Improved Sensor to Enhance PCS Reliability

Presented To: National Ignition Facility Pulsed Power Group

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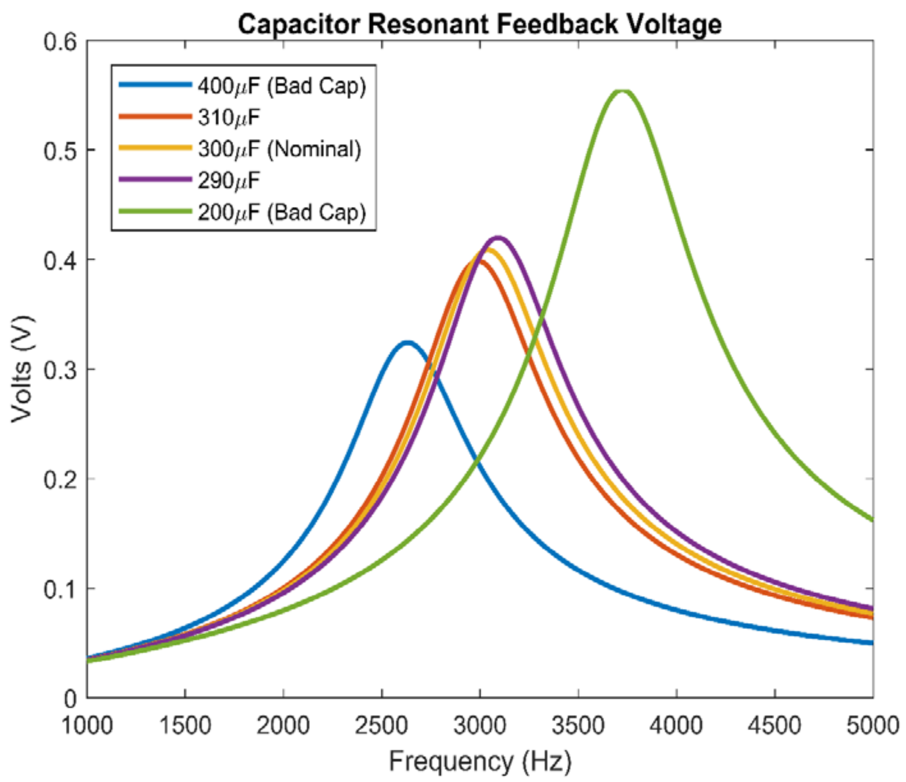
Executive Summary

- Goal was to create a capacitance-measuring sensor.
- Surpassed requirements of better than 10 uF resolution, repeatability.
  - Achieved 7 uF worst-case resolution (within 2.5%).
  - Achieved 4 uF repeatability (within 1%).
- Designed CAPSCAN GUI
  - Compensates for:
    - Frequency dependence.
    - Position-dependent inductance.
    - Capacitor ESL. (Effective Series Inductance)
- Performance evaluated on 3 bank modules.

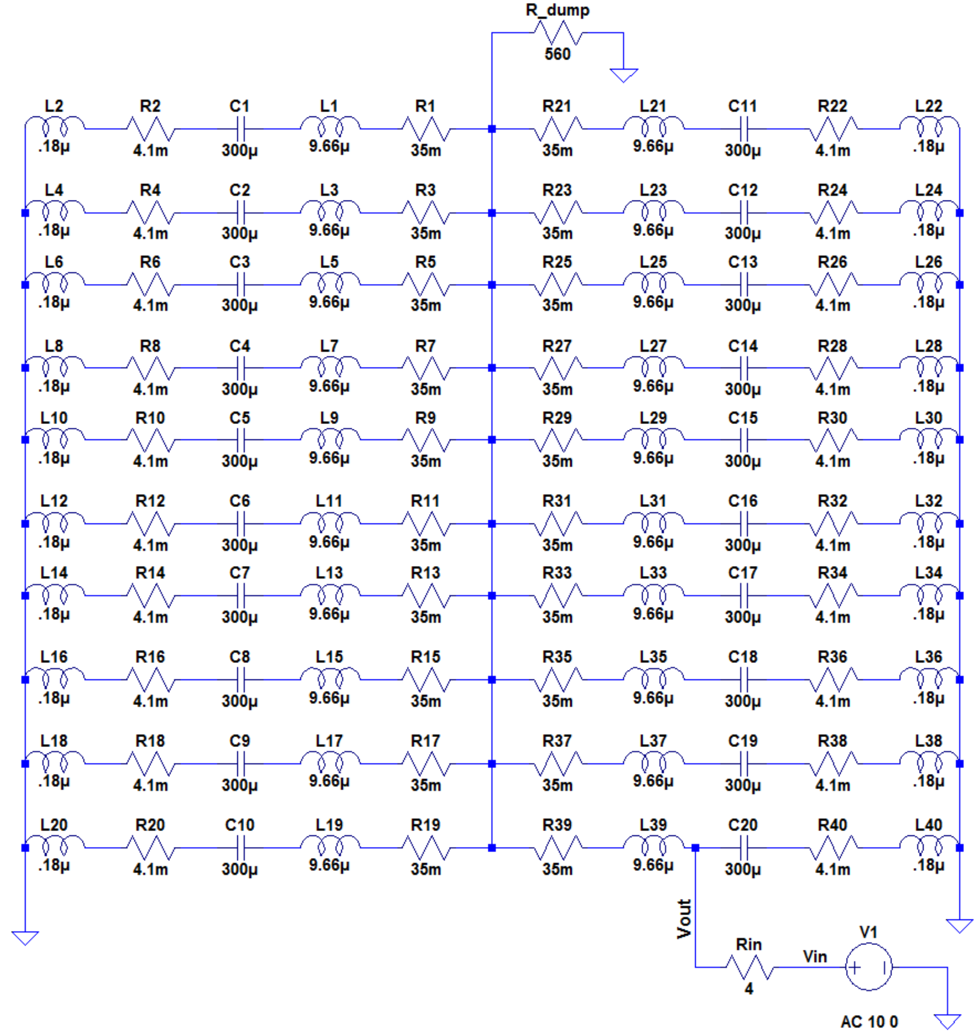
Monitoring capacitance without disconnecting the capacitors can be accomplished using RF

- By tracking changes in capacitance, NIF operators can detect impending capacitor failure.
- NIF capacitors generally lose capacitance in increments of 10 uF.
- CAPSCAN operates by sending a frequency sweep into a NIF capacitor, and uses the resonant peak to determine capacitance.



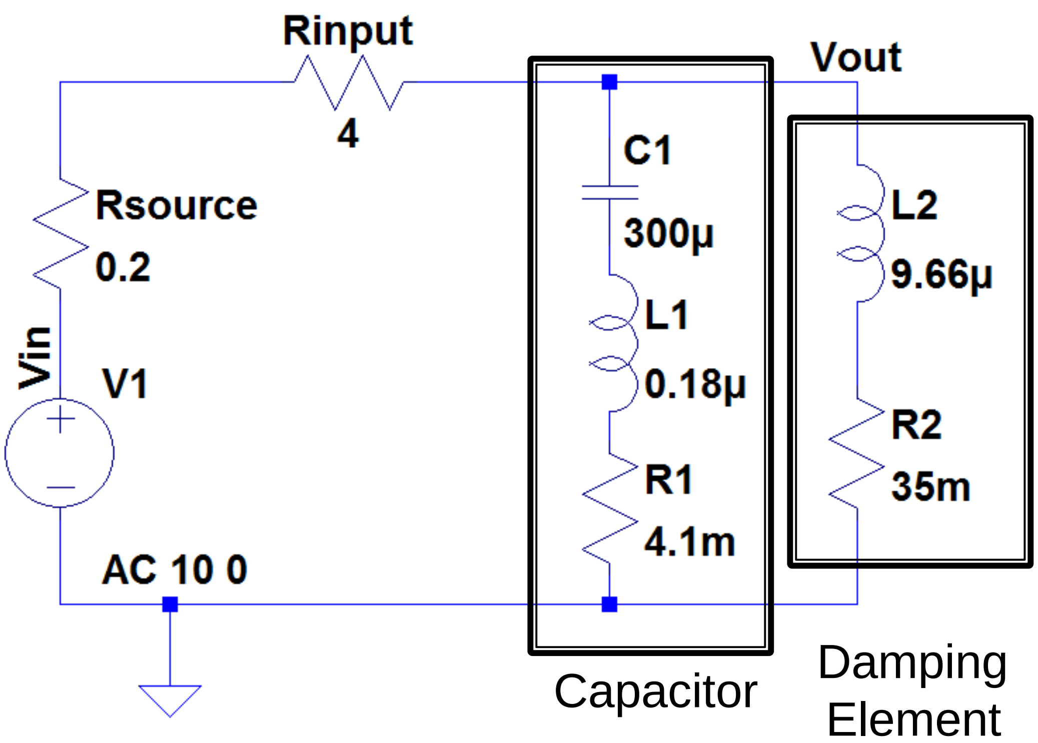
Bank module includes 20 tank circuits

- Each Main Energy Storage Module (MESM) contains 20x 300uF capacitors and 20x inductors.
- Parasitic inductances have noticeable effects on capacitance measurement.



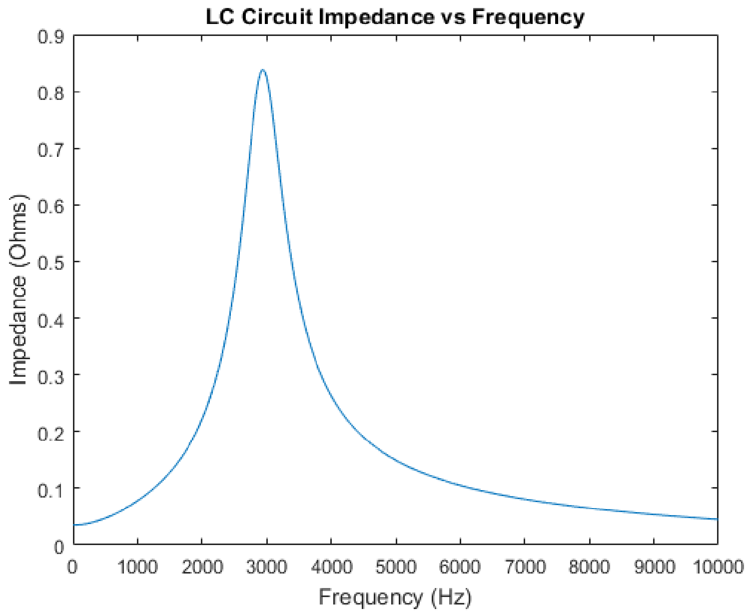
Simplified schematic after module is safed

- During the safing procedure, the dump resistor is shorted to ground.
- All other capacitors and inductors can be ignored.
- Vin is a sinusoid swept from 1 kHz to 5 kHz.
- CAPSCAN measures the voltage across the LC circuit.



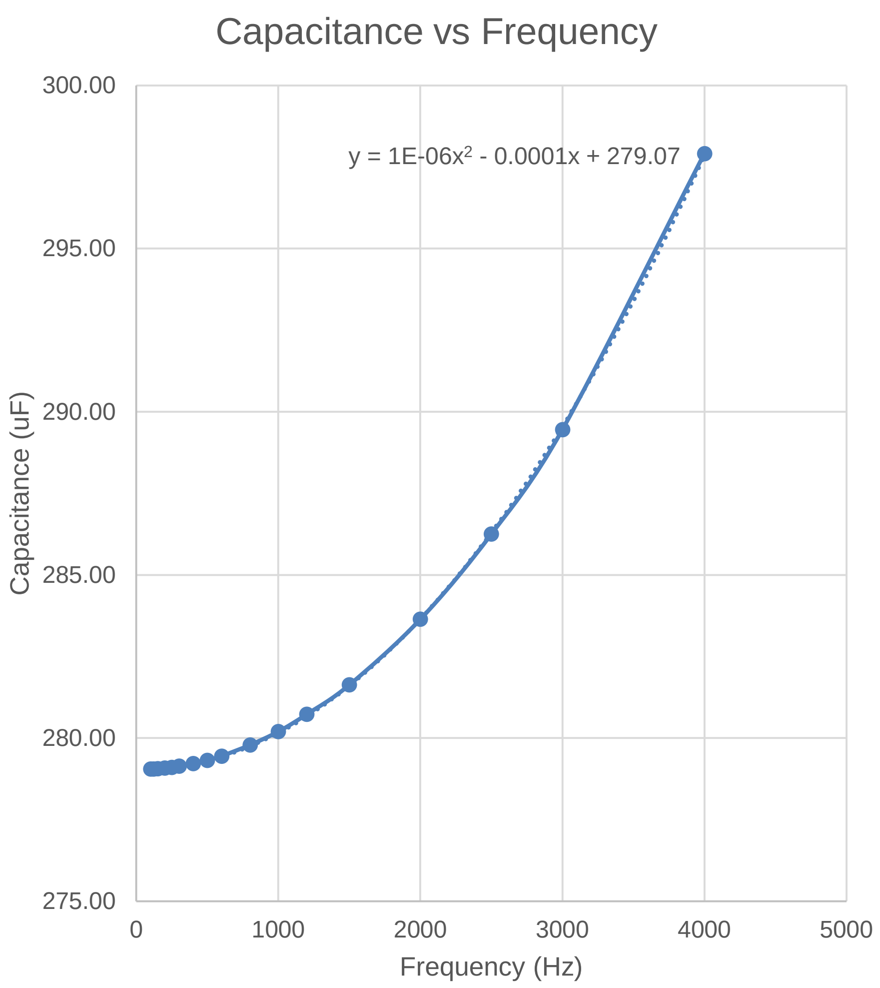
Resonant peak used to extract capacitance

- The capacitor and inductor display resonance at roughly 3 kHz
- Resonance occurs when the reactive components of the LC circuit cancel each other.
- $C = \frac{1}{(2\pi f_{res})^2 (L - ESL_{Cap})}$

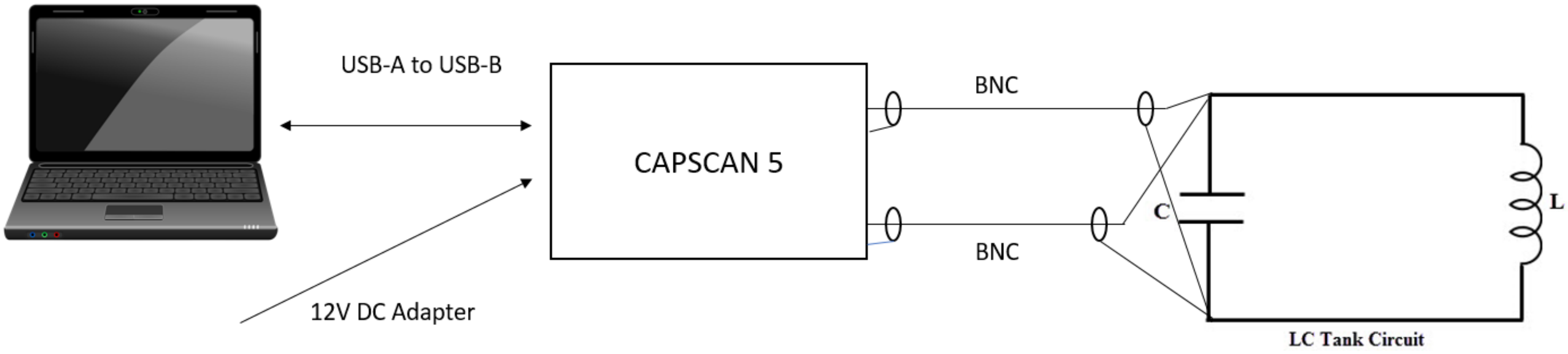


Capacitors are frequency dependent

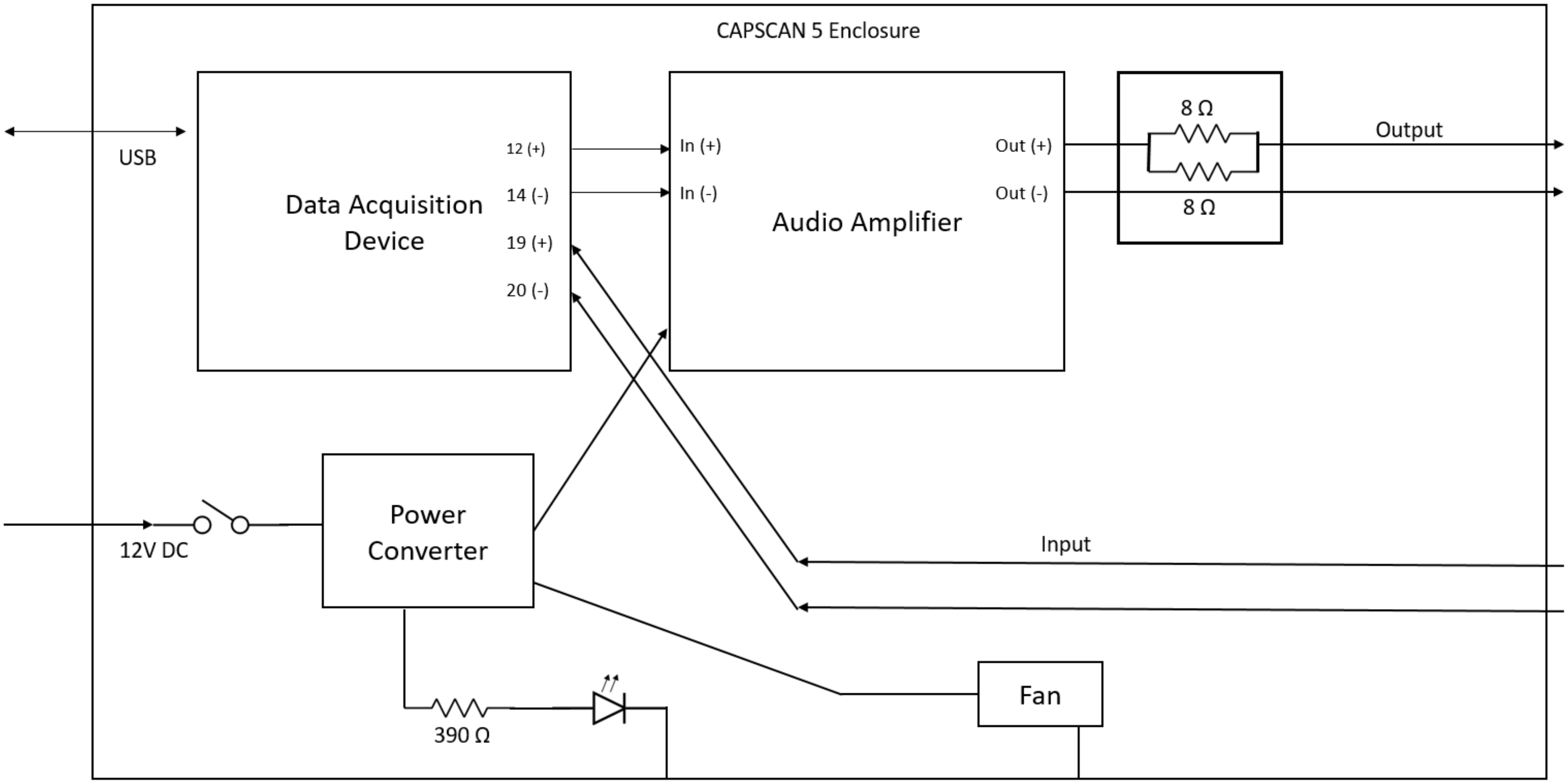
- During testing, it was discovered that NIF Capacitors and Inductors are frequency dependent.
- Capacitance at resonance (3 kHz) is different from nameplate capacitance (measured at 100 Hz).
- CAPSCAN must be able to report capacitance at 100 Hz given capacitance at resonance.



Simplified CAPSCAN system overview



CAPSCAN sensor internal schematic

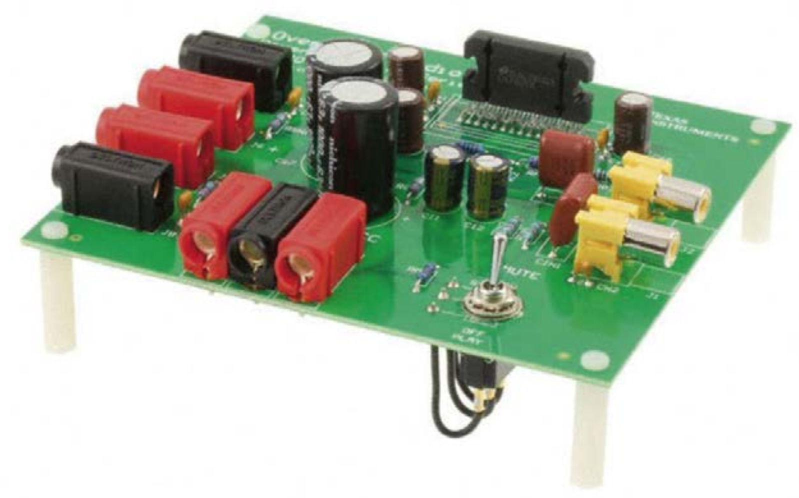


We used a National Instruments data acquisition device for improved performance

- CAPSCAN 5 replaces the sound card used in previous iterations with an NI Data Acquisition Device.
- Using the DAQ allows for much more precise measurements and eliminates the distortion and crosstalk observed in the sound card.
- Simultaneous read/write.
- Can only output 2mA, so a high-powered amplifier is needed.

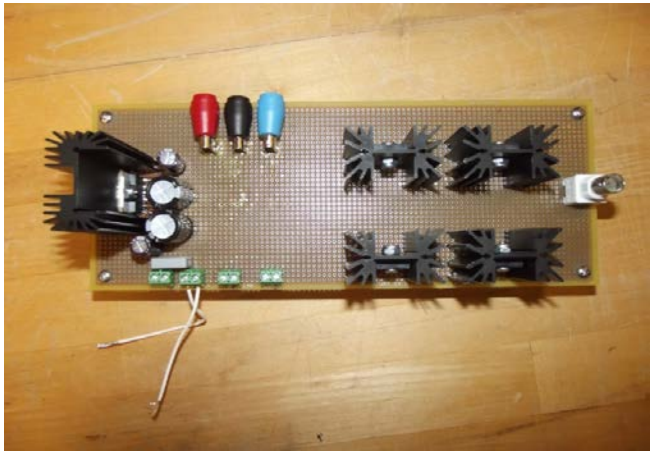
Signal-to-noise ratio improved with a better amplifier

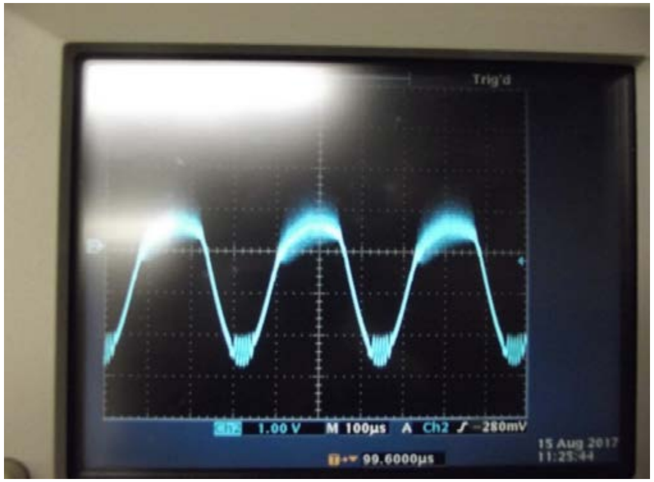
- High power output (up to 60 W).
- Class AB analog amplifier.
- Consistent measurements.
- Obsolete chip, but some evaluation boards are still sold through Digikey and TI.



An alternative custom amplifier was considered

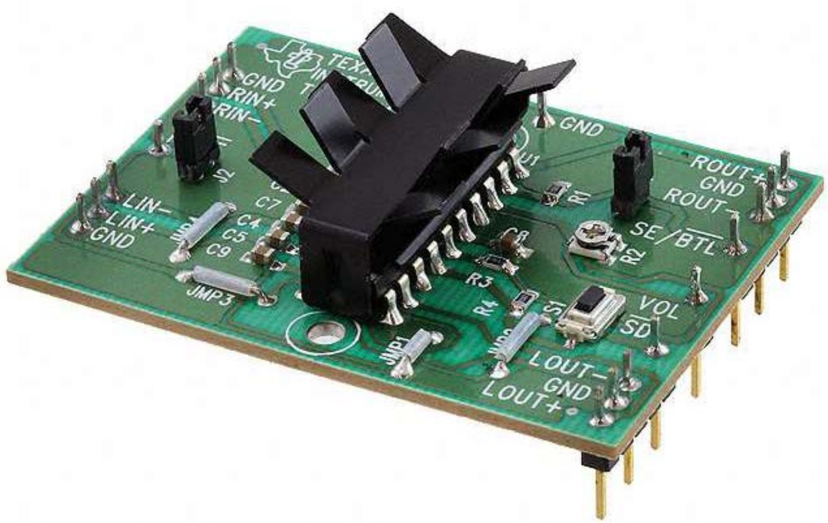
- Up to 30W per channel into an 8 Ohm load.
- Rejected due to high levels of distortion due to LC load.
- Distortion could be caused by error in circuit design/layout. Custom amplifier circuits worth exploring further in future iterations.

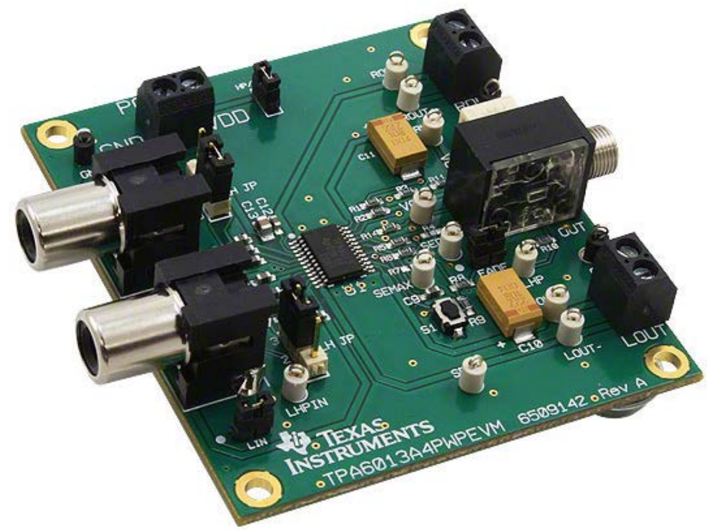




Other alternative amplifiers can be used

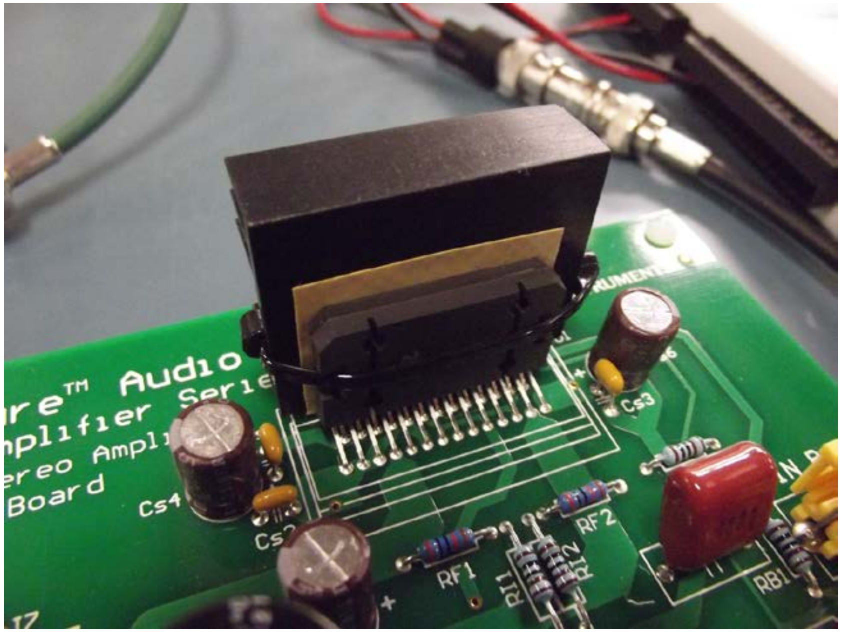
- Several replacement amplifiers were evaluated and can be used in place of the current amplifier.





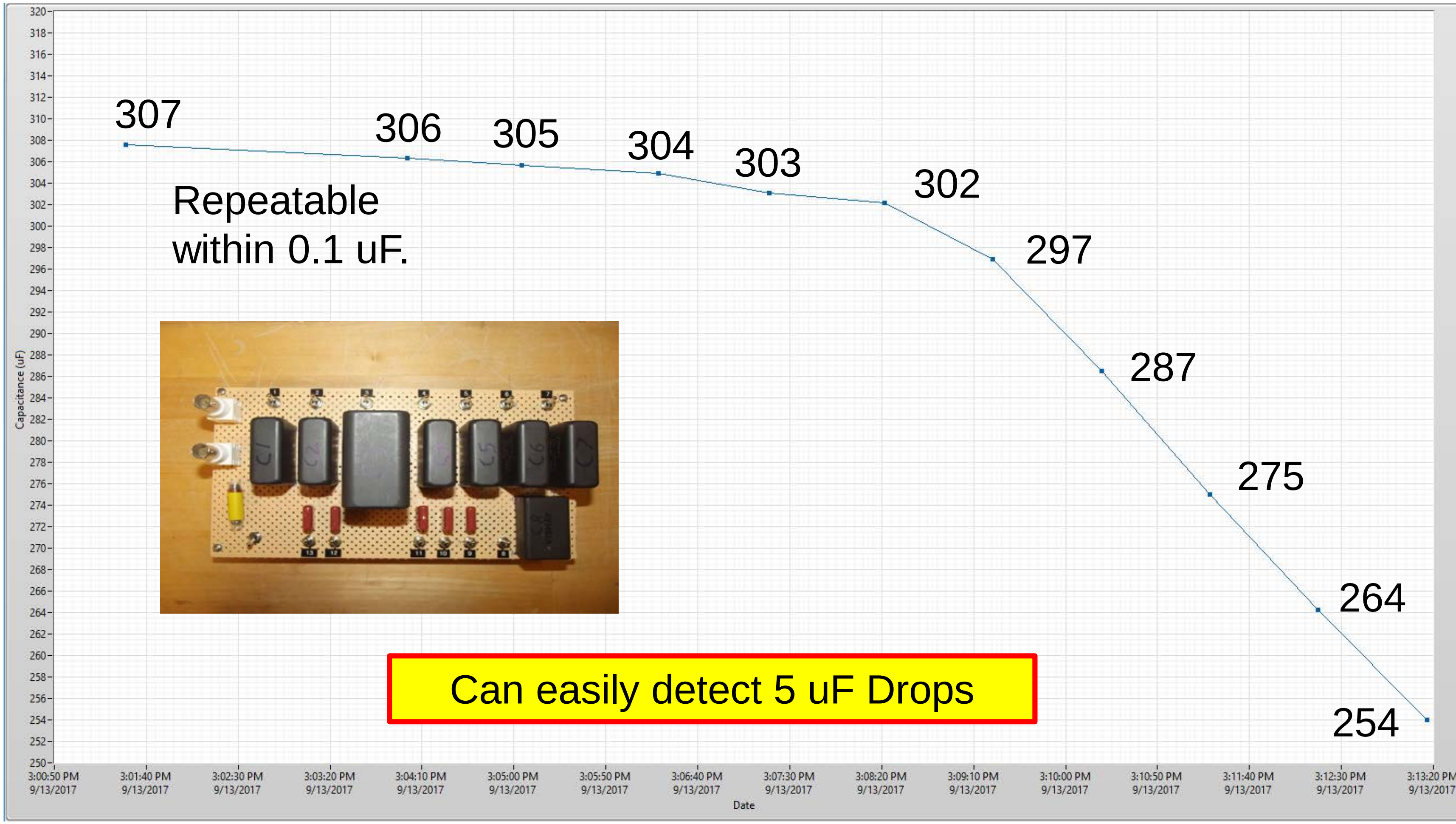
Power output increased by using a heatsink

- Audio Amplifier requires a heatsink for optimum performance.
- No heatsink: 8W max (40 C ambient temperature)
- With heatsink: 24W max (40 C ambient temperature)
- Maximum measured temperature with heatsink:
  - 65 C heatsink temperature

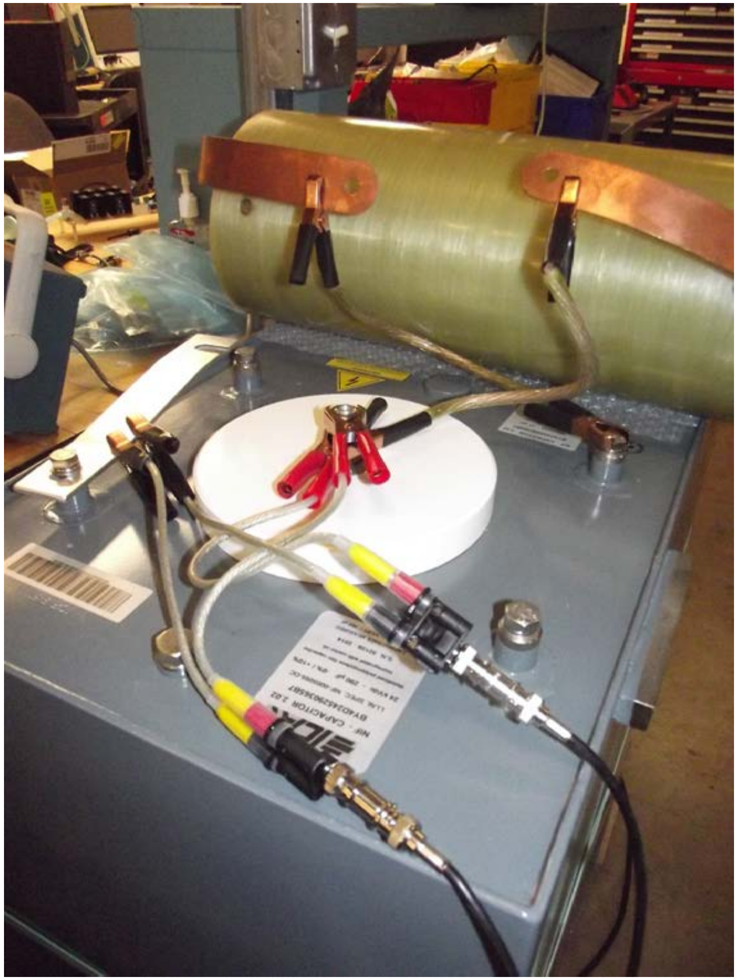


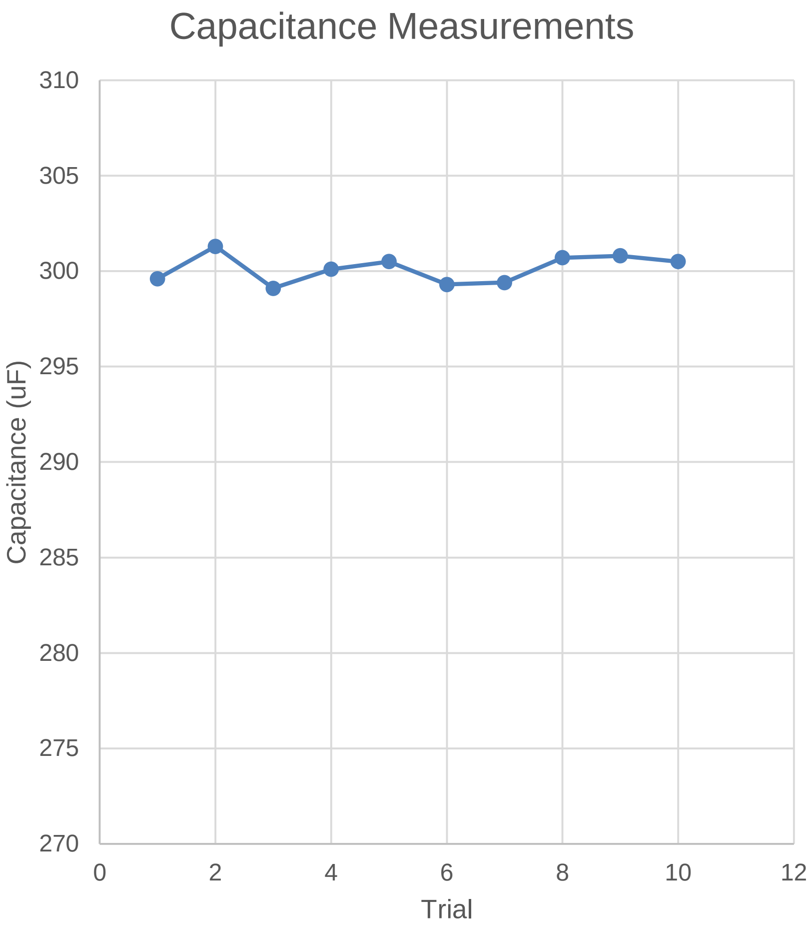
We were able to show CAPSCAN can detect small changes in capacitance

Failing Capacitor
Simulation



Repeatability down to 3 uF



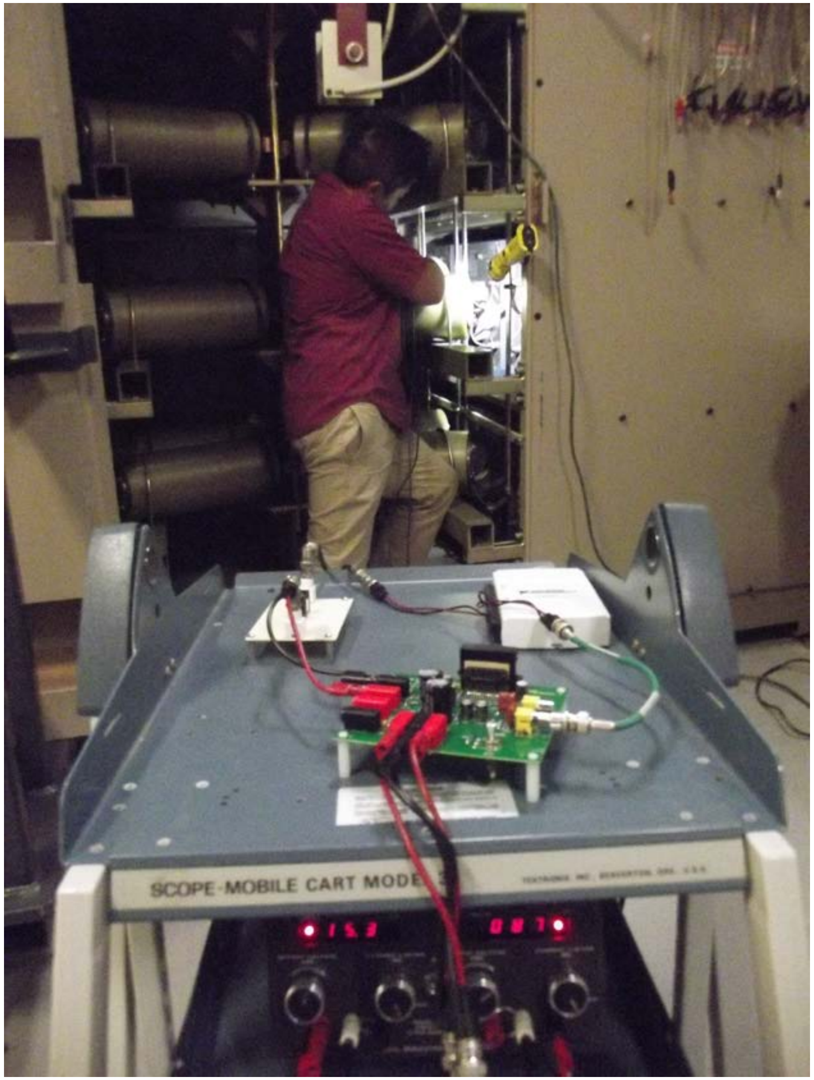


We were able to get good results on bulged capacitor measurements

- 7 bulged capacitors were measured, with 5 measurements per capacitor.
- Values compared to measurements from a commercial LCR meter.

Actual Value (uF)	Average Error (uF)	Error Range (uF)
292.1	3.51	1.23
291.7	1.33	0.95
275.8	0.19	0.43
292.7	2.45	0.9
292.4	2.81	1.8
284.5	1.64	2.22
279.1	1.18	1.49

We then measured the real bank module



I discovered inductance varies with position inside the module

- Inductance changes based on capacitor location.
- PSPICE model shows similar position-dependent effects.
- Used resonant frequency, nameplate capacitance to calculate inductance.

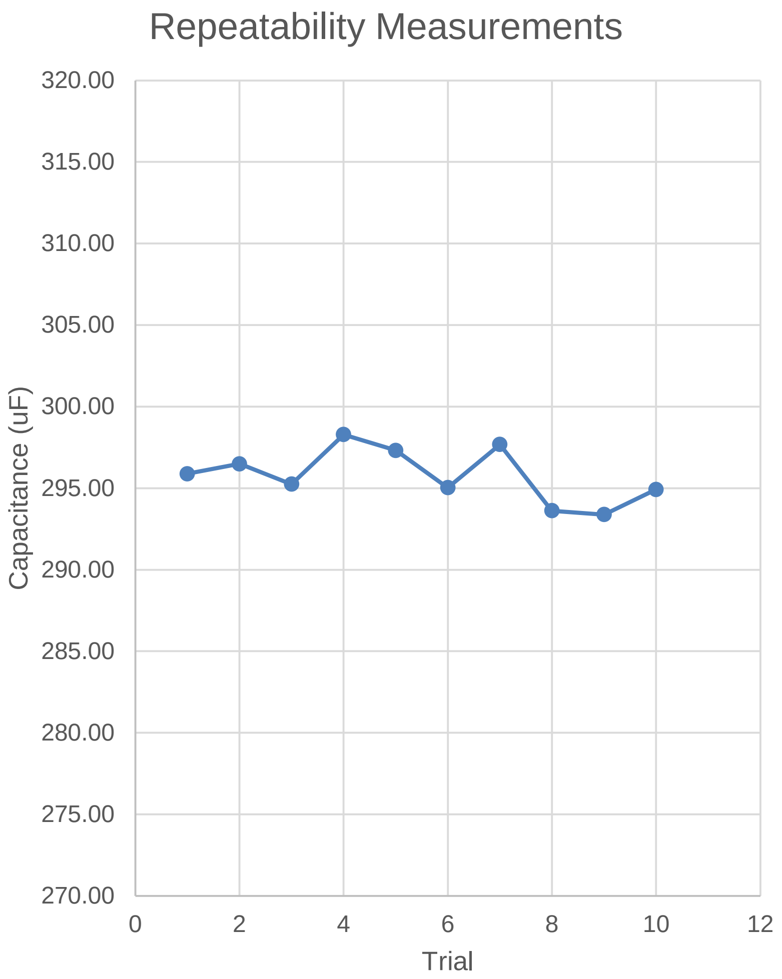
	Left (uH)	Right (uH)
Row 1	9.62	9.84
	9.67	9.67
	9.62	9.84
Row 2	9.70	9.79
	9.51	9.53
	9.66	9.53
Row 3	9.62	9.69
	9.49	9.51
	9.70	9.67
Row 4	9.88	9.96
	9.81	9.83
	10.01	10.17

I was able to show that error is within 2%

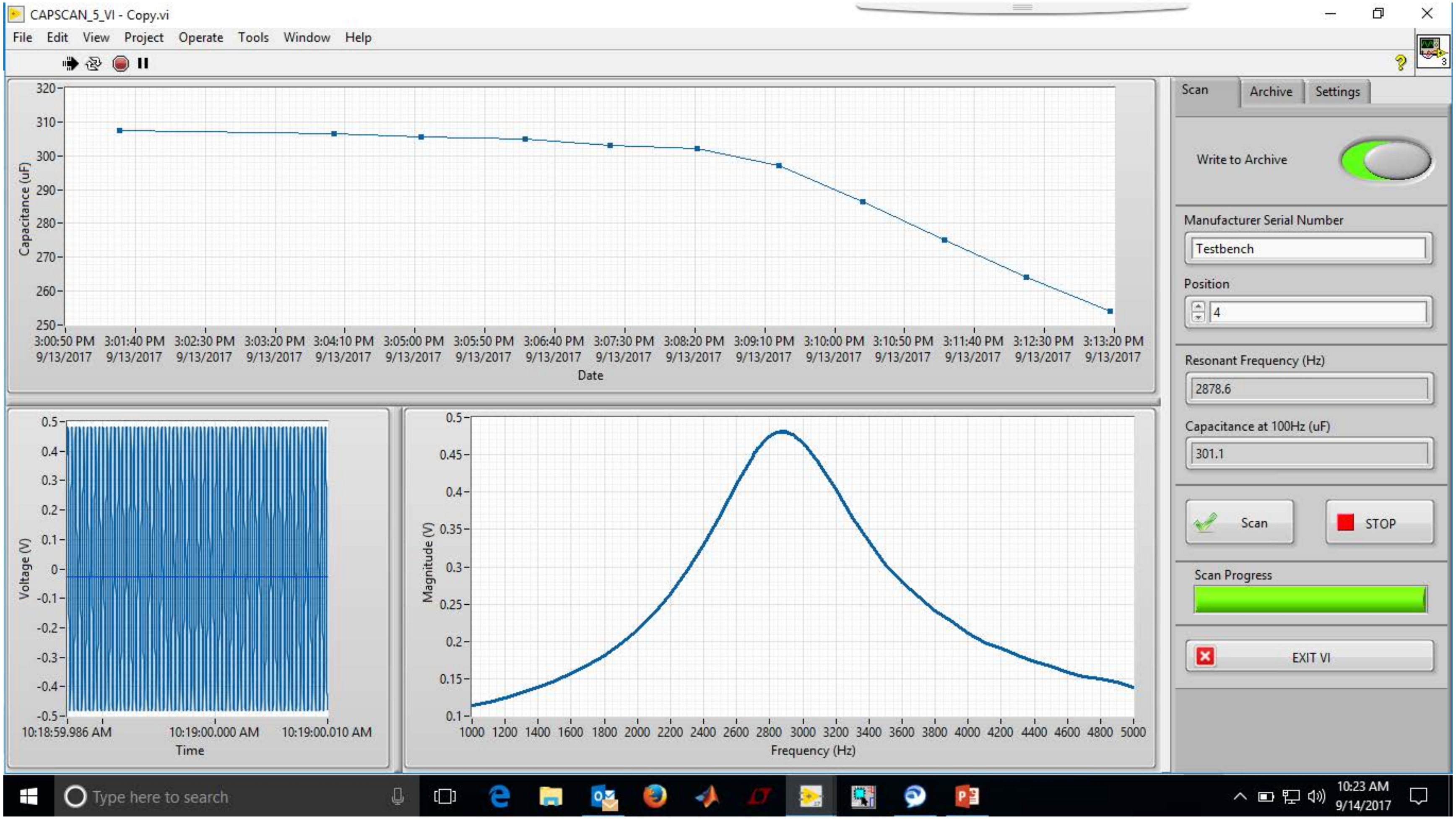
Bu13 Bm7				
Capacitor	Nameplate (uF)	C Calculated (100 Hz)	Error (uF)	% Error
1				
2				
3	302	**299.34**	2.66	0.88
4	302	**299.49**	2.51	0.83
5	298	**295.19**	2.81	0.94
6	299	**298.73**	0.27	0.09
7	300	**294.84**	5.16	1.72
8	298	**292.85**	5.15	1.73
9	301	**298.12**	2.88	0.96
10	299	**295.21**	3.79	1.27
11	298	**294.58**	3.42	1.15
12	300	**297.59**	2.41	0.80
13				
14				
15				
16				
17	299	**295.18**	3.82	1.28
18	300	**300.50**	0.50	-0.17
19	299	**297.12**	1.88	0.63
20	299	**297.75**	1.25	0.42
21	302	**298.14**	3.86	1.28
22	301	**298.05**	2.95	0.98
23	299	**297.56**	1.44	0.48
24	300	**296.38**	3.62	1.21

…and repeatability is within 1%

- 298 uF Capacitor.
- Measurements within a 4.3 uF range.
- Maximum error 4.6 uF. Average error 2.3 uF.



Custom GUI allows you to extract and archive capacitance for any capacitor serial number

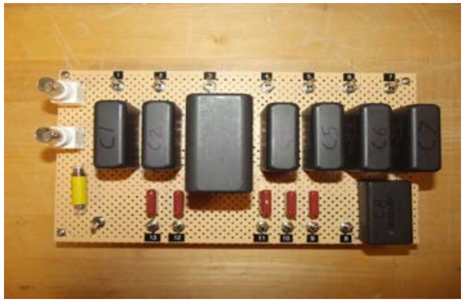


CAPSCAN features and improvements

- Scan time within 1 minute
  - 20 minutes required by previous generations.
- Accuracy within 7 uF, repeatability within 5 uF.
  - 20-40 uF error in previous generations.
- Track capacitance of 4000 capacitors in the NIF facility.
- Improved simplicity.
  - Removed calibration and debugging user settings from CAPSCAN 4.0
- Export measurements to Excel or other applications for advanced data processing.

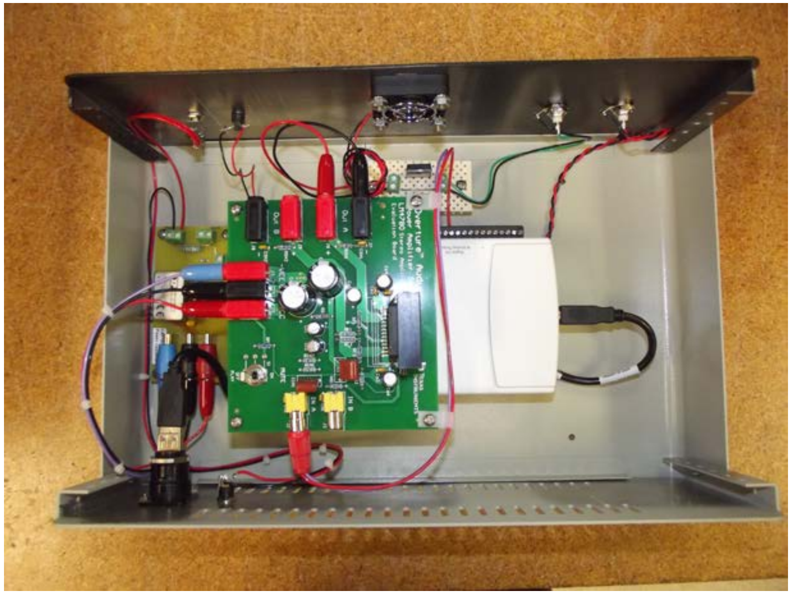
Results are better than design requirements

- In general, accuracy is limited by accuracy of inductance value.
- LC Circuit, Bulged Capacitors:
  - <= 4 uF error.
  - Consistent within 2 uF.
  - Approximations valid for bulged capacitors.
- Testbench:
  - 5 uF error maximum. (Within 1.5%)
  - Consistent within 0.1 uF.
- Bank Modules:
  - Accuracy limited by knowledge of inductance.
  - Accurate within 7 uF (2.5% error).
  - Consistent measurements within +/- 2.5 uF (1% error).



Results are better than design requirements

- Tested on 3 bank modules.
- Software used by 2 NIF technicians (Huy and Miguel).
- Deployable design has been developed.



Suggestions for future improvements

- Design a custom audio amplifier or explore cheaper, smaller, or lower-power amplifiers.
- Add additional data analysis capabilities to the LabView program.
  - Search archive for worst-case capacitors.
- Improve accuracy, repeatability, and speed through improved averaging or curve fitting techniques.
- Better characterize MESM inductance for each capacitor position.
- Find better ways to connect probes to capacitors for improved usability.

What I learned

- Amplifier Design
- Presentation Skills
- SPICE Simulation
- Thermal Analysis
- LabView Programming
- Packaging Design

Acknowledgements

- Bruno Le Galloudec
- Glen James
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- Lou Pades
- Evan Carrol
- Tony Runtal
- Joe Foley
- Tyron Bettis
- Michael Sherburne
- Steve Fulkerson
- Paul Hammon

Thank You

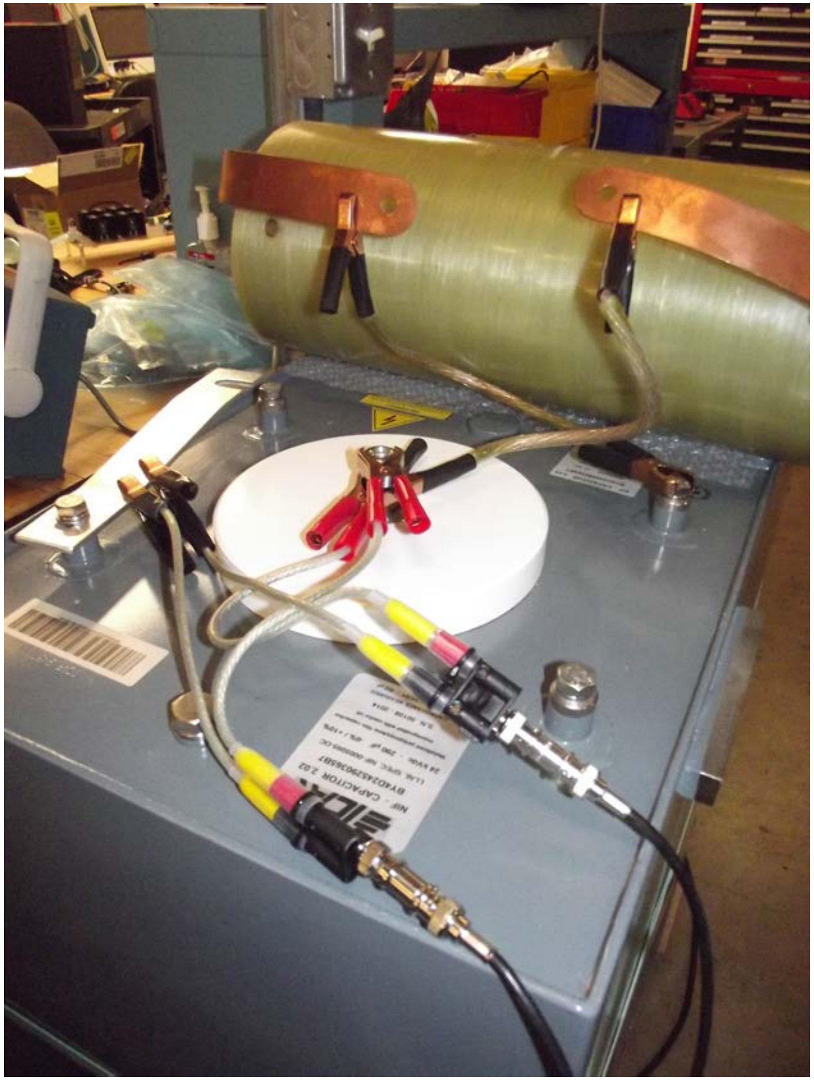
Pictures

Pictures

Pictures


NIF - CAPACITOR 2.02
BY4D245290365B7
LLNL SPEC. NIF - 0005095 - 0B
24 kV dc - 290 µF -0%/+10%
Metallized polypropylene film capacitor
impregnated with castor oil
S.N.37941-2001
CAPACITANCE MEASURED
AT THE DELIVERY 303 µF

Pictures



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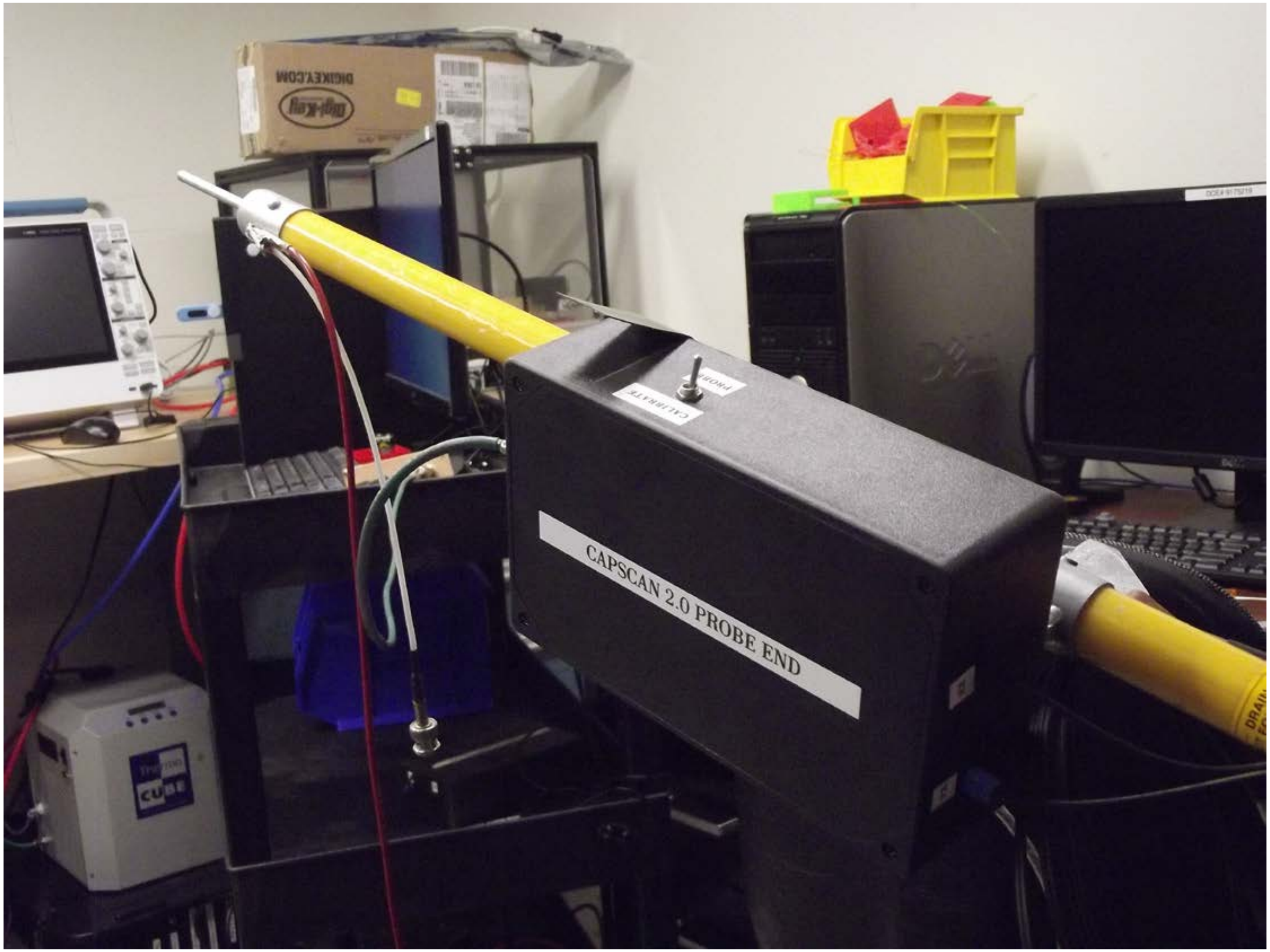

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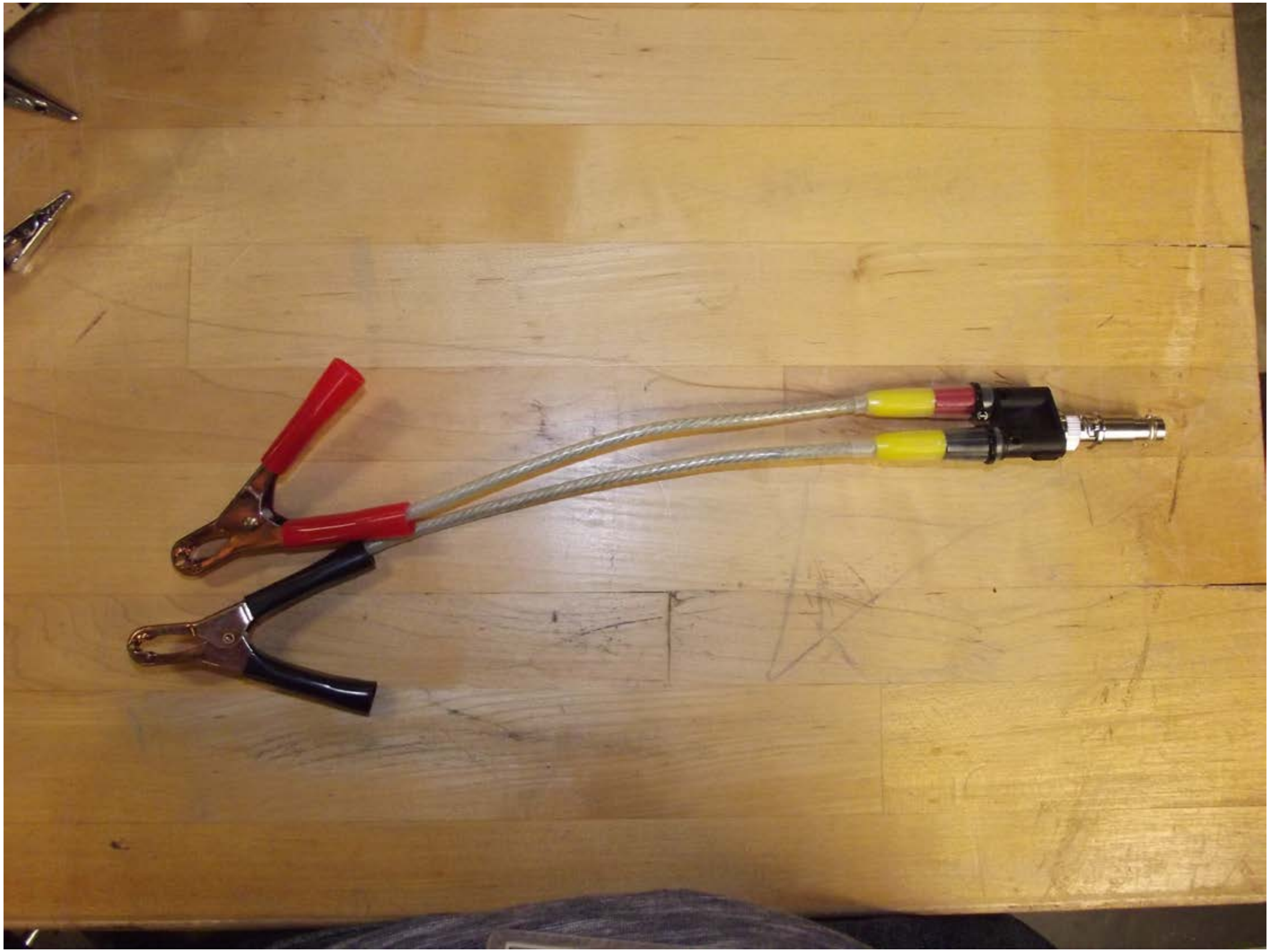

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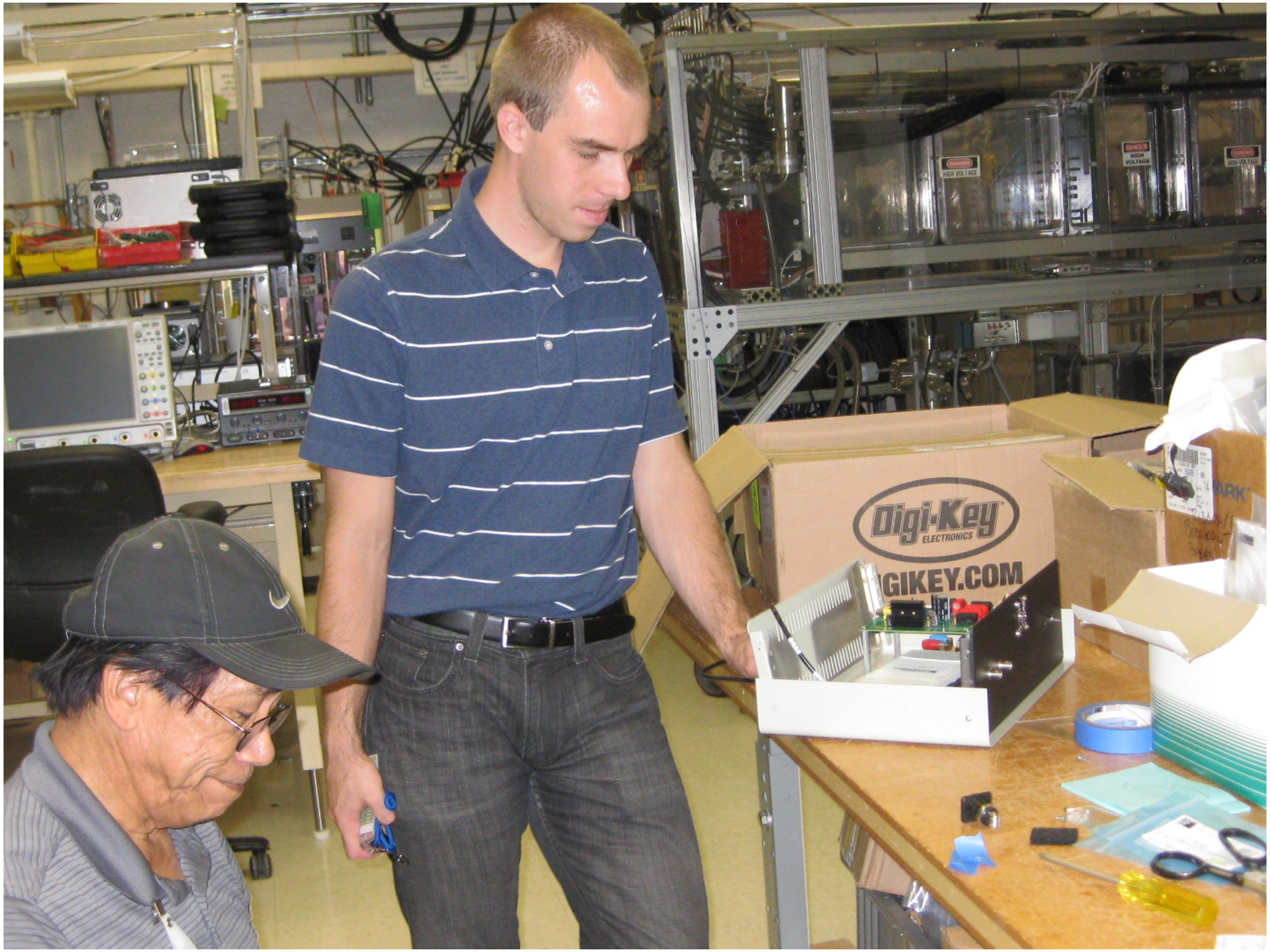

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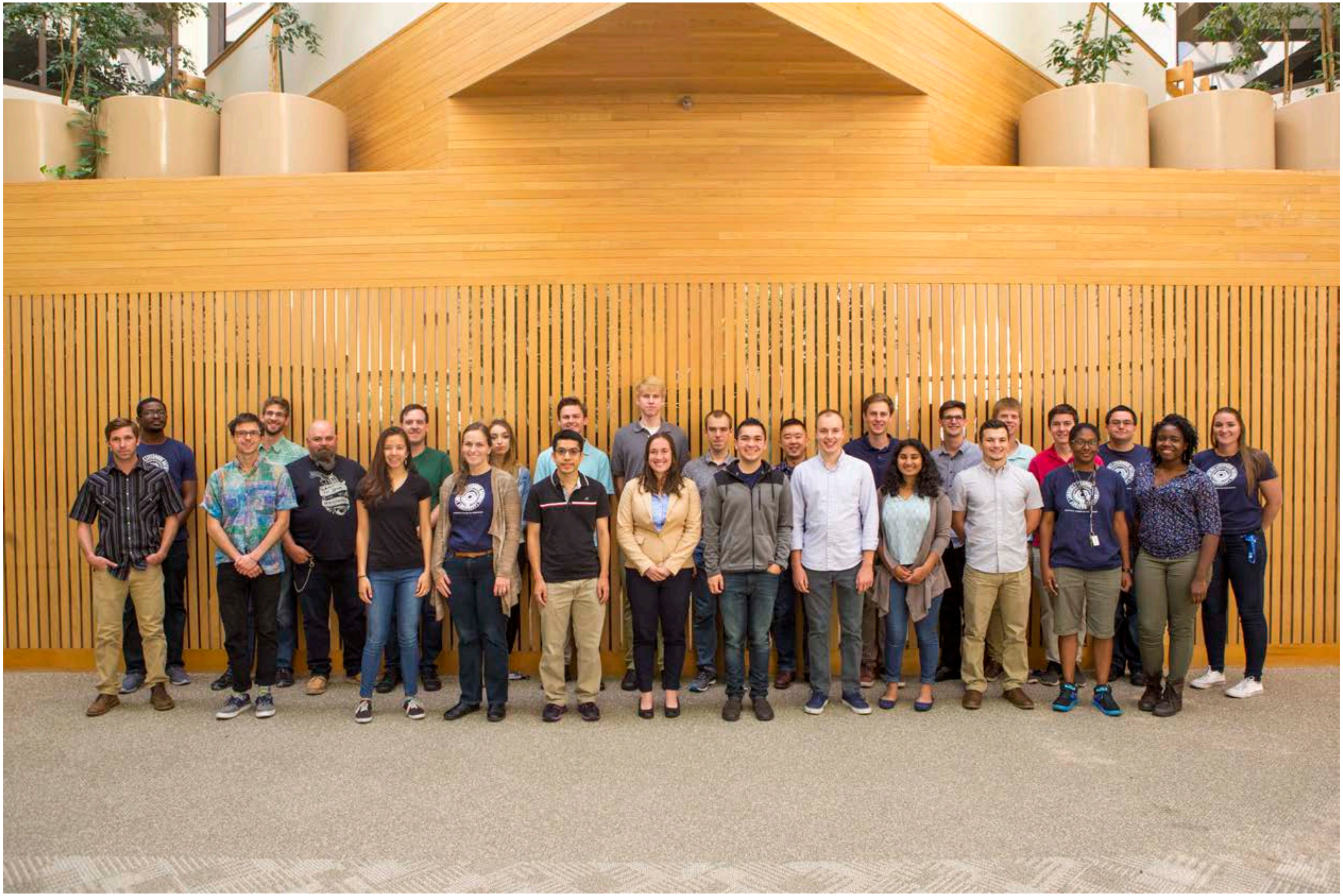

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