NASA's Evolutionary Xenon Thruster (NEXT) Power Processing Unit (PPU) Capacitor Failure Root Cause Analysis

The NASA's Evolutionary Xenon Thruster (NEXT) project is developing an advanced ion propulsion system for future NASA missions for solar system exploration. A critical element of the propulsion system is the Power Processing Unit (PPU) which supplies regulated power to the key components of the thruster. The PPU contains six different power supplies including the beam, discharge, discharge heater, neutralizer, neutralizer heater, and accelerator supplies. The beam supply is the largest and processes up to 93+% of the power. The NEXT PPU had been operated for approximately 200+ hours and has experienced a series of three capacitor failures in the beam supply. The capacitors are in the same, nominally non-critical location – the input filter capacitor to a full wave switching inverter. The three failures occurred after about 20, 30, and 135 hours of operation. This paper provides background on the NEXT PPU and the capacitor failures. It discusses the failure investigation approach, the beam supply power switching topology and its operating modes, capacitor characteristics and circuit testing. Finally, it identifies root cause of the failures to be the unusual confluence of circuit switching frequency, the physical layout of the power circuits, and the characteristics of the capacitor.

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James F. Soeder, Luis Pinero – NASA Glenn Research Center
Robert Scheidegger – NASA Glenn
John Dunning – Alpha-port Inc.,
Art Birchenough – QinetiQ-NA Inc.

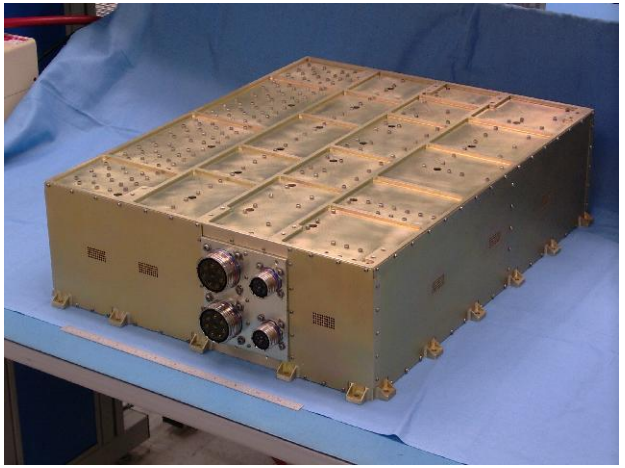
Discussion Topics

- PPU background
- Failure #3 Investigation
- Key Findings
  - Beam module testing and analysis
  - Capacitor testing and analysis
- Electrical Testing to Mimic in Circuit Phenomena
- Failure Conclusions and Corrective Actions
- Summary

NASA's Evolutionary Xenon Thruster (NEXT) Background

- 7.0 kW ion propulsion system
- Leverages elements from NSTAR (DEEP Space I)
- Designed to meet propulsion requirements of Jupiter/Saturn DRMs
- PPU was constructed with the objective of flight-like form/fit/function
- Multiple functional test cycles conducted in ambient/vacuum with resistive load/thruster
- Environmental qualification-level testing planned until string of failures occurred

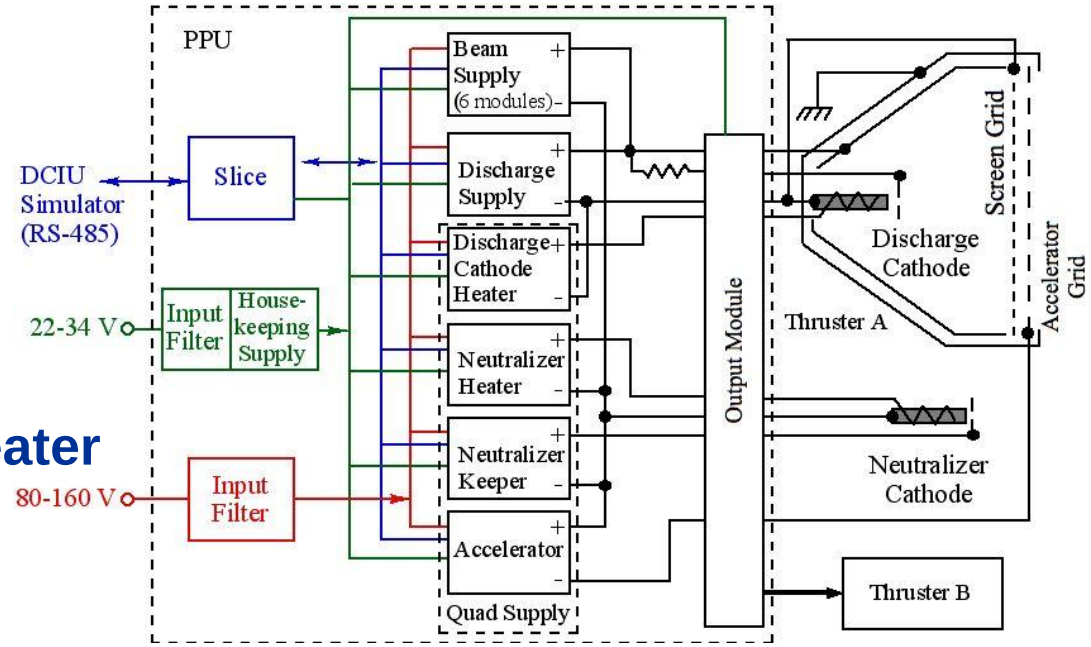
NEXT Thruster



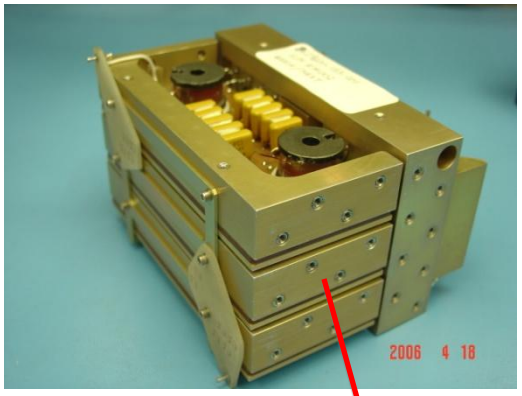
NEXT PPU

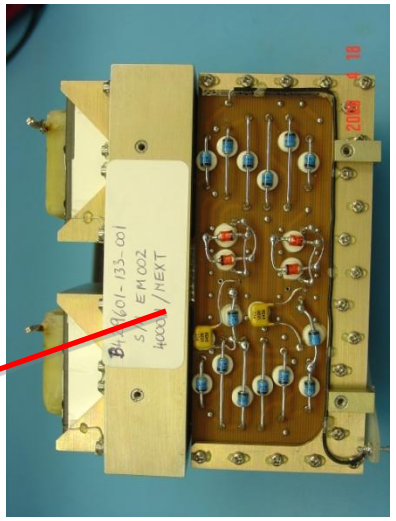
NEXT Power Processing Unit (PPU)

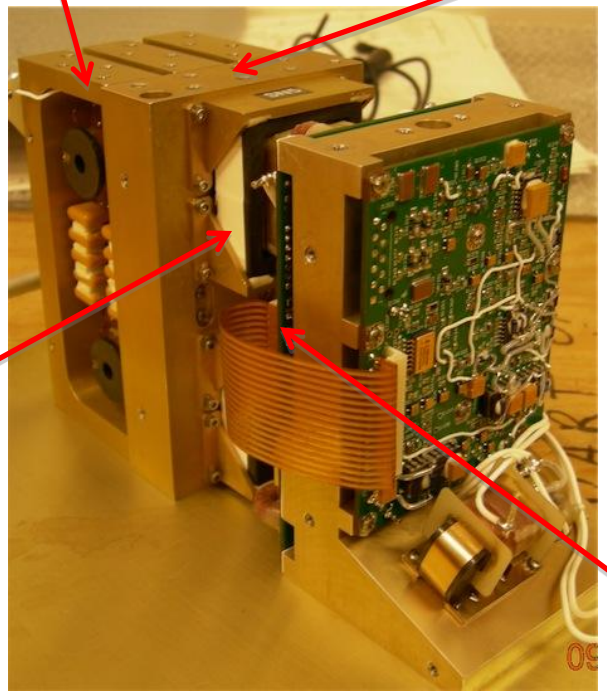
- **Modular Design featuring 7 power supplies**
  - **Discharge supply**
  - **Quad supply containing**
    - **Accelerator**
    - **Neutralizer keeper**
    - **Discharge cathode heater**
    - **Neutralizer heater**
  - **Housekeeping power**
  - **Beam supply**
    - **Processes 93% total power**
    - **Up to 96% efficient**
    - **Contains 6 parallel modules**
    - **Input Voltage: 80 to 160 V**
    - **Output voltage: 275 to 1800 V**

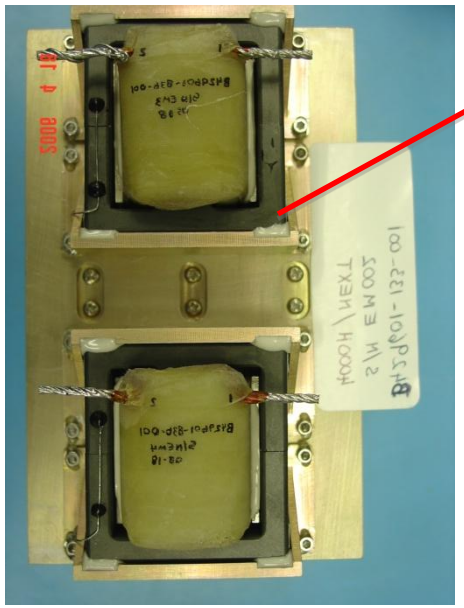


BEAM MODULE

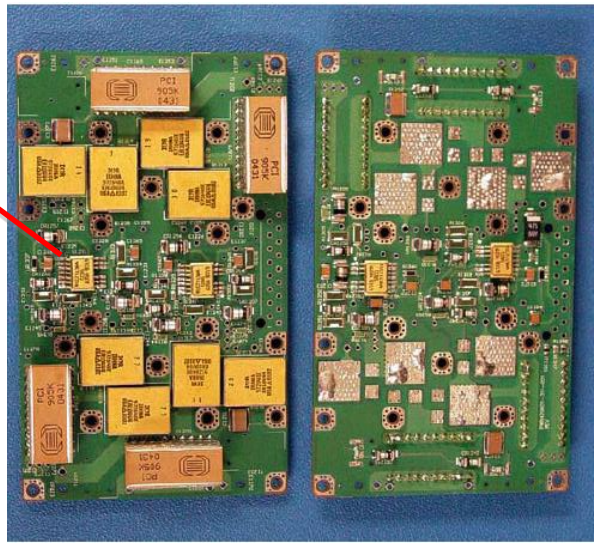








POWER PWB

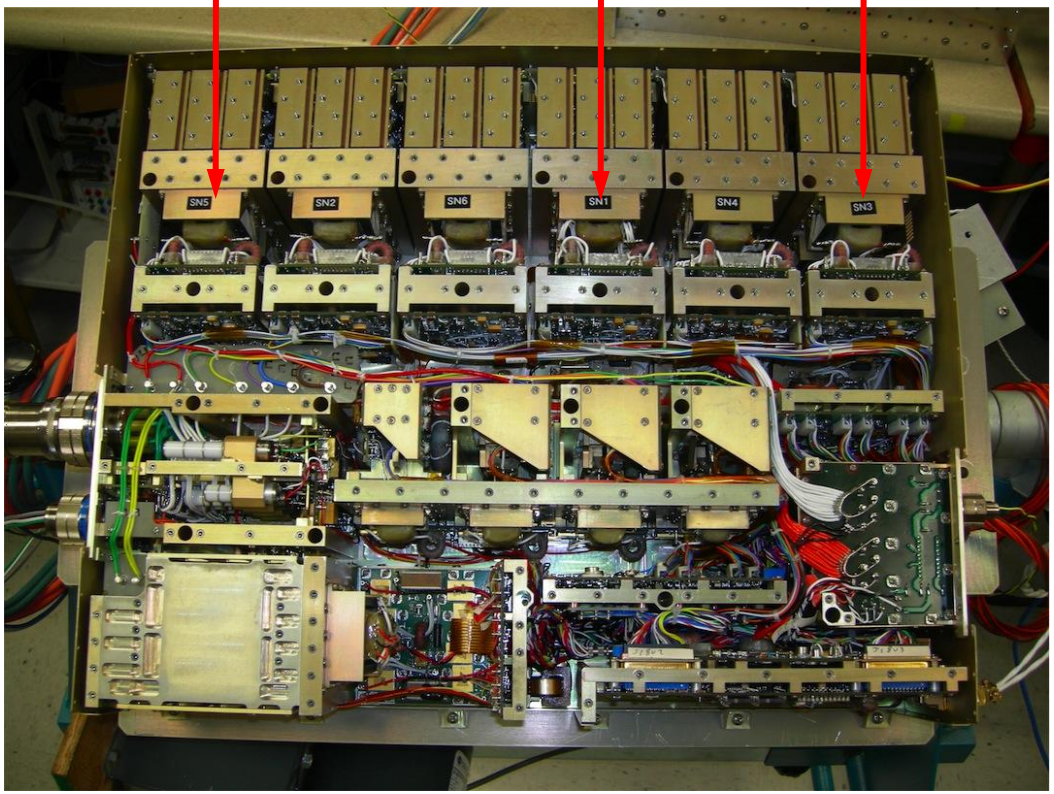


Background MLC Capacitor Failures

1st failure
Module #1
March 2008

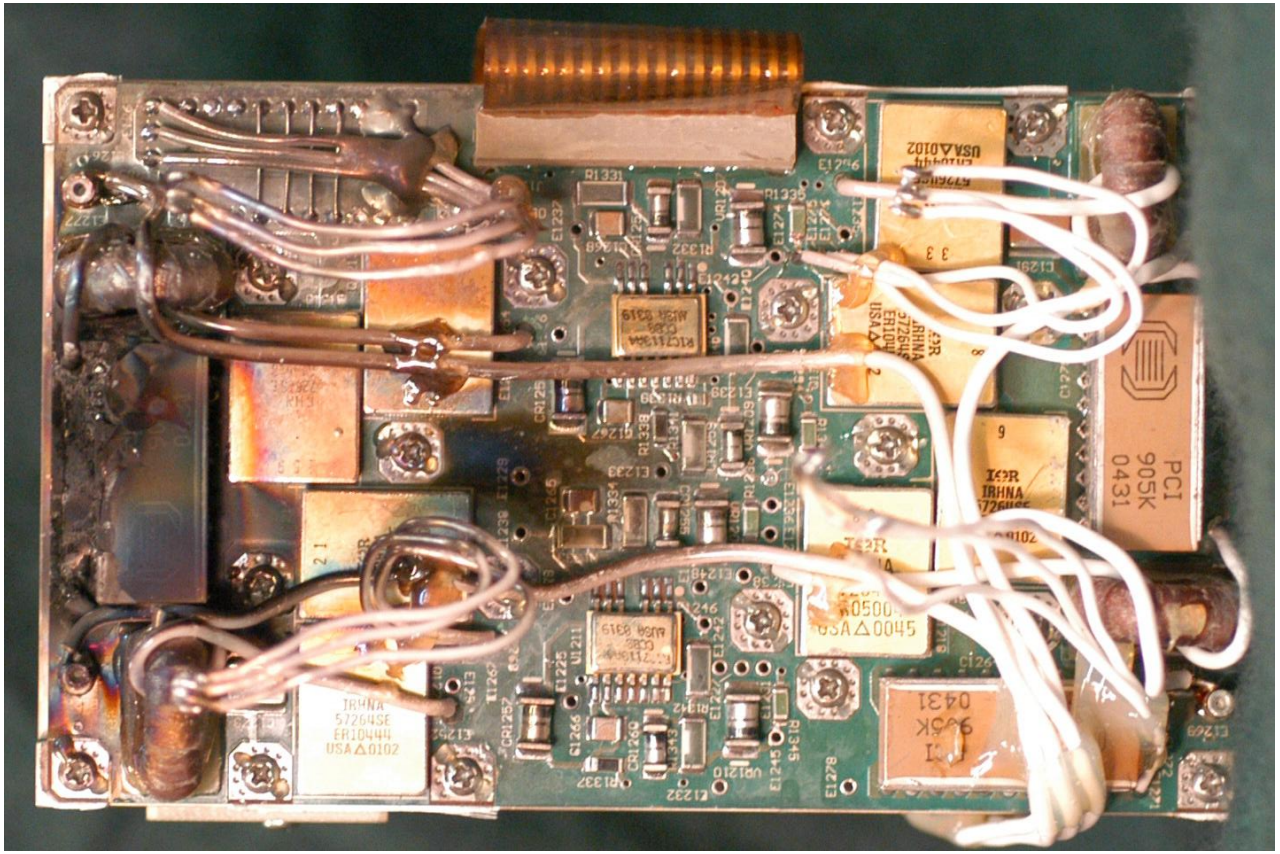
3rd failure
Module #4
April 2010

2nd failure
Module #6
Feb 2009



Failure #3 Investigation

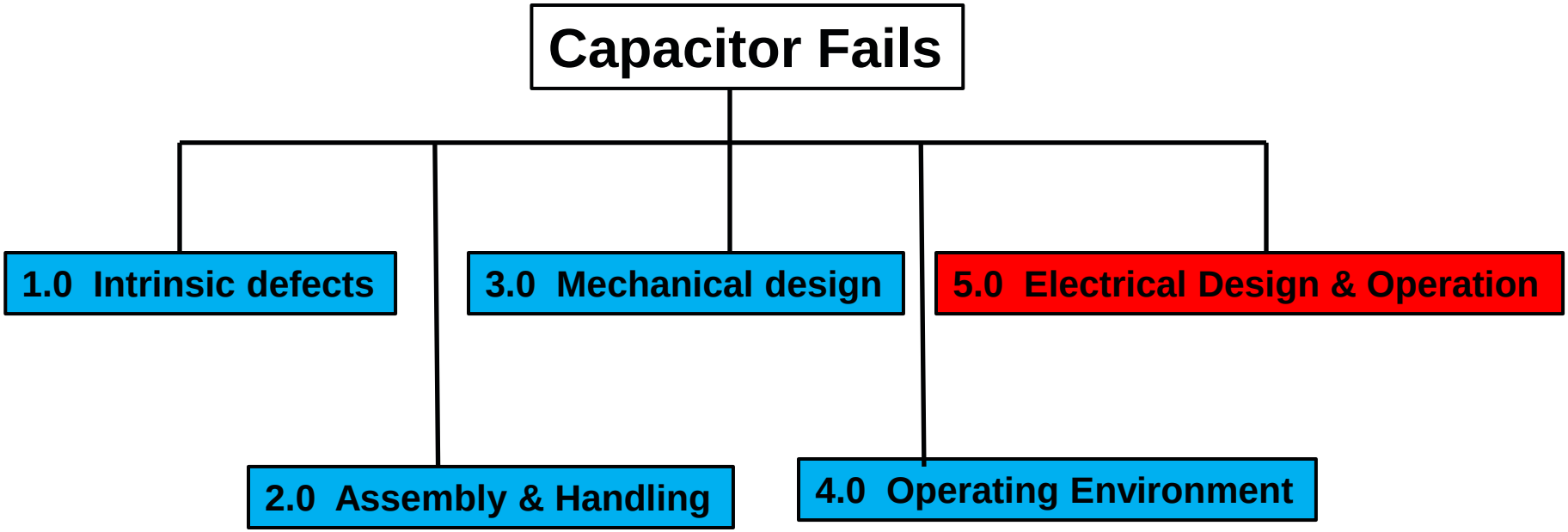
Module #4 PC Board (Post Failure)



Module #4 failure

- **Top capacitor**
- **50˚C baseplate temp.**
- **Operating at 3.5 kW**
- **4 modules @ 820 W/module**
- **Failed during forced recycle**
- **160 V input**
- **< 136 hrs operating in vacuum**

PPU Capacitor Failure Tree



Color Code

Very Likely	
Likely	
Not Likely	
Cleared	

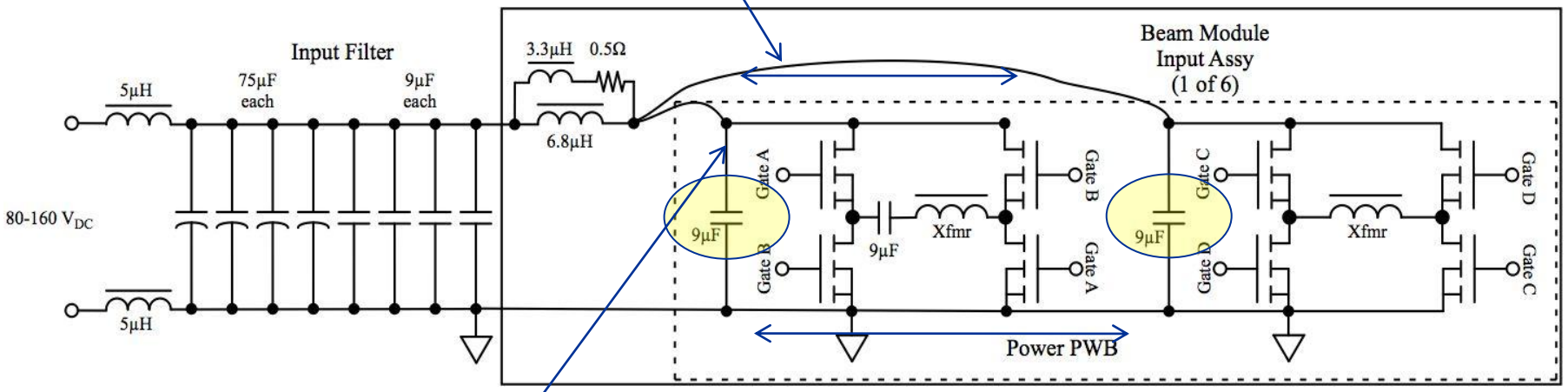
Key Findings

Beam module testing and analysis

Beam Supply
Simplified Schematic

Circulating Current

16A p-p @ 200kHz



Ripple Current

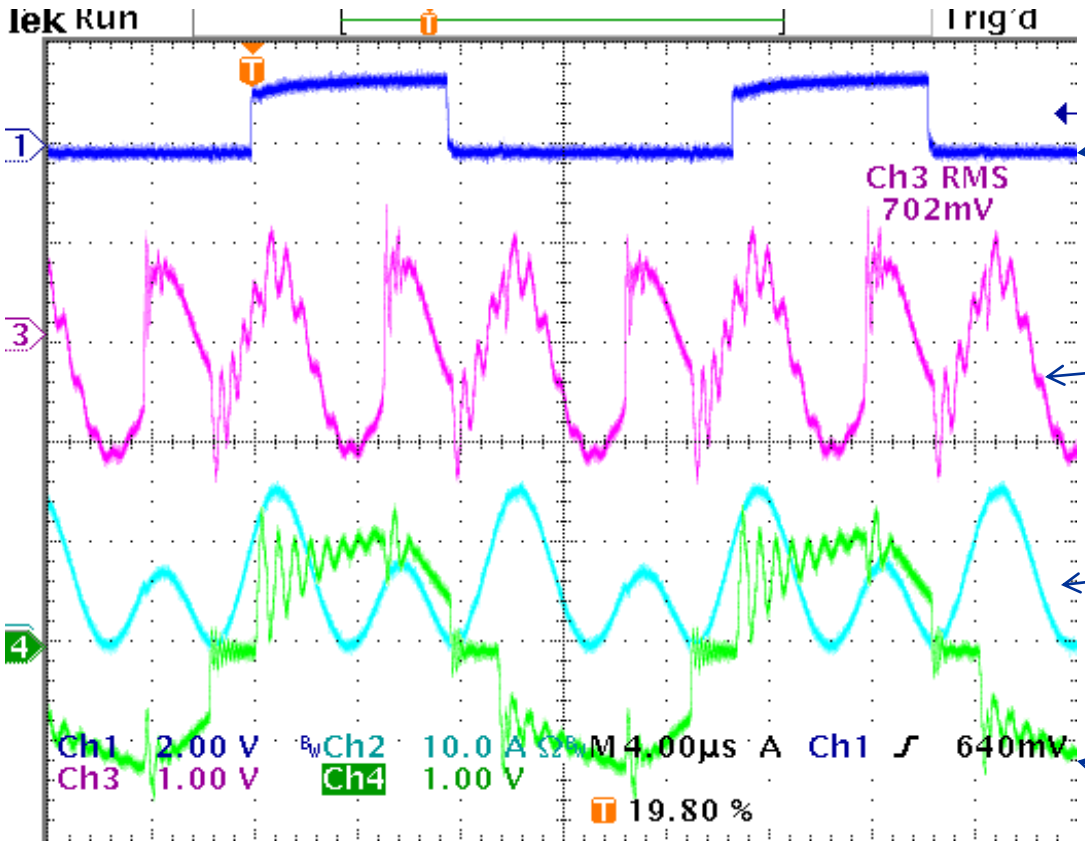
20A p-p @ 200kHz

Failures #1 &# 2

Failure #3

Circulating Current between Two Capacitors In Phase Shift Mode

Cap Current and Circulating Current



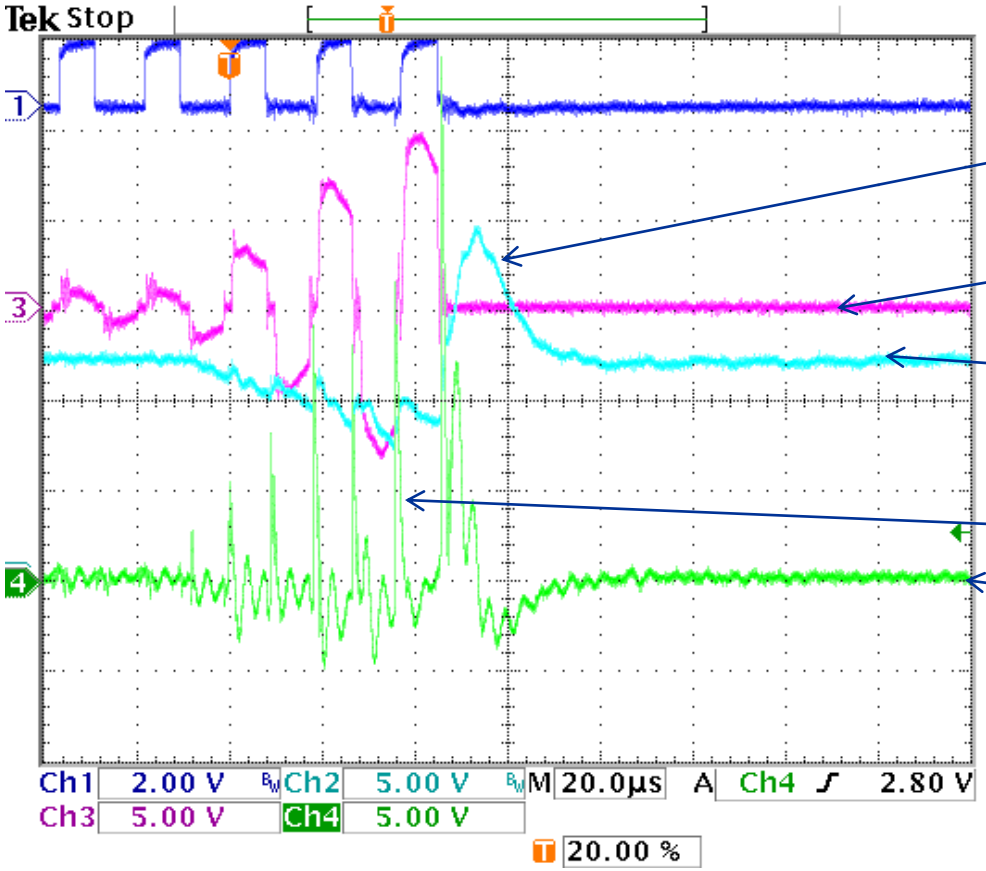
Gate Drive

Capacitor Ripple Current is 20 A p-p @ 200 kHz

Capacitor Circulating Current is 16 A p-p @ 200 kHz

Transformer Current

Capacitor Current and Voltage During a Fault



Voltage Hump

Transformer Current
50 amps / div

Cap Voltage
50 Volts/ div

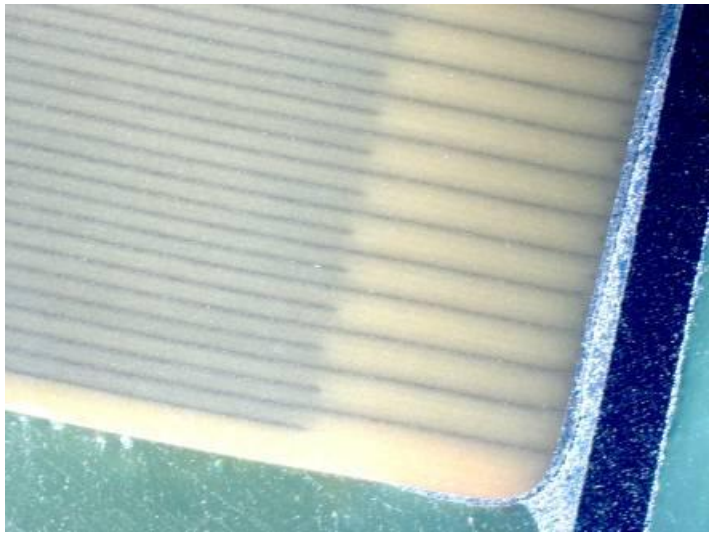
Current Spikes

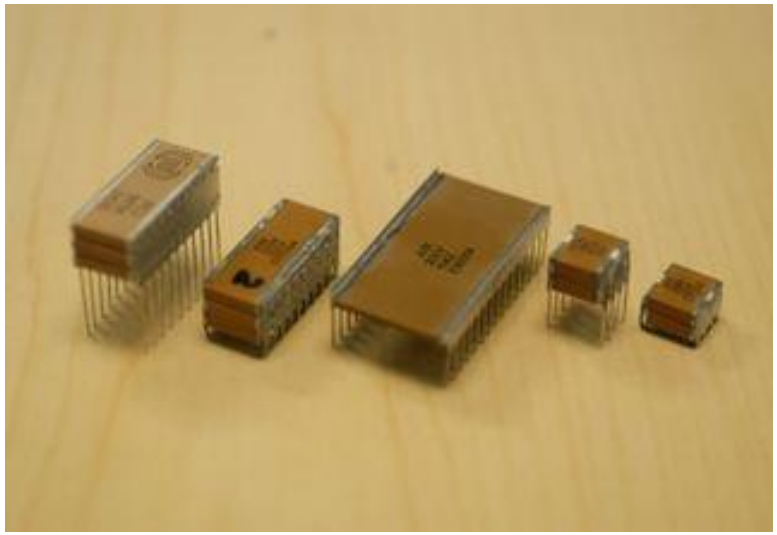
Cap Current
50 amps / div

Key Findings

Capacitor testing and analysis

Ceramic Capacitors

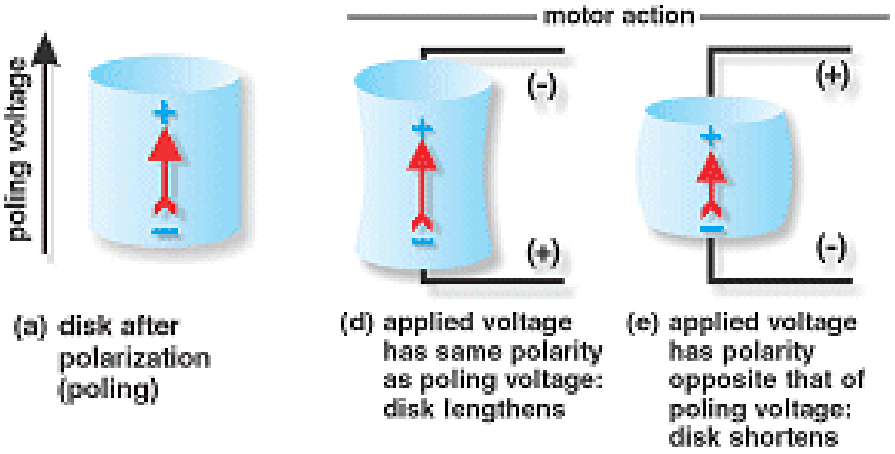




- A ceramic capacitor is constructed of alternating layers of metal and ceramic, with the ceramic material acting as the dielectric.
- A typical dielectric material is X7R – a form of Barium Titanate
  - Minor Dopants change the electrical and mechanical properties
- Barium Titanate can be highly piezoelectric based on the additives used

Piezoelectricity

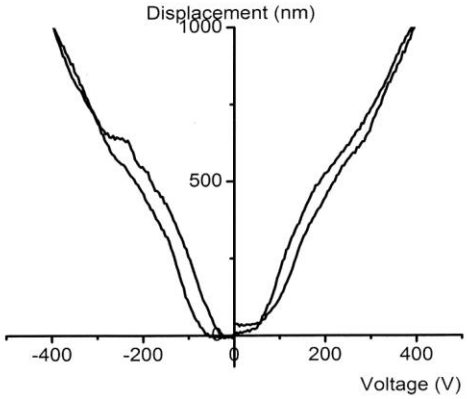
Piezoelectricity is a form of electricity created when certain crystals are bent or otherwise deformed. These same crystals can also be made to bend slightly when a small current is run through them,



Barium Titanate (the capacitor dielectric) is piezoelectric

Displacement = f (Electric Field)

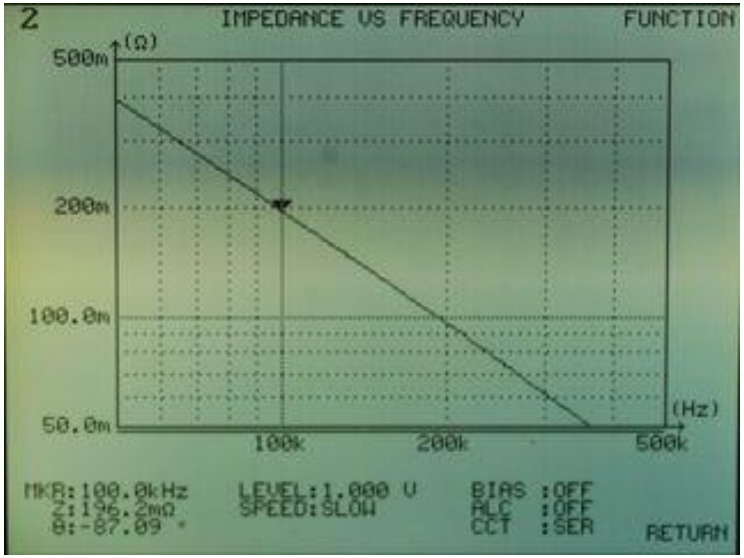
GRC Measured Data on Custom Capacitor



Ceramic Capacitor Used in the Beam Supply

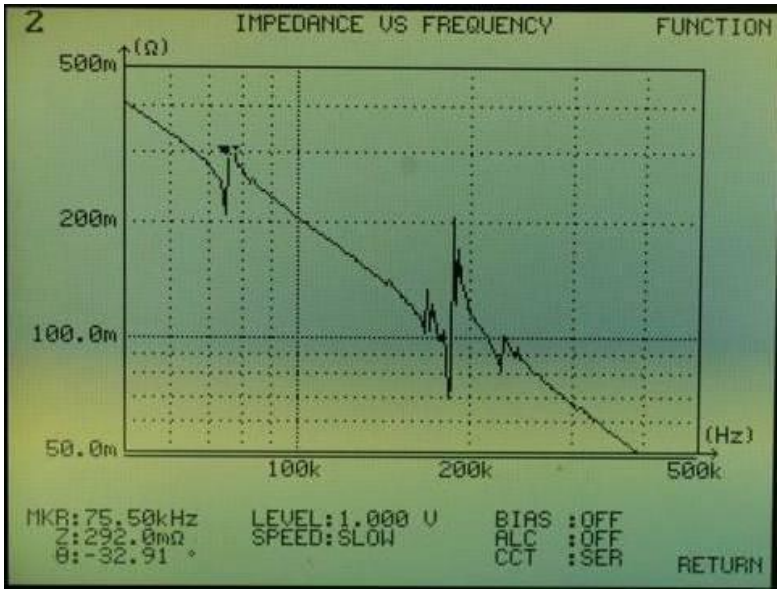
- Custom Part – 9uf; 300 Volt ceramic capacitor; case code #3
- This custom dielectric formulation is highly piezoelectric
  - Easily polarized by applied voltage at elevated temperature
  - Internal mechanical resonances a function of case dimensions
    - Frequency = (Velocity of Sound in Dielectric) / 2* (Length Dimension)
  - Electrical behavior is a strong function of frequency near resonances
  - Capacitance drops with applied voltage

New Custom Caps from Stock



Not subjected to temperature or voltage

Custom Caps Burned-In @ 125˚C and 600 V_{DC}



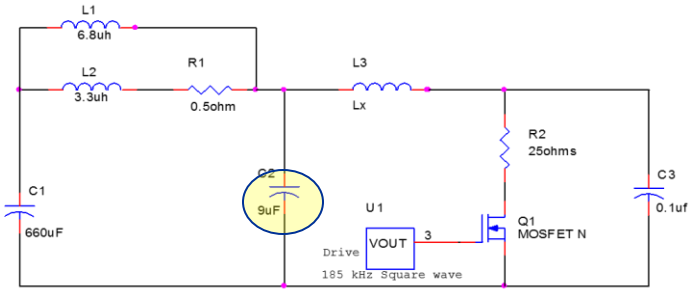
- **Temperature and voltage polarizes the dielectric creating the piezoelectric effect.**
- **Spike in the impedance indicate piezoelectric resonant frequencies.**
- **Resonant frequencies are function of ceramic slab dimensions and material.**

Electrical Testing to Mimic in Circuit Phenomena

Test Circuits

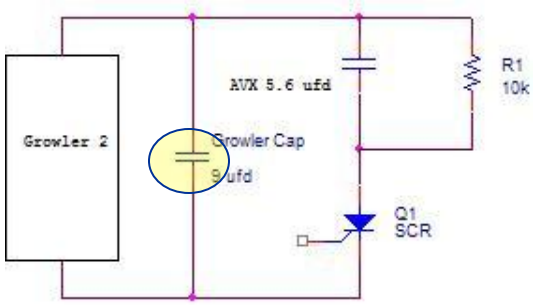
Growler

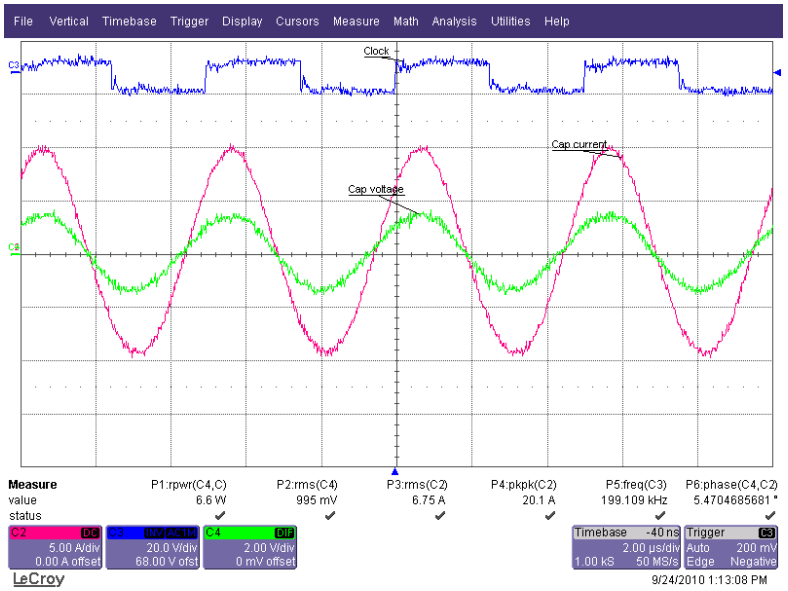
- Provides 7.5 amps rms of sinusoidal circulating current @ 170 to 220 kHz



Growler / V-Thumper

- Augment the growler circuit with a 75 volt transient 3 times / second to simulate recycle conclusion



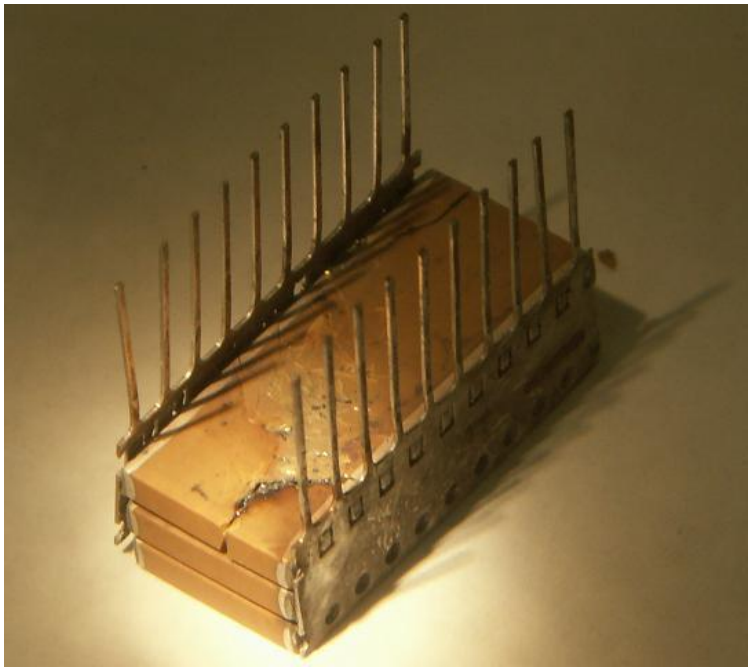


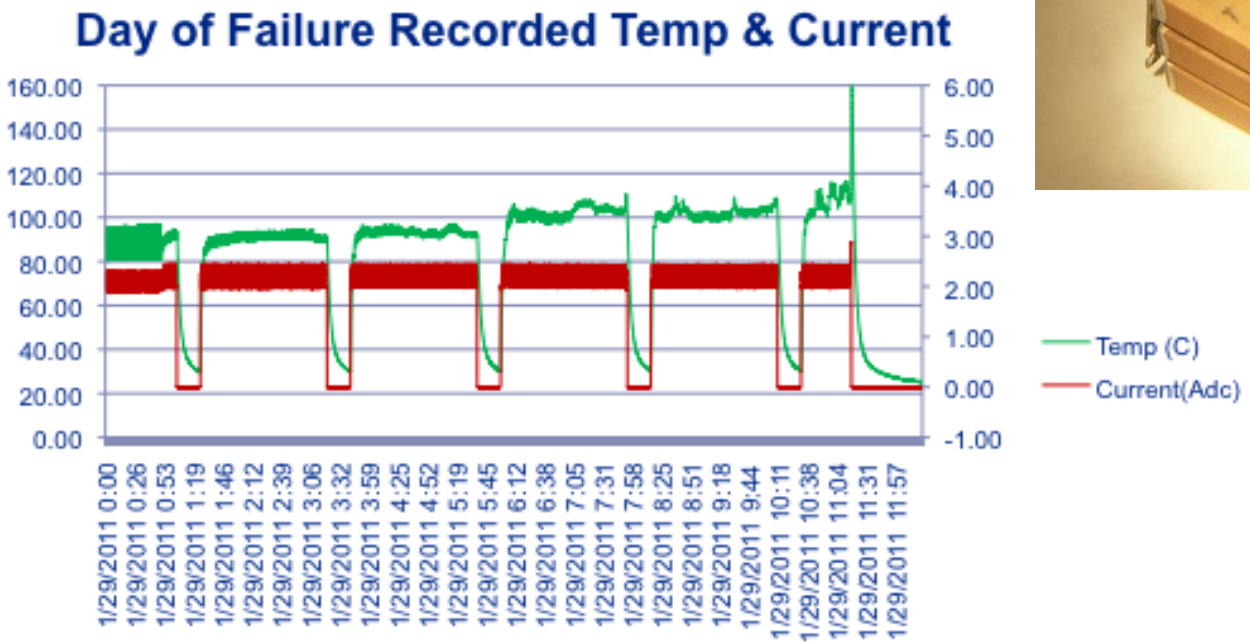
- 200kHz
- 5.47 degree phase lag

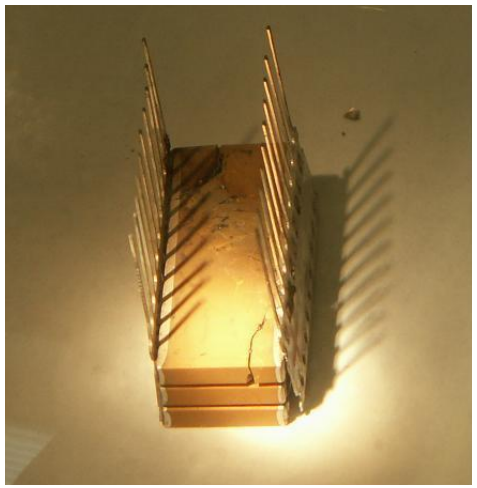
FRB Cap Failure #3

Failure Specifics

- 345 total hours
- In Vacuum & Air
- Exercised at 192-205 kHZ
  (90sec sweep)

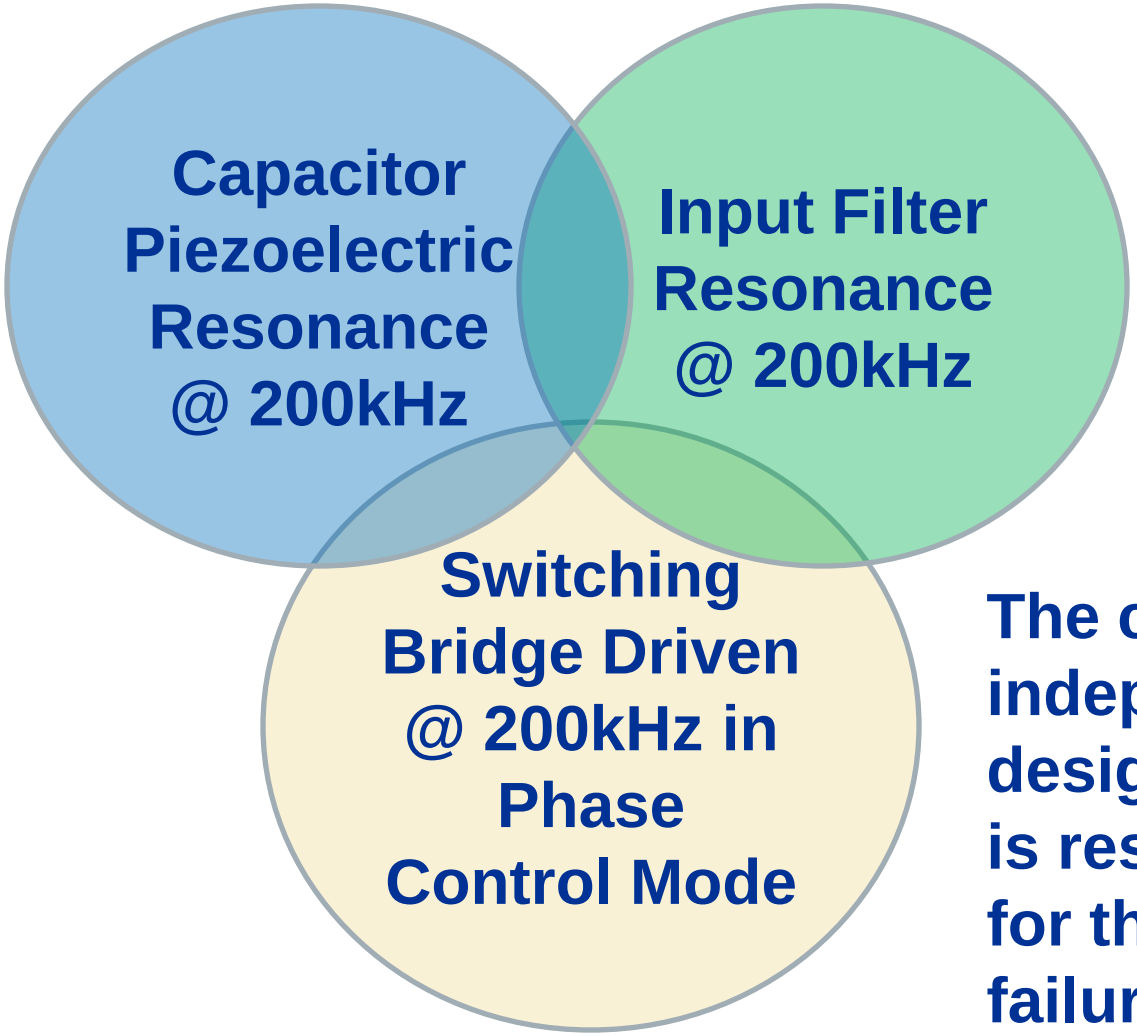






Failure Conclusions and Corrective Action

Summary of Failure Mechanism

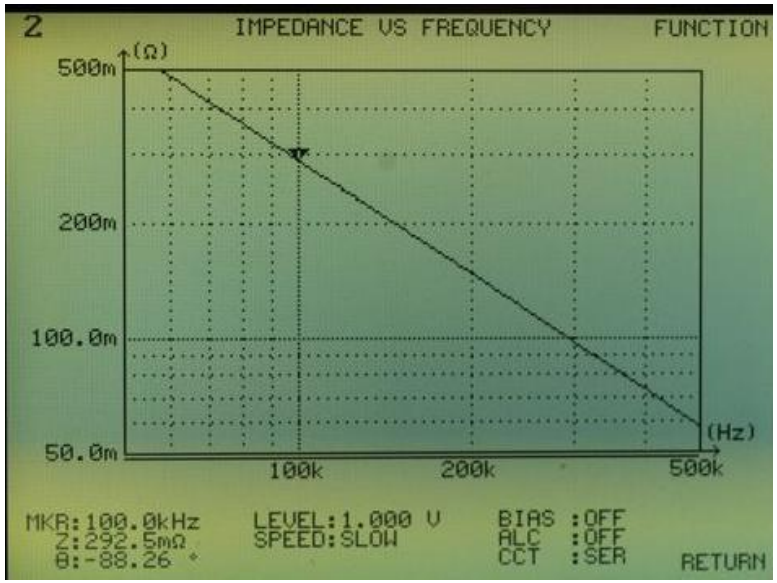


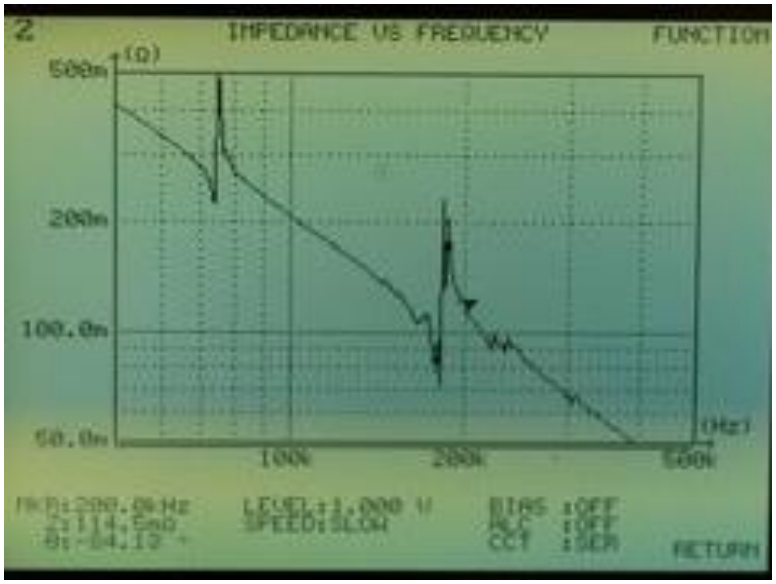
The confluence of 3 independent design elements is responsible for the capacitor failure

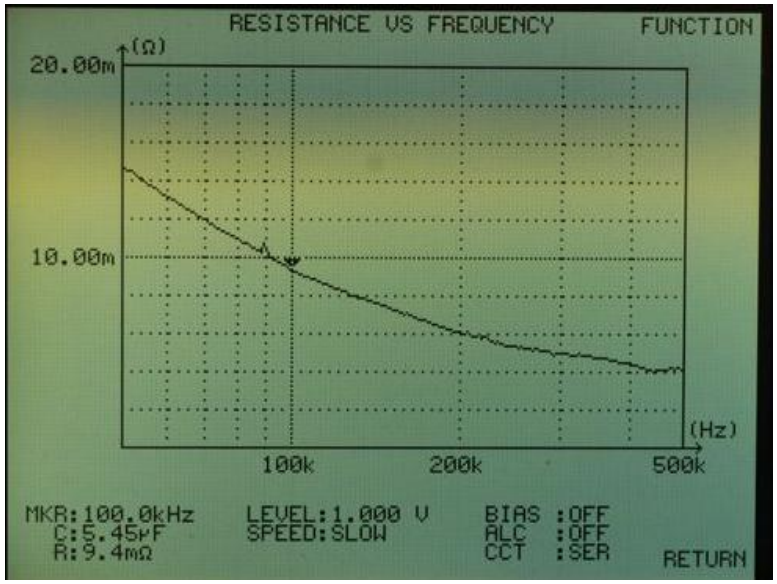
Replacement 5.6µF/500V

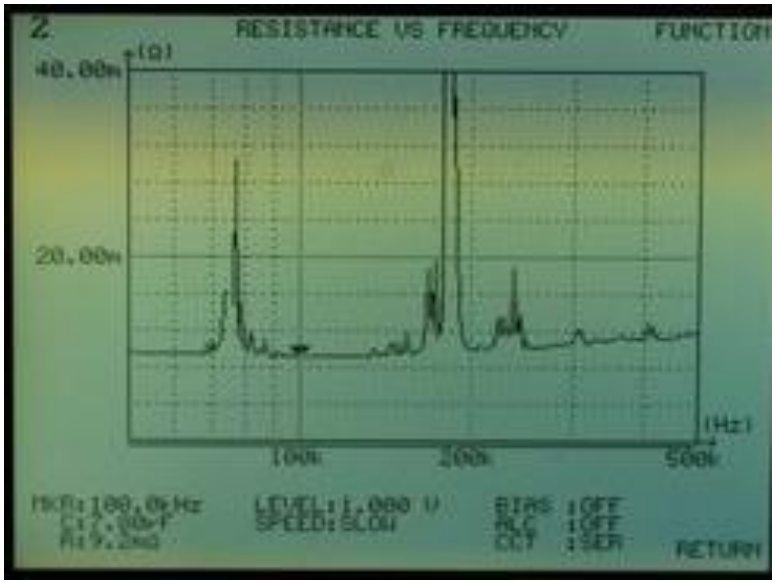
0 volt Bias

Custom 9µF/300V

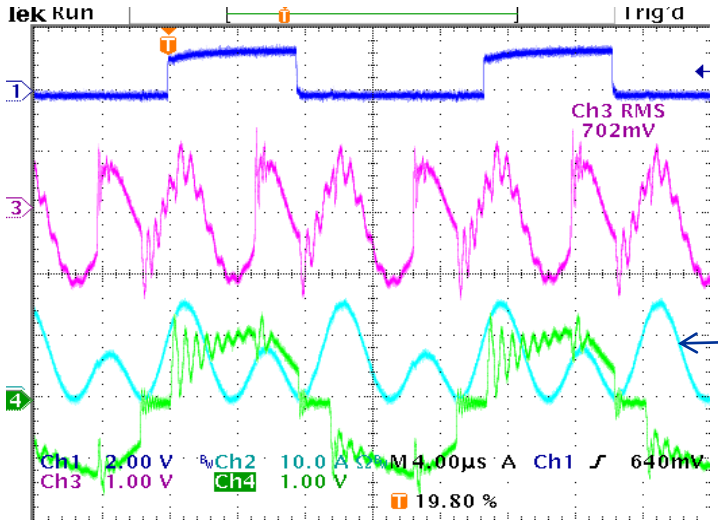




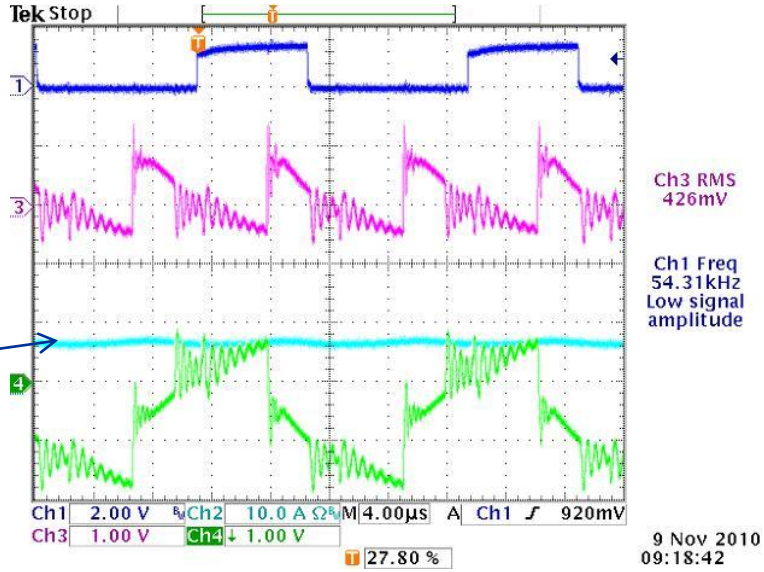




Reduce Circulating Current



Capacitor Circulating Current

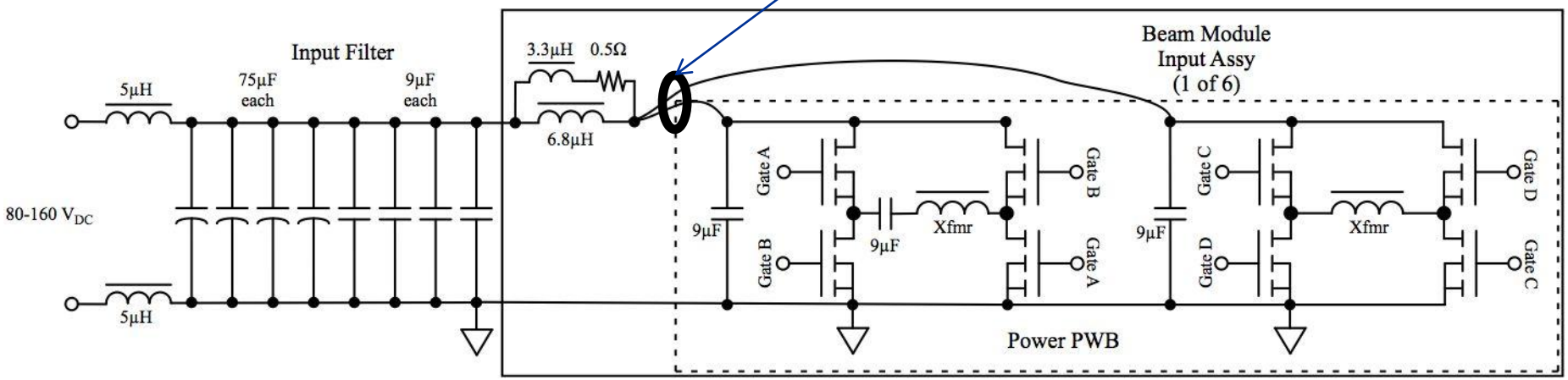


Before

After

Added MPP* Core Differential Mode Choke

*** Molybdenum Permalloy Powder**



Summary

- Piezo-electric characteristics of the Custom Capacitor at the operating frequency of the beam power supply led to its failure in this application
- Circulating currents at the operating frequency within the bridge aggravated the problem
- Recycle of the beam supply may be final trigger of the failure but is not the primary cause
- Replace capacitors with a non-piezoelectric capacitor
- Add MPP Core to eliminate circulating current

Capacitor problem has been solved