« Mystery Losses » In Multi Air Gap (MAG) Inductor & Quantification By Means Of Advanced Thermometry

PSMA Workshop - Power Magnetics @ High Frequency
San Antonio, March 3, 2018

Dominik Neumayr
Power Electronic Systems Laboratory
ETH Zurich

ETH zürich

« Mystery Losses » In Multi Air Gap (MAG) Inductor & Quantification By Means Of Advanced Thermometry

PSMA Workshop - Power Magnetics @ High Frequency
San Antonio, March 3, 2018

D. Neumayr, D. Bortis, J. W. Kolar
Power Electronic Systems Laboratory
ETH Zurich

Outline

Introduction — 2 slides
Origin Of Losses in MAG Inductor — 9 slides
Electrical Surface Loss Measurement — 3 slides
Thermometric Surface Loss Measurement — 9 slides
Experimental Results — 3 slides
Conclusion & Outlook — 2 slides

Introduction | *Multi Air Gap (MAG) Inductor*

▶ High Frequency MAG Inductor – Application Details

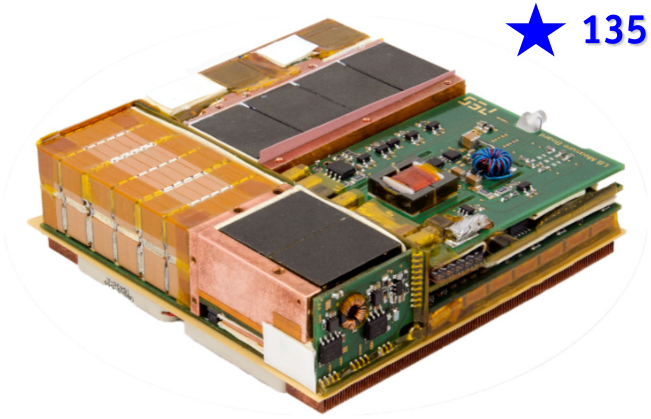
■ Google Little Box – 2kW 1-Φ PV Inverter

- 135 W/in³ (8.2 kW/dm³)
- 96.3% Efficiency @ 2kW / 95 % CEC Efficiency

- Active Power Buffer (Smart Capacitor)

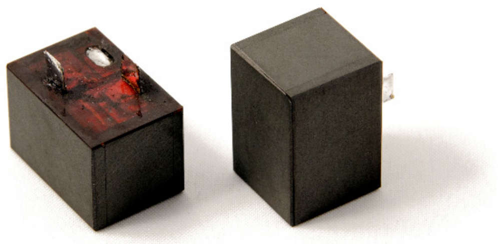
- Triangular Current Mode Modulation
- Switching Frequency: 230 kHz – 1 MHz

- Min./Max. Pk-Pk Ripple: 8 A / 30 A
- I_{pk} = 25 A

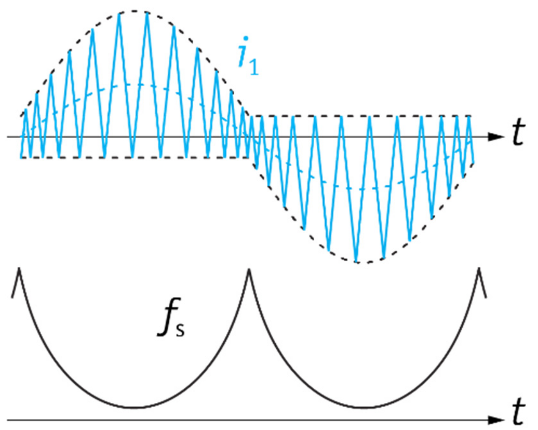


★ 135 W/in³

▲ Dimensions – 8.9cm x 8.8cm x 3.1cm



▲ High Frequency MAG Inductor
Dimensions – 14.5 x 14.5 x 22 mm³

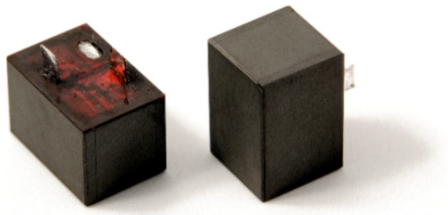


▲ Inductor Current and Frequency Variation of TCM

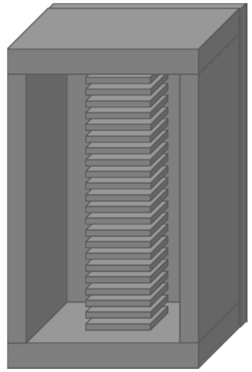
▶ High Frequency MAG Inductor – Construction Details

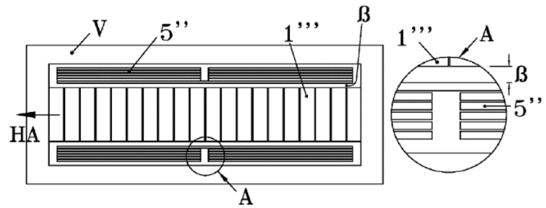
- Multi-Airgap Inductor with Multi-Layer Foil Winding Arrangement Minim. Prox. Effect
- Very High Filling Factor / Low High Frequency Losses
- Magnetically Shielded Construction Minimizing EMI
- Intellectual Property of F. Zajc / Fraza

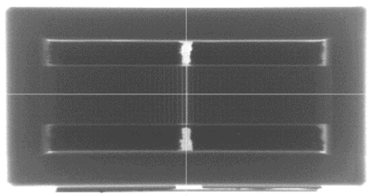
    - L = 10.5 µH
    - 20 µm Copper Foils / 4 Parallel / 2 x 8 Turns
    - 25 Stacked 0.6mm Thick Ferrite Plates
    - 80 µm Air Gap Between Plates
    - DMR51 Core Material (Similar to N59 and 3F4)
    - Terminals in No-Leakage Flux Area
    - 20mΩ Winding Resistance / Q≈600



▲ Dimensions – 14.5 x 14.5 x 22 mm^3





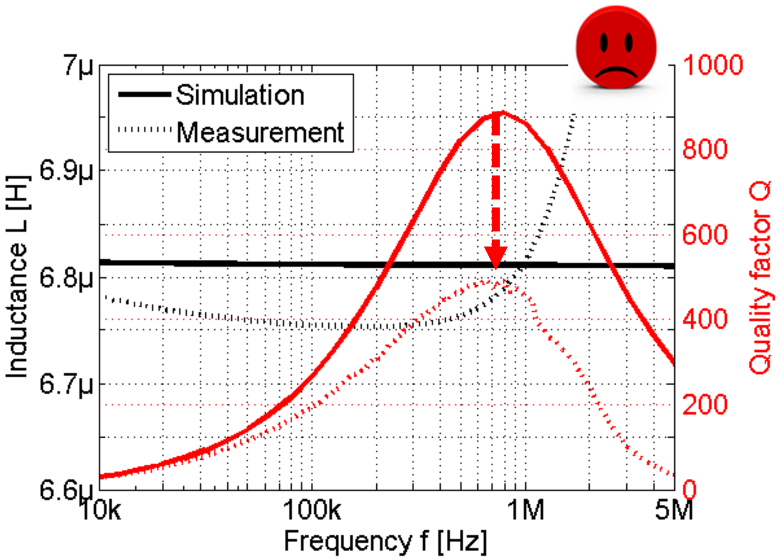


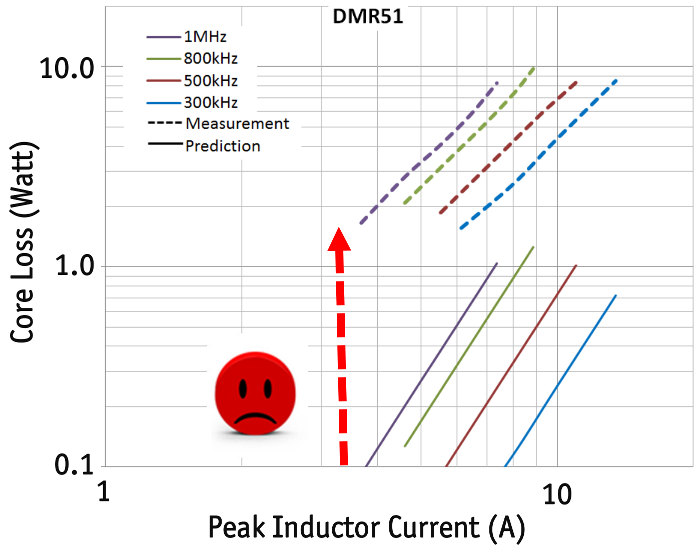
- Literature: Prof. Sullivan [1-2], F. Zajc [3-4]

▶ High Frequency MAG Inductor – Mystery Losses

- **Power Loss of HF Inductor Sign. Higher Then Anticipated**
  - Exp. Testing of 7 μH Prelim. Inductor Design
  - 50 x 0.3 mm Thick Stacked Plates

- **Up To A Factor 10 Higher Core Loss (!)**





* Measurement Results From Fraunhofer IZM

Origin of “Mystery Losses” in MAG Inductor

Assembly Imperfections

Mech. Tolerances

Abrasive Machining

▶ "Mystery Losses" in MAG Inductor

(A) Mech. Tolerance & Assembly Imperfections Causes Flux Crowding

(B) Residual Pressure Applied to Ferrite as a Consequence of Assembly / Construction

(C) Mech. Stress Induced During Abrasive Machining of Ferrite

→ Ferrite Prop. Altered in Surface Layer
→ Excess Loss in MAG Structure (Core Composed of Thin Plates)

▶ Main Focus of Today's Talk: Quantification of Surface Loss in MnZn Ferrite

- **Exp. Results Obtained For FERROXCUBE's 3F4 Ferrite (μ_i = 900, 1 -2 MHz, B_s = 350 mT)**

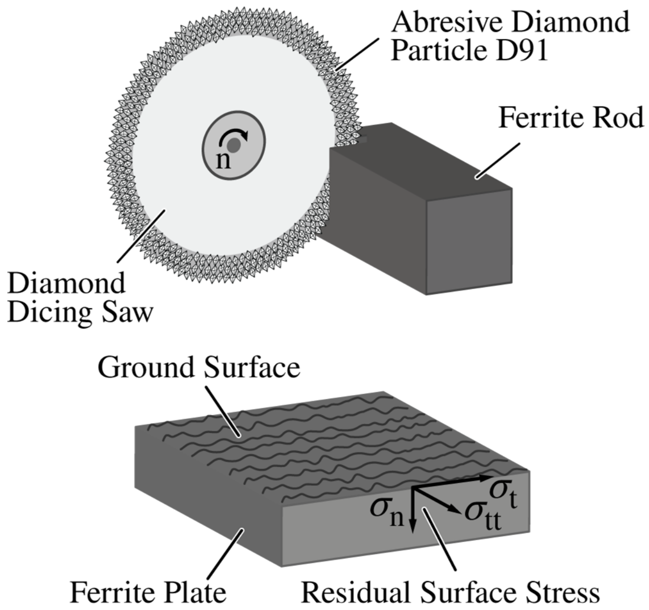
Origin of “Mystery Losses” in MAG Inductor

Increase In Magnetic Loss Caused By Machining Of Ferrite

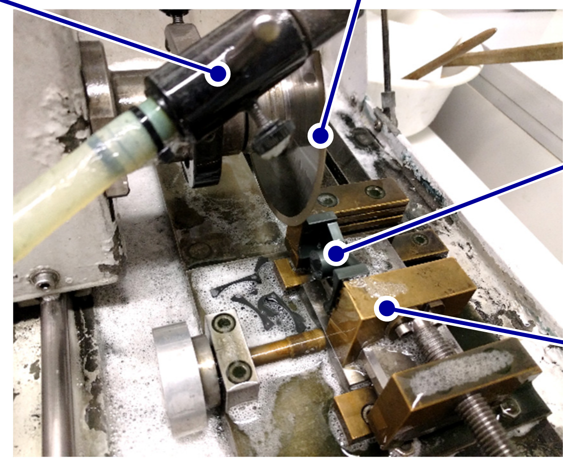
▶ Hypothesis - Increase In Magnetic Loss Caused By Machining Of Ferrite

■ Cutting of Thin Plates From Ferrite Rod W/ Diamond Saw

- Abrasive Machining Introduces Mech. Stress in Surface
- Ferrite Properties in Surface Altered → Increase of Loss Factor



▲ Dimension Of Specimen: **7 mm x 6.4 mm x 1 mm**

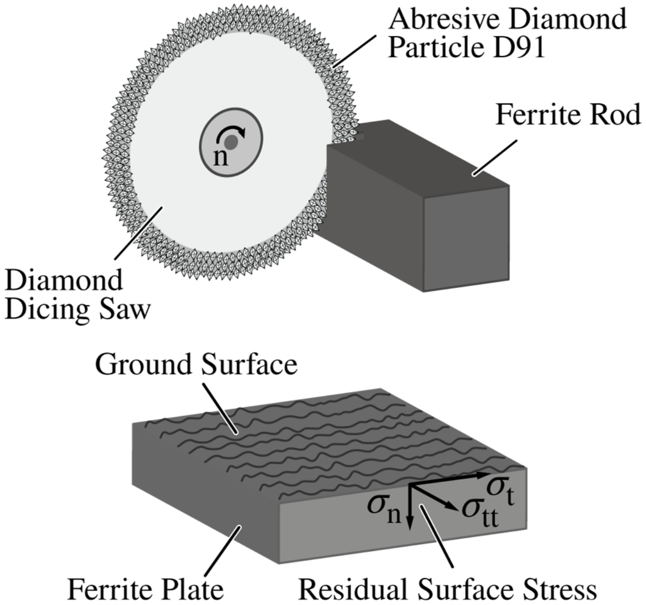


▲ Linear Precision Saw With Diamond Blade.
Blade: Ø 125 x 0.60 x 12.7 mm,
Settings: 5000 RPM, Manual Feed

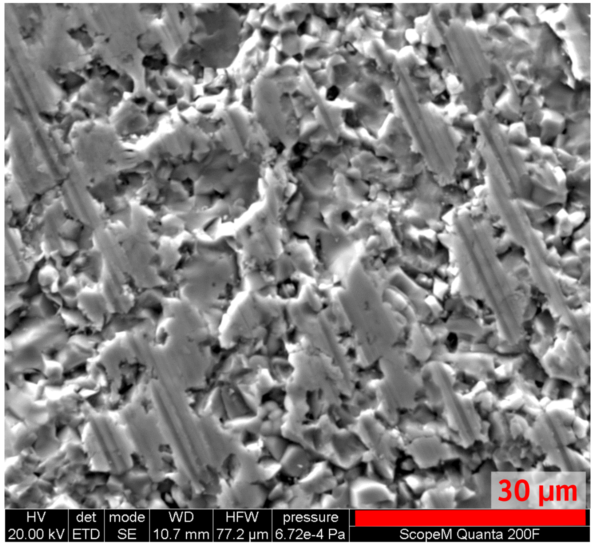
▶ Hypothesis - Increase In Magnetic Loss Caused By Machining Of Ferrite

■ Cutting of Thin Plates From Ferrite Rod W/ Diamond Saw

- Abrasive Machining Introduces Mech. Stress in Surface
- Ferrite Properties in Surface Altered → Increase of Loss Factor



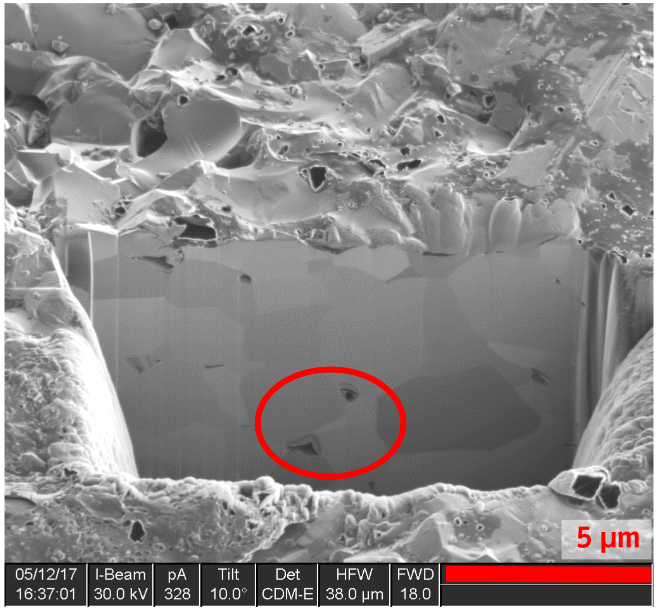
▲ Dimension Of Specimen: **7 mm x 6.4 mm x 1 mm**

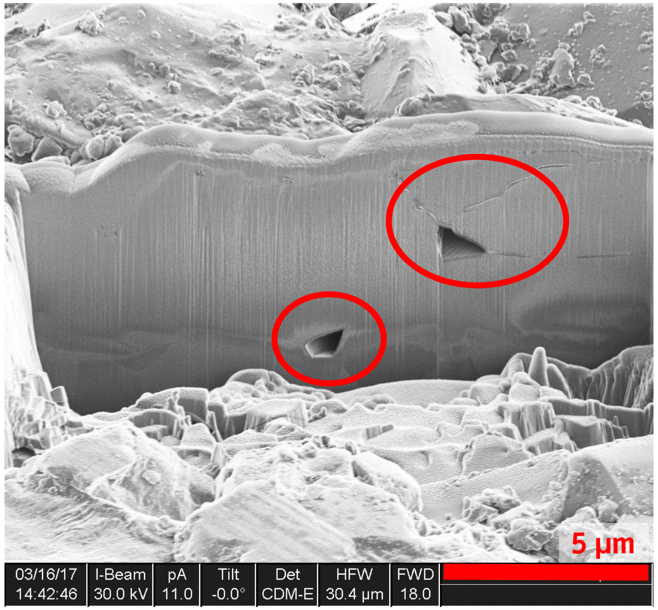


▲ SEM Image of Surface Condition of MnZn Ferrite (3F4) After Machining

▶ Subsurface Condition Of Machined Ferrite (1)

■ Focused Ion Beam (FIB) Prep. of Ferrite Sample And Scanning Electron Microscopy (SEM)





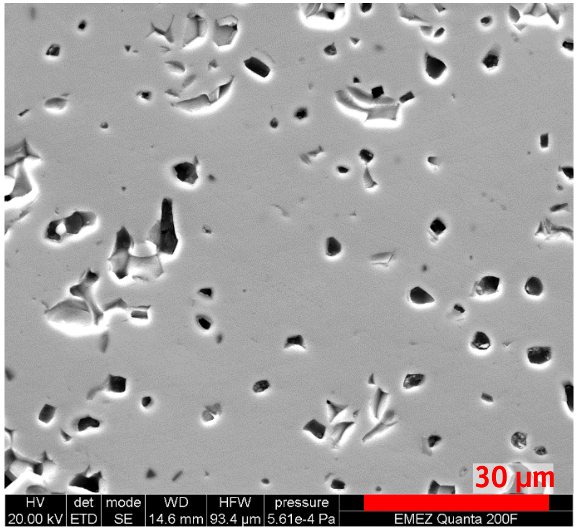
▲ FIB-SEM Images Revealing Subsurface Condition of Machined MnZn Ferrite (3F4)

■ Are These Cavities and Cracks 5 µm – 10 µm Below the Surface Causing All the Trouble?

► Subsurface Condition Of Machined Ferrite (2)

■ **Polishing of Plate Surface With Decreasing Grain Size**

- 2400 SiC → 4000 SiC → Colloidal Silica SiO2 & Polishing Cloth
- Approx. 500 µm Of Surface Removed → Bulk Material Exposed



▲ SEM Images of MnZn Ferrite (3F4) After Removing 500 µm Thick Layer at Surface

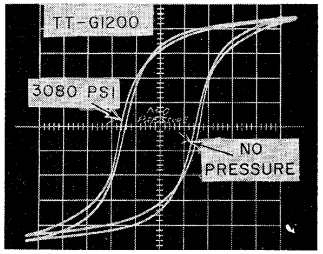
■ **Bulk Ferrite Also Exhibits Cavities →Result of Imperfect Sintering Process**

Note: This Is NOT Vendor But Technology/Process Specific Since Cavities in the Bulk Have Been Observed Ferrite Samples Provided by Various Vendors

Brief Literature Overview

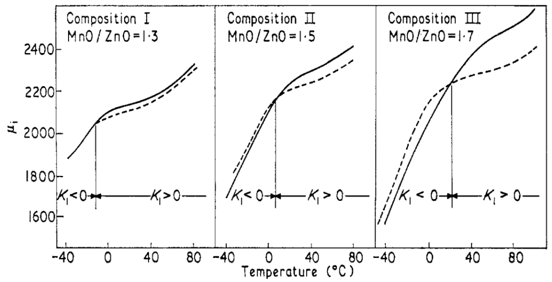
► Mech. Stress Alters Ferrite Properties – Literature Overview (1)

[1] 1964 E. Stern & D. Temme
- BH-Loop of Garnet and NiZn Ferrite Altered by Compressive Stress
- Machining Changes BH Curve in Surface

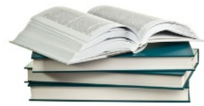


1960 1970 1980 1990

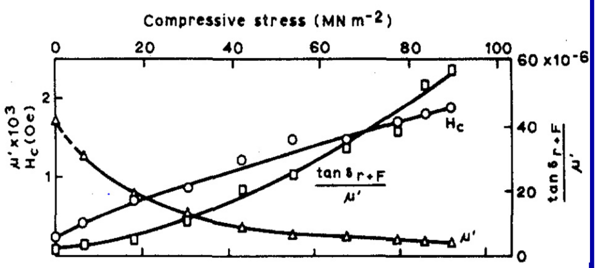
[2] 1970 J. E. Knowles
- Grinding Distorts (μ,T) - Relationship of Ferrite
- Grinding Causes Grain Deformation and Introd. Mech. Stress in Surface
- High μ Materials More Sensitive



► Mech. Stress Alters Ferrite Properties – Literature Overview (2)

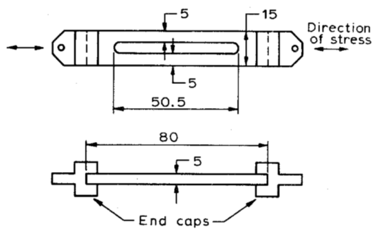


[4] 1974 J. E. Knowles
- Compressive Stress Reduces μ
- Loss-Factor $\tan\delta / \mu = \mu'' / (\mu')^2$ Increased In Surface Layer
- Coercive Force Higher In Surface Layer

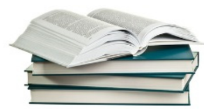


1960 1970 1980 1990

[3] 1974 E.C. Snelling
- Measurement of μ, tan δ, H_c on Spec. Shaped Ferrite Specimens
- Compressive & Tensile Stress Directly Applied To Specimen
- Same Findings As Knowles

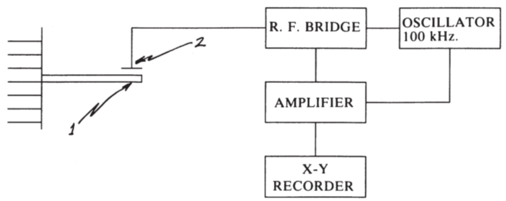


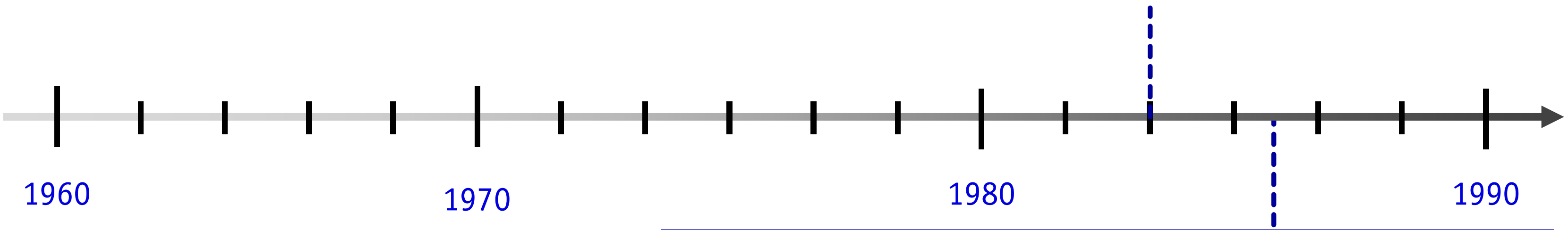
▶ Mech. Stress Alters Ferrite Properties – Literature Overview (3)



[5] 1984 E. Klokholm & H. L. Wolfe

- «Magnetically Dead» Surface Layer Thickness Estim. by Magnetostrictive Resp.
- MnZn / NiZn Ferrite Exhibit 40 μm / 95 μm Thick Dead Layer

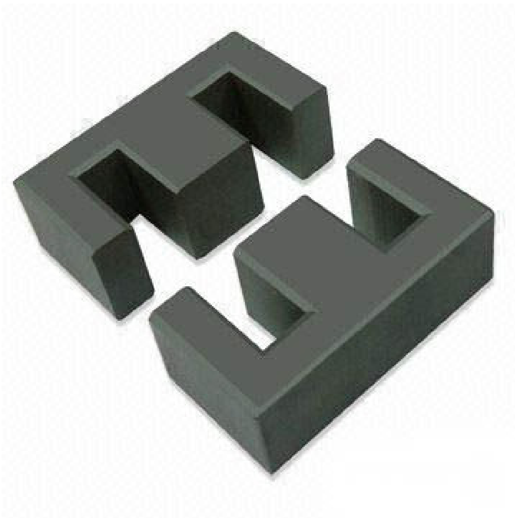


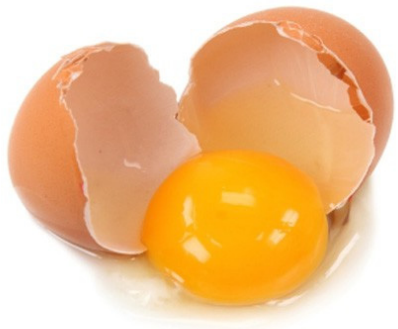


[6-7] 1987/1988 S. Chandrasekar Et Al.

- Comp. of Grinding and Lapping of Ferrites
- Lapping Causes Greater Residual Stress Than Grinding
- Etching Does Not Introduce Stress But Surface Too Rough

► For Good Electrical Performance Ferrite Must Be Treated As Careful As RAW Eggs





Surface Loss Test Setup

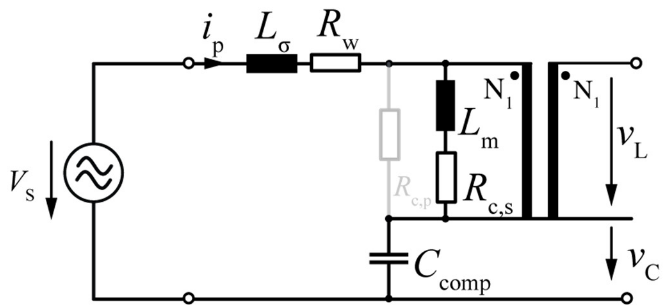
Electrical vs. Thermometric Measurement of Core Loss

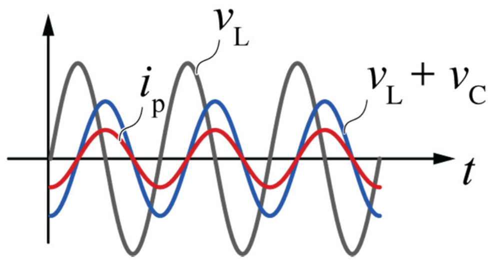
Electrical Surface Loss Measurement

► Electrical Measurement Of Surface Loss In A Nutshell

■ Survey of Core Loss Test Methods – Prof. Sullivan [9] / Bruce Carsten [10]

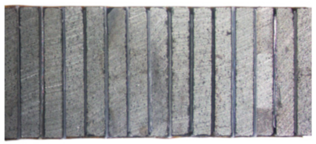
- Virginia Tech 2-Winding Resonant Method (Dr. Mingkai Mu)
- In-Phase Meas. of Voltage And Current
- Qvar Compensation → Precise Power Instrumentation





■ Quantifying Surface Loss By Means of Subtraction Measurements

- Electrical Loss Meas. of MAG Sample And Solid Ferrite

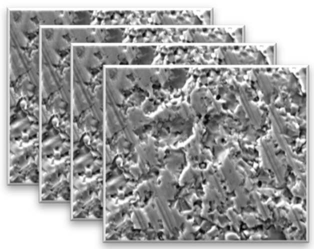


▲ Stack Of 1mm Plates

–

▲ Solid Sample

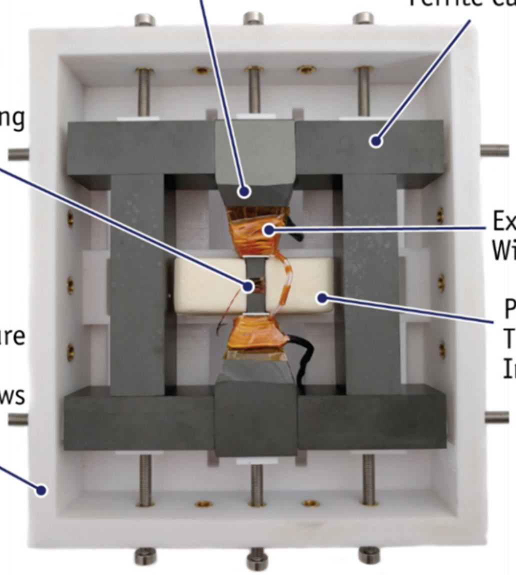
=

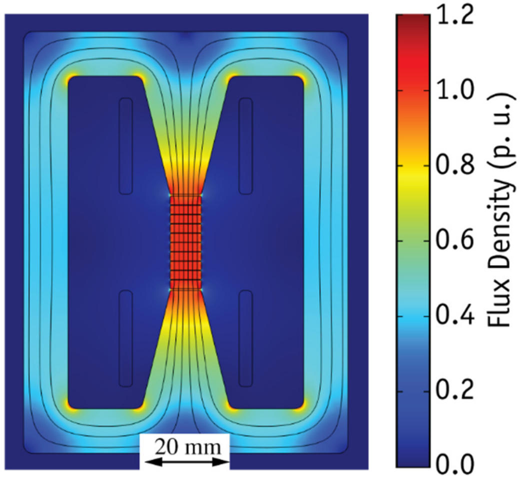


$P_{core} + P_{Surface}$ − P_{core} = $P_{Surface}$

▶ Test Fixture / Magnetic Circuit

- Impress Hom. Sinusoidal Flux Density Of Desired Ampl. and Frequ. in Sample
- E-Type Fixture For Swift Installation of Different Samples





▲ FEM Simulation of Flux Density Distribution in Test Circuit And Sample

- FEM Opt. Dimensions W/ Large Core Cross Section Comp. To Sample and Tapered Center Limb
  → Min. Loss In Test Circuit
- Inductance of Setup L_m = 50 .. 60 µH (Depends on Installed Sample)

▶ Downside Of Electrical Surface Loss Test Method

- Meas. of Total Power Loss In Setup → Loss in Sample + Test Circuit + Res. Capacitor
- Back-Of-The-Envelope Calc. For (15 x 1mm Plate) MAG Sample and "Mid-Range" Operating Point: 125 mT / 400 kHz

▲ Stack Of 1mm Plates

Surface Loss of MAG Sample ≈ 1.90 W

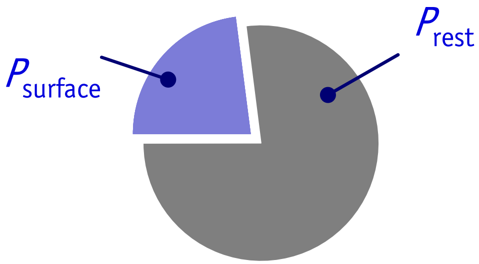
Core Loss of MAG Sample ≈ 1.25 W

Test Circuit Core Loss ≈ 3.75 W

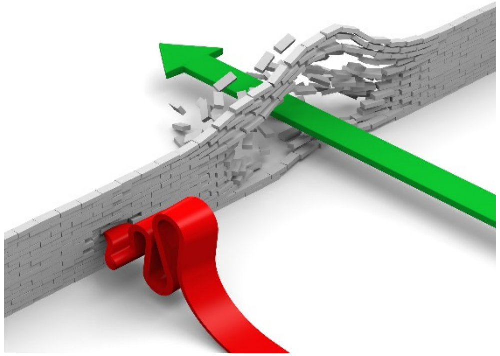
Resonance Capacitor Loss ≈ 1.20 W

→ $P_{tot} \approx 8.10$ W

→ $P_{surface} / P_{tot} \approx 23.4\%$



- For High Accuracy and Precision A «Direct» Sample Loss Meas. Approach Is Desired

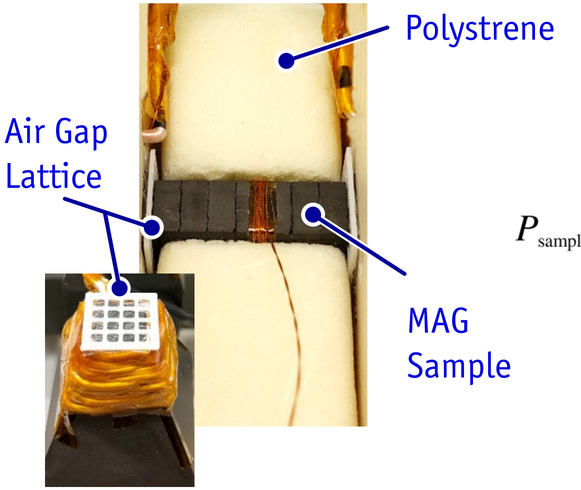


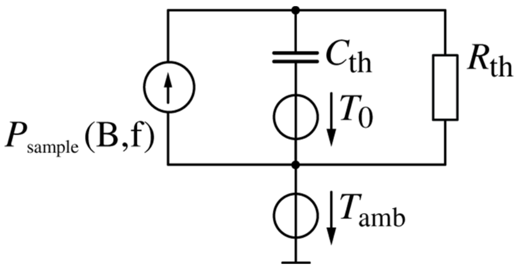
Thermometric Surface Loss Measurement

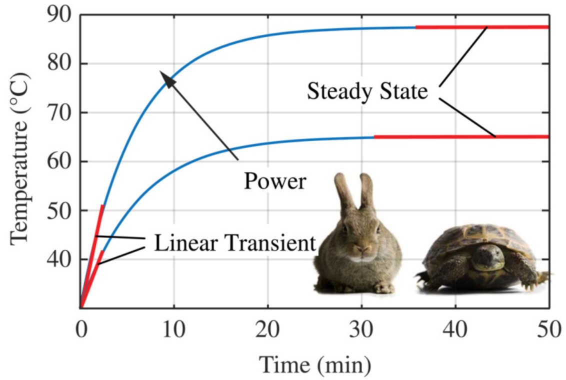
▶ Thermometric Measurement / Temperature Rise Monitoring (1)

■ Power Dissipation in Ferrite Results in Temperature Change

- Thermal Behavior Modelled W/ RC Circuit
- $C_{th} \approx 4$ J/K , Max. R_{th} W/ Insulation & Air Gap Lattice

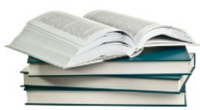






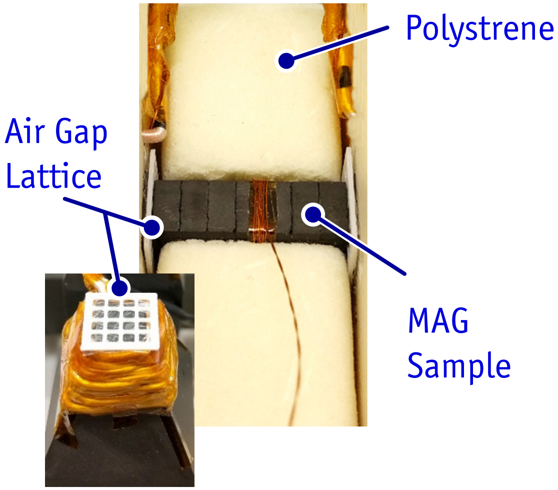
■ Temperature Rise (NOT Steady-State) Measurement

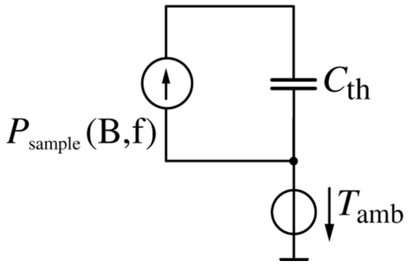
- ΔT= 1.5°C - 5°C Suffices → Change of Ferrite Prop. Negligible
- Meas. Time Only a Few Sec. Up To 150 Sec
- Temp. Rise Core Loss Method Published By V. Loyau Et Al. in 2009 [11-12], H. Shimoji Et Al. in 2011 [13]

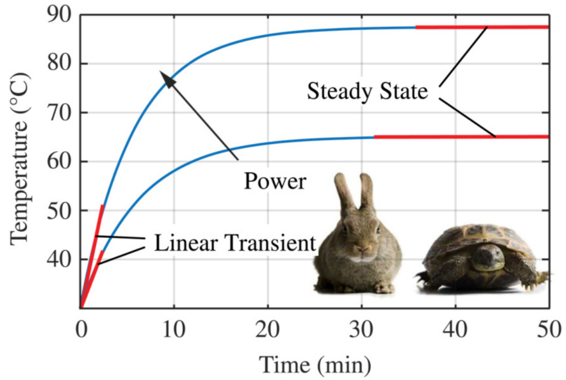


▶ Thermometric Measurement / Temperature Rise Monitoring (1)

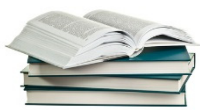
■ **Power Dissipation in Ferrite Results in Temperature Change**
- Thermal Behavior Modelled W/ RC Circuit
- $C_{th} \approx 4$ J/K , Max. R_{th} W/ Insulation & Air Gap Lattice







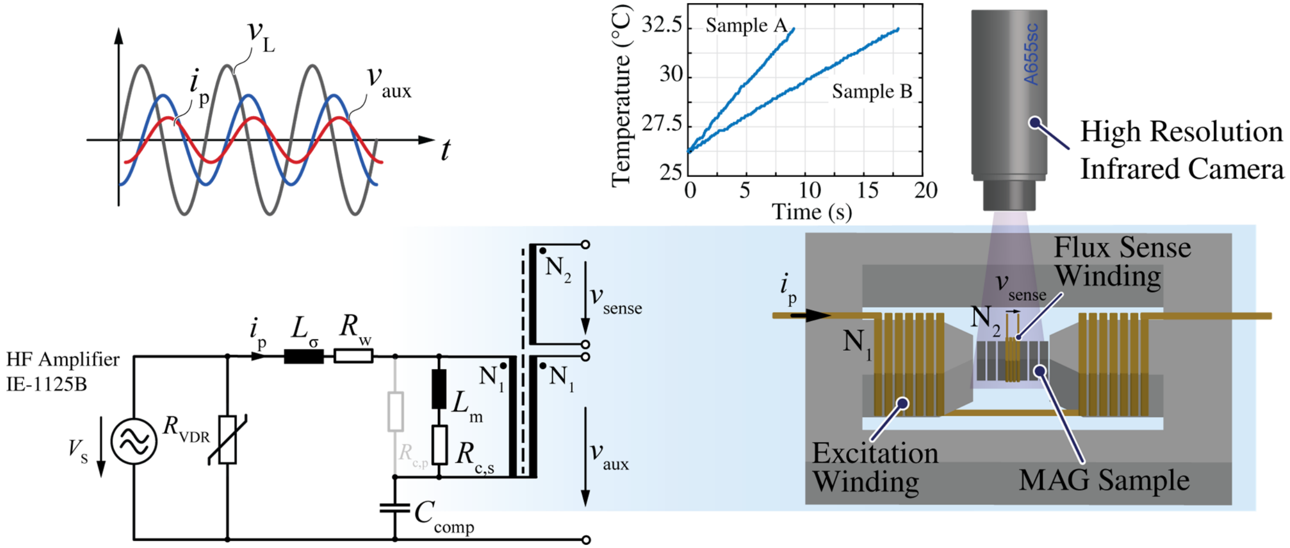
■ **Temperature Rise (NOT Steady-State) Measurement**
- ΔT= 1.5°C - 5°C Suffices → Change of Ferrite Prop. Negligible
- Meas. Time Only a Few Sec. Up To 150 Sec
- Temp. Rise Core Loss Method Published By V. Loyau Et Al. in 2009 [11-12], H. Shimoji Et Al. in 2011 [13]



▶ Thermometric Measurement / Temperature Rise Monitoring (2)

■ Temp. Rise Monitoring W/ Infrared Camera (Microbolometer)

- Attachment of Sensor On Ferrite Sample Impractical
- Thermographic Meas. Allows to Verify Hom. Flux Density in Sample



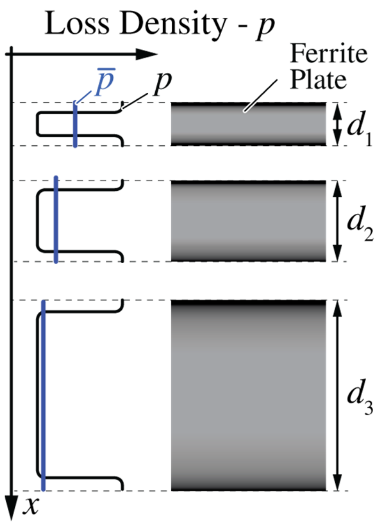
▲ Temp. Rise Monitoring of Ferrite Sample W/ Infrared Camera

- **FLIR A655sc** W/ Close-Up Lens
- Differential Temp. Meas. Accuracy ± 0.2°C

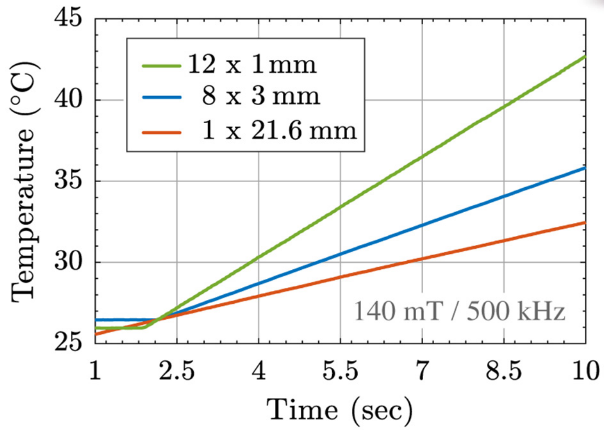
▶ Thermometric Surface Loss Measurement Principle In A Nutshell

■ Hypothesis: Core Loss Density In Surface Layer Higher Than In Bulk

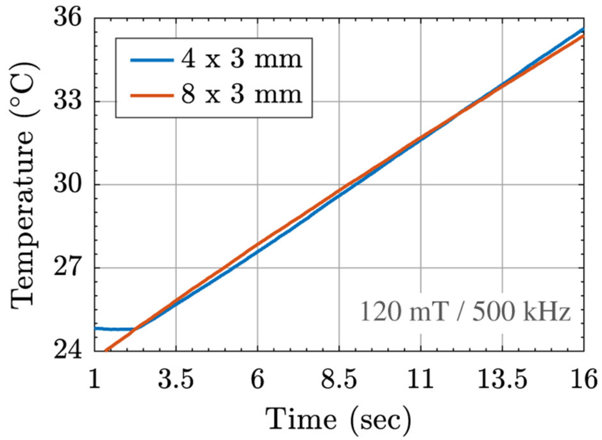
- $P = \kappa\, d_\mathrm{p} A_\mathrm{p} + \tilde{\kappa}_S A_\mathrm{p}$
- Thinner Plates Feat. a Higher Avg. Loss Density
- Thinner Plates Exhibit Faster Temp. Rise
- Stacking of Thin Plates Does NOT Affect Temp. Rise



▲ Avg. Loss Density Depends On Plate Thickness



▲ Temperature Rise For Plates W/ Different Thickness



▲ Temperature Rise For Different # of Stacked Plates

▶ Thermometric Surface Loss Measurement Principle In A Nutshell

■ Linear Model Approach

- Only C_{th} Of Ferrite Considered, R_{th} Neglected

$$\kappa = \frac{(\Delta t_B d_A - \Delta t_A d_B)}{(d_A - d_B)\Delta t_A \Delta t_B} c_{th}\rho\Delta T \quad \left(\frac{mW}{cm^3}\right)$$

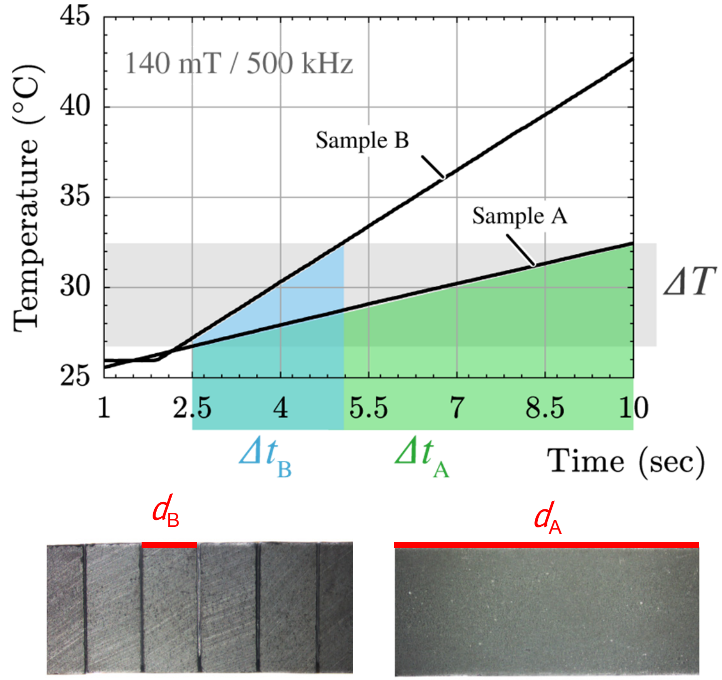
$$\tilde{\kappa}_S = \kappa d_S = \frac{d_A d_B(\Delta t_A - \Delta t_B)}{(d_A - d_B)\Delta t_A \Delta t_B} c_{th}\rho\Delta T \quad \left(\frac{mW}{cm^2}\right)$$

■ Simplifying Assumptions

- Material Prop. ρ, c_{th} In Surface Layer and Bulk Similar
- $d_s << d_A, d_B$
- Power Loss Const. During Measurement

■ Refinement W/ More Elaborate Models

- Exponential Model (1st Order RC)
- $T_0 \neq T_{amb}$
- Precise Mapping $\Delta t \rightarrow$ P For Low Meas. Error

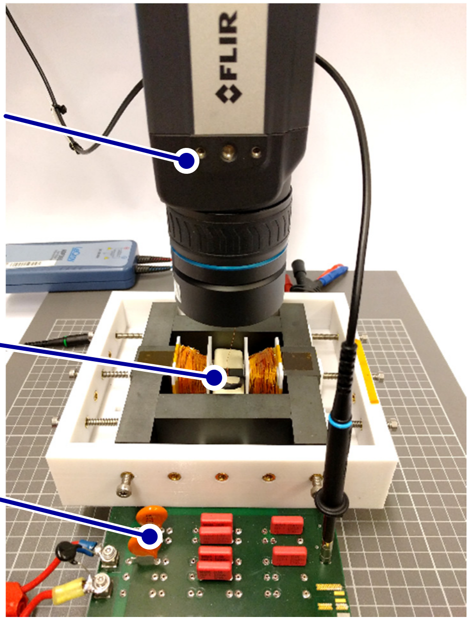


▲ Visualization of Param. for Computation of Loss Density From Temp. Rise Recordings

▶ Temperature Rise Recording (1)

■ Temperature Rise Comparison of Solid Core and MAG Sample

- Sinusoidal Excitation 100 mT / 400 kHz
- Solid 3F4 (1 x 21.6 mm) vs. MAG 3F4 (7 x 3mm)
- ΔT = 10 °C, T_0 = 26.3 °C



▲ Surface Loss Test Setup W/ Res. Cap. Bank and Infrared Camera

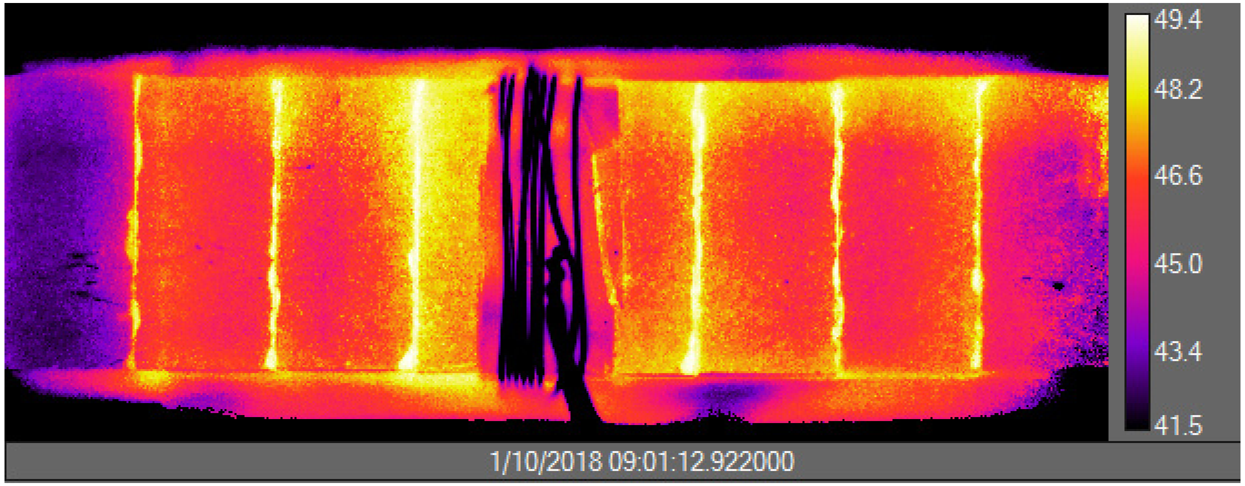
▲ 3F4 Solid Sample Temperature Rise – 100 mT / 400 kHz

▲ 3F4 MAG Sample (7 x 3mm) Temperature Rise – 100 mT / 400 kHz

▶ Temperature Rise Recording (2)

■ **Image Detail Enhancement (FLIR APE Algorithm) And Narrow Scale Limits**

- Entire Color Range Mapped To 41.5 °C and 49.4 °C



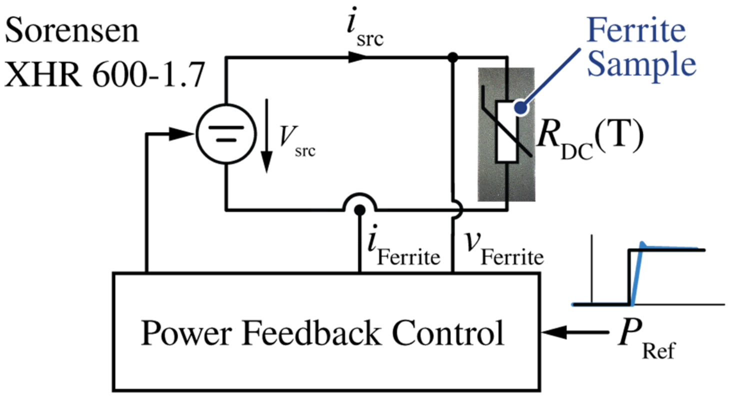
▲ 3F4 MAG Sample (8 x 3mm) Temperature Rise Snapshot at 47 °C Avg. Sample Temperature

■ **Loss Density Seems To Be Highest Close To Plate Surface**

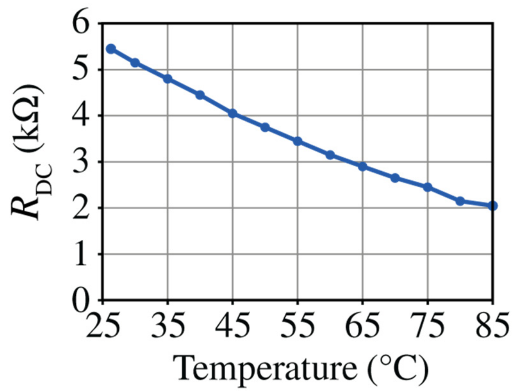
▶ Identification Of Thermal Parameters (1)

■ Determine Thermal Parameters (R_{th}, C_{th}) of Ferrite Sample

- Impress Constant Power Loss in Ferrite W/ DC Current
- DC Resistance Decreases W/ Temperature (ΔT = 30°C → ΔR = -30%)
- Feedback Control To Keep Power Loss Constant



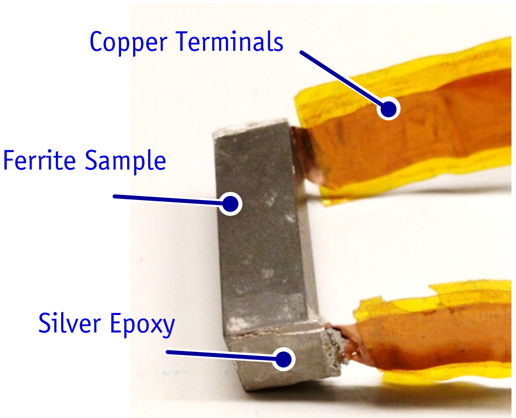
▲ Feedback Control of DC Power Dissipation in Ferrite



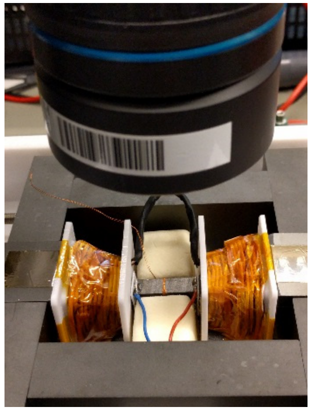
▲ DC Resistance of 3F4 MnZn Ferrite as a Function of Temperature

▶ Identification Of Thermal Parameters (2)

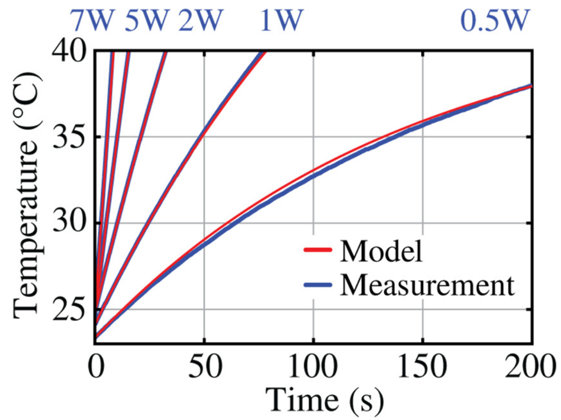
- **LMS Regression To Extract Model Parameters From Measurement**
  - Record Temp. Response of Sample Subject To Stepwise Increase In Power
  - Repeat for Several Power Levels
  - Cover Loss Typ. For Measurement Range (B, f)



▲ Copper Termination for DC Calibration



▲ Sample Installed in Test Circuit During Calibration Measurements



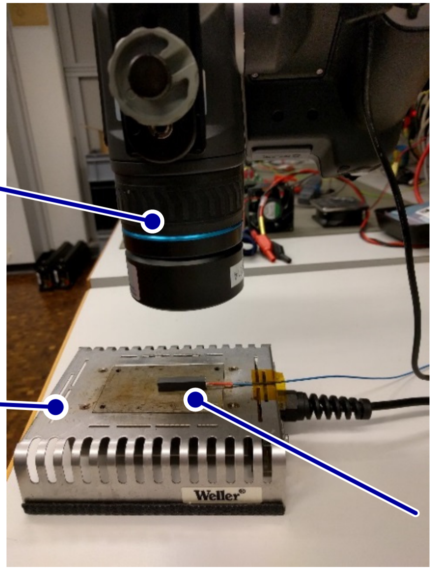
▲ Temperature Rise of Calibrated Model and Rec. Measurements

- Obtained Parameter Values: C_{th} = 3.83 J/K, R_{th} = 37.8 K/W
- Computed From Vendor Data: C_{th} = 3.6 J/K

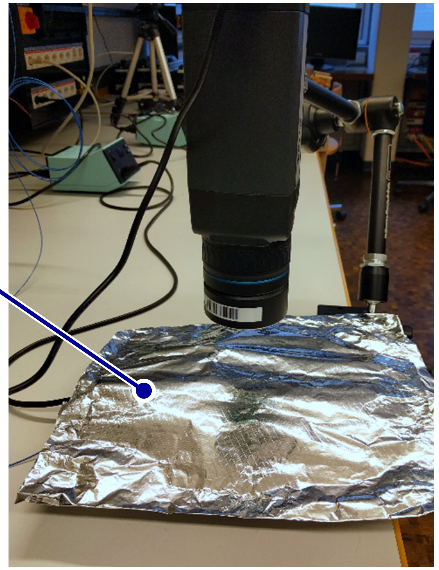
▶ Calibration Of Thermometric Setup

- **Determine Emissivity of Ferrite (ε ≈ 0.86)**
  - Tune **ε** Such That Infrared Camera Matches Optical Temp. Sensor

- **Determine Reflected Temperature Of Infrared Camera**
  - Using Aluminum Foil or Any Other Low-ε Material
  - T_{cam} ≈ 28-30 °C



▲ Determine Emissivity Of Ferrite



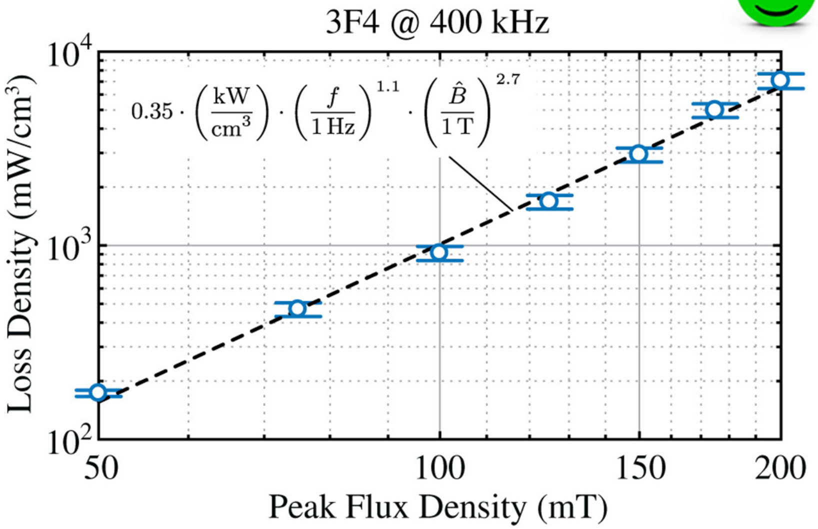
▲ Determine Reflected Temperature

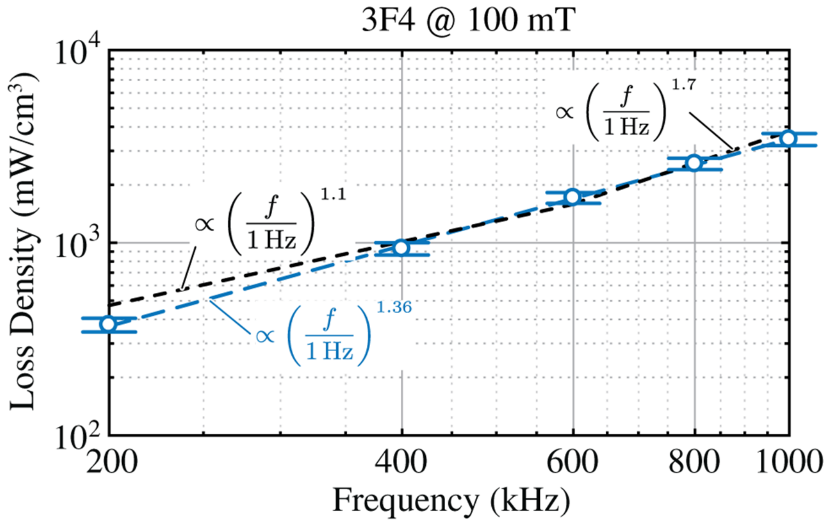
Experimental Results

3F4 Loss & Surface Loss Density

▶ Experimental Results – 3F4 Loss Density (mW/cm³) @ ≈ 25°C

- **Meas. Error Bounds ± 10 % (Worst Case)**
  - Determined By Min. Meas. Time And Temp. Reading Accuracy
- **Good Agreement With Datasheet/ SE Param. Of Vendor**
  - $p = 0.0085 \times \left(\frac{f}{1\mathrm{Hz}}\right)^{1.36} \times \left(\frac{\hat{B}}{1\mathrm{T}}\right)^{2.55} \left(\frac{\mathrm{mW}}{\mathrm{cm}^3}\right)$

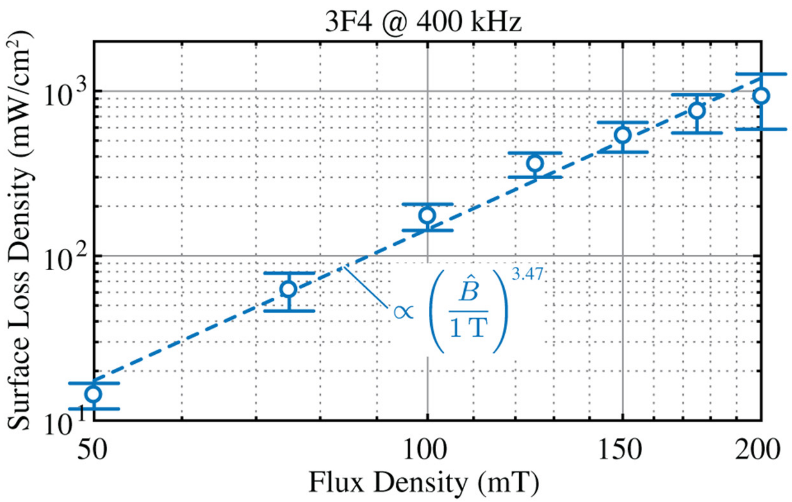


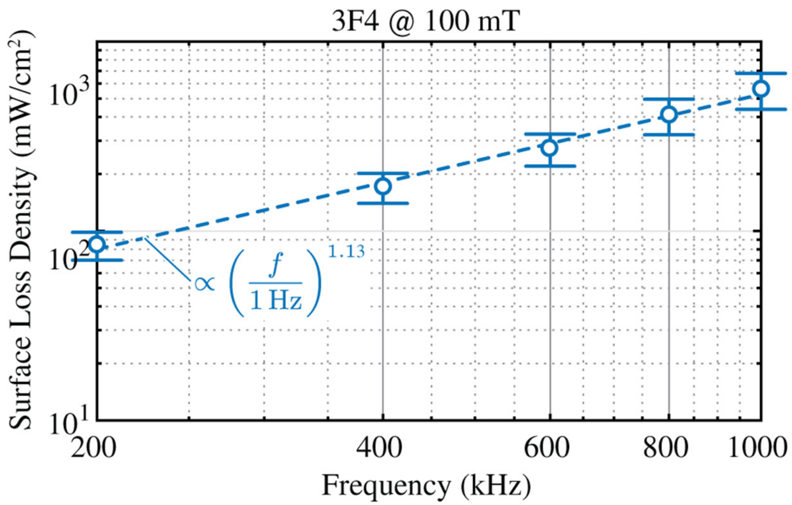


▶ Experimental Results – 3F4 Surface Loss Density (mW/cm²) @ ≈ 25°C

- **Meas. Error Bounds ± 25 % (Worst Case At 200 mT)**
  - Determined By Min. Meas. Time And Temp. Reading Accuracy

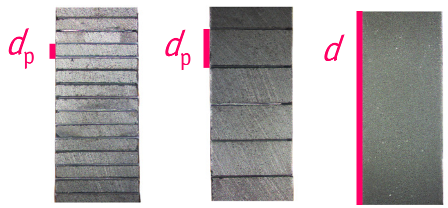
- **Surface Loss Steinmetz Parameter (Per Interface)**
  - $p_{Surf} = 0.0615 \times \left(\frac{f}{1\mathrm{Hz}}\right)^{1.13} \times \left(\frac{\hat{B}}{1\mathrm{T}}\right)^{3.47} \left(\frac{\mathrm{mW}}{\mathrm{cm}^2}\right)$
  - $p = 0.0085 \times \left(\frac{f}{1\mathrm{Hz}}\right)^{1.36} \times \left(\frac{\hat{B}}{1\mathrm{T}}\right)^{2.55} \left(\frac{\mathrm{mW}}{\mathrm{cm}^3}\right)$

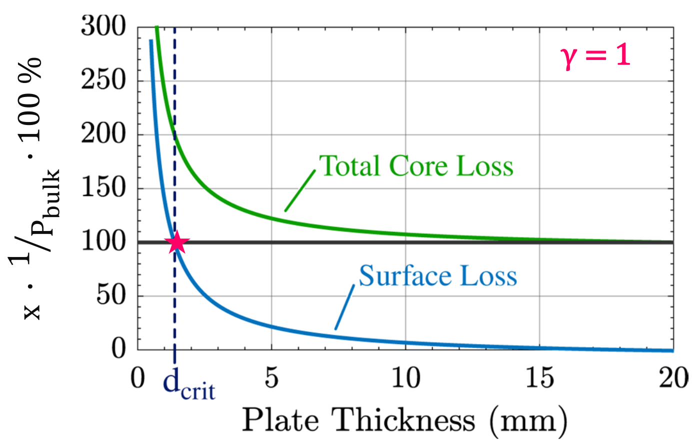




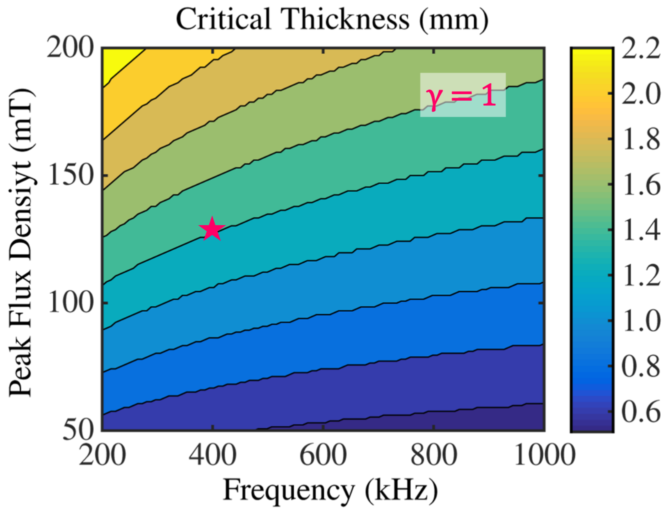
▶ Experimental Results – 3F4 Critical Plate Thickness

- **Composition Of Core With Plates Of Thickness d_p**
- $$\frac{P_{Surf}}{P_{bulk}} = \frac{\kappa_S (N-1) A_S}{\kappa N d_p A_S} \cong \frac{\kappa_S}{\kappa} \cdot \frac{1}{d_p} = \gamma, \quad d = N \cdot d_p$$
- **"Critical Thickness" $d_{p,crit}$ When $P_{Surf} = \gamma P_{bulk}$**



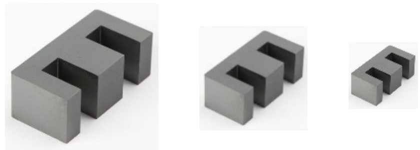


▲ 3F4 Critical Thickness For Obtained SE Parameter at 125 mT / 400 kHz



▲ 3F4 Critical Thickness Over Entire Meas. Range

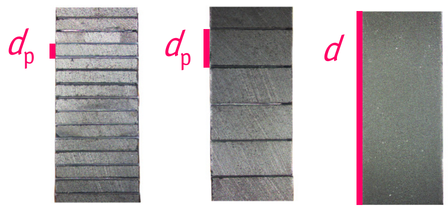
- **Critical Thickness Independent Of Actual Cross Section Area!**

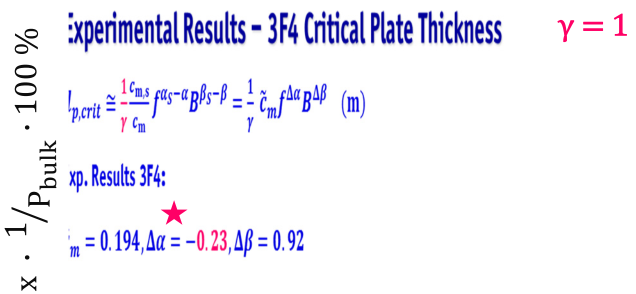


▶ Experimental Results – 3F4 Critical Plate Thickness

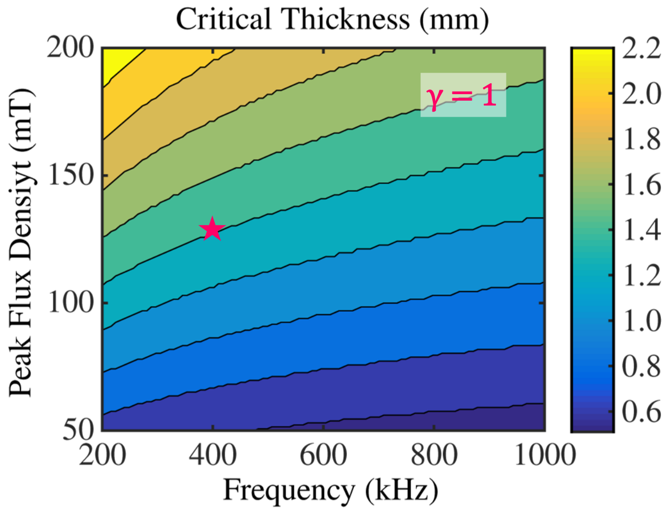
- $d_{p,crit} \cong \frac{1}{\gamma}\frac{c_{m,s}}{c_m} f^{\alpha_S-\alpha} B^{\beta_S-\beta} = \frac{1}{\gamma}\,\tilde{c}_m f^{\Delta\alpha} B^{\Delta\beta}$ (m)
- **Exp. Results 3F4:**

  $\tilde{c}_m = 0.194, \Delta\alpha = -0.23, \Delta\beta = 0.92$



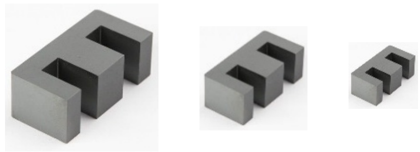


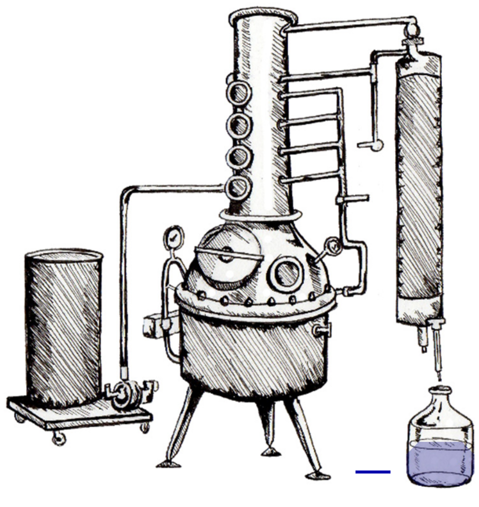
▲ 3F4 Critical Thickness For Obtained SE Parameter at 125 mT / 400 kHz



▲ 3F4 Critical Thickness Over Entire Meas. Range

- **Critical Thickness Depends on Material, Machining Process And Post-Processing Treatment**





Source: whiskeybehavior.info

Conclusion & Outlook

► Conclusion

- Abrasive Machining of Ferrite Causes Core Loss Increase
- Thermometric Measurement Principle Allows Quantification of Surface Loss
- 3F4 Surface Loss SE Parameter $\beta_S > \beta$, $\alpha_S < \alpha$
- Total Loss in MAG Structure (Composite Core) Increases With $1/d_p$
- Critical Plate Thickness Reached When $P_{Surf}/P_{bulk} = \gamma$
- ... Independent Of Actual Cross Section Area
- ... Depends on Material, Machining Process & Post-Processing Treatment

Acknowledgement:

fraza
FERROXCUBE
Fraunhofer IZM
Empa Materials Science and Technology
laboratory for nanometallurgy

▶ Outlook

- **Literature Suggests Post-Processing Treatments To Restore Intrinsic Properties: Etching and/or Polishing of Machined Surface, Annealing Treatment**

- **So Far No Success In Reducing Surface Losses**
  - Etching Treatment With 60 °C Phosphoric Acid (Instead of HCL)
  - High Temp. Annealing In N_2 Atmosphere (Manufacturer Know-How Needed)

- **Green Grinding Reduces Surface Loss By ≈ 40 % 50 mT – 100 mT Range (Increased β_S)**

- **What About NiZn Ferrite?**

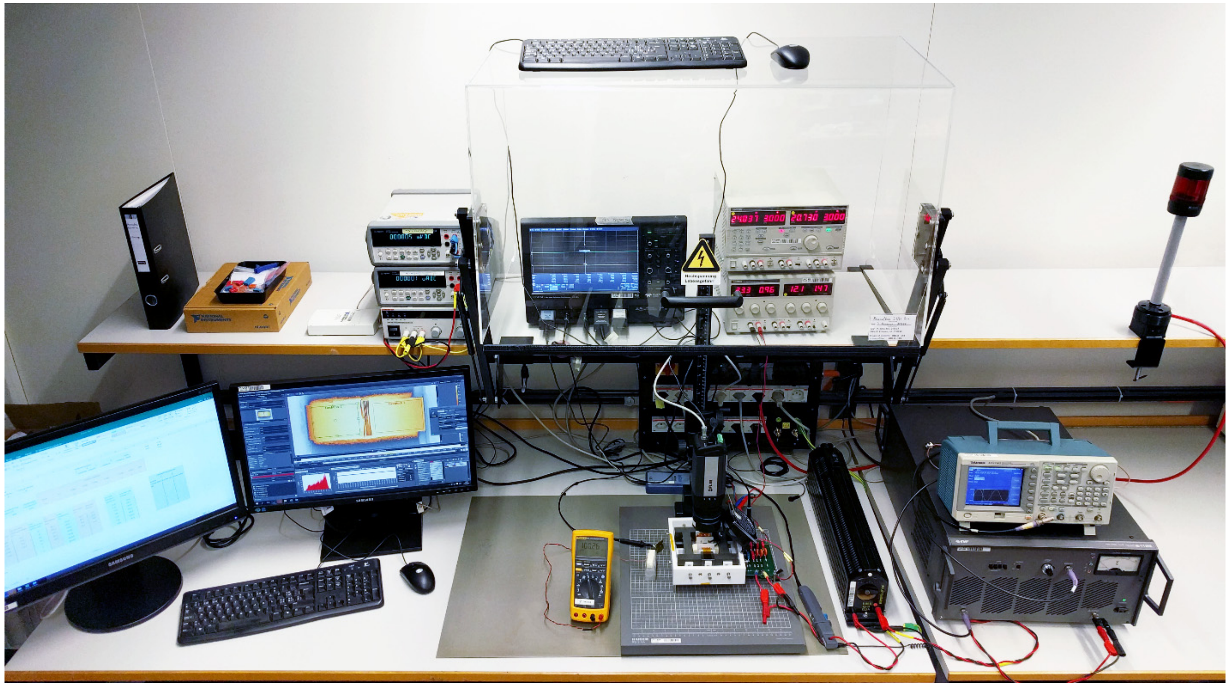
- **Investigate DC Bias Dependency of Surface Loss**

- **Follow Up on Ideas/Suggestions Of Magnetics Community …**

Acknowledgement: fraza, FERROXCUBE, Fraunhofer IZM, Empa Materials Science and Technology, laboratory for nanometallurgy

Thank You!

Questions?



▶ List Of Literature (1)

[1] J. Hu and C. R. Sullivan, "The Quasi-Distributed Gap Technique for Planar Inductors: Design Guidelines," in Proc. of the IEEE Industry Application Conference, 1997.

[2] C. R. Sullivan, H. Bouayad, and Y. Song, "Inductor design for low loss with dual foil windings and quasi-distributed gap," in Proc. of the IEEE Energy Convers. Congr. Expo. (ECCE), 2013.

[3] Franc Zajc, "Flat Band Winding For An Inductor Core." U.S. Patent US 2012299681A1.

[4] Franc Zajc, "Winding Arrangement for Inductive Components and Method for Manufacturing a Winding Arrangement for Inductive Components." U.S. Patent US201214647066.

[5] E. Stern and D. Temme, "Magnetostriction Effects in Remanence Phase Shifters," IEEE Trans. Microw. Theory Tech., Vol. 13, No. 6, pp. 873–874, 1965.

[6] J. E. Knowles, "The Effect of Surface Grinding Upon the Permeability of Manganese-Zinc Ferrites," Jounral of Applied Physics, Vol. 3, pp. 1346 -1351,1970.

[7] E.C. Snelling, "The Effect Of Stress On Some Properties Of MnZn Ferrite," IEEE Transactions on Magnetics, Vol. 10, pp. 4–6, 1974.

[8] J. E. Knowles, "The Origin of the Increase in Magnetic Loss Induced by Machining Ferrites," IEEE Trans. Magnetics, Vol. 11, pp. 44–50, 1975.

[9] E. Klokholm and H. L. Wolfe (1984), "Surface Damage in Manganese Zinc and Nickel Zinc Ferrites," In: Kossowsky R., Singhal S.C. (eds) Surface Engineering. NATO ASI Series (Series E: Applied Sciences), vol 85. Springer, Dordrecht.

[10] S. Chandrasekar, M. C. Shaw and B. Bushan, "Comparison of Grinding and Lapping of Ferrites and Metals," Journal of Trinology vol. 109, pp. 76-82, 1987.

[11] S. Chandrasekar and B. Bushan, "Control of Surface Finishing Residual Stresses in Magnetic Recording Head Materials," Journal of Trinology vol. 110, pp. 87-92, 1988.

► List Of Literature (2)

[12] B. Bharat, Tribology and Mechanics of Magnetic Storage Devices, Springer-Verlag New York, 1996.

[13] Charles R. Sullivan, "Survey of Core Loss Test Methods" . ONLINE: http://sites.dartmouth.edu/power-magnetics/files/2017/03/Survey-of-Core-Loss-Test-Methods-Sullivan.pdf

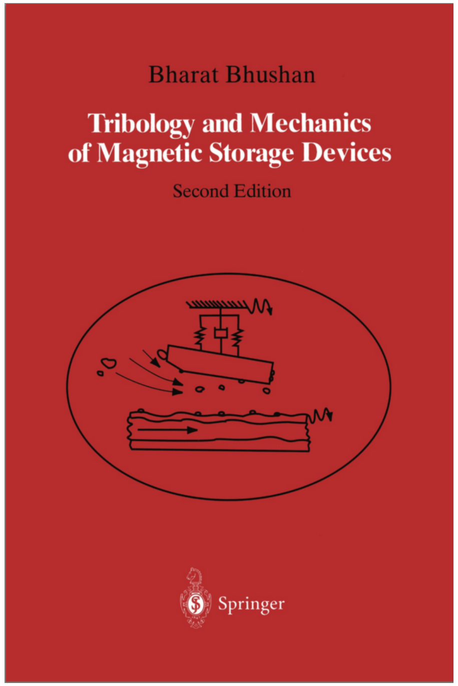
[14] Bruce Carsten, "Waveforms For Simulating Magnetic Cores". ONLINE: http://www.psma.com/sites/default/files/uploads/files/Magnetics%20Workshop%202017/Carsten_Waveforms%20for%20Simulating%20Magnetic%20Cores.pdf

[15] V. Loyau, M. Lo Bue, and F. Mazaleyrat, "Measurement of Magnetic Losses By Thermal Method Applied To Power Ferrites at High Level of Induction and Frequency," Rev. Sci. Instrum., Vol. 80, No. 2, 2009.

[16] V. Loyau, M. Lobue, and F. Mazaleyrat, "Comparison of Loss Measurement in a Ferrite With Wwo Calorimetric Methods," IEEE Trans. Magn., Vol. 46, No. 2, pp. 529–531, 2010.

[17] H. Shimoji, B. E. Borkowski, T. Todaka, and M. Enokizono, "Measurement of Core-Loss Distribution Using Thermography," IEEE Trans. Magn., Vol. 47, No. 10, pp. 4372–4375, 2011.

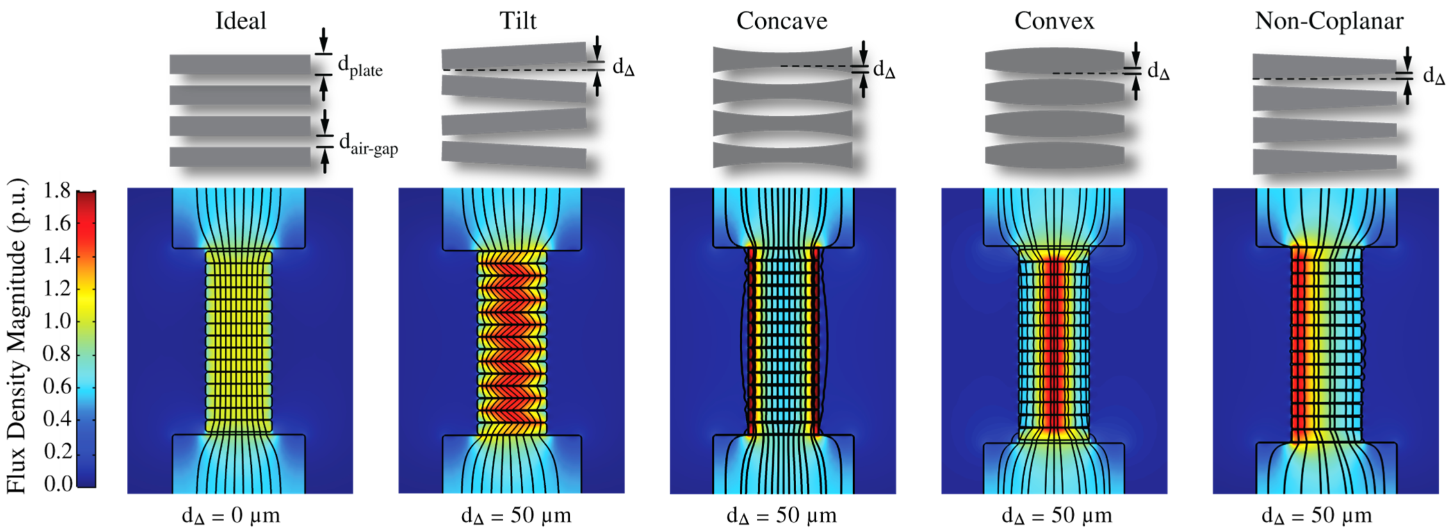
► Mech. Stress Alters Ferrite Properties – Literature Overview (4)



[8] B. Bushan Book *"Tribology and Mechanics of Magnetic Storage Devices"* Provides Good Overview Of Challenges Associated With The Machining Of Ferrite

▶ Appendix - Assembly Imperfections (1)

- **Plane Parallel Positioning of Plates Difficult To Achieve in Practice**
  - Mechanical Tolerances of Plates (e. g. plate surfaces not parallel)
  - Assembly Imperfections (e. g. Tilt between Plates)
- **Variation of Air Gap Length Causes Inhomogeneous Flux-Density Distribution**
- **2D FEM To Assess Implications of Mech. Tolerances On Power Loss in MAG Structure**

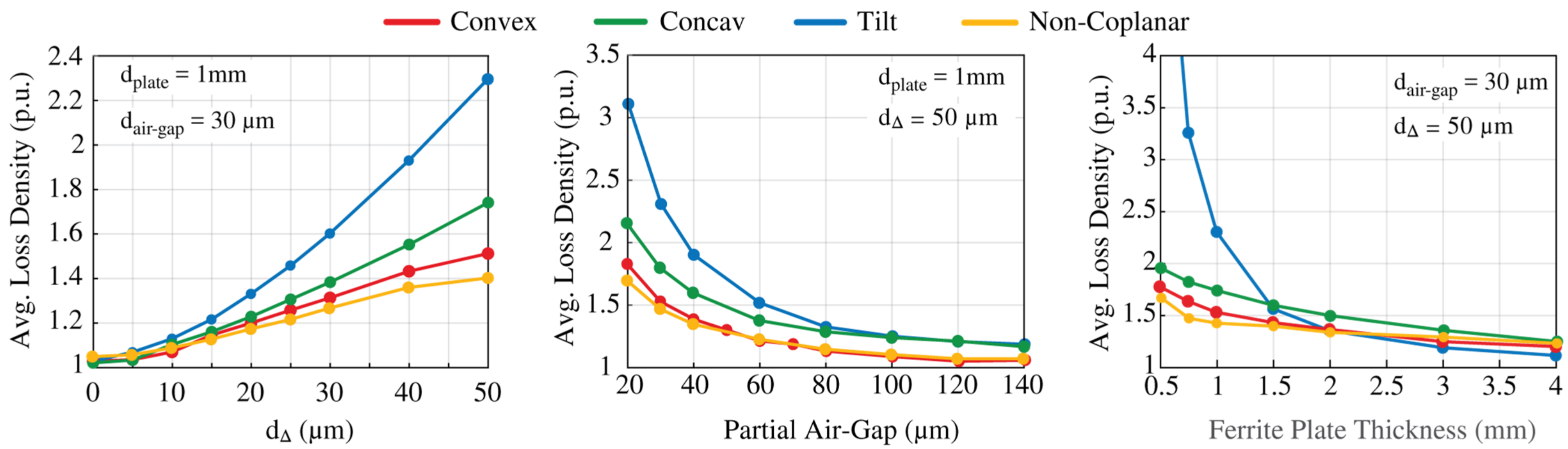


▲ 2D FEM Showing Non-Homogeneous Flux Density Distribution Caused By Mech. Tolerances

► Appendix - Assembly Imperfections (2)

■ 2D FEM To Assess Implications of Mech. Tolerances On Power Loss in MAG Structure

- Increase of Avg. Loss Density of MAG Structure With Respect To Ideal Case (p.u.)
- Max. Deviation/Imperfection Of d_{Δ} = 50 µm Considered in Simulation
- Dependance of Avg. Loss Density On Individual Air-Gap Length And Ferrite Plate Thickness

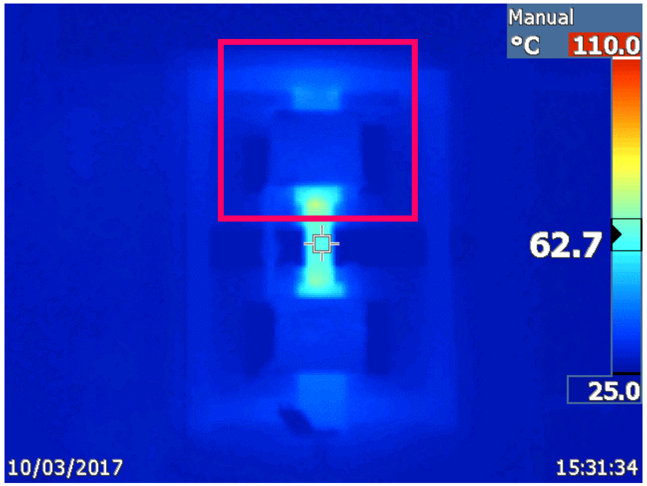


■ Strong Impact Of Tilt Between Plates On Avg. Loss Density

- Up to a Factor 5 Increase Of Loss Density For Very Thin Plates
- 3 mm Plates And 100 µm Air-Gap → Loss Density Unaffected By Mech. Tolerance

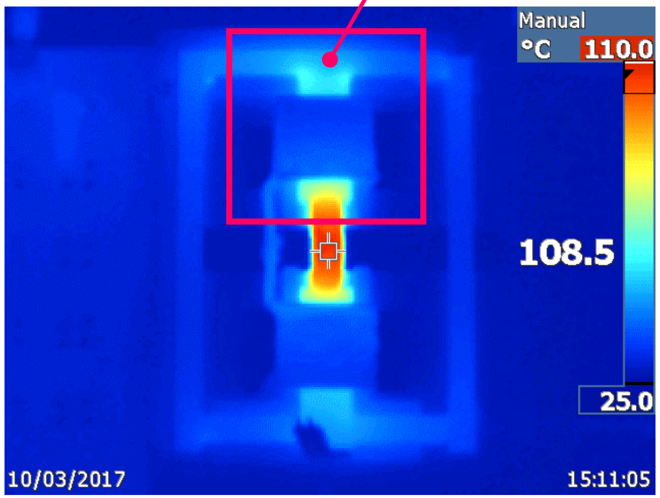
▶ Appendix - Issues Associated With Electrical Surface Loss Test Method

- **Keep Tot. Inductance Of Test Setup Identical Between Measurements With Different Sample**
  - Requires Trimming of Total Air-Gap (Solid Sample and f.i. 15 AG Sample Exhibit Similar Inductance Value)
  - Identical Excitation Current Causes Similar Cap. Losses
  - However … Actual Core Loss in Test Circuit Depends on Installed Sample (Despite Trimmed Inductance) Because of Leakage Flux Variation



▲ Temp. Rise Of Prelim. Test Circuit With Solid Sample. 100mT/500 kHz For 90 Sec.

Excess Power Dissipation in Core



▲ Temp. Rise Of Prelim. Test Circuit With 20 AG Sample. 100mT/500 kHz For 90 Sec.

▶ Issues Associated With Electrical Surface Loss Test Method (1)

- **Meas. of Total Power Dissipation In Setup → Loss in Sample + Test Circuit + Res. Capacitor**

- **Back-Of-The-Envelope Calculation For (15 x 1mm Plate) MAG Sample And "Mid-Range" Operating Point: 125 mT / 400 kHz**

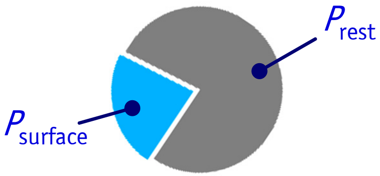
▲ Stack Of 1mm Plates

Surface Loss Of MAG Sample: $14 \times (0.7\text{ cm} \times 0.64\text{ cm}) \times 300\text{ mW/cm}^2 \approx 1.9\text{ W}$
Core Loss Of MAG Sample: $15 \times (0.7\text{ cm} \times 0.64\text{ cm} \times 0.1\text{ cm}) \times 1865\text{ mW/cm}^3 \approx 1.25\text{ W}$
From Exp. Results 3F4 Presented Later

Test Circuit Core Loss: $3 \times 1.25\text{ W} = 3.75\text{ W}$
Approx. From FEM Study (Prev. Slide)

Resonance Capacitor Loss:
Required Excitation Current $I_p \approx 3.5$ A RMS (From Exp. Measurements)
Installed Film Capacitors (Film) In Total 2.5 nF With Equivalent ESR = 100 mΩ (Based On Datasheet Values)
→ $(3.5\ A)^2 \times 0.1\ \Omega \approx 1.2\text{ W}$

→**Total Measured Loss:** $P_{tot} = 8.1\text{ W}$
→**Surface Loss % From Tot. Loss:** $P_{surface}/P_{tot} \times 100\% = 23.4\ \%$

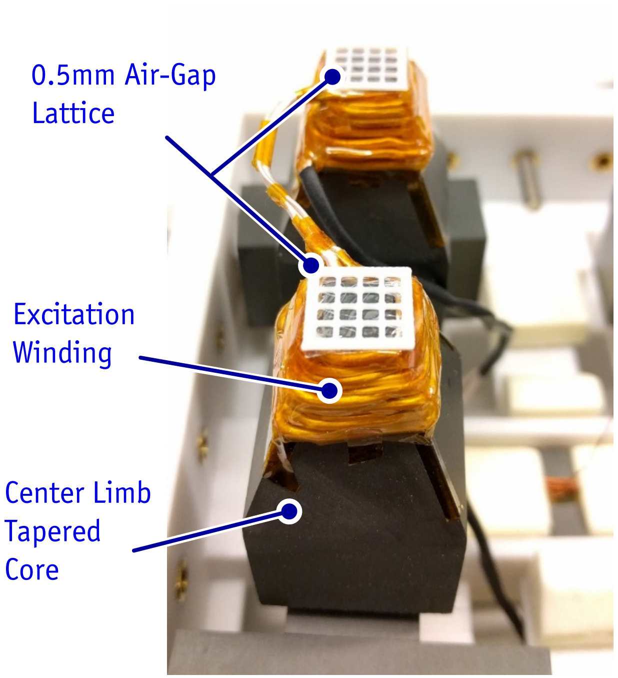


- **For Low Meas. Error A «Direct» Approach To Obtain Surface Loss Is Desired**

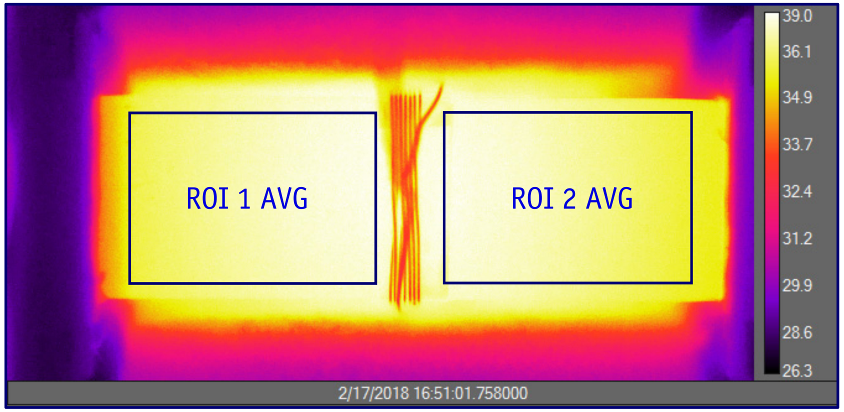
▶ Appendix - Temperature Rise Recording ROI AVG

■ Temperature Gradient Along Sample

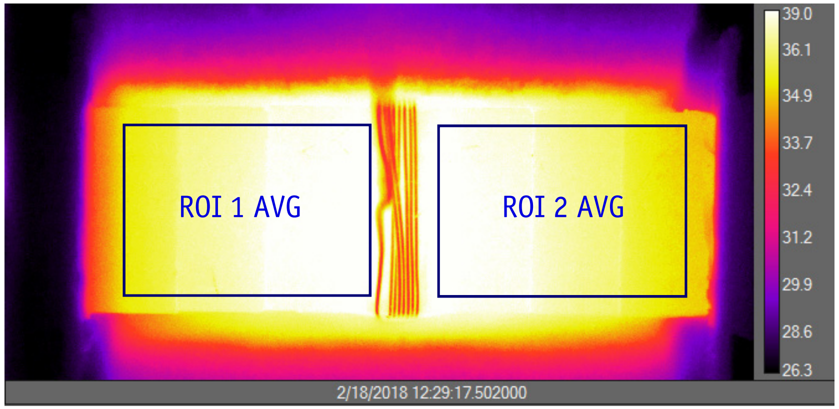
- Heat Conduction From Sample To Test Circuit Despite Air-Gap Lattice
- ROI Average → Avg. Temp. Of Sample



▲ Tapered Center Limb Core With Air-Gap Lattice



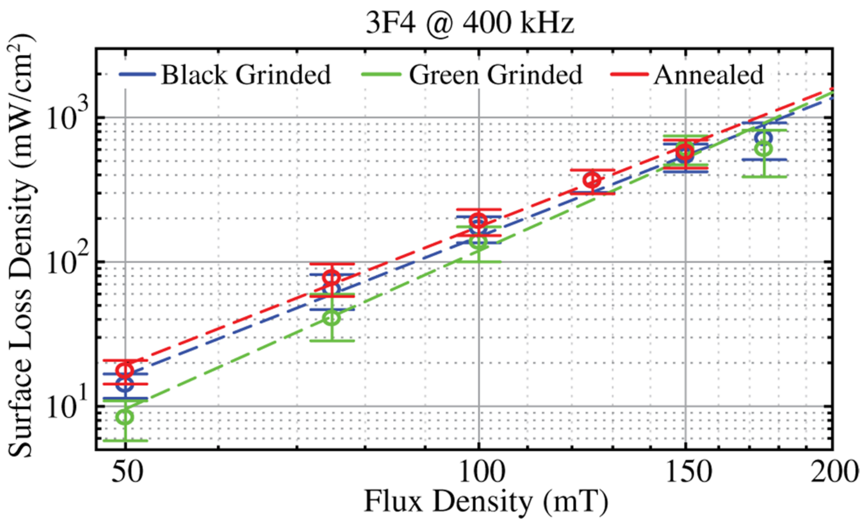
▲ 3F4 Solid Sample Temperature Rise – 100 mT / 400 kHz



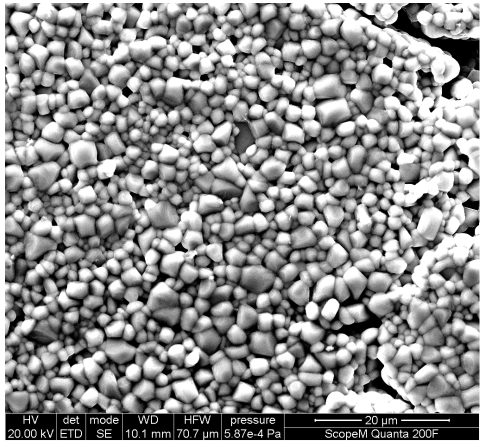
▲ 3F4 MAG Sample (7 x 3mm) Temperature Rise – 100 mT / 400 kHz

► Experimental Results – Treatments To Reduce Surface Loss

■ **Post Machining Treatments To Reduce Surface Loss**
- Polishing And/Or Etching Of Plates To Remove Deteriorated Surface Layer
- Heat Treatment To Release. Mech. Stress
- Green Grinding - Machining Before Sintering Of Plates



▲ Post. Processing Treatments To Reduce Surface Loss
Black Grinded – Machined after Sintering (Reference Sample)



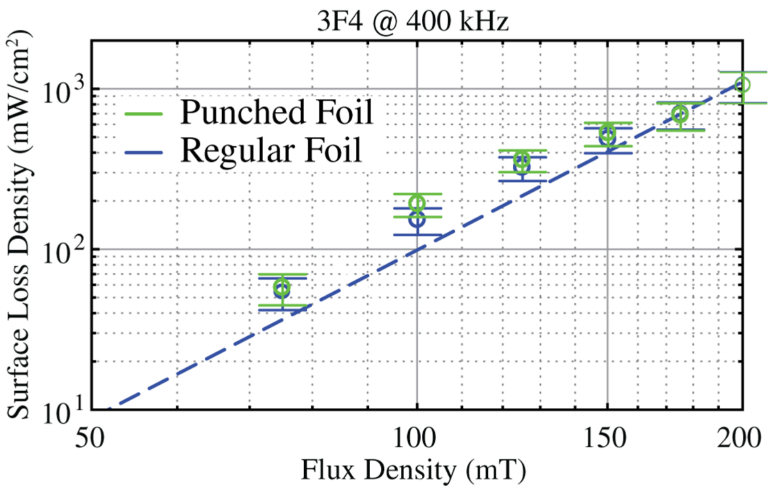
▲ SEM OF Green Grinded Plate Surface
(Grinding Prior To Sintering)

■ **Green Grinding Reduces Surface Loss By ≈ 40 % In The Range Of 50 mT – 100 mT**
■ **No Improvement With HCL Etching and Annealing So Far (Still Under Investigation)**

► Experimental Results – Losses Caused By Microvibrations?

- **Magnetostriction Causes Vibration Of Plates**
  - Mech. Friction Between Mylar Foil (Gap Material) And Ferrite
  - Power Dissipation Caused By Friction Between Surfaces

- **Hypothesis: Red. Tot. Area Of Mylar Foil → Red. Of Loss**
  - Use Punched Foil To Still Ensure Correct Distance Between Plates



▲ Punched Mylar Foil

- **Contradicted By Experimental Evidence**
  - Magnetomechanical Interaction Of Ferrite Surface With Gap Material Is Not Causing The Losses