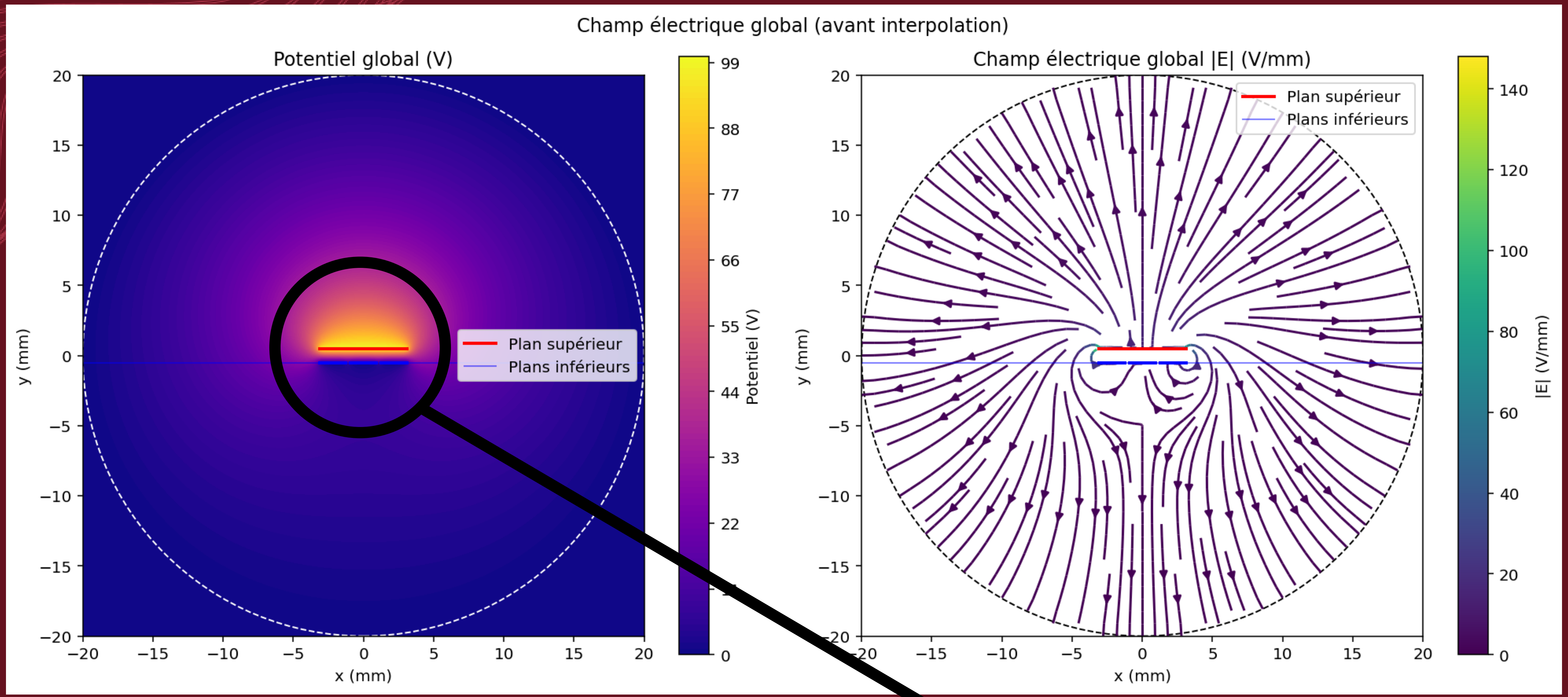
- Use of the Mean Value Theorem

$$V(M) = \langle V(P) \rangle$$

- If we take an arbitrary point M and surround it with a sphere, the mean value of the potential at all points on the sphere's surface is equal to the potential at point M.

- If we approximate the Laplacian with $\Delta V \approx \frac{4(V_{moy} - V_{i,j})}{h^2}$,

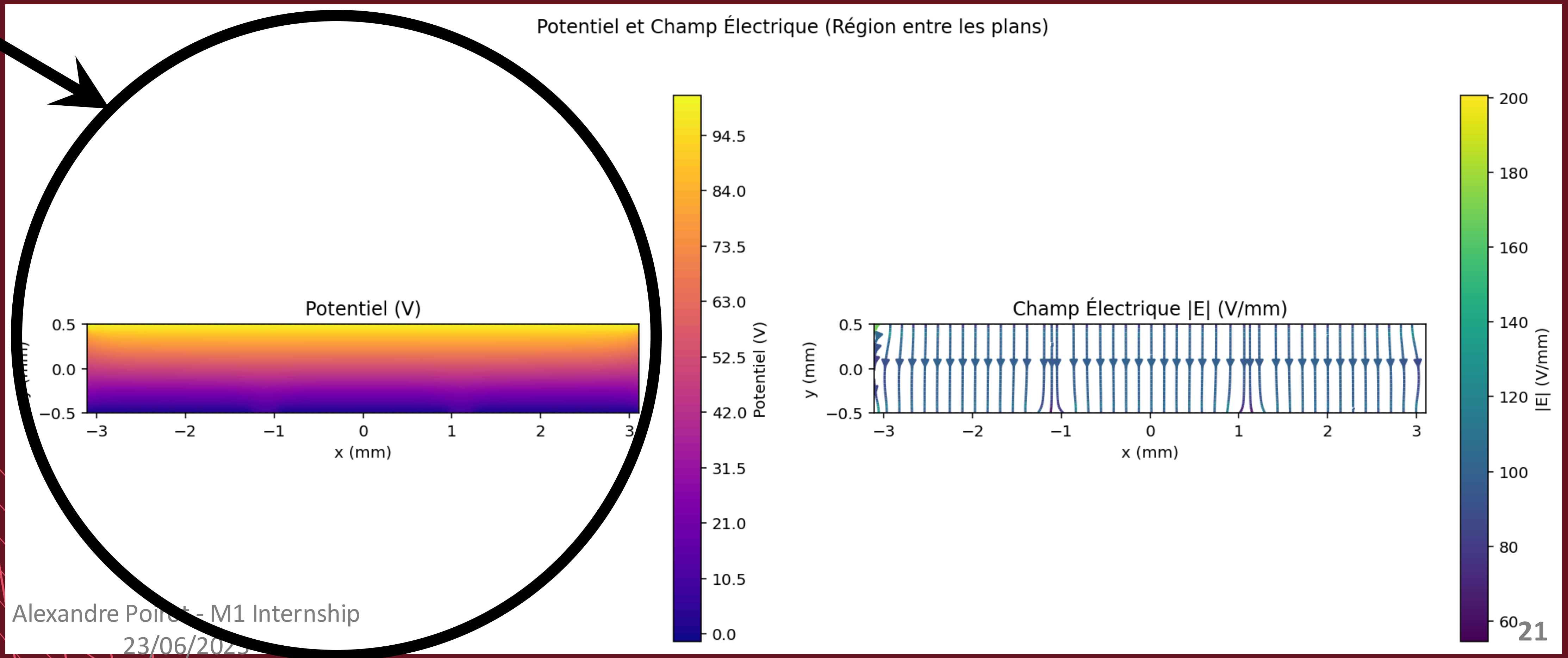
  it comes down to solving: $V_{i,j} = V_{moy}$



Numerical solution of Laplace's equation using a diffusion-based approach:

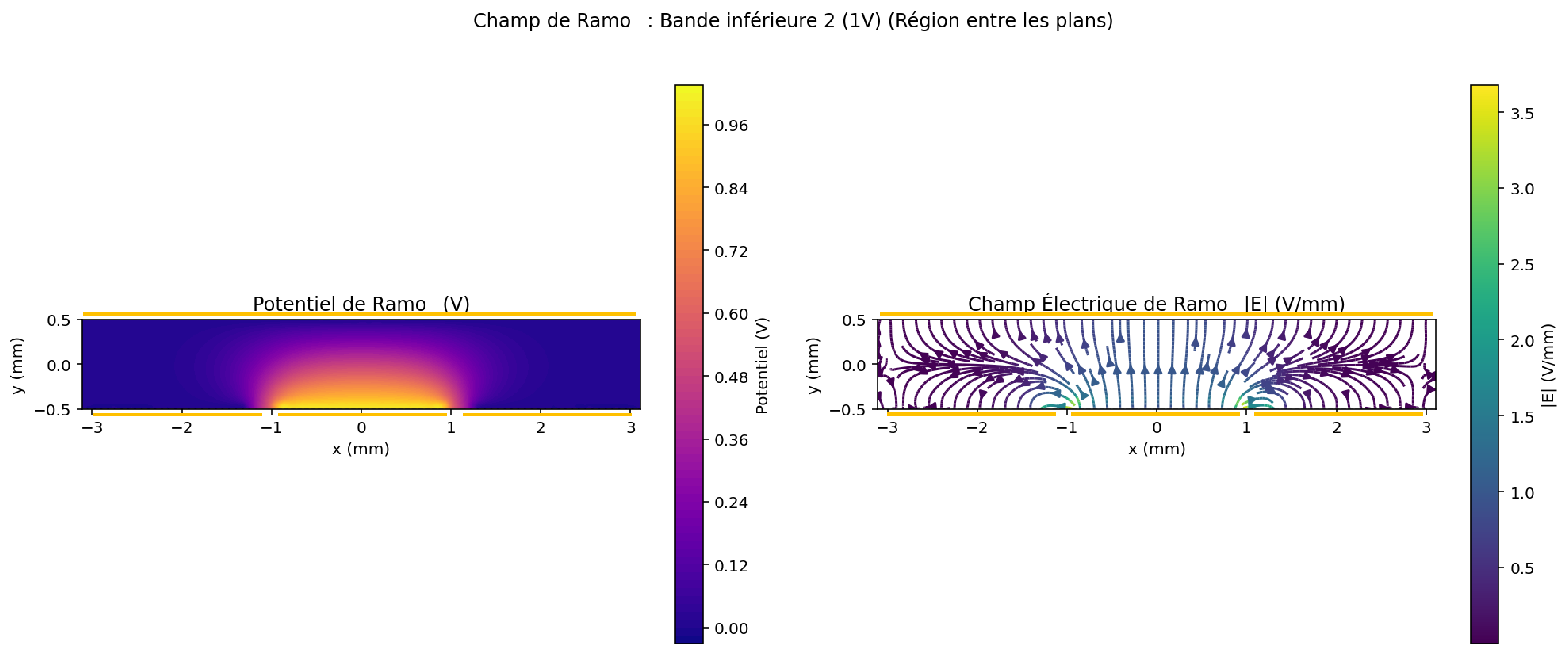
$$\Delta V = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}$$

Low-resolution calculation followed by interpolation in the region of interest (ROI)



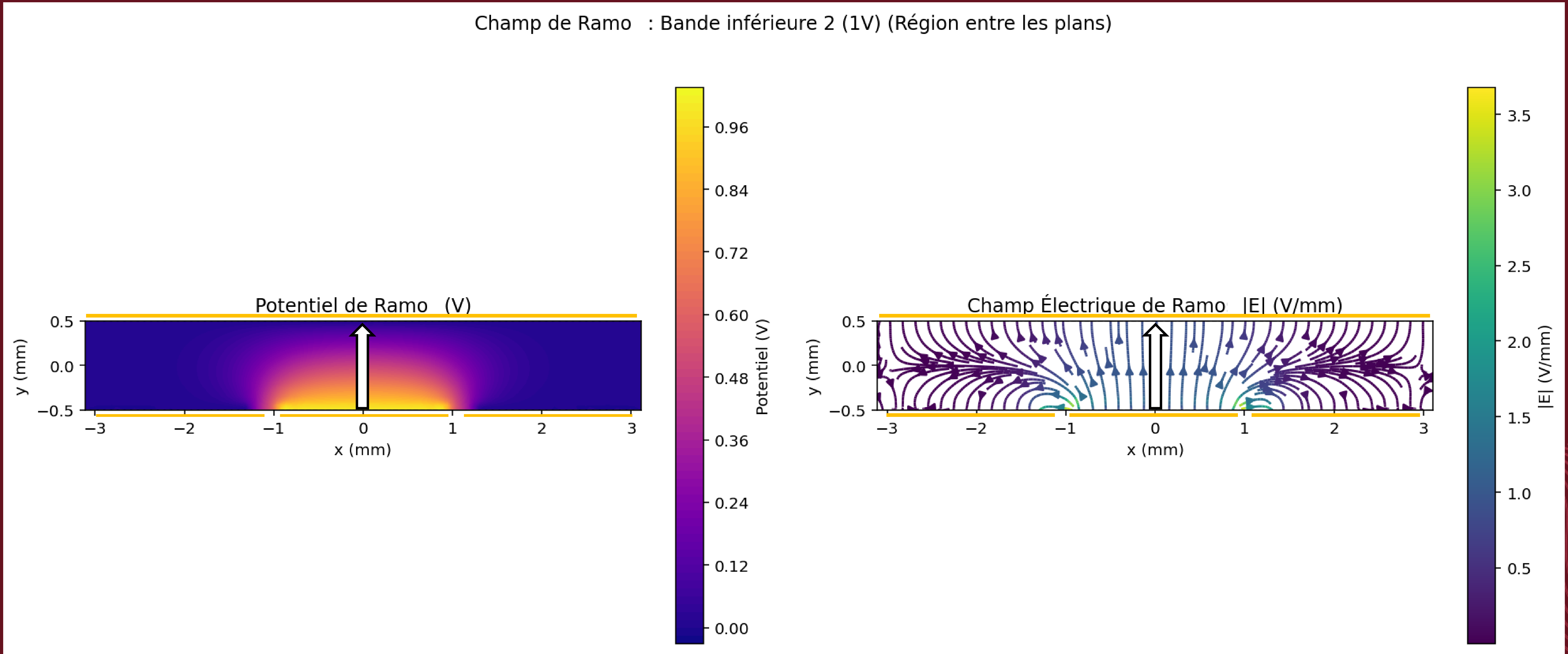
Simulating Ramo field and studying electron dynamics in this field (1/3)

The electron's movement is not influenced by the Ramo field, but by the real field.



Simulating Ramo field and studying electron dynamics in this field (2/3)

The electron's movement is not influenced by the Raman field, but by the real field.



Simulating Ramo field and studying electron dynamics in this field (3/3)

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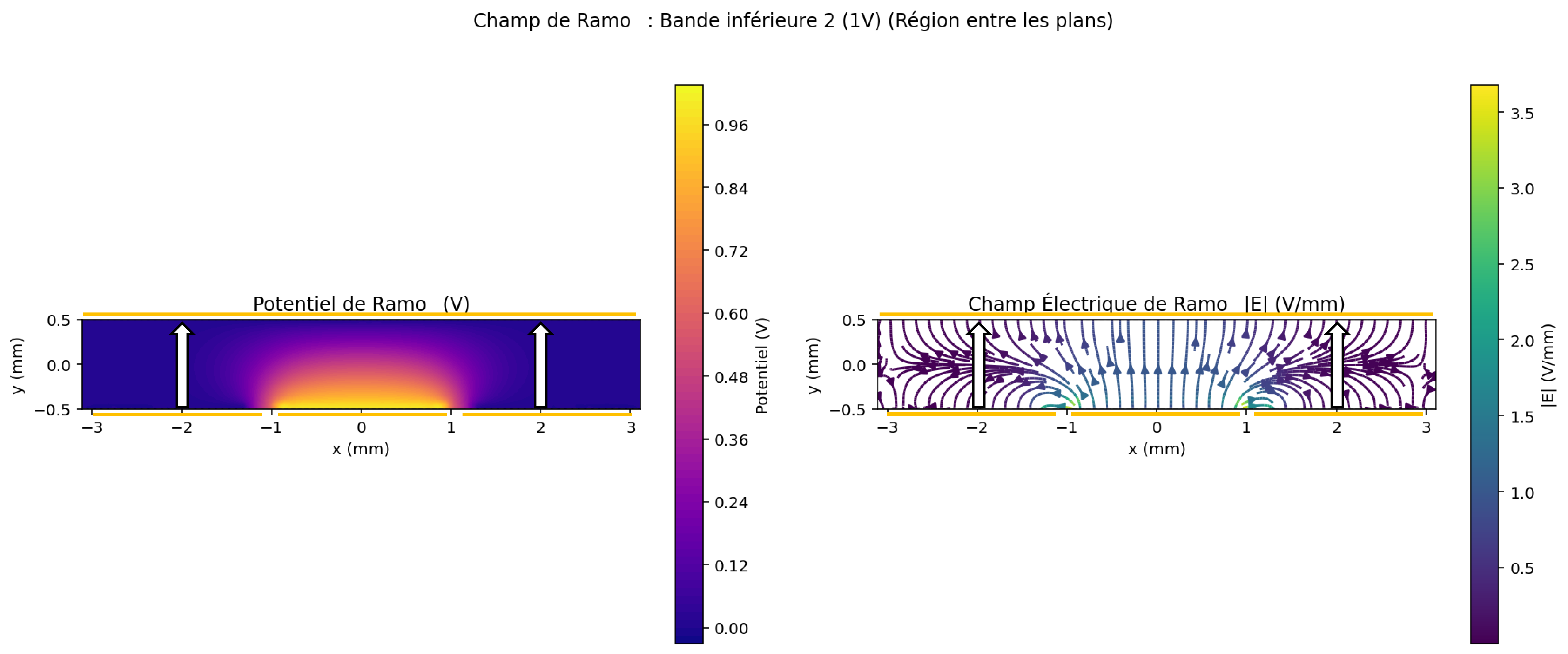
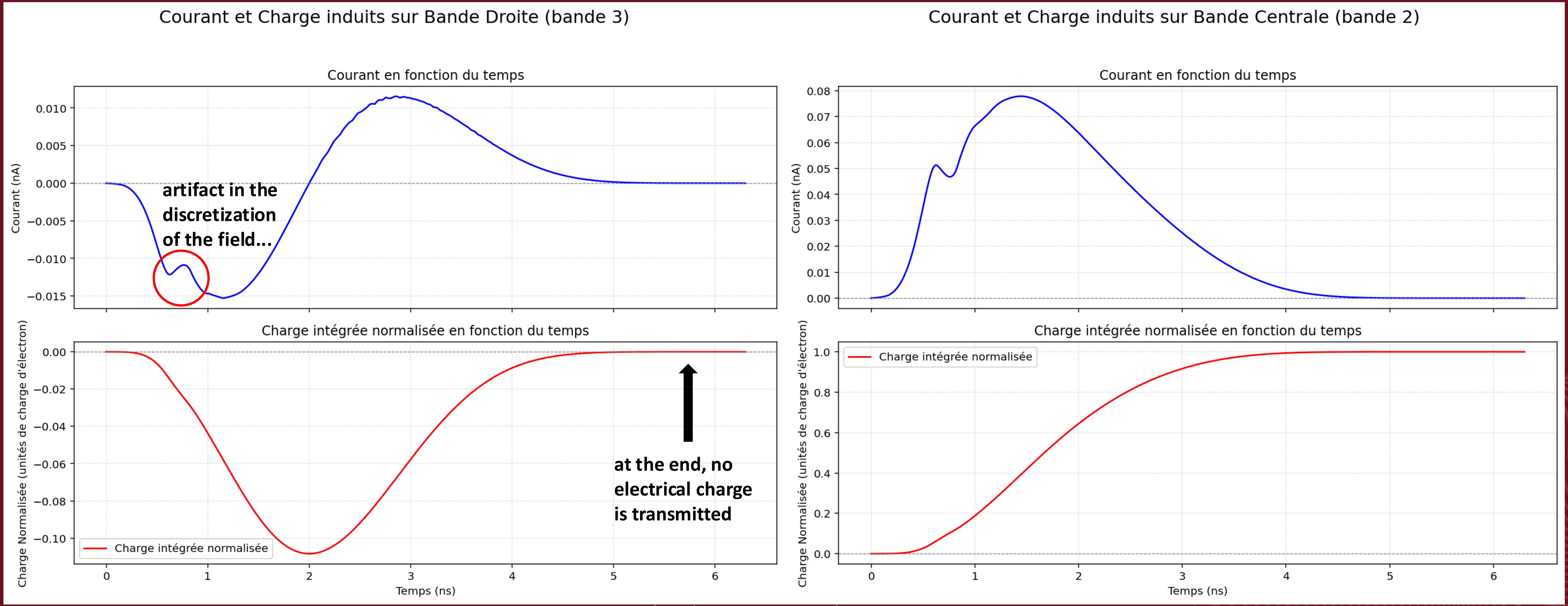


Simulation of Ramo current in transmitter and neighboring stripes

The current in the parallel strips is of the same magnitude as that in the transmitter strips



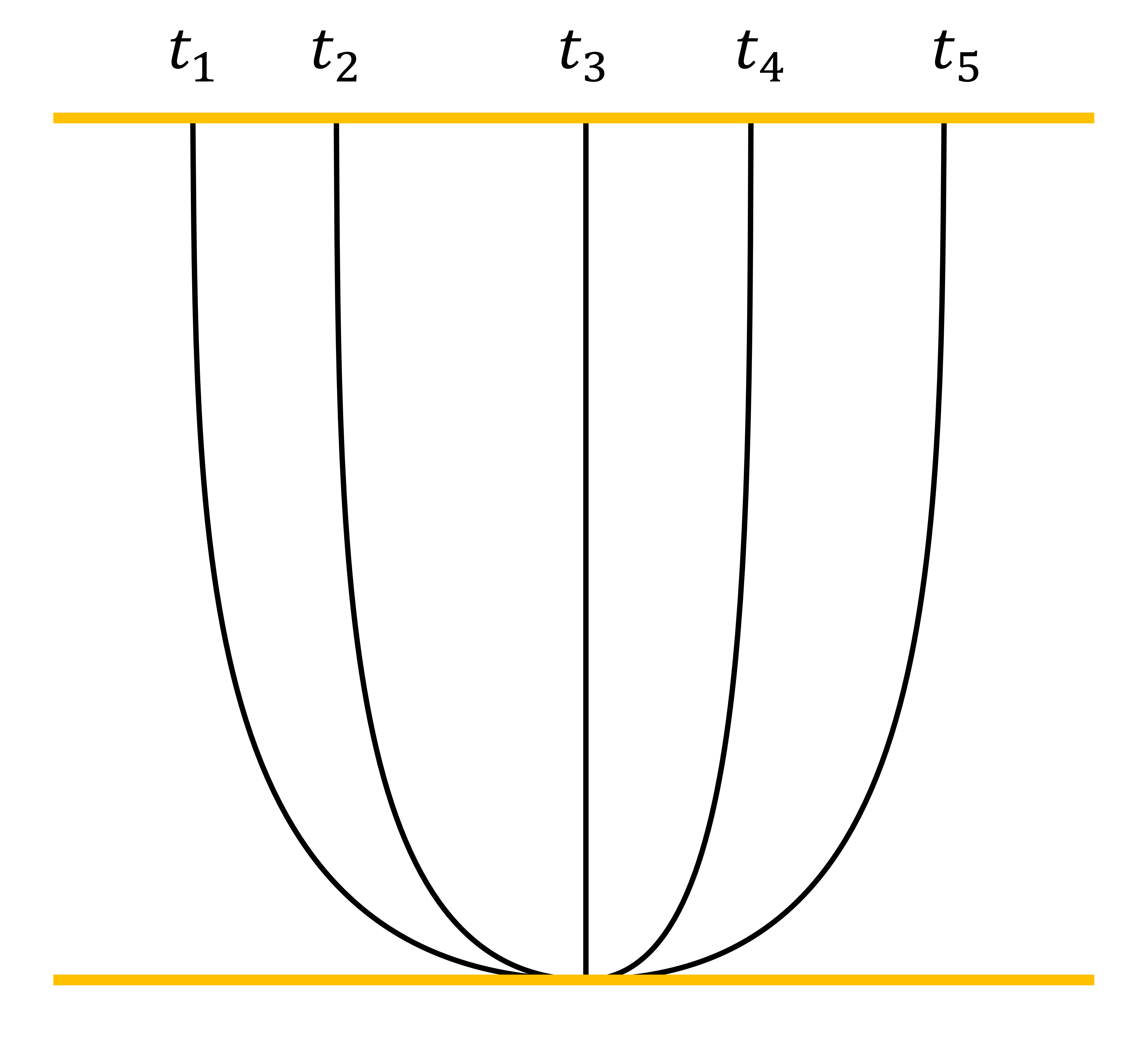
Future work:

Investigation of Time Resolution

- Measurement of hadron therapy beam energy using the time-of-flight method
- Impact of electron trajectory variability
- Analysis of signal shape for trigger optimization

Various possible paths that electrons can take

- what signal will this generate once Shockley-Ramo is applied ?

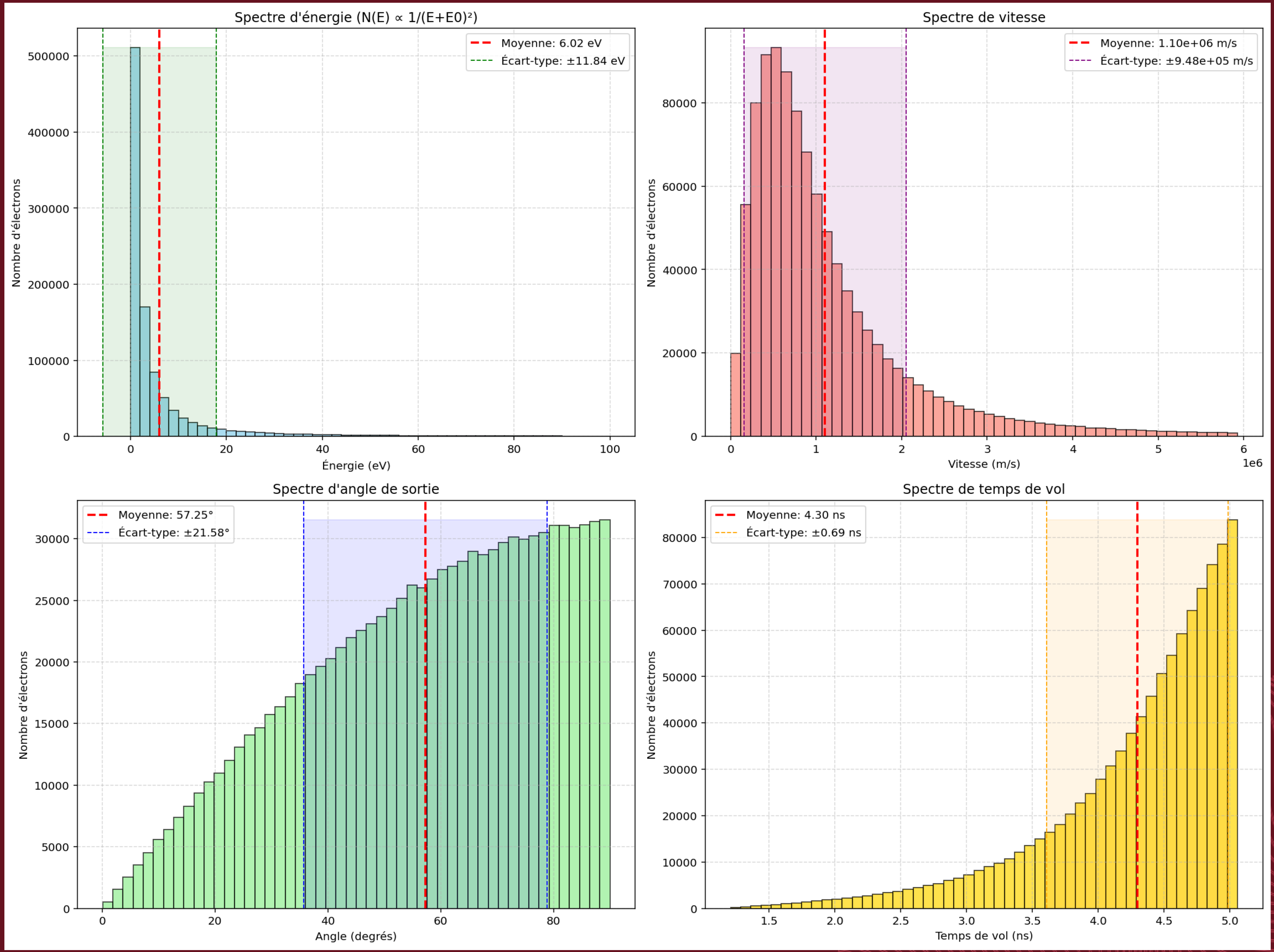


Preliminary statistical analysis of time variance:

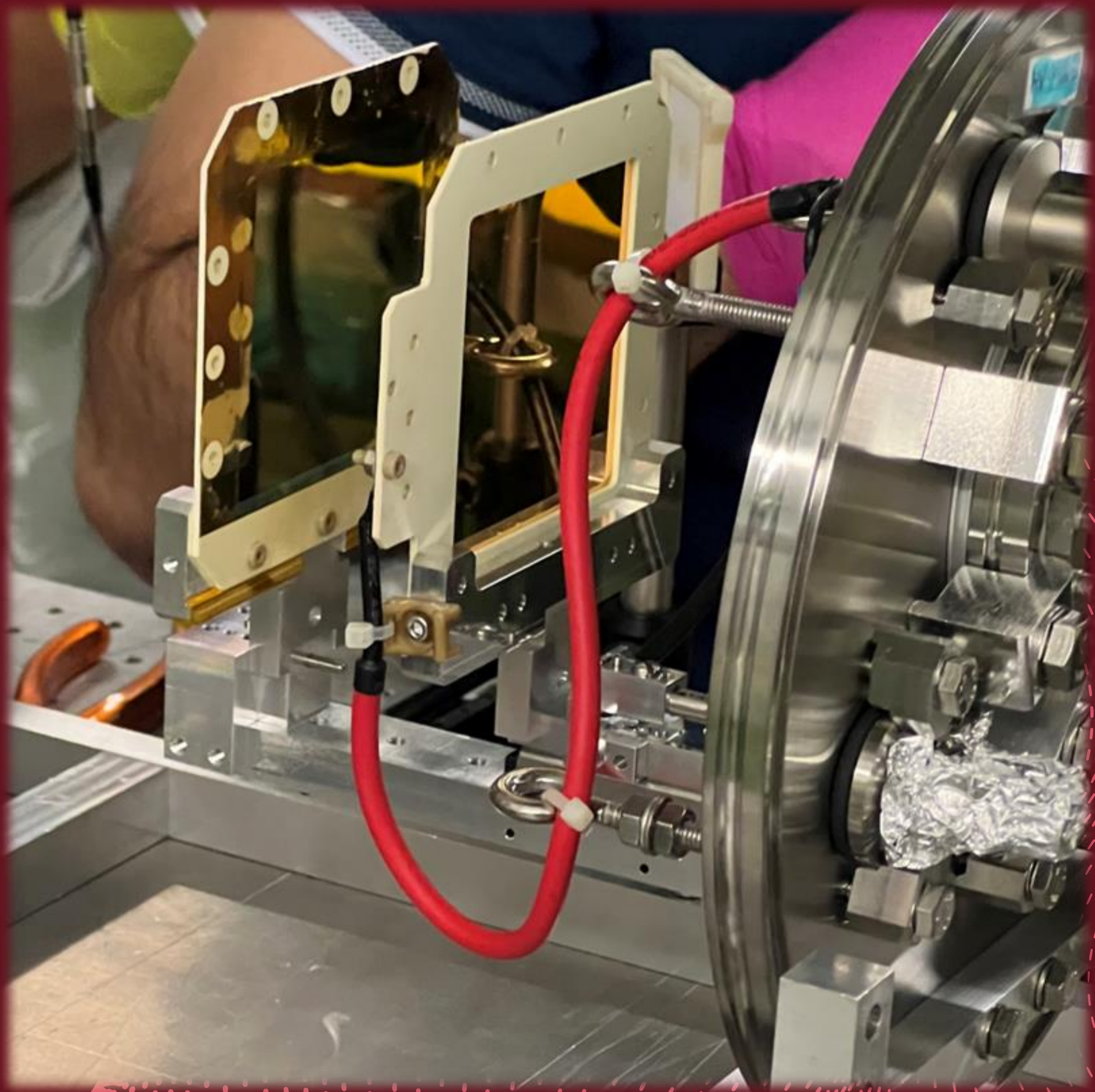
with a uniform distribution of solid angles of incidence and the following energy spectrum:

$$N(E) \propto \frac{1}{(E + E_0)}$$

where E_0 is the average binding energy of electrons in the material (e.g. $\sim 5 - 50\ eV$ for gold)



Thank you for your attention!



References

- Thiebaux, C.; Bernardi, L.; Delagnes, E.; Gastaldi, F.; Gebreyohannes, F. T.; Geerebaert, Y.; Gevin, O.; Guillaumat, R.; Haddad, F.; Koumeir, C.; Magniette, F.; Manigot, P.; Poirier, F.; Servagent, N.; Verderi, M. First Results of Pepites, a New Transparent Profiler Based on Secondary Electrons Emission for Charged Particle Beams. 2022, 4 pages, 0.578 MB. https://doi.org/10.18429/JACOW-IBIC2022-MOP21

- He, Z. Review of the Shockley–Ramo Theorem and Its Application in Semiconductor Gamma-Ray Detectors. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2001, 463 (1–2), 250–267. https://doi.org/10.1016/S0168-9002(01)00223-6

- [3] Fontbonne, J.-M. ; Ecole Joliot-Curie. Principes fondamentaux de l'instrumentation nucléaire. Sciencesconf. https://ejc2015.sciencesconf.org/conference/ejc2015/pages/Instrumentation_Nucle_aire.pdf