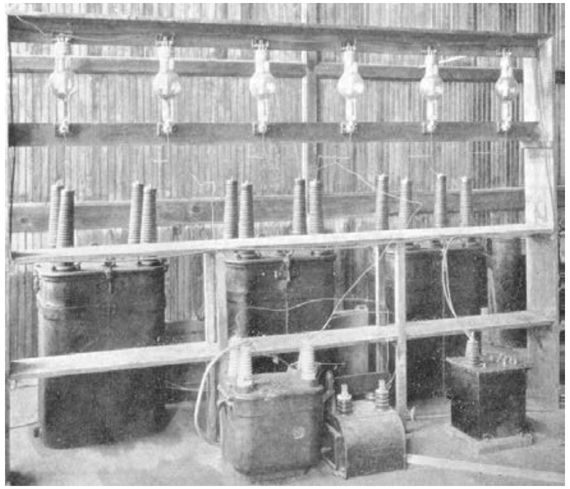
Massachusetts Institute of Technology

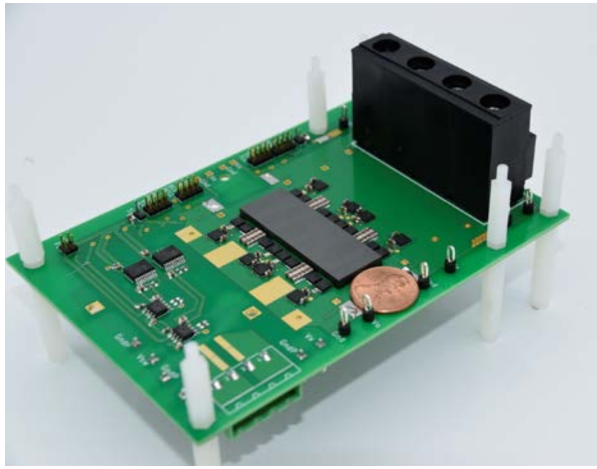
Power Electronics Research Group

Opportunities, Progress and Challenges in High-Frequency Power Conversion

David Perreault



20 kW Kenotron Rectifier, Circa 1926
(From Prince and Vodges, 1927)



1 kW, 1 MHz 400-12V Converter, Circa 2021
(Mike Ranjram, ASU)

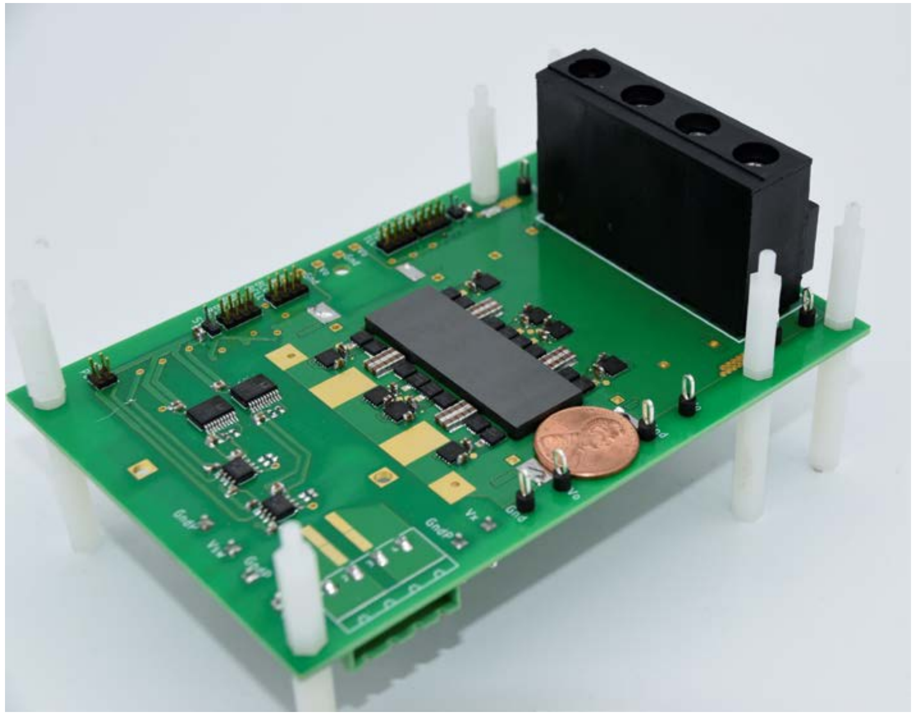
??

Circa 2036

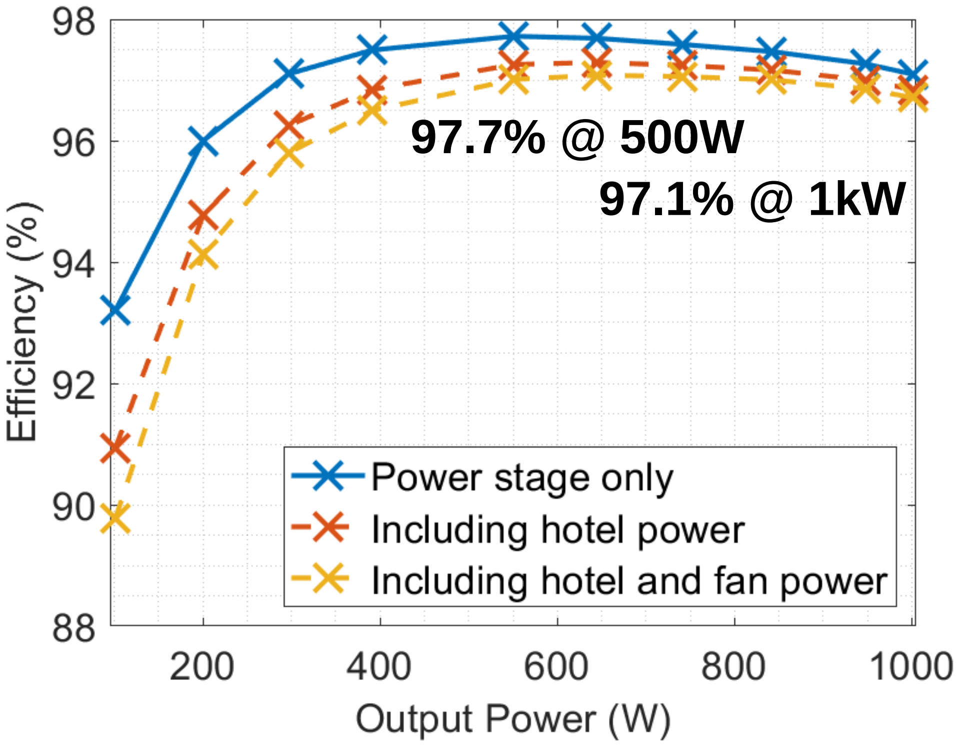
Advancing Frequency

- **Current technology supports power electronics at the kW scale operating at low MHz frequencies**
  - **Example: Datacenter converter, 380 V to 12 V @ 1 kW, η > 97%, f_{sw} ~1 MHz**

High Power Density



High efficiency



M. Ranjram et al, "A 380-12V, 1kW, 1 MHz Converter Using a Miniaturized Split-Phase Fractional Turn Planar Transformer," *TPEL* Feb. 2022.

Advancing Frequency

- **Current technology supports power electronics at the kW scale operating at low MHz frequencies**

- **We have the opportunity to advance kW-scale power electronics to operate at *still much higher* frequencies**
  - **e.g., 10+ MHz**
  - **in the "High-Frequency" (HF, 3-30 MHz) range**

- **Outline both the *opportunities* and the *challenges* in moving to these frequencies**

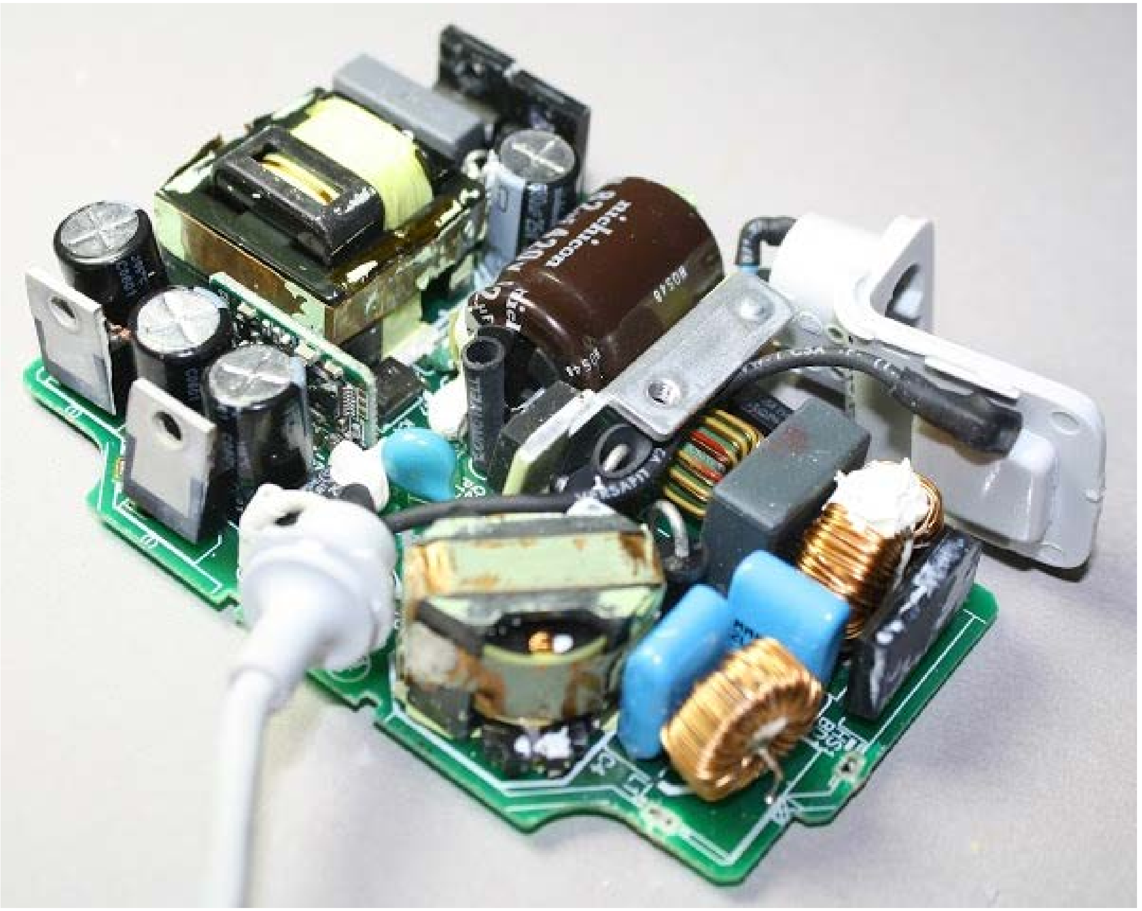
Goals for Frequency Increases

- **Goals**
  - **Miniaturization (smaller, lighter)**
  - **Increased performance (bandwidth,…)**
  - **Improved construction / integration**
  - **Enable new applications**
  - **Reduced cost (eventually…)**

- **Energy storage requirements vary inversely with frequency: C, L proportional to 1/f**

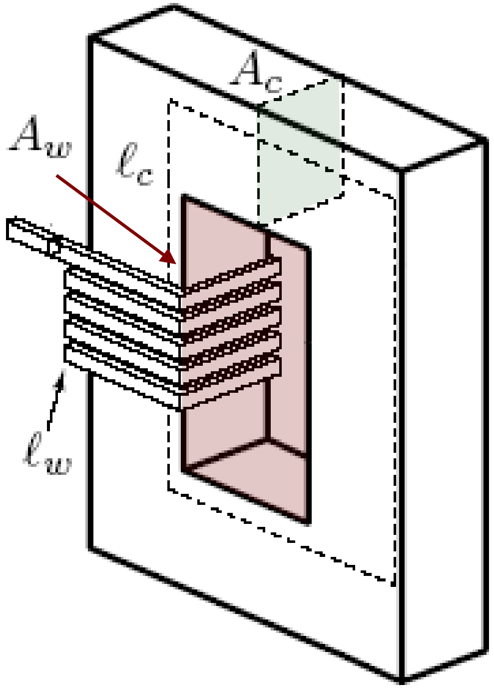
Passive Components Dominate

- **Passive components dominate size, weight and loss**
  - **Both power stage and filters are important**
  - **Magnetics are especially challenging**



Miniaturizing Magnetics is *Fundamentally* Difficult

- **Scaling laws work *against* miniaturization of power magnetics**
  - **Simplified case: power handling (VA) of a fixed-frequency ac inductor**
    - **Flux density B_0 limited by core loss**
    - **Current density J_0 limited by winding loss**



- **Power handling ∝ (linear dimension)^4**
- **Volume ∝ (linear dimension)^3**
- **Power density (power/vol) ∝ (linear dimension)**
- **Magnetics get worse at smaller sizes!**

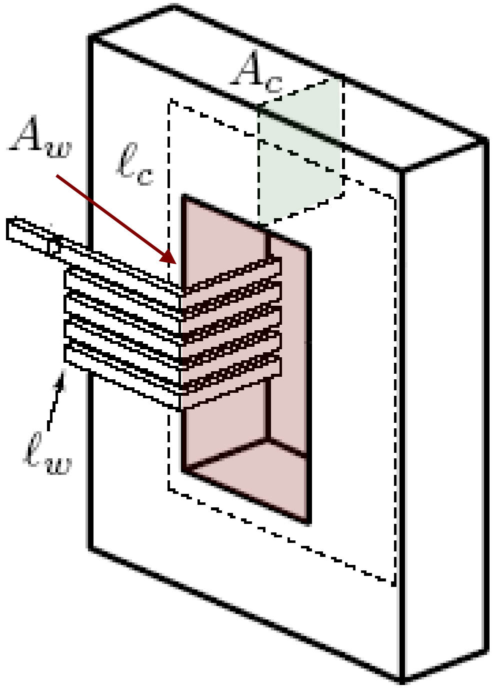
$$VA = V \cdot I \propto (N f B_0 A_C) \cdot \left(\frac{J_0 A_W}{N}\right) = f \cdot B_0 \cdot J_0 \cdot \boxed{(A_C A_W)}$$

Sullivan, et. al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," *International Symposium on 3D Power Electronics Integration and Manufacturing*, June 2016

Miniaturizing Magnetics is *Fundamentally* Difficult

- **Scaling laws work *against* miniaturization of power magnetics**

- **In principle, higher frequency can enable greater power handling**
  (or smaller size at constant power)



$$VA = V \cdot I \propto (N f B_0 A_C) \cdot \left(\frac{J_0 A_W}{N}\right) = \boxed{f} \cdot B_0 \cdot J_0 \cdot (A_C A_W)$$

Sullivan, et. al., "On Size and Magnetics: Why Small Efficient Power Inductors are Rare," *International Symposium on 3D Power Electronics Integration and Manufacturing*, June 2016

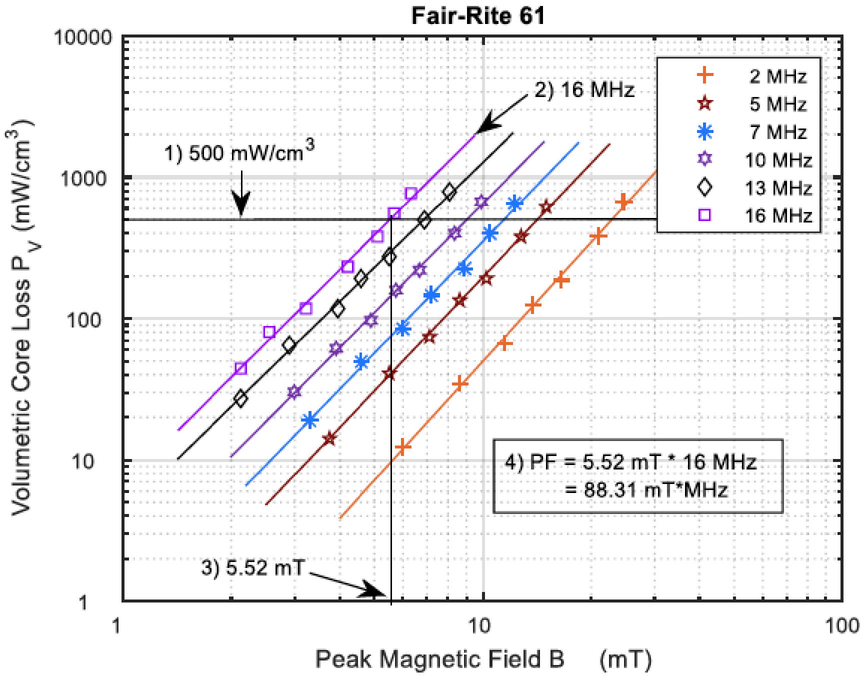
Frequency Challenges

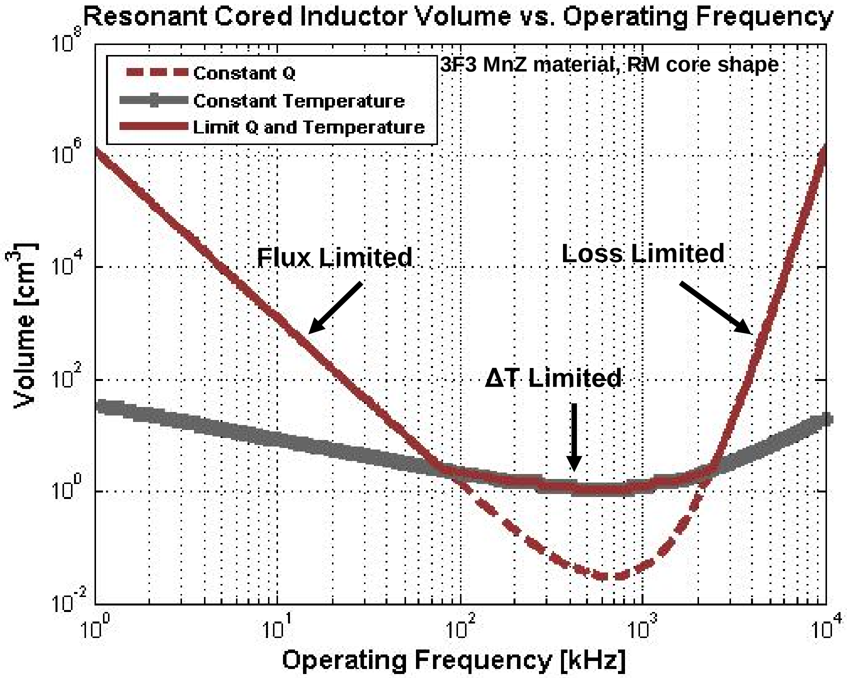
- **Factors in increasing switching frequency**
  - **Magnetic component design**
  - **Power devices**
  - **Sensing and control circuitry**
  - **Parasitics and packaging**
  - **Circuit design**

Scaling of Magnetics Size with Frequency

- **Magnetic component size *can* decrease with frequency, but only over a limited frequency range (limited by core loss)**
  - **Allowable flux density B_0 decreases with f at constant loss density**

$$VA = V \cdot I \ \propto (N f B_0 A_C) \cdot \left(\frac{J_0 A_W}{N}\right) = \boxed{f \cdot B_0} \cdot J_0 \cdot (A_C A_W)$$

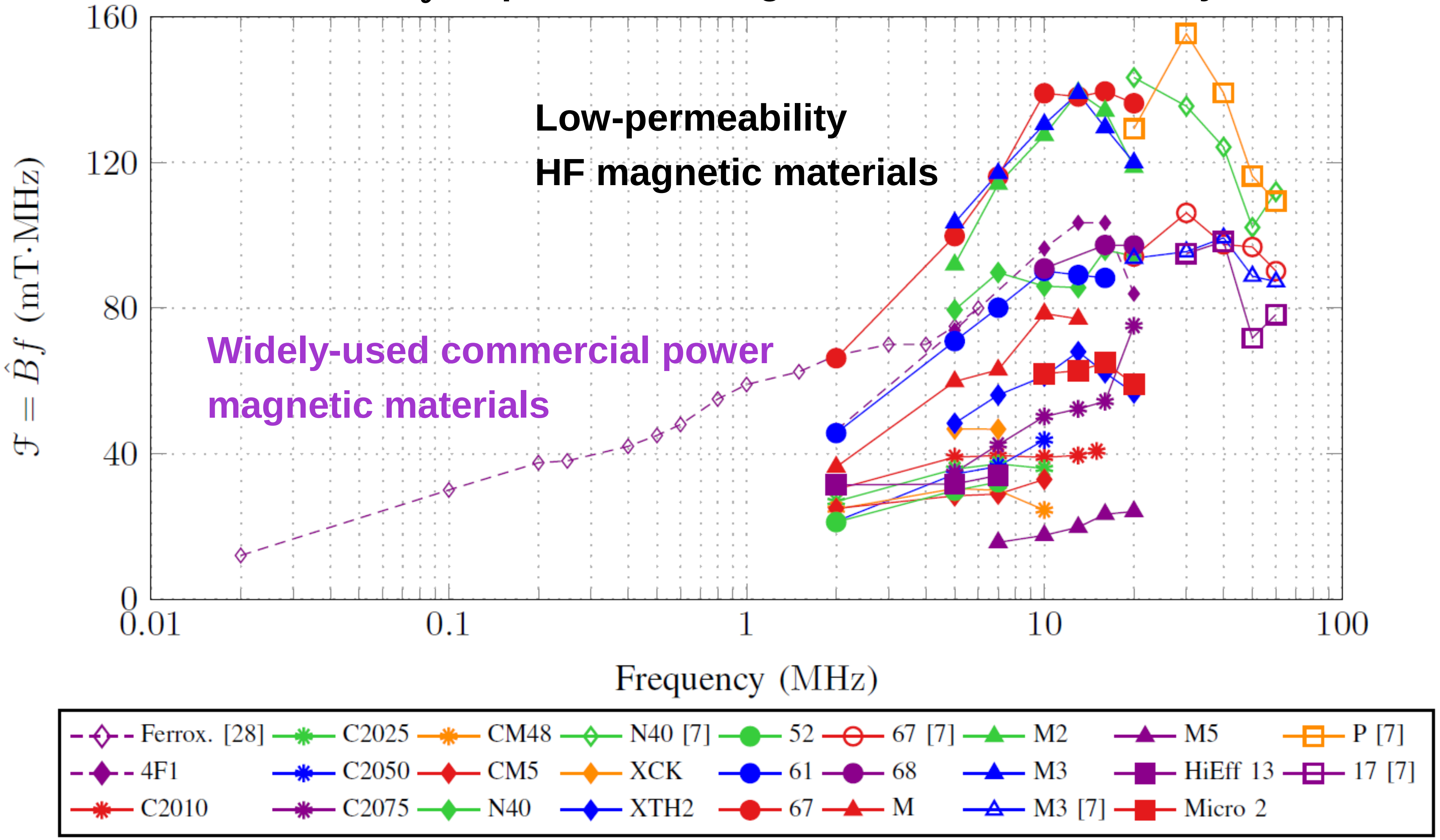




Example: Resonant inductor providing |Z| = 10 Ω (1.6 uH at 1 MHz), Q_{min} = 100, ΔT < 75 °C, |Iac| = 0.5 A

Magnetic Material Performance Factor at HF

Performance factor $B_0 f$ **: power handling at *constant loss density and volume***



A.J. Hanson et al, "Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency," *IEEE Transactions on Power Electronics*, Vol. 31, No. 11, pp. 7909-7925, November 2016.

Implications for Miniaturization

- **Continued opportunity for miniaturization with frequency**
  - **Main power stage (core-loss-limited) magnetics density: Performance factor improves to ~30 MHz with available materials**
  - **Other components (e.g., in EMI filters, etc.) scale inversely with frequency and can substantially improve at higher frequency**

High-Frequency Magnetics Design

- ***Design of improved high-frequency power magnetics remains a high-impact research challenge***
  - **Leverage high-frequency magnetic materials (e.g., at low μ)**
  - **Address skin and proximity effects, especially at high current**
    - **Cu skin depth ~21 μm at 10 MHz, 25˚C**
    - **Litz wire presently less useful above several MHz**
      - **50 AWG wire diameter is ~25 μm**

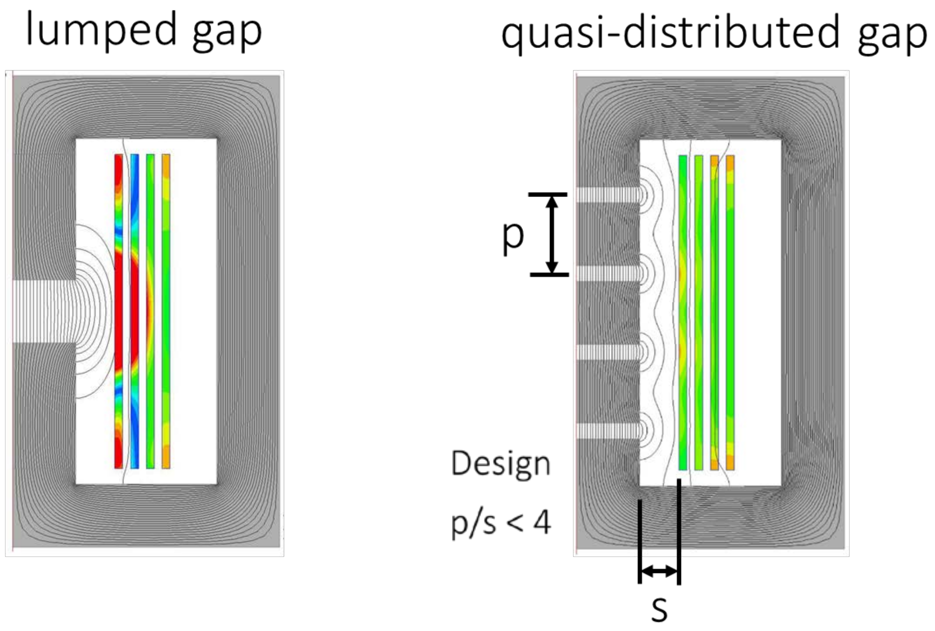
- **High performance designs in the HF range are achievable**

HF Magnetics

Must address key challenges that dominate at HF

Challenge 1: Fringing field loss

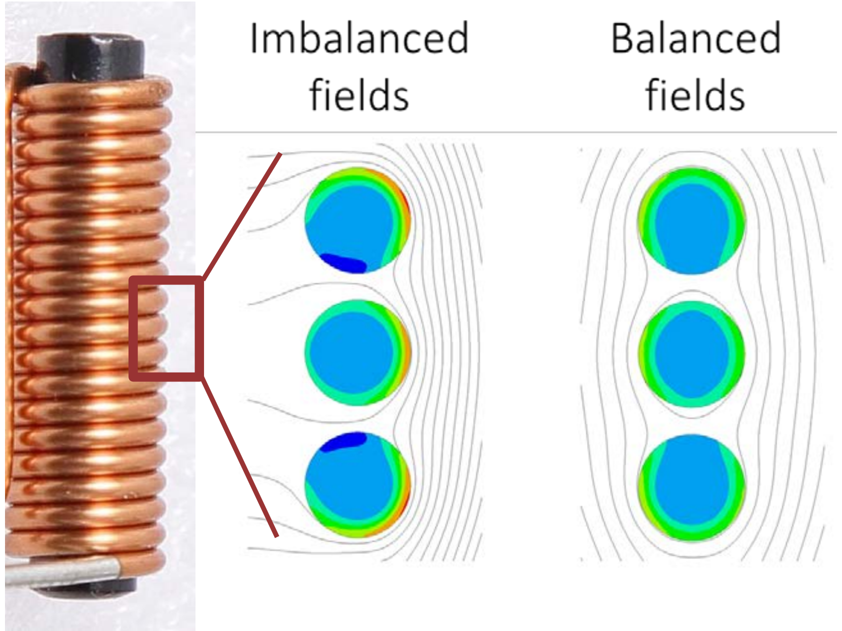
- Fringing fields at energy storage gap lead to eddy current losses (proximity effect)



Solution 1: Use quasi-distributed gaps that do not impose HF fringing fields at conductor

Challenge 2: Current distribution (skin effect)

- Conventional designs have imbalanced H fields that give poor winding utilization

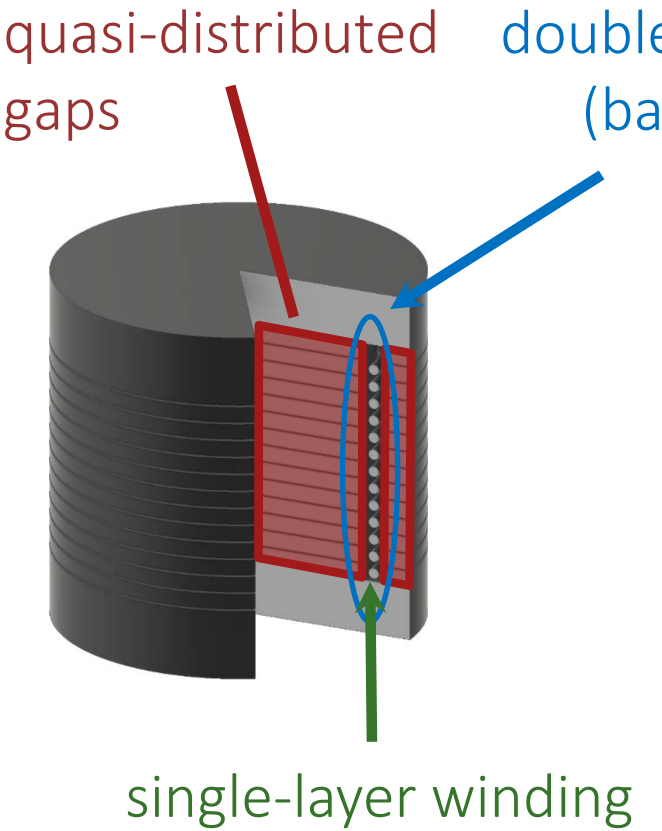


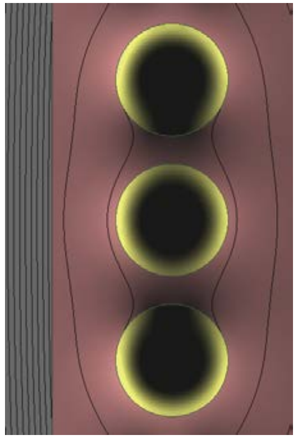
Solution 2: Design a magnetic structure that balances the fields around the windings, enabling better conductor utilization

R. Yang et. al. “A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications,” *IEEE Transactions on Power Electronics*, 2019.

Example: Low-Loss HF Inductors

- **Leverage quasi-distributed gaps and field balancing for reduced conductor loss**
  - **Twice the Q of conventional inductors using the same magnetic material**





16.6 uH, 2 A, 3 MHz performance	5/9/10/48 (litz)
Experimental Q	**980**
Simulated Q	1000

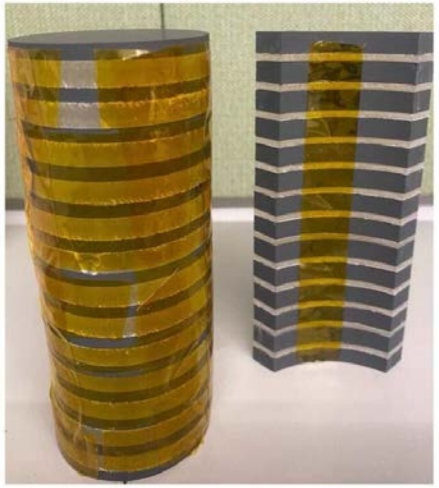
R. Yang et. al. "A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications," *IEEE Transactions on Power Electronics*, 2019.

Approach scalable to a wide range of applications

R. Yang et. al. "Design Flexibility of a Modular Low-Loss High-Frequency Inductor Structure," *IEEE Transactions on Power Electronics*, 2021.

Example: High-Power High-Frequency Inductor

- **570 nH, 13.56 MHz inductor , Q = 1150 @ 80 $A_{pk,\ ac}$ / 3.9 $kV_{pk,ac}$**
  - **155 kVA @ 13.56 MHz**
  - **Fully self-shielded**
  - **Smaller, more efficient than conventional designs (Q=1150 @ vol = 1.6 l)**
  - **Designed for use in high-power RF applications (power amplifiers, matching networks)**



Outer core and Inner core

Winding

Inner core + outer core top view

Endcaps

Inductor with Shield

M. Joisher et. al. "High-Performance High-Power Inductor Design for High-Frequency Applications," *APEC 2024*. (Tuesday, Session T.08)

Power Devices

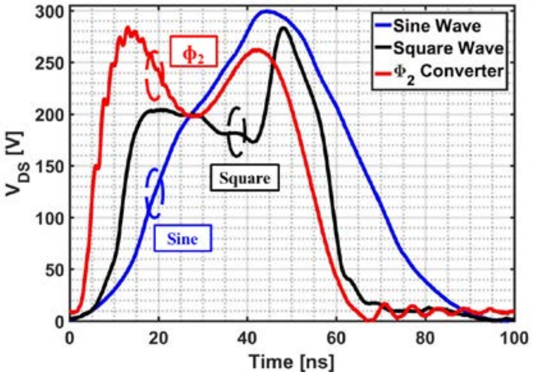
- **Power devices have advanced tremendously**
  - **Improved performance factors ($R_{gate} \cdot C_{gate}$, $R_{on} \cdot C_{oss}$) facilitate operation at 10s of MHz**
  - **High current per unit die area facilitates small devices**
- **Important challenges remain for HF**
  - **Hysteresis losses in output capacitors (“C_{oss} loss”)**
    - **Si & GaN transistors and SiC diodes**
  - **Dynamic on-state resistance**
    - **in GaN transistors**

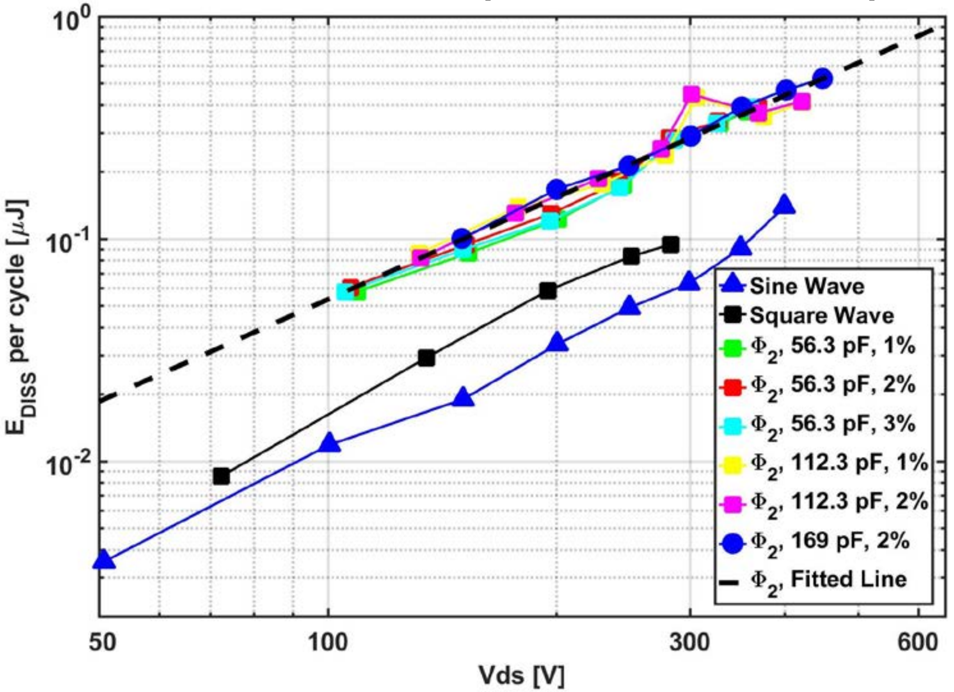
Power Devices – C_{oss} Loss

- C_{oss} loss important at HF; may exceed conduction loss
  - Energy loss/cycle can increase with frequency
  - Loss characteristics can depend heavily on waveshape

Loss per cycle parameterized in frequency
650 V GaN device (Zulauf 2018, Stanford)

Loss per cycle @ 10 MHz vs. waveshape
650 V GaN device (Zulauf 2018, Stanford)

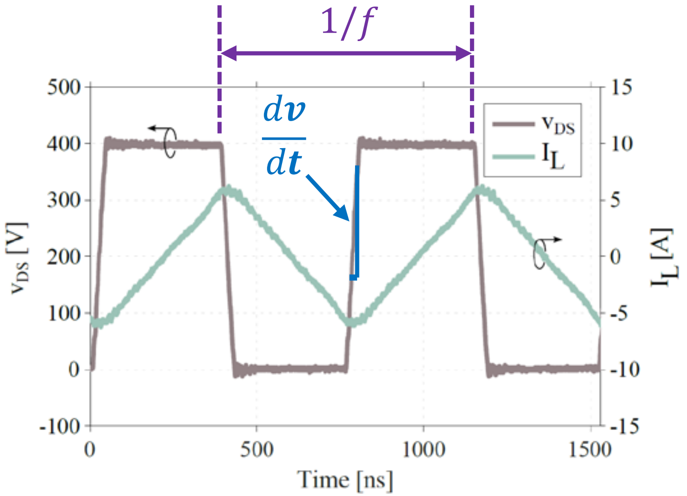




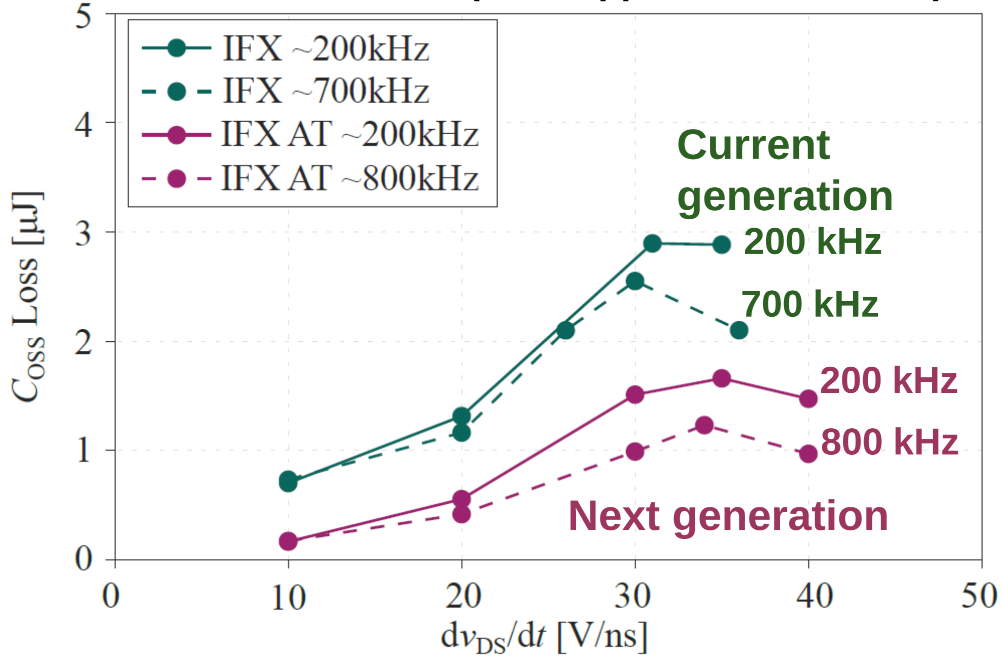
G. Zulauf et. al. "Coss Losses in 600 V GaN Power Semiconductors in Soft-Switched, High- and Very-High-Frequency Power Converters," *TPEL,* Dec. 2018.

Power Devices – C_{oss} Loss

- It is important for device manufacturers to improve HF device losses including dynamic $R_{ds,on}$ and C_{oss} loss
- Recent results are promising (trapezoidal-wave case)
  - Limited loss increase with dv/dt
  - Loss/cycle gets better with frequency
  - Newest gen devices greatly improved



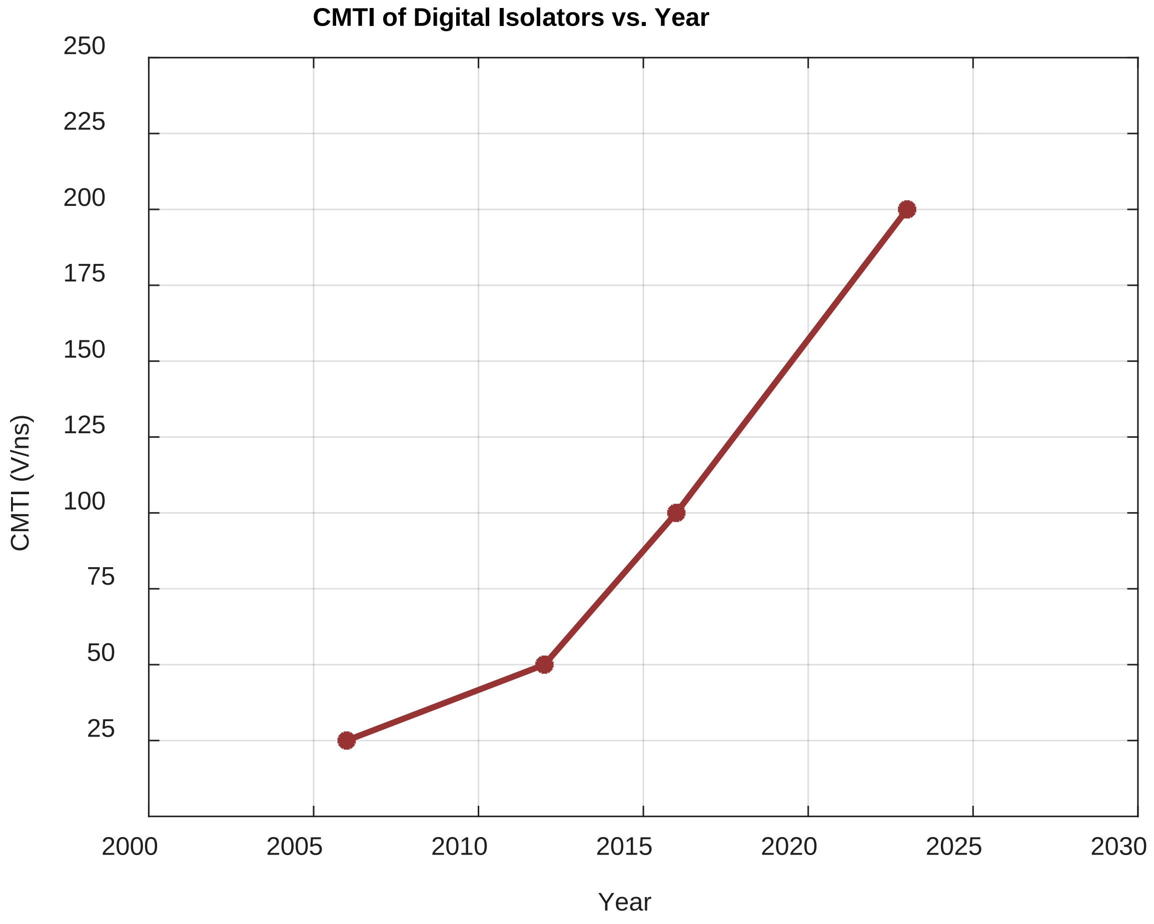
Loss per cycle for trapezoidal voltage vs. dv/dt parameterized in switching frequency
600 V GaN devices (de Felippis 2024, Infineon)



S. de Filippis et. al. "Experimental Characterization of Dynamic C_{OSS} Losses in 600V GaN HEMTs based on a Novel and Simple Calorimetric Method," *APEC 2024.* (Wednesday, Session T14)

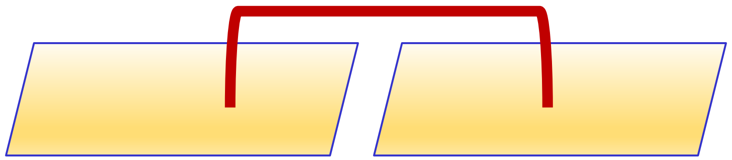
Sensing and Control

- **Sensing and control circuits have likewise advanced tremendously**
  - **Both processes and circuit design**
- **Continued advances *are* needed**
  - **But often not the limiting factor**
- **If needed, address via design**
  - **Avoid controls requiring low latency**
  - **Leverage circuits with low-side switching**



Parasitics and Packaging

- **For a given component / device size, parasitic effects become more dominant as frequency increases**
  - **Capacitive currents increase, inductive voltages increase**
  - **Inductive parasitic effects also scale up with current (device area) and voltage (spacing requirements)**
  - **Impacts loss, EMI, etc.**



- **Advances in packaging, interconnects/layout , fabrication and materials will be valuable to continue increases in frequency**

- **Augment with circuit design techniques to mitigate and/or usefully absorb parasitics**
  - **e.g., as often done in single-switch inverters and rectifiers**

Electromagnetic Interference (EMI)

- **EMI is often cited as a roadblock to higher frequencies**
  - **Structures of a given size do emit more easily at higher frequencies**

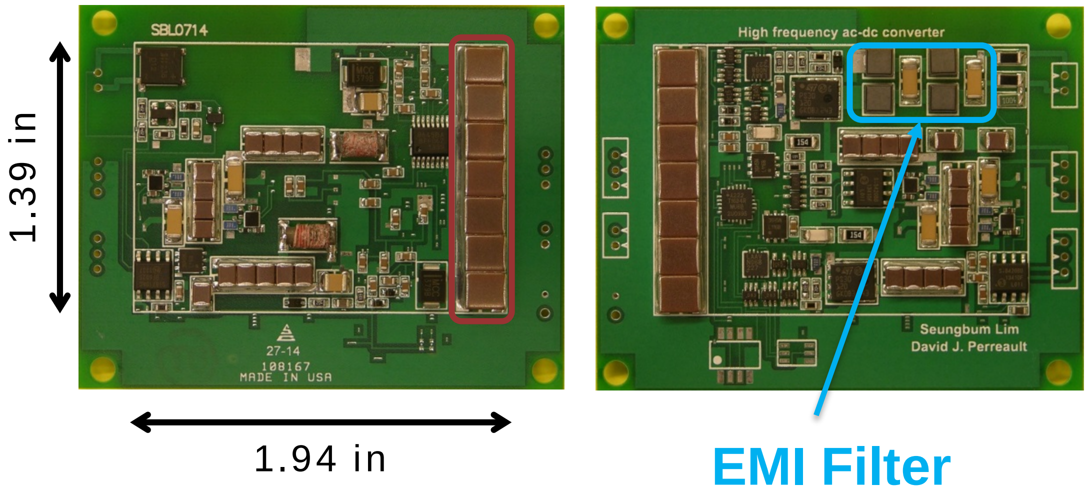
However:

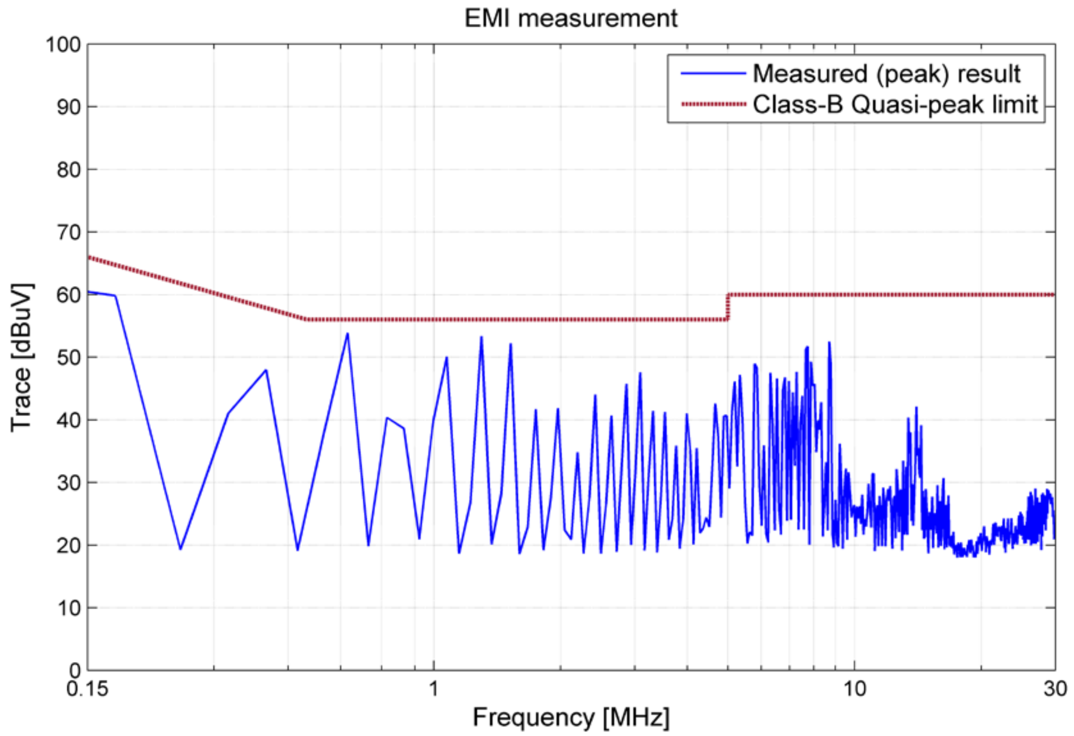
- **Techniques already exist to curb unwanted emissions at much higher frequencies and rf power levels than considered here**
  - **Widely applied in rf power design (e.g., rf transmitters)**

- **EMI filter size can get much *smaller* at higher frequencies**
  - **It's not a bug, it's a feature!**

EMI Example: LED Driver (30 W, f_{sw} 5 – 10 MHz)

- **30 W LED Driver: switching frequency 5 – 10 MHz (variable)**
  - **120 V_{ac} input, 35 V dc output, 30 W @ 50 W/in³**





- **Meets FCC Class B**
- **Filter small relative to total solution size**
  - **Whole converter smaller than the EMI filter of a conventional design**

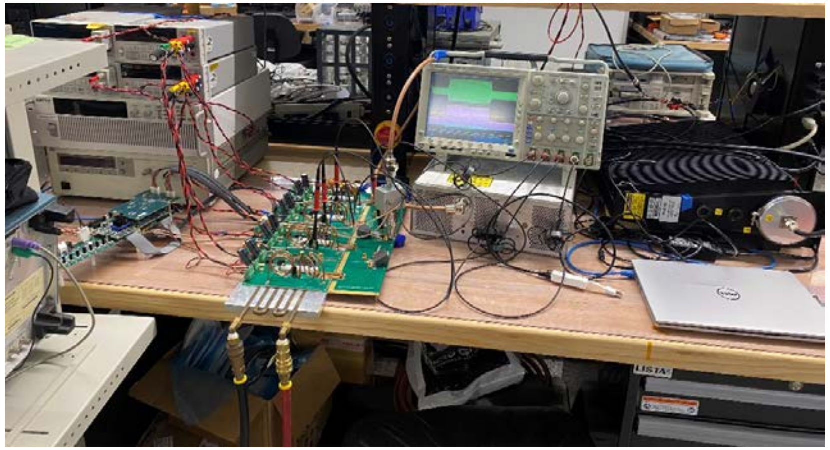
S. Lim et. al., "AC-DC Power Factor Correction Architecture Suitable for High Frequency Operation," *TPEL*, April 2016.

Paths Towards HF Power Electronics

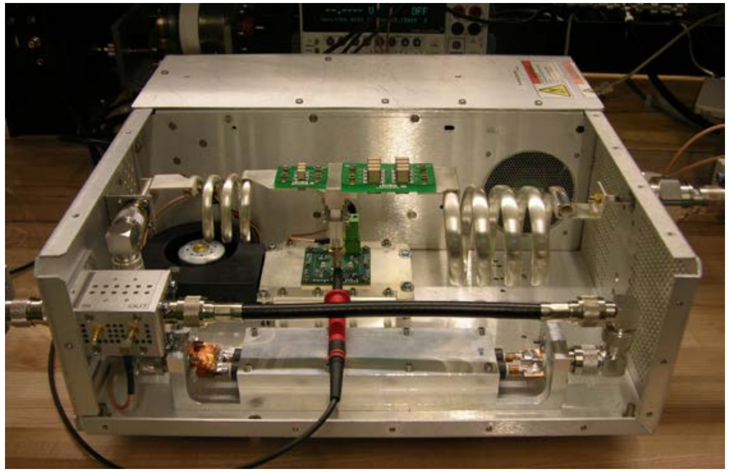
- **The path to HF facilitated by “beachhead” applications**
  - **Applications deriving compelling benefits from high-frequency operation**
- **Useful for developing and validating new devices, components, and design techniques**
- **Serve as early markets for HF designs and components**

Beachhead Applications for HF Power Electronics

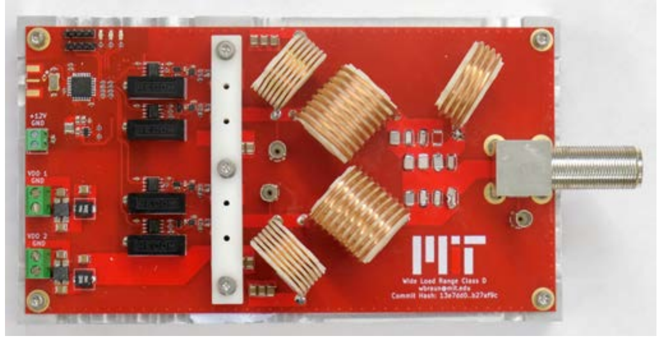
Industrial RF Power



5 kW, 13.56 MHz inverter
(H. Zhang, MIT 2022)

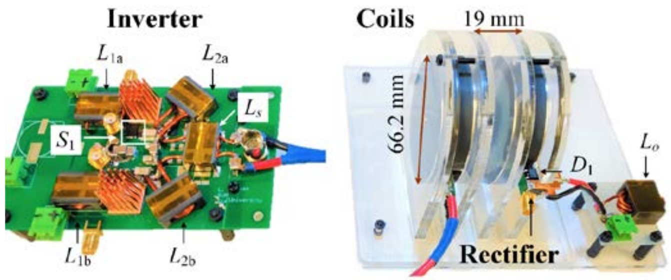


1.5 kW, 13.56 MHz TMN
(A. Al Bastami & A. Jurkov, MIT 2020)

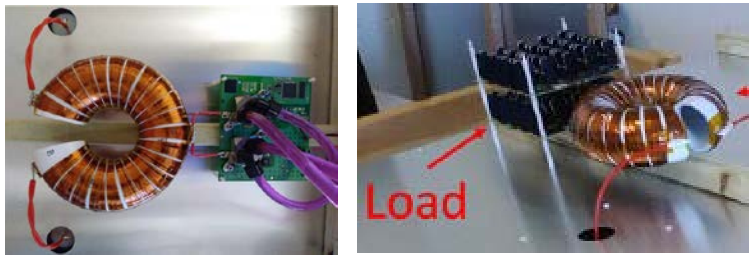


1 kW, 13.56 MHz, η 95.4% inverter
(W. Braun, MIT 2019)

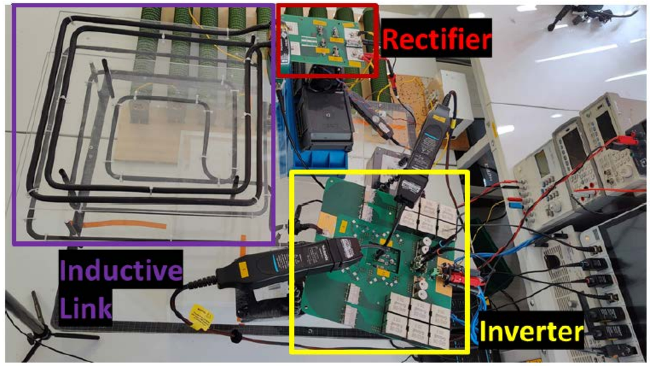
HF Wireless Power Transfer



1 kW, 6.78 MHz, η 95% IPT
(Gu & Rivas, Stanford 2021)



3.7 kW, 13.56 MHz, η 93% CPT
(Regensberger, Cornell 2022)



3 kW, 3.39 MHz, η 95% IPT
(Nikiforidis, Imperial 2023)

Summary: *There is still plenty of room at the top!*

- ***Much*** **higher frequency power electronics appear possible**
  - **e.g., 10’s of MHz at kW+ power scales**

- **Benefits to miniaturization, performance, applications,…**

- **Many challenges to be addressed**
  - **Magnetics, devices, packaging, circuit design and control**

- **We have the tools to get there**
  - **The next years are going to be exciting!**

HF Magnetics – Continued Challenges

- **Improved means to carry high currents at HF frequencies remains an important open challenge**
  - **Carrying current in many “layers” with low proximity-effect loss desirable**

Example: "Switching Cell in Package"

- **Customized packaging to reduce switching loop inductance**

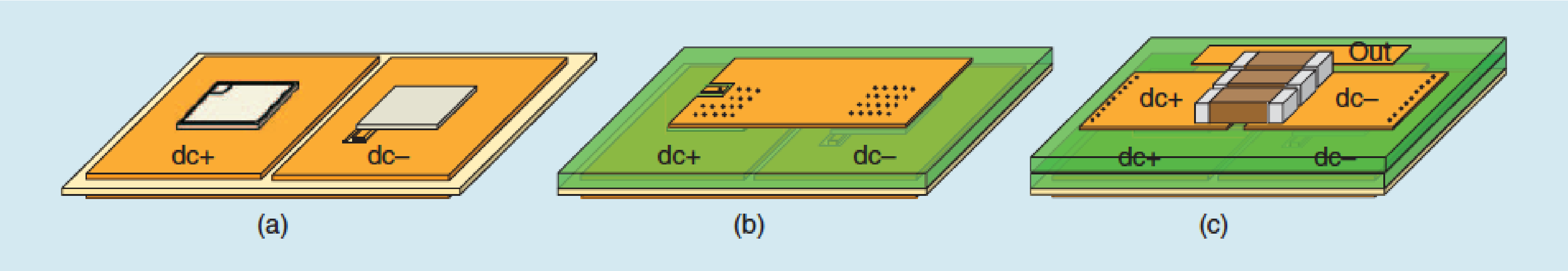


FIG 7 An SCiP setup starting with two MOSFETs on a ceramic substrate [with direct copper boding (DCB)] with (a) one regular chip and one flipped, (b) a next layer in PCB technology connecting the semiconductors for out connection, and (c) a last layer closing the dc link with primary dc-link capacitors.

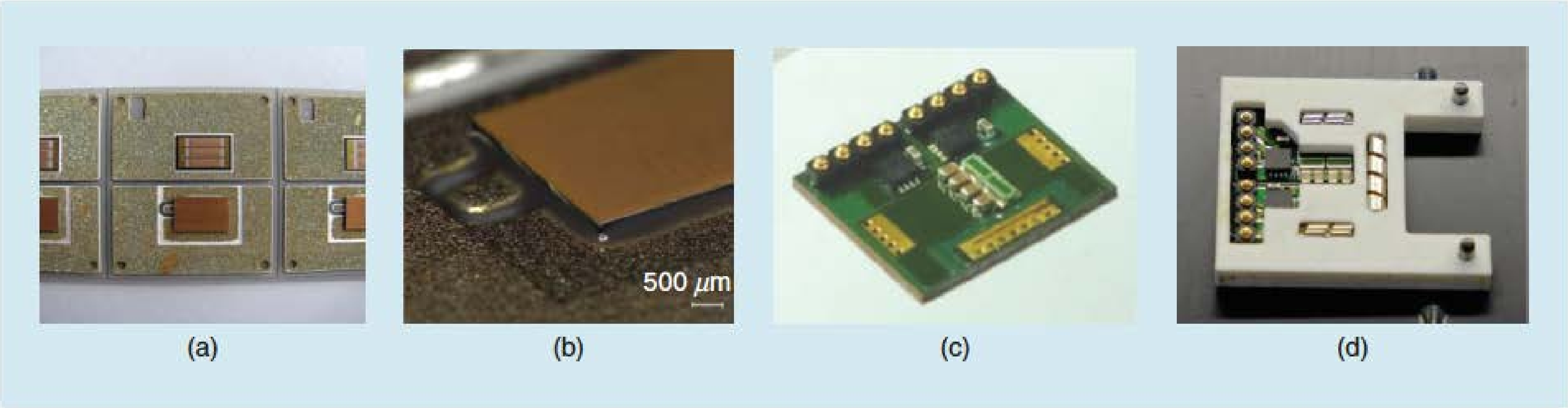
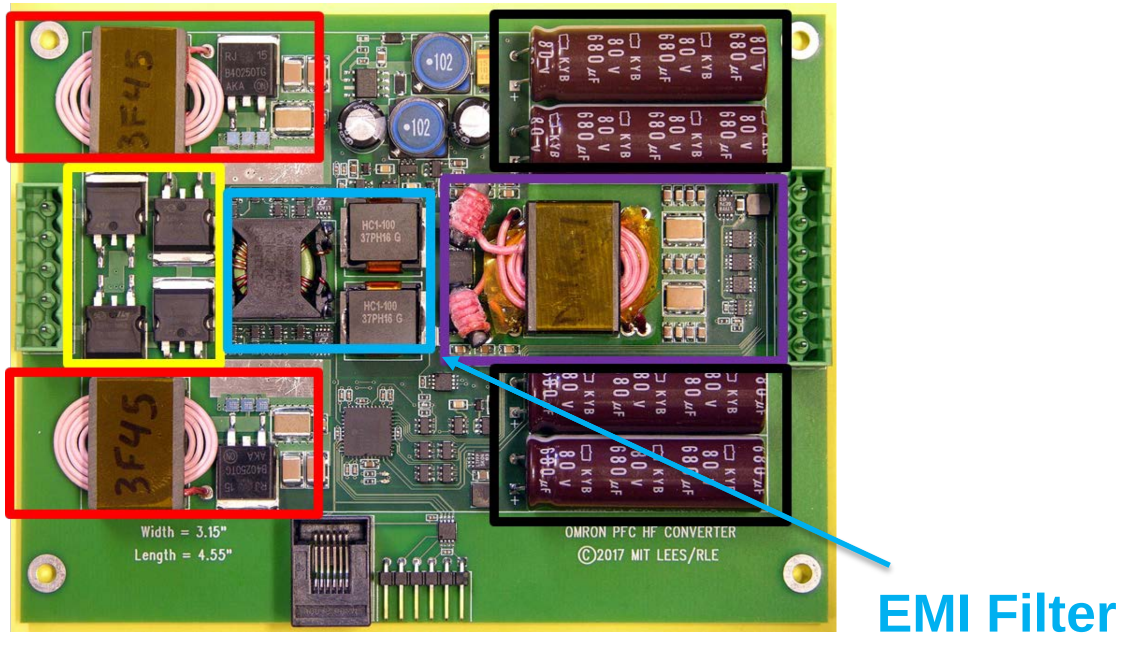


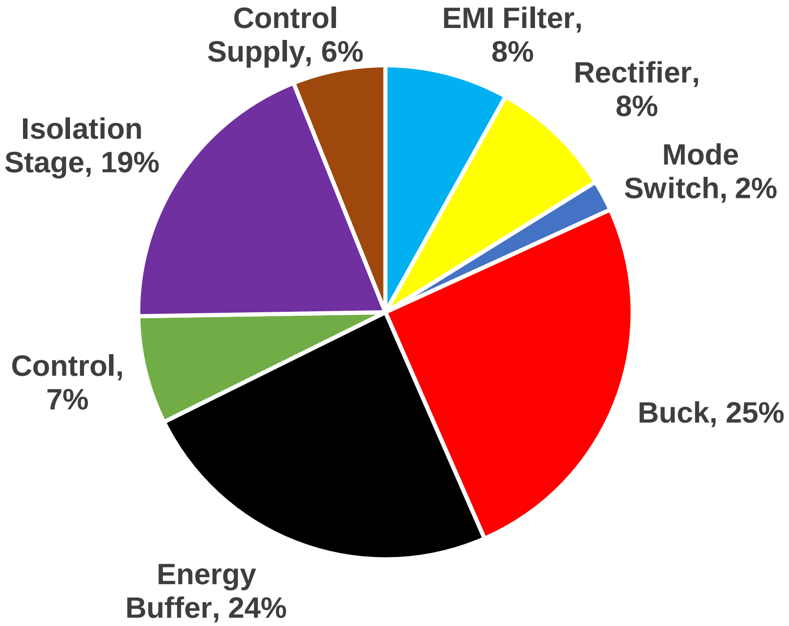
FIG 8 The production steps: (a) chips with DCB, (b) the underfill of a flipped chip, (c) PCB layers manufactured and SMD components assembled, and (d) a module including electrical interfaces and a plastic frame to fulfill the creepage distance. (Photos courtesy of Eckart Hoene, Fraunhofer IZM.)

E. Hoene et. al. "Outlook on Developments in Power Devices and Integration," *IEEE Power Electronics Magazine*, March 2018

EMI Example: PFC Power Supply (250 W, f_{sw} 1 – 4 MHz)

- **250 W PFC Power Supply: switching frequency 1–4 MHz (variable)**
  - **Universal ac input, 24 V dc output, 250 W @ 35 W/in^3**
  - **Meets 80+ Platinum efficiency standard (95.33% at full load)**



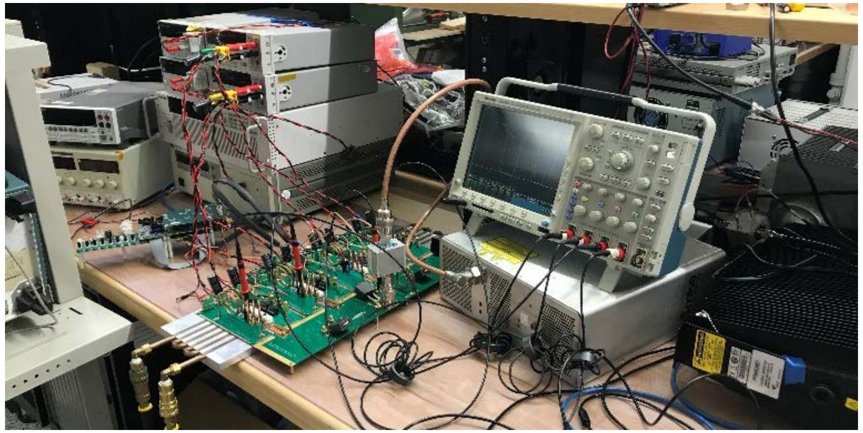


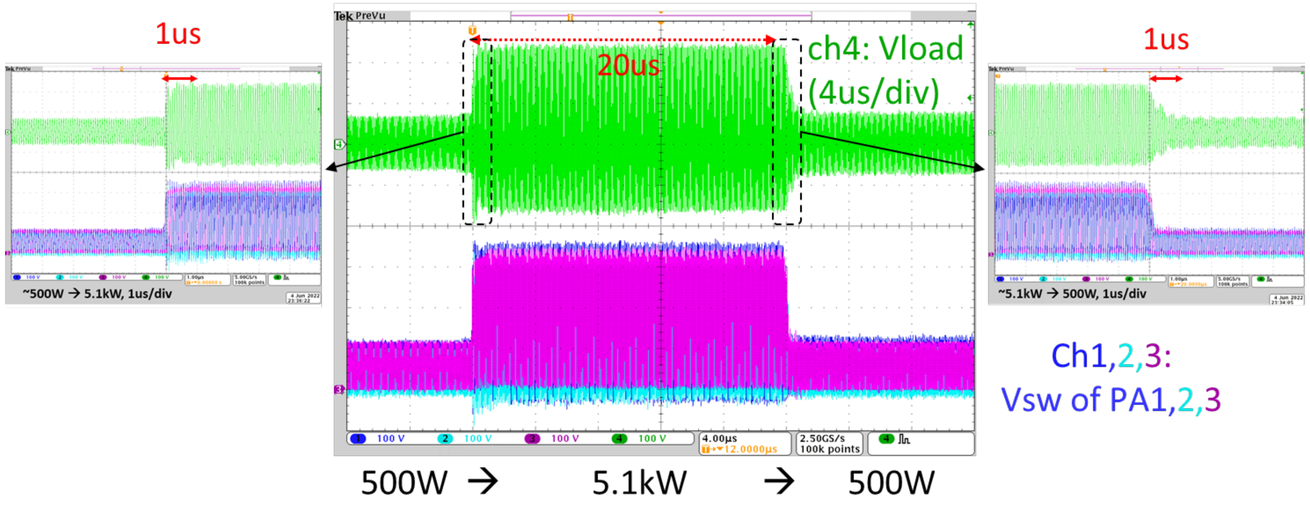
- **Filter small relative to total solution size (8% of total box volume)**

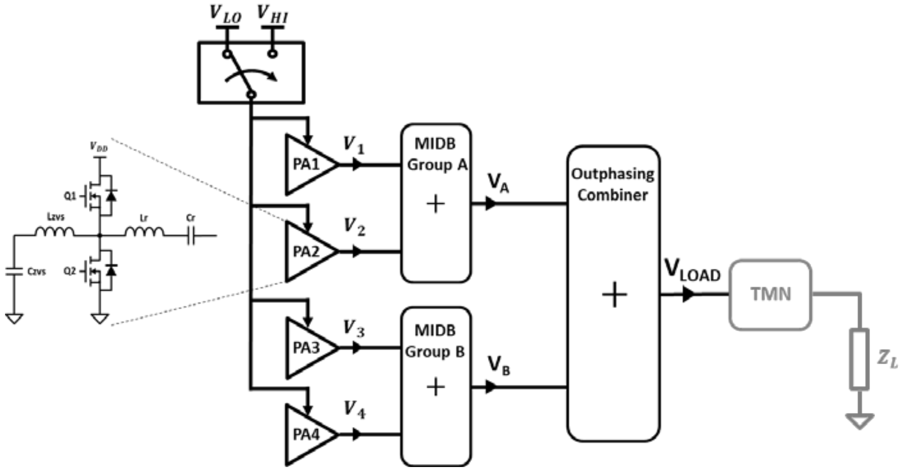
J. Santiago-Gonzalez et. al., "Single-Phase Universal-Input PFC Converter Operating at High Frequency," *JESTIE*, October 2023

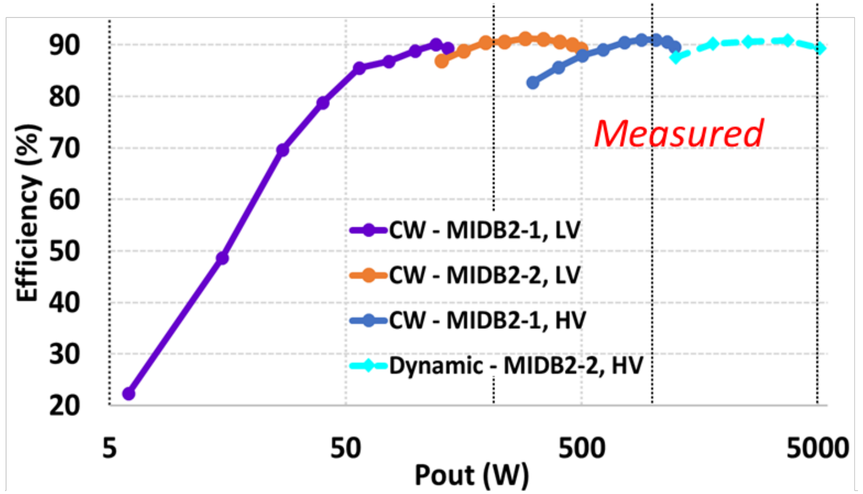
Example: 5 kW, 13.56 MHz Inverter

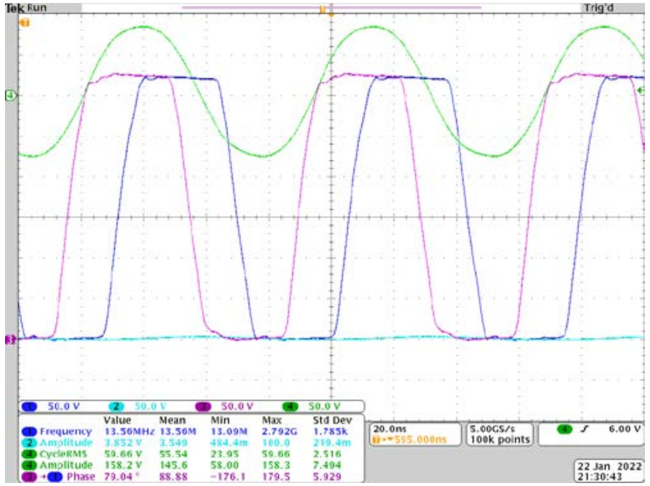
- 5 kW, 13.56 MHz inverter w/ fast response and wide power range







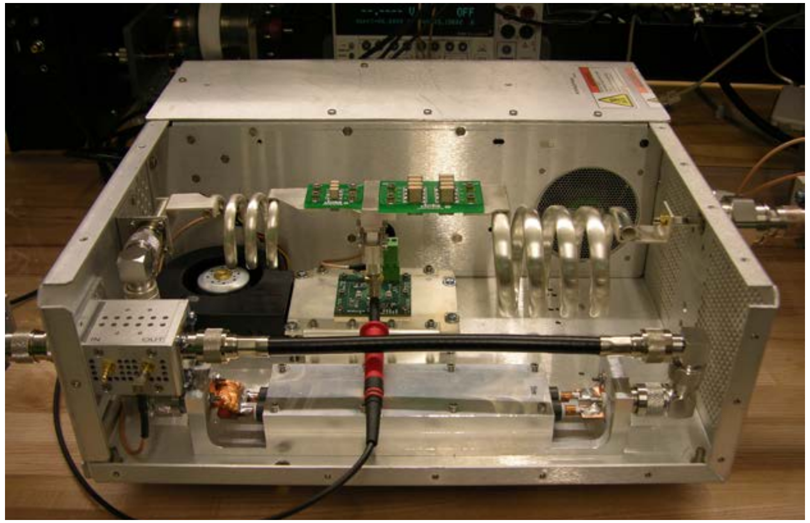


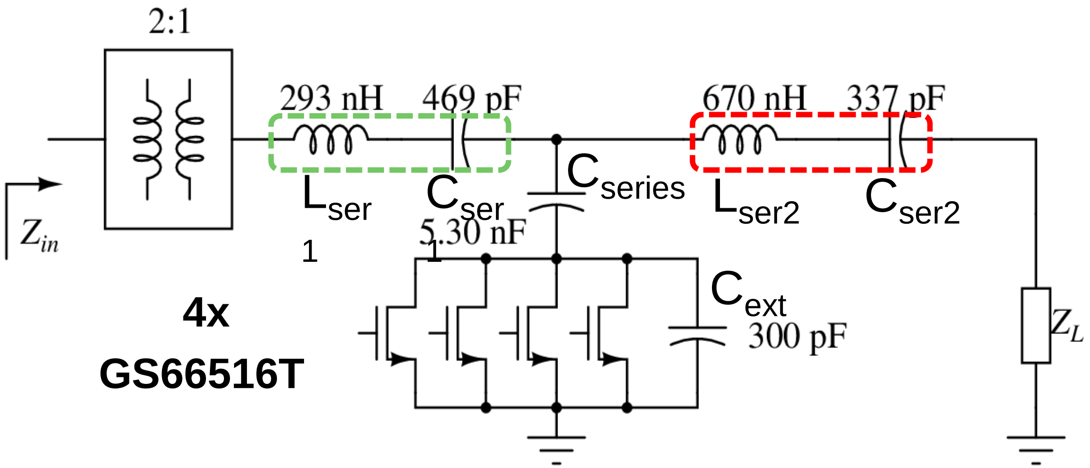


H. Zhang, "Techniques for Efficient Wide-Range Radio-Frequency Power Generation," MIT PhD Thesis, 2022.

Example: 1.5 kW, 13.56 MHz PSIM TMN

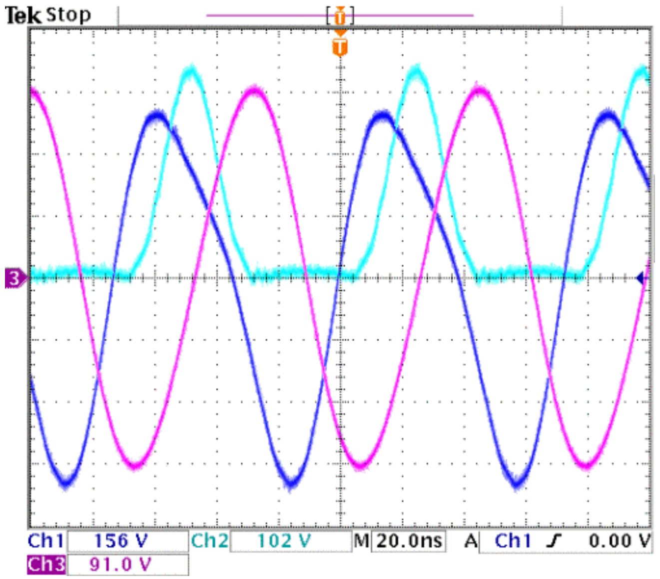
- **Tunable Matching Network (switched-mode ac/ac converter)**

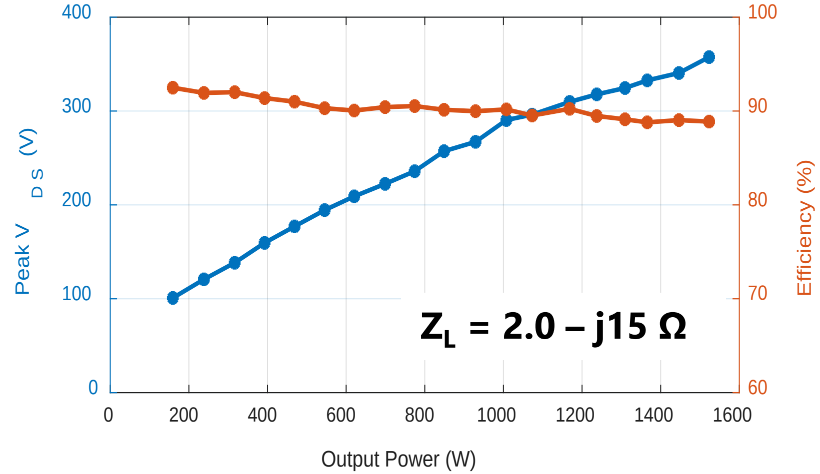




4x GS66516T

Matching 2-j15 Ω to 50 Ω at 1500 W output power



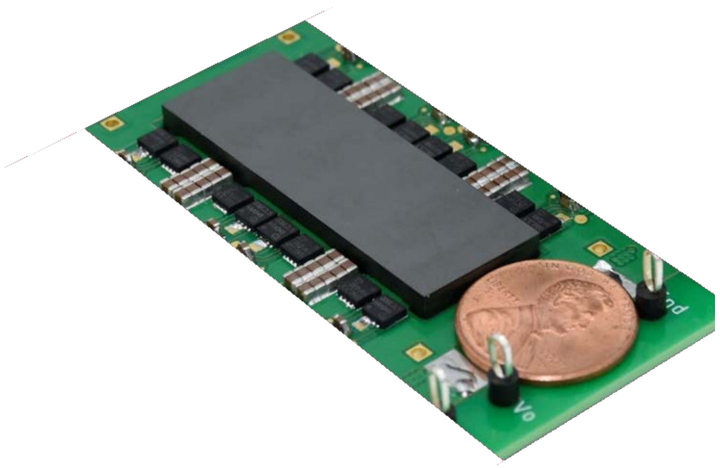


A. Bastami et al, "A 1.5 kW Radio-Frequency Tunable Matching Network Based on Phase-Switched Impedance Modulation," *OJPE*, 2020.

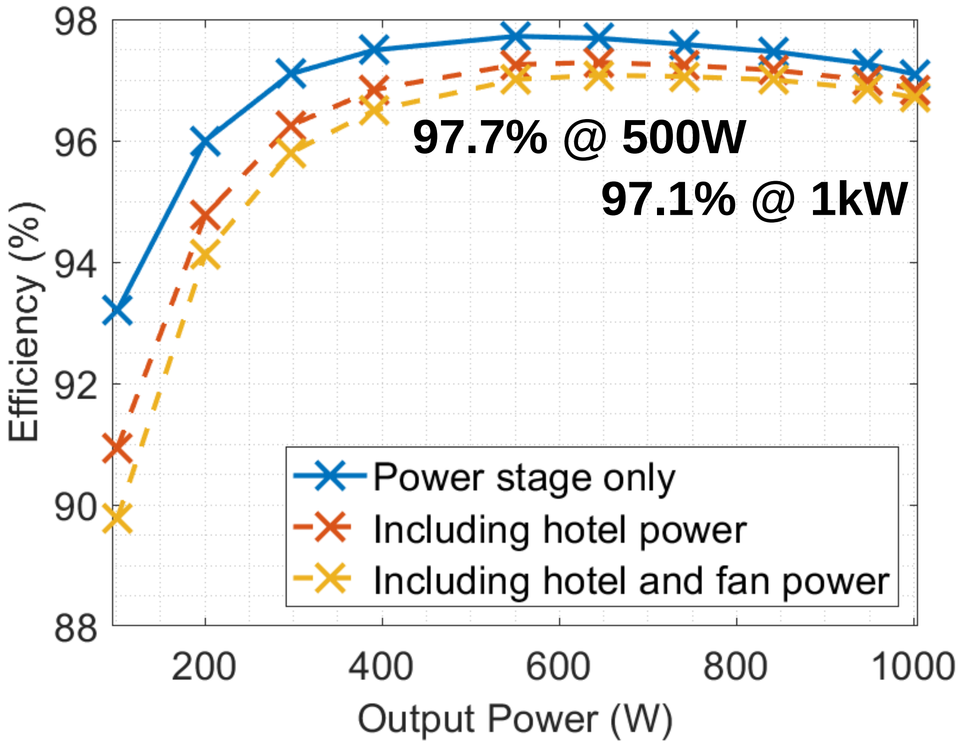
Advancing Frequency

- **Current technology supports power electronics at the kW scale operating at low MHz frequencies**
  - **Example: Datacenter converter, 380 V to 12 V @ 1 kW, η > 97%, f_{sw} ~1 MHz**

High Power Density



High efficiency



M. Ranjram et al, "A 380-12V, 1kW, 1 MHz Converter Using a Miniaturized Split-Phase Fractional Turn Planar Transformer," *TPEL* Feb. 2022.