Electronic readout techniques

Michael Lupberger
(University of Bonn)

RD51 MPGD School

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With material from:
B. Ketzer & M. Lupberger
Lecture on *Physics of Particle Detectors* (2022/23)
and B. Ketzer
Lecture on *Advanced Gaseous Detectors* (2019)

OUTLINE

Part 1: A brief introduction

- Recap: Signal formation and Shockley-Ramo Theorem
- Electronic readout overview
- Discrete components
- Readout concepts
- Multi-channel readout and front-end chips

Part 2: SRS demonstration

- The VMM front-end chip
- Overview on the RD51 Scalable Readout System
- SRS-VMM
- Live demo

RECAP: SIGNAL FORMATION

Gaseous detector: Ionisation/excitation of gas atoms

- Ionisation separates e^- from A^+
- Electric field ⇒ further separation, drift, (amplification)
- Moving charges induce signals on field electrodes
- Possibility to use theses signals to infer
  - Where
  - When
  - How strong

  the interaction with the detector medium was

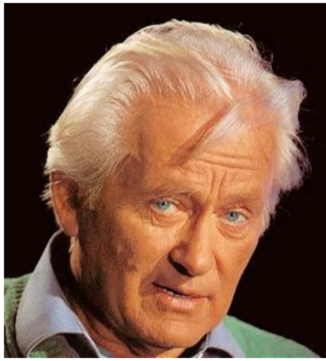
NUCLEAR INSTRUMENTS AND METHODS 62 (1968) 262–268; © NORTH-HOLLAND PUBLISHING CO.

THE USE OF MULTIWIRE PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

G. CHARPAK, R. BOUCLIER, T. BRESSANI, J. FAVIER and Č. ZUPANČIČ

CERN, Geneva, Switzerland

Received 27 February 1968

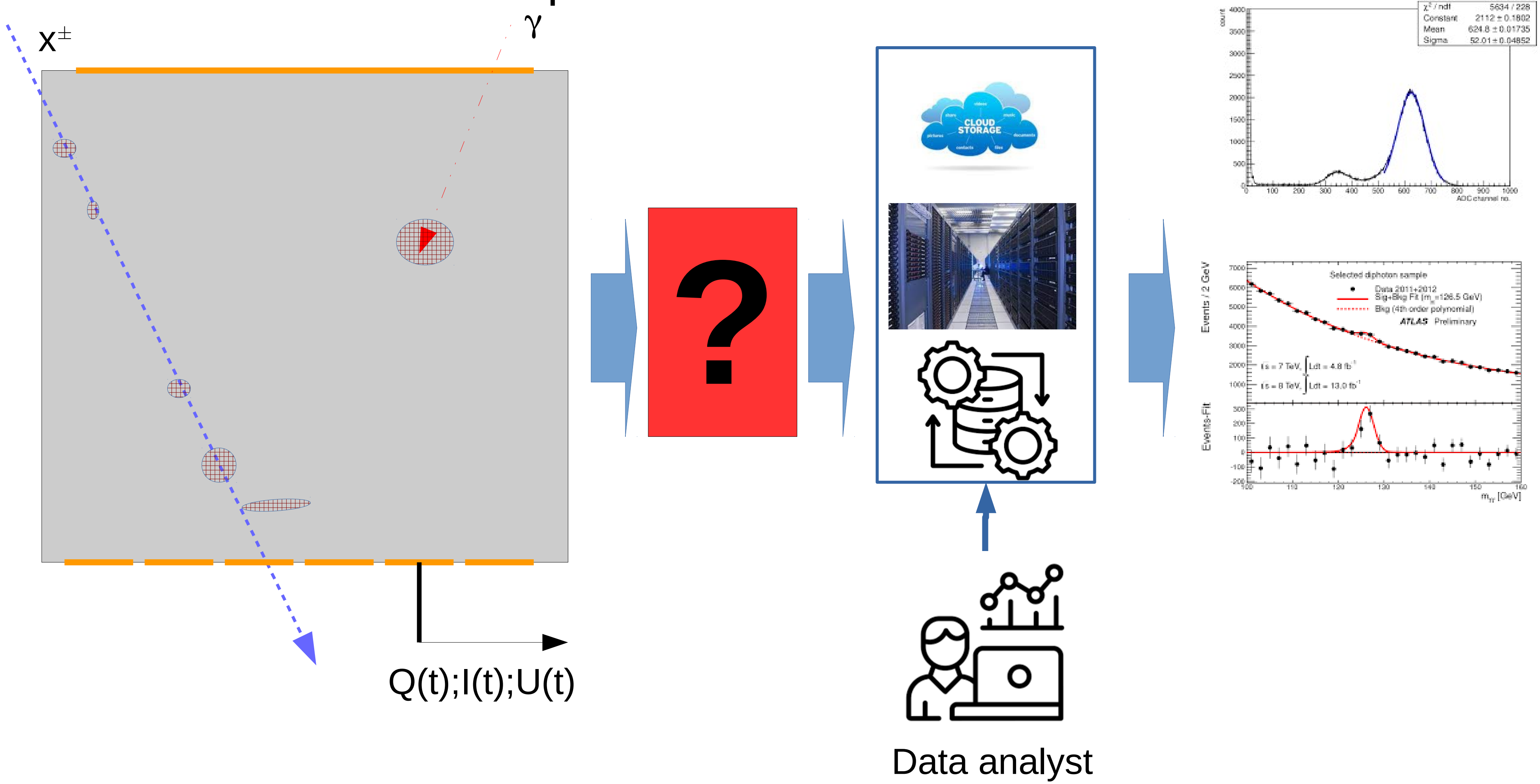


Nobel Prize 1992 to Georges Charpak

for his invention and development of particle detectors, in particular the multiwire proportional chamber

RECAP: SIGNAL FORMATION

Electronic readout techniques



RECAP: SHOCKLEY–RAMO THEOREM

Current I on given electrode i induced by moving charge

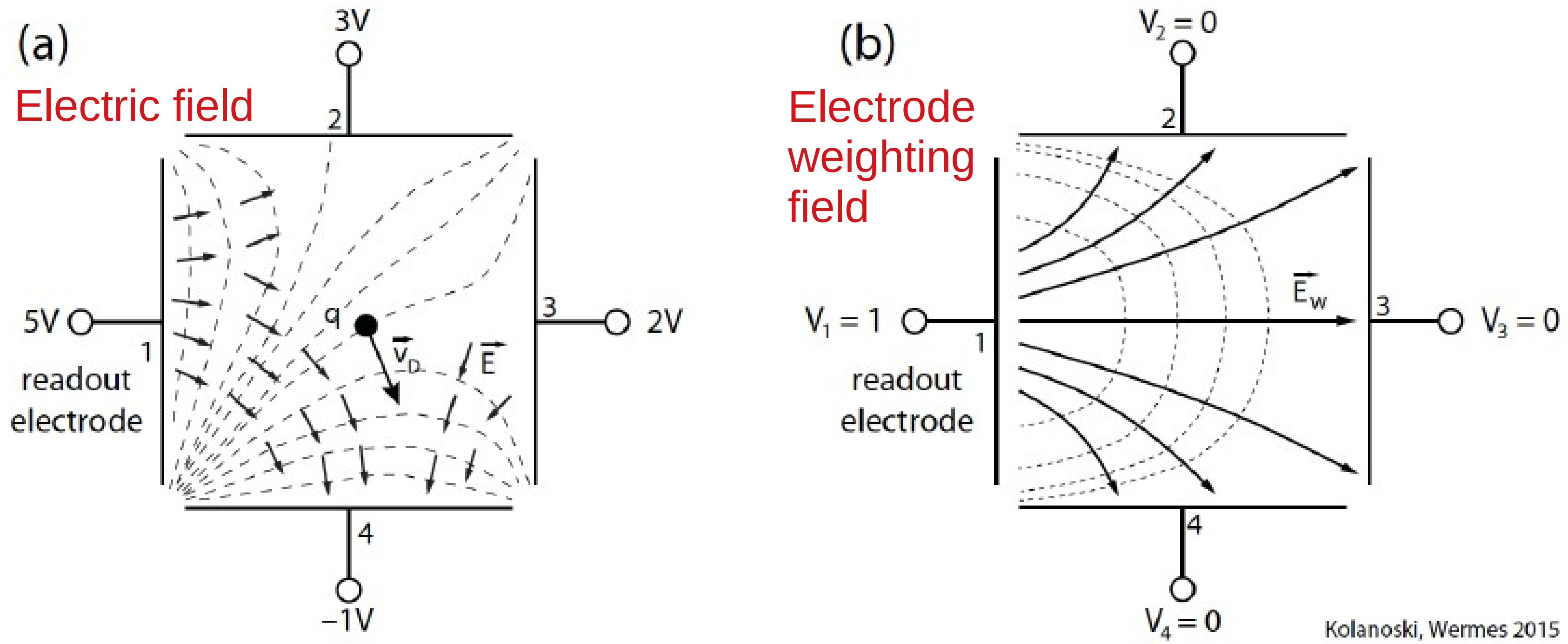
$$I_i(t) = \frac{q}{U_i} \nabla \phi_i \left[\boldsymbol{x}_0(t)\right] \cdot \frac{\mathrm{d}\boldsymbol{x}_0(t)}{\mathrm{d}t} = -\frac{q}{U_i} \boldsymbol{E}_i \left[\boldsymbol{x}_0(t)\right] \cdot \boldsymbol{v}(t)$$

The current induced on a grounded electrode by a point charge q moving along a trajectory $\boldsymbol{x}_0(t)$ is $I_i(t)$, where $\boldsymbol{E}_i(\boldsymbol{x}_0)$ is the electric field in the case where the charge q is removed, electrode i is set to voltage U_i, and all other electrodes are grounded.

- Convention: $U_i = 1$
- $\mathbf{E}_i(\mathbf{x}_0)$: Weighting field of electrode i at position $\mathbf{x}_0$
- $\mathbf{E}_i \neq \mathbf{E}_{det,el}$: Weighting field in general different to detector electric field
- $\hat{\mathbf{e}}_{\mathbf{E}i} \neq \hat{\mathbf{e}}_{\mathbf{v}}$: Direction of weighting field different to charge trajectory

RECAP: WEIGHTING FIELD

What the electrode *sees*, example:



Important:

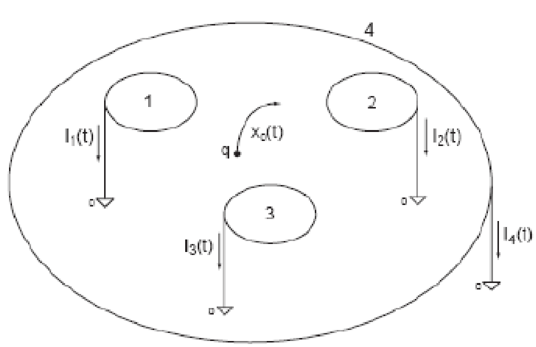
- Weighting field decoupled from charge movement
- Weighting field only given by detector electrode configuration
- Charge movement only given by E and B field and space charge

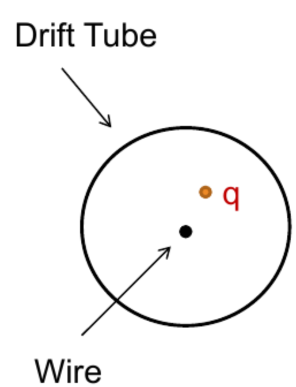
RECAP: INDUCED CHARGE

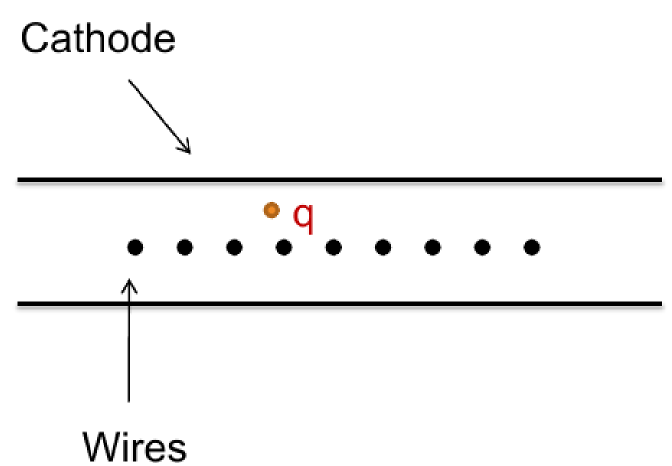
- Charge induced on electrode *i* by charge *q* moving from point 1 to 2 is

$$Q_i = \int_{t_1}^{t_2} I_i(t)\mathrm{d}t = -\frac{q}{U_i}\int_{t_1}^{t_2} \boldsymbol{E}_i[\boldsymbol{x}(t)]\,\dot{\boldsymbol{x}}(t)\mathrm{d}t = \frac{q}{U_i}\left[\phi_i(\boldsymbol{x}_1) - \phi_i(\boldsymbol{x}_2)\right]$$

  independent of actual path
- Once all charges have arrived at the electrodes, the total induced charge in a given electrode is equal to the charge that has been collected at this electrode
- In case there is an electrode enclosing all others, the sum of all induced currents is zero at any time







RECAP: SHOCKLEY–RAMO THEOREM

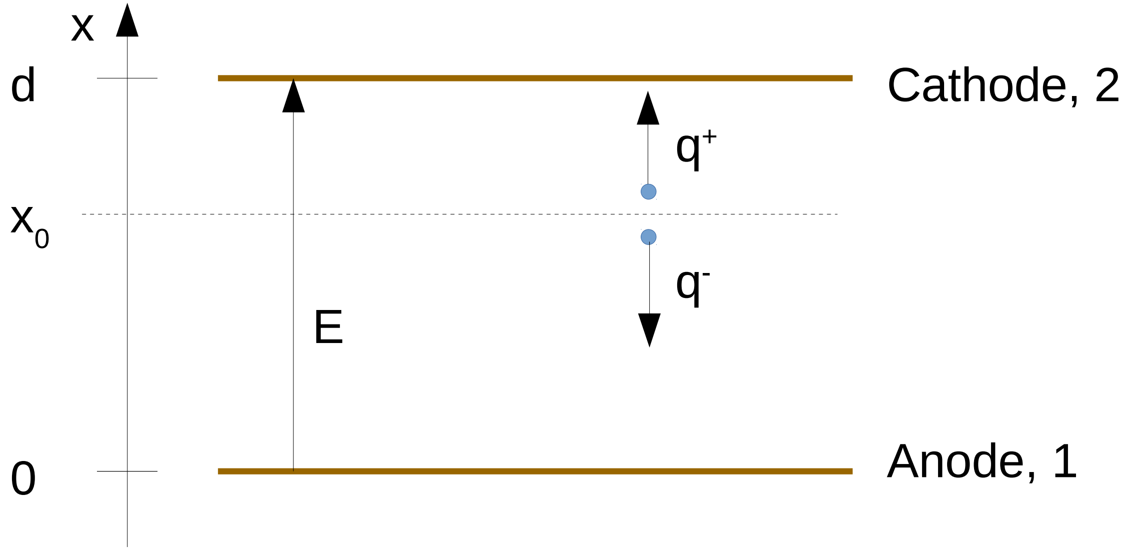
Practical application: Receipt to calculate signal current

- Determine the weighting field $\mathbf{E}_i(\mathbf{x}_0)$ for electrode i by setting its potential to U_i(==1) and all other electrodes j to $U_{j\neq i}=0$
- Determine the velocity and direction $\mathbf{v}(t)$ of the moving charge q, which can be usually inferred from the real field between electrodes (so determine the real field)
- Calculate $i(t)=q/U_i\, \mathbf{E}_i(\mathbf{x}_0)\, \mathbf{v}(t)$ (U_i==1)

The space-time-relation $\mathbf{x}(t)$ gives the temporal evolution of the signal current i(t) at electrode i. Through integration from t_0 to t, the induced signal charge $Q_{S,i}(t)$ can can be calculated:

$$Q_{S,i}(t) = -\int_{t_0}^{t} i_{S,i}(t')\,dt' = -q\int_{t_0}^{t} \vec{E}_{w,i}\,\vec{v}\,dt'$$
$$= -q\int_{\vec{r}(t_0)}^{\vec{r}(t)} -\nabla\phi_{w,i}\,d\vec{r} = q\left[\phi_{w,i}(\vec{r}(t)) - \phi_{w,i}(\vec{r}(t_0))\right]\,.$$

EXAMPLE: PARALLEL PLATE



$$\vec{E}(\vec{x}) = E(x) = \frac{U_1}{d}$$

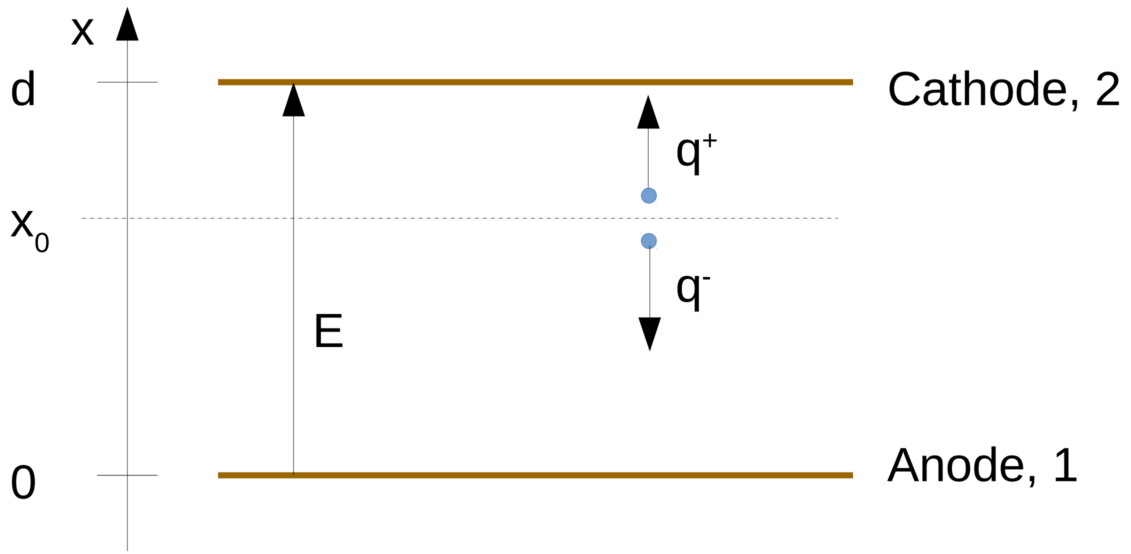
$$C = \frac{\epsilon \epsilon_0 A}{d}$$

1. Weighting field:

- Set anode (readout electrode) to $U_1 = 1 \Rightarrow \Phi_1 = \Phi(x=0) = U_1 = 1$
- Set cathode (all other electrodes) to GND $\Rightarrow \Phi_2 = \Phi(x=d) = 0$

$$\Rightarrow \Phi_1(x) = \frac{U_1}{d}(d-x) = \frac{(d-x)}{d} \Rightarrow \vec{E}_1(\vec{x}_0) = E_1(x) = \frac{U_1}{d} = \frac{1}{d}$$

EXAMPLE: PARALLEL PLATE



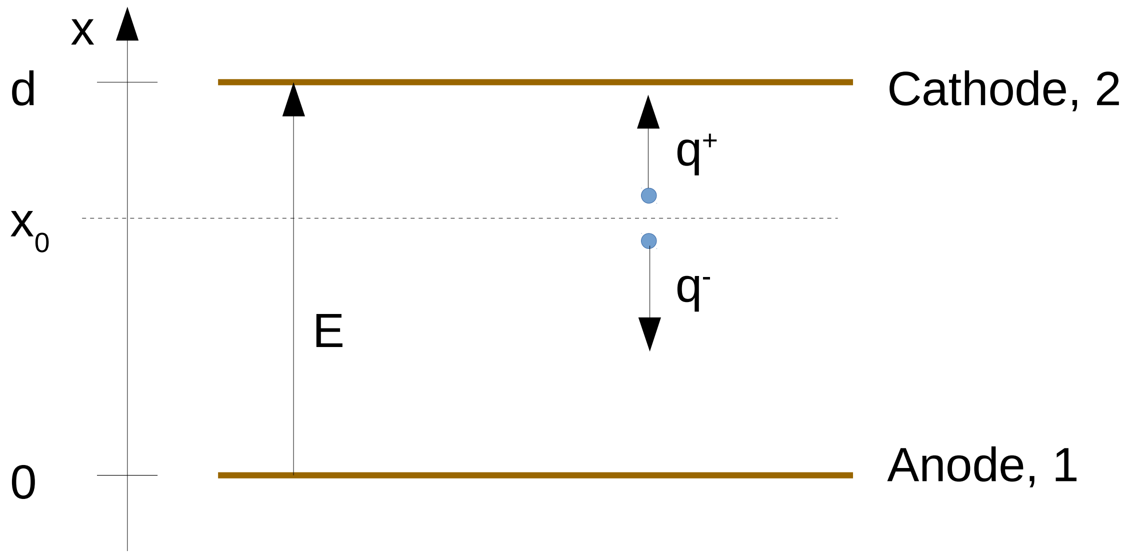
$$\vec{E}(\vec{x}) = E(x) = \frac{U_1}{d}$$

$$C = \frac{\epsilon \epsilon_0 A}{d}$$

2. Velocity and direction of charges **v**(t):

- $\dot{x} = \frac{dx}{dt} = u = \mu E = \mu \frac{U_1}{d}$
- $x(t=0) = x_0 \Rightarrow x(t) = \mu \frac{U_1}{d} t + x_0$
- Ions and electrons contribute to signal! $u_{ion} \ll u_e$

EXAMPLE: PARALLEL PLATE



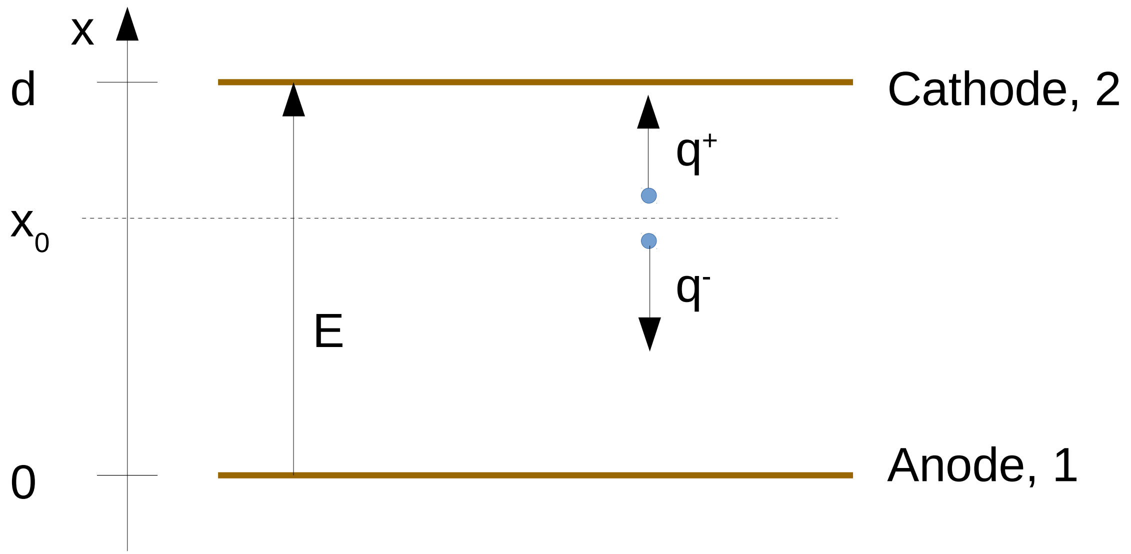
$$\vec{E}(\vec{x}) = E(x) = \frac{U_1}{d}$$

$$C = \frac{\epsilon \epsilon_0 A}{d}$$

3. Ramo:

- $I_1(t) = -\frac{q}{U_1} E_1[x(t)] \cdot \dot{x}(t) = -\frac{q}{U_1} \frac{U_1}{d} u = -\frac{q}{d} u$
- Ions and electrons contribute to signal: $I_{1,e}(t), I_{1,ion}(t)$
- Take care on correct sign and charge for u_e and u_{ion}

EXAMPLE: PARALLEL PLATE



$$\vec{E}(\vec{x}) = E(x) = \frac{U_1}{d}$$

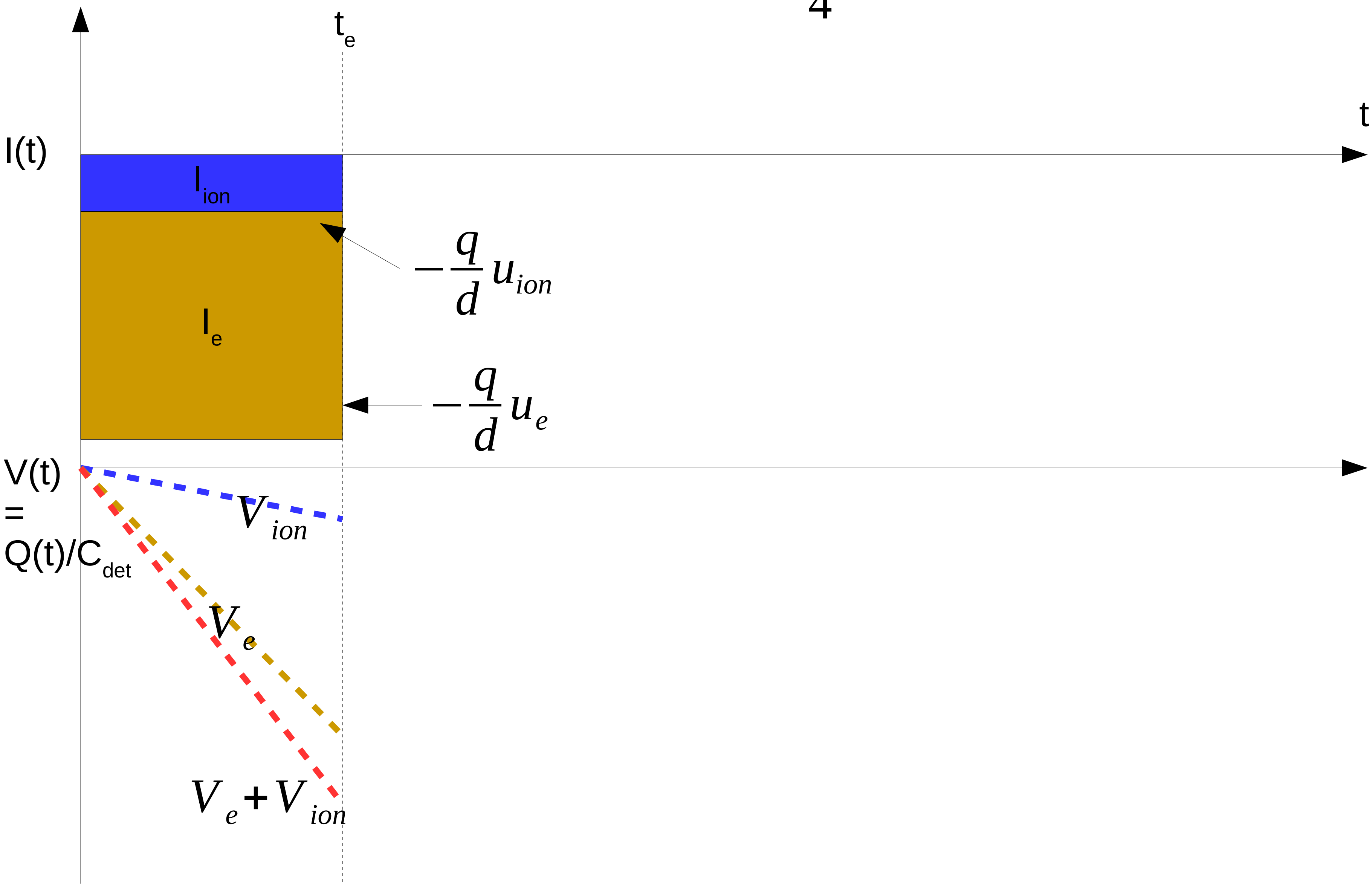
$$C = \frac{\epsilon \epsilon_0 A}{d}$$

1st time interval: both charges drifting: $t < t_e = \frac{x_0}{u_e}$

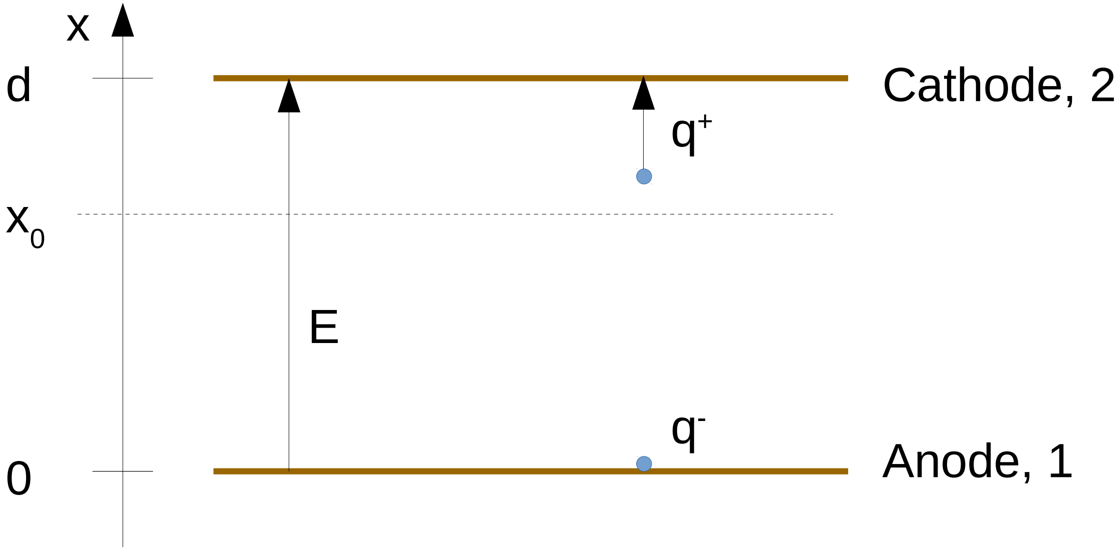
- $I_1(t) = I_{1,e}(t) + I_{1,ion}(t) = -\frac{q}{d} u_{ion} - \frac{-q}{d}(-u_e) = -\frac{q}{d}(u_{ion} + u_e)$
- $Q_1(t) = \int_0^t I_1(t')\,dt' = -\frac{q}{d}(u_{ion} + u_e) \cdot t$

EXAMPLE: PARALLEL PLATE

$$u_{ion} = \frac{1}{4} u_e$$



EXAMPLE: PARALLEL PLATE



$$\vec{E}(\vec{x}) = E(x) = \frac{U_1}{d}$$

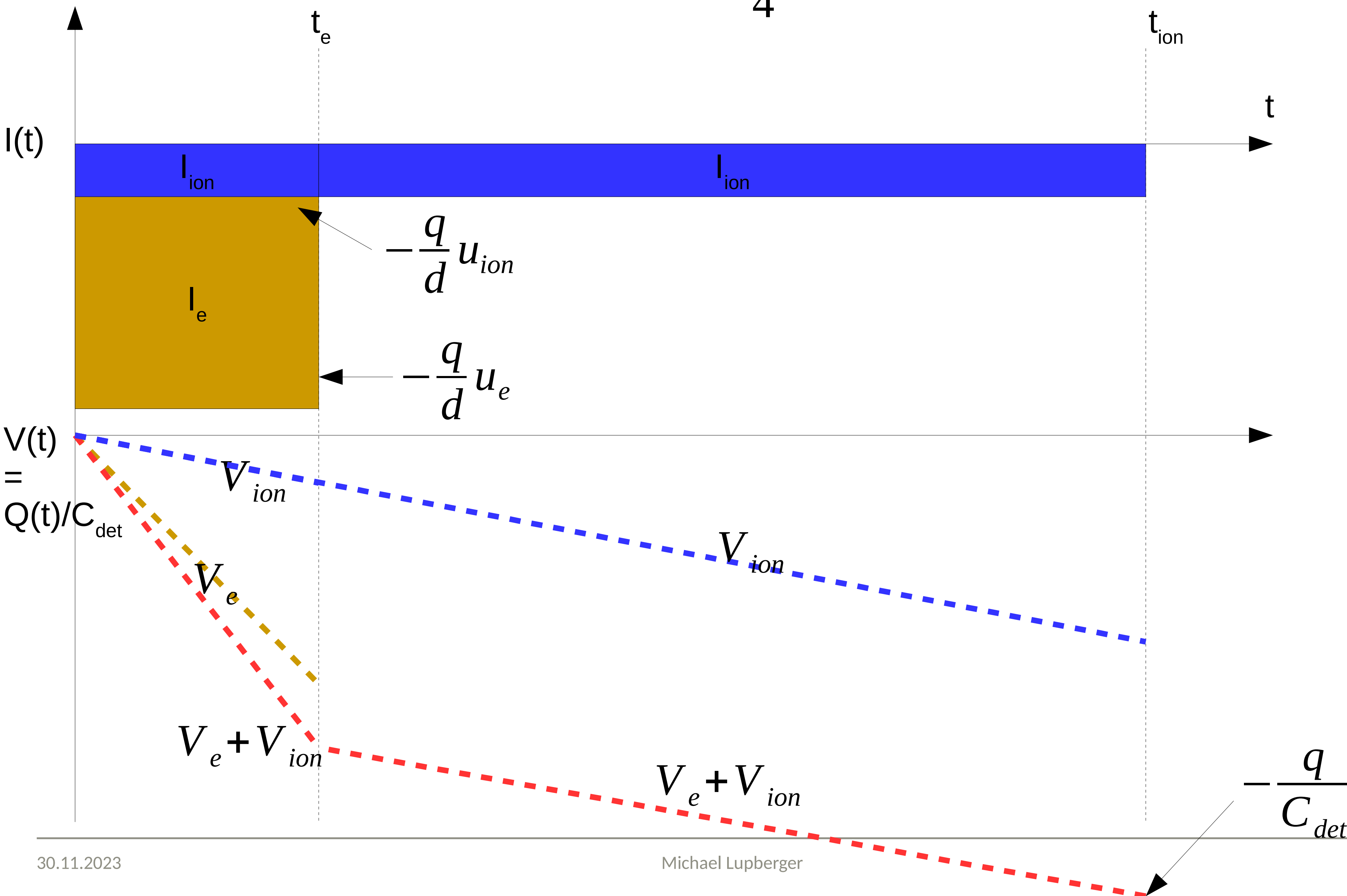
$$C = \frac{\epsilon \epsilon_0 A}{d}$$

2nd time interval: electron has arrived anode, ion drifts $\quad t_e < t < t_{ion} = \frac{d - x_0}{u_{ion}}$

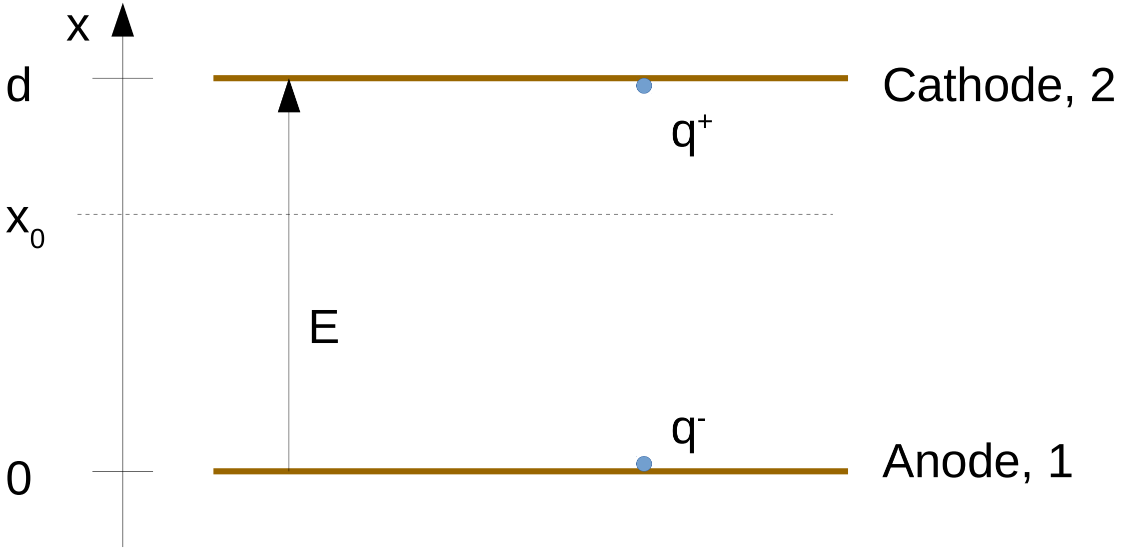
- $I_1(t) = I_{1,ion}(t) = -\frac{q}{d} u_{ion}$
- $Q_1(t) = \int_{t_e}^{t_{ion}} I_1(t')\,dt' = -\frac{q}{d}(u_{ion} \cdot t + x_0)$

EXAMPLE: PARALLEL PLATE

$$u_{ion} = \frac{1}{4} u_e$$



EXAMPLE: PARALLEL PLATE



$$\vec{E}(\vec{x}) = E(x) = \frac{U_1}{d}$$

$$C = \frac{\epsilon \epsilon_0 A}{d}$$

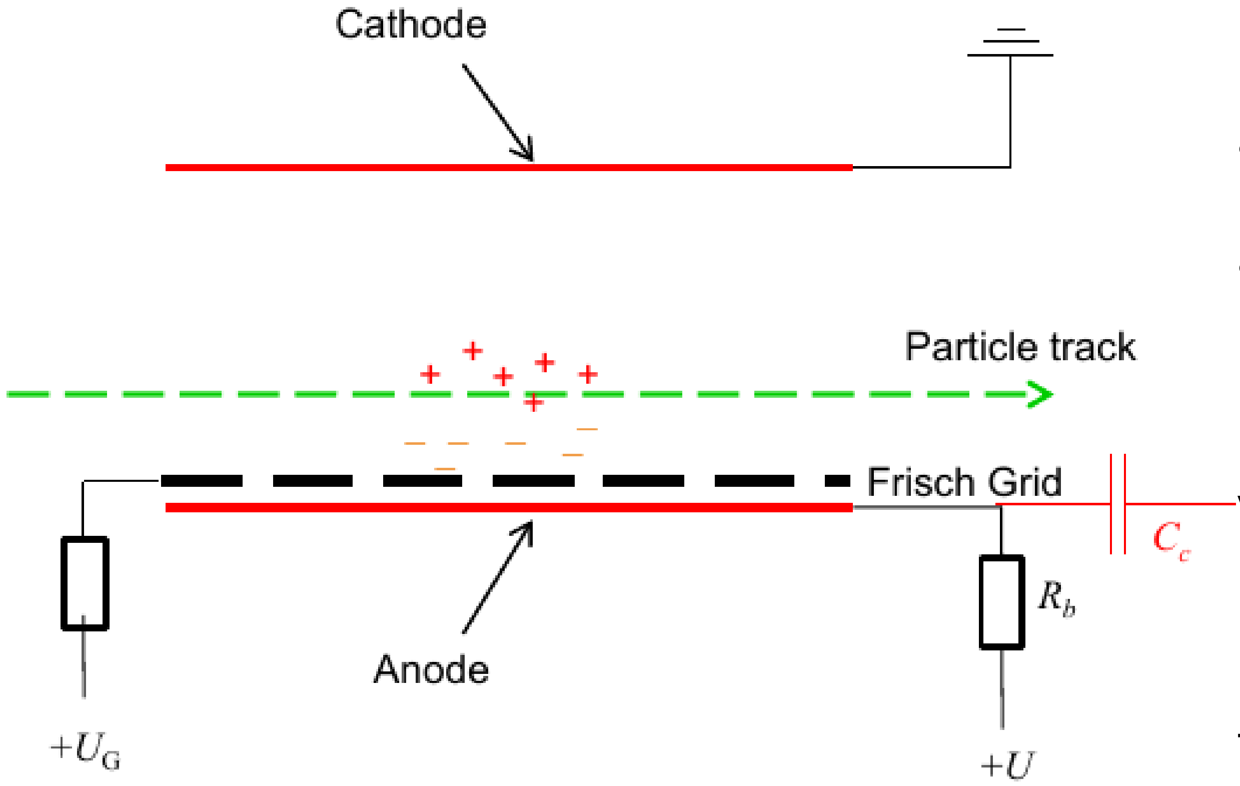
3rd time interval: electron and ion have arrived electrodes $t > t_{ion} = \frac{d - x_0}{u_{ion}}$

- $I_1(t) = I_{1,ion}(t) = I_{1,e}(t) = 0$
- $Q_1(t) = \int_0^{t_{ion}} I_1(t')\,dt' = -\frac{q}{d}(d+0) = -q$

PLANAR CONFIG: FRISH GRID

Drawback of chamber discussed until now:
Signal shape depends on x_0 (particle penetration point)

Remedy: grid at potential U_G in front of anode with $0 < U_G < U_{cath}$

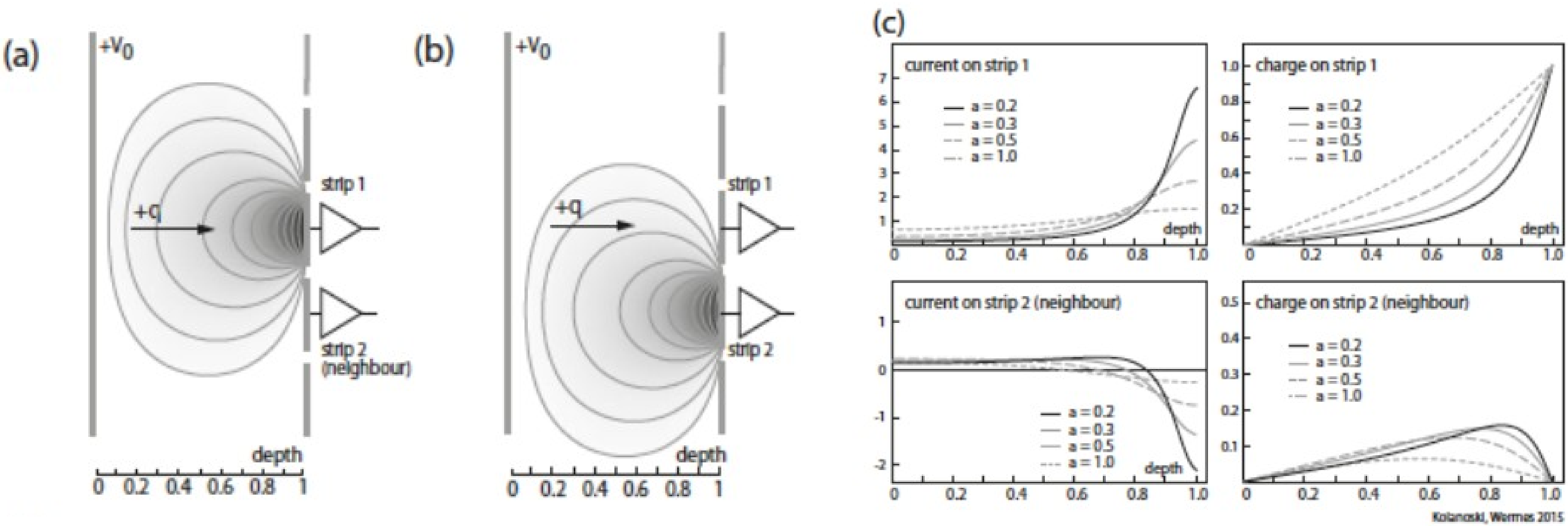


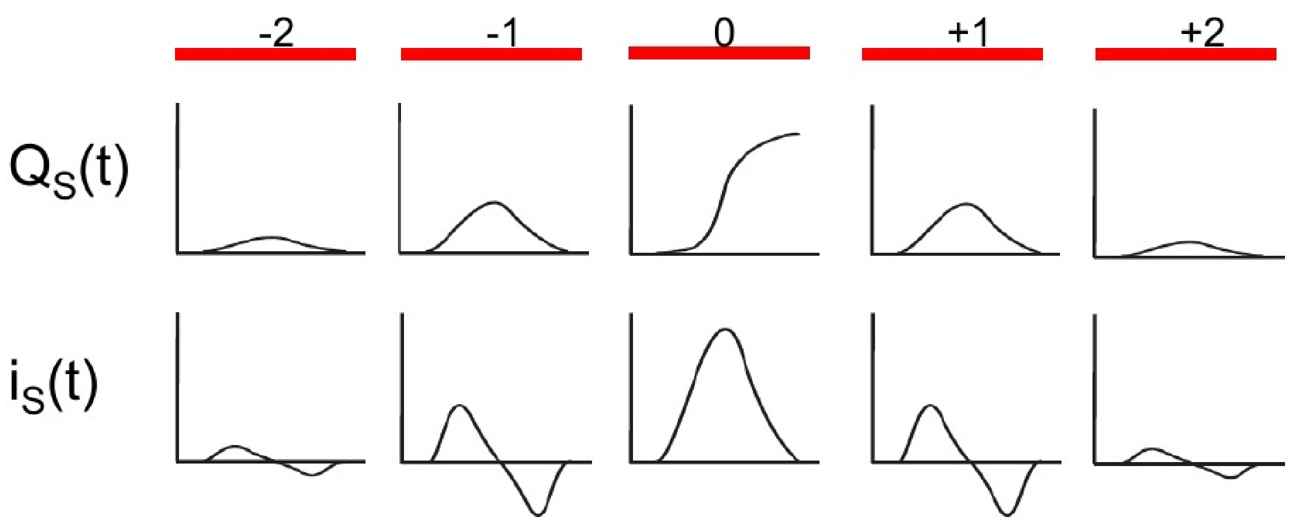
Frisch Grid:
- Drifting charges induce mirror charges on grid
- Signal is induced on anode only after electrons passed the grid

⇒ Ion signal from ionisation large region (drift, ionisation) not visible

Usually amplification at anode
⇒ short electron pulse + long tail from ions from avalanche

SEGMENTED ELECTRODES

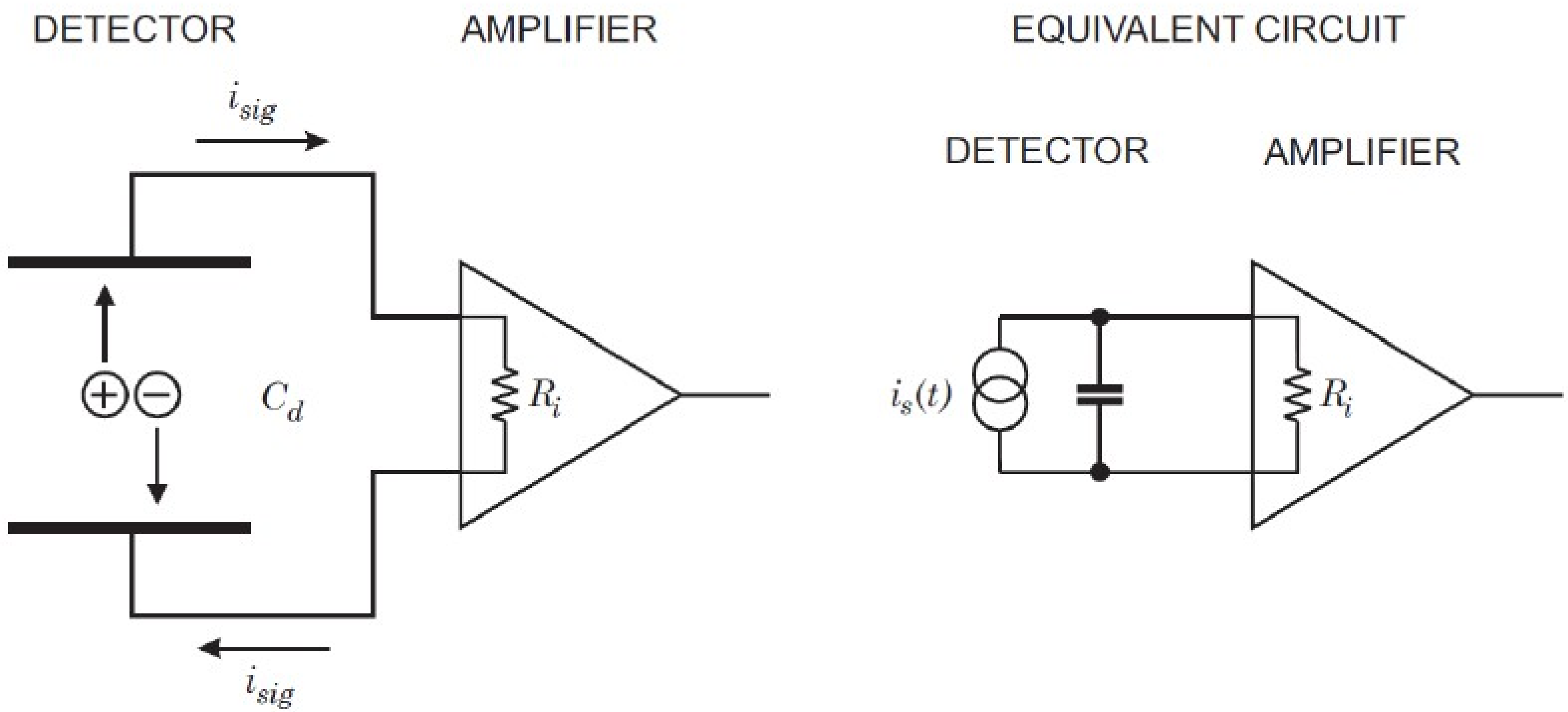




ELECTRIC SIGNAL

A detector is a current source

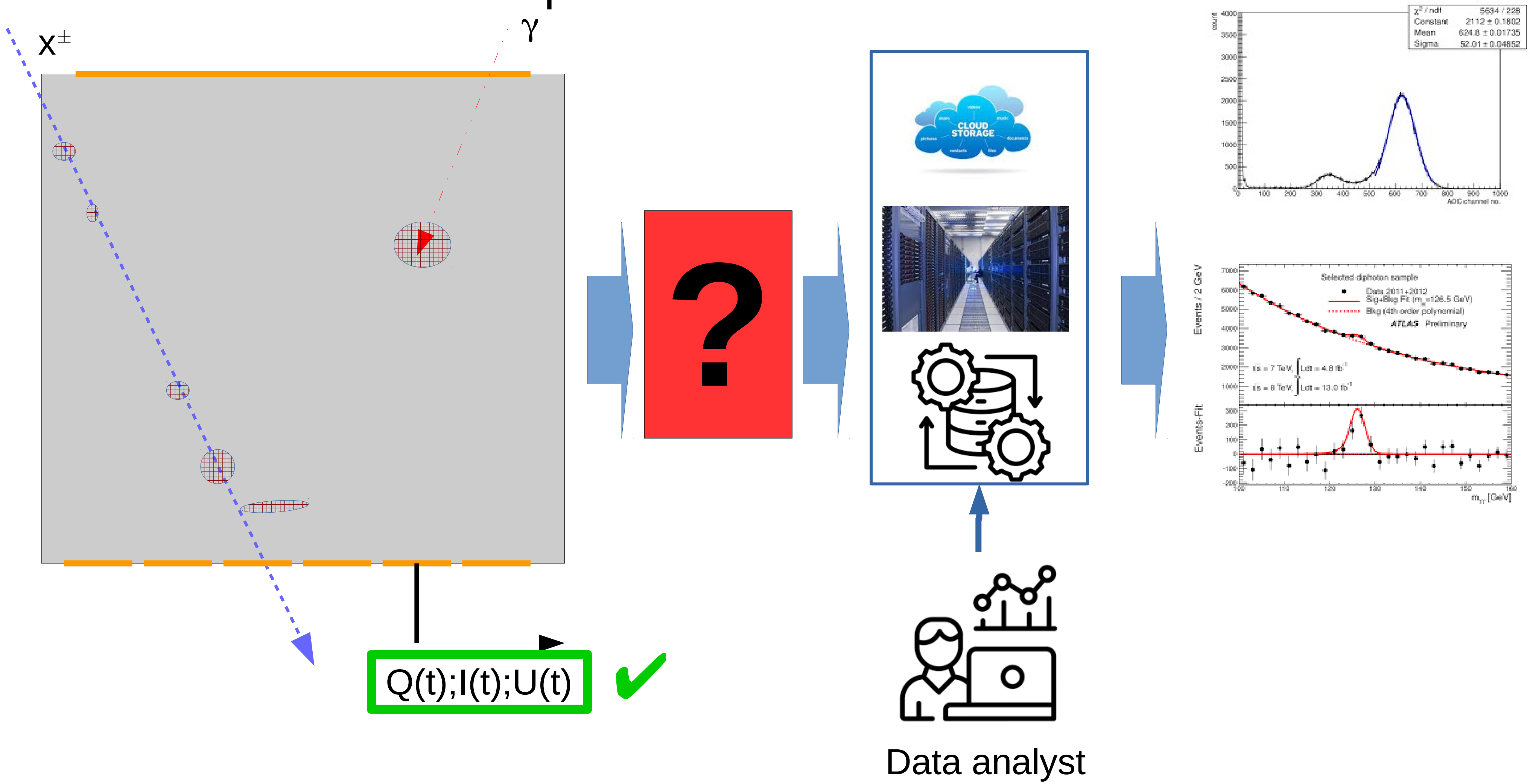
- delivers a current pulse independent of the load
- one can convert current into charge (integral) or voltage (via R or C)



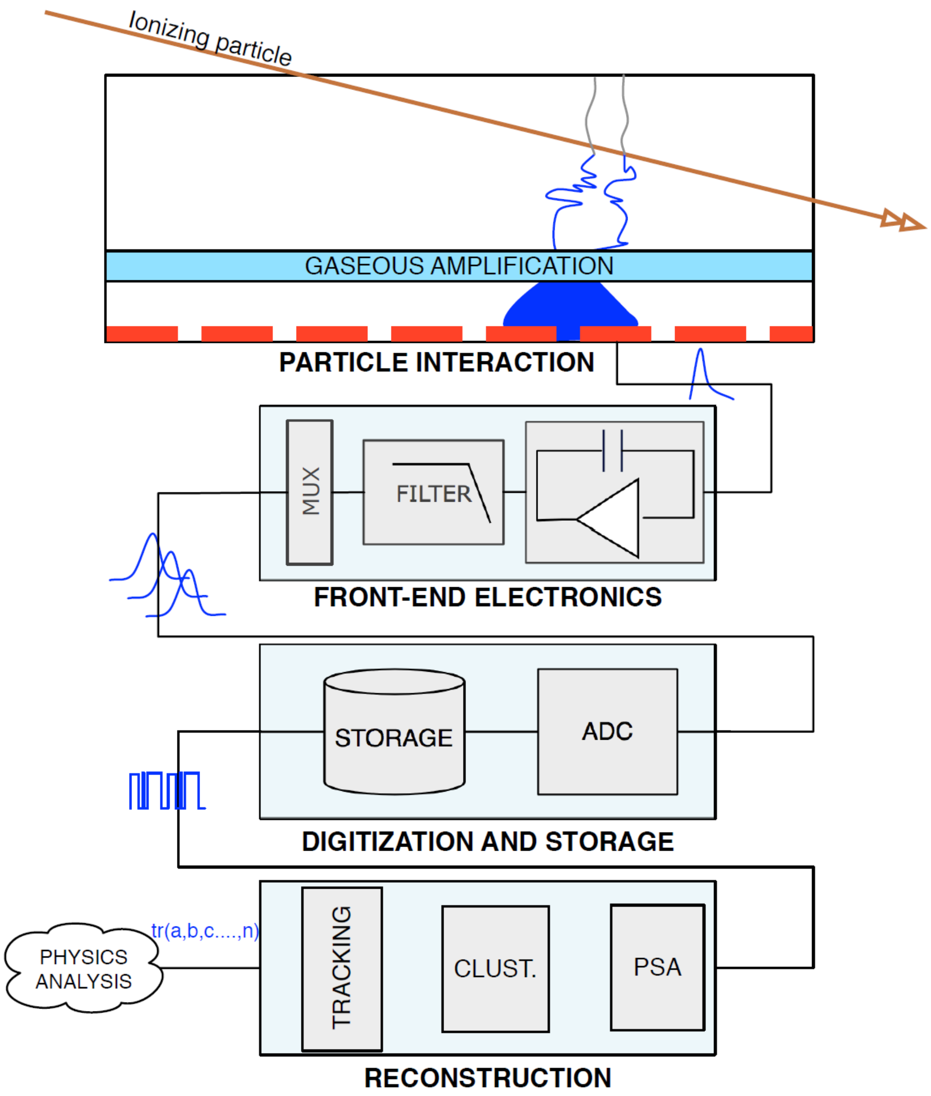
[H. Spieler, Semiconductor detector systems, Oxford, 2005]

ELECTRONIC READOUT OVERVIEW

Electronic readout techniques

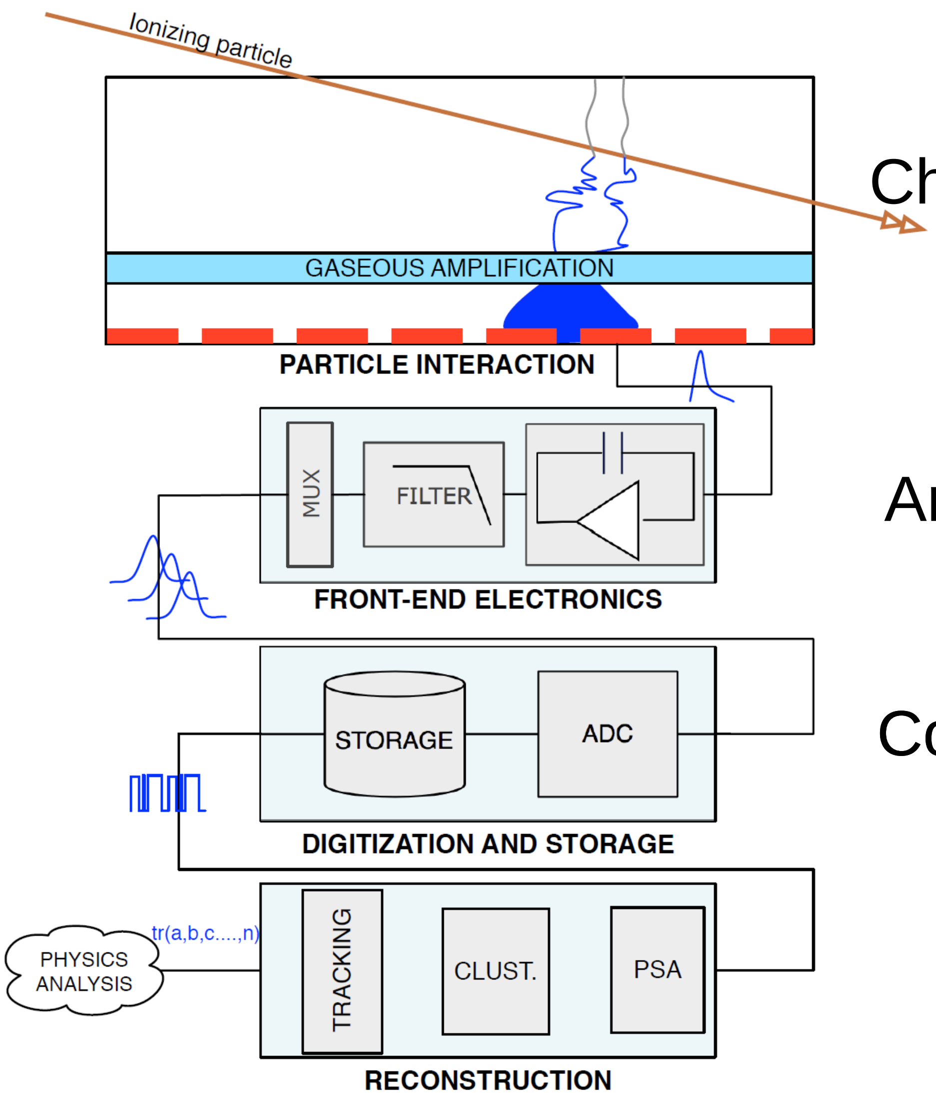


ELECTRONIC READOUT OVERVIEW



[M Vandenbroucke, PhD thesis, TUM, 2012]

ELECTRONIC READOUT OVERVIEW



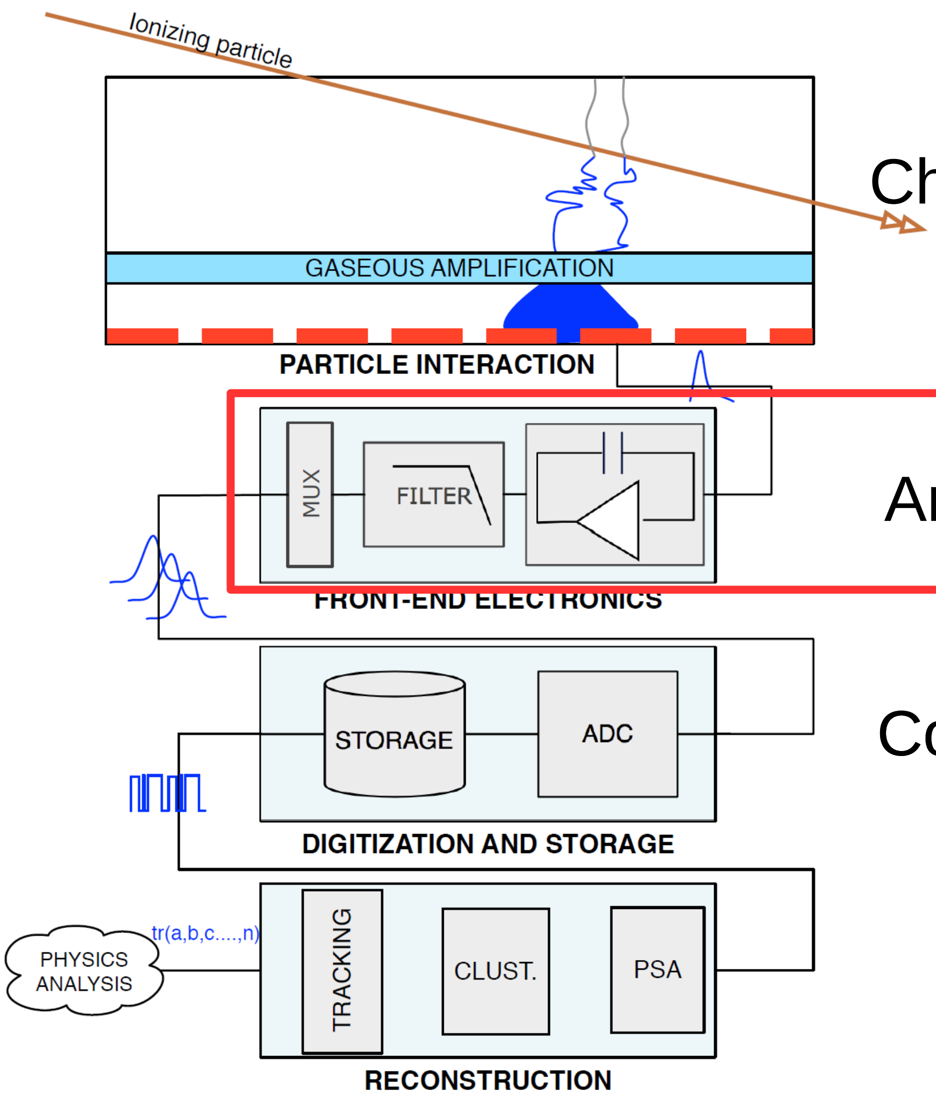
Charge induction

Analogue electronics

Conversion to digital

[M Vandenbroucke, PhD thesis, TUM, 2012]

ELECTRONIC READOUT OVERVIEW



Charge induction

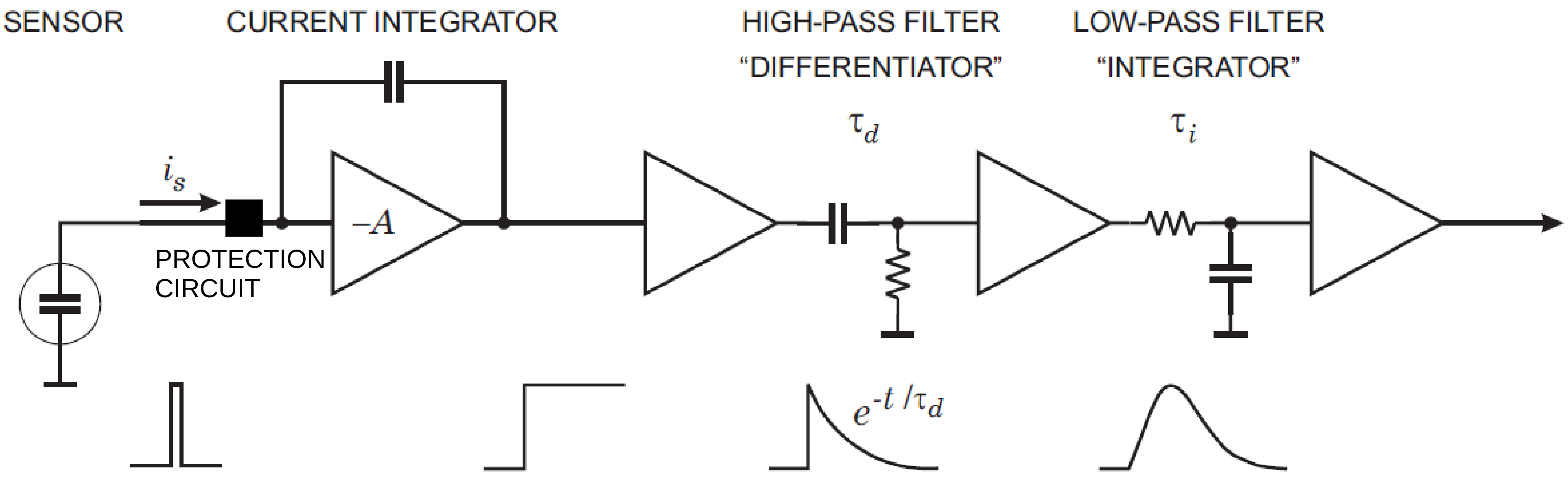
Analogue electronics

Conversion to digital

[M Vandenbroucke, PhD thesis, TUM, 2012]

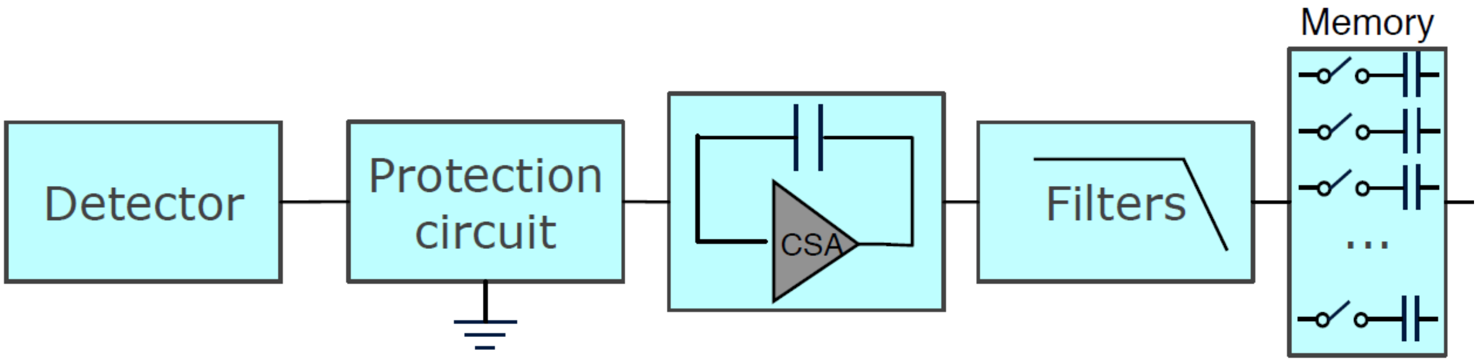
ANALOGUE ELECTRONICS

Example analogue readout chain



[H. Spieler, Semiconductor Detector Systems, Oxford 2005]

ANALOGUE ELECTRONICS

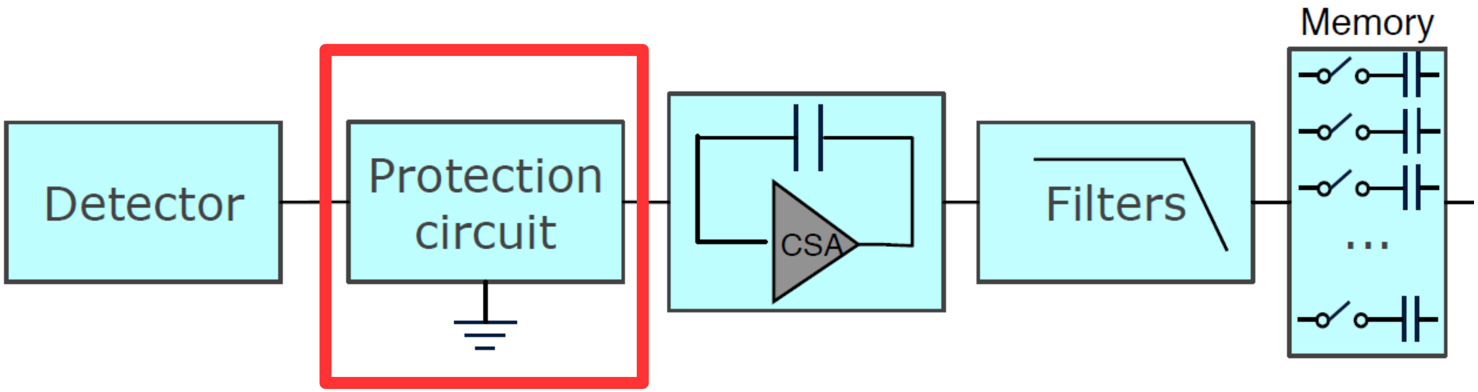


Purpose of pulse processing:
1. Acquire electrical signal from detector, typically a short current pulse
2. Optimise time response of the system to enhance:
- Minimum detectable signal (yes/no) → S/N ratio
- Energy measurement → Linearity
- Event rate → Dead time/Throughput
- Time of arrival (timing) → Time-invariance/Stability
- Insensitivity to sensor pulse shape → Linearity

3. Digitize signal and store for subsequent analysis

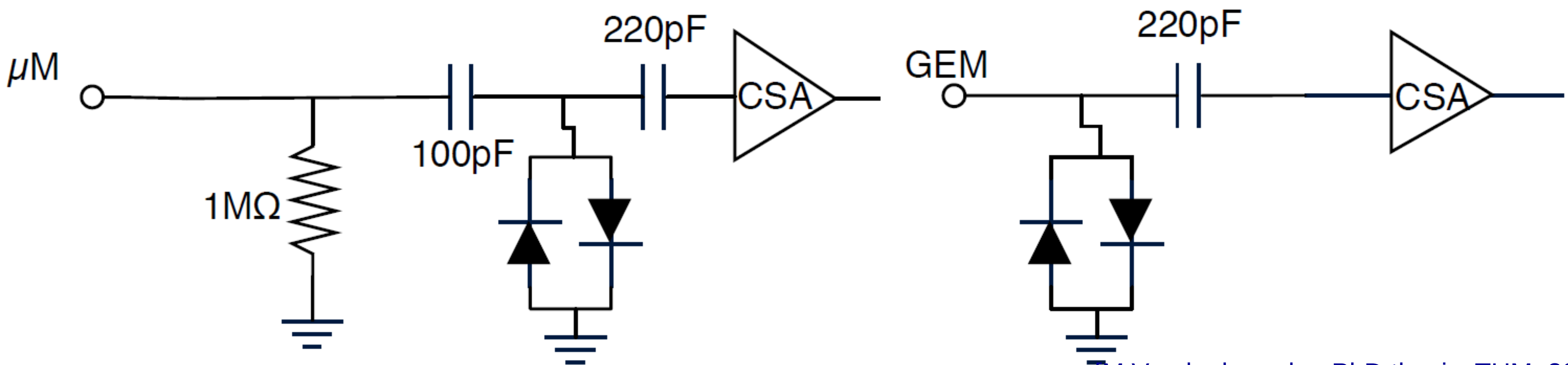
Layout of such a system heavily depends on application!

ANALOGUE ELECTRONICS



PROTECTION CIRCUIT

Gaseous detectors signal: Sparks and large signals (Landau tail)
→ protect electronics from high charge/current/power



[M Vandenbroucke, PhD thesis, TUM, 2012]

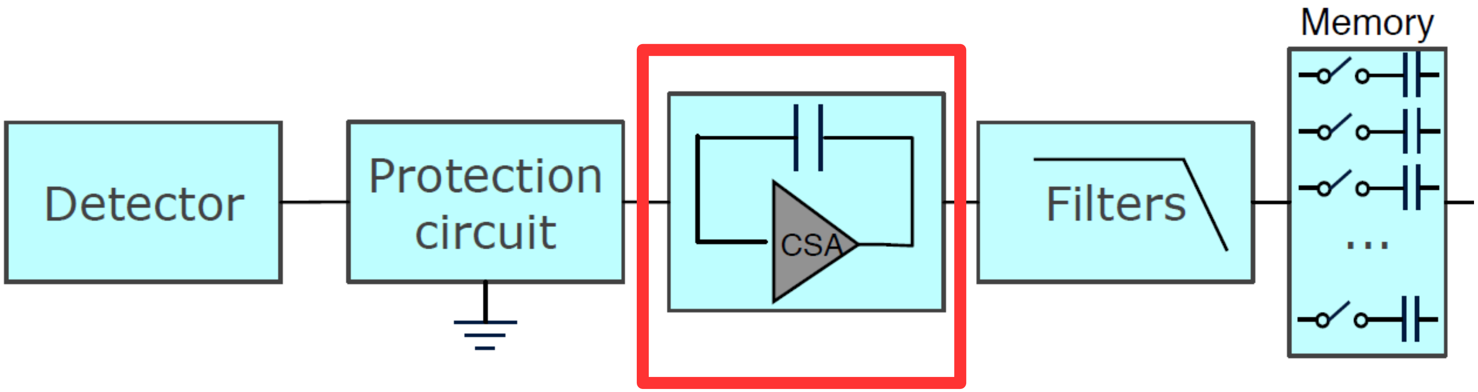
Micromegas:

- fast recovery from discharges needed, i.e. complete discharge of mesh to be avoided
- large bias resistor, input voltage approaches mesh voltage
- charge into amplifier limited by capacitor

GEM:

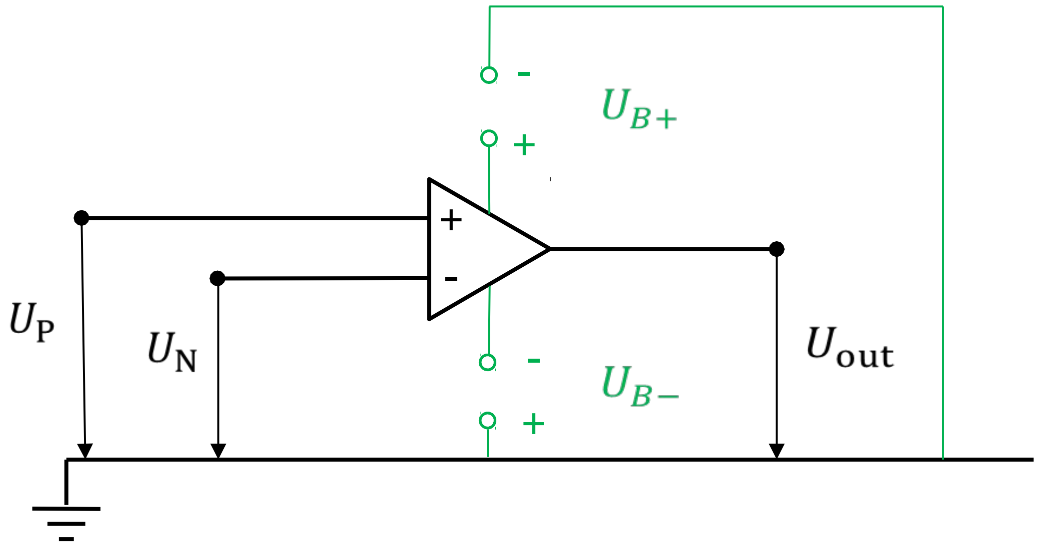
- diodes: ground every signal above minimum forward bias
- AC coupling to isolate from leakage currents of diodes
- potential defined through diodes

ANALOGUE ELECTRONICS



PREAMPLIFIER

Basic component: operational amplifier



„+“: non-inverting input

„-“: inverting input

$\Rightarrow$

$$U_P > U_N \Rightarrow U_{out} > 0$$
$$U_P < U_N \Rightarrow U_{out} < 0$$

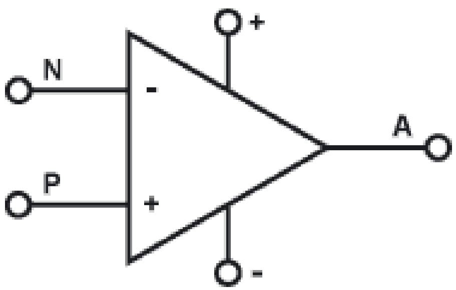
Differential voltage amplification (gain):

$$U_{out} = A_D(U_P - U_N) = A_D U_D$$ (open-loop gain, i.e. without feedback)

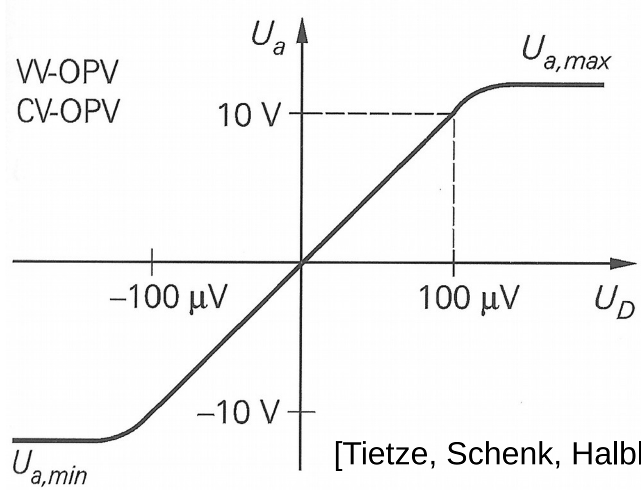
typ. $10^4 < A_D < 10^6$

PREAMPLIFIER

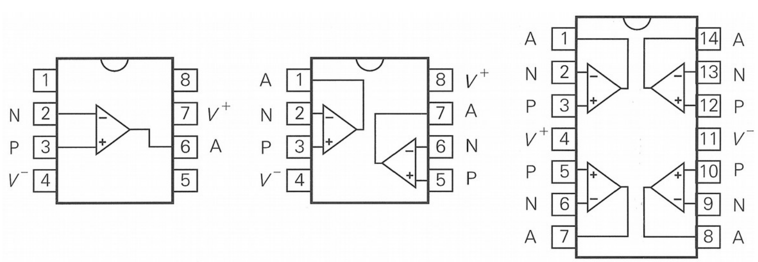
Transmission characteristics



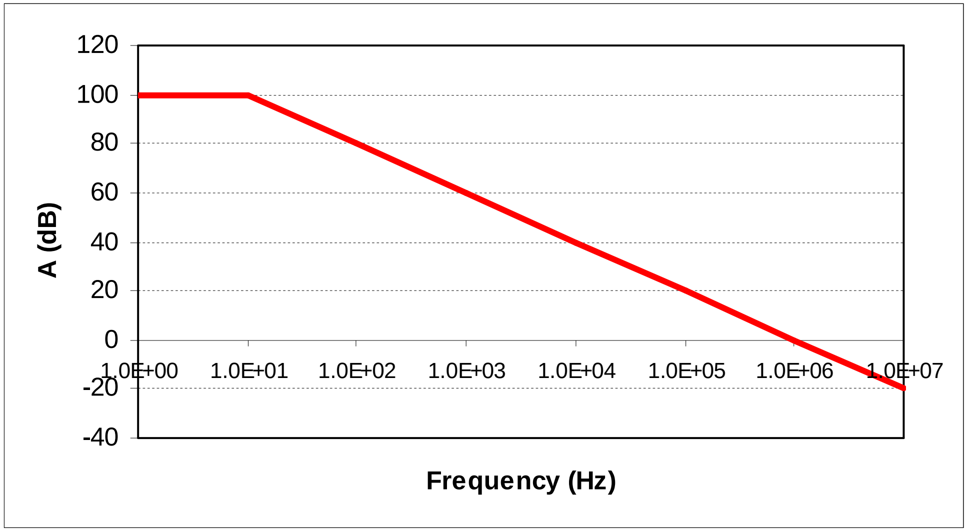
Circuit symbol



[Tietze, Schenk, Halbleiter-Schaltungstechnik, Springer, 1999]



Housing and pin assignment



Gain

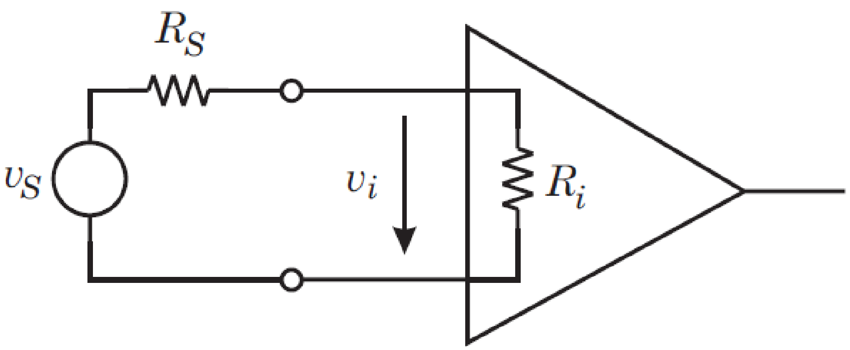
PREAMPLIFIER

Voltage-sensitive amplifier

- voltage generator has zero source resistance
- actual source resistance represented by R_S
- designed to minimize loss of signal voltage at amplifier input
- signal voltage at the amplifier input

$$v_i = \frac{R_i}{R_S + R_i} v_S$$

Equivalent circuit



- for $R_i \gg R_S \quad \Rightarrow \quad v_i \approx v_S$, i.e. amplifier input resistance (or impedance) must be large compared to source resistance (impedance)
- for voltage output: output resistance small compared to input of the following stage

PREAMPLIFIER

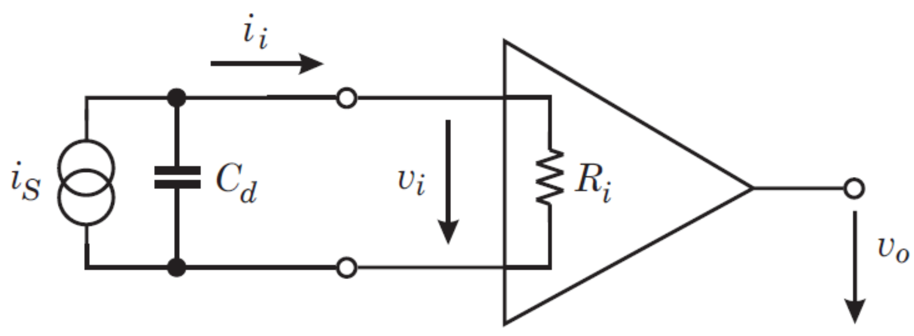
Capacitive sources

Until now: resistive sources

Now: capacitive sources

- sensor signal: current pulse of magnitude i_S and duration t_c
- signal charge: $Q_S = \int i_S(t)dt \approx i_S\, t_c$
- with voltage gain A_v the output voltage is $v_0 = A_v\, v_S$

Equivalent circuit



Whether amplifier operates in current or voltage mode depends on t_c and $R_i C_d$

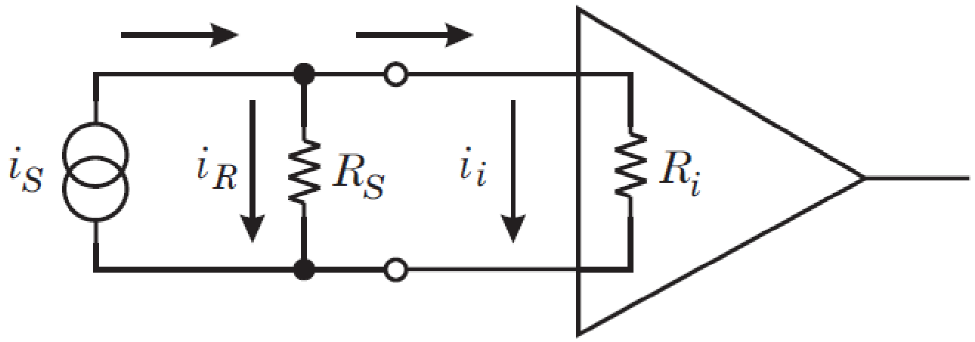
1. $R_i C_d \ll t_c$: sensor capacitance discharges rapidly $\Rightarrow v_0 \propto i_S(t)$ (instantaneous current), i.e. system operates in current mode
2. $R_i C_d \gg t_c$: detector capacitance discharges slowly $\Rightarrow$ signal current is integrated on sensor capacitance before discharging through input resistance $\Rightarrow v_0 = V_0 \exp\left(-\frac{t}{R_i C_d}\right),\; V_0 = Q_S / C_d \propto \int i_S(t)dt$, i.e. system operates in voltage mode

PREAMPLIFIER

Current-sensitive amplifier

- signal source represented by current generator with infinite source resistance
- finite source resistance represented by shunt resistance
- fraction of current flowing into amplifier

Equivalent circuit



$$i_i = \frac{R_S}{R_S + R_i} i_S$$

- For $R_i \ll R_S \Rightarrow i_i \approx i_s$, i.e. amplifier input resistance (or impedance) must be small compared to source resistance (impedance)
- for current drive: output resistance high compared to input of the following stage

PREAMPLIFIER

Feedback

Caveat:

- Amplification depends on transistor characteristics (e.g. gain, resistance)
  ⇒ can vary from device to device, depends on temperature T!

Dependence of currents on T (diode) ⇒ working point may be unstable

Remedy: negative feedback ⇒ couple output into input so that part of input is compensated

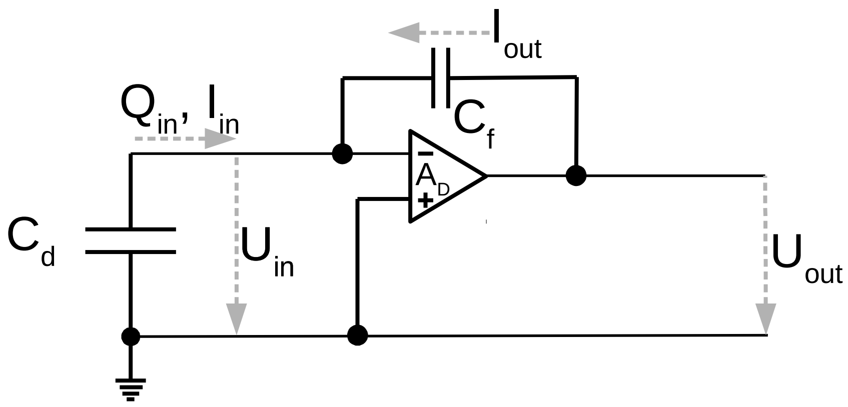
- Improves stability
- Improves linearity
- Improves bandwidth (but gain * bandwidth = const.)
- Make system predictable

PREAMPLIFIER

Charge-sensitive amplifier

Integrator:

- inverting voltage amplifier with high input resistance
- feedback capacitor C_f



Rule: No current into inverting input

$$\Rightarrow I_{\text{in}} = -I_{out} = -C_f \frac{dU_{out}}{dt}$$

$$\Rightarrow U_{out} = \frac{-1}{C_f}\left[\int_0^t I_{\text{in}}\,dt + Q_0\right] = \frac{-Q_{\text{in}}(t)}{C_f}$$

Charge on C_f at t=0

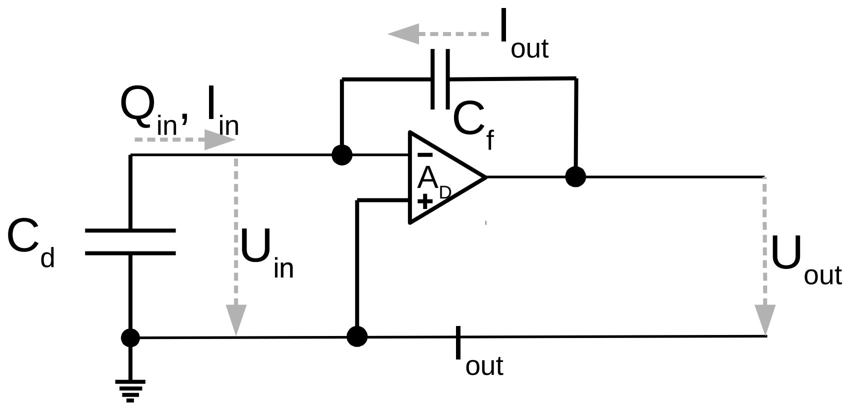
$\Rightarrow U_{out}$ is independent of C_d!

Note:

- Potential difference over C_f:
  $$U_f = U_{\text{in}} - U_{out} = U_{\text{in}}(A_D + 1) = \frac{Q_f}{C_f}$$
- Charge on C_f:
  $$Q_f = Q_{\text{in}}$$

PREAMPLIFIER

Charge-sensitive amplifier



Effective input capacitance:

$$Z_{in} = \frac{1}{i\omega C_{in}} \qquad C_{in} = \frac{Q_{in}}{U_{in}} \qquad U_{out} = A_D(U_P - U_N) = -A_D U_{in}$$

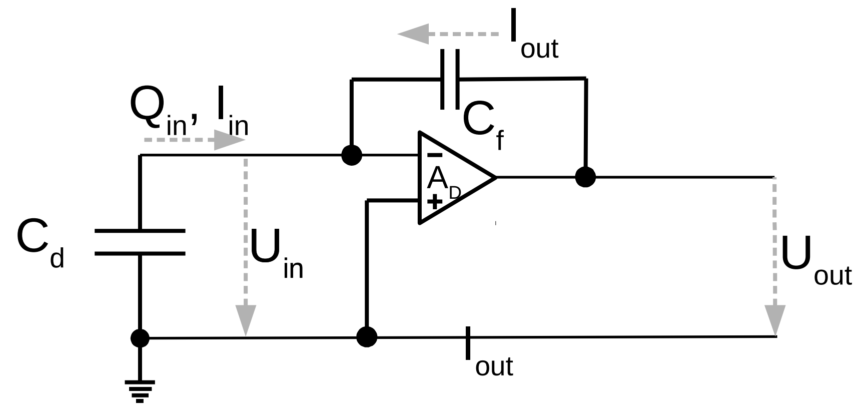
$$U_{in} = \frac{Q_f}{C_f} + U_{out} = \frac{Q_{in}}{C_f} - A_D U_{in}$$

$$\Rightarrow U_{in}(1 + A_D) = \frac{Q_{in}}{C_f} \Rightarrow \frac{Q_{in}}{U_{in}} \equiv \underline{C_{in} = C_f(A_D + 1)}$$

Dynamic input capacitance

⇒ total impedance $Z_{in} = \frac{1}{i\omega C_{in}}$ is low!

PREAMPLIFIER



Charge-sensitive amplifier

Charge amplification:

$$A_Q = \frac{U_{out}}{Q_{\text{in}}} = \frac{-A_d U_{\text{in}}}{U_{\text{in}} C_{\text{in}}} = -\frac{A_D}{C_{\text{in}}} = -\frac{A_D}{C_f (A_D + 1)} \approx -\frac{1}{C_f}$$

$A_D >> 1$

A part of charge Q generated in detector stays on C_d!

$$Q = Q_D + Q_f = C_D U_{\text{in}} + C_f (U_{\text{in}} - U_{out}) = U_{\text{in}} (C_D + C_{\text{in}})$$

$$C_{\text{in}} = C_f (A_D + 1) < \infty$$

$$\Rightarrow Q_{rest} = U_{\text{in}} C_D = Q \frac{C_D}{C_D + C_{\text{in}}}$$

Example: A_D = 1000, C_f = 1 pF, C_D = 10 pF

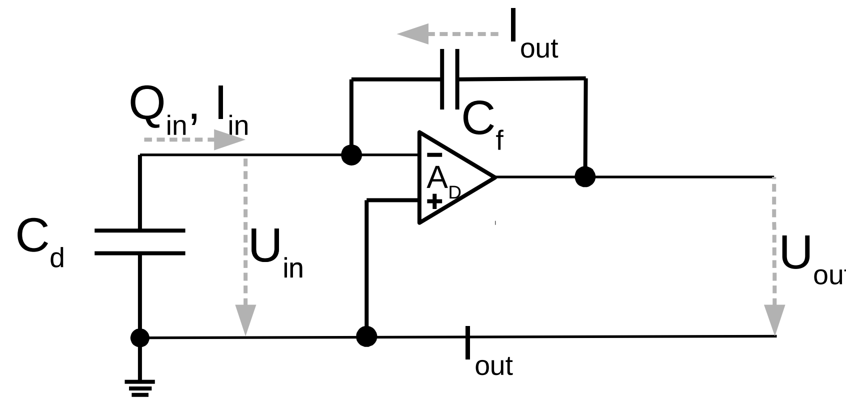
⇒ Signal charge Q_S = Q – R_{rest} = 99 % Q (C_D = 10 pF) | 67 % Q (C_D = 500 pF)

Q_{rest} ⇒ capacitive cross-talk between strips or pixels

Ideally: Q_{rest} = 0 ⇒ C_{in} >> C_D!

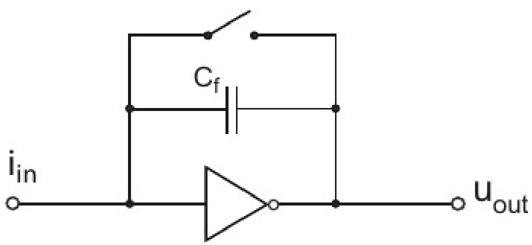
PREAMPLIFIER

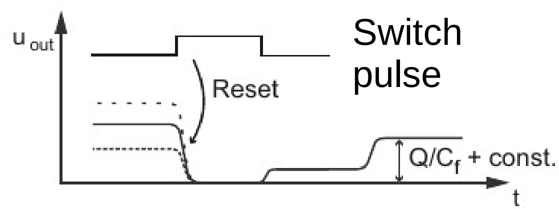
Charge-sensitive amplifier

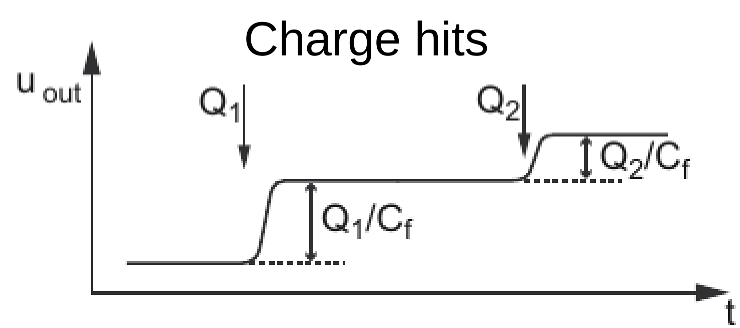


Discharge of C_f:

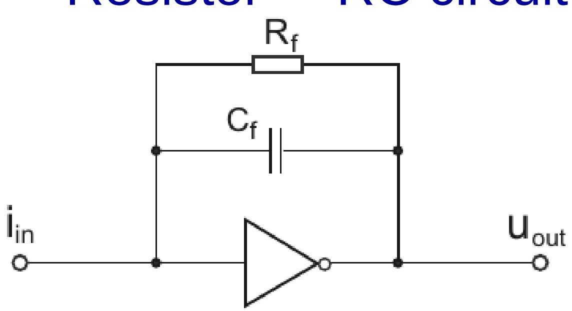
- Transistor = Reset switch

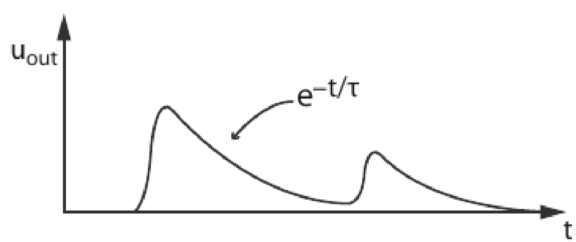




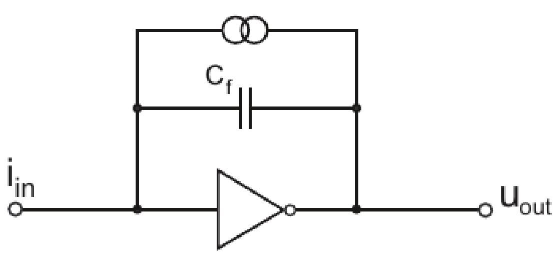


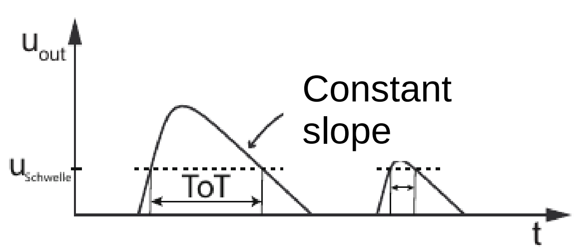
- Resistor ⇒ RC circuit





- Constant current source

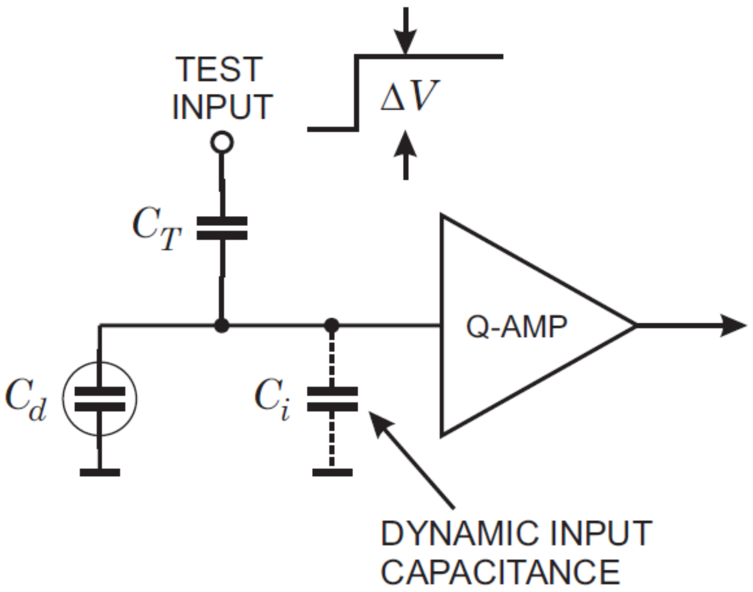




CALIBRATION

Use known input charge:

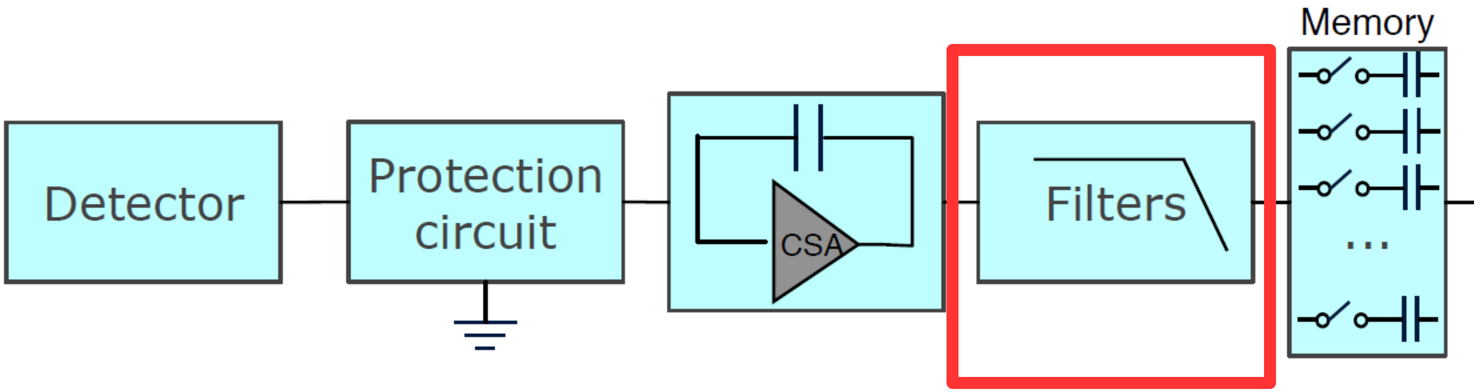
- add test capacitor C_T to input
- inject well-defined charge via voltage step ΔV
- if $C_i \gg C_T$, the voltage step ΔV at the test input is applied almost completely across the test capacitance ⇨ injection of charge $C_T\,\Delta V$ into the input
- More precisely:



$$Q_T = \frac{C_T}{1 + \frac{C_T}{C_i + C_d}} \cdot \Delta V \approx C_T \left(1 - \frac{C_T}{C_i + C_d}\right) \Delta V$$

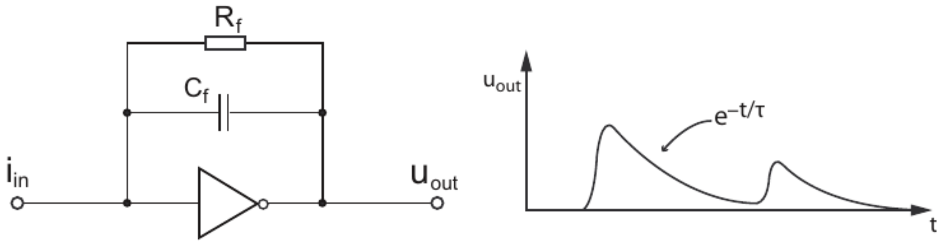
⇒ calibrate system with detector connected for best accuracy!

ANALOGUE ELECTRONICS



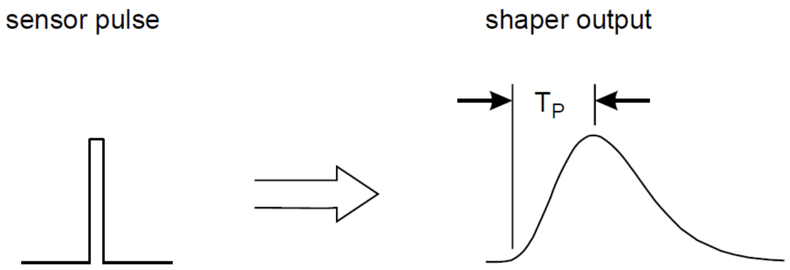
SHAPER

Further pulse shaping necessary for
- Reducing pile-up
- Increasing signal to noise ratio

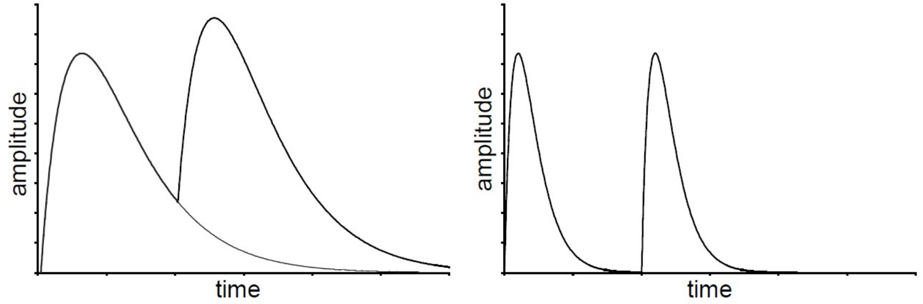


Two conflicting objectives:

- Limit bandwidth to match measurement time: too large a bandwidth will increase the noise without increasing the signal



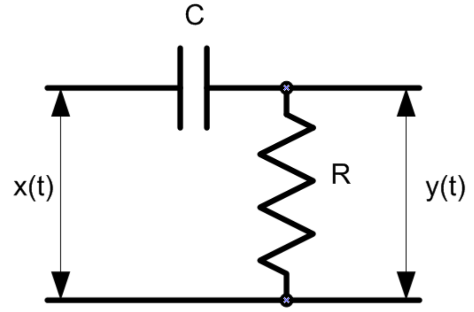
- Constrain pulse width so that successive signal pulses can be measured without overlap (pile-up): increases signal rate, but also electronic noise

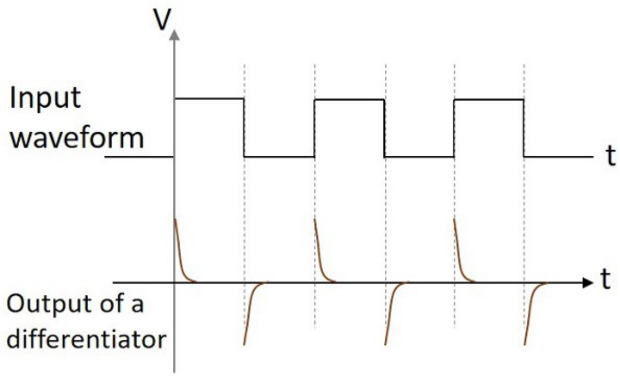


SHAPER

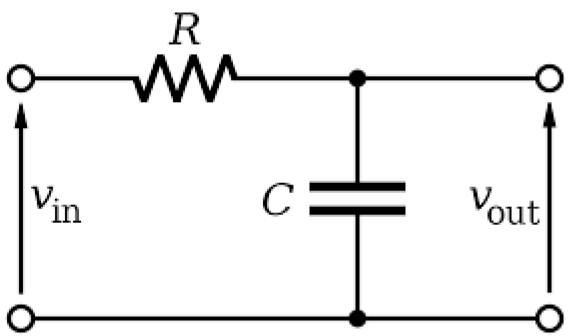
Pulse shaping filters

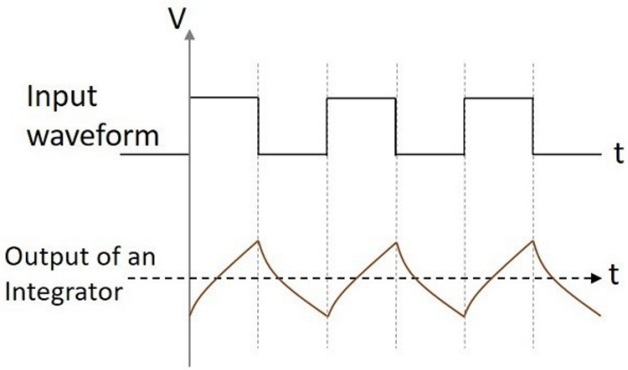
- High pass – differentiator





- Low pass - integrator

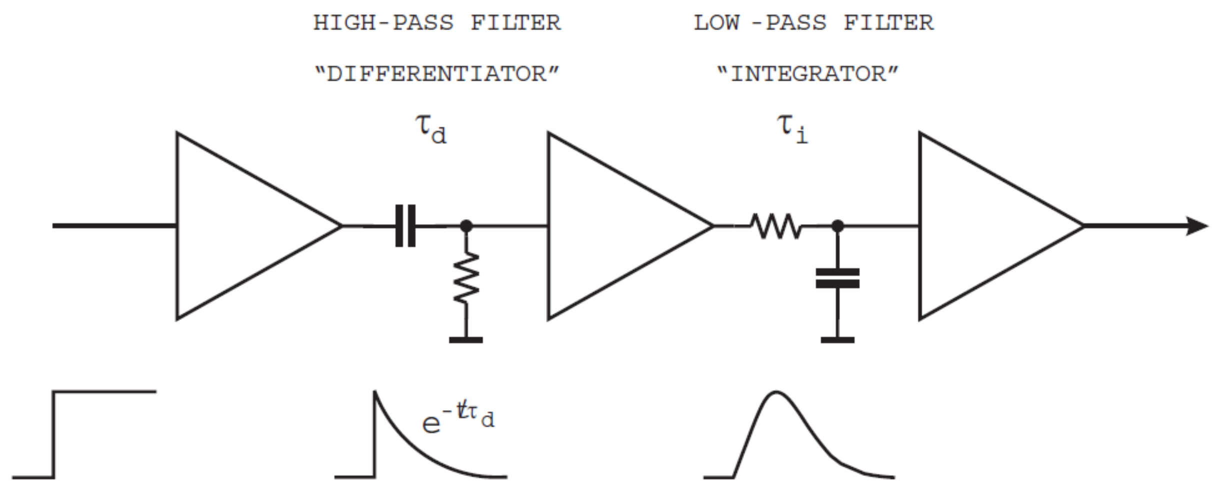




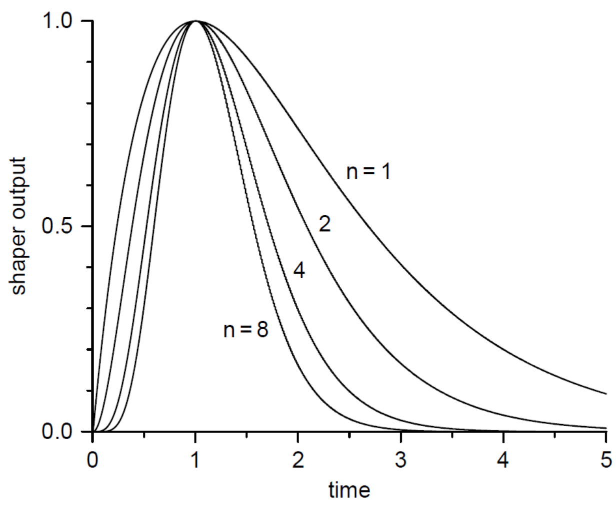
SHAPER

CR-RC shapter

[H. Spieler, Semiconductor Detector Systems, Oxford Univ. Press, 2005]



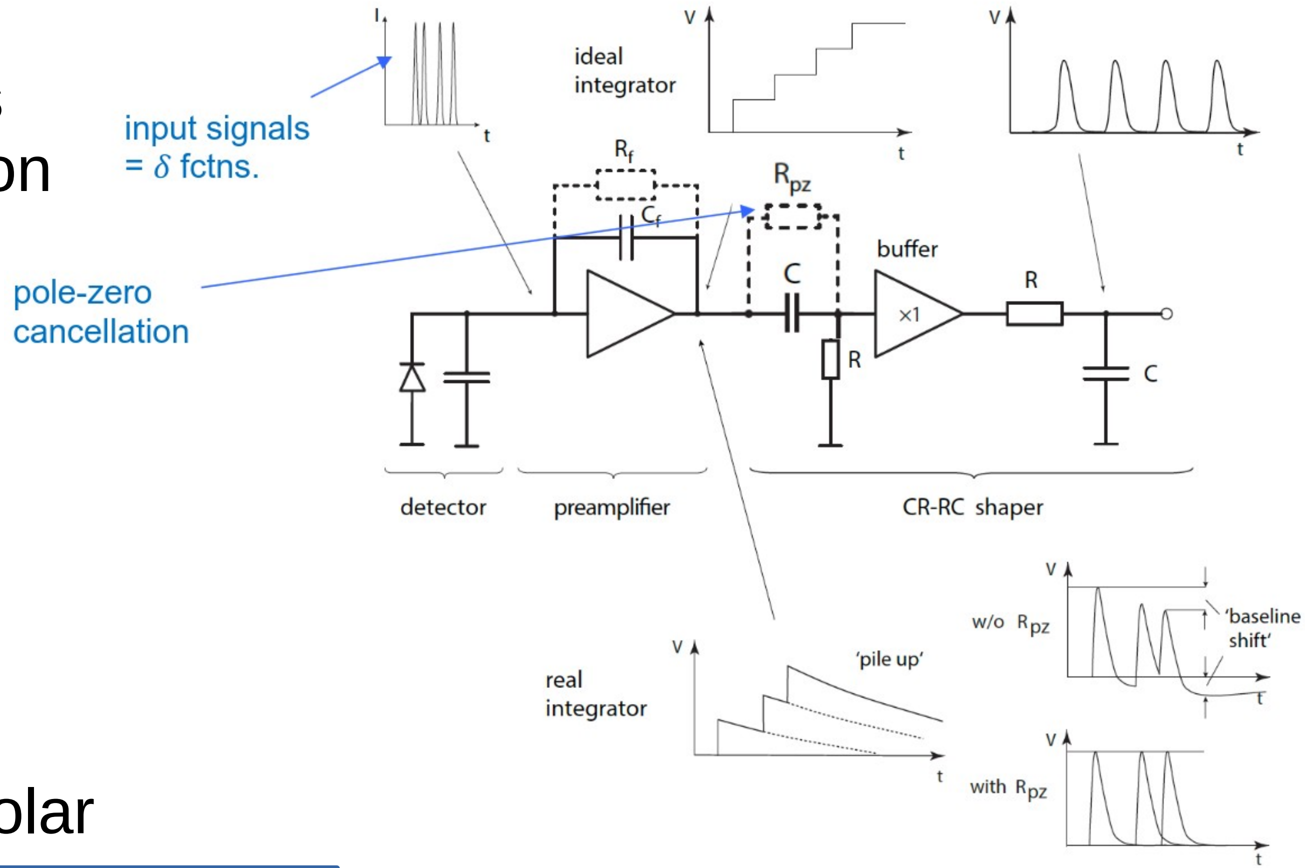
→ More symmetric pulse shapes: CR-nRC shaper



SHAPER

Further additions

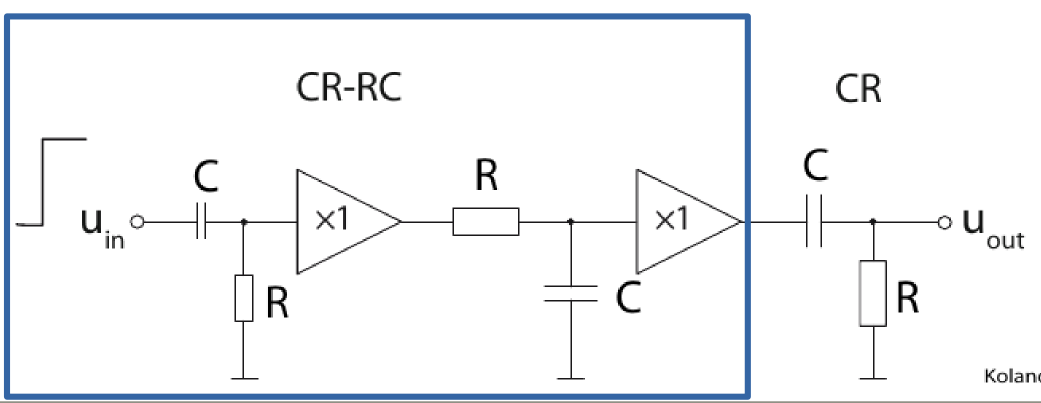
• Pole cancellation

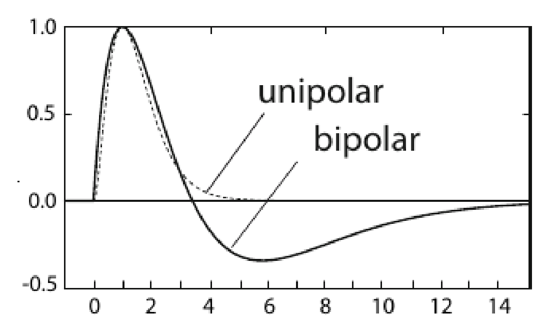


ideal

real

• Bipolar → unipolar



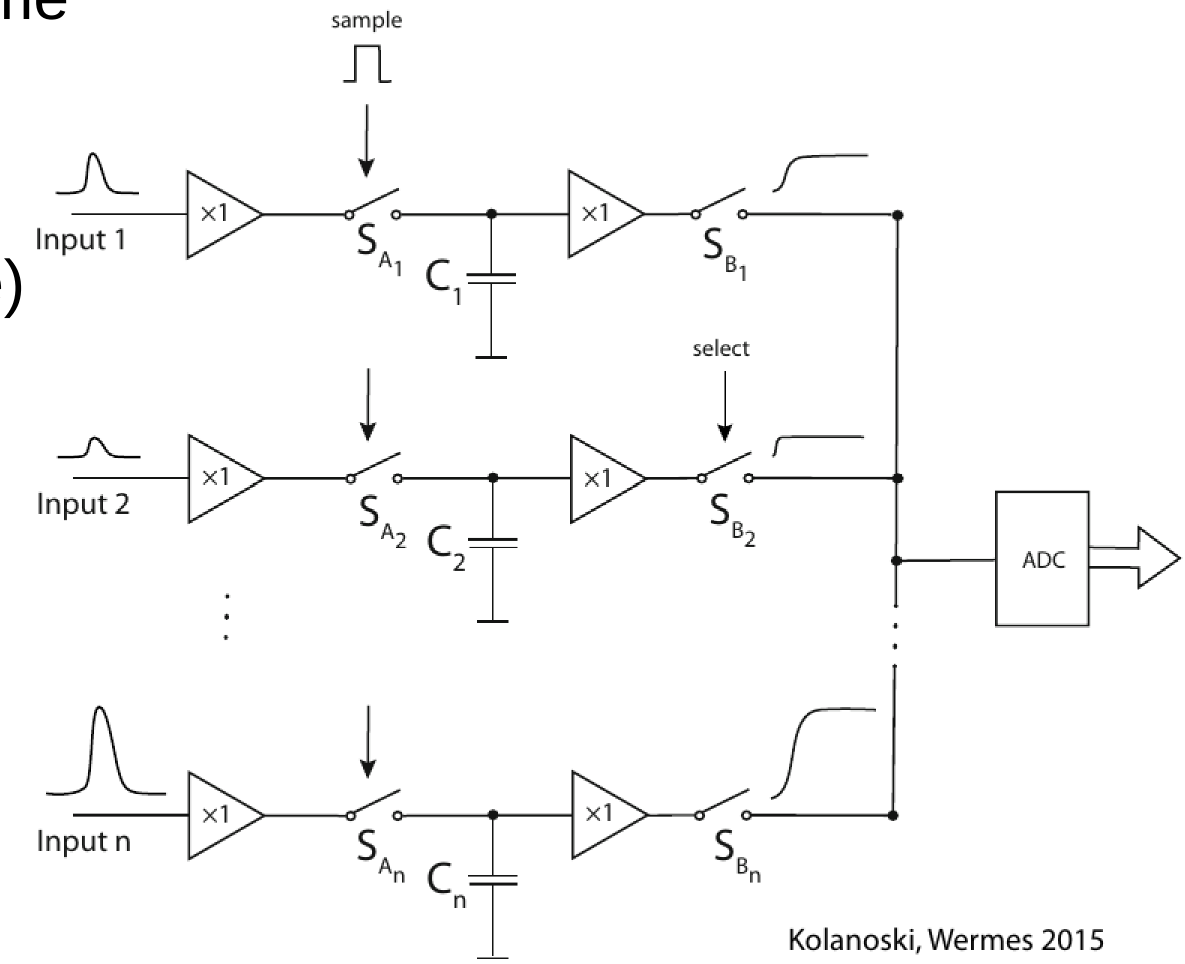


Kolanoski, Wermes 2015

DIGITISATION

Sample & hold

- If signal shape and arrival time are ~ known
  ⇒ spread signal on inputs
- Successively close/open switches S_{Ai} and S_{Bi} (sample)
  ⇒store analogue signals at different times (hold)
- Serially read path I with Analogue to Digital (ADC) converter



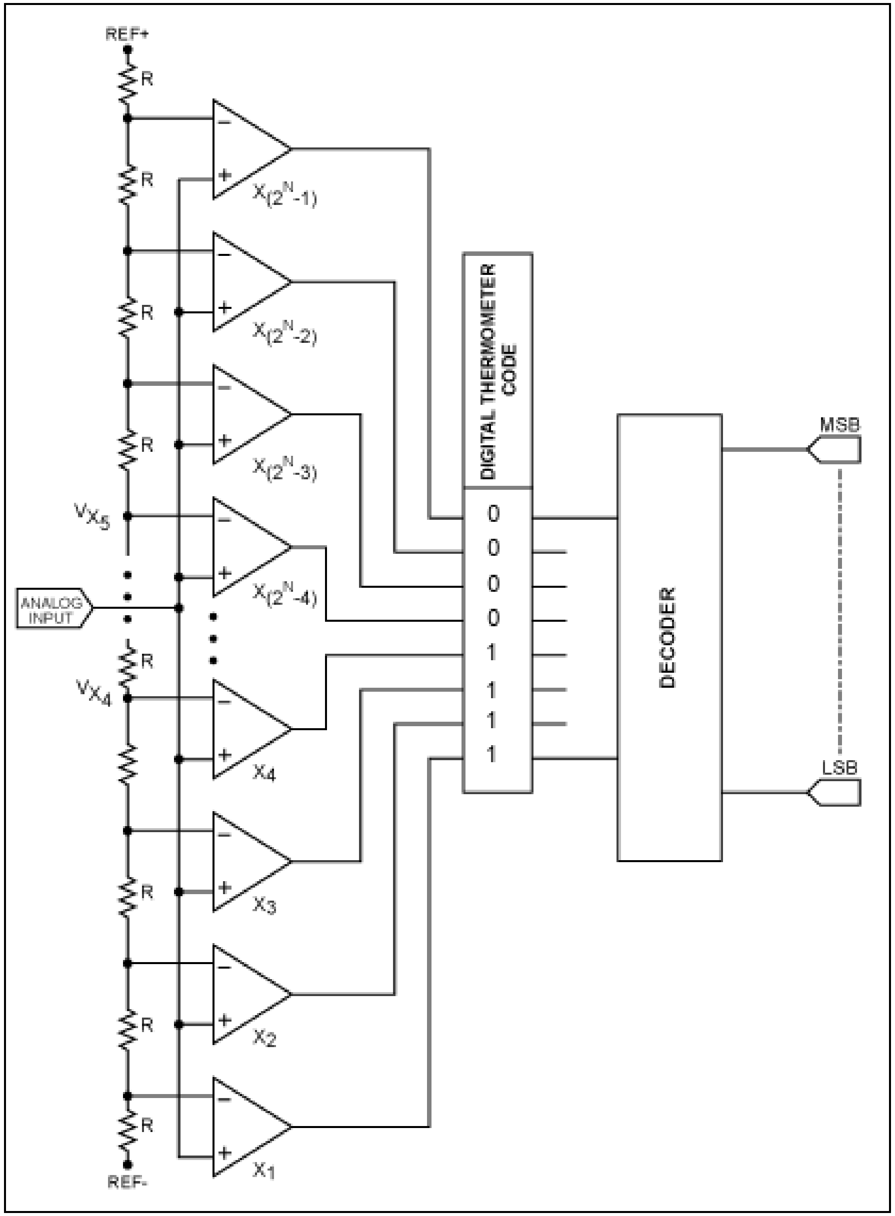
Kolanoski, Wermes 2015

DIGITISATION

Flash ADC

- parallel A/D converter ⇒
  2^n-1 comparators for n bits

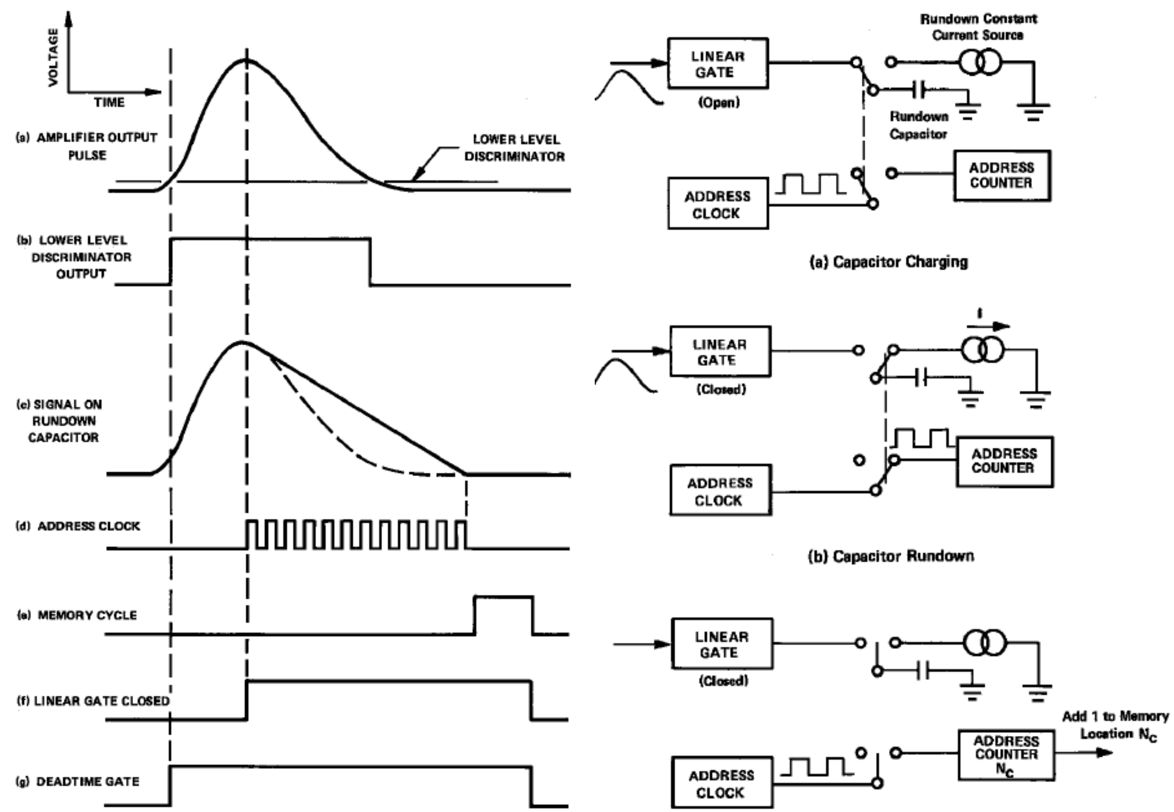
- Pro:
  - conversion time very short: ~ 1 ns
    ⇒ high-bandwidth applications: ~Gsps
- Con:
  - accuracy limited by number of comparators typ. 8 bit
  - high power consumption
  - differential non-linearity ~1%



DIGITISATION

Wilkinson ADC

- stretching of input signal
- charging of a capacitor by input signal
- discharging of capacitor at constant rate (current source)
- counter determines the number of clock pulses until voltage on capacitor reaches baseline



+ excellent differential linearity
- slow:

  conversion time = $n \cdot T_{CLK}$

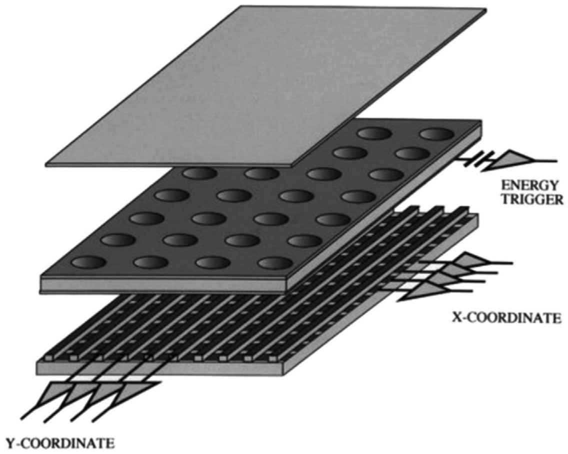
  n = channel # $\propto$ pulse height

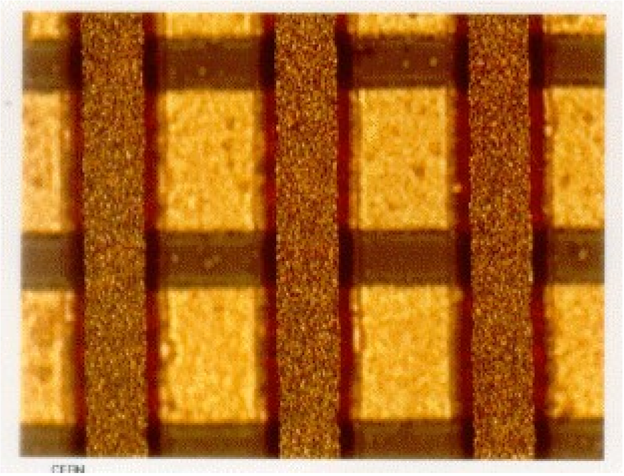
  $\approx 40\mu s$ for 100MHz and 12 bit

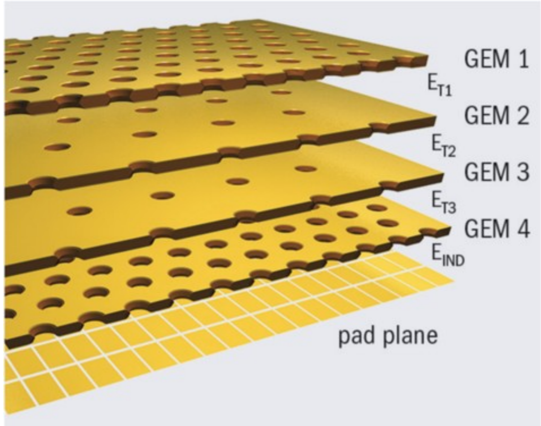
MULTI-CHANNEL READOUT

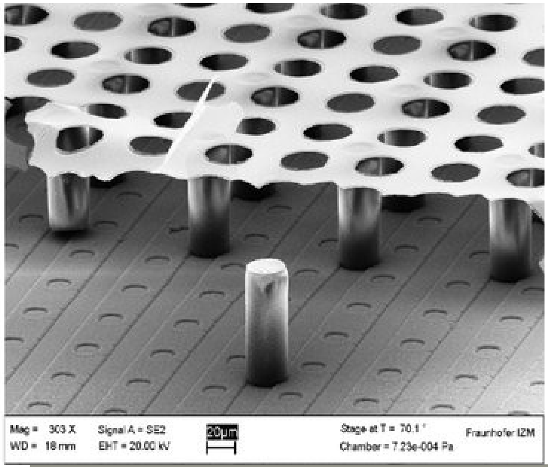
Gaseous detector readout

- Strips (1D, **2D**, X-V-U)
- Pads
- Pixel





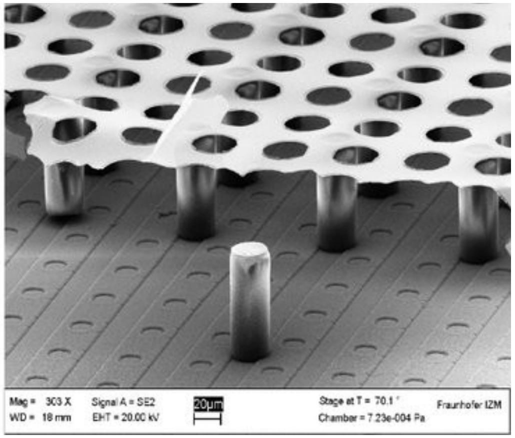


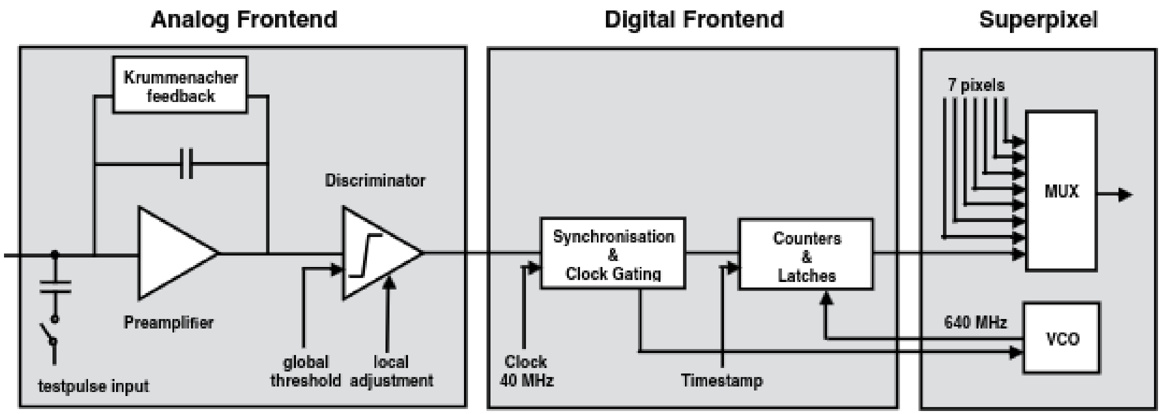


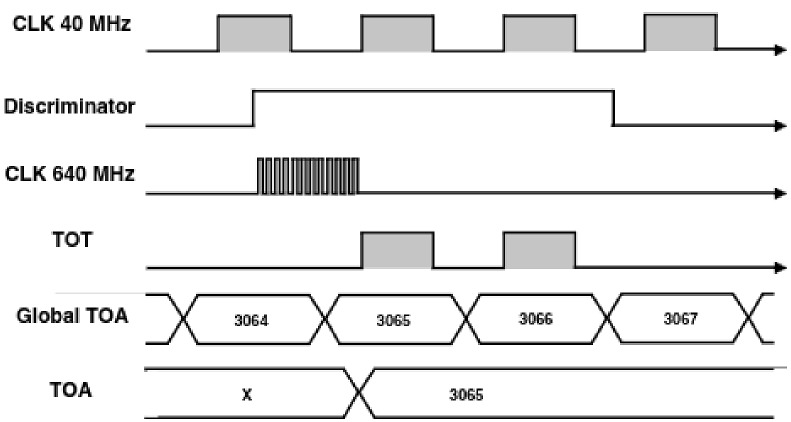
MULTI-CHANNEL READOUT

Gaseous detector readout

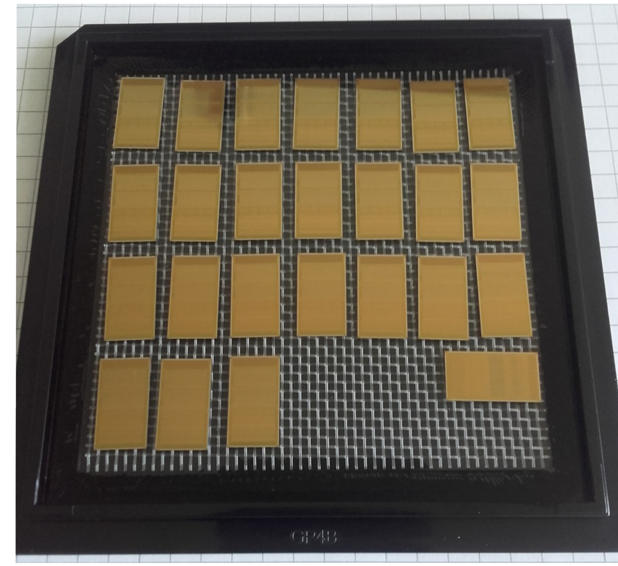
- High rates and large #channels → little space
  ⇒ discrete components → integrated circuit (IC)
- Application Specific Integrated Circuits (ASIC)
- Example of fully integrated gaseous detector:
  GridPix = Timepix(3)ASIC + Micromegas







MULTI-CHANNEL READOUT



Gaseous detector readout

- High rates and large #channels → little space
  ⇒ discrete components → integrated circuit (IC)
- Application Specific Integrated Circuits (ASIC)
- ASIC connected to strips/pads

  Example: VMM3a