This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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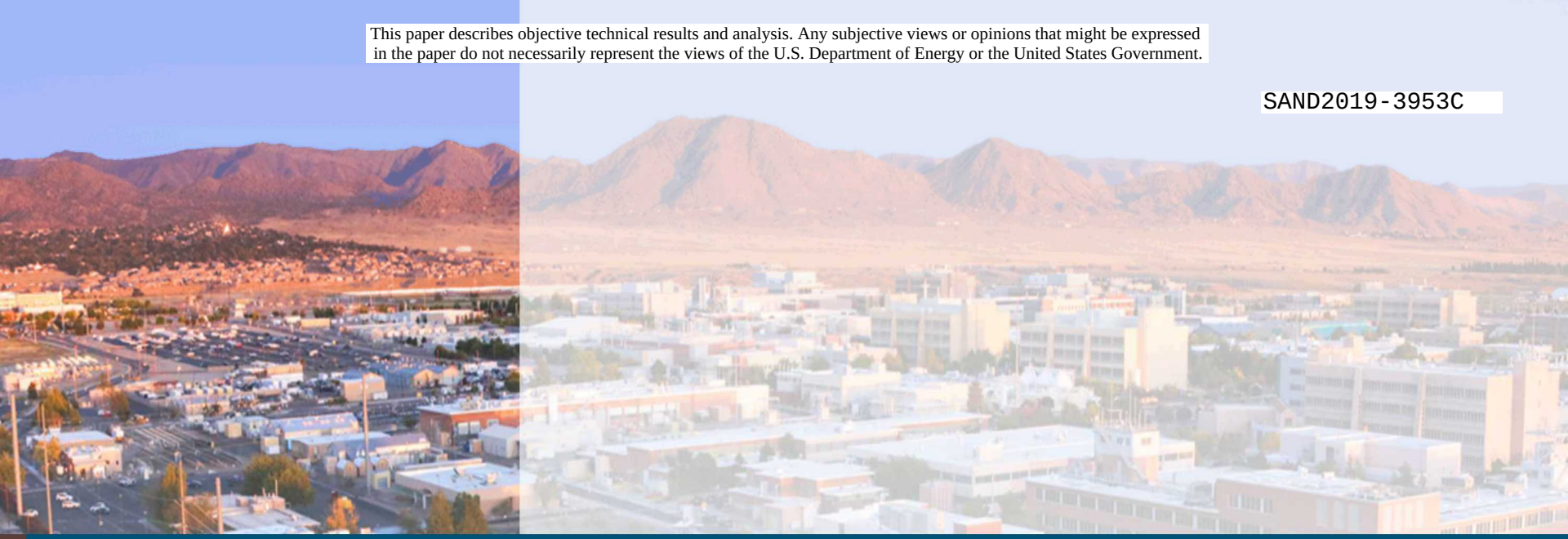

HPEM in Combined EM and Mechanical Vibe Environments

2019 Annual Directed Energy Science and Technology Symposium
Destin, FL

Jeffery T. Williams, Isak C. Reines, Larry K. Warne, Richard A. Jepsen, Roy K. Gutierrez, Brian C. Owens, Rebecca S. Coats and Lorena I. Basilio

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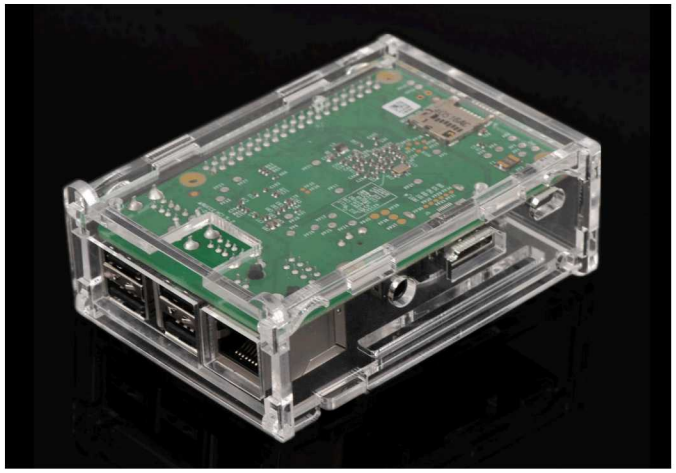
Combined Environments

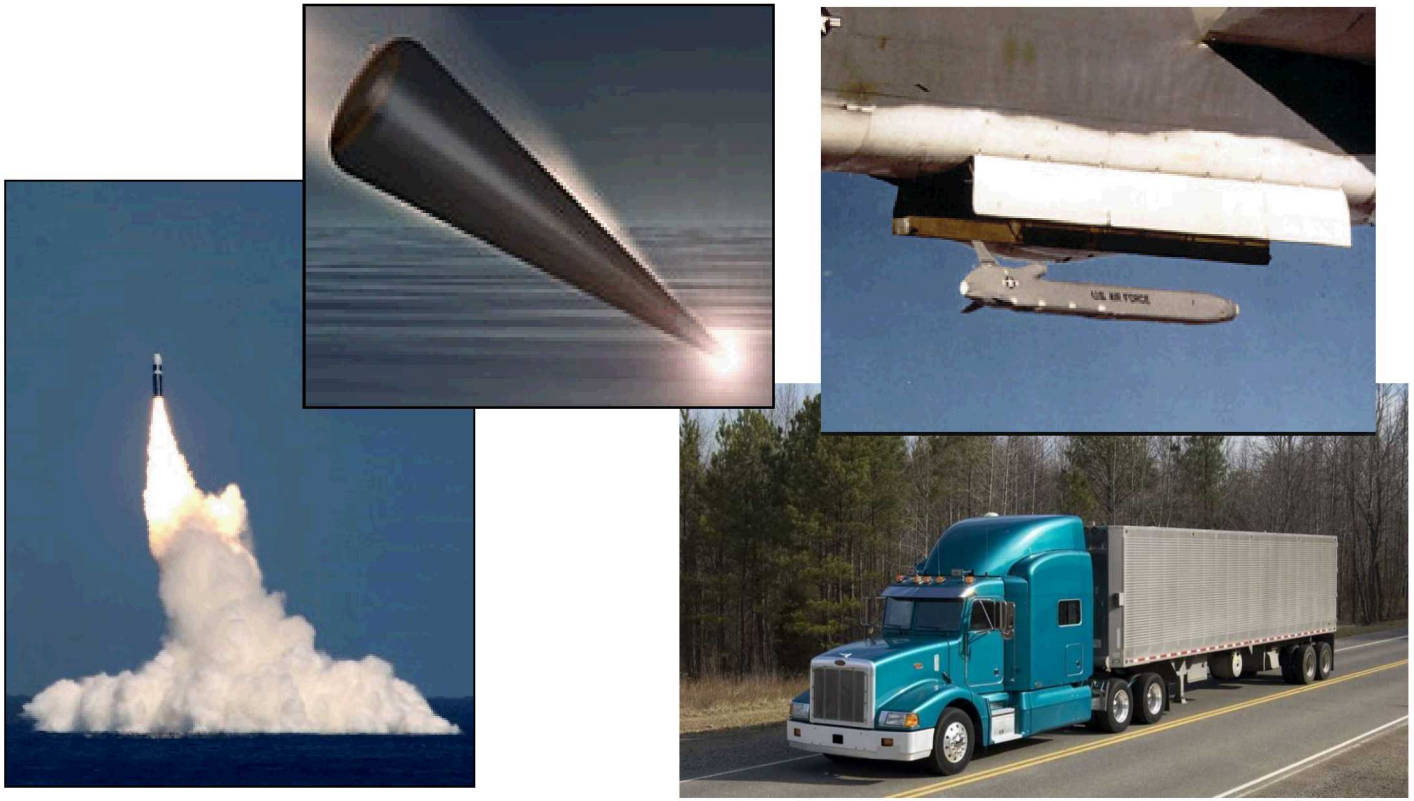
Combined Environments (CE) is our term for what would generally be called Multi-Physics. Its legacy is associated with Sandia's history in systems certification for different "environments"

We are considering combined electromagnetic and mechanical vibration environments (EM/vibe).

The primary focus of this Combined Environments effort is to understand how mechanical influences/changes affect the electrical performance of a system.



Environments

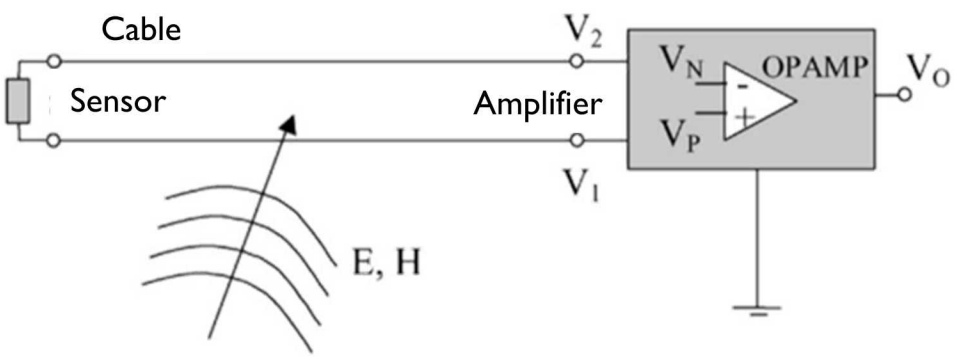


- Mechanical vibrations induce relatively slow (100's-1000's Hz) dimensional changes to electromagnetic points of entry (POE). POE: joints, apertures, holes, connectors,…
- These dimensional changes influence the electromagnetic coupling through the POE; thereby, amplitude modulating the coupled fields.
- Amplitude modulated fields can result in observable effects in electric circuits and other sensitive components.

Effects on Electronic Circuits

- Some analog electronic circuits tend to naturally demodulate (rectify) amplitude modulated (AM) signals. As a result, the lower frequency baseband components are separated from the higher frequency carrier.

OP Amp (differential stage at input)



$$v_{out}(t) \sim \alpha_1 v_{in} + \alpha_2 v_{in}^2(t)$$

(notional)

$$v_{in}(t) = (1 + mA(t))\sin(\omega_C t + \phi)$$

$$v_{out}(t) \sim \alpha_1(1 + mA(t))\sin(\omega_C t + \phi_1) + \alpha_2(1 + 2mA(t) + m^2A^2(t))\,[\sin(\phi_2) + \sin(2\omega_C t + \phi_3)]$$

filtered out by circuit response (parasitics)

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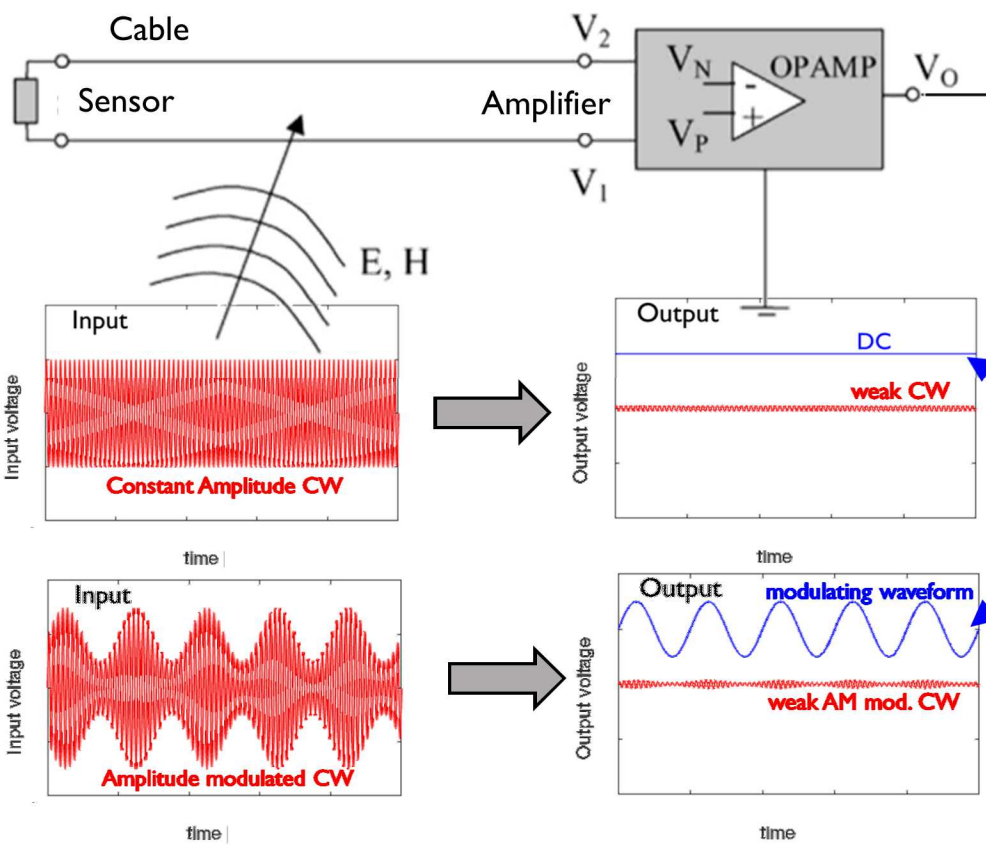
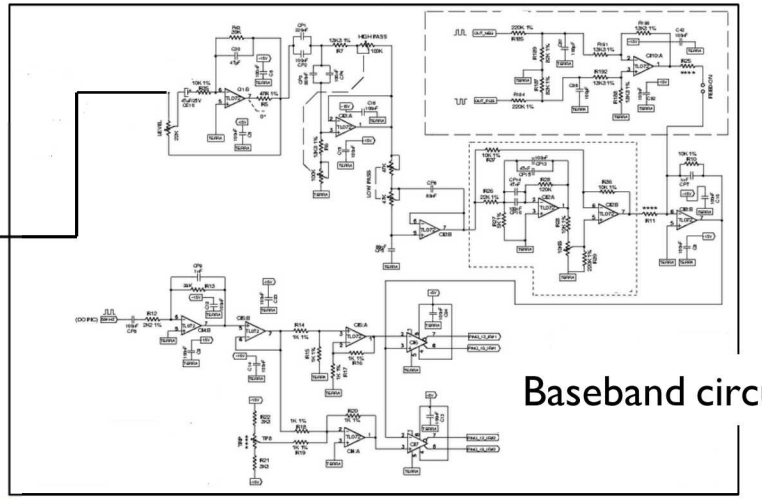




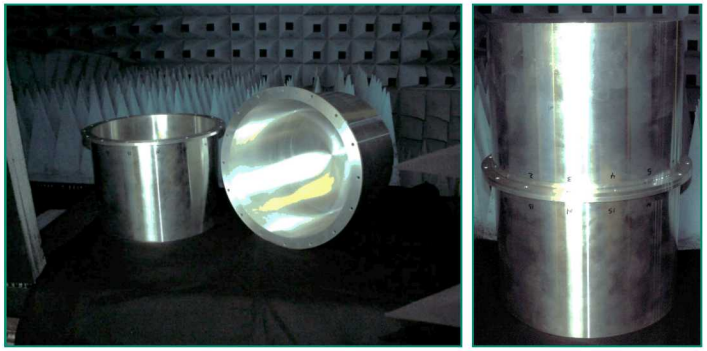
Baseband circuit

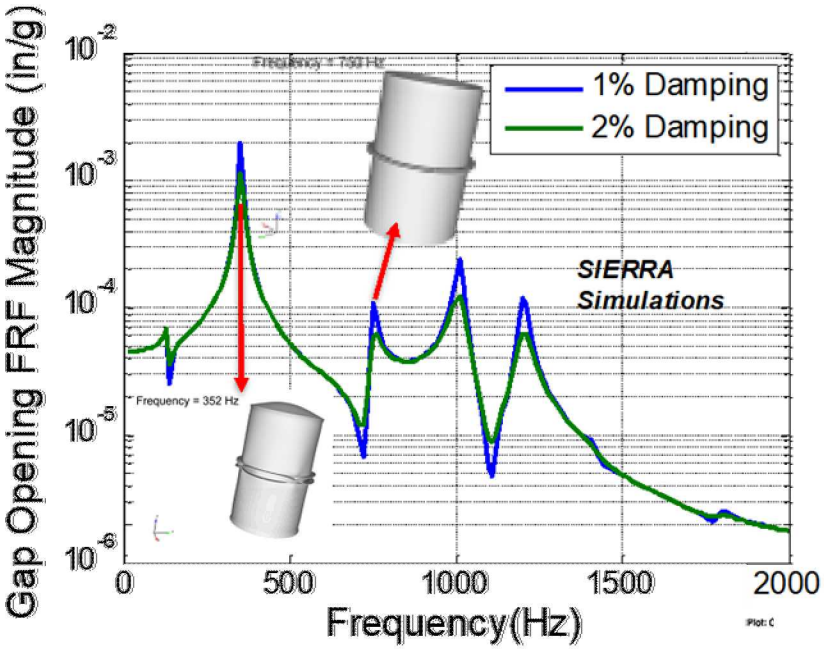
These baseband signals can affect** the performance of the circuits connected to the output.

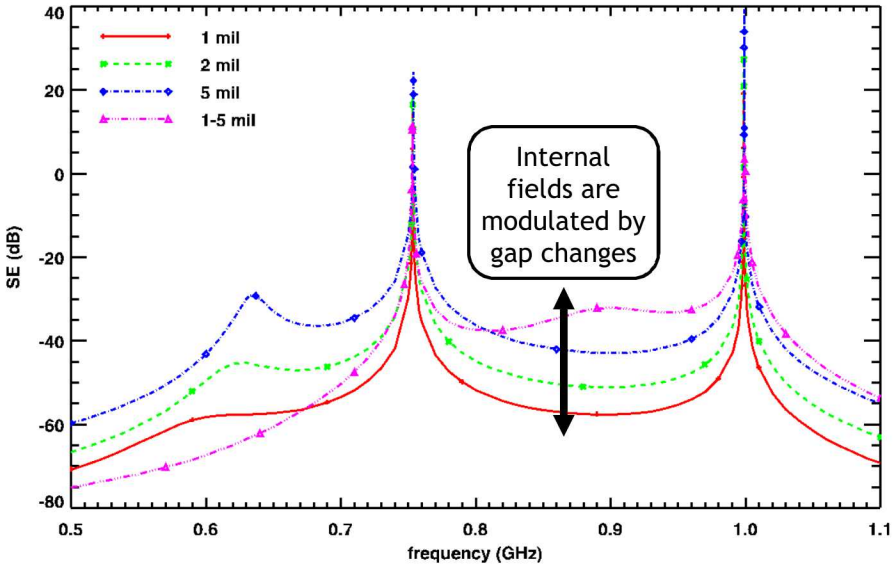
** Dependent upon baseband circuit functionality.

Preliminary Mechanical & Electrical Simulations

- Flat flanged cylinder
- Bolted joint
- Shims are used to define aperture slot dimensions



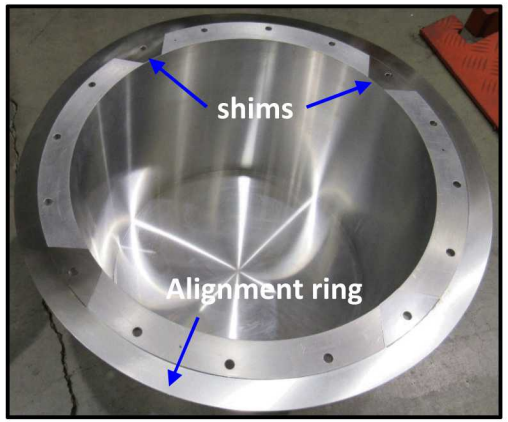


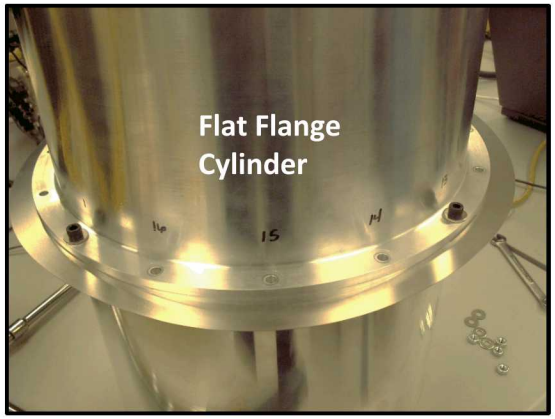


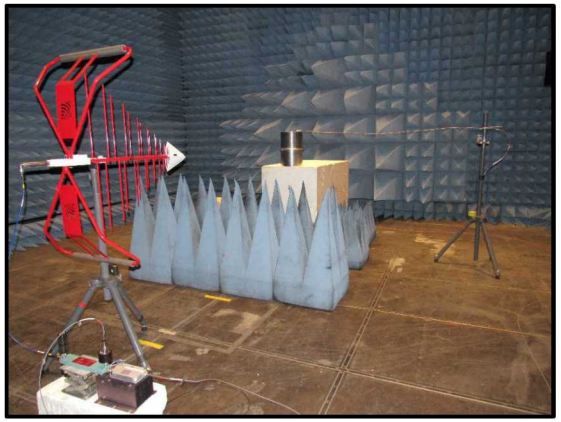
FRF: frequency response function

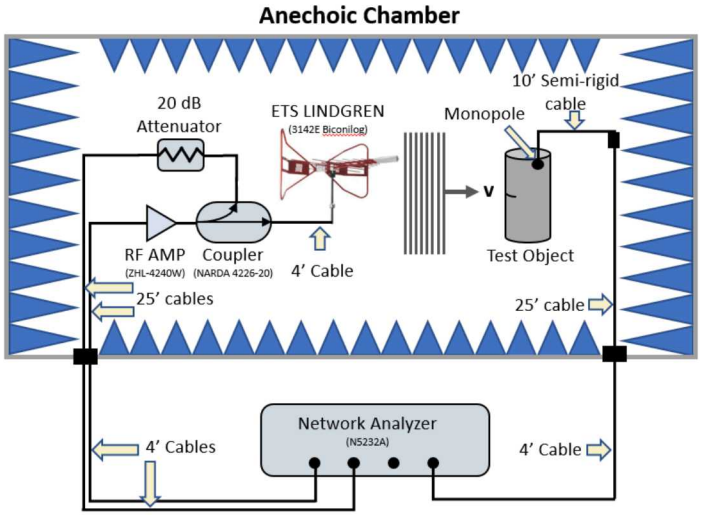
Static EM Shielding Effectiveness Setup

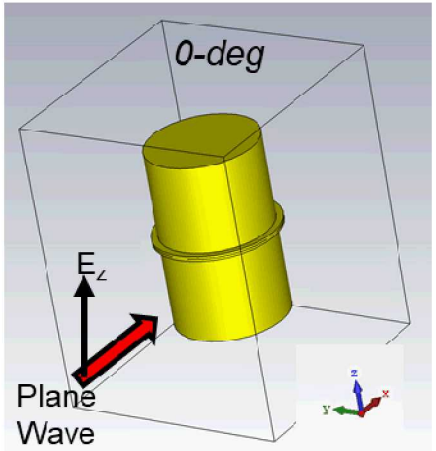
- Shielding effectiveness (SE) measurements performed in an anechoic chamber





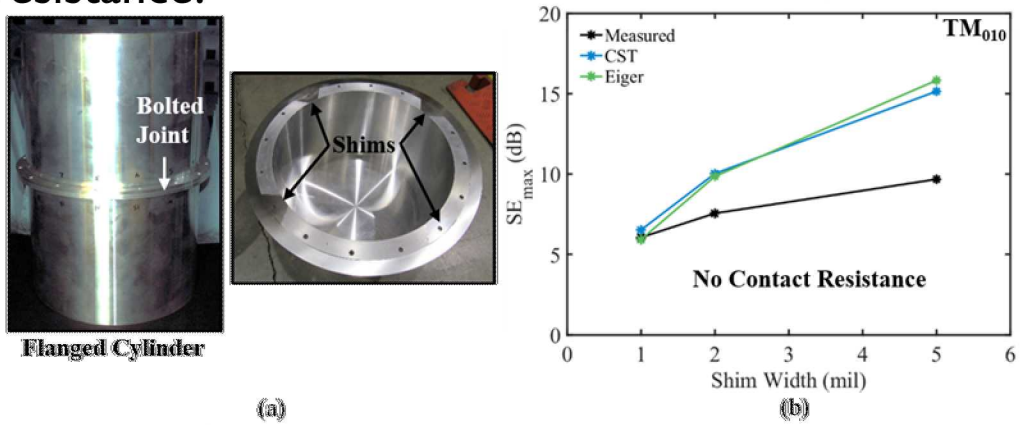






Flat Flange Cylinder Static Shielding Results

- Static (w/o vibe) shielding effectiveness measurements and simulations performed with 1, 2, and 5 mil thick stainless steal shims (4x aperture slots).
- Sandia Eiger and commercial software CST were utilized.
- Very good agreement achieved with the addition of the joint contact resistance.



Vessel 2 Static Shielding Results

- Static (w/o vibe) shielding effectiveness measurements and simulations performed with 1, 2, and 5 mil thick stainless steal shims (4x aperture slots).
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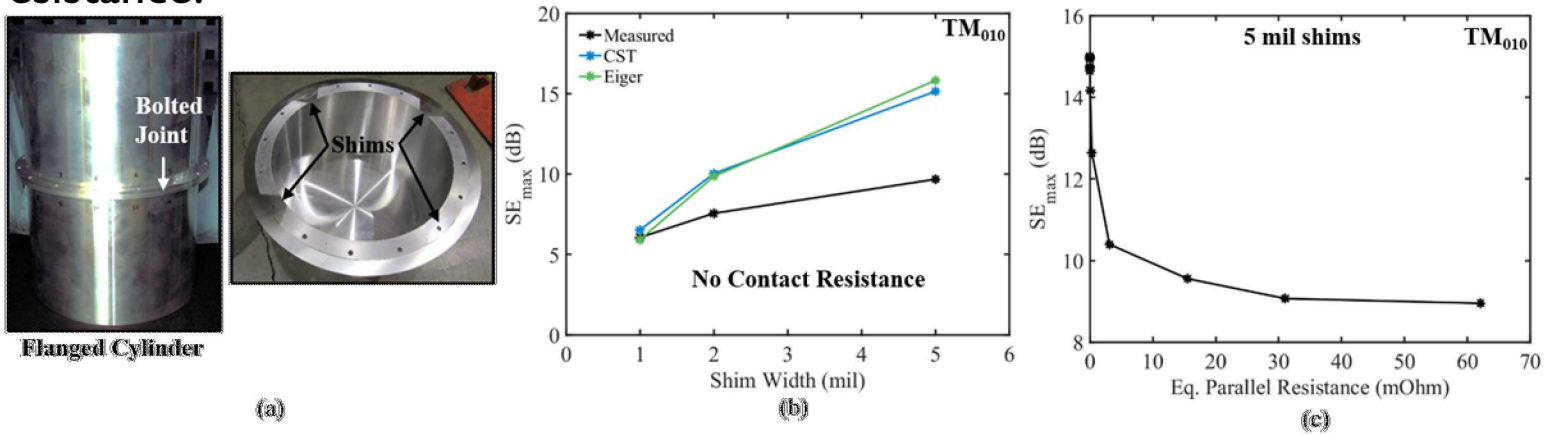

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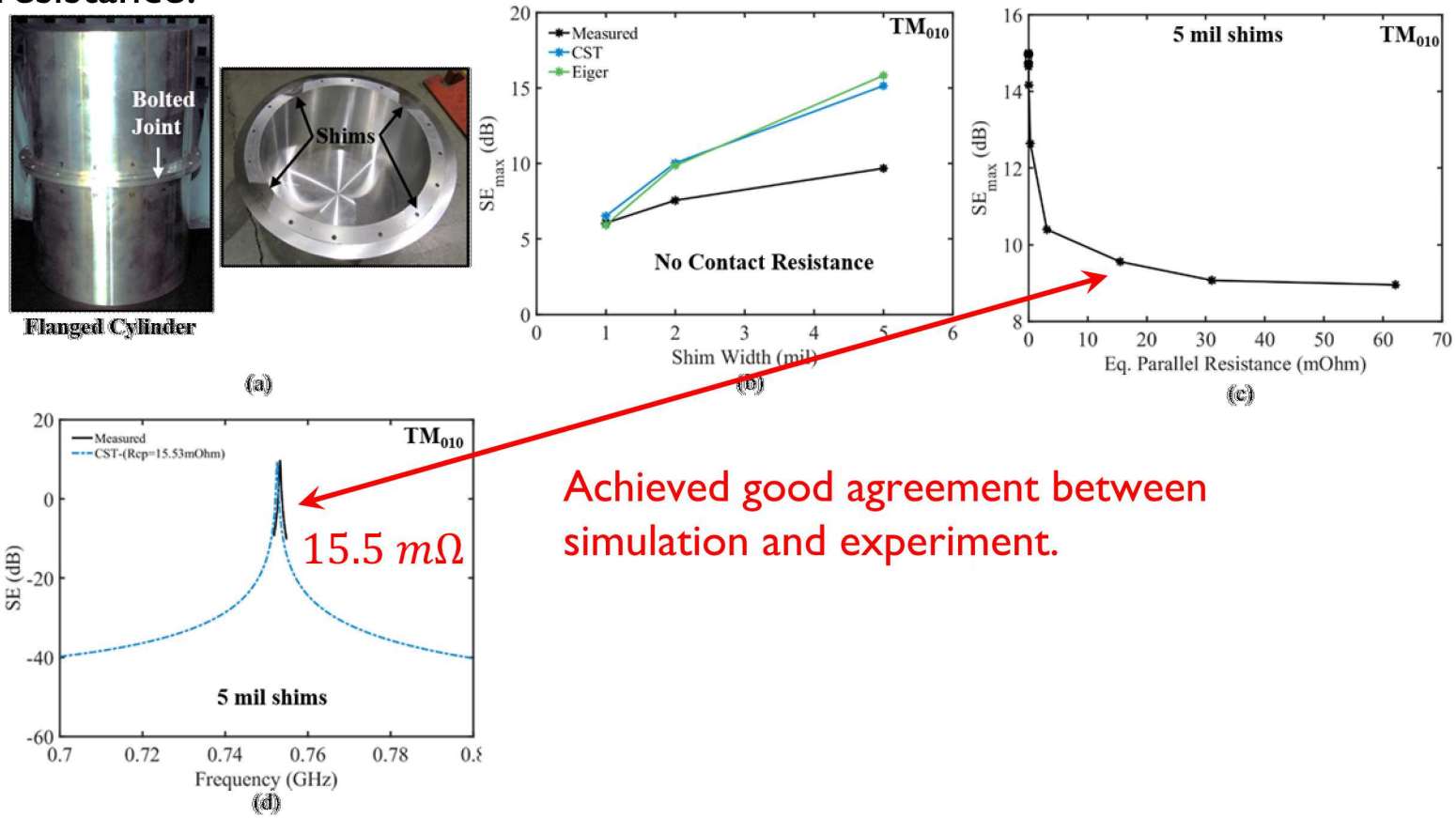

Achieved good agreement between simulation and experiment.

Vessel 2 Static Shielding Results

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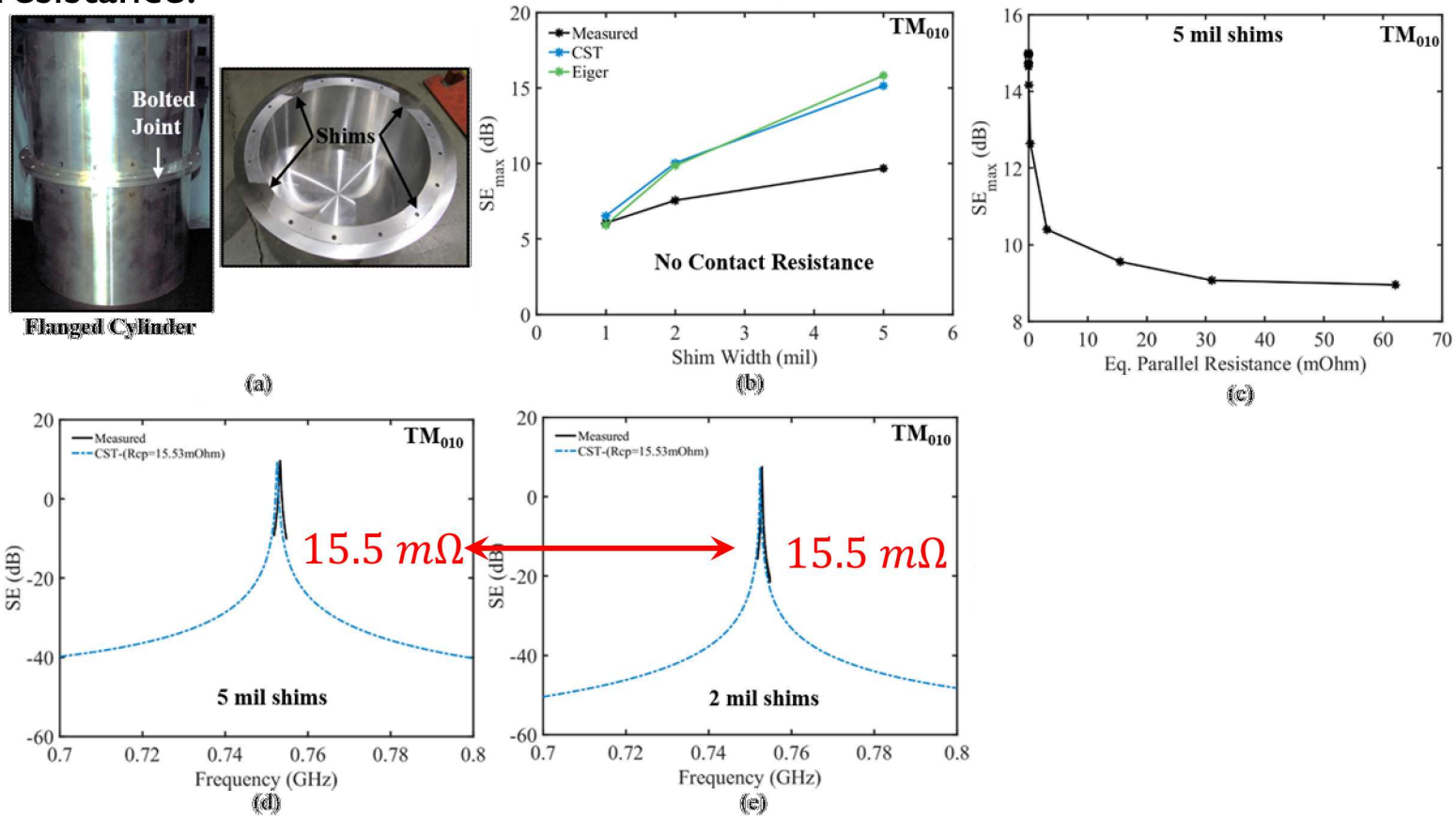

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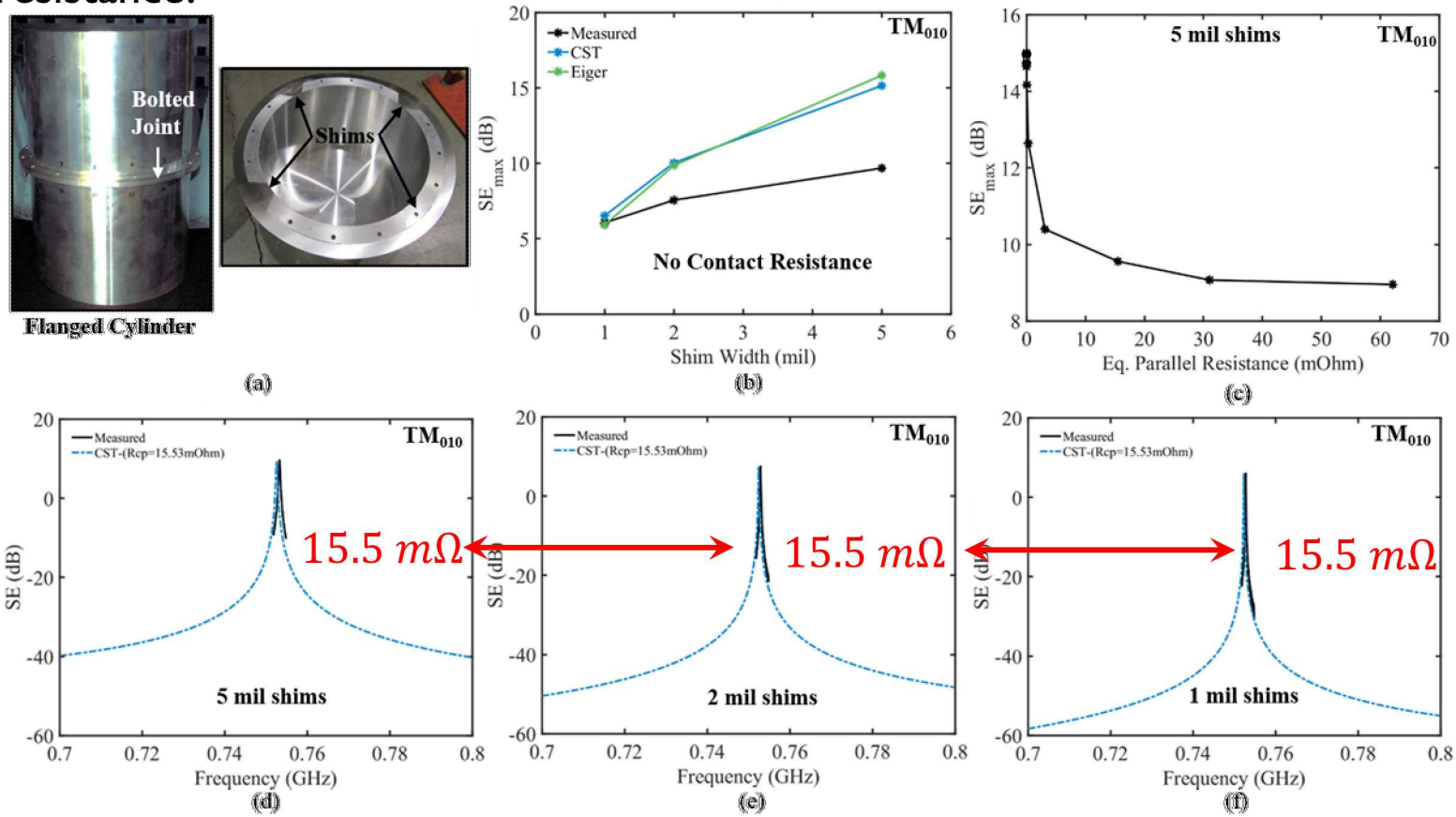
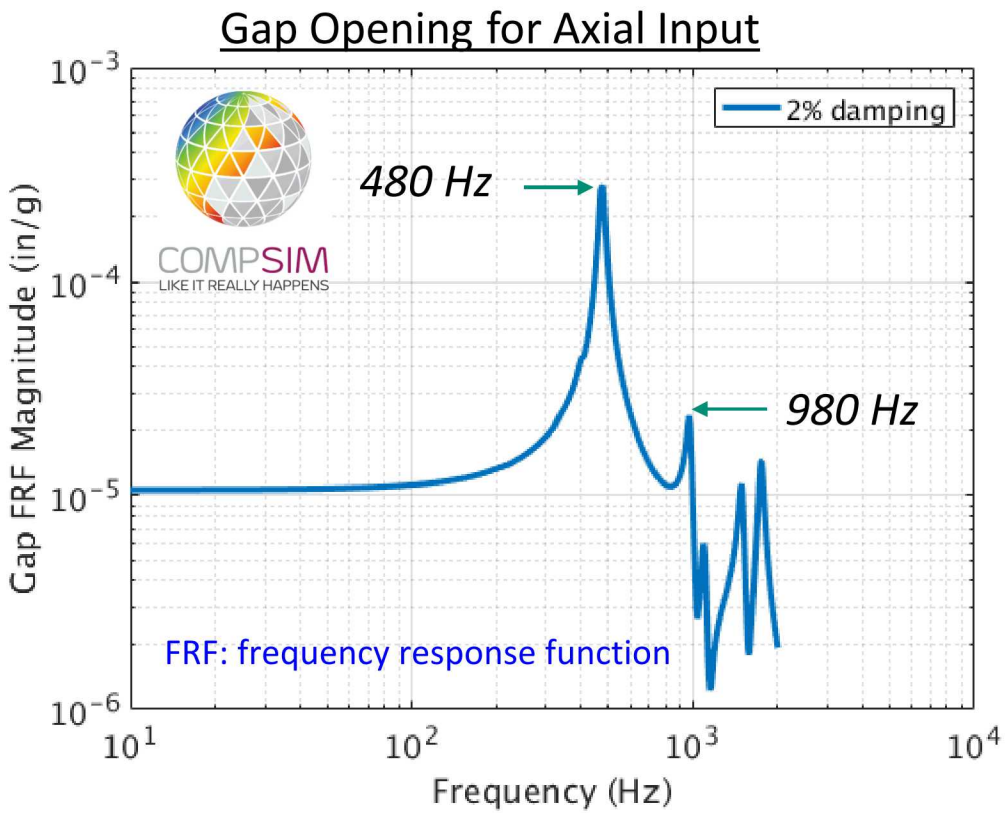
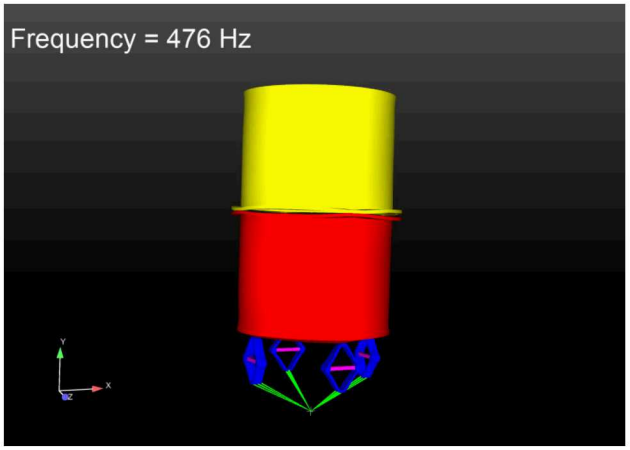
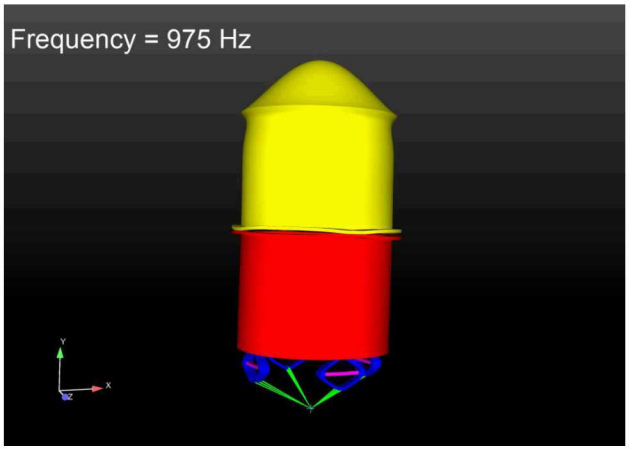
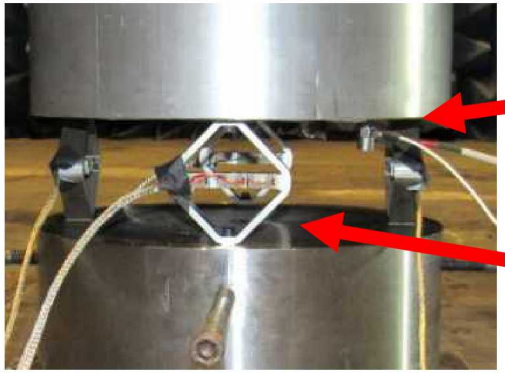


Flat Flange Mechanical Simulations









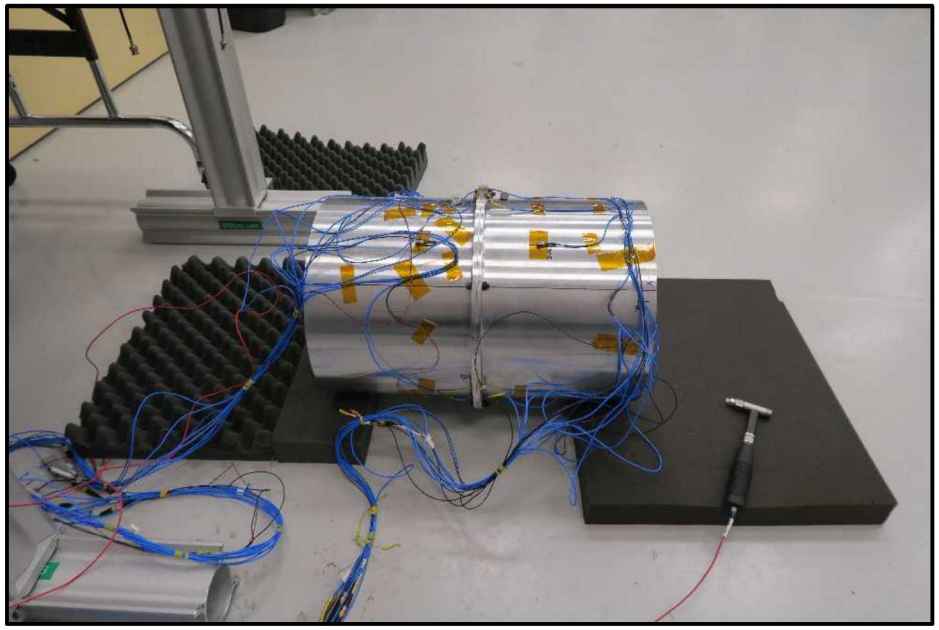
Accelerometer

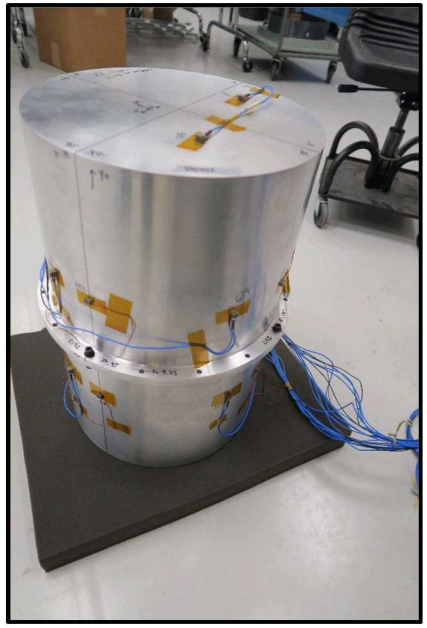
Single Input, Single Output (SISO) control system

Piezoelectric vibration actuators

Results from Brian C. Owens

Flat Flange Modal Analysis & Measurements





Modal Frequencies: Test & Analysis

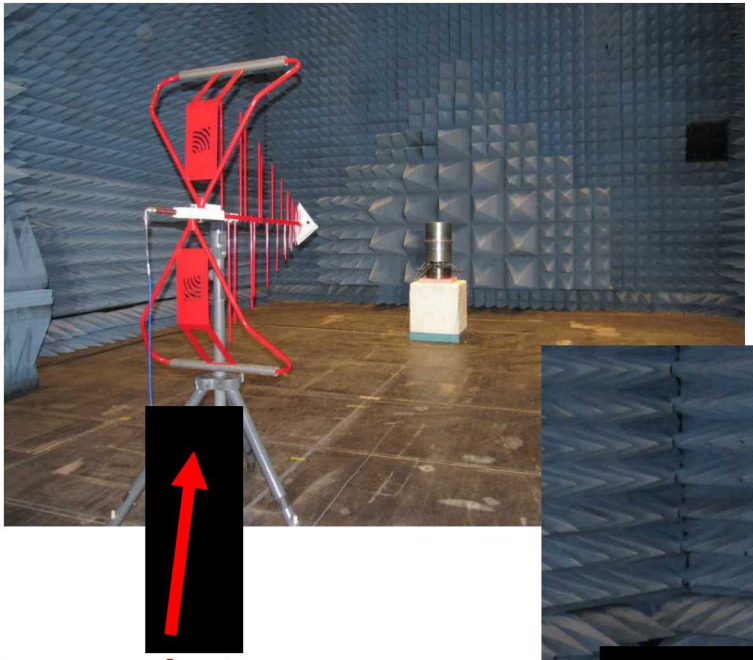
Mode Description	Frequency (Hz)		% Err
	Test	*Simulation*	
1st Ovaling	405	407	0.5
1st Axial	480	476	-0.8
2nd Ovaling	685	675	-1.5
3rd Ovaling	960	964	0.4
2nd Axial	995	975	-2.0
3rd Axial	1120	1097	-2.1

Multiple Input, Multiple Output (MIMO) control system

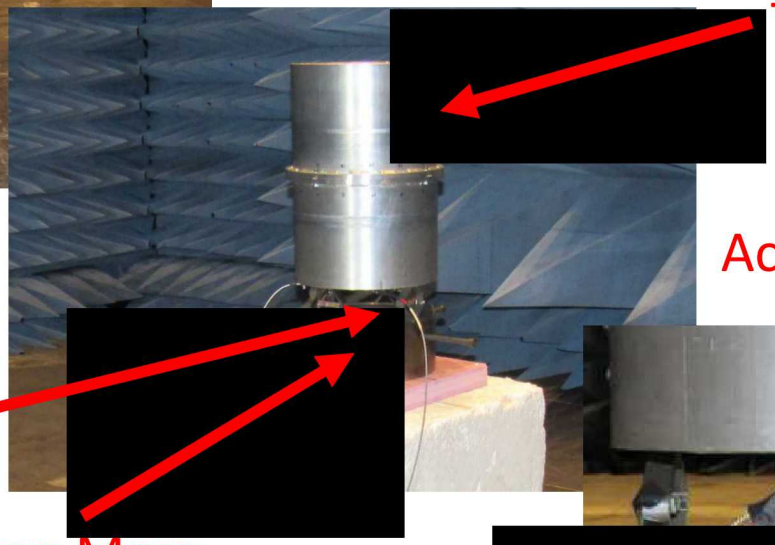
- Very good agreement in modal frequencies.
- Will require more mechanical data for in-depth model validation (shapes, damping, etc.).
- Multiple input, multiple output (MIMO) control system.

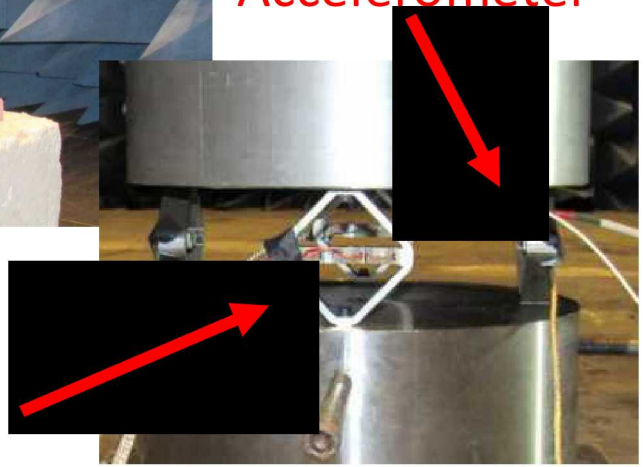
Results from Brian C. Owens

Coupling EM-Vibe Measurement Setup



Testing in a large anechoic chamber





Test Cylinder

Accelerometer

Source Antenna

Monopole probe

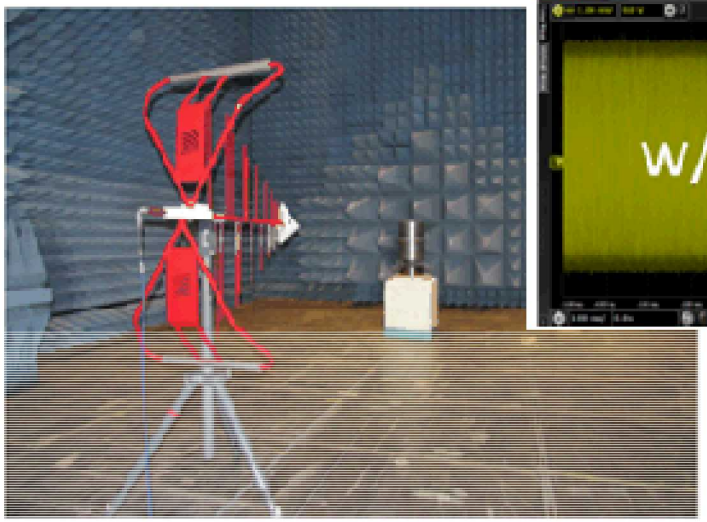
Reaction Mass

Piezoelectric vibration actuators

EM-Vibe Demonstration

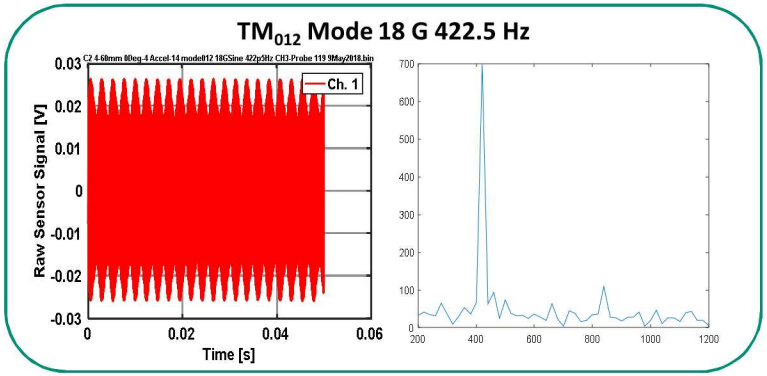
- All actuators are feed in phase with a single-axis accelerometer mounted on cylinder base (SISO vibe control system)

Oscilloscope Measurements



Signal received on monopole probe within the cylinder

Modulation at frequency of mechanical resonance



COMPSIM
LIKE IT REALLY HAPPENS

eiger

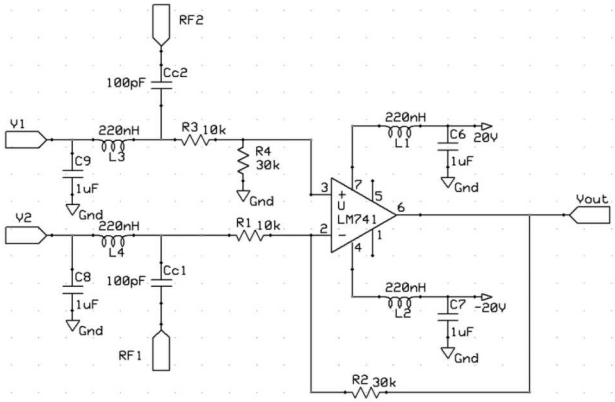
Gemma

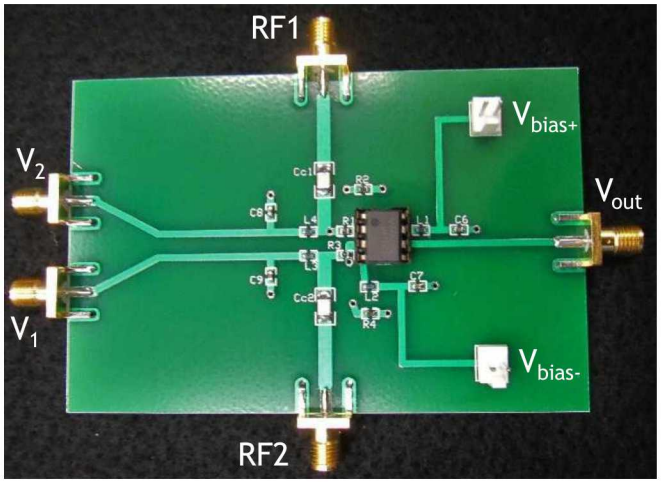
Xyce
PARALLEL ELECTRONIC SIMULATOR

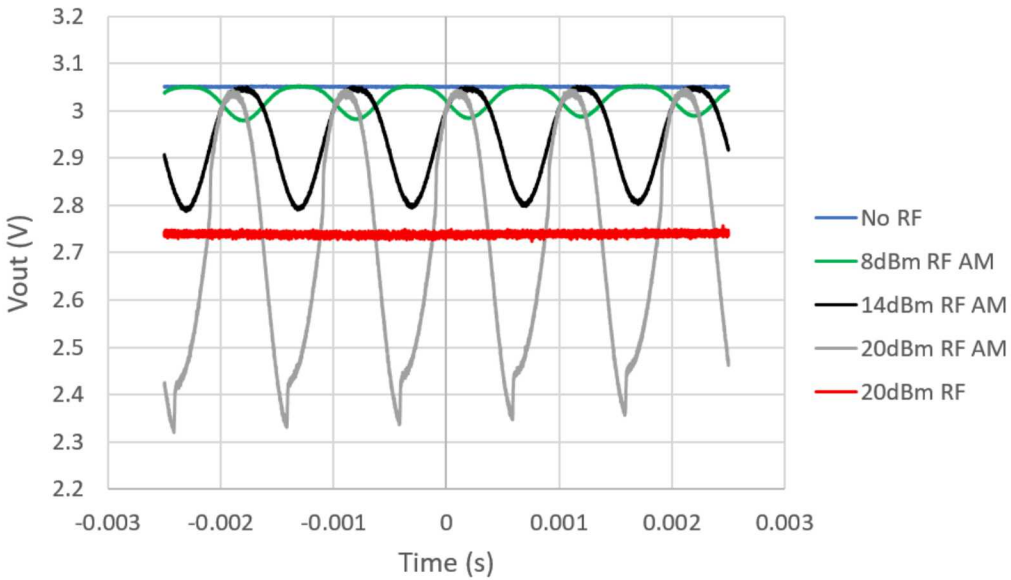
Preliminary Direct Injection Measurement Results

DI

- Direct power injection into inverting side of the op-amp
  - 1 GHz CW carrier signal
  - 1 kHz AM with 80% modulation depth
  - Various RF power levels



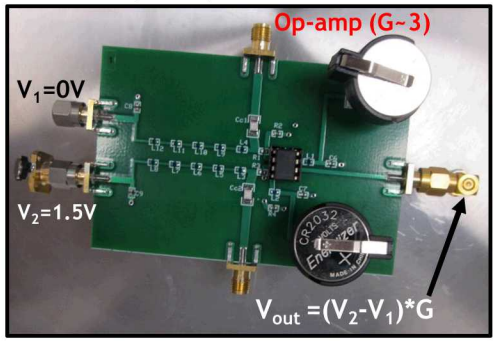


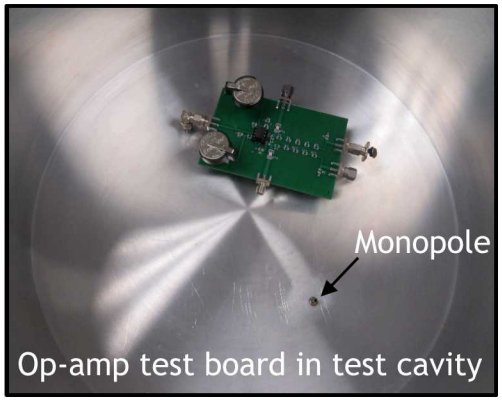


Circuit Demodulation Inside Flat Flange Cylinder

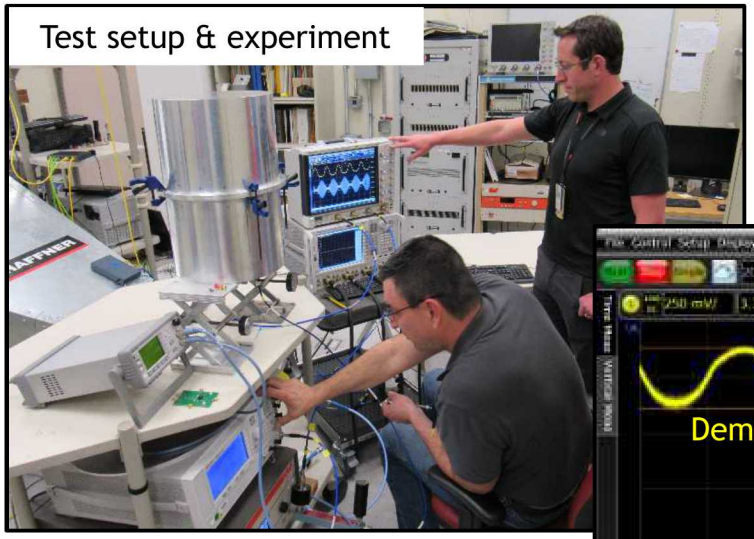
- The differential op-amp circuit is placed inside the cylindrical test cavity.
- Internal cavity fields (997 MHz) are amplitude modulated (1kHz) through a monopole antenna to replicate the internal fields under EM/Vibe conditions with an external EM source.
- Similar to the results from direct power injection the op-amp demodulates the signal producing an AM modulated signal at the output

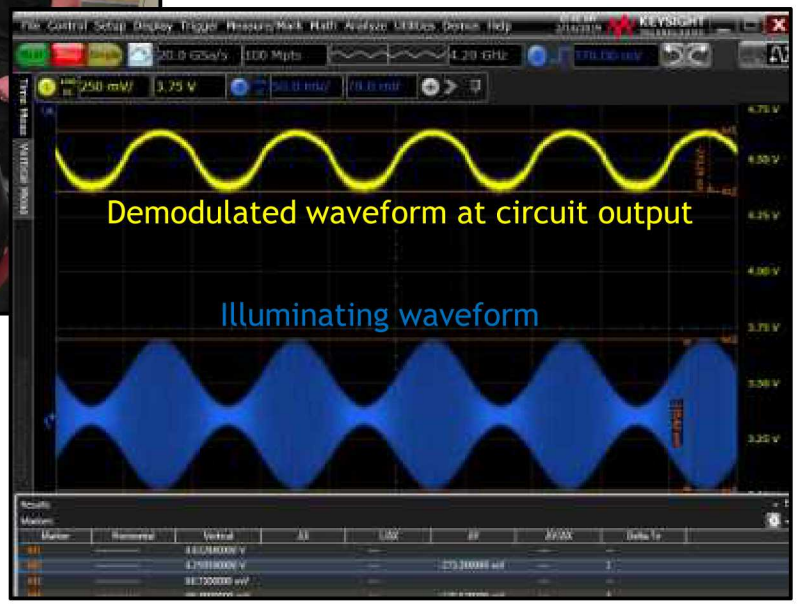
Op-amp test board





Test setup & experiment

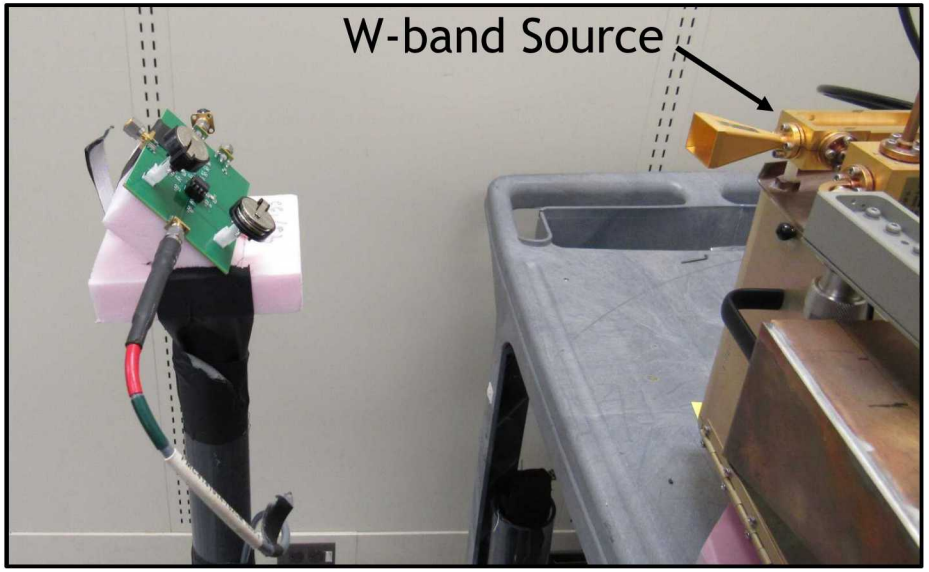




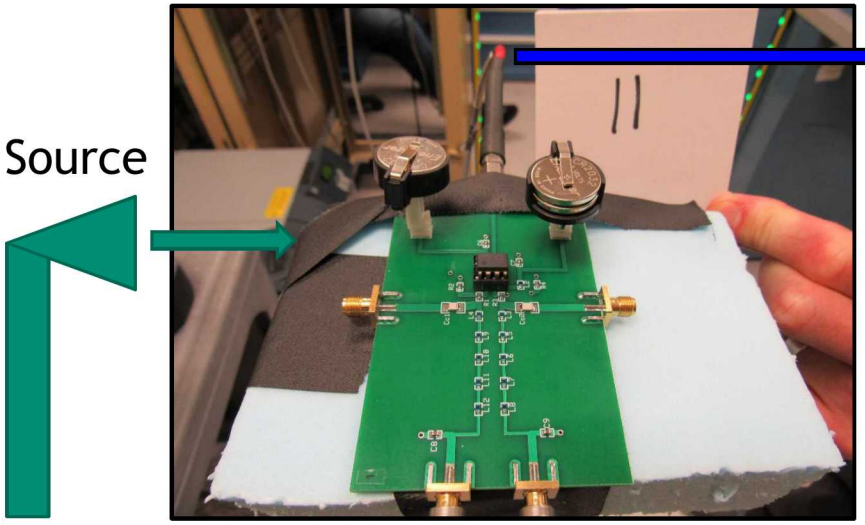
Measured Internal Cavity Field

Preliminary W-Band Circuit Testing

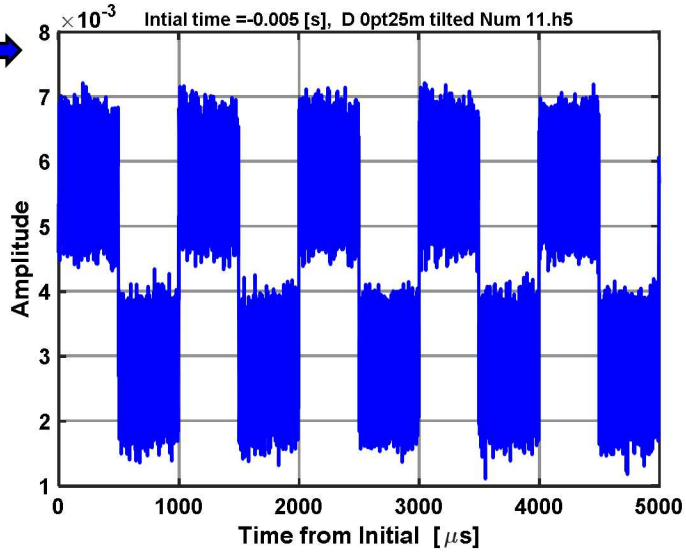
Circuit board illuminated with 94 GHz signal square-wave modulated at 1 kHz.



Circuit Orientation for Maximum Coupling



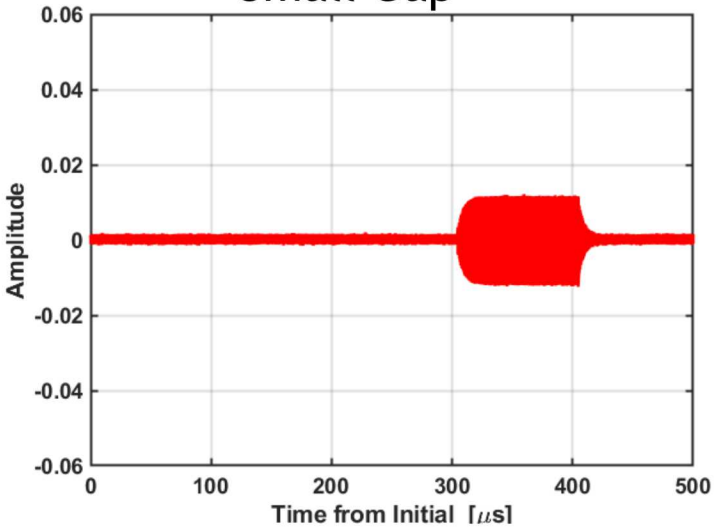
Circuit Output



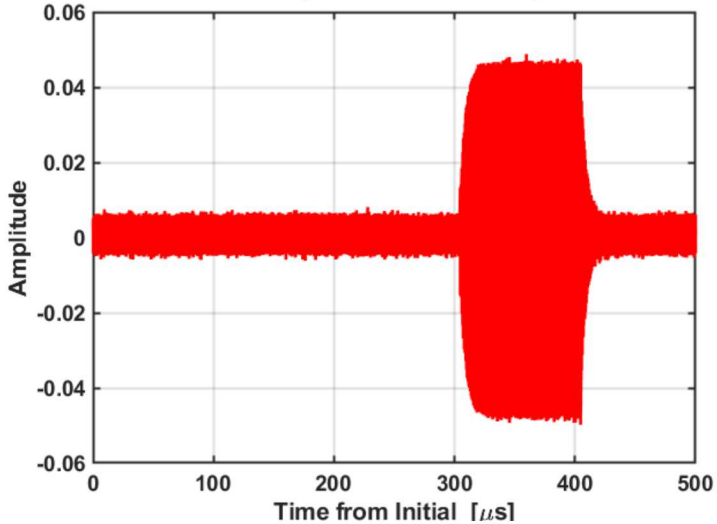
How Does Vibe Affect Pulsed HPEM?

As POE expands due to mechanical resonance more of the pulse energy gets into the cavity.

Small Gap



Expanded Gap



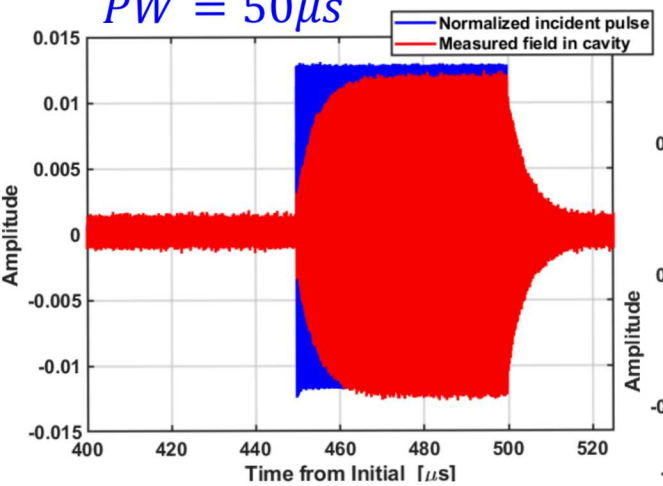
But to get the full affect of the HPEM pulse, it must be long enough to charge or "fill" the cavity.

Fill-Time

- A resonant circuit reaches full charge in approximately Q cycles.
- Test cavity mode (TM_{0l2}) has $Q \sim 20{,}000$ at $f_0 = 1$ GHz, thus the $t_{fill} \sim 20\mu s$.

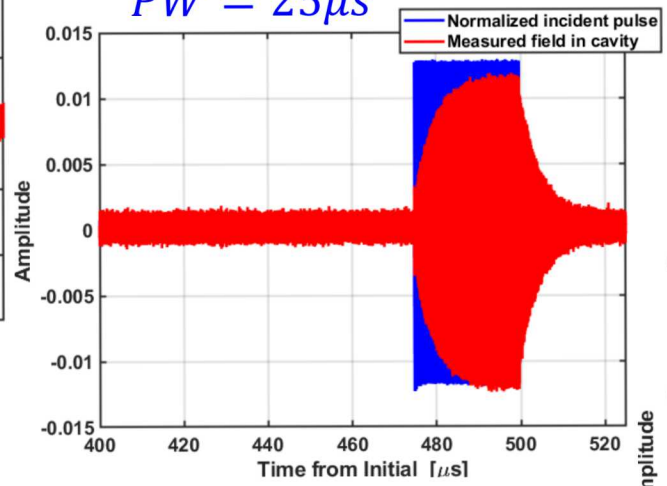
Expanded Gap

$PW = 50\mu s$



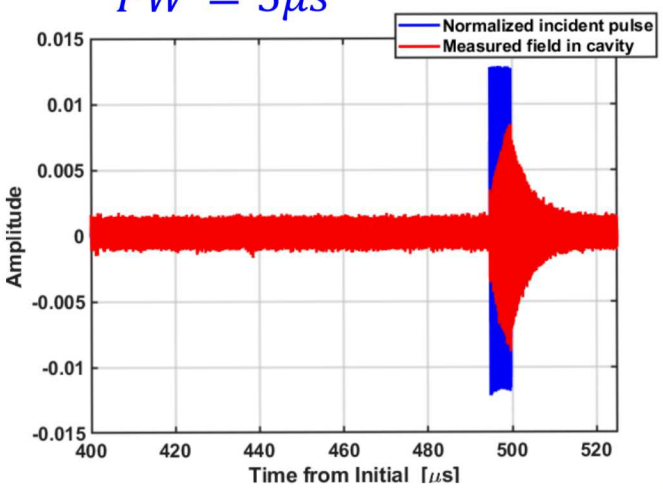
$PW > t_{fill}$

$PW = 25\mu s$



$PW \sim t_{fill}$

$PW = 5\mu s$

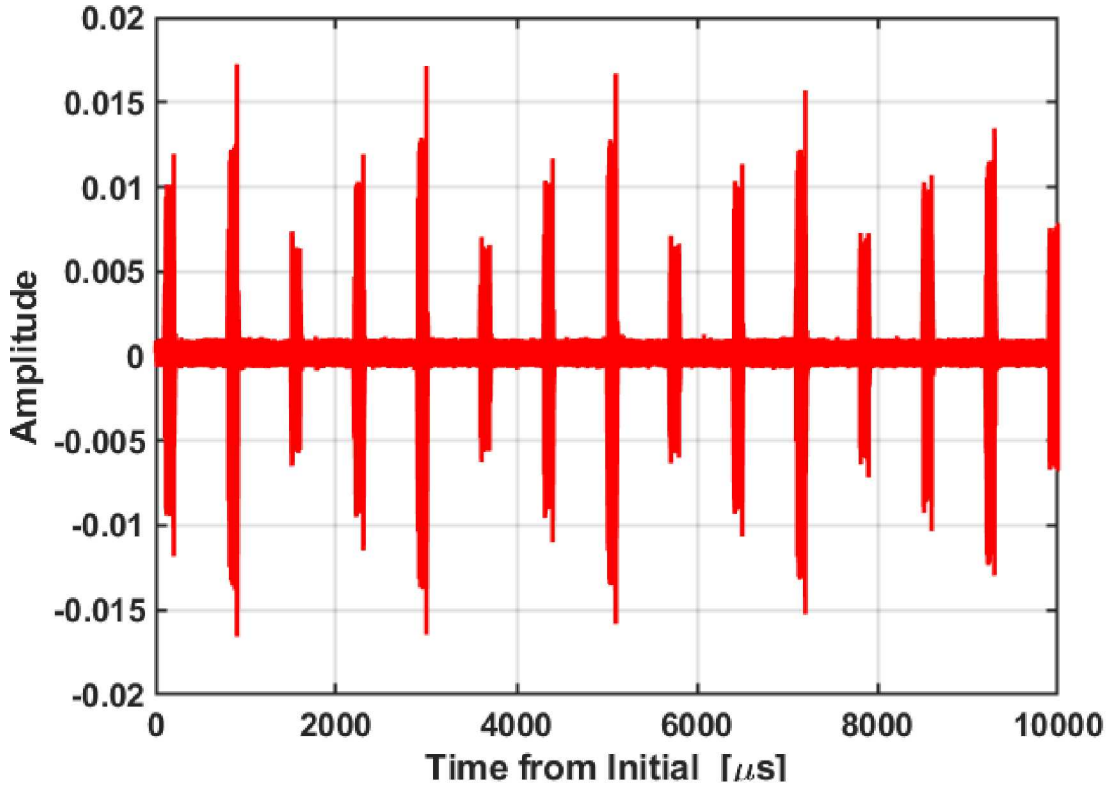


$PW < t_{fill}$

For HPEM pulse to effectively couple into a cavity, the $Q_{source} > Q_{cavity}$.

Pulsed Repetition Rate

Using a pulsed HPEM source that has a repetition rate on the order of the mechanical vibration rate increases the opportunity to get larger pulses into the cavity.



Vibe rate ~492 Hz, PRF ~1430 Hz

PRF- pulse repetition frequency

Summary

- Developing an EM/Mechanical Vibe Combined Environments program to enable the prediction of how mechanical vibrations affect the performance of electrical systems.
- Efforts to date include
  - demonstration of coupled field modulation associated with mechanical vibration.
  - demonstrated demodulation effect by differential amplifiers.
  - establishing workflow techniques for an end-to-end mechanical/electromagnetic simulation of CE problems.
- Future efforts include
  - continued validation of simulation and measurements.
  - investigate additional joints of interest and other POE's.
  - quantify circuit effects associated with modulated fields.

Questions?

Backup Slides

Coupled Workflow: SIERRA & EIGER

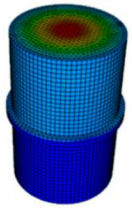
COMPSIM
LIKE IT REALLY HAPPENS

Develop EIGER Mesh

- Implement slot domains
- Identify cavity surfaces of interest

eiger

EIGER Mesh w/ map features



Develop SIERRA Mesh

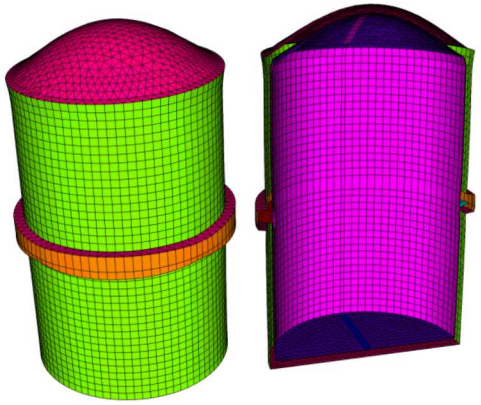
- Identify regions corresponding to slot domain regions
- Identify regions corresponding to surfaces of interest

Perform SIERRA Structural Analysis

SIERRA Mesh w/ map features & displacement results

Mapping Suite

EIGER Mesh w/ mapped disp. results & slot gaps



Translation Tool

EIGER Exodus mesh w/ deformed coordinates and slot gaps @ time = t_i

Deformed EIGER Analysis

Mechanical Analysis:

- ✔ Static Loads
- ✔ Transient Shock
- ✔ Transient Vibration
- ✔ Freq. Domain Sine Vibe
- ⚠ Freq. Domain Random Vibe