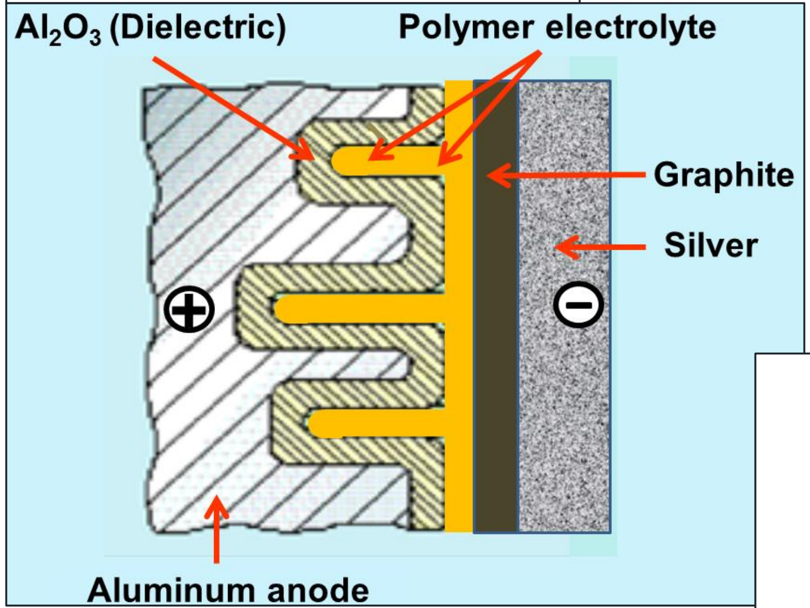
IMPEDANZSPEKTREN VERSCHIEDENER KONDENSATORTECHNOLOGIEN

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

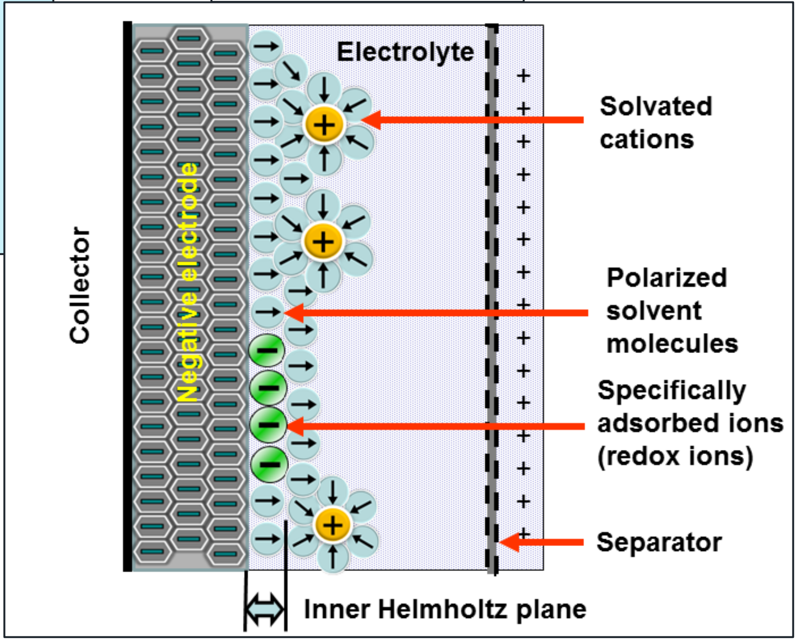
WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

VIELFALT DER KONDENSATORTECHNOLOGIEN

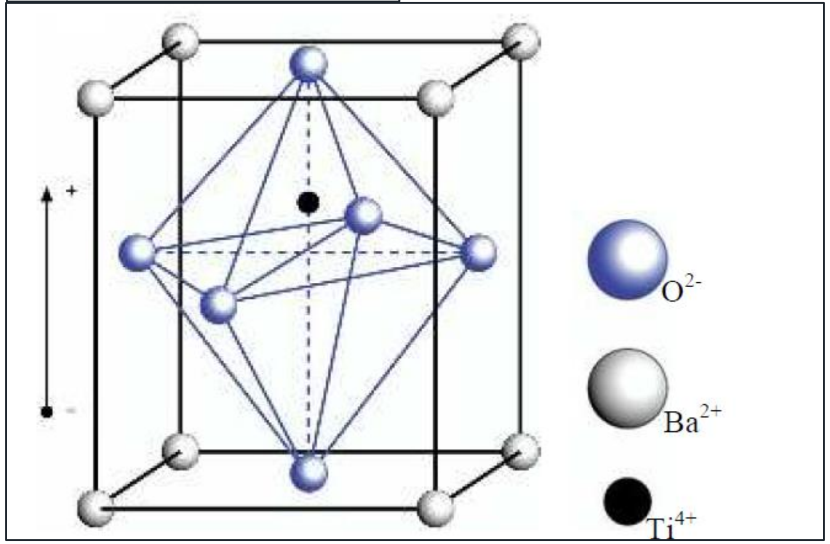
Polymer electrolytic capacitor



Supercapacitor



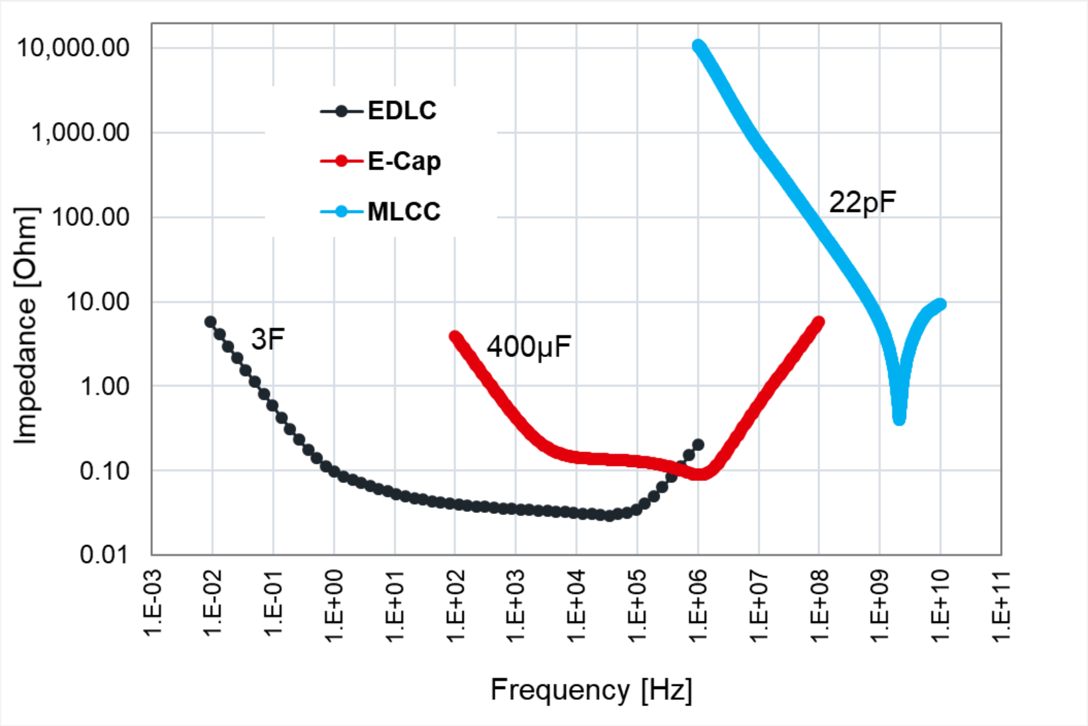
Ceramic Capacitors

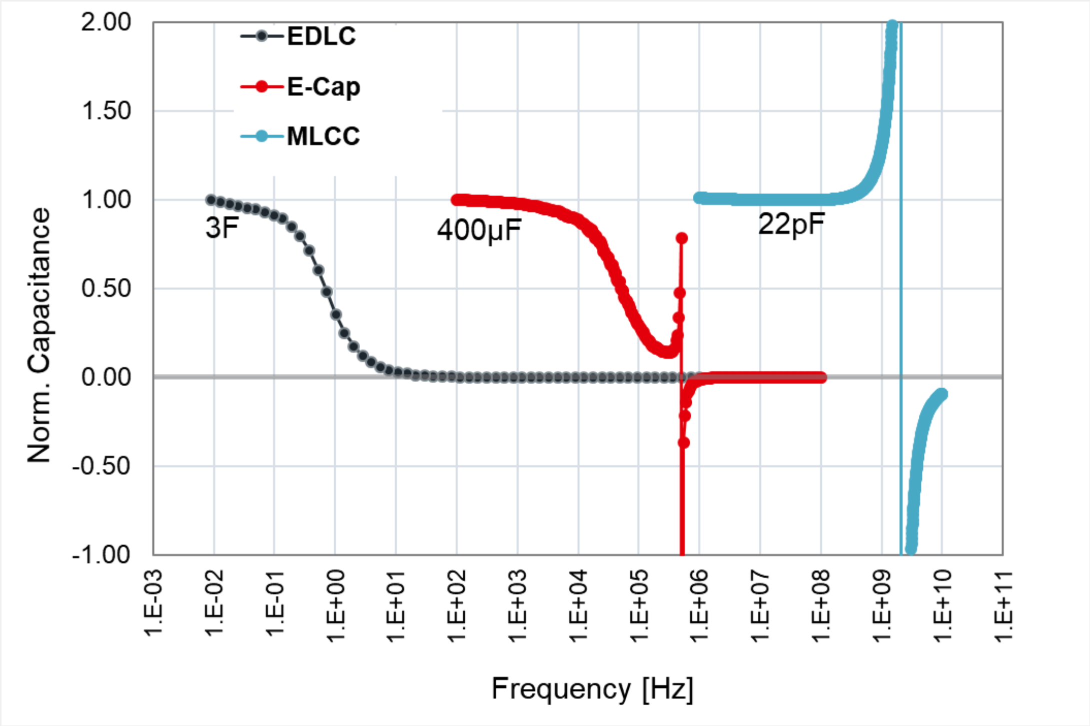


Und noch viel mehr…

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

SPEKTREN VON KONDENSATOREN



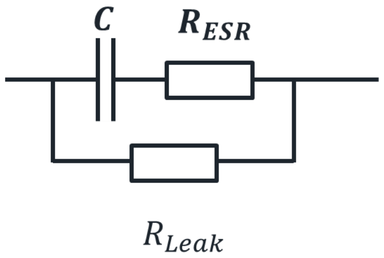


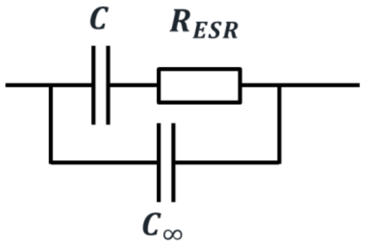
So viele Kondensatorfamilien, so viele Spektren ...

VIELZAHL VON ERSATZSCHALTUNGEN/-MODELLEN

Debye-like models

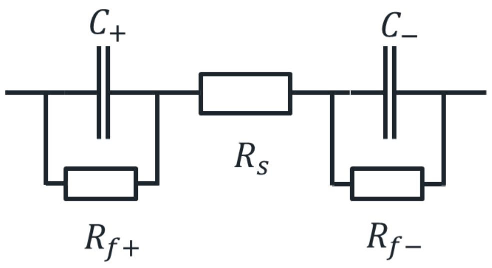
- Supercapacitors
- E-Caps

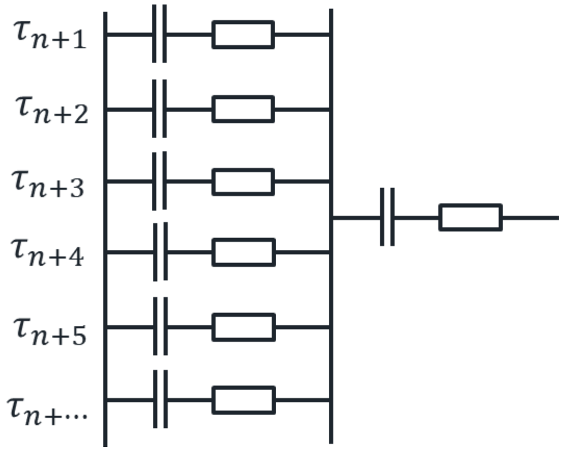




Electrode interface models

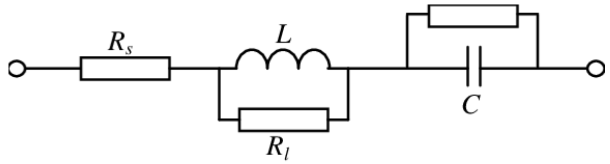
- Supercapacitors (EDLC)
- E-Caps
- Polymer Caps

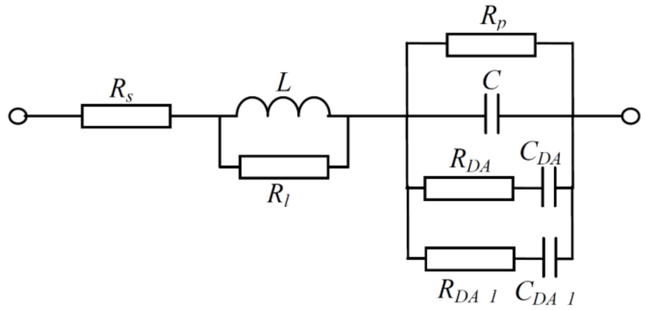




Lorentz oscillator

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





Any many more…

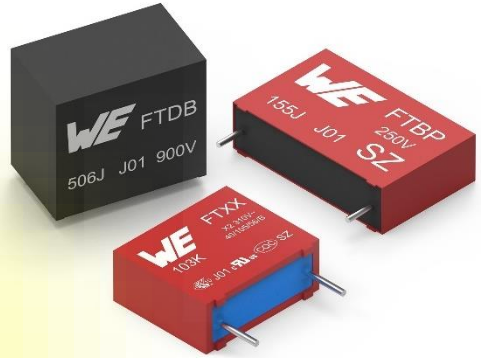
Fletcher, S., Black, V.J. & Kirkpatrick, I. A universal equivalent circuit for carbon-based supercapacitors. J Solid State Electrochem 18, 1377–1387 (2014). https://doi.org/10.1007/s10008-013-2328-4

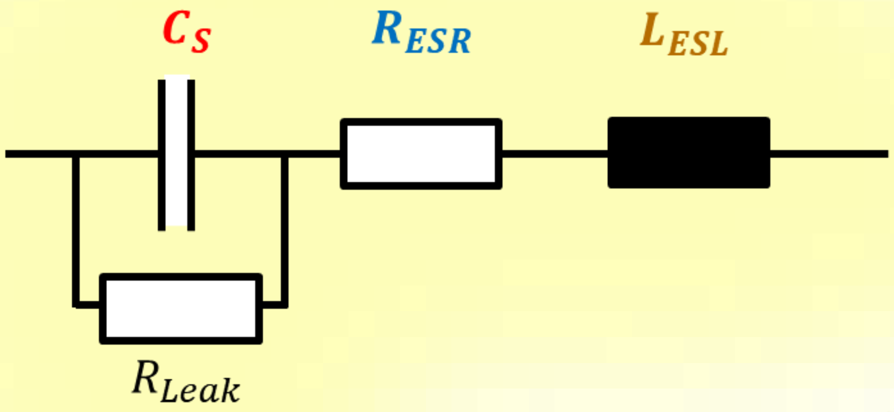
Modeling of metallized polymer films capacitor's impedance, Maawad Makdessi et al., IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society (2012)

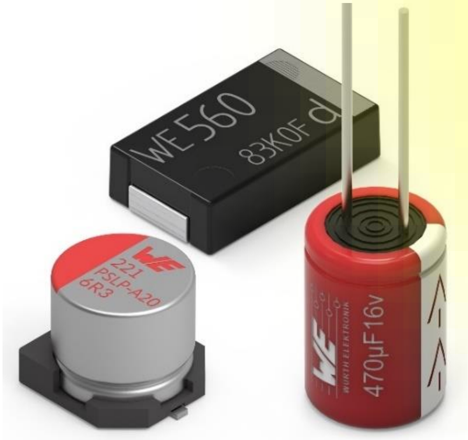
EIN ERSATZSCHALTKREIS FÜR ALLE KONDENSATOREN

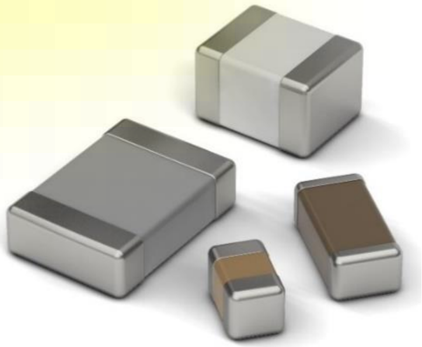
Glücklicherweise...

wir brauchen nur einen.







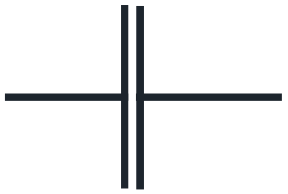


OUTLINE

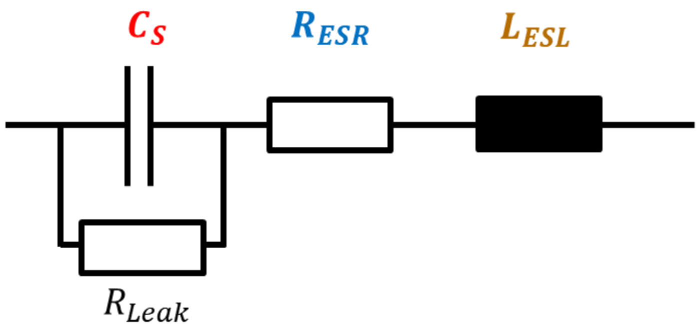
- Einführung des Modells
- Interpretation der berechneten und gemessenen
- Impedanz- und Kapazitätsspektren
  - Hochkapazitiv
  - Niedrigkapazitiv
- Genauigkeit und ESR

ERSATZSCHALTUNG VON KONDENSATOREN

Im Layout verwendetes Kondensatorzeichen:



Kondensator wie er tatsächlich modelliert ist:

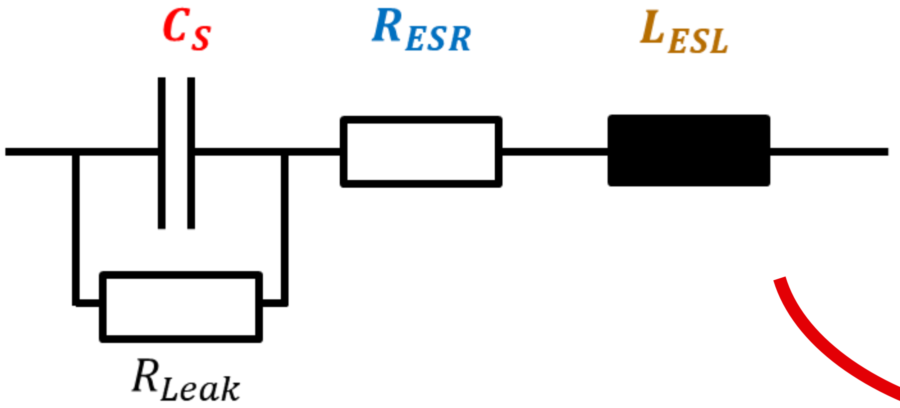


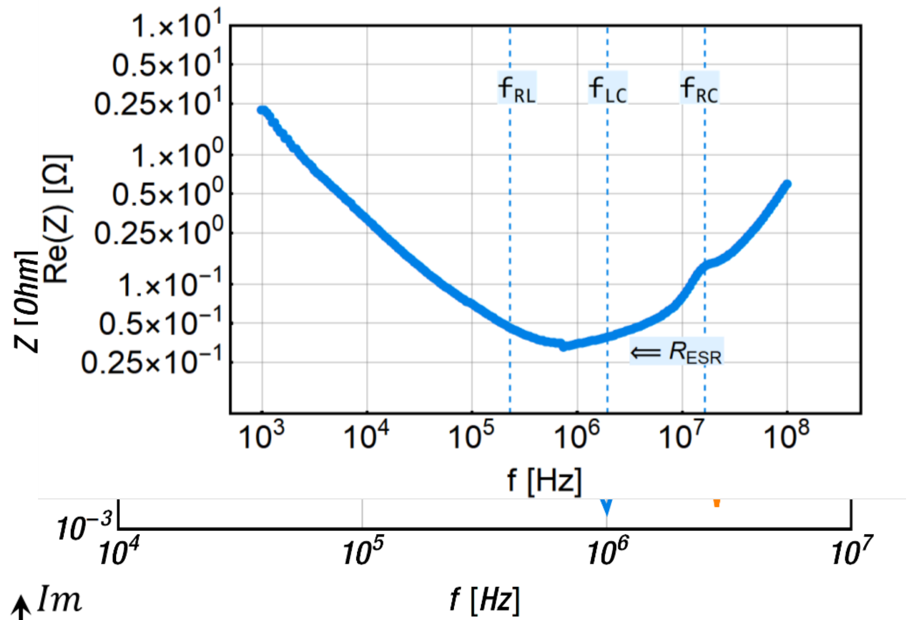
Ein Kondensator besteht aus:

- reinem Kondensator
- Widerstand und
- Induktor

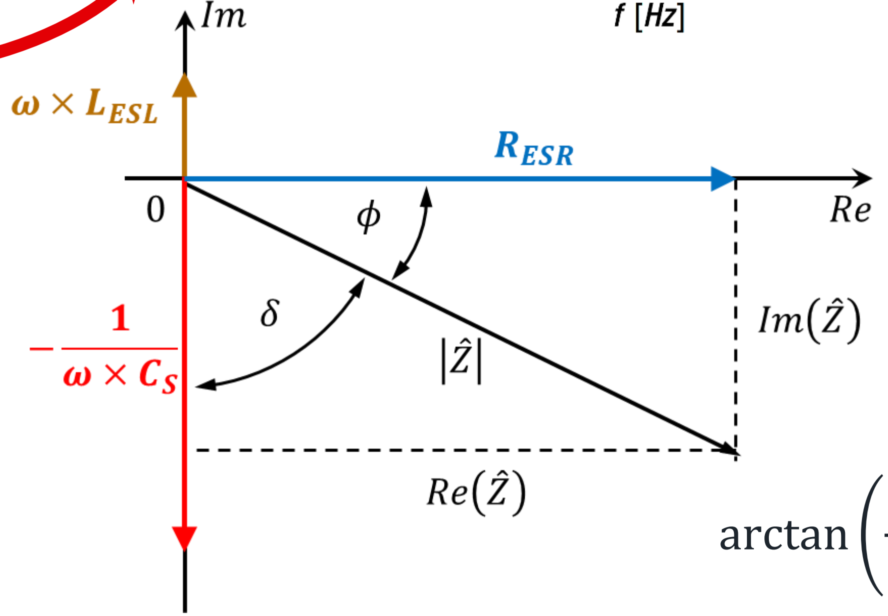
ERSATZSCHALTBILD

Darstellungen





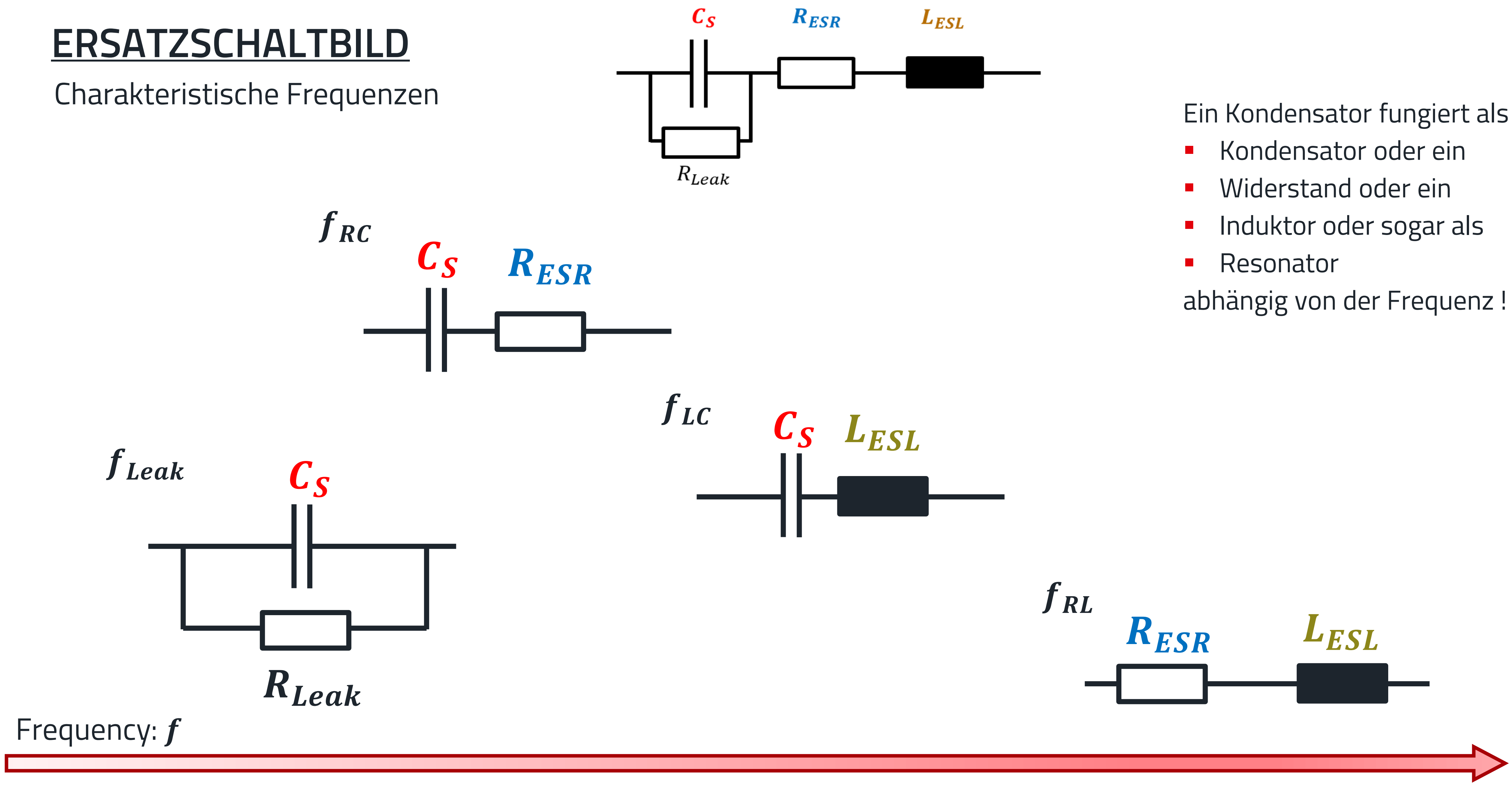
$$\hat{Z}(\omega) = \boldsymbol{R}_{\mathbf{ESR}} + i \cdot \omega \boldsymbol{L}_{\mathbf{ESL}} + \frac{\boldsymbol{R}_{\mathbf{Leak}}(i\omega \boldsymbol{C}_{\mathbf{S}})^{-1}}{\boldsymbol{R}_{\mathbf{Leak}} + (i\omega \boldsymbol{C}_{\mathbf{S}})^{-1}}$$



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

ERSATZSCHALTBILD

Charakteristische Frequenzen



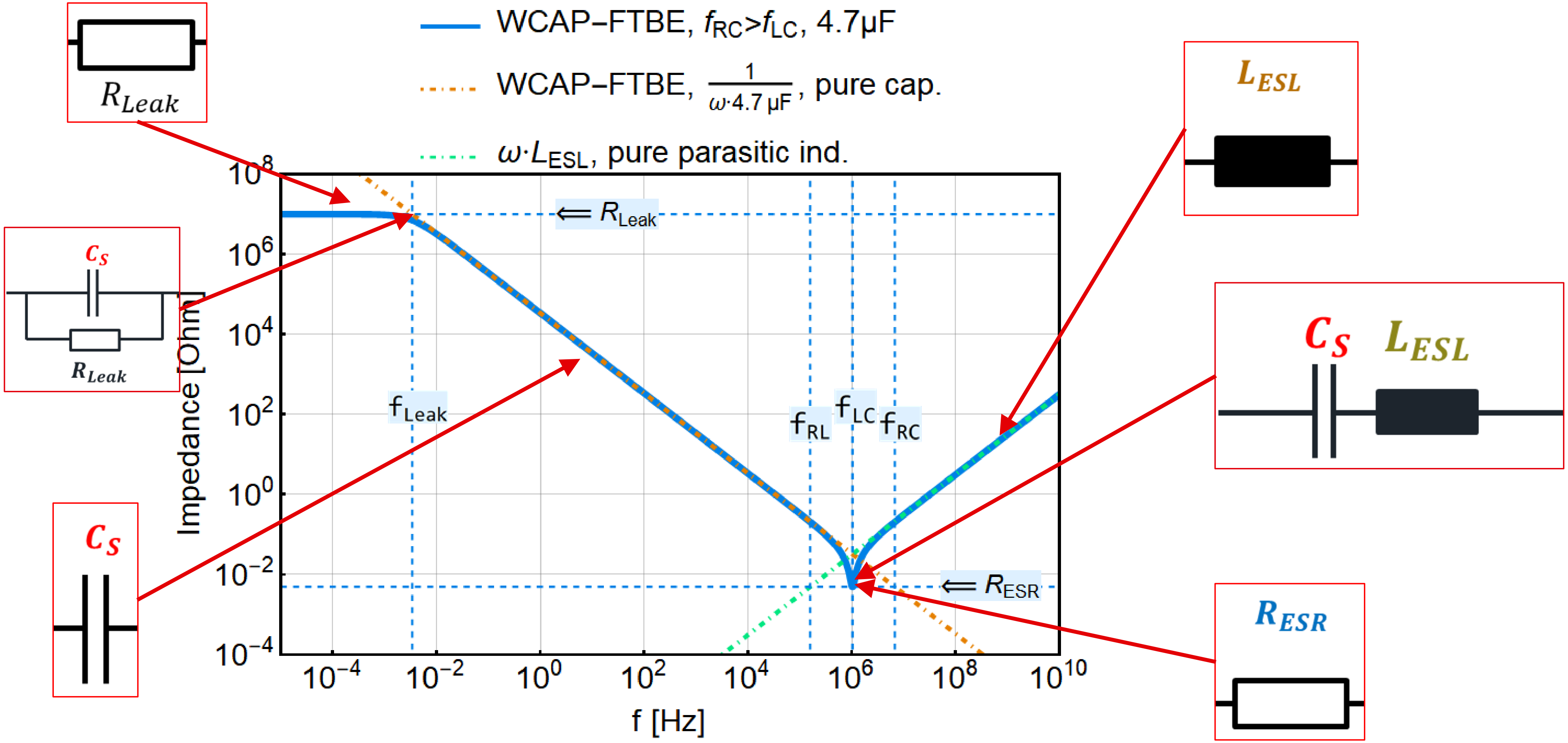
Ein Kondensator fungiert als ein

- Kondensator oder ein
- Widerstand oder ein
- Induktor oder sogar als
- Resonator

abhängig von der Frequenz !

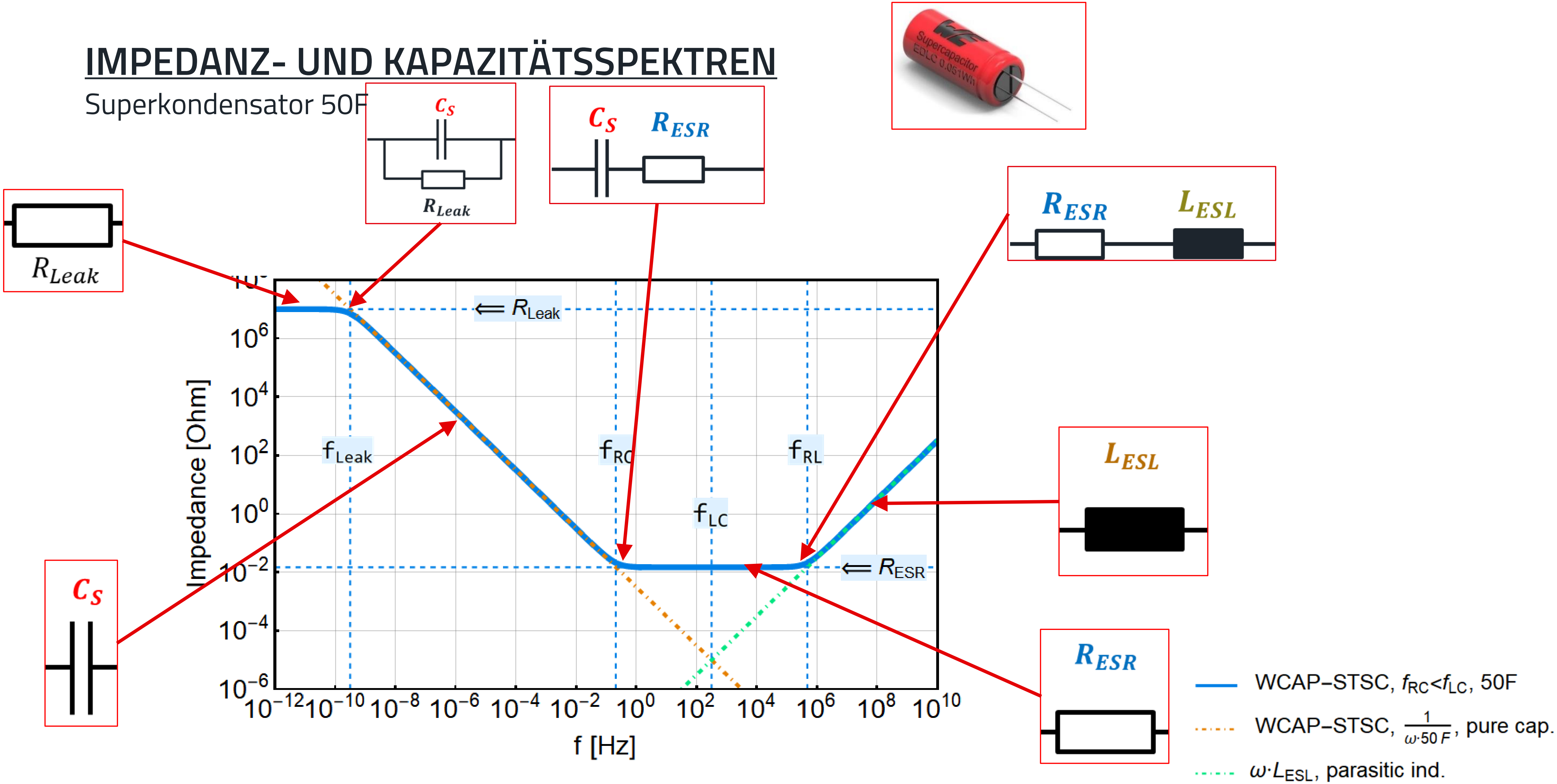
IMPEDANZ- UND KAPAZITÄTSSPEKTREN

Folienkondensatoren



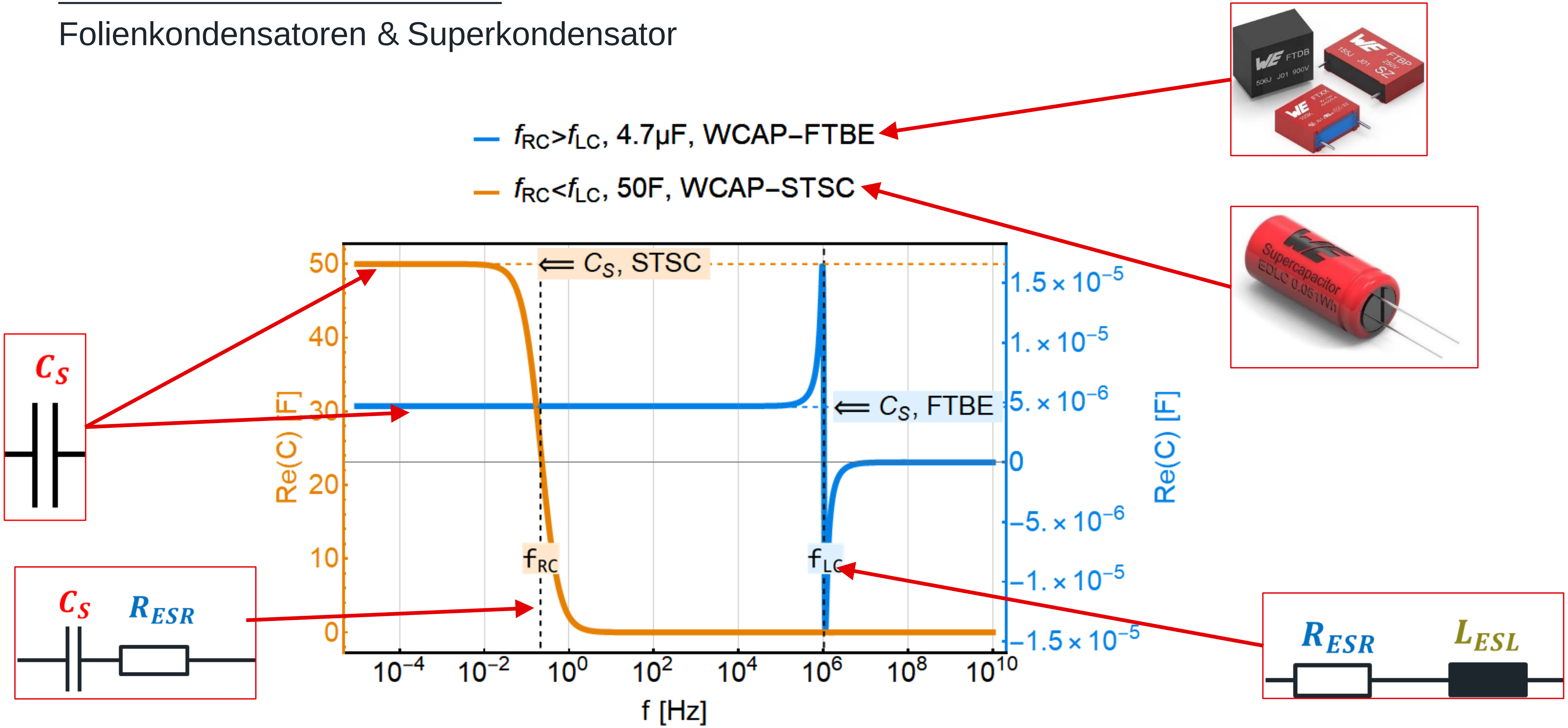
IMPEDANZ- UND KAPAZITÄTSSPEKTREN

Superkondensator 50F

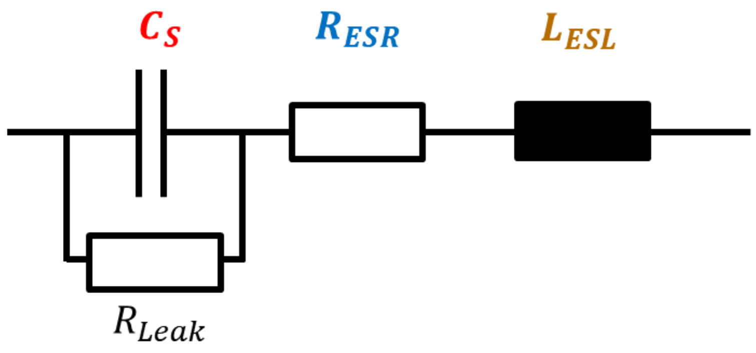


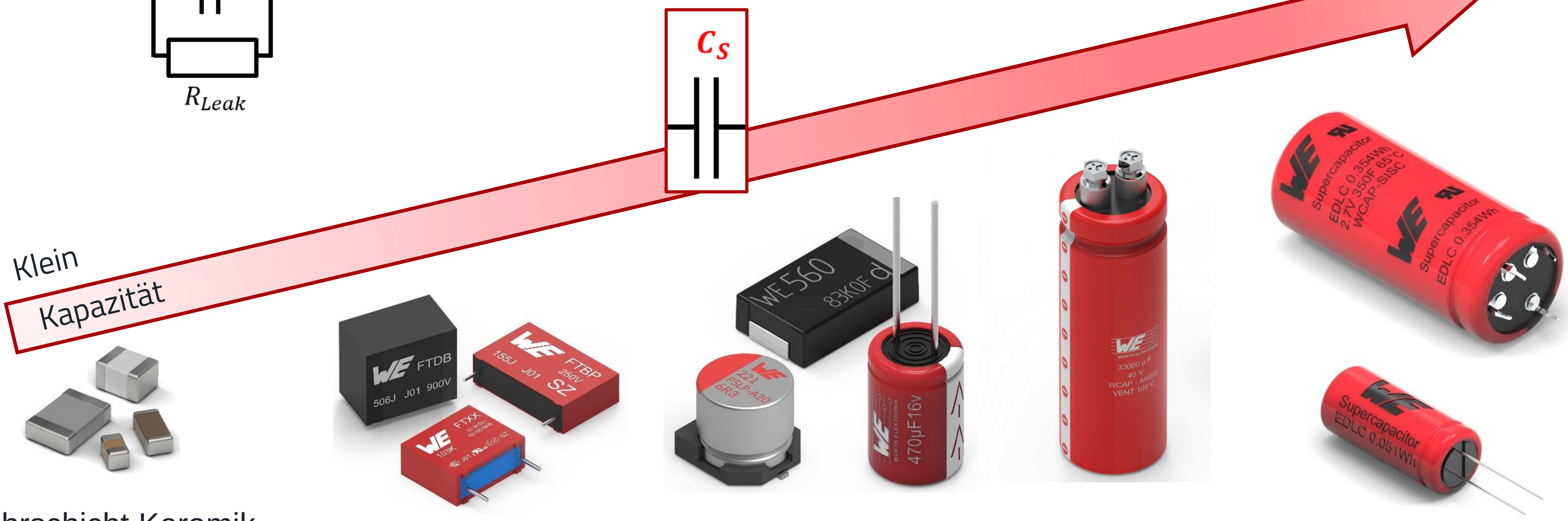
KAPAZITÄTSSPEKTREN

Folienkondensatoren & Superkondensator



ERSATZSCHALTUNG VON KONDENSATOREN





Mehrschicht Keramik

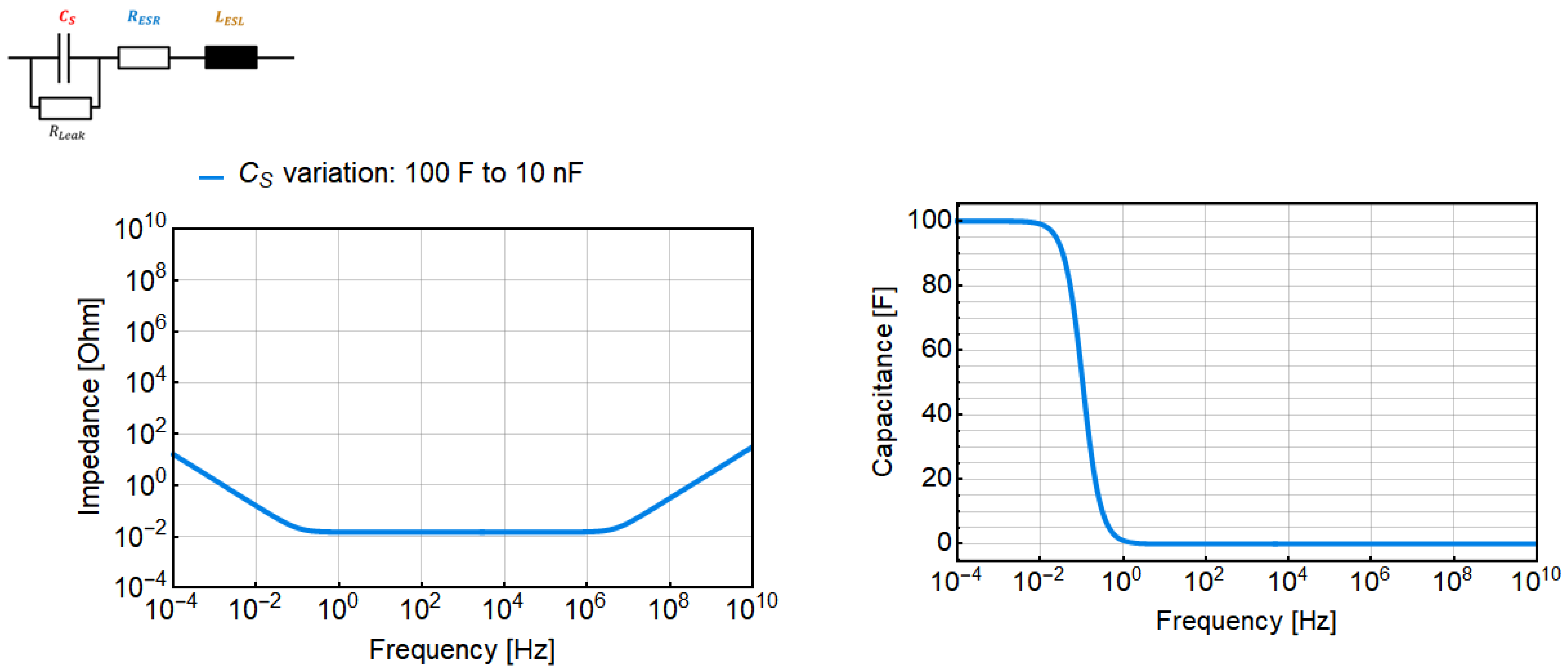
Kondensatoren

Folienkondensatoren, Elkos, Hybrids

Superkondensator

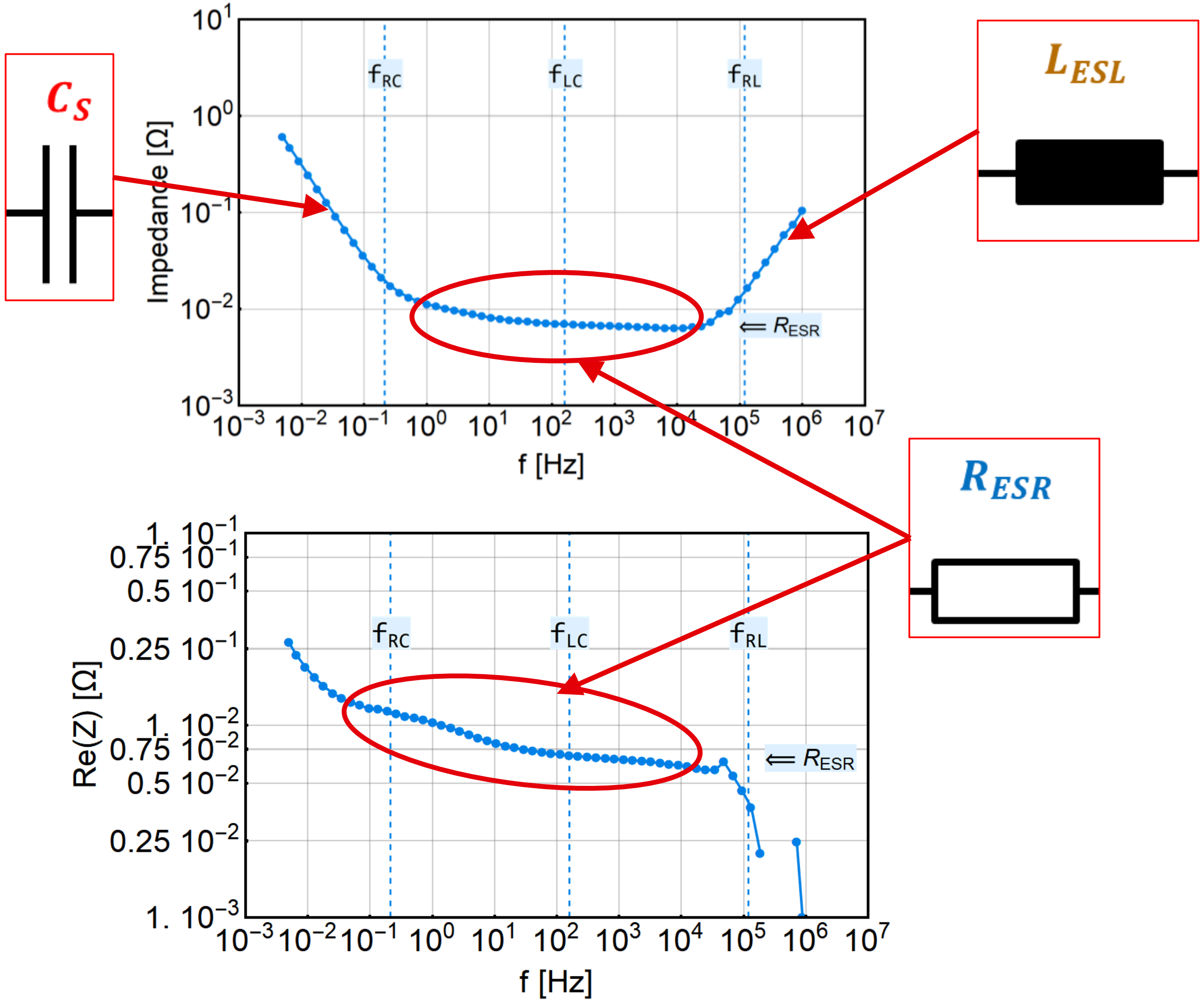
ERSATZSCHALTUNG VON KONDENSATOREN

CS



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

IMPEDANZ- UND KAPAZITÄTSSPEKTREN

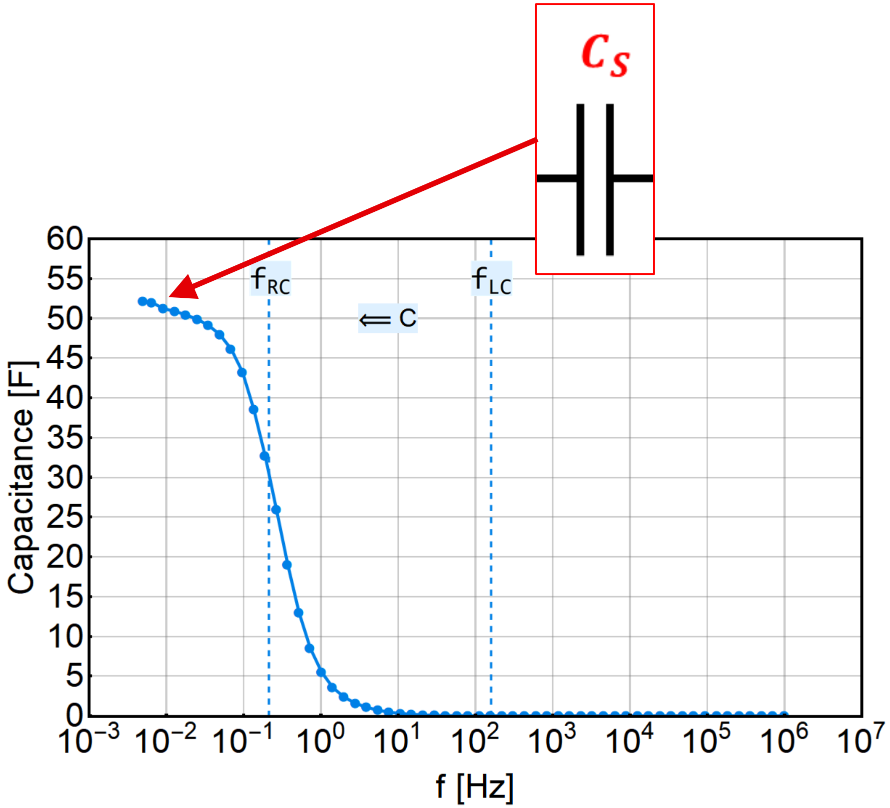


Supercapacitor 50F

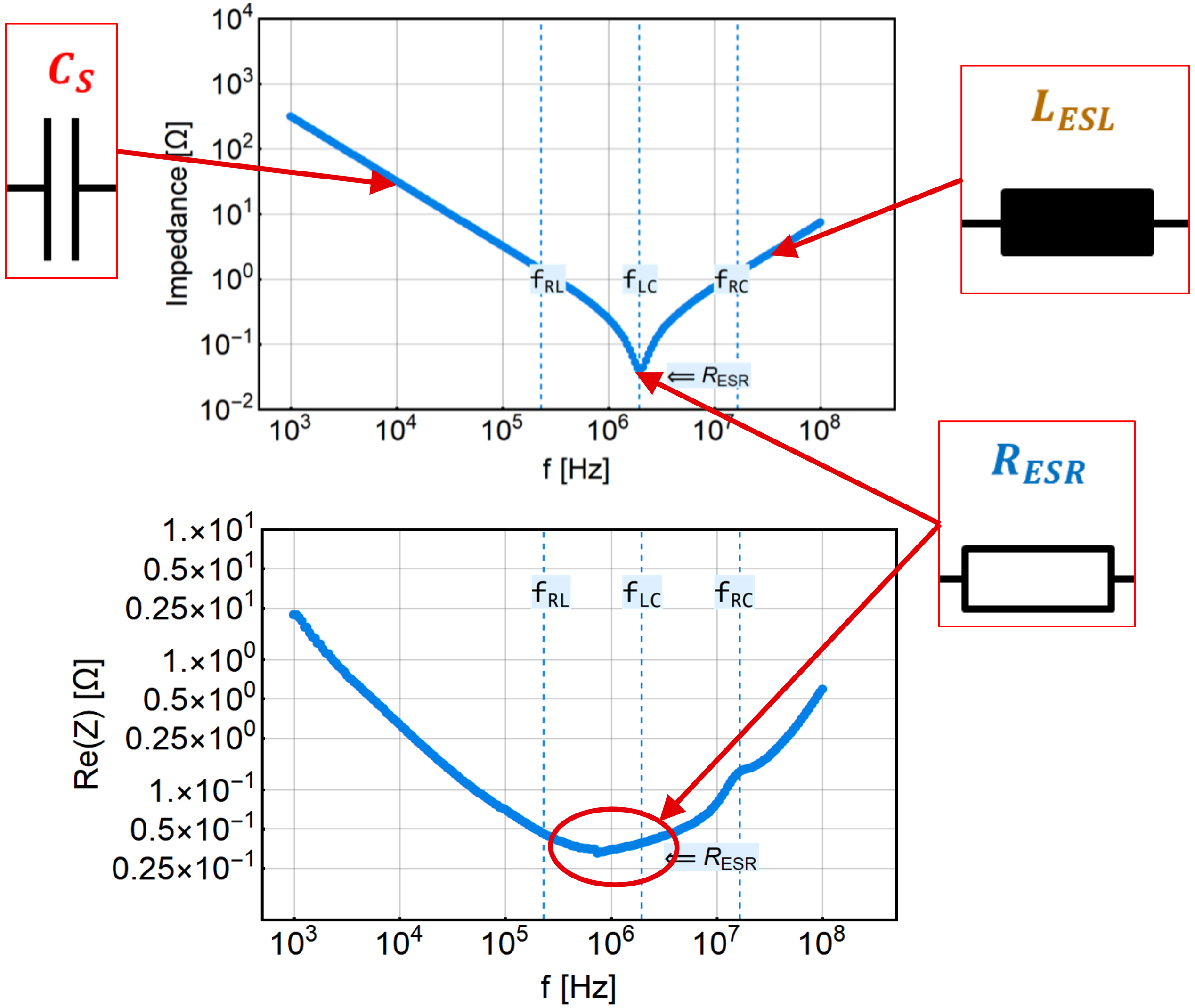
$$C_S(0.01\ Hz) = 51\ F$$

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

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

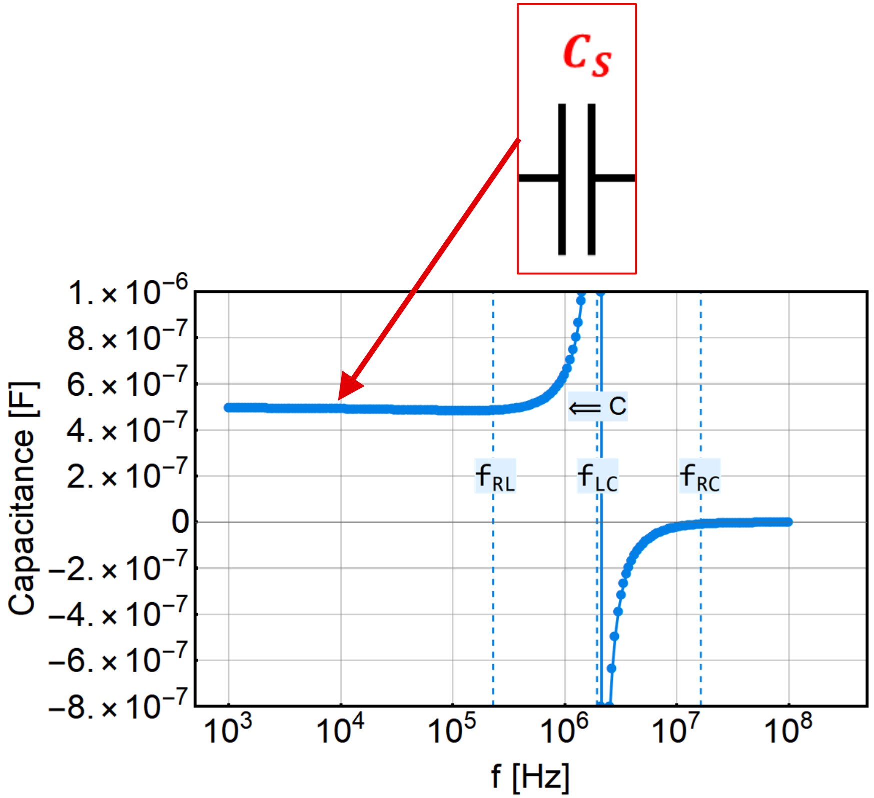


IMPEDANZ- UND KAPAZITÄTSSPEKTREN



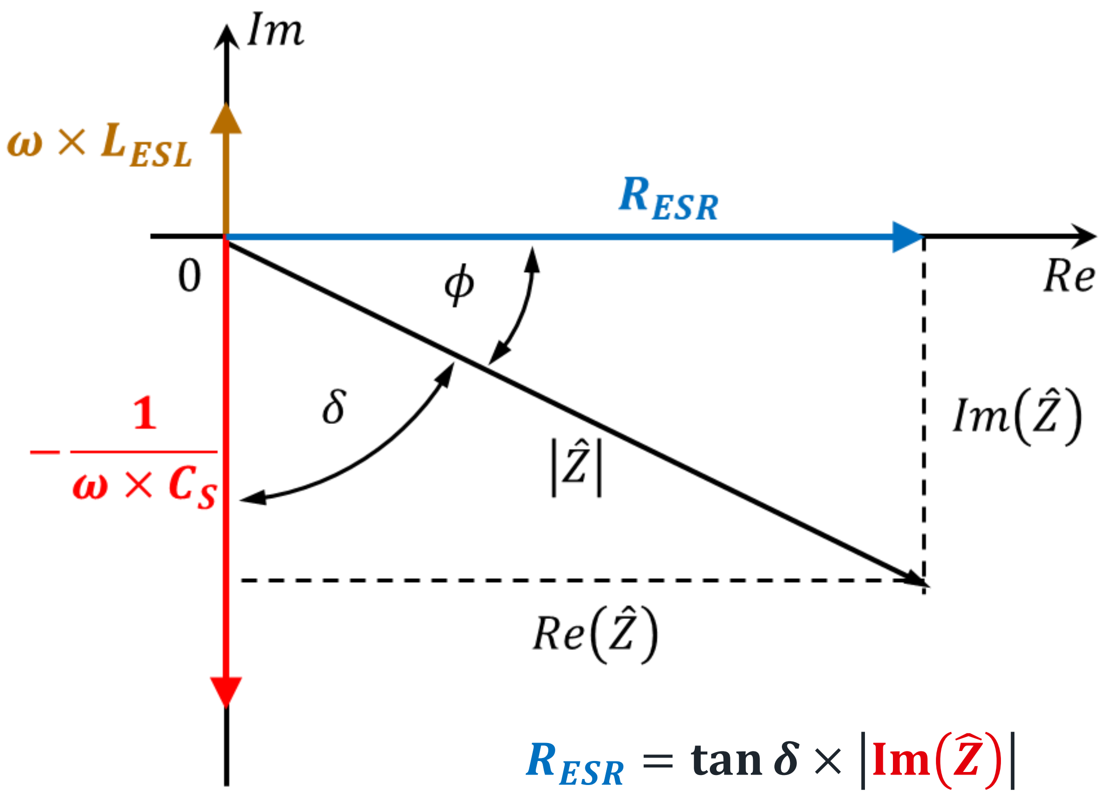
Film Capacitors

$$C_S(1\ \mathrm{kHz}) = 495\ \mathrm{nF}$$
$$R_{\mathrm{ESR}}(1\ \mathrm{kHz}) = 2.2\ \Omega$$
$$R_{\mathrm{ESR}}(f_{LC} = 1.94\ \mathrm{MHz}) = 0.04\ \Omega$$



MESSGENAUIGKEIT

Film Capacitors



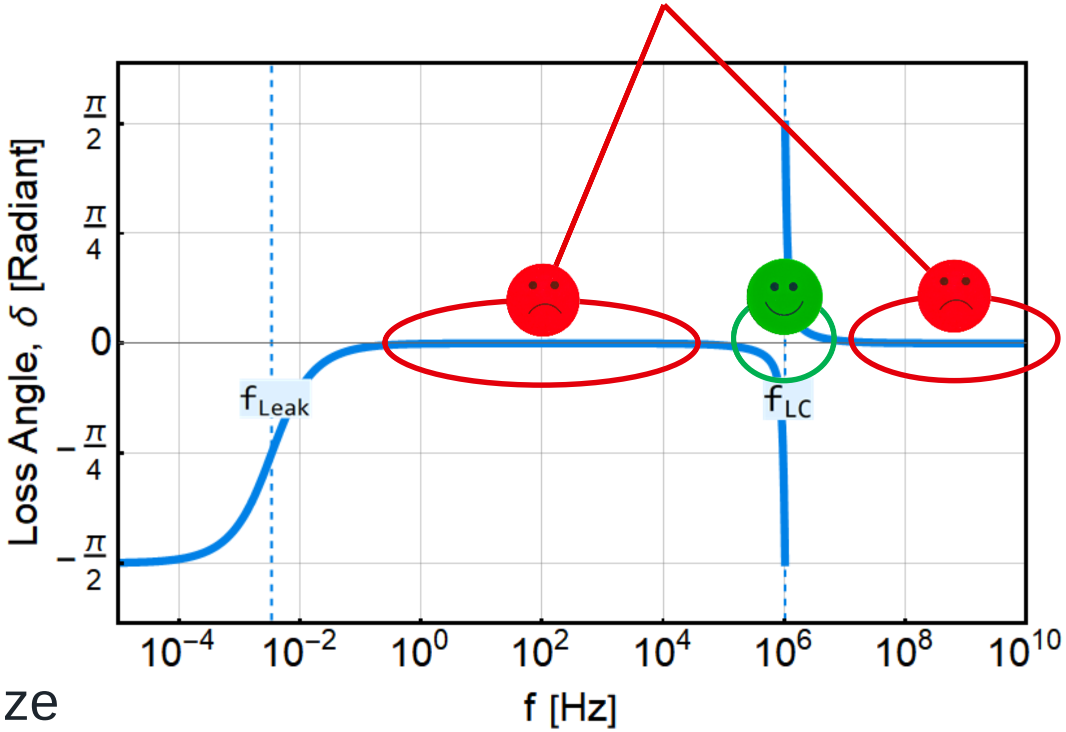
$$R_{ESR} = \tan\delta \times |\mathrm{Im}(\hat{Z})|$$

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

Auflösungsgrenze

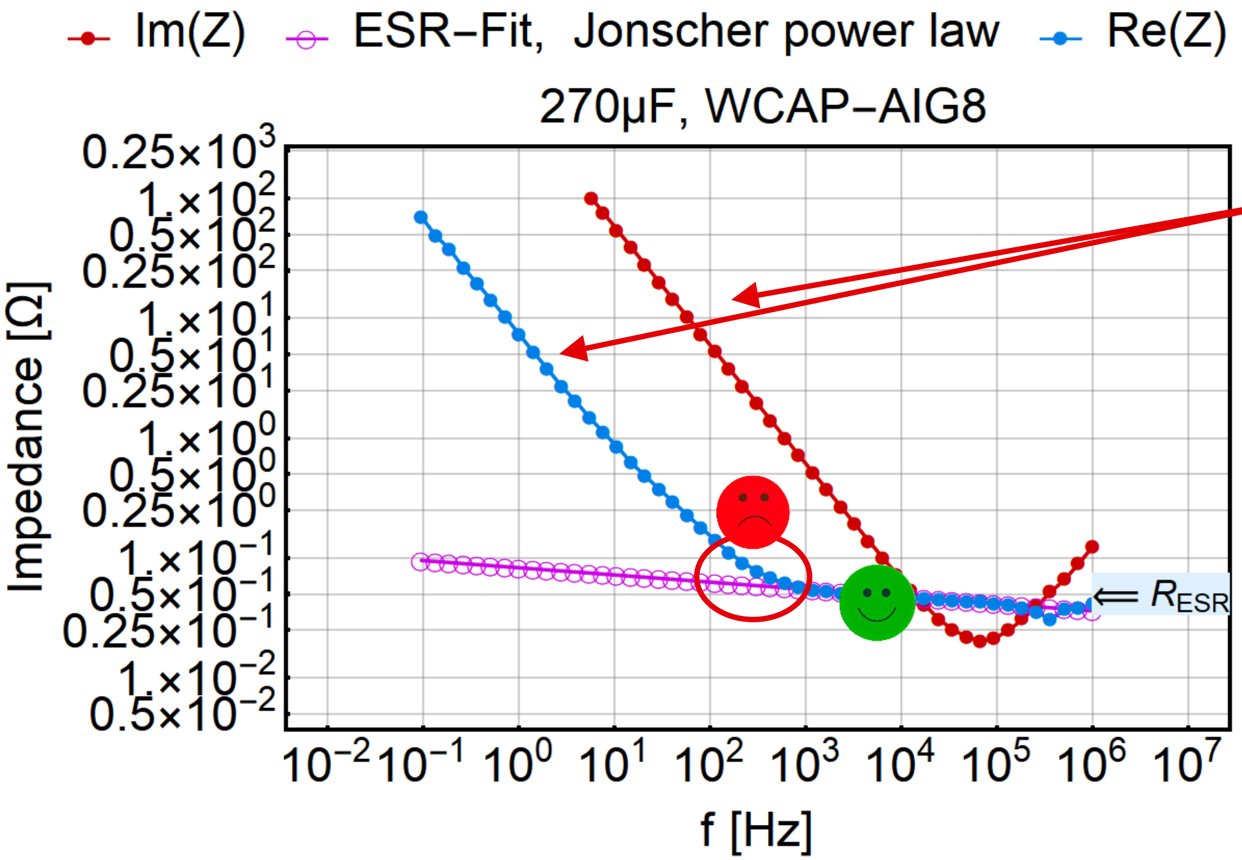
$\tan\delta \rightarrow 0$

Cannot be resolved !



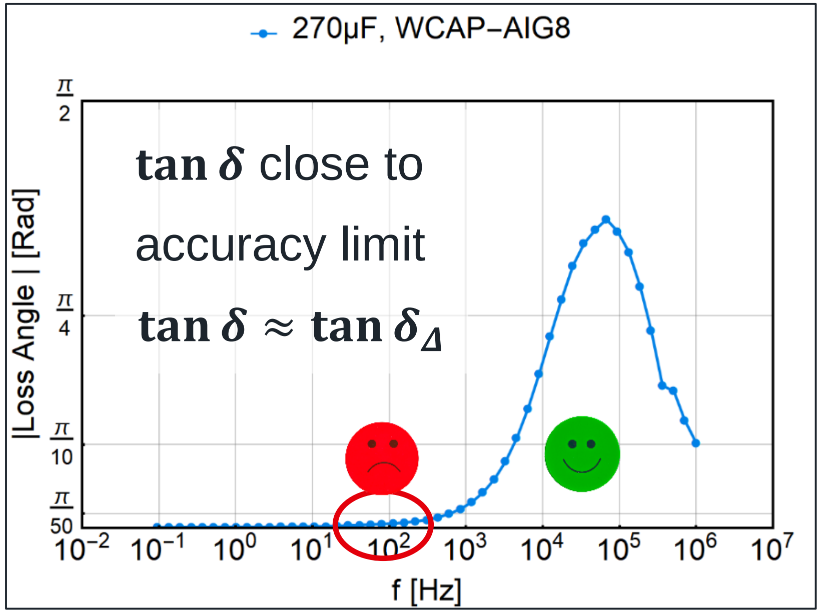
MESSGENAUIGKEIT

E-Caps



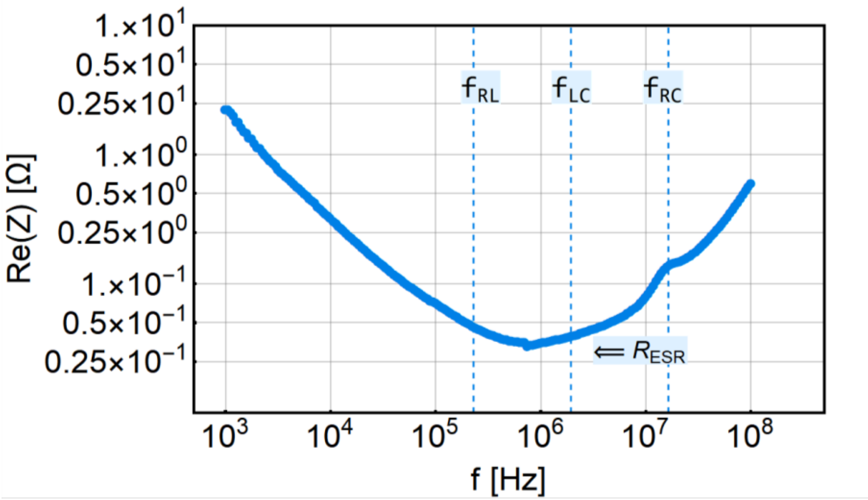
$$R_{ESR} = \tan \delta_{\Delta} \times |\mathrm{Im}(\hat{Z})|$$

- Konstanteer $\tan \delta_{\Delta}$ führt zu parallelen Kurvenverläufen im Log-Log-Plot



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)

MESSGENAUIGKEIT



Wenn $\left|Im(\hat{Z})\right|$ ansteigt, so auch der $\boldsymbol{R_{ESR}}$, scheint es!

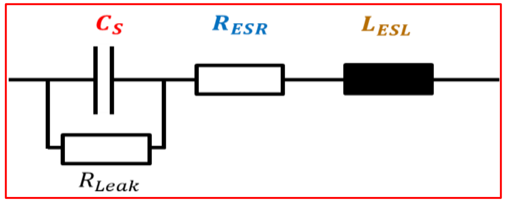
Nimmt $\boldsymbol{R_{ESR}}$ tasächlich zu?

Schwer zu sagen, denn…

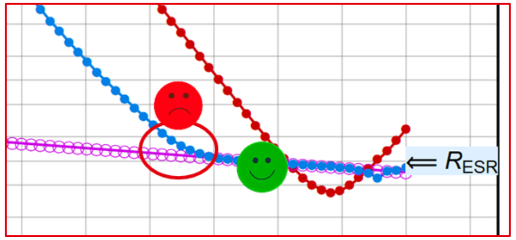
$\mathbf{tan}\ \boldsymbol{\delta}$ kann nicht mehr genau gemessen werden.

$\boldsymbol{R_{ESR}}$ is wahrscheinlich **deutlich überschätzt**!

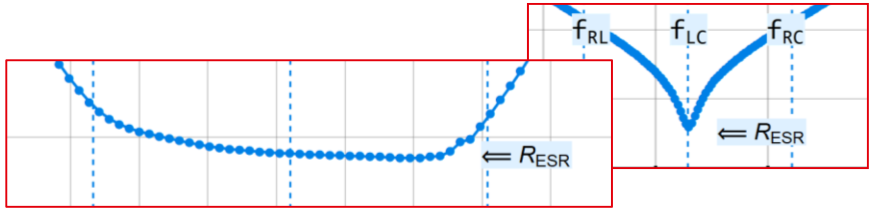
ZUSAMMENFASSUNG



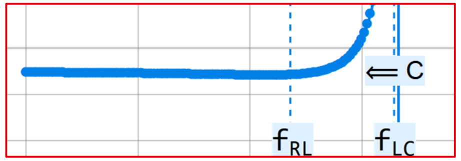
- Nur ein Modell ausreichend: beschreibt alle wichtigen Merkmale von Impedanzspektren



- Die Verlustwinkelauflösung begrenzt ESR-Messungen
  - Steiler Anstieg des ESR weist auf Auflösungsgrenze hin



- ESR-Werte am Minimum entnehmen



- Kapazität wird bei niedrigen Frequenzen gemessen.

Fragen & Antworten

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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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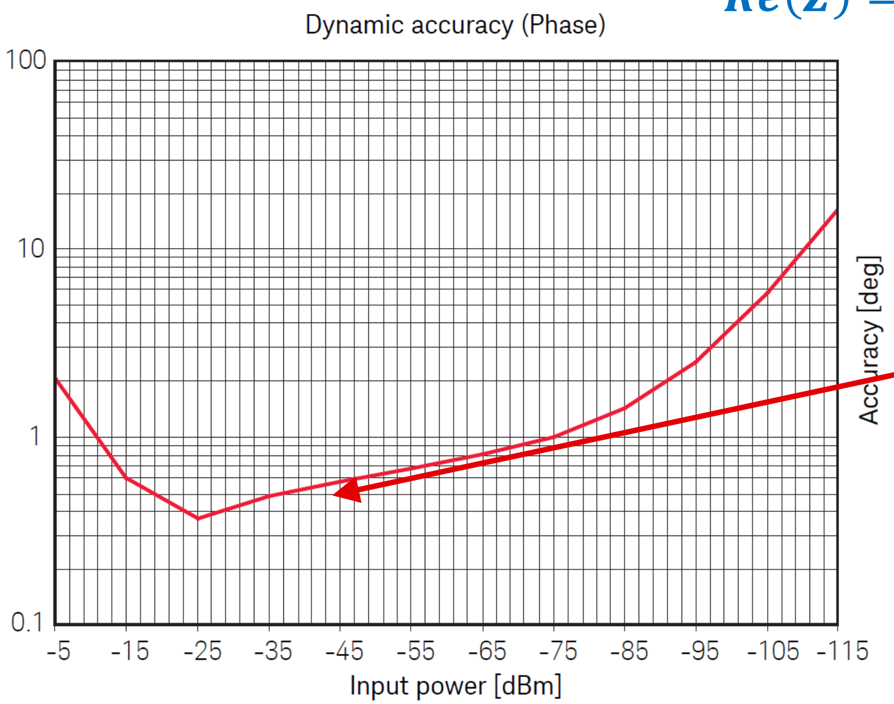
Dr. René Kalbitz studied physics at the University of Potsdam and at the University of Southampton (GB). After completing his diploma degree, he gained is PhD in the field of organic semiconductors and insulators at the University of Potsdam. He was able to gain further experience in the field of applied 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]

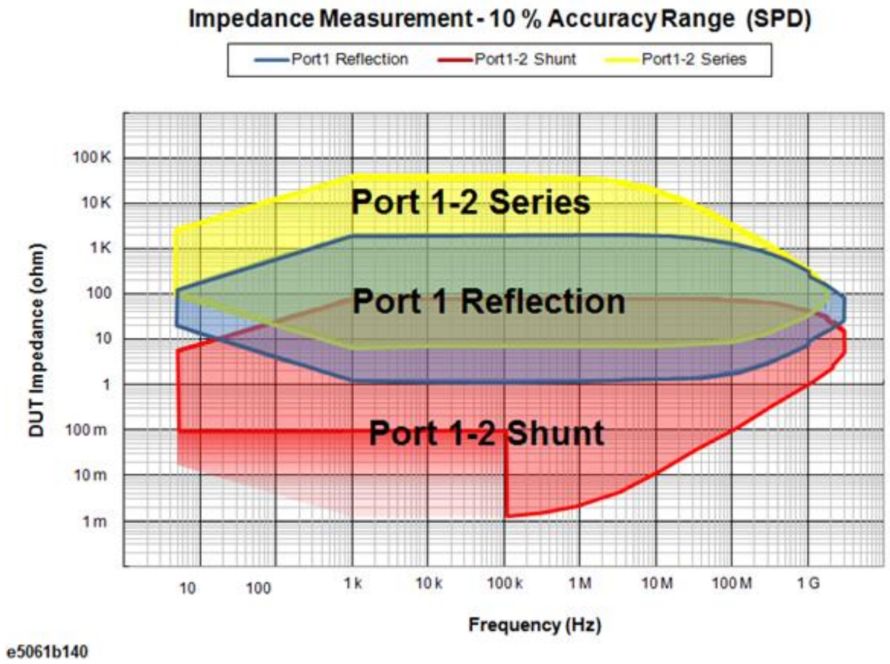
IMPEDANCE AND CAPACITANCE SPECTRA

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

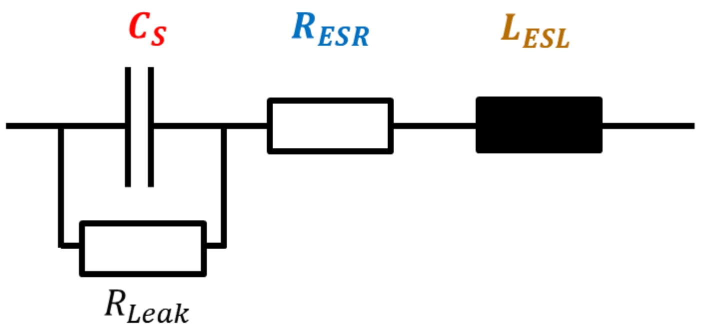


δ_Δ accuracy limit

Measured δ cannot be smaller than δ_Δ



EQUIVALENT CIRCUIT OF CAPACITORS



Characteristic Frequencies:

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

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

- $L_{ESL} - C$

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

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

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

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

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

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

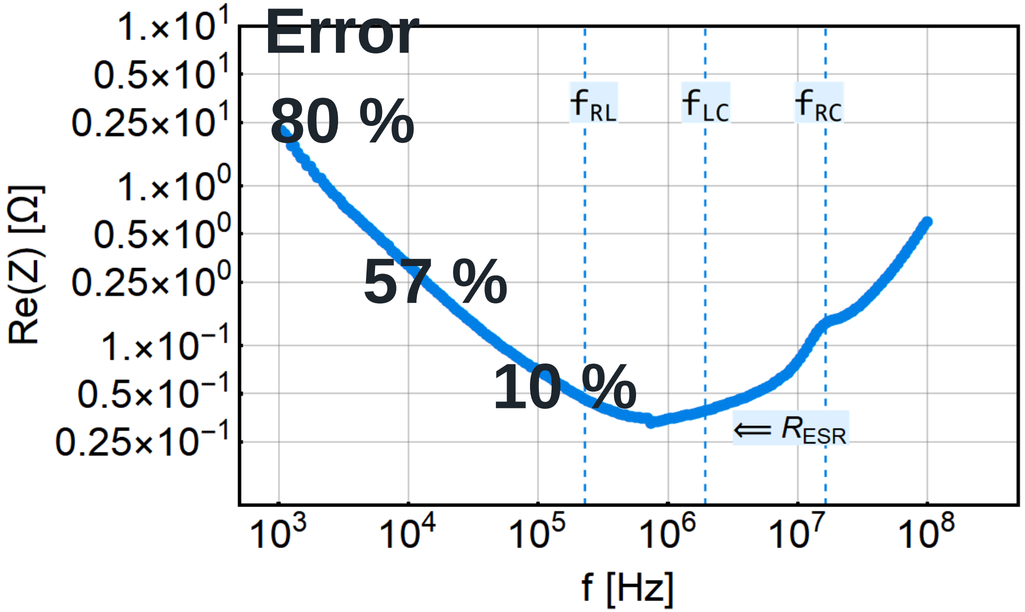
above f_{RL}: Reactance X_L dominates

$\rightarrow$ L_{ESL}can be extracted

IMPEDANCE AND CAPACITANCE SPECTRA

$C_S = 4.7\ \mathrm{nF}$

Parameter	Value	Value	Value
f_e in kHz	**450**	**10**	**1**
$\mathrm{Im}(\hat{Z})$ in Ω	0.75	33.86	338.63
$\mathrm{Re}(\hat{Z})$ 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**



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