Characterization and Impact of Large-Signal Dielectric Properties in MnZn Ferrites

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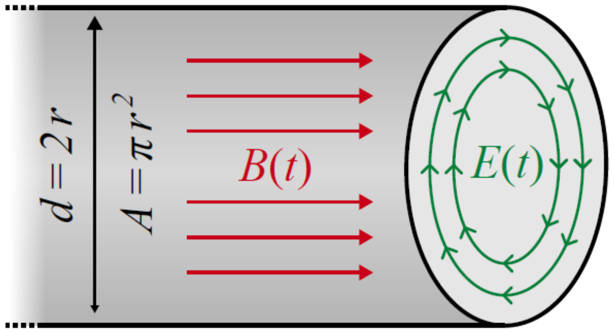
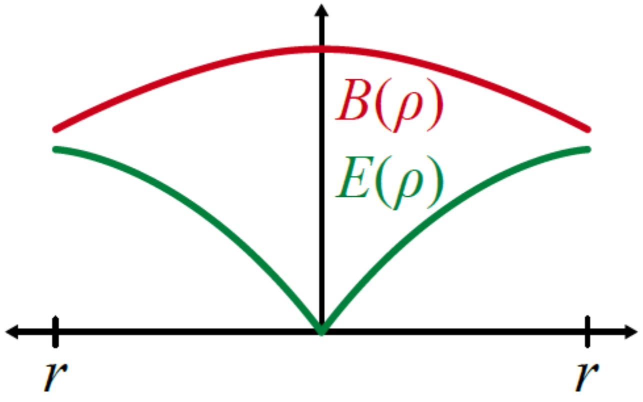
DARTMOUTH ENGINEERING

Introduction

- **Ferrite material**
  - Low losses & wide frequency range
  - Broadly used in power magnetics
- **Dielectric effects**
  - Varying magnetic field ⇒ induced electric field
  - Induced electric field ⇒ eddy-current & dielectric effects
  - Dependent of the core shape and size
- **Dimensional resonance**
  - $\mu_r \in [500, 5000]$ and $\varepsilon_r \in [10^4, 10^6]$
  - Extremely slow propagation speed
- **Impact on the core performance?**

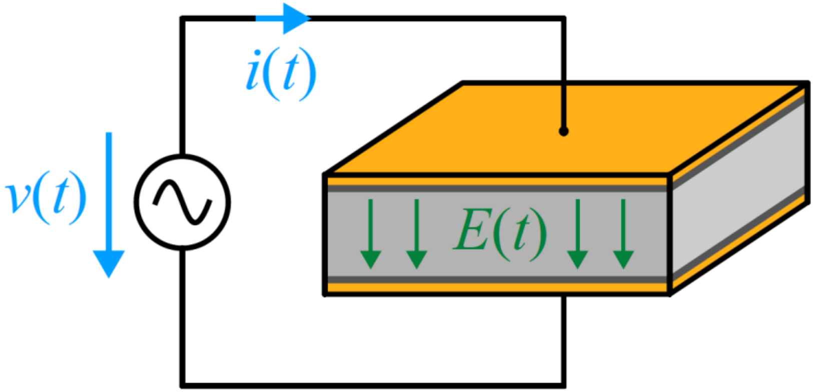




Characterization of the Dielectric Properties

Plate Capacitor Setup

- Ferrite **plate capacitor**
- Ferrite has a very **low conductivity**
- **Pressure contact**
  - Difficult to obtain a reliable contact
  - Mechanical stress is changing the ferrite properties
- **Chemical contact**
  - Silver (epoxy / colloidal) or carbon paint
  - Difficult to obtain a reproducible low-ohmic contact
  - Contact is non-linear (observed with silver)
  - Contact is humidity-dependent (observed with silver)
- **How to obtain good contacts?**

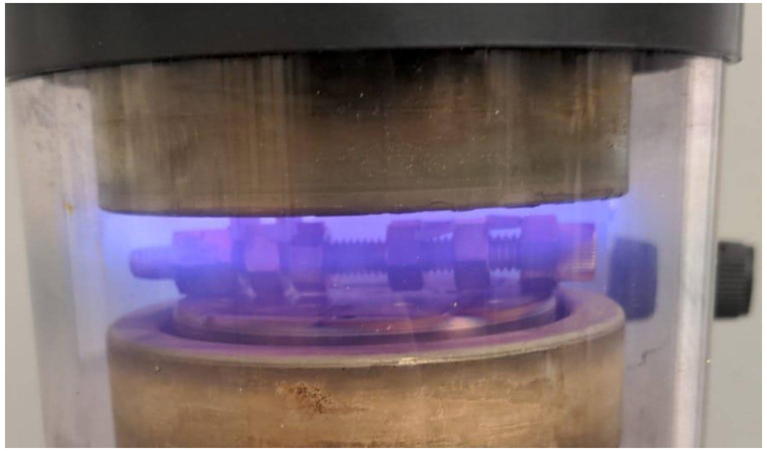


[Ted Pella]

[MG Chemicals]

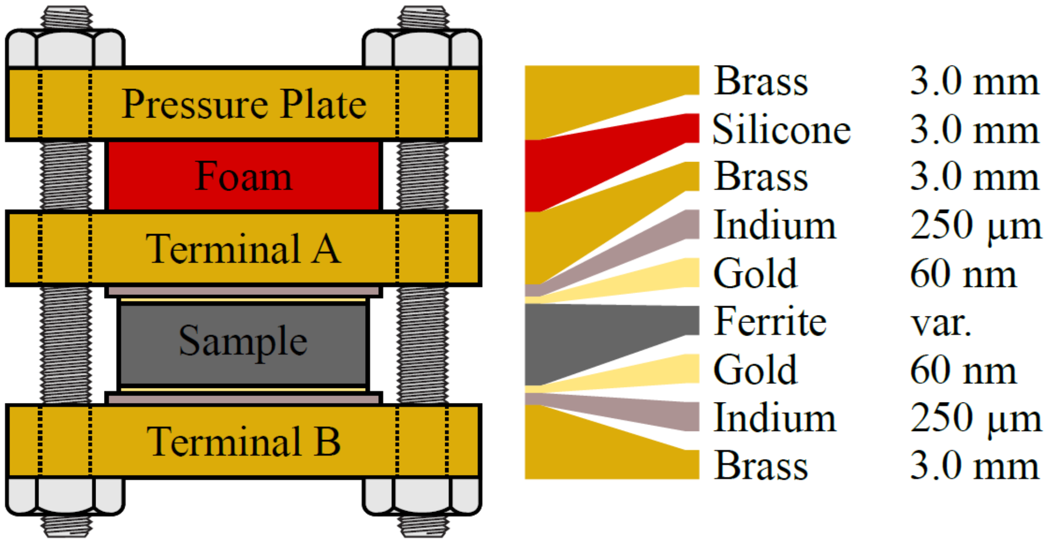
Gold Sputtering

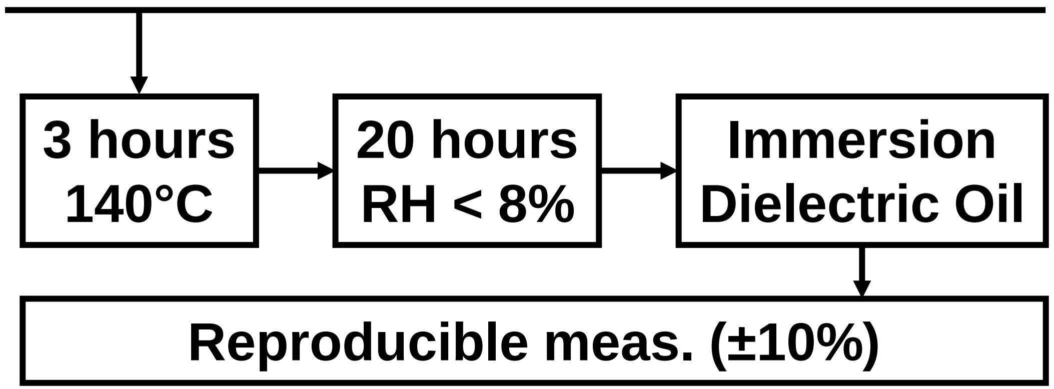
- **Sputter coater**
  - Plasma with low-pressure argon
  - Typical process for SEM
- **Advantages**
  - It’s shiny!!!
  - Cold process
  - Gold is non-reactive
  - No surface tension
  - Coating of the individual grains
- **Deposition: 60 nm of gold**



Test Fixture

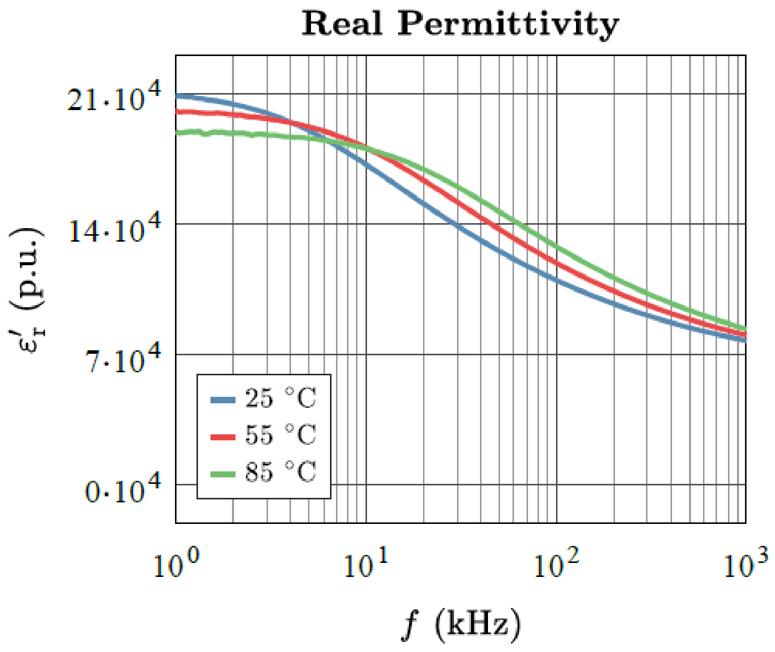
- **Ferrites** are **not** perfectly **flat**
- **Indium foil**
  - Malleable metal
  - Homogeneous contact
  - Thermally conductive
- **Mounting**
  - Brass: wiring and heat sink
  - Silicone: limit pressure
- **Conditioning**
  - Drying: reproducible condition
  - Oil: prevent humidity diffusion
  - Oil: temperature control

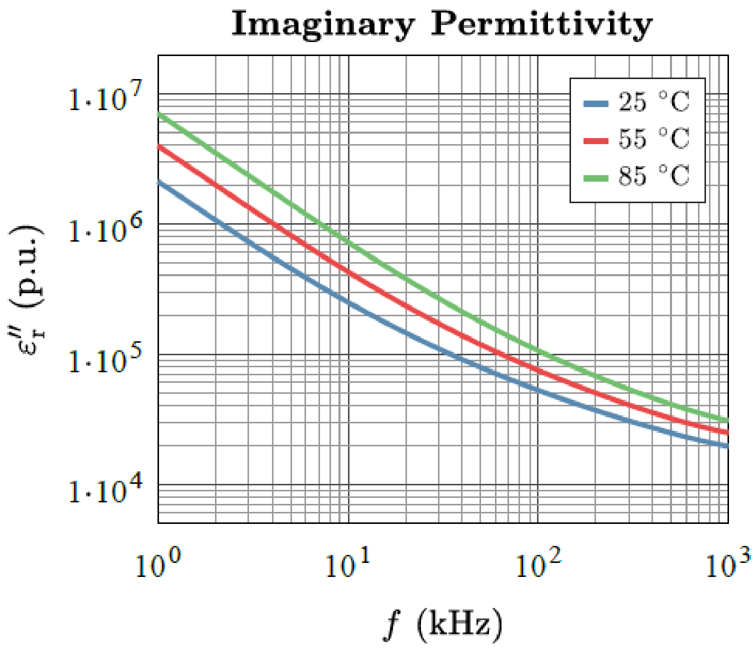


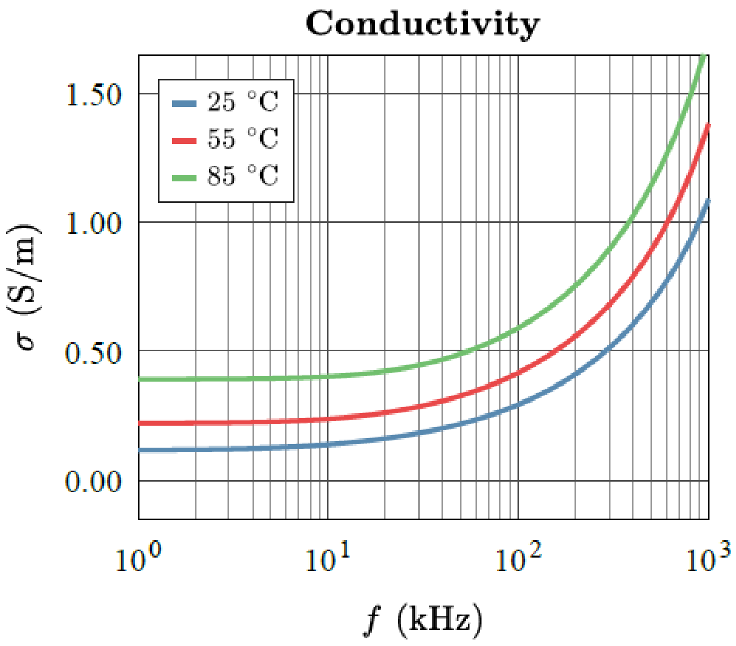


Small-Signal Properties

- **EPCOS/TDK N87**
  - Impedance analyzer
  - $\hat{E} < 0.05\ \mathrm{V/mm}$
- **Permittivity**
  - Extremely large
  - Decrease with frequency
- **Conductivity**
  - Increase with frequency
  - Increase with temperature



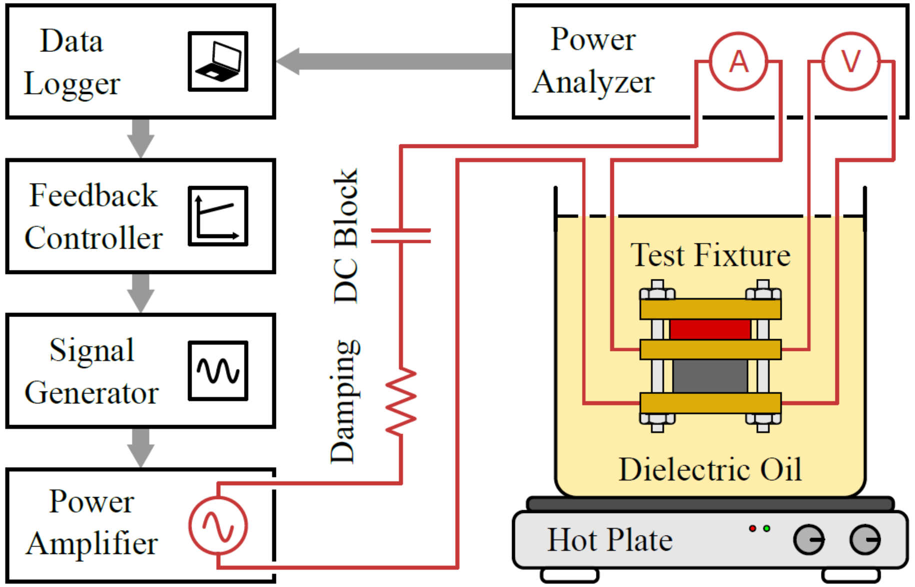


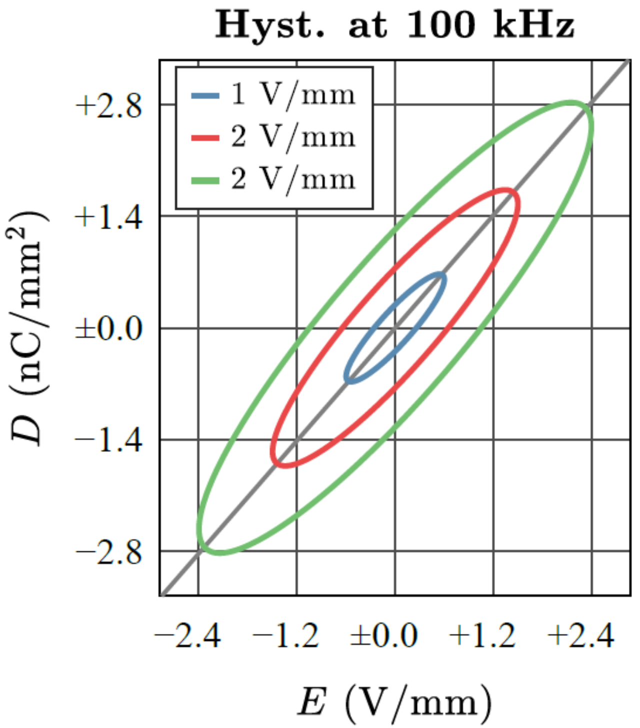


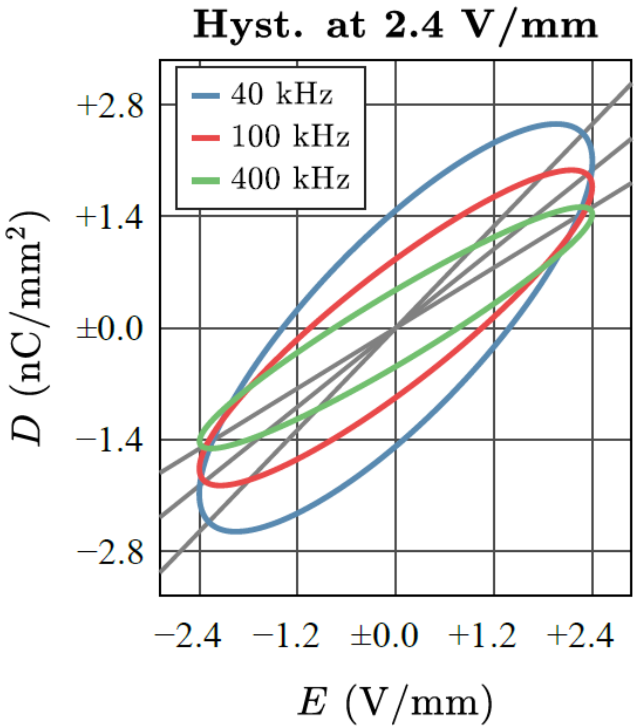
$$\boxed{\sigma = \varepsilon_0 \varepsilon_r'' 2\pi f}$$

Large-Signal Measurements

- **EPCOS/TDK N87**
  - Power analyzer
  - Power amplifier
- **Amplitude variation**
  - Ellipsoid hysteresis loops
  - Permittivity is mostly linear
- **Frequency variation**
  - Permittivity is dropping
  - Loss per cycle is dropping

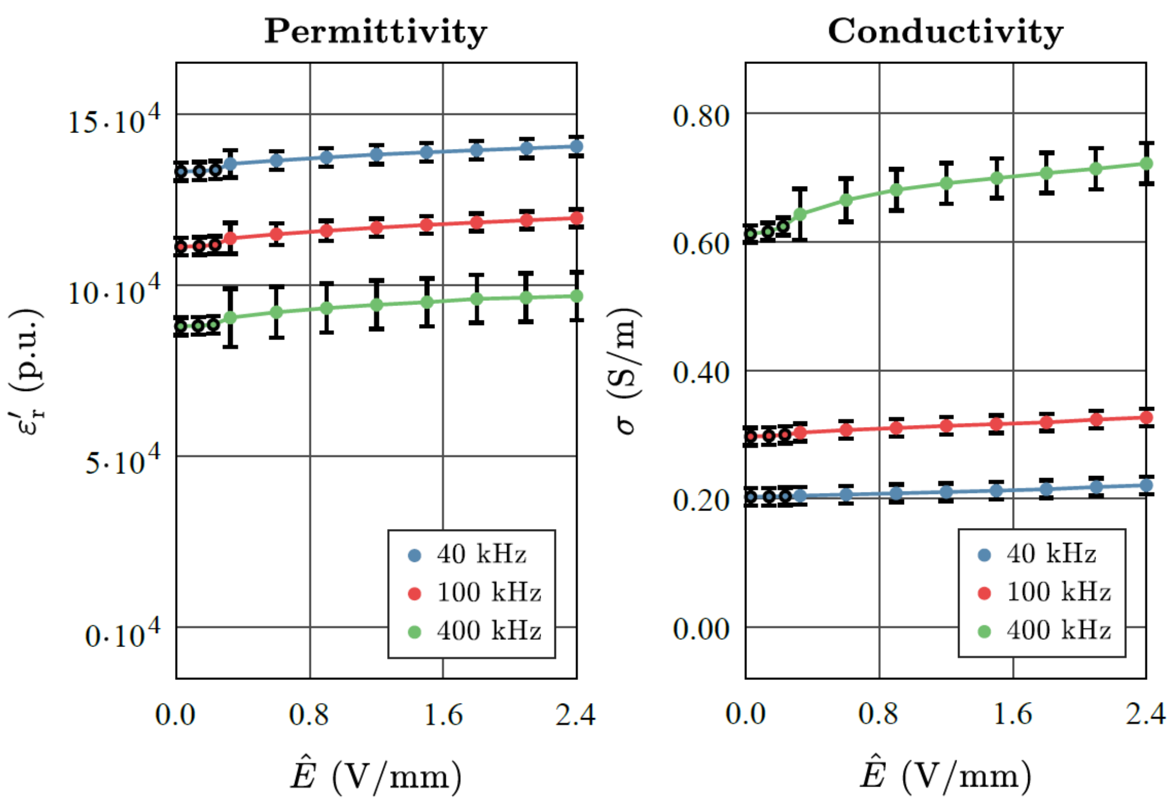






Large-Signal Measurements

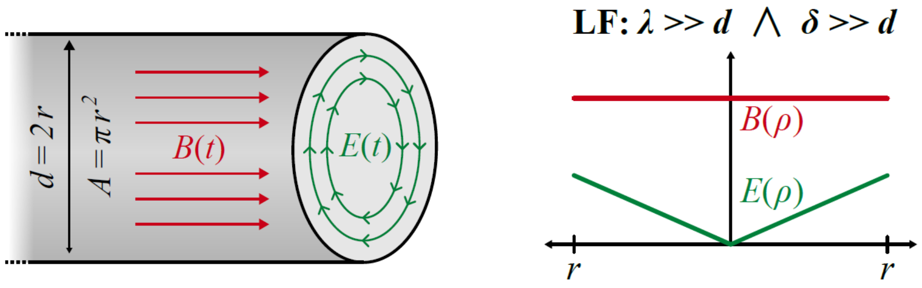
- **Permittivity**
  - Decrease with the frequency
  - Almost amplitude independent
- **Conductivity**
  - Increase with the frequency
  - Slight increase with the amplitude
  - Consistent with microscopic models
  - Increased conductivity ⇒ increased losses
- **EPCOS/TDK N87: slightly non-linear**

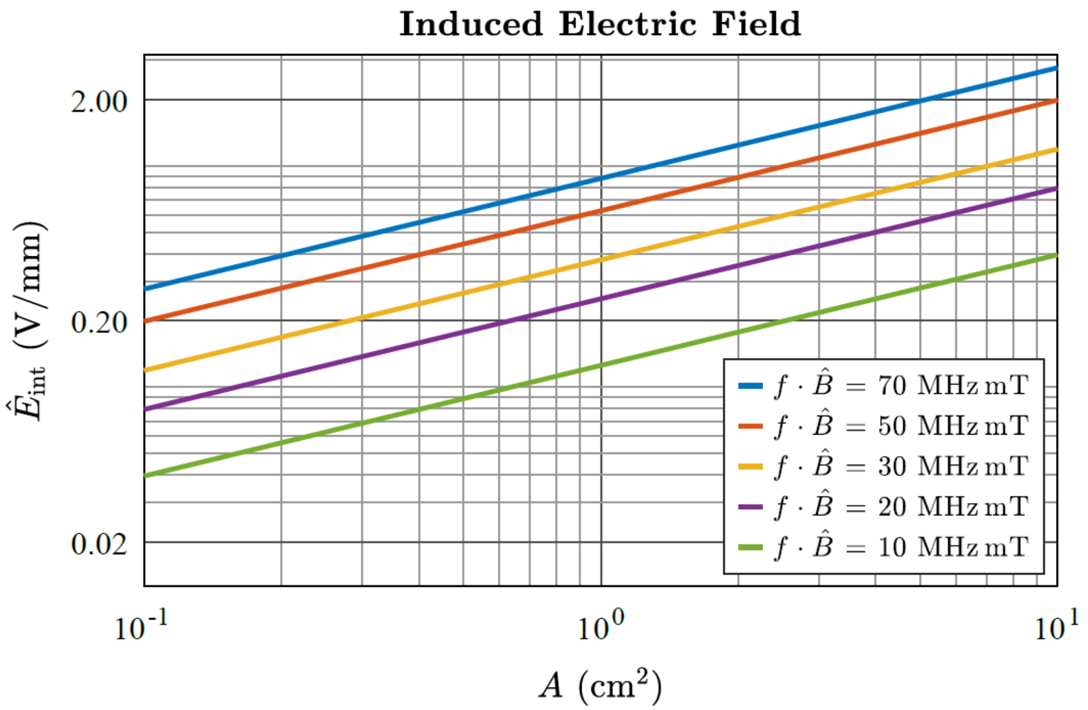


Impact of the Dielectric Properties

Induced Electric Field

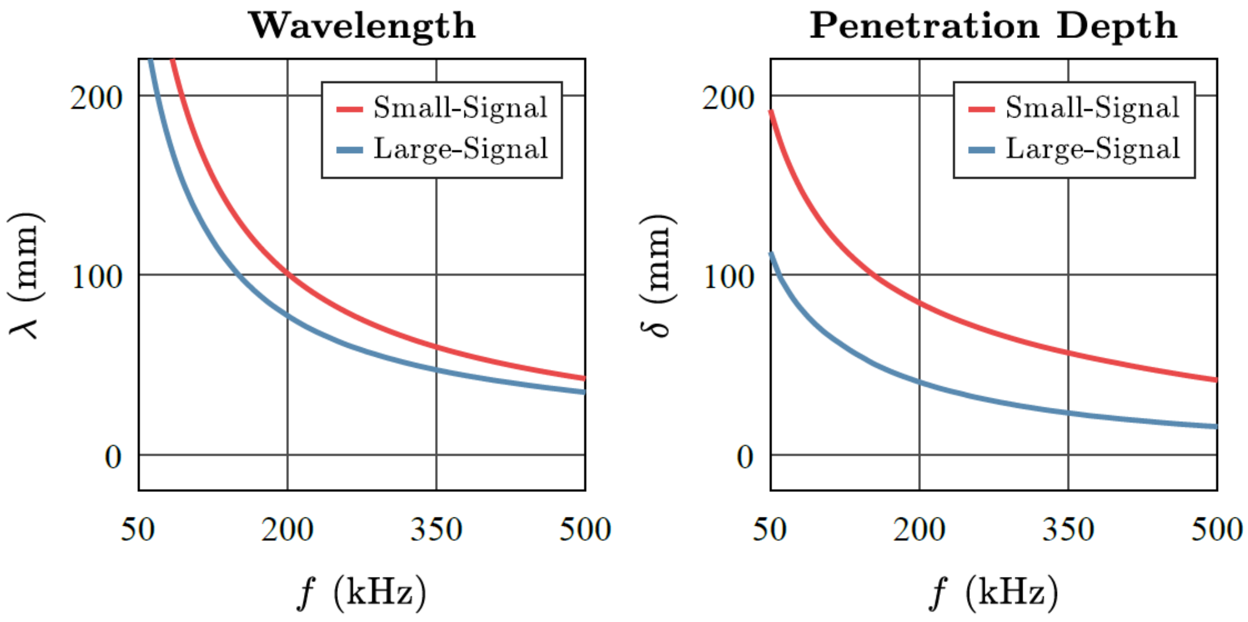
- **Ferrite cylinder**
  - Homogeneous magnetic flux
  - Faraday’s law of induction
- **Electric field distribution**
  - Quasi-static approximation
  - Linear increase with the radius
  - Spatial RMS value of the field
  - $\hat{E}_{\text{int}} = \sqrt{\frac{1}{A}\iint \left|\hat{E}\left(\rho\right)\right|^2 \mathrm{d}A}$
- **Induced field: up to 2 V/mm**
- **Corresponds to the meas. range**





Dimensional Resonance

- **Fundamental principle**
  - Varying magnetic flux ⇒ induced el. field
  - Induced el. field ⇒ el. eddy current
  - El. eddy current ⇒ magnetic field
- **Characterization**
  - Wavelength (lossless resonance)
  - Penetration depth (loss damping)
  - $k = 2\pi f \sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r} = \frac{2\pi}{\lambda} - \mathrm{j}\frac{1}{\delta}$

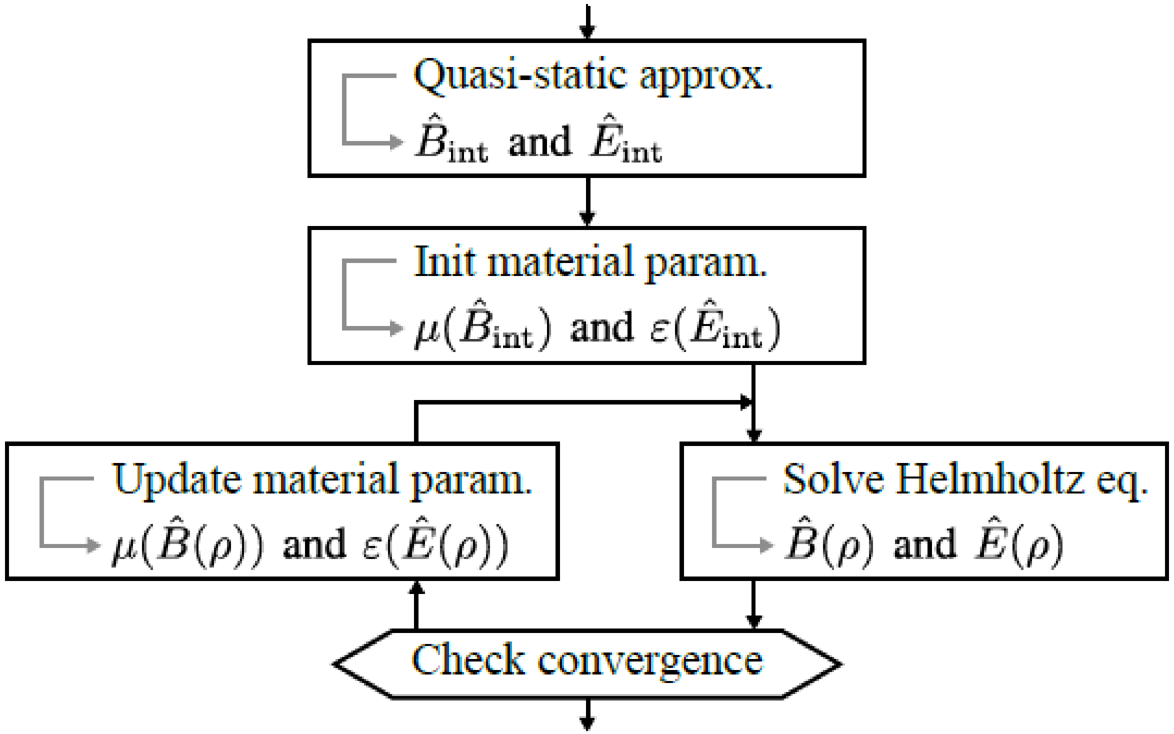


[EPCOS/TDK N87, $A = 5\ \mathrm{cm}^2$, $\hat{B} = 100\ \mathrm{mT}$]

- **Resonances are more critical with large-signal models**
- **Mostly due to the non-linear permeability**

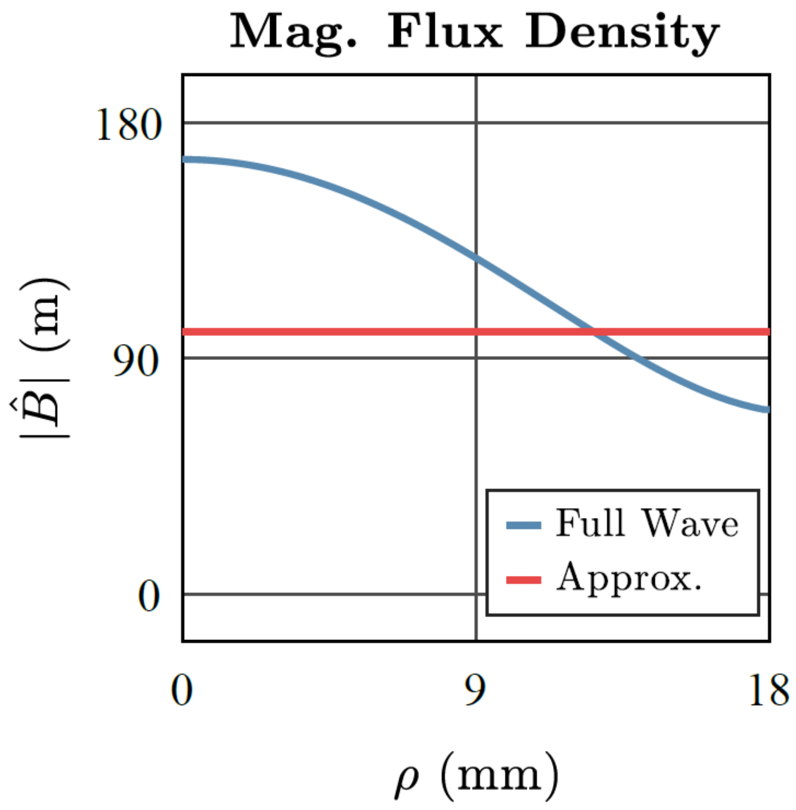
Field Calculation

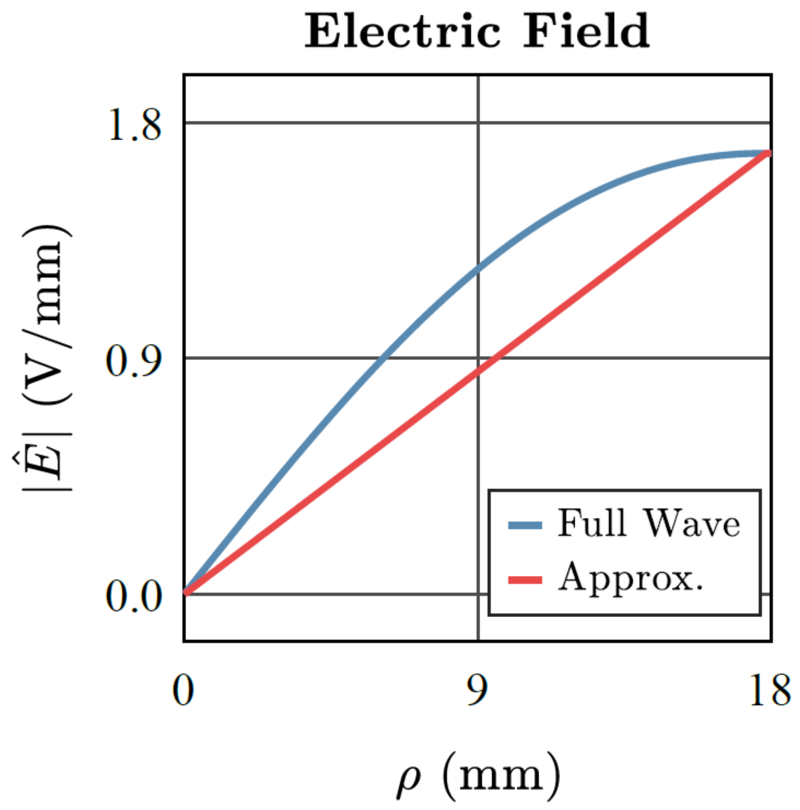
- **Quasi-static approximation at LF**
- **Helmholtz wave equation at HF**
  - $\nabla^2 \vec{E} = -k^2 \vec{E}$
  - $\nabla \times \vec{E} = -\mathrm{j}2\pi f \vec{B}$
  - $\left| \iint \vec{B} \cdot \mathrm{d}\vec{A} \right| = \hat{B}_{\mathrm{src}} A$
- **Material parameters**
  - Large-signal parameters
  - Spatially-dependent
  - Locally linearized



Electric / Magnetic Field Distribution

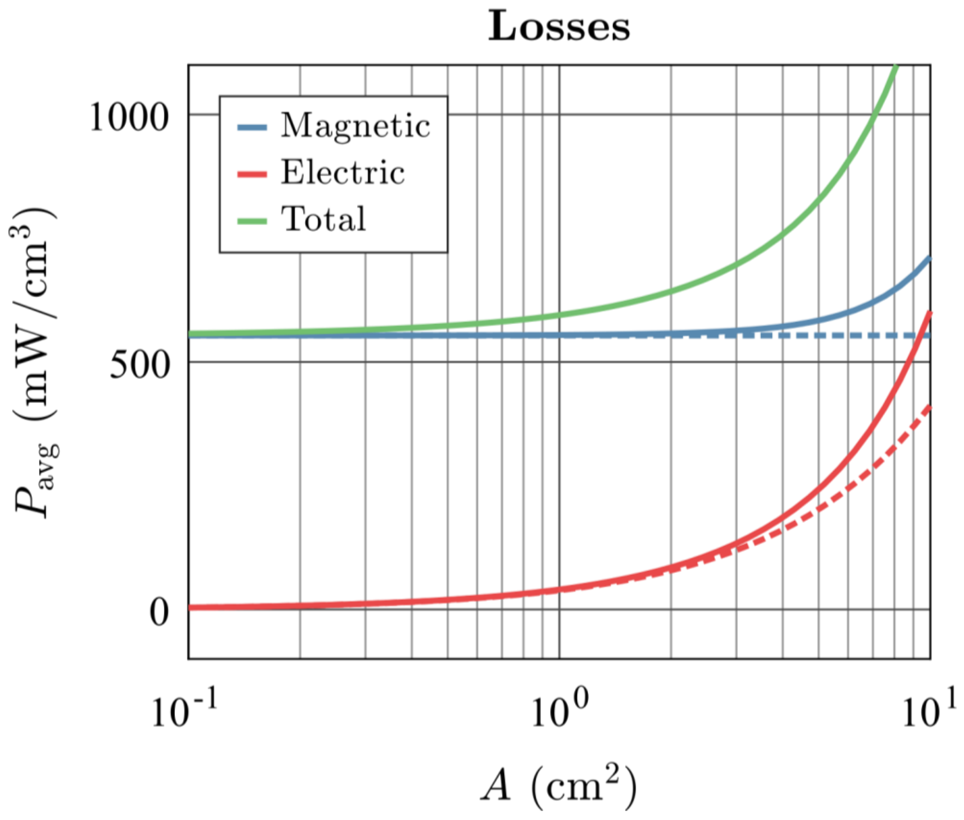
- **EPCOS/TDK N87**
  - 10 cm^2 cross section
  - 300 kHz and 100 mT
- **Comparison**
  - Quasi-static approximation (red)
  - Full-wave solution (blue)

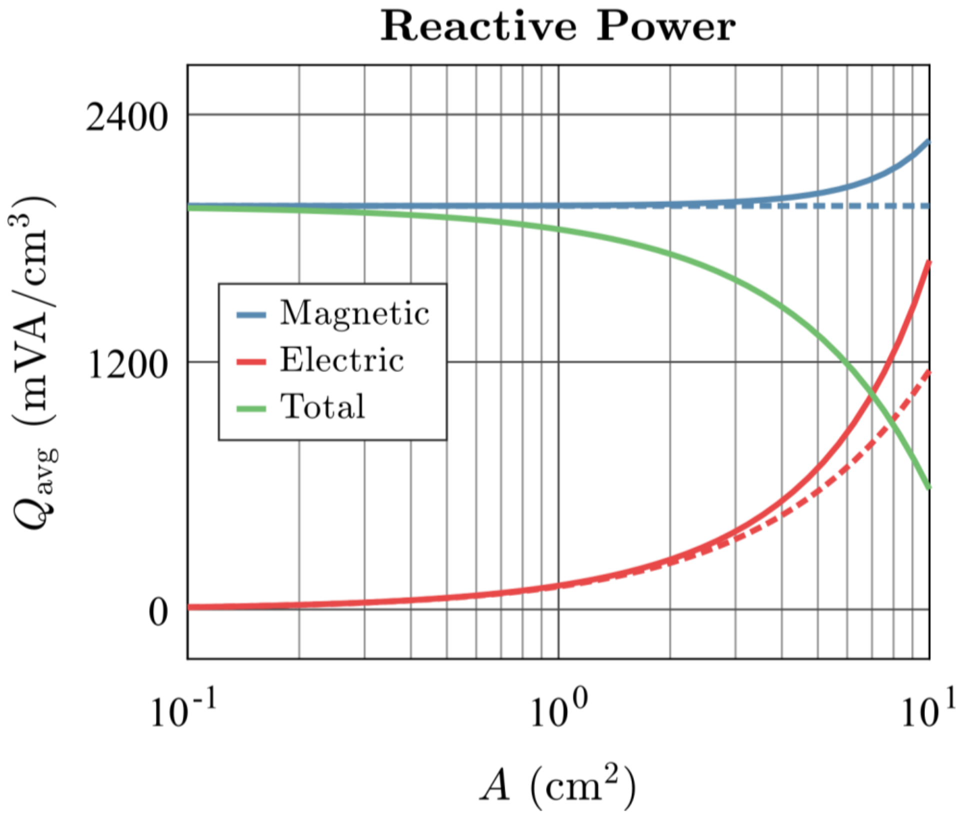




Impact of the Dielectric Effects

- **EPCOS/TDK N87**
  - Variable cross section
  - 300 kHz and 100 mT
- **Comparison**
  - Quasi-static approximation (dotted)
  - Full-wave solution (solid)





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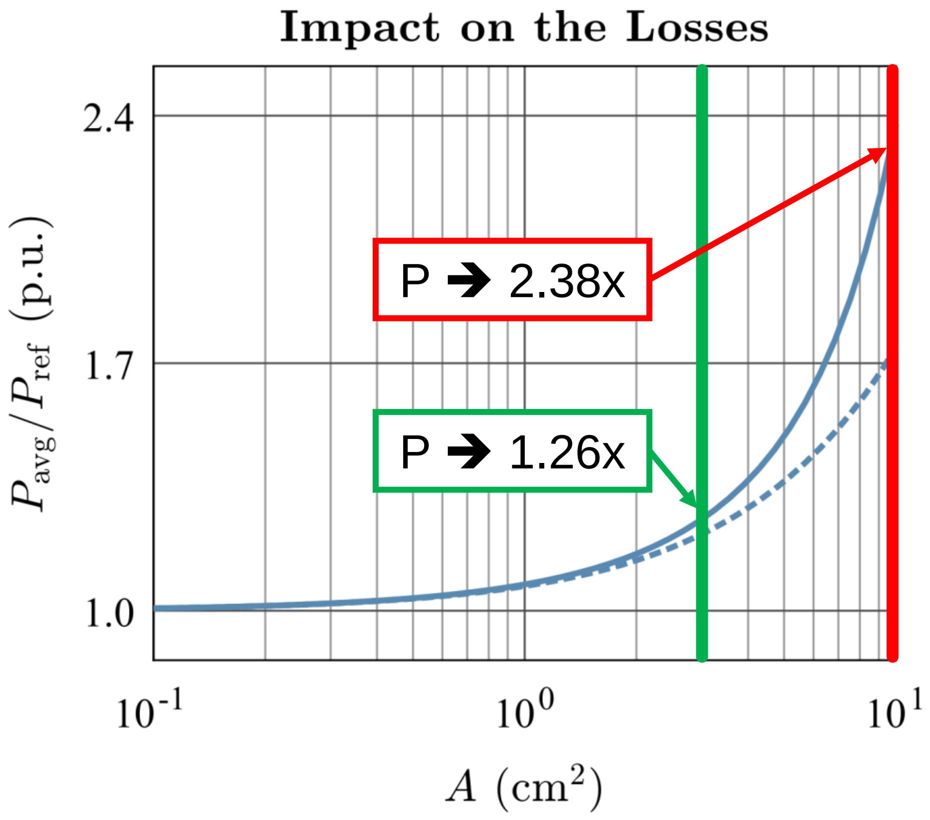

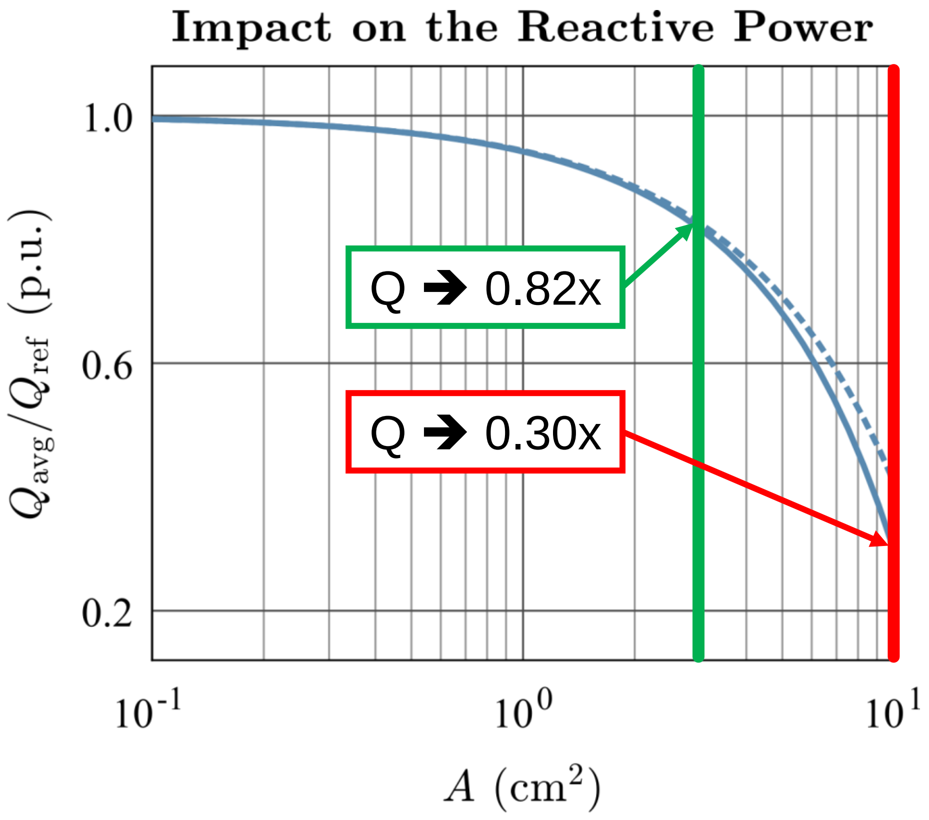

Conclusion

Conclusion

- **Measurement of dielectric properties**
  - Test fixture and conditioning are critical
  - Gold sputtering / indium foil / oil

- **Large-signal dielectric properties**
  - Increase of the conductivity with amplitude
  - Non-linearities are not massive

- **Dimensional effects**
  - More critical with large-signal parameters
  - Helmholtz wave equation with large-signal parameters
  - With dimensional resonance: more than 100% additional losses
  - Below dimensional resonance: up to 25% additional losses

Dataset & Code

GitHub

github.com/otvam/large_signal_ferrite_apec24

zenodo

doi.org/10.5281/zenodo.10059533

Thank you!
Questions?

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