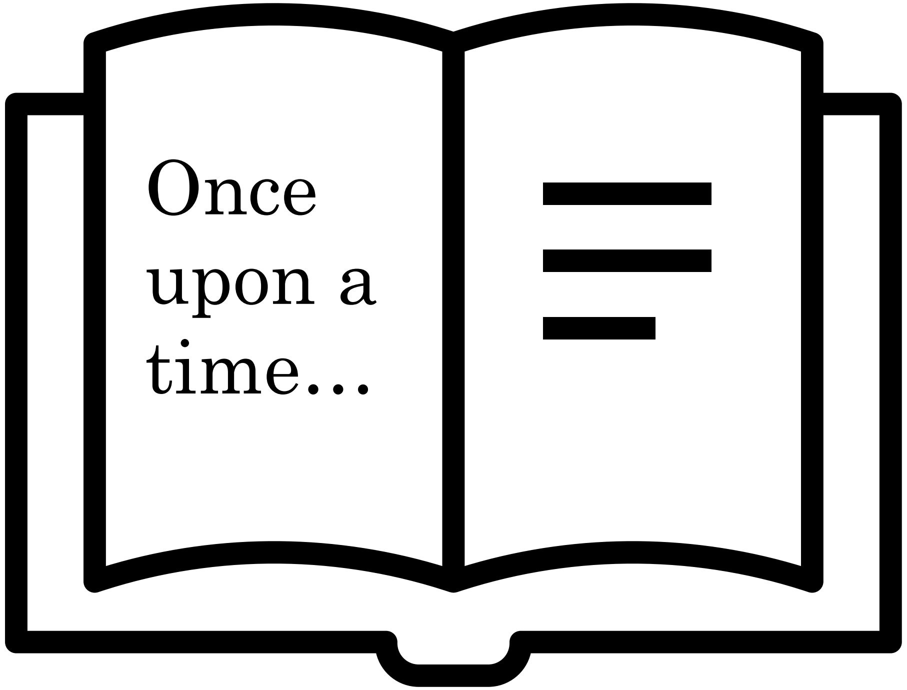
Custom Magnetics
Stories of Conflict, Tradeoff and Creation

Victor W. Quinn

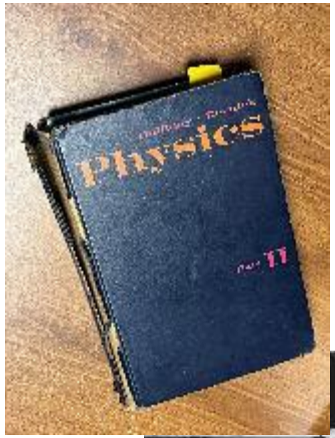
Stories of Conflict, Tradeoff and Creation

- Inherent Conflict
- Moving forward … Risk Mitigation
- Densities Teeter
- Shell Games
- Reactive Tradeoffs
- Inductor or Capacitor?
- Adventures in Design
- For the love of Custom Magnetics …

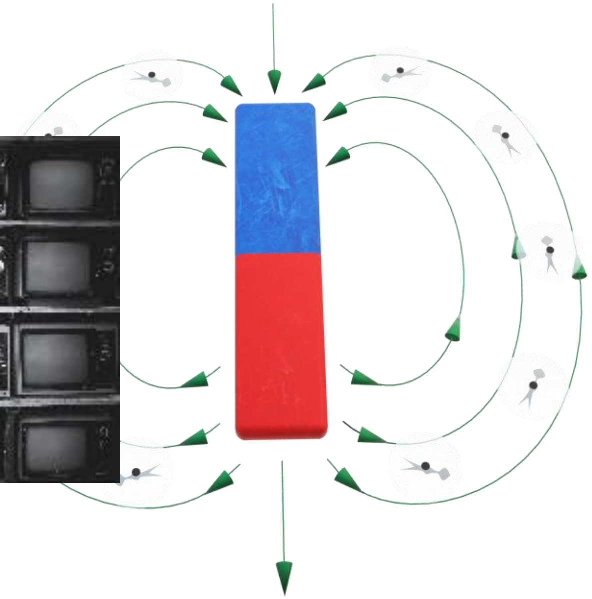


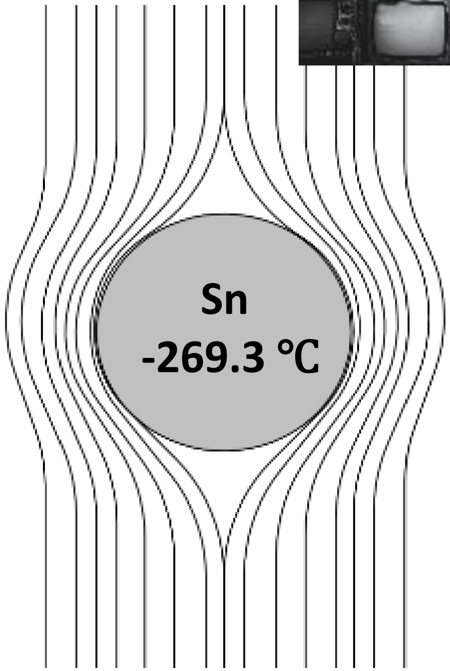
Induced by Magnetics

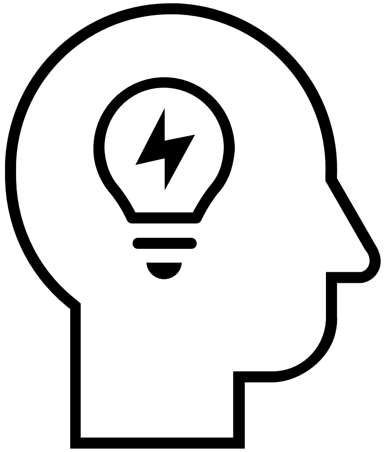
- NASA heroes & model rockets
- Resnick & Halliday Part II (Chapter 33)
- Meissner Effect Sn (bobbin winding)
- CRT Tubes vs Magnetics



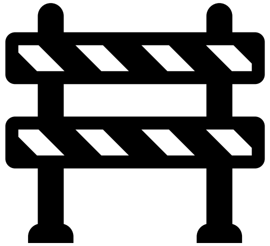








Inherent Conflict

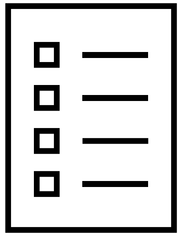


- Technical Challenge
  - design method
  - component material
  - design verification
  - production method
  - production control

- Resource Constraints
  - personnel
  - time
  - material
  - equipment

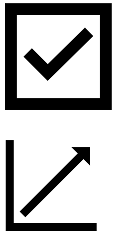
CONFLICTS

- Customer Need



  - performance
  - reliability
  - cost
  - schedule

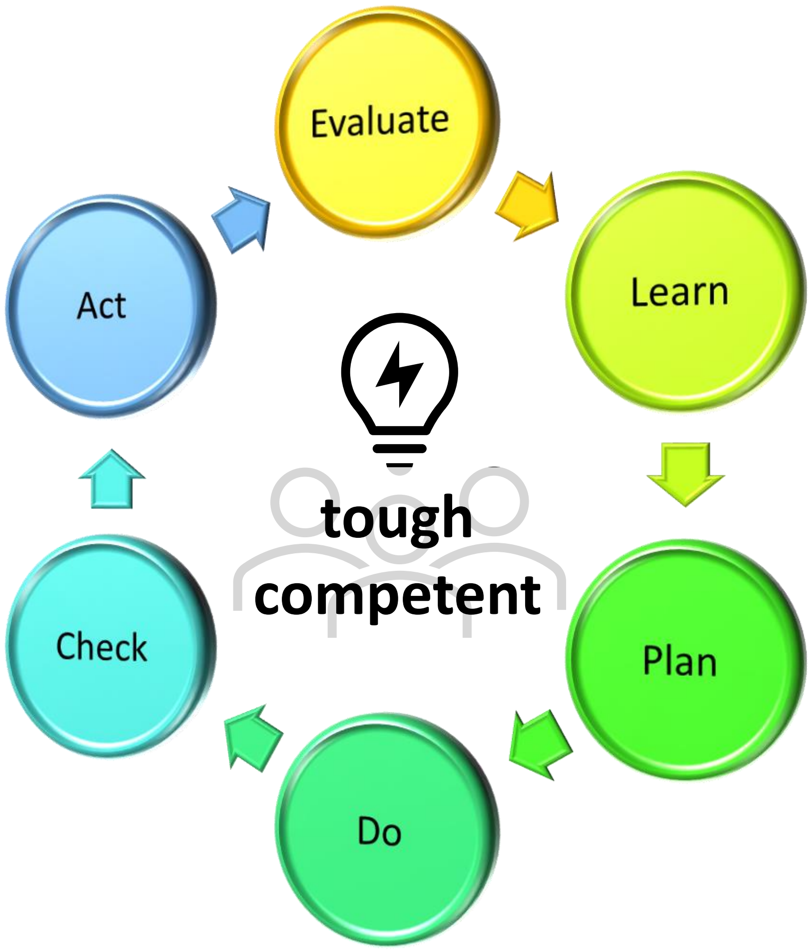
- Business Opportunity



  - technical achievement
  - revenue growth

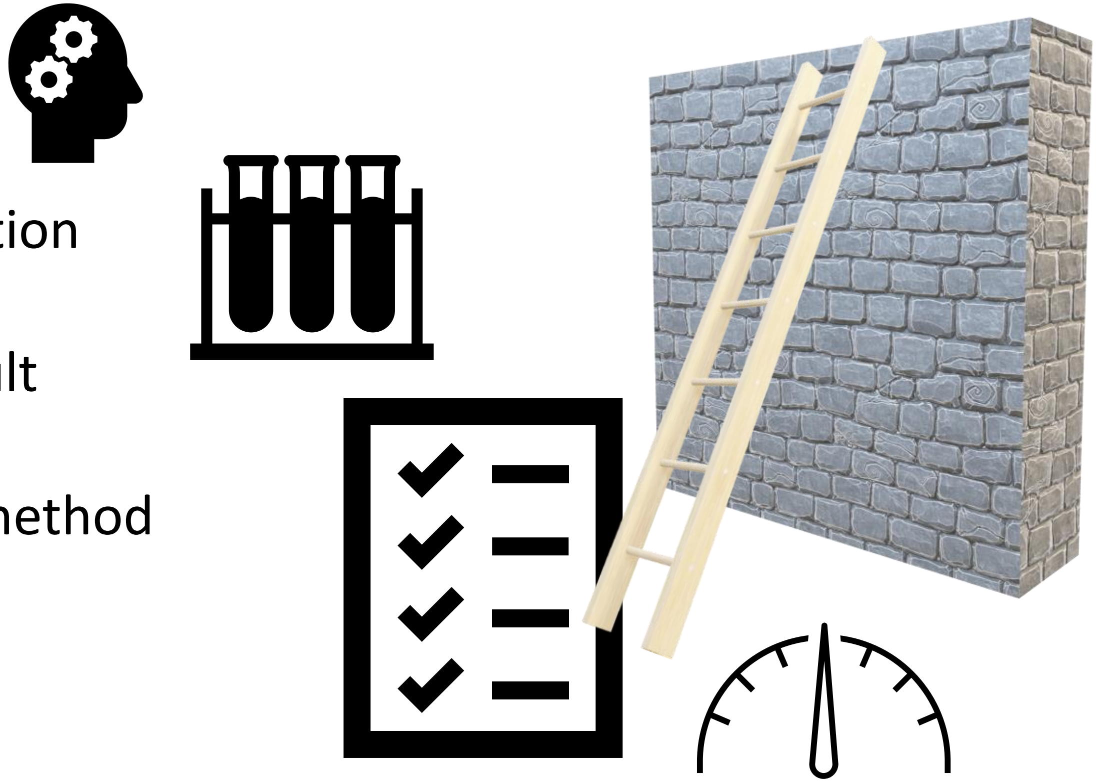
Realization …

- Technology advancement
  - we don’t know what we don’t know
- Limited resources
  - we can’t do everything we wish to do



Moving Forward … Risk Mitigation

concept → prototype → verify → finalize → validate → qualify → control



- Selectively Research
  - systematic investigation to support innovation
- Design of Experiments
  - evaluate how selected variables affect result
- Test Comprehensively
  - verify convergence of results with design method
- Control Process
  - proactively monitor

Custom Magnetics

Performance Requirements

- conversion
- isolation
- efficiency - heat management
- energy management & leverage
- quality - conducted & radiated emission
- reliability – MTBF
- agency (safety & disposal)

Environmental Stress

- mechanical shock & vibration
- thermal extremes & shock
- assembly processes (high temperature solder, solvents, wash)

MAGNETICS DESIGN
size – efficiency – reliability - cost
compliance is given
holistic approach
availability / obsolescence

Packaging & Interface

- high current
- high voltage
- high frequency
- heat transfer

Risk Management

- FMEA Failure Mode & Effects Analysis
- PCP Process Control Plan
- PPAP Production Part Approval Process

Testability & Control

- components
- assembly
- within system

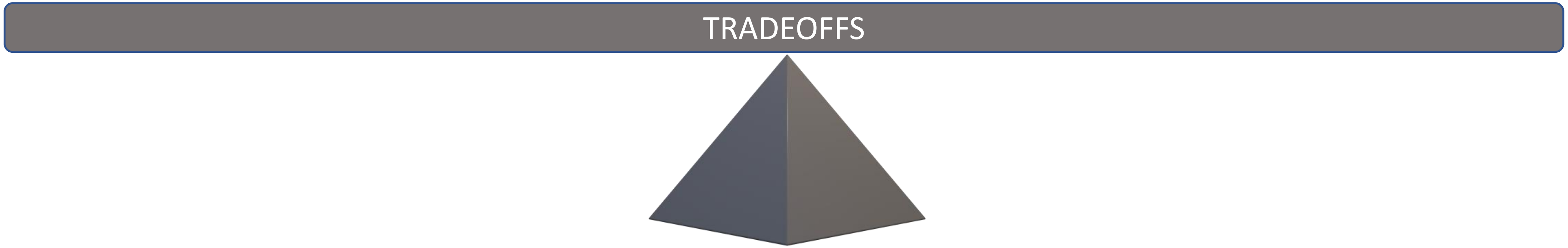
Densities Seesaw (*ci-ça*)

$$Coil\ Loss\ \ \alpha\ (J^{2}) \qquad\qquad Core\ Loss\ \ \alpha\ (\Delta B^{\beta})$$

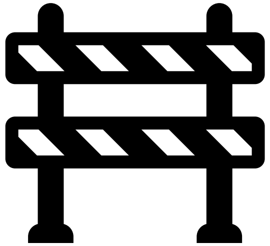
to minimize total loss - neglecting saturation

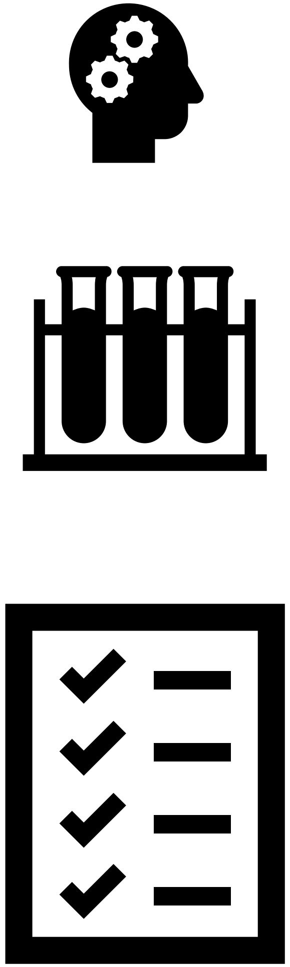
$$\frac{Core\ Loss}{Winding\ Loss} = \frac{2}{\beta}$$

J (current density) $\qquad$ ΔB (flux density)



What do we know about cores?





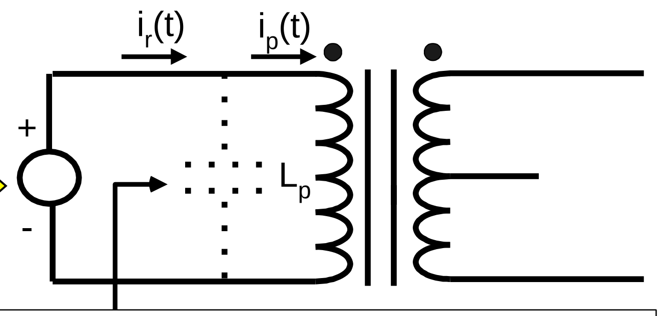
- nonlinear - inconsistent
- increasing frequency
- bias & transients
- interfaces & packaging impacts
- wide temperature range
- reliability

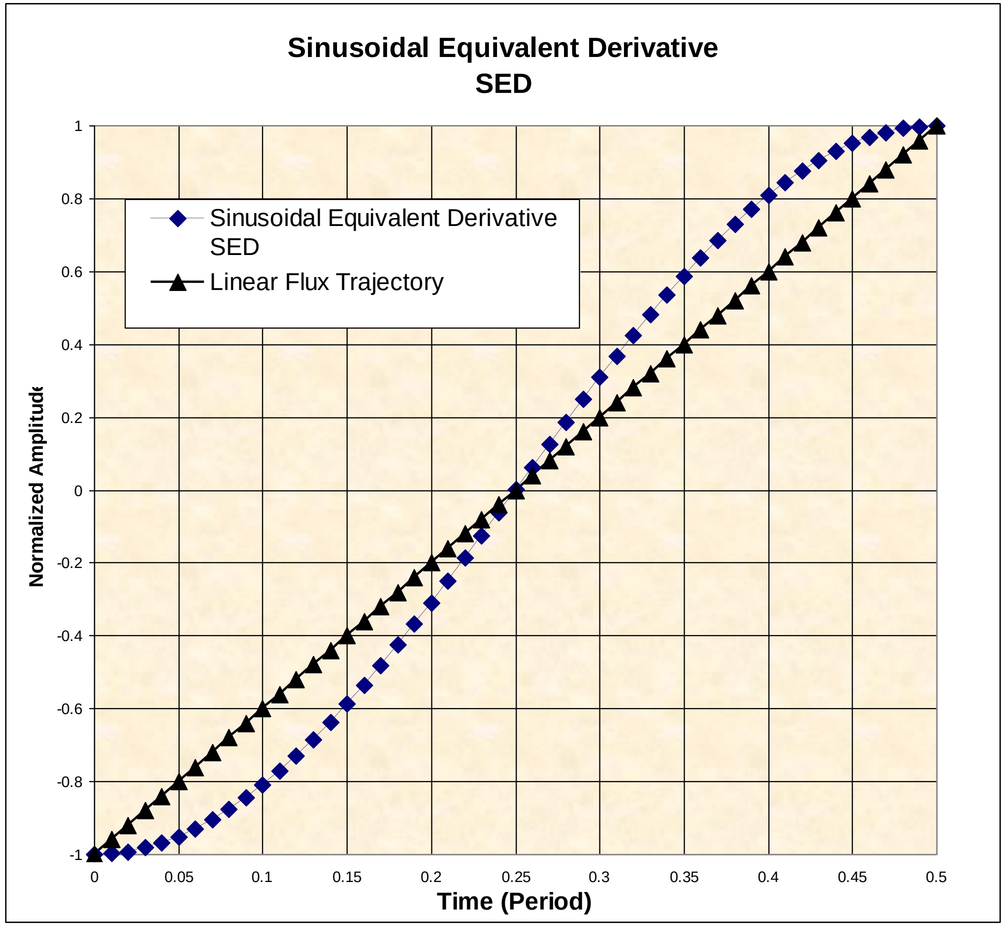
So we test … and test repeatedly …

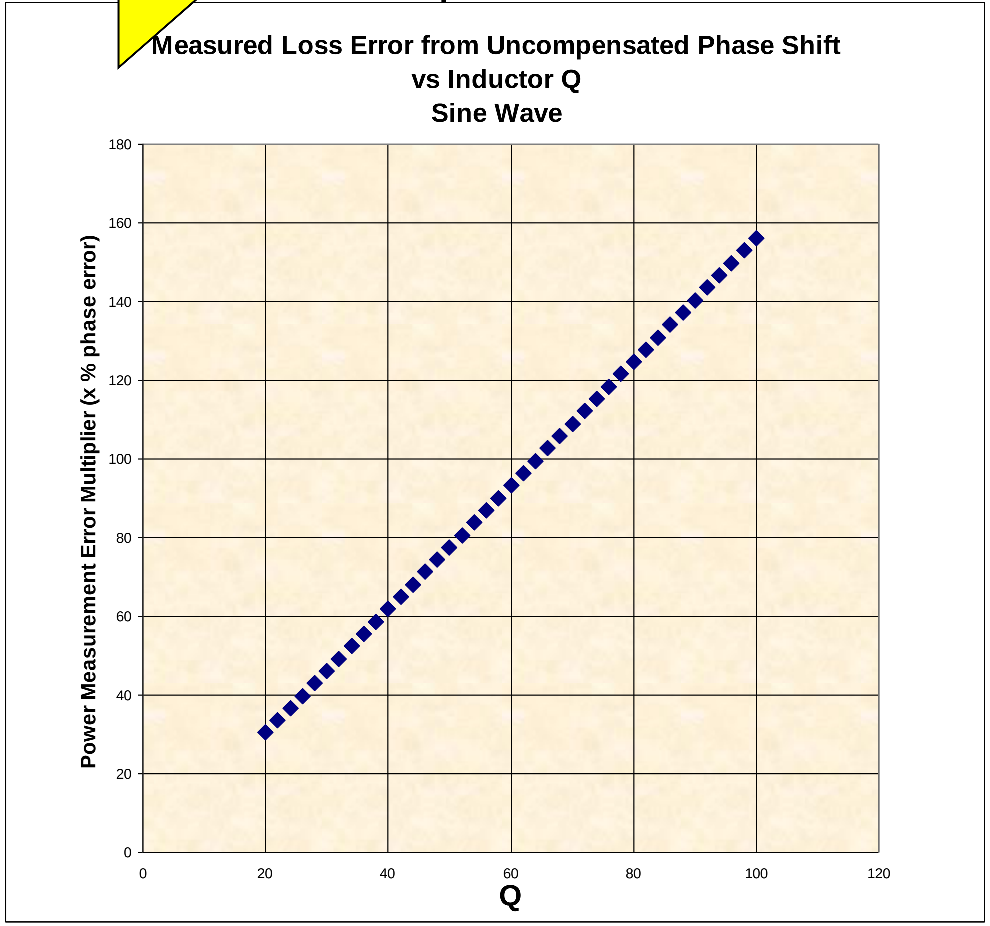
- Loss density, incremental permeability, hysteresis loop versus AC field density
  - over frequency, temperature
- Complex permeability versus DC bias field density
  - over frequency, temperature
- Other normalized methods to evaluate composite materials in flux path

High AC Swing

Parallel resonant capacitor facilitates accurate loss measurement

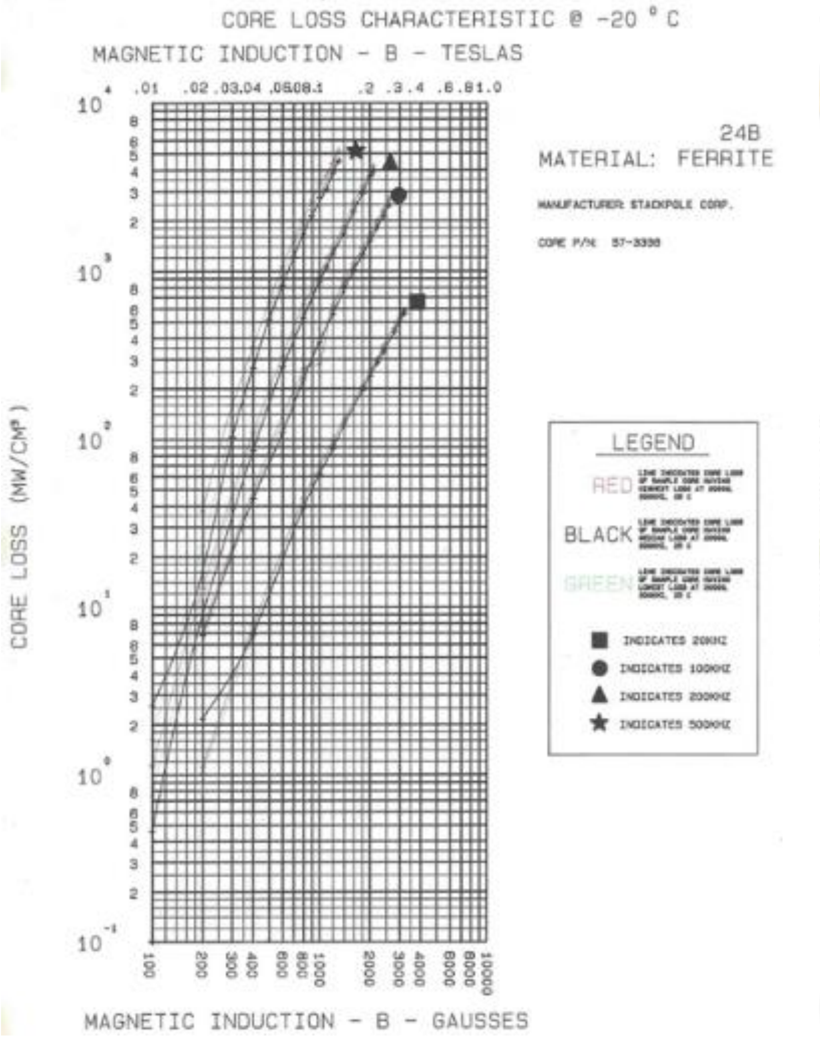


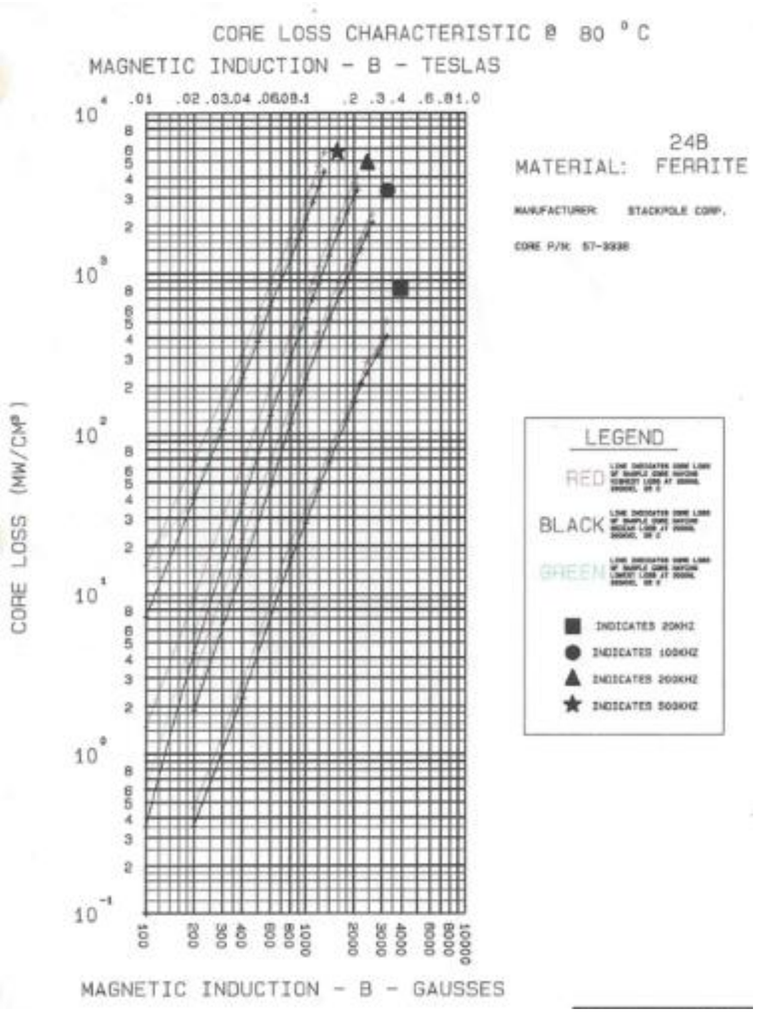


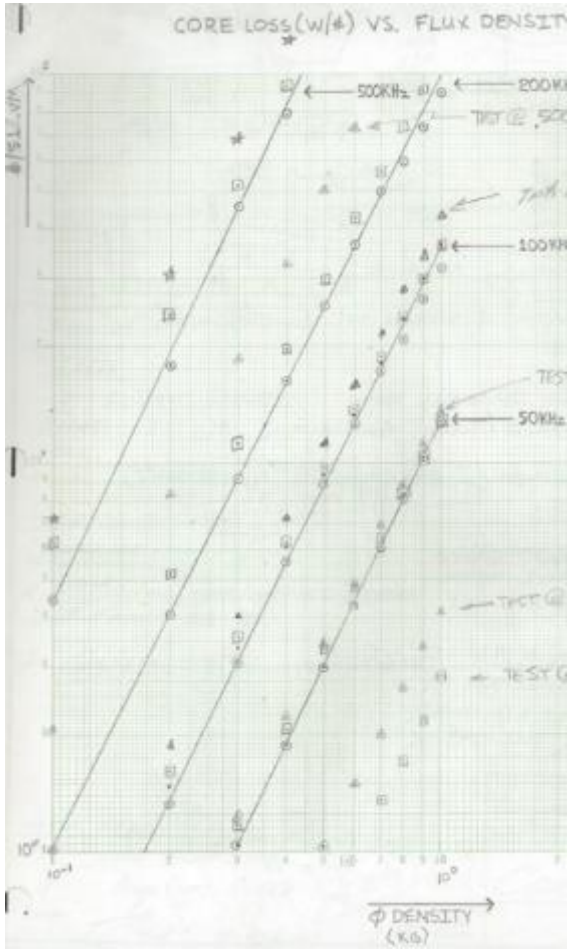


Resonant circuit facilitates measurement.

Core Test: Loss DOE



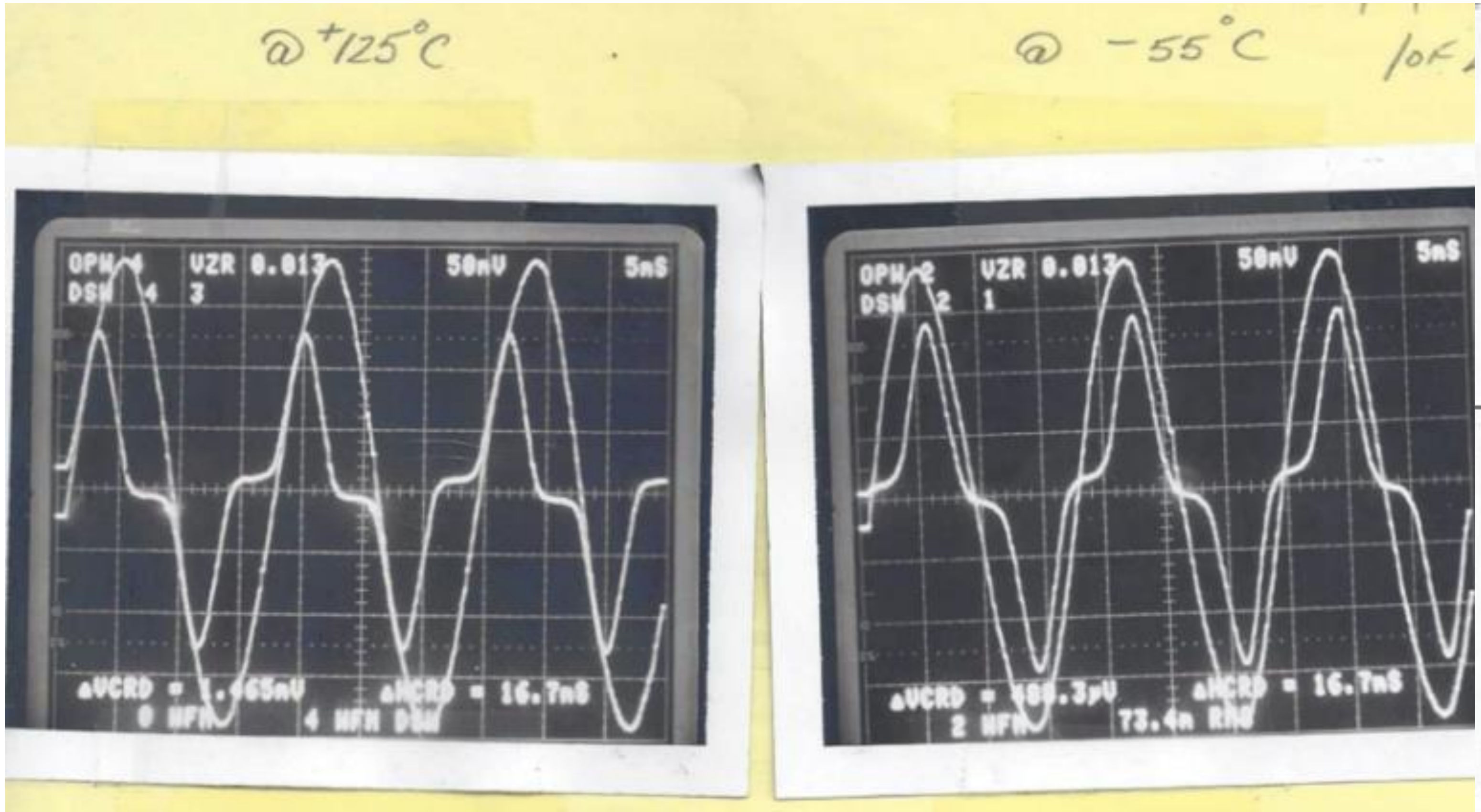




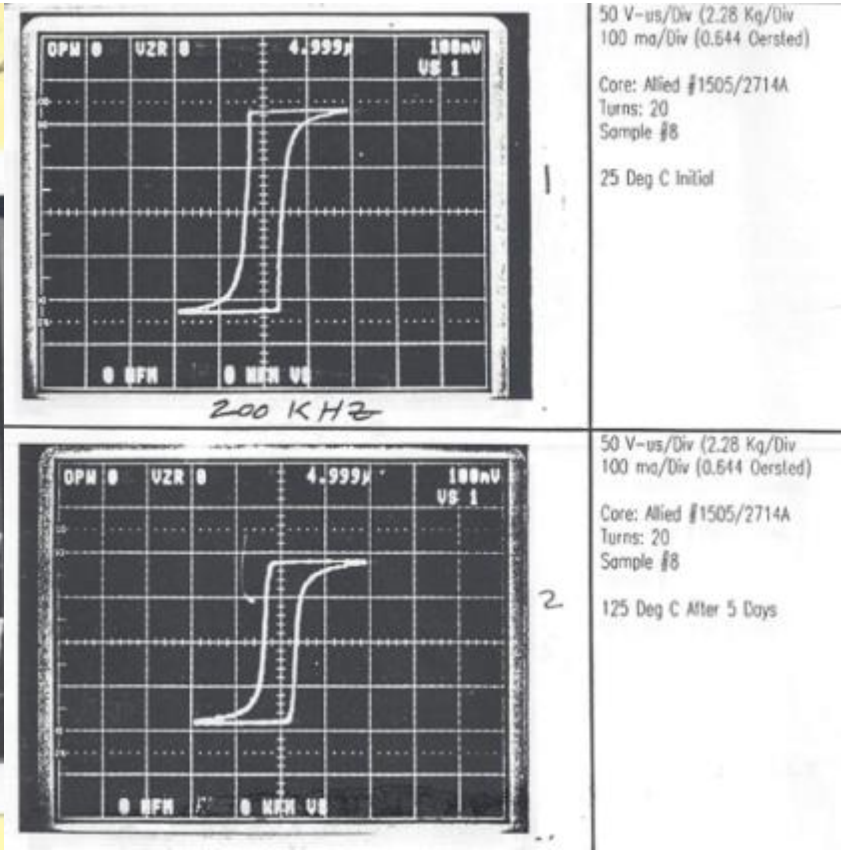
Collect and expand data with each new product development.

Core Test: Hysteresis DOE

Co/Fe/V ribbon



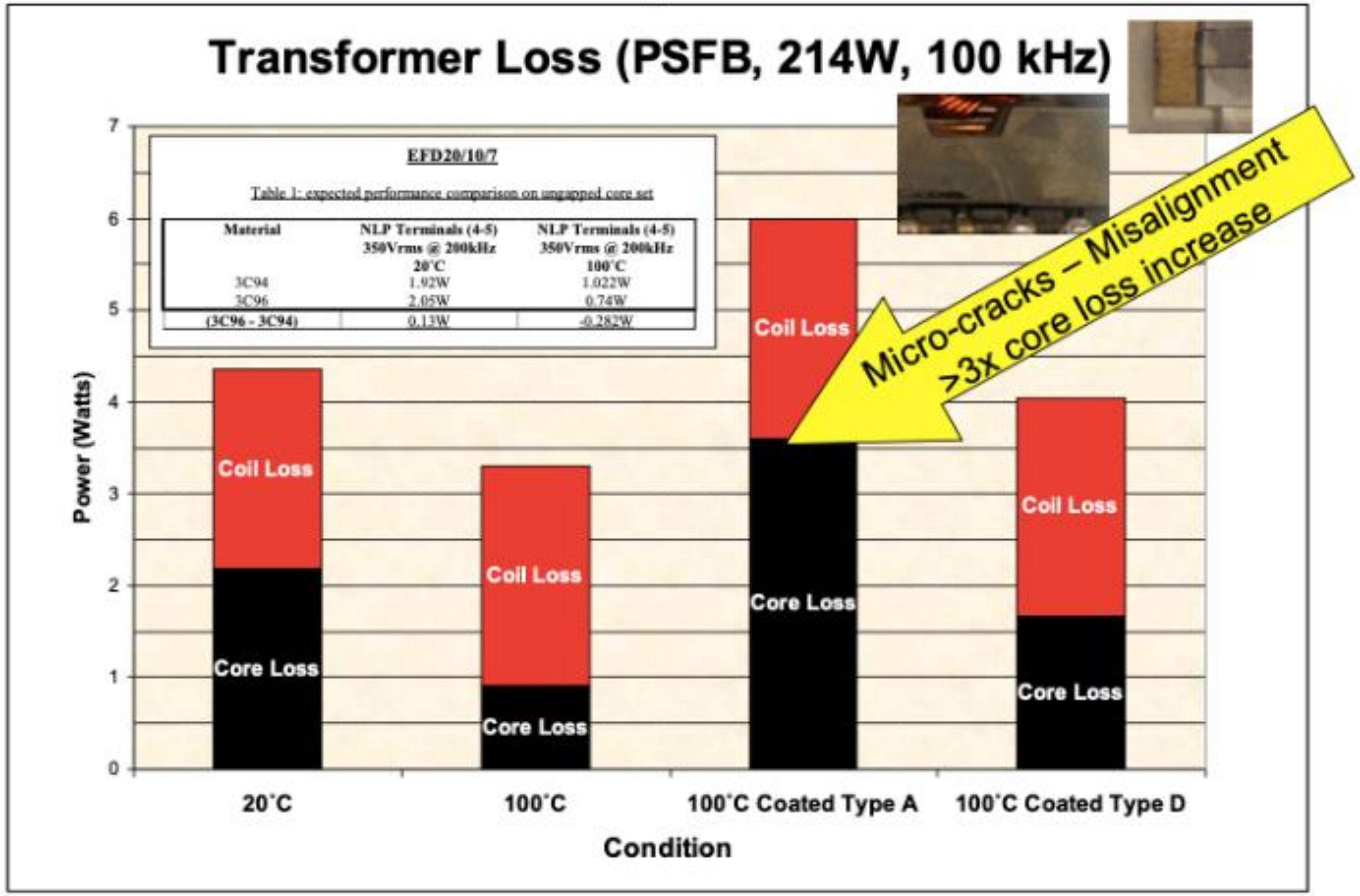
Co based amorphous ribbon



Characterize non linearities and verify endurance.

Core Test: Loss Validation

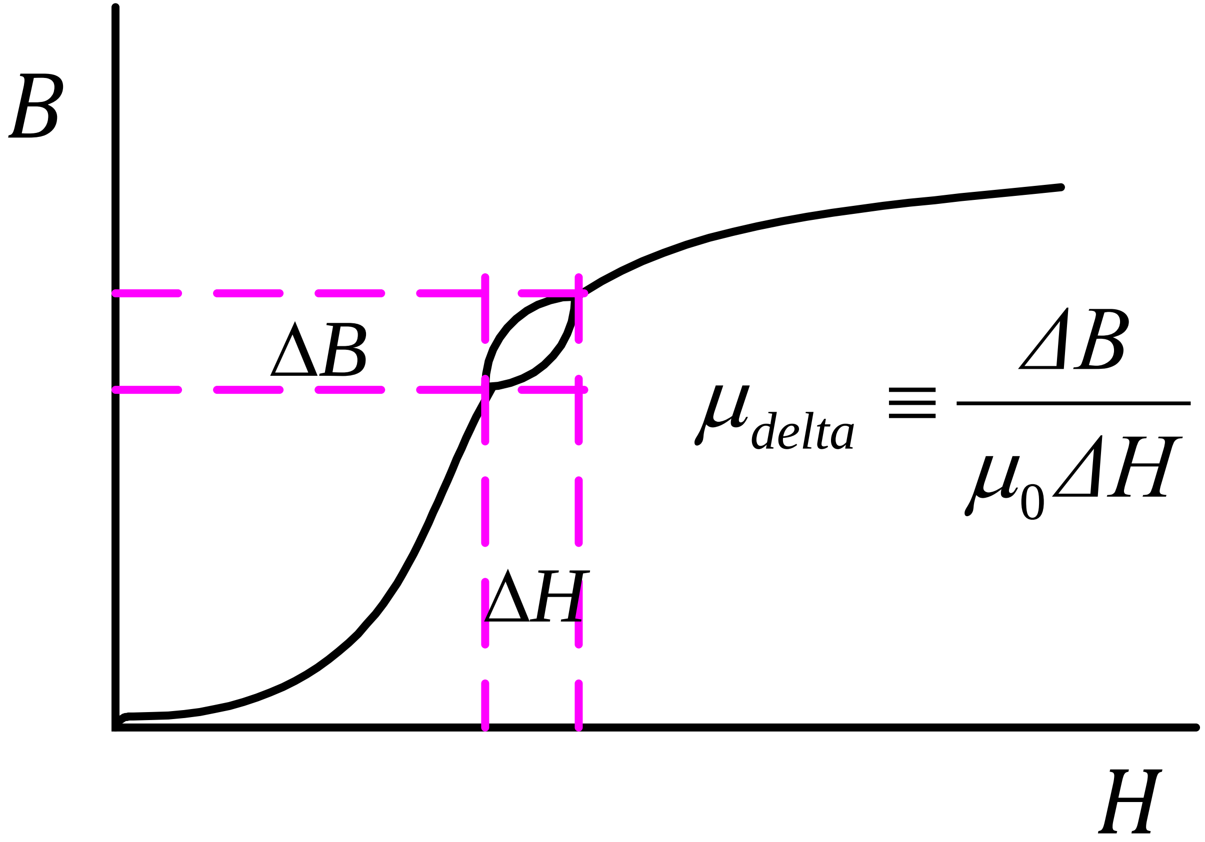
Core Loss Experiences



Material	NLP Terminals (4-5) 350Vrms @ 200kHz 20˚C	NLP Terminals (4-5) 350Vrms @ 200kHz 100˚C
3C94	1.92W	1.022W
3C96	2.05W	0.74W
(3C96 - 3C94)	0.13W	-0.282W

Validate results after manufacturing processes.

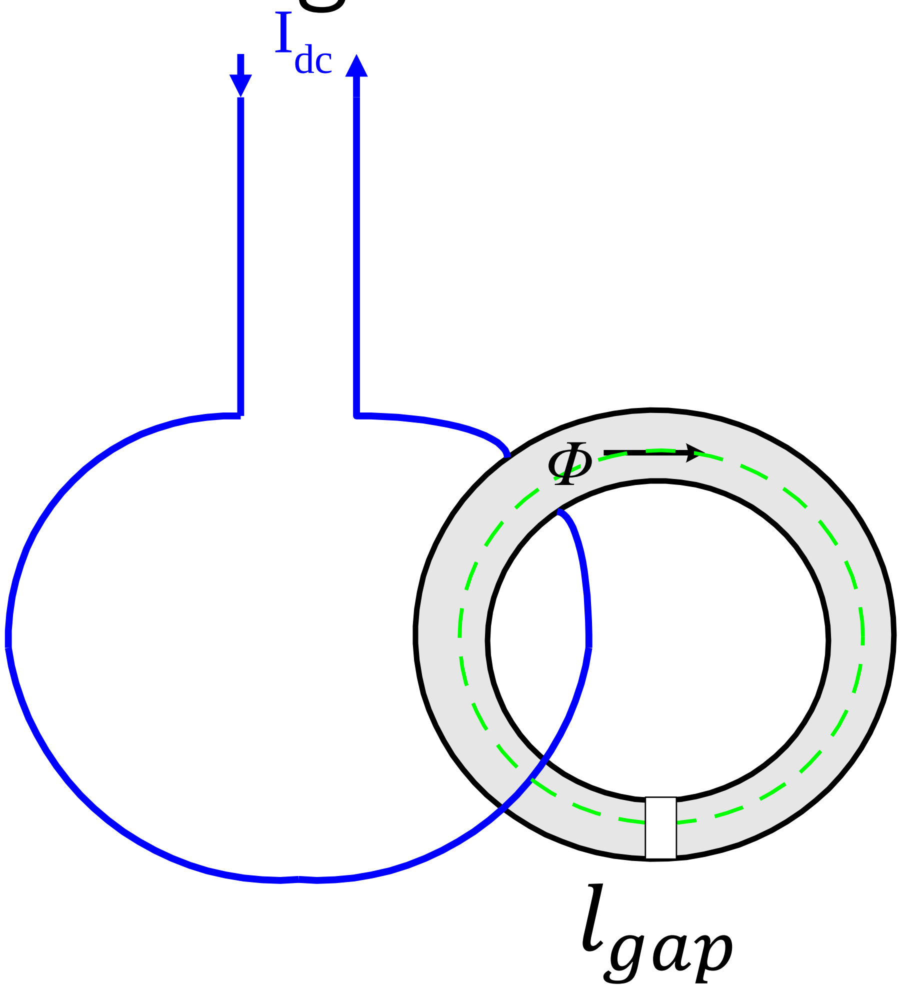
Incremental AC Permeability with Bias

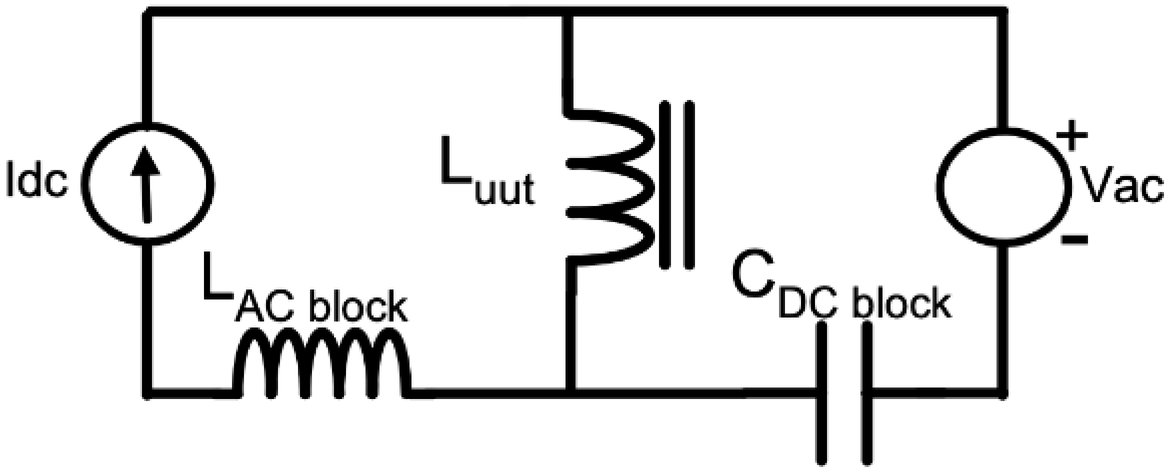


$$\mu_{delta} \equiv \frac{\Delta B}{\mu_0 \Delta H}$$

Permeability depends on nonlinear AC and DC magnetization.

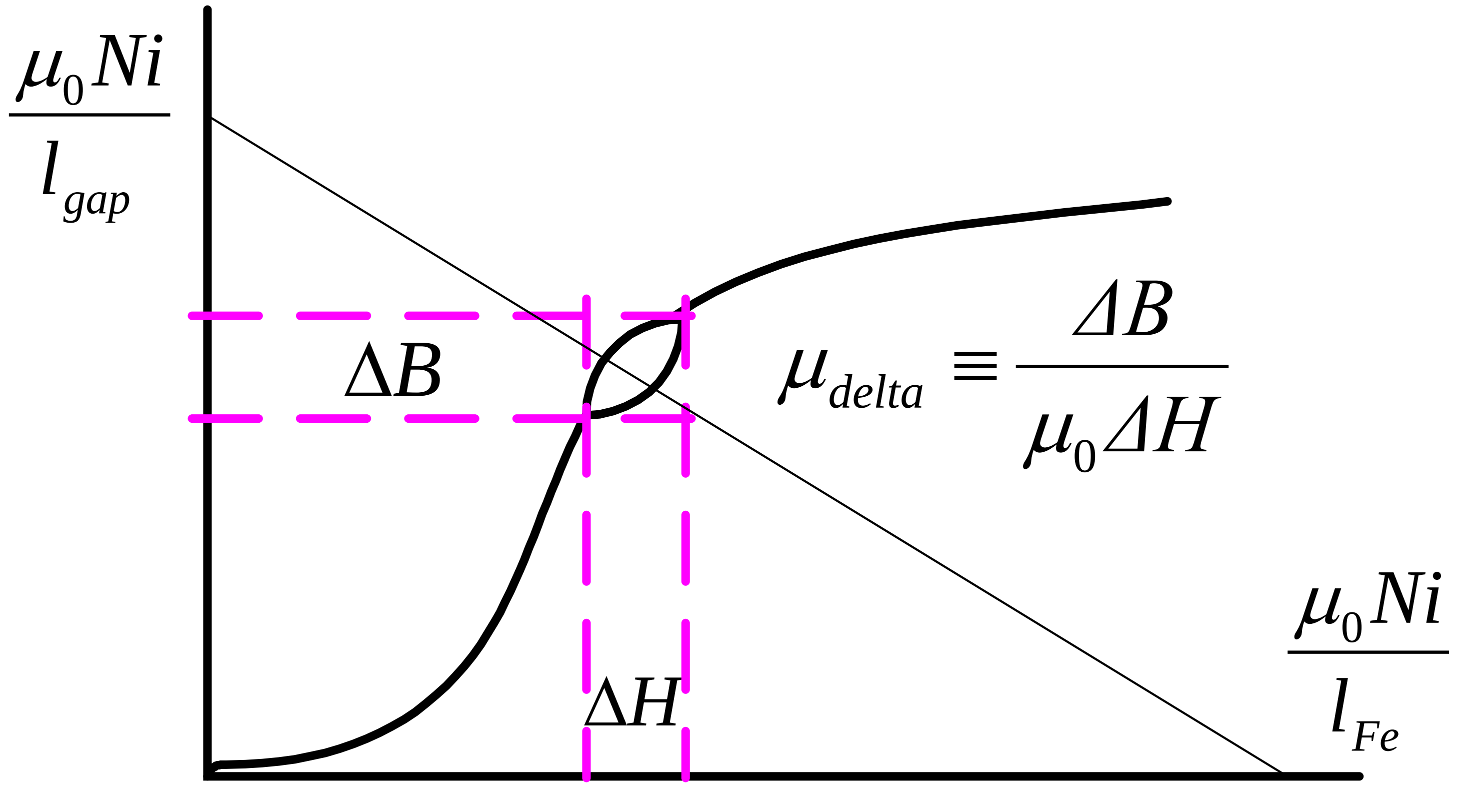
Core Test: High DC Bias DOE





Test circuit facilitates AC measurement with superimposed bias.

Core Test: DC Quiescent Point



Develop DOE conditions based on normalized field densities.

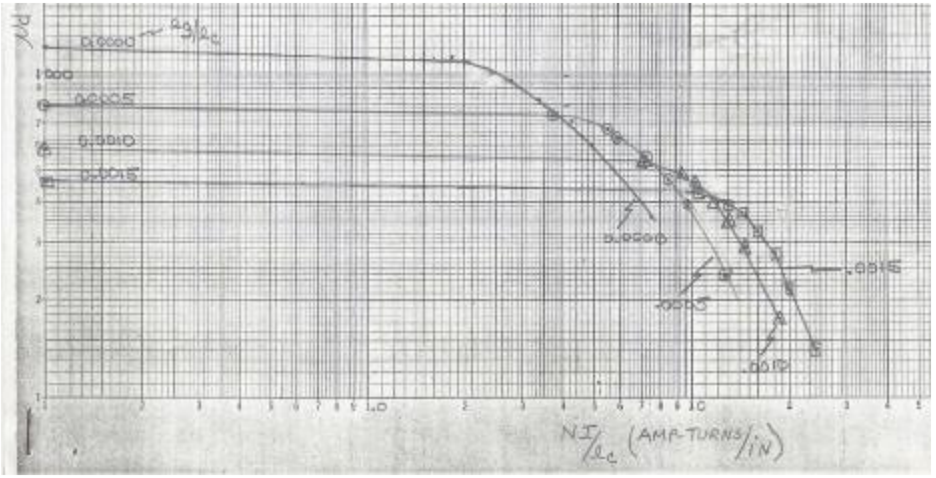
Core Test: Biased Permeability DOE

$$L \propto \frac{N^2 A_{Fe}}{l_{Fe}} \left[\frac{\mu_{delta}}{\frac{l_{gap}}{l_{Fe}} \mu_{delta} + 1} \right]$$

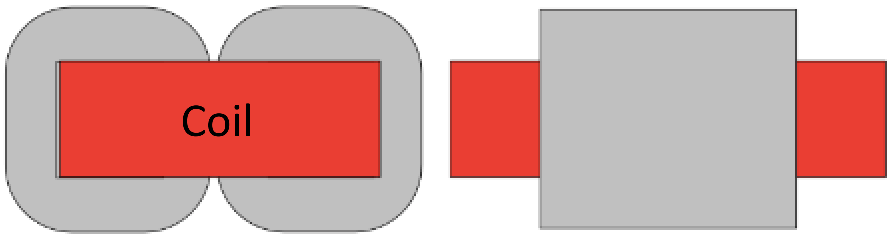
$$B_{Fe} \propto \frac{Ni}{l_{Fe}} \left[\frac{\mu_{DC}}{\frac{l_{gap}}{l_{Fe}} \mu_{DC} + 1} \right]$$

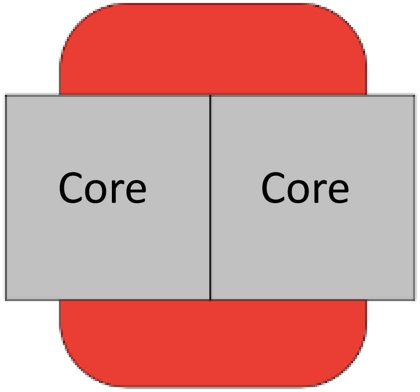
Perform DOE based on:

- given AC density
- given DC density
- setting composite core at given effective permeability

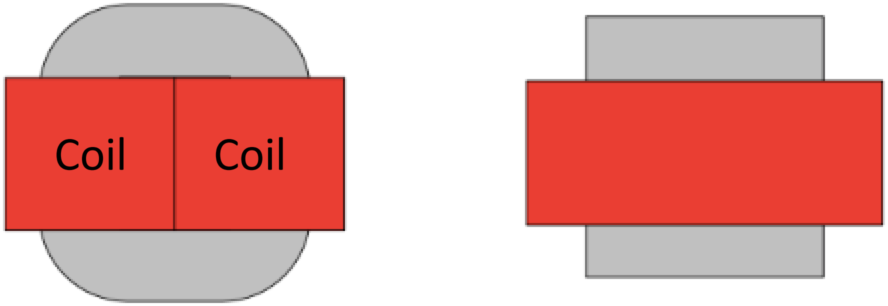


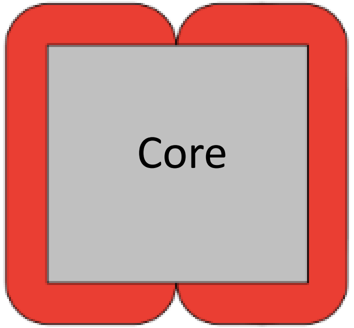
Shell Games





E Core type

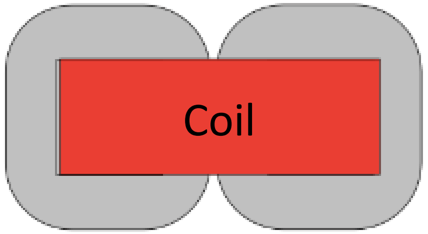


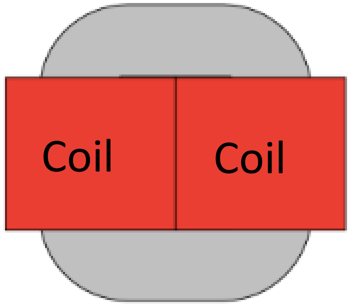


U Core type

For a given volume, configuration possibilities seem endless.

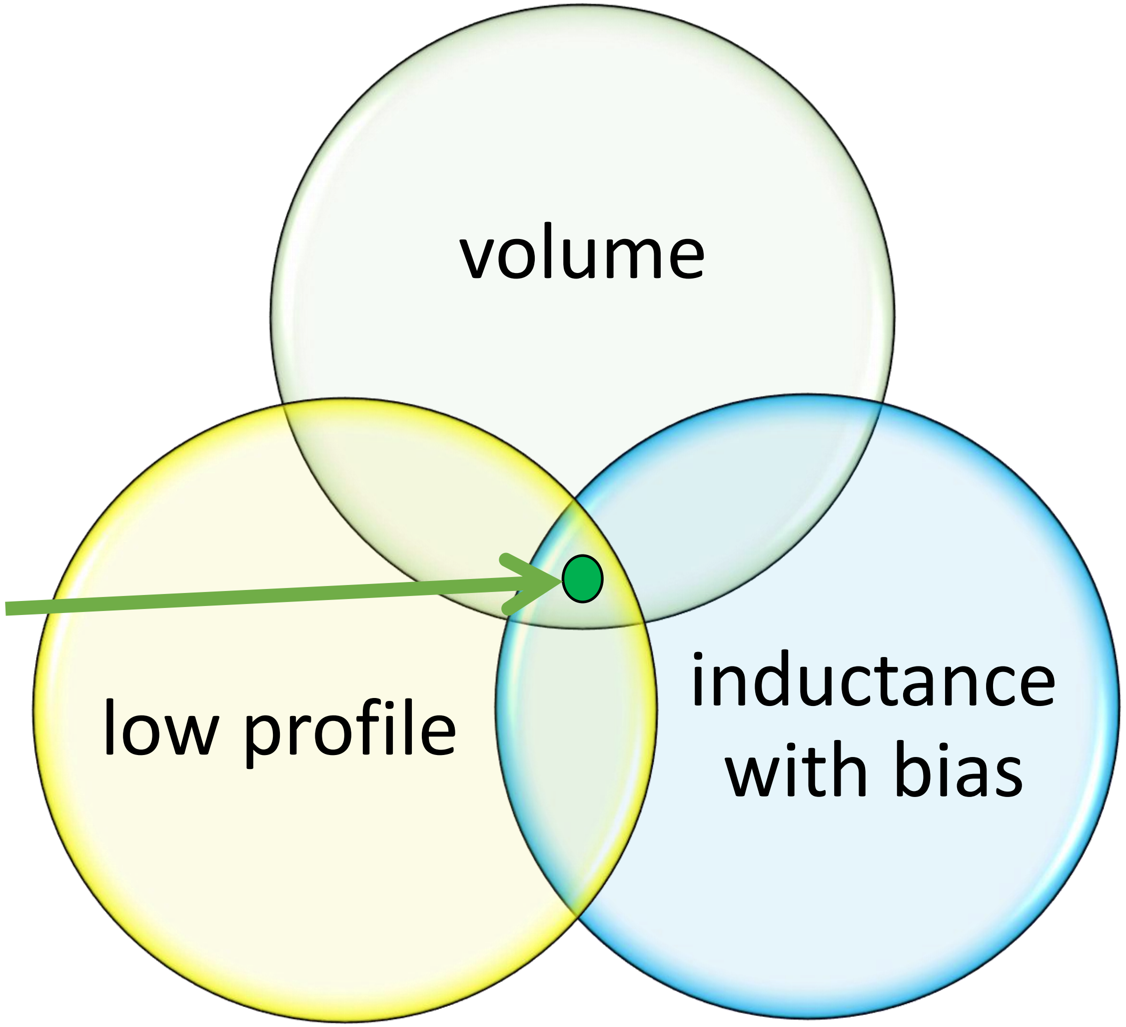
Shell Games





E Core type U Core type

Use iterative computer method to select lowest loss configuration for increasing constraints:



Shell Games: Expected Relationships

$$VA_{Rating} \propto A_{core} \cdot A_{window} \cdot J_{AC} \cdot B_{AC} \cdot frequency$$

$$L_{DC} {I_{DC}}^2 \propto A_{core} \cdot A_{window} \cdot J_{DC} \cdot B_{DC}$$

$$\frac{dL}{L} \sim \frac{1}{\frac{l_{gap}}{l_{path}} \mu_{\Delta} + 1} \frac{d\mu_{\Delta}}{\mu_{\Delta}}$$

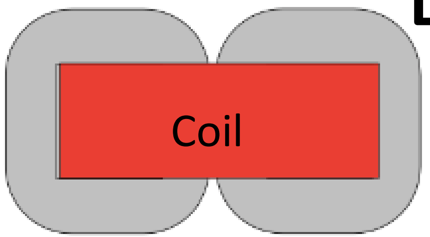
$$Coil\ Loss_{DC} \propto l_{gap}$$

$$B_{DC} \propto B_{AC} \propto \frac{1}{\sqrt{l_{gap}}}$$

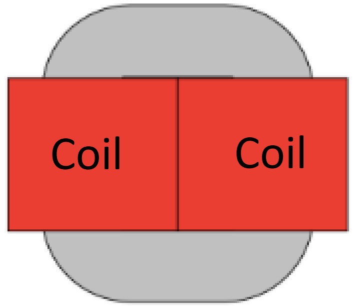
Understanding relationships facilitates tradeoffs.

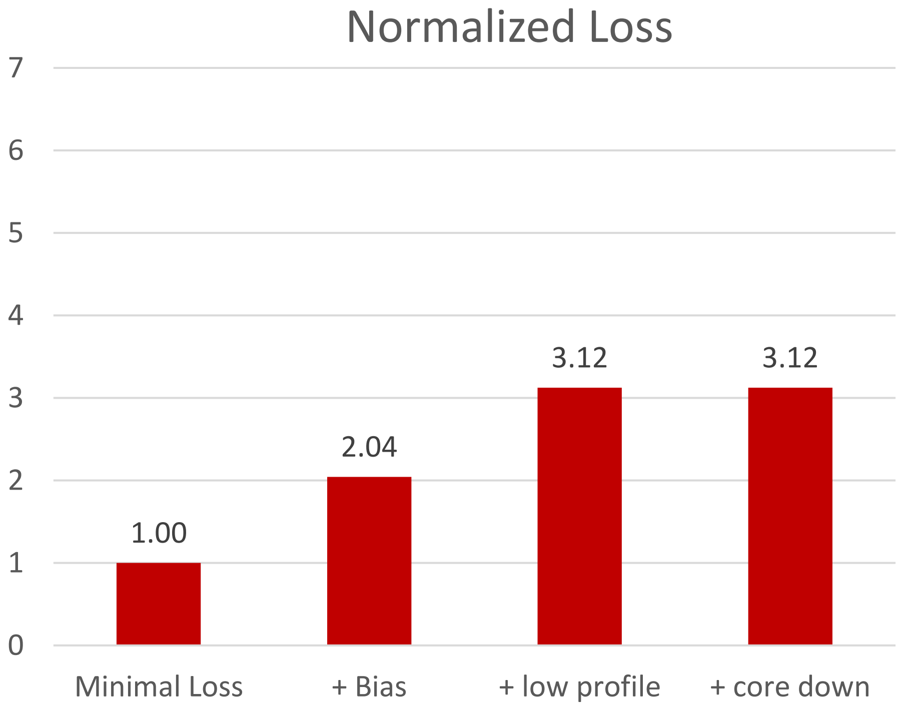
Shell Games

E Core type



U Core type



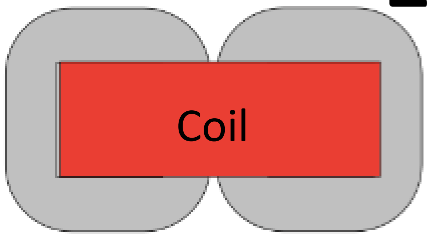


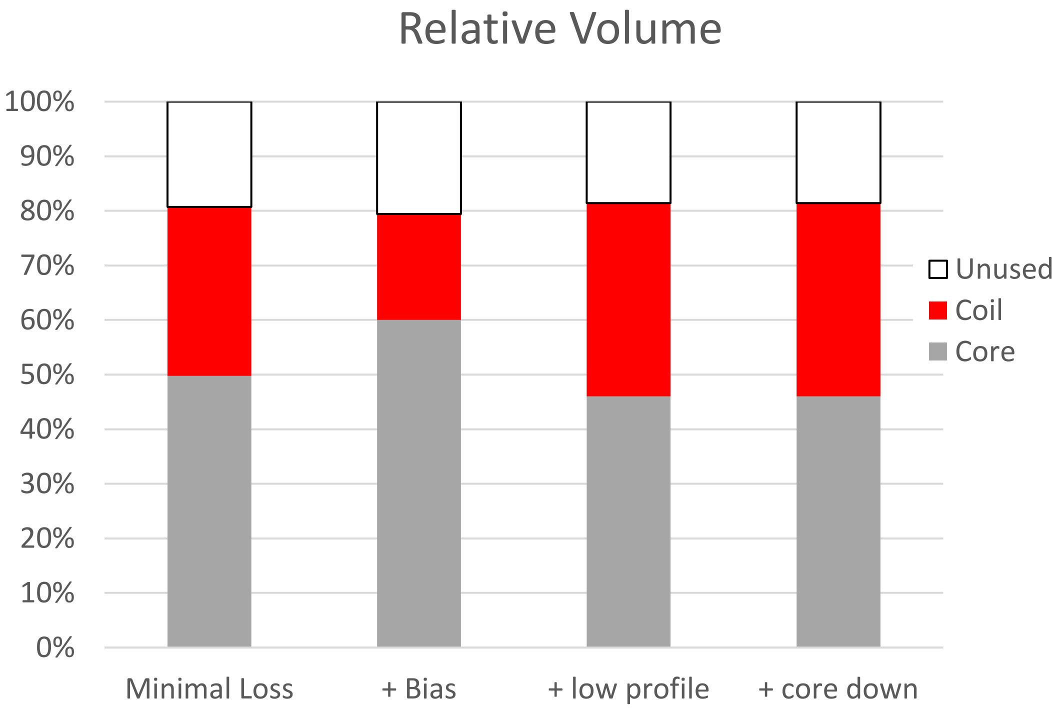
U core yields minimal loss at low profile when coil surface may be at base.

E core yields minimum loss at low profile when core is required at base.

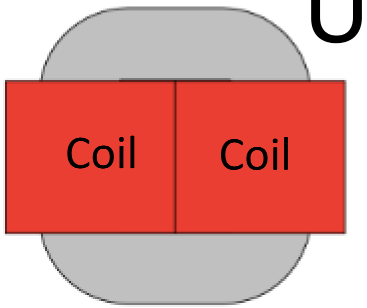
Shell Games

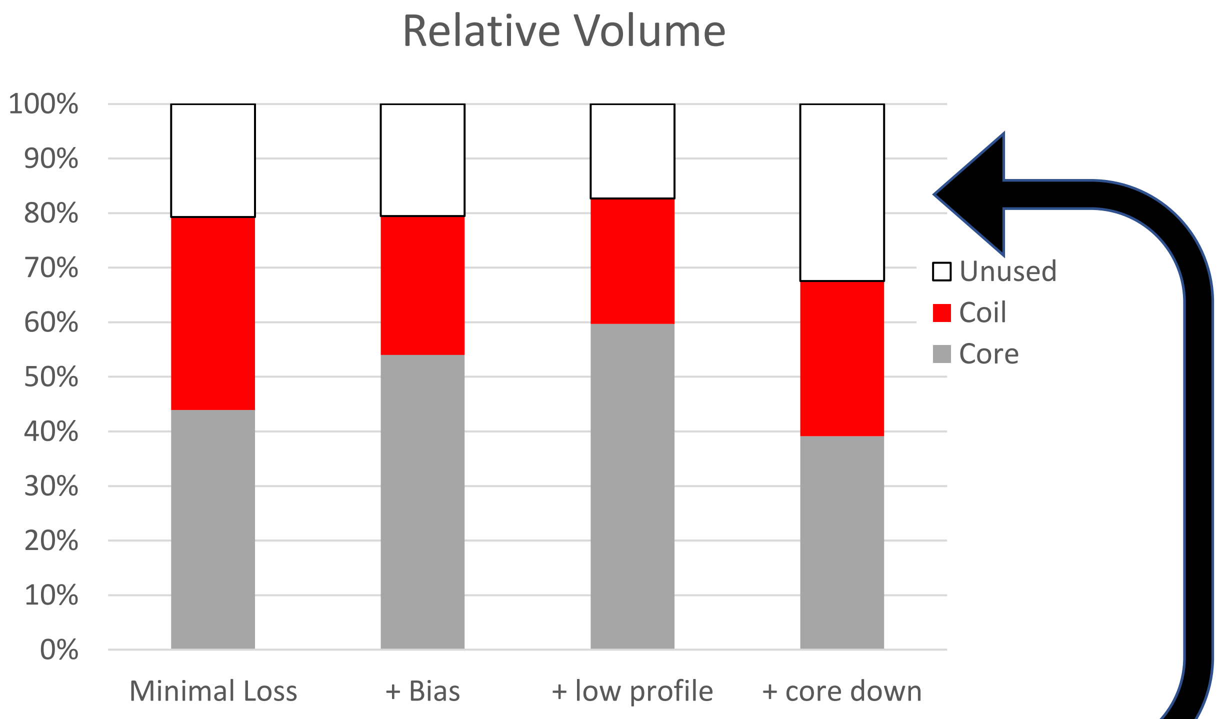
E Core type





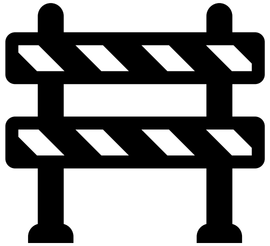
U Core type

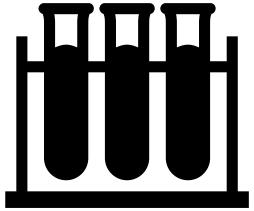


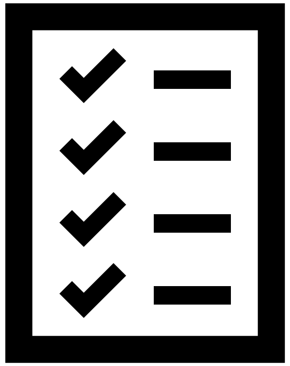


Core down increases unused volume at low profile.

What do we know about coils?





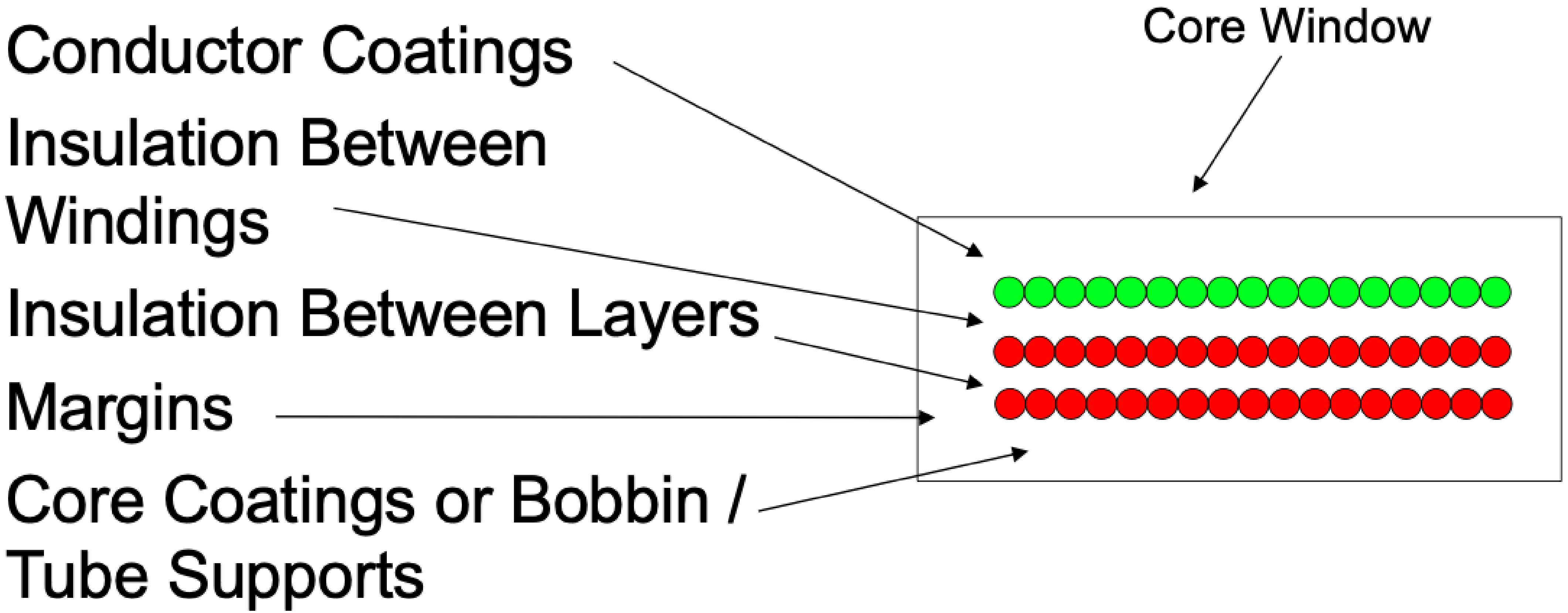


- linear – but process impacts
- insulation lowers net cross section
- often complex waveforms
- connections & packaging impacts
- wide temperature range
- reliability

So we evaluate, tradeoff …
and evaluate again …

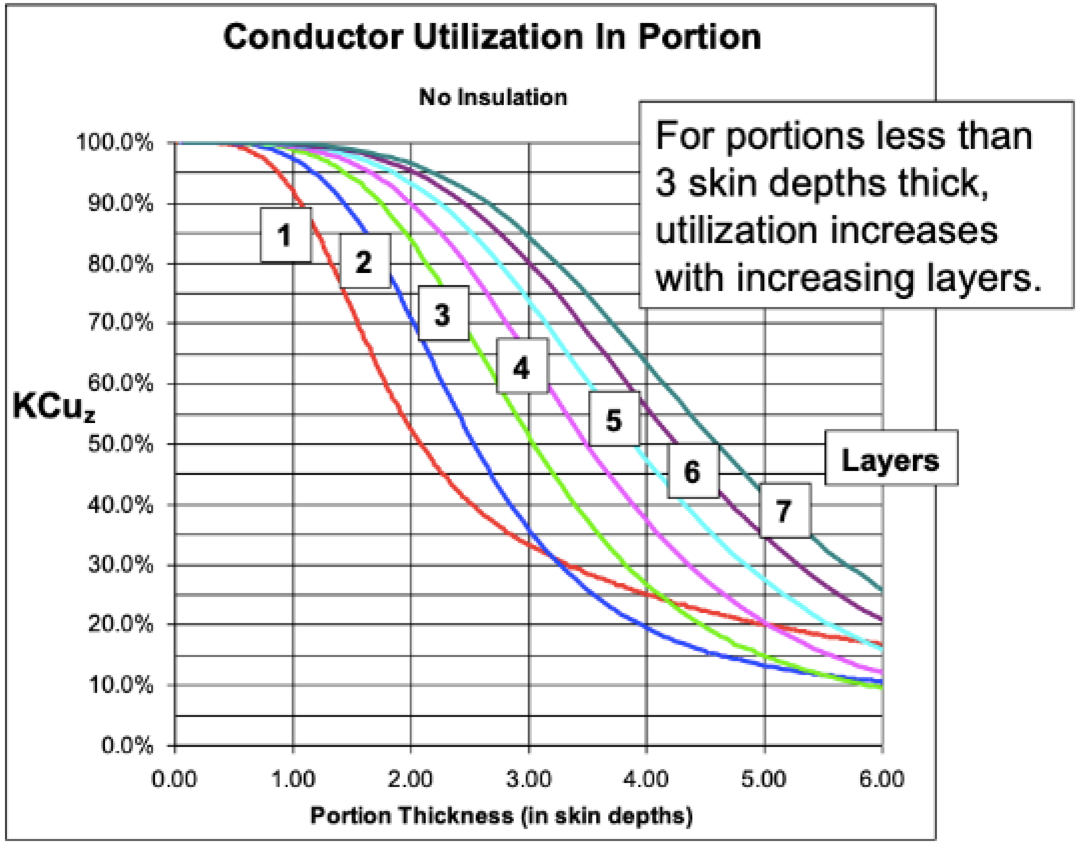
- Interleaves can increase effective utilization at high frequency
- Insulation reduces available window for conductors
- High current connections & terminals can drive total loss and design configuration
- Parallel conductors may not be effective from disparate coupling
- Normalized methods can facilitate understanding

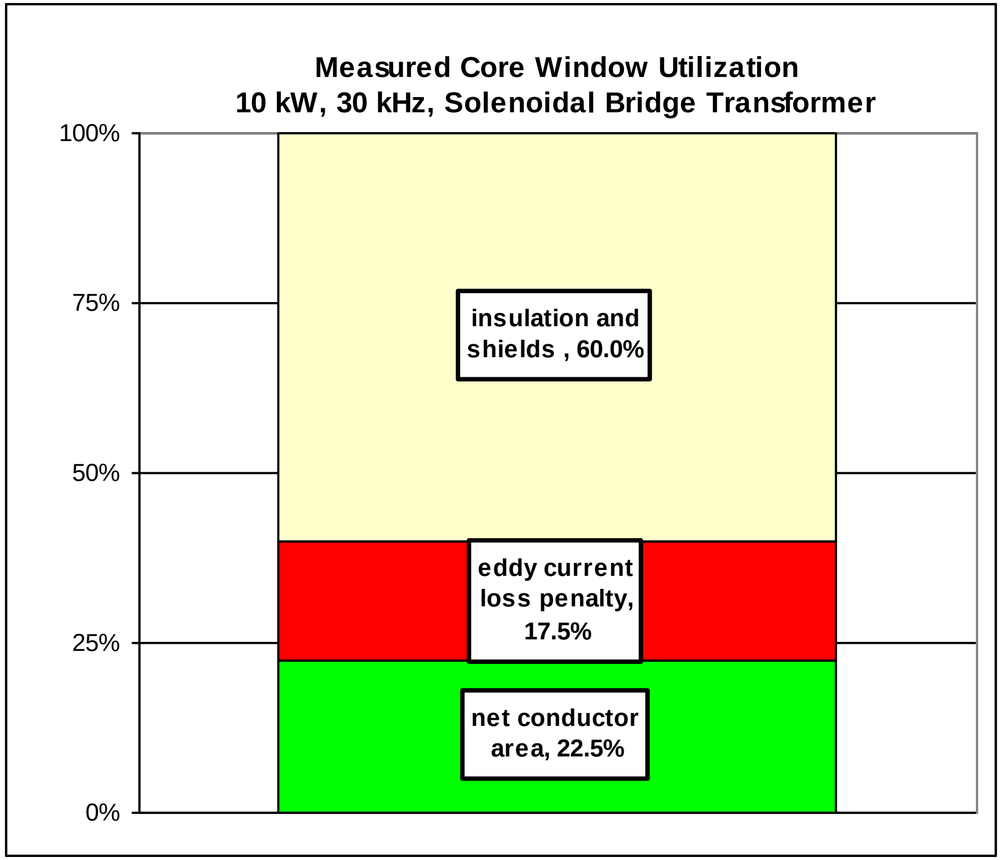
Window Utilization: Insulation Penalty



Insulation can lower utilization to less than a third of window.

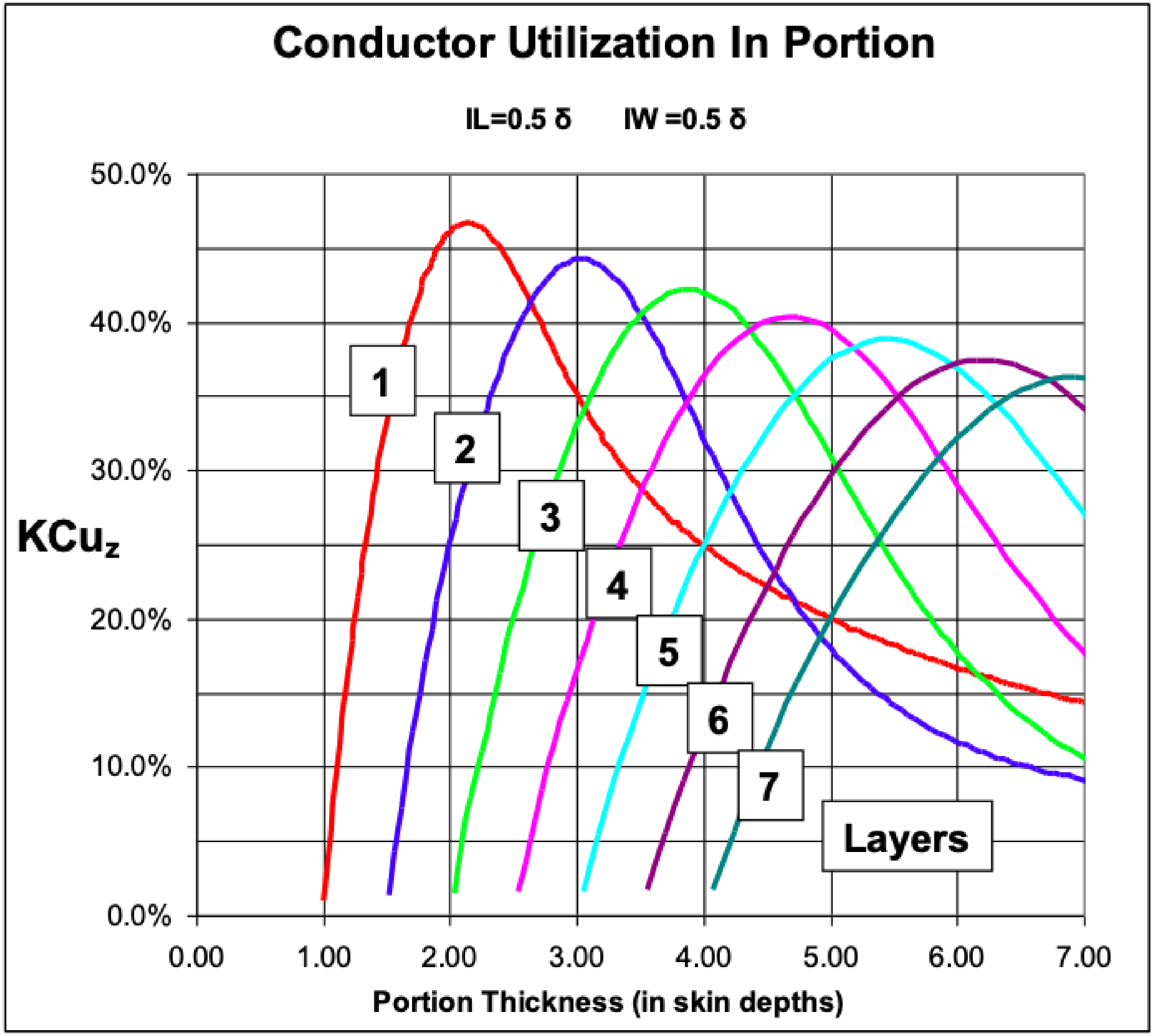
Window Utilization: Eddy Current Impact





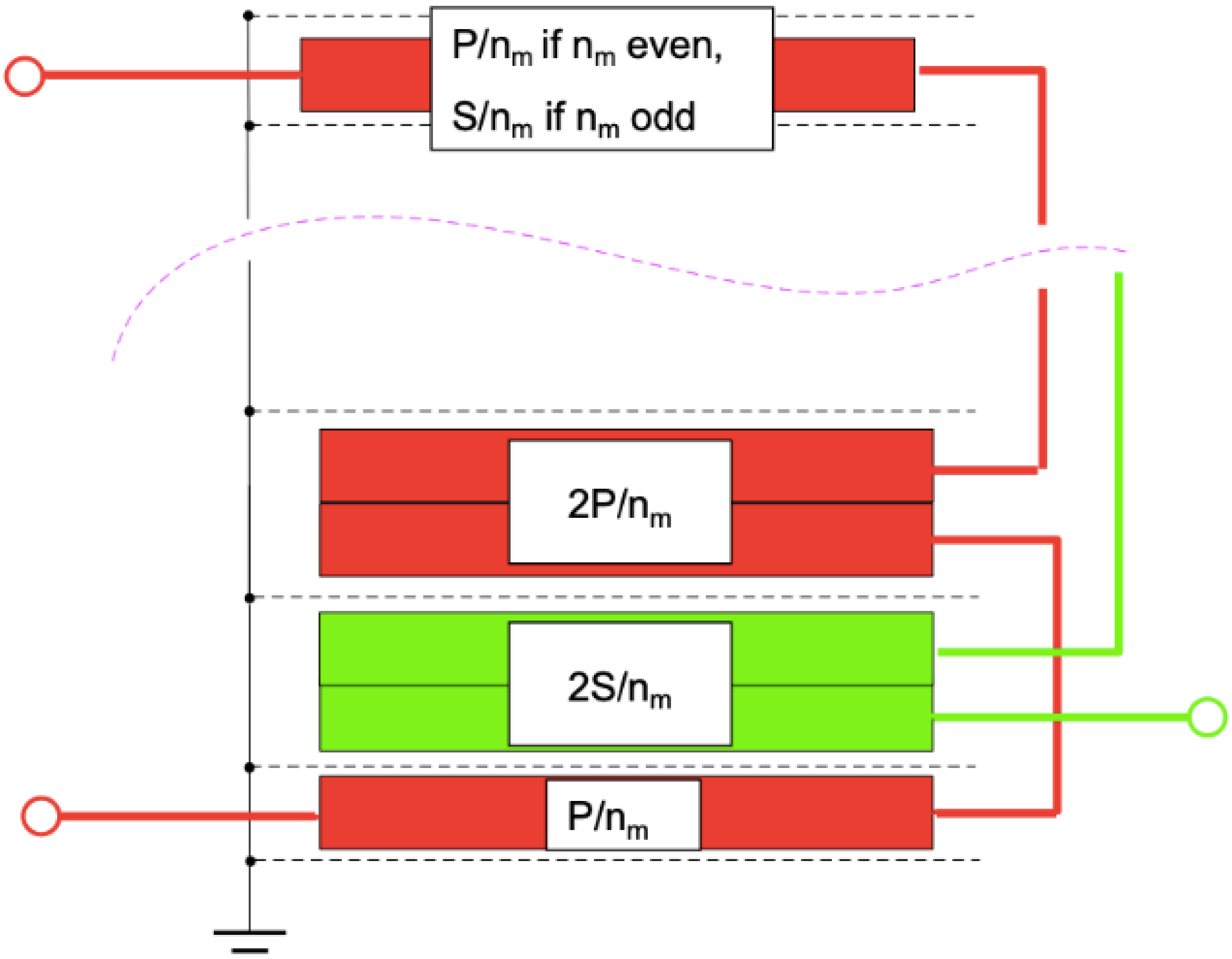
Dynamic field effects can lower utilization significantly further.
Coil loss is nonuniform, concentrated in layers at higher field strength.

Net Utilization (combined impacts)



Maximal conductor utilization is achieved with single layer portions, but large number of portions is required using multiple interleaves.

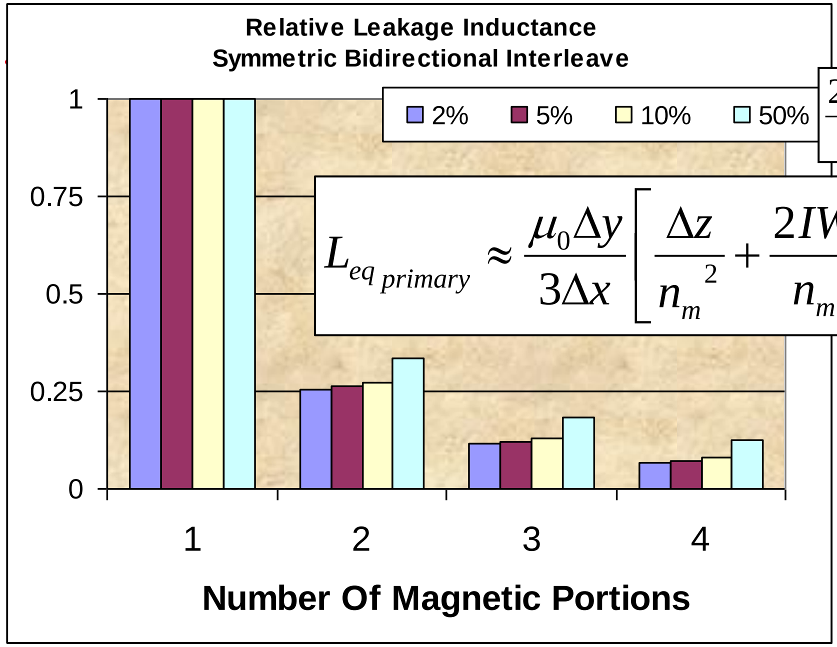
Bidirectional Interleaves



n_m	n_{ep}	n_{es}
1	1	1
2	2	1
3	2	2
4	3	2

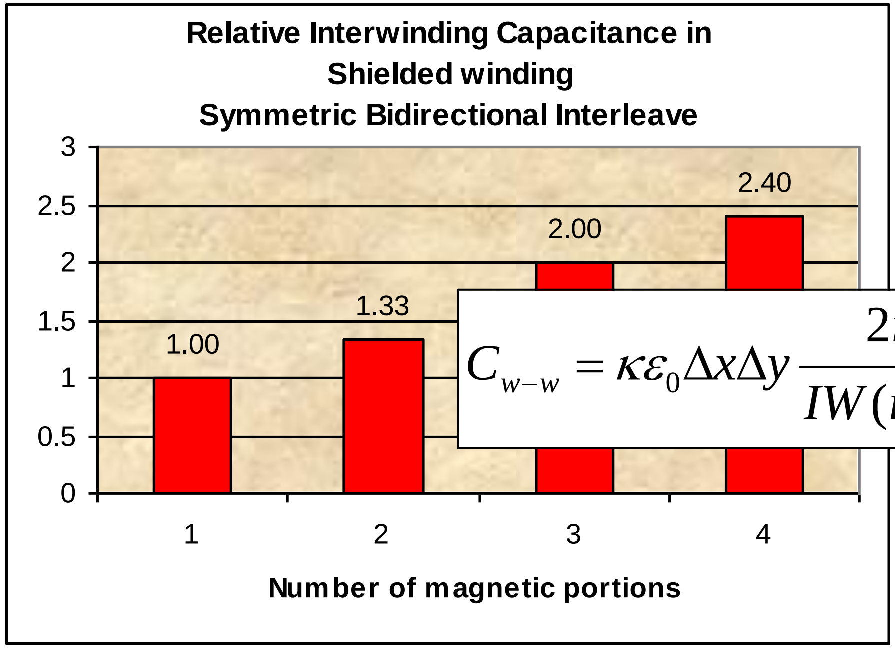
For uniform construction; Primary must have at least n_m total layers. If n_m even, secondary must have at least $n_m/2$ total layers. For n_m odd, secondary must have at least nm total layers.

Reactive Tradeoffs



$$\frac{2IW}{\Delta z}$$

$$L_{eq\ primary} \approx \frac{\mu_0 \Delta y}{3\Delta x}\left[\frac{\Delta z}{n_m^{\ 2}} + \frac{2IW}{n_m}\right] N_p^{\ 2}$$



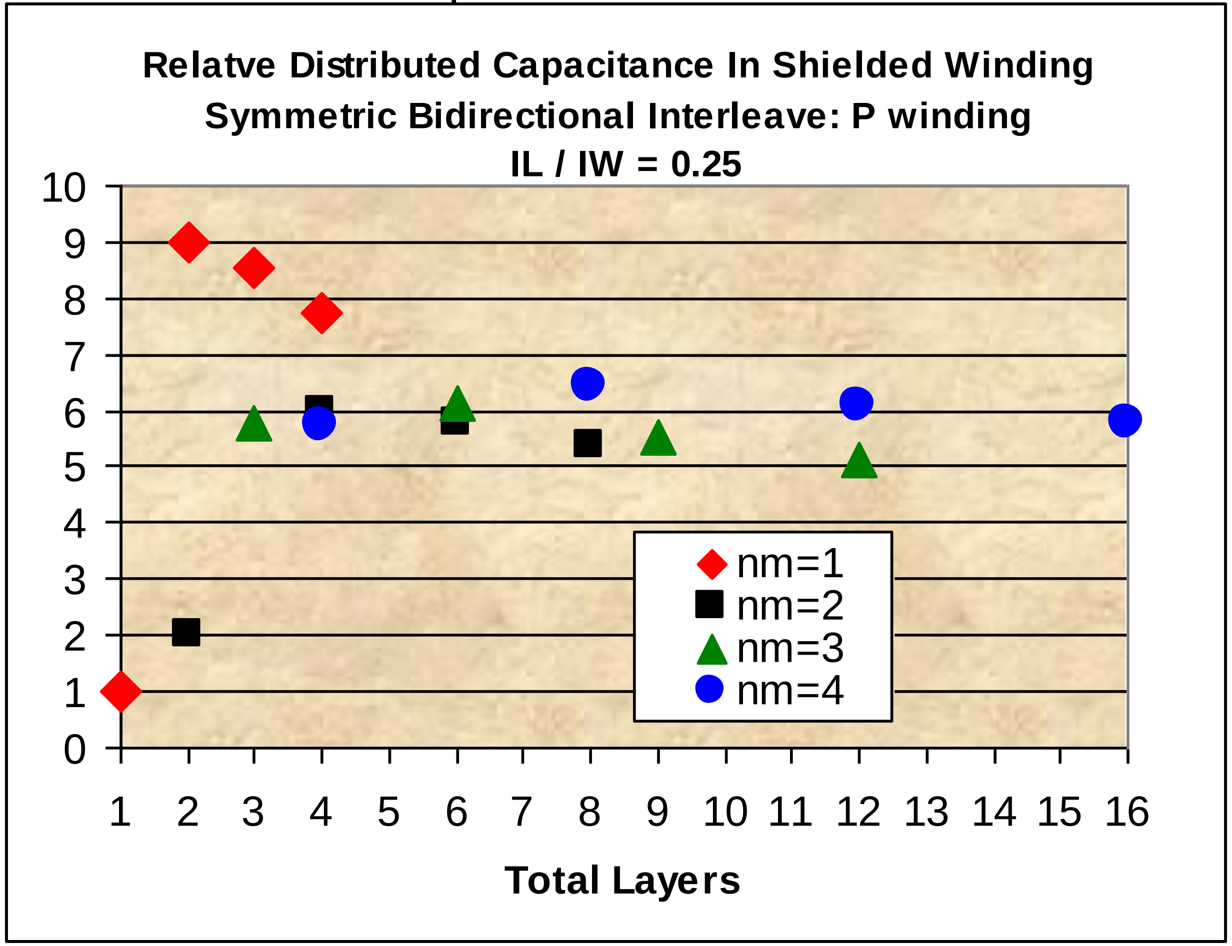
$$C_{w-w} = \kappa \varepsilon_0 \Delta x \Delta y \frac{2 n_{ep} n_{es}}{IW\left(n_{ep} + n_{es}\right)}$$

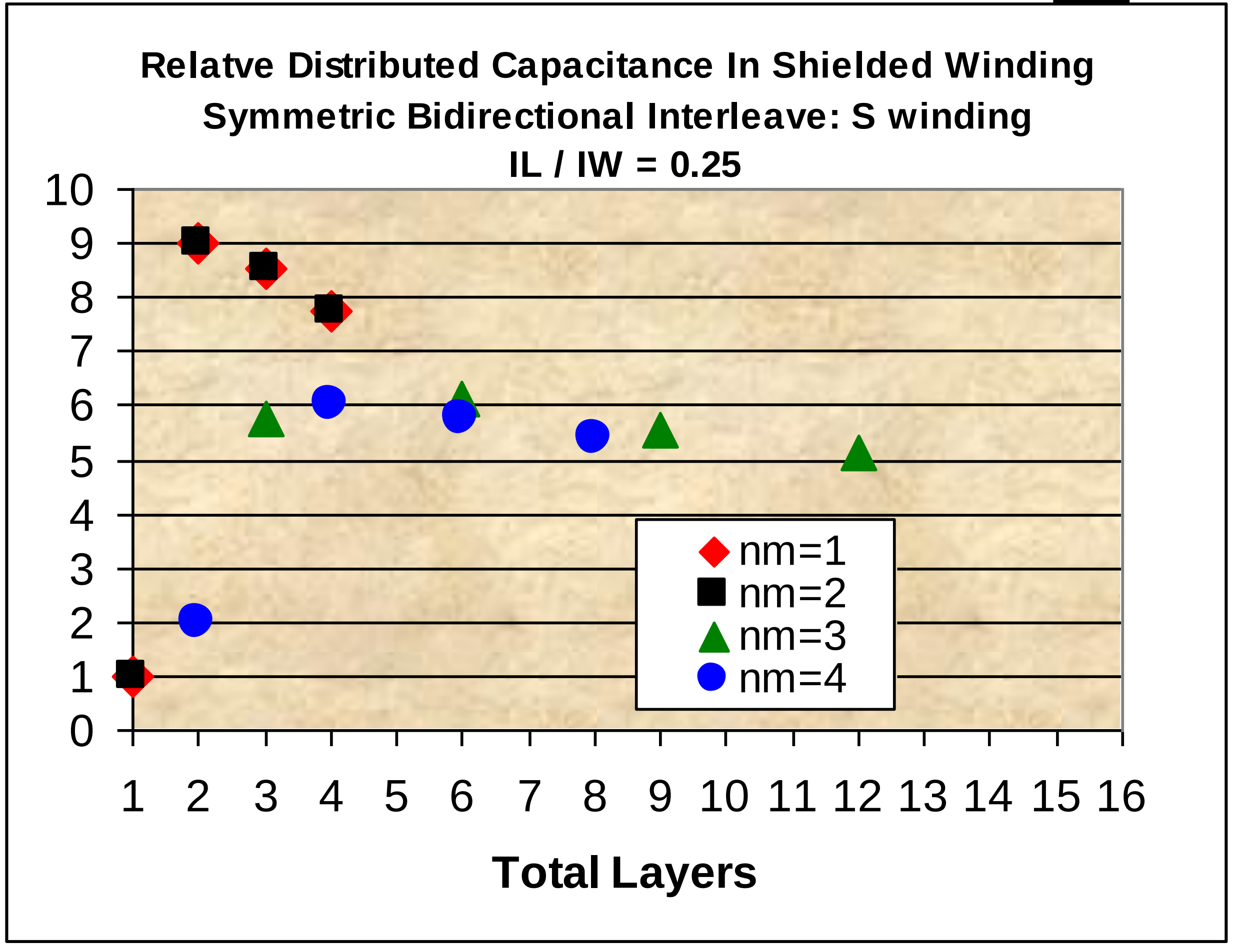
TRADEOFFS

Distributed Capacitance

inductor or capacitor?

$$Normalized\ Distributed\ Capacitance_{portion} = \frac{\kappa\varepsilon_0 \Delta x \Delta y}{6\ IW}$$

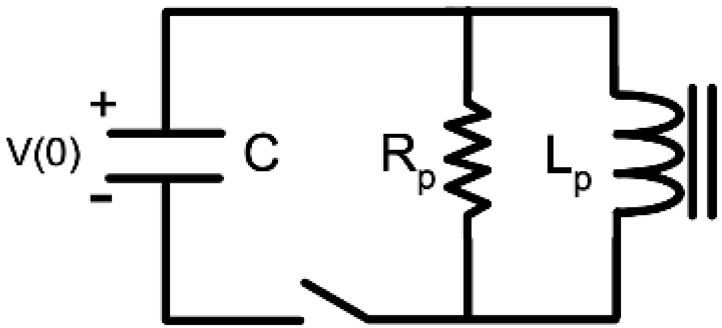




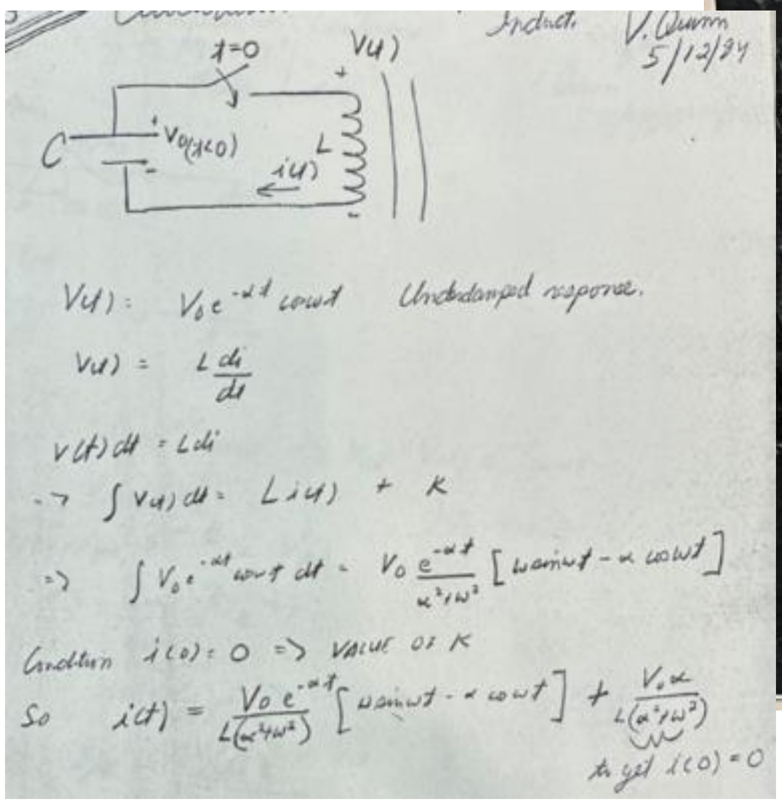
For single interleave, splitting high voltage winding into two discrete portions is beneficial to reduce total coil distributed capacitance.

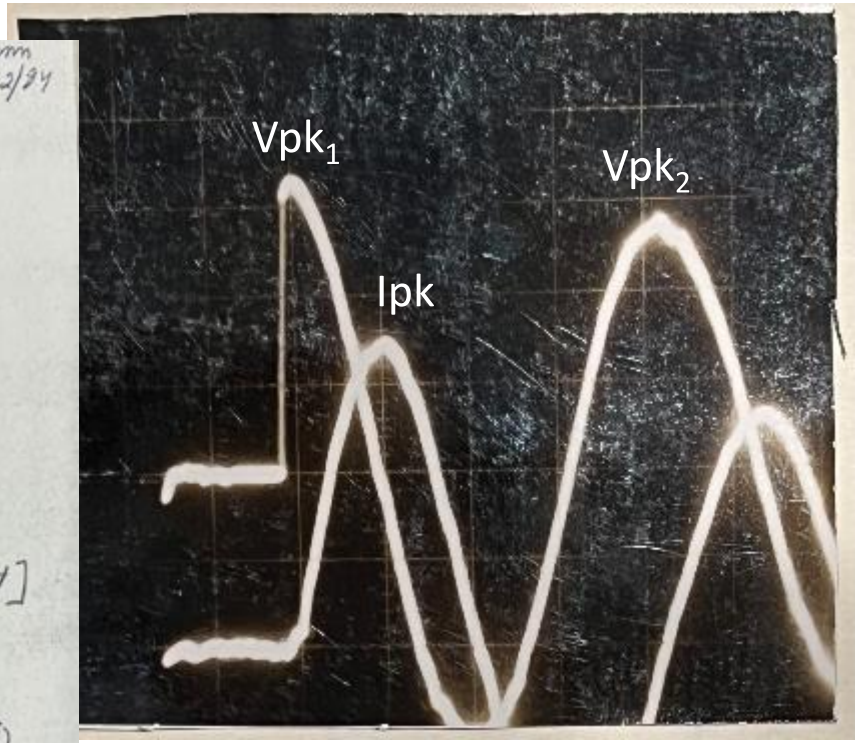
Adventures in Design

Snubber Inductor



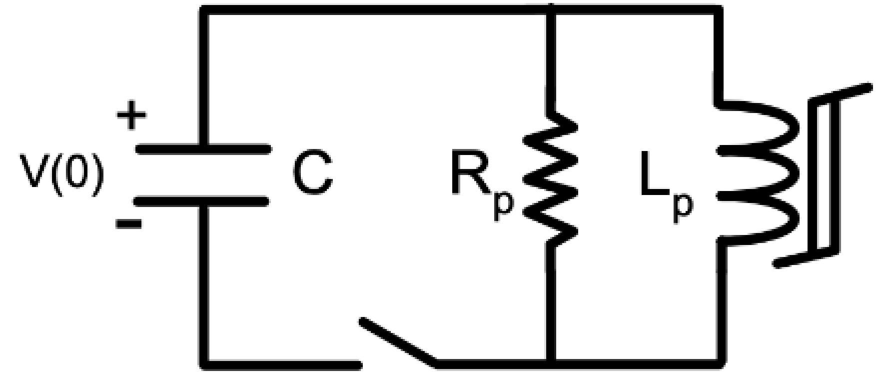
$$L = \frac{(Vpk_1)^{\frac{3}{4}}\,(Vpk_2)^{\frac{1}{4}}}{\omega\, Ipk}$$





High amplitude and high frequency can be achieved using resonant methods.

High Energy Inductor

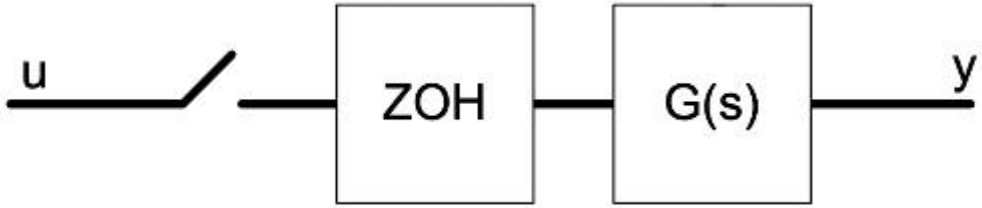


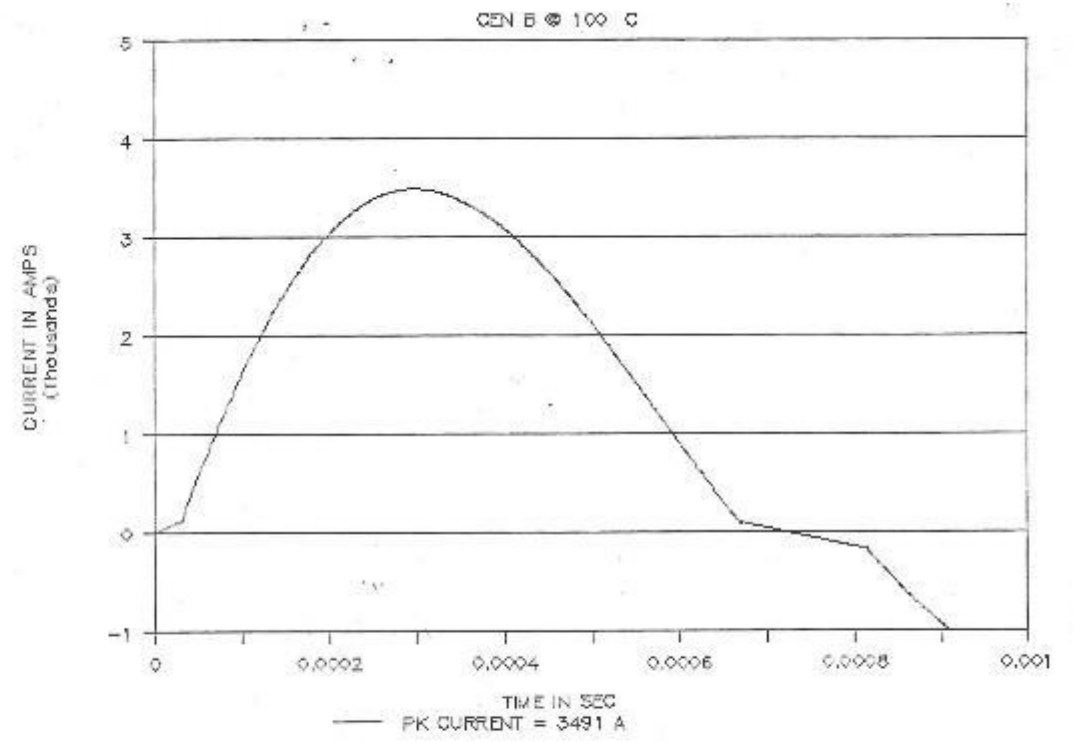
150 J capacitor discharge

$$\dot{x} = Ax + Bu$$

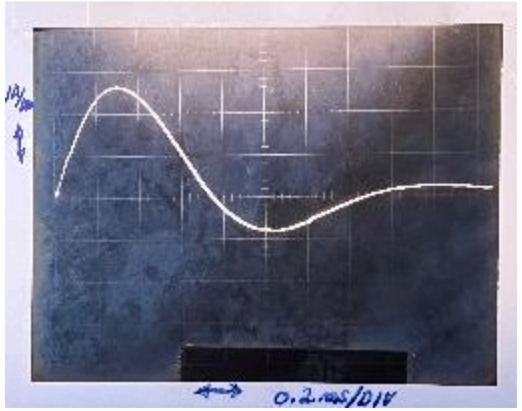
$$y = Cx + Du$$

$$G(s) = C(sI - A)^{-1}B + D$$



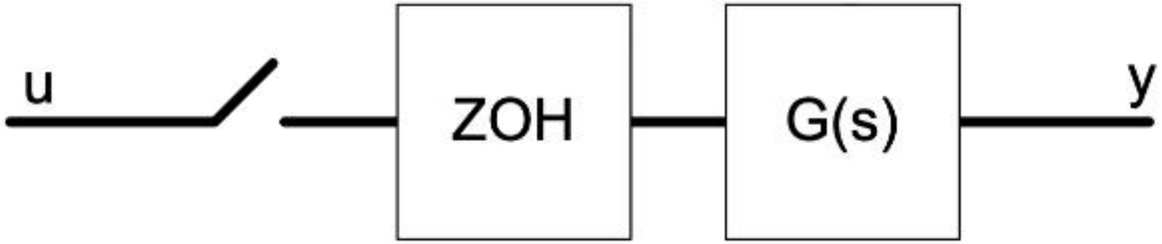


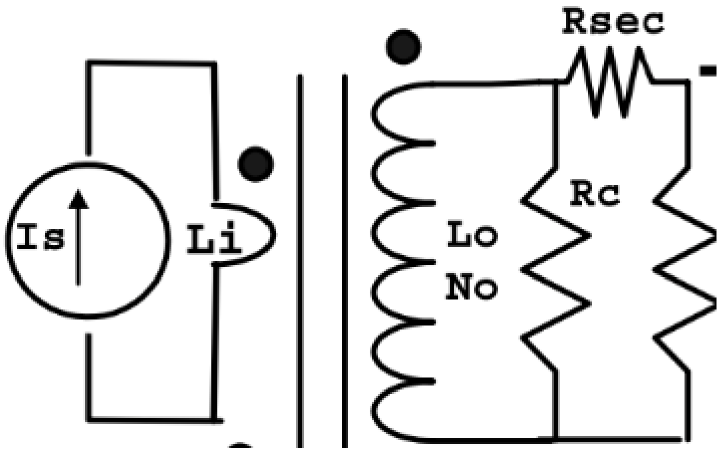
$$x(k+1) = F\,x(k) + G\,u(k)$$

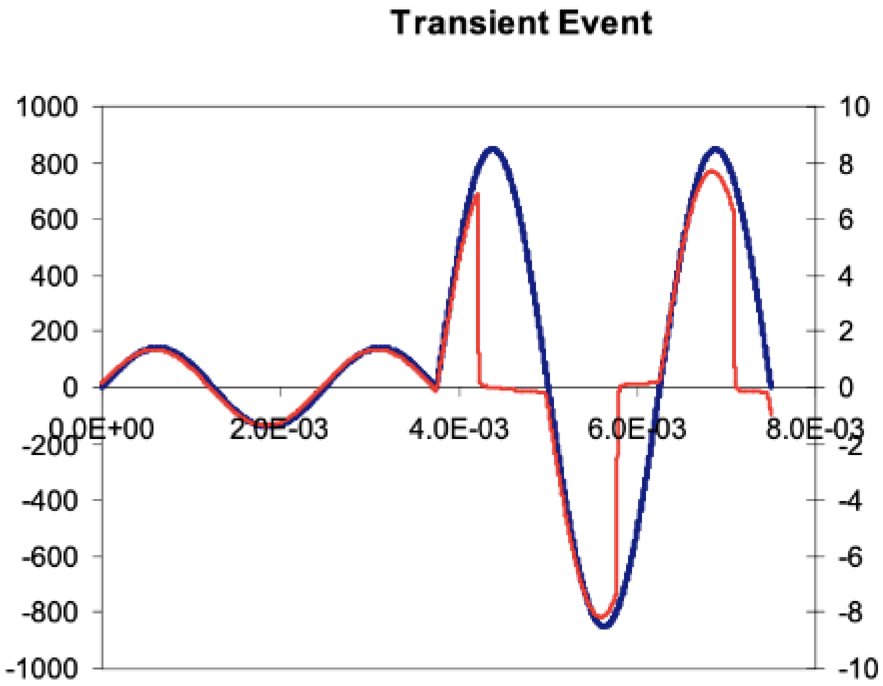


State equations with ZOH can simulate nonlinearity.

Saturating Current Transformer

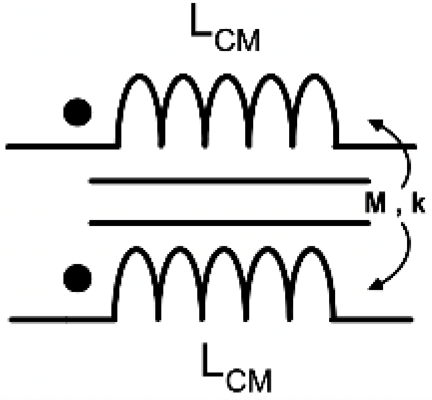






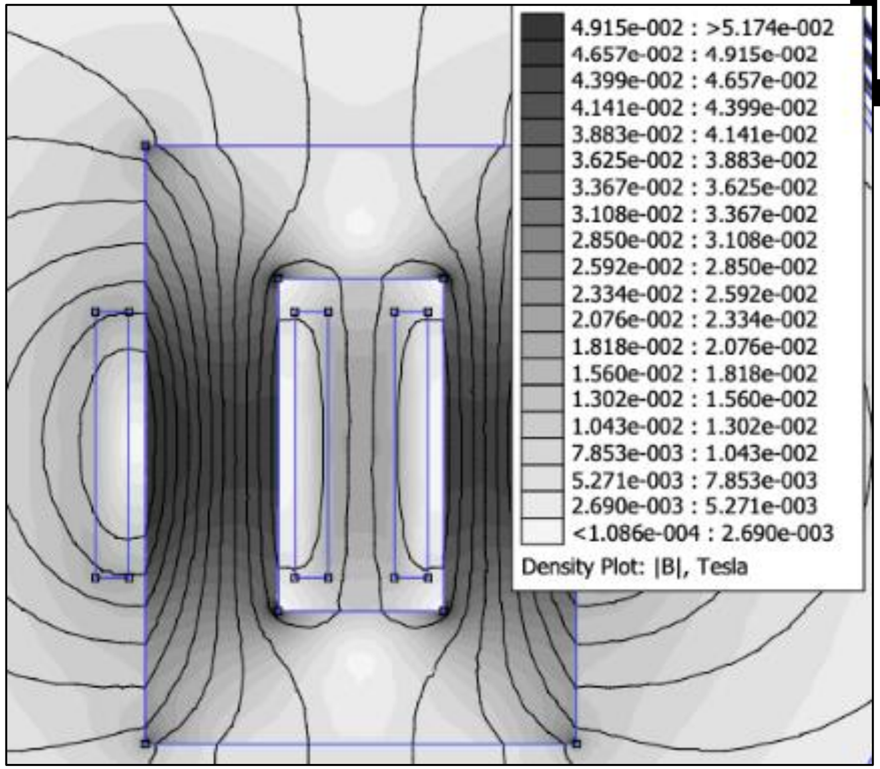
Transient forcing functions can be considered and incorporated into custom design method.

DM Problems with CM Inductor



$$L_{DM} = (1-k)2L_{CM}$$

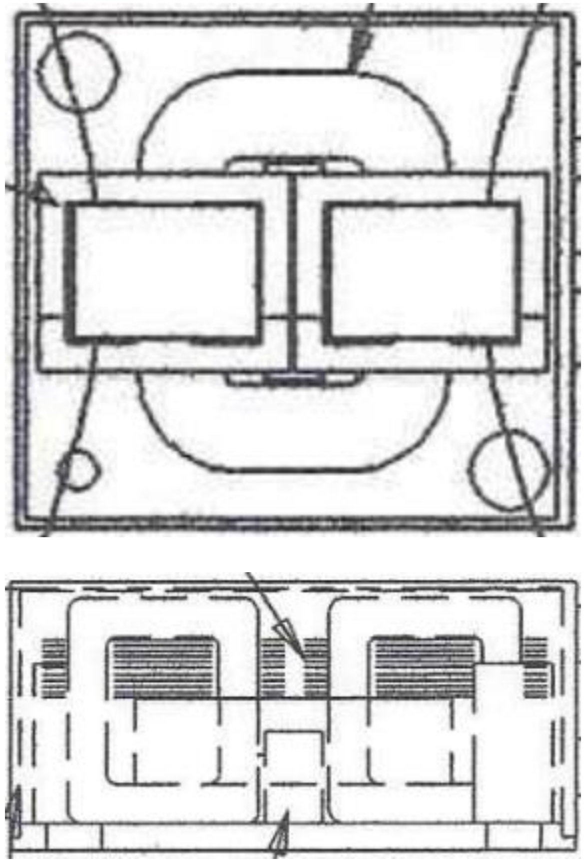
$$k \sim 96.8\%$$

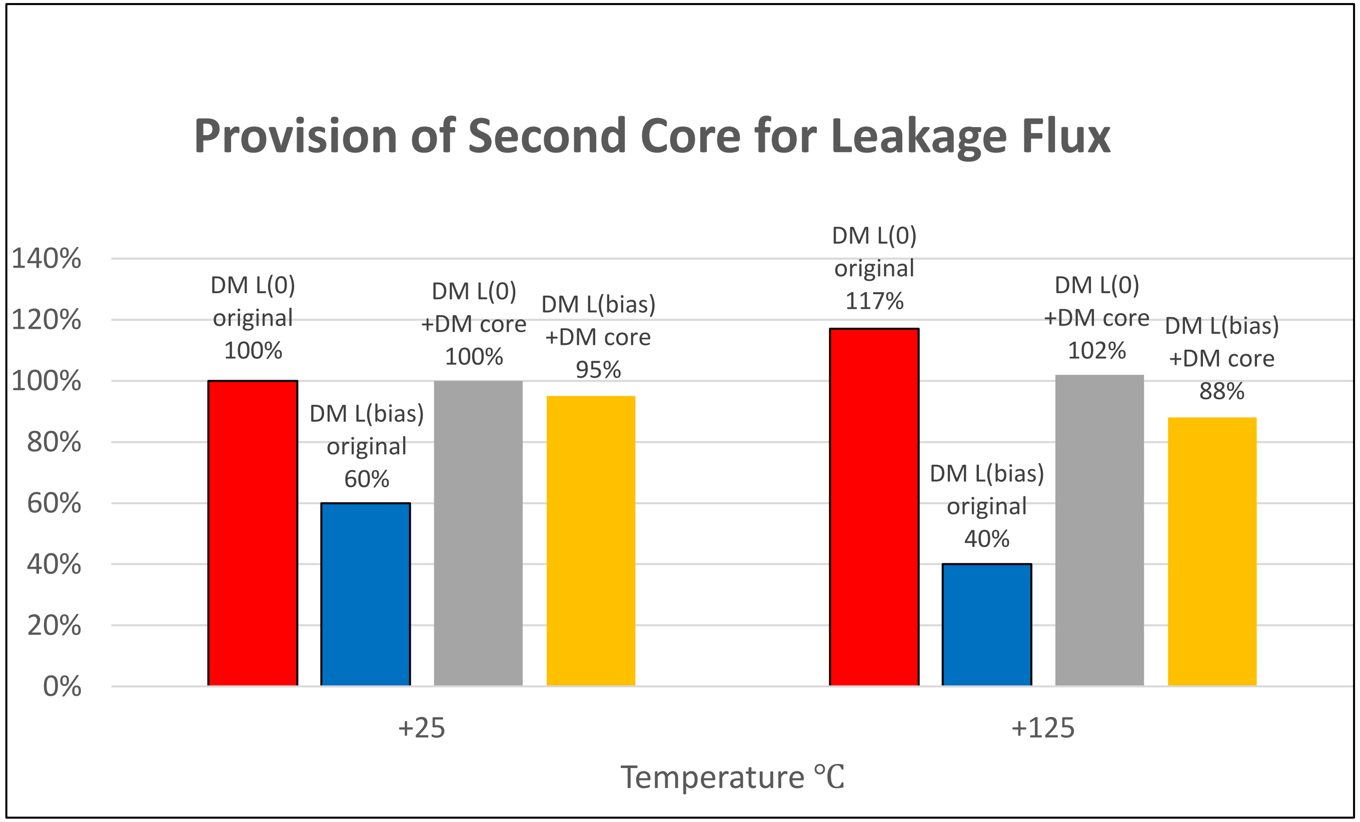


- DC Leakage Flux
  - Intercepts ferrite CM core
  - Polarizing CM core and reducing effective permeability for DM flux especially at high temperature

Add laminated core to enhance leakage flux with improved control.

Consistent DM Inductance

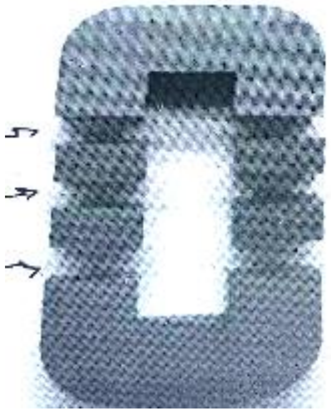


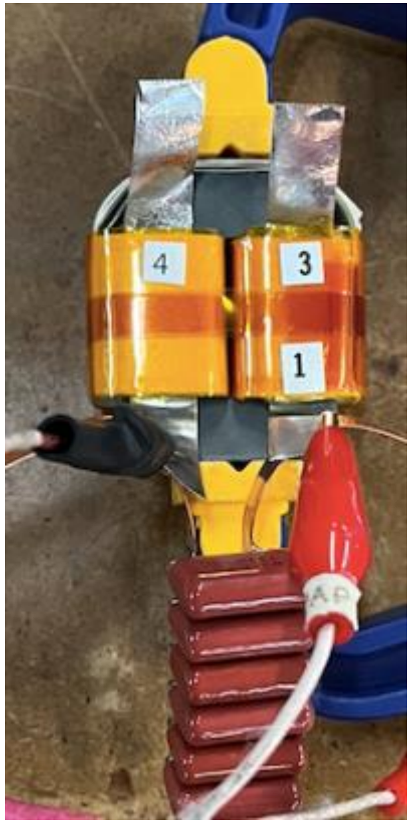


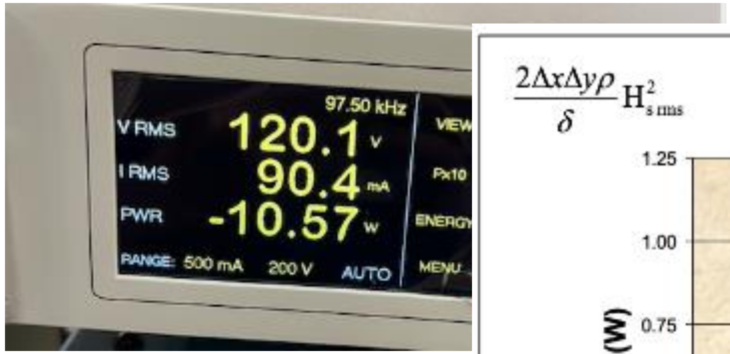
Added core enables controlled DM inductance.

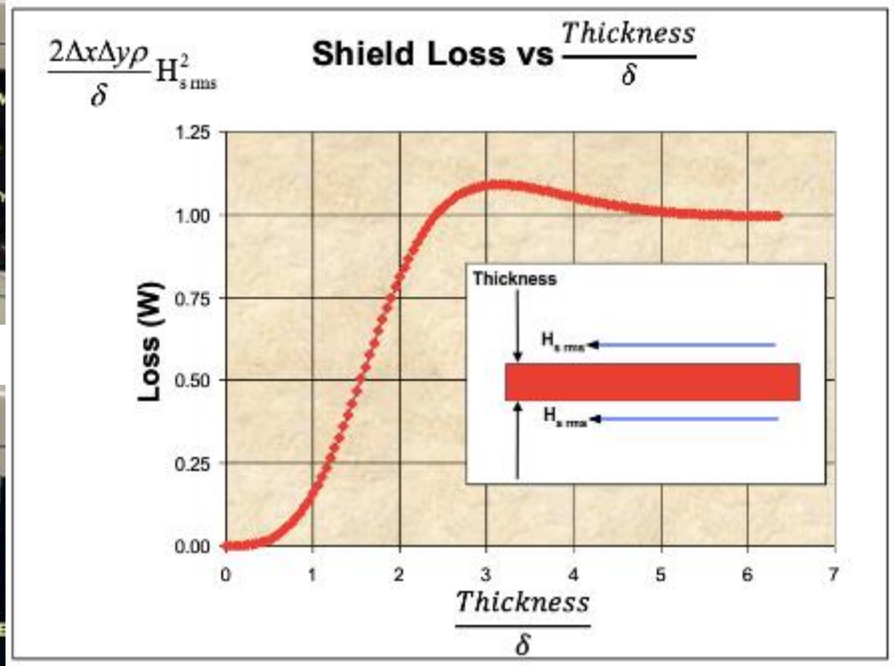
Improved design achieves DM inductance at bias current over temperature.

Distributed Gap Control







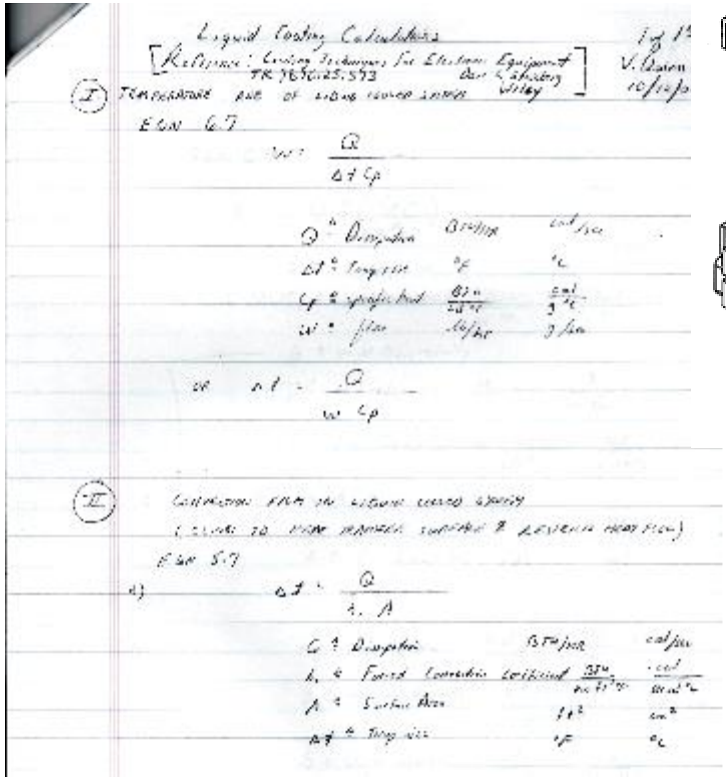


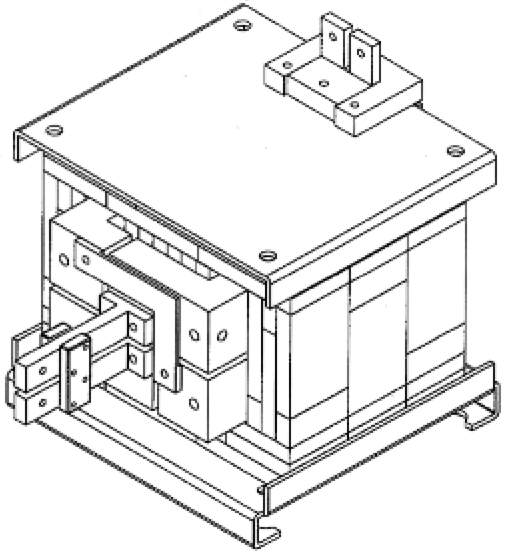
High amplitude testing successfully controls gapping process results.

High Voltage, High Frequency, High Power (Short Sheets with Acute Edges)

High Voltage

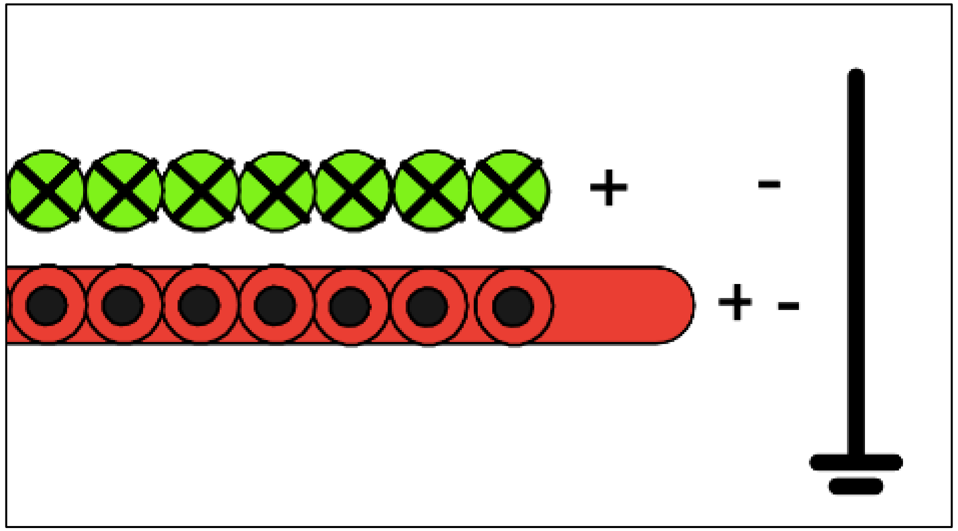
- Electric field control
- Dielectric uniformity
- Void reduction
- Crack reduction
- Interwinding & Intrawinding Test Methods





Successful custom magnetics design requires understanding in diverse technical fields.

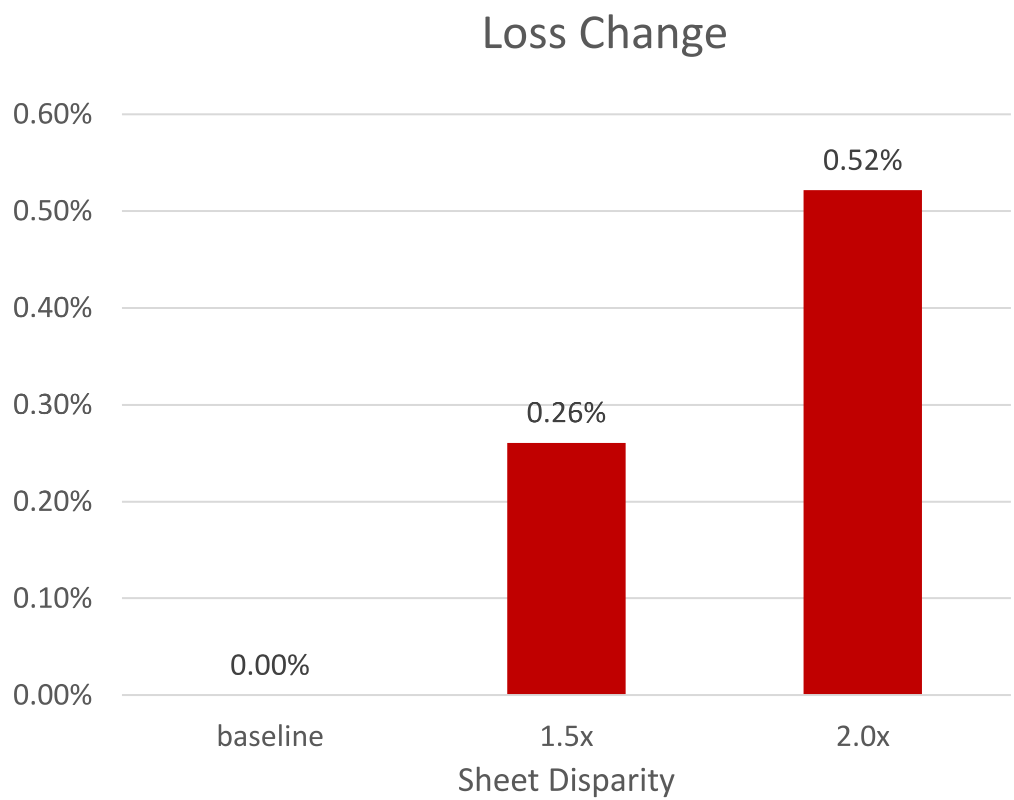
Acute Edge

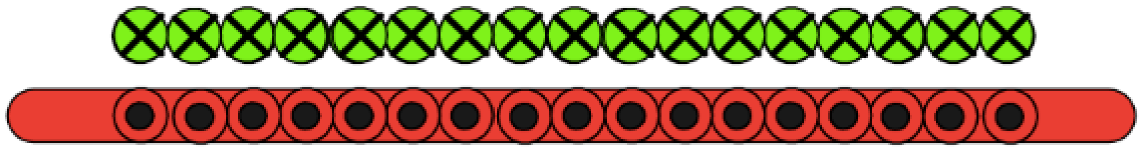


edge radius mils	5
clearance mils	50
Approximate Field Enhancement Factors:	
sphere & plane	9.90
cylinder & plane	3.76
adjacent cylinders	2.51

Thin conductors as preferred for high frequency current cause significant electric field enhancement at sheet edges.

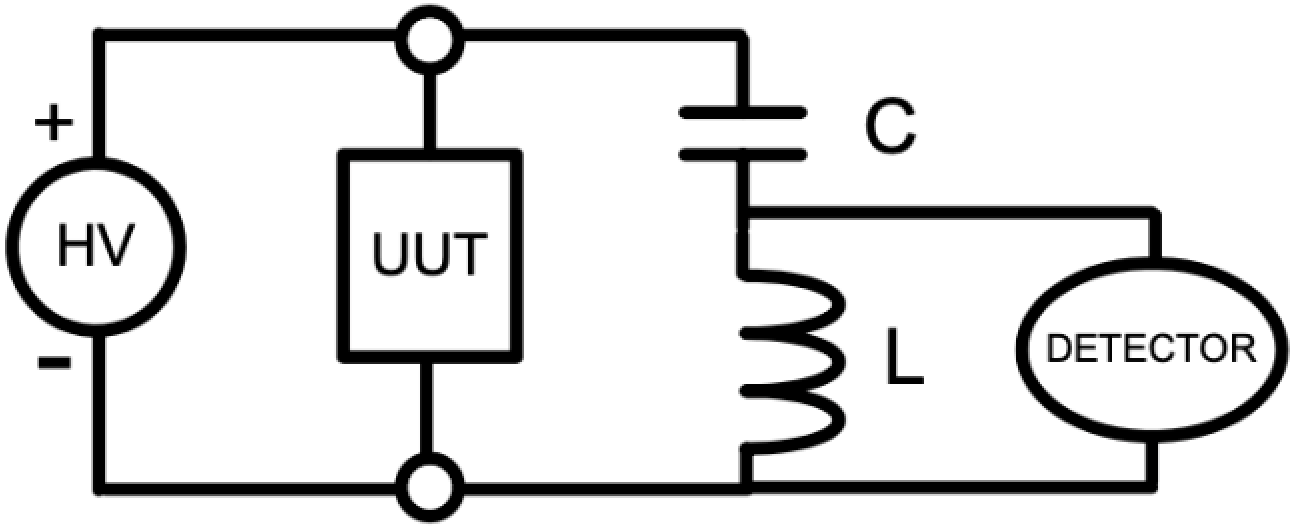
Short Sheet





Disparate wider sheet provides negligible loss reduction benefit.

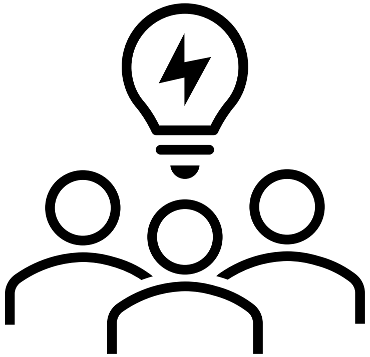
Partial Discharge Test Methods

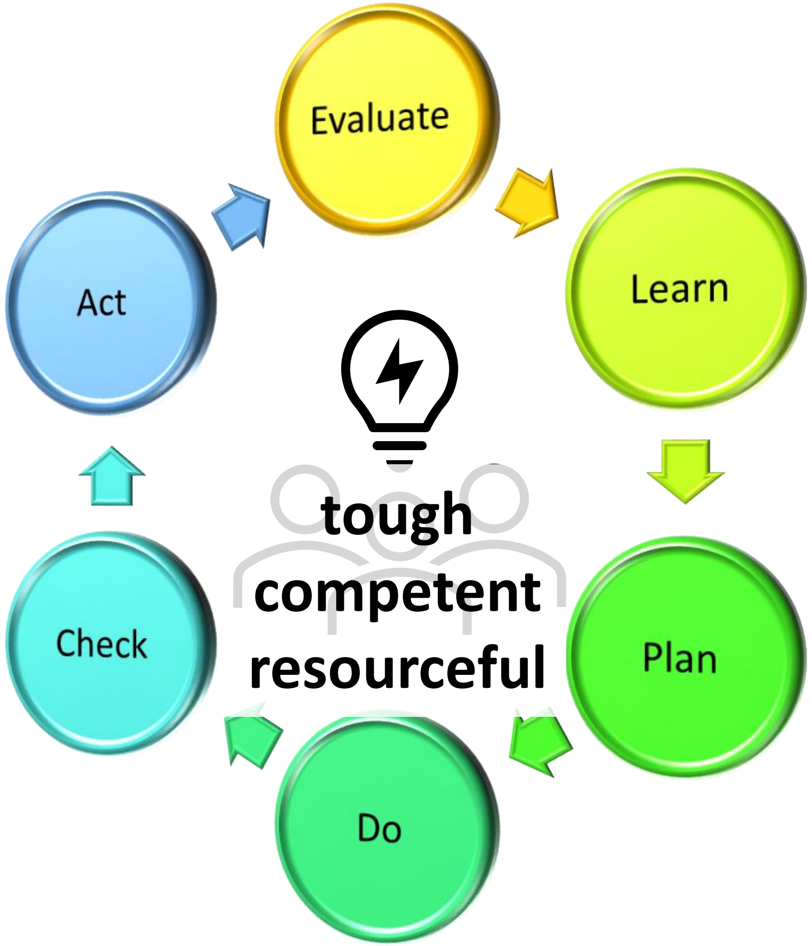


Custom Partial Discharge equipment is needed for HV intrawinding test condition.

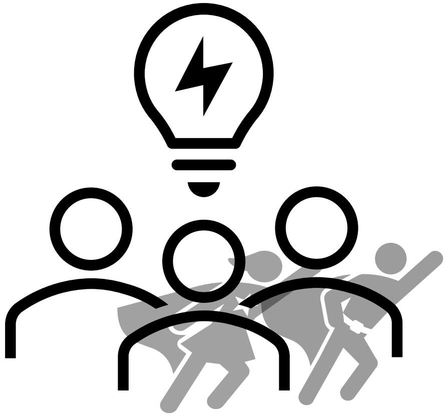
We celebrate …

- Technology advancement
  - we don't know what we don't know
- Limited resources
  - we can't do everything we wish to do





For the love of Custom Magnetics …
The story continues …



Reference and Recognition

https://www.psma.com/publications

With sincere and deep appreciation for James J. Carey who took a risk and gave a fledgling Physics graduate an opportunity to become a magnetics design engineer … mentoring me along a path to merge academic theory with practical measurement.