High Voltage Pulse Capacitors

CalRamic Technologies LLC

High Voltage Pulse Capacitors

Table of Contents

- Introduction
- Typical Applications
- Capacitors Vs Batteries
  - Ragone Plot
- Capacitor Selection
  - Dielectric Material Comparison
  - Design Considerations
- Ceramic Capacitor Basics
  - Capacitor Definition
  - Generating Capacitance (C)
  - Capacitance and Charge (Q)
  - Energy Density (E)
  - Capacitor Equivalent Circuit
  - Impedance (Z)
  - Temperature (ΔTC) & Voltage Coefficient (ΔVC)
  - Resonance Frequency (f_R)
  - ESR (Ω) and Time Constant (τ)
- Pulse Capacitor Basics
- Summary

High Voltage Pulse Capacitors

Introduction

Design engineers working on high voltage pulse applications have always been left to consider a variety of device or component options for delivering the required energy.

- Power density
- Energy density
- Frequency Response
- Load characteristics
- Loss characteristics (ie. ESR & ESL)
- Pulse width and duty cycle
- Mechanical robustness
- Etc…

This presentation is intended to provide guidance in this selection process by comparing the more common choices and offering recommendations on the preferred option. Of course, recommendations presented here are based on a number of assumptions and it incumbent on the design engineer to validate their selection by first testing the device under actual application conditions.

100% USA Manufactured In Reno, NV

CalRamic Technologies LLC

Ways A Capacitor Can Be Used

Function	Application
Energy Storage	• Battery Replacement
Pulse Discharge	• Detonator • Aircraft Carrier Launcher • Laser • Radar
Voltage Stabilization	• Hold Up • Reservoir • Snubber • Smoother • Switch Mode • Audio Base Line Stiffener • DC Link
Phase Shifting	• Motor Run • Power Factor Correction
Filtering - Multiple Frequencies	• DC Blocking • AC Coupling • Safety Capacitors - X Cap / Y Cap • Low Pass Filter • High Pass Filter • Band Pass Filter

High Voltage Pulse Capacitors

Typical Applications

There is a growing need for high voltage pulse capacitors with the largest drivers in the medical and military / defense sectors. Typical applications would include….

- Military
  - Radar
  - Missiles
  - High Power Microwave (HPM) for anti-drone systems
  - Fuze (Detonator Capacitors)
- Medical
  - X-Ray equipment

Pulse Capacitors

What Are Pulse Capacitors

Pulse capacitors are specialized energy-storage devices designed to:

- Charge relatively slowly
- Discharge extremely quickly
- Deliver very high current pulses
- Operate reliably under high electrical stress

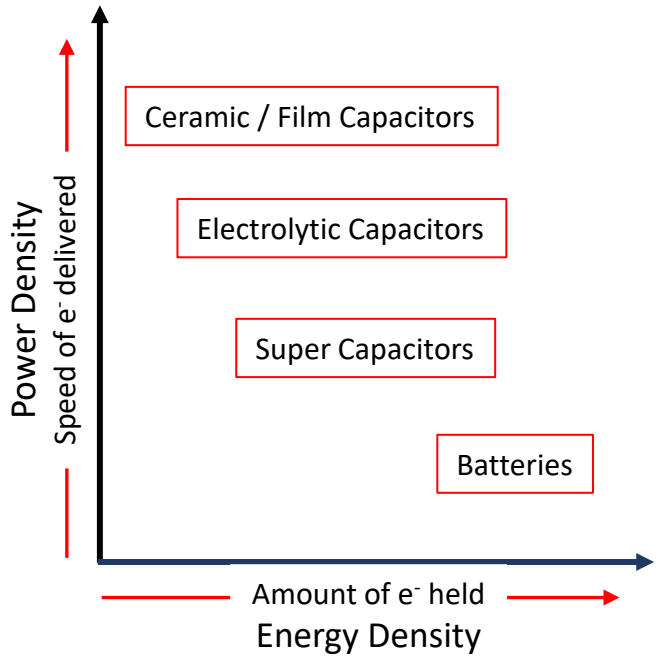
Unlike conventional capacitors that release energy gradually, pulse capacitors are optimized for short-duration, high-power energy bursts

High Voltage Pulse Capacitors

Capacitors Vs Batteries

- The two most obvious choices one might consider for a pulse application power source would be capacitors and batteries
- Both options are capable of delivering energy, but capacitors offer a distinct advantage in terms of how the energy can be delivered
- Batteries are not typically considered for pulse applications

Ragone Plot



High Voltage Pulse Capacitors

Capacitor Selection

- Capacitor options typically include ceramic, film and electrolytic
  - Ceramic and film exhibit better Power Density and response time over electrolytic
  - With regards to loss characteristics, ceramic and film are again superior over electrolytic with regards to DF, ESR and ESL
  - Class I ceramics as a rule perform faster than Class II ceramics
  - Ceramic capacitor designs offer better power per unit volume
  - Calramic capacitors offer a significant advantage in terms of voltage rating where single layer discs can achieve voltage rating of up to 50kV
  - CalRamic manufactures capacitor assemblies with voltage ratings greater than 100kV

Capacitor Selection

Selection Process

- Selection of a suitable pulse capacitor requires that the engineer consider a number of performance characteristics including…

Parameters:

- Voltage Rating
- Capacitance
- Max/Min Temperature
- Environment
- Shock and Vibration
- Capacitance Stability
- Mode of Failure
- Energy Density
- ***Power Density***
- Ripple Current
- ***Peak Current***
- ***Operating Frequency***
- ***Resonance Frequency***
- Polarity
- Cost

Parasitics:

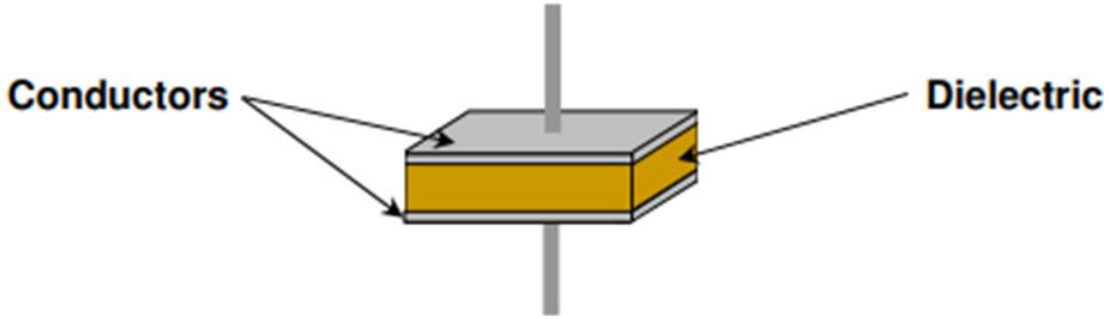
- ***ESR / DF***
- ***ESL***
- IR / Leakage Current
- Corona / Partial Discharge
- Hysteresis / Dielectric Absorption

Properties:

- Temperature Coefficient
- Voltage Coefficient

Capacitor Basics

Capacitor Definition



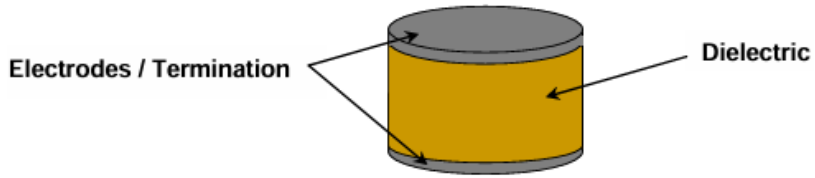
A capacitor is defined as a device that stores energy. Simply stated, when one joule of energy is put into an ideal capacitor, one joule of energy can then be removed from that capacitor as required. The reason for this is that the energy put into the capacitor is stored in an electrostatic field.

Ceramic Capacitors

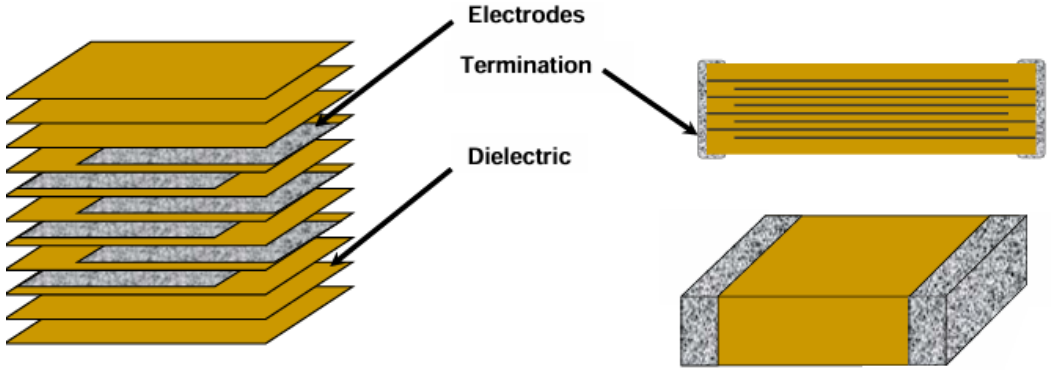
Ceramic Capacitor Construction

- In its most basic form, a Single Layer capacitor is comprised of three (3) essential components, two (2) metal plates or conductors, separated and insulated by the third part called the dielectric
- In order to increase capacitance ceramic capacitor designs have evolved into more complex structures compromised of multiple layer construction

Single Layer Disc Capacitor

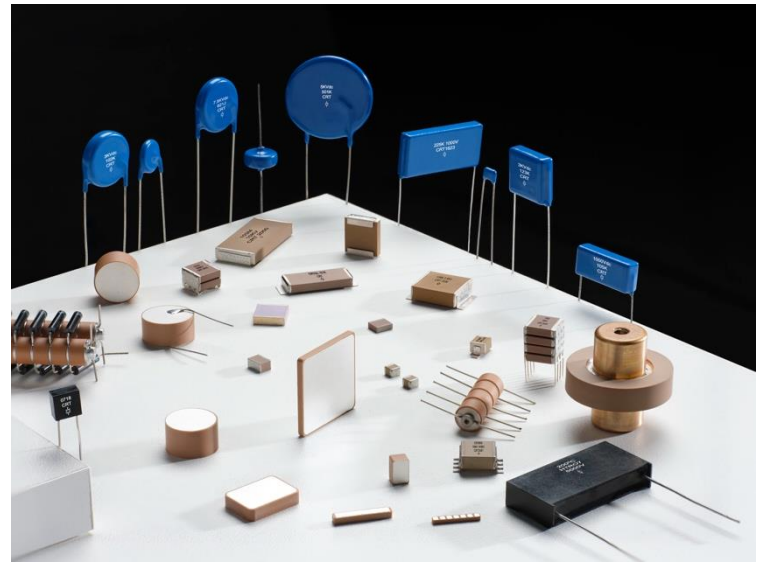


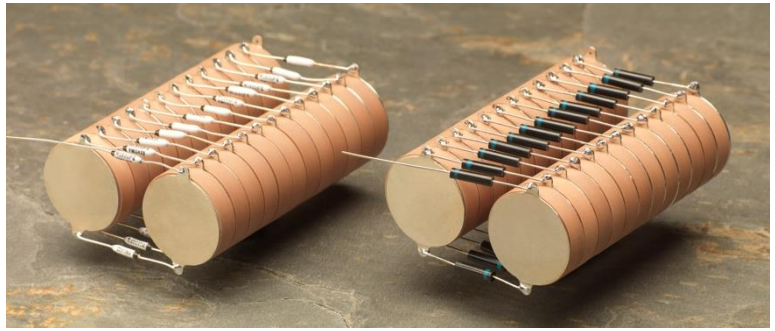
Multilayer Capacitor (MLCC)



High Voltage Ceramics

- Where more capacitance and / or higher voltage ratings are needed individual capacitors can be designed into both parallel and series configurations
- These arrays can typically be designed to meet unique customer design constraints

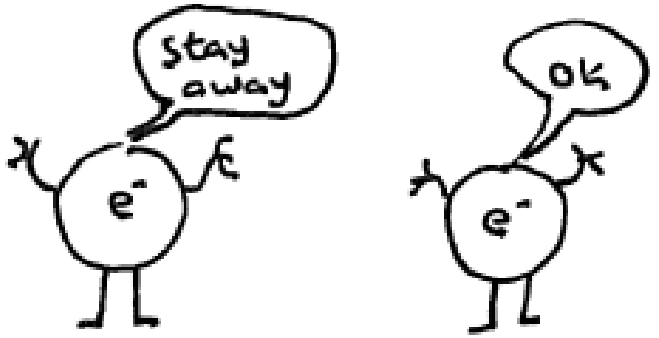




Examples Of High Voltage Ceramics

Capacitor Basics

Generating Capacitance



Electrons don't like each other and electrons trying to stay away from each other determines

- How a capacitor stores energy
- How a capacitor charges
- How a capacitor discharges
- How current is knocked out of phase with voltage

Capacitor Basics

Capacitance & Charge (Q / e^-)

$$C = K_o K \times \frac{A}{t} \quad \text{(Measured in Farads)}$$

Where K_o = Permittivity of Free Space K = Dielectric Constant

A = Area t = Dielectric Thickness

But you need voltage in order to generate a charge

$$Q = CV \quad \text{(Measured in coulombs)}$$

Where Q = Charge C = Capacitance V = Voltage

Capacitor Basics

Calculating Electron Charge (e^-)

- Basic capacitor rated for 1 F @ 1 V

  $Q = CV = 1\ F \times 1\ V = 1\ F \cdot V$

  $F = A \cdot sec / V$ So $Q = 1\ A \cdot sec / V \times V = 1\ A \cdot sec$

  $A = 6.24 \times 10^{18}\ e^- / sec$

  $Q = (6.24 \times 10^{18}\ e^- / sec) \times sec = 6.24 \times 10^{18}\ e^-$

Therefore, there are 6.24×10^{18} electrons capable of doing work

- CalRamic SMPS3BR106K201NS480 rated for 10 µF @ 200 V

  $Q = 0.00001\ F \times 200\ V = 0.002\ A \cdot sec$

  $= 0.002 \times 6.24 \times 10^{18} = 1.25 \times 10^{16}$ e-

Therefore, there are 1.25×10^{16} electrons capable of doing work

Capacitor Basics

Energy Density (E)

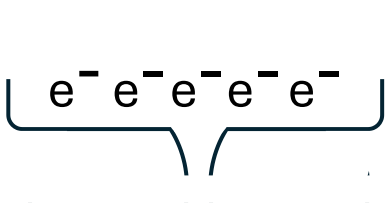
$$E = \tfrac{1}{2}CV^2$$

Say we have two capacitors: 5 F at 1 V and 1 F at 5 V

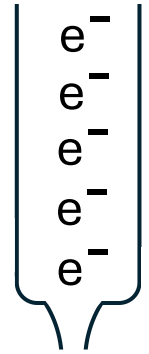
Q for both is 5 coulombs

Energy of 5 F at 1 V: $E = \tfrac{1}{2}\,5 \cdot 1^2 = 2.5$ joules

Energy of 1 V at 5 F: $E = \tfrac{1}{2}\,1 \cdot 5^2 = 12.5$ joules



5 F at 1 V
2.5 joules

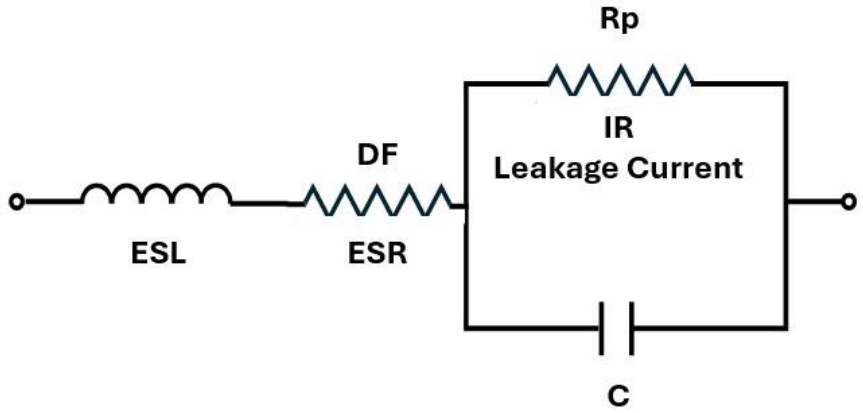


1 F at 5 V
12.5 joules

Capacitor Basics

Capacitor Equivalent Circuit

- No capacitor is perfect and exhibits losses
- This can be represented by an equivalent circuit outlining how a capacitor behaves



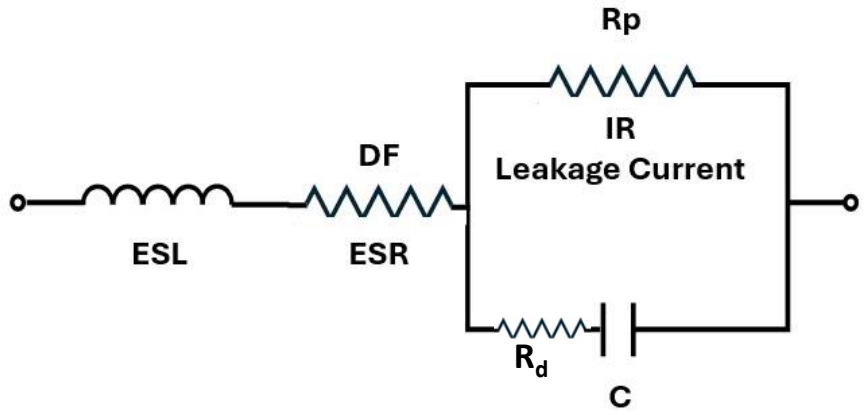
Where:

ESL	=	Equivalent Series Inductance
ESR	=	Equivalent Series Resistance
DF	=	Dissipation Factor
IR	=	Insulation Resistance
Rp	=	Parallel Resistance
C	=	Capacitance

Capacitor Basics

Equivalent Circuit With Dielectric Effect

- R_d is the losses of the dielectric as compared to the lead configuration, termination and lead geometry
- Dielectric selection is critical when designing pulse capacitors



- Class 1 Ceramics, such as NPO's, can provide high stability and greater power density
- Class 2 ceramics, such as X7R's, may have higher energy densities but may be too slow for very fast pulses

100% USA Manufactured In Reno, NV

Dielectrics

Dielectric Material Comparison

CalRamic Technologies LLC

Characteristic	Ceramic						Film		Electrolytic	
	NPO	X7R	X5R	X5U	Y5V	Z5U	Polyester	Polyprop	Aluminum	Tantalum
Operating Temp	-55 to +125ºC	-55 to +125ºC	-55 to +85ºC	-55 to +85ºC	-30 to +85ºC	+10 to +85ºC	-55 to +125ºC	-55 to +105ºC	-40 to +105ºC	-55 to +125ºC
K Value	15 – 150	600 – 5000	600 – 5000	3500 – 7000	7000 - 22000	7000 – 22000	3.1 – 3.3	2.1 – 2.3	7 - 10	24
DF	0.10%	2.5%	2.5%	2.5%	5%	5%	1%	0.10%	8%	20%
Voltage Rating	5V – 50kV	5V – 50kV	5V – 50kV	5V – 50kV	5V – 50kV	5V – 50kV	100 – 600V	100 – 600V	3 – 550V	6 – 125V
ΔTC	±30PPM/ ºC	±15%	±15%	+22/- 56%	+22/- 82%	+22/- 56%	±12%	±1%	+10/- 40%	±15%
ΔVC	Negligible	Good	Good	Fair	Fair	Fair	Minimal	Minimal	N/A	Minimal
ESR	Excellent	Good	Good	Good	Fair	Fair	Fair	Fair	Poor	Poor
ESL	Low	Low	Low	Low	Low	Low	Fair	Fair	High	High
Dielectric Absorption	0.50%	2.5%	2.5%	2.5%	N/A	N/A	0.50%	0.10%	10%	N/A
Frequency Response	Superior	Excellent	Excellent	Excellent	Excellent	Excellent	Average	Excellent	Poor	Poor

Parasitics

Parasitics

Parasitics are unwanted properties that play a significant role in the capacitor selection process. They are inherent in the dielectric material or exist as a result of construction design.

Parasitics:

- DF/ESR
- ESL
- Insulation Resistance (IR) / Leakage Current
- Hysteresis / Dielectric Absorption
- Partial Discharge (Corona)

Properties:

- Temperature Dependent Capacitance
- Voltage Dependent Capacitance

Resonance Frequency

Resonance Frequency (f_R)

- The resonance frequency, f_R is the frequency at which a capacitor is no longer behaving as a capacitor and starts to display inductive behavior.

- At f_R the capacitive reactance (X_C) and inductive reactance (X_L) cancel each other out and the impedance of the capacitor is the same as the ESR.

$$\text{Impedance} = Z = \sqrt{ESR^2 + (X_C - X_{ESL})^2}$$

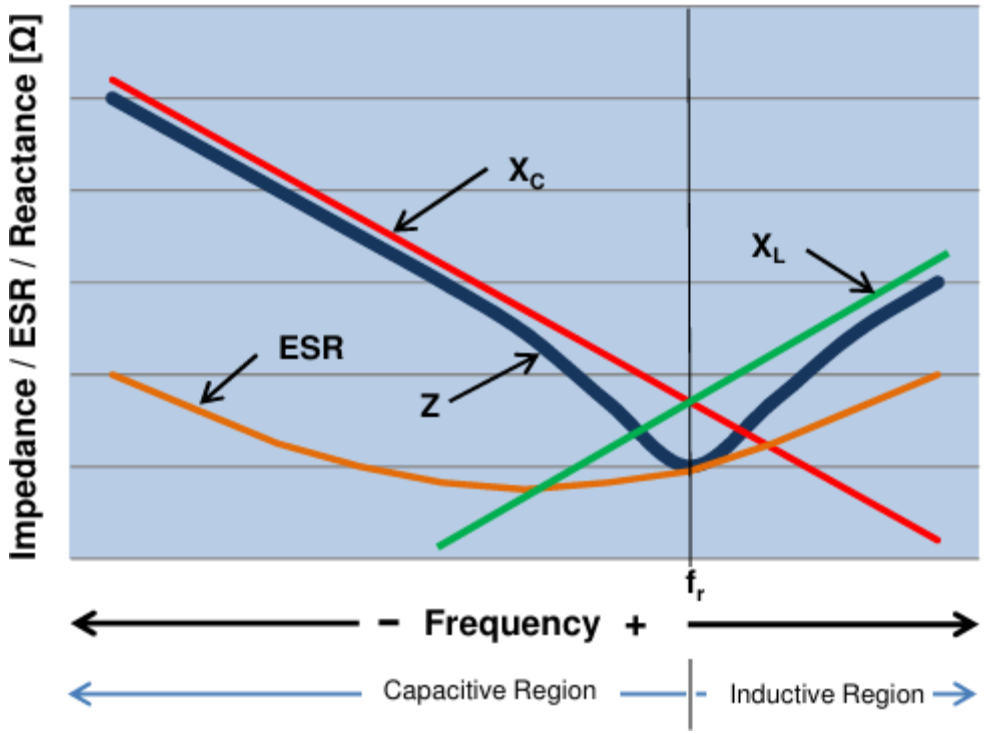
$$X_C = 1 / (2\pi f \times C) \quad \& \quad X_{ESL} = 2\pi f \times ESL$$

$$\text{At } f_R \quad X_C = X_{ESL}$$

$$f_R = \frac{1}{2\pi * \sqrt{C * ESL}}$$

Impedance Graph

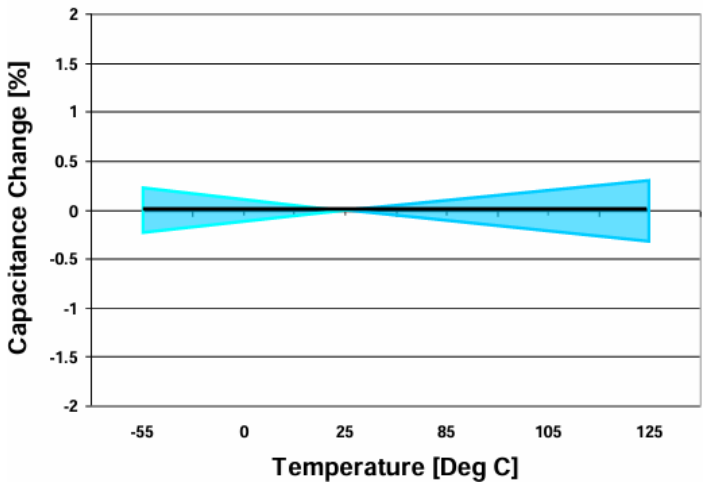
Typical Impedance Graph

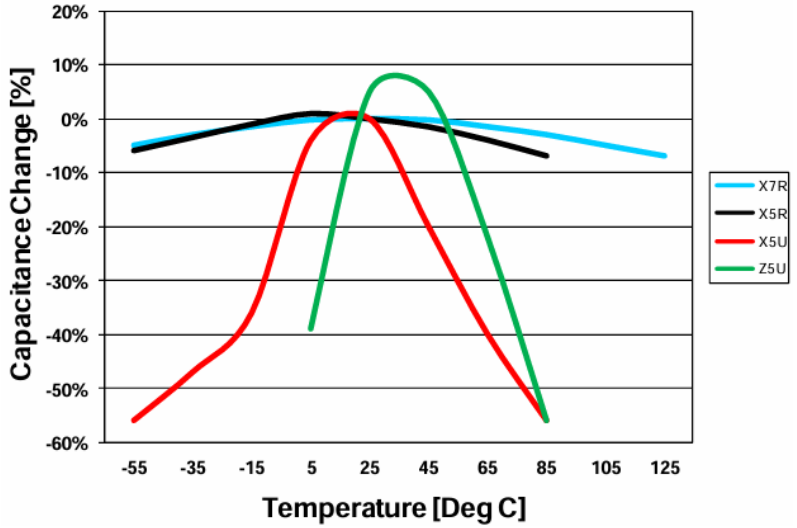


Temperature Coefficient

Temperature Coefficient

- Basic capacitor rated for 1 F @ 1 V

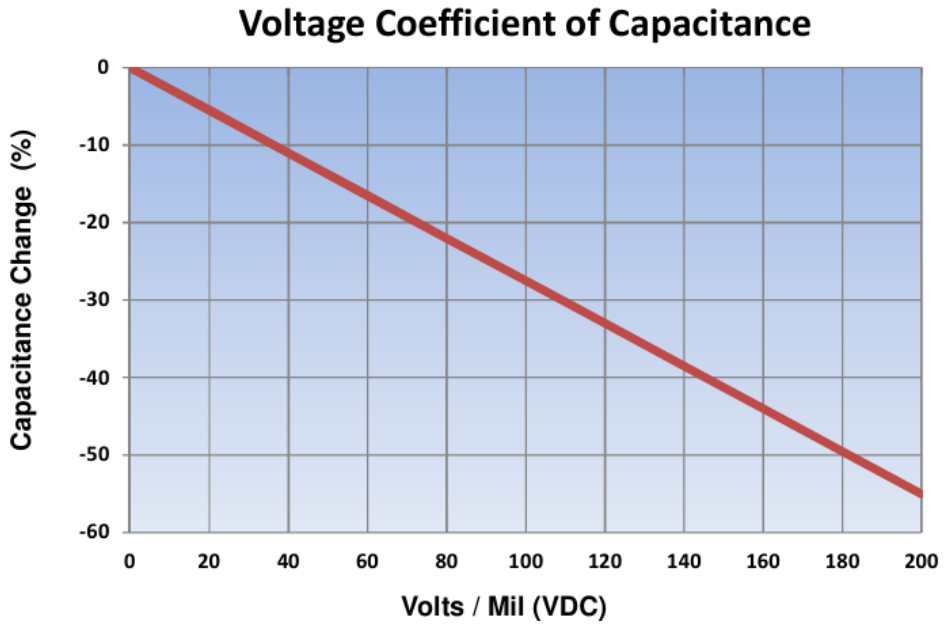




Voltage Coefficient

Voltage Coefficient

- Capacitance can change when voltage is applied
- This is especially evident with Class II dielectrics like X7R



Military Designation	DC Voltage – Temperature Coeffiecient	Voltage Characterization
BX	+15 / -25% @ WVDC & -55 to +125℃	< 500 VDC
BR	+15 / -40% @ WVDC & -55 to +125℃	≥ 500 VDC
BZ	+15 / -45% @ 60% WVDC & -55 to +125℃	≥ 500 VDC

ESR Affect On Pulse Discharge

Time Constant (τ)

$$\tau \text{ (Time Constant)} = RC$$

- 5τ is the amount of time in seconds that it takes for a capacitor to be considered fully discharged

$$5\tau = 5 * (ESR \times C)$$

Impedance Characteristics

Impedance Formulas

$$Z = \sqrt{ESR^2 + (X_L - X_C)^2}$$

$$X_C = 1 / (2\pi f \times C) \quad \& \quad X_L = 2\pi f \times L$$

$$V = I \times Z$$

$$\tau \text{ (Time Constant)} = ZC$$

Impedance Characteristics

Effect Of ESR And ESL On Time Constant

$$Z = \sqrt{ESR^2 + X_L^2}$$

Example: If a capacitor with a frequency of 1 MHz

$$ESR = 0.010\ \Omega \quad \text{and} \quad ESL = 2\ nH$$

$$X_L = 2\pi f \times ESL = 0.013\ \Omega$$

$$\text{Then } Z = \sqrt{(0.010)^2 + (0.013)^2} = 0.016\ \Omega$$

Pulse Capacitor Basics

Calculating Current in a Pulse Capacitor

$$I = C \times dV/dt$$

$$dt \approx ZC$$

$$I \approx C \times dV/ZC$$

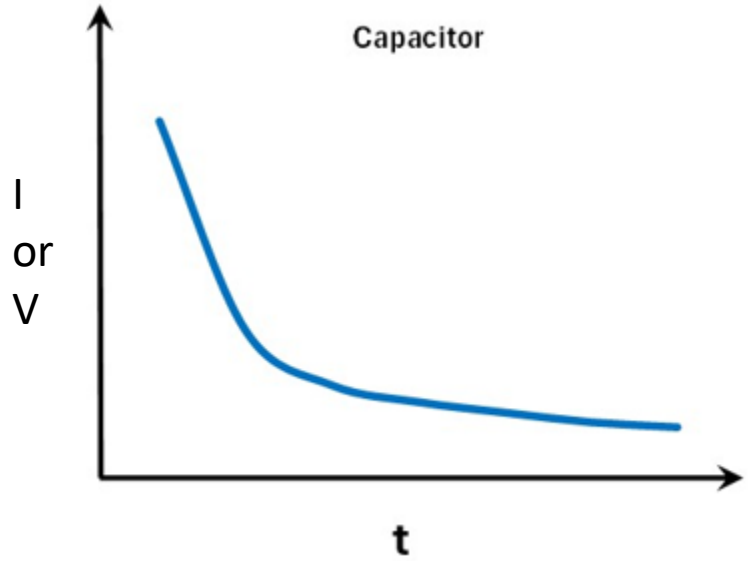
$$V = I \times Z$$

$$I = V / Z$$

- The time constant has a direct impact on the resonance frequency and how fast the capacitor can discharge

Pulse Capacitor Basics

Instantaneous Current in a Pulse Capacitor



$$I = I_o \times e^{-(t/RC)} \; f$$

$$V = V_o \times e^{-(t/RC)} \; f$$

Pulse Capacitor Basics

Calculating Power In A Pulse Capacitor

$$P = E / t$$

$$E = E = \tfrac{1}{2}CV^2$$

- Because stored energy increases with the square of voltage, higher-voltage pulse capacitors can deliver substantially greater energy during discharge

Pulse Capacitor Basics

Reducing Parasitics In A Circuit

- Lead configuration
- Electrode geometry
- Mounting
  - Create as short of conductive path as possible
  - Create as straight a conductive path as possible

- The aim is to minimize resistance and inductance

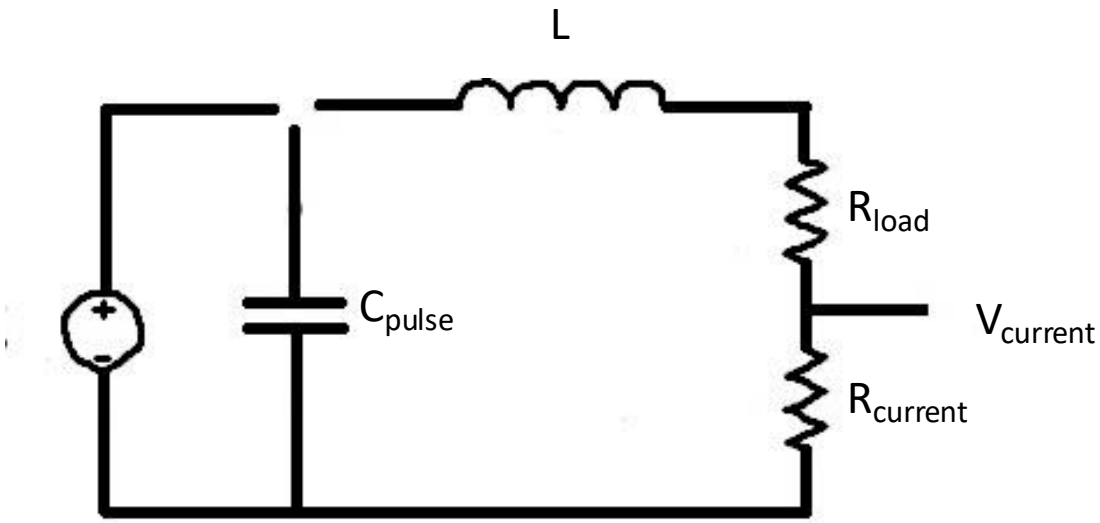
- The faster you need the electrons, the more difficult it is to design

100% USA Manufactured In Reno, NV

CalRamic Technologies LLC

Pulse Capacitor Basics

Typical Pulse Discharge Testing Circuit

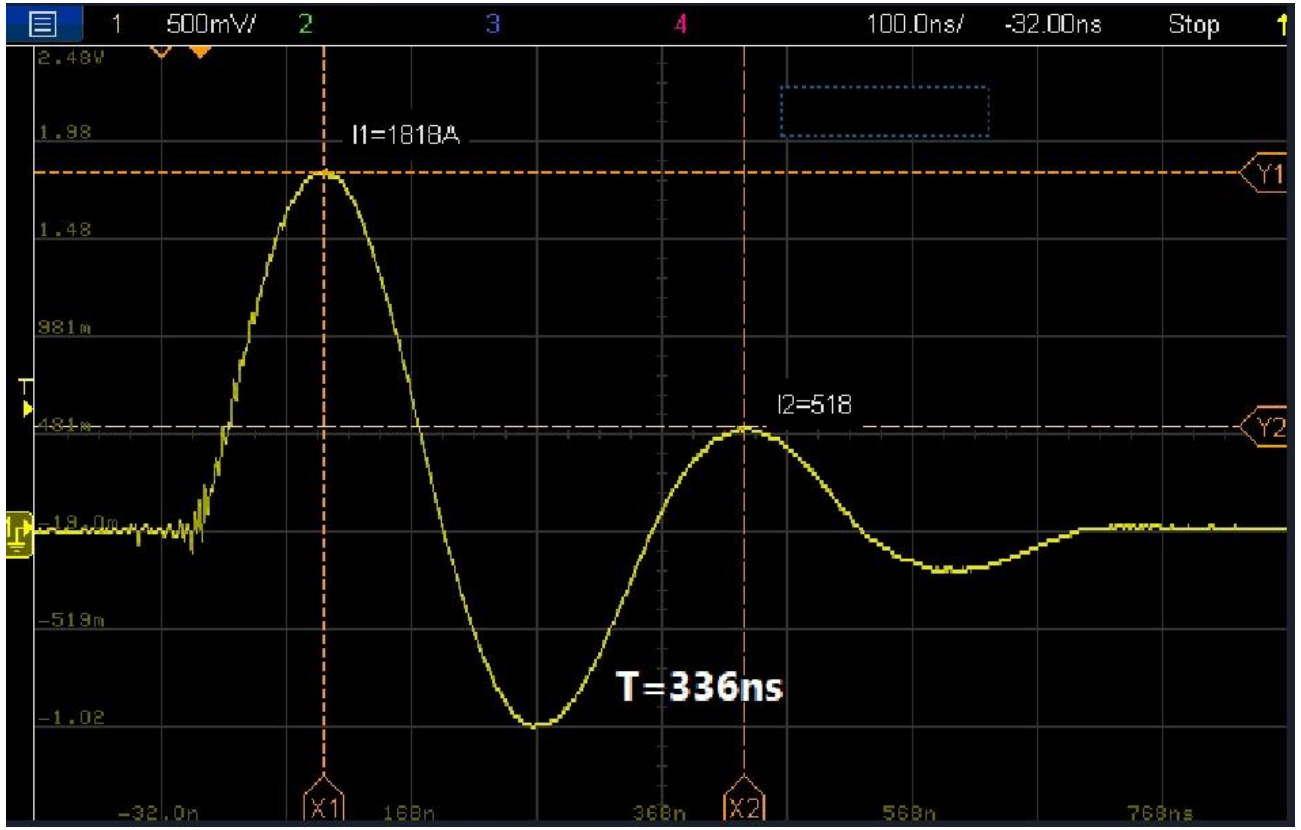


100% USA Manufactured In Reno, NV

CalRamic Technologies LLC

Pulse Capacitor Basics

Typical Pulse Discharge

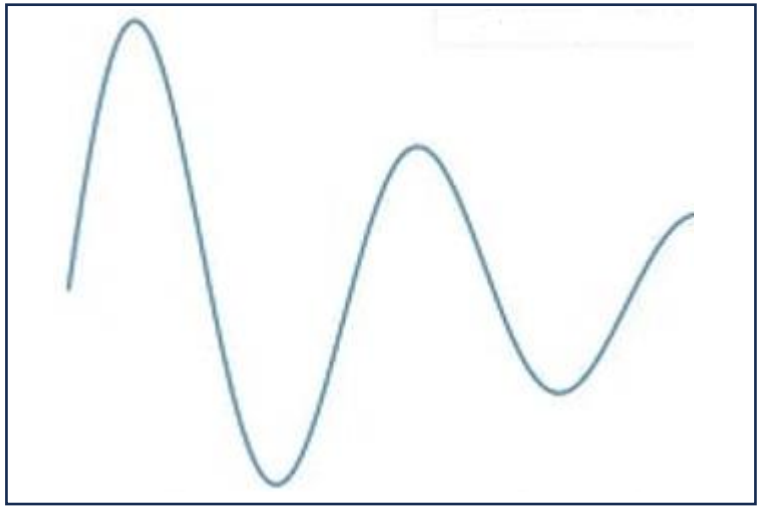


Pulse Capacitor Basics

Taking Advantage Of An Underdamped Circuit

Underdamped Pulse Waveform

V
or
I



Time

$(4 \times L/C) > R^2$

- In certain applications you can take advantage of inductance to achieve a high peak current

Capacitors for Pulse Applications

Summary

- The Pulse Discharge Capacitor Market is positioned for sustained growth, driven by defense modernization, renewable energy integration, medical imaging advancements, and industrial automation.
- Capacitors are an integral part and essential component in almost all aspects of today's technological Ceramic capacitors in particular offer distinct advantages because of their low ESR and ESL characteristics, superior frequency response and higher voltage ratings when compared to other capacitor types and batteries
- Pulse capacitors are designed for rapid discharge
- Pulse capacitors in general are simple in design but complex in behavior
- Parasitic and performance characteristics dictate capacitor selection
- High voltage pulse capacitors are engineered and designed to deliver high energy bursts essential for direct energy weapons and X-Ray generation needed for advanced medical imaging equipment

Contact Details

CalRamic Technologies LLC
5462 Louie Lane
Reno, NV 89511
Main: (775) 851-3580
http://calramic.com

David Zawacki
Vice President / Managing Director
(775) 851-3580 Ext. 200
Dzawacki@calramic.com

Andrew Schweber
Technical Sales Manager
(775) 851-3580 Ext. 204
Aschweber@calramic.com

Michael Roach
Technical Sales Manager
(508) 991-0409
Mroach@calramic.com

"Partnering With Our Clients for Combined Success"