Capacitor Failure Investigation Results for the NEXT Ion Thruster Power Processing Unit (PPU)

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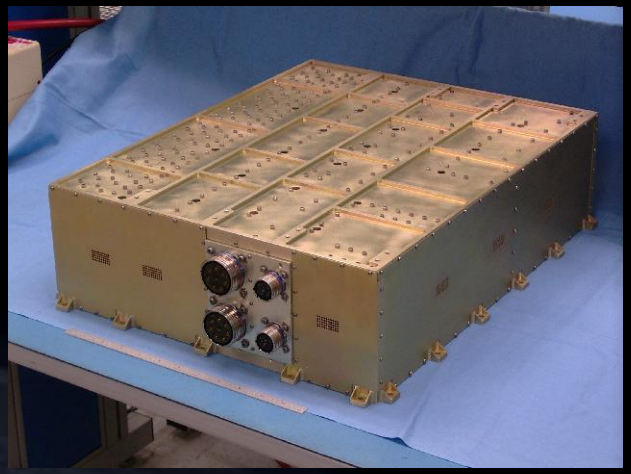
Discussion Topics

- 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

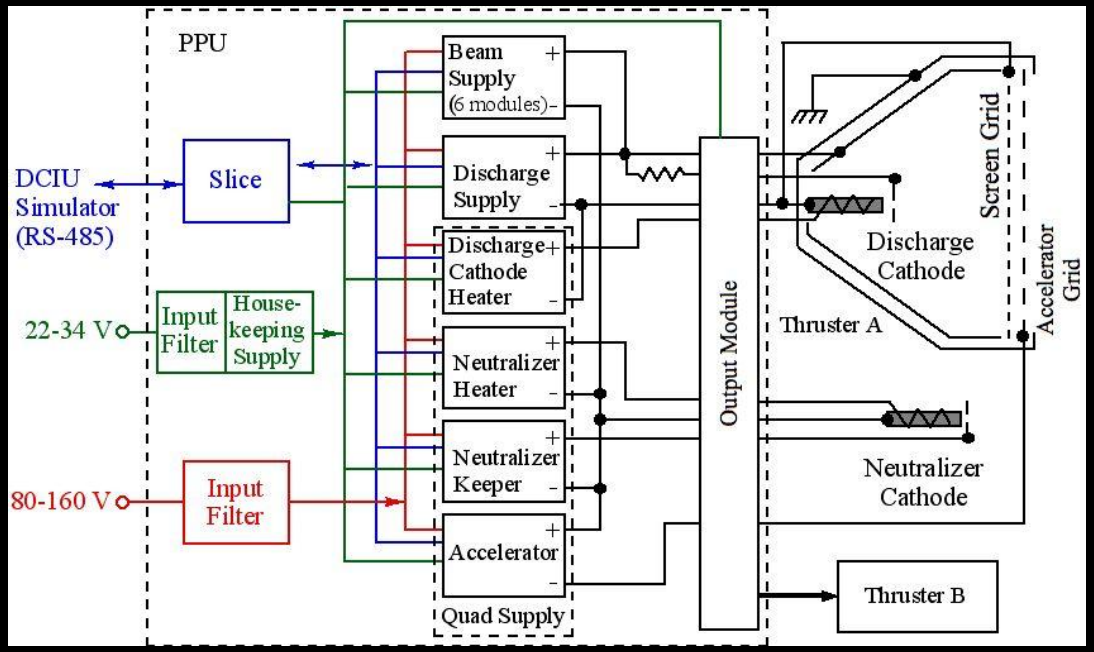
NEXT Thruster



NEXT PPU

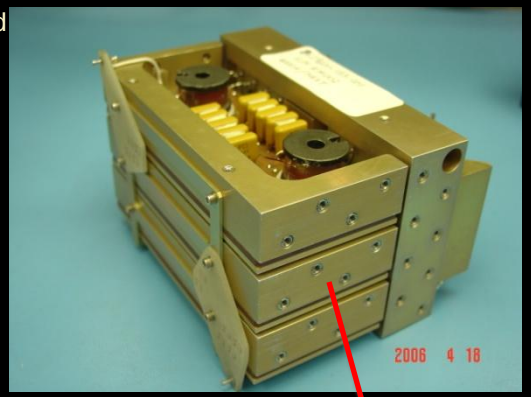
NEXT Power Processing Unit

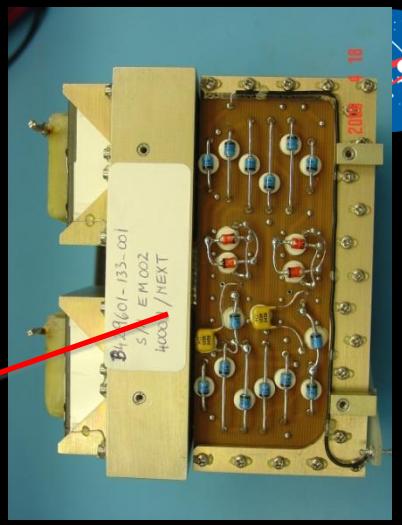
- Modular design featuring 7 power supplies
  - Discharge supply
  - Quad supply containing
    - Accelerator
    - Neutralizer keeper
    - Discharge cathode heater
    - Neutralizer heater
  - Housekeeping power
  - Beam supply
    - Processes 93% total power
    - Up to 96% efficient
    - Contains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

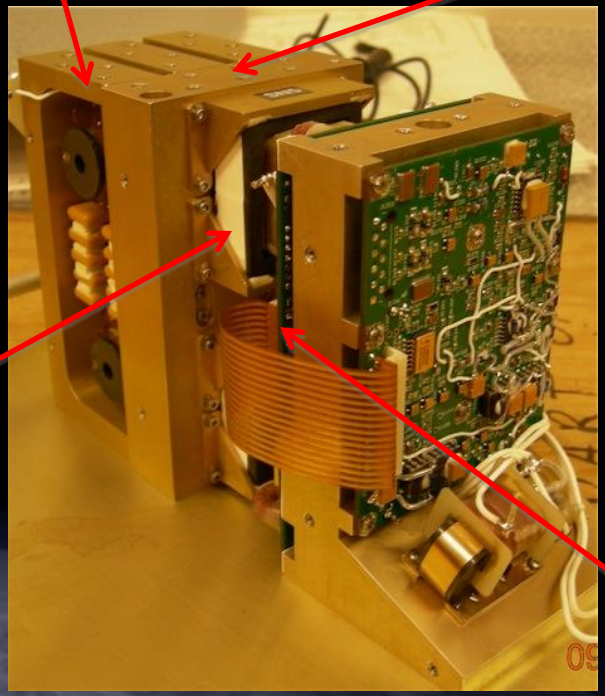


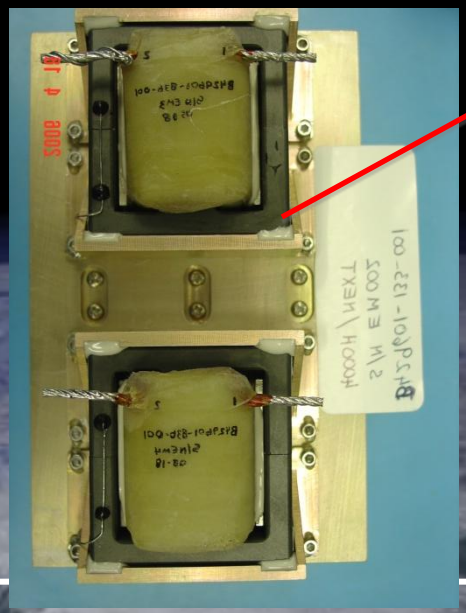
National Aeronautics and

BEAM MODULE

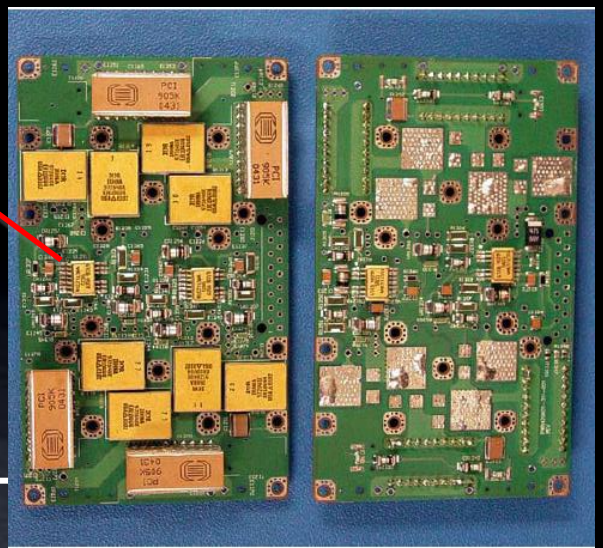








POWER PWB

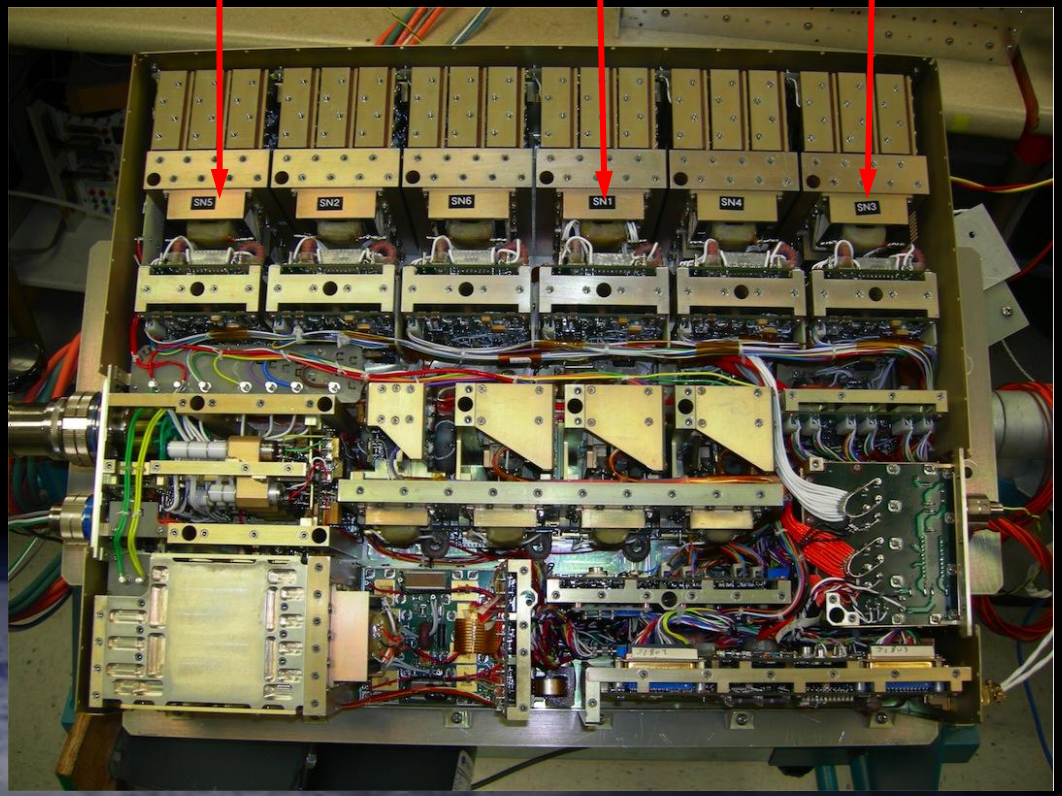


Background MLC Capacitor Failures

1st failure
Module #1
March 2008

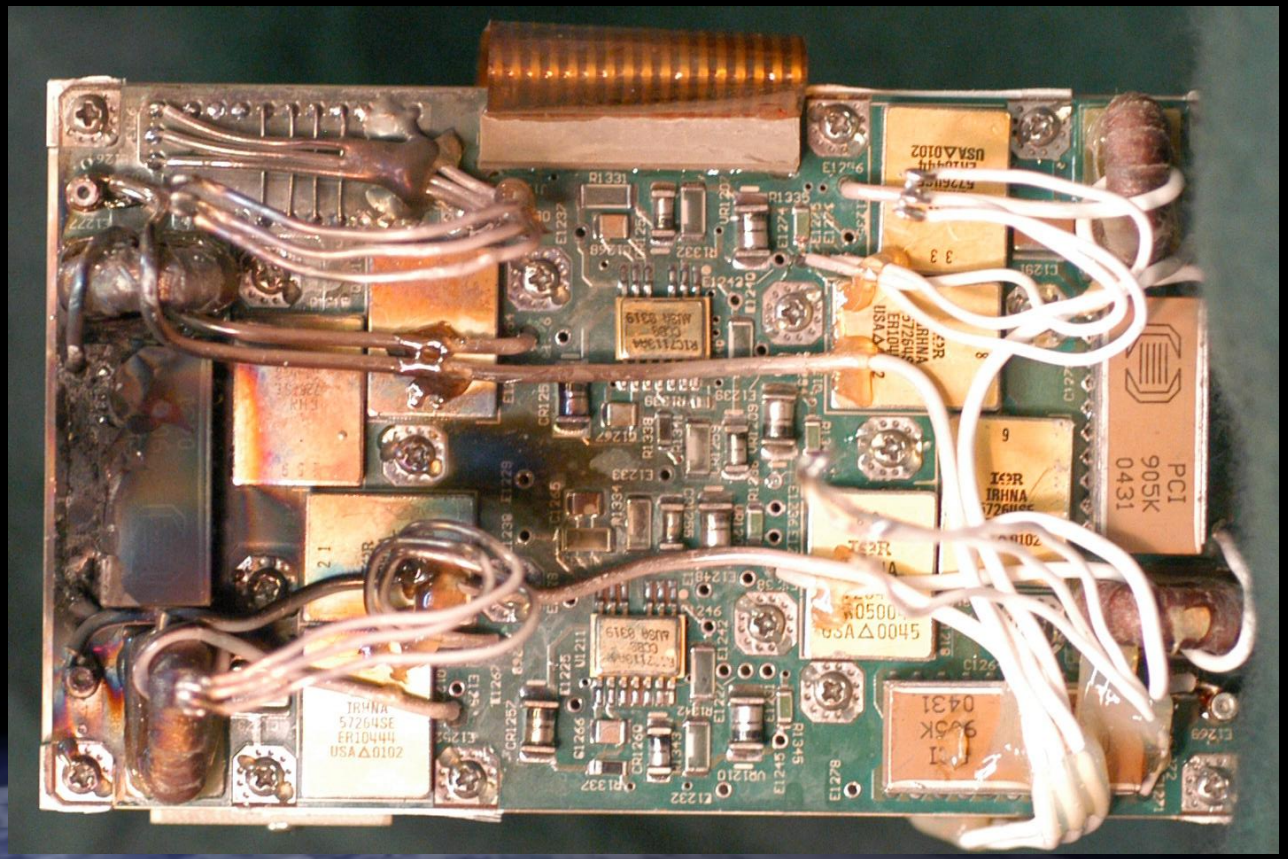
3rd failure
Module #4
April 2010

2nd failure
Module #6
Feb 2009



Failure #3 Investigation

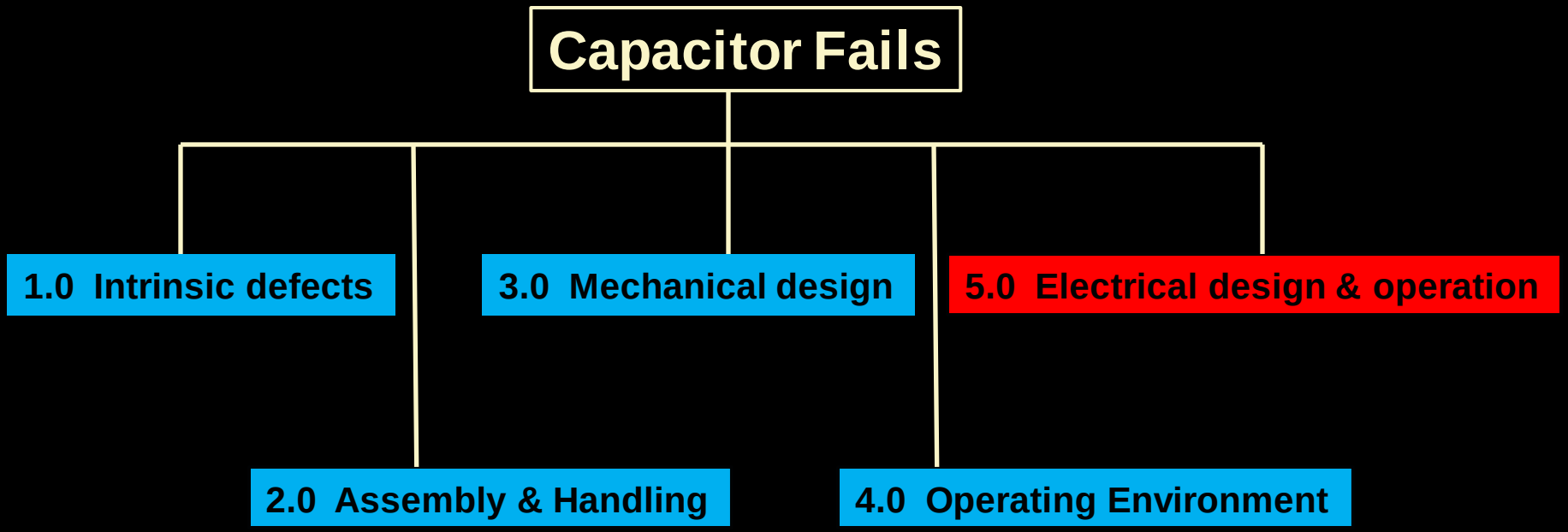
Module #4 PC Board (Post Failure)



Module #4 failure

- **Top capacitor**
- **50˚C baseplate temp.**
- **Operating at 3.5kW**
- **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	
Clear	

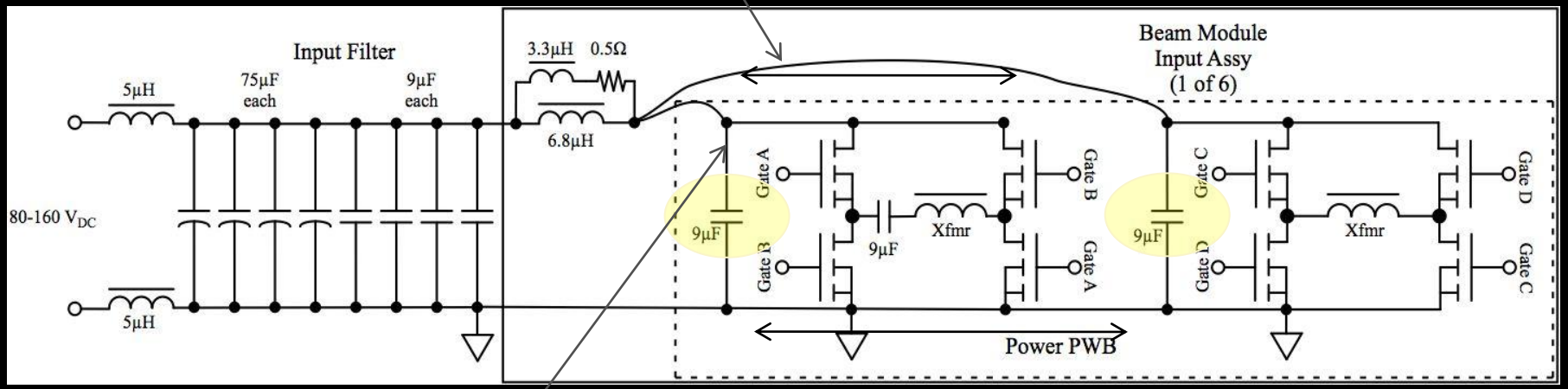
Key Findings

Beam module testing and analysis

Beam Supply Simplified Schematic

Circulating Current

16A p-p @ 200kHz



Ripple Current

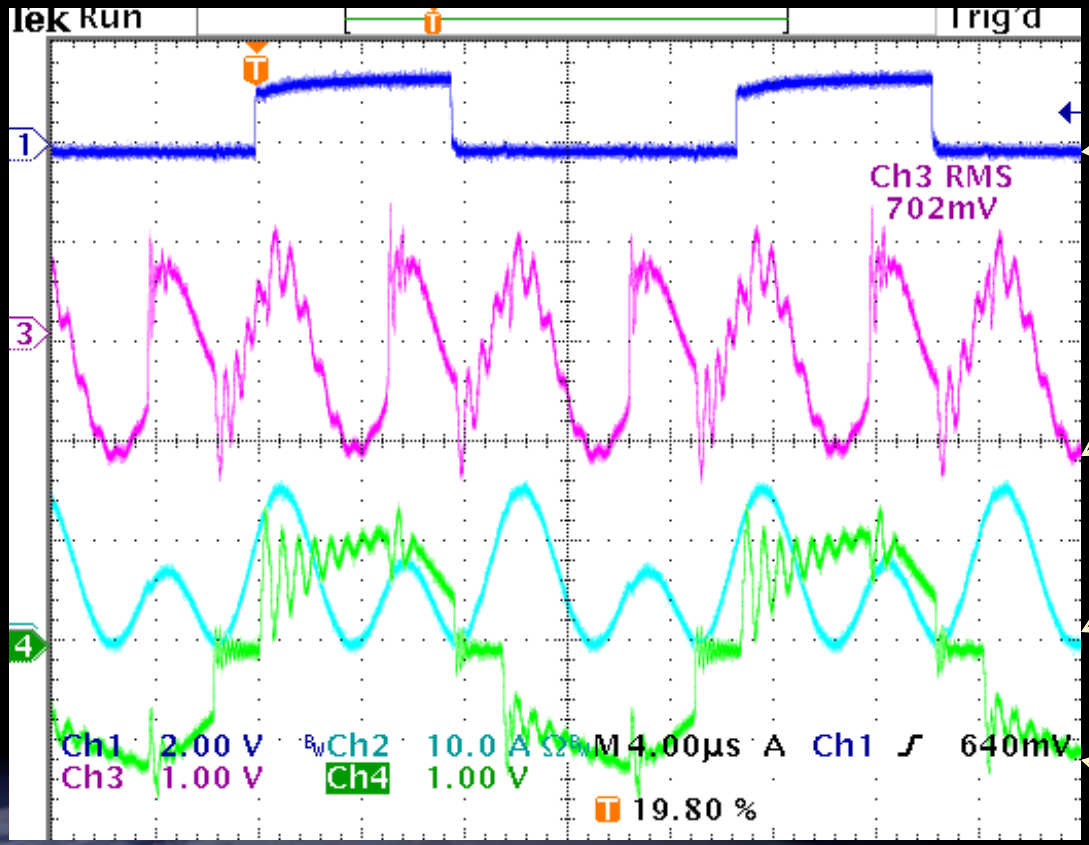
20A p-p @ 200kHz

Failures #1 &# 2

Failure #3

Circulating Current between Two Capacitors In Phase Shift Mode

Cap Current and Circulating Current



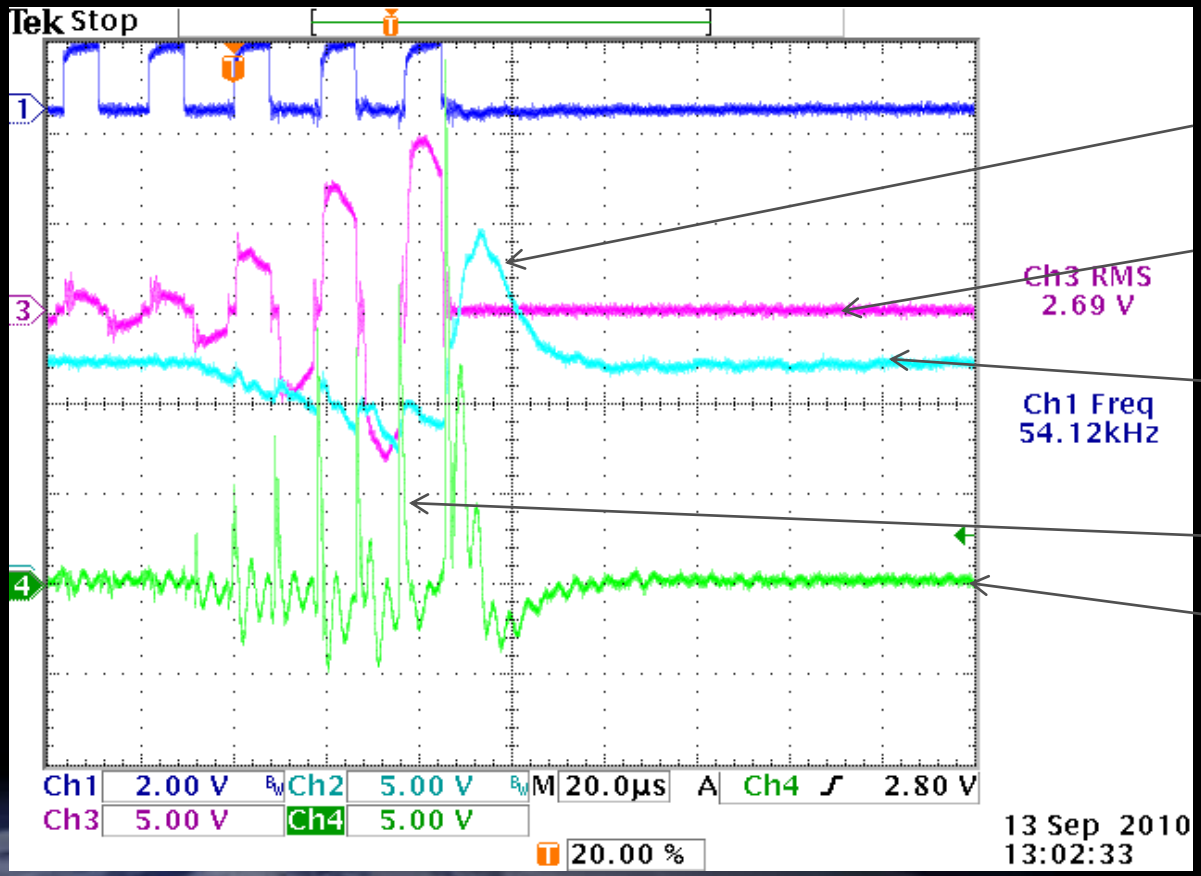
Gate Drive

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

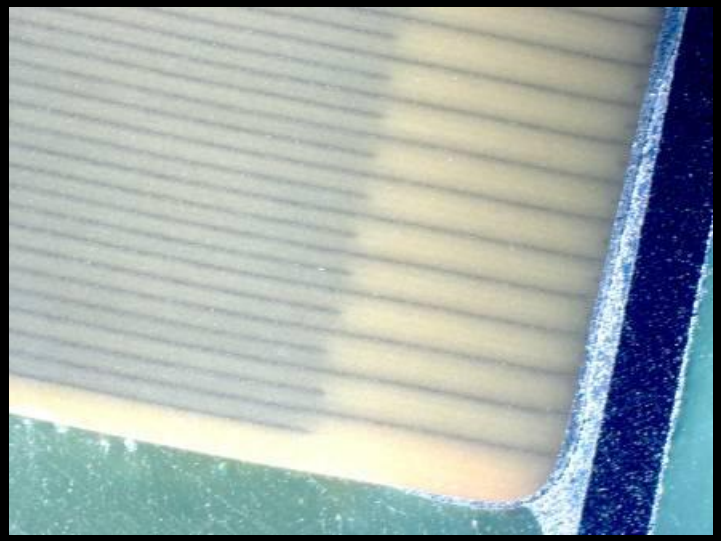
Current Spikes

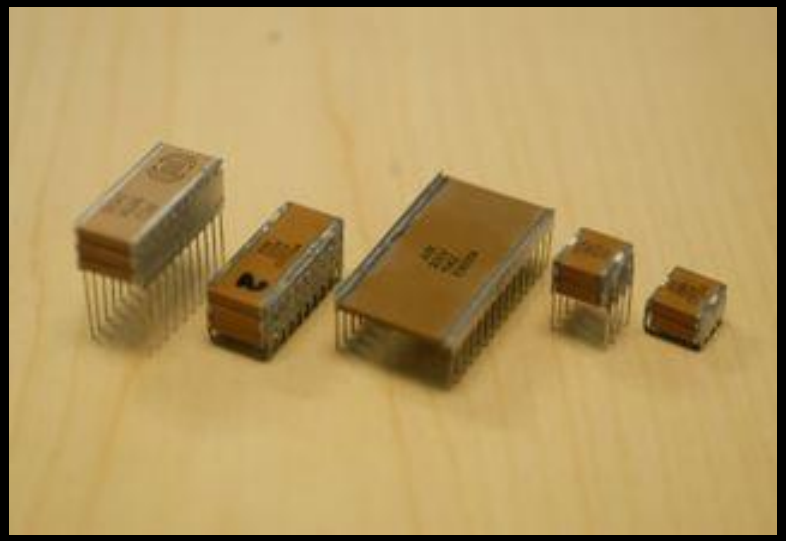
Cap Current
50 amps / div

Key Findings

Capacitor testing and analysis

Ceramic Capacitors





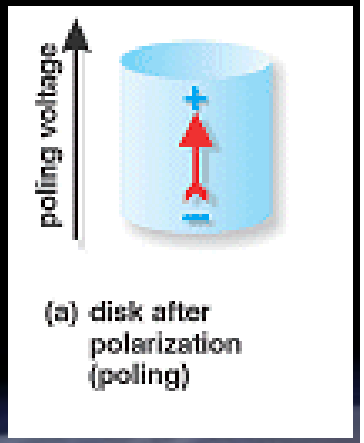
- A ceramic capacitor is constructed of alternating layers of metal and ceramic, with the ceramic material acting as the dielectric.
- A typical dielectric material is X7R – a form of Barium Titanate
  - Minor Dopants change the electrical and mechanical properties
- Barium Titanate can be highly piezoelectric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

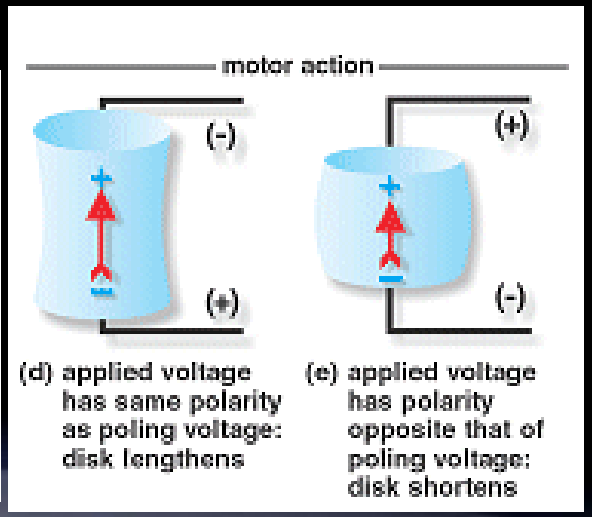
Ceramic Capacitor Used in the Beam Supply

- 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

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,

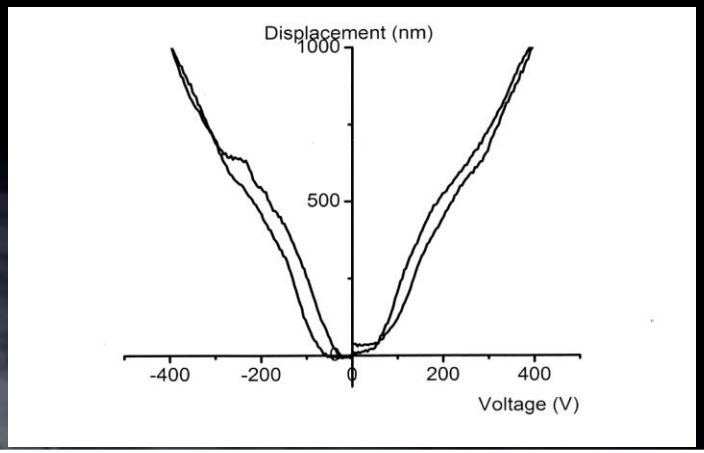




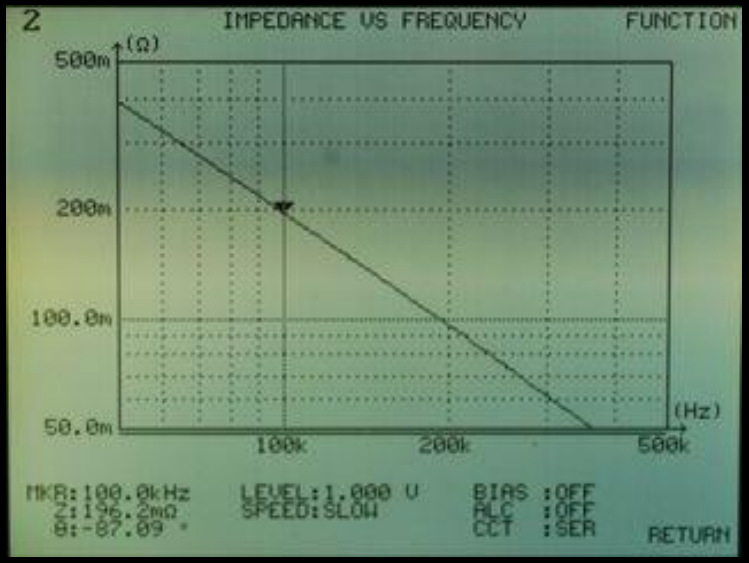
Barium Titanate (the capacitor dielectric) is piezoelectric

Displacement = f (Electric Field)

GRC Measured Data on Custom Capacitor

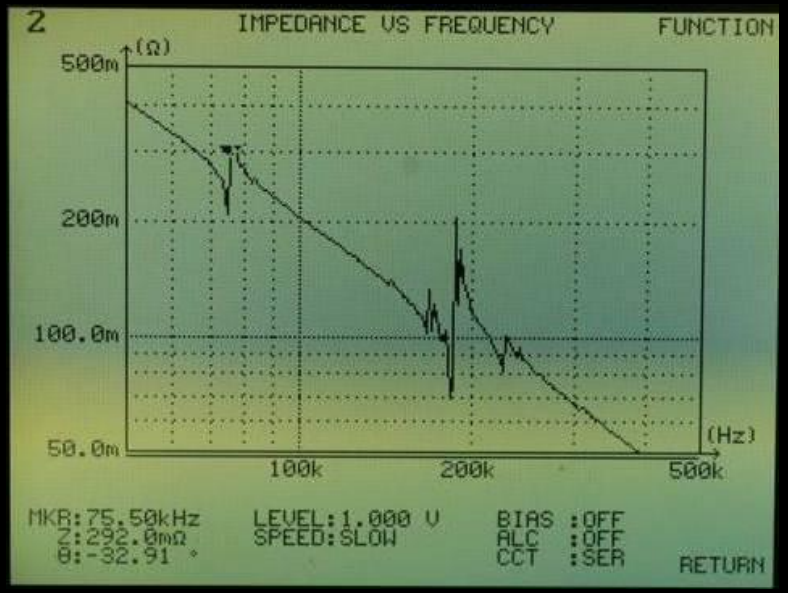


New Custom Caps from Stock



Not subjected to temperature or voltage

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



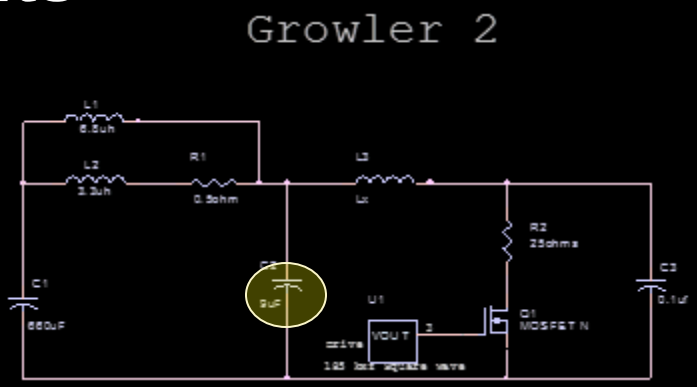
- Temperature and voltage polarizes the dielectric creating the piezoelectric effect.
- Spike in the impedance indicate piezoelectric resonant frequencies.
- Resonant frequencies are function of ceramic slab dimensions and material.

Electrical Testing to Mimic in Circuit Phenomena

Test Circuits

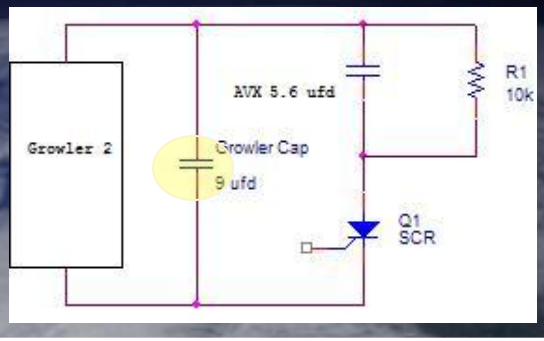
Growler

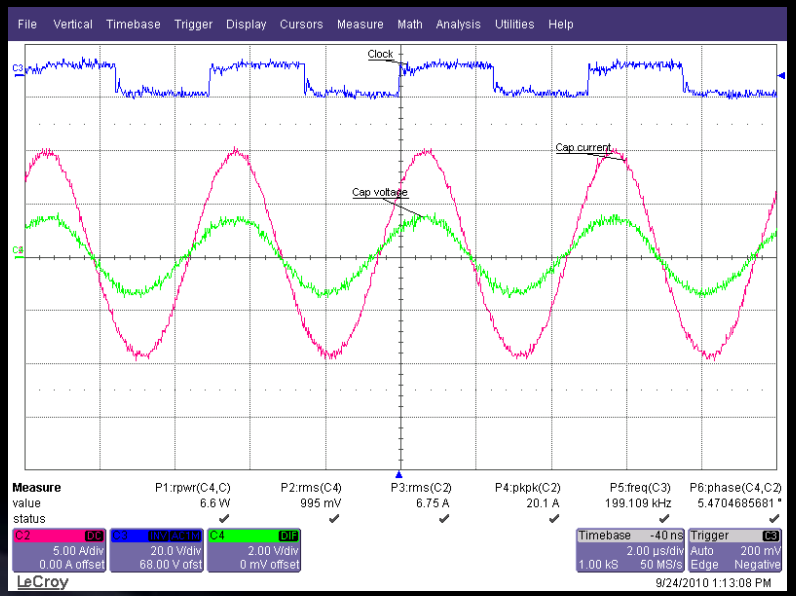
- Provides 7.5 amps rms of sinusoidal circulating current @ 170 to 220 kHz



Growler / V-Thumper

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



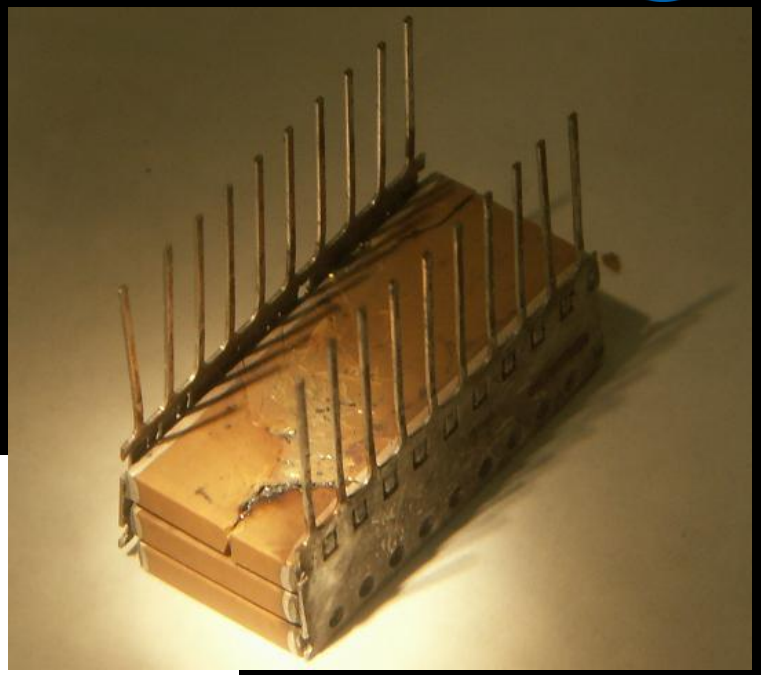


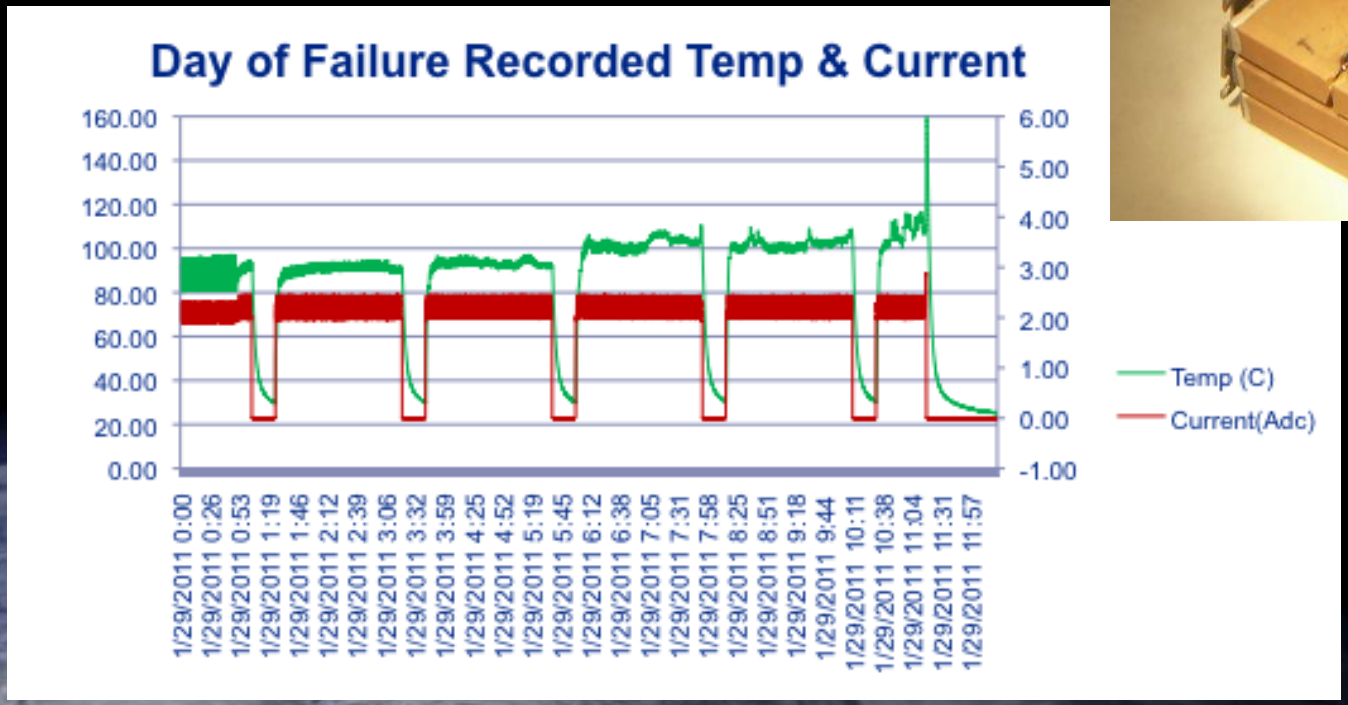
- 200kHz
- 5.47 degree phase lag

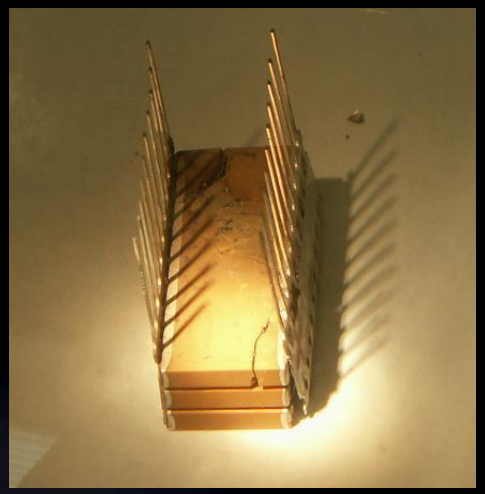
FRB Cap Failure #3

Failure Specifics

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

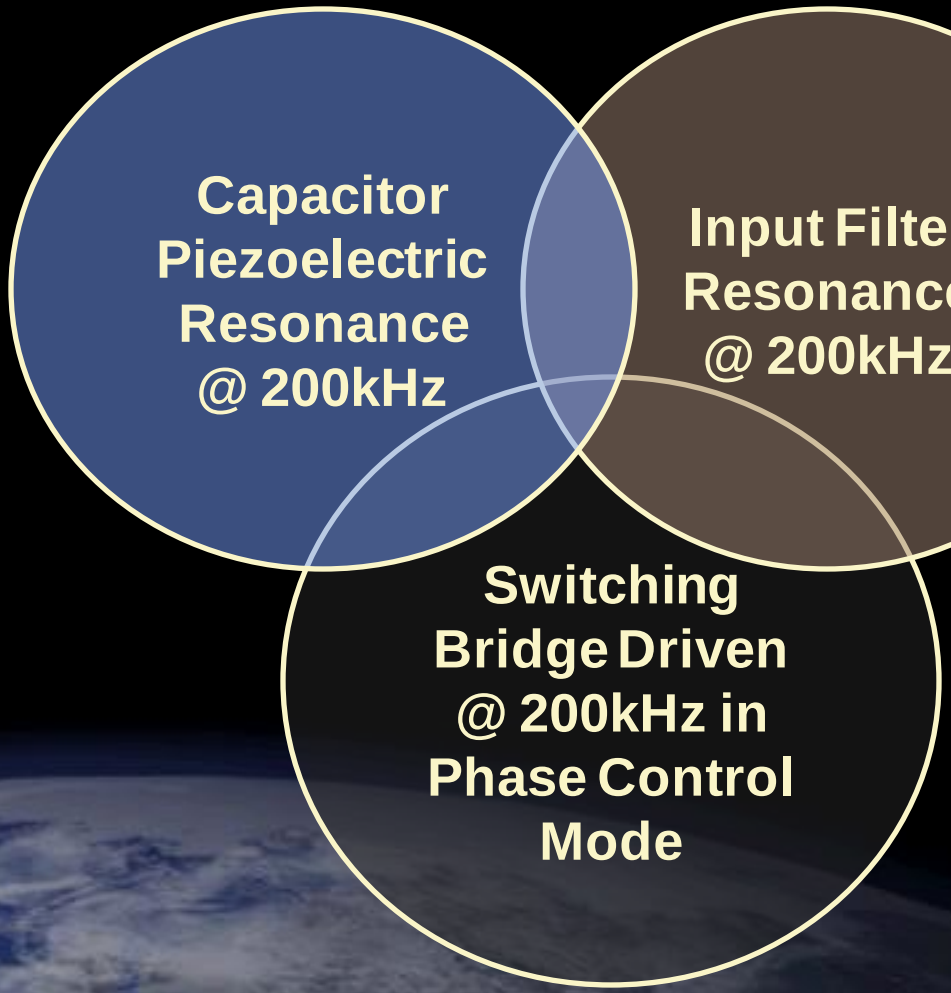






Failure Conclusions and Corrective Action

Summary of Failure Mechanism

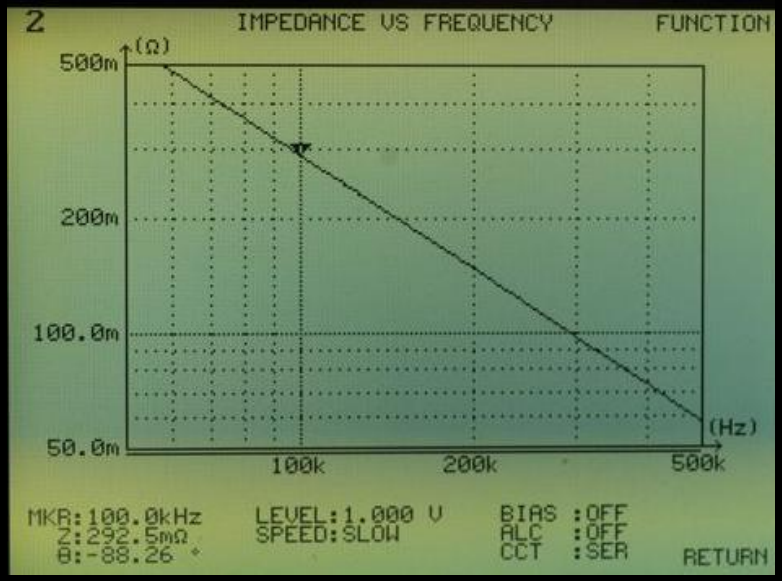


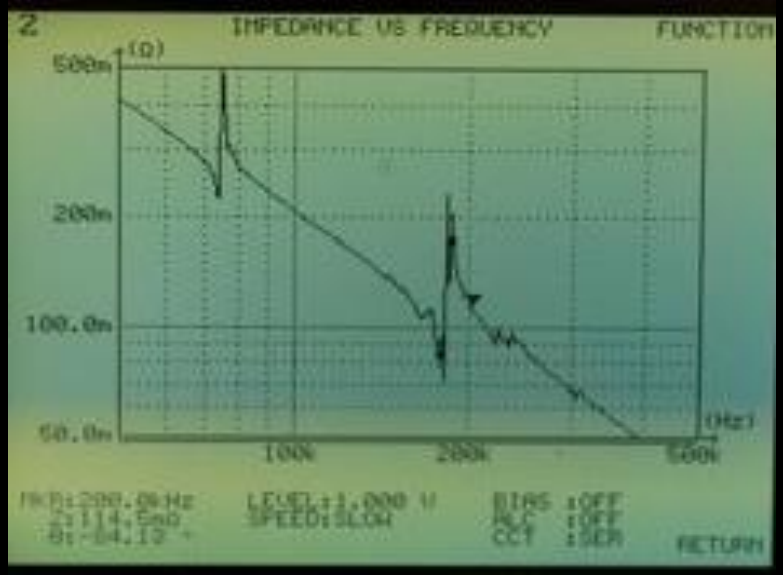
The confluence of 3 independent design elements is responsible for the capacitor failure

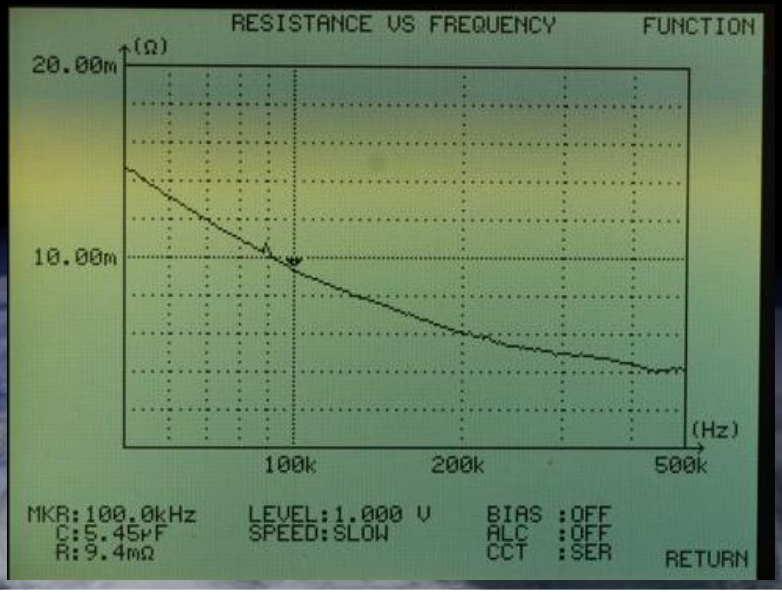
Replacement 5.6µF/500V

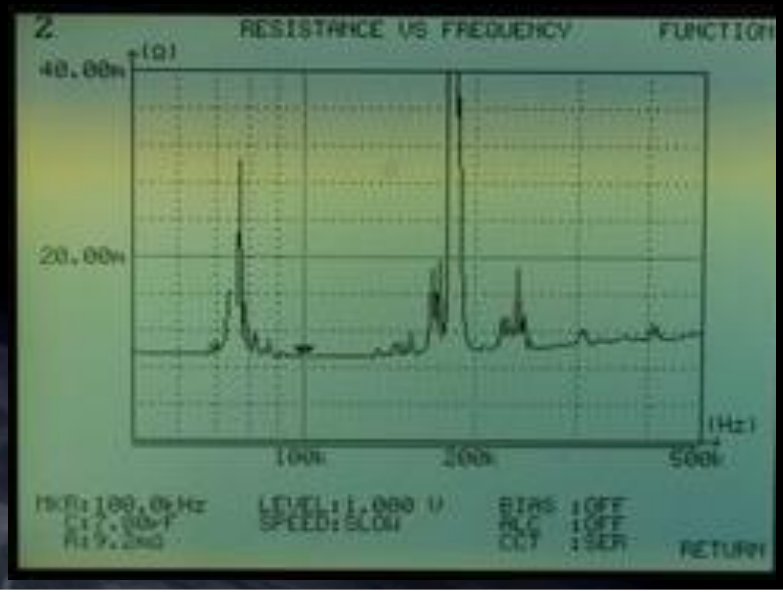
0 volt Bias

Custom 9µF/300V

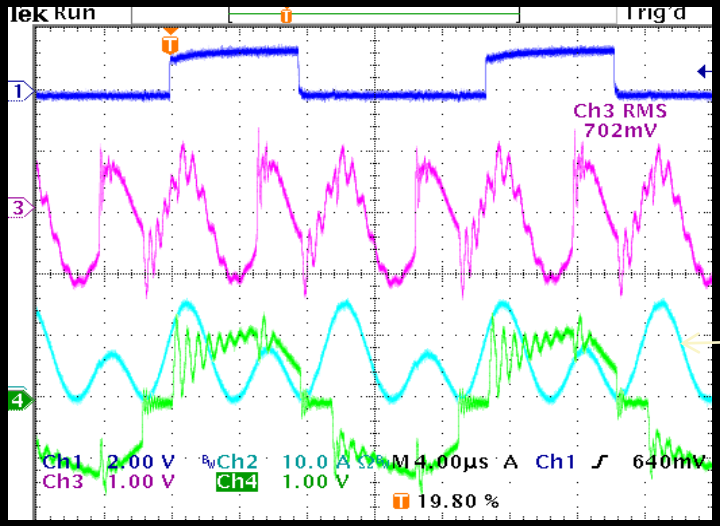




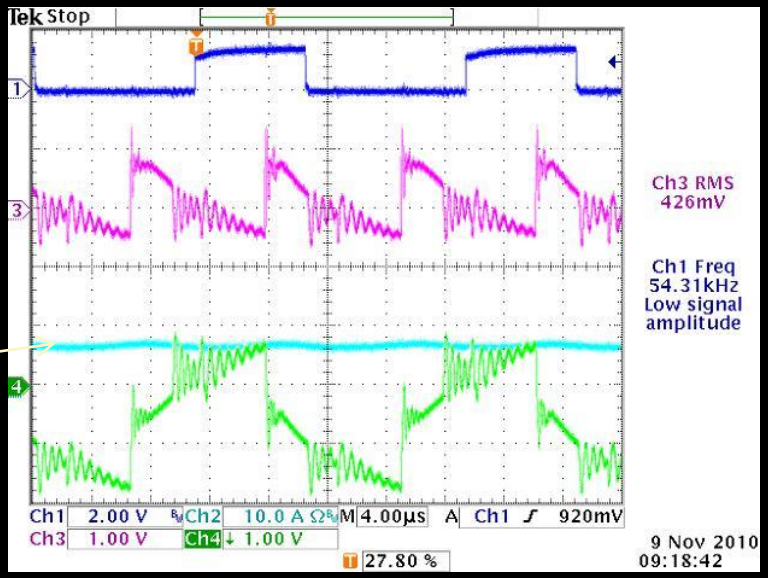




Reduce Circulating Current



Capacitor Circulating Current

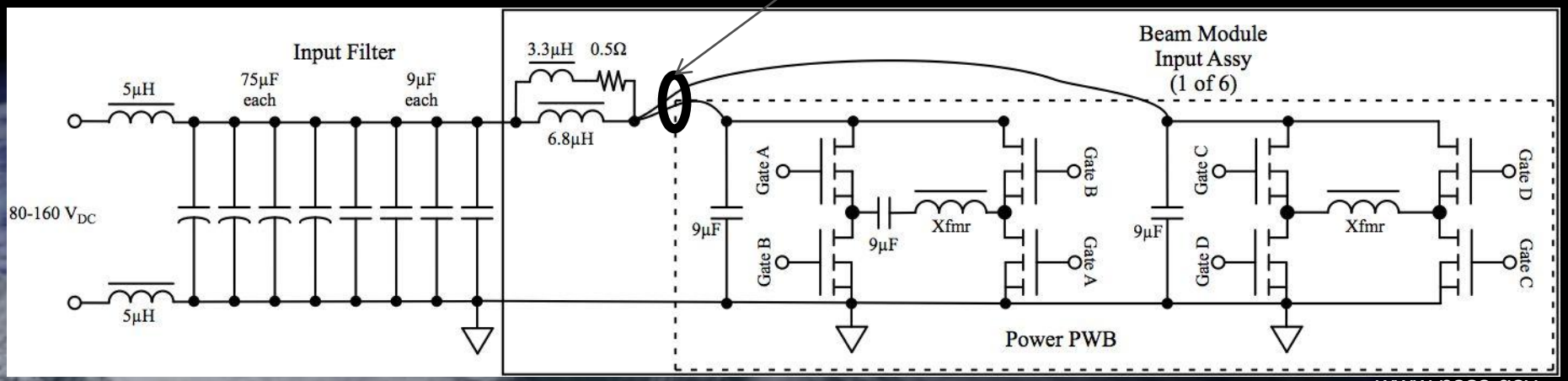


Before

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