DIGITAL WE DAYS 2024

FUNDAMENTALS OF CAPACITOR TECHNOLOGY AND THEIR APPLICATIONS

Lukas Hölscher

WÜRTH ELEKTRONIK
MORE THAN
YOU EXPECT

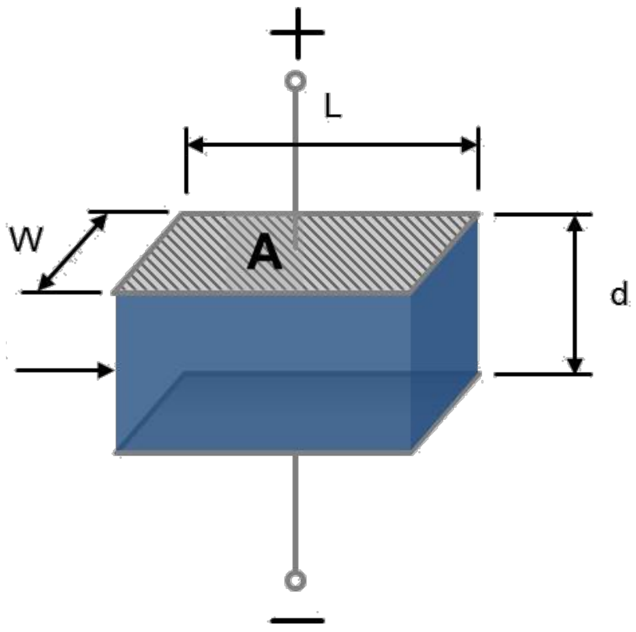
AGENDA

- Technical Basics & Overview
- Technologies
  - MLCC
  - Film Capacitors
  - Aluminum Capacitors
  - Supercapacitors
- Summary
- Questions

BASICS OF CAPACITORS

Overview & Basics of Capacitors

- Construction of a plate Capacitor



$$C = \varepsilon * \frac{A}{d} = \varepsilon_0 * \varepsilon_r * \frac{A}{d}$$

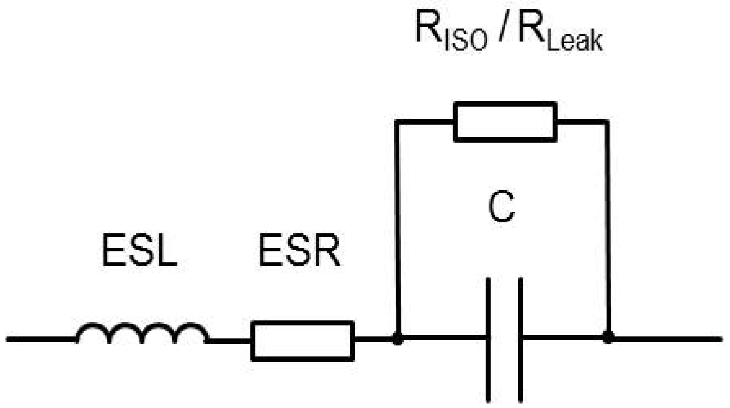
C – Capacitance [F]
A – plate surface
d – plate distance
ε_0- absolute Permittivity
ε_R- relative Permittivity

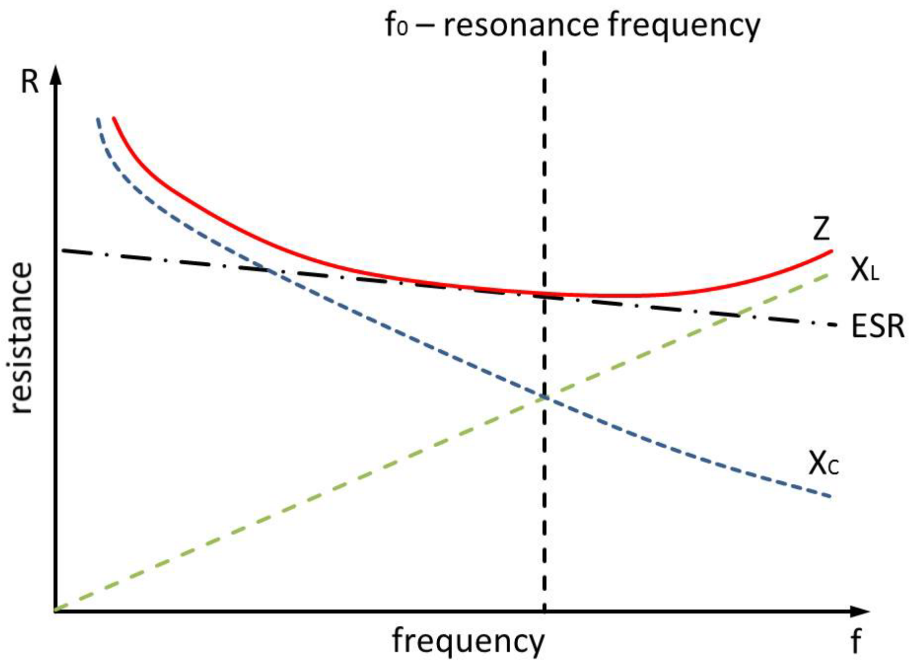
Material	relative Permittivity – (ε_R) (typical values @20°C)
Vaacum	1
Air	1,00059
Paper	1,6...2
Paraffin paper	2
Polystyrene	2,3
Polypropylene	2,5
Polyethylene	2,5 ...4,5
Glass	5
Aluminumoxide	9,3
Tantalumpentoxide	26
Niobiumpentoxide	42
Ceramic Class 1	10...500
Ceramic Class 2	700...>100000

BASICS OF CAPACITORS

Equivalent circuit

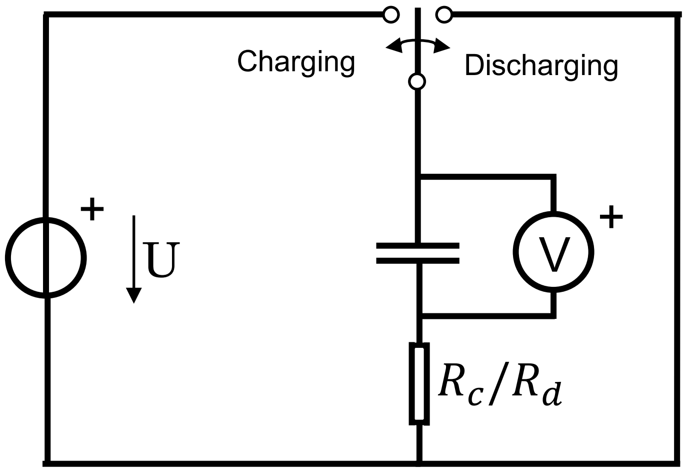
- Every passive component has parasitic side effects next to its main functions





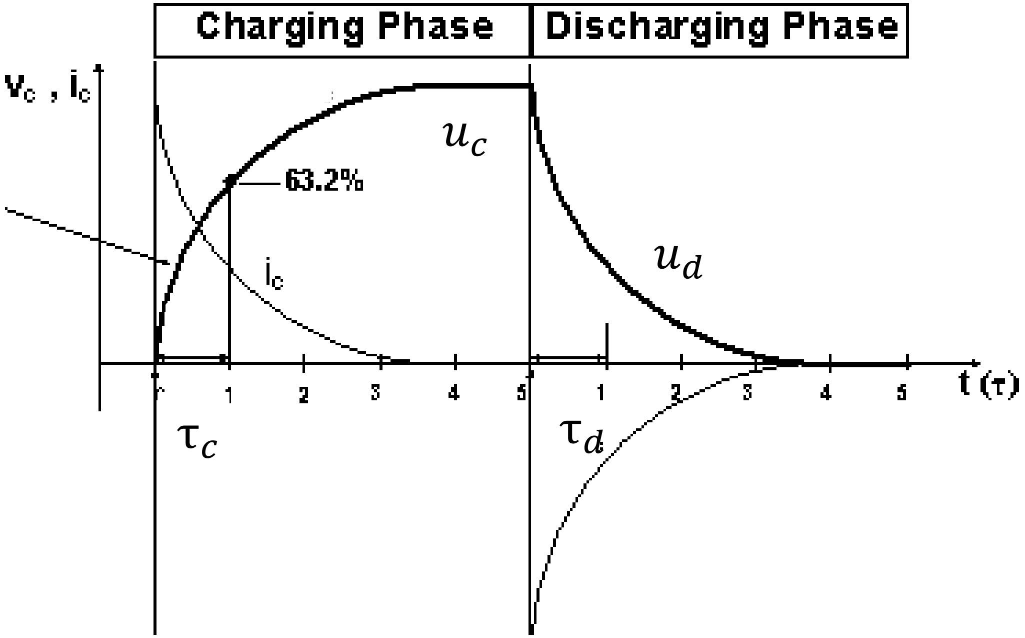
BASICS OF CAPACITORS

Charging / Discharging of a Capacitor



Charging Phase
V_c versus τ_c

τ_c	Magnitude (V)
0	0%
1 τ_c	63.2%
2 τ_c	86.5%
3 τ_c	95%
4 τ_c	98.2%
5 τ_c	100%



Charging:

$$\tau_c = R_c \cdot C$$

$$u_c = U(1 - e^{\frac{-t}{\tau_c}})$$

$$i_c = \frac{Ue^{-\frac{t}{\tau_c}}}{R_c}$$

Discharging:

$$\tau_d = R_d \cdot C$$

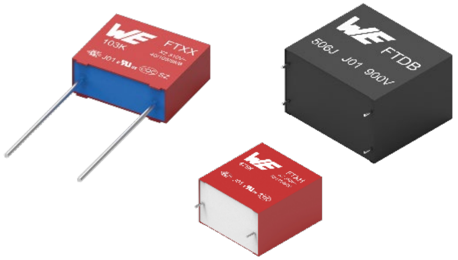
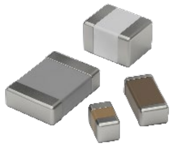
$$u_d = U \cdot e^{\frac{-t}{\tau_d}}$$

$$i_E = -\frac{Ue^{\frac{-t}{\tau_d}}}{R_d}$$

BASICS OF CAPACITORS

Capacitor Types

- **Capacitor Types**
  - **fixed capacitance**
    - Film Capacitor
      - Paper Film Capacitor
      - Plastic Film Capacitor
    - Ceramic Capacitor
      - Class 1
      - Class 2
    - Electrolytic Capacitor (E-Caps)
      - Aluminum Electrolytic Capacitor
      - Tantalum Electrolytic Capacitor
      - Niobium Electrolytic Capacitor
    - Super Capacitor
      - Electric Double Layer Capacitor
      - Pseudo Capacitor
      - Hybrid Capacitor
    - Mica Capacitor
    - Glass Capacitor
    - Feedthrough Capacitor
  - **variable capacitance**
    - Rotary Capacitor
    - Trimming Capacitor

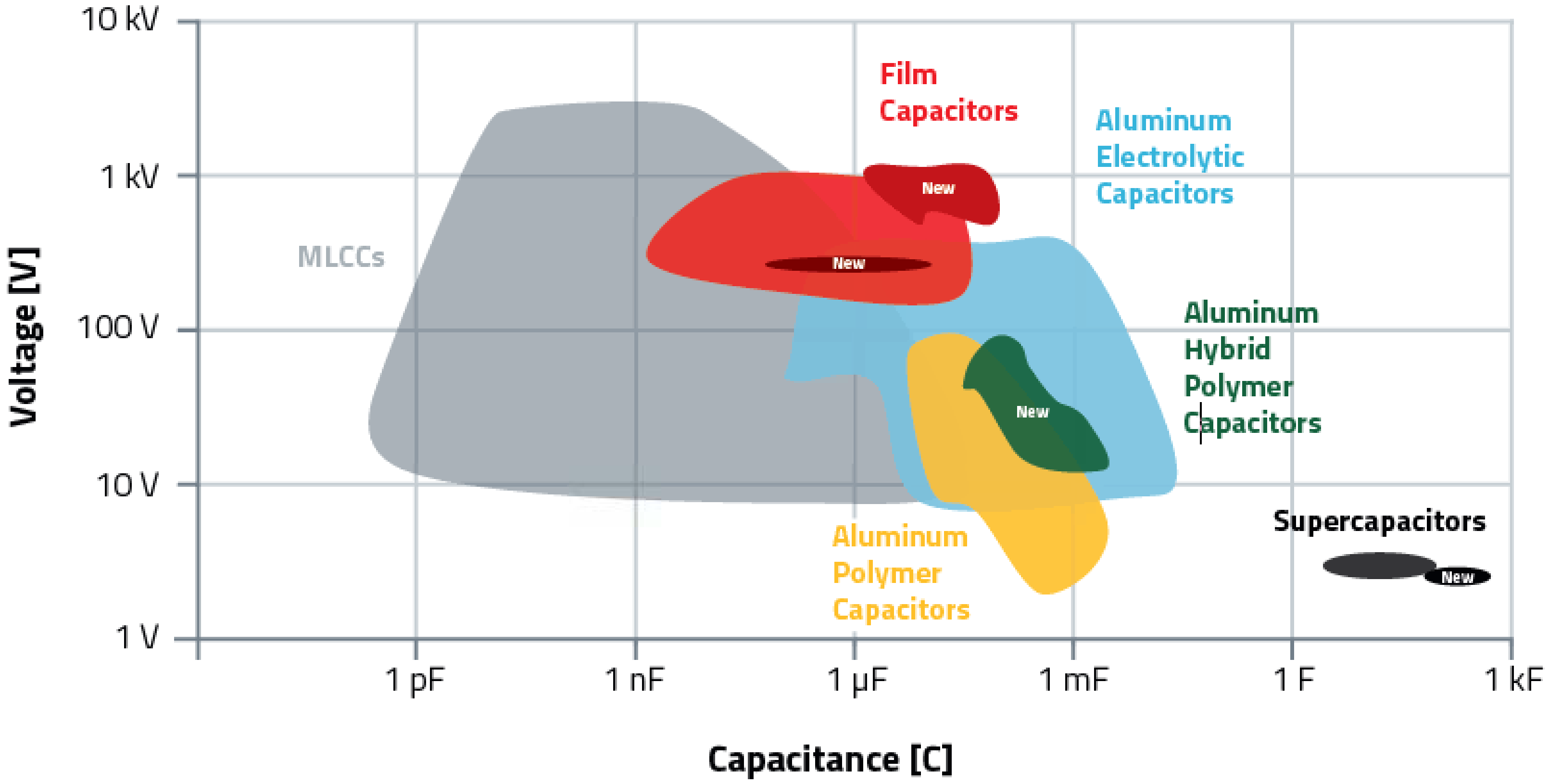



BASICS OF CAPACITORS

Technology	Max. Capacitance	Max. Voltage	Max. Current	Max. Temperature range	Application examples
Aluminum Electrolytic Capacitors	> 1F	ca. 650 V	ca. 0,05 A/µF	85 °C up to 150 °C	smoothing, storage, DC-Link
Aluminum Polymer Capacitors	> 4 mF	ca. 250 V	Ca. 0,1 A/µF	85 °C up to 150 °C	smoothing, filtering
Al. Hybrid Polymer Capacitors	> 1 mF	ca. 400 V	Ca. 0,1 A/µF	85 °C up to 150 °C	smoothing, filtering, DC Link
Film Capacitors	> 8 mF	ca. 3 kV	ca. 1 A/µF	max. 110 °C	DC Link, interference suppression, filtering
MLCC	> 100 µF	ca. 10 kV	ca. 10 A/µF	85 °C up to200 °C	interference suppression, coupling, filtering
Supercapacitors	> 350 F	ca. 3.3 V	ca. 0,21 A/F	65° up to 85 °C	UPS, storage

BASICS OF CAPACITORS

Overview of technologies



New Series of Supercapacitors:

- Snap-In; WCAP-SISC

New Series of Film Capacitors:

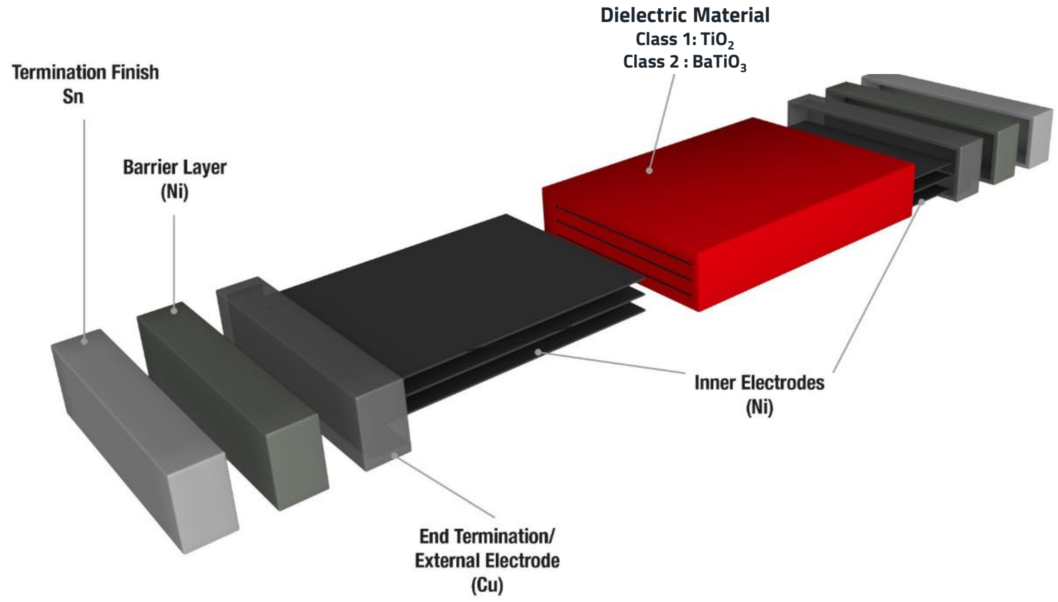
- DC-Link; WCAP-FTDB
- THB Class X2; WCAP-FTXH

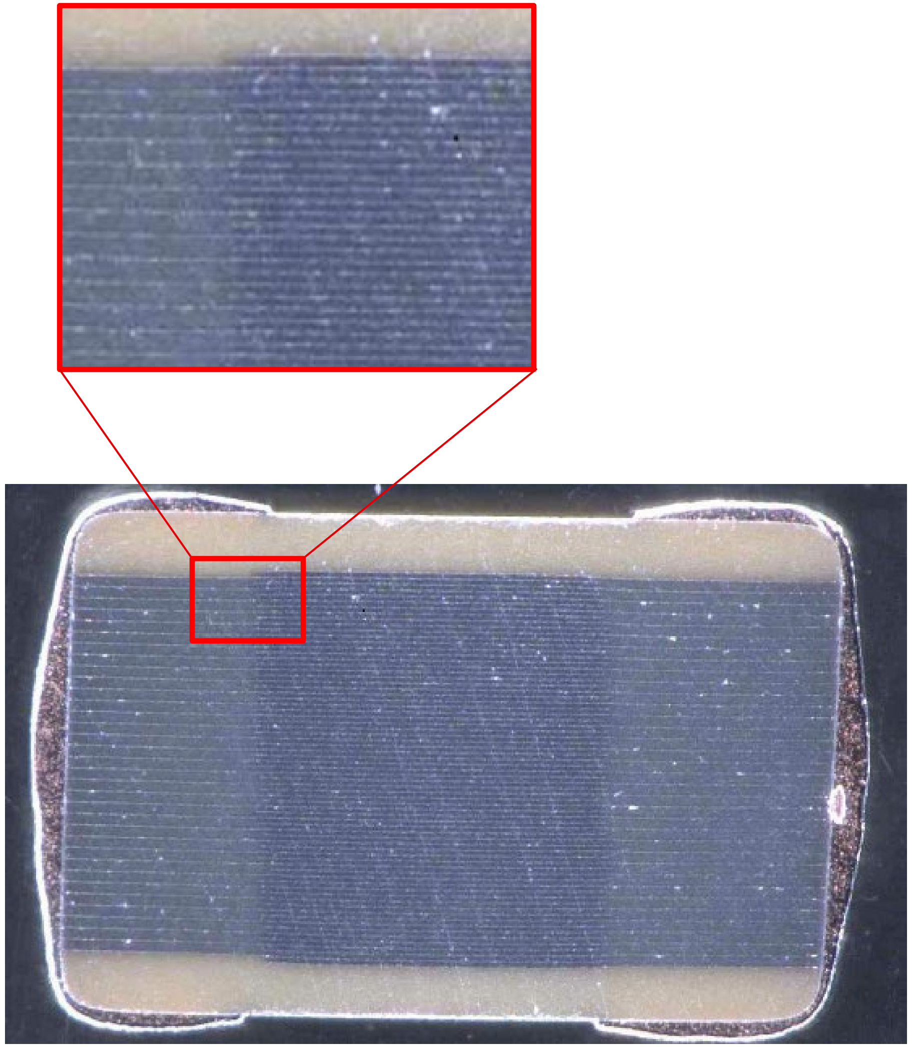
New Series of Aluminum Hybrid Polymer Capacitors:

- Radial THT; WCAP-HTG5, WCAP-HTAH, V-Chip SMT; WCAP-HSG5, WCAP-HSAH

MLCC (MULTILAYER CERAMIC CAPACITOR)

Composition of general purpose MLCCs



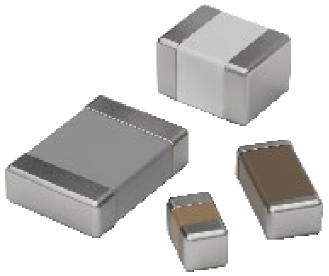


Example cross section of a general purpose MLCC

MLCC (MULTILAYER CERAMIC CAPACITOR)

Class 1 and Class 2 MLCCs

- **Class 1 Ceramic** – (e.g. NP0 / C0G → Titandioxid TiO_2, paraelektrisch)
  - Relative small Permitivity ε_r >> small capcitance values possible (ca. 100 nF)
  - linear temperature dependency
  - Next to no aging
  - Very small voltage dependency
  - Suitable for high frequency applications

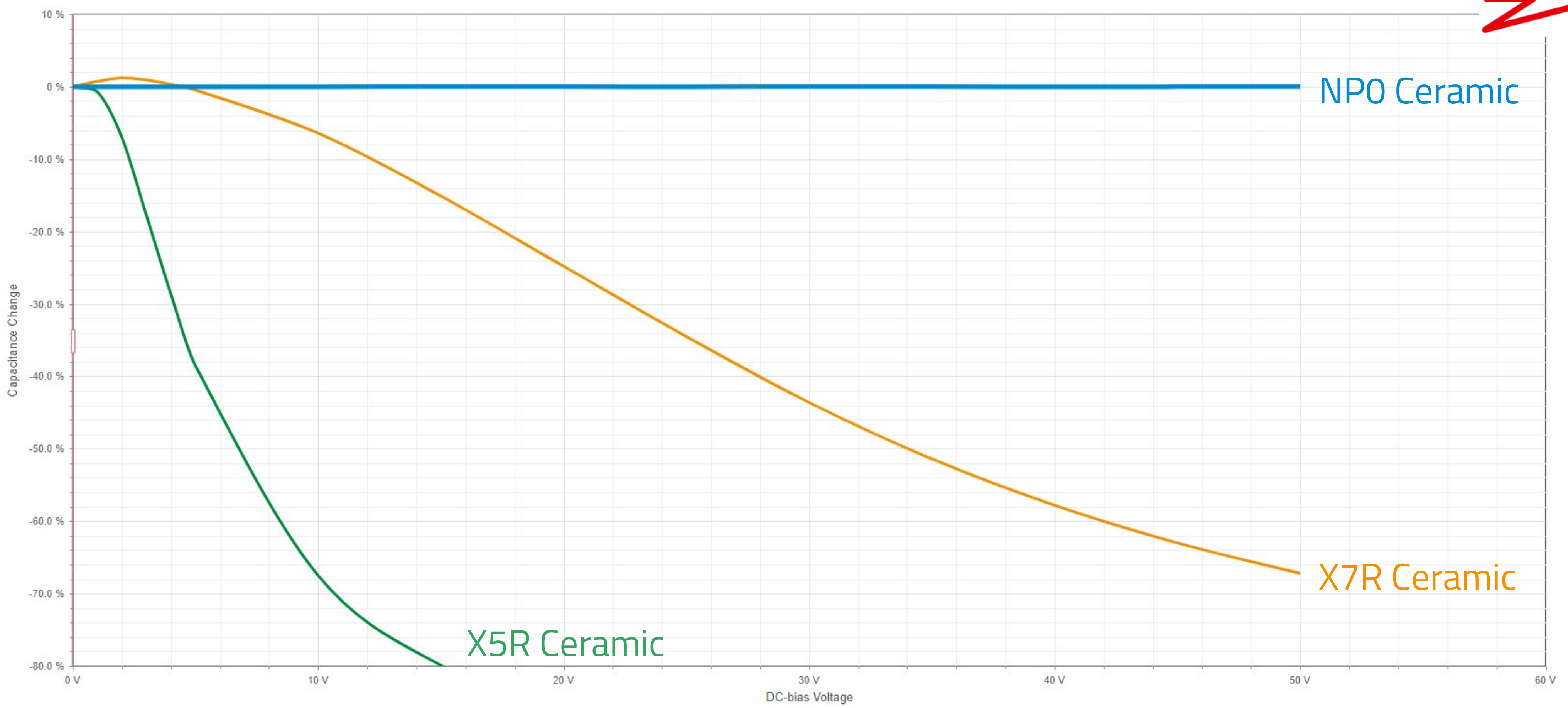


- **Class 2 Ceramic** – (e.g. X7R, X5R, Y5V, … → Bariumtitanate $BaTiO_3$, ferroelectric)
  - Relative high Permitivity ε_r → High capacitance values available(>300 µF)
  - Nonlineare temperatur dependency
  - Aging
  - High Voltage depency in many cases

MLCC (MULTILAYER CERAMIC CAPACITOR)

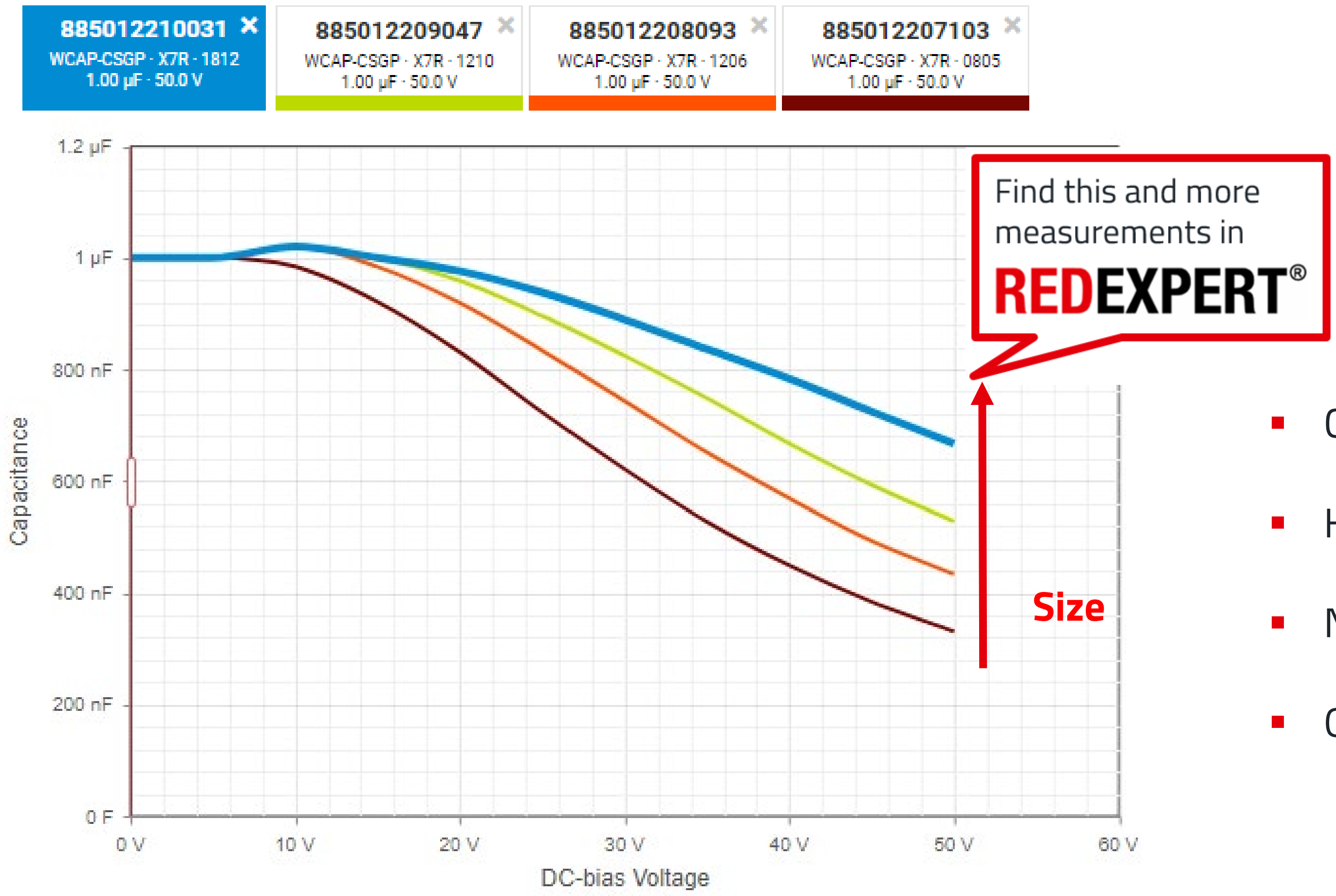
Voltage Dependancy of the capacitance Value (DC-Bias)

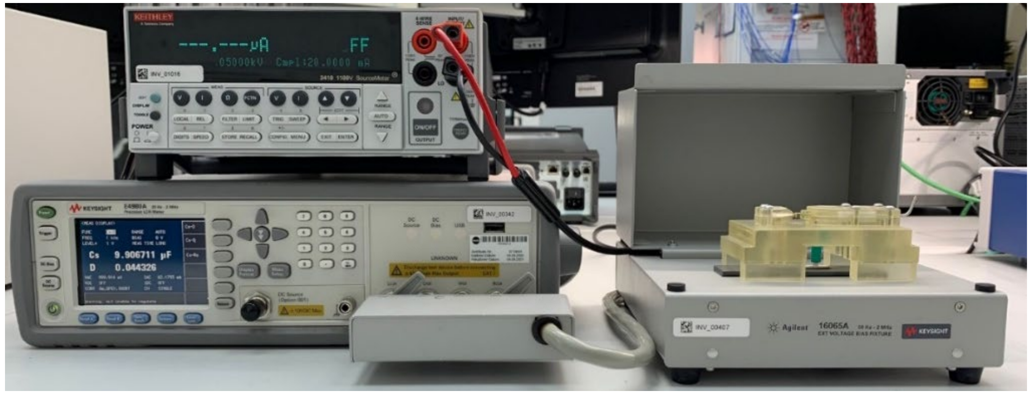
Find this and more measurements in REDEXPERT®



MLCC (MULTILAYER CERAMIC CAPACITOR)

Voltage Dependancy of the capacitance Value (DC-Bias)



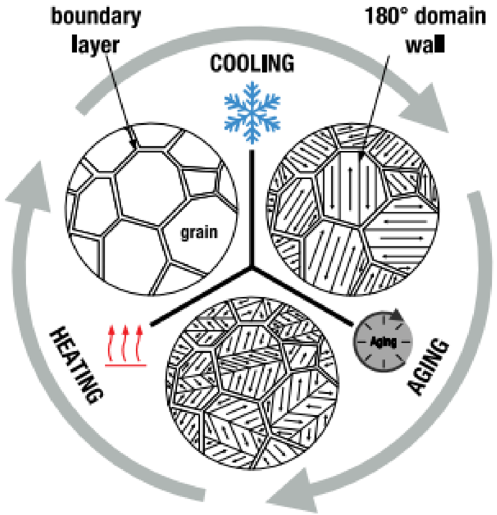


- Capacitance drop affects only Class II Ceramic Capacitors
- Heavily dependent on size
- No specification on the datasheet!
- Only reference curves or simulation models

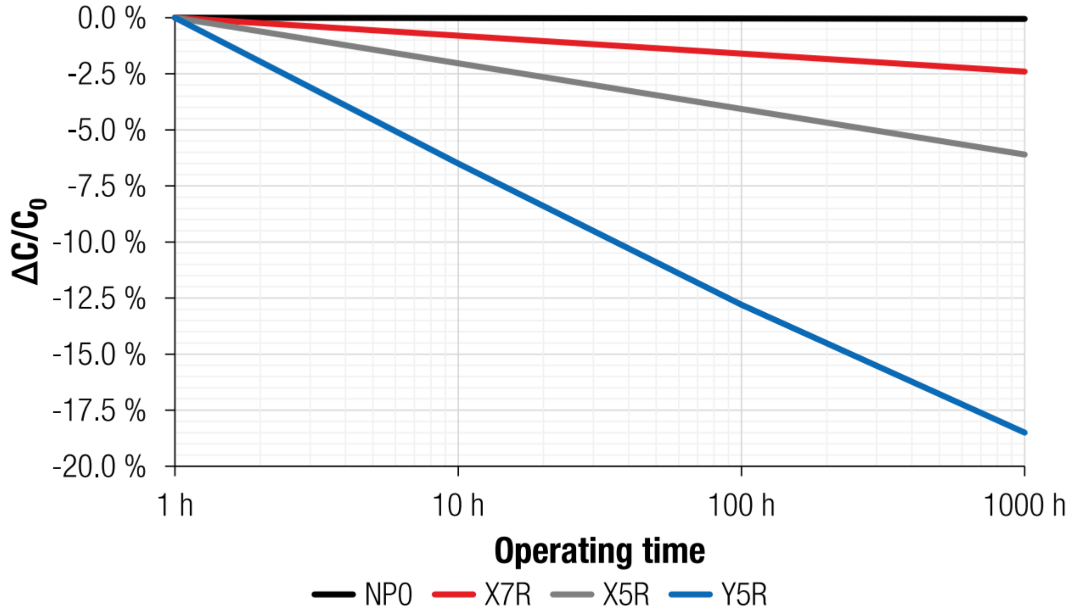
MLCC (MULTILAYER CERAMIC CAPACITOR)

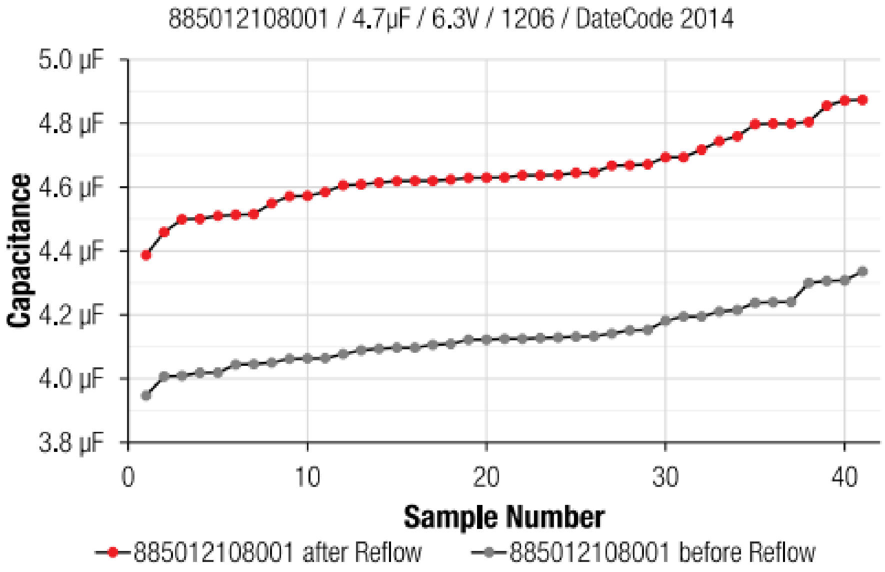
Aging of MLCCs

- Aging process due to changes in crystal structure
- Decreased permittivity cause capacitance loss
- Class 1 (NP0) no aging
- Class 2 has different aging
- Behavior depends on ceramic materials



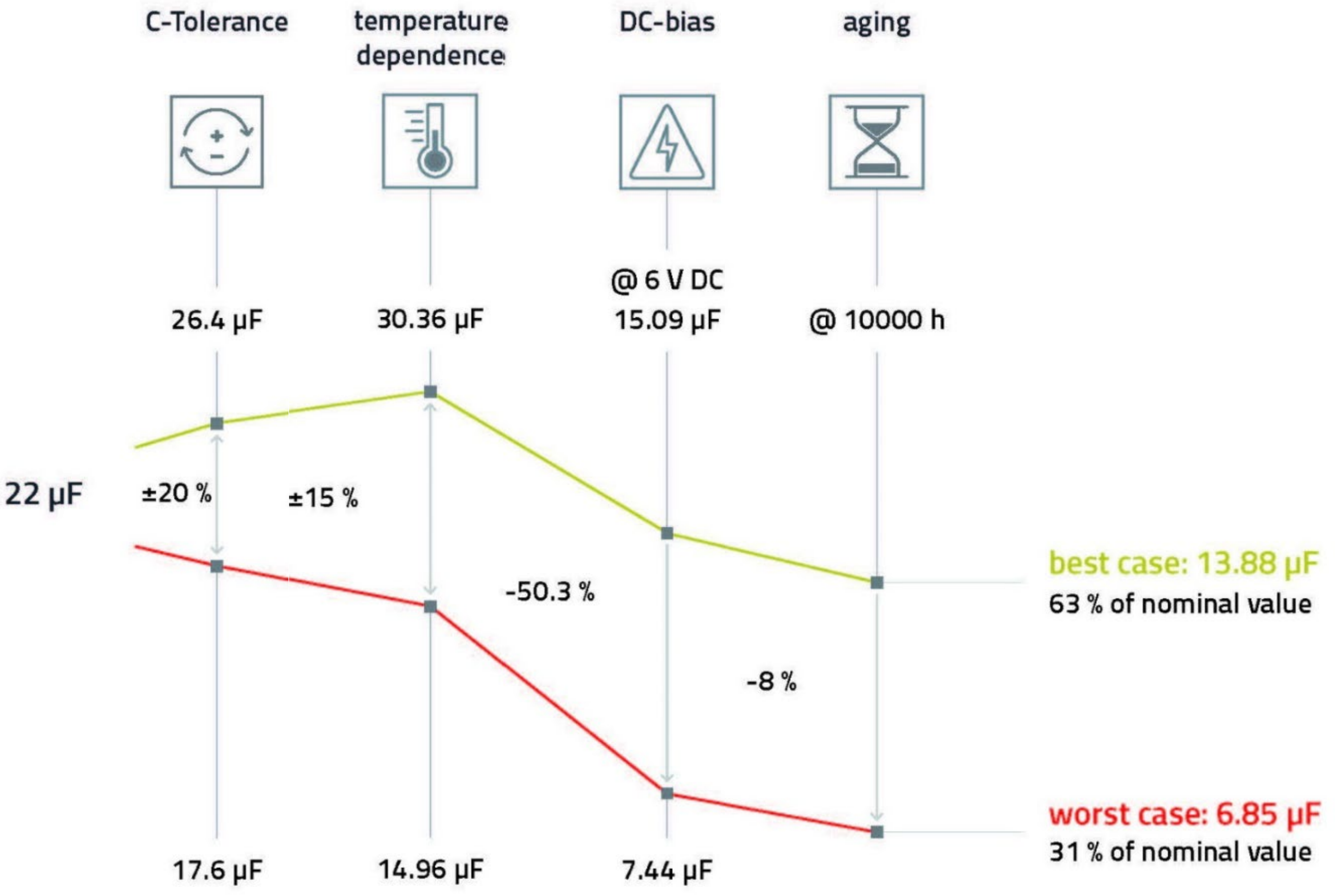
Check the **Application Note SN011** for more information about MLCC Aging





MLCC (MULTILAYER CERAMIC CAPACITOR)

Capacitance yield of Class 2 ceramics



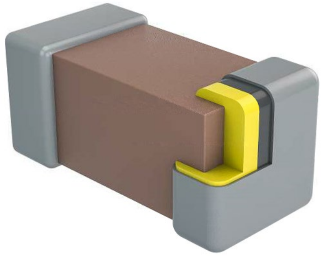
=>Best case about one third lost of capacacitance

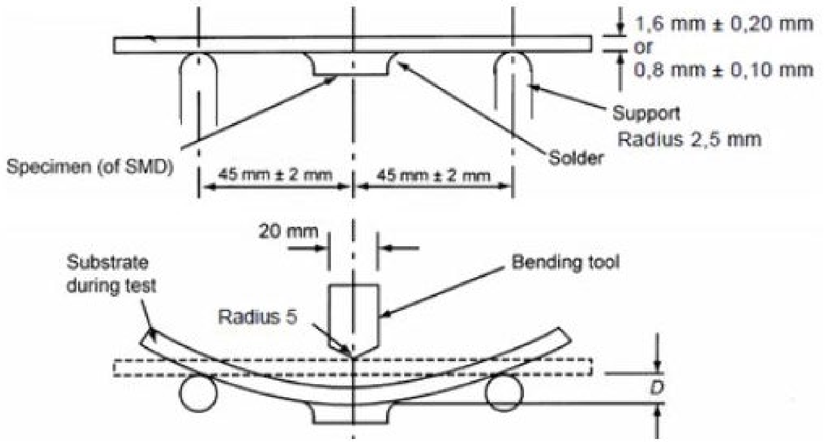
=>Worst case about two thirds lost of capacacitance

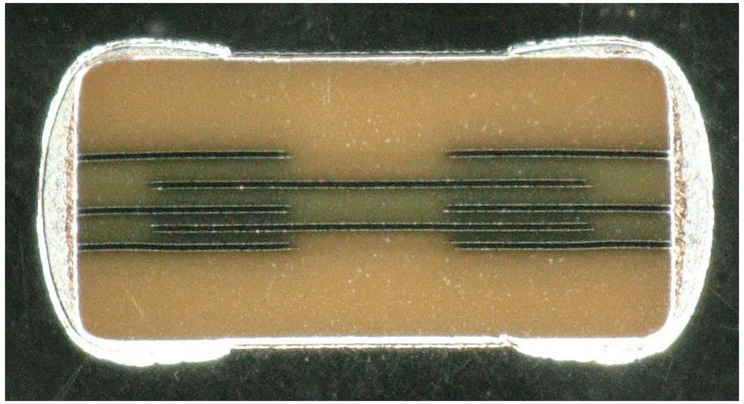
MLCC (MULTILAYER CERAMIC CAPACITOR)

Special Cases

- Soft termination Capacitor



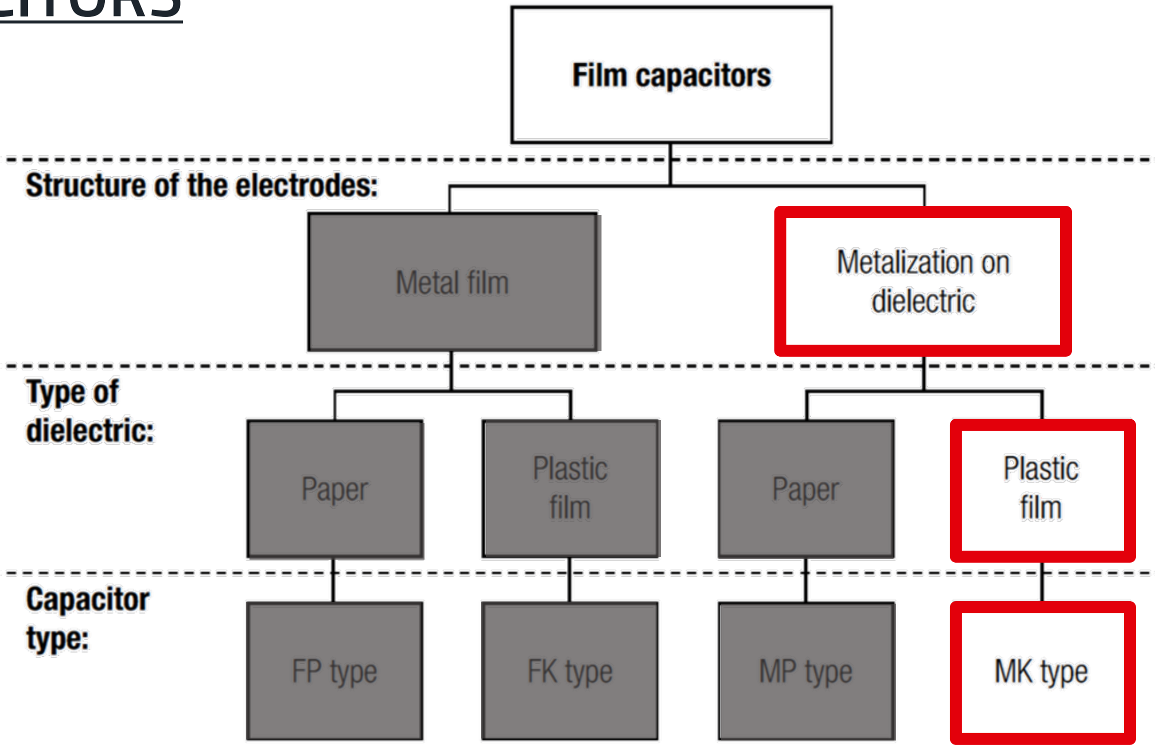




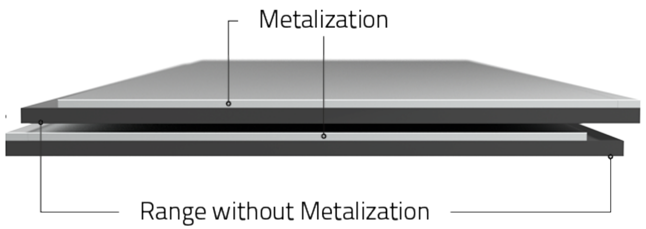
- Safety Capacitors for power supply application (X1/X2/Y2)

FILM CAPACITORS

Construction

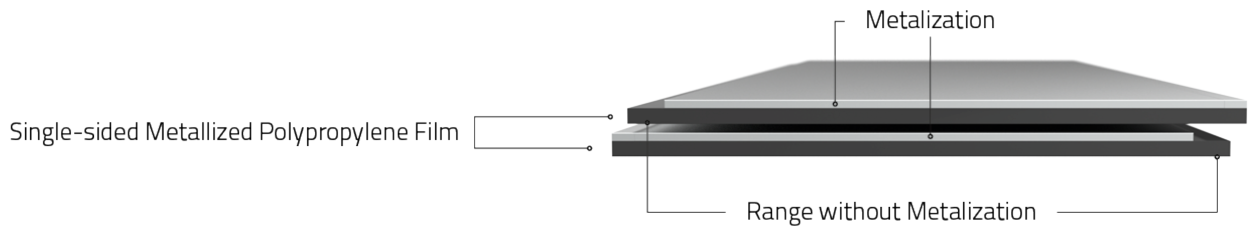


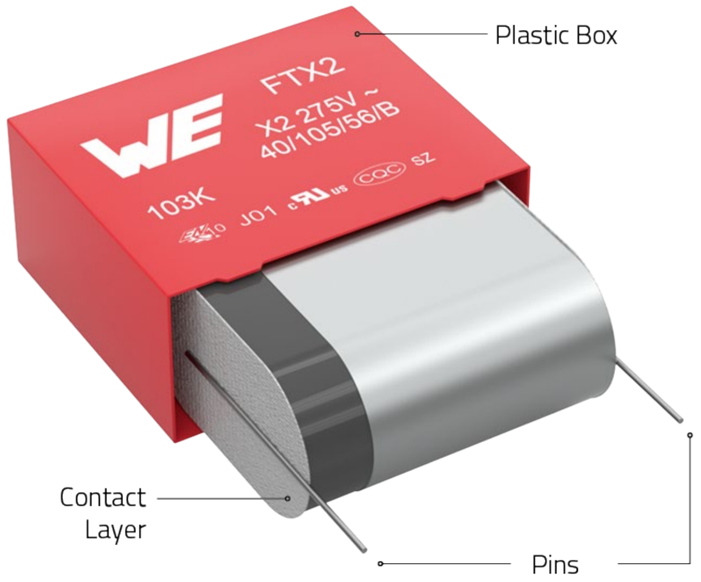
Dielectric	Code for the FK capacitor	Code for the MK capacitor
Polyester (PETP)	KT	MKT
Polycarbonate (PC)	KC	MKC
Polypropylene (PP)	KP	MKP
Polystyrene (PS)	KS	MKS

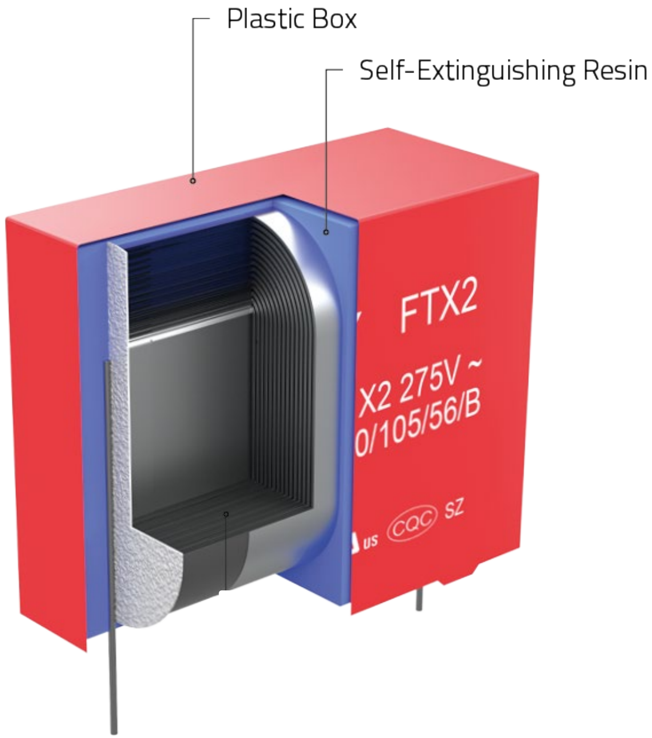


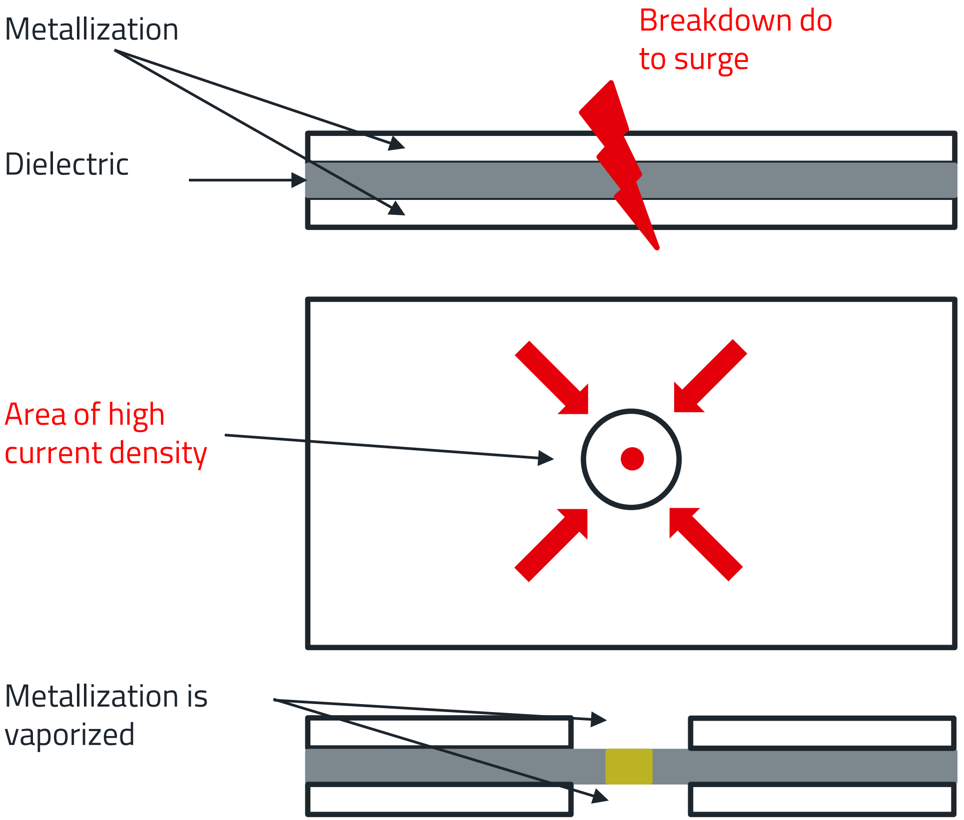
FILM CAPACITORS

Construction and self-healing process



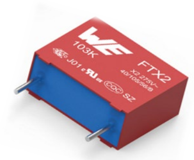


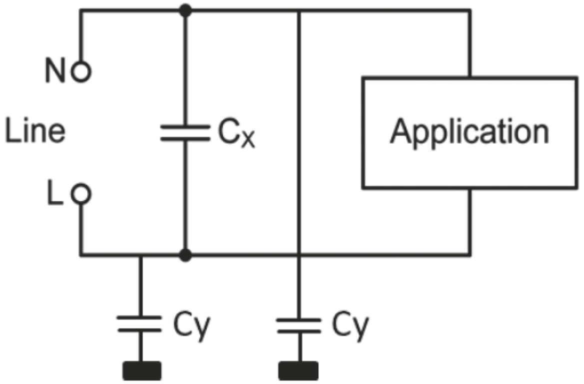




FILM CAPACITORS

AC- Safety Film Capacitors





- X-Capacitors
  - Filtering of differential mode interferences
  - Application protection against voltage peaks of the power grid
  - Network protection against voltage peaks of the application

- Y-Capacitors
  - Filtering of common mode interferences
  - Capacitance value normally less than a few nF
  - Limited capacitance to reduce leakage current to earth

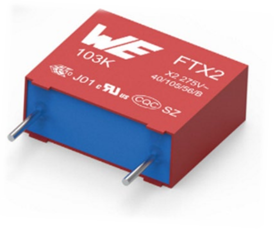
- Safety Classes according IEC 60384-14 / UL 60384-14:

Safety Class	Max. Impulse according IEC- 60384-14
X1	4kV (C≤ 1μF)
X2	2,5 kV (C≤ 1μF)
Y1	8 kV
Y2	5 kV

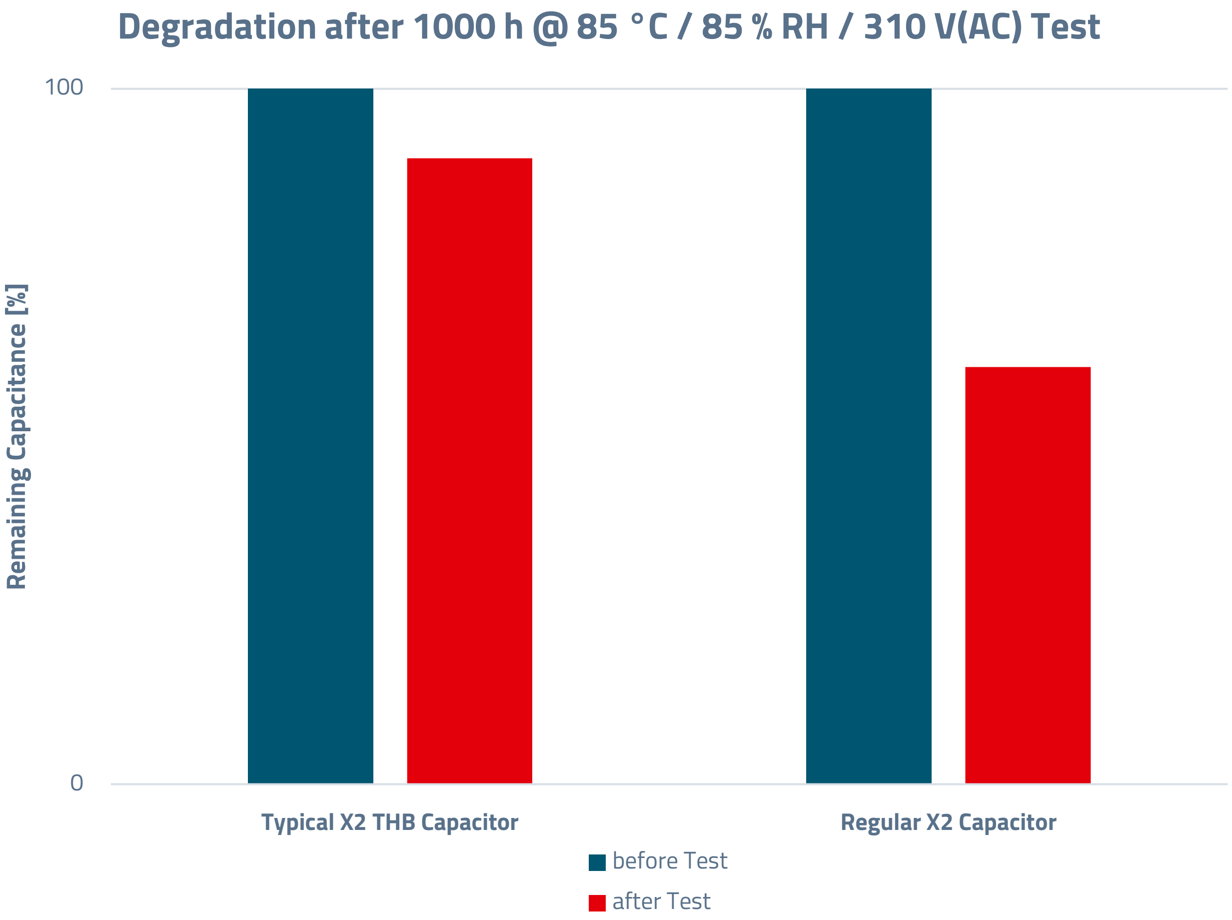
FILM CAPACITORS

THB X2 Capacitors

- Standard X2 Capacitor:
  - Cost effective
  - Sensitive to humidity & temperature
  - Comparable small sizes



- THB X2 Capacitor:
  - Very low moisture absorption
  - Slightly bigger sizes than regular X2 Film Capacitors
  - Very good for long lifetimes

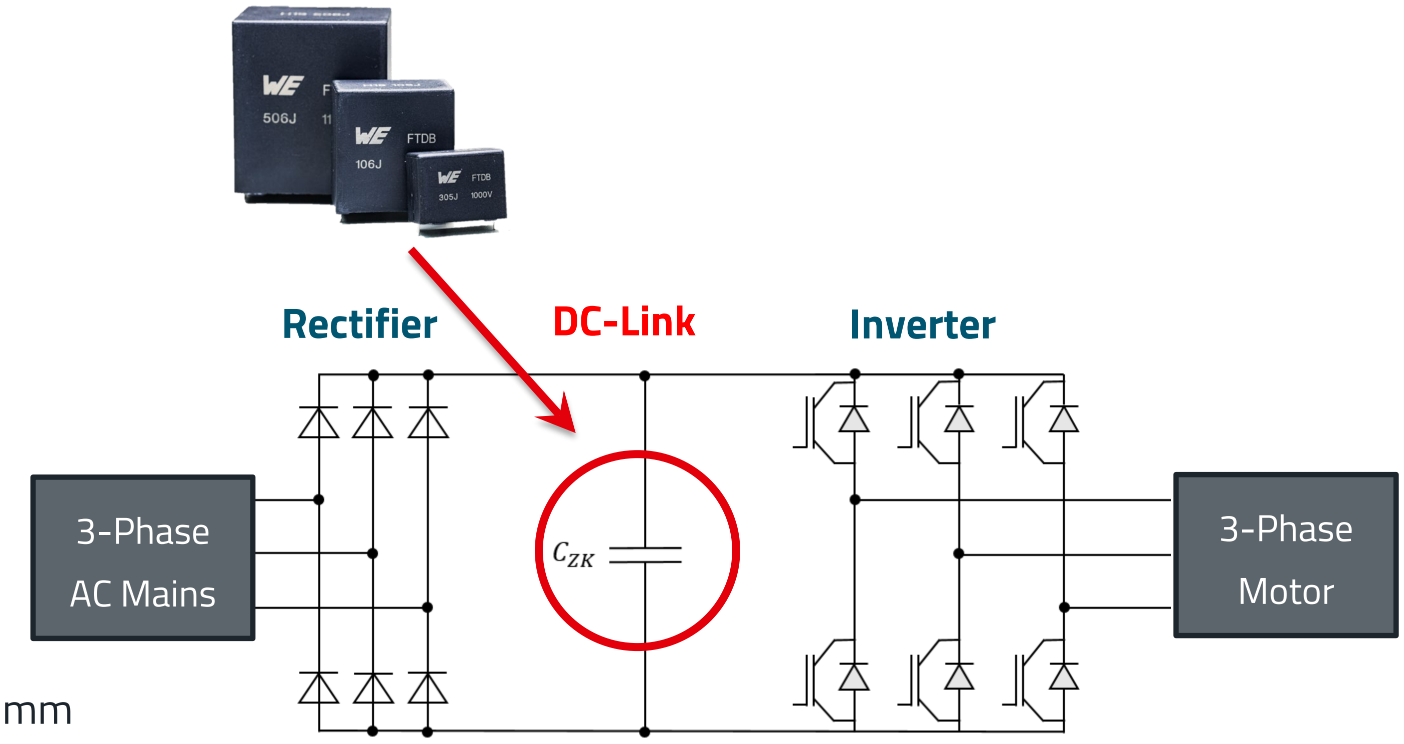


FILM CAPACITORS

DC Link Capacitors

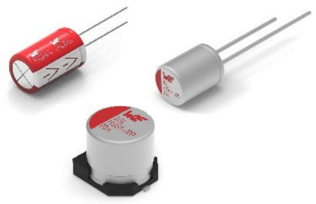
WCAP-FTDB DC-Link Series

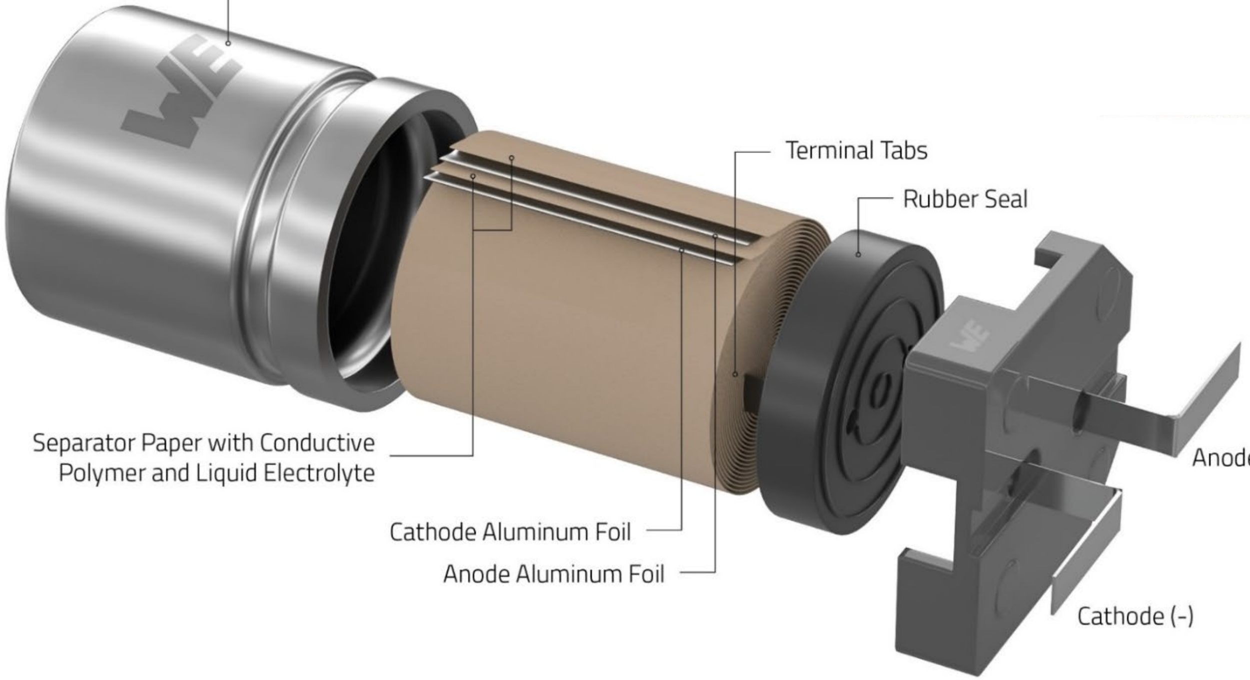
- Boxed THT - MKP Film Capacitors
  - Capacitance: 1 µF up to 75 µF
  - Voltage: 500 V_{DC} up to 1200 V_{DC}
  - MKP: Polypropylene metallized film
  - Temperature: -40°C up to 105°C
  - Pitch / Pin distance: 27.5, 37.5 and 52.5 mm
  - High ripple current capability
  - Self-healing properties
  - Very long expected load life

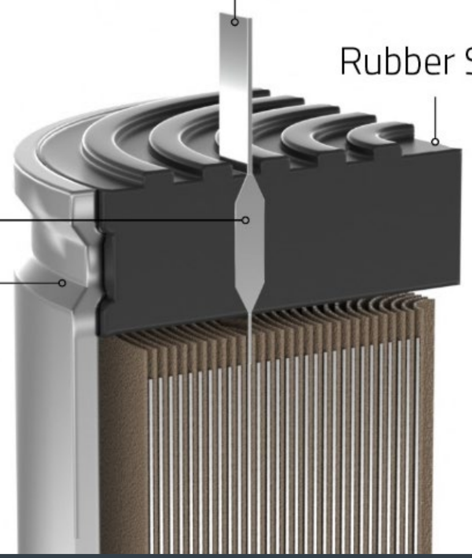


ALUMINUM CAPACITORS

Construction

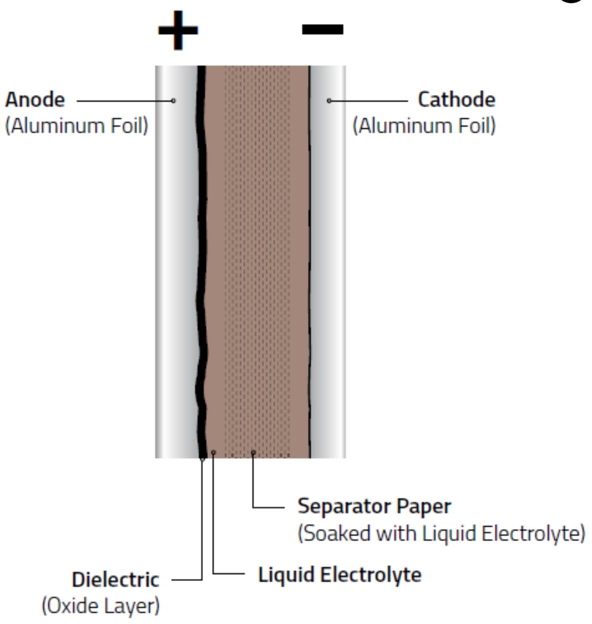


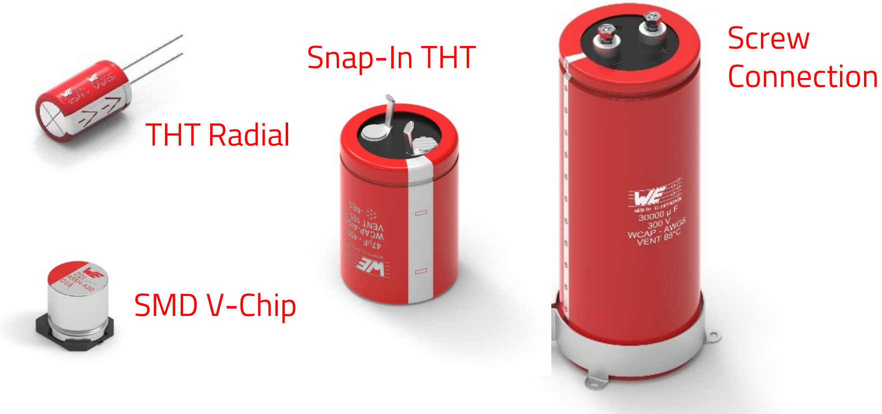




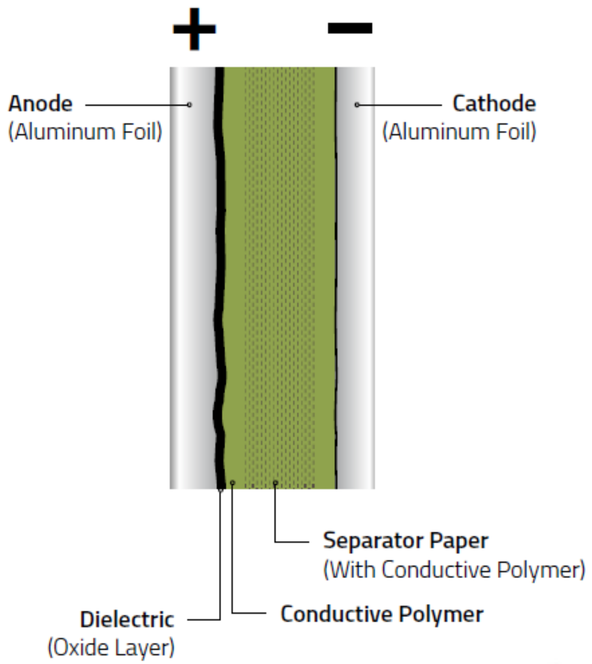
ALUMINUM CAPACITORS

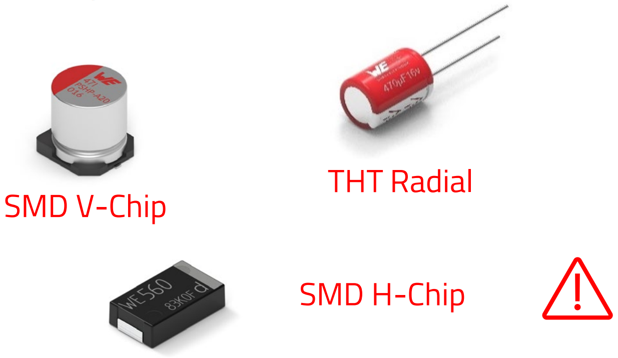
Aluminum Electrolytic



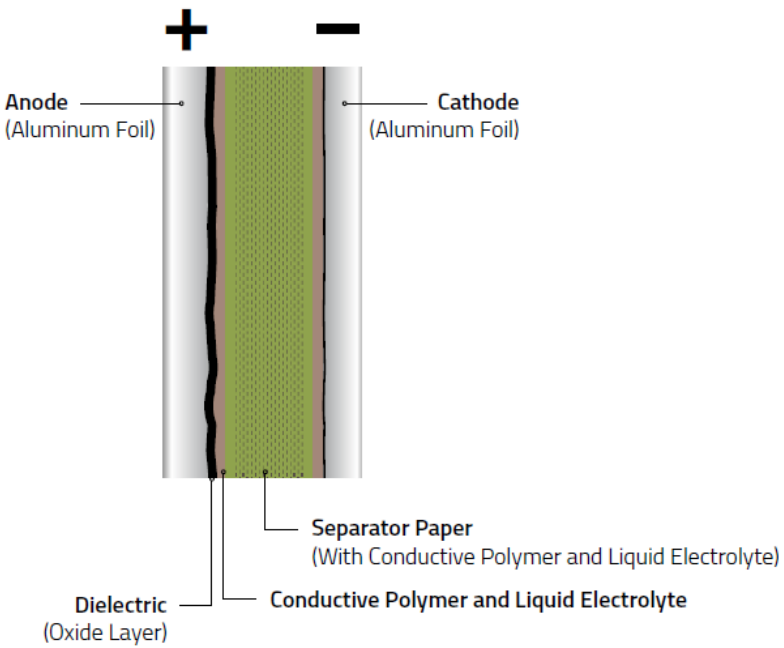


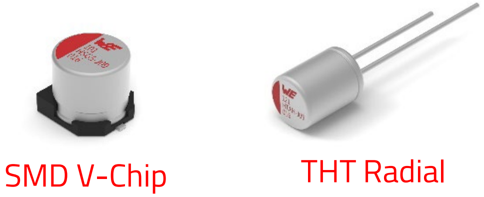
Aluminum Polymer





Hybrid Polymer





ALUMINUM CAPACITORS

Aluminum Electrolytic

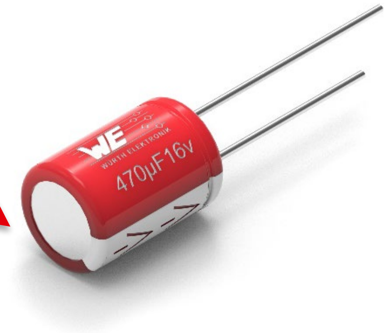
Safety vent

- Highest voltage ratings (Up to
- Biggest sizes and other connection types (Screw, Snap-in)
- Properties improve at high temp.
- Dielectric self-healing

- Electrolyte drying can be a problem for long load time

Aluminum Polymer

No vent

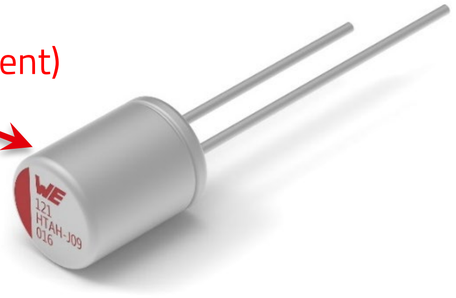


- Very low ESR
- Very high ripple current
- Very long lifetime
- Stable at very low temperature

- Limited voltage and size
- “High” leakage current
- Could be susceptible to vibration

Hybrid Polymer

No sleeve
(sometimes vent)



- Low ESR
- High ripple current
- Low leakage current
- Best performance over temperature
- Lifetime better than electrolytic

- Limited voltage and size
- More complicated production (cost)

ALUMINUM CAPACITORS

Lifetime: Different technologies and how to estimate

$$L_X = L_{Nom} * 2^{\frac{T_{MAX} - T_A}{10}}$$

- Alum. Electrolytic Capacitors
- Alum. Hybrid Capacitors
- Alum. Polymer Capacitors (SMD H-Chip construction only)

$$L_X = L_{Nom} * 10^{\frac{T_{MAX} - T_A}{20}}$$

- Alum. Polymer Capacitors (THT and V-Chip SMD)

L_x = Expected lifetime of component

L_{Nom} = Endurance of component (see datasheet)

T_{max} = Maximum allowed temperature of component

T_A = Component ambient temperature within application

Endurance conditions

Lifetime Performance:

Test Conditions	Endurance
Lifetime	10000 h @ 105 °C
Voltage	V_R applied
Current	I_R applied
Δ C	≤ ±30 % of initial measured value
DF	≤ 200 % of the initial specified value
ESR	≤ 200 % of the initial specified value
Leakage Current	≤ the initial specified value

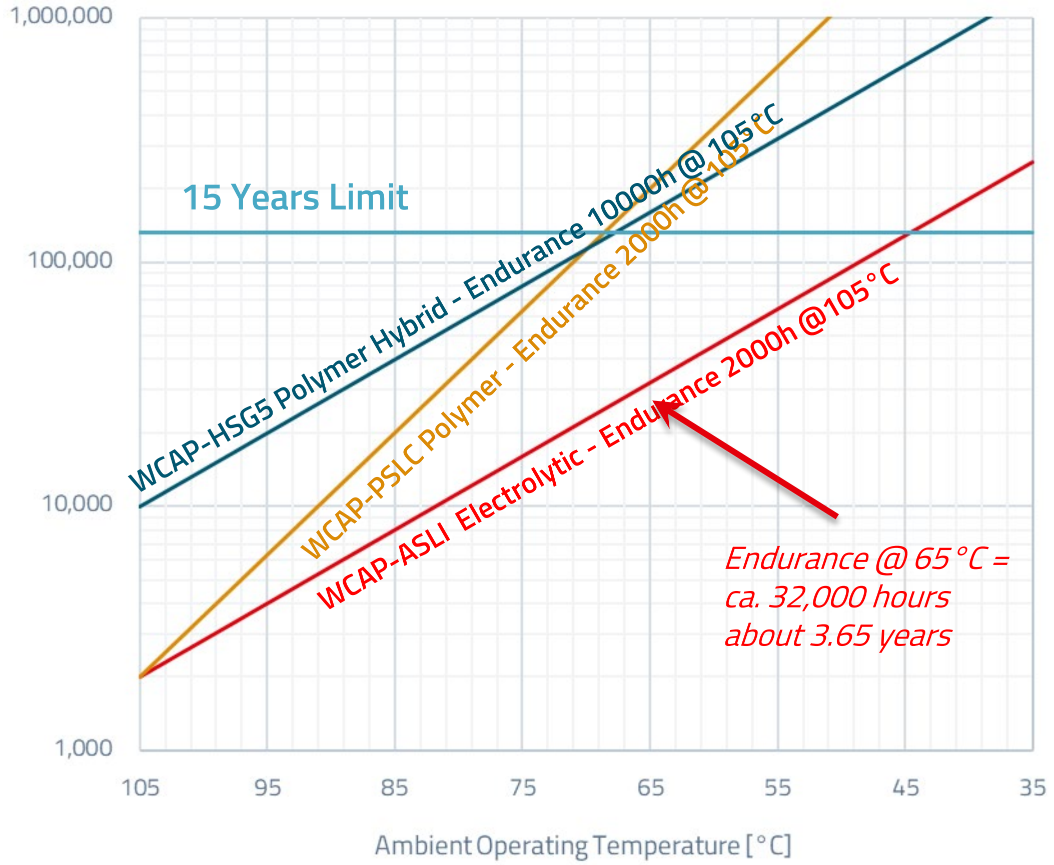
End-of-life definition

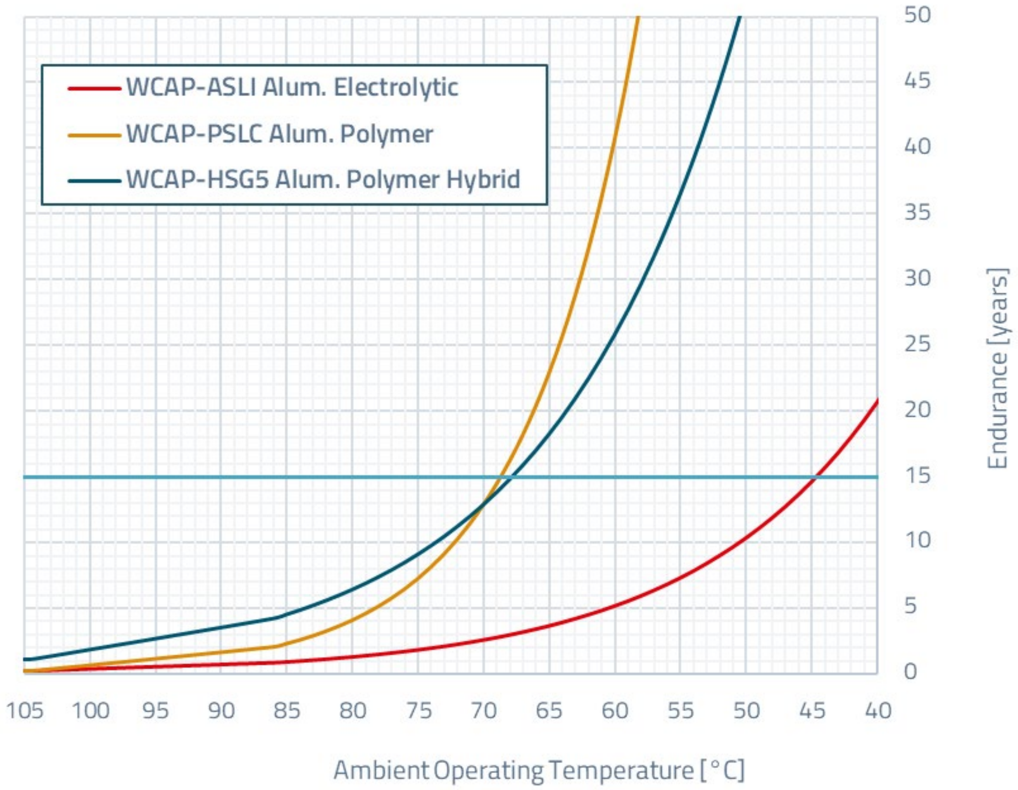
Lifetime Performance:

Test Conditions	Useful Life	Endurance
Lifetime	6000h, @ 105°C	4000h, @ 105°C
Voltage	U_R applied	U_R applied
Current	I_R	I_R
Δ C	≤± 20% of initial value	≤ ±10% of initial value
DF	≤ 200% of initial specified limit	≤ 130% of the initial specified limit
Leakage Current	≤ the initial specified value	≤ the initial specified value

ALUMINUM CAPACITORS

Plot and compare lifetime – endurance formulas

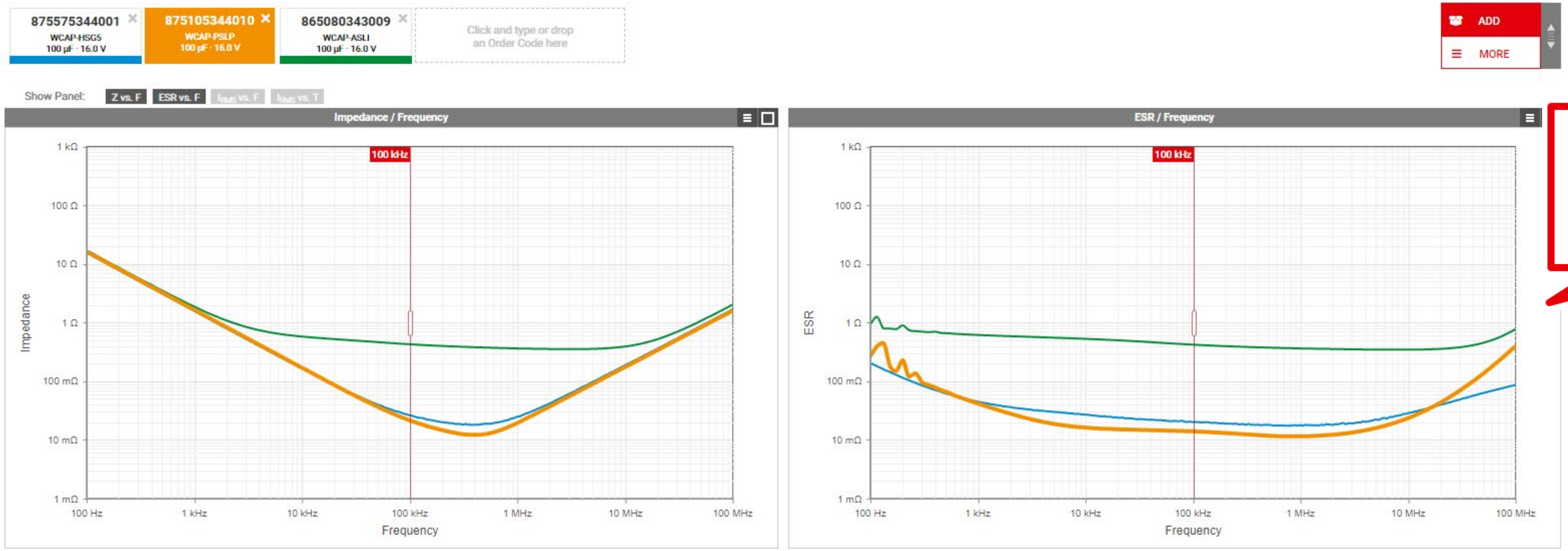




ALUMINUM CAPACITORS

Comparison of the technolgies

Technology	Capacitance [µF]	Voltage [VDC]	Size [mm]	ESR [mOhm, typ]	RC [mA]	LC [µA]	Temperature range	Endurance [@105°C]	Expected Lifetime [h, @65°C]
Electrolytic	100	16	6.3x6.6	420	255	16 +	-55 to 105	2000	3.65 years max
Hybrid	100	16	6.3x6.6	20.1 +	1300 +	16 +	-55 to 105	10000 +	13 years max +
Polymer	100	16	6.3x6.6	14 + +	2690 + +	400	-55 to 105	2000	13 years max +



Find this and more measurements in

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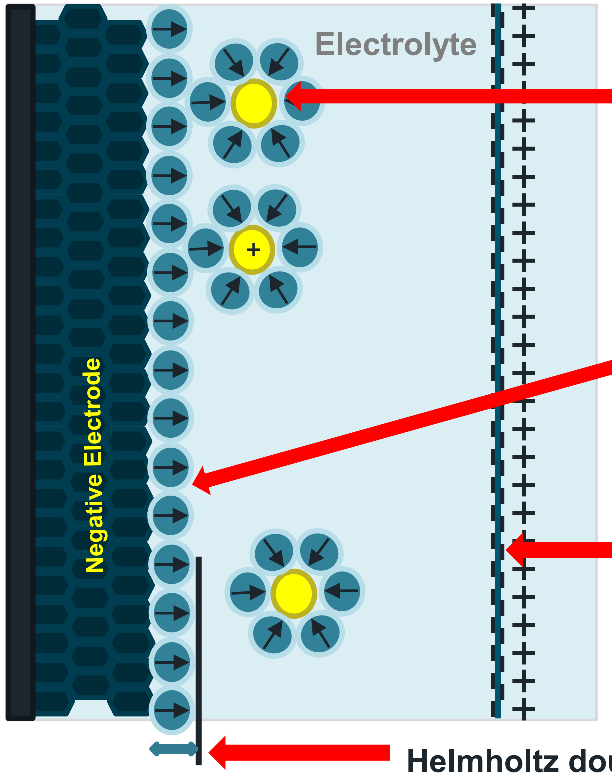
SUPERCAPACITORS

Composition of Supercapacitors

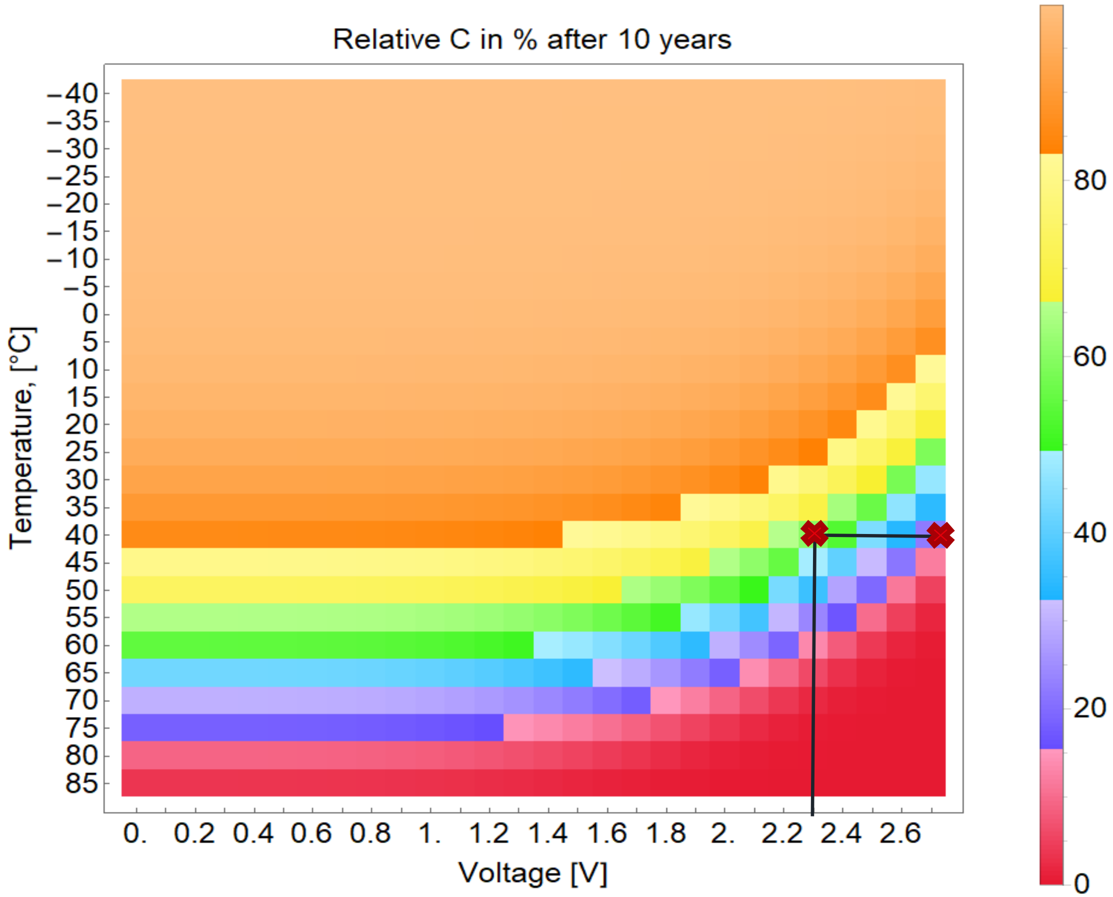
Characteristics EDLCs:
(Electronic Double Layer Capacitors)

- Very huge capacitance
- Limited Voltage Range
- Temperature range 65°C up to 85°C
- Very low ESR values
- Comparatively high leakage Currents



SUPERKONDENSATOREN

Lifetime expectancy of Supercapacitors



Residual Capacitance after 10 years

For example:

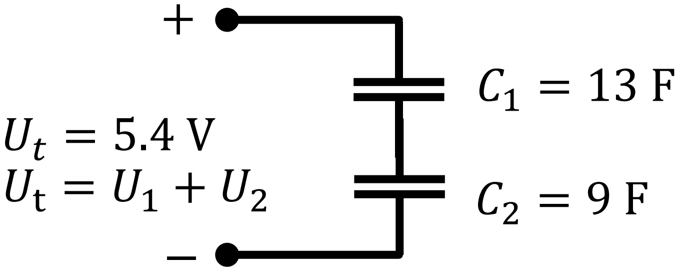
At 2,3 V and 40 °C expected residual capacitance around 60%

At 2,7 V and 40 °C expected residual capacitance around 20%

SUPERCAPACITORS

Balancing

- **Worst Case Scenario:**
  - 2 Supercapacitors with a Capacitance of 10 F (tol.: -10%, +30%) are being put in series and are charged at 5,4 V.)
  - Worst case: $C_2 = 9\ F(-10\%)$, $C_1 = 13\ \mathrm{F}\ (+30\%)$
  - This results in the following Voltage levels:



$$U_2 = \frac{C_1}{C_2 + C_1} U_t$$

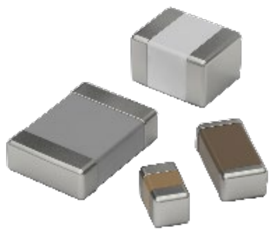
$$U_2 = \frac{13F}{9F+13F} 5.4V = 3.19V$$

(Caution Overvoltage!)

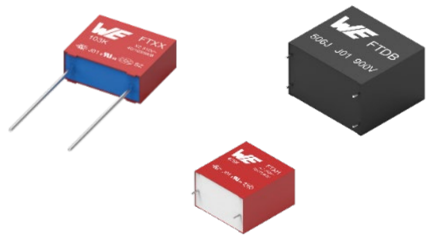
DC-LINK CAPACITOR: SPECIFICATION AND APPLICATION

Summary

MLCC
- Smallest sizes
- High Voltage available
- Class 1 Ceramic very stable over Temperature, Voltage and Time
- Class 2 Ceramic big capacitance but need to account for C loss.
- Safety Capacitors available
- Limit possible cracking with soft termination

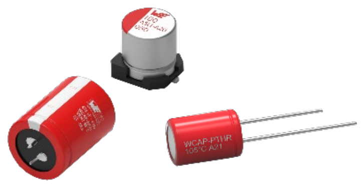


Film Capacitor
- Suitable for high Voltage
- Self-healing properties
- Safety Capacitors available
- Sensitive to humidity & temperature



Supercapacitor
- Very high Capacitance for power supply
- Strongly adviced Balancing if connected in series

Aluminum Capacitor
- Aluminum Electrolyte
  - cost efficient
  - big variety in size
- Aluminum Polymer
  - Suited for longevity applications
  - Low ESR values
  - Not suited for:
    - Battery powered applications
    - High vibration applications
- Aluminum Hybrid Polymer
  - Suited for longevity applications
  - Suited for high temp applications



Questions

& Answers

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

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