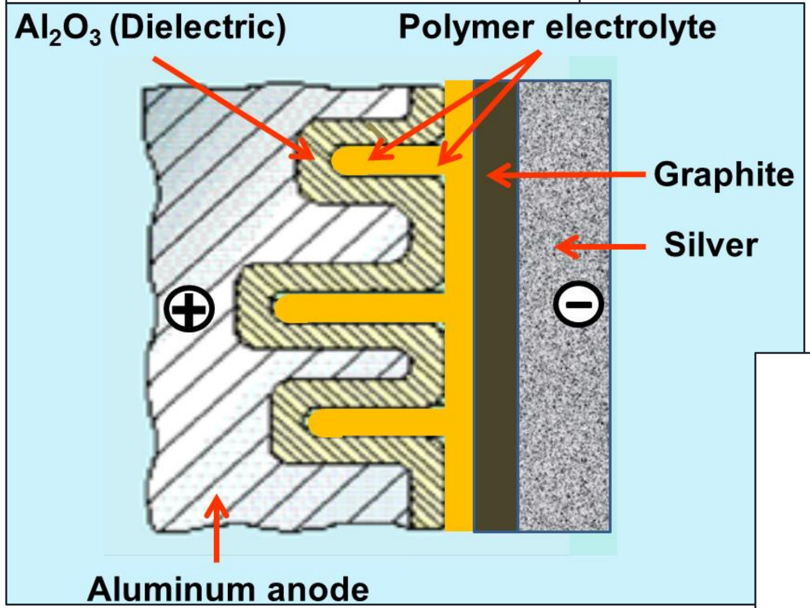
IMPEDANCE SPECTRA OF DIFFERENT CAPACITOR TECHNOLOGIES

Dr. René Kalbitz – Power Management Capacitors and Resistors
Partnered with Digi-Key Electronics

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

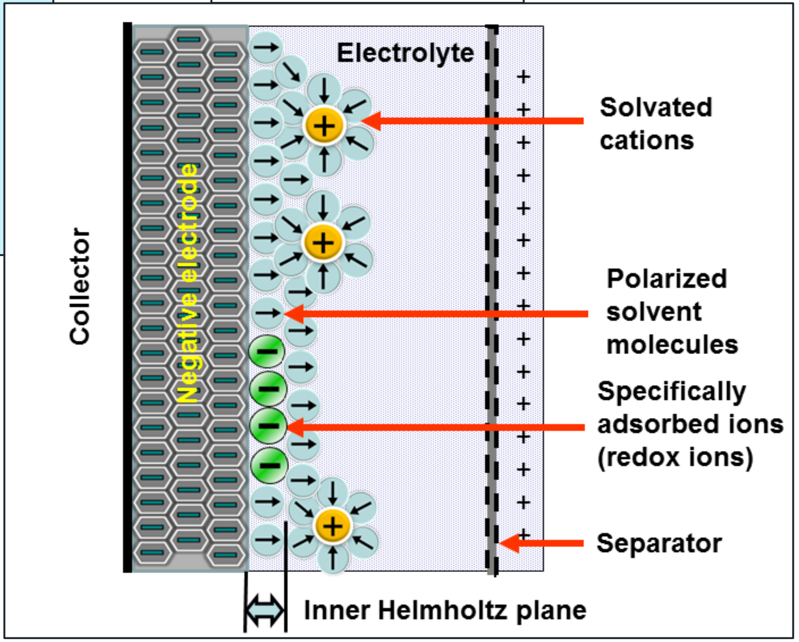
MANIFOLD OF CAPACITOR TECHNOLOGIES

Polymer electrolytic capacitor



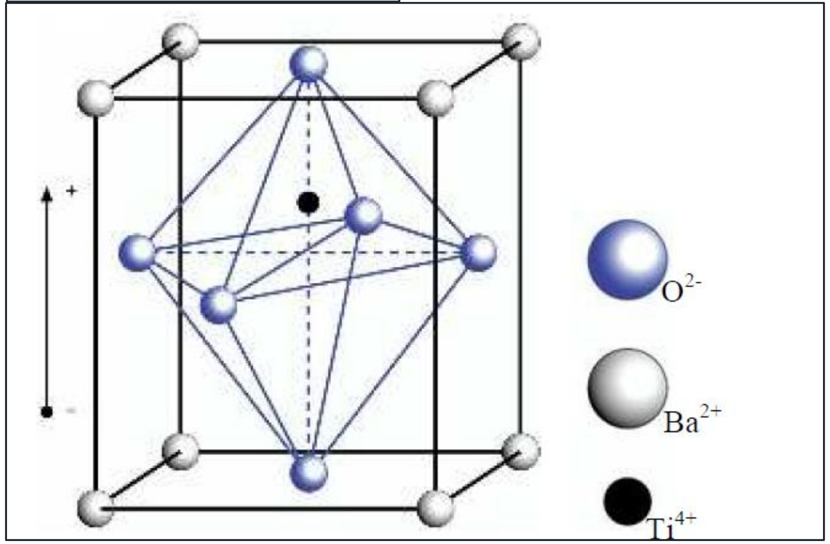
https://en.wikipedia.org/wiki/Polymer_capacitor

Supercapacitor



https://en.wikipedia.org/wiki/Supercapacitor

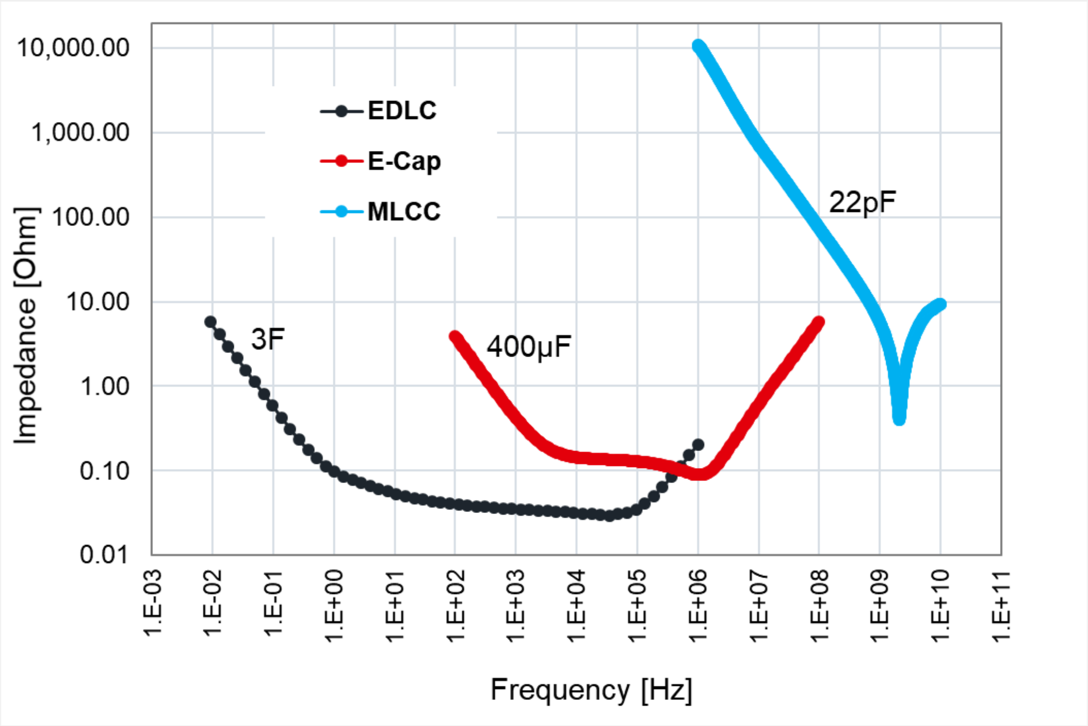
Ceramic Capacitors

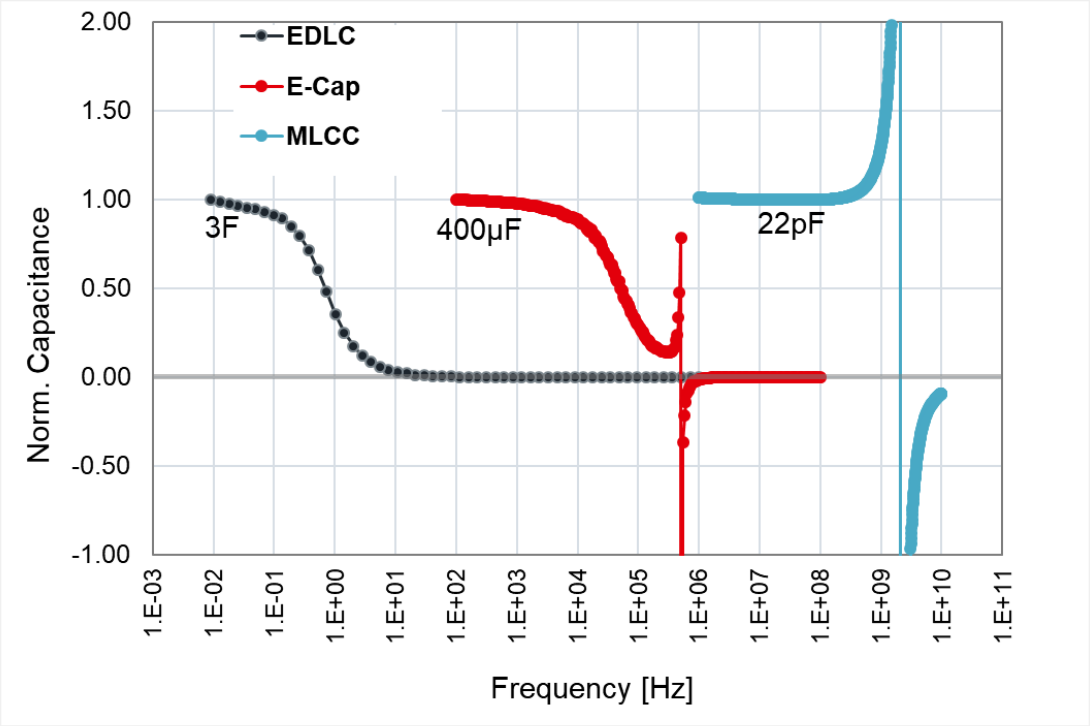


https://en.wikipedia.org/wiki/Ceramic_capacitor

Any many more...

SPECTRA OF CAPACITORS



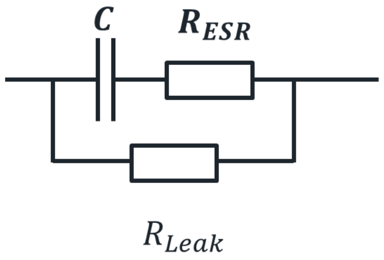


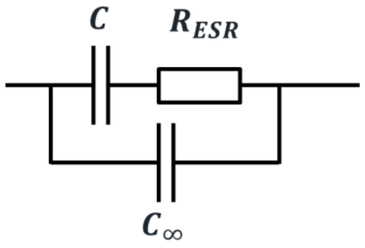
So many capacitors families, so many spectra ...

MANIFOLD OF EQUIVALENT CIRCUITS / MODELS

Debye-like models

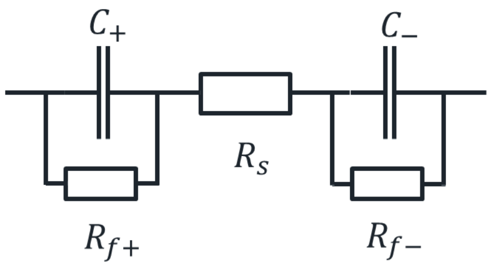
- Supercapacitors
- E-Caps

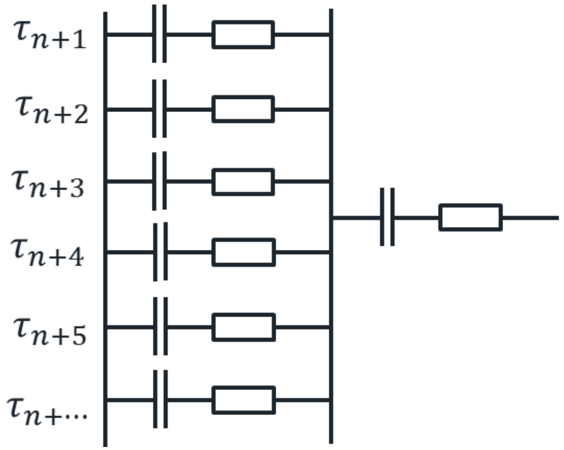




Electrode interface models

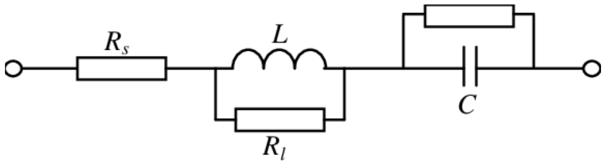
- Supercapacitors (EDLC)
- E-Caps
- Polymer Caps

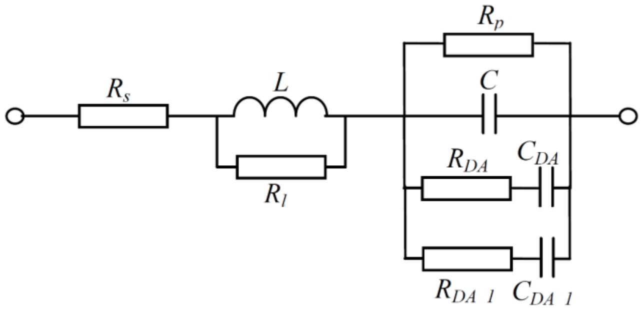




Lorentz oscillator

- MLCCs
- Film Capacitors
- E-Caps
- Polymer Caps





Any many more…

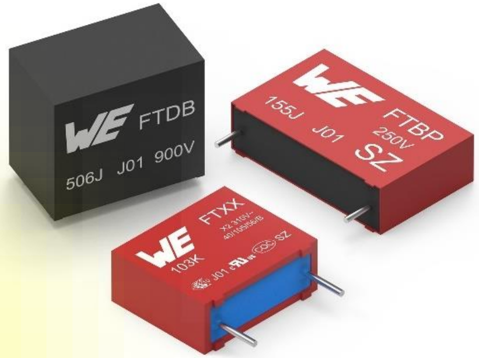
Fletcher, S., Black, V.J. & Kirkpatrick, I. A universal equivalent circuit for carbon-based supercapacitors. J Solid State Electrochem 18, 1377–1387 (2014). https://doi.org/10.1007/s10008-013-2328-4

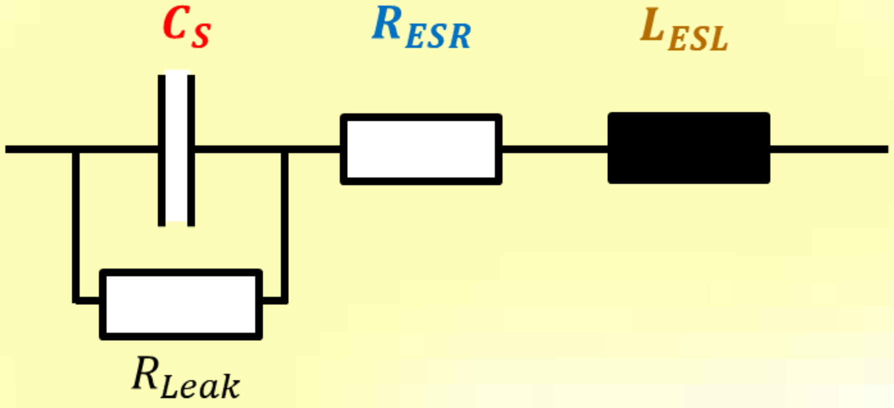
Modeling of metallized polymer films capacitor's impedance, Maawad Makdessi et al., IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society (2012)

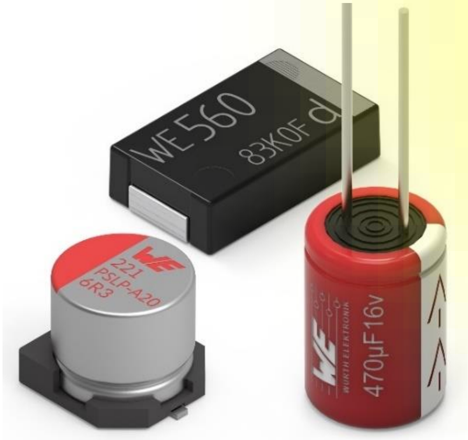
ONE EQUIVALENT CIRCUIT FOR ALL CAPACITORS

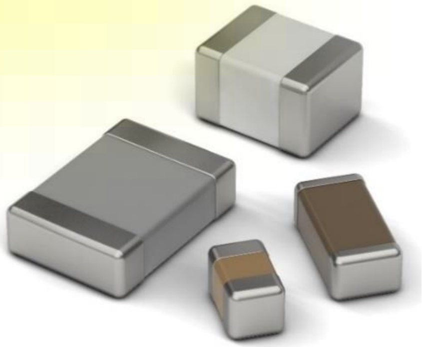
Luckily…

we only need one.







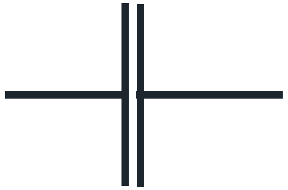


OUTLINE

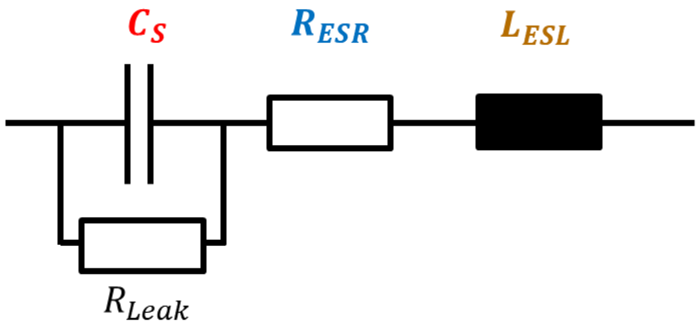
- Introduction of model
- Interpretation of impedance and capacitance spectra calculated and measured
    - High capacitive
    - Low capacitive
- Accuracy and ESR

EQUIVALENT CIRCUIT OF CAPACITORS

Capacitor sign used in your layout:



Capacitor as it actually is:

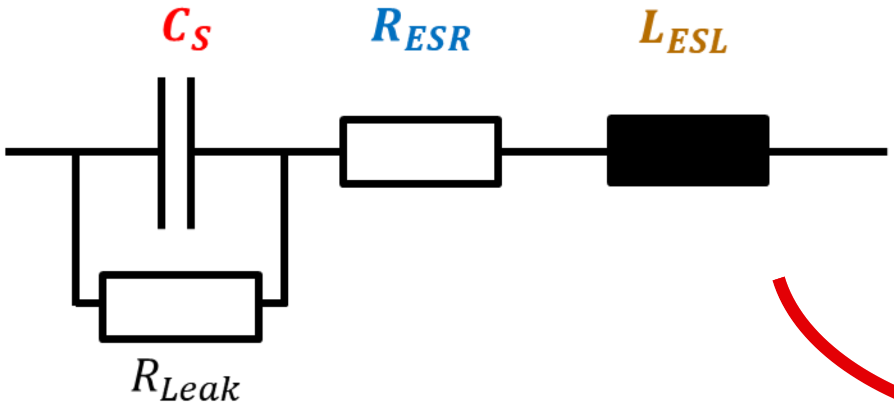


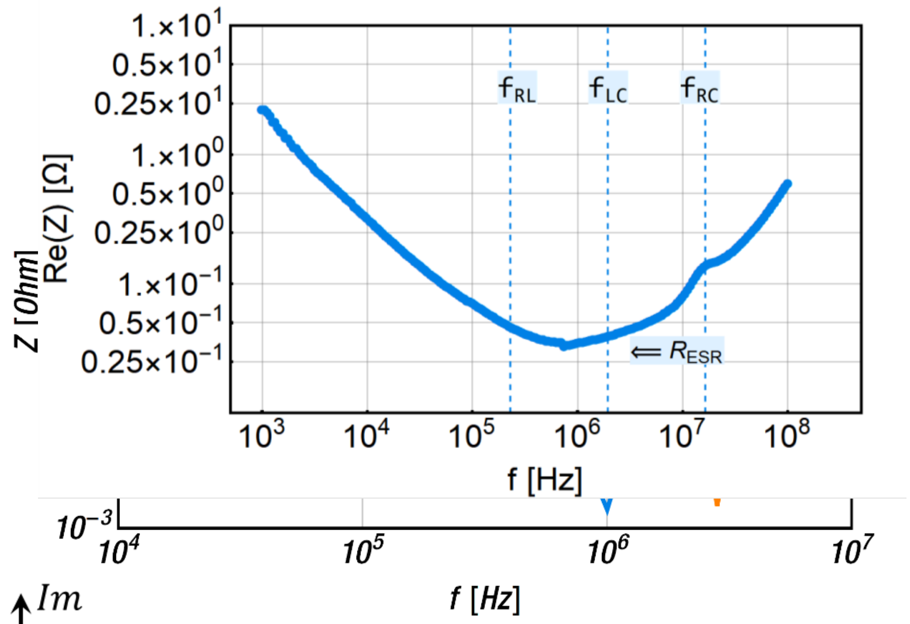
A capacitor consists of:

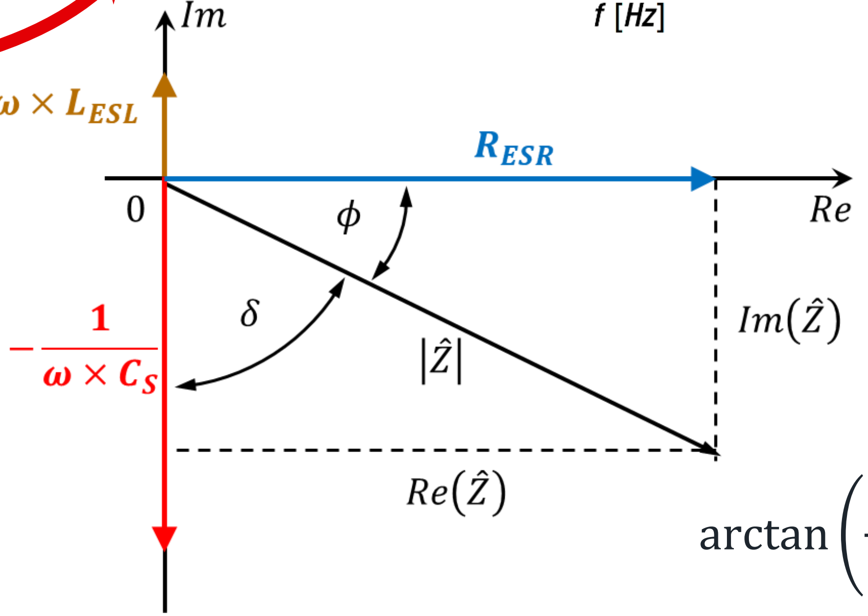
- a pure capacitor
- resistors
- and inductor

EQUIVALENT CIRCUIT

Representations





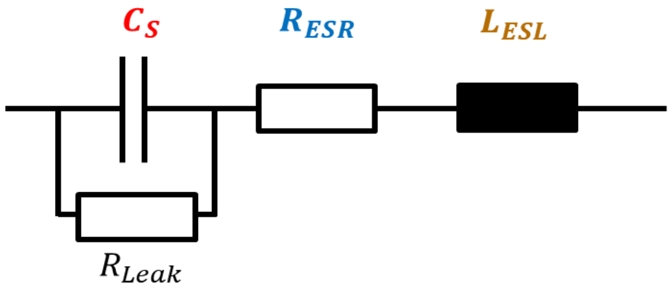


$$\hat{Z}(\omega) = R_{ESR} + i \cdot \omega L_{ESL} + \frac{R_{\mathrm{Leak}}(i\omega C_S)^{-1}}{R_{\mathrm{Leak}} + (i\omega C_S)^{-1}}$$

$$\arctan\left(\frac{\mathrm{Re}(\hat{Z})}{|\mathrm{Im}(\hat{Z})|}\right) = \delta$$

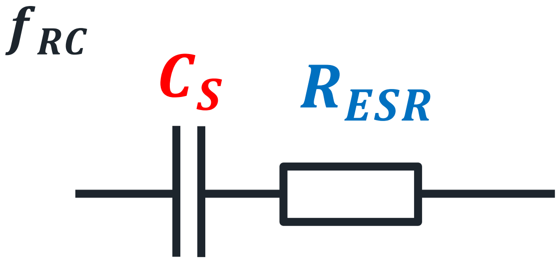
EQUIVALENT CIRCUIT

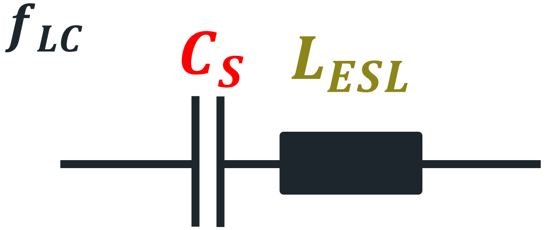
Characteristic Frequencies

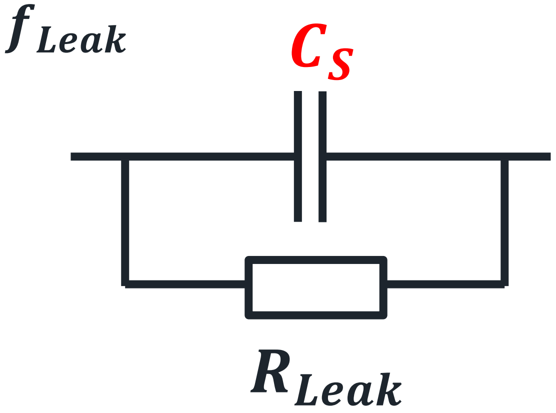


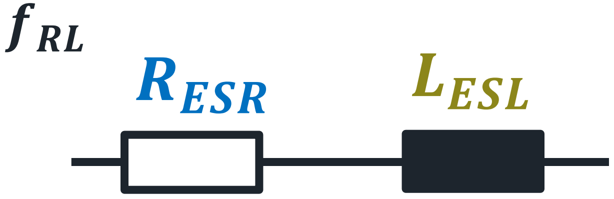
A capacitor acts as a
- a capacitor
- or a resistor
- or a inductor
- or even as a resonator

depending on the frequency !





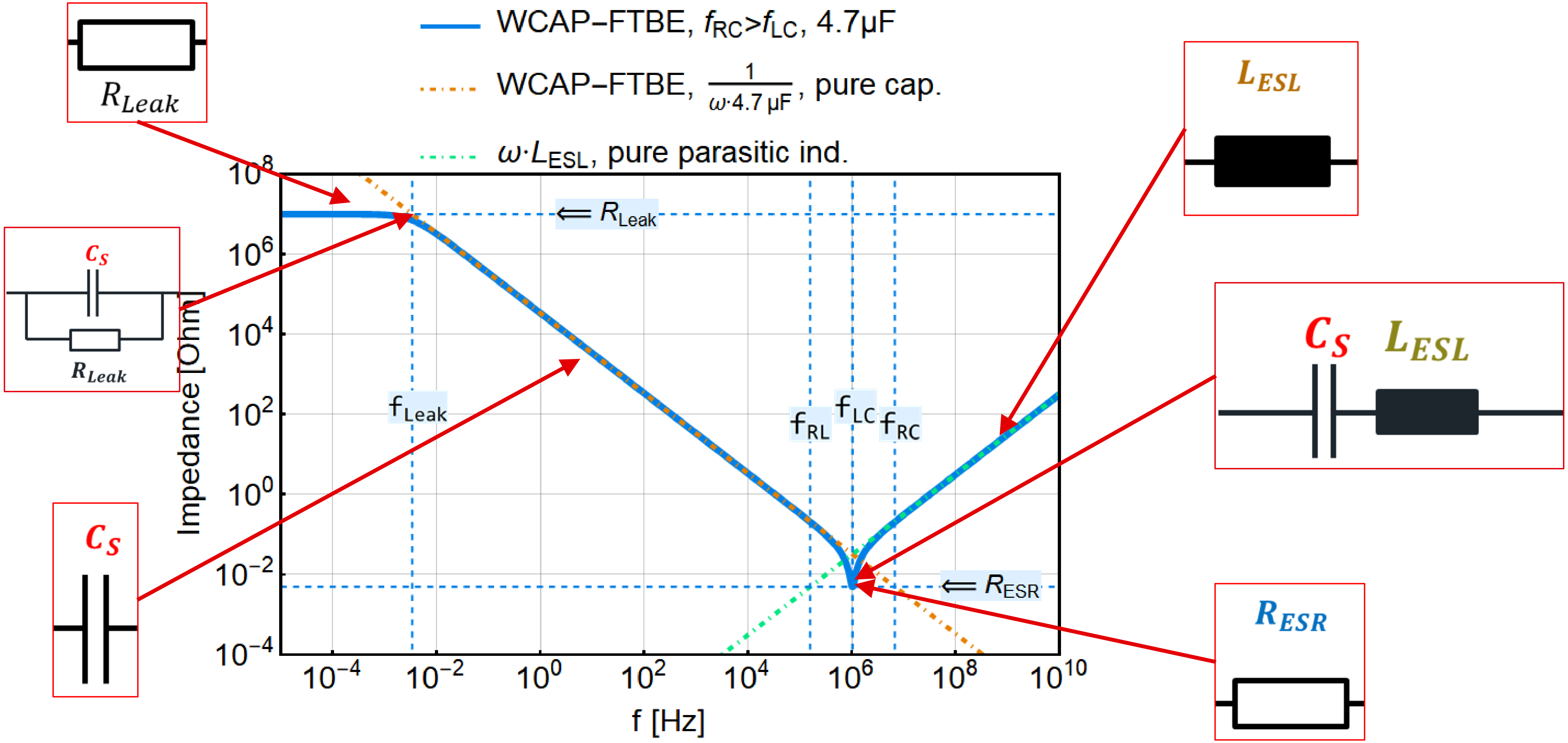




Frequency: f

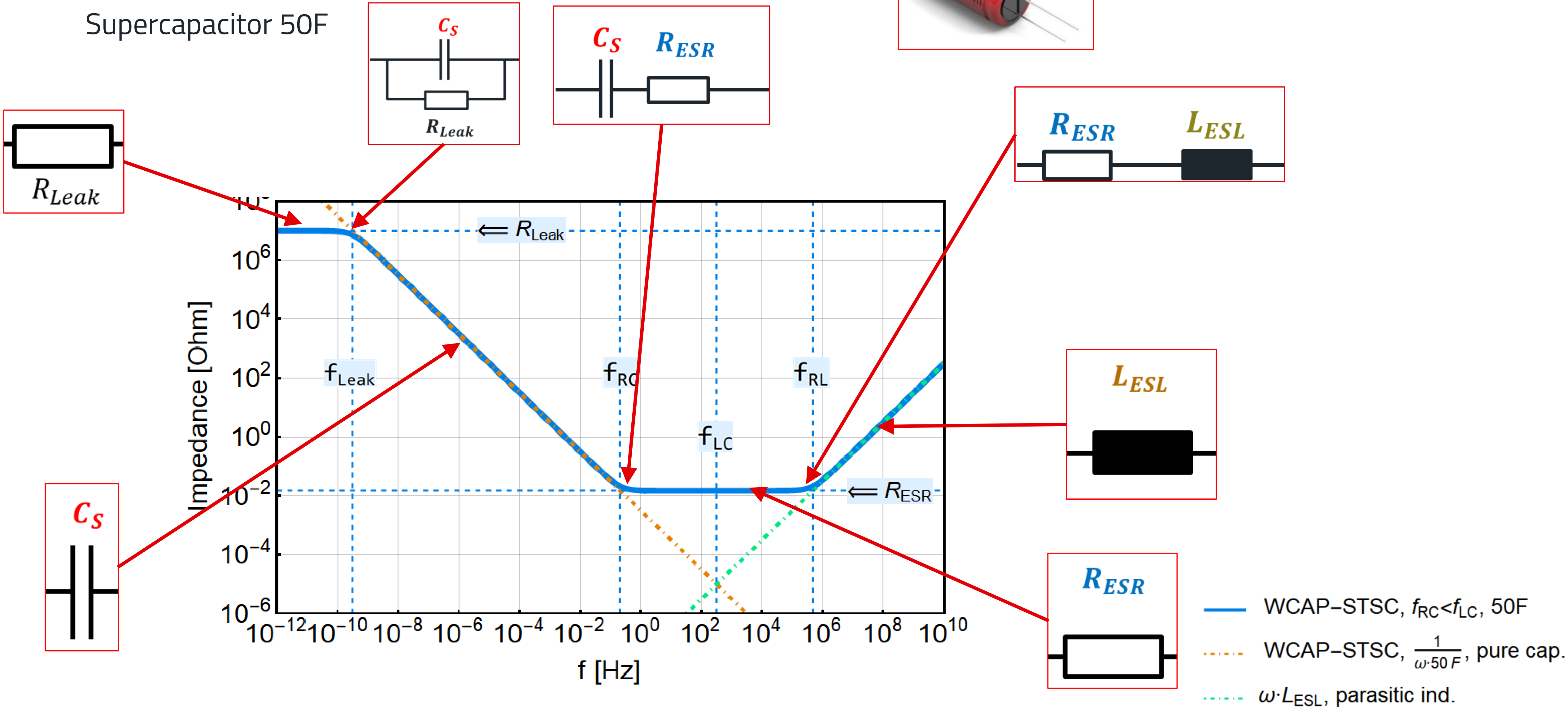
IMPEDANCE AND CAPACITANCE SPECTRA

Film Capacitors



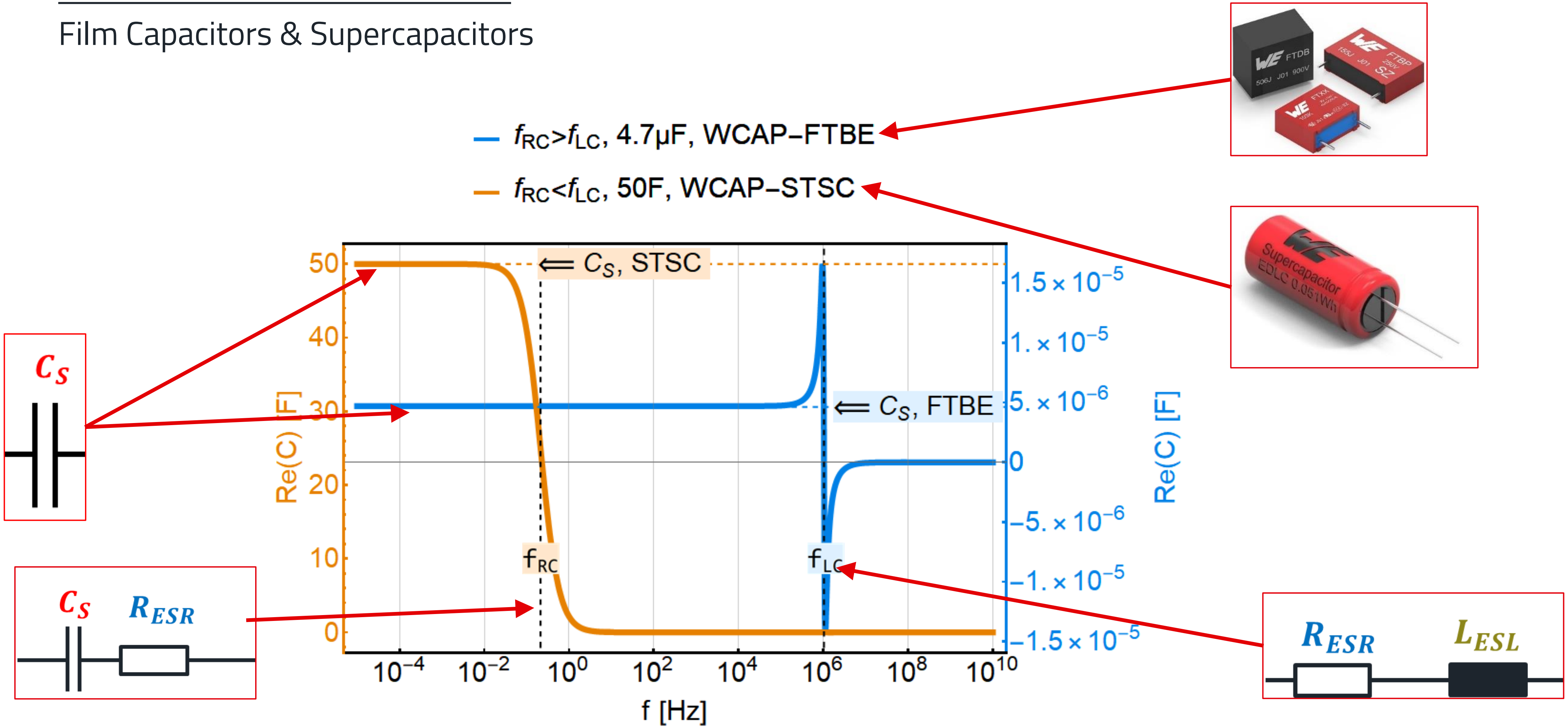
IMPEDANCE AND CAPACITANCE SPECTRA

Supercapacitor 50F

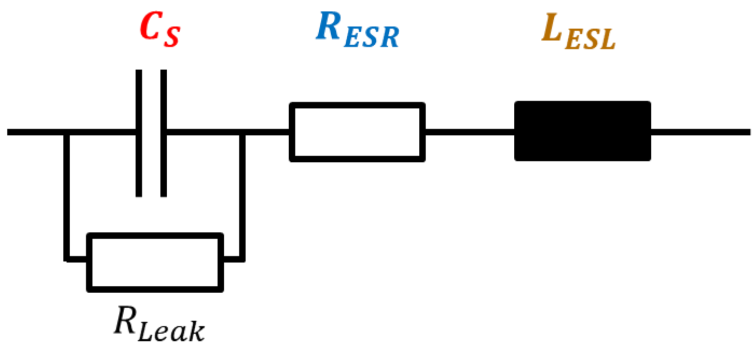


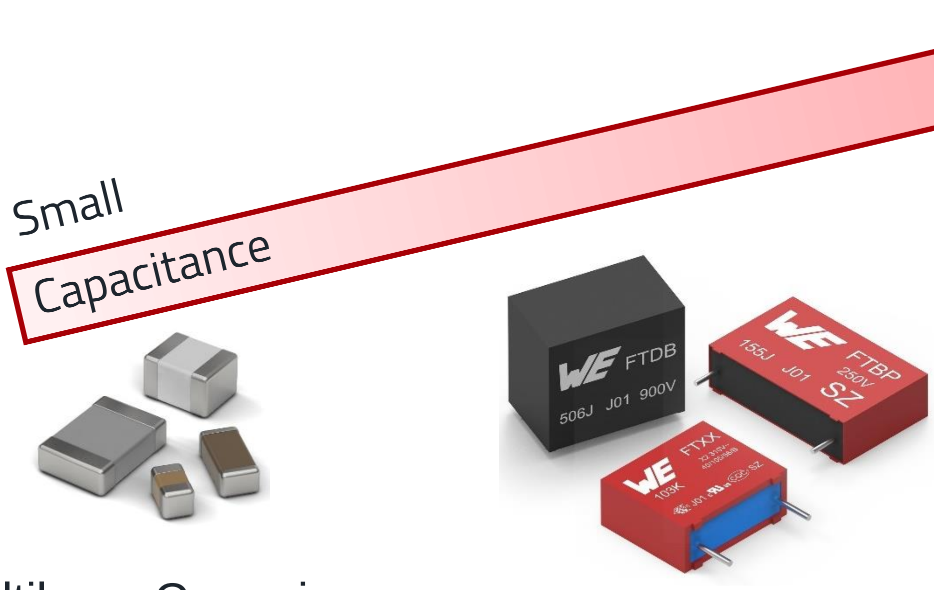
CAPACITANCE SPECTRA

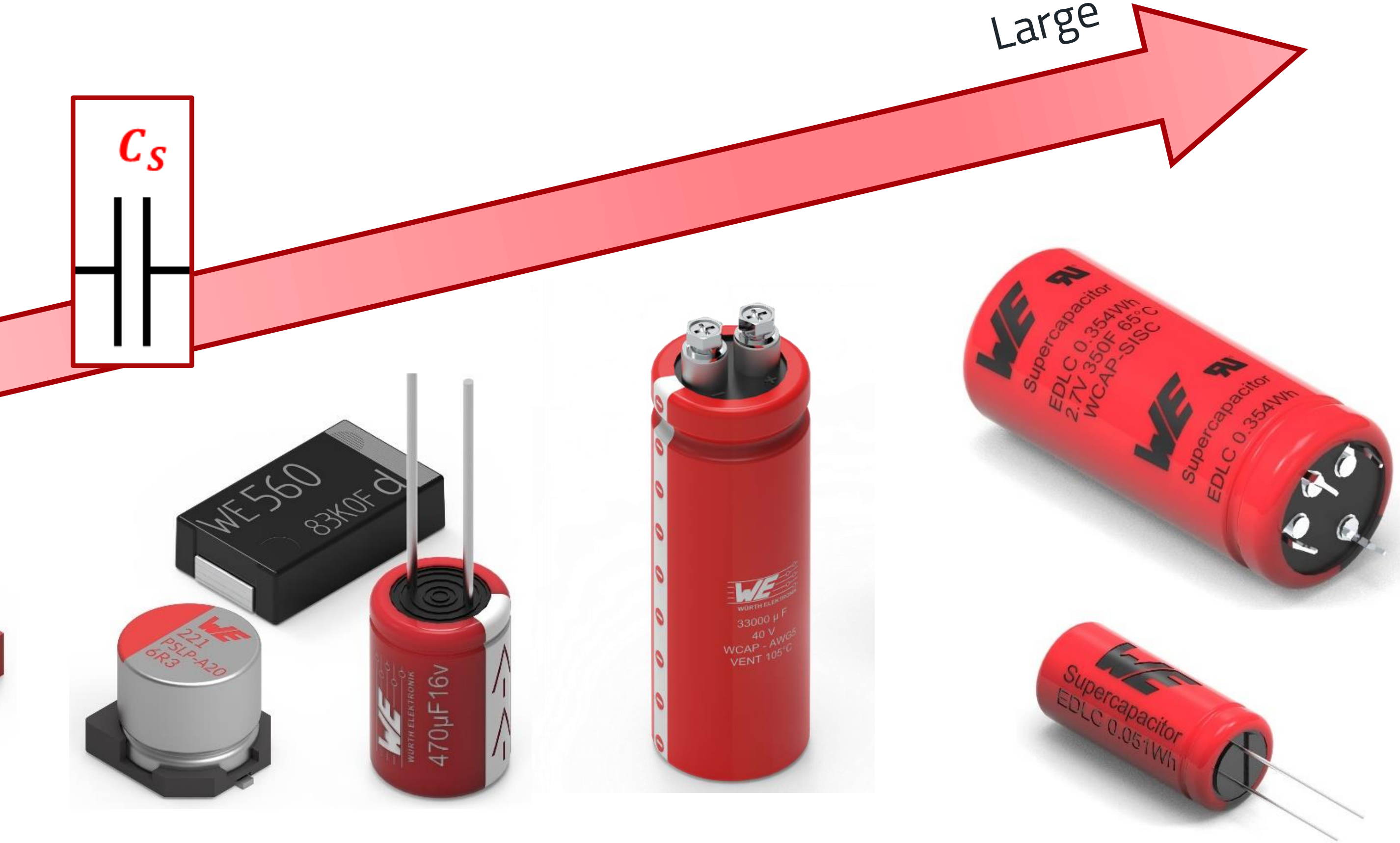
Film Capacitors & Supercapacitors



EQUIVALENT CIRCUIT OF CAPACITORS





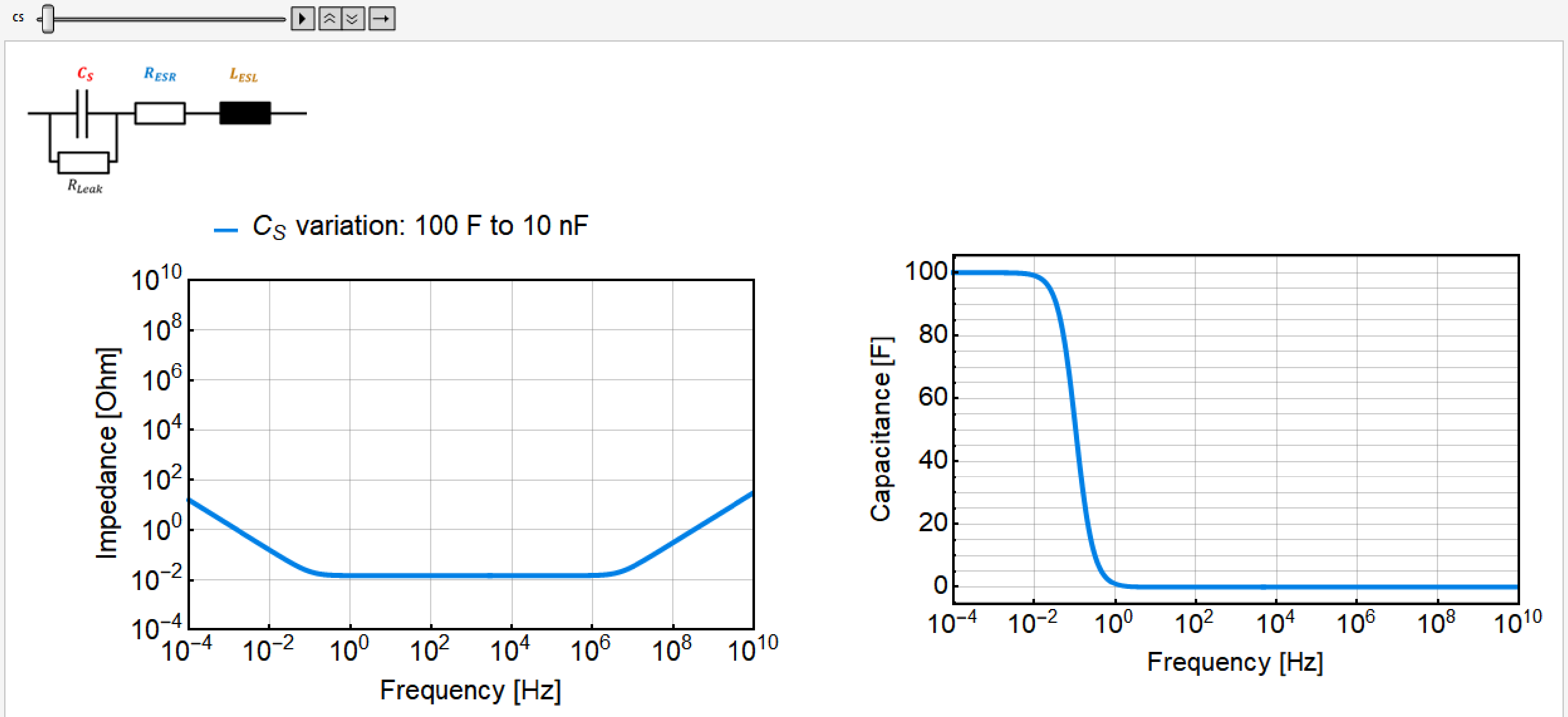


Multilayer Ceramic Capacitors

Film Capacitors, E-Caps, Hybrids

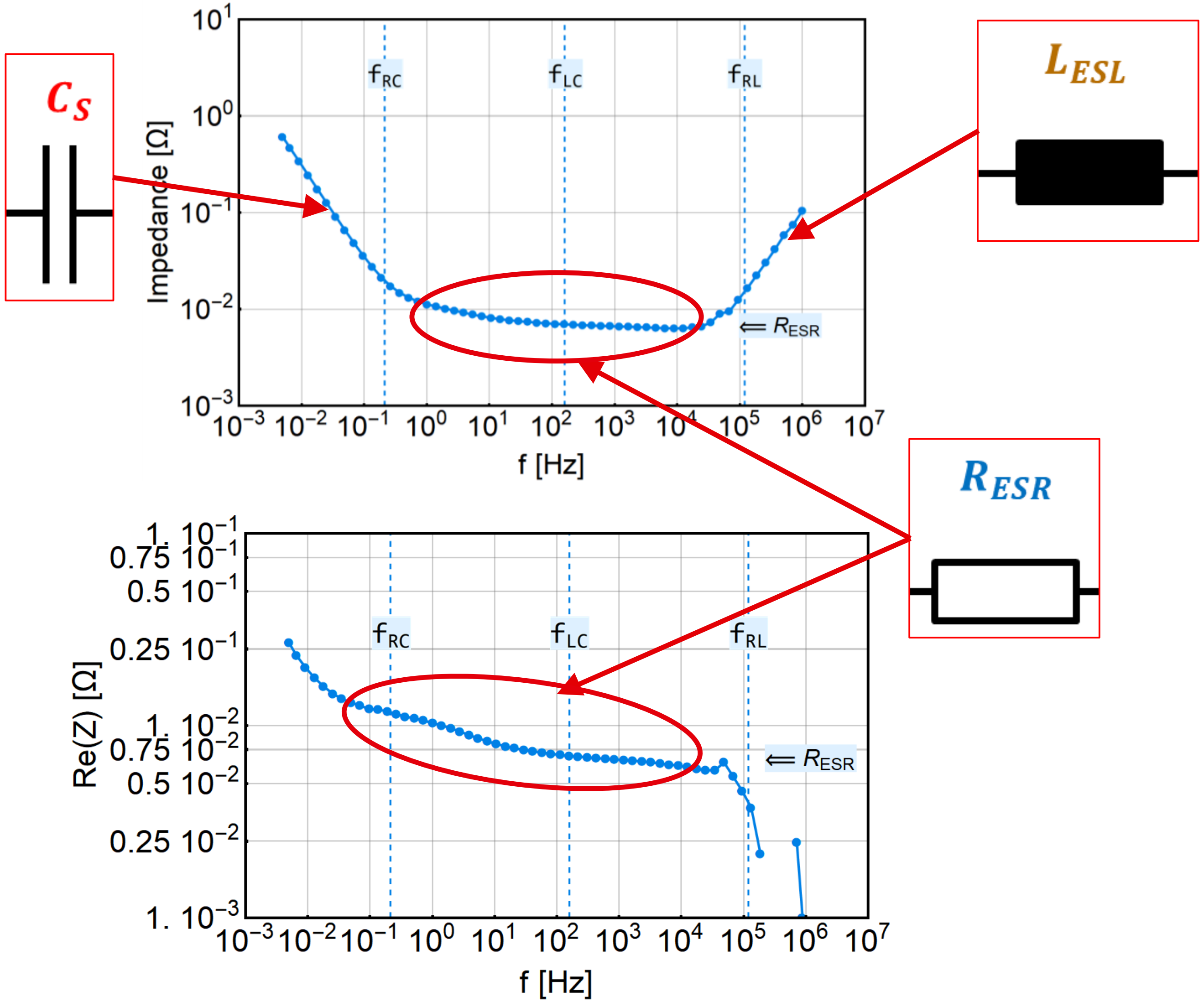
Supercapacitors

EQUIVALENT CIRCUIT OF CAPACITORS



$C_S = 1. \times 10^2$ F
$R_{ESR} = 0.015\ \Omega$
Inductivity, $L_{ESL} = 5\times10^{-9}$ H
Insulation Res., $R_{Leak} = 1\times10^{7}\ \Omega$

IMPEDANCE AND CAPACITANCE SPECTRA

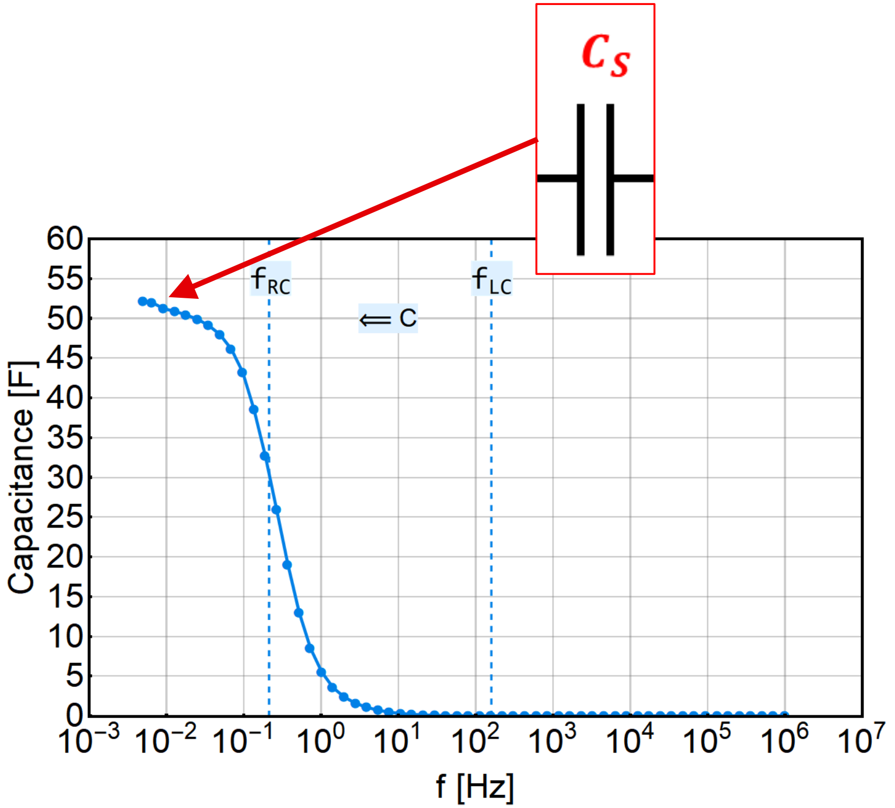


Supercapacitor 50F

$$C_S(0.01\ Hz) = 51\ F$$

$$R_{ESR}(f_{RC} = 0.2\ Hz) = 0.012\ \Omega$$

$$R_{ESR}(f_{LC} = 160\ Hz) = 0.007\ \Omega$$



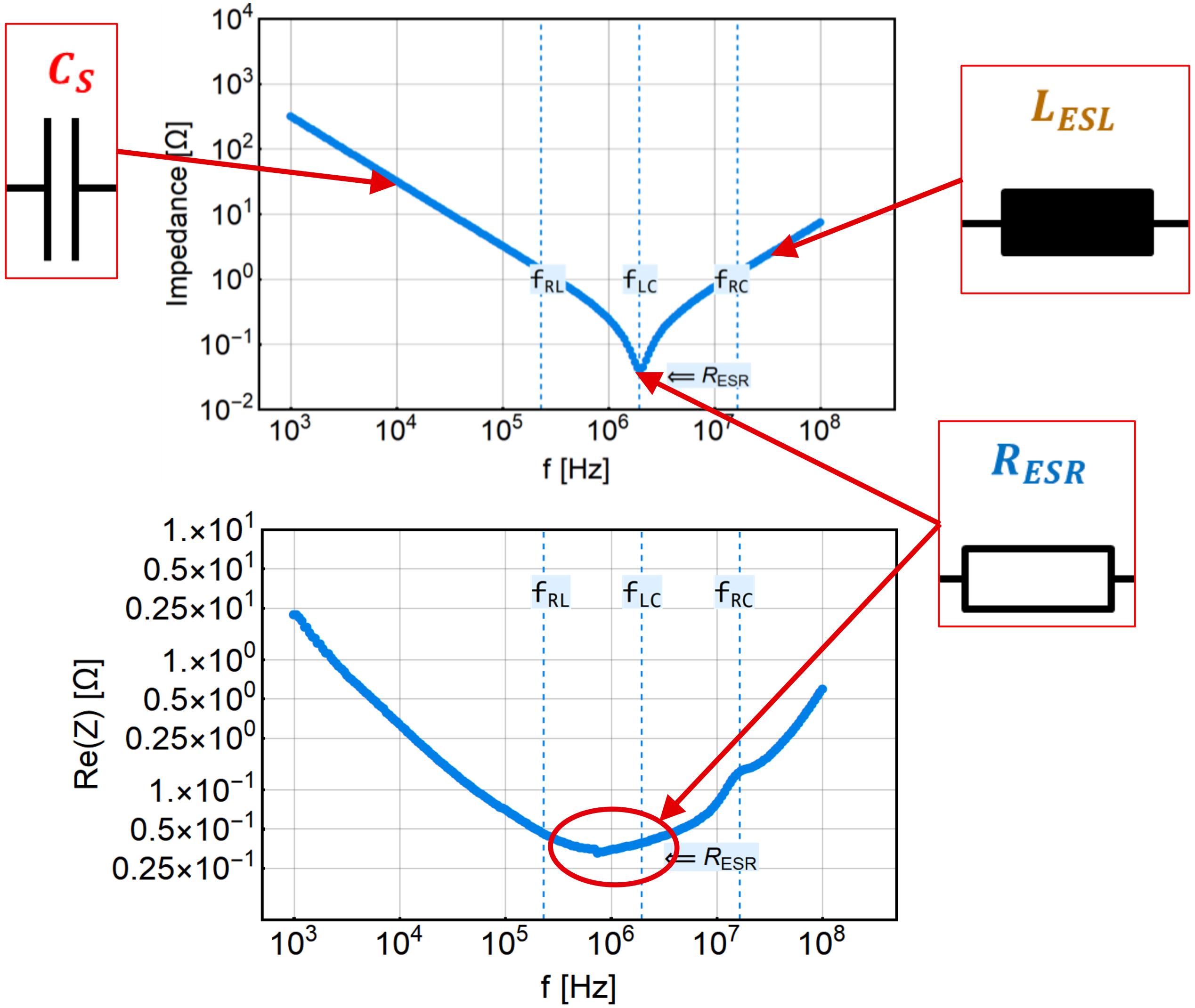
IMPEDANCE AND CAPACITANCE SPECTRA

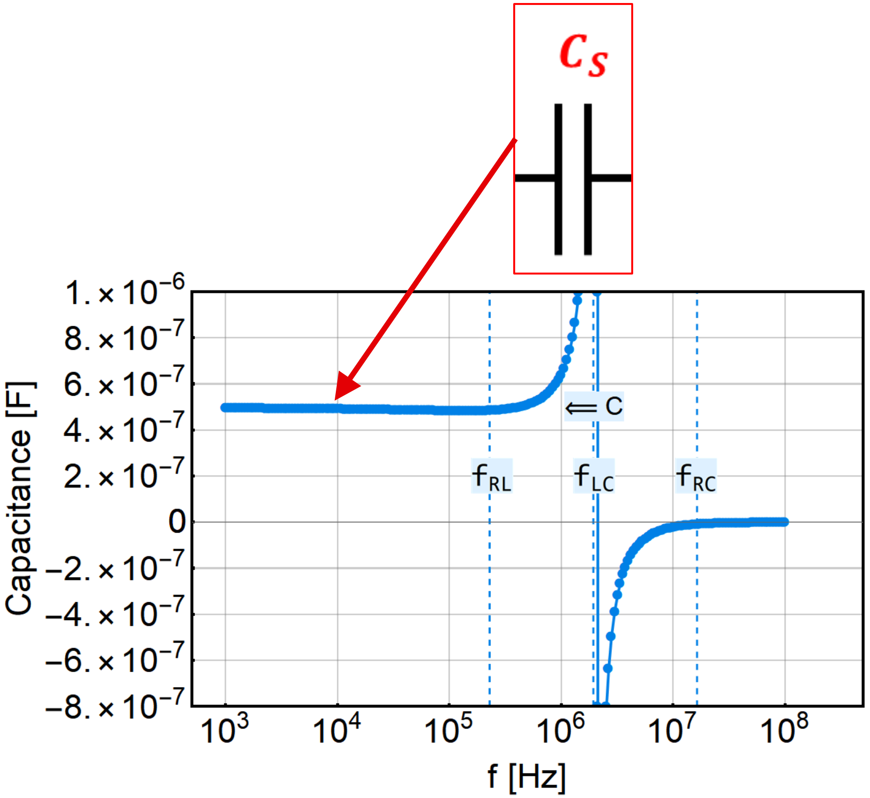
Film Capacitors

$C_S(1\ \text{kHz}) = 495\ \text{nF}$

$R_{\text{ESR}}(1\ \text{kHz}) = 2.2\ \Omega$

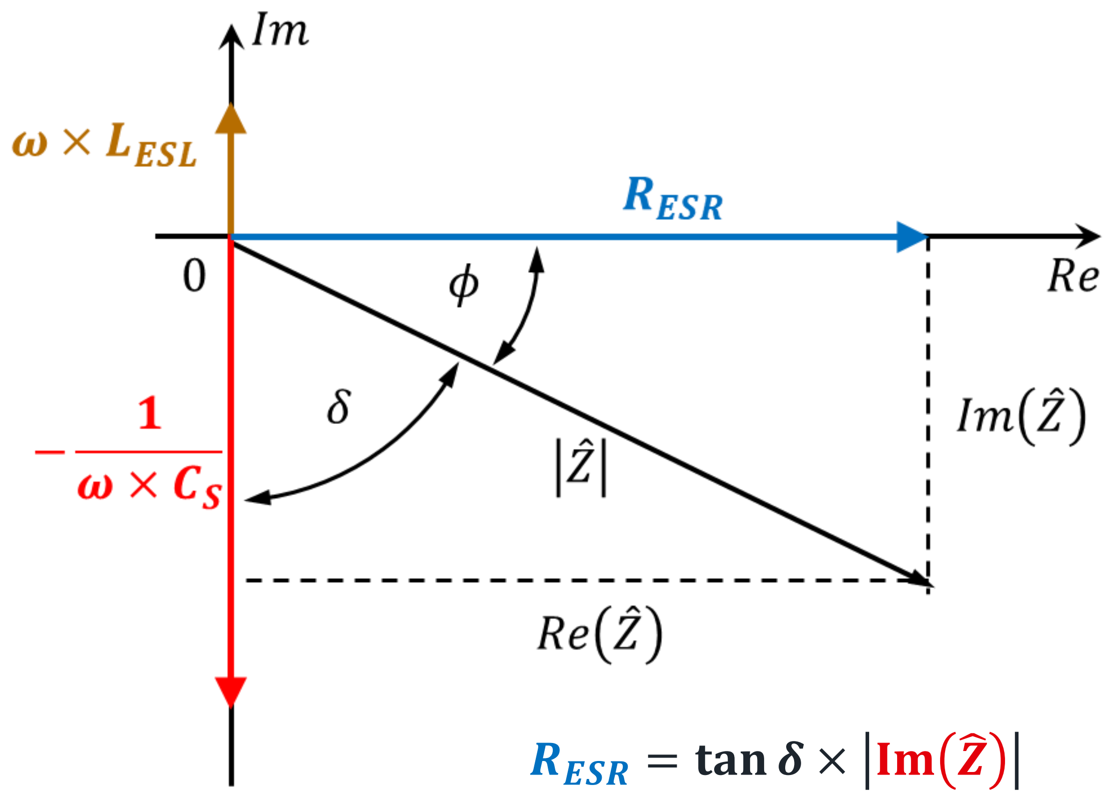
$R_{\text{ESR}}(f_{LC} = 1.94\ \text{MHz}) = 0.04\ \Omega$





MEASUREMENT ACCURACY

Film Capacitors



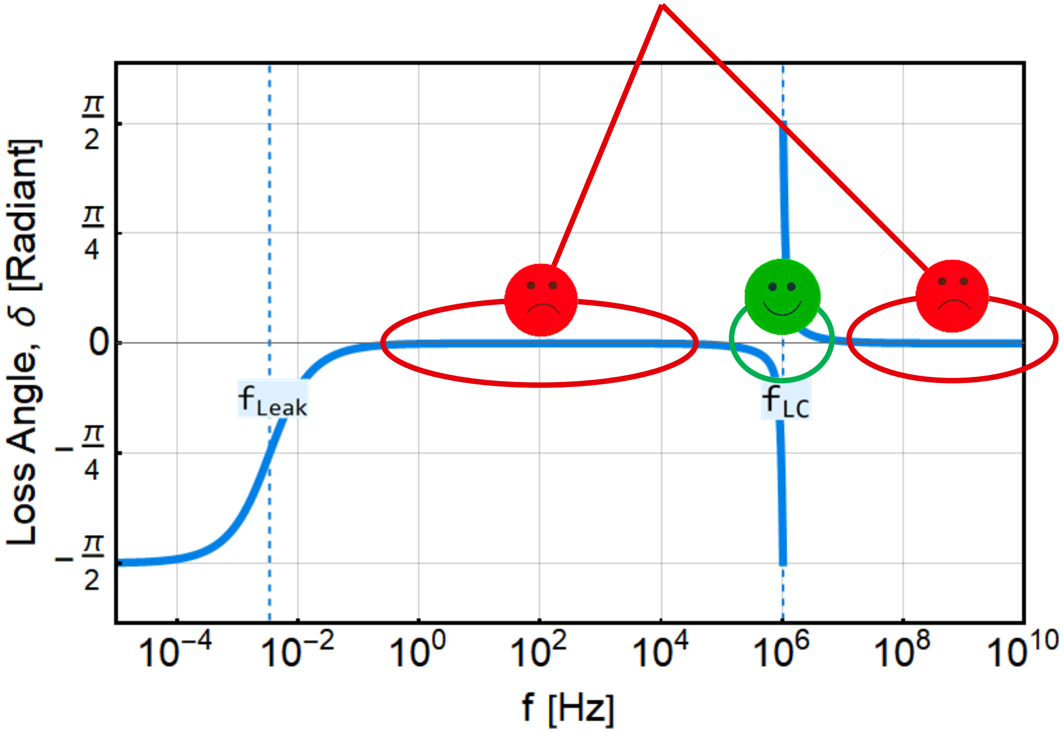
$$R_{ESR} = \tan\delta \times |\mathrm{Im}(\hat{Z})|$$

$$\delta \geq \delta_{\Delta}$$

accuracy limit

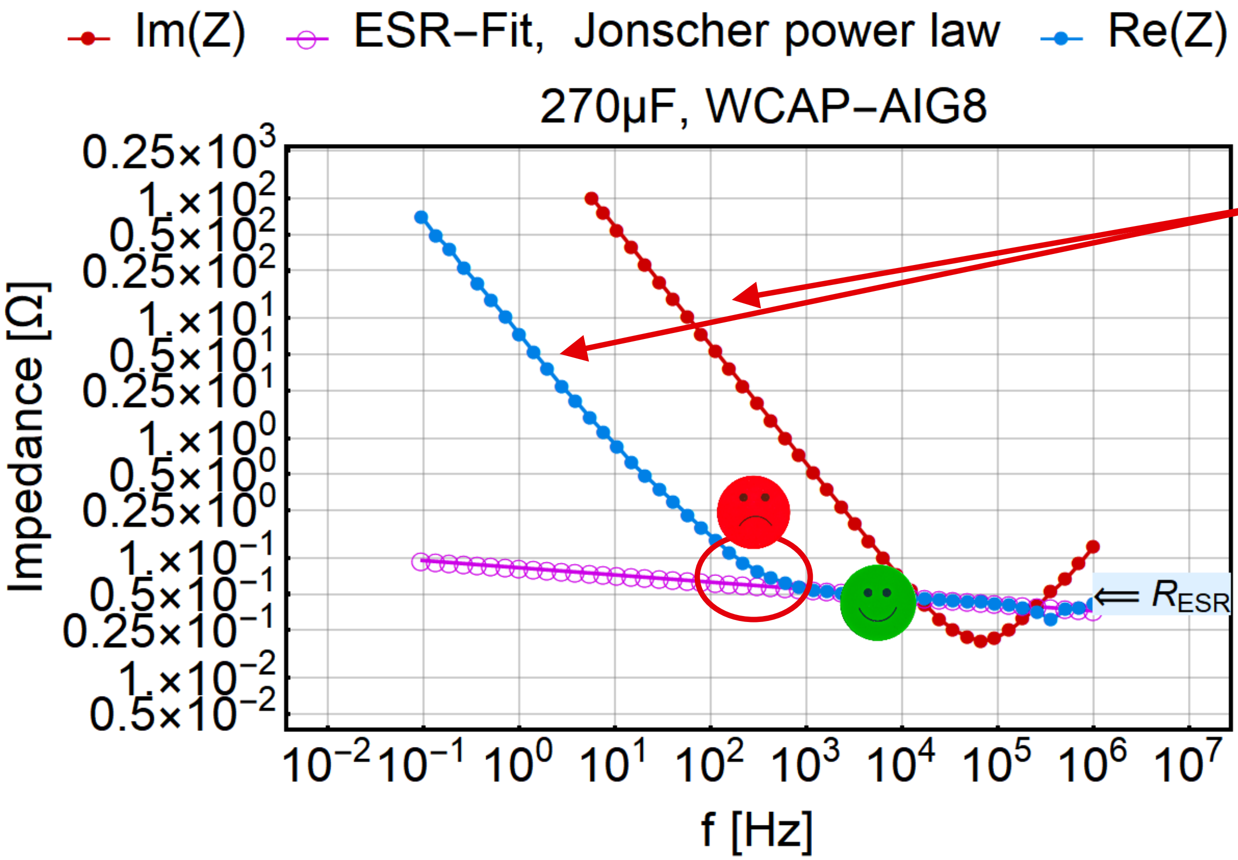
$\tan\delta \to 0$

Cannot be resolved !



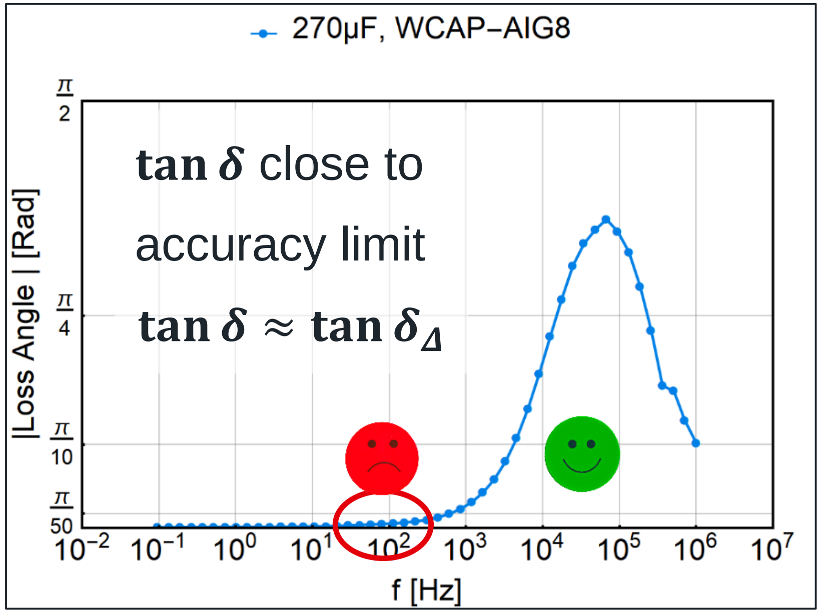
IMPEDANCE AND CAPACITANCE SPECTRA

E-Caps



$$R_{ESR} = \tan \delta_{\Delta} \times |\mathrm{Im}(\hat{Z})|$$

- Constant $\tan \delta_{\Delta}$ leads to parallel graphs in log-log plot

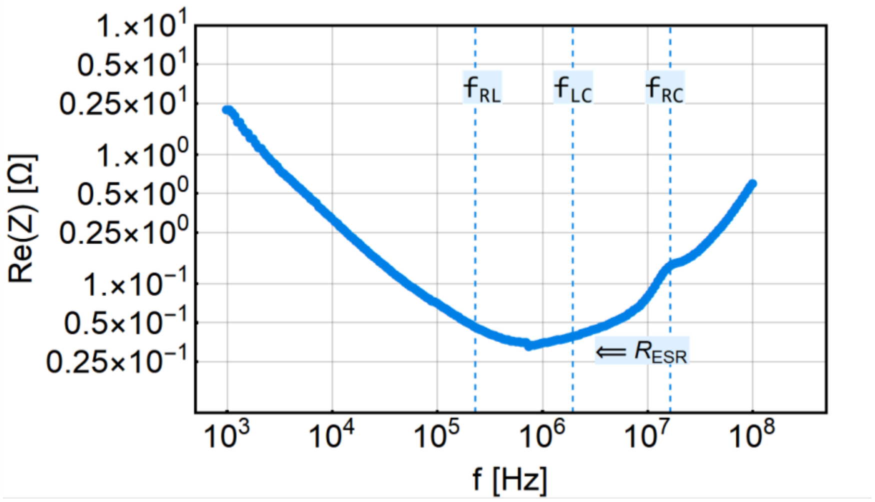


$\tan \delta$ close to accuracy limit

$\tan \delta \approx \tan \delta_{\Delta}$

S.K. Shaurasia, Studies on structural, thermal and AC conductivity scaling of PEO-LiPF$_6$ polymer electrolyte with added ionic liquid [BMIMPF$_6$], AIP Advances **5**, 077178 (2015)

IMPEDANCE AND CAPACITANCE SPECTRA



If $|Im(\hat{Z})|$ increases, so does R_{ESR}, it seams!

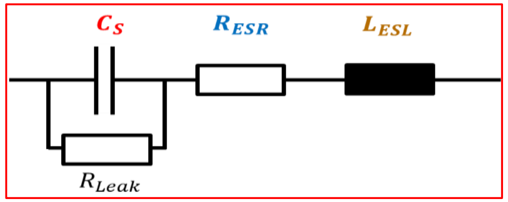
Does this mean the R_{ESR} is actually increasing?

Hard to say, since…

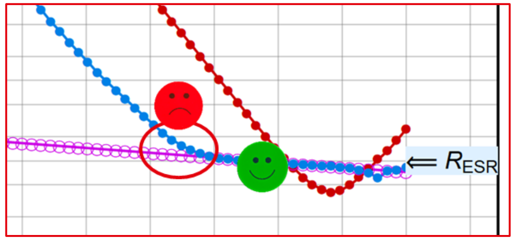
$\tan\delta$ cannot be measured accurately.

R_{ESR} is probably **largely overestimated**!

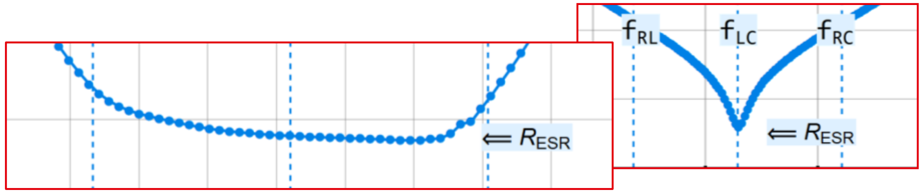
CONCLUSION



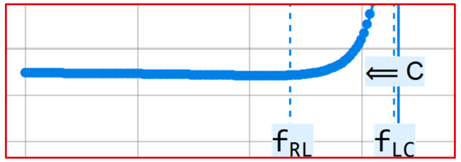
- Only one model sufficient: describes all important features of impedance spectra



- Loss angle resolution limits ESR measurements
  - Steep increase of ESR indicates resolution limit



- Only trust ESR values at the minimum



- Capacitance is extracted at low frequencies.

Questions

& Answers

We are here for you now!
Ask us directly via our chat or via E-Mail.

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BIOGRAPHY / CONTACT DETAILS

René Kalbitz, Ph.D.

Product Manager,
Supercapacitors
eiCap / eiRis Capacitors and
Resistors Division

Background:

- Experience in
  - application-oriented research
  - development of organic electronics,
  - polymer analysis
- Responsible for Supercapacitors

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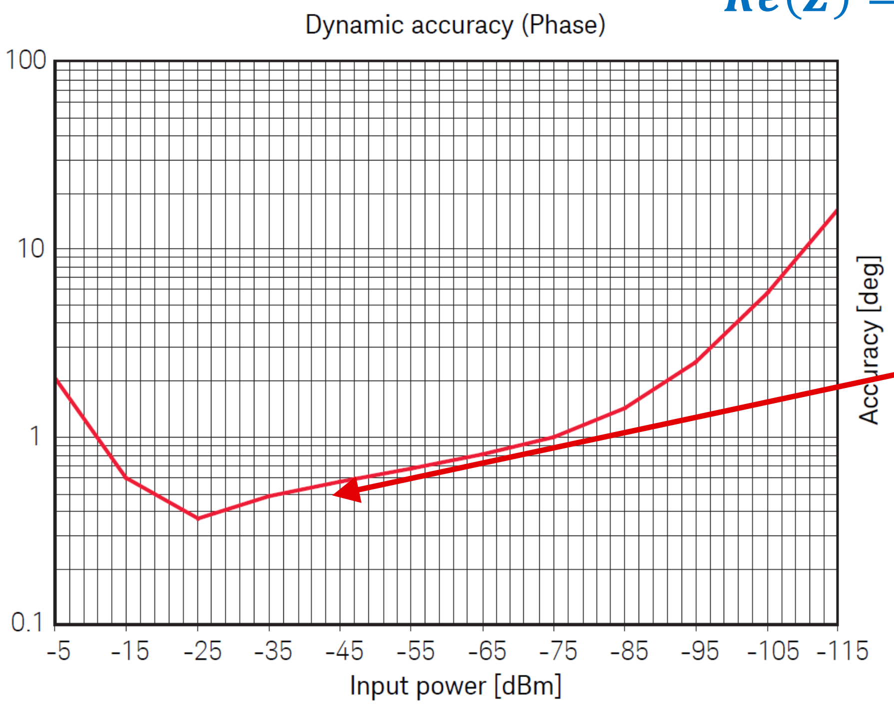
Dr. René Kalbitz studied physics at the University of Potsdam and at the University of Southampton (GB). After completing his diploma degree, he gained is PhD in the field of organic semiconductors and insulators at the University of Potsdam. He was able to gain further experience in the field of applied research at the Fraunhofer Institute for Applied Polymer Research. He has been employed at Würth Elektronik as a product manager for supercapacitors since 2018 and oversees research and development projects in the field of capacitors.

[REPOSITORY]

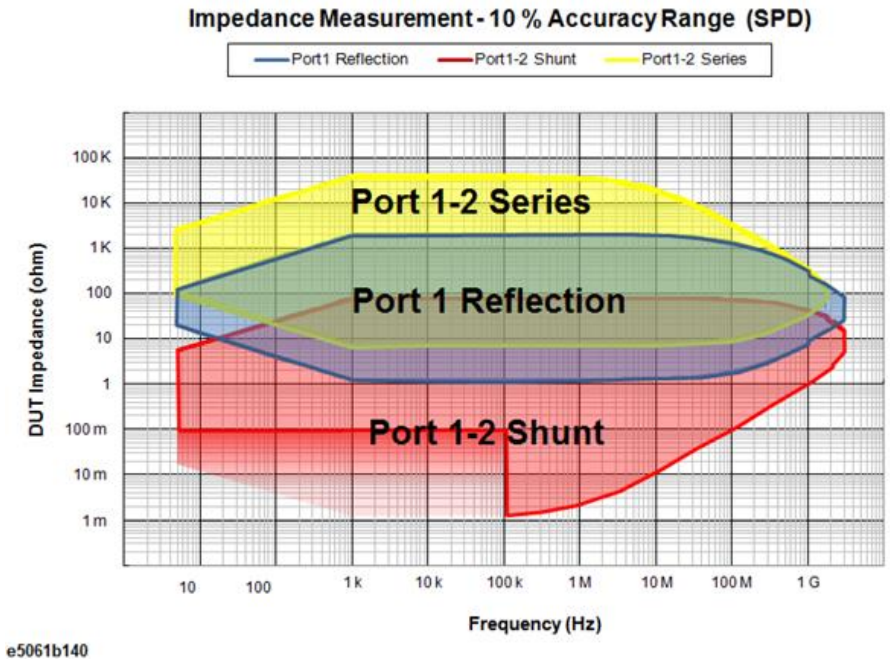
IMPEDANCE AND CAPACITANCE SPECTRA

$$Re(Z) = R_{ESR} = \tan\delta \times |Im(\hat{Z})|$$

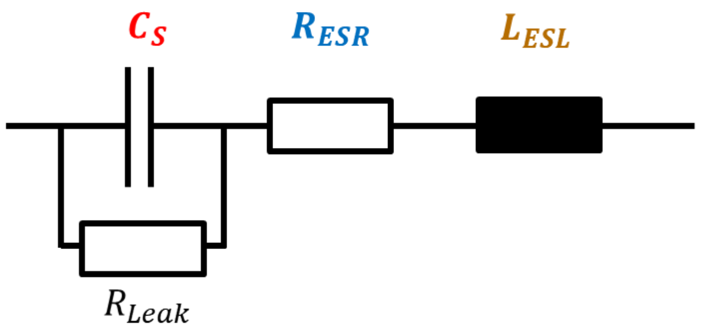


δ_Δ accuracy limit

Measured δ cannot be smaller than δ_Δ



EQUIVALENT CIRCUIT OF CAPACITORS



Characteristic Frequencies:

- $R_{\mathrm{ESR}} - C$:

$$f_{RC} = \frac{1}{2 \cdot \pi \cdot R_{ESR} \cdot C_S}$$

- $L_{ESL} - C$

$$f_{LC} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{ESL} \cdot C_S}}$$

- $R_{\mathrm{Leak}} - C$:

$$f_{Leak} = \frac{1}{2 \cdot \pi \cdot R_{Leak} \cdot C_S}$$

- $R_{\mathrm{ESR}} - L$:

$$f_{RL} = \frac{R_{ESR}}{2 \cdot \pi \cdot L_{ESL}}.$$

below f_{RC}: Reactance X_C dominates

$\rightarrow$ C_S can be extracted

at f_{LC}: Reactance X_L, X_C cancel out

$\rightarrow$ R_{ESR} can be extracted

below f_{Leak}: R_{Leak} dominates

$\rightarrow$ R_{Leak}can be extracted

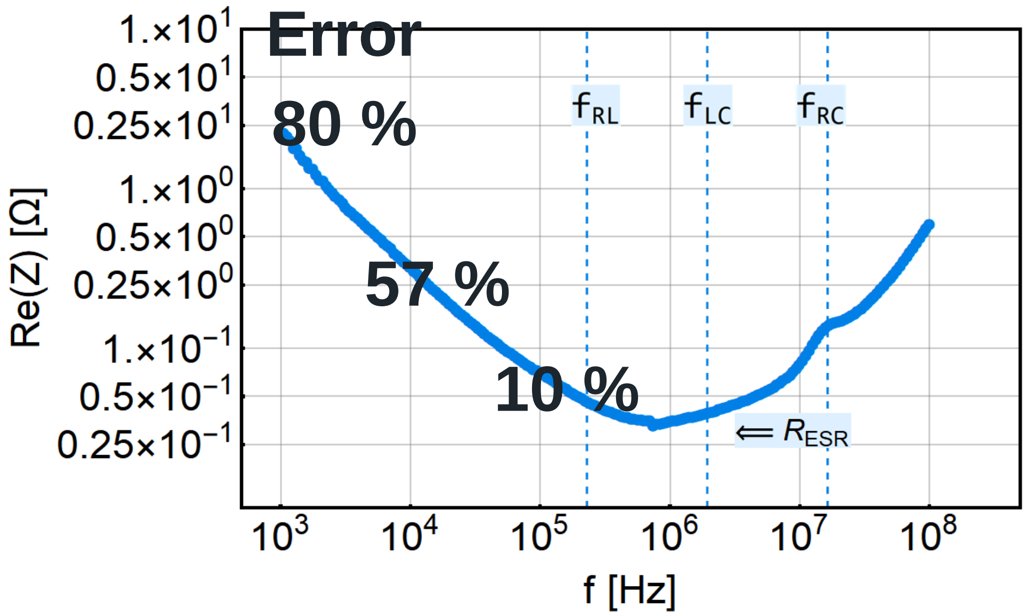
above f_{RL}: Reactance X_L dominates

$\rightarrow$ L_{ESL}can be extracted

IMPEDANCE AND CAPACITANCE SPECTRA

$C_S = 4.7\ \text{nF}$

Parameter	Value	Value	Value
f_e in kHz	**450**	**10**	**1**
$\text{Im}(\hat{Z})$ in Ω	0.75	33.86	338.63
$\text{Re}(\hat{Z})$ in Ω	0.039	0.31	2.23
δ_Δ in °	0.30	0.30	0.30
$\tan\delta$	0.052	0.009	0.007
δ in °	2.967	0.525	0.377
Δ in %	**10.1**	**57.2**	**79.5**



$$Re(Z) = R_{ESR} = \tan\delta \times \left|\text{Im}(\hat{Z})\right|$$