
# Emulation of Plasma Load Reactances by Saturation Control of Low-Permeability Inductors


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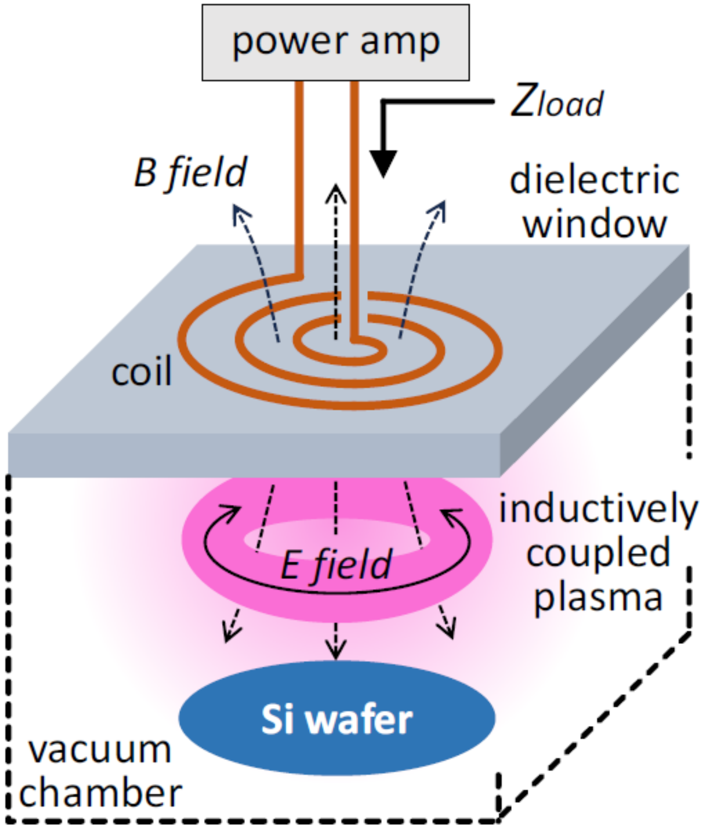
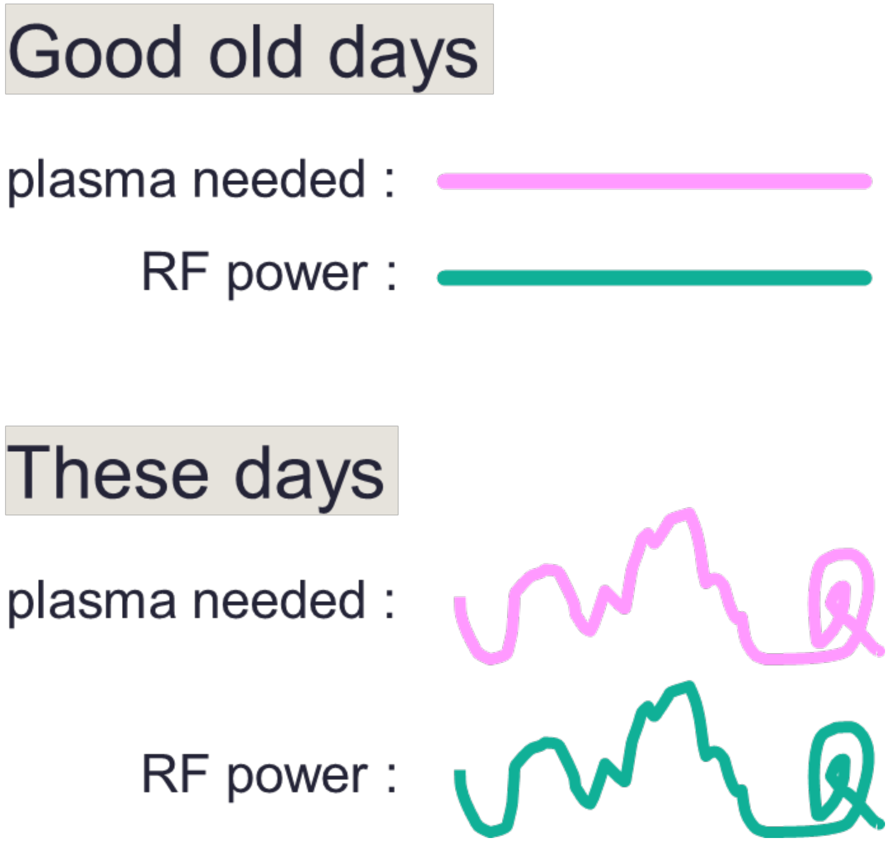
# Advanced RF Generator Have Complex Behavior

- Dr. Sangyheon Park (our collaborator from Lam) sums up the project very well:

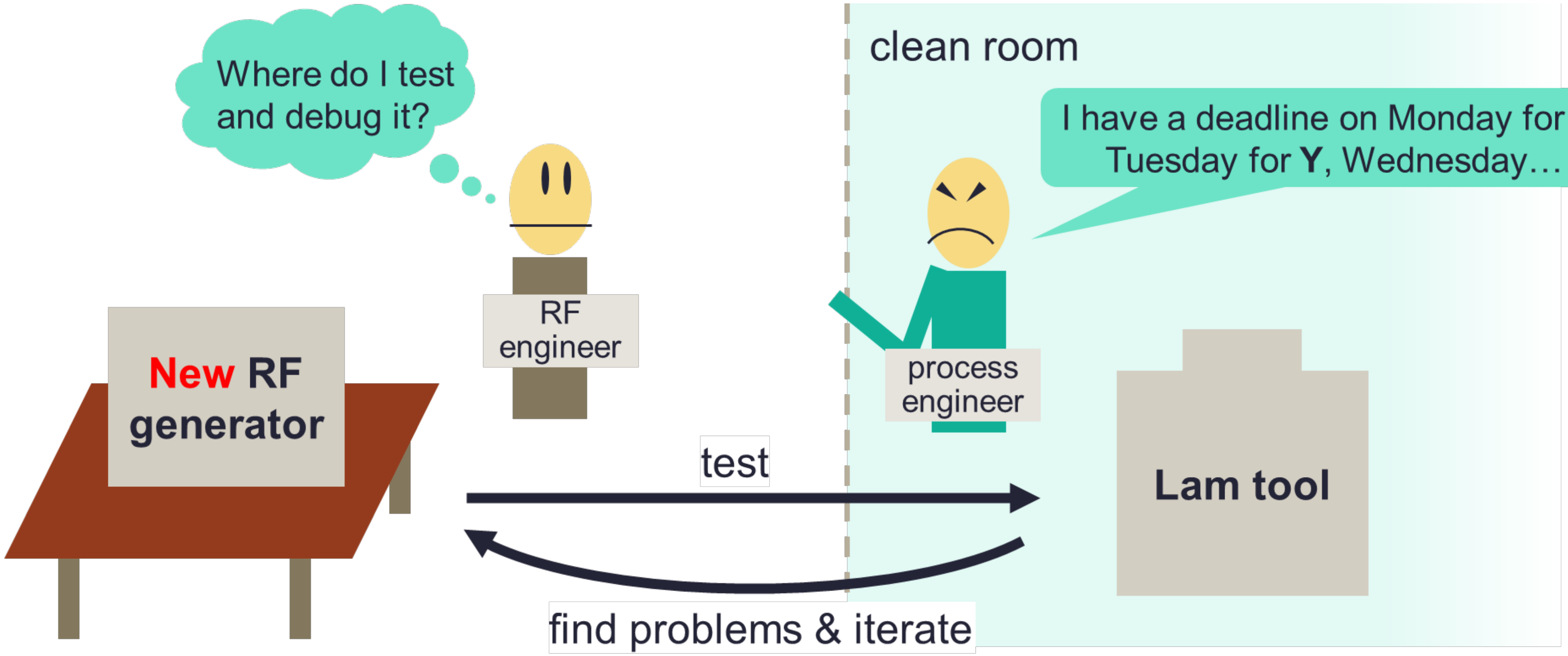



Creates a need for advanced RF generators

Figures courtesy of Dr. Sanghyeon Park

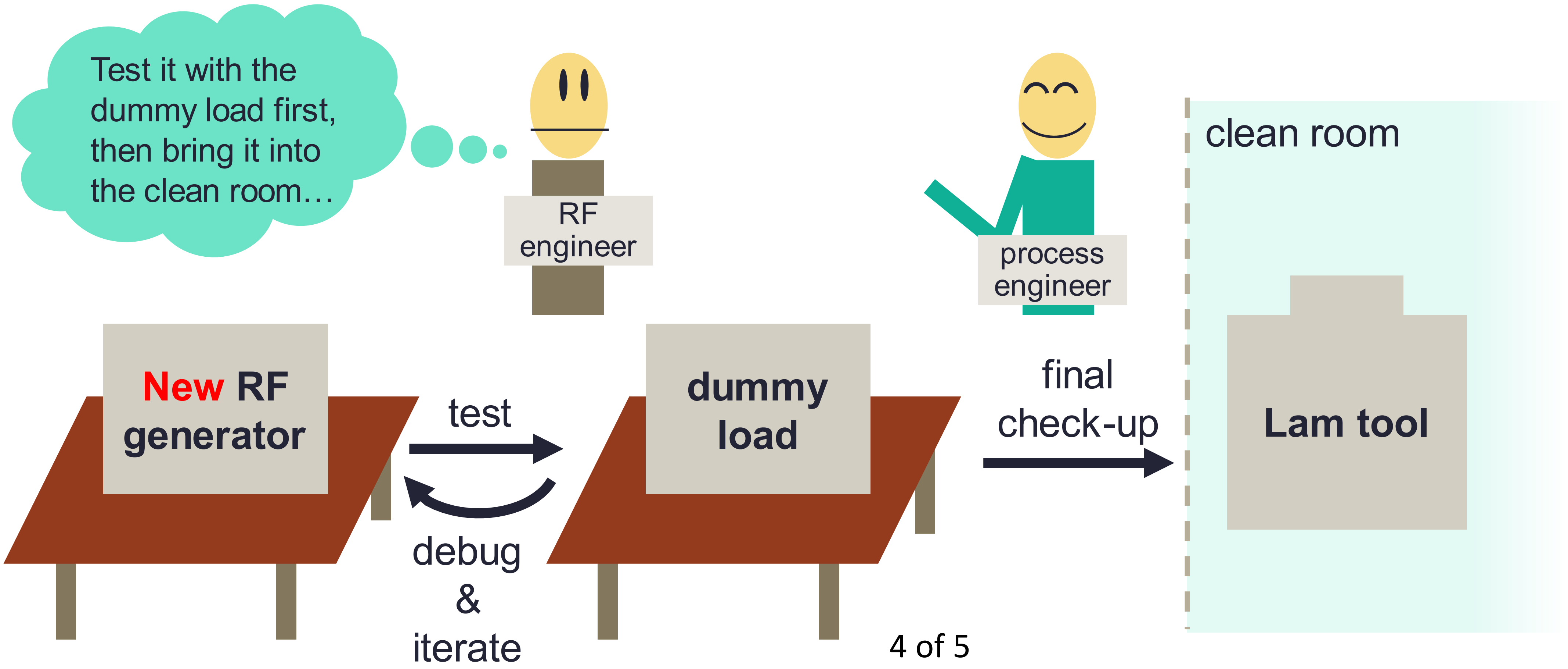
# Problem: Validation and Debugging is Complicated




- New RF generator: miniaturized, lower cost, faster, etc.
- To validate a new RF generator, must install it in a real tool and run it.
- Tool time is a rare commodity, process engineers have immediate deadlines, RF engineers may need weeks/months to iterate and root out all the issues.

Figure courtesy of Dr. Sanghyeon Park

# Solution: A Dummy Load that Can Mimic Plasmas

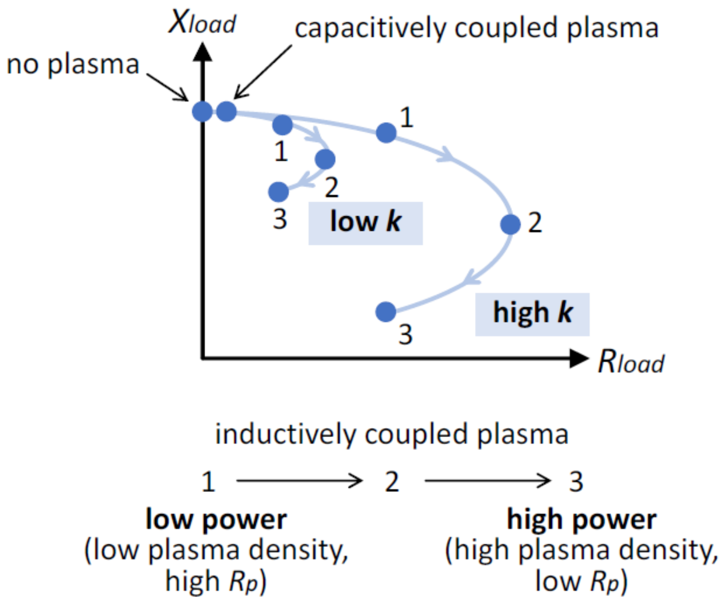



- Programmable load allows consistency and speeds up debugging.
- Ideally, dummy load *perfectly* matches the plasma, but even a close representation is useful.

Figure courtesy of Dr. Sanghyeon Park

# Modeling Inductively-Coupled Plasmas (ICPs)

## Plasma impedance is highly dynamic




Time varying Inductance and Resistance

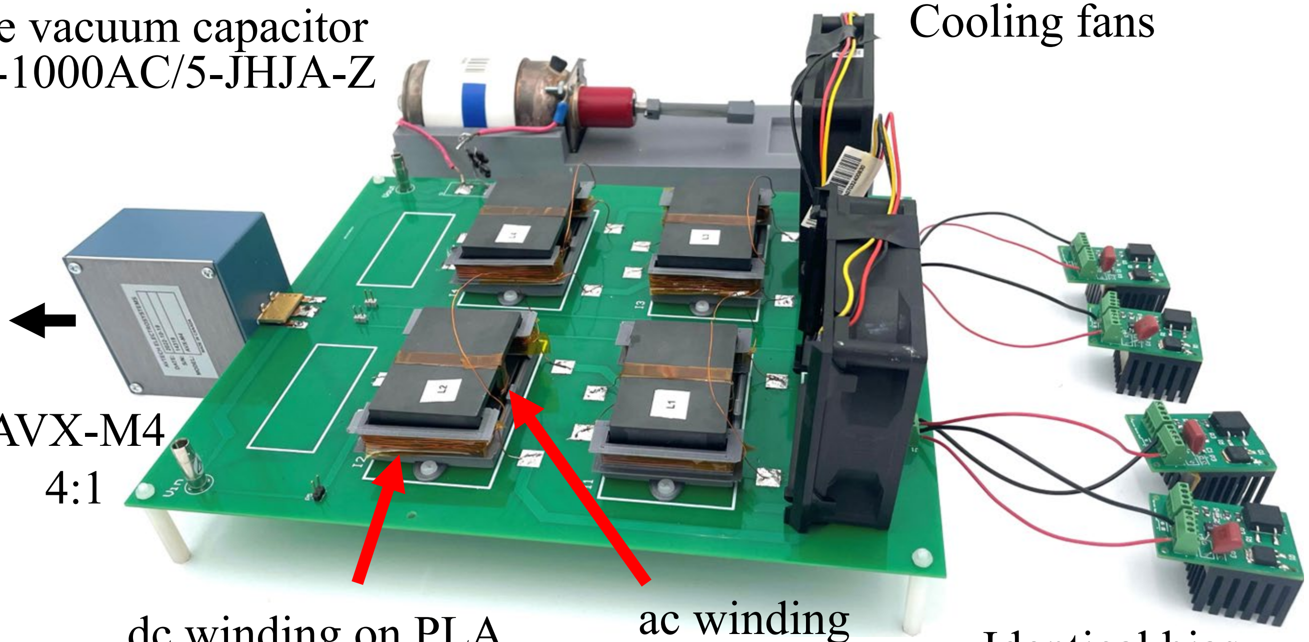
Dummy load needs:

- Variable resistance (a known unknown, e.g., fixed + controlled resistors).
- Variable reactance – an unknown unknown - 20% variation in 100$\mu s$.

J. G. Kassakian, D. J. Perreault, G. C. Verghese, and M. F. Schlecht, *Principles of Power Electronics*, 2nd edition. New York: Cambridge University Press, 2023

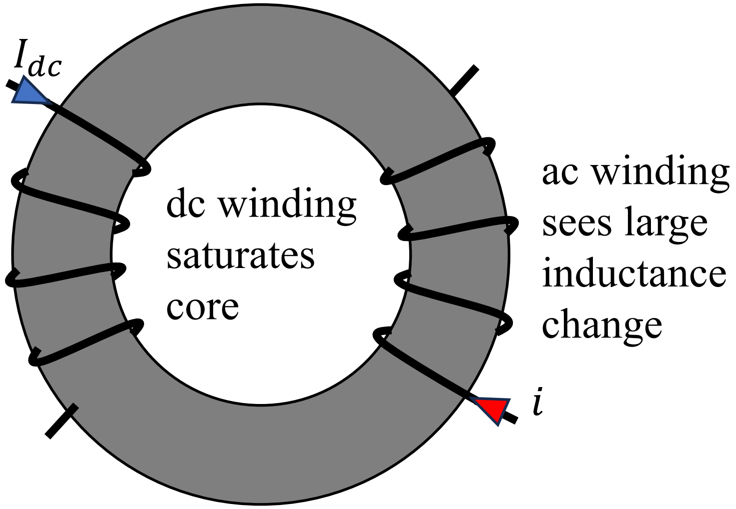
# Our Contribution: HF, Low Permeability, Saturable Inductor Array Design Approach

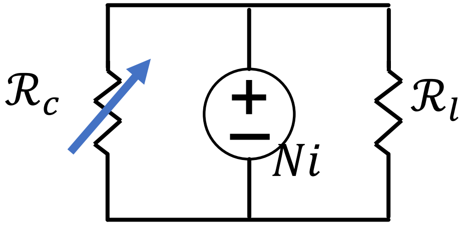
- Dummy load: 2.5$\mu H$ inductor carrying 20$A_{pk}$ at 13.56MHz.
- Too large for a single off-the-shelf core, so use a modular design (series/parallel inductors).



# A Rich History of Saturation Control

**Saturable Reactor**




$$L = N^2 \left( \frac{1}{\mathcal{R}_c} + \frac{1}{\mathcal{R}_l} \right)$$

P. Mali, Magnetic Amplifiers Principles and Applications. New York: John F. Rider Publisher, Inc., 1960.

Pros:

- Large inductance due to no gap.
- Large inductance change due to full saturation.

Cons:

- DC windings may see large inductance.
- AC and DC windings are directly coupled(can be mitigated in a multi-core approach).
- Need to ensure small-signal excitation near saturation to avoid distortion.

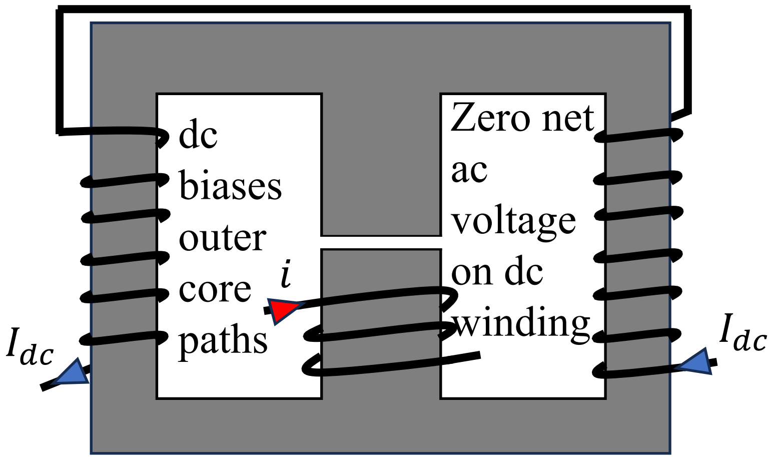
# A Rich History of Saturation Control

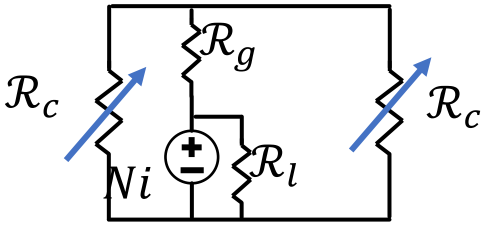
Pros:

- Mitigates AC to DC coupling.
- Can be used with gapped construction.

D. Medini and S. Ben-Yaakov, “A current-controlled variable-inductor for high frequency resonant power circuits,” in Proceedings of 1994 IEEE Applied Power Electronics Conference and Exposition - ASPEC’ 94, Feb. 1994, pp. 219–225 vol.1.

## Multi-Leg Inductor




$$L = N^2\left(\frac{1}{\frac{\mathcal{R}_c}{2} + \mathcal{R}_g} + \frac{1}{\mathcal{R}_l}\right)$$

Cons:

- DC winding may see large inductance.
- E-cores (currently) uncommon for high-frequency FR67 core material.
- Lower inductance variation if a gap is used.

# A Rich History of Saturation Control

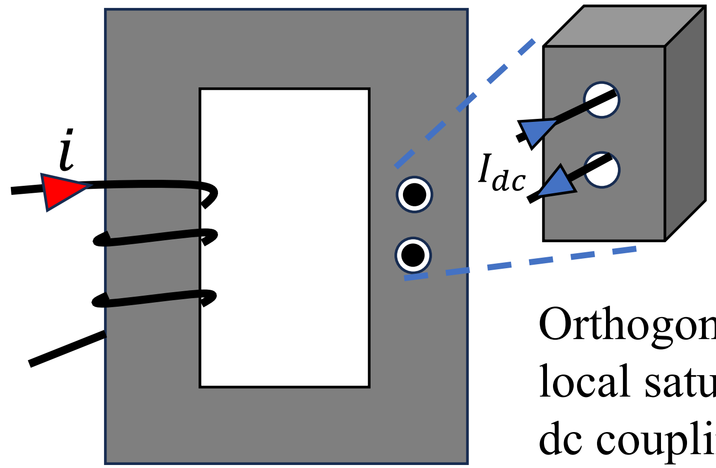
Pros:

- Total decoupling of AC and DC systems.
- Low inductance on DC windings.

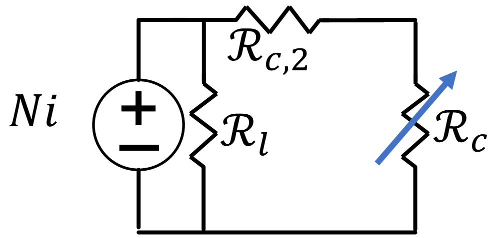
Cons:

- Hard to construct.
- May yield low inductance change.

## Virtual Air Gap




Orthogonal dc bias, local saturation, no a[c]/ dc coupling




$$L = N^2\left(\frac{1}{R_c + \mathcal{R}_{c,2}} + \frac{1}{\mathcal{R}_l}\right)$$


D. S. Dolan and P. Lehn, "Analysis of a Virtual Air Gap Variable Reactor," in 2007 IEEE Power Electronics Specialists Conference, Jun. 2007, pp. 1182–1187, iSSN: 2377-6617.

# Research Questions

Are saturable inductors viable for emulating the reactance of a plasma load?

That is, can we:

1. Achieve ~20% inductance change with reasonable bias circuitry?
2. Ensure linearity of the inductor under saturation?
3. Achieve a dynamic inductance response at 100$\mu s$?
4. Show that a saturable inductor can be modularly scaled?

# Key Difference: HF Materials Have Low Permeability

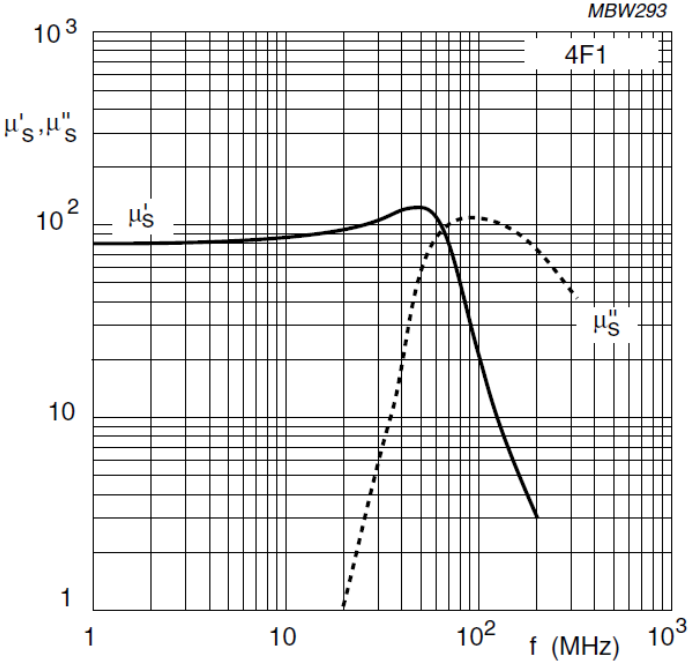
<u>We need a magnetic material with:</u>

- Inductive behavior at 13.56 MHz.
- Strong susceptibility to saturating fields.

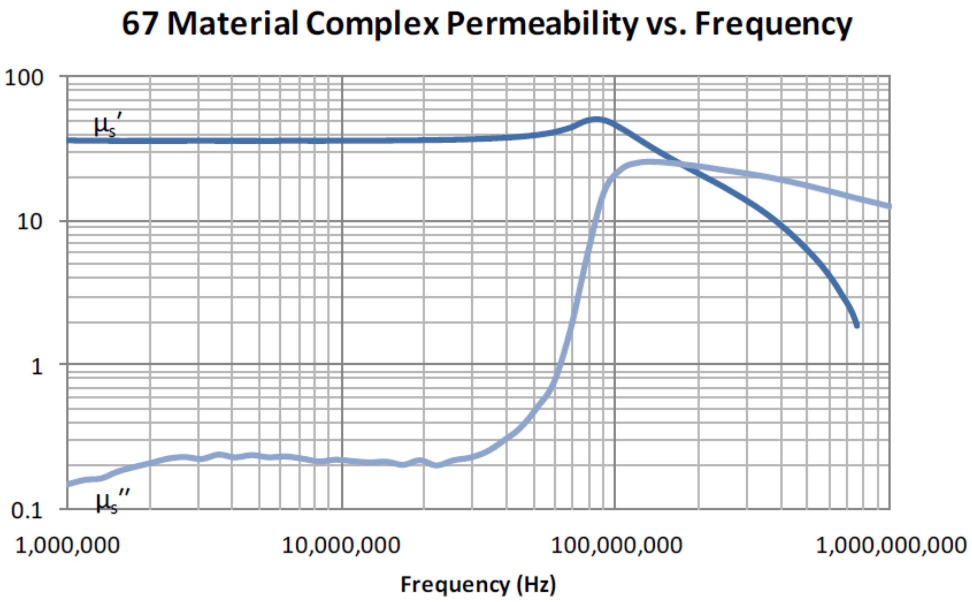
<u>Options:</u>

NiZn ferrites:

Ferroxcube 4F1,Fair-rite FR67



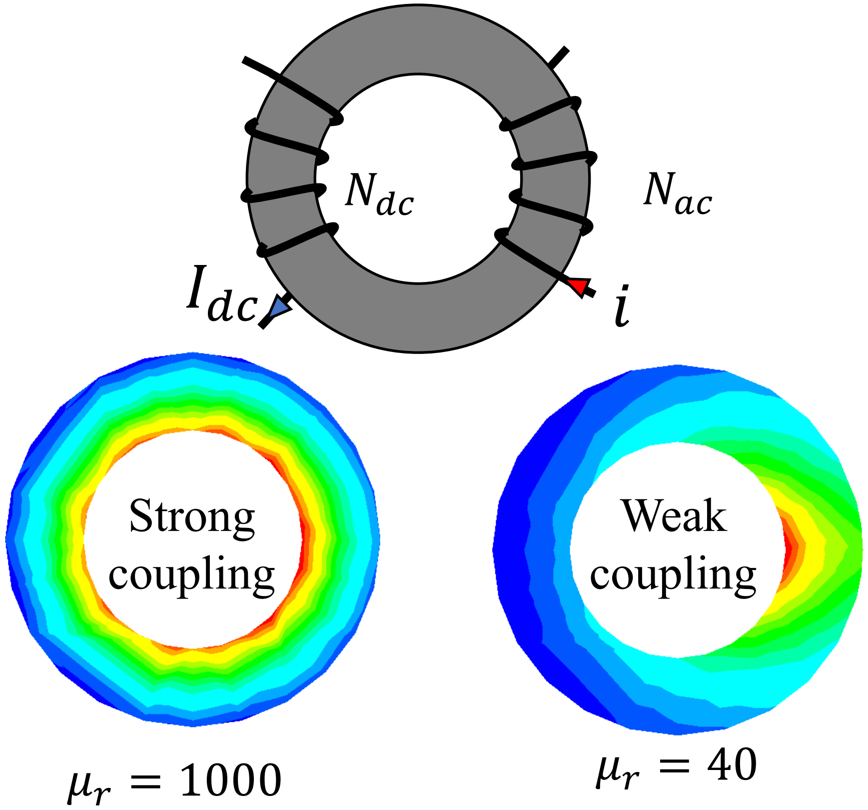

$\mu_r \approx 80$




$\mu_r \approx 40$

# Low Permeability Changes Saturation Strategies

Saturable Reactor



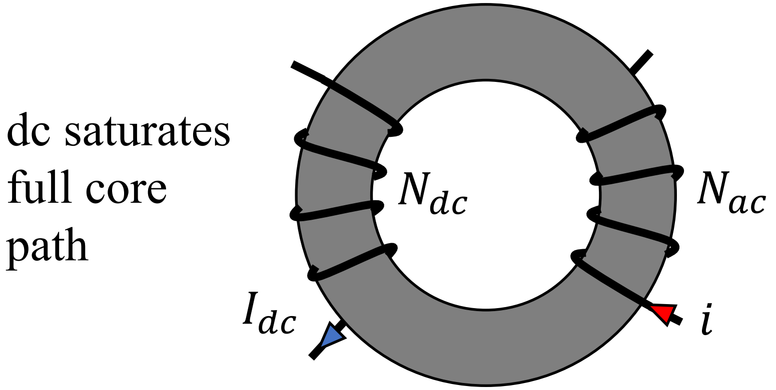

- Saturation strategies mimic virtual air gap!
- Likely to be linear; unlikely to get big inductance change (but 20% isn't very big).
- We have adopted a multi-legged approach. (Please refer to the accompanying paper for a comprehensive analysis of the tradeoffs and selection criteria).

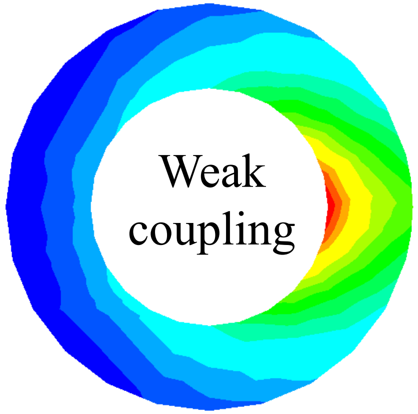
# Low Permeability Challenges

1. **Weak coupling and localized saturation**

- These can be very leaky designs.
- Leakage inductance difficult thing to predict "on paper" (simple magnetic circuit analysis not appropriate).
- Inductance is a strong function of the ac winding geometry.
- Saturation is a strong function of the dc winding geometry.

Saturable Reactor



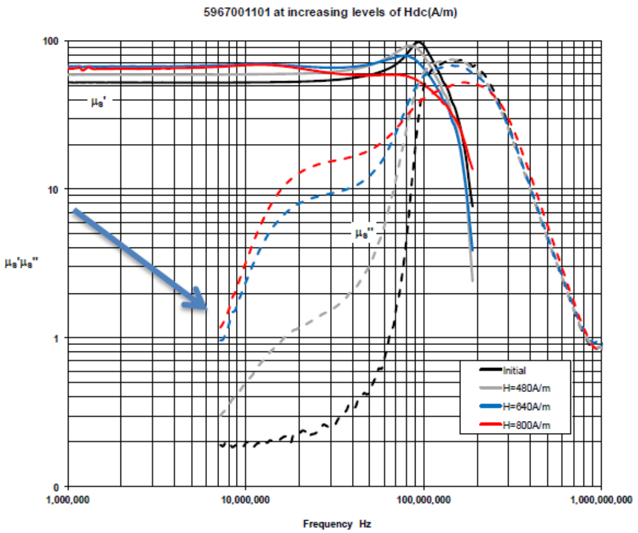

$\mu_r = 40$

# Low Permeability Challenges

## 2. Perminvar characteristics

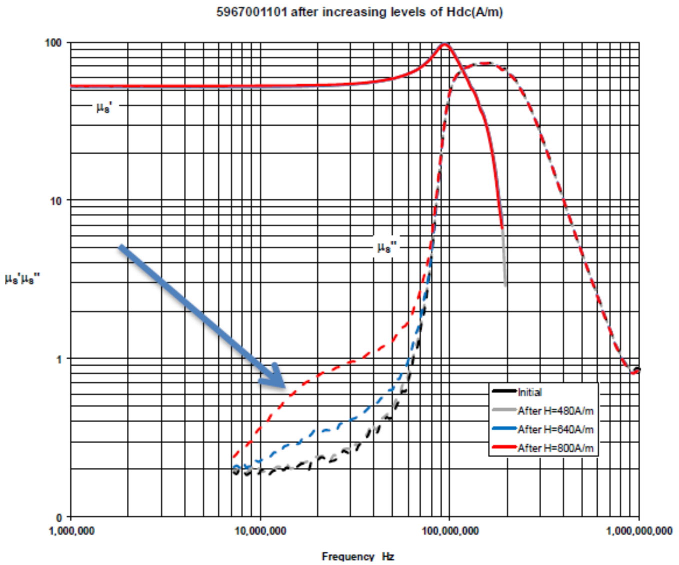
- FR67 has properties that change under high magnetic fields.

- **Action:** “pre-bias” cores by subjecting them to field intensity > 800 A/m




During DC bias exposure

**Effects of DC bias**




After DC bias exposure

- If a part is exposed to a DC bias that is too high, there is an irreversible changes to the losses.



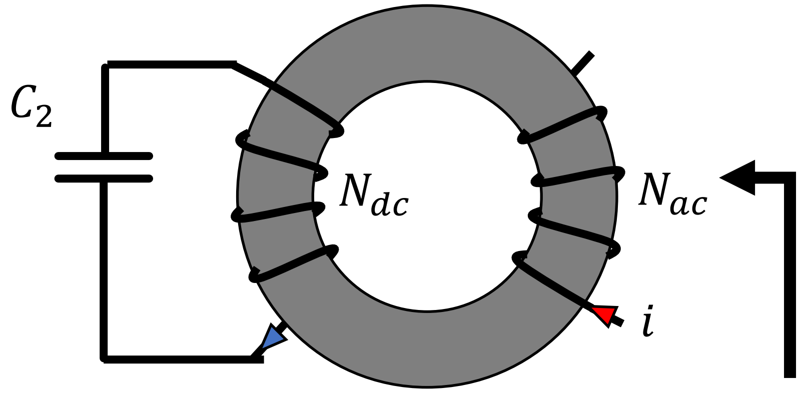
R. Parker and M. Arasim, “Low Loss 67 Material for High Frequency Power Applications,” Mar. 2016

# Low Permeability Challenges

## 3. Self-resonance

- We target high inductance ($2.5\mu H$) – a small effective capacitance (55.1pF) can yield 13.56MHz resonance.
- In particular, capacitance across dc windings can be problematic.
- **Action**: Minimize dc turns count

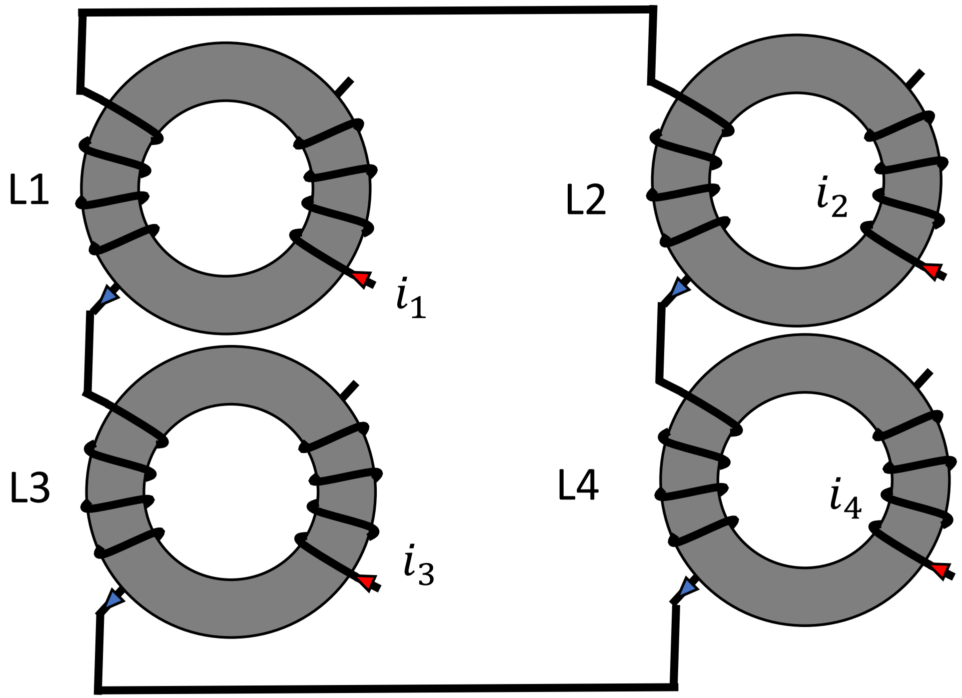
  But recognize that parasitics are inherently difficult to model.




$$C \propto C_2 \cdot \left(\frac{N_{dc}}{N_{ac}}\right)^2$$

# Low Permeability Challenges

**4. Un-gapped constructions**




- Want to maximize inductance variation, so avoid gap.
- Incur the typical challenges, permeability depends on: temperature, lot-to-lot variation.
- **Action**: Allow individual biasing of cores in an array.

**Design Approach?**

- These Low permeability challenges impede a design “on paper”, without experimental characterization.
- So, forgo an analytical design framework and develop an “experiment in the loop” design approach, to show the concept has legs.

# Design Approach

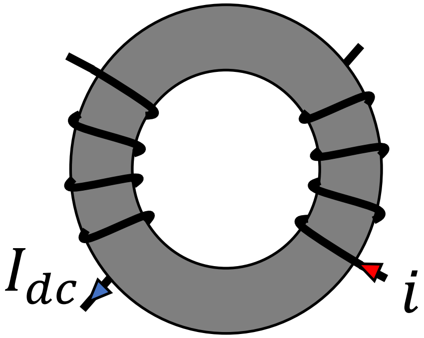
1. Select a core material and core set

   Use the largest available cores to minimize the size of the array.

2. Design the ac turns

   Start with $A_L$ from datasheet, measure, then (likely) decrease $N_{ac}$.

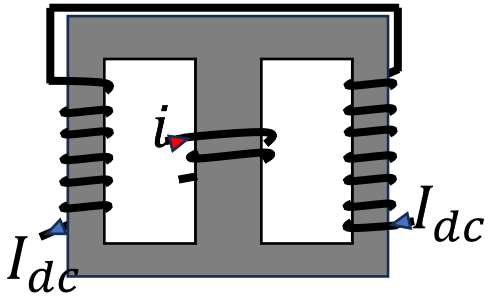
<u>T61/35.5/12.7, FR67</u>




Datasheet: 55 $nH/N^2$

Designed value $N_{ac} = 5$
125 $nH/N^2$

<u>E58/11/38, 4F1</u>



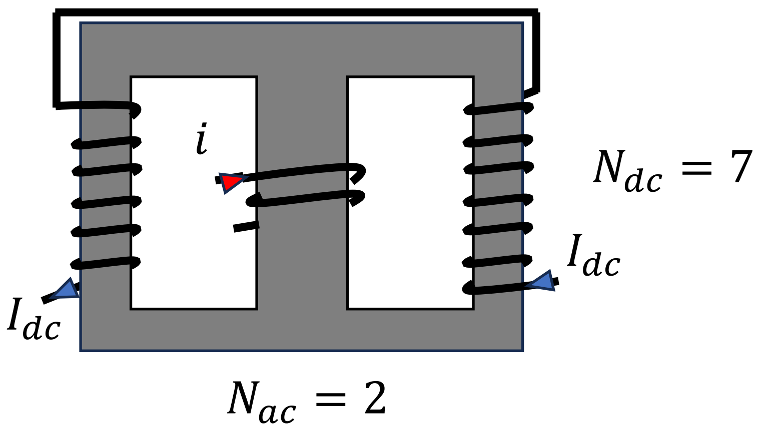

Datasheet: 450 $nH/N^2$

Designed value $N_{ac} = 2$
650 $nH/N^2$

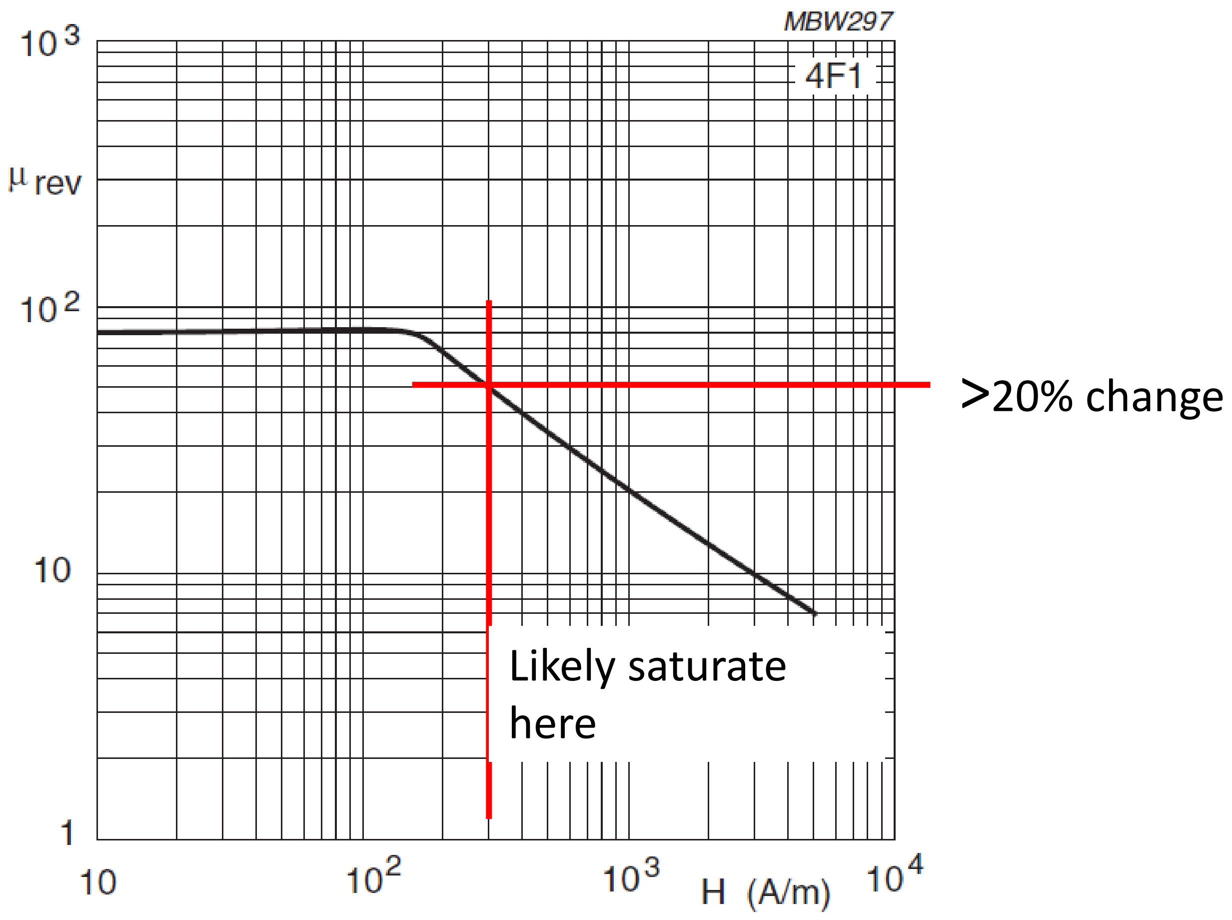
# Designing the dc turns

3. Then, use a single magnetostatic ANSYS simulation to determine dc biasing MMF applied by dc turns (e.g., $H_{bias} = 18N_{dc}I_{dc}$).

E58/11/38, 4F1




- Start with manufacturer bias information (if available)

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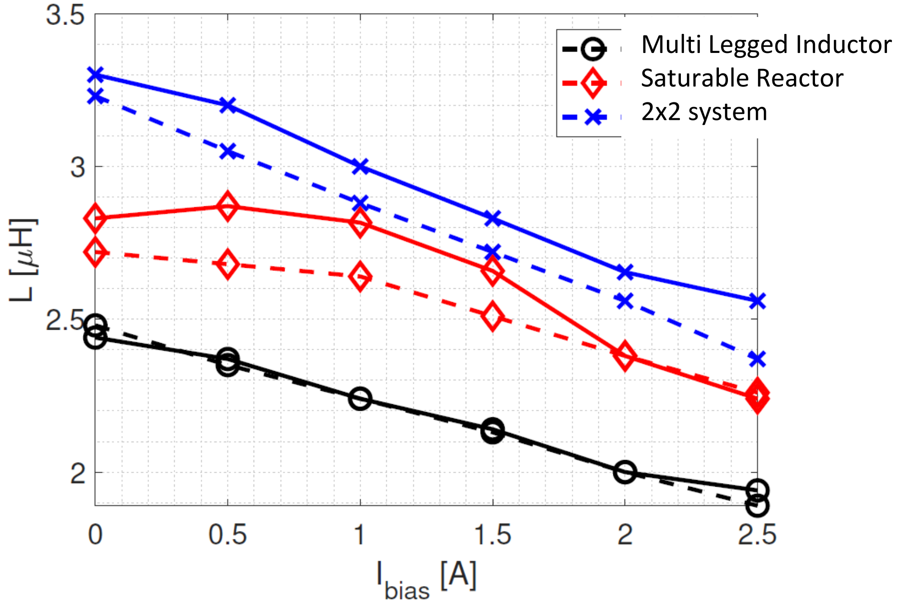
# Small signal and Large signal testing

4. Small signal testing

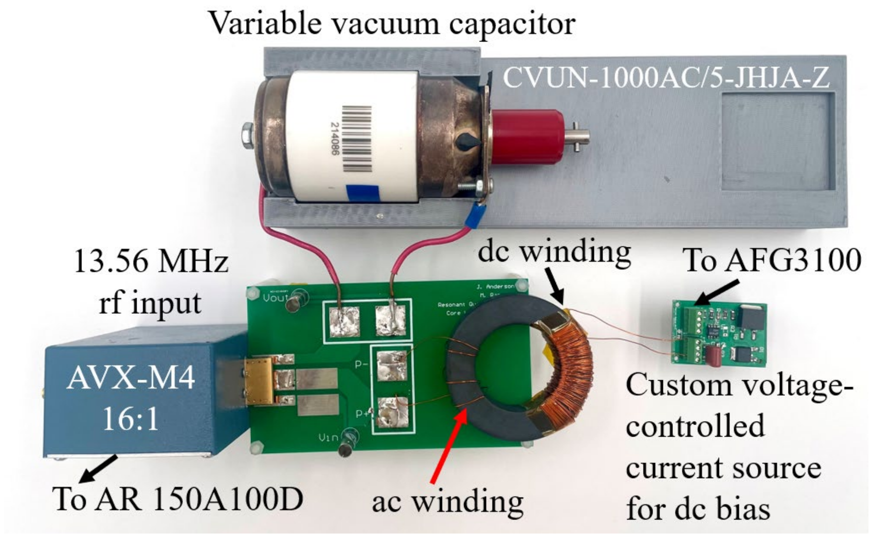
Use an impedance analyzer to measure dc bias response. Target 0-2.5A for ease of bias implementation.

5. Large signal testing

Ensure the linearity of the inductor under saturation with large signals applied to it.



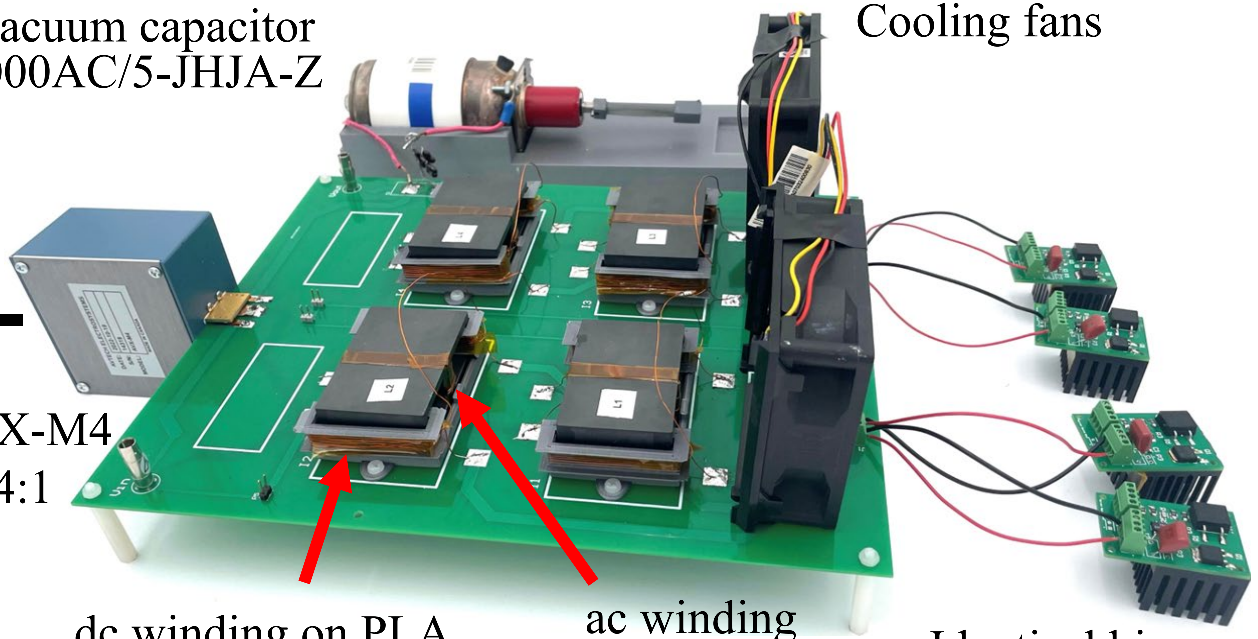

Solid line- Large signal
Dashed line – Small signal



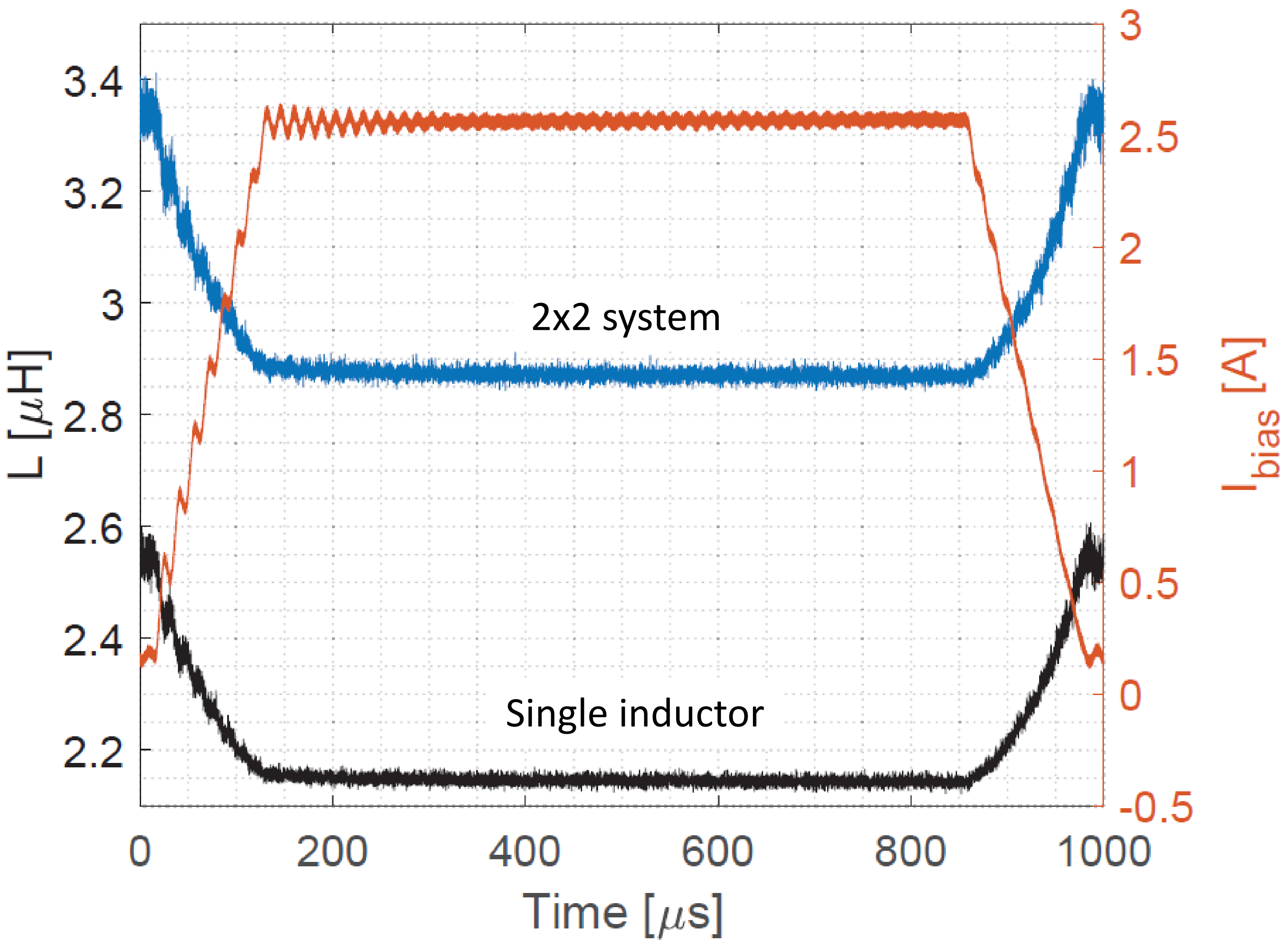

Large signal setup (Using series L and C resonance to calculate core loss and inductance value )

# 2 x 2 Variable Inductor with Multi Leg Approach

- Each inductor is individually controlled through its dedicated bias circuit.



# Achieves 20% L Variation in 0.1 ms




- No special coordination between different array elements, they all receive the same bias command.
- Large signal data – no non-linearity observed.
- Limit is slew rate of current source .

# Contributions and Conclusions

1. Presented plasma generation and modeling overview.
2. Incorporated low permeability saturation control into established high permeability methods.
3. Outlined Design approach for creating low permeability variable reactors with DC bias control.
4. Shared small and large signal testing outcomes, including dynamic inductance change and core loss data, confirming inductor suitability for plasma emulation systems.
5. Experimentally validated a downscaled 2x2 inductor prototype.