



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**

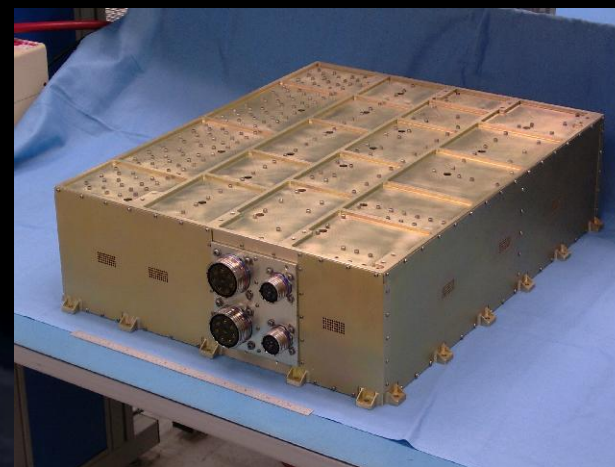


NASA's Evolutionary Xenon Thruster (NEXT) Background

- 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



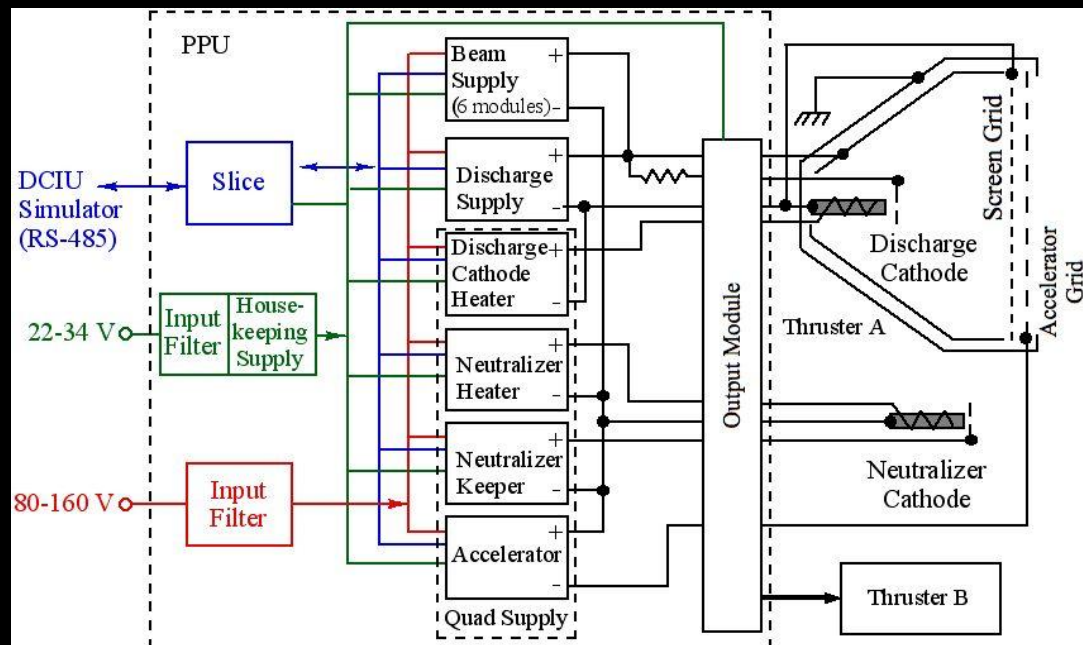
NEXT Thruster



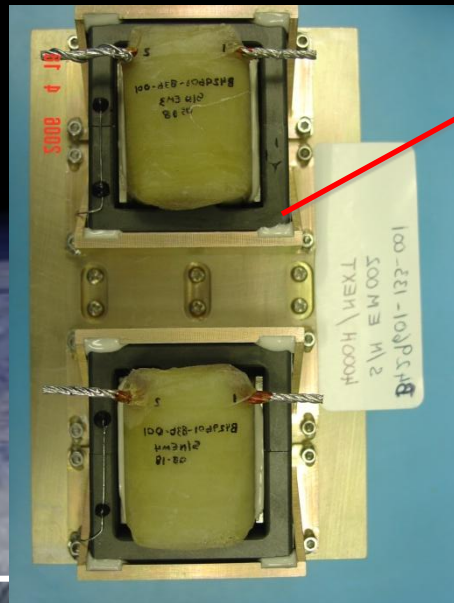
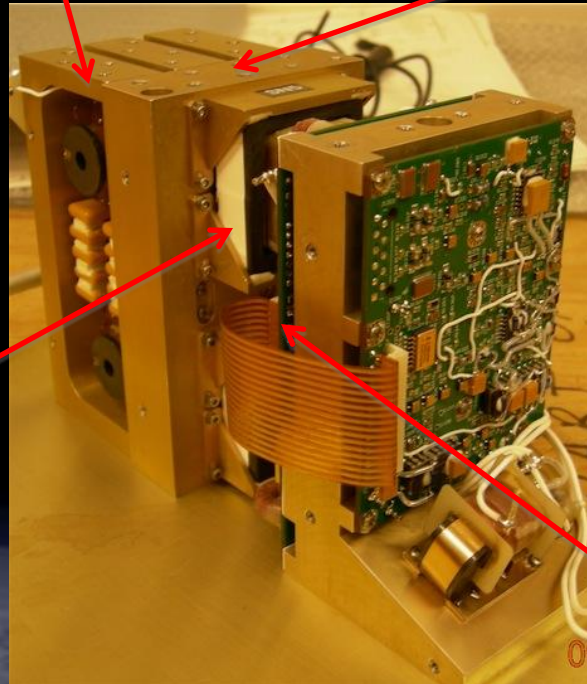
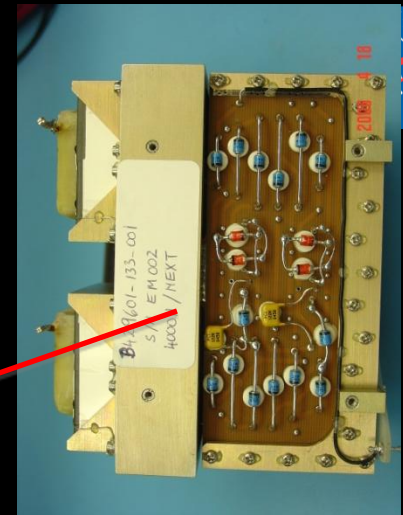
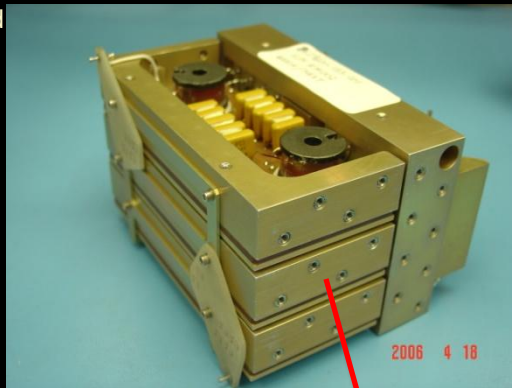
NEXT PPU

NEXT Power Processing Unit

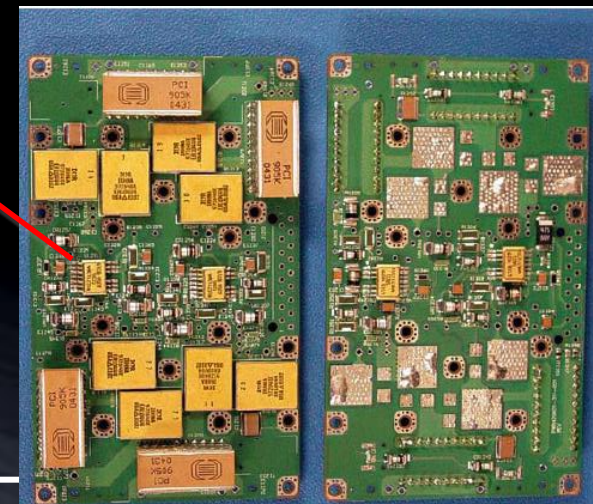
- **Modular design featuring 7 power supplies**
 - **Discharge supply**
 - **Quad supply containing**
 - **Accelerator**
 - **Neutralizer keeper**
 - **Discharge cathode heater**
 - **Neutralizer heater**
- **Housekeeping power**
- **Beam supply**
 - **Processes 93% total power**
 - **Up to 96% efficient**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



BEAM MODULE



POWER PWB

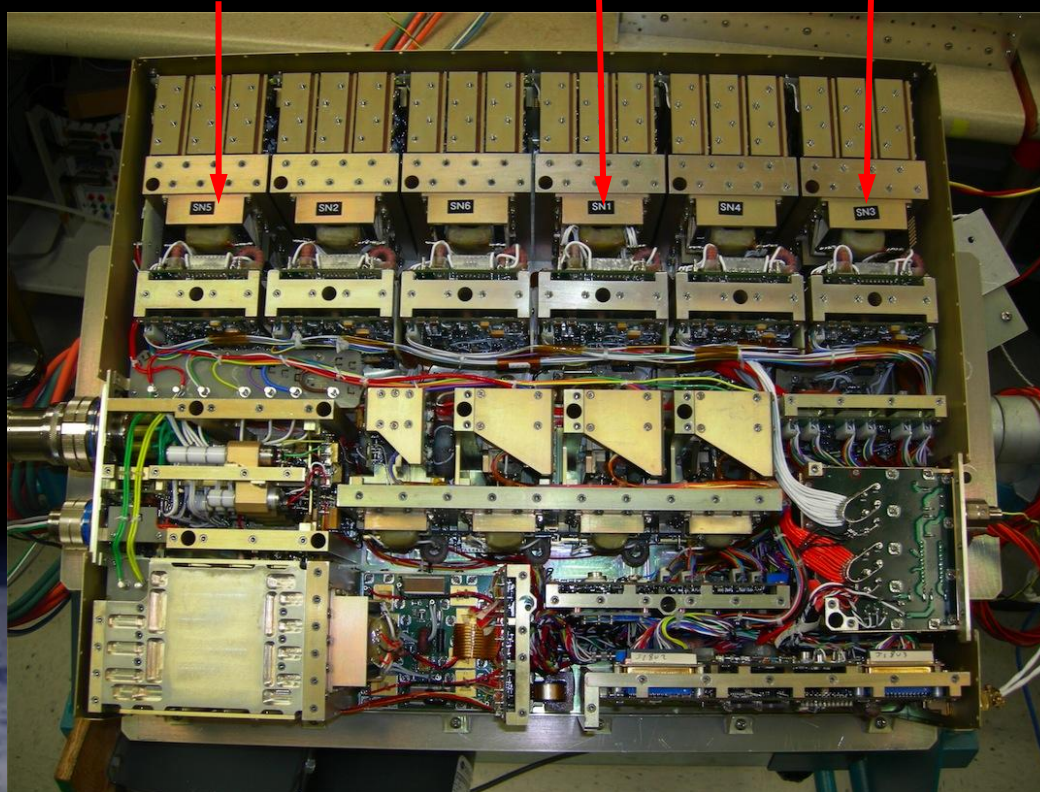


Background MLC Capacitor Failures

1st failure
Module #1
March 2008

3rd failure
Module #4
April 2010

2nd failure
Module #6
Feb 2009

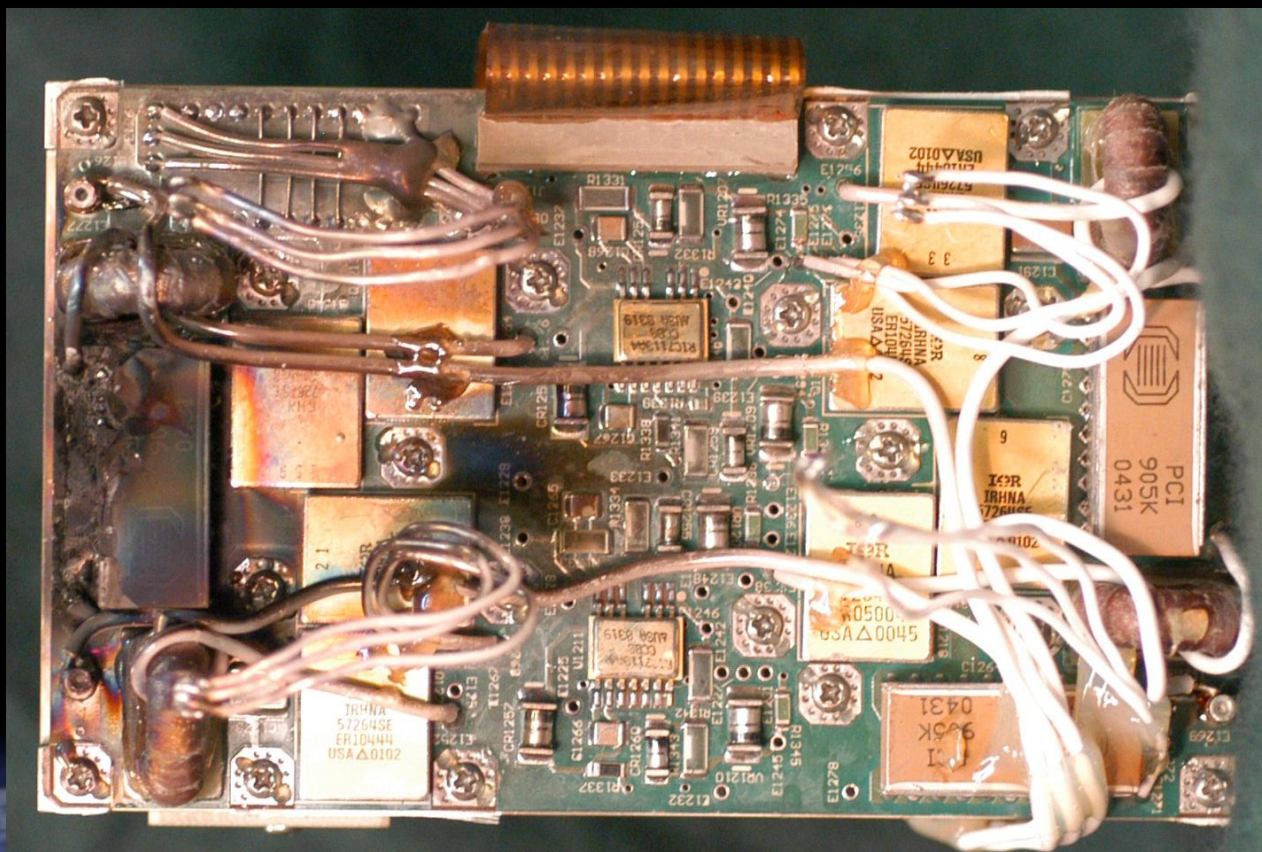




Failure #3 Investigation



Module #4 PC Board (Post Failure)

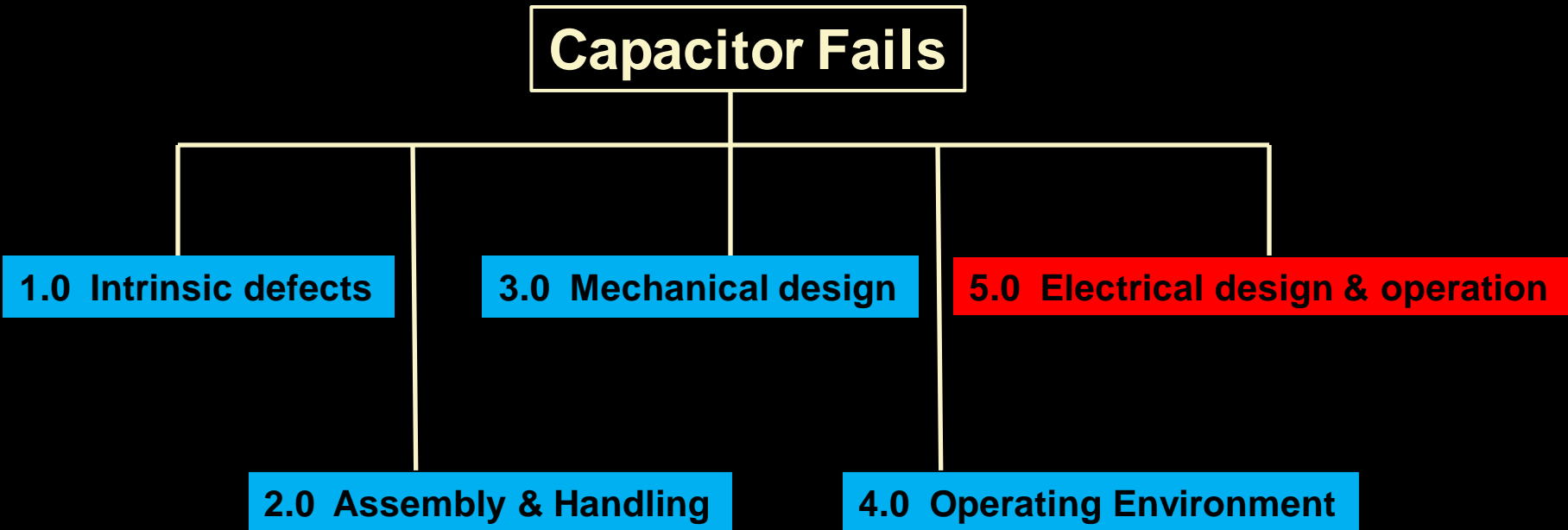


Module #4 failure

- 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	Red
Likely	Yellow
Not Likely	Green
Clear	Blue



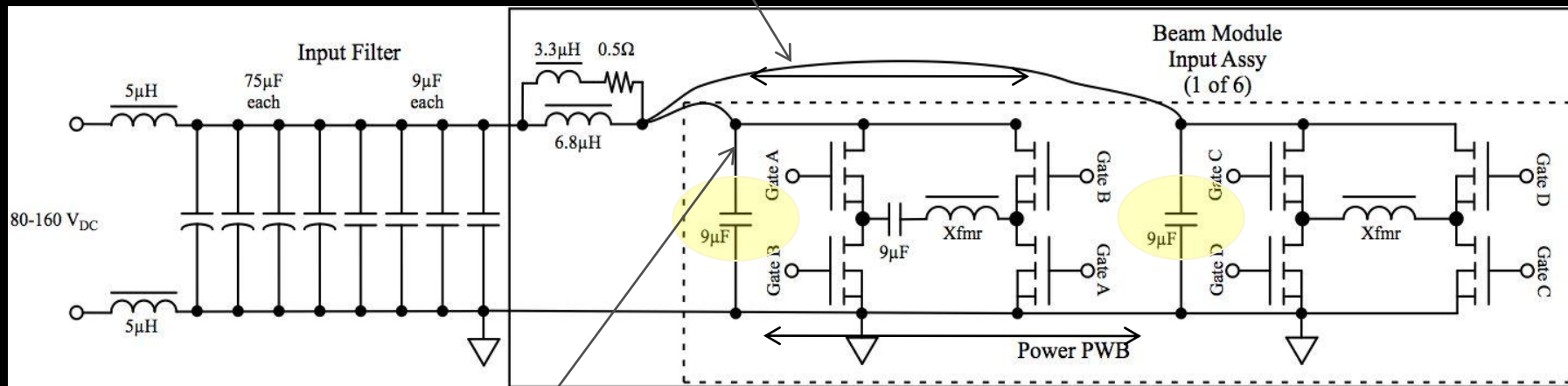
Key Findings

Beam module testing and analysis



Beam Supply Simplified Schematic

Circulating Current
16A p-p @ 200kHz



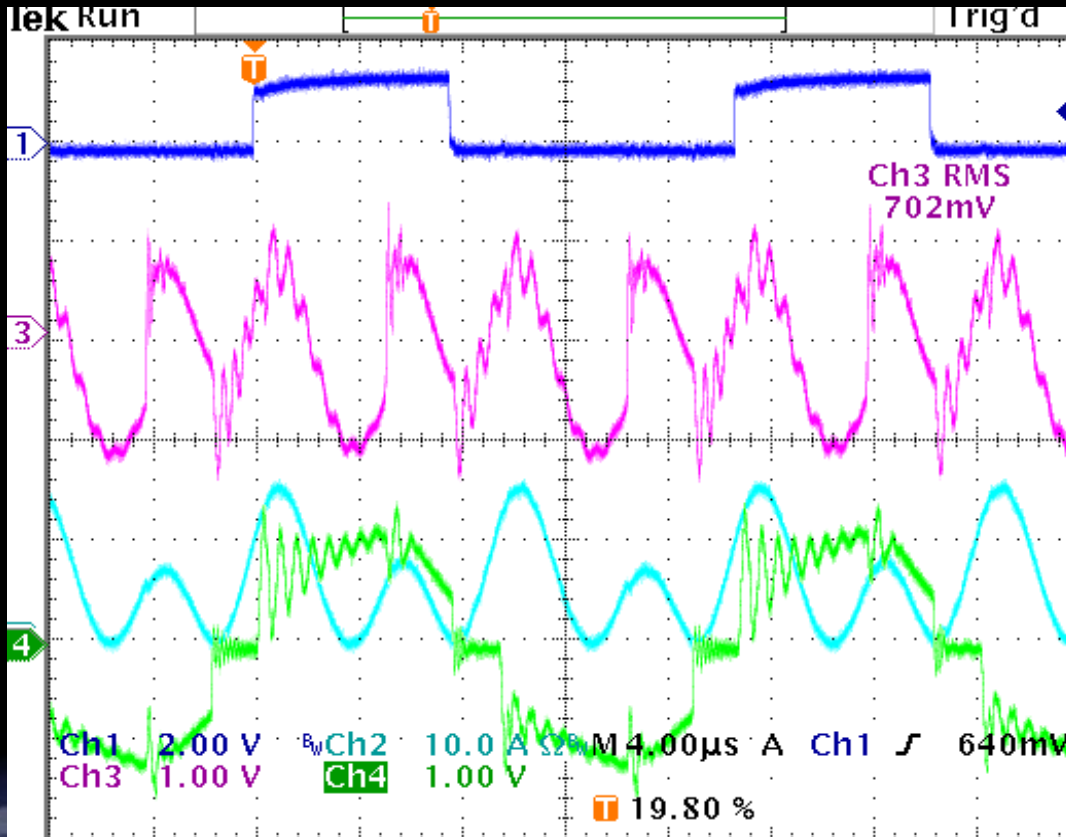
Ripple Current
20A p-p @ 200kHz Failures #1 & #2

Failure #3

**Circulating Current between Two Capacitors
In Phase Shift Mode**



Cap Current and Circulating Current



Gate Drive

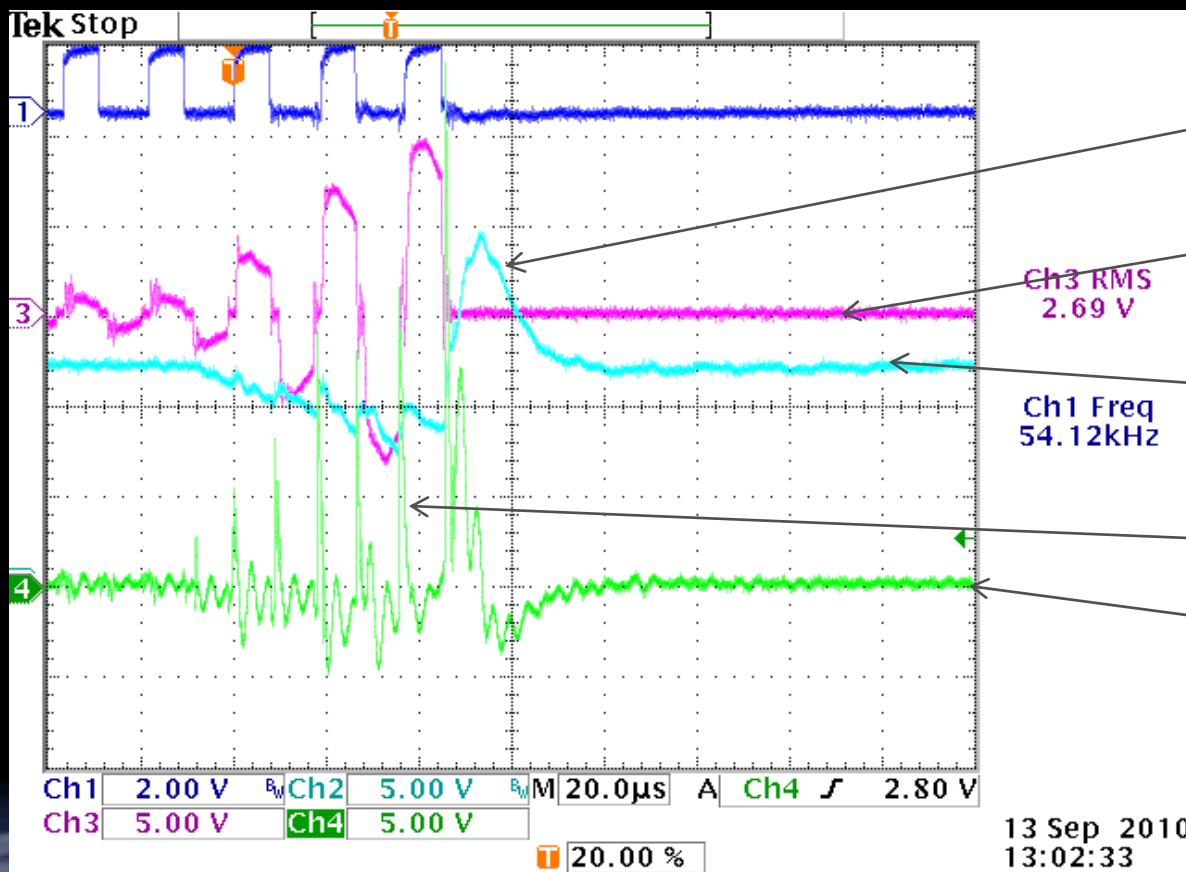
Capacitor Ripple Current is 20 A p-p @ 200 kHz

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

Ch3 RMS
2.69 V

Cap Voltage
50 Volts/ div

Ch1 Freq
54.12kHz

Current Spikes

Cap Current
50 amps / div

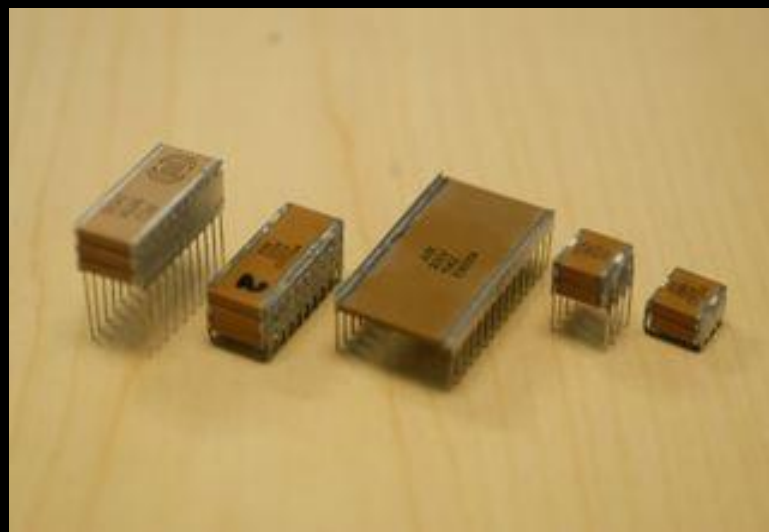
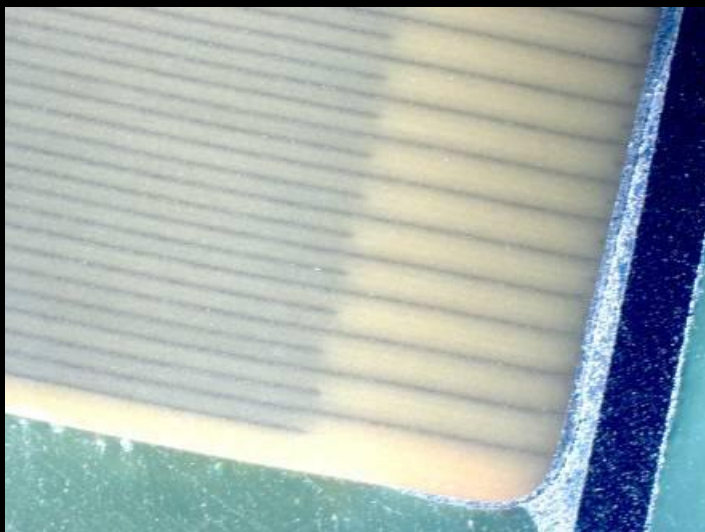


Key Findings

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

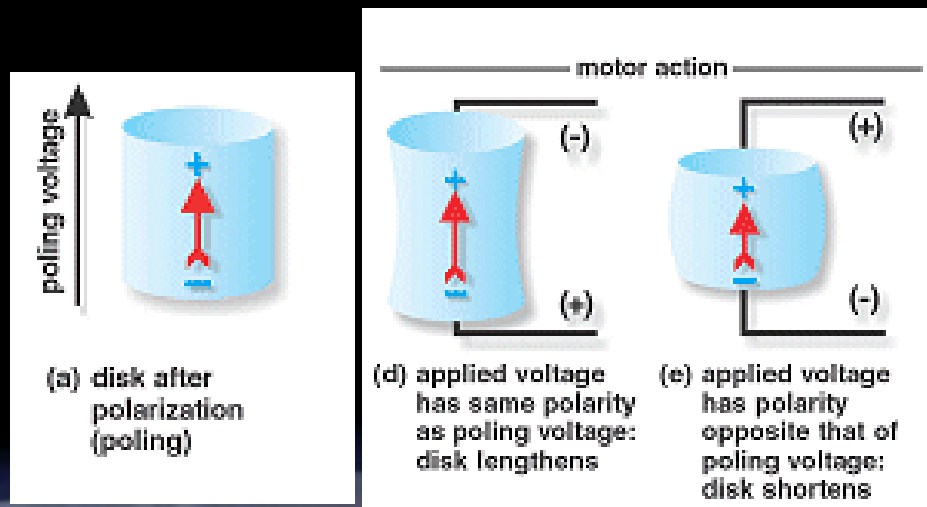


Ceramic Capacitor Used in the Beam Supply

- **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

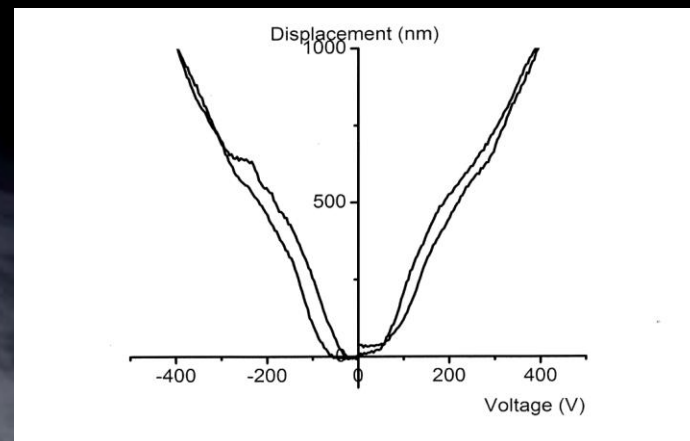
Piezoelectricity is a form of electricity created when certain crystals are bent or otherwise deformed. These same crystals can also be made to bend slightly when a small current is run through them,



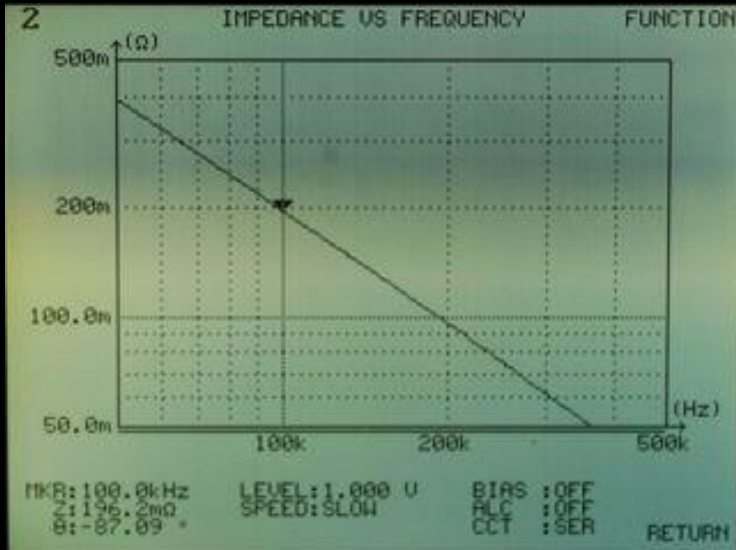
GRC Measured Data on Custom Capacitor

Barium Titanate (the capacitor dielectric) is piezoelectric

Displacement = f (Electric Field)

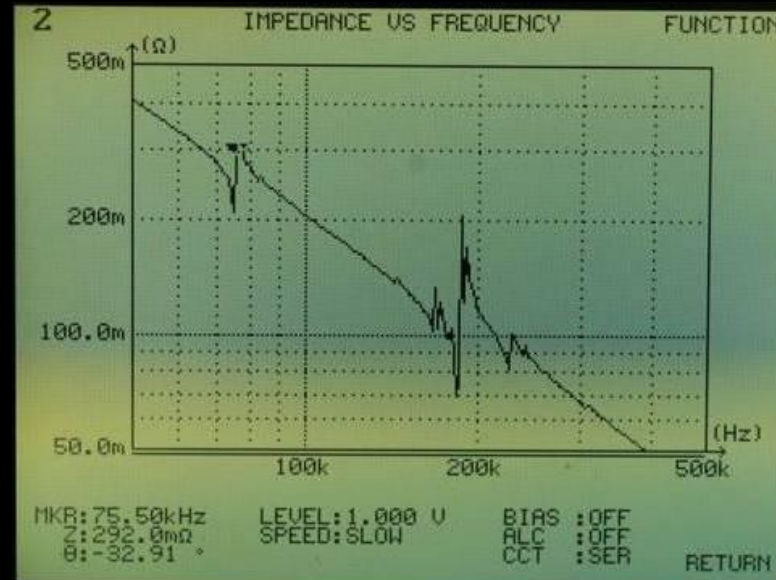


New Custom Caps from Stock



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



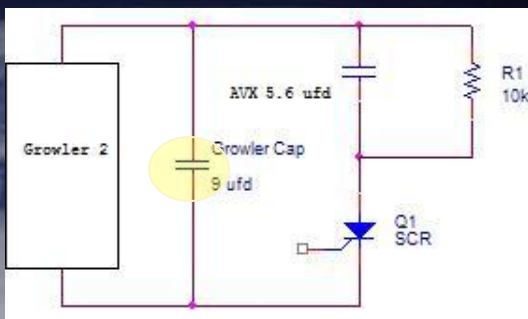
Test Circuits

Growler

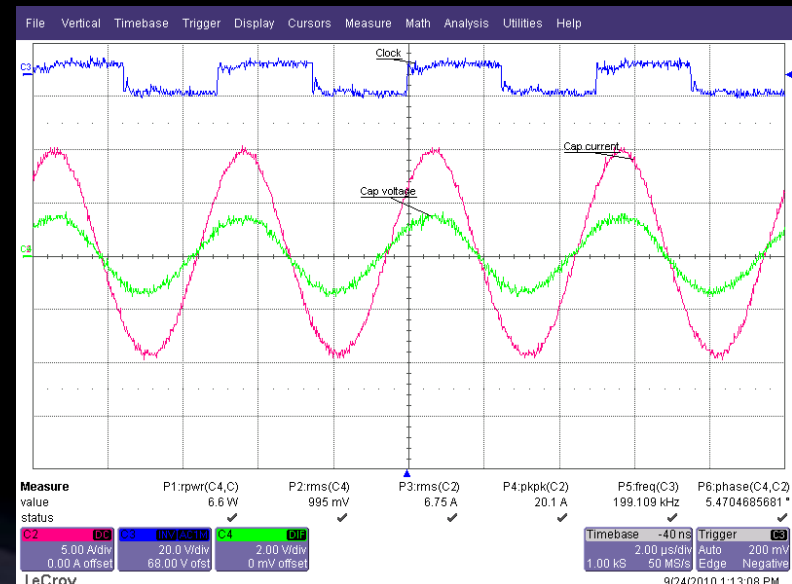
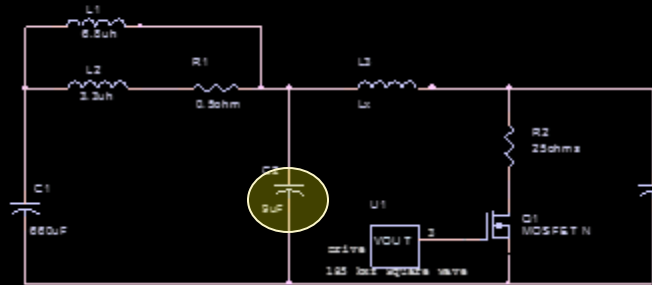
- Provides 7.5 amps rms of sinusoidal circulating current @ 170 to 220 kHz

Growler / V-Thumper

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



Growler 2



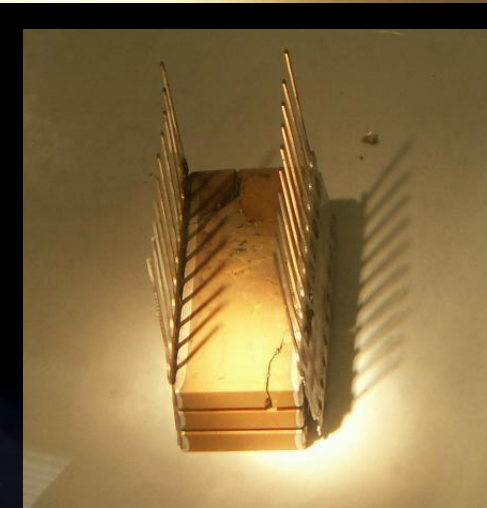
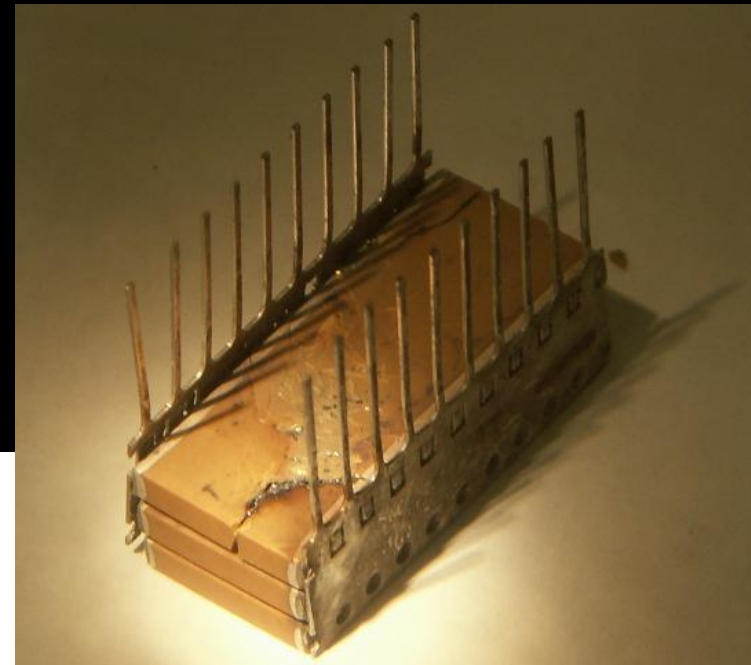
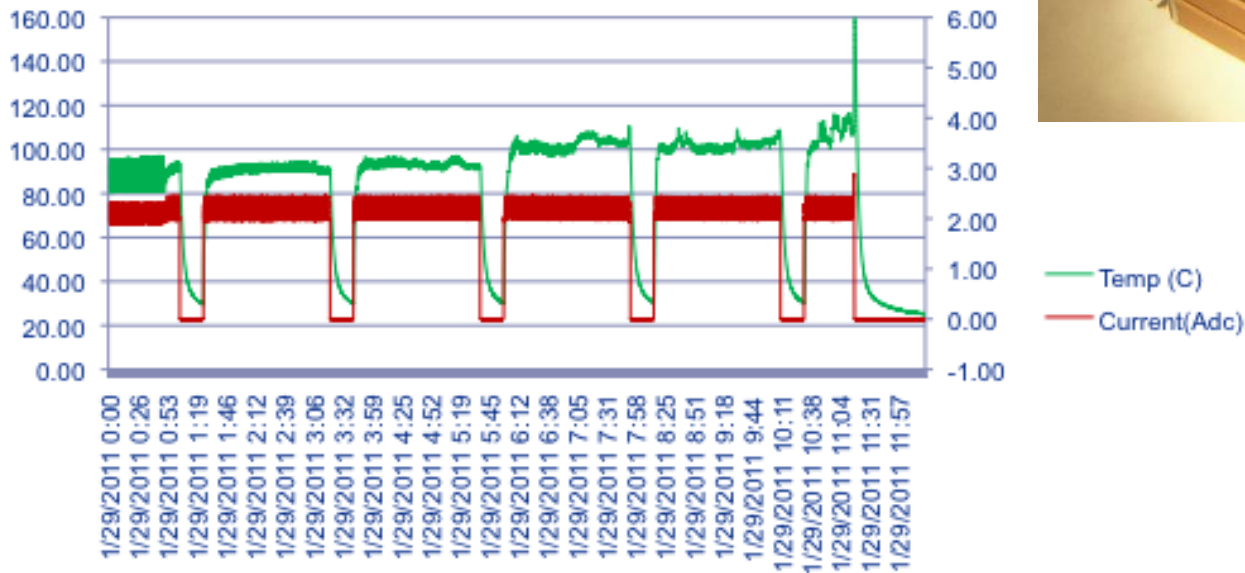
- 200kHz
- 5.47 degree phase lag

FRB Cap Failure #3

Failure Specifics

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

Day of Failure Recorded Temp & Current



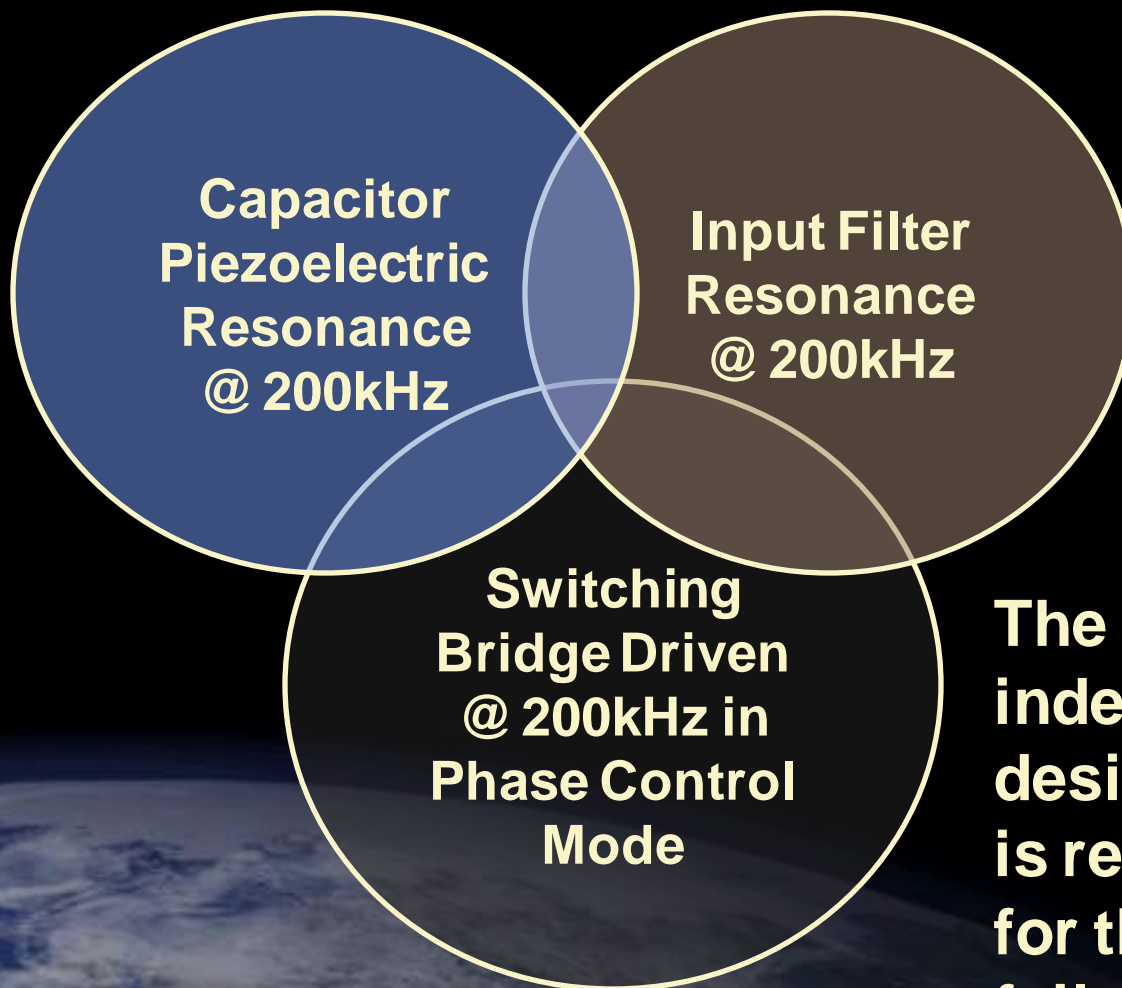


Failure Conclusions and Corrective Action





Summary of Failure Mechanism

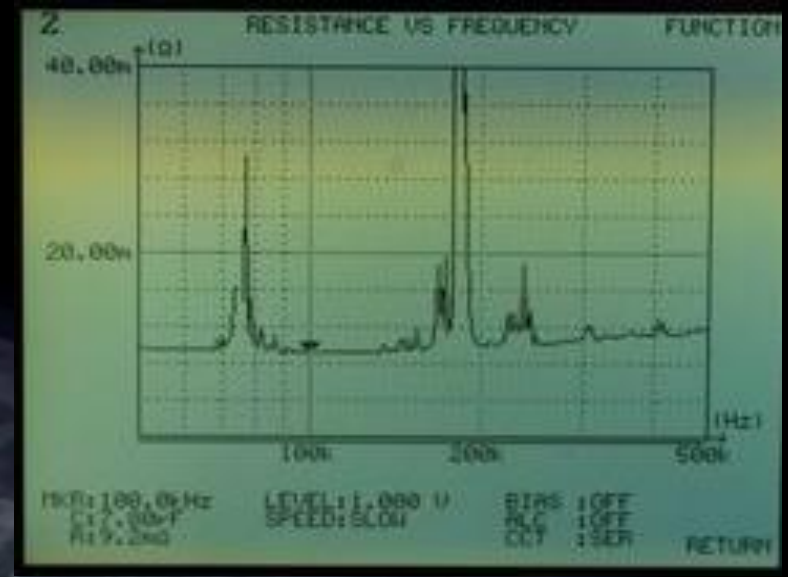
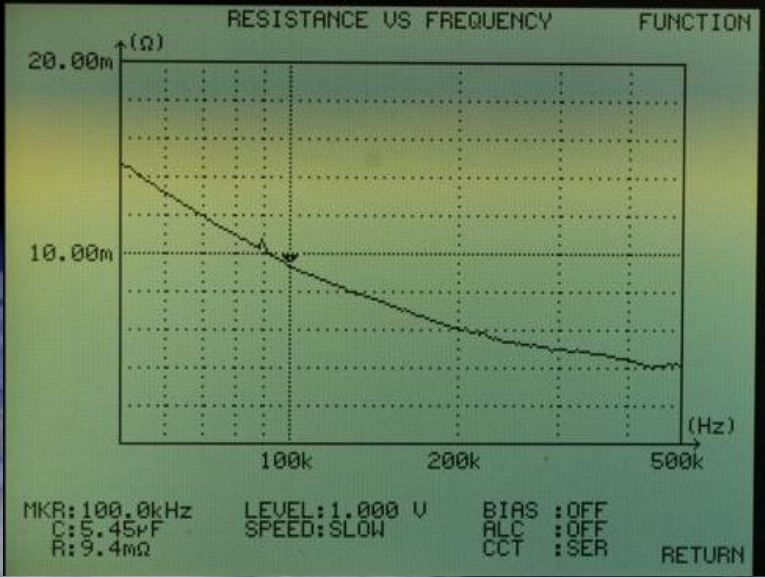
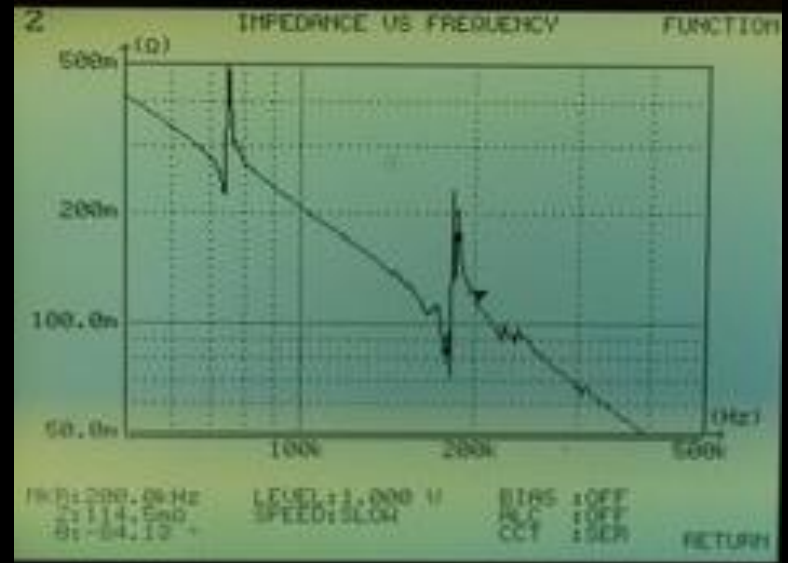
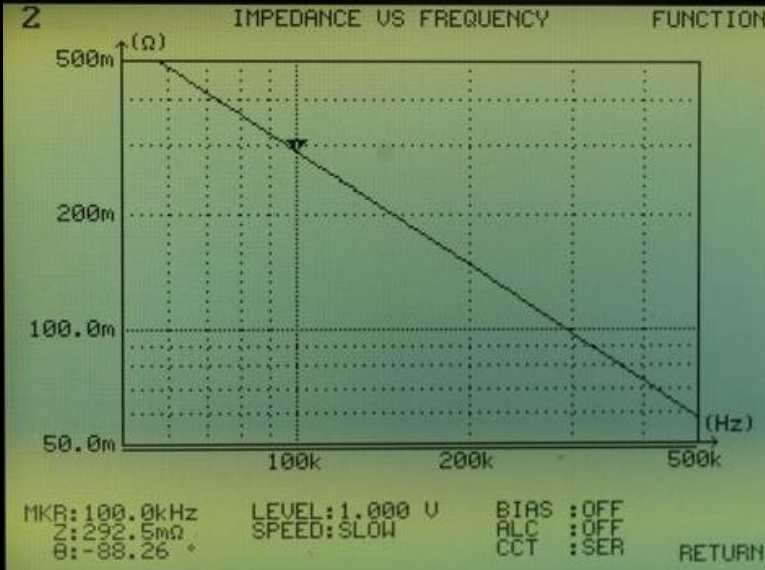


The confluence of 3 independent design elements is responsible for the capacitor failure

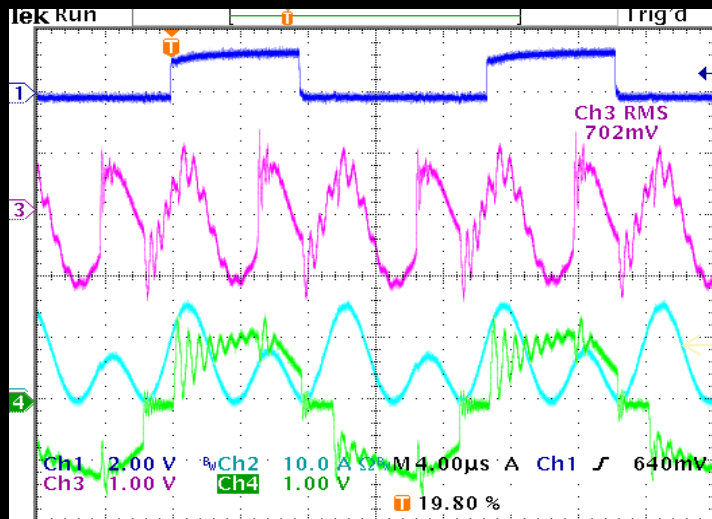
Replacement 5.6 μ F/500V

0 volt Bias

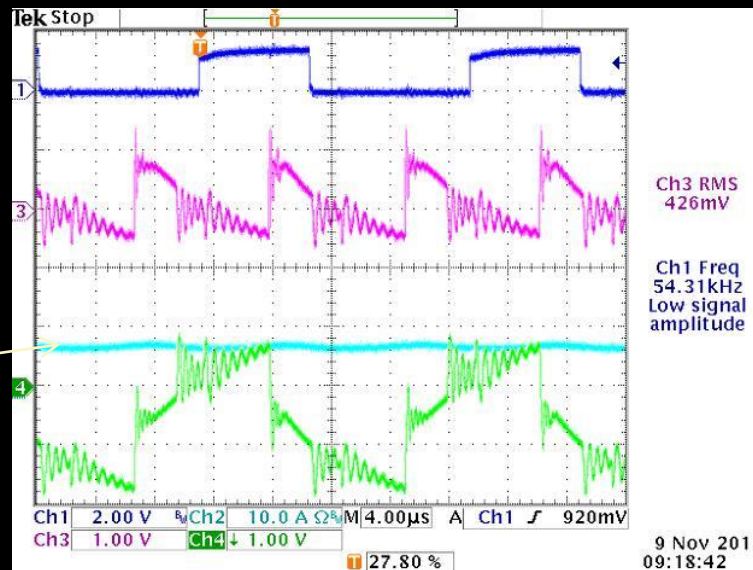
Custom 9 μ F/300V



Reduce Circulating Current



Before

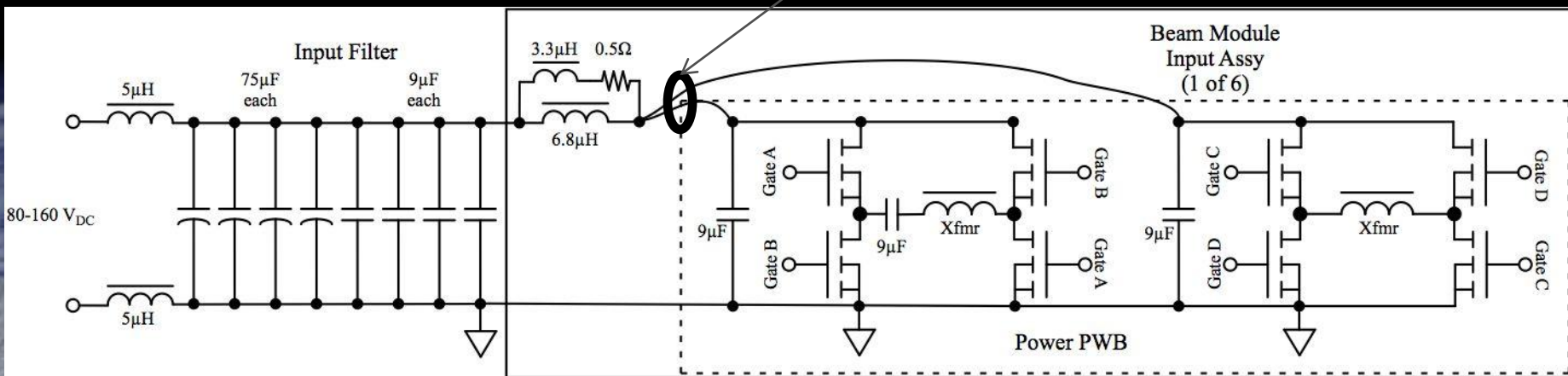


After

Capacitor
Circulating
Current

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