THE IMPACT OF PACKAGING ON SOFT MAGNETIC CORE PERFORMANCE

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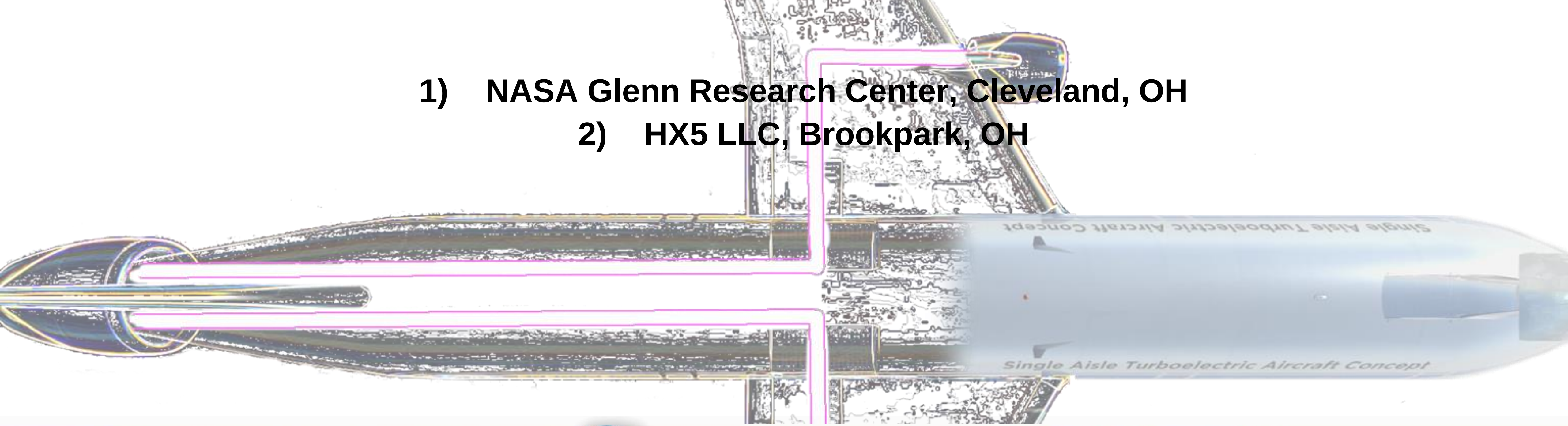


Why Packaging?

TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or flight)

TRL 7
- System prototype demonstration in a flight environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or flight)

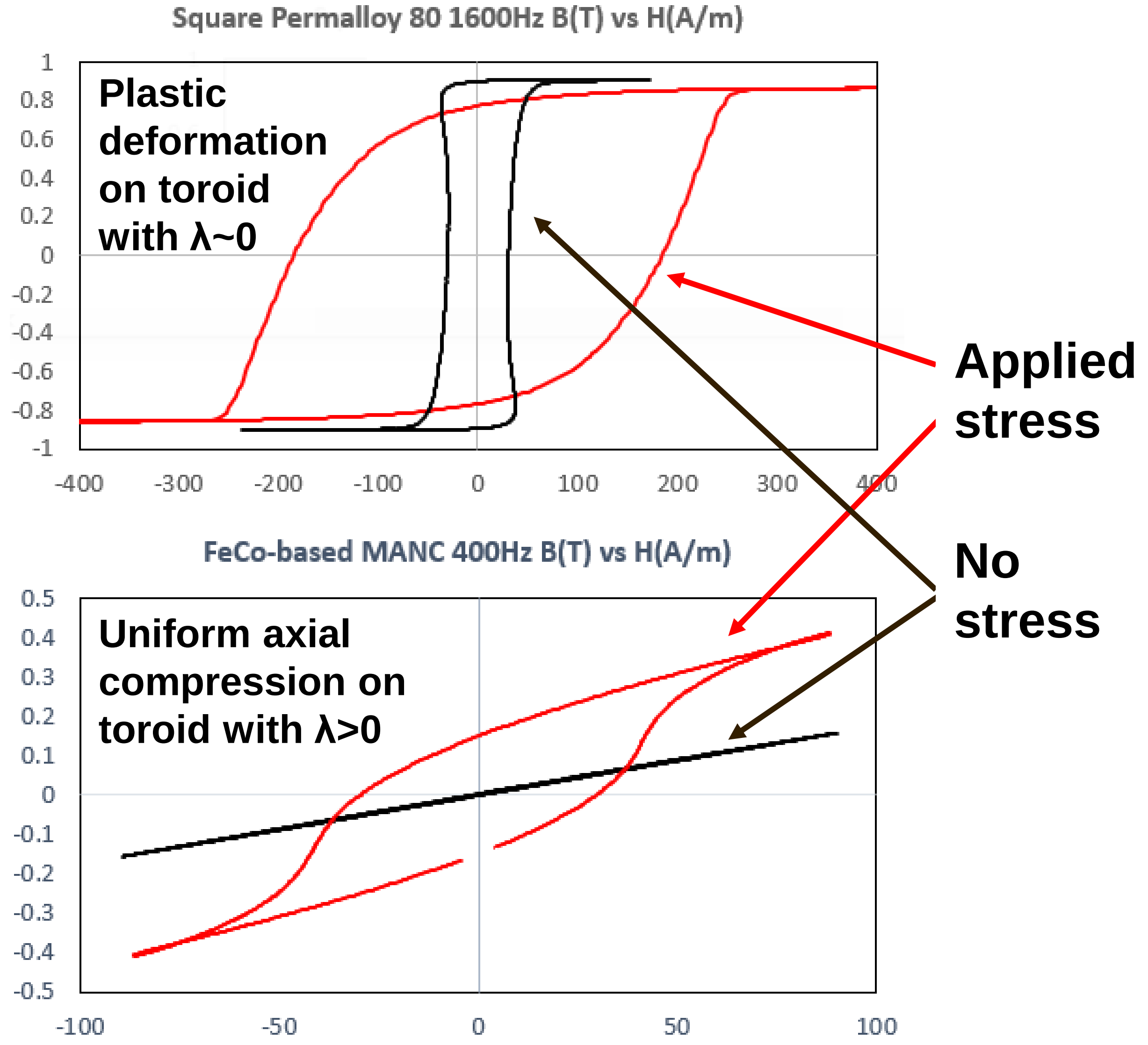
TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported

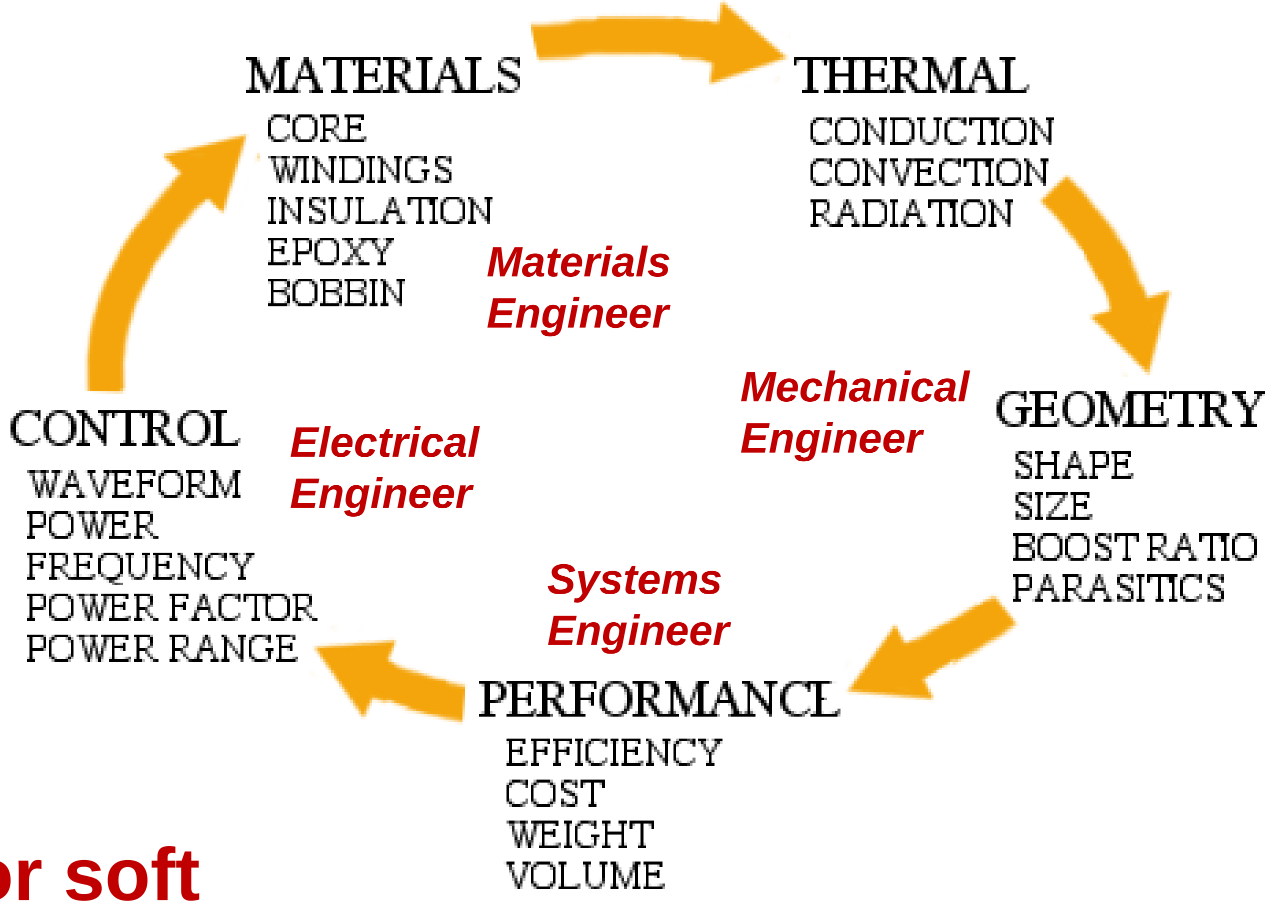


Overview

<u>Application</u>: Magnetics for MW scale power conversion with high power density, usually kHz→MHz

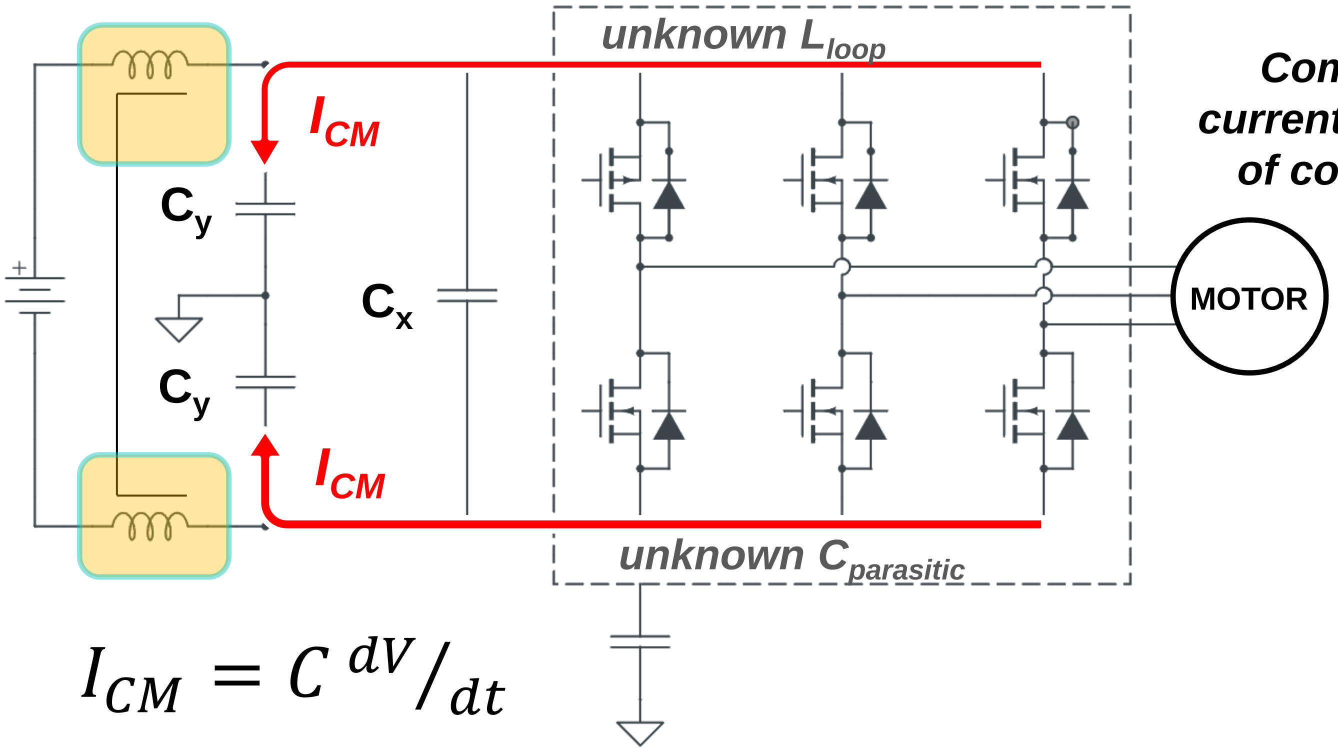
<u>Challenges</u>:

1. **Operation closer to margin limits and/or integration of new materials and components at the subsystem level**
2. **How to simulate the design space efficiently to enable complex systems?**



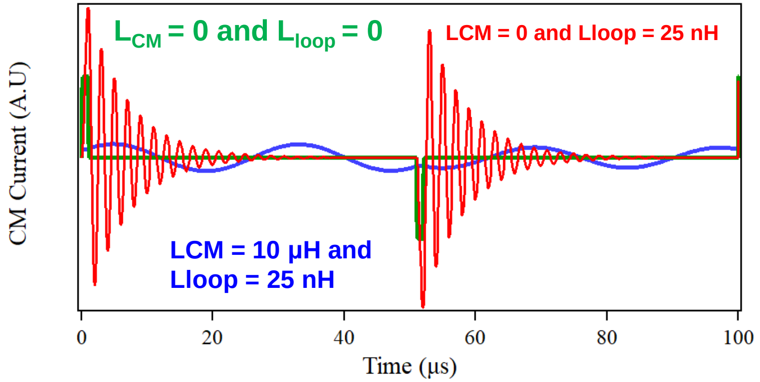
<u>Goal</u>: Develop design guidelines for soft magnetic nanocomposite core packaging

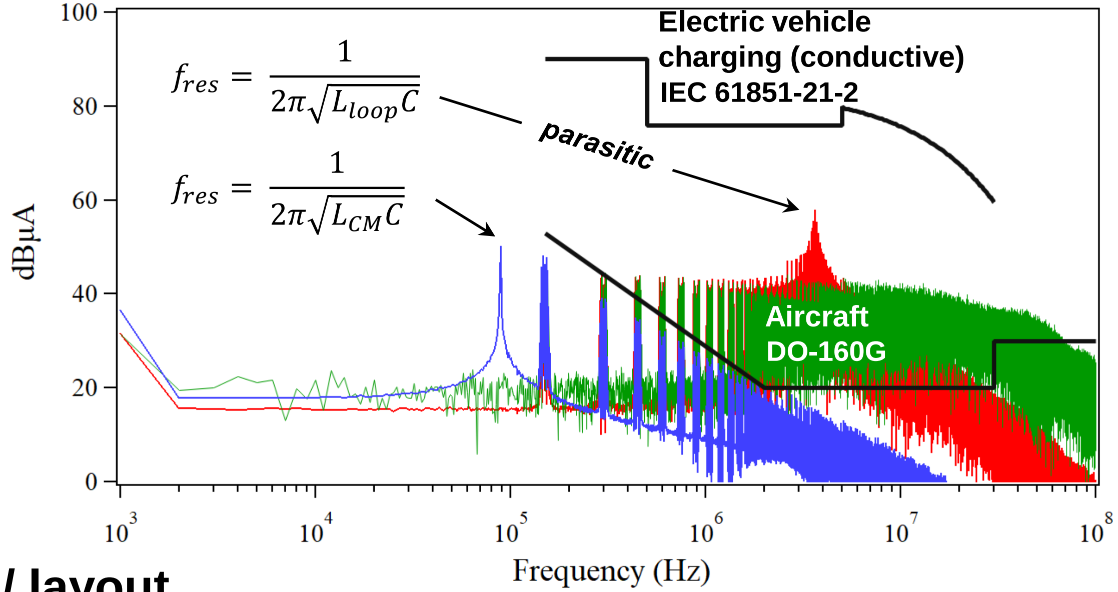
Common Mode Noise in Simple Electric Vehicle



$$I_{CM} = C\, {}^{dV}/_{dt}$$

Common mode current is one source of conducted EMI





- **Parasitic impedances related to components and geometry / layout**
- **C_y is limited by safety to ~1µF for <1kV**
- **Fast dV/dt in WBG and UHBG semiconductors creates large CM currents in ground planes and chassis**

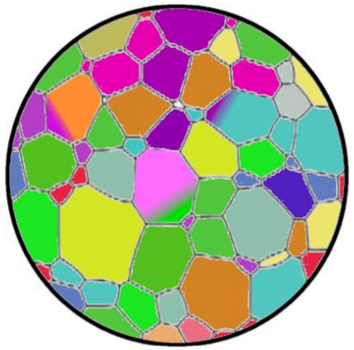
Conducted EMI standards control noise f > 150kHz with parasitic resonances common in the 1-10 MHz range
Performance, safety, and reliability related to topology, layout, controls, and materials

What do we need from packaging?

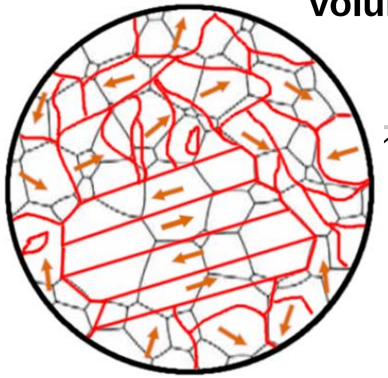
- Decouple winding stress from the core material
- Provide mechanical mounting to withstand vibration and shock
- Provide adequate thermal path
- Provide adequate electrical insulation
- Fit into the surrounding components

Hysteresis: Magnetic and Mechanical

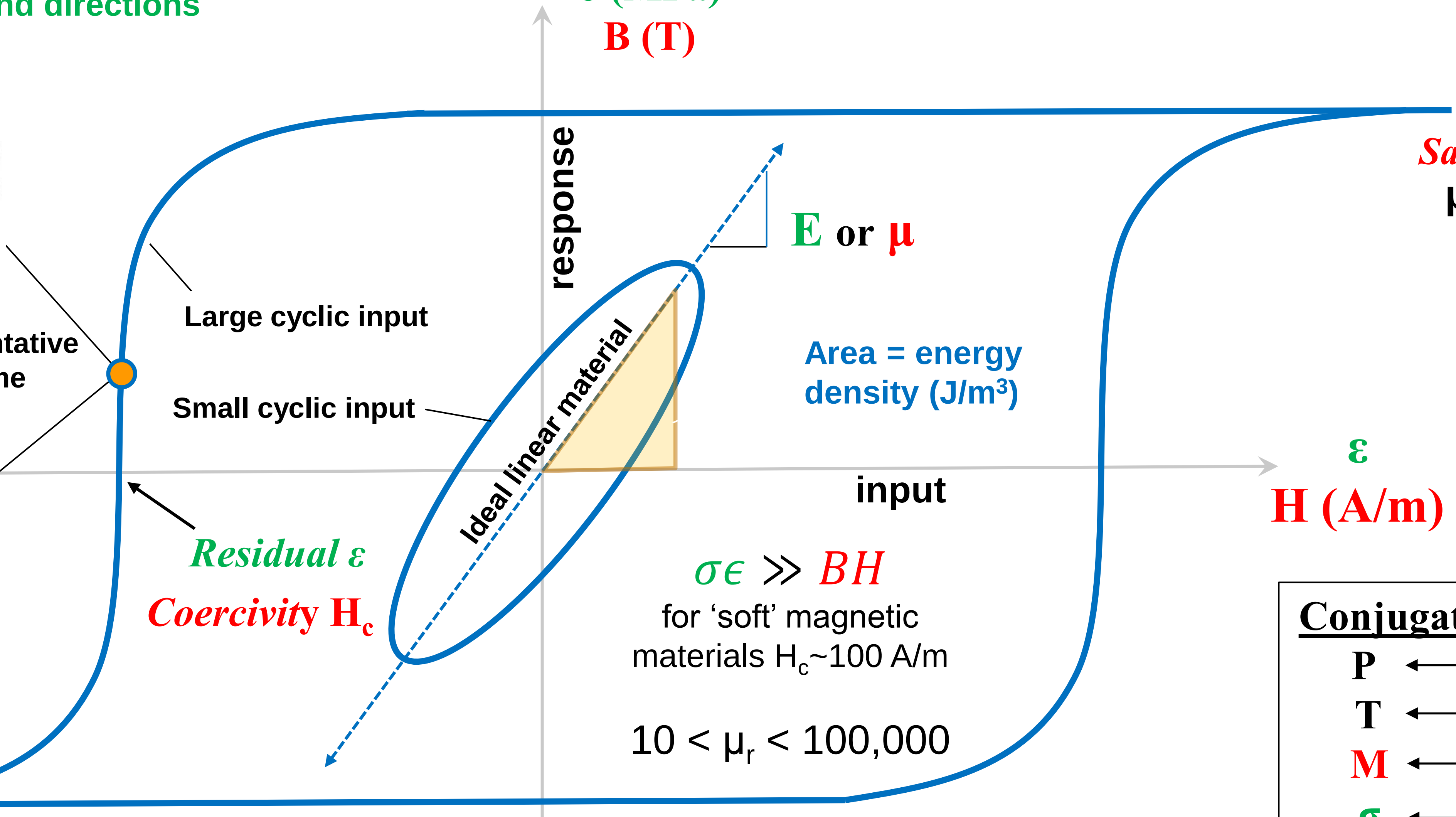
Inter and intragranular strain:
Different magnitudes and directions



Representative volume



Domain structure:
Same magnitude
different directions



Conjugate pairs

P	⟷	V
T	⟷	S
M	⟷	H
σ	⟷	ε

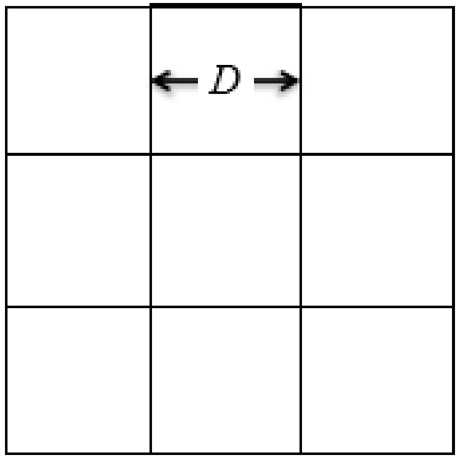
Single phase Random Anisotropy Model

magnetostriction

$$\begin{bmatrix} \varepsilon \\ P \\ B \\ \Delta S \end{bmatrix} = \begin{bmatrix} C^{\sigma}_{\varepsilon} & C^{E}_{\varepsilon} & C^{H}_{\varepsilon} & C^{\Delta T}_{\varepsilon} \\ C^{\sigma}_{P} & C^{E}_{P} & C^{H}_{P} & C^{\Delta T}_{P} \\ C^{\sigma}_{B} & C^{E}_{B} & C^{H}_{B} & C^{\Delta T}_{B} \\ C^{\sigma}_{\Delta S} & C^{E}_{\Delta S} & C^{H}_{\Delta S} & C^{\Delta T}_{\Delta S} \end{bmatrix} \begin{bmatrix} \sigma \\ E \\ H \\ \Delta T \end{bmatrix}$$

piezomagnetic

$$L^3_{ex} = ND^3$$



$$\langle K \rangle = \frac{K_1^4 D^6}{\psi_0^6 A^3}$$

Characteristic length scale of applied stress is usually ‘global’ compared to grain size

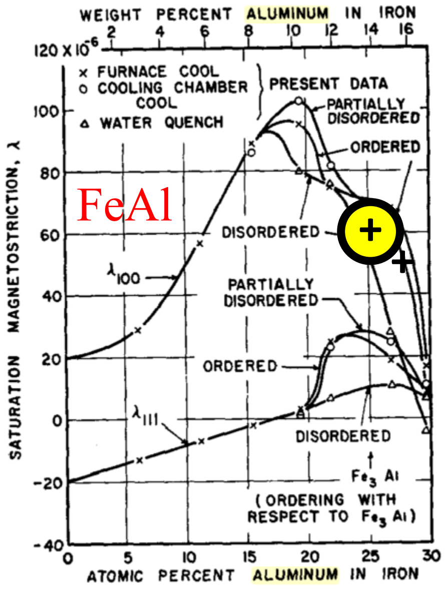
- Coupling terms $\mathrm{B} = \mu H$ and $\epsilon = E\sigma$ measurable for static conditions
- Dynamic conditions can be described using complex μ^* or E^*

What about dynamic conditions for $B = {C^{\sigma}_{B}}^{*}\sigma + \mu^* H$ ...

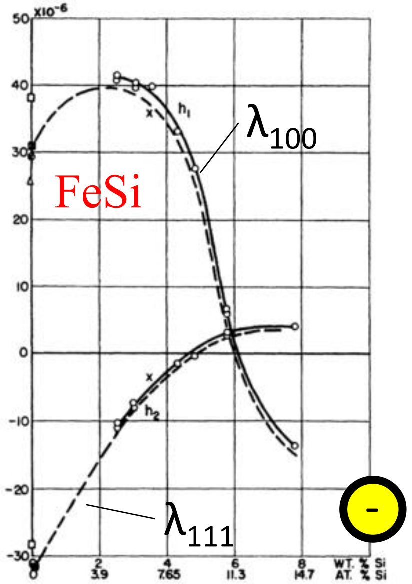
Often, we want ${C^{\sigma}_{B}}^{*} \rightarrow 0$

Opposing magnetostriction: $\lambda_1 v_1 + \lambda_2 v_2 \sim 0$

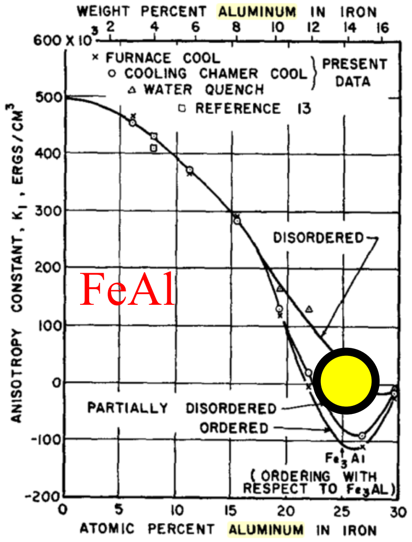
Sendust ($Fe_{74}Al_{11}Si_{15}$) ~ v_{Fe_3Al} ($\lambda_s > 0$) + v_{Fe_3Si} ($\lambda_s < 0$)



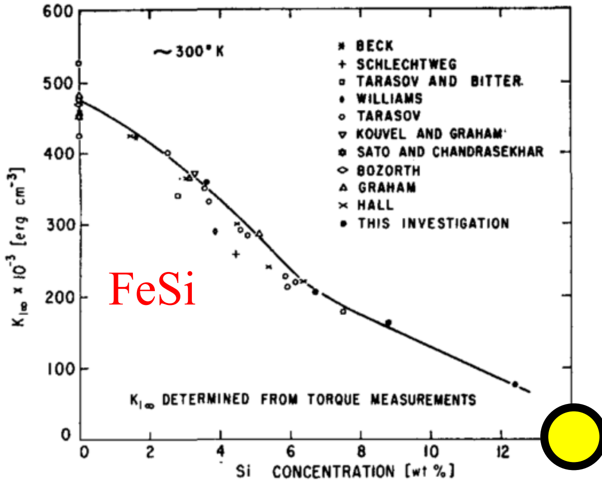
Hall, JAP *30* (1959)



Carr & Smoluchowski, *Phys Rev* 83 (1951)



Hall JAP *30* (1959)



Arajs, et al JAP 32 (1961).

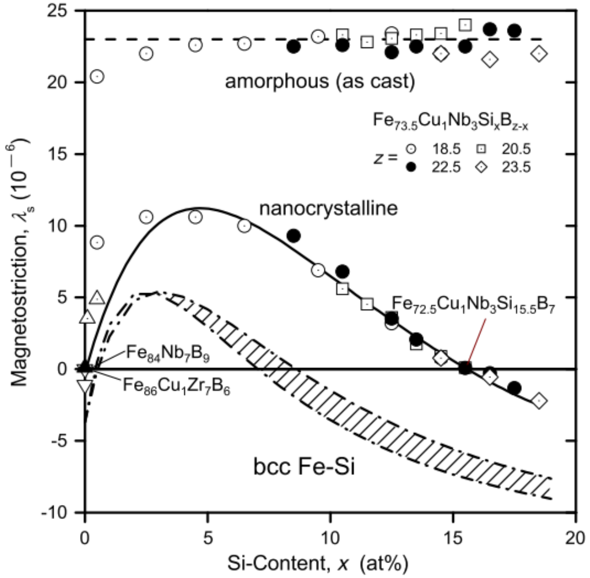
… both have small K_1

We can reduce magneto-elastic coupling either with zero magnetostriction material or by mixing positive and negative magnetostrictive phases in a composite

Same mechanism used in Finemet…

$v_{amorphous}$ ($\lambda_s > 0$) + v_{Fe_3Si} ($\lambda_s < 0$)

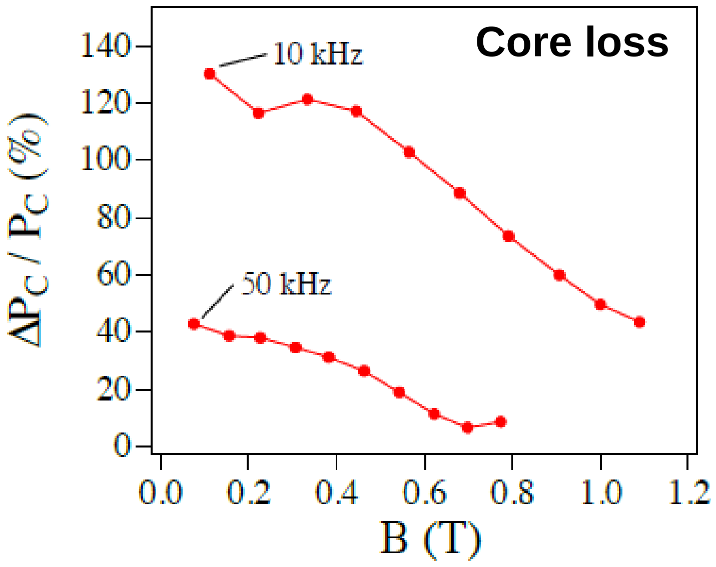
Here, average <K> ~ 0 by the random anisotropy principle and Si partitions to the crystal

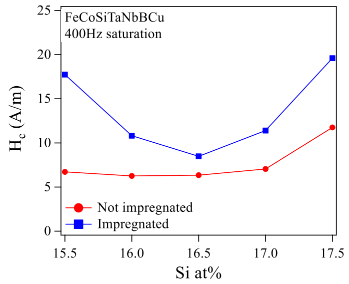


Herzer, *Acta Mat* 61 (2013)

Epoxy Impregnation Stress

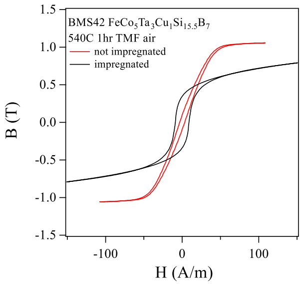
$$\lambda_{nanocomposite} = v_{crystal}\,\lambda_{crystal} + (1 - v_{crystal})\,\lambda_{matrix}$$

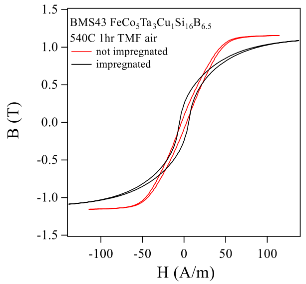


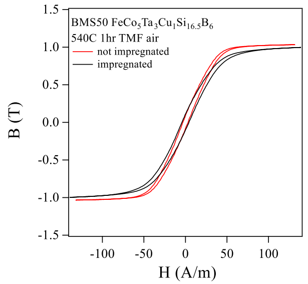


Material data sheet core losses do not include packaging stress.

In FeSi-based nanocomposites, we can balance volume fraction (v) with magnetostriction (λ) of crystal and matrix phases.



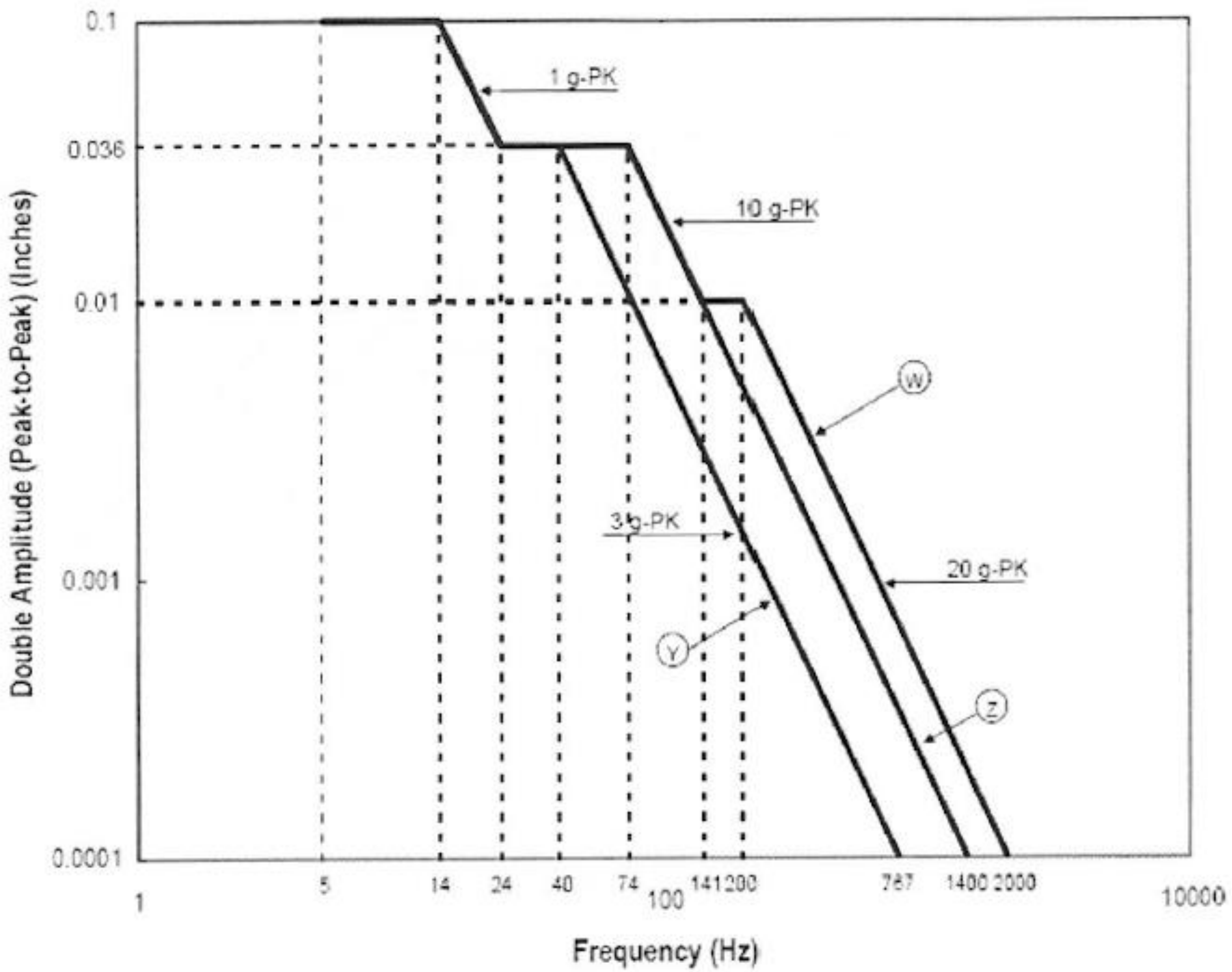




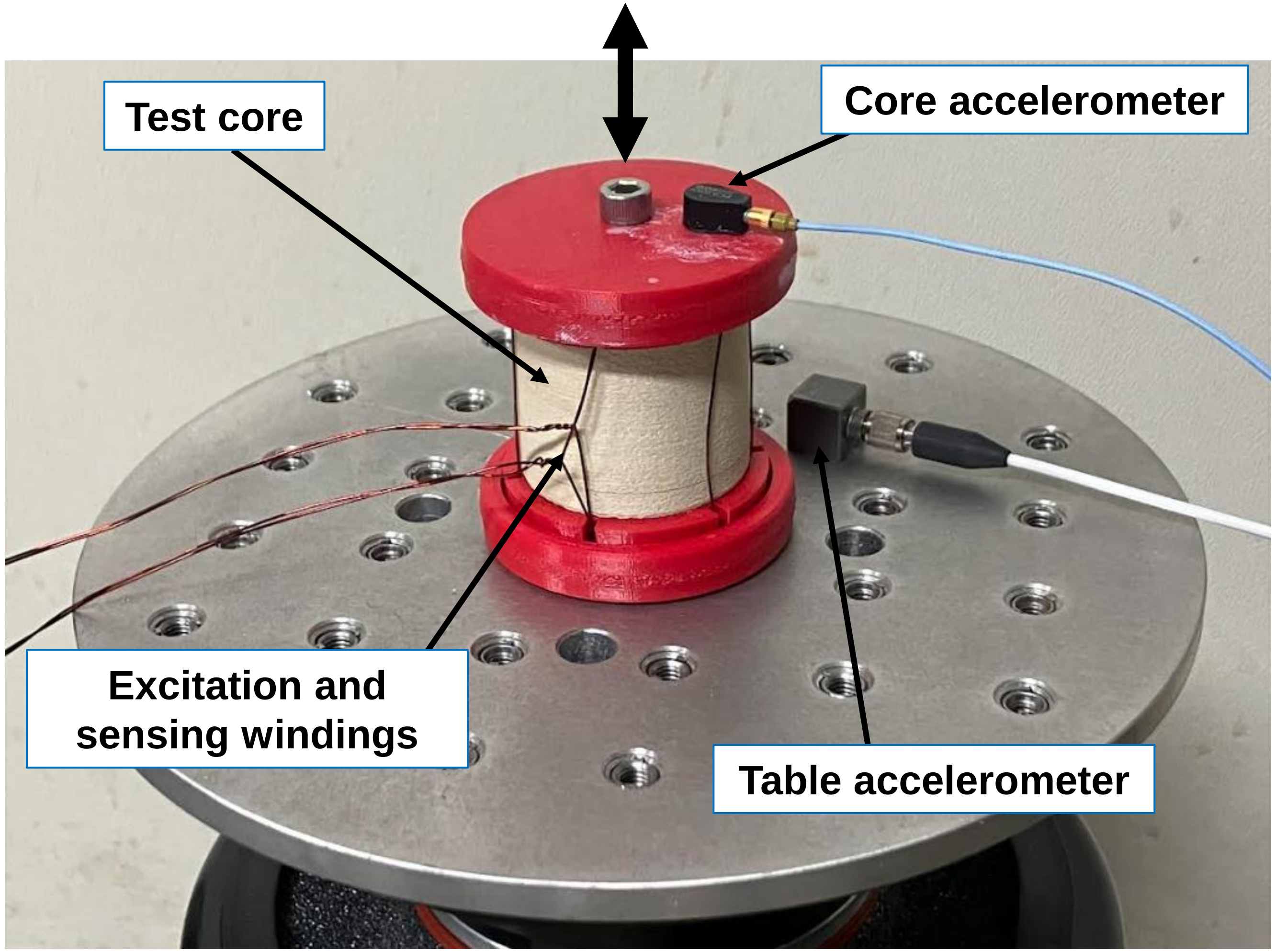
Increasing Si

Mechanical and Thermal Requirements

- **Thermal: Typically, <150C with heat sinks as required.**
- **Mechanical: 3 axis vibration 20g through 2kHz (DO-160G Section 8)**
  - **Vibration + electrical function**
  - **Usually measured in components**
- **Packaging Options: Casings, potting, windings, mounts**
- **Problems within components and problems in neighboring components…**

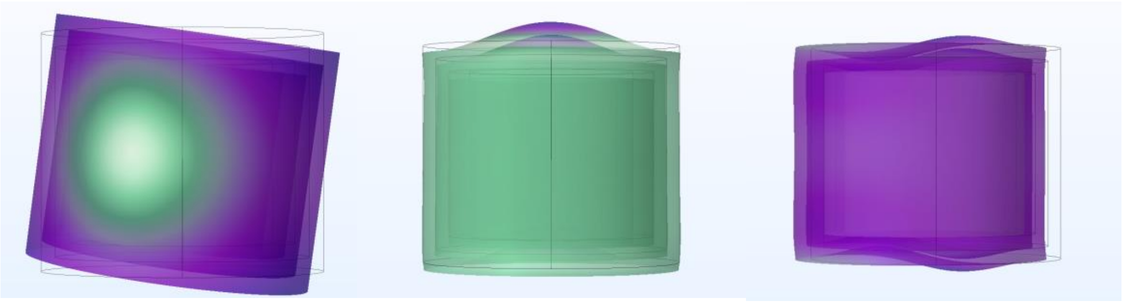


Vibration Stresses

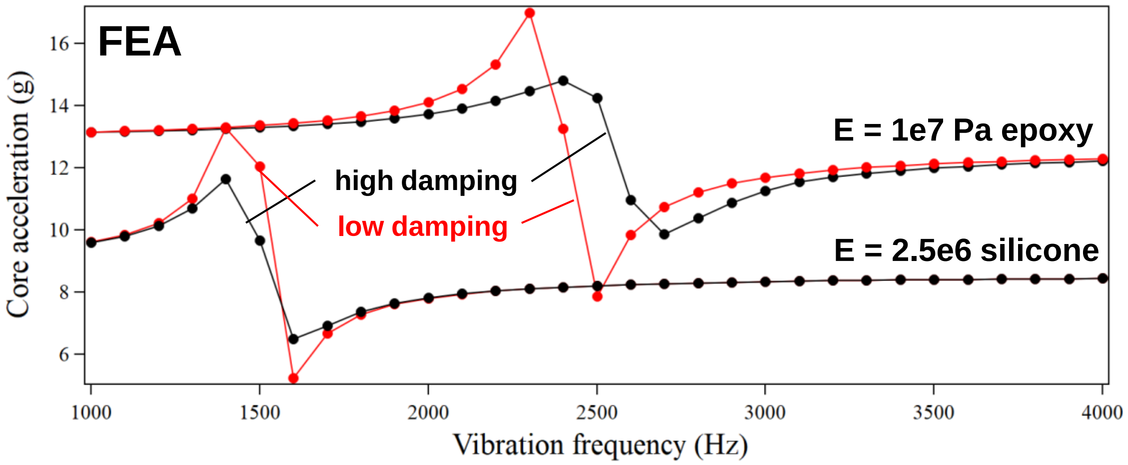


FEA resonant modes: Box + potting + core

f_1 = 1384 Hz　f_2 = 2410 Hz　f_3 = 2832 Hz

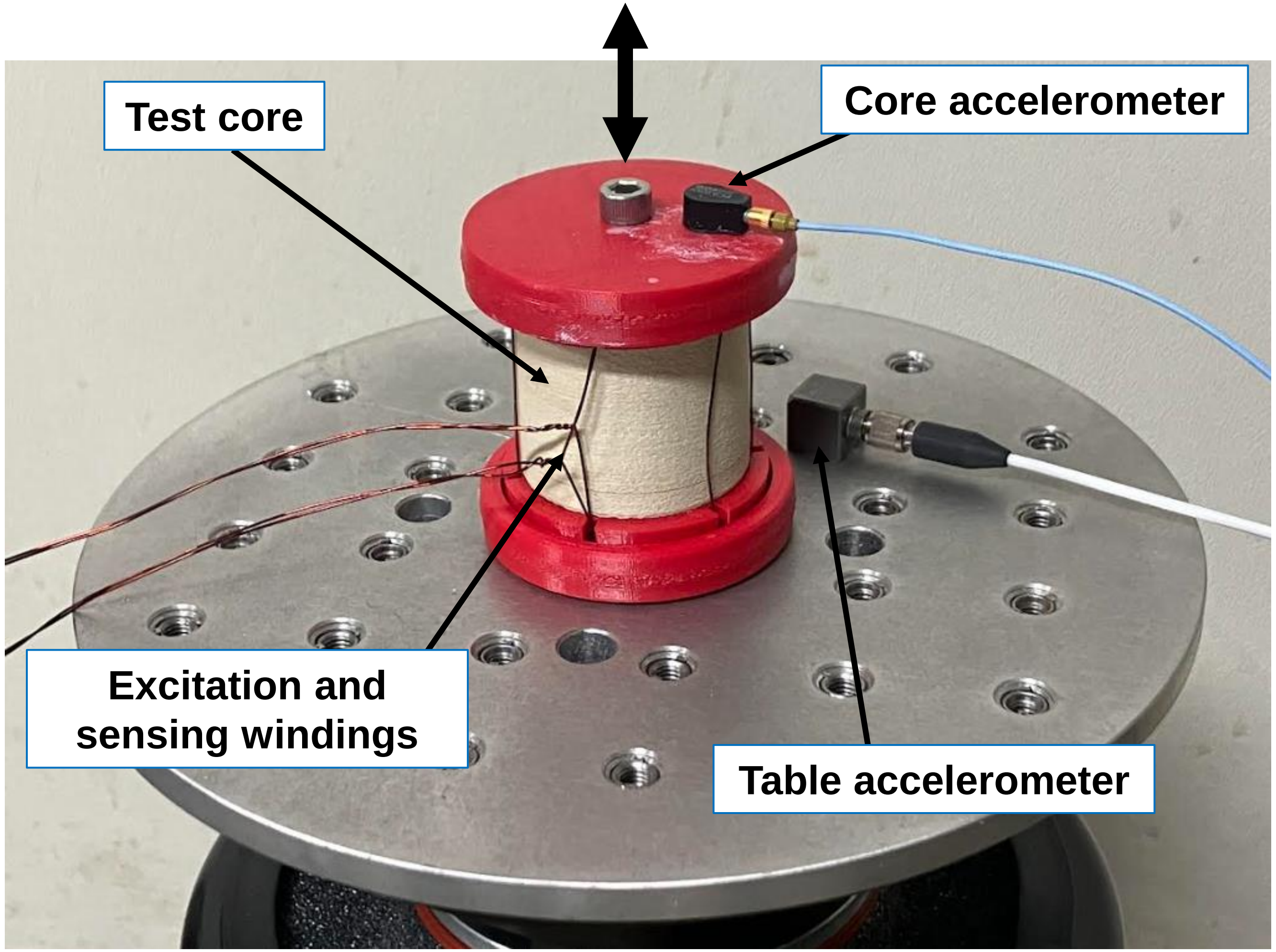


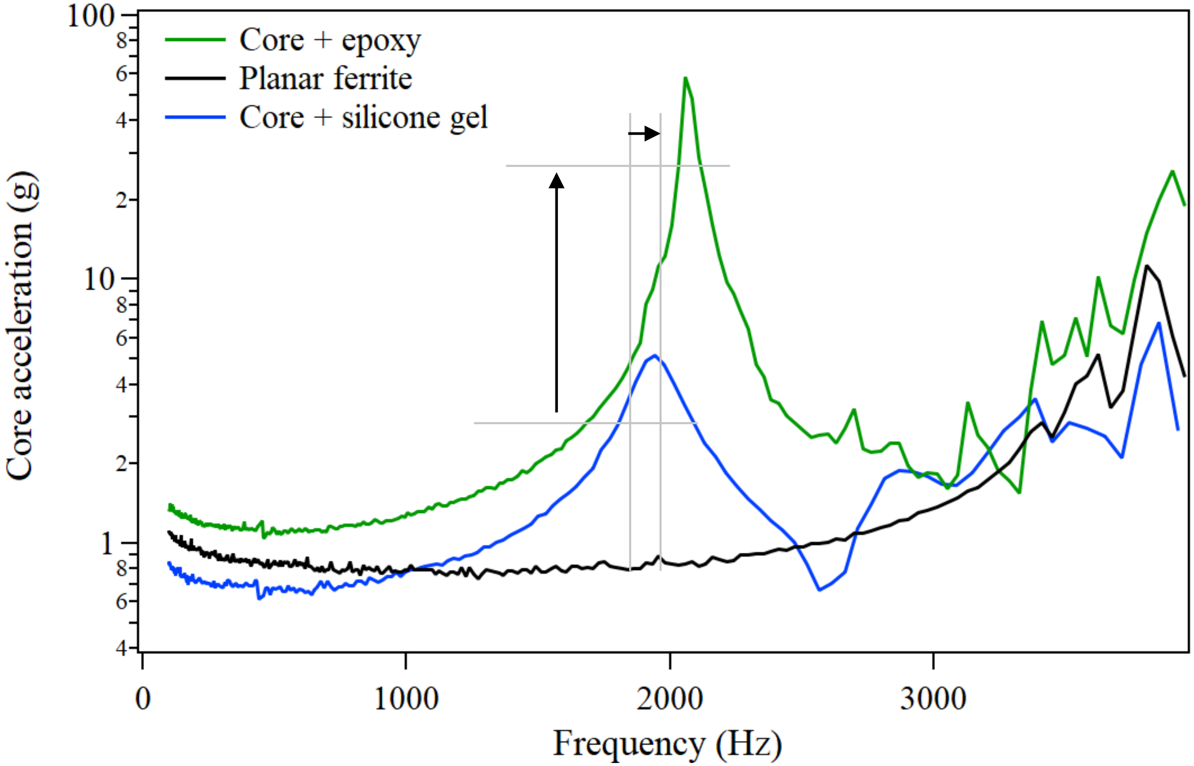
F = ma ~ 100N for a 0.1kg core in 100g
σ = 0.34 MPa over the bottom surface of the toroid



Vibration stresses are small, but resonant modes *could* produce high localized core stress

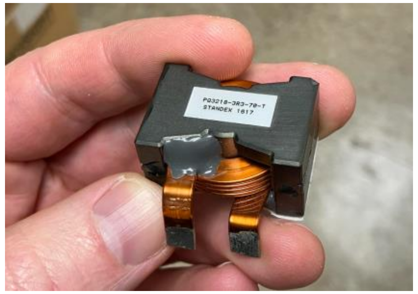
Vibration Stresses



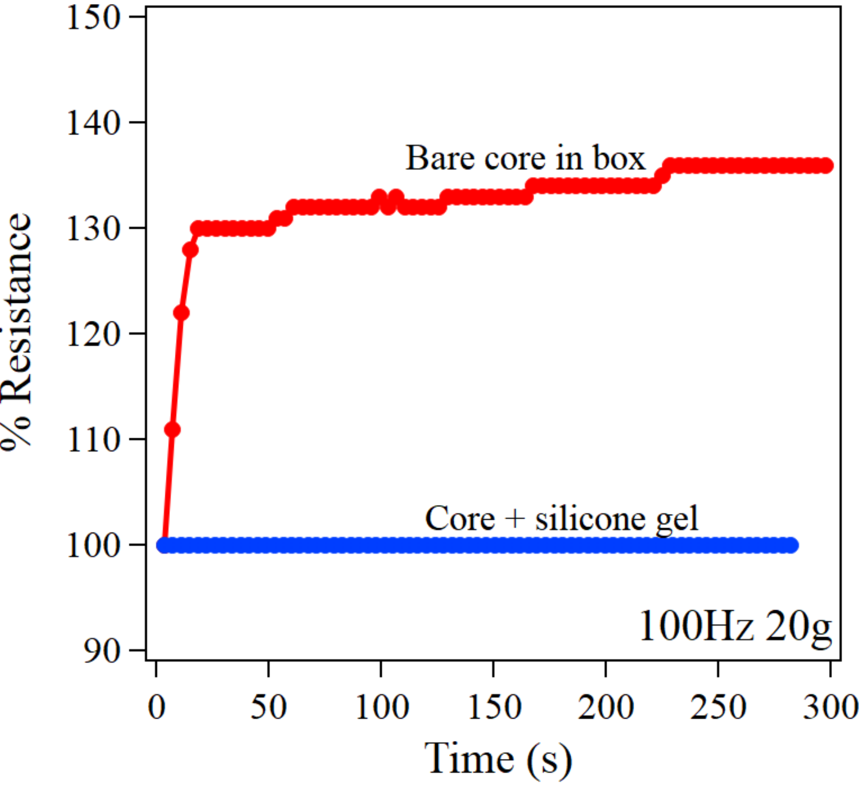


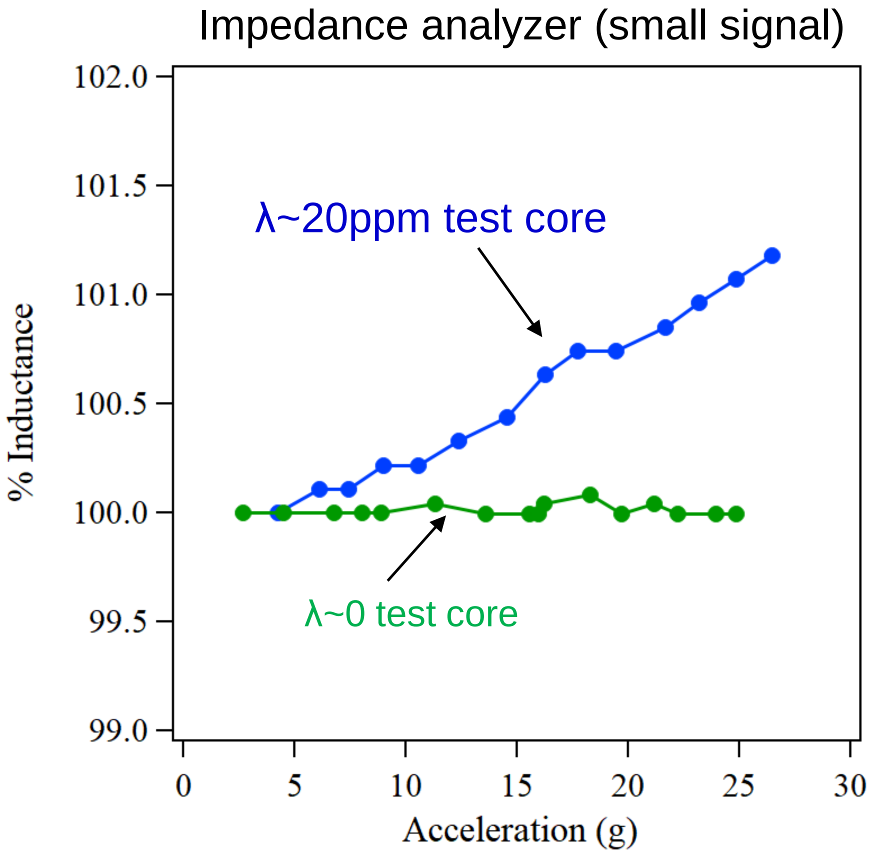
Silicone potting produces lower resonant frequency and lower acceleration compared to epoxy potting.

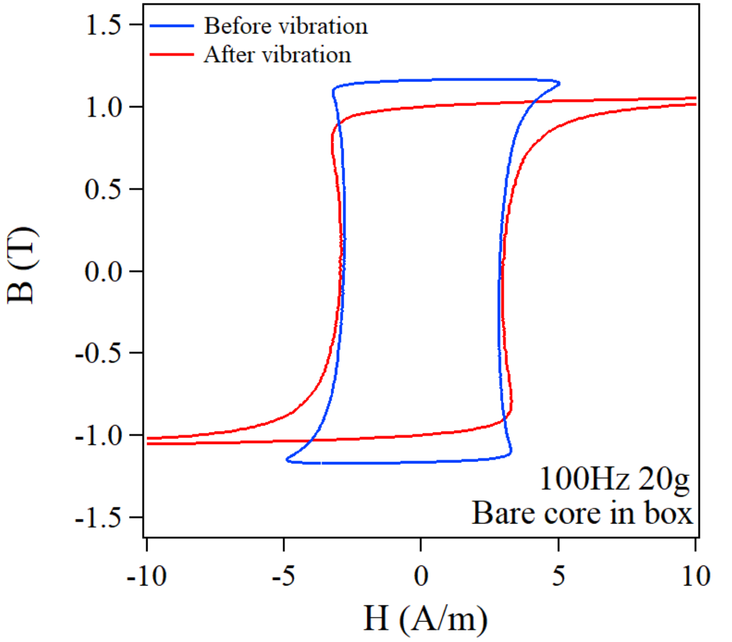
Comparison with rigid mount: STANDEX ferrite inductor

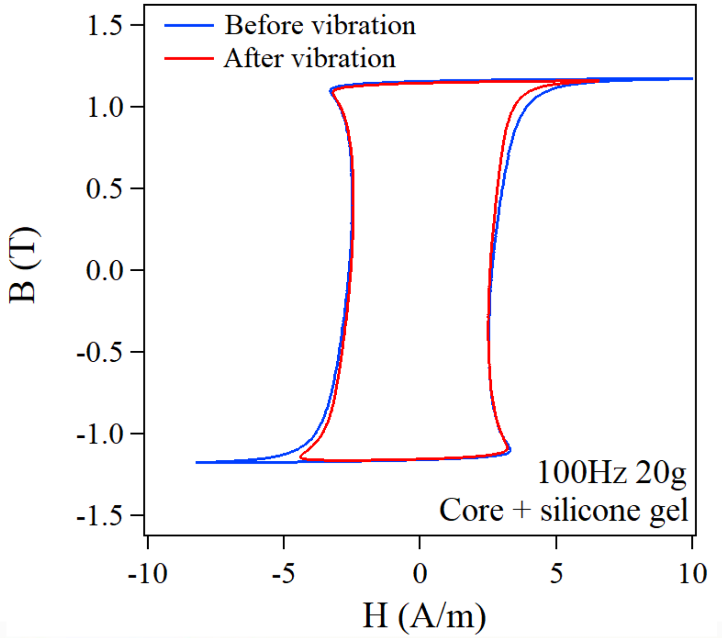


Vibration Stresses



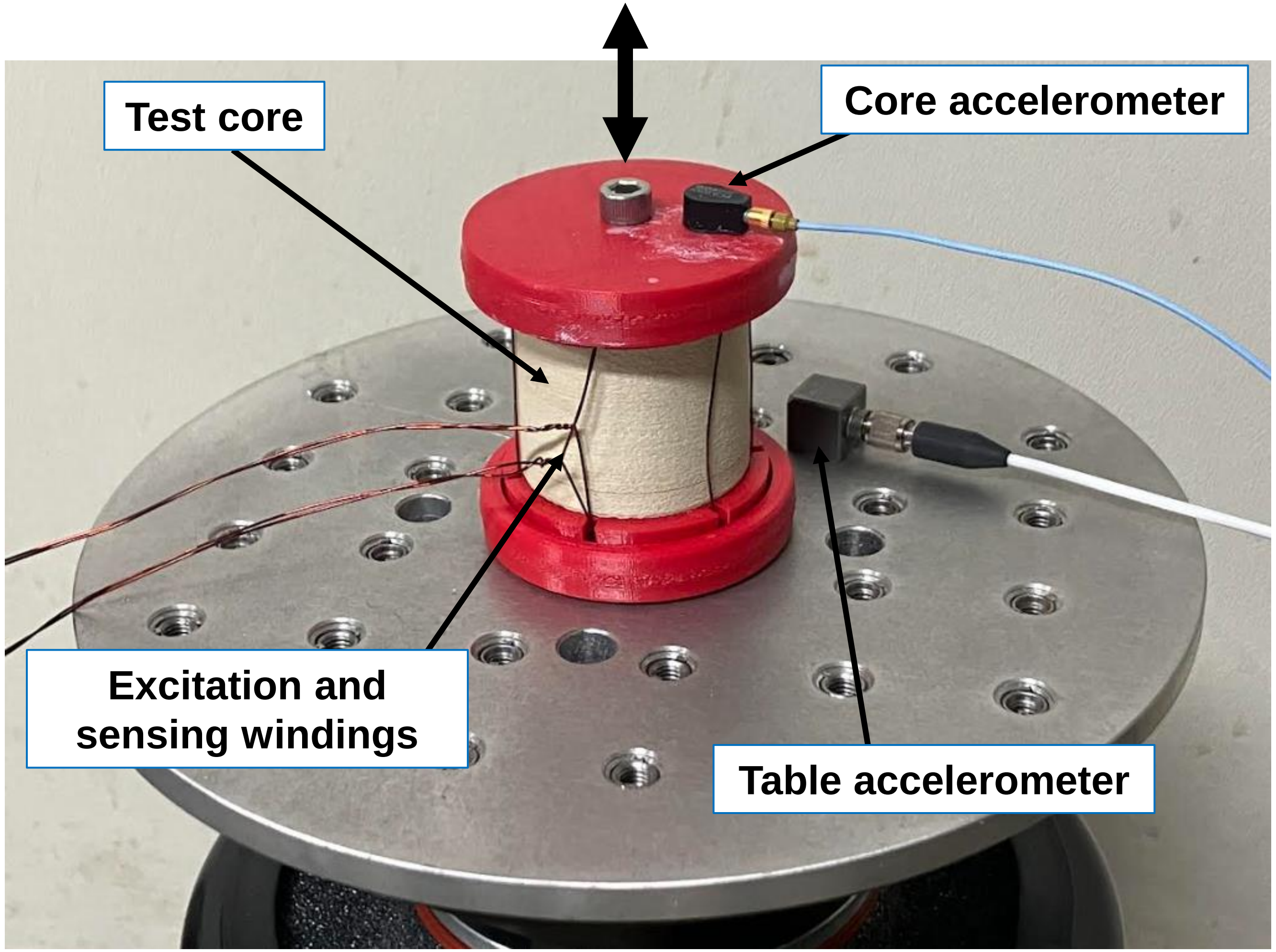


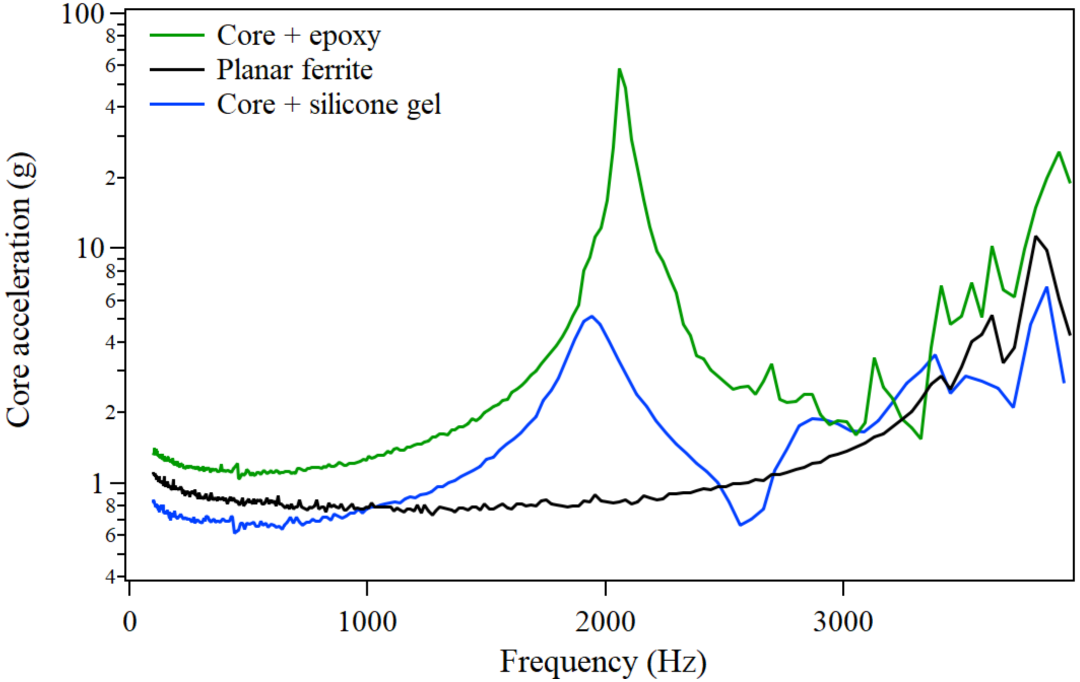


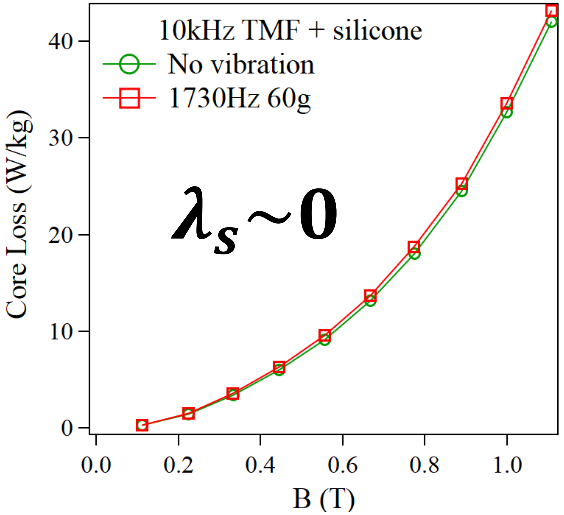


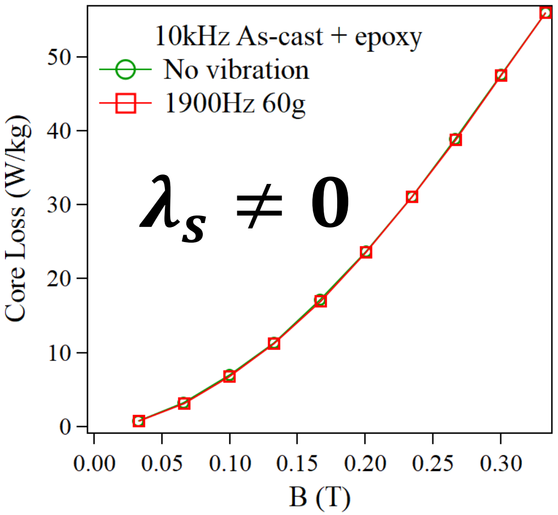
- Negligible change ~1% in inductance from 20g 100Hz vibration in z-axis for gel potted cores
- Measured >10% inductance change for epoxy impregnated cores vibrated in x-axis

Vibration Stresses



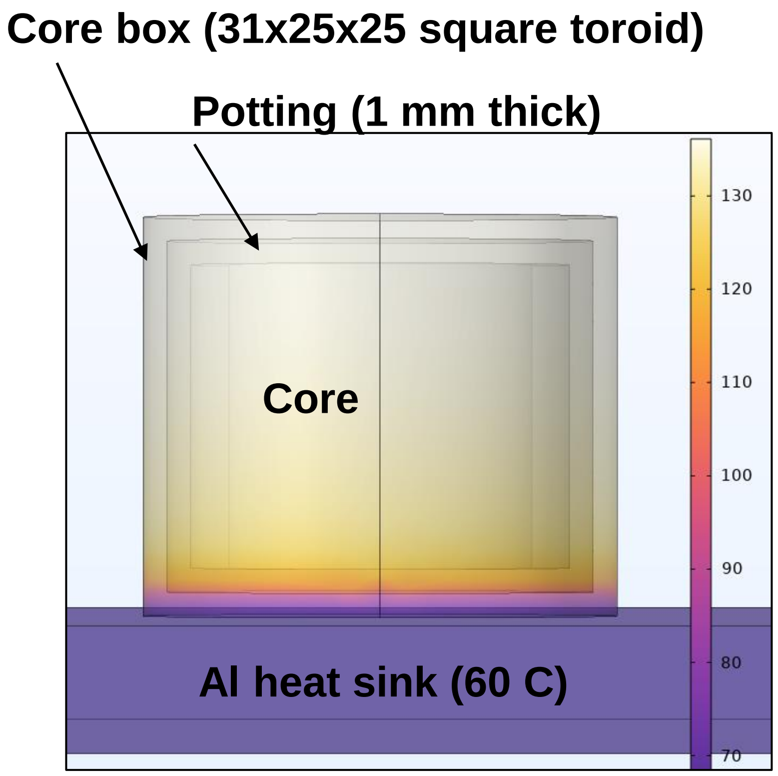


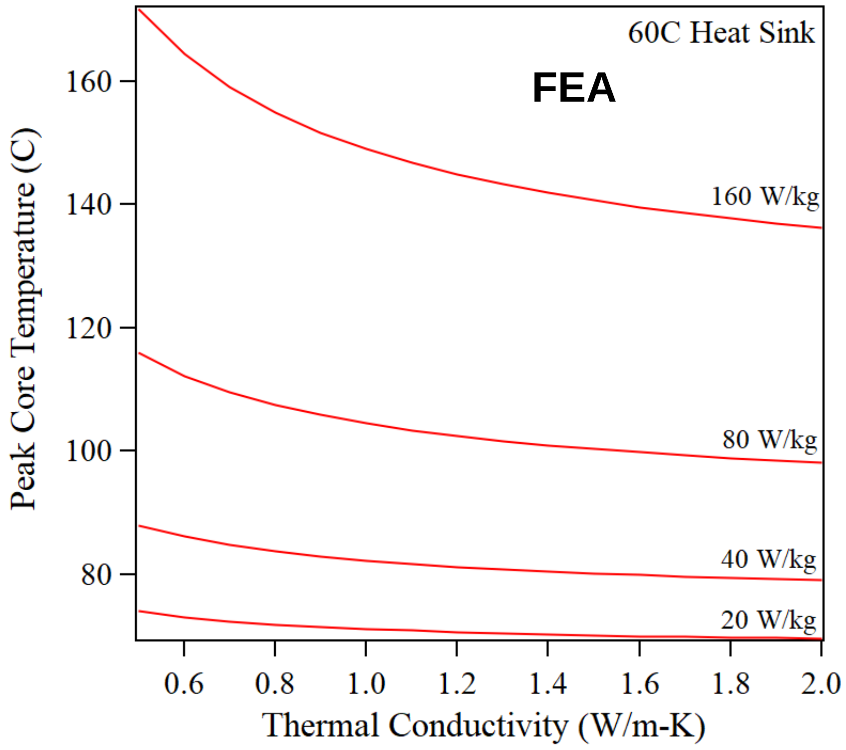


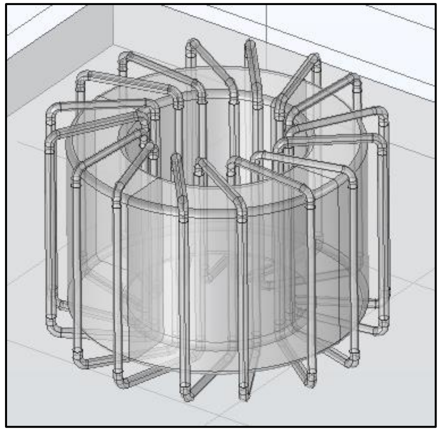


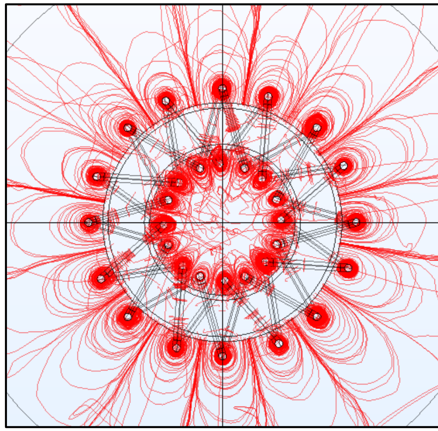
Negligible change in measured losses at peak resonant frequency… stress is small

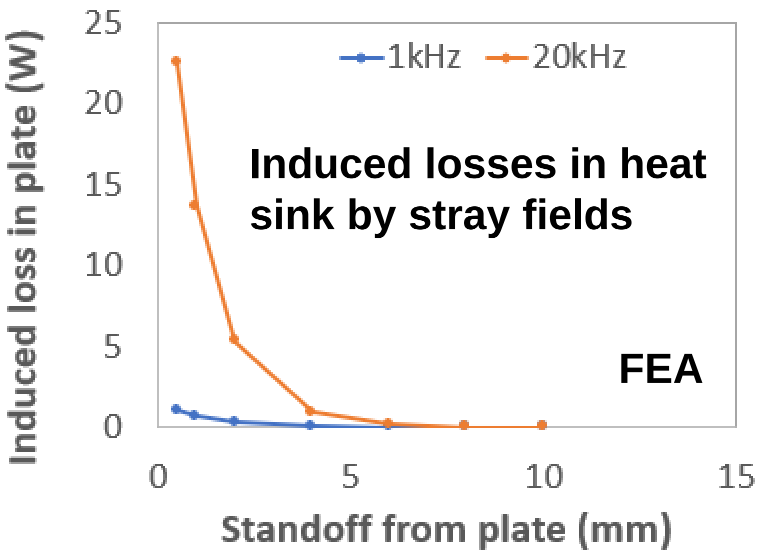
Heat Transfer and Electrical Conductivity









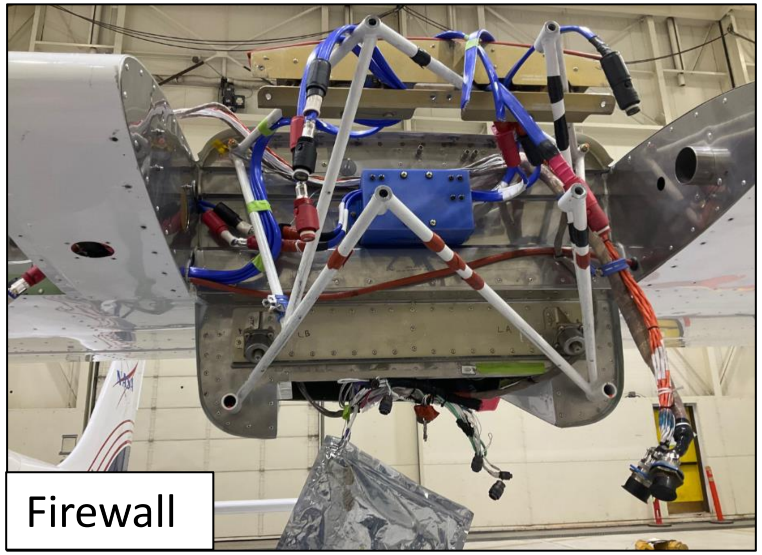


For small potting dimensions, thermal conductivity of potting is small compared to core losses. High thermal (electrical) conductivity materials near windings may produce significant loss.

X-57 EMI Filters

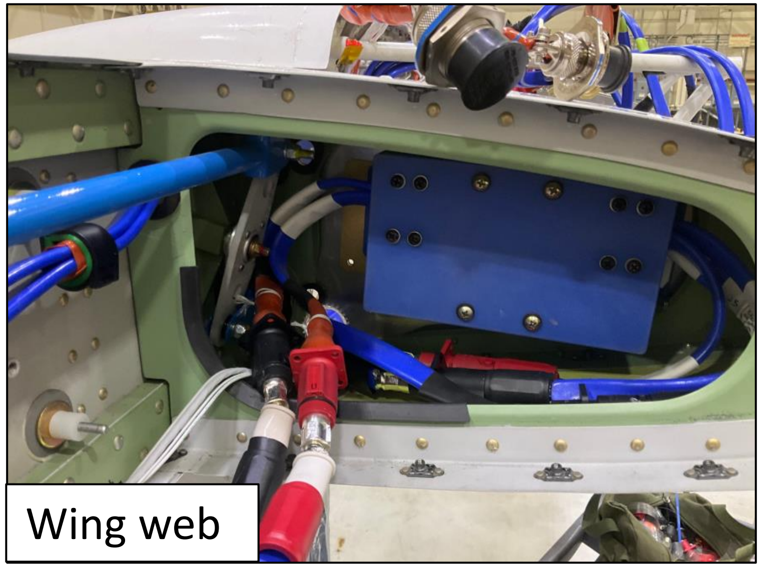
Design requirements

L = 14µH,   Ic = $10A_p$,   ID > 17 mm



Firewall

X-57 mounting locations



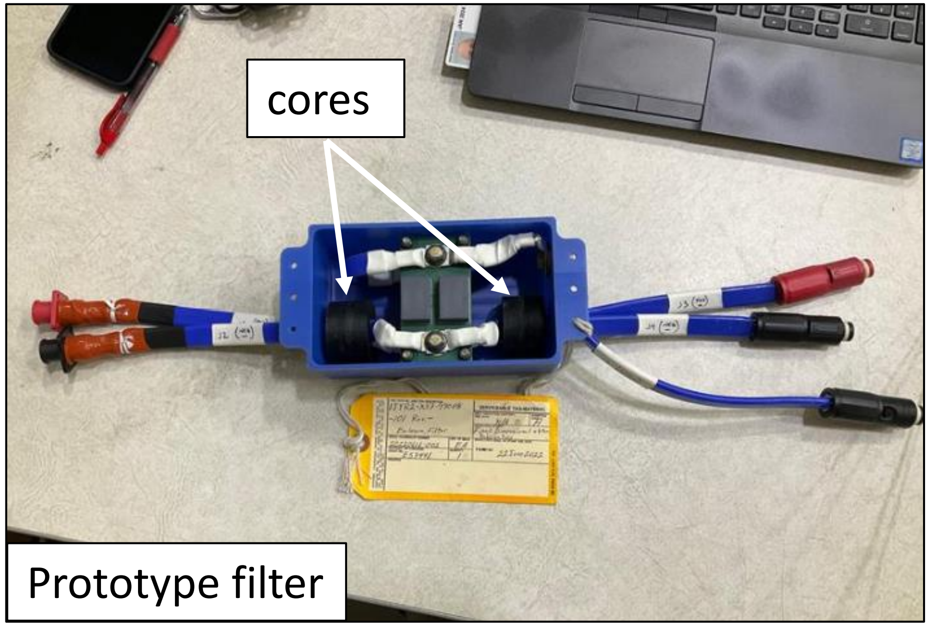
Wing web

Design comparison

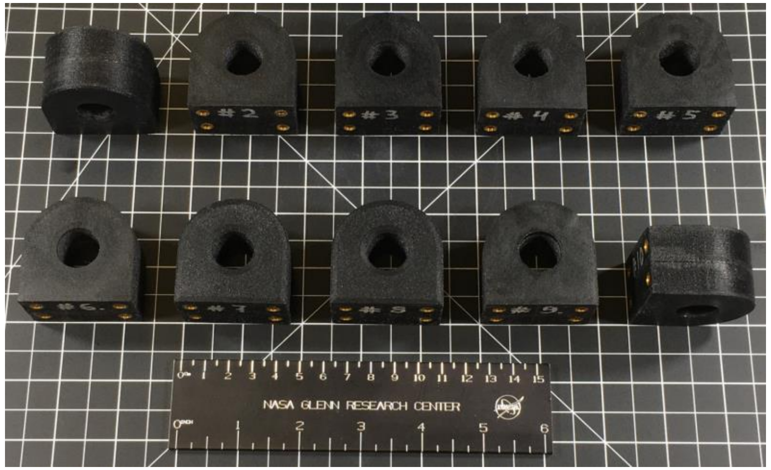
	Ferrite (SOA)	Nanocomposite
Toroid	21x53x51 (mm)	21x40x25 (mm)
B_m (T)	0.3	0.8
μ_r	1600	5300
Mass (g)	454 ← **3X** —	145

Reduction in size and mass – compared to SOA

Filter design passed vibration test at Armstrong Flight Research Center



Prototype filter



Packaging Design Space: Tradeoffs

High thermal conductivity

Good thermal conduction. Potential for induced eddy current loss.

thermal

mechanical

Soft / High damping Mount

Silicone gel potting
Low resonance frequency
Low core loss

vibration effects likely to increase with core size

Rigid / Low damping Mount

Epoxy potting
High resonance frequency
High peak g
High core loss

Poor thermal conduction. Low potential for induced eddy current loss.

Low thermal conductivity

Conclusions

- Each design is different and should be validated
- Silicone gel can be an effective potting material for fragile MANCs under DO-160G vibrations
- Softer mounts can shift vibrations to lower frequency in neighboring components
- Design Tradeoffs:
  - high/low thermal and electrical conductivity
  - Soft/rigid mounting

Thank you to NASA AATT Electrified Aircraft Propulsion