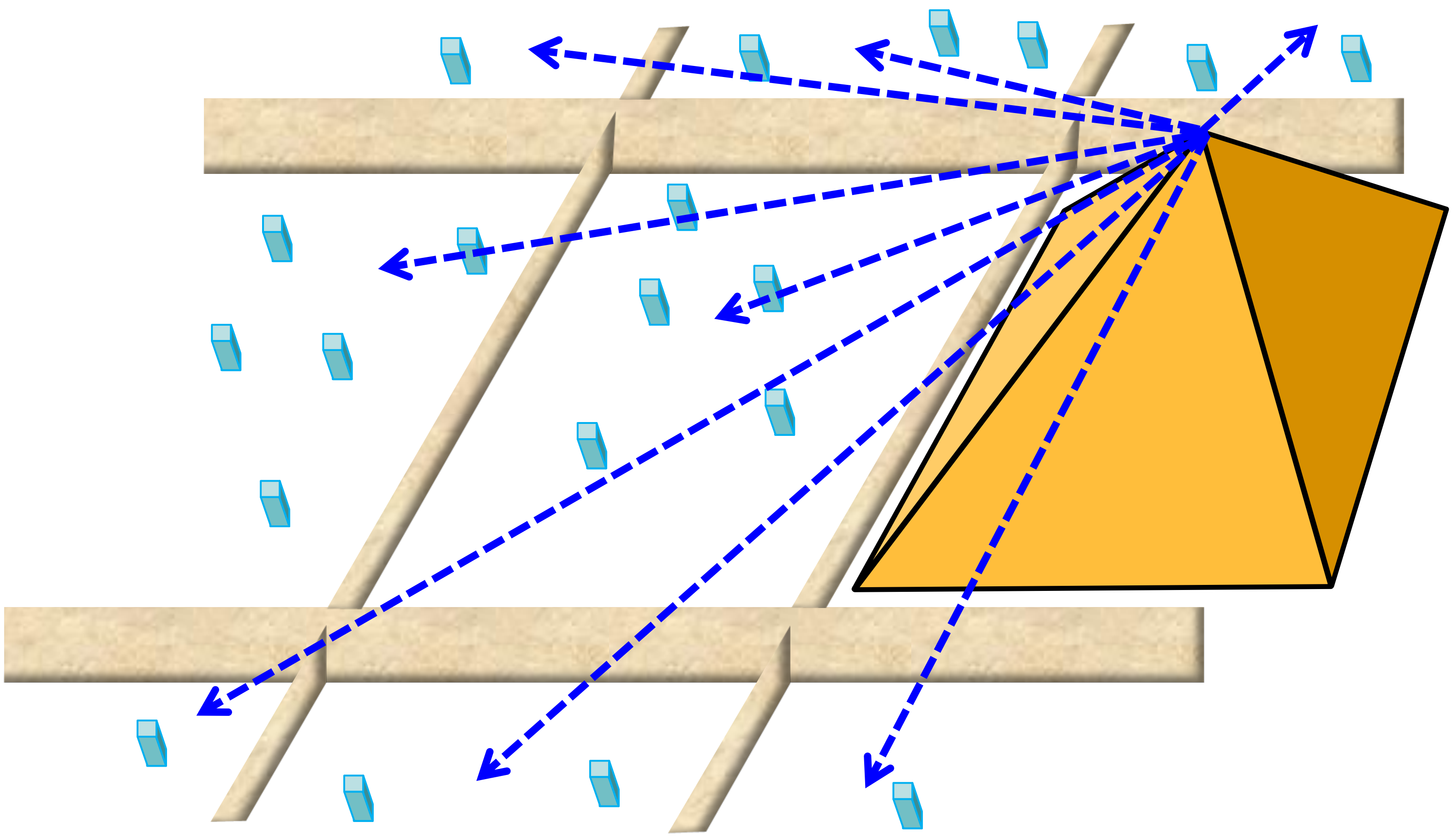
Outline

- **The Intention of these Lectures**

Today:

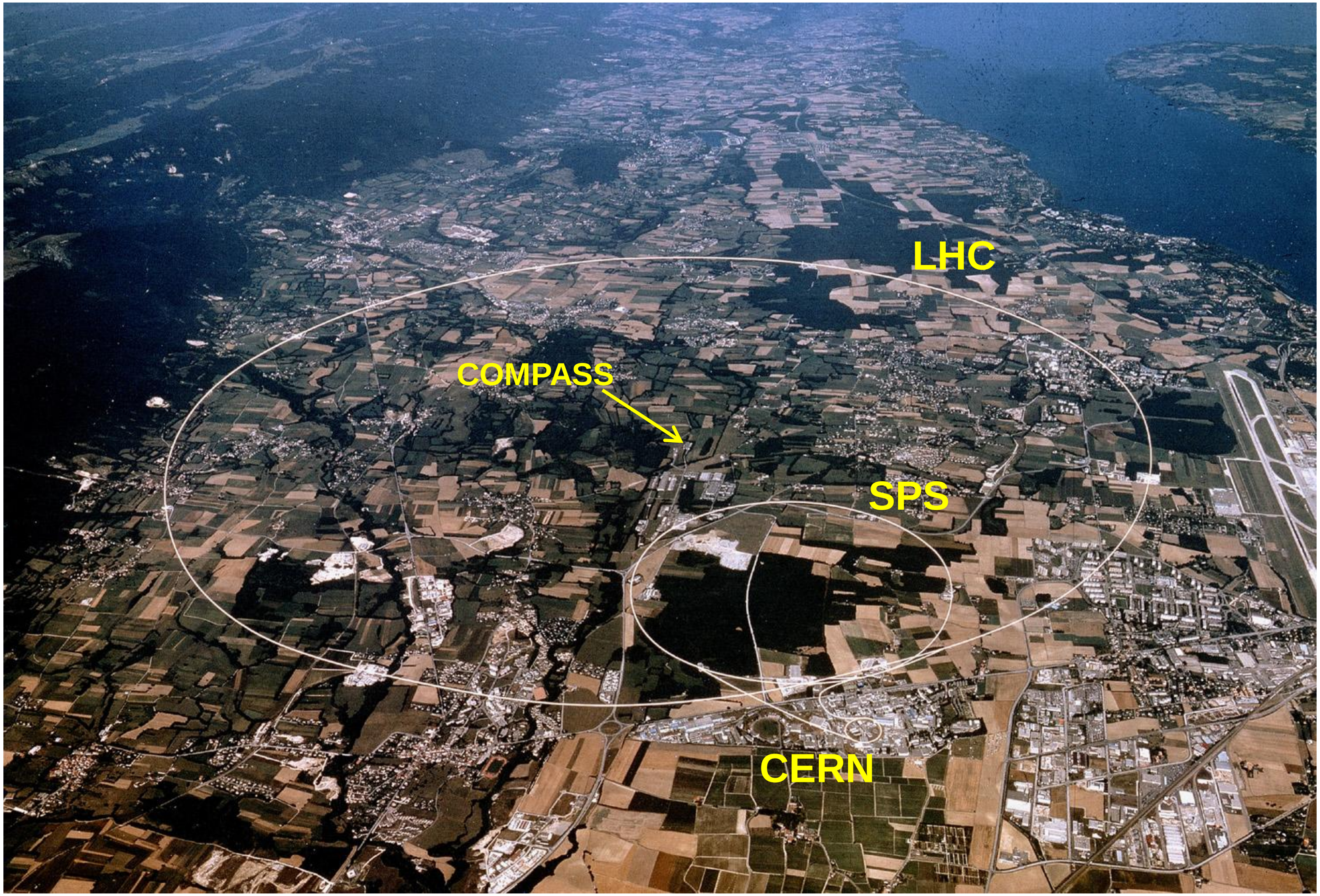
- **The „Beauty“ of Detectors**
- **The Purpose of Front-End Electronics**
- **Basics: Passive Devices**
- **Signal Transmission of Cables and EM-Fields**
- **Summary**

The Pyramid of Knowledge



Electronics I

– The „Beauty“ of Detectors –



Electronics I

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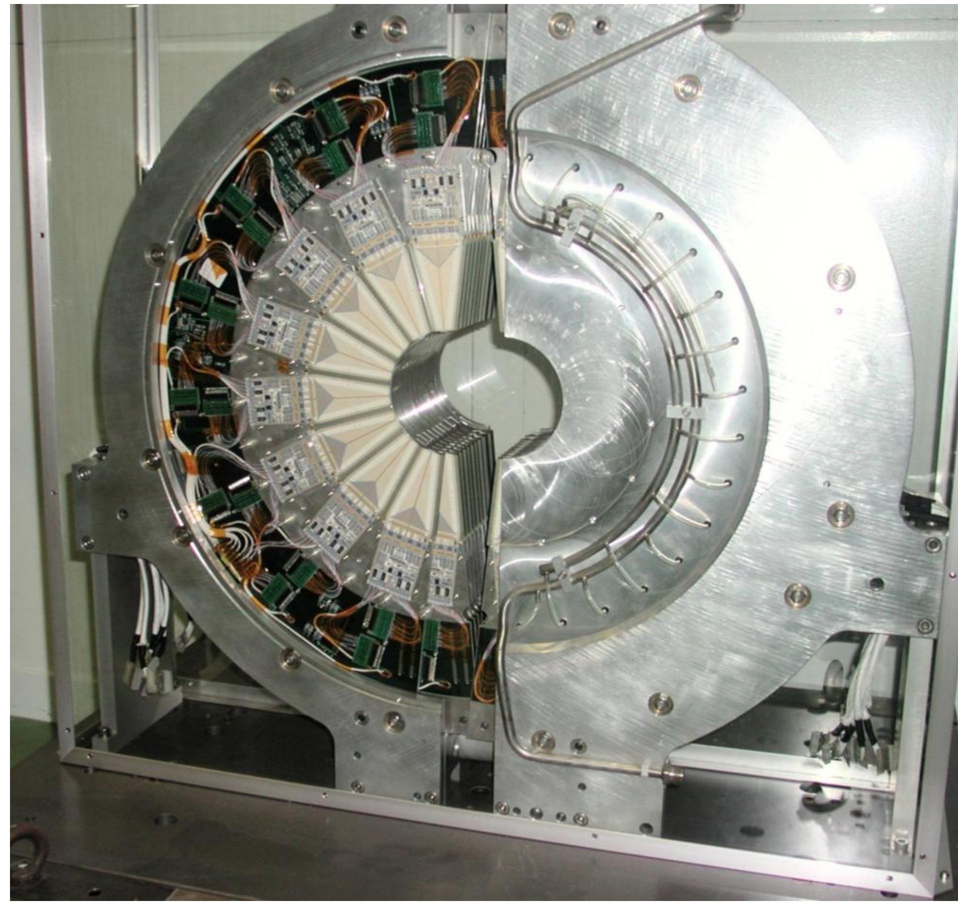
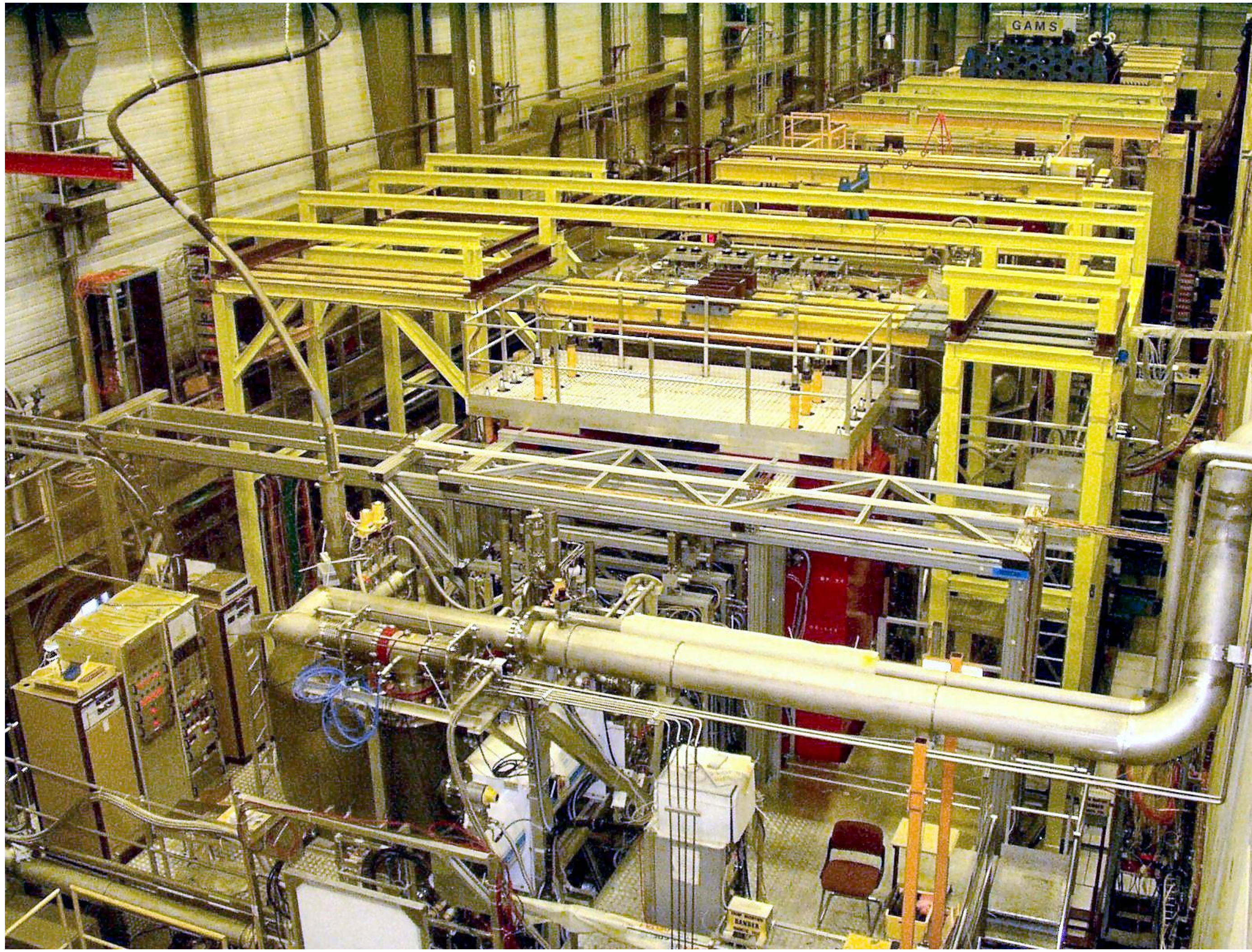


Electronics I

– The „Beauty“ of Detectors –

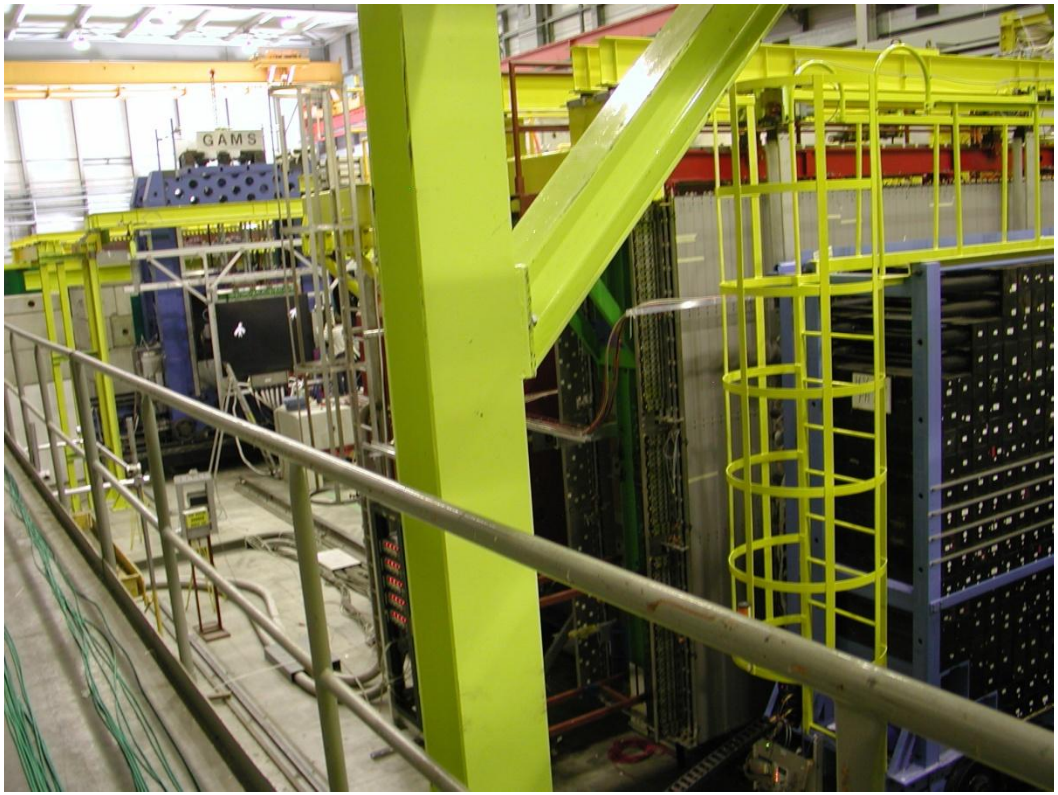
COMPASS

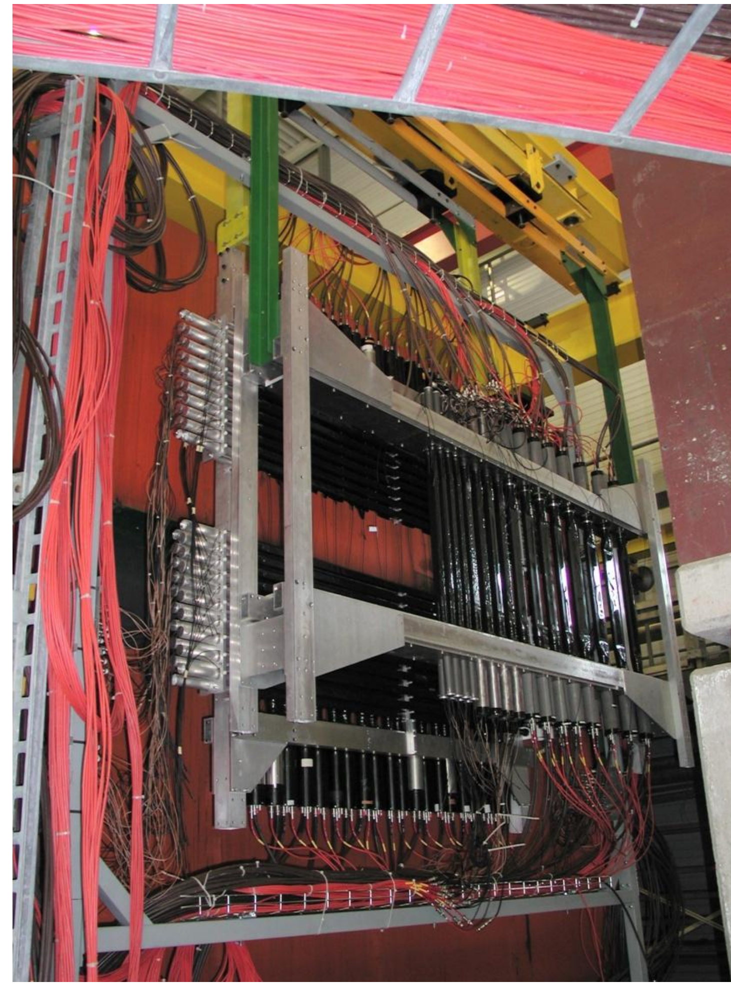
(**CO**mmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy)



Electronics I

– The „Beauty“ of Detectors –

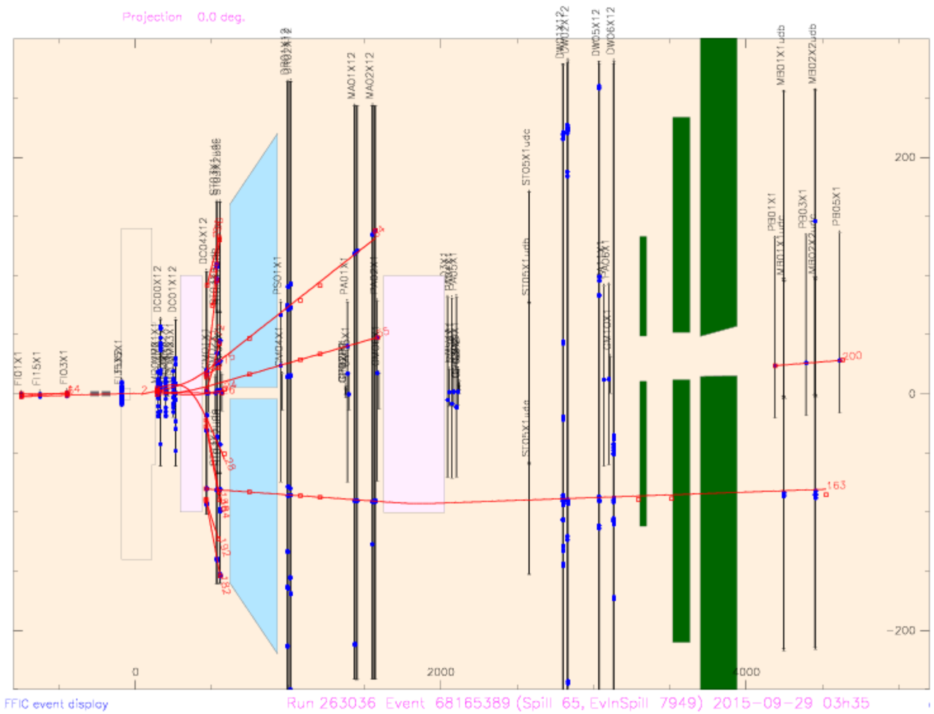




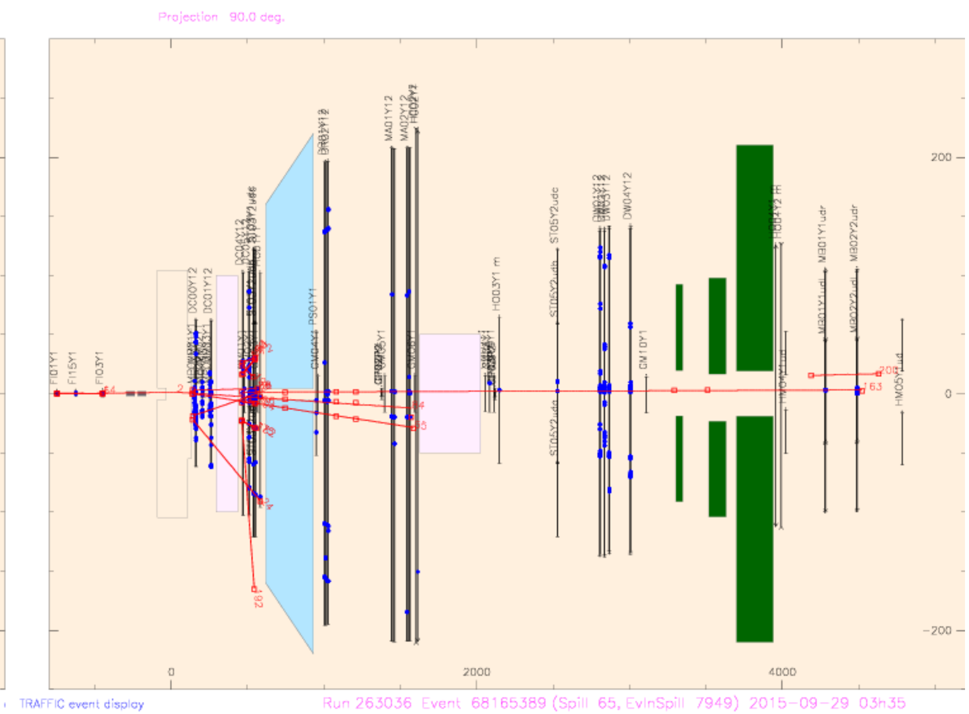
Electronics I

– The „Beauty“ of Detectors –

Top View



Side View

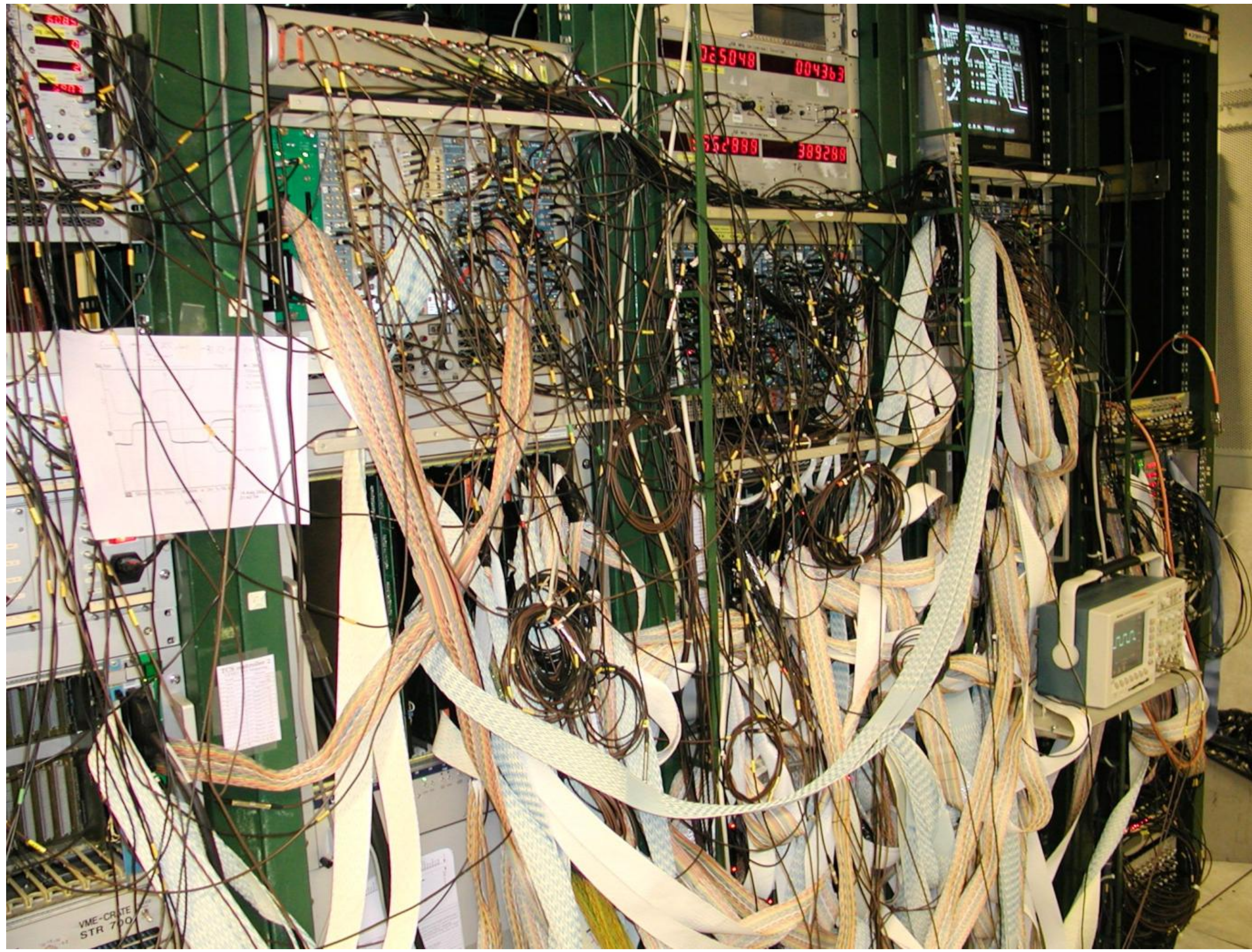


Clusters, Charged Particle Tracks, Spectrometer Magnets, RICH, Muon Filter and Detector

← ~50 m →

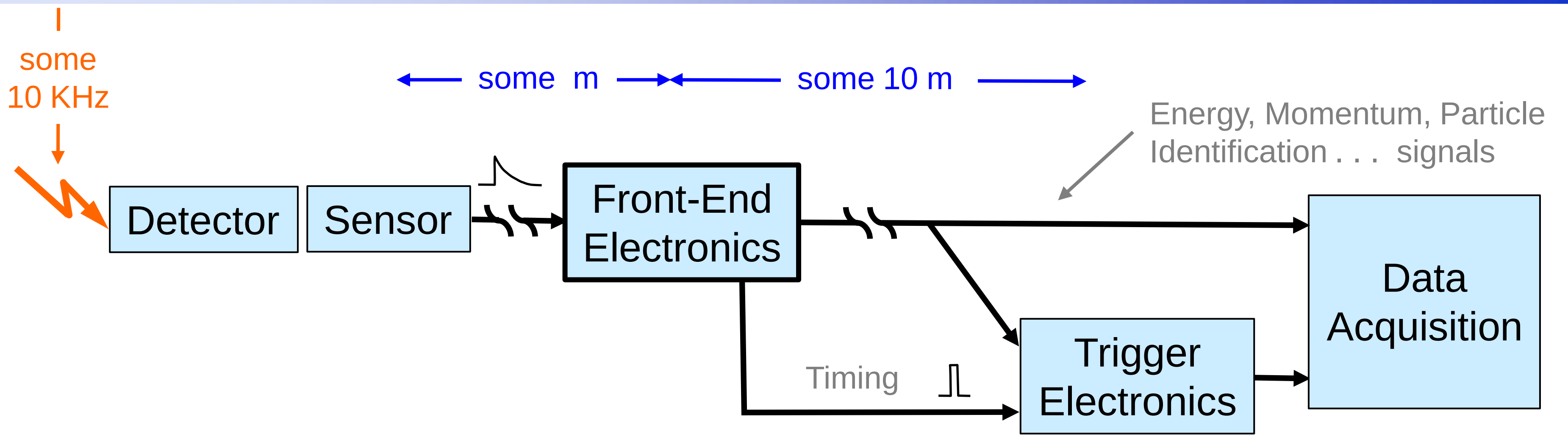
@ c = $3{\cdot}10^8$ m/s this takes ~170 ns

Trigger Electronics



Electronics I

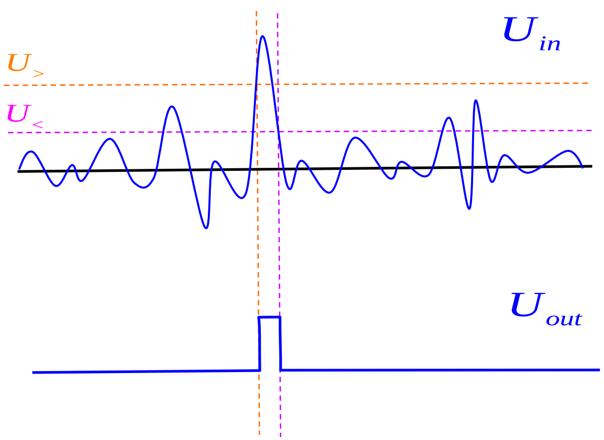
– The Purpose of Front-End Electronics –

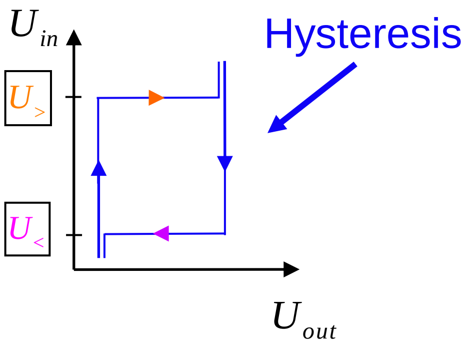


Tasks of Front-End

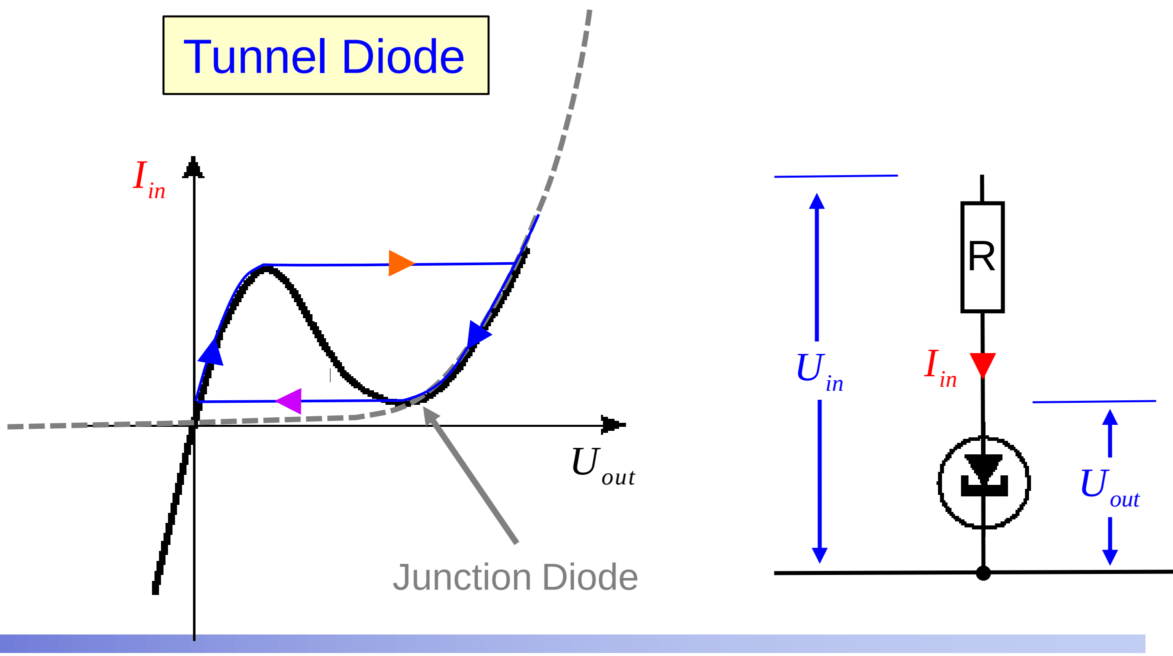
- Shapes signals (reduce noise)
- Amplifies signal
- First level trigger (Discriminator)
- Provides timing signal

Discriminator





Tunnel Diode

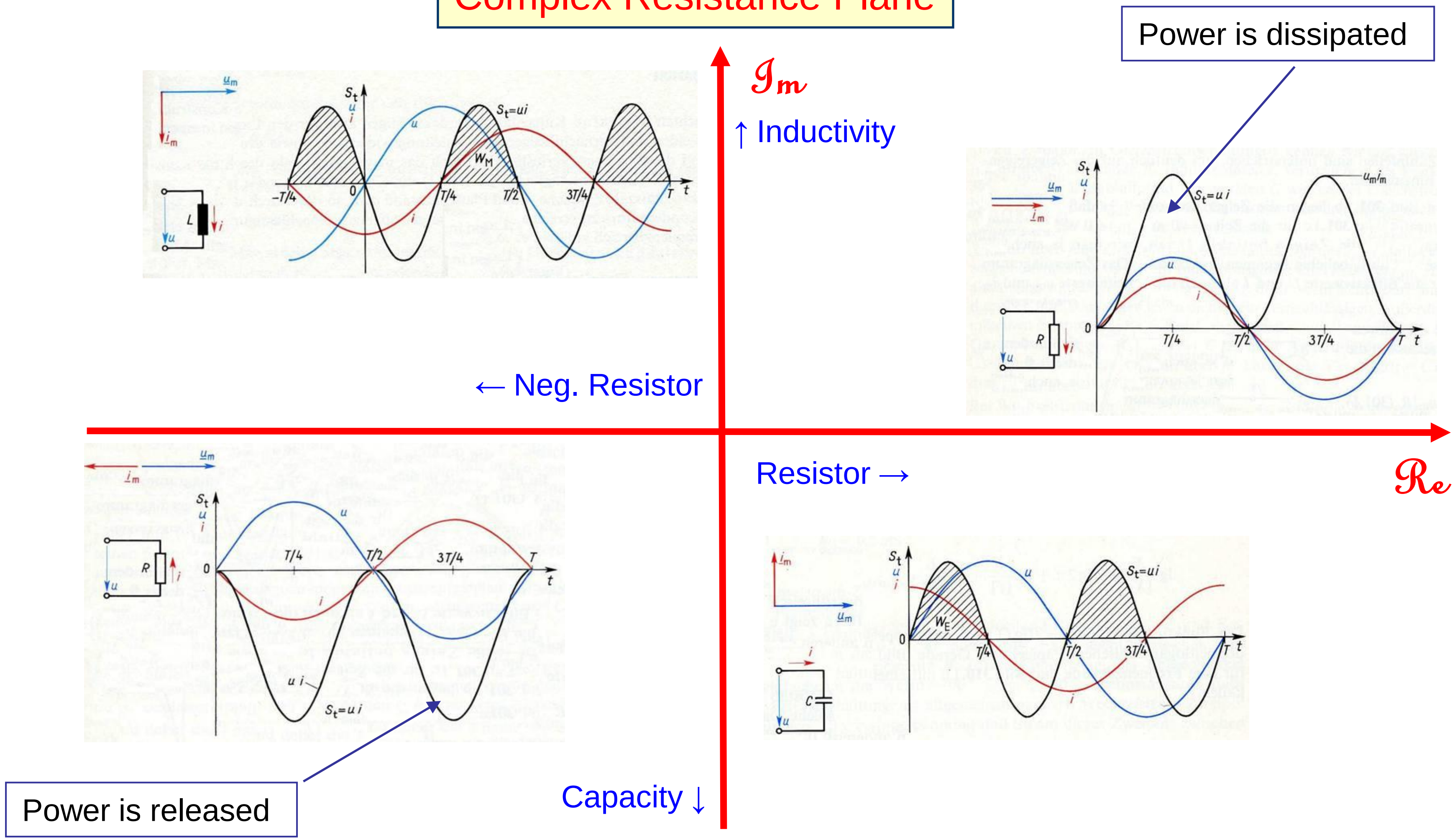


Electronics I

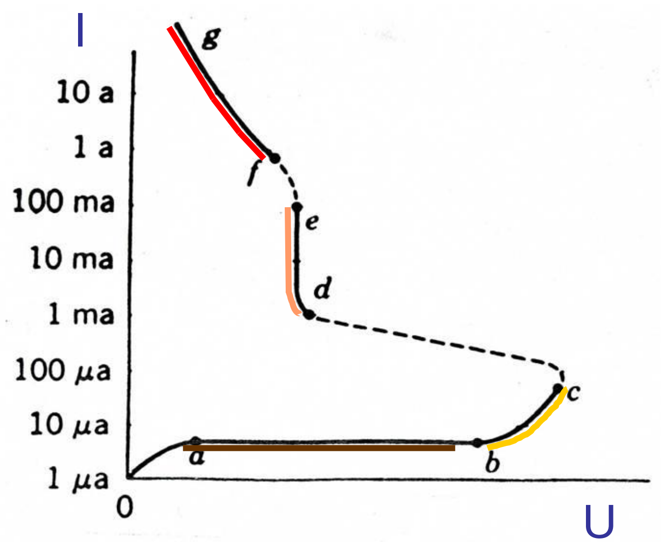
– Basics: Passive Devices –

	Resistor	Capacity	Inductivity
Def.:	$U = R \cdot I$ $U = U_0 \cdot \cos \omega t$ $R = \frac{U}{I} = R \frac{U_0 \cdot \cos \omega t}{U_0 \cdot \cos \omega t}$	$Q = C \cdot U$ $I = dQ/dt = C \cdot dU/dt$ $R_C = \frac{U}{I} = \frac{U_0 \cdot \cos \omega t}{C \cdot \omega \cdot U_0 \cdot (-\sin \omega t)}$	$U = L \cdot dI/dt$ $I = I_0 \cdot \sin \omega t$ $R_L = \frac{U}{I} = L \cdot \omega \cdot \frac{I_0 \cdot \cos \omega t}{I_0 \cdot \sin \omega t}$
$\Rightarrow$	**U** and **I** are in phase	**U** advances **I** by 90°	**U** lags **I** by 90°
Elegant Ansatz: $\cos \omega t + i \cdot \sin \omega t \equiv e^{i\omega t}$	R	$R_C = \frac{1}{i\omega C} = -i \frac{1}{\omega C}$	$R_L = i\omega L$
Very general: $e^{\rho} \cdot e^{i\omega t} = e^{i\omega t + \rho} =: e^{s}$	R	$R_C = \frac{1}{sC}$	$R_L = sL$

Complex Resistance Plane



Universal Gas Discharge Plot

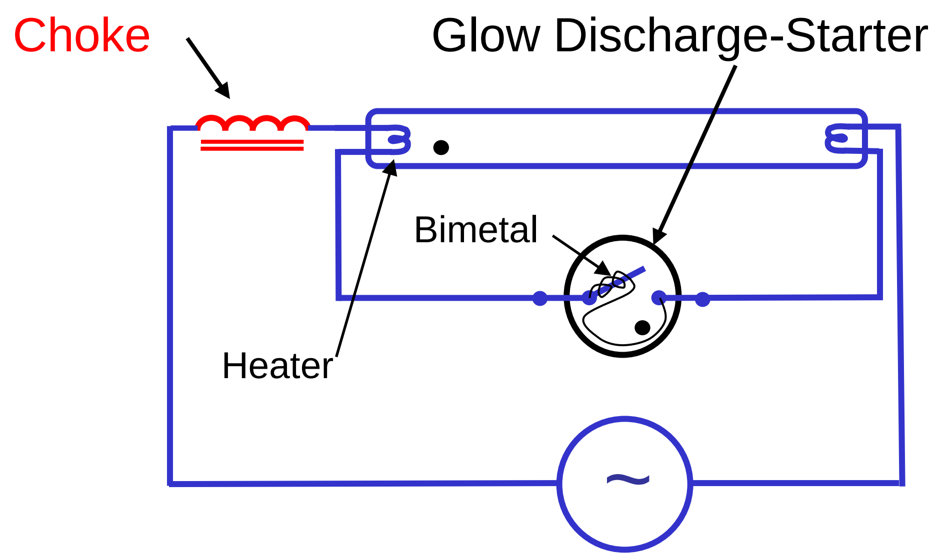


Dark current
Ionisation starts } Vavcuum tubes

Glow discharge — Glow discharge lamp, Fluorescent lamp, Voltage stabilizer

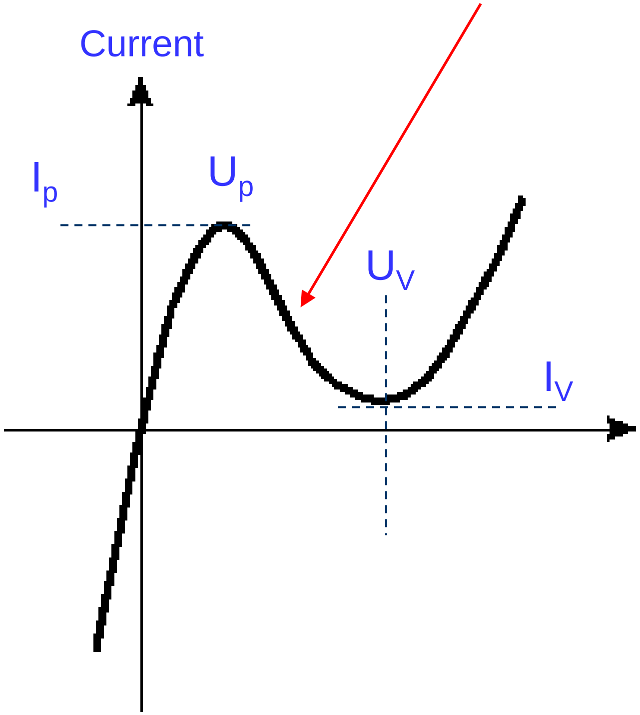
Arc discharge — Ignition spark in a car, Arc welding, Lightning protection, Lightning

Fluorescent Lamp Circuit

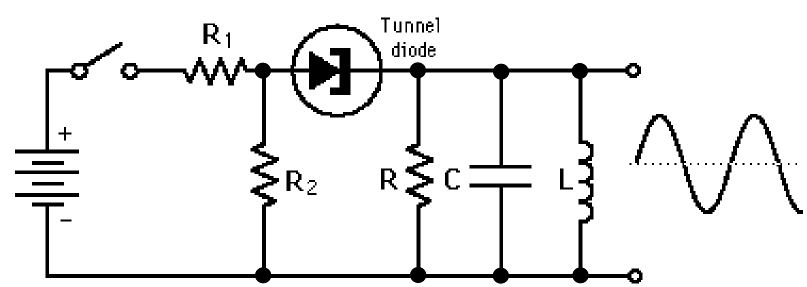


Tunneldiode

Negative Differential Resistance → De-attenuation of circuits



Tunneldiode-Oscillator



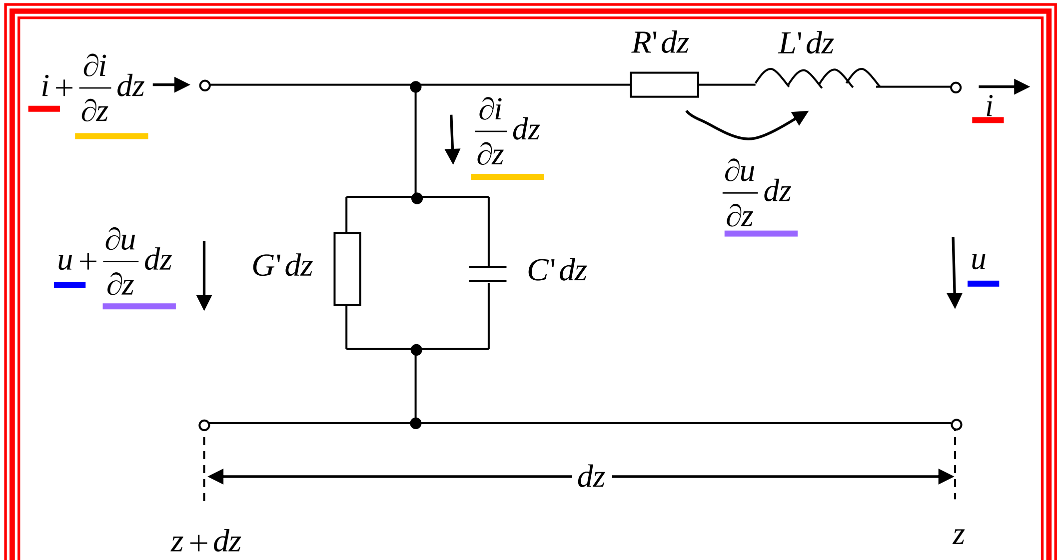
Frequency
≤ 10 GHz

Electronics I

– Signal Transmission of Cables and EM-Fields –

Equivalent lumped circuit of a transmission line element **dz** of a lossy homogeneous line.

(The „primed“ quantities denote the derivative with respect to the position **z**)



From the equivalent circuit it is read the

Telegraph Equations:

$$\frac{\partial U}{\partial z}=R'I+L'\frac{\partial I}{\partial t}$$

$$\frac{\partial I}{\partial z}=G'U+C'\frac{\partial U}{\partial t}$$

Solution:

$$U(z,t)=U_h e^{i\omega t}e^{+\gamma z}+U_r e^{i\omega t}e^{-\gamma z}$$

$$I(z,t)=I_h e^{i\omega t}e^{+\gamma z}-I_r e^{i\omega t}e^{-\gamma z}$$

The solution is a superposition of a forth running wave (Index: h, +z) and a back running wave (Index: r, -z). Consider that the forth- and back-running currents have to be subtracted from each other, whereas the voltage amplitudes have to be added.

$$\mathrm{U}(z,t) = \mathrm{U}_h e^{i\omega t} e^{+\gamma z} + \mathrm{U}_r e^{i\omega t} e^{-\gamma z}$$
$$\mathrm{I}(z,t) = \mathrm{I}_h e^{i\omega t} e^{+\gamma z} - \mathrm{I}_r e^{i\omega t} e^{-\gamma z}$$

with:

$$\gamma^2 = (\alpha + i\beta)^2 = R'G' + i\omega(R'C' + L'G') - \omega^2 L'C' \quad or$$
$$= (R' + i\omega L')(G' + i\omega C')$$

Here **γ** is the complex valued **propagation constant**, which comprises as real part the **attenuation** (constant) **α** and as imaginary part the **phase constant β**.

For: $R'G' \ll \omega^2 L'C'$ (high frequency approximation)

$$\Rightarrow \quad \beta \approx \omega\sqrt{L'C'}$$
$$\alpha \approx \frac{1}{2}\left(R'\sqrt{\frac{C'}{L'}} + G'\sqrt{\frac{L'}{C'}}\right) \to \approx \frac{1}{2} R'\sqrt{\frac{C'}{L'}}$$

Annotation:

- Usually G´ is very small (good isolator) and can be neglected therefore.
- The phase constant β gives the change in phase per unit of length.

Electronics I

– Signal Transmission of Cables and EM-Fields –

Characteristic impedance

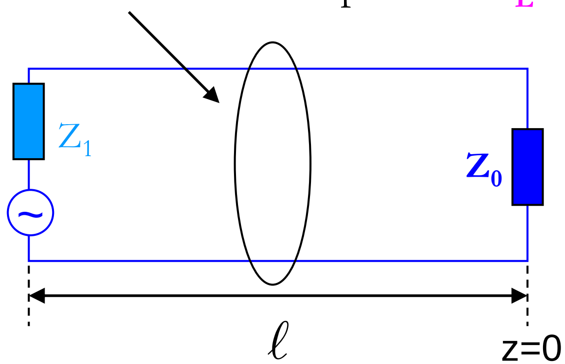
(Wave impedance)

$$Z_L \stackrel{!}{=} \frac{U_h}{I_h}$$

From the solution of the Telegraph Equ.:

$$Z_L = \sqrt{\frac{R' + i\omega L'}{G' + i\omega C'}} \approx \sqrt{\frac{L'}{C'}}$$

Typical Situation



With the solution of the telegraph equations one finds:

$$Z(z,t) = \frac{U(z,t)}{I(z,t)} = Z_L \cdot \frac{1 + U_r / U_h e^{-2\gamma z}}{1 - U_r / U_h e^{-2\gamma z}} = Z_L \cdot \frac{1 + r e^{-2\gamma z}}{1 - r e^{-2\gamma z}}$$

For z = 0: $Z_0 = Z(0) = Z_L \cdot \frac{1+r}{1-r} \quad \Rightarrow \quad r = \frac{Z_0 - Z_L}{Z_0 + Z_L}$

$$Z(\ell) = Z_L \cdot \frac{e^{\gamma\ell} + re^{-\gamma\ell}}{e^{\gamma\ell} - re^{-\gamma\ell}} = Z_L \cdot \frac{Z_0 \cosh(\gamma\ell) + Z_L \sinh(\gamma\ell)}{Z_0 \sinh(\gamma\ell) + Z_L \cosh(\gamma\ell)} \Rightarrow Z(\ell) = Z_L \cdot \frac{Z_0 + Z_L \tanh(\gamma\ell)}{Z_L + Z_0 \tanh(\gamma\ell)}$$

$$Z(\ell) = Z_L \frac{Z_0 + Z_L \tanh(\gamma \ell)}{Z_L + Z_0 \tanh(\gamma \ell)} \qquad \gamma = \alpha + i\beta$$

1) $Z_0 = 0 \Rightarrow \quad Z(\ell) = Z_L \tanh(\gamma \ell)$

$\alpha \approx 0: \quad Z(\ell) = i Z_L \tan(\beta \ell)$

$$r(\ell = 0) = \frac{Z_0 - Z_L}{Z_0 + Z_L} = -1$$

2) $Z_0 = \infty \Rightarrow \quad Z(\ell) = Z_L \frac{1}{\tanh(\gamma \ell)}$

$\alpha \approx 0: \quad Z(\ell) = Z_L \frac{-i}{\tan(\beta \ell)}$

$$r(\ell = 0) = +1$$

3) $Z_0 = Z_L \Rightarrow \quad Z(l) = Z_L$

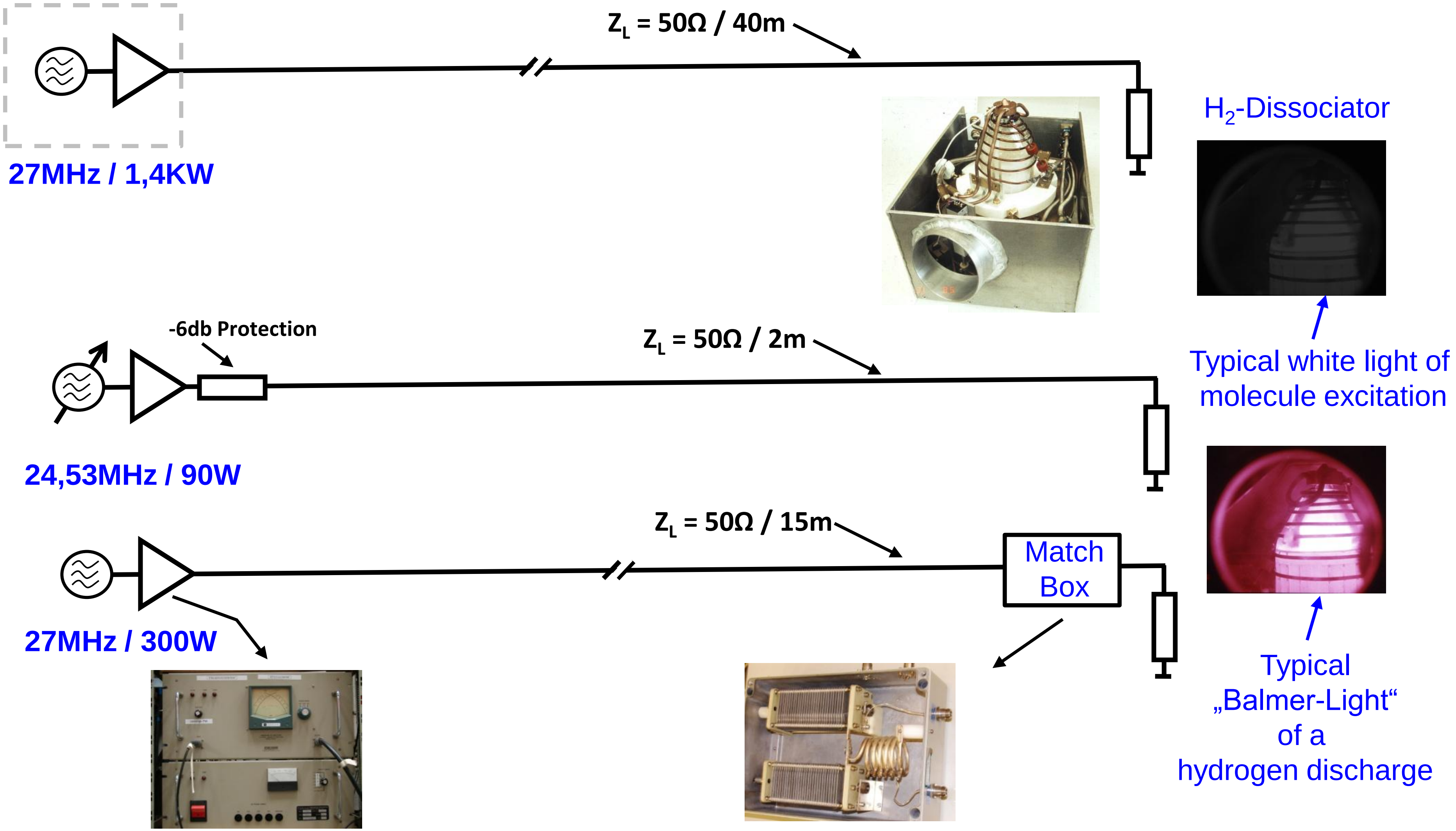
> $\Rightarrow$ Only matching avoids reflection and $Z(\ell)$ becomes Z_L i.e. independent from the cable length.

Remark:

50 Ω transmission lines can be shown to have the least transmission losses. The losses are only due to the skin-effect

Electronics I

– Signal Transmission of Cables and EM-Fields –



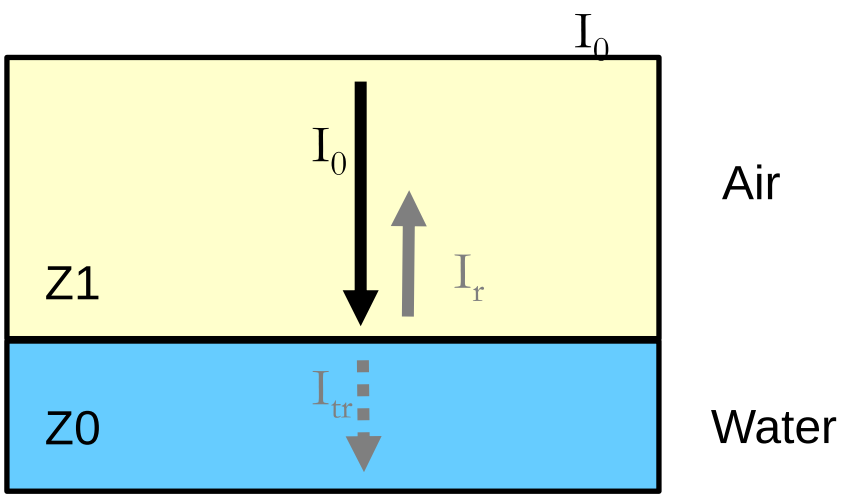
Reflection of sound waves at boundaries:

Wave impedance in a medium: $Z = \varrho \cdot v$

Degree of reflection $R = r^2$:

$I_r = R \cdot I_0$

$$R = \left(\frac{Z_0 - Z_1}{Z_0 + Z_1} \right)^2$$

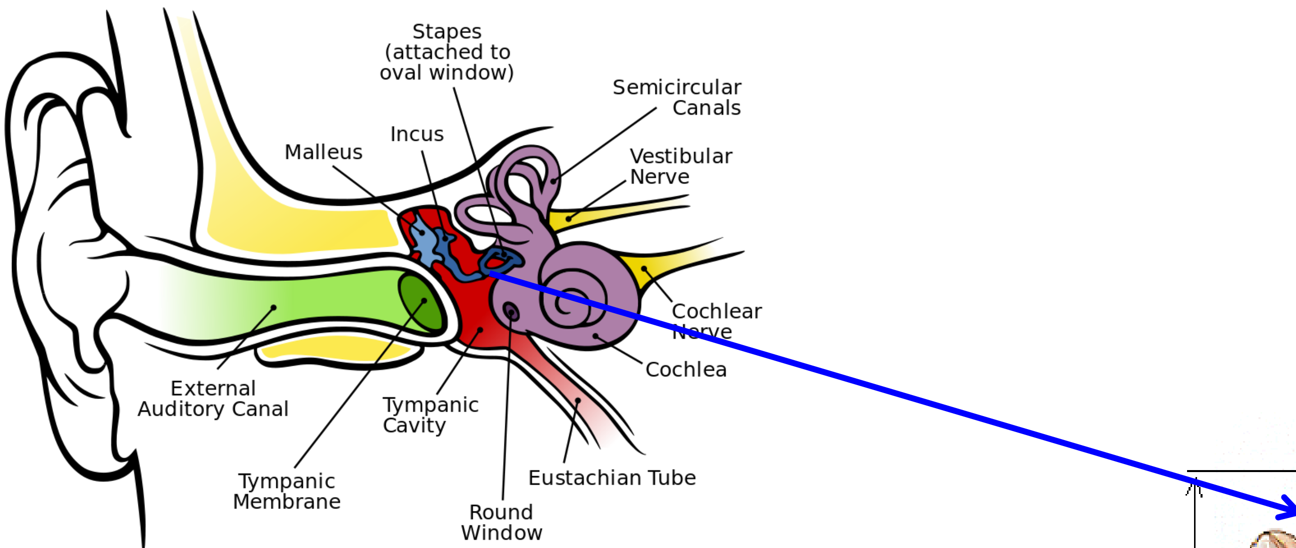


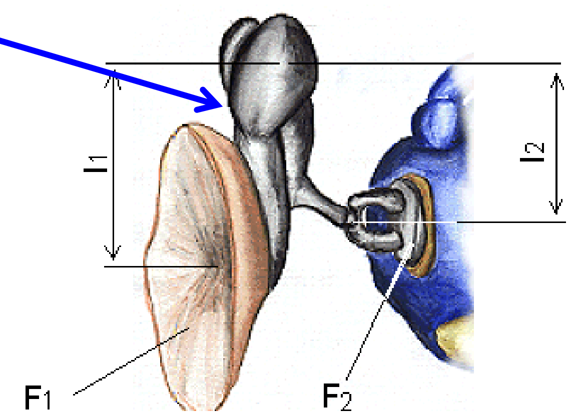
Example: Air – Water

Air: $c = 331\,m/s$; $\varrho = 1{,}29\,kg/m^3$ $\Rightarrow Z_{air} \simeq 4{,}3 \cdot 10^2\ kg/m^2s$

Water: $c = 1485\,m/s$; $\varrho = 1000\,kg/m^3$ $\Rightarrow Z_{Water} \simeq 1{,}5 \cdot 10^6\ kg/m^2s$

$\Rightarrow r = 0{,}999$ ($r = 99{,}9\%$)





By various measures of matching only 40% (instead of 99.9%) of the sound is reflected

Electromagnetic Fields

From Maxwell´s equation follows :

$$\text{curl } \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \qquad \text{div } \vec{H} = 0$$

$$\text{curl } \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \qquad \text{div } \vec{E} = 0$$

<u>This results in the solution of the telegraph equation:</u>

if it is chosen :

$$\rightarrow R' = 0; \quad u = \vec{E} \quad \text{or} \quad u = \vec{H}; \quad G' = \sigma; \; L' = \mu; \; C' = \varepsilon$$

In general:

Phase velocity: $v_p = \frac{\omega}{\beta}$ (Responsible for „shape preservation")

Group velocity: $v_g = \frac{d\omega}{d\beta}$ (Information- and energy transport)

$$\rightarrow \frac{1}{v_g} = \frac{1}{v_p}\left(1 - \frac{\omega}{v_p}\frac{dv_p}{d\omega}\right)$$

is $\frac{dv_p}{d\omega} = 0$, then $v_p = v_g$

In particular:

- Multiple connected lines:

  Phase constant: $\beta = 2\pi / \lambda = \omega\sqrt{L'C'}$ $\quad v_p = \frac{1}{\sqrt{L'C'}}$ $\quad v_p \neq f(\omega) \rightarrow$ "Shape preservation"

- „Free field":

  Phase constant: $\beta = \omega\sqrt{\mu\varepsilon}$ $\quad v_p = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_0\mu_r\varepsilon_0\varepsilon_r}} = \frac{c_0}{\sqrt{\mu_r\varepsilon_r}}$ $\quad$ with: $c_0 = \frac{1}{\sqrt{\mu_0\varepsilon_0}}$

Free space impedance

$$Z_L \xrightarrow{R'=G'=0} \sqrt{\frac{L'}{C'}}$$

$$Z_F \xrightarrow{\sigma=0} \sqrt{\frac{\mu}{\varepsilon}} \xrightarrow{\mu_r=\varepsilon_r=1} \sqrt{\frac{\mu_0}{\varepsilon_0}} = \boxed{377\,\Omega}$$

Conductor : $\frac{\sigma}{\omega\varepsilon} >> 1$

$$\alpha \approx \sqrt{\frac{\mu\sigma\omega}{2}} =: \frac{1}{\delta}$$

$$\beta \approx \frac{1}{\delta}$$

Skin depth

$$\gamma = \sqrt{(R' + j\omega L')(G' + j\omega C')}$$

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta$$

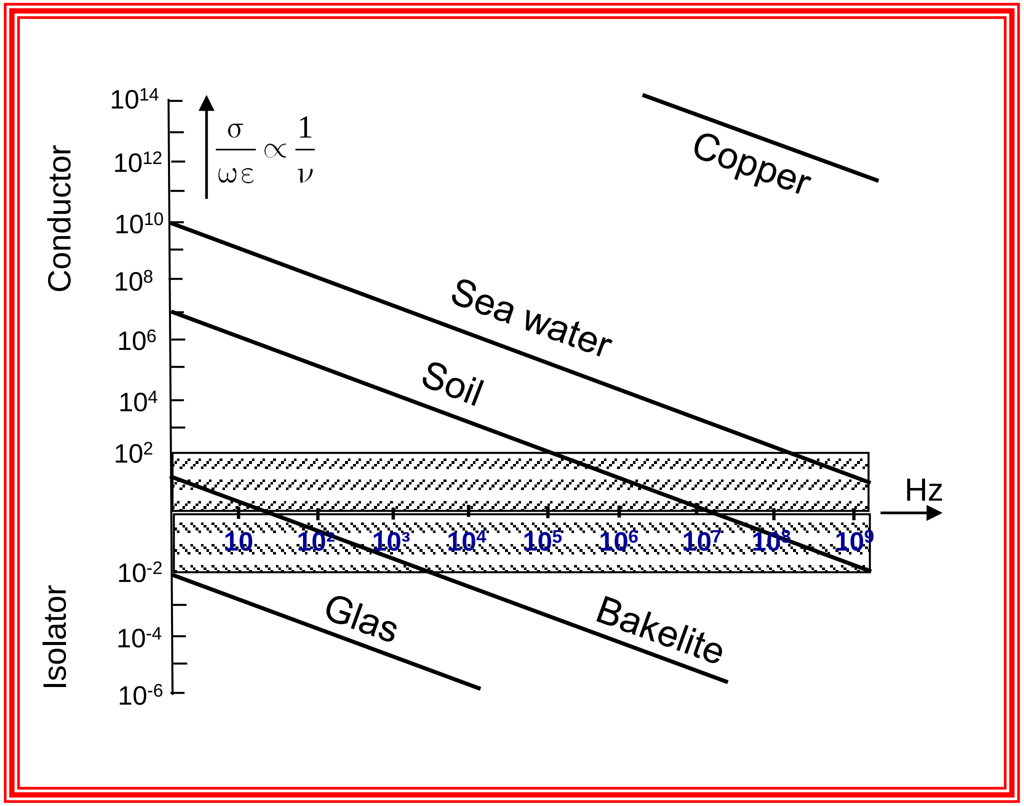
$$\beta \cong \omega\sqrt{L'C'} \quad \star$$

$$\alpha \cong \frac{1}{2}\left(R'\sqrt{\frac{C'}{L'}} + G'\sqrt{\frac{L'}{C'}} \right) \quad \star\star$$

Isolator : $\frac{\sigma}{\omega\varepsilon} << 1$

$$\beta \approx \omega\sqrt{\mu\varepsilon} \quad (\text{from}^{\star})$$

$$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} \quad (\text{from}^{\star\star},\ \text{since } R' = 0)$$



$$\frac{\sigma}{\omega\,\varepsilon} >> 1 \Rightarrow \alpha \cong \sqrt{\frac{\mu\sigma\omega}{2}} =: \frac{1}{\delta}$$

$$\frac{\sigma}{\omega\,\varepsilon} << 1 \Rightarrow \alpha \cong \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}$$

Electronics I

– Summary –

- e^s is a very general ansatz for evaluating AC-circuits.
- Negative resistance can give rise to unexpected oscillations.
- Reflections at open end $r = +1$
  shorted end $r = -1$
  matched end $r = 0$, $\Rightarrow Z(\ell) = Z_L$
- 50 Ω lines have the least losses.
- Solutions of the telegraph equation apply to EM-fields too.
- Transmission lines and free field radiation of EM-fields preserve the shape of signals.
- An antenna has to match the free field impedance (377 Ω) and at its foot the impedance of the transmission line.
- Due to $\frac{\sigma}{\omega\varepsilon}$ it takes frequencies $\gtrsim$ 1 GHz to make brick walls appear transparent.