TEXAS
The University of Texas at Austin

Multi-MHz Magnetics Off and On Chip

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2024 Power Electronics and Energy Conversion Workshop
at Sandia National Laboratories

The MHz Barrier

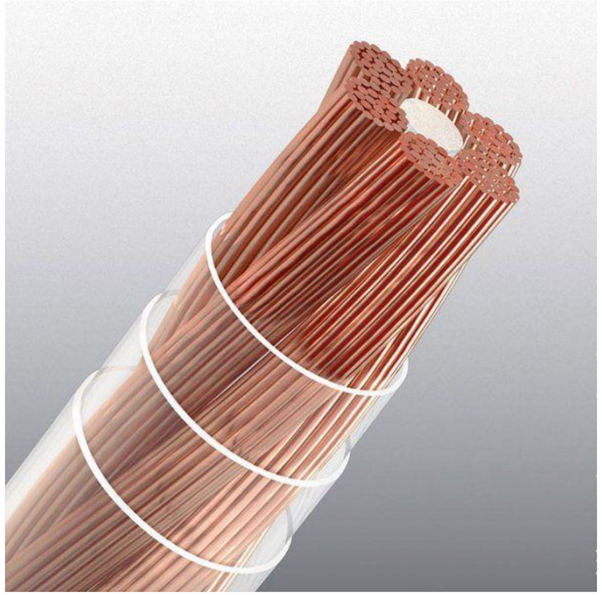
Power electronics switching frequencies are approaching or have surpassed 1 MHz at power levels <1 W and >100 kW

There are a bunch of things that ***don't work*** or that we ***don't know*** (well) about designing magnetics past a few MHz

- What core materials are good? [1] What metrics constitute "good"? [2]
- How should core loss and full component losses be measured? [3-4]
- **How can ac copper loss be mitigated? [5-10]**
- What do we do about dimensional resonance? [11]
- When should air core components be used? [2,12]
- **What can be achieved with IC integration?**

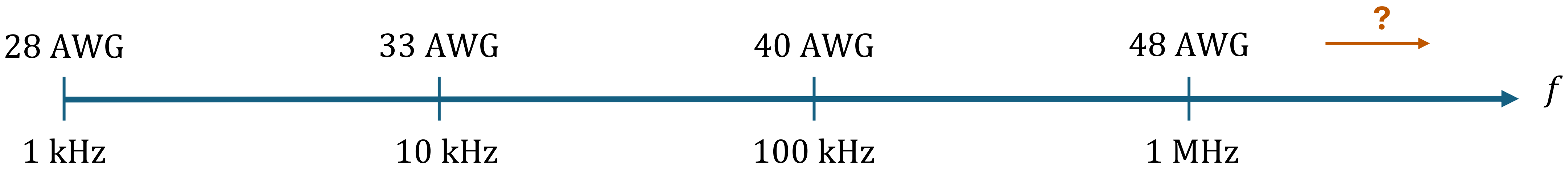
Managing copper loss in the MHz regime

Braided parallel strands of wire (litz wire) with D_{strand} < Skin Depth can suppress the skin and proximity effects at hundreds of kHz



48 AWG is already very expensive and only good up to a few MHz.

Litz will not save us in the MHz regime!



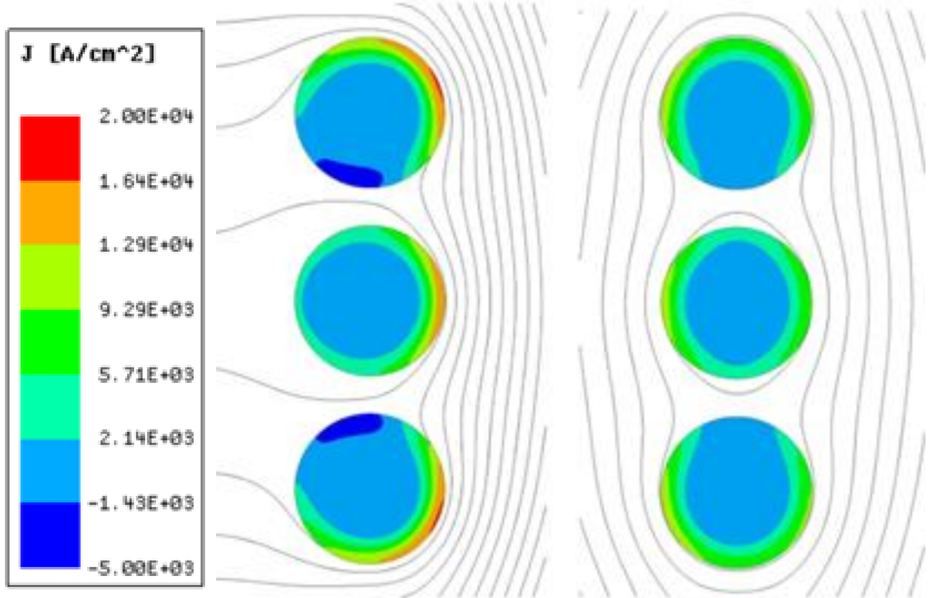
Where does current actually flow at HF?

High-frequency current flows within a single skin depth of the surface of a conductor **where the H field is strongest.**

The terms “skin effect” and “proximity effect” are deeply misleading.

- They both come from solving the magnetic diffusion equation. Separating them is artificial
- The true “skin effect” is almost never encountered. Current only flows evenly over the entire surface in the case of a circular conductor in isolation.
- The “proximity effect” has very little to do with proximity. Conductors being close to each other does not necessarily increase the proximity effect

Just remember that current crowds near strong H fields.



Core Inside Core Both Sides

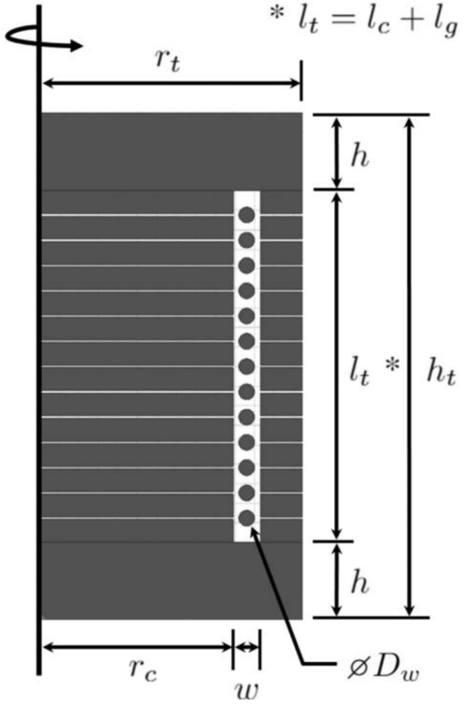
Double sided conduction in inductors

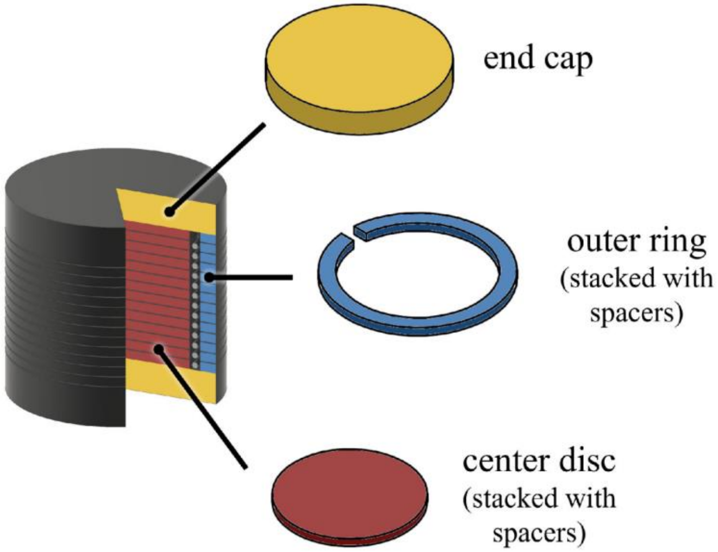
Consider a pot-core inductor with single-layer winding and the H fields adjacent to the conductors.

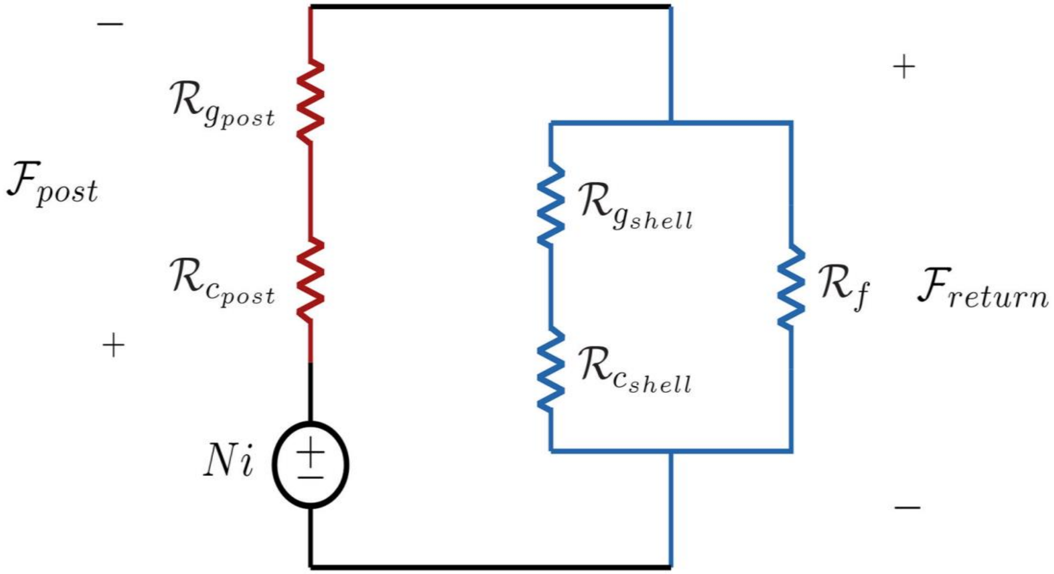
The H field up the inner side of the winding is $H_{inside} = \mathcal{F}_{post}/l_t$

The H field down the outer side of the winding is $H_{outside} = \mathcal{F}_{return}/l_t$

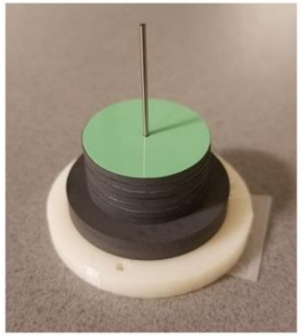
⇒ **To achieve $H_{inside} = H_{outside}$, we must engineer $\mathcal{F}_{post} = \mathcal{F}_{return}$**

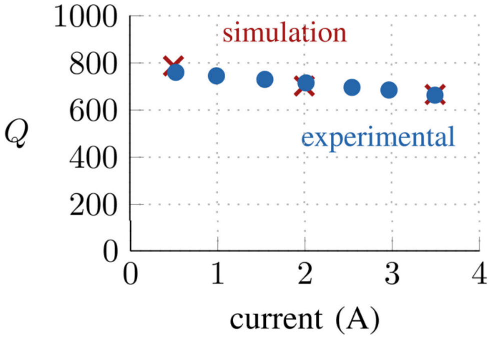


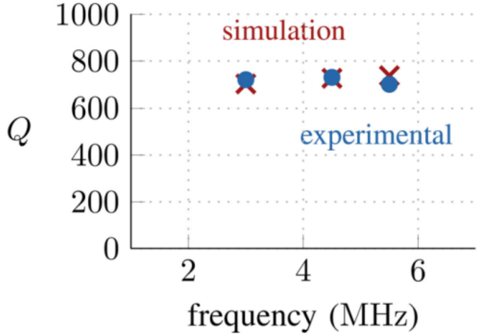


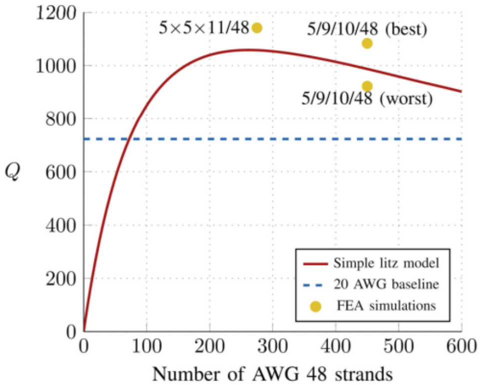


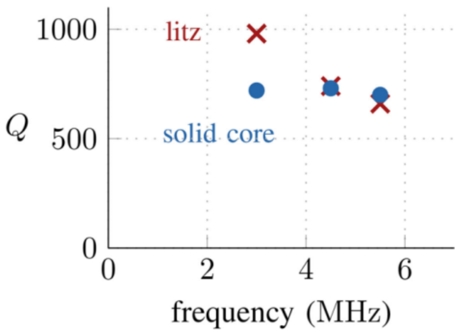
Inductor test results



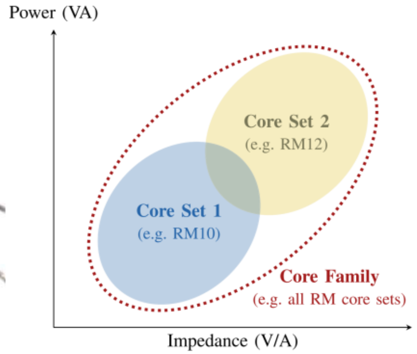






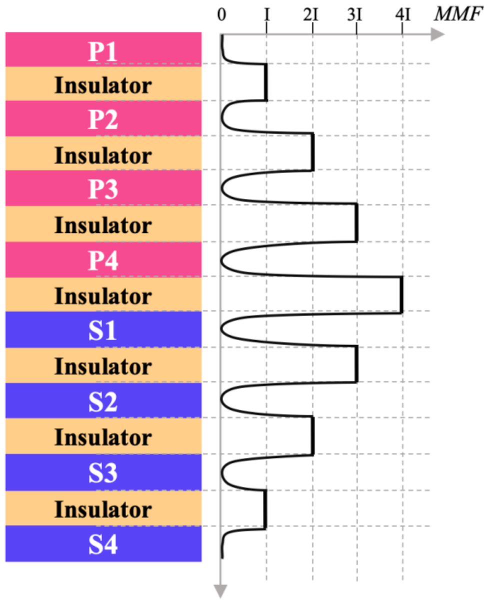


Prototypes achieved **quality factors of ~800** with solid-core wire and ~1000 with litz (but not at all frequencies!)



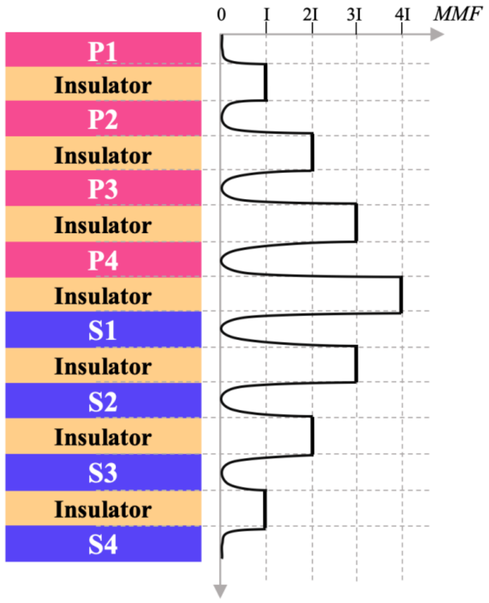
Designing for double-sided conduction revealed a **modular** inductor structure capable of covering a wider application space with fewer piece types to manufacture

Double sided conduction in transformers



(a) Non-Interleaved Winding

Double sided conduction in transformers



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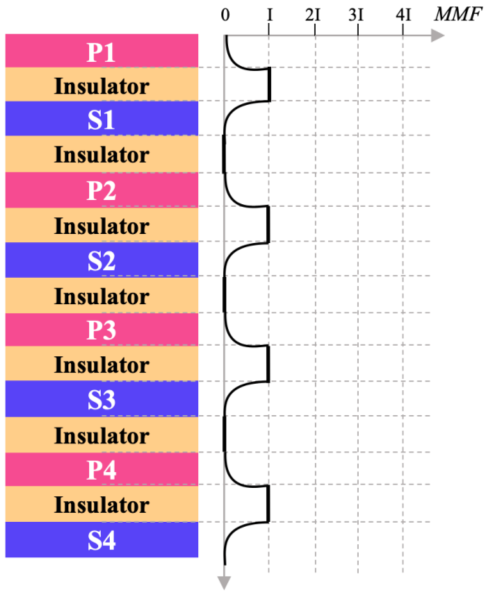
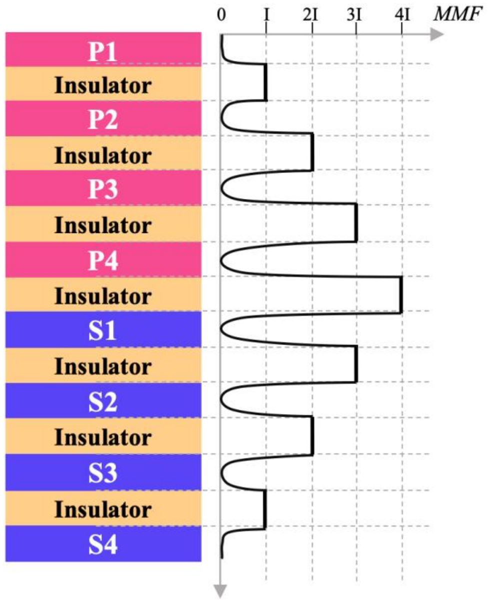


(b) Traditional Interleaved Winding

Double sided conduction in transformers



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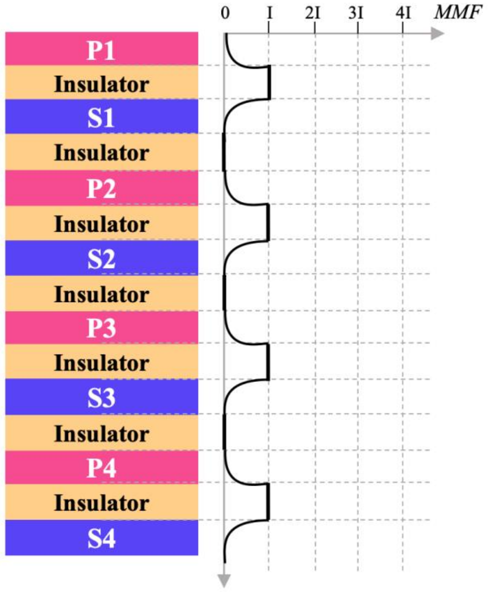
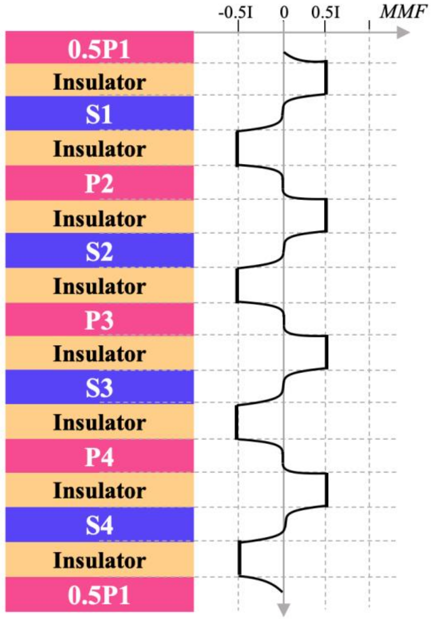
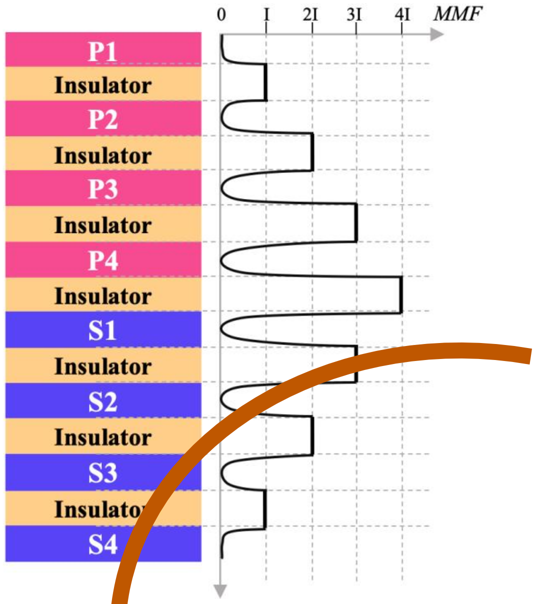


(b) Traditional Interleaved Winding



(c) Proposed interleaved 'Double Sided Conduction' winding

Double sided conduction in transformers



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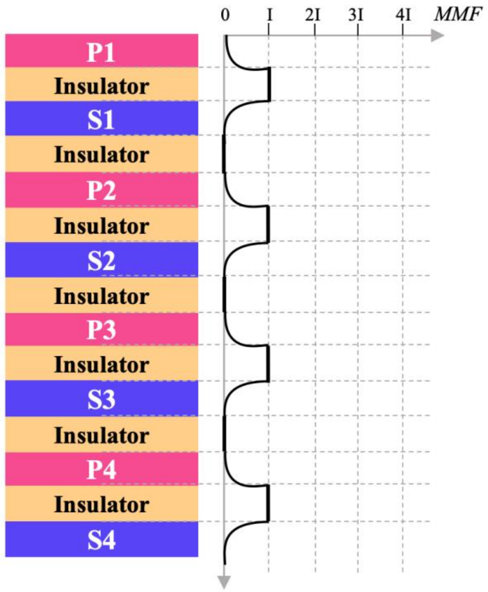

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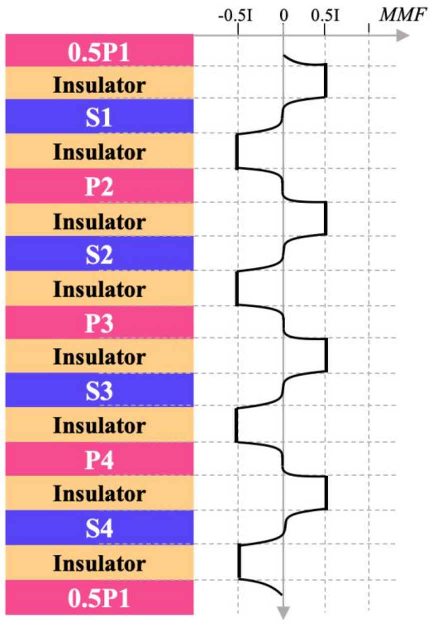

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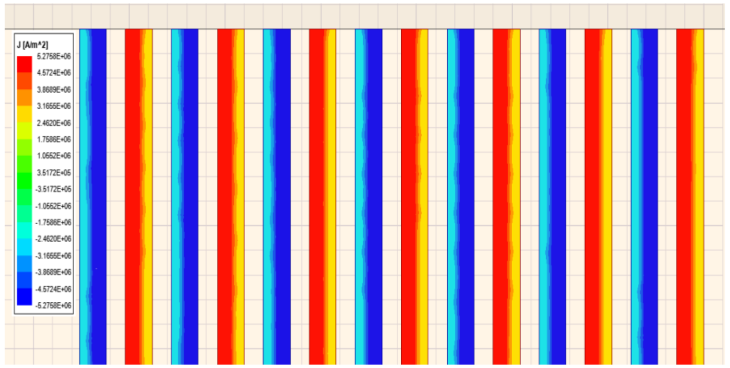
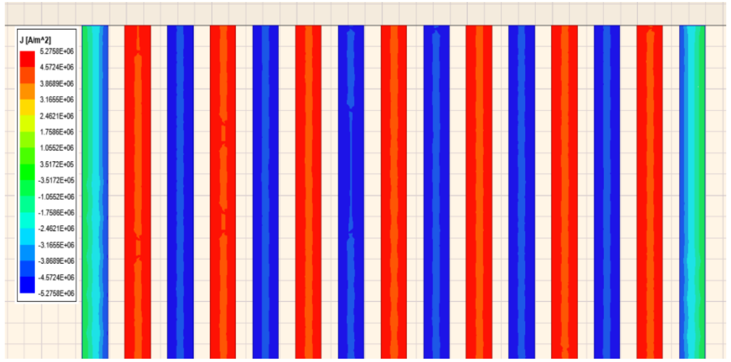


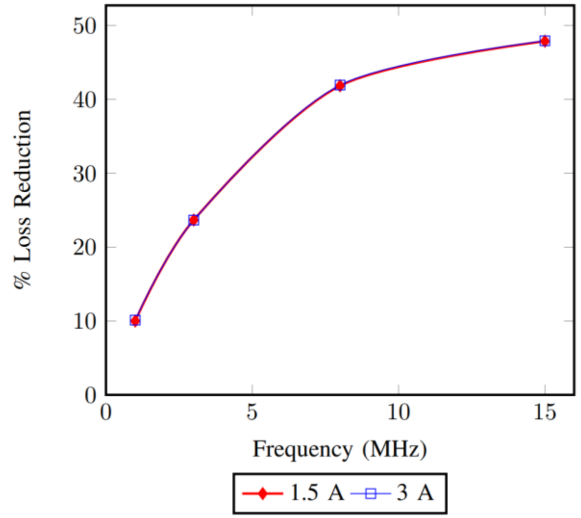


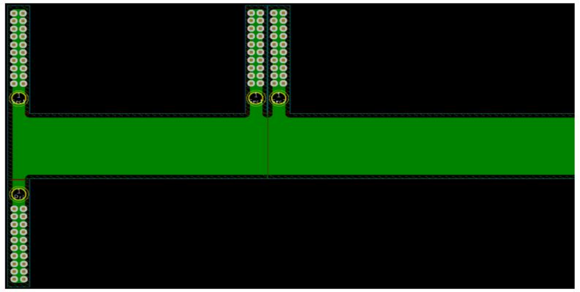
Transformer test results

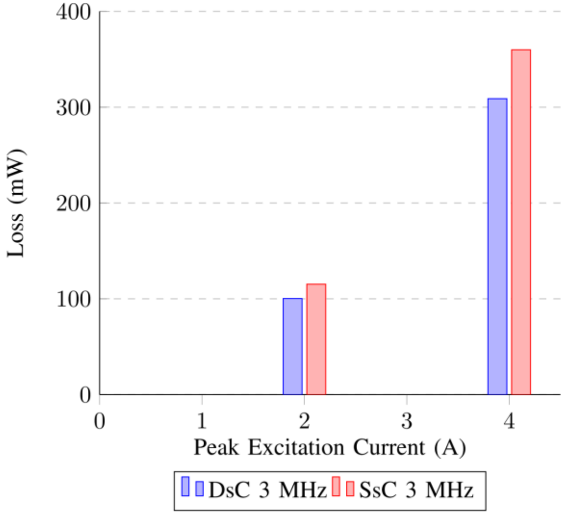
Copper loss reduces by 50% when skin depth limited.

Experimentally built with flexible PCB

Experimentally achieved ~20% loss reduction as expected at 3 MHz

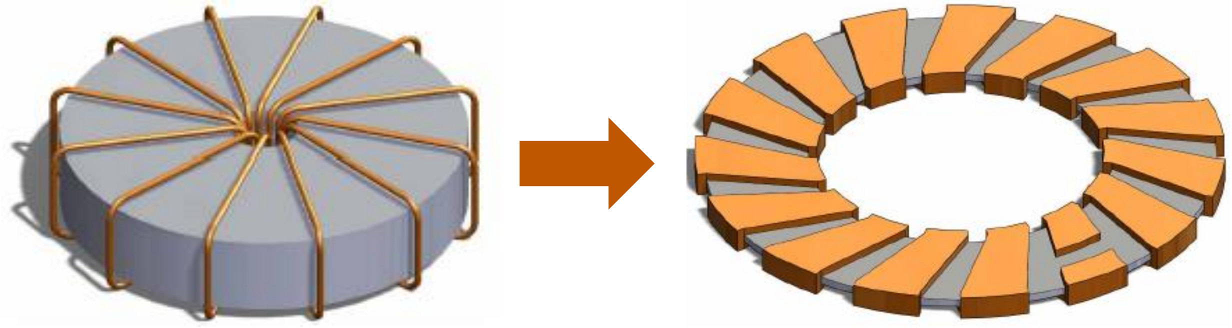




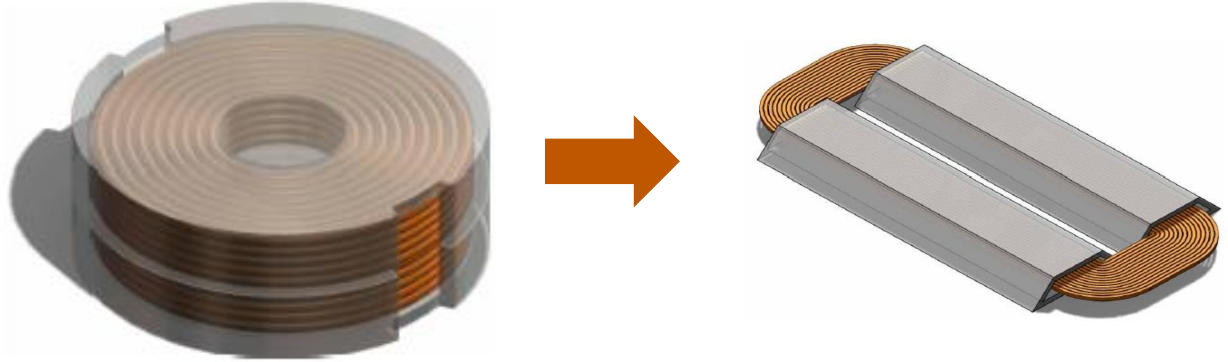


MHz Opportunity - Integration

Core-Type



Shell-Type



- Enables massive integrated processing
- Lower interconnect losses
- More conducive for high-volume fabrication

This is one of my favorite examples of a successful **collaboration**

- Prof. Alex Hanson, UT Austin – power electronics
- Prof. Jean Anne Incorvia, UT Austin – magnetic materials
- Dr. Jianliang Lin, Southwest Research Institute – oxide sputtering

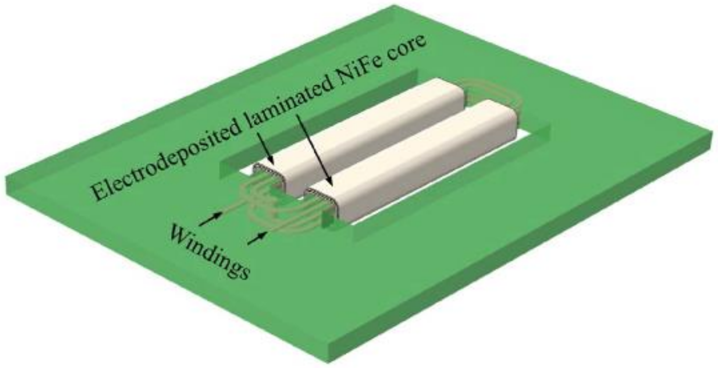
With funding from a UT Austin/SwRI seed grant
and a NASA NSTGRO fellowship

Fast growth or low loss?

Metallic

Fast electroplating

More eddy currents

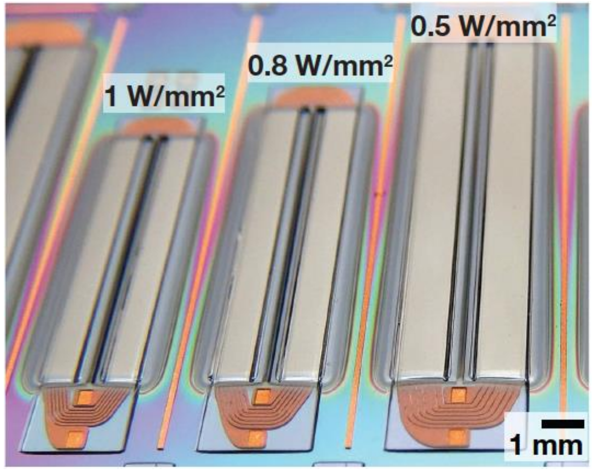


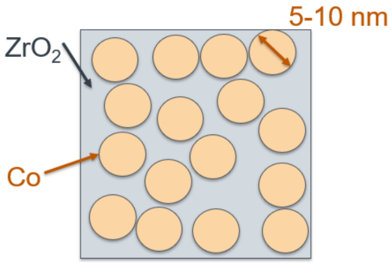
NiFe core material

Ceramic/Composite

Slow sputtering

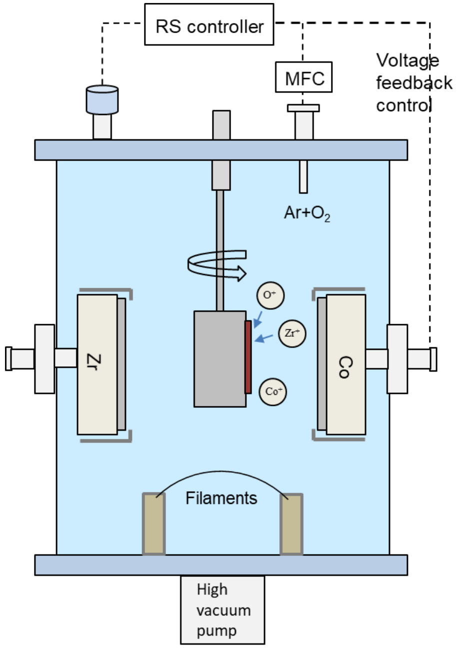
High resistivity

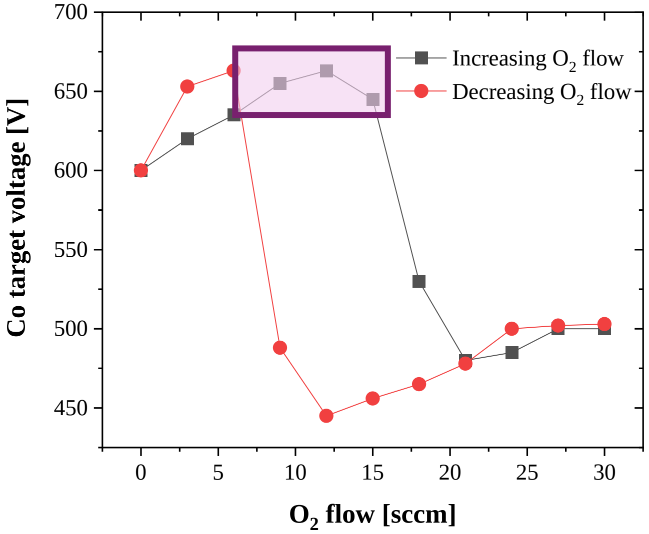




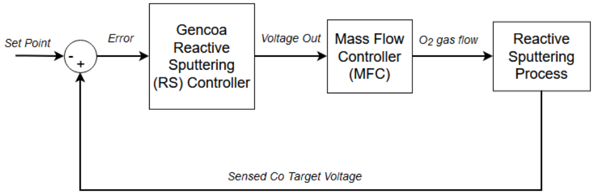
CoZrO core material

Improving sputter rate



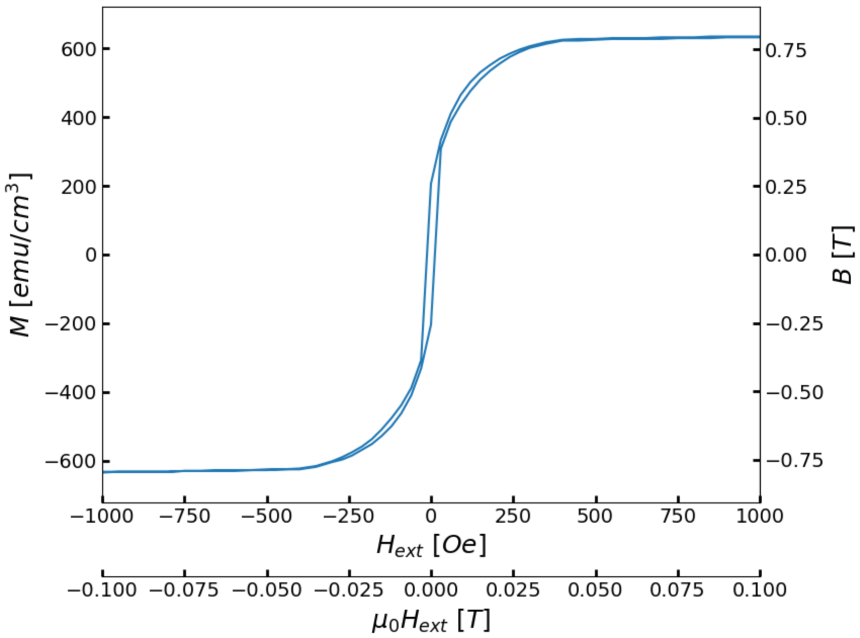


Study	Material	Deposition Rate (nm/min)
Kumar et al. [1]	Co	4.5
Cronin et al. [2]	CoZrTa	20.8
Harburg et al. [3]	CoZrO	20
Our System	**CoZrO**	**125**



4.6 hr vs. 29 hr to sputter 35 μm layer

Performance is not sacrificed



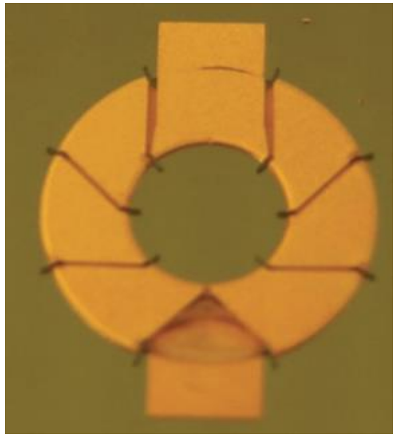
	Our Sample	**Harburg et al. [1]**
Co (%)	78.2	58.4
Zr (%)	9.3	7.1
O (%)	12.5	34.5
B_{sat} (T)	0.74	1.2
μ	57	80-100
H_c (Oe)	11.5	20

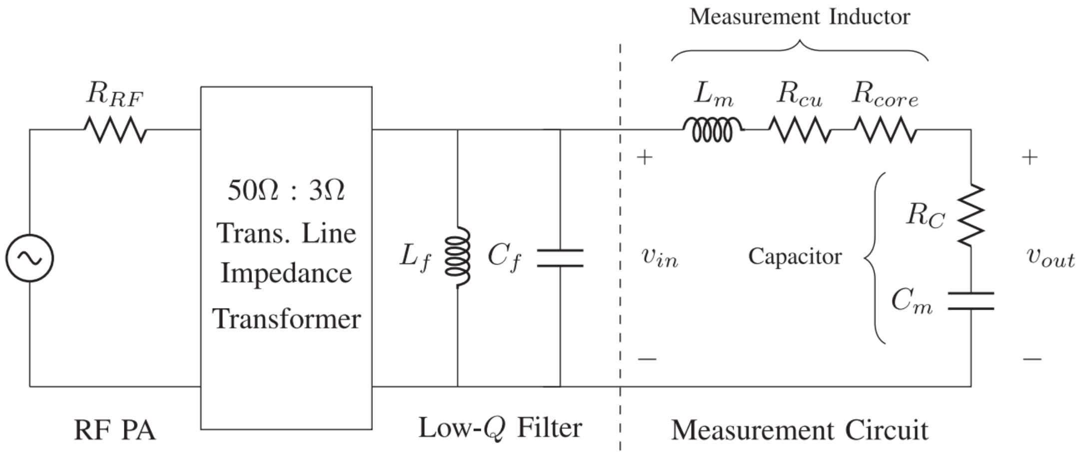
- High Saturation > 0.6 T (plenty)
- High Permeability (μ) ~ 60 (plenty)
- Low Coercivity (H_c) < 20 Oe

These are all *static* metrics. CoZrO really shines at high frequency

We will shortly test components at 10-50 MHz

- Components with CoZrO demonstrated excellent performance almost a decade ago. We aim to demonstrate similar or improved performance with materials that were more quickly grown
- Near-complete core-type (toroid, U-core) component process flow
- Resonant techniques for measuring loss at 10-50 MHz





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