Introduction to Gaseous Detectors

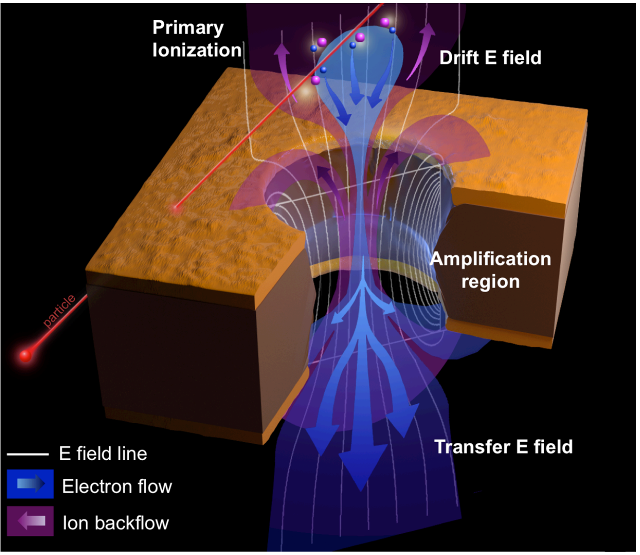
Detector Signals

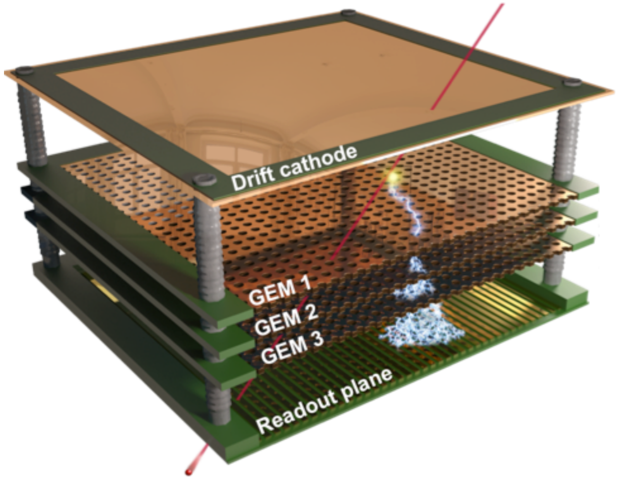
Jeremie A. MERLIN

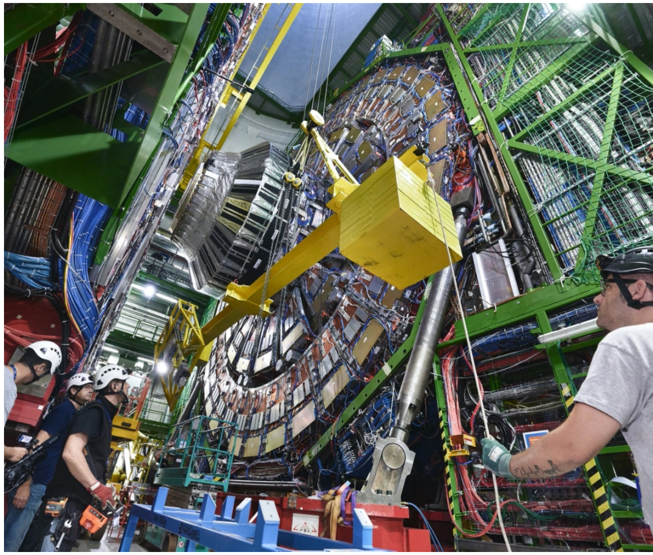
Detector lecture - III

Organized at University of Seoul, Seoul

January, 2024







Introducing Myself

Jeremie A. Merlin
Particle Physicist
Specialized in Detector Physics

- I joined the CMS GEM upgrade project in 2011

- My main responsibility is to coordinate the development of the triple-GEM technology for the CMS upgrade and to manage the production and quality control of the detectors

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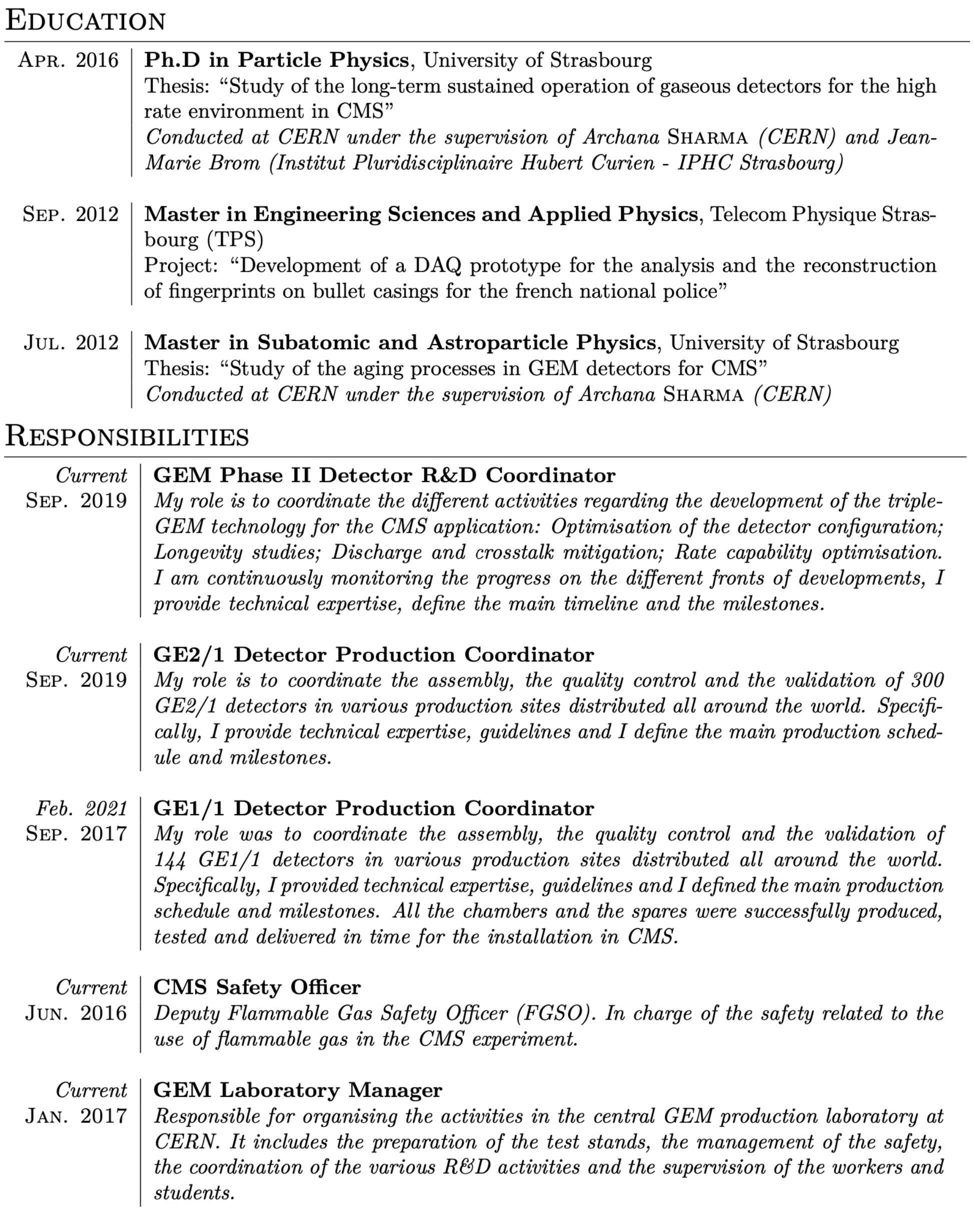


EDUCATION

APR. 2016 | **Ph.D in Particle Physics**, University of Strasbourg
Thesis: "Study of the long-term sustained operation of gaseous detectors for the high rate environment in CMS"
Conducted at CERN under the supervision of Archana SHARMA *(CERN) and Jean-Marie Brom (Institut Pluridisciplinaire Hubert Curien - IPHC Strasbourg)*

SEP. 2012 | **Master in Engineering Sciences and Applied Physics**, Telecom Physique Strasbourg (TPS)
Project: "Development of a DAQ prototype for the analysis and the reconstruction of fingerprints on bullet casings for the french national police"

JUL. 2012 | **Master in Subatomic and Astroparticle Physics**, University of Strasbourg
Thesis: "Study of the aging processes in GEM detectors for CMS"
Conducted at CERN under the supervision of Archana SHARMA *(CERN)*

RESPONSIBILITIES

Current SEP. 2019 | **GEM Phase II Detector R&D Coordinator**
My role is to coordinate the different activities regarding the development of the triple-GEM technology for the CMS application: Optimisation of the detector configuration; Longevity studies; Discharge and crosstalk mitigation; Rate capability optimisation. I am continuously monitoring the progress on the different fronts of developments, I provide technical expertise, define the main timeline and the milestones.

Current SEP. 2019 | **GE2/1 Detector Production Coordinator**
My role is to coordinate the assembly, the quality control and the validation of 300 GE2/1 detectors in various production sites distributed all around the world. Specifically, I provide technical expertise, guidelines and I define the main production schedule and milestones.

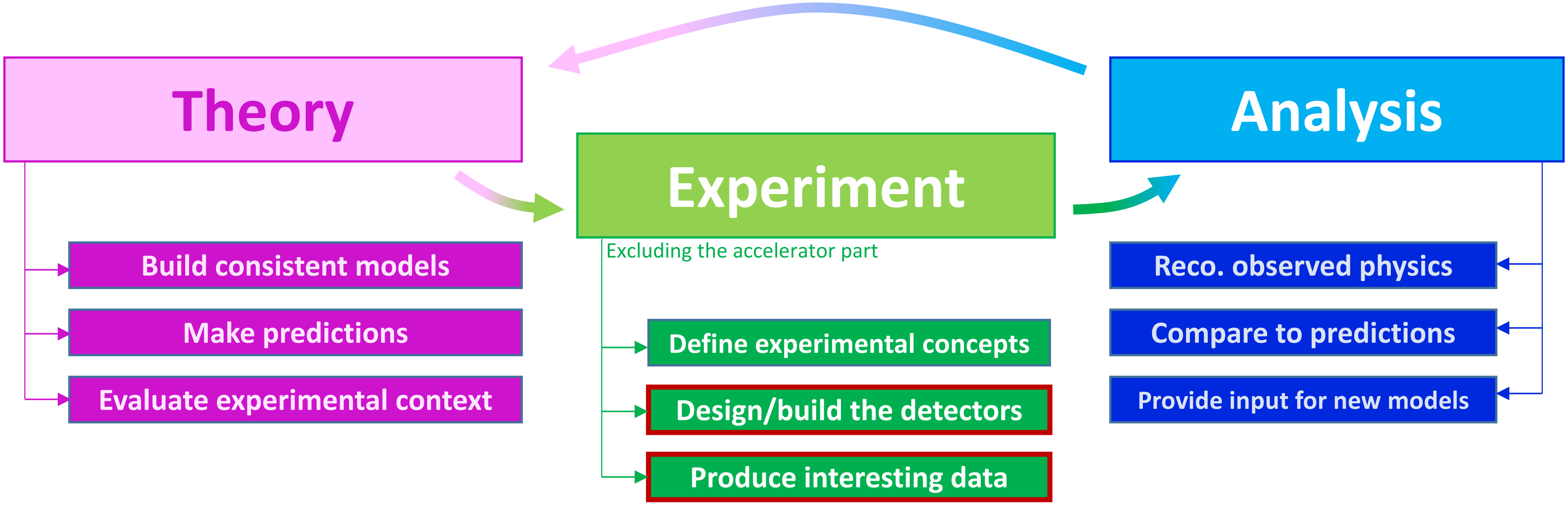
Feb. 2021 SEP. 2017 | **GE1/1 Detector Production Coordinator**
My role was to coordinate the assembly, the quality control and the validation of 144 GE1/1 detectors in various production sites distributed all around the world. Specifically, I provided technical expertise, guidelines and I defined the main production schedule and milestones. All the chambers and the spares were successfully produced, tested and delivered in time for the installation in CMS.

Current JUN. 2016 | **CMS Safety Officer**
Deputy Flammable Gas Safety Officer (FGSO). In charge of the safety related to the use of flammable gas in the CMS experiment.

Current JAN. 2017 | **GEM Laboratory Manager**
Responsible for organising the activities in the central GEM production laboratory at CERN. It includes the preparation of the test stands, the management of the safety, the coordination of the various R&D activities and the supervision of the workers and students.

Introduction

Simplified view



Theory

- Build consistent models
- Make predictions
- Evaluate experimental context

Experiment

Excluding the accelerator part

- Define experimental concepts
- Design/build the detectors
- Produce interesting data

Analysis

- Reco. observed physics
- Compare to predictions
- Provide input for new models

- **Experimental physics - Detector physics**

- What is the final purpose ? → Detect particles
- **How to detect particle ? → Based on the particle/matter interaction processes**
- How to design and build detectors ? → various options

(- How to install and operate detectors)

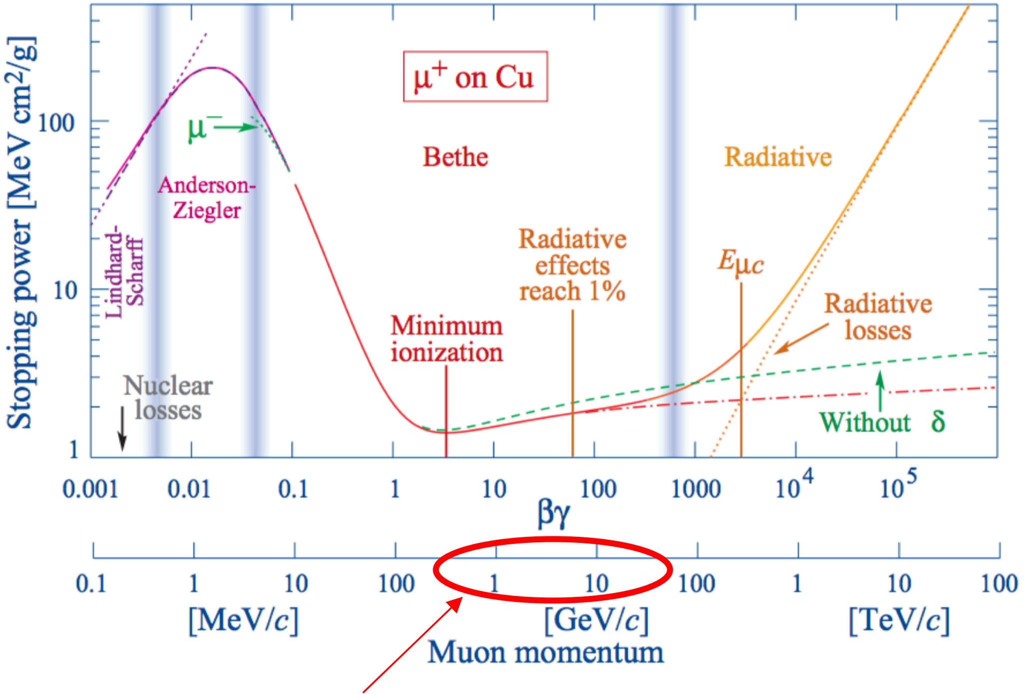
- **Lets see some examples**

Charged Particles

Coulomb interactions between charged particle and atomic electrons

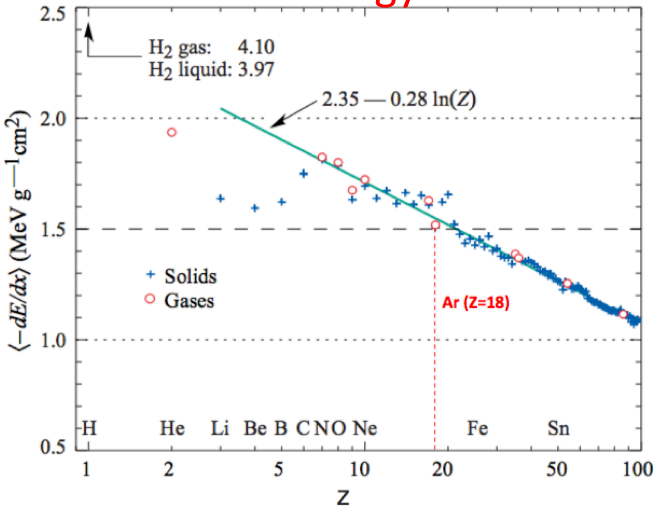
→ Energy loss is derived from the Bethe-Bloch formula:

$$-\left\langle\frac{dE}{dx}\right\rangle = \frac{2\pi e^4 z^2}{m_e c^2 \beta^2} NZ \left[ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_m}{I^2}\right) - 2\beta^2 - \delta(\beta\gamma)\right]$$



Interesting energy range close to the minimum ionizing (MIP)

MIP energy loss



With Ar atoms (Z=18):

$$-\left\langle\frac{dE}{dx}\right\rangle = \mathbf{1.53\ MeV\ g^{-1}cm^2}$$

Energy loss in 3mm Ar gas :

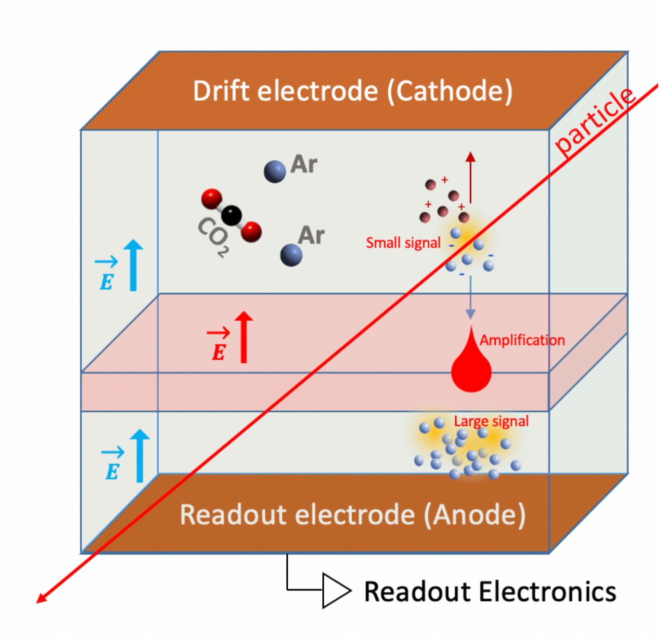
$$\Delta E = -\left\langle\frac{dE}{dx}\right\rangle \times\rho\times d = \mathbf{861\ eV/(3mm)}$$

Ionization – total number of primary **e⁻** :

$$n_T = \Delta E\times\left[\frac{70\%}{W_i(Ar)} + \frac{30\%}{W_i(CO_2)}\right] = 861\times\left[\frac{0.7}{26} + \frac{0.3}{33}\right] \sim \mathbf{31\ pairs}$$

Understand the context

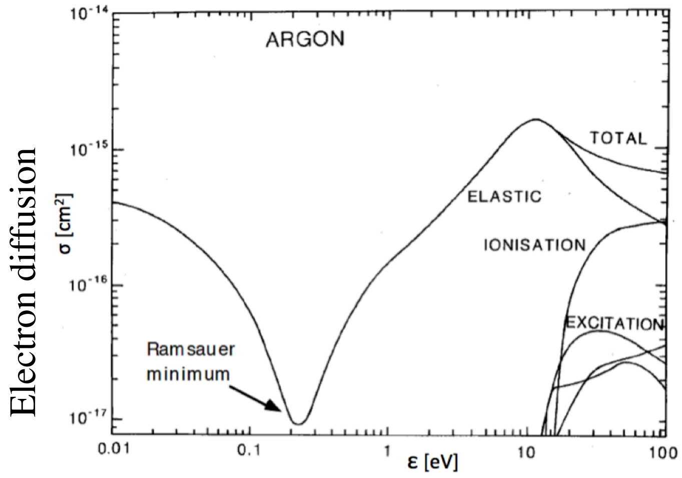
Transport and Amplification

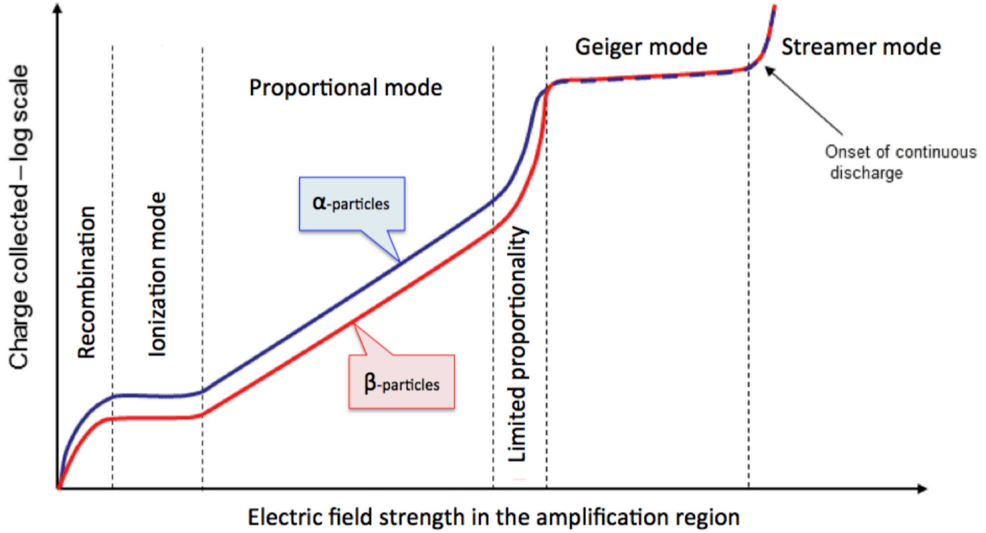


- **Charge transport and diffusion in gas medium**
- **Amplification process**

$$M = exp\left[\int_{x_1}^{x_2} \alpha(x)dx\right]$$

- **Gas mixture**
  - Ionization
  - Quenching gases
  - Cold gases





Gas	Z	Density [mg cm^{-3}]	E_X [eV]	E_I [eV]	W_I [eV]	$(dE/dx)_{MIP}$ [keV cm^{-1}]	N_P [cm^{-1}]	N_T [cm^{-1}]
He	2	0.179	19.8	24.6	41.3	0.32	3.5	8
Ne	10	0.839	16.7	21.6	37	1.45	13	40
Ar	18	1.66	11.6	15.7	26	2.53	25	97
Xe	54	5.495	8.4	12.1	22	6.87	41	312
CH_4	10	0.667	8.8	12.6	30	1.61	28	54
iC_4H_{10}	34	2.49	6.5	10.6	26	5.67	90	220
C_2H_6	18	1.26	8.2	11.5	26	2.91	48	112
CO_2	22	1.84	7.0	13.8	34	3.35	35	100
CF_4	42	3.78	10.0	16.0	54	6.38	63	120

Some gas transport properties

Various Signal Natures

→ **Charges are released by the interaction of a crossing particle**

→ **Charges can interact with the detector medium**

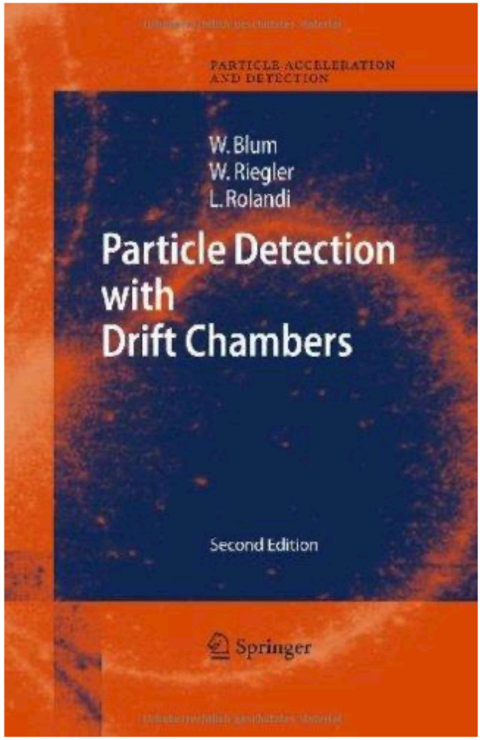
→ **How to "readout" the charges ?**

- **Cloud chambers:** charges create drops
- **Bubble chambers**: charges create bubble
- **Emulsion chambers**: charges change the film opacity
- **Spark chambers**: charges trigger streamers
- **Gas and solid-state detectors**: charges induce **electrical signals**

Charges can be amplified to induce larger signals

What is the process behind signal generation ?

+ W. Riegler at RD51 shool (2014)



PARTICLE ACCELERATION AND DETECTION

W. Blum
W. Riegler
L. Rolandi

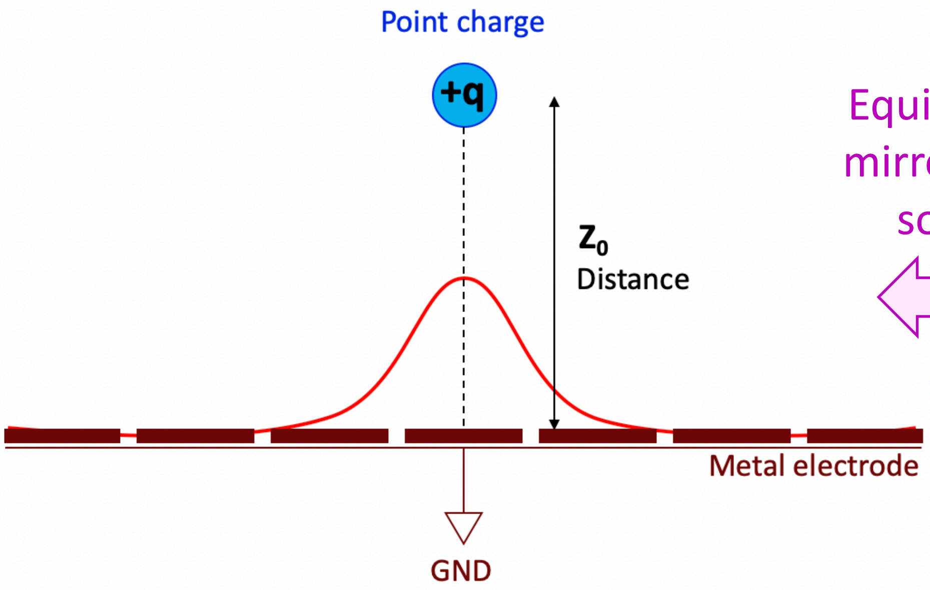
Particle Detection with Drift Chambers

Second Edition

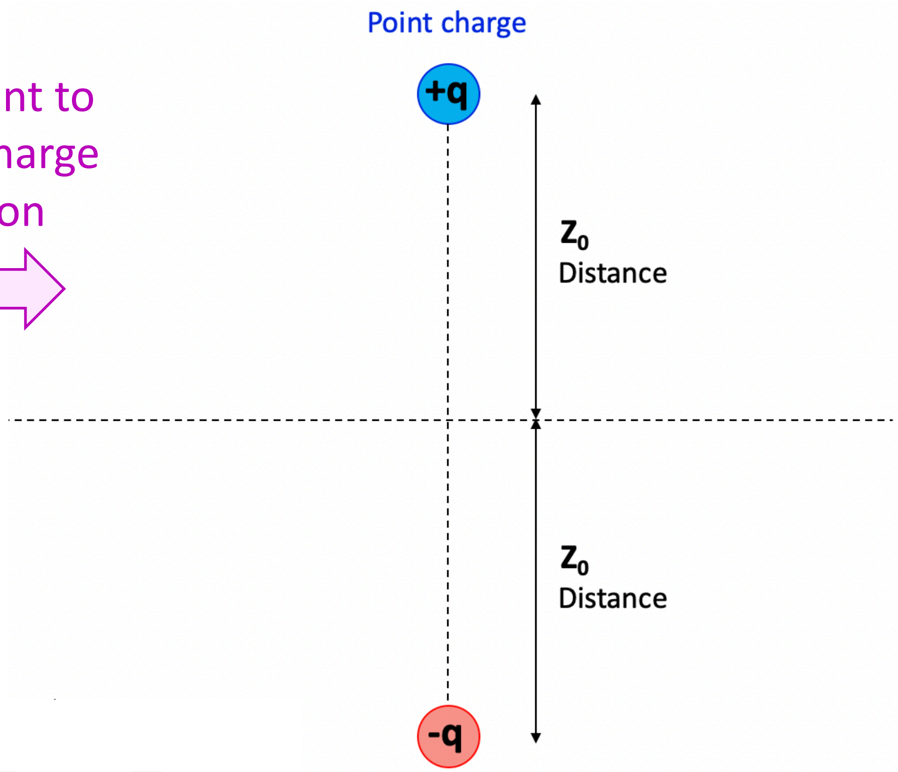
Springer

Induced Signals

- A point charge at a distance Z_0 of a grounded metal plate induces a surface charge



Equivalent to mirror charge solution



- From Coulomb's law:

$$E_z(x, y) = -\frac{q z_0}{2\pi\varepsilon_0 (x^2 + y^2 + z_0^2)^{\frac{3}{2}}} \qquad E_x = E_y = 0$$

permittivity

Induced Signals

❖ Electrostatics (Poisson equation):

Charge density

$$\Delta\varphi = -\frac{\rho}{\varepsilon_0} \qquad \vec{E} = -\vec{\nabla}\varphi$$

Electric potential

❖ From Gauss' law:

Enclosed volume

$$\oint \vec{E}\, d\vec{A} = \frac{1}{\varepsilon_0}\oint \rho\, dV$$

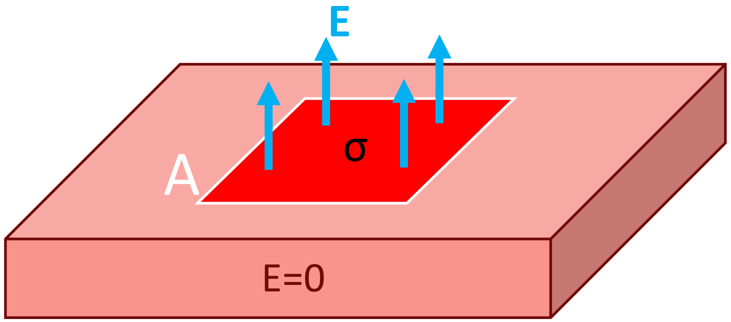
Surface

Surface charge density

$$\sigma = \frac{q}{A}$$

Perfect conductor

- Electric field E is perpendicular to the metal surface
- Charges are only on the surface



Perfect conductor

$$E\,A = \frac{1}{\varepsilon_0}\,\sigma\,A \qquad \rightarrow \qquad \boxed{\sigma = \varepsilon_0 E}$$

Induced Signals

- Combining Coulomb’s law and Gauss’ law we find the surface charge density:

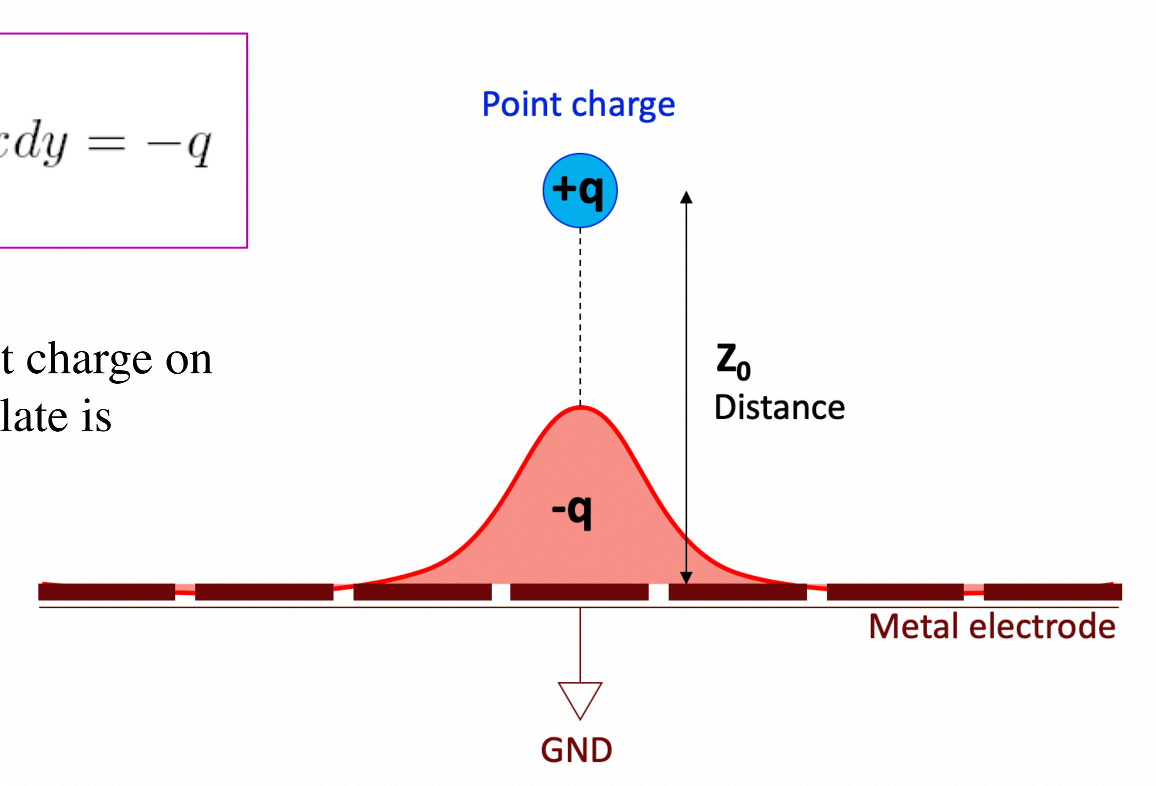
$$\sigma(x,y) = \varepsilon_0 E_z(x,y) = -\frac{q z_0}{2\pi(x^2+y^2+z_0^2)^{\frac{3}{2}}}$$

- Integrating over the entire surface we find the total induced charge:

$$\boxed{Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sigma(x,y)dxdy = -q}$$

The total charge induced by a point charge on a infinitely large grounded metal plate is equal to the point charge

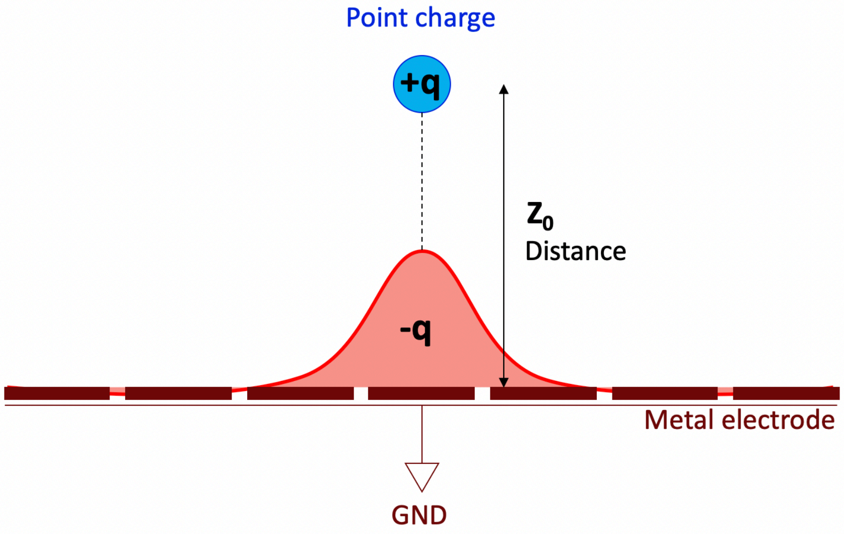
→ Regardless the distance Z_0

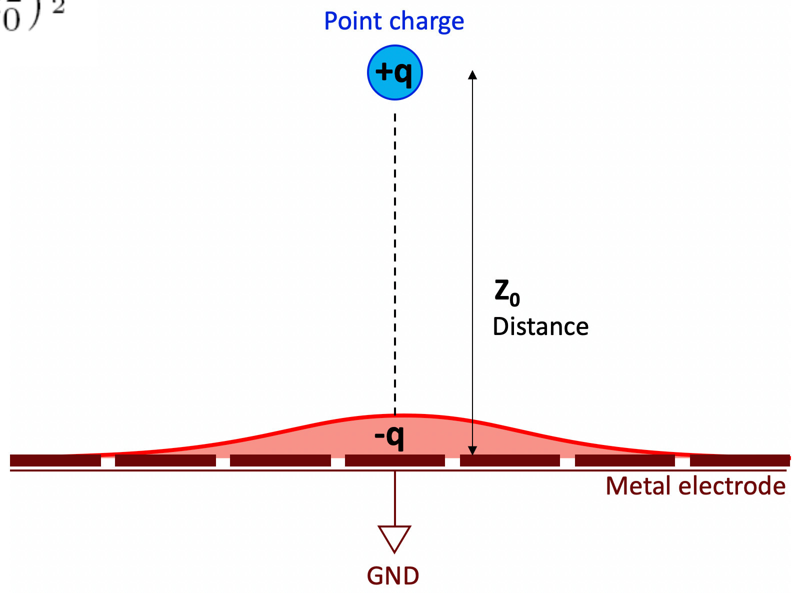


Induced Signals

- But the surface charge distribution depends on the distance Z_0

$$\sigma(x,y) = \varepsilon_0 E_z(x,y) = -\frac{q z_0}{2\pi(x^2+y^2+z_0^2)^{\frac{3}{2}}}$$





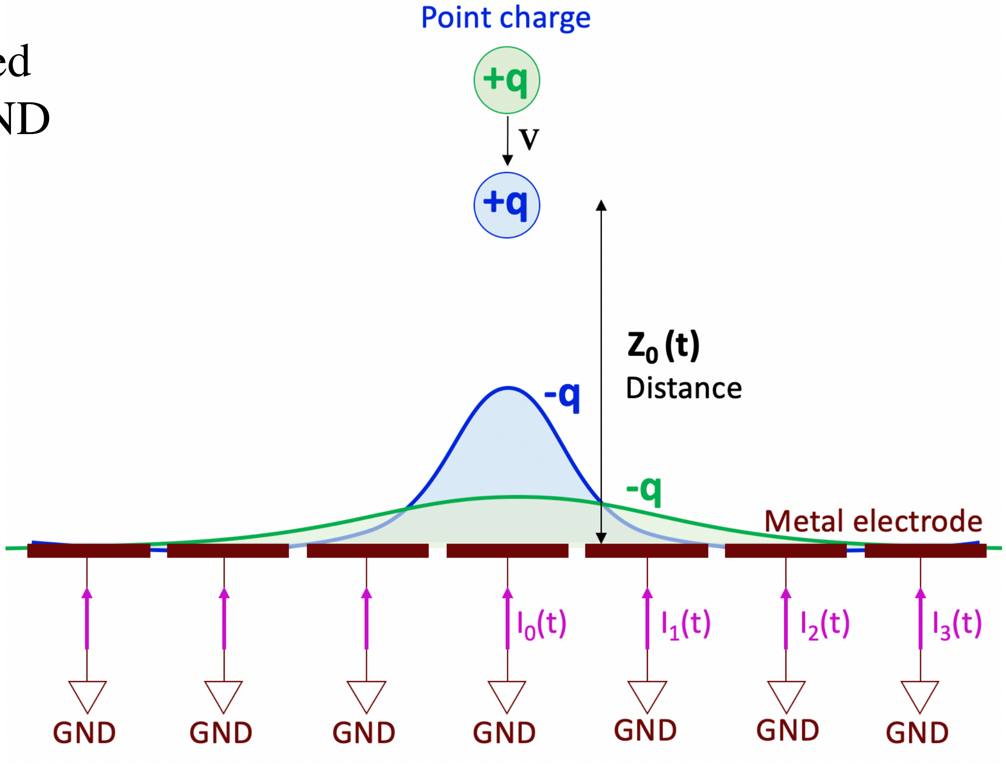
The further the point charge is, the more spread the total charge

→ If the metal electrode is divided into multiple strips, each strips will “see” a different induced charge that changes with the point charge distance

→ The sum of all strips induced charges still remain equal to the point charge

Induced Signals

- ❖ If the point charge is moving, an induced current will flow between strips and GND



Stationary case

$$\boxed{Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sigma(x,y)dxdy = -q}$$

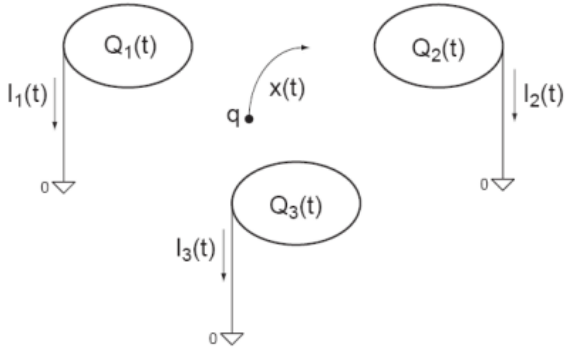
Moving charge case

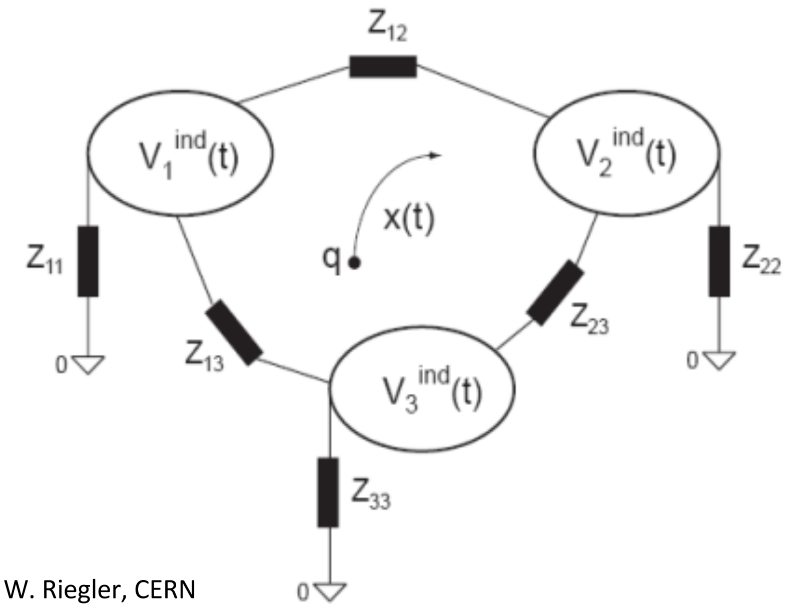
$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2} \sigma(x,y)dxdy = -\frac{2q}{\pi}\arctan\left(\frac{w}{2z_0}\right) \qquad z_0(t) = z_0 - vt$$

$$I_1^{ind}(t) = -\frac{d}{dt}Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0}\frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]}v$$

Induced Signals

- But … in reality, RO strips are not connected to GND but to readout electronics and have interconnections between them
- How to calculate the induced voltage on each strip ?

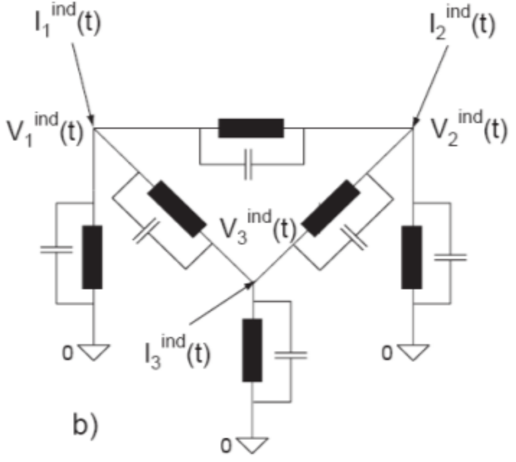




W. Riegler, CERN

Step 1: calculate the induced current on grounded electrodes

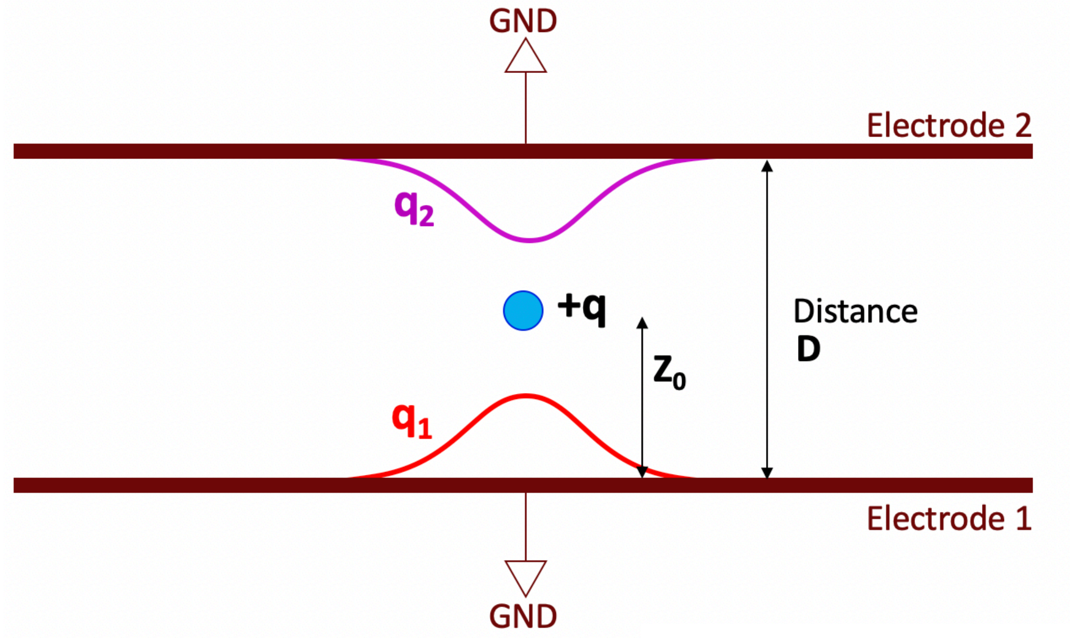
Step 2: use calculated currents as ideal current sources in a circuit including interconnections and mutual capacitances



Not covered in this lecture → mostly using simulation programs

Example

- Example with the parallel plate configuration



Electric Potential ⟶ $$\phi(r,z) = \frac{q}{\varepsilon_0 \pi D} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi}{D} z\right) \sin\left(\frac{n\pi}{D} z_0\right) K_0\left(\frac{n\pi}{D} r\right)$$

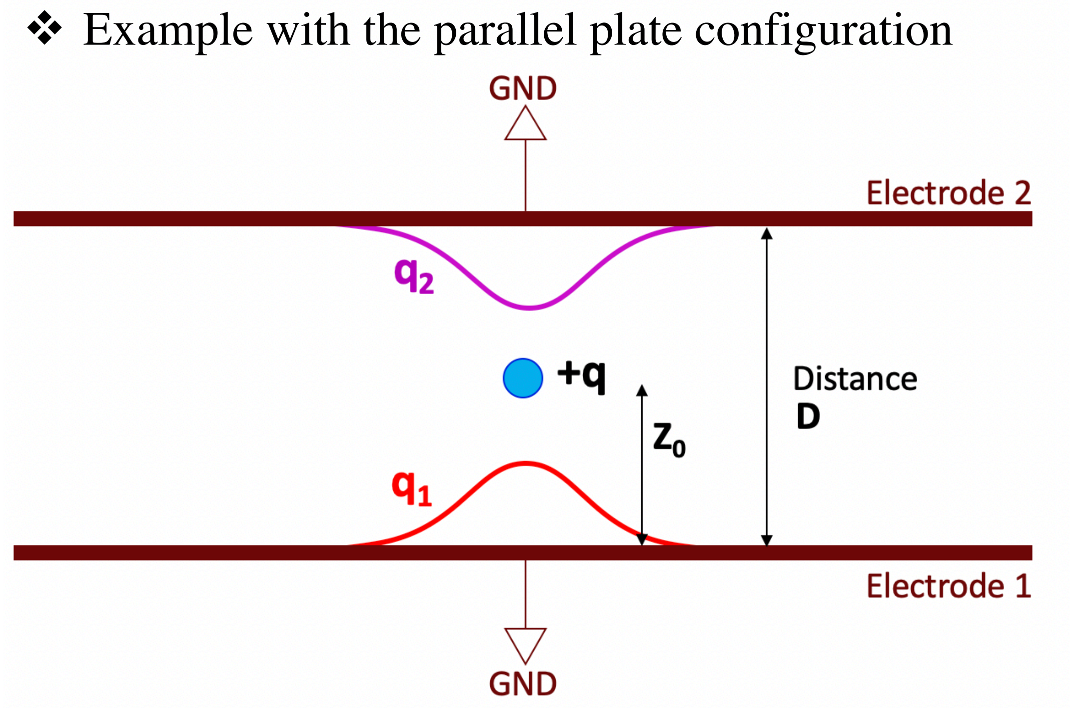
Electric field ⟶ $$E(r,z) = \frac{q}{\varepsilon_0 \pi D} \sum_{n=1}^{\infty} \frac{n\pi}{D} \cos\left(\frac{n\pi}{D} z\right) \sin\left(\frac{n\pi}{D} z_0\right) K_0\left(\frac{n\pi}{D} r\right)$$

Surface charge density ⟶ $$\sigma_1(r) = \varepsilon_0 E(r, z=0) = \frac{q}{\pi D} \sum_{n=1}^{\infty} \frac{n\pi}{D} \sin\left(\frac{n\pi}{D} z_0\right) K_0\left(\frac{n\pi}{D} r\right)$$

[5] C. Y. Fong, C. Kittel, Induced Charge on Capacitor Plates, Am. J . Phys. 35(1967)1091.

Example

- Example with the parallel plate configuration



Induced charge on Electrode 1

$$q_1 = \int_0^{\infty} 2r\pi\sigma(r)dr = \frac{q}{\pi D}\sum_{n=1}^{\infty}\frac{n\pi}{D}\sin\left(\frac{n\pi}{D}z_0\right)\int_0^{\infty} 2r\pi K_0\left(\frac{n\pi}{D}r\right)dr = \frac{2q}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin\left(\frac{n\pi}{D}z_0\right) = -q\left(1-\frac{z_0}{D}\right)$$

Similarly

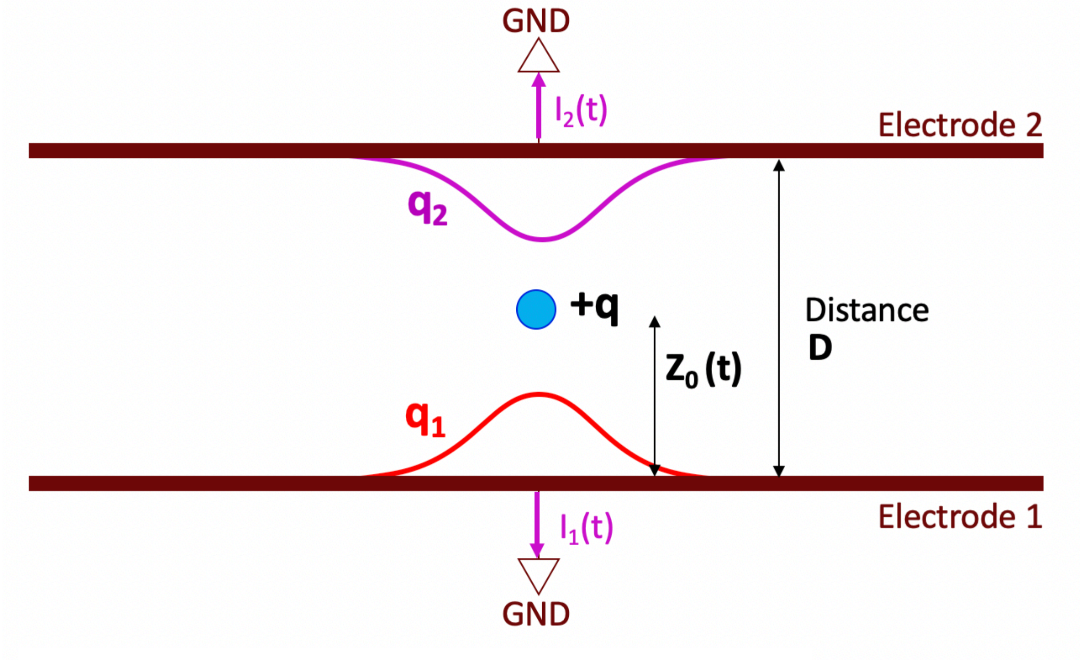
Induced charge on Electrode 2

$$q_2 = \ldots = -q\,\frac{z_0}{D}$$

$$\boxed{q_1 + q_2 = -q}$$

Example

- Example with the parallel plate configuration



- The sum of all induced charges is equal to the moving charge at any time
- The sum of all induced current is zero at any time

Complicated calculation method: need to calculate total field variations from fixed space charges, moving charge and bias voltage

→ Easier way to calculate the induced signals?

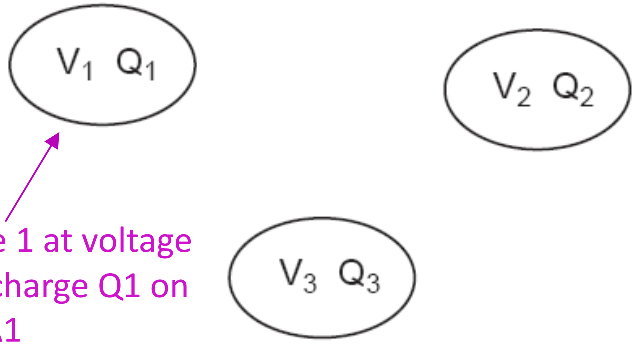
$$q_1 = -q\left(1 - \frac{z_0}{D}\right) \qquad q_2 = -q\frac{z_0}{D} \qquad z_0(t) = vt$$

$$q_1(t) = -q\left(1 - \frac{vt}{D}\right) \qquad q_2(t) = -q\frac{vt}{D} \qquad \boxed{q_1(t) + q_2(t) = q}$$

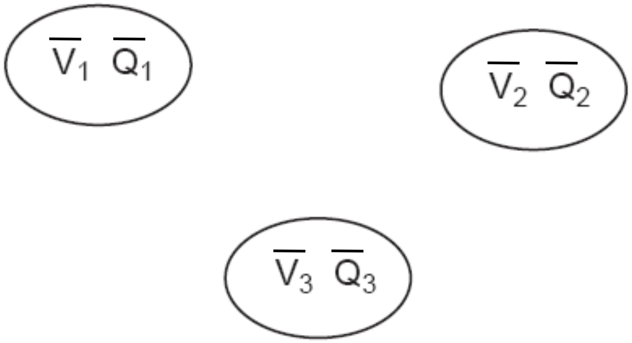
$$I_1(t) = -\frac{dq_1(t)}{dt} = -\frac{qv}{D} \qquad I_2(t) = -\frac{dq_2(t)}{dt} = +\frac{qv}{D} \qquad \boxed{I_1(t) + I_2(t) = 0}$$

Induced Signals

- Lets consider two electrostatic states



Electrode 1 at voltage V1 with charge Q1 on surface A1



Laplace equation: $\Delta\varphi = 0$ $\qquad$ $\Delta\psi = 0$

Boundary conditions: $\varphi|_{\vec{A}_1} = V_1 \quad \varphi|_{\vec{A}_2} = V_2 \quad \varphi|_{\vec{A}_3} = V_3$ $\qquad$ $\psi|_{\vec{A}_1} = \overline{V}_1 \quad \psi|_{\vec{A}_2} = \overline{V}_2 \quad \psi|_{\vec{A}_3} = \overline{V}_3$

$$Q_1 = \oint_{\vec{A}_1} -\vec{\nabla}\varphi\, d\vec{A} \qquad Q_2 = \oint_{\vec{A}_2} -\vec{\nabla}\varphi\, d\vec{A} \qquad Q_3 = \oint_{\vec{A}_3} -\vec{\nabla}\varphi\, d\vec{A}$$

$$\overline{Q}_1 = \oint_{\vec{A}_1} -\vec{\nabla}\psi\, d\vec{A} \qquad \overline{Q}_2 = \oint_{\vec{A}_2} -\vec{\nabla}\psi\, d\vec{A} \qquad \overline{Q}_3 = \oint_{\vec{A}_3} -\vec{\nabla}\psi\, d\vec{A}$$

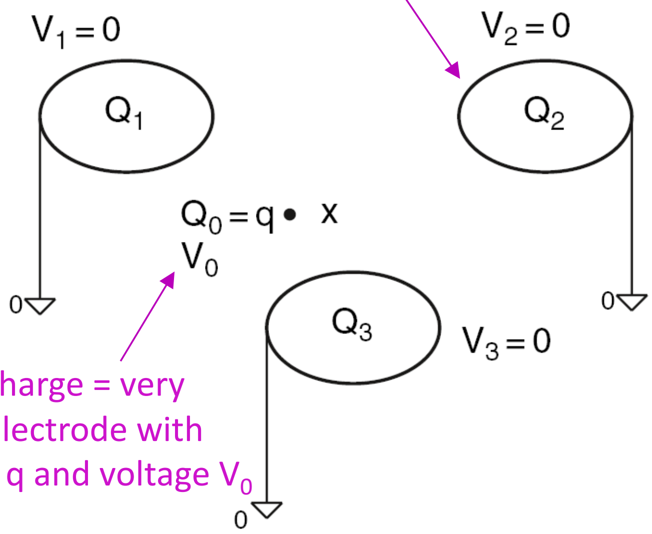
Green’s second identity: $$\oint_{\vec{A}} \left(\varphi\vec{\nabla}\psi - \psi\vec{\nabla}\varphi\right) d\vec{A} = \oint_{V} (\varphi\Delta\psi - \psi\Delta\varphi)\, dV$$

Green’s Reciprocity Theorem: $$\boxed{\sum_{n=1}^{N} Q_n \overline{V}_n = \sum_{n=1}^{N} \overline{Q}_n V_n}$$

This relation ”connects” the two electrostatic states

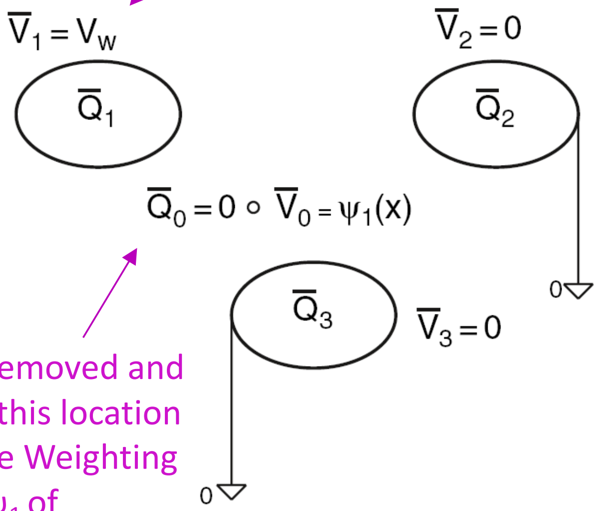
Induced Signals

- Lets consider two electrostatic states and a point charge



All electrodes grounded

Point charge = very small electrode with charge q and voltage V_0



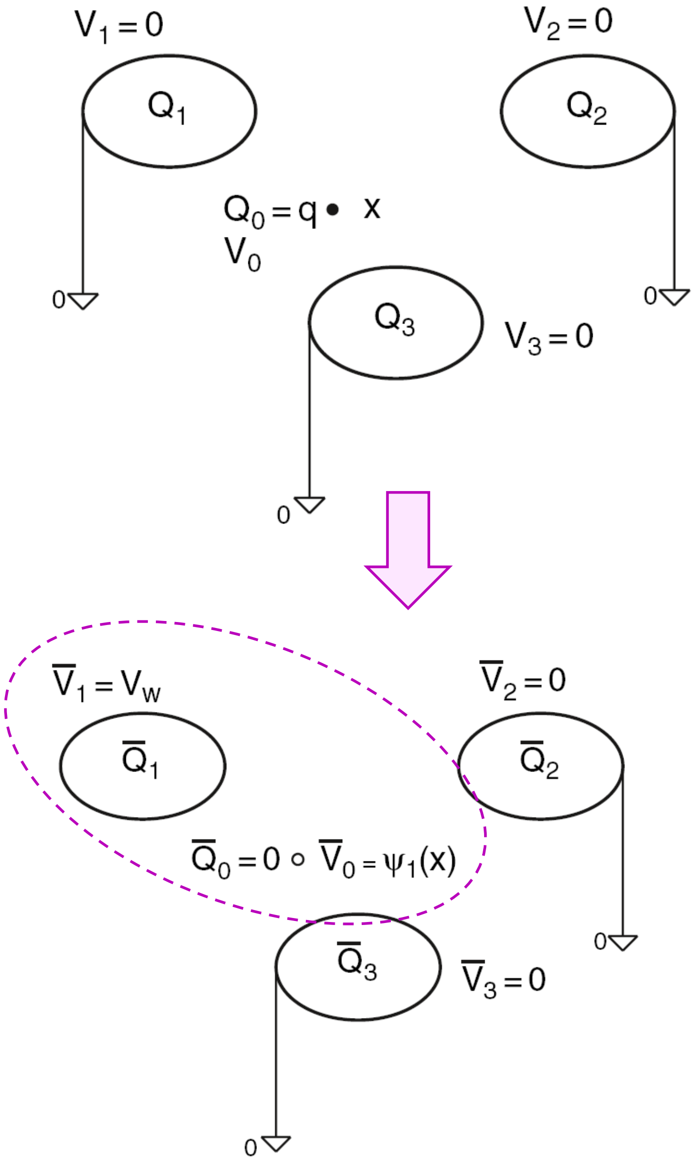
Electrode 1 now at voltage V_w

Charge is removed and voltage at this location is set to the Weighting Potential ψ_1 of electrode 1

Using the Reciprocity Theorem: $$\sum_{n=1}^{N} Q_n \overline{V}_n = \sum_{n=1}^{N} \overline{Q}_n V_n$$

We get: $$q\overline{V}_0 + Q_1 V_w = 0 \quad \rightarrow \quad \boxed{Q_1 = -q\frac{\overline{V}_0}{V_w}.}$$

Induced Signals



Methodology:

The charge induced by the point charge (at position x) on a grounded electrode can be calculated:

1. Remove the point charge
2. Put the electrode in question at voltage V_w
3. Put all other electrodes to ground

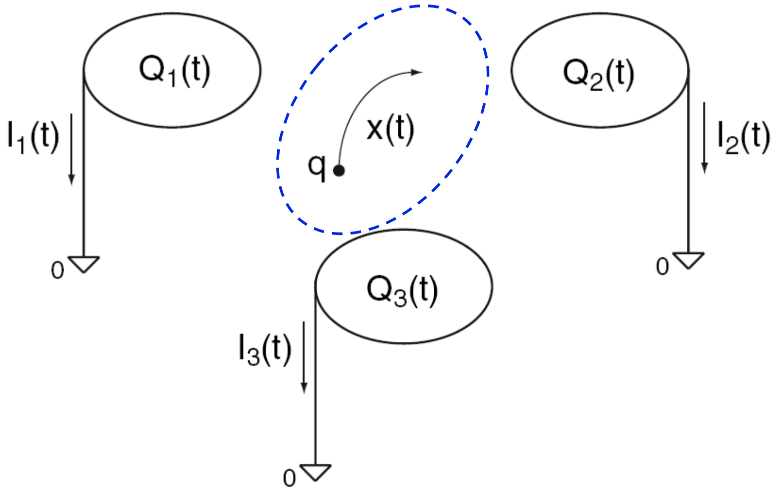
→ It defines the Weighting potential ψ_1 at position x
→ The induced charge is therefore given by:

$$\boxed{Q_1 = -\frac{q}{V_w}\psi_1(x)}$$

Induced Signals

- ❖ What happens when the charge is moving ?

→ Ramo-Shockley theorem



Static

$$\boxed{Q_1 = -\frac{q}{V_w}\psi_1(x)}$$

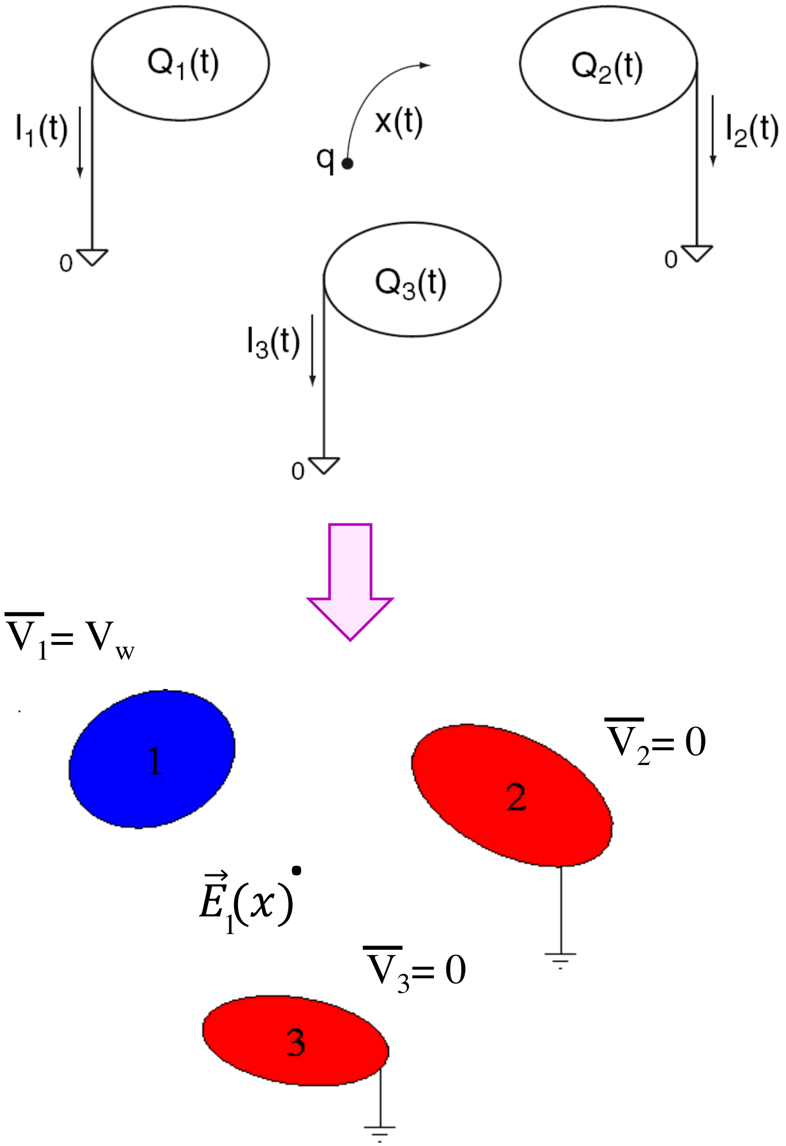
Moving along trajectory x(t)

$$\boxed{Q(t) = -\frac{q}{V_u}\psi_1(\vec{x}(t))}$$

- ❖ Induced current:

$$I_1(t) = -\frac{dQ_1}{dt} = \frac{q}{V_w}\vec{\nabla}\psi_1(\vec{x}(t))\,\frac{d\vec{x}(t)}{dt} = \underbrace{-\frac{q}{V_w}\vec{E}\left(\vec{x}(t)\right)}_{\text{Weighting field}}\overbrace{\vec{v}(t)}^{\text{True carrier velocity}}$$

Induced Signals



Methodology: **Ramo-Shockley theorem**

The charge induced by a moving point charge on a trajectory x(t) on a grounded electrode can be calculated:

1. Remove the point charge
2. Put the electrode in question at voltage V_w
3. Put all other electrodes to ground

→ It defines the Weighting Field E_1 at position x(t)

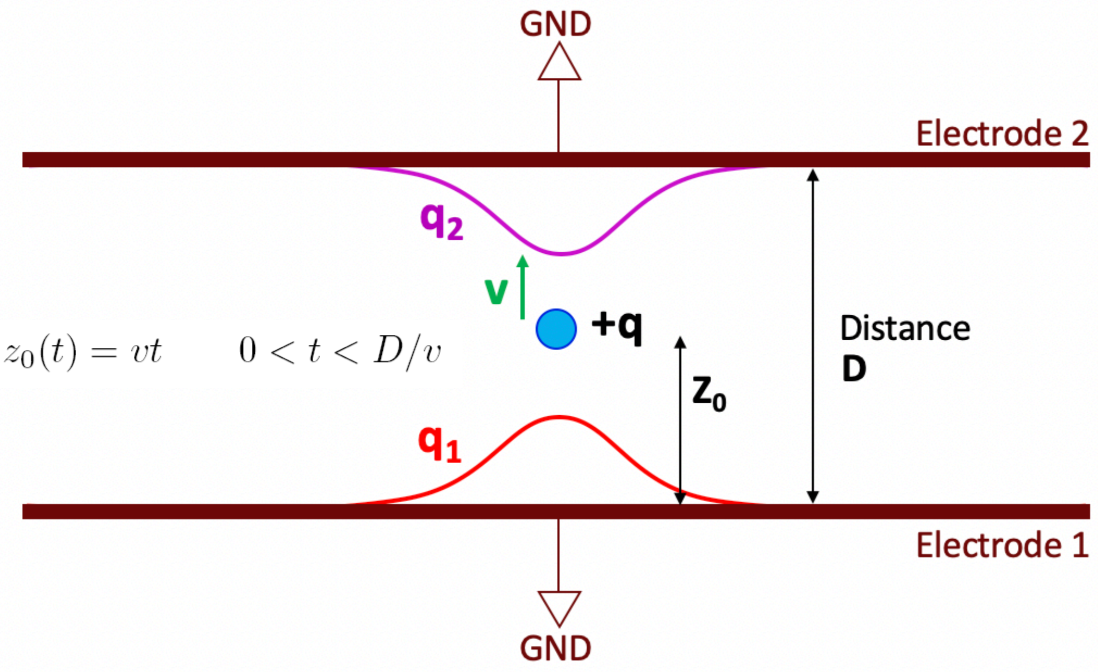
→ The induced current is therefore given by:

$$\boxed{I_n(t) == -\frac{q}{V_w}\,\vec{E}_n\left(\vec{x}(t)\right)\,\vec{v}(t)}$$

❖ Removing the charge means we just need to solve the Laplace equation and not the Poisson equation

Example

❖ Example with the parallel plate configuration



$z_0(t) = vt \qquad 0 < t < D/v$

Weighting field E_1 of plate 1: Remove charge, set Electrode 1 to V_w and keep Electrode 2 grounded

$$E_1 = \frac{V_w}{D}$$

Weighting field E_2 of plate 2: Remove charge, set Electrode 2 to V_w and keep Electrode 1 grounded

$$E_2 = -\frac{V_w}{D}$$

❖ And so the induced currents: (same as the previous method on slide 15)

$$I_1 = -\frac{q}{V_w}\frac{V_w}{D}E_1\,v = -\frac{qv}{D} \qquad I_2 = -\frac{q}{V_w}\frac{V_w}{D}E_2\,v = \frac{qv}{D}$$

Induced Signals

- A charge q moving from position x_0 to x_1 induces the following charge:

$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind}(t)dt = -\frac{q}{V_w}\int_{t_0}^{t_1} \boldsymbol{E}_n[\boldsymbol{x}(t)]\,\dot{\boldsymbol{x}}(t)dt = \frac{q}{V_w}[\psi_n(\boldsymbol{x}_1) - \psi_n(\boldsymbol{x}_0)]$$

- A pair of charges +q and -q produced at position x_0 and moving to positions x_1 and x_2 respectively induce the following charge on electrode n:

$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind}(t)dt = \frac{q}{V_w}[\psi_n(\boldsymbol{x}_1) - \psi_n(\boldsymbol{x}_2)]$$

- If charge +q moves to electrode n and charge –q moves to another electrode, the total induced charge on electrode n is equal to +q, because ψ_n equals V_w on electrode n but 0 on other electrodes

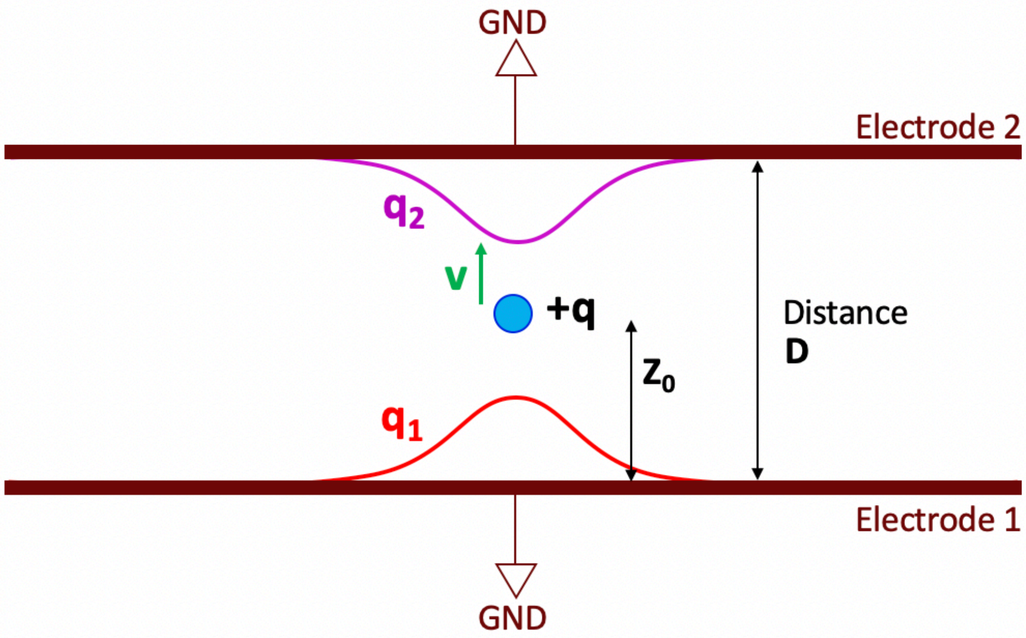
- In case both charges move to different electrodes, the total induced charge on both electrodes is 0

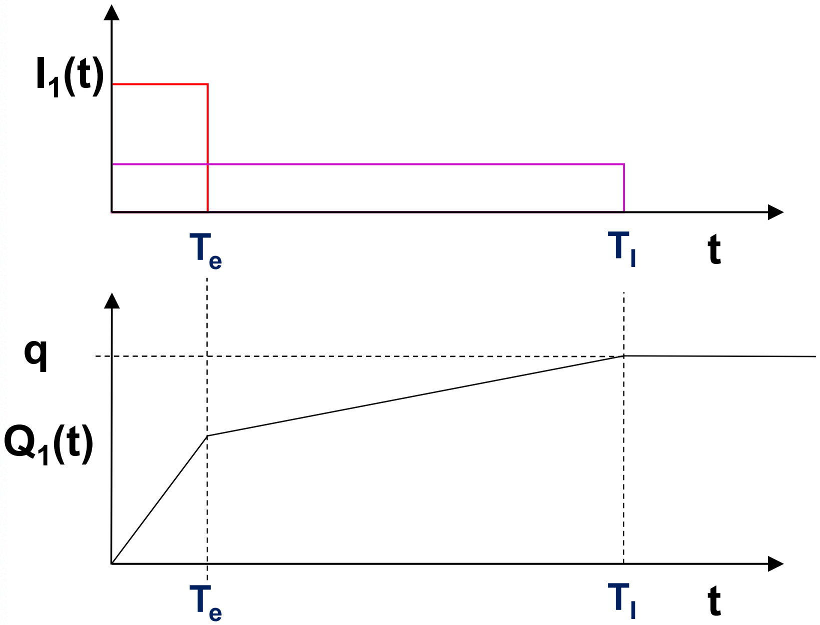
- After all charges have arrived to all electrodes, the total induced charge on a given electrode corresponds to the charge that arrived to this electrode

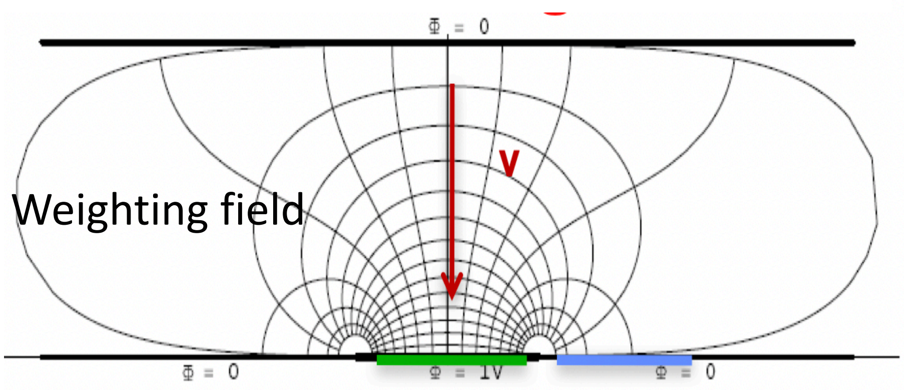
→ Signals on electrodes that don't receive charge are then strictly bipolar

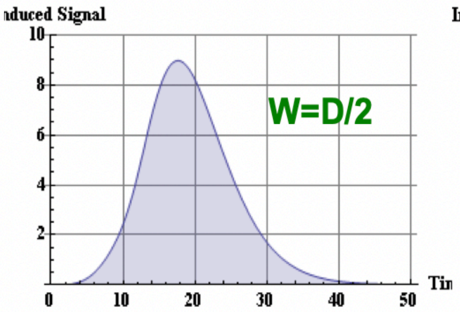
Induced Signals

- Example with the parallel plate configuration

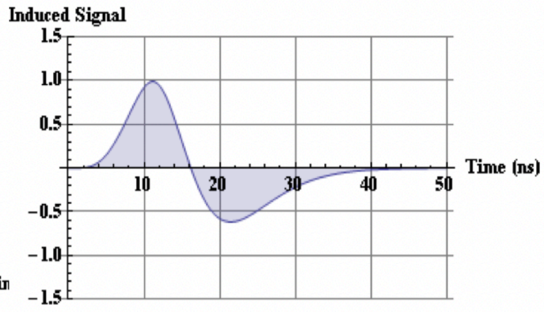








Central Strip



First Neighbor

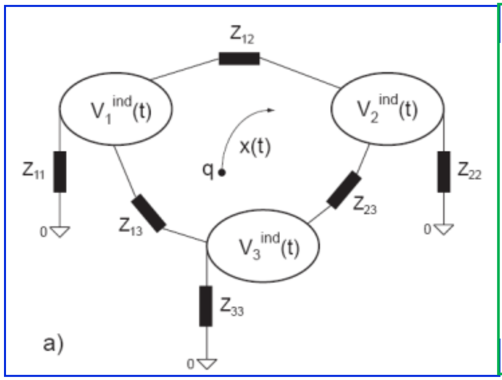
Summary

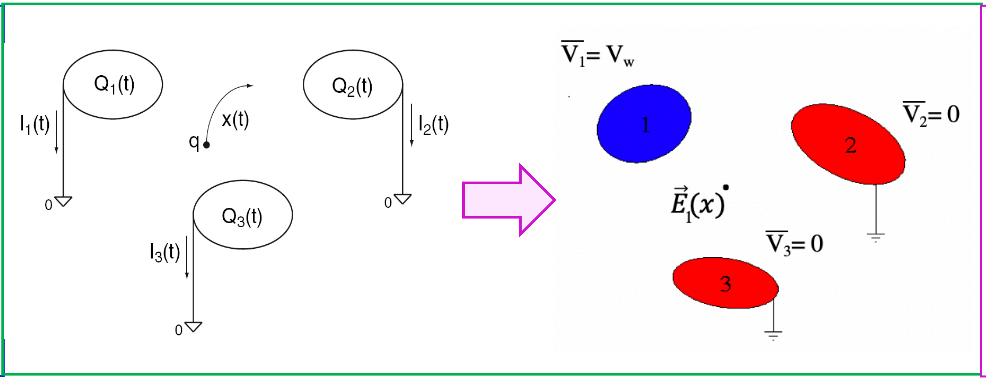
Methodology to evaluate the true signals induced on electrodes by a moving charge

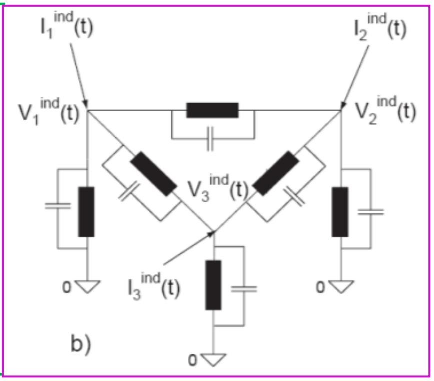
1. Calculate the charge trajectory in real electric field

2. Remove the interconnection elements, connect the electrodes to ground and calculate the current induced by the moving charge on a grounded electrode:
   - **Ramo-Shockley theorem →** remove the moving charge and put the electrode to V_w and other electrodes to GND, calculate the weighting electric field to obtain the induced currents

3. Use the induced currents as ideal current sources on a circuit where electrodes are reduced to simple nodes connected with mutual electrode capacitances (calculated from the weighting fields)







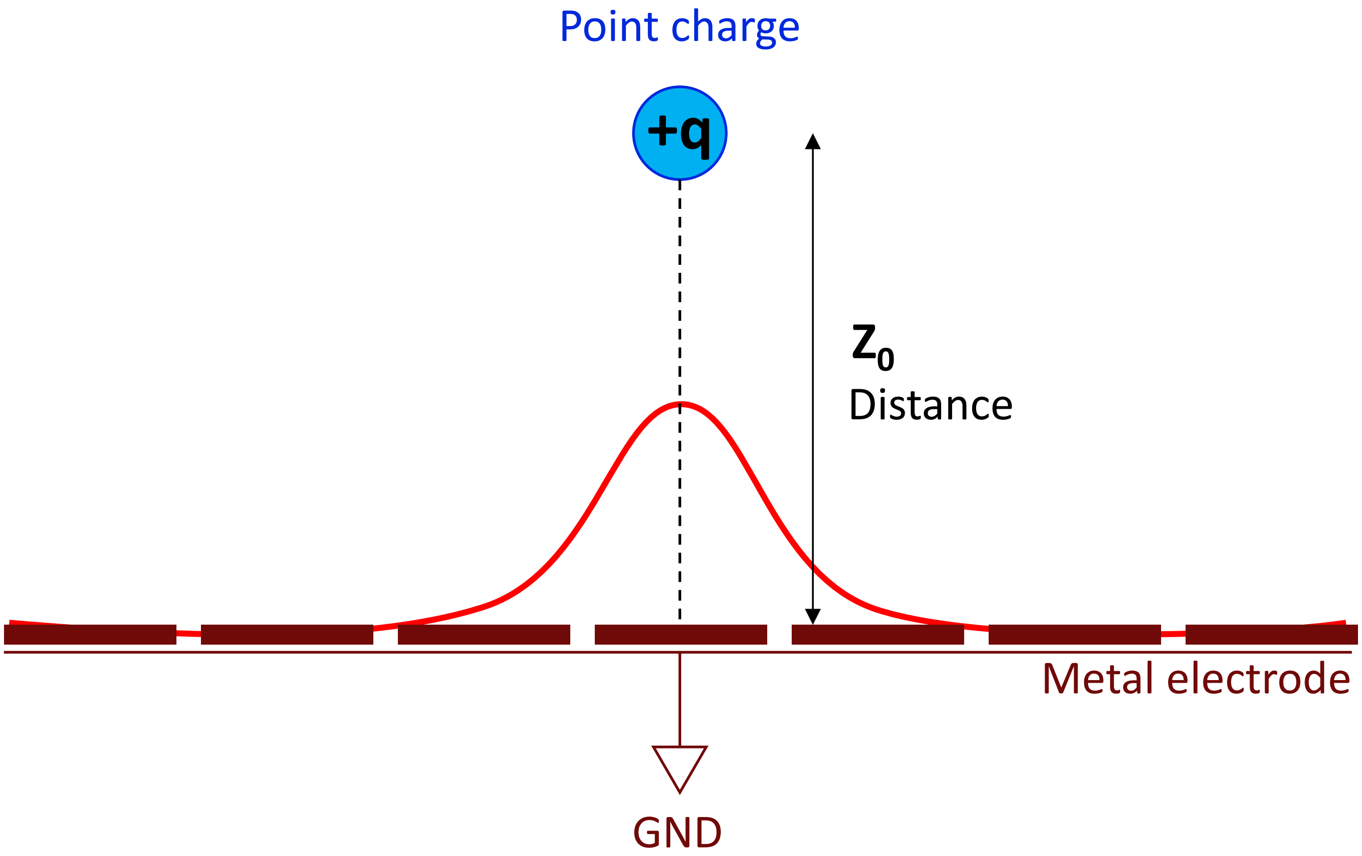
The end

The end

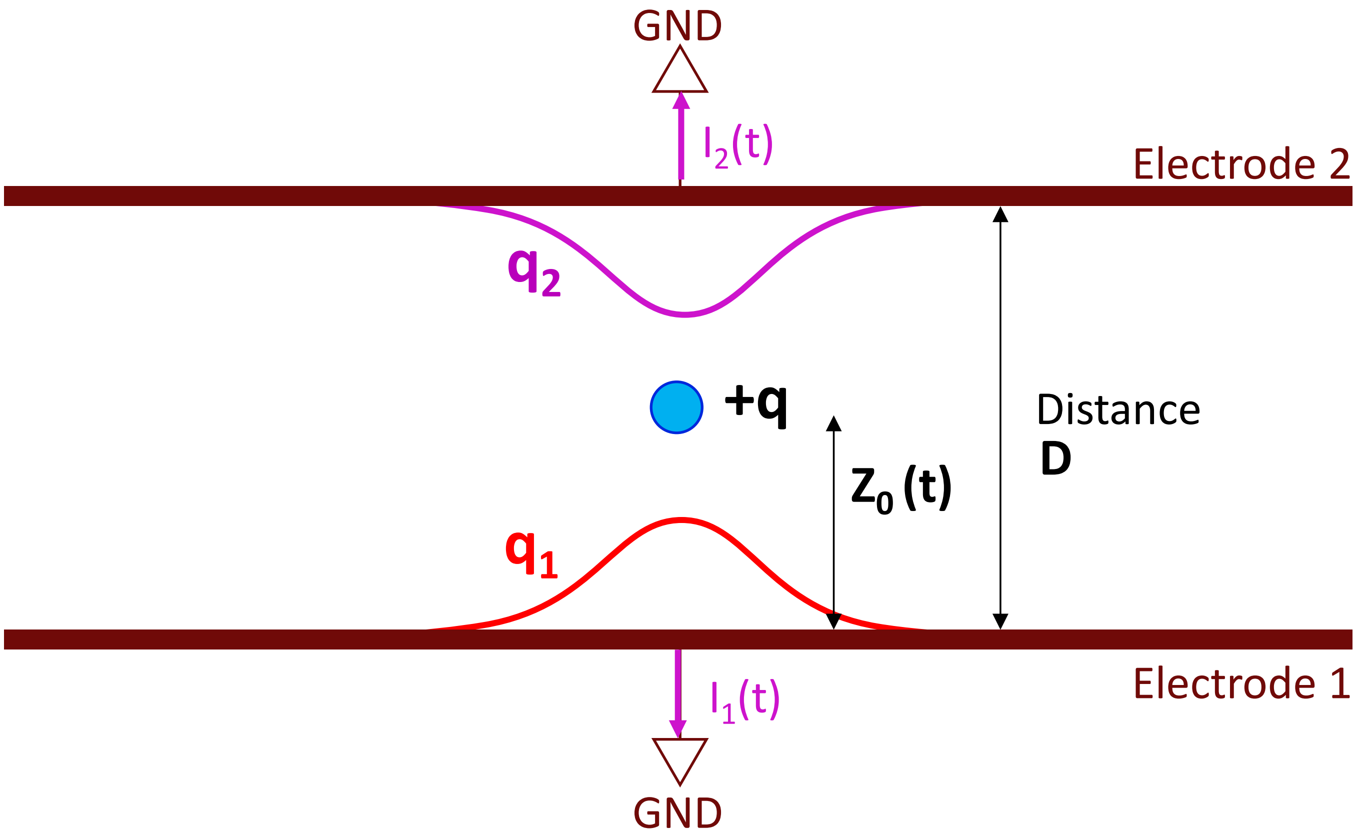
Thank you

Any Questions ?

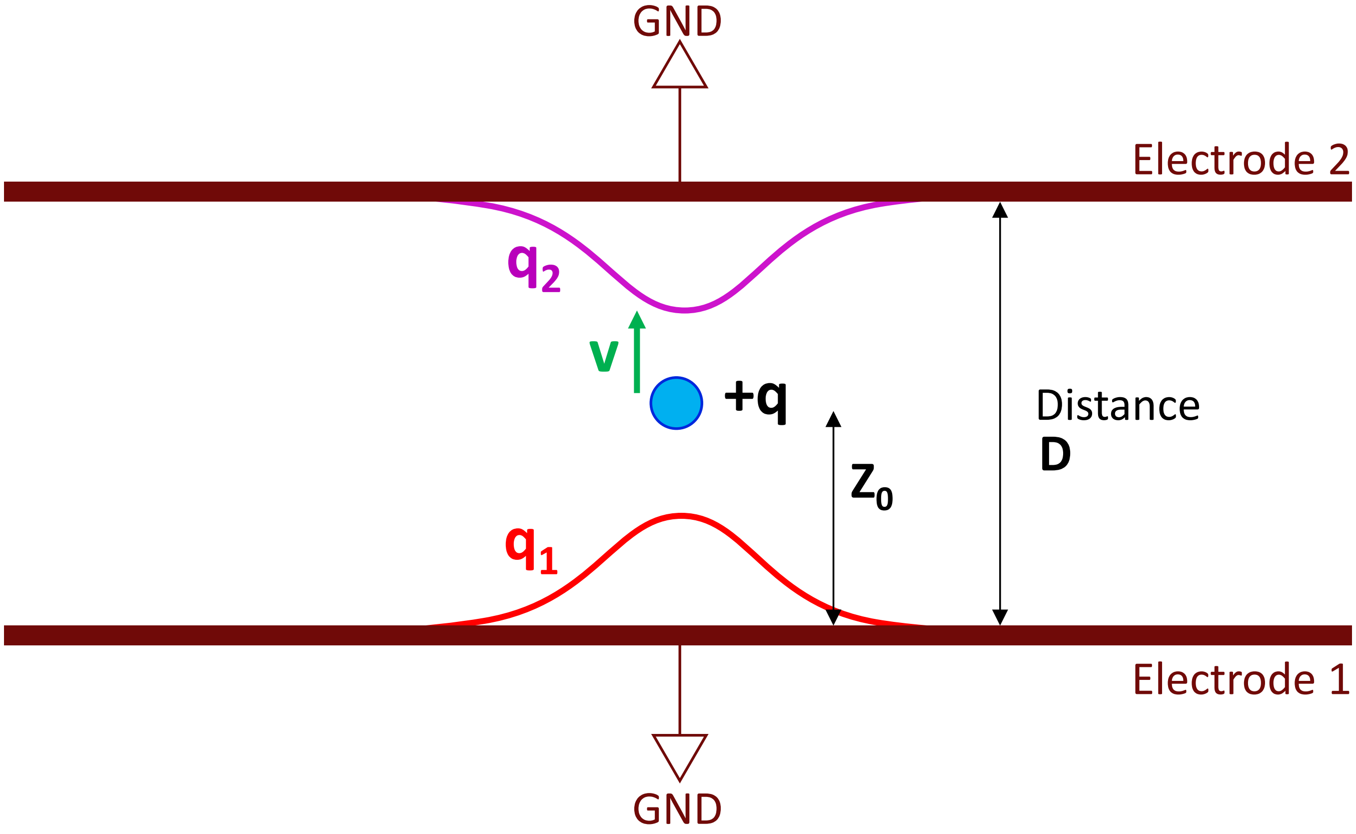
GEM Applications



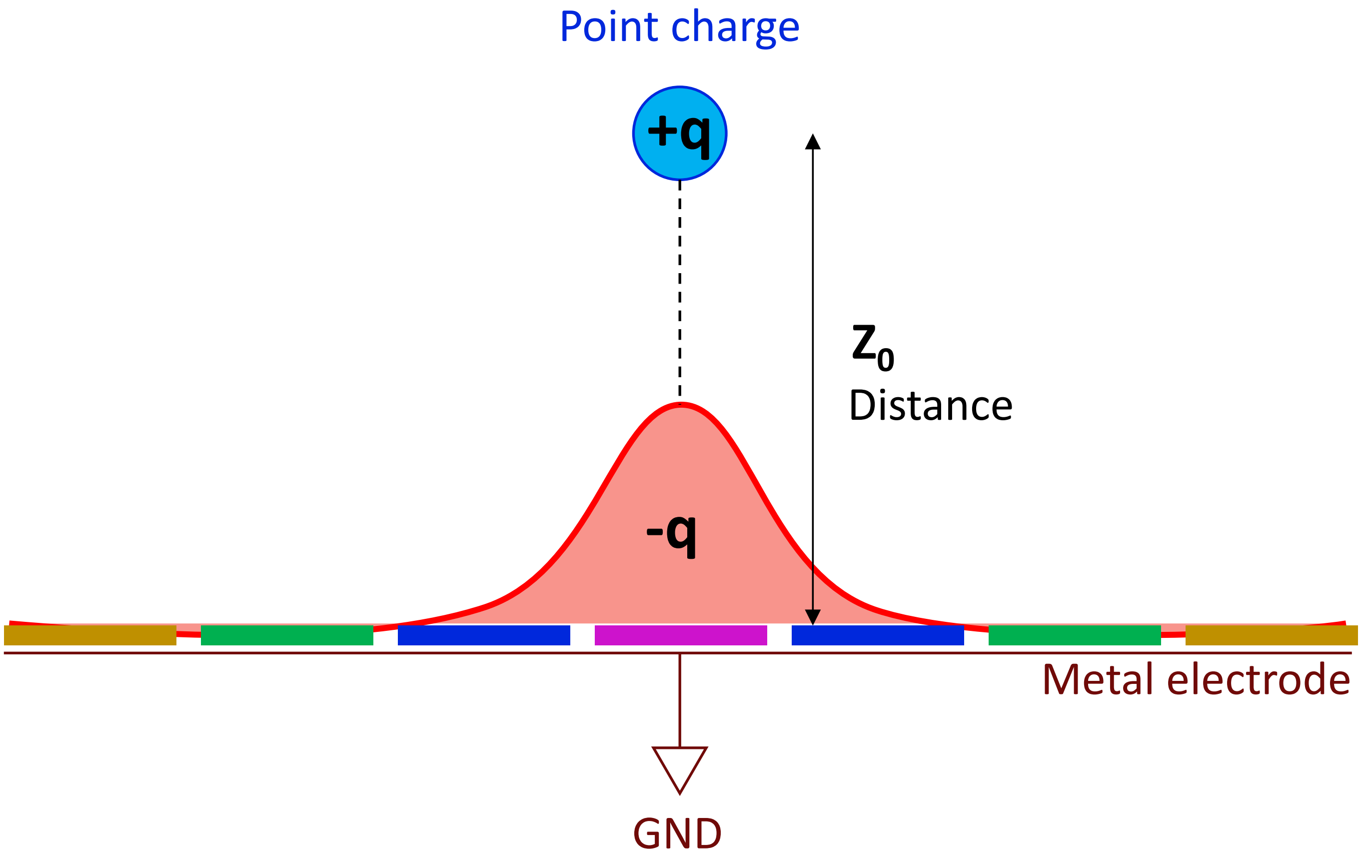
GEM Applications



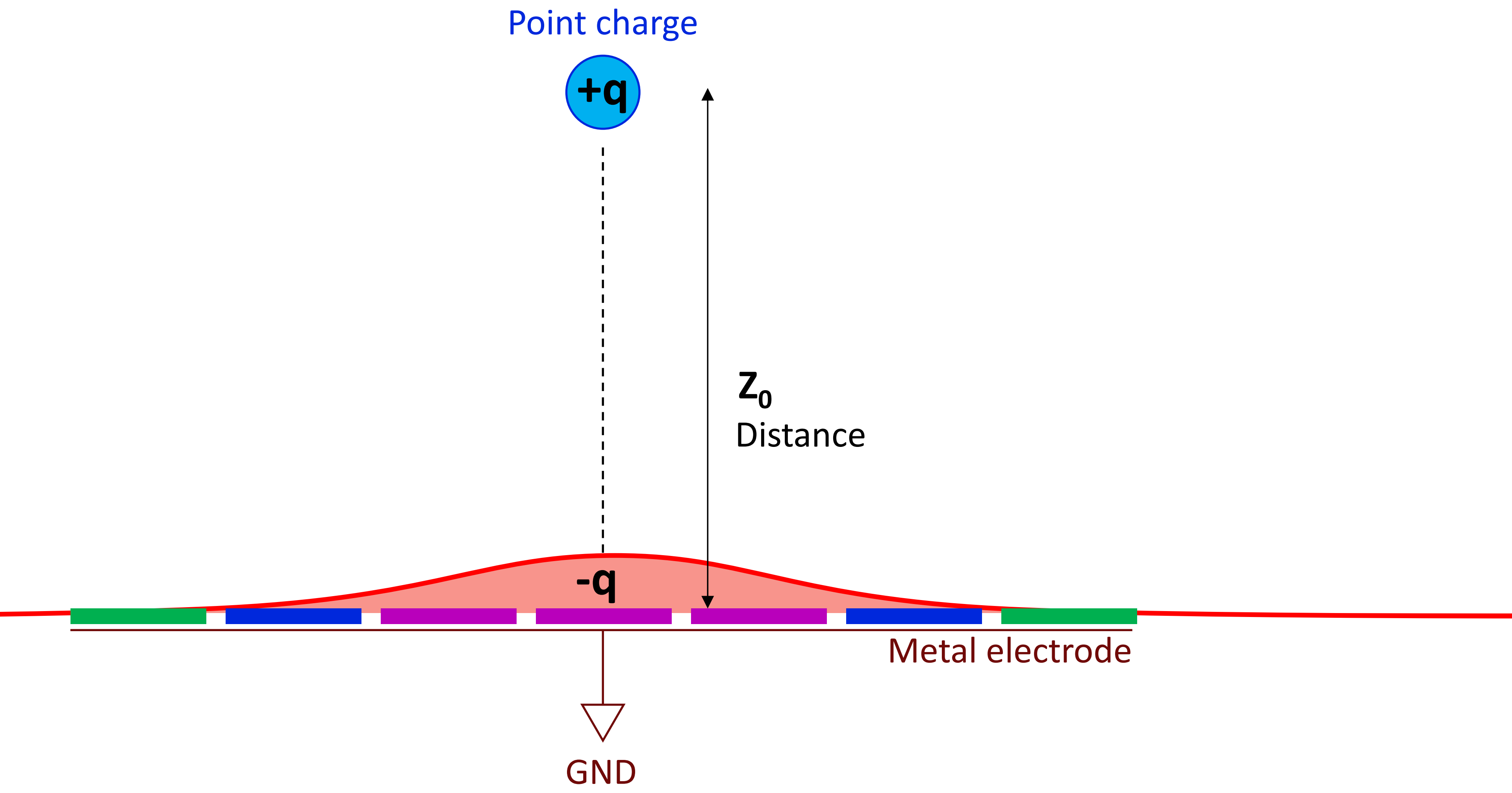
GEM Applications



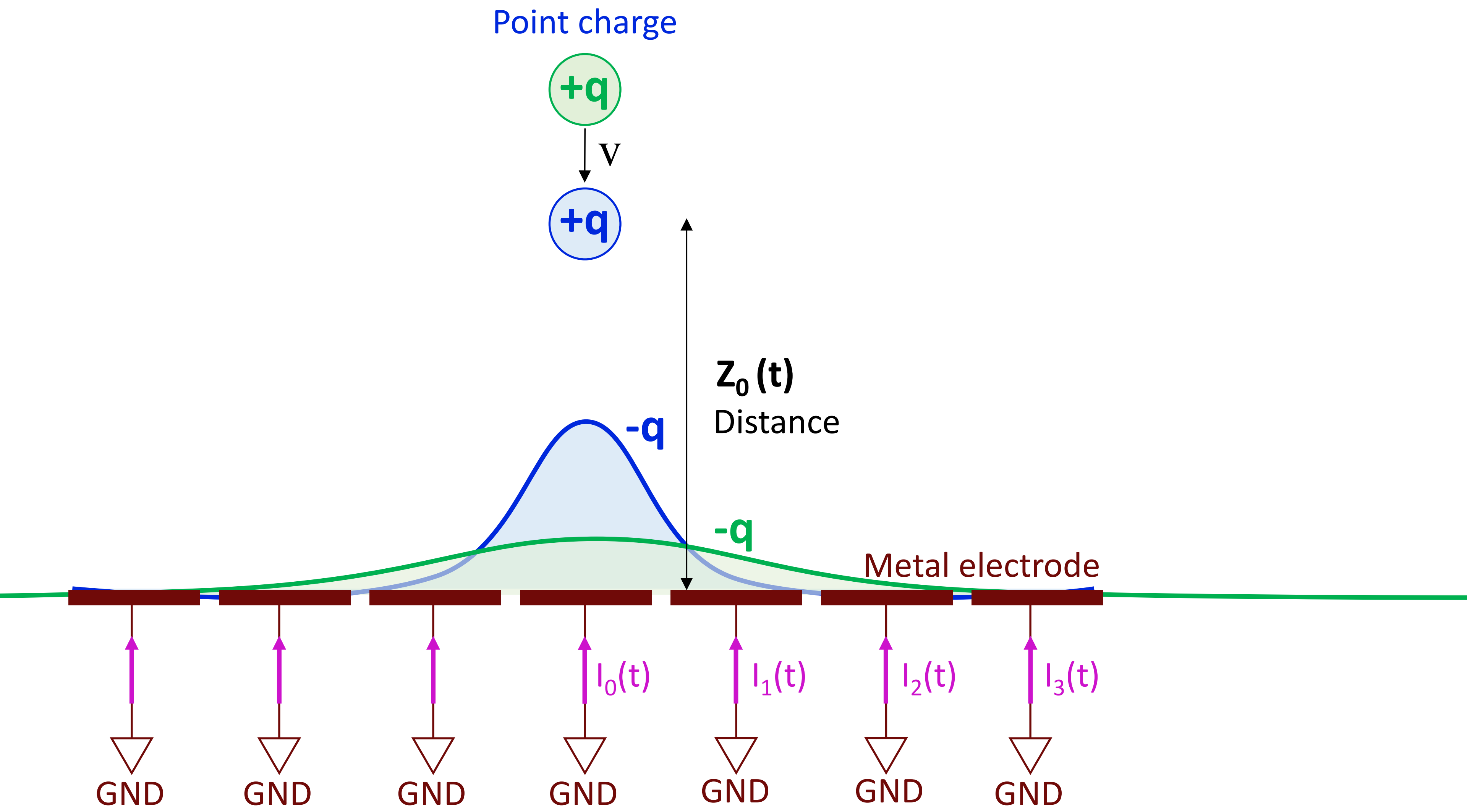
GEM Applications



GEM Applications



GEM Applications



GEM Applications

Point charge