DRD1 Collaboration Meeting

Simulating signal formation in detectors with resistive elements

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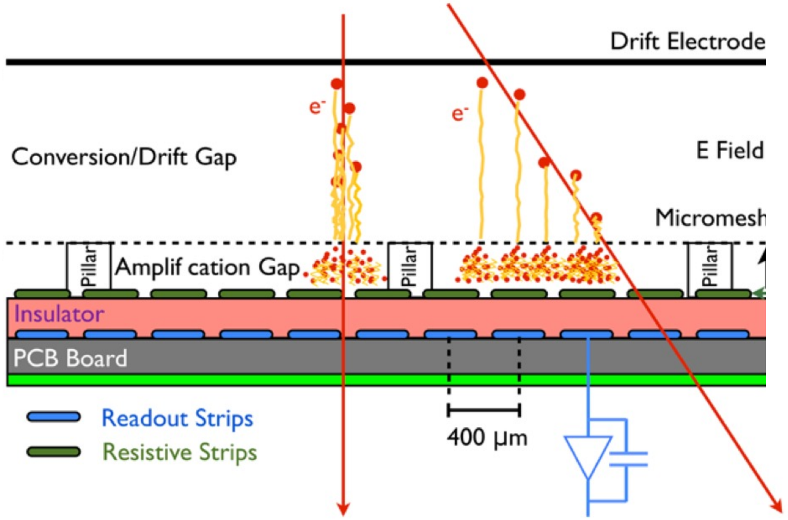
Introduction

We want to use Garfield++ and a finite element method to numerically calculate the signal formation in detectors with resistive elements by applying an extended form of the Ramo-Shockley theorem.

Outline:

- Ramo-Shockley theorem extension for conductive media
- Transmission line model
- Signal simulation for a resistive strip MicroMegas
- Signal measurement of a resistive strip MicroMegas
- Comparison
- Summary

Resistive strips MicroMegas



Alexopoulos et al., Nucl. Instrum. Meth. A 640 (2011) 110.

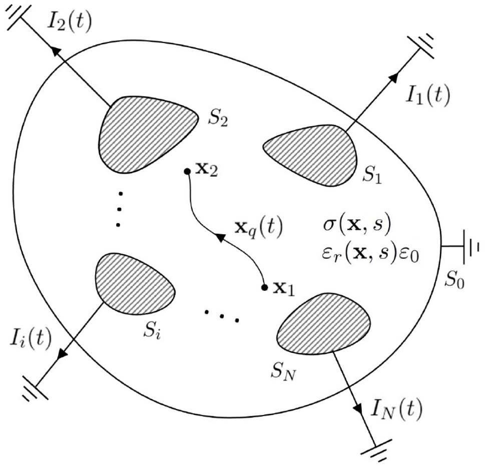
Garfield++:
https://garfieldpp.web.cern.ch/garfieldpp/

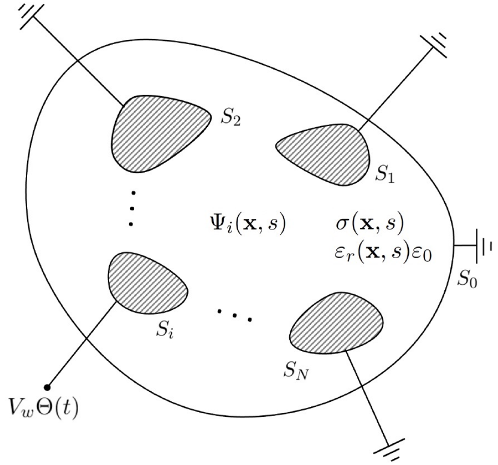
COMSOL Multiphysics:
https://www.comsol.ch

Ramo-Shockley theorem extension for conducting media

Ramo-Shockley theorem extension for conducting media

For detectors with resistive elements, the time dependence of the signals is not solely given by the movement of the charges in the drift medium but also by the time-dependent reaction of the resistive materials.





$$I_i(t) = -\frac{dQ_i(\mathbf{x}(t))}{dt}$$

$$I_i(t) = -\frac{q}{V_w}\int_0^t \mathbf{H}_i\left[\mathbf{x}_q(t'), t - t'\right] \cdot \dot{\mathbf{x}}_q(t')\, dt'$$

$$\mathbf{H}_i(\mathbf{x}, t) := -\nabla \frac{\partial \Psi_i(\mathbf{x}, t)}{\partial t}$$

The dynamic $\psi_i(\mathbf{x}, t)$ can be calculated for a grounded electrode using the following steps:

- Remove the drifting charges
- Put the electrode at potential V_w at time t = 0
- Grounding all other electrodes

W. Riegler, Nucl. Instrum. Meth. A 535 (2004), 287-293.
W. Riegler, Signals in Particle Detectors, CERN's Academic Training Lecture Regular Programme (2019): https://indico.cern.ch/event/843083/

Ramo-Shockley theorem extension for conducting media

The time-dependent weighting potential is comprised of a static prompt and a dynamic delayed component:

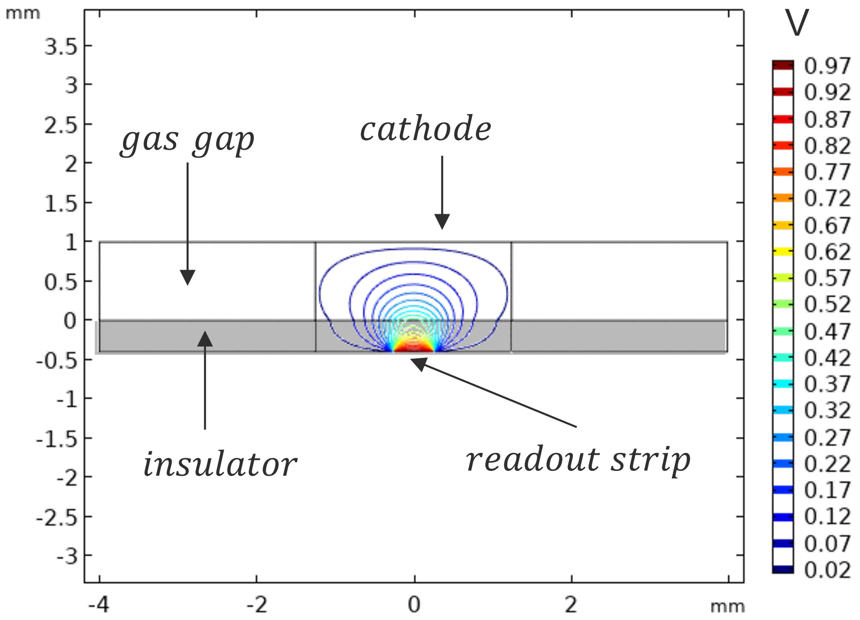
$$\psi_i(\mathbf{x},t) \doteq \psi_i^p(\mathbf{x}) + \psi_i^d(\mathbf{x},t) \quad \text{where} \quad \psi_i^d(\mathbf{x},0) = 0$$

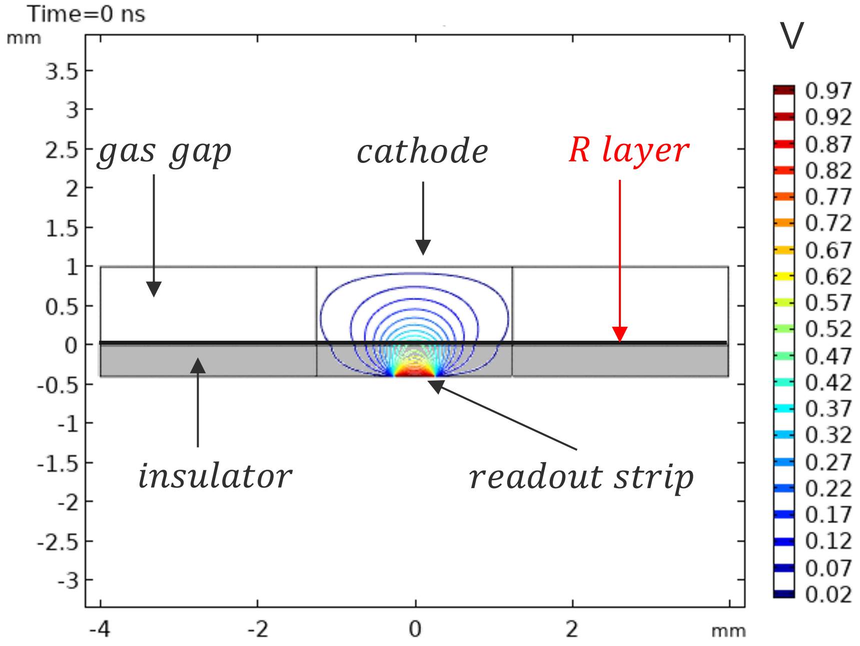
The current induced by a point charge q is given by:

$$I_i(t) = \underbrace{-\frac{q}{V_w}\mathbf{E}_i^p(\mathbf{x}_q(t)) \cdot \dot{\mathbf{x}}_p(t)}_{\text{Direct induction}} \underbrace{- \frac{q}{V_w}\int_0^t dt' \, \mathbf{H}_i^d\left[\mathbf{x}_q(t'), t - t'\right] \cdot \dot{\mathbf{x}}_q(t')}_{\text{Reaction from resistive material}}$$

Direct induction

Reaction from resistive material





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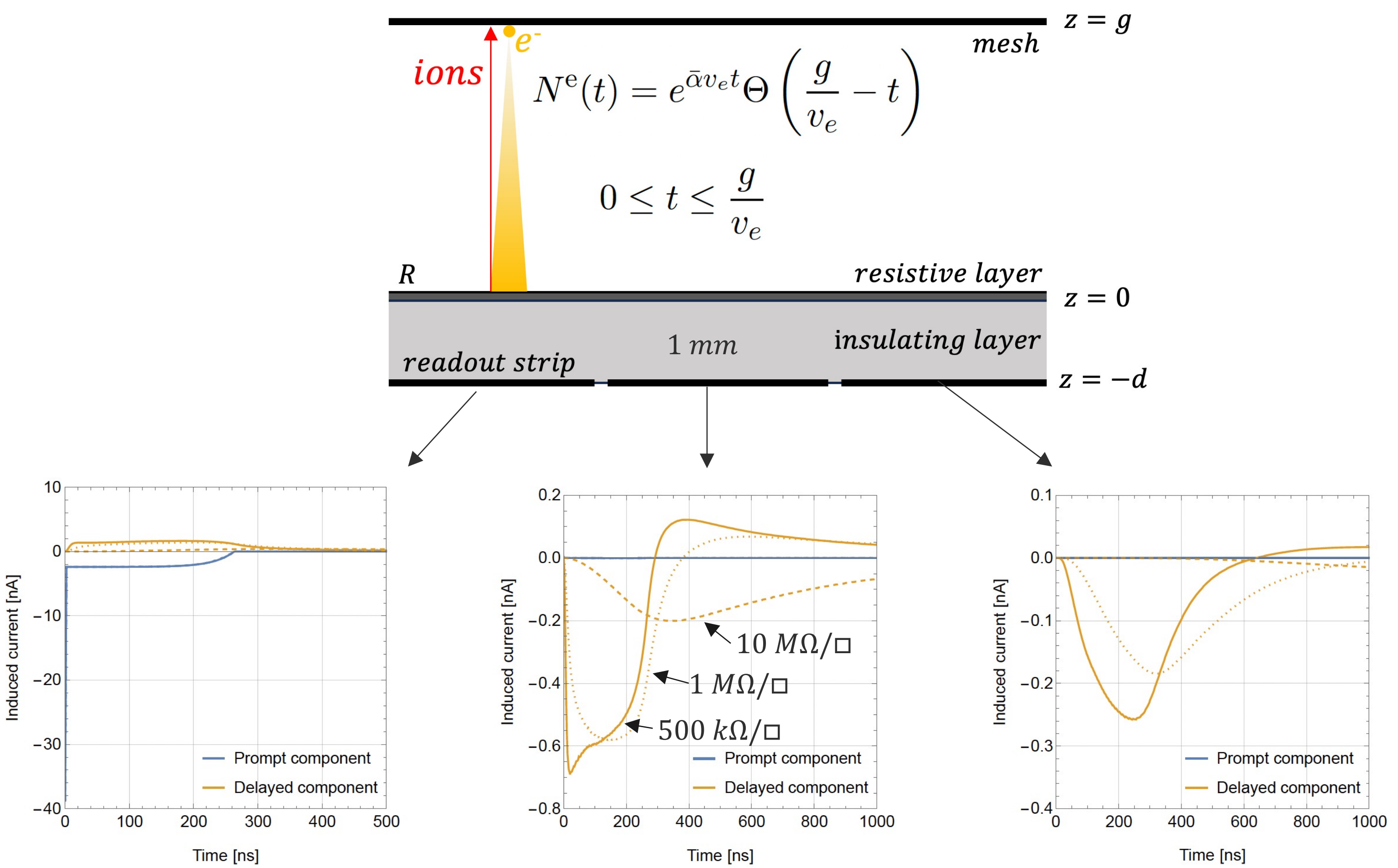
Signal ‘spreading’ in a thin resistive layer

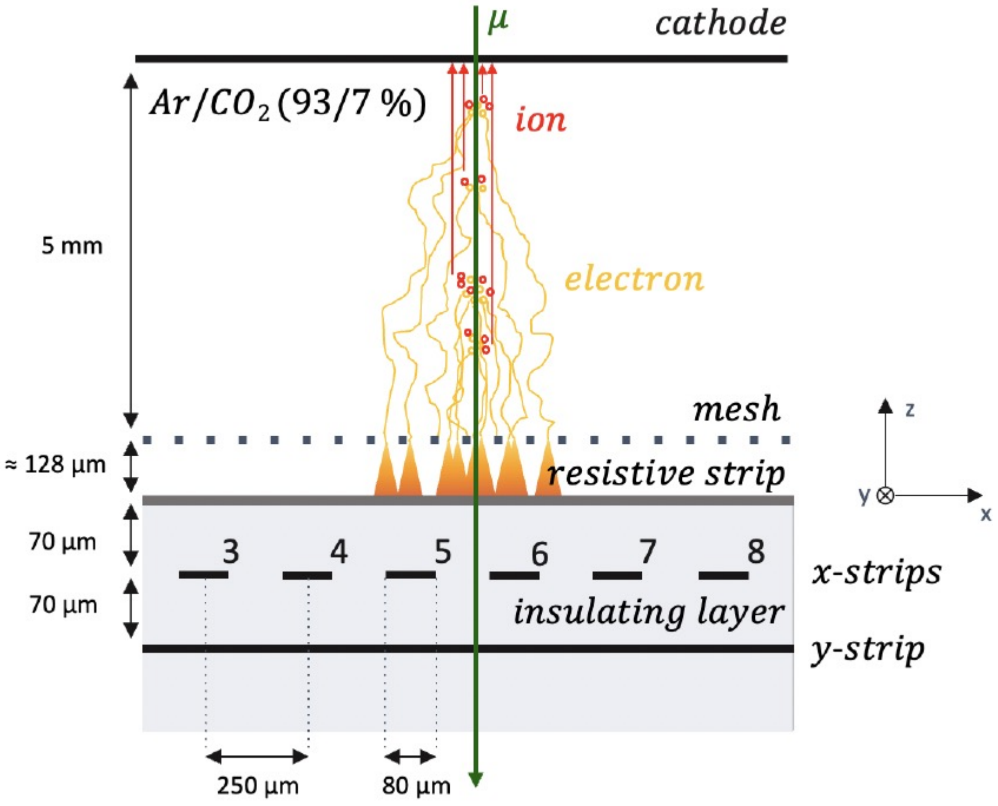
Let us examine a Townsend avalanche occurring within the amplification gap of a MicroMegas detector, resulting in a signal being generated on the readout strips.

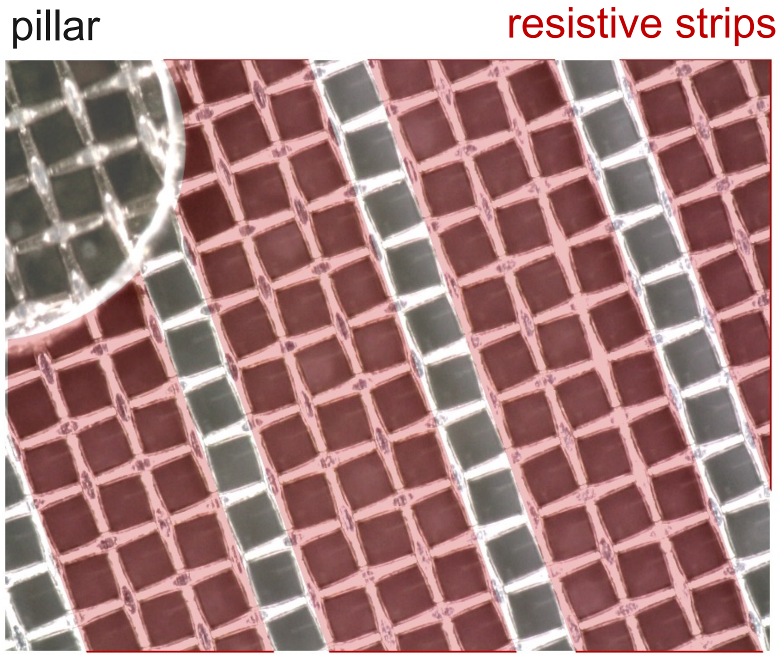


Signal simulation for a resistive strip MicroMegas

Resistive strip MicroMegas: detector layour

The resistive strips present in the geometry of this MicroMegas geometry is known for its spreading of the signal over the strips running orthogonal to them.

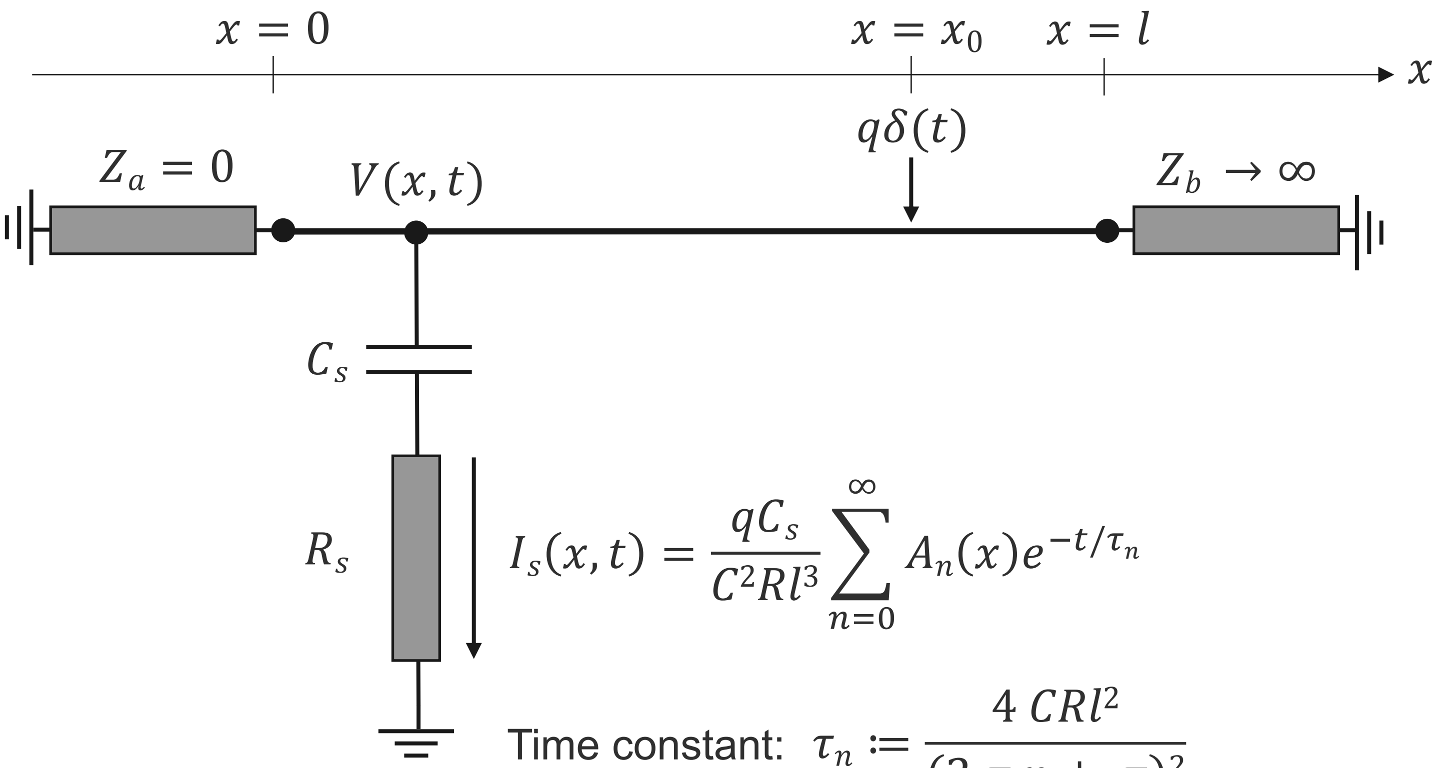




T. Alexopoulos, et al., Nucl. Instrum. Meth. A 640 (2011) 110.
M. Byszewski1 and J. Wotschack, JINST 7 C02060 (2011).

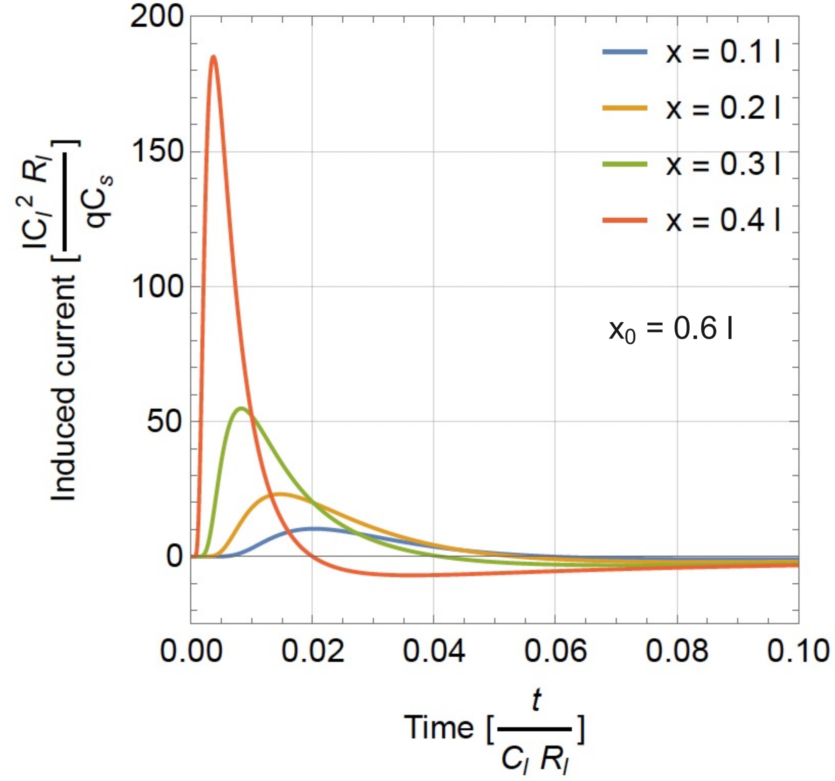
Transmission line model

We can derive an analytical expression for the current flowing from an electrode capacitively coupled to ground, which is capacitively coupled to a transmission line on which a charge q is injected at t = 0.



$$I_s(x,t) = \frac{qC_s}{C^2Rl^3}\sum_{n=0}^{\infty} A_n(x)e^{-t/\tau_n}$$

Time constant: $\tau_n := \frac{4\,CRl^2}{(2\,\pi\,n +\,\pi)^2}$



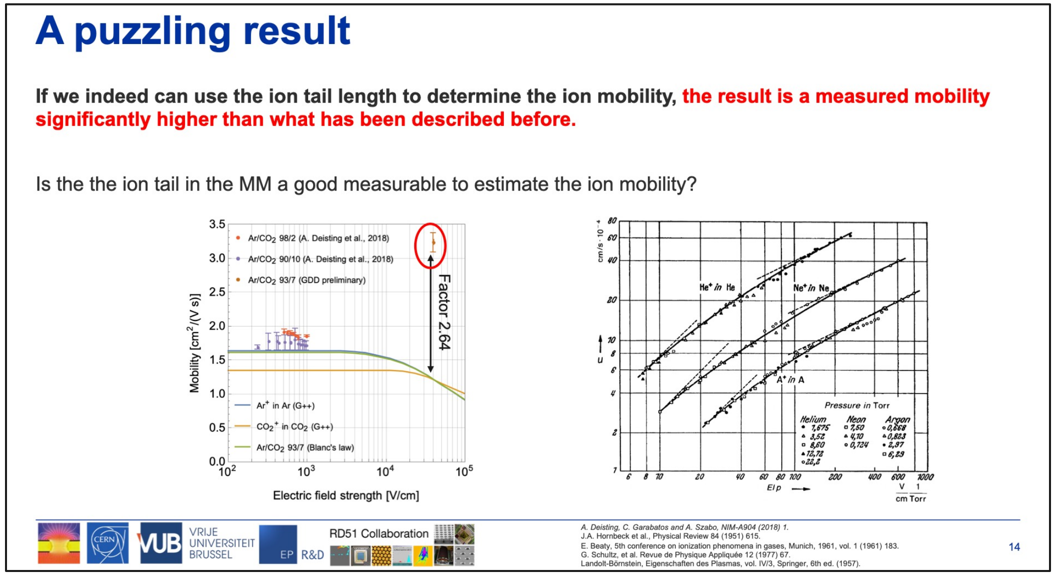
Here we have made some assumptions: $R_s \ll C_s$, no transconductance (G = 0), and inductance (L = 0).

A numerical approach of this problem can be found in J. Galán, JINST 7 (2012) C04009.

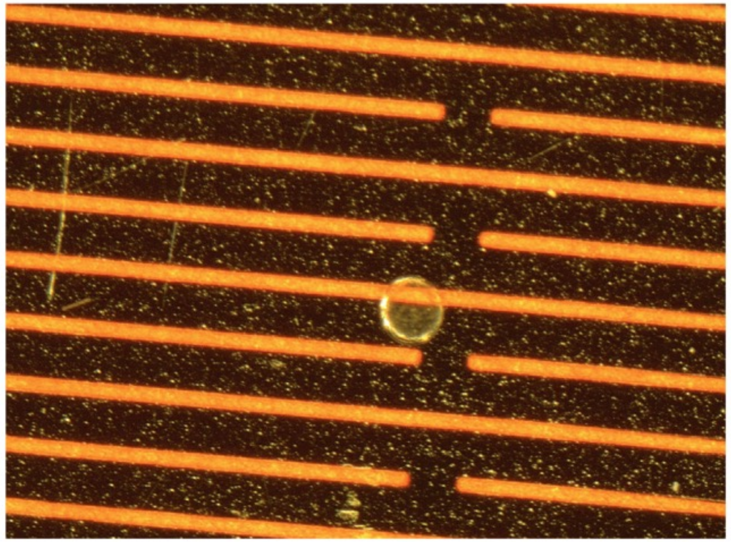
Simulation

We needed to take into consideration different aspects:

- **Accurately represent the boundary conditions:** coordinate mapping of the model to the full active area (✓)
- **Height of the mesh:** measured to be 120.23 ± 1.42 µm (✓)
- **Duration of the ion tail:** measured to be below 100 ns using single channel PICOSEC MM prototype (✓)
- **Termination of the resistive strips:** simulation including external termination circuit showed minimal impact (✓)
- **Interconnection of the resistive strips:** for simplicity not included into the simulation (✗)



For a result on the ion tail length: D. Janssens,"Ion mobility in a MicroMegas detector: a puzzle between measurement and simulation", RD51 Collaboration Meeting.

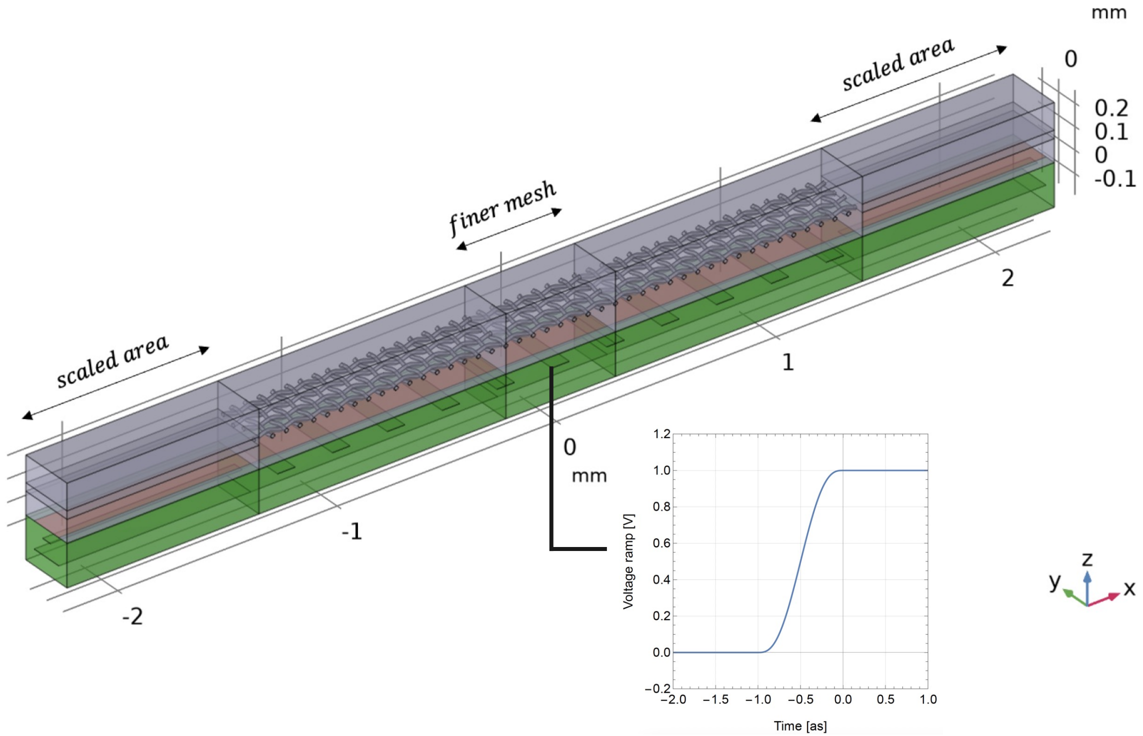


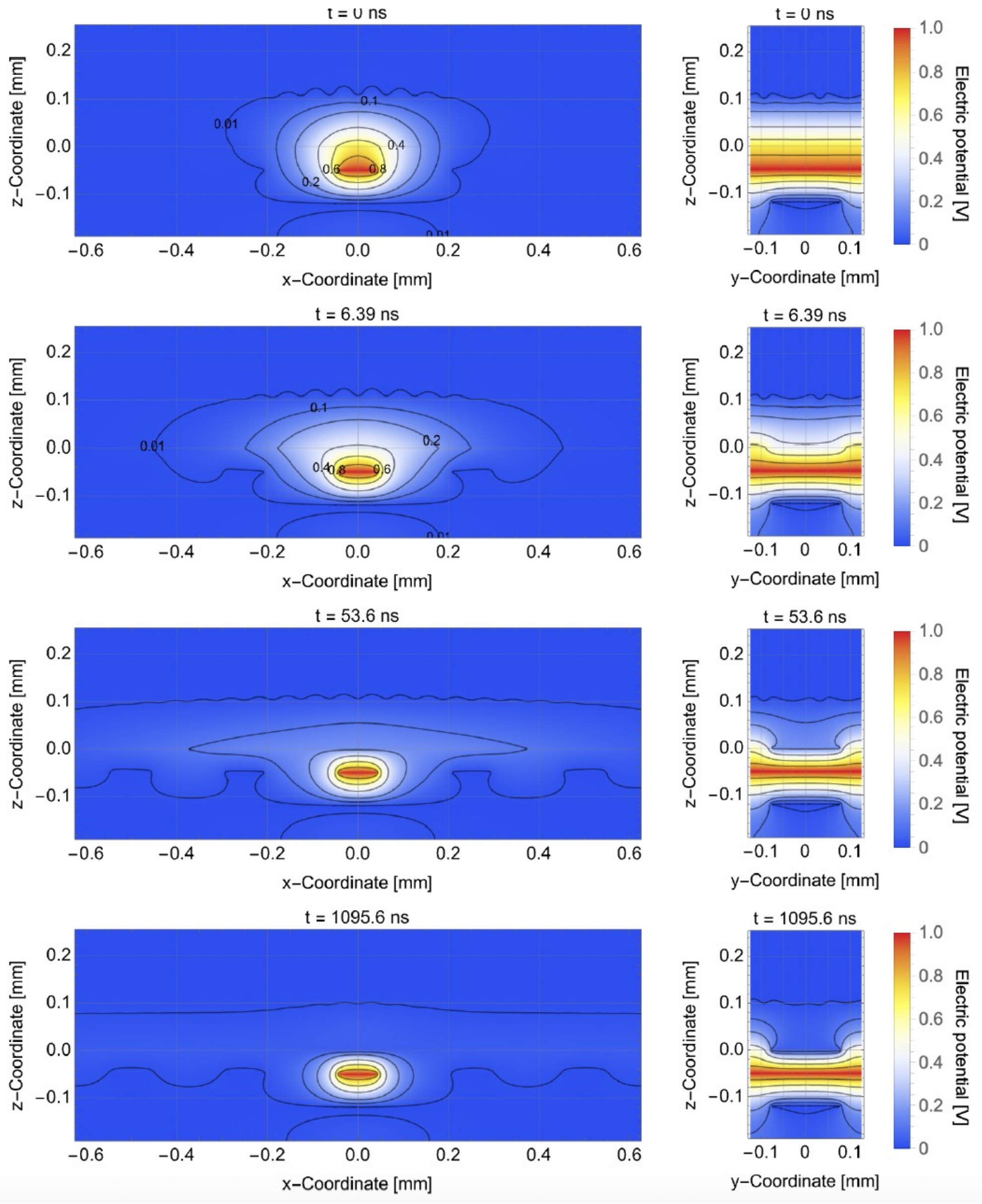
M. Bianco, et al., NIM-A814 (2016) 117.

Simulation

Using a finite element method approach, the weighting potential is calculated numerically.

The solution is represented by N time-sliced potential maps, where linear interpolation is used to cover the entire time range.





For more details on the simulation method:
D. Janssens et al., Nucl. Instrum. Meth. A 1040 (2022)
D. Janssens et al., JINST 18 (2023) 08, C08010

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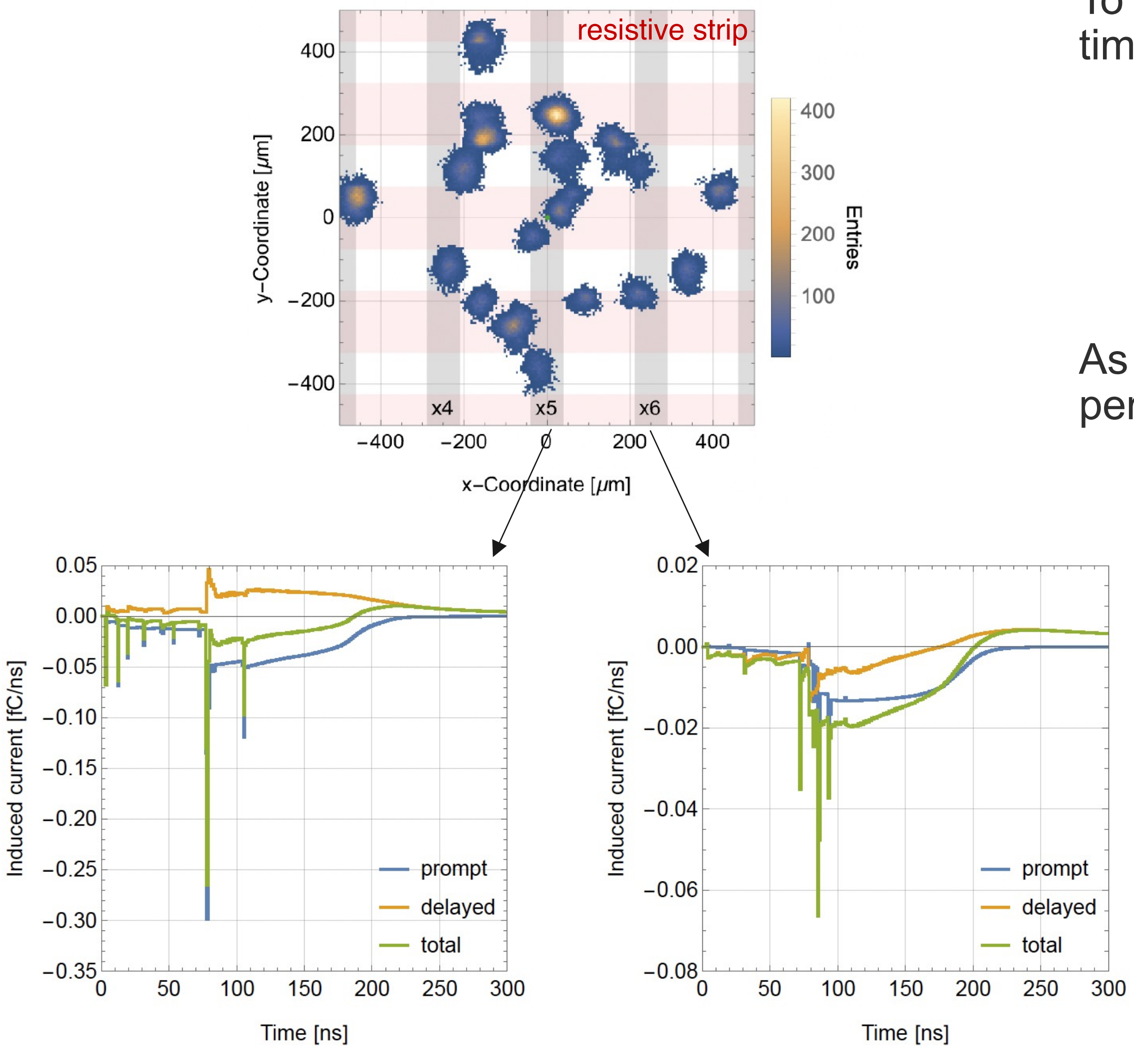
Simulation

electron endpoints for a 150 GeV/c μ event



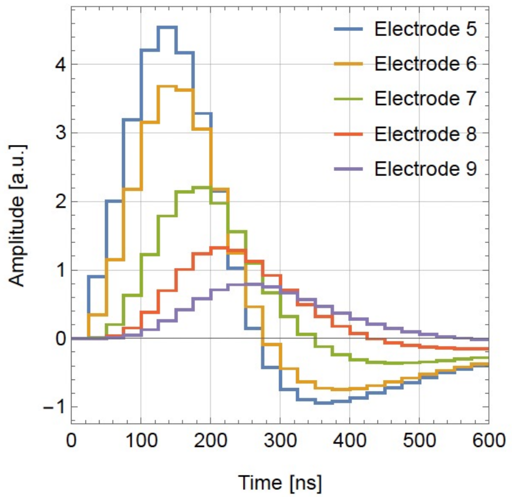
To emulate the response of the APV25 ASIC we assumed a peaking time of 50 ns, and a first order shaping

$$f(t) = g e^{n} \left(\frac{t}{t_p} \right)^{n} e^{-\frac{t}{\tau}}$$

As this chip is sampling at 40 MHz, the bulk of the simulations were performed using 25 ns wide time bins.

convolution

APV25

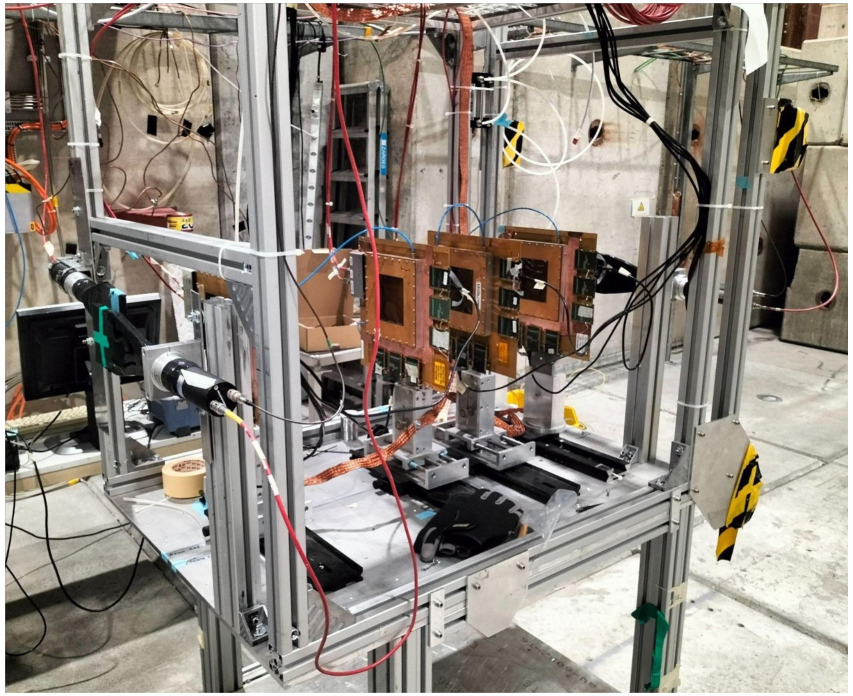


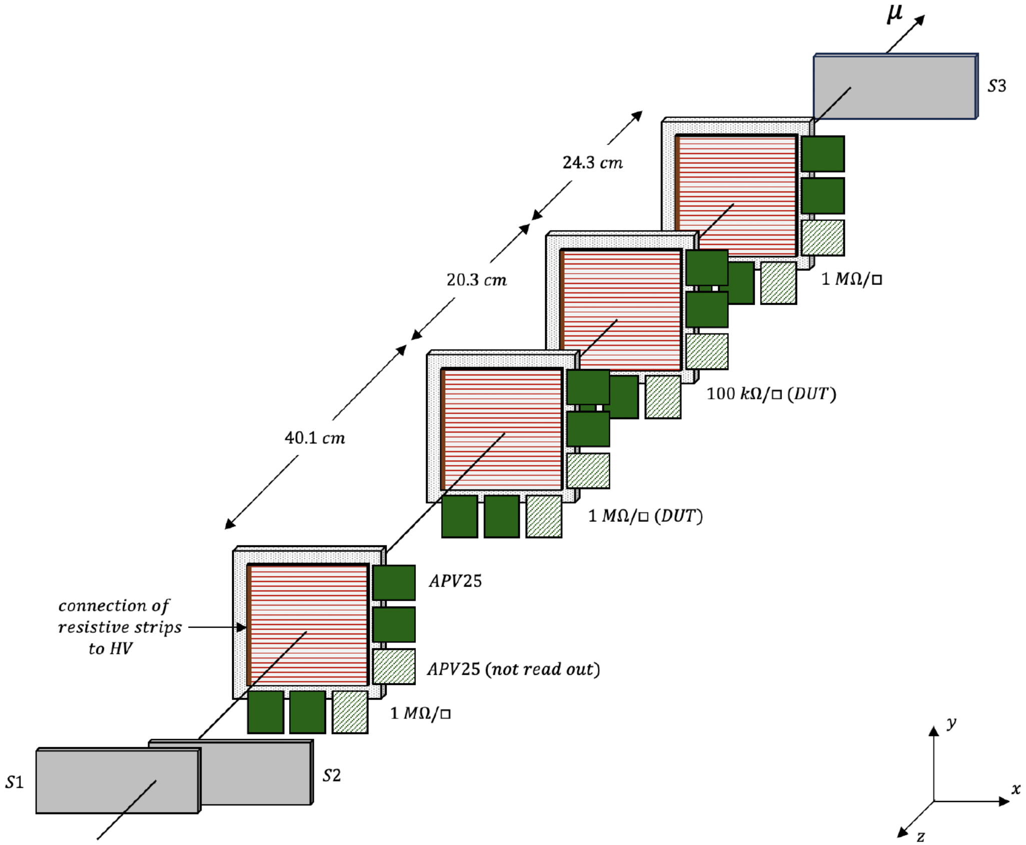
As an example of a unipolar shaper, we took the APV25 with parameters taken from this link

Signal measurement of a resistive strip MicroMegas

Measurement

During the RD51 test beam campaigns at the CERN SPS H4 beamline we measured the induced signal in two different resistive strip bulk MicroMegas detectors are used a tracking telescope read out by APV25 ASICs.

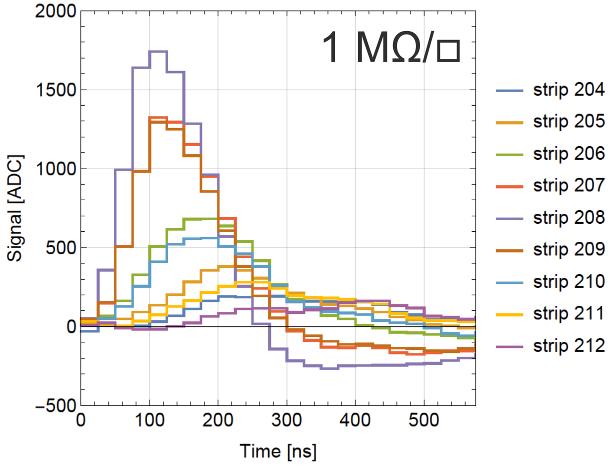


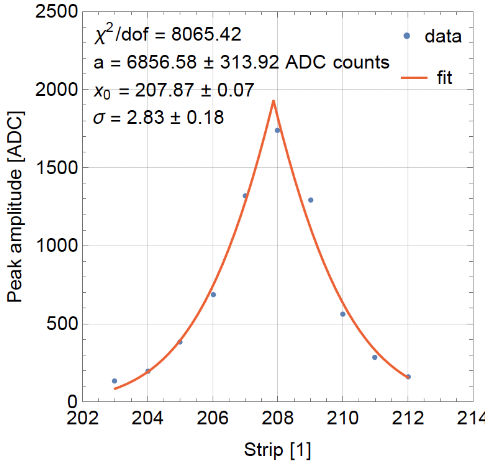


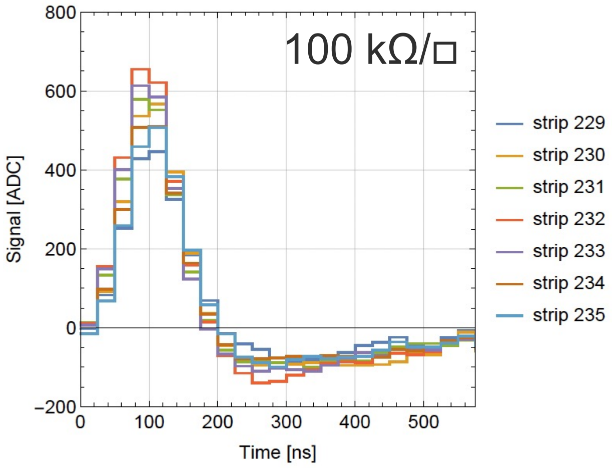
Measurement

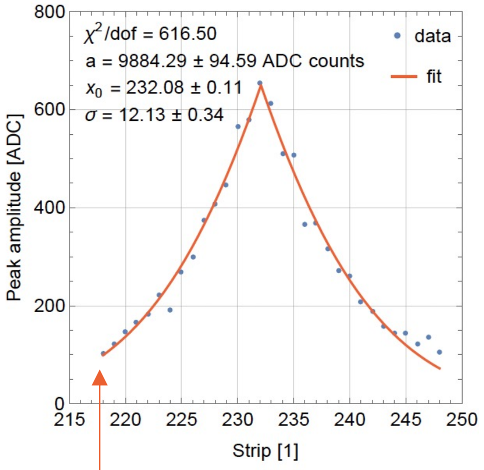
The raw signal shapes were recorded for two sets of surface resistivities (nominal values of 100 kΩ/□ and 1 MΩ/□). The recorded data reflect the impact of the change in surface resistivity.

Example of recorded events:





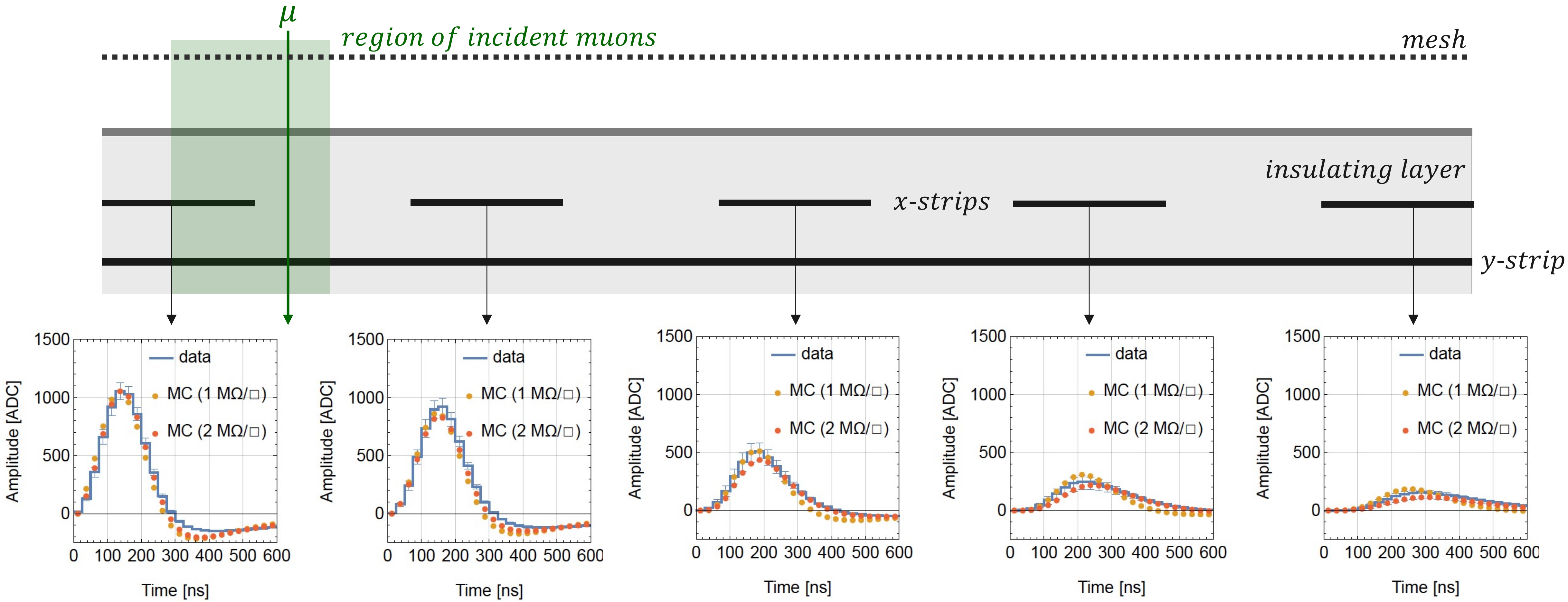




$$f(x) = a\frac{|x-x_0|\left(\mathrm{erf}\left(\frac{|x-x_0|}{\sqrt{2}\sigma}\right)-1\right)+\sqrt{\frac{2}{\pi}}\sigma e^{-\frac{(x-x_0)^2}{2\sigma^2}}}{\sigma^2}$$

Comparison between simulation and measurement

For the comparison we look at the average induced current response of neighboring strips. This averaging is performed over muon events positioned between the leading and the next-to-leading strip.



Summary

We want to benchmark on the level of the signal shape to gauge the accuracy of the signal induction modeling in the presence of resistive elements. For this, we take the resistive strip MM as an example.

- We discussed the numerical approach used for applying the extended form of the Ramo-Shockley theorem to the calculation of induced signals in resistive particle detectors.
- Different techniques are used (such as coordinate scaling and implementing external impedance elements) to represent the signal shape over the complete time range accurately.
- Both the amplification gap size and ion tail duration were measured, and their corresponding values included in the simulation.
- Within the systematic uncertainty of the calculation – mainly driven by the uncertainty regarding the precise surface resistivity value – the simulation results agree with the experimental data.

Thank you for your attention!