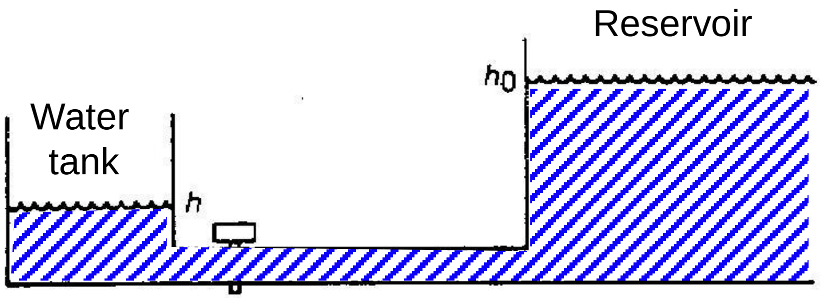
Outline

- **Efficient Characterization of the Dynamics of Systems**
- **L-C Resonator**
- **R-C Low-Pass / C-R High Pass Filters**
- **Example: Fast Timing Signal from a Slow Rising Signal**
- **Digitized Front-End**
- **Summary**

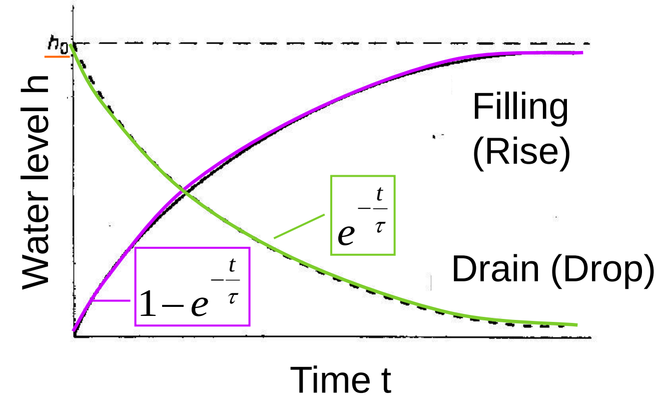
→ …hiskp.uni-bonn.de → lectures → archive
- Electronics for Physicists (in SS)
- Advanced Electronics and Signal Processing (in WS)

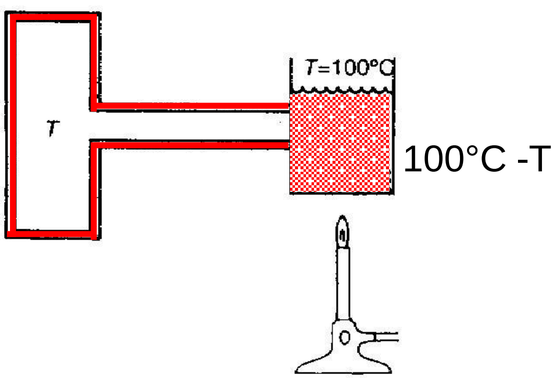
Electronics II

– Efficient Characterization of the Dynamics of Systems –

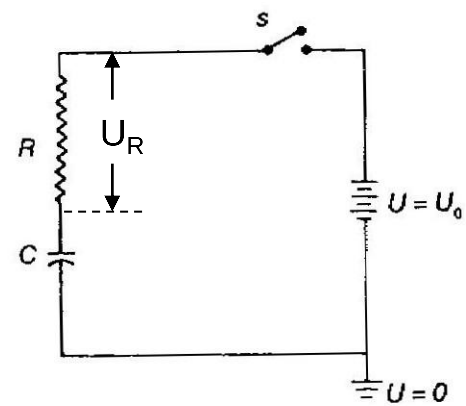


- The water tank is filled from a reservoir of unlimited capacity;
- The water level approaches **exponetially** h_0.





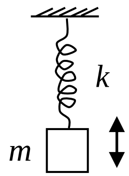
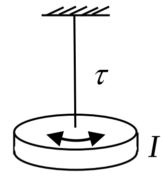
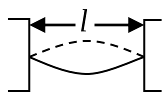
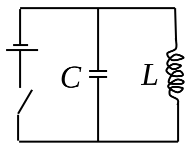
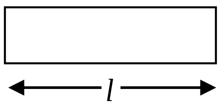
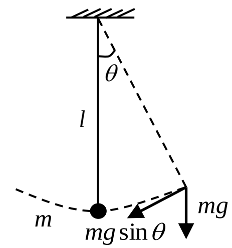
The temperature of a piece of metal approaches exponetially 100°C.



The voltage across the capacitor C approaches exponetially U_0

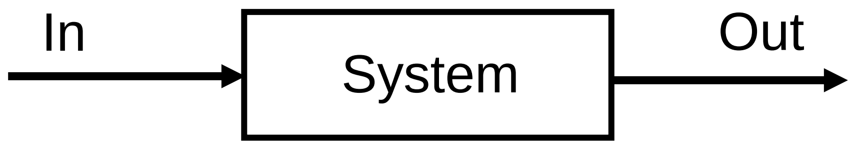
Electronics II

– Efficient Characterization of the Dynamics of Systems –

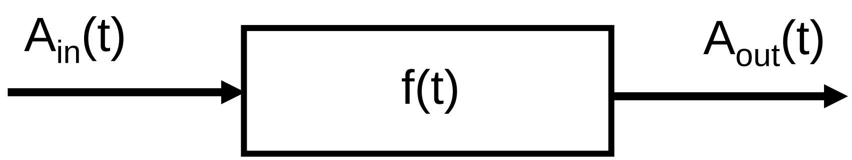
	Oscillator	Torsion Pendulum	String	Oscillatory Circuit	Echo Chamber	Pendulum
						
Excitation	Pull down mass and release it	Turn disk and let loose	Pluck spring	Close switch, after that open. Charge oscillates through the coil and between the disks of the capacitor	Make a banger explode in a chamber	Move mass and let loose
Eigen frequency	$\frac{1}{2\pi}\sqrt{\frac{k}{m}}$	$\frac{1}{2\pi}\sqrt{\frac{\tau}{I}}$	$\frac{1}{2l}\sqrt{\frac{Z}{\mu}}$	$\frac{1}{2\pi}\sqrt{\frac{1/C}{L}}$	$\frac{1}{4l}\sqrt{\frac{E}{\rho}}$	$\frac{1}{2\pi}\sqrt{\frac{mg/l}{m}} = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$
Rigidity	Spring constant k	Torsion constant τ of the wire	Pulling force Z in the string	Reciprocal of the capacity 1/C	Adiabatic volume elasticity E of the gas inside the chamber	Restoring force per displacement, mg/l
Inertia	Mass	Moment of inertia I of the disk	Lengths density μ of the string	Inductivity of the coil	Density ρ of the gas in the chamber	Mass

Electronics II

– Efficient Characterization of the Dynamics of Systems –



Refinery
Aeroplane
Musical instrument
Electronic Circuit
Nucleus



$$\int_0^t A_{in}(t-\tau)\cdot f(\tau)\,d\tau = A_{out}(t)$$

The Laplace Transform

- Is a „generalized“ Fourier Transform $f(t) \rightarrow F(s)$; $s = i\omega + \varrho$
- „Algebraizes“ linear differential equations (that represent the dynamics of systems with concentrated energy „reservoirs“ like L, C, . . .)
- A convolution in the time domain corresponds to a multiplication of the Laplace transform

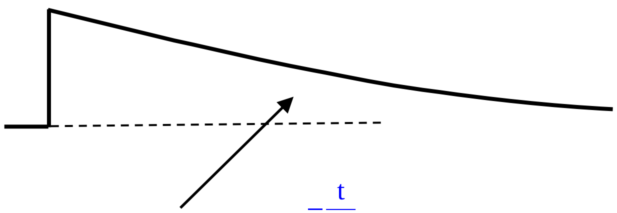
Scheme:

$$
\begin{tikzcd}
f(t) \arrow[r, "\mathfrak{L}"] \arrow[d] & F(s) \arrow[d] \\
\int_0^t A_{in}(t-\tau)\cdot f(\tau)\,d\tau \arrow[d] & A_{in}(s)\cdot F(s) \arrow[d] \\
A_{out}(t) & A_{out}(s) \arrow[l, "\mathfrak{L}^{-1}"']
\end{tikzcd}
$$

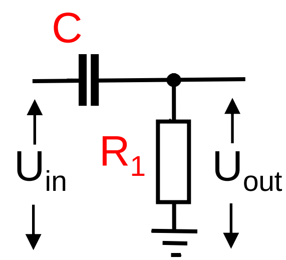
Electronics II

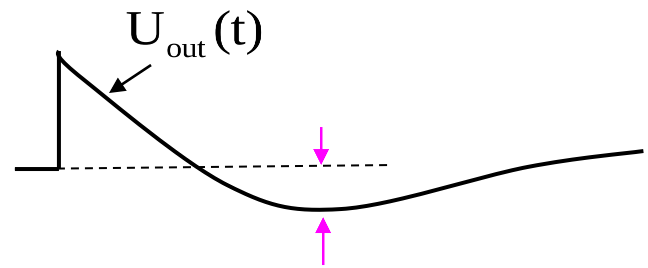
– Efficient Characterization of the Dynamics of Systems –

$\mathbf{F(s)} = \int_0^{\infty} e^{-st} F(t)\,dt$	**f(t)**	**Remark**
$a\,F_1(s) + b\,F_2(s)$	$a\,f_1(t) + b\,f_2(t)$	Linearity
$s\,F(s) - f(0)$	$f\,'(t)$	Derivative
$s^n F(s) - s^{(n-1)} f(0) - s^{(n-2)} f'(0) \ldots - f^{(n-1)}(0)$	$f^{(n)}(t)$	n^{th} derivative
$\frac{1}{s-a}$	e^{at}	
$\frac{F(s)}{s}$	$\int_0^t f(\tau)\,d\tau$	Integral
$\frac{F(s)}{s^n}$	$\int_0^t \ldots \int_0^t f(\tau)\,d\tau^n = \int_0^t \frac{(t-\tau)^{n-1}}{(n-1)!} f(\tau)\,d\tau$	n-fold integral
$A(s) \cdot F(s)$	$\int_0^t A(t) \cdot f(t-\tau)\,d\tau$	Convolution in the time domain



$$U_{in}(t) = U_0 e^{-\frac{t}{T_0}}$$





Undershoot

$$\boxed{U_{in}(s) = U_0 \frac{1}{s + 1/T_0}}$$

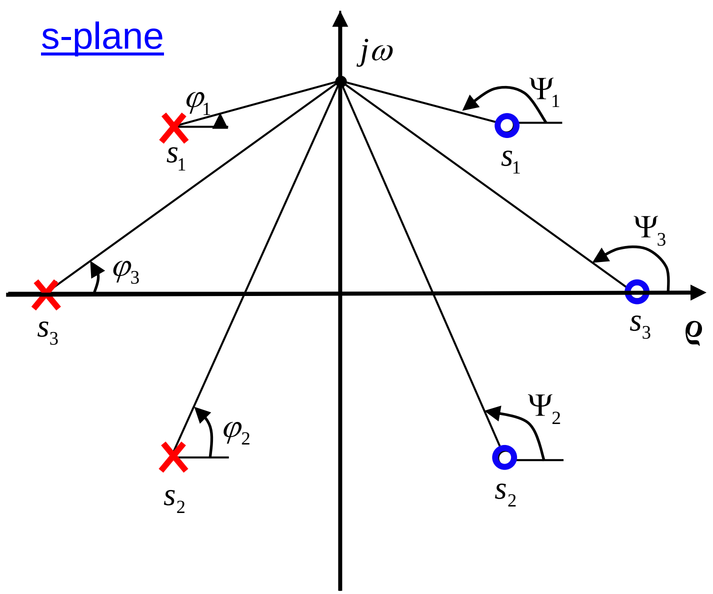
$$\boxed{T(s) = \frac{U_{out}(s)}{U_{in}(s)} = \frac{R_1}{\frac{1}{sC} + R_1}}$$

$$\boxed{U_{in}(s) \cdot T(s) = U_0 \frac{s}{(s + 1/T_0)(s + 1/CR_1)} = U_{out}(s)}$$

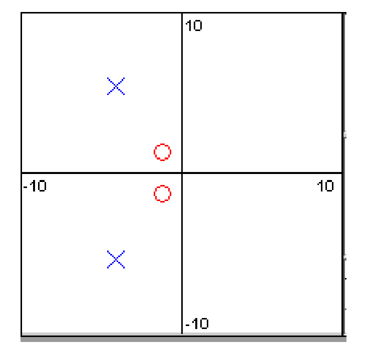
$$U_{out}(t) = U_0 \frac{1}{(CR_1 - T_0)} \overbrace{\left(CR_1 e^{-\frac{t}{T_0}} - T_0 e^{-\frac{t}{CR_1}} \right)}$$

- For physically feasible systems applies: n ≤ m

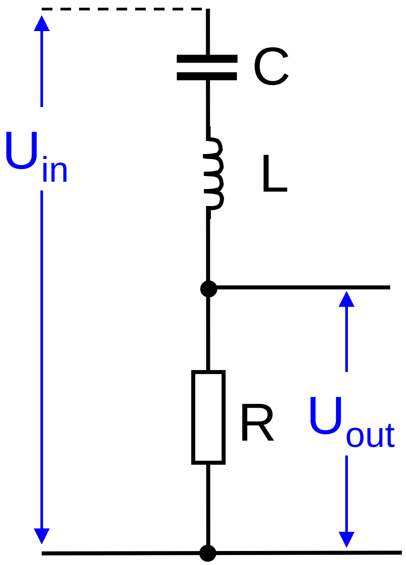
$$T(s) = \frac{U_{out}(s)}{U_{in}(s)} = \frac{\sum_{\ell=0}^{n} b_\ell \cdot s^\ell}{\sum_{k=0}^{m} a_k \cdot s^k} = k \frac{\prod_{\ell=1}^{n} |s - s_{N_\ell}|}{\prod_{k=1}^{m} |s - s_{P_k}|} \cdot e^{i\left(\sum_{\ell=1}^{n} \psi_\ell - \sum_{k=1}^{m} \varphi_k\right)}$$

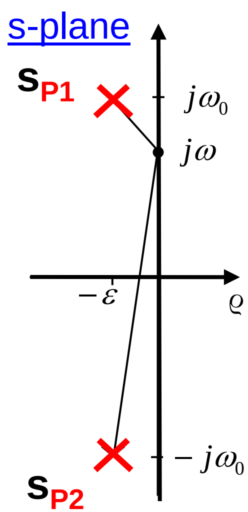


Pole/Zero Applet

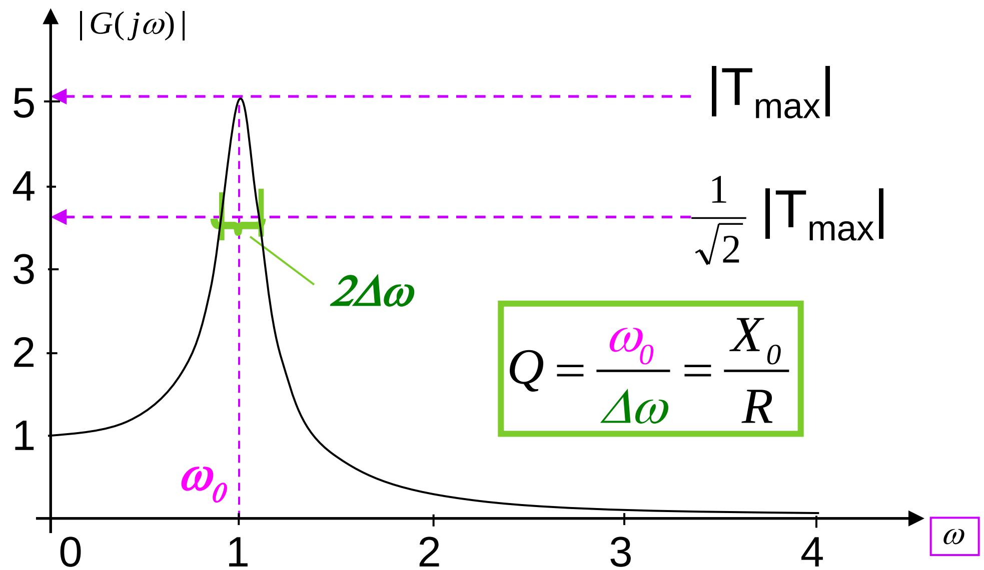


P/N-Scheme of a system with frequency sensitive behaviour:



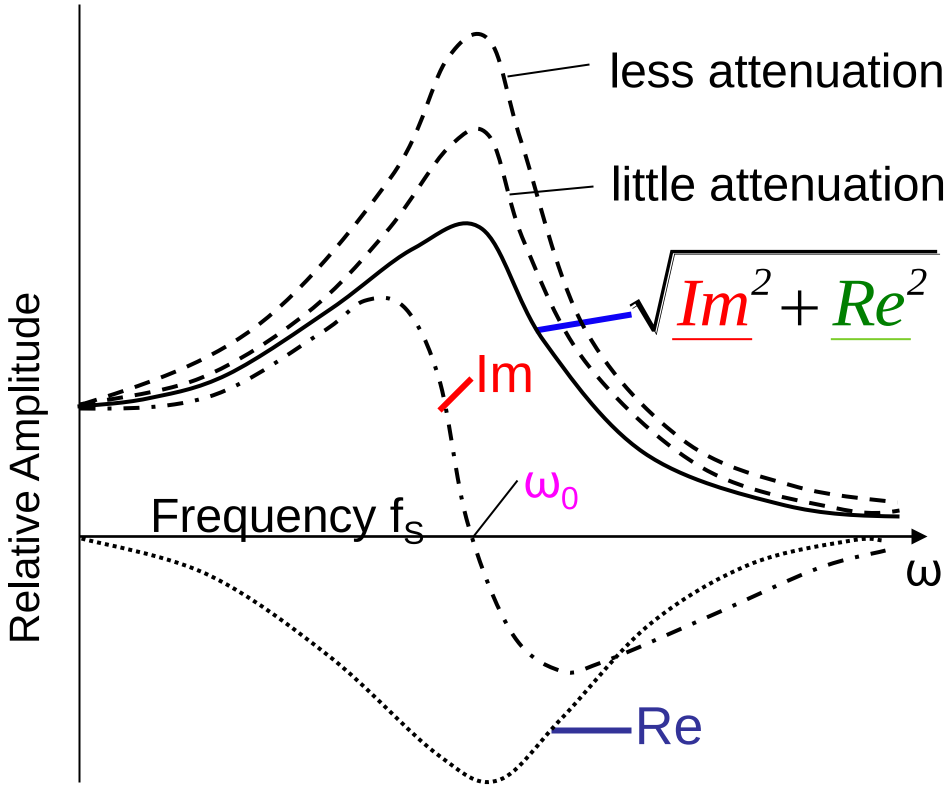


$$s_{p_1} = s_{p_2}^*$$



$$Q = \frac{\omega_0}{\Delta\omega} = \frac{X_0}{R}$$

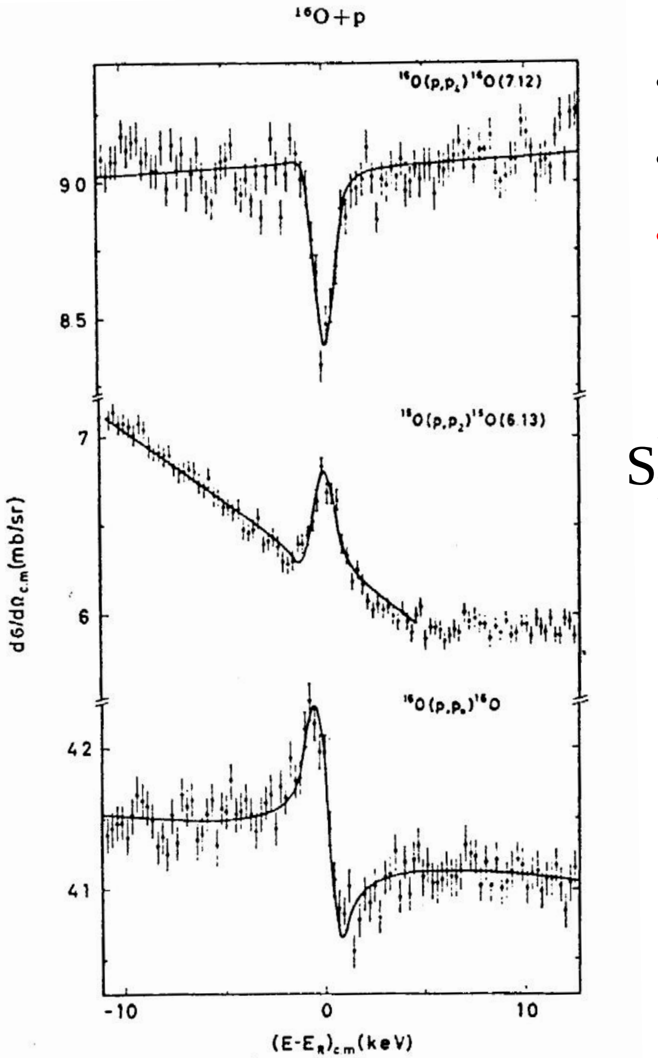
$$T(s) = \frac{1}{1 + Q\cdot\left(\frac{s}{\omega_0} + \frac{\omega_0}{s}\right)} \xrightarrow[\omega=\omega_0+\delta\omega,\,\rho=0]{\text{Small bandwidth approximation}} \frac{1}{1 + i\,\frac{\omega-\omega_0}{\Delta\omega}} = \frac{\Delta\omega}{\Delta\omega + i(\omega-\omega_0)}$$



$$\omega_0 = \sqrt{\frac{1}{LC}} \qquad X_0 = \sqrt{\frac{L}{C}}$$

$$Q = \frac{X_0}{R}$$

Examples	**Q**
L-C oscillator circuit	**100**
Soil for earthquake waves	**250-1400**
Tuning fork	**4,5 10^4**
Plucked violin string	**10^3**
Cavity resonator	**10^4**
Quartz crystal	**10^6**
Excited atom	**10^7**



- Excitation function of $^{16}O(p,p)^{16}O$; Resonance in ^{17}F.
- The solid curve is the the theoretical fit.
- Expanding the small band approximation of the standard form of a resonance by $\hbar$ leads to the Breit-Wigner resonance equation:

$$S_{LJ}^{R} = S_{LJ} - i\frac{\Gamma_p}{E-(E_0 - i\Gamma/2)} \underbrace{exp\{2i(\mu_{LJ}+\sigma_L+\Phi^R)\}}_{\boxed{e^{i\varphi}}}$$

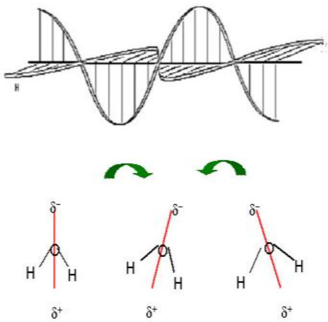
$$\propto \boxed{\frac{\text{const.}}{\Gamma/2 + i(E-E_0)}} \cdot e^{i\varphi}$$

θ_{lab}=168,3°

$$\boxed{\begin{aligned} E_0 &= 11193 \pm 2,3\ keV \\ \Gamma &= 0,20 \pm 0,04\ keV \end{aligned}}$$

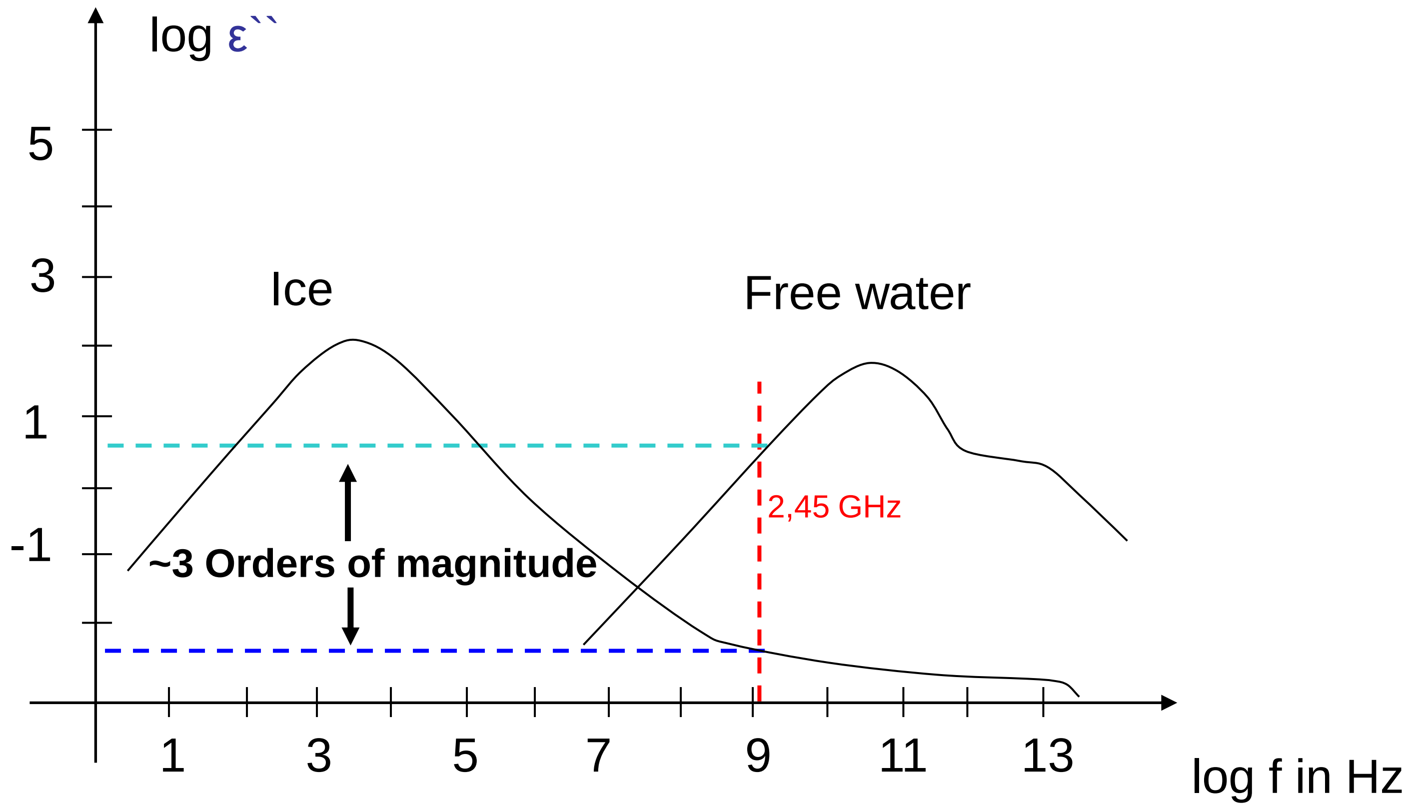
From: Nucl. Phys. A263 (1976) 460

Dipol-Rotation

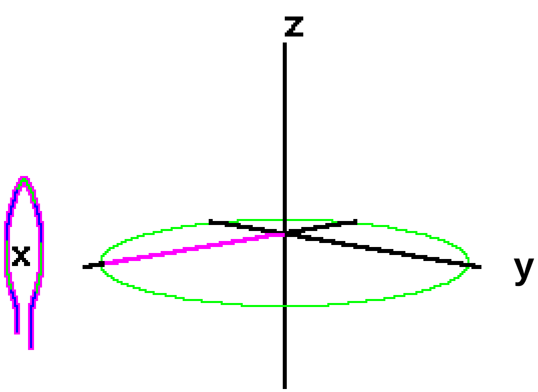


Dielectric Absorption of Water and Ice

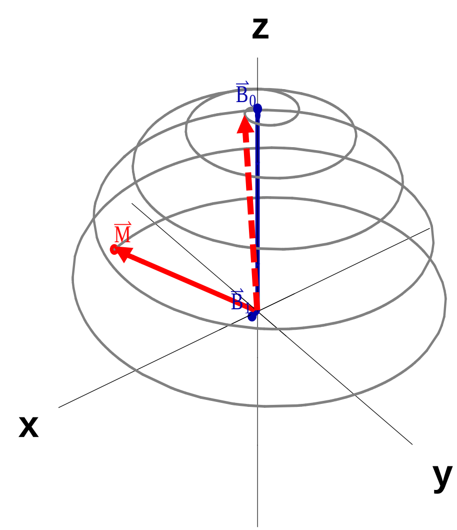
(Microwave Oven)



Nuclear **M**agnetic **R**esonance → **M**agnetic **R**esonance **T**omography



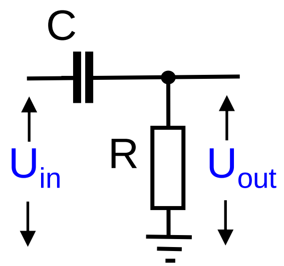
90° „Puls“ for magnetization $\vec{\mathbf{M}}$



Lamor frequency for protons**: 42.577 478 92(29) MHz / Tesla =** $\gamma_p/2\pi$

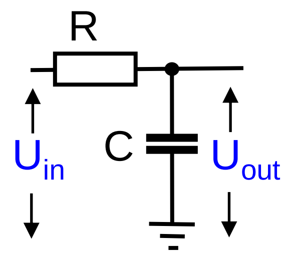
γ_p, the gyromagnetic ratio of a proton, is a **fundamental constant**.

C-R Highpass



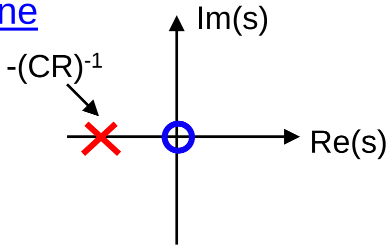
$$T(s) = \frac{U_{out}(s)}{U_{in}(s)} = \frac{R}{R + \frac{1}{sC}} = \frac{sCR}{sCR+1}$$

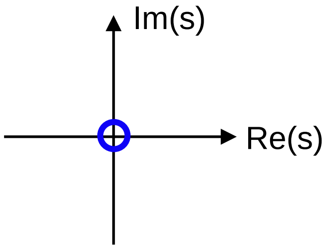
R-C Lowpass . . . 2nd order . . . 3rd order

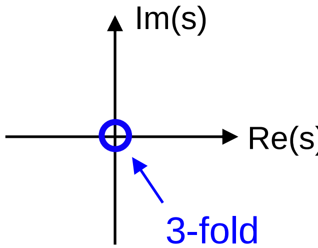


$$T(s) = \frac{U_{out}(s)}{U_{in}(s)} = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} = \frac{1}{sCR+1} \quad . . . \quad = \frac{1}{(sCR+1)^2} \quad . . . \quad = \frac{1}{(sCR+1)^3}$$

s-plane







C-R – (R-C)^n Combination:

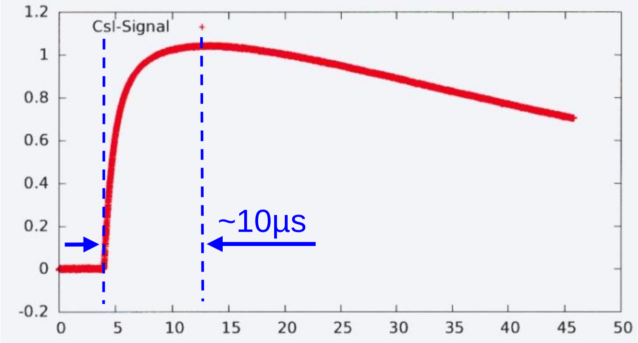
$$T(s) = \frac{sCR}{(1+sCR)^{n+1}}$$

Electronics II

– Fast Timing Signal from a Slow Rising Signal –

CsJ Signal

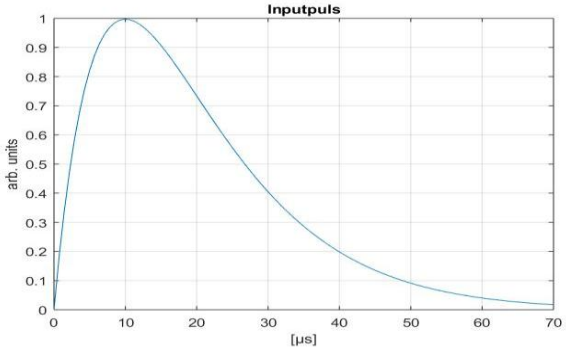
Approximated Signal



µs

$$U_{in}(t) = A \cdot t \cdot e^{-t/Tau}$$

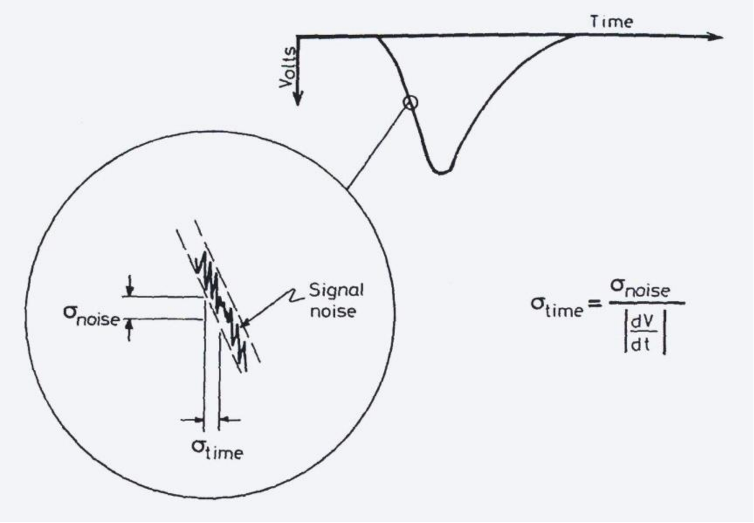
$$U_{in}(s) = \frac{A}{(s + 1/Tau)^2}$$



Task:
Generate a **fast timing signal within 300ns** by a C-R – (R-C)^n Filter

Define Figure of Merit (**FM**)

- The noise should be reduced substantially : Reduce bandwidth (BW)
- The slope should be as steep as possible to become insensitive to noise : Trigger at maximum steepness within 300ns



$$\Rightarrow \mathbf{FM} = \frac{dU_{out} / dt}{BW}$$

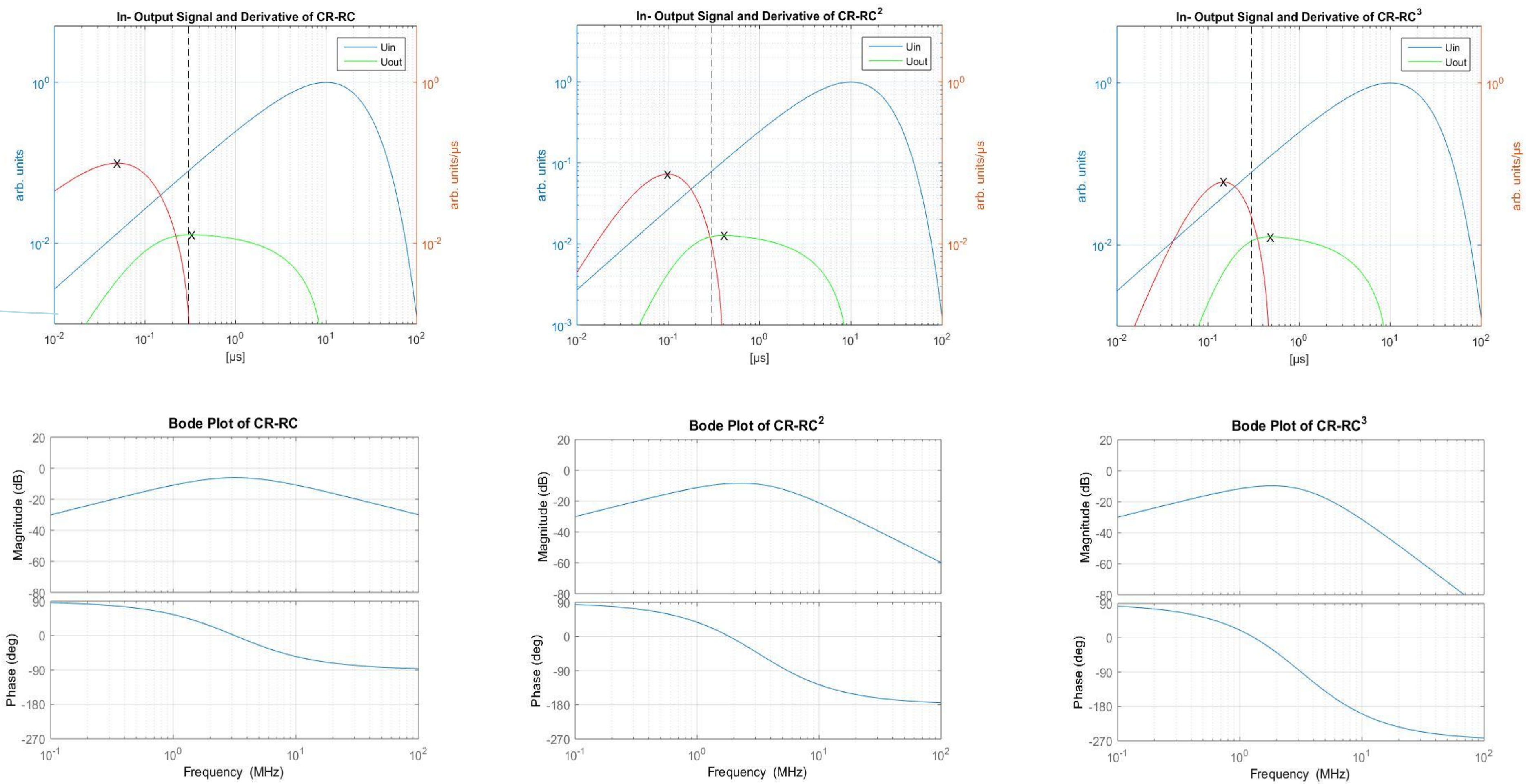
Code Examples

```
% Generate plots for the filters
for i = 2:4
clear s t U_in U_out dU_out ddU_out LTI f y_in y_out x LT
syms s t U_in U_out dU_out ddU_out LTI f y_in y_out x LT
str = strcat('Data for: ', txt(i-1))
fprintf('\n')                              % line feed / carriage return
U_in = A*t*exp(-t/Tau);
LTI = s*CR/(1+s*CR)^i;                          % Linear time invariant filter
LTI6=10^-6*s*CR/(1+s*CR/10^6)^i;                % save LTI for Bode Plots

% Calculations of output signal and its derivative
f= LTI*laplace(U_in);
U_out =ilaplace(f);
dU_out = diff(ilaplace(f), t);

% Calculate in- and outputsignal for plots
x = logspace(-2, 2, 100);
xout = x;
y_in = U_in;
y_in = subs (y_in, t, x);                  % substitute t by x for y_in
```

```
% BodePlot of the bandwidth

[nums, dens] = numden(LTI6);              % determine vector representation of LTI6
num = sym2poly(nums);
den = sym2poly(dens);
LT = tf(num, den);                        % determine zthe transferfunction of the filters
figure;
opts = bodeoptions('cstprefs');
opts.FreqUnits = 'MHz';
opts.Grid = 'on';
opts.XlimMode = 'auto';
opts.YlimMode = 'manual';
opts.YLim = {[-80, 20]; [-270, 90]};
opts.PhaseUnits = 'deg';
opts.Title.FontSize = 12;
Txt = strcat ('Bode Plot of ', txt(i-1));
opts.Title.String = Txt;
h = bodeplot(LT, opts);
```

Electronics II

– Fast Timing Signal from a Slow Rising Signal –



Results

CR = 50ns	Uout		dUout/dt					
	Ampl.	tmax [ns]	Ampl.	tmax [ns]	Fmin	Fmax	Bandwidth	FM
CR – CR	0.013	0.327	0.099	0.050	1.320	7.693	6.373	0,016
CR -CR^2	0.013	0.412	0.072	0.099	0.998	4.504	3.506	0,021
CR - CR^3	0.013	0.488	0.060	0.149	0.836	3.445	2.609	**0,023**

The trigger time should be set @ ~150ns for a C-R – (C-R)^3 filter to be **most insensitive to noise.**

Electronics II

– Digitized Front-End –

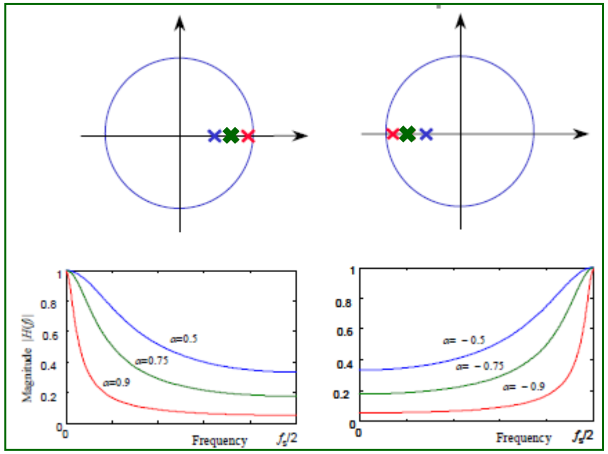
Tasks of Digitized Front-End:

- Shapes signals (reduce noise)
- Amplifies signal
- First level trigger (Discriminator)
- Provides timing signal
- Provides time stamp
- Suppresses Zeros

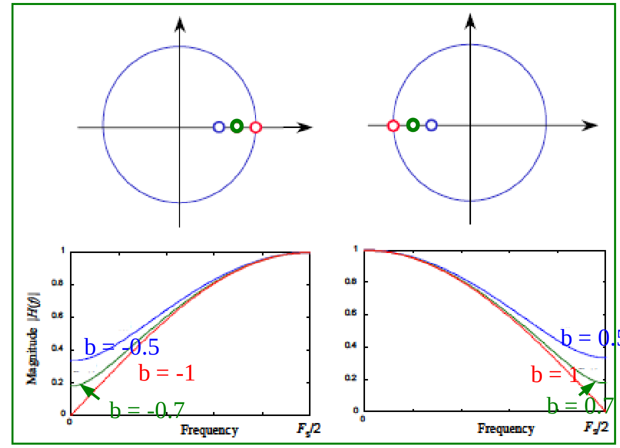
Necessary for Digitized Front-End:

- Fast **A**nalogue → **D**igital **C**onverter
- **R**eal **T**ime (**K**ernel) operating system
- Special (Harvard) processor architecture, that allows summing & multiplication within 1 clock cycle with:
  - **D**igital **S**ignal **P**rocessor Slices
  - Gigabit Tranceivers
  - Dual ported memory
  - Ring buffers
- Calculations utilize special Laplace Transform: **z-Transform:**
  For a stable system → Poles inside unit circle

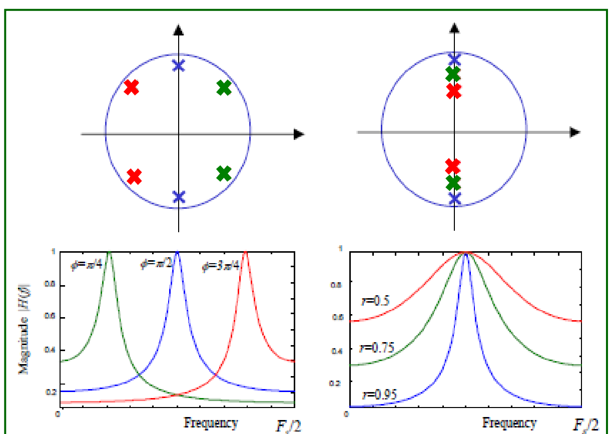
Low- Highpass



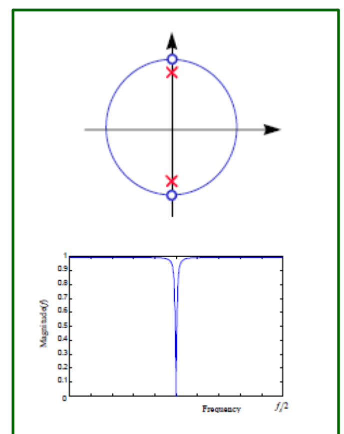
High- Lowpass



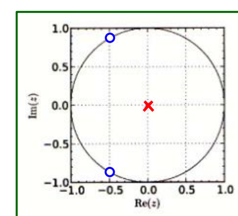
Resonators



Notch Filter



3-Tap Moving Average



Hardware Realization

ASIC
Application **S**pecific
Integrated **C**ircuit

FPGA
Field **P**rogrammable
Gate **A**rray

ASIC vs. FPGA

	ASIC	FPGA
Cost per chip	low	various
NRE cost (one time production cost)	(very) high	none
Power efficiency	+++	-
Area efficiency	+++	--
Performance vs. power, area	+++	--
Flexibility	---	+++
Development/programming complexity	very high	various

ASICS used when
- Highest performance
- High volume production
- Power & area constraints
- Special requirements
  - Analog + digital functions
  - Radiation tolerance
  - ...

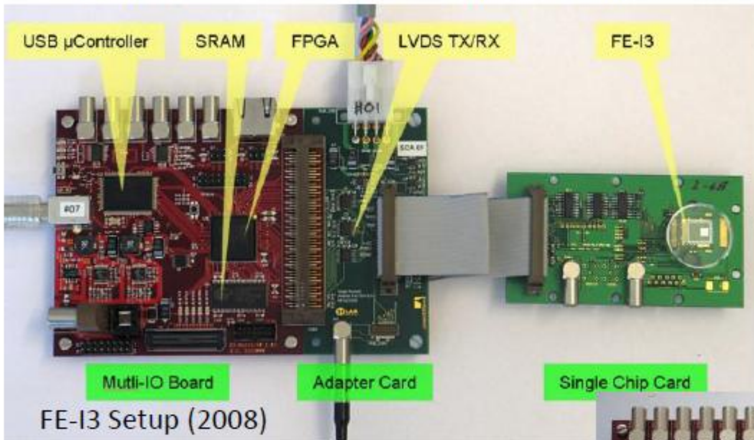
FPGAs used when
- Max. flexibility
- Low – medium volume production
- Power & area not critical
- Digital only

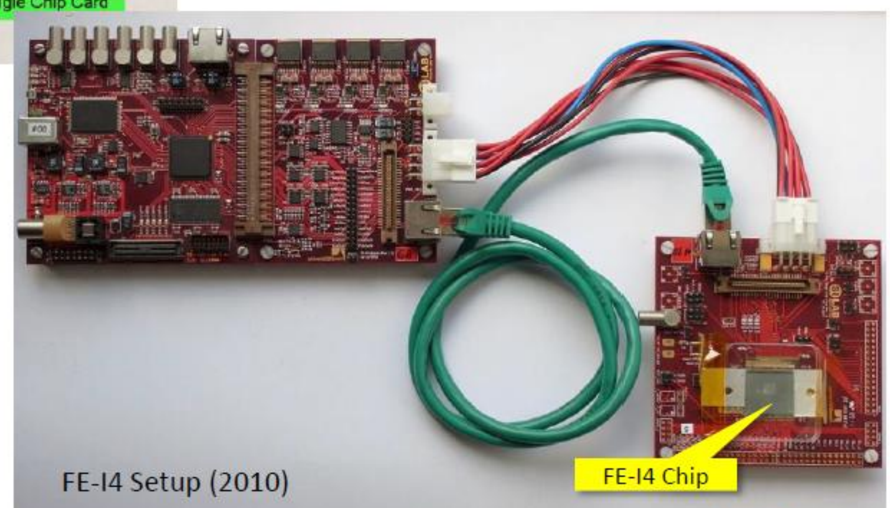
Introduction to FPGAs, H. Krüger, Bonn University, 2015

Electronics II

– Digitized Front-End –

- Test system for ATLAS FE-I4 pixel chip





Introduction to FPGAs, H. Krüger, Bonn University, 2015

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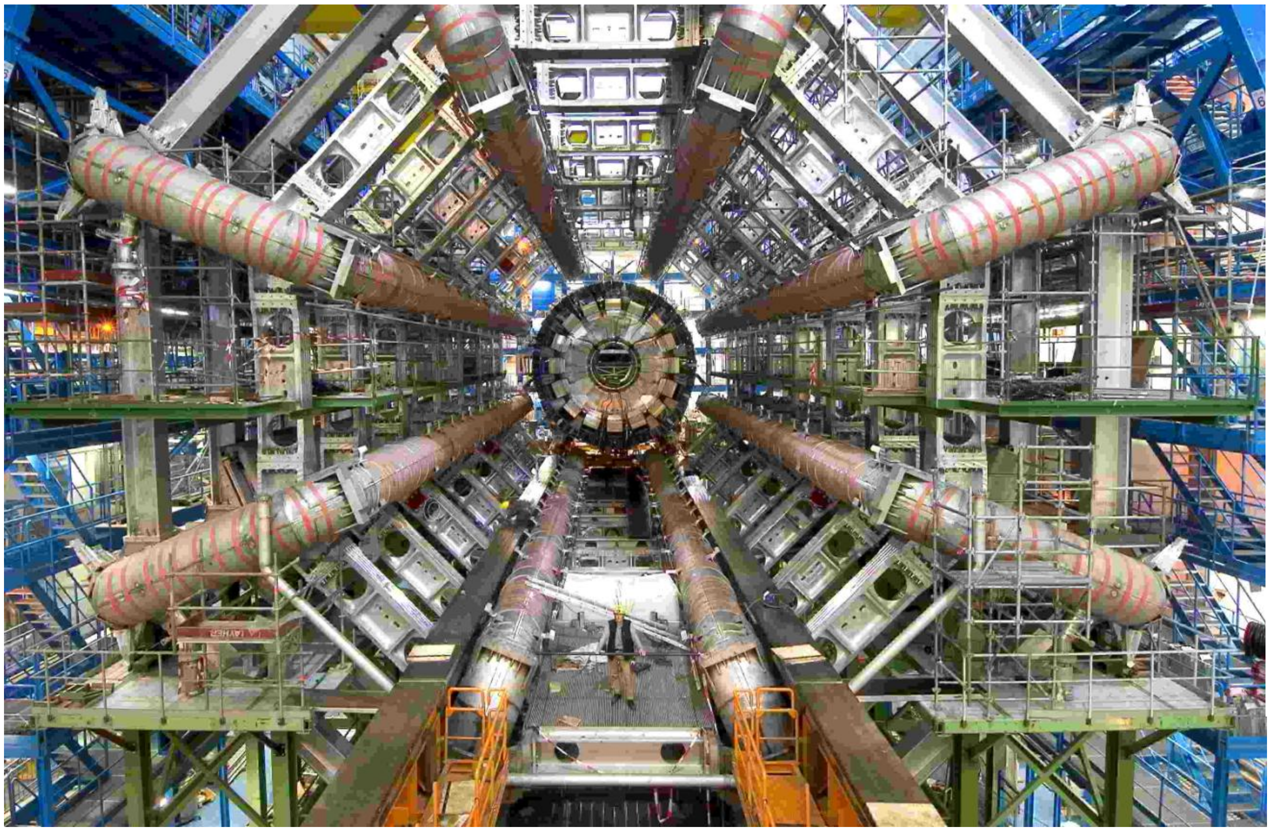
Electronics II

– Digitized Front-End –

- ATLAS Pixel detector read-out
  - Pixel Module → back of crate card (BOC) → read out driver (ROD)



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Electronics II

– Summary–

- The dynamics of systems with concentrated energy reservoirs is represented by **L**inear **D**ifferencial **E**quations (**LDE**).
- The Laplace Transform is a standard means to solve LDEs & convolutions.
- Poles & Zeros in the complex s-plane represent concisely the dynamics of a system.
- MRI is based on the precise knowledge of the gyromagnetic ratio γ of particles.
- The z-Transform accomplishes in the digitized world what the Laplace Transform does in the analogue world.
- Digitized signal processing is governed by the hardware performance of fast ADCs, ASICs, FPGAs & DSPs.