High- Performance High-Power Inductor Design for High-Frequency Applications

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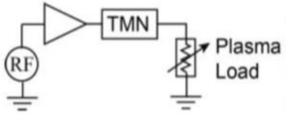
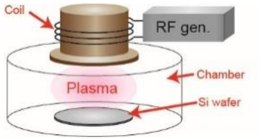
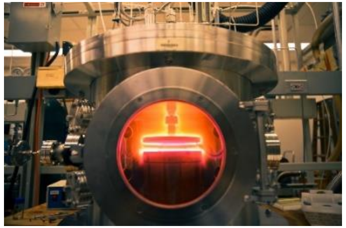
High-Power Inductors

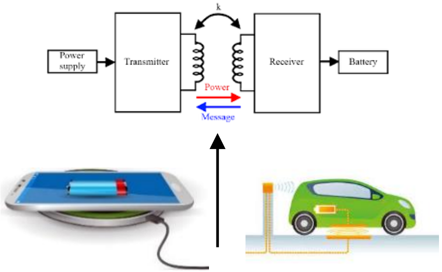
RF Plasma Generation





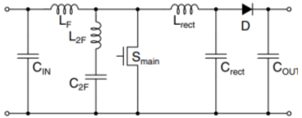


Wireless Power Transfer



HF (3-30 MHz) Applications

Switched Mode Power Converters



Air-core inductors dominate this application space due to the **design challenges** posed by **copper and core losses** in **cored magnetics** at HF

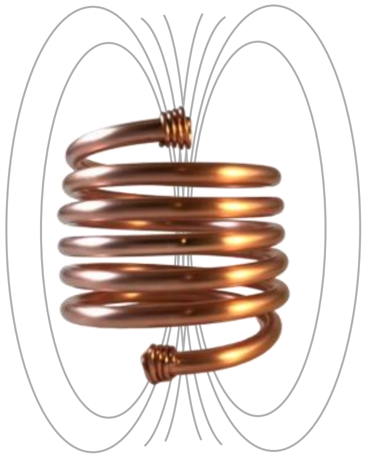
Air-core Inductors

Simple and easy to fabricate

Uncontrolled and unshielded fields lead to

- Electromagnetic Interference (EMI)
- Eddy current losses

Requires placement in a metal enclosure isolated from other circuit component



Bottleneck for system **miniaturization** and **efficiency**

HF Cored Inductors

High performance core material

NiZn Ferrite

Low-loss design techniques

Field Shaping

Quasi-distributed gaps

→ High Q

> 1100 at 10 Apk

Large fringing fields

EMI

Eddy current losses

500 nH 80 A_{pk} @ 13.56 MHz

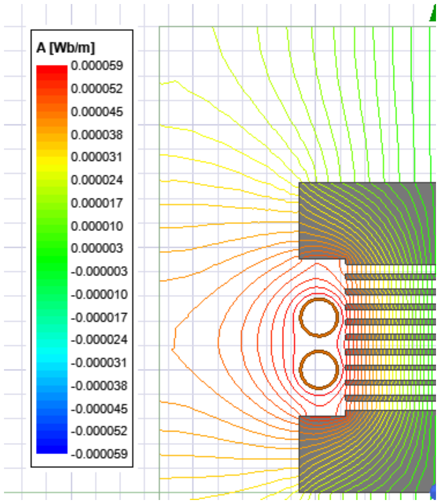


Image credit : R. S. Bayliss

Need HF cored inductors that are **efficient** and provide **self-shielding**

R. S. Bayliss et al. “Design, implementation, and evaluation of high-efficiency high-power radio-frequency inductors,” APEC, 2021.

Self-Shielded Inductor

Goal : Achieve **high Q** while ensuring **minimal external magnetic field**

- Design guidelines

  Modified pot core structure with an outer shield

  Low-loss design techniques

  Mitigating and modeling 3D effects

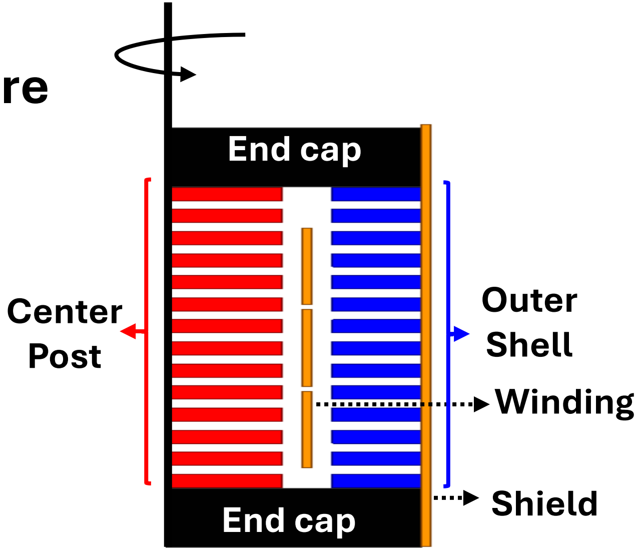
- Experimental verification
- Performance comparison to an air-core inductor

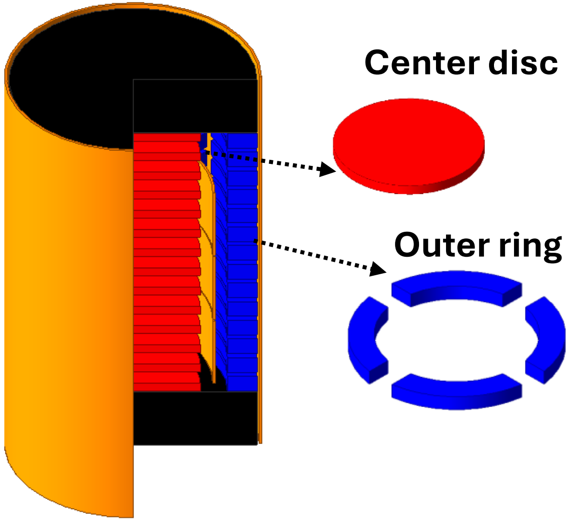
Self-Shielded Inductor

Goal : Achieve **high Q** while ensuring **minimal external magnetic field**

Modified pot-core structure

with an outer shield





Self-Shielded Inductor

Goal : Achieve **high Q** while ensuring **minimal external magnetic field**

Low-loss design techniques

1. Field shaping
2. Quasi-distributed gaps

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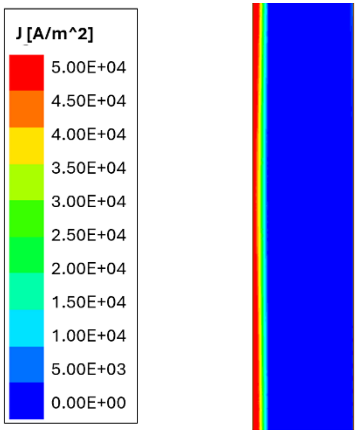


Current crowds due to imbalanced fields (single-sided conduction)

R. S. Yang et al. "A low-loss inductor structure and design guidelines for high-frequency applications," IEEE TPEL, 2019

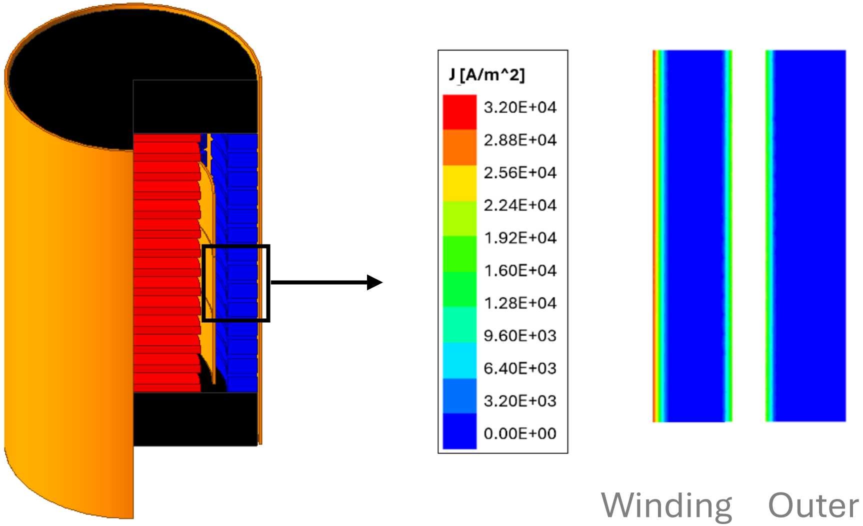
Self-Shielded Inductor

Goal : Achieve **high Q** while ensuring **minimal external magnetic field**

Low-loss design techniques

1. Field shaping
2. Quasi-distributed gaps

Reduces **conduction losses** in both the **winding** and the **shield**



Winding Outer Shield

R. S. Yang et al. “A low-loss inductor structure and design guidelines for high-frequency applications,” IEEE TPEL, 2019

Self-Shielded Inductor

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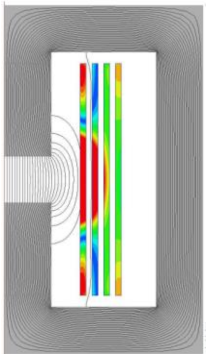
Low-loss design techniques

1. Field shaping
2. Quasi-distributed gaps

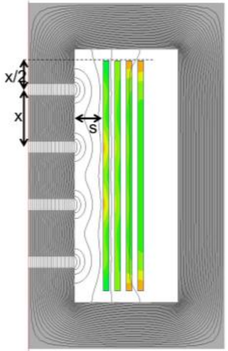
Reduces **winding losses** that arise due to large fringing-fields

Single large gap



Large fringing fields

Quasi-distributed gaps



Evenly distributes MMF

Image : C. Sullivan, PSMA, 2016, High frequency magnetics design overview and winding loss [PPT Slides]
J. Hu and C. Sullivan, “The quasi-distributed gap technique for planar inductors: design guidelines,” IAS , 1997

Self-Shielded Inductor

Goal : Achieve **high Q** while ensuring **minimal external magnetic field**

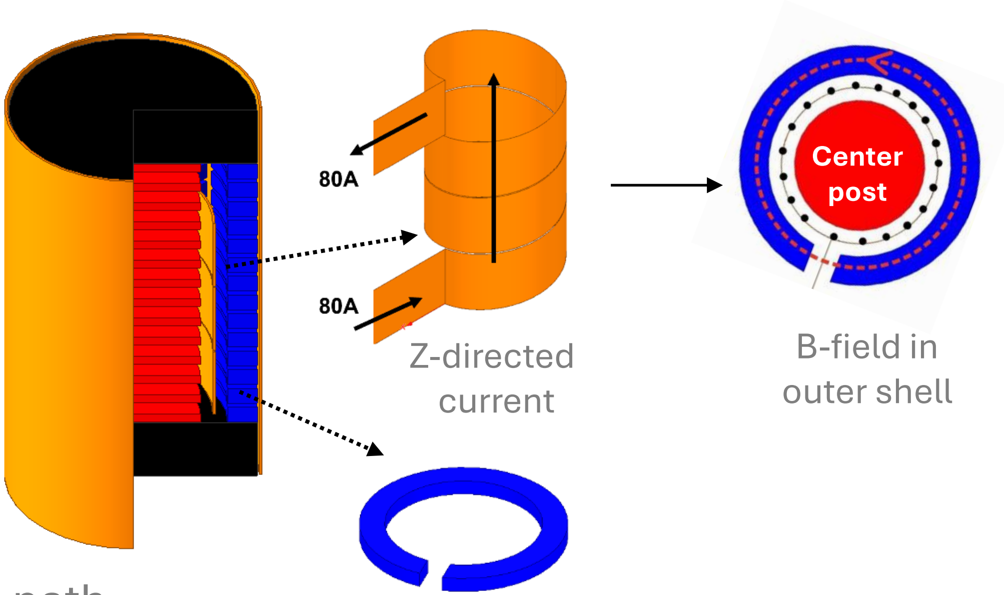
Low-turn count → 3D effects

Phi-directed fields

- Core loss in outer shell
- Additional inductance

Outer shell notches

- Increases reluctance of phi-directed path



Z-directed current

B-field in outer shell

Outer shell notch

Self-Shielded Inductor

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Low-turn count → 3D effects

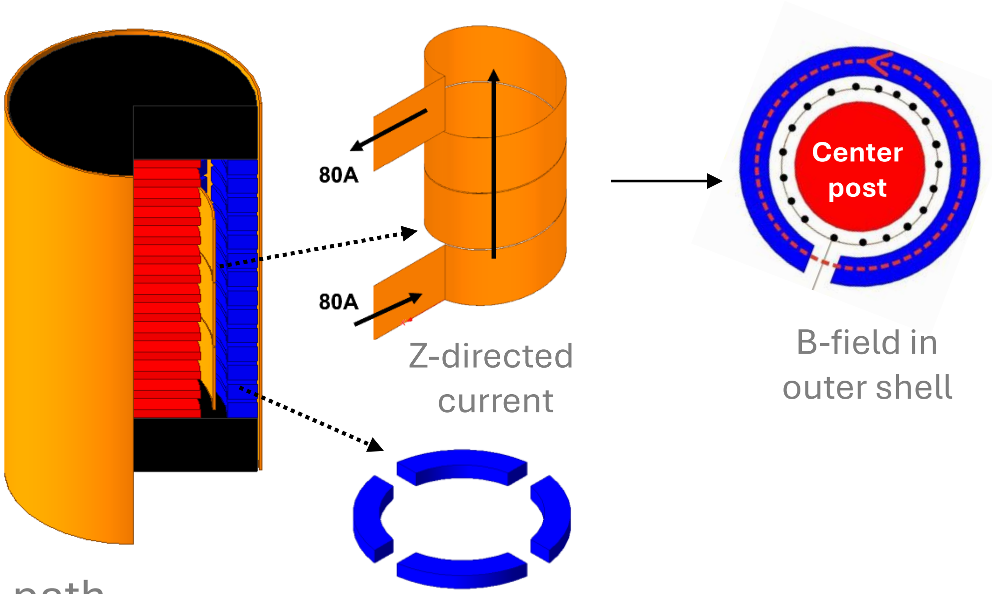
Phi-directed fields

- Core loss in outer shell
- Additional inductance

Outer shell notches

- Increases reluctance of phi-directed path

Reduces **core loss** in outer shell



Self-Shielded Inductor

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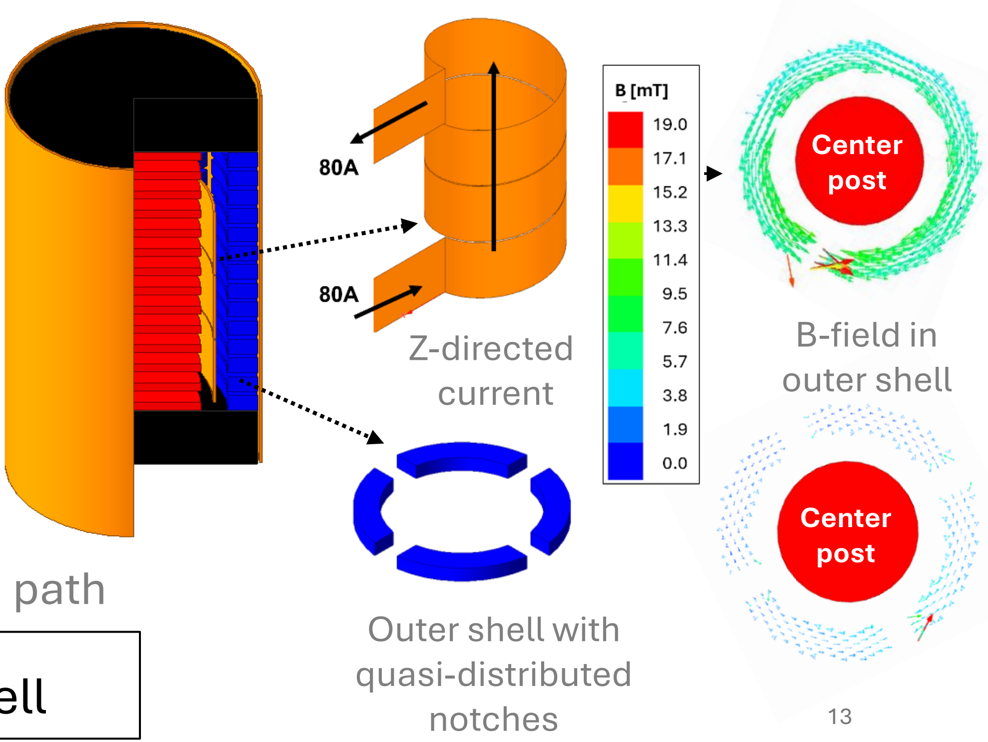


Self-Shielded Inductor

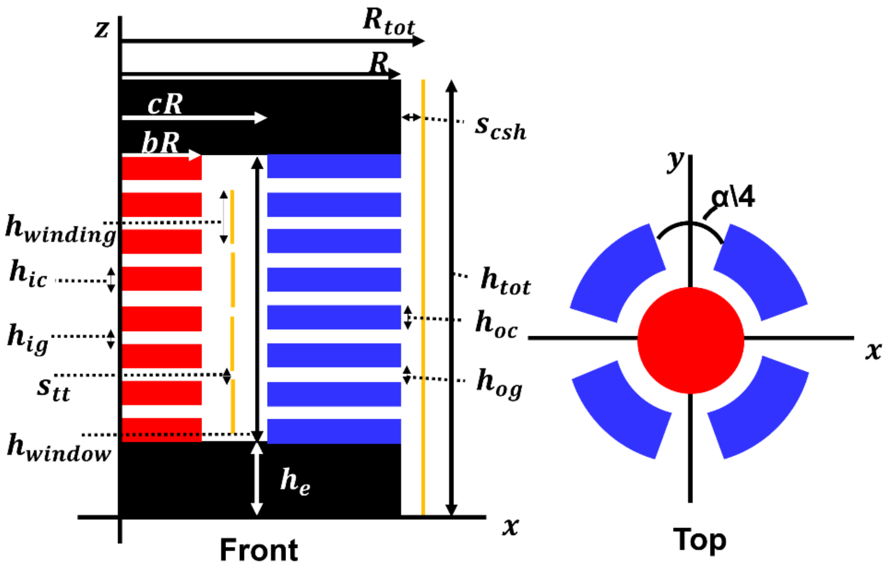
Goal : Achieve **high Q** while ensuring **minimal external magnetic field**

3D effects can significantly influence inductor's **total loss and inductance**

Modeling

3D effects

Design **optimization** and **automation**

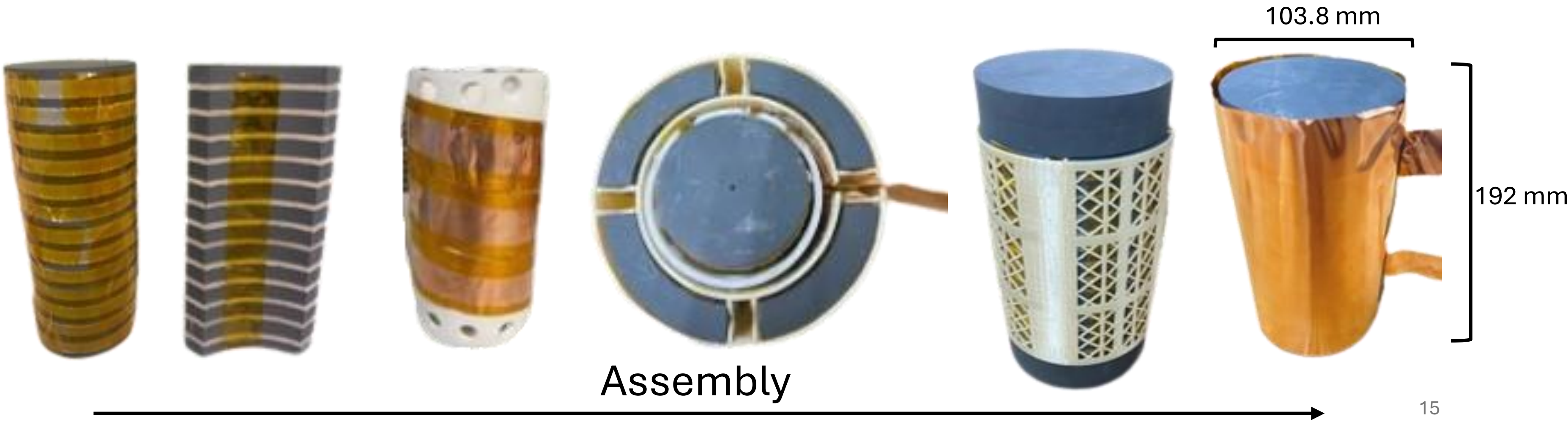


optimization parameters

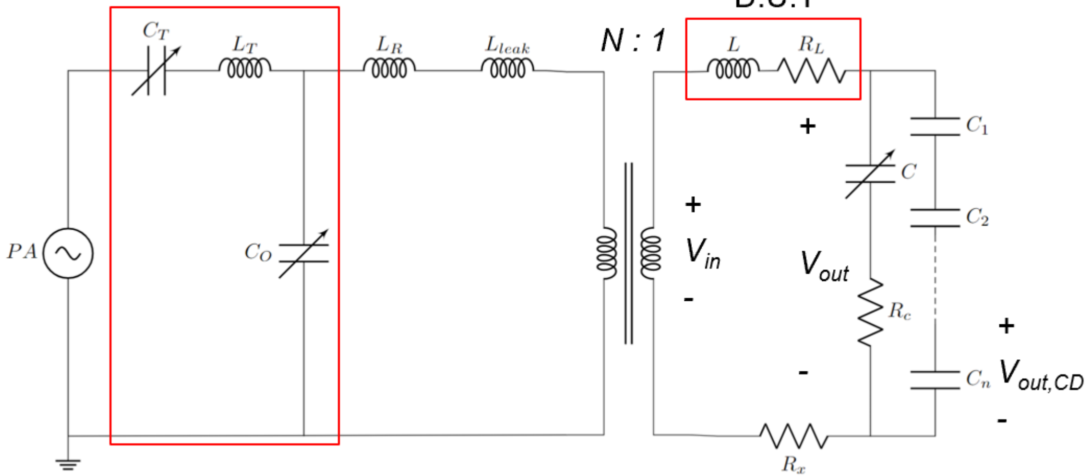
Self-Shielded Inductor Prototype

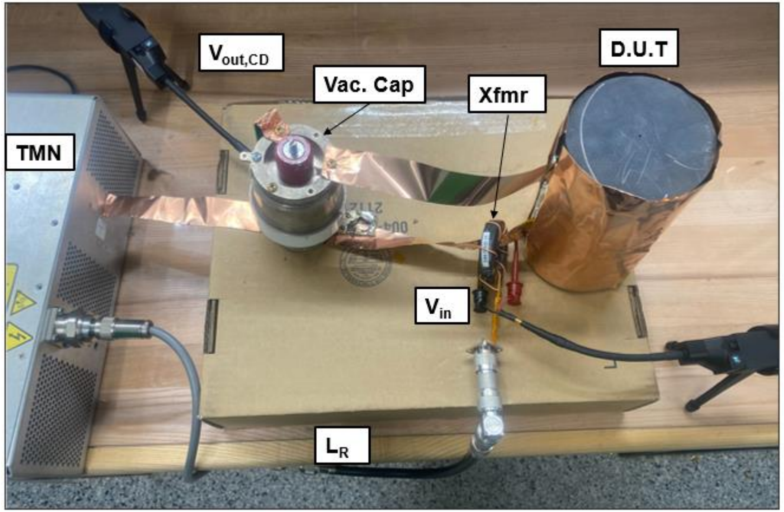
Optimized for total loss for the given design constraints

Design Constraints	
Inductance	570 nH
Frequency	13.56 MHz
Peak Current	80 A
Power Rating	155 kVA
Volume	1.6 L
Material	Fair-Rite 67



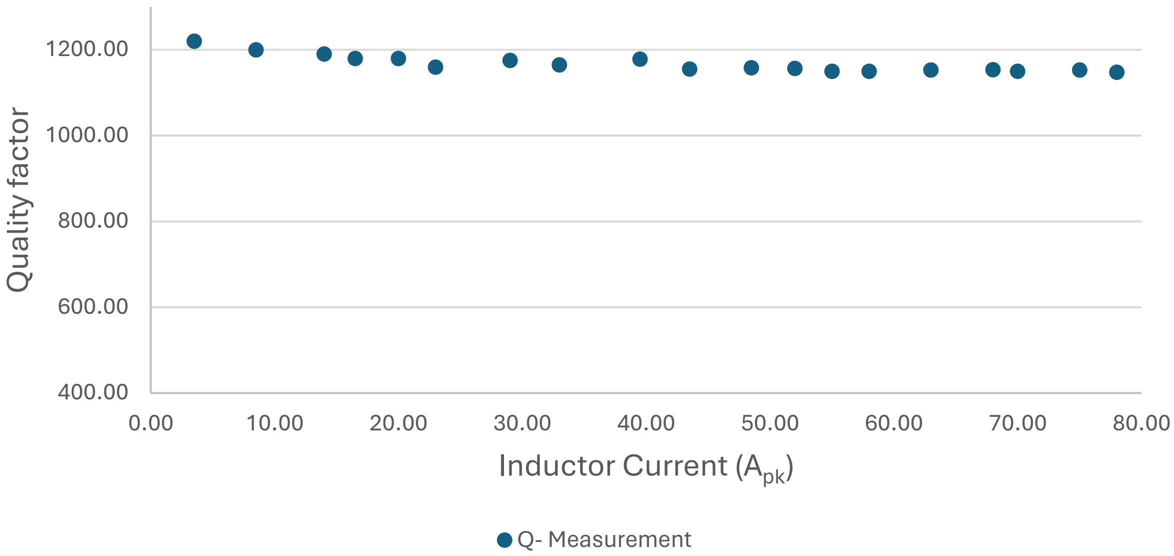
Q - Measurement Setup





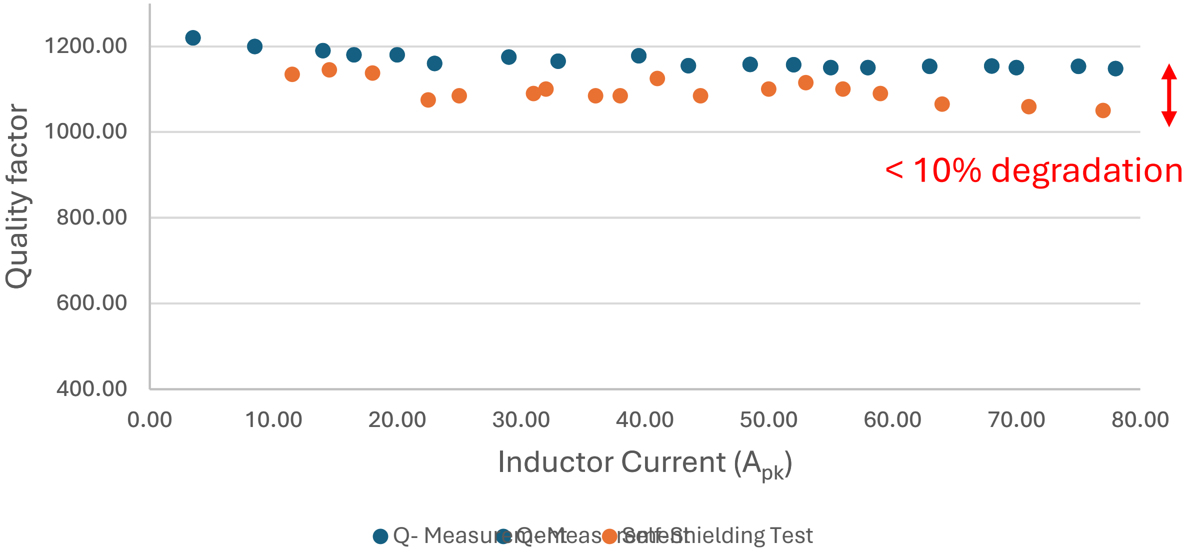
Matching Network and transformer coupled resonant tank

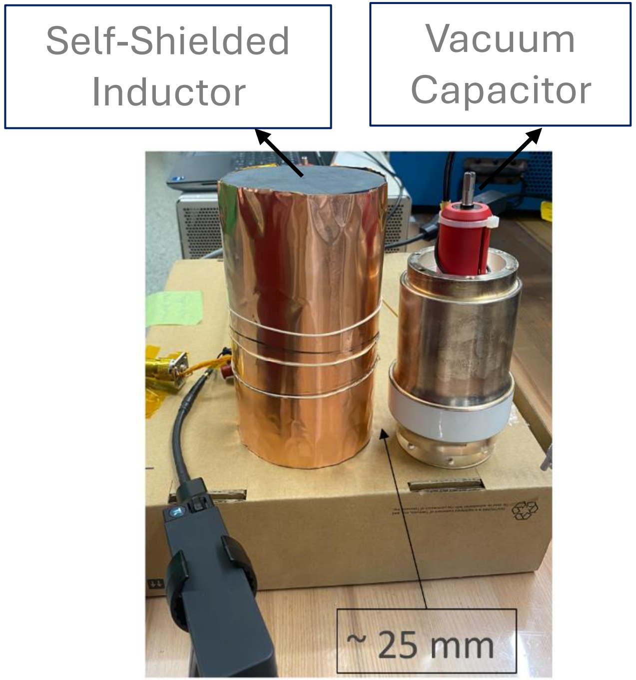
Results



Quality factor
1200.00
1000.00
800.00
600.00
400.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
Inductor Current (A_{pk})
Q- Measurement

Results





Self-Shielding Test Setup

High Q (1050, <10 % degradation) near a large metallic object **(~25 mm)**

Air-core Comparison

	Air-core Inductor	**Self-Shielded Inductor**
Inductance	585 nH	570 nH
Large – signal Q measurement	750	1150

Air-core Comparison

5.25x Q

→

3.5x lower volume

	Air-core Inductor	Self-Shielded Inductor
Inductance	585 nH	570 nH
Large – signal Q measurement	750	1150
Shielding Q measurement	**200**	**1050**
Volume	**5.57 L**	**1.6 L**

Self-Shielded inductor provides improved combination of **efficiency** and **size**

Self-Shielded Inductor

Achieves a **high Q** while ensuring **minimal external magnetic field**

Modified pot core structure with an outer shield

Low-loss design techniques

- Field shaping
- Quasi-distributed gaps

Mitigating and modeling 3D effects

- Phi –directed fields
- End-turns effect

Prototype	
Inductance	570 nH
Frequency	13.56 MHz
Peak Current	80 A
Power Rating	155 kVA
Quality factor	1050 **(5.25x higher)**
Volume	1.6 L **(3.5x lower)**

Enable improved **efficiency** and **miniaturization** of high-power HF applications

References

1. R. S. Bayliss, R. S. Yang, A. J. Hanson, C. R. Sullivan, and D. J. Perreault, “Design, implementation, and evaluation of high-efficiency high-power radio-frequency inductors,” in APEC, 2021
2. R. S. Yang, A. J. Hanson, B. A. Reese, C. R. Sullivan, and D. J. Perreault, “A low-loss inductor structure and design guidelines for high-frequency applications,” IEEE Transactions on Power Electronics, 2019
3. R. S. Yang, A. J. Hanson, C. R. Sullivan, and D. J. Perreault, “Design flexibility of a modular low-loss high-frequency inductor structure,” IEEE Transactions on Power Electronics, 2021
4. J. Hu and C. Sullivan, “The quasi-distributed gap technique for planar inductors: design guidelines,” in IAS , 1997