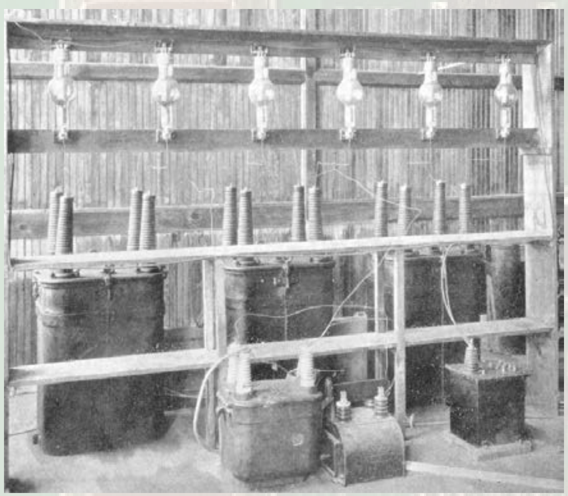
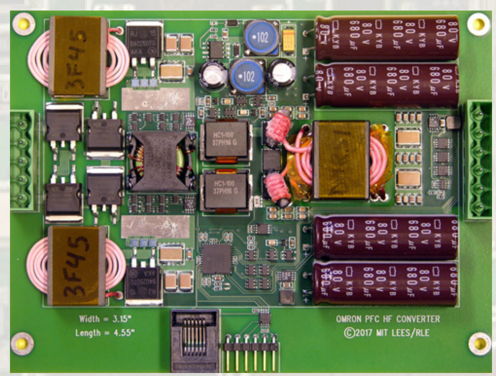
Powering the Future: Research Overview of the MIT Power Electronics Research Group

CICS Review

May 2021



20 kW Kenotron Rectifier, Circa 1926
(From Principles of Rectifier Circuits, Prince and Vogdes, McGraw Hill 1927)



PFC Power Supply, Circa 2017
(Juan Santiago-Gonzalez, MIT)

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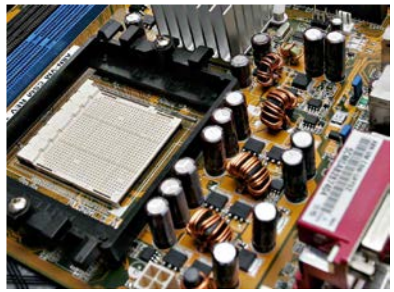
Circa 2030

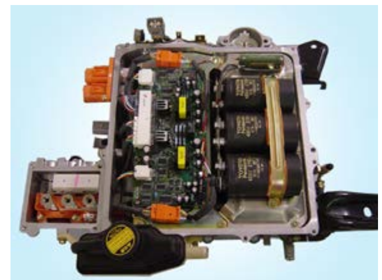
Power Electronics Challenges

- **All kinds of systems are limited by energy and how it is controlled and processed**

Efficient Lighting (LED driver)



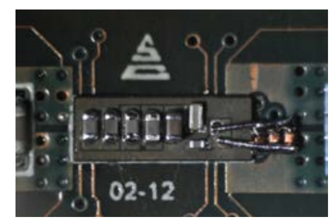
Computers (Power Supply)



Transportation (Inverter for Prius)

Renewable Energy (Microinverter)

- **Needs**
  - **Miniaturization (smaller, lighter)**
  - **Higher efficiency (converters *and* systems)**
  - **Higher performance (better systems)**
  - **Applications (create entirely new *system* opportunities)**

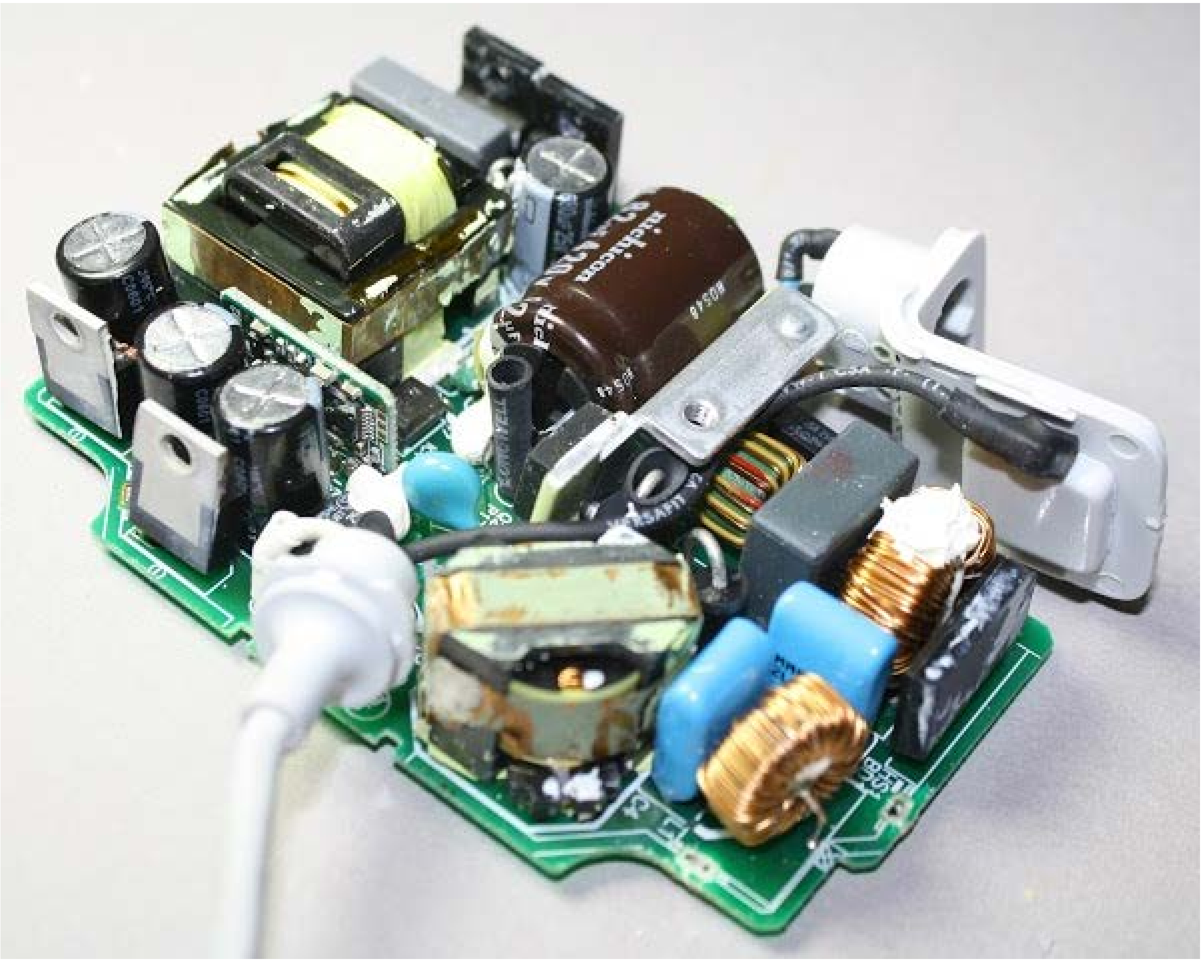


Mobile Devices (Power management)

Develop and apply technologies for improved power conversion

Passive Components Dominate

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



Opportunities for Advances

- **Improvements in semiconductor devices, integrated circuits / controls, magnetic materials and packaging open the door to better power electronics**

- **More *sophisticated* converter designs now possible**
  - **Increase complexity but greatly improve size, efficiency and performance**
- **Much *higher-frequency* converters now possible**
  - **(10-100x higher than conventional approaches)**
  - **Substantial reductions in energy storage / passives**
- **Improved passive components and integration**
  - **Better materials, designs, integrated construction**
  - **Alternative energy storage mechanisms (e.g., piezoelectrics)**
- **New power electronics *applications* now possible**
  - **Advances enable new electronic functions**

New System Architectures and Topologies

- **Design has historically been driven by a desire (and need) for simplicity**

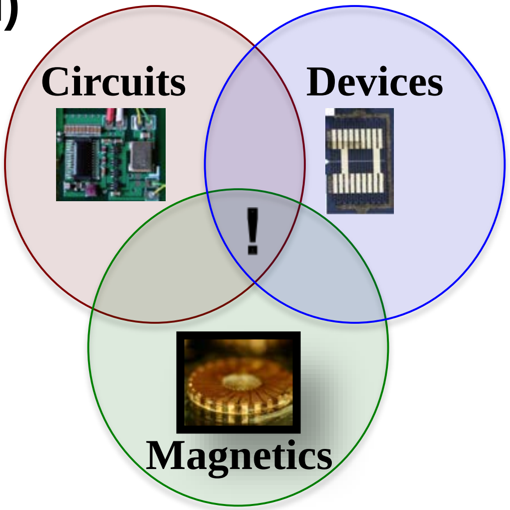
- **Advances in semiconductor devices, integrated circuits, controls and passive integration techniques favor adoption of more sophisticated power conversion architectures and topologies**

- **We are exploring new design approaches that have higher complexity but leverage technology advances provide smaller, more efficient and higher-performance solutions**

Today's talk by Mike Ranjram is an example of this approach

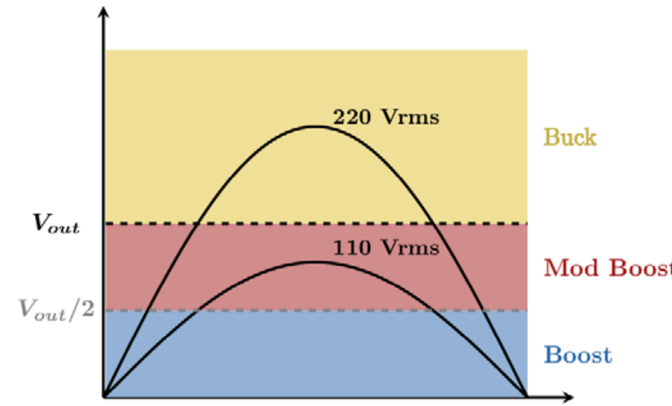
Frequency Increases

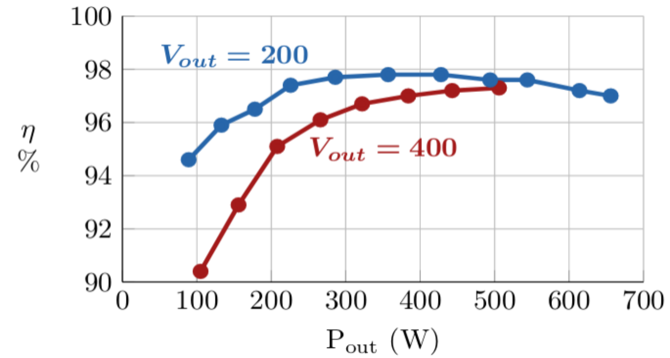
- Objective: develop technologies to enable miniaturized, integrated power electronics operating at HF (3 – 30 MHz) and above
- To achieve miniaturization and integration:
  - Circuit architectures, topologies and controls for HF/VHF
    - Develop approaches that overcome loss and best leverage devices and components available for a target space
  - Devices
    - Optimization of integrated power devices, design of RF power IC converters, application of new devices (e.g., GaN)
  - Passives
    - Synthesis of integrated passive structures incorporating isolation and energy storage
    - Investigation and application of magnetic materials at HF & VHF
  - Integration
    - Integration of complete systems

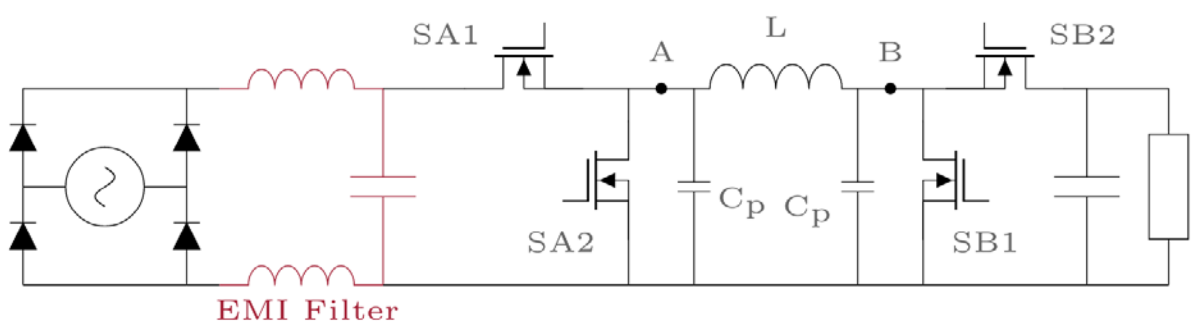


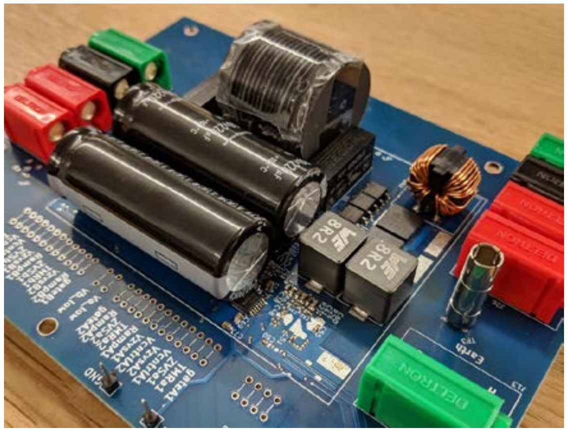
HF PFC converter (1-3 MHz operation)

- HF Power Factor Correction (PFC) converter
  - 660 W PFC: ~98% efficient, 80 W/in³
- In addition to magnetics, leverages:
  - System architecture: to reduce energy transformation
  - Circuit design: HF ZVS power stage
  - HF sensing, level-shifting and driving techniques
  - Layered control
    - Low-delay ZVS switching control
    - Feedback requiring only low-frequency measurements, calculations





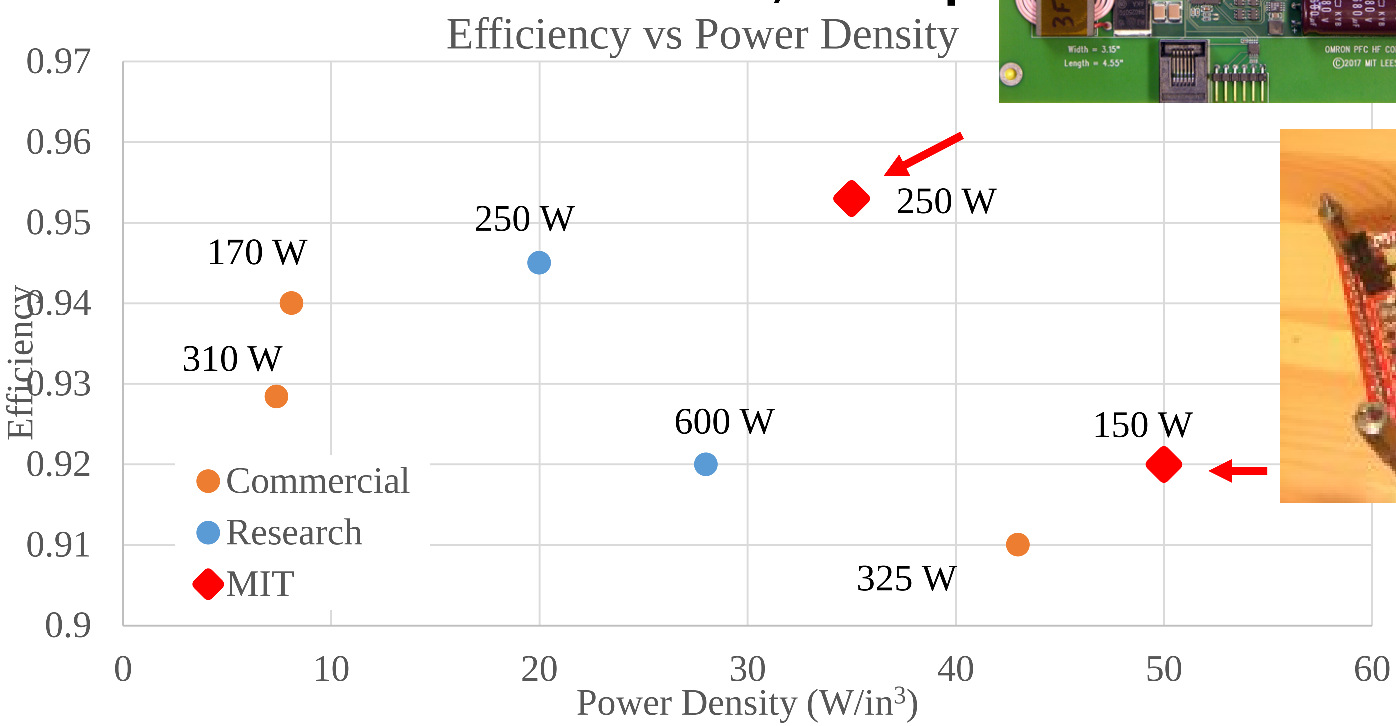


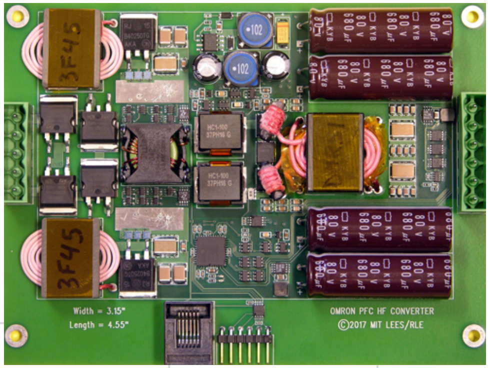


A.J. Hanson et al, "A High-Frequency Power Factor Correction Stage with Low Output Voltage," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, March 2020.

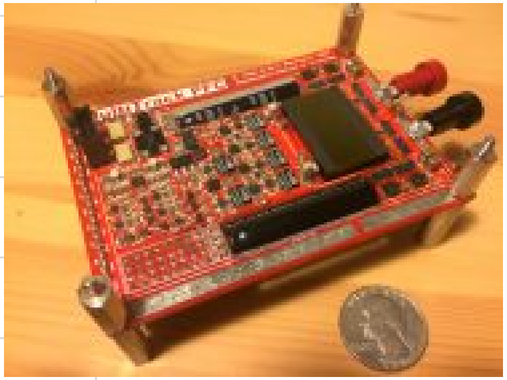
High-density, high-efficiency universal input ac-dc power supplies

- universal input 85 Vac-265 Vac
- Isolation, low-voltage output
- Power Factor Correction, holdup





HF PFC power supply
250 W, 24 V out
35 W/in3, 95.3% eff

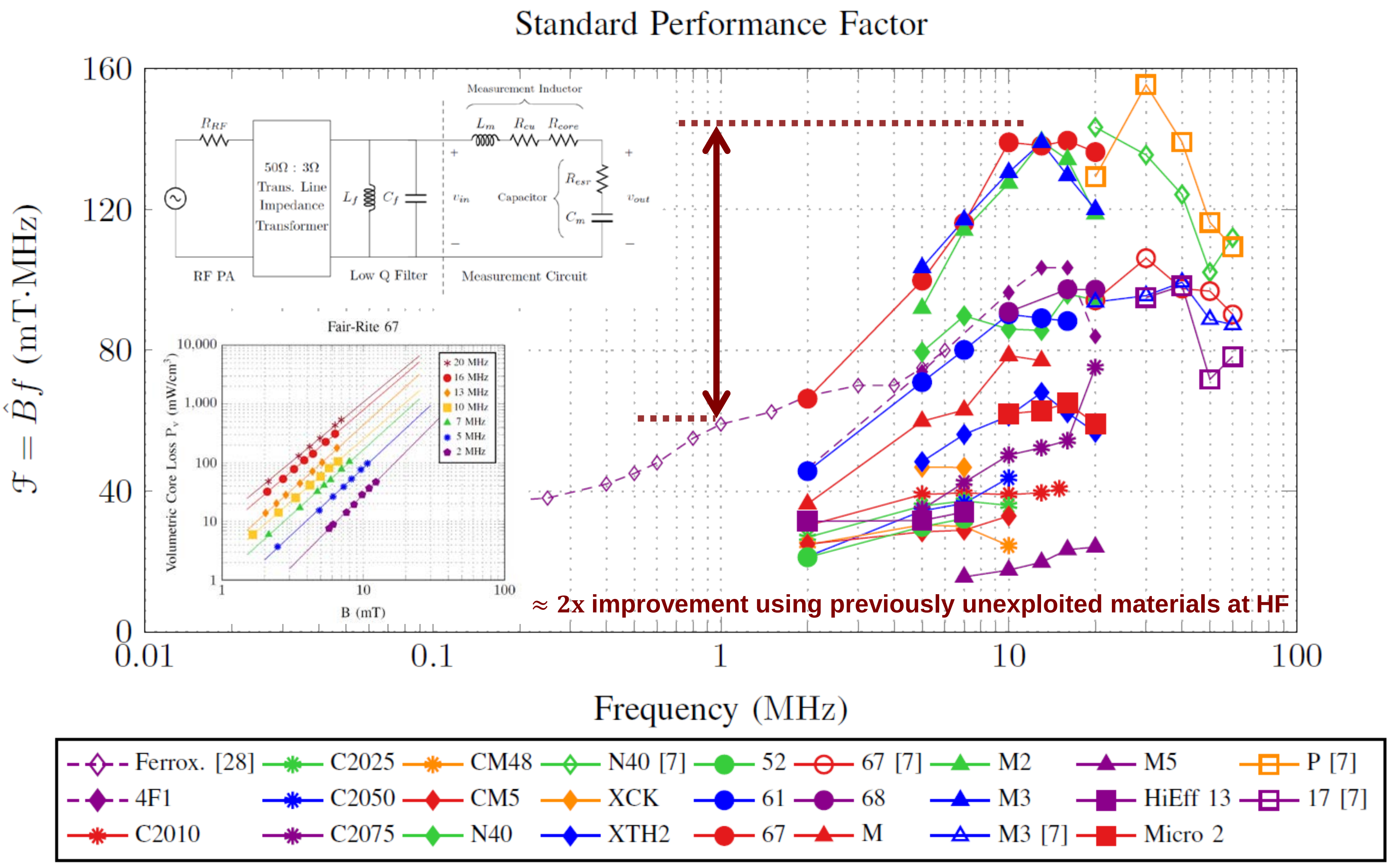


Multitrack PFC power supply
150 W, 12 V out
50 W/in3, 92% eff

Advances in architecture and High-Frequency Operation

HF Magnetic Material Investigation

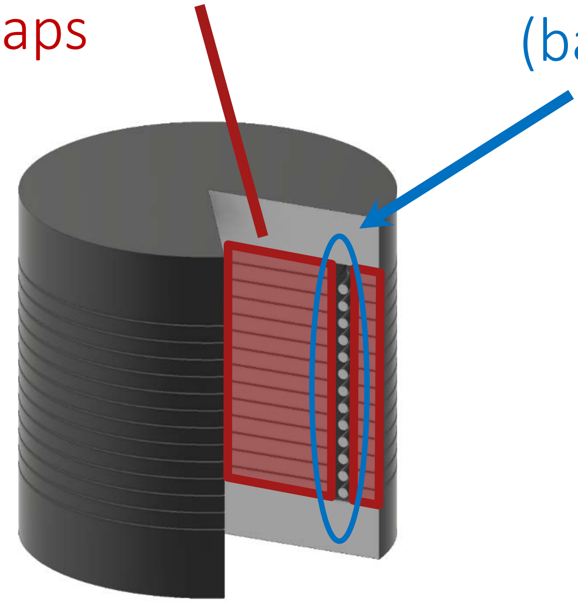
Available magnetic materials enable improvements to beyond 10 MHz !

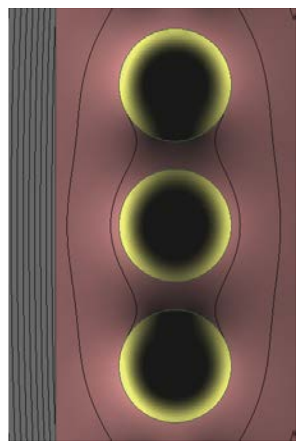


- **Leverage quasi-distributed gaps and field balancing for reduced conductor loss**

quasi-distributed gaps

double-sided conduction (balanced H fields)





Approach scalable to a wide range of applications; *twice* the Q of conventional inductors (Yang, APEC'20)

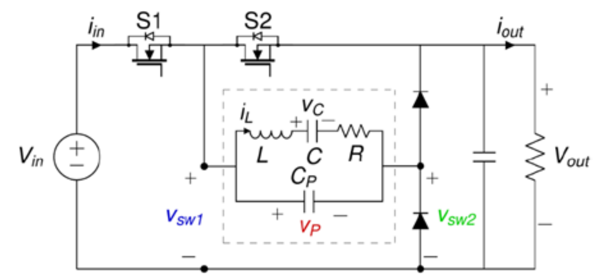
16.6 uH, 2 A, 3 MHz performance	5/9/10/48 (litz)
Experimental Q	**980**
Simulated Q	1000

High-Power High-f version: 13.56 MHz, 500 nH, 70 A Design, Est. Q > 1200 (Bayliss, MIT 2020)

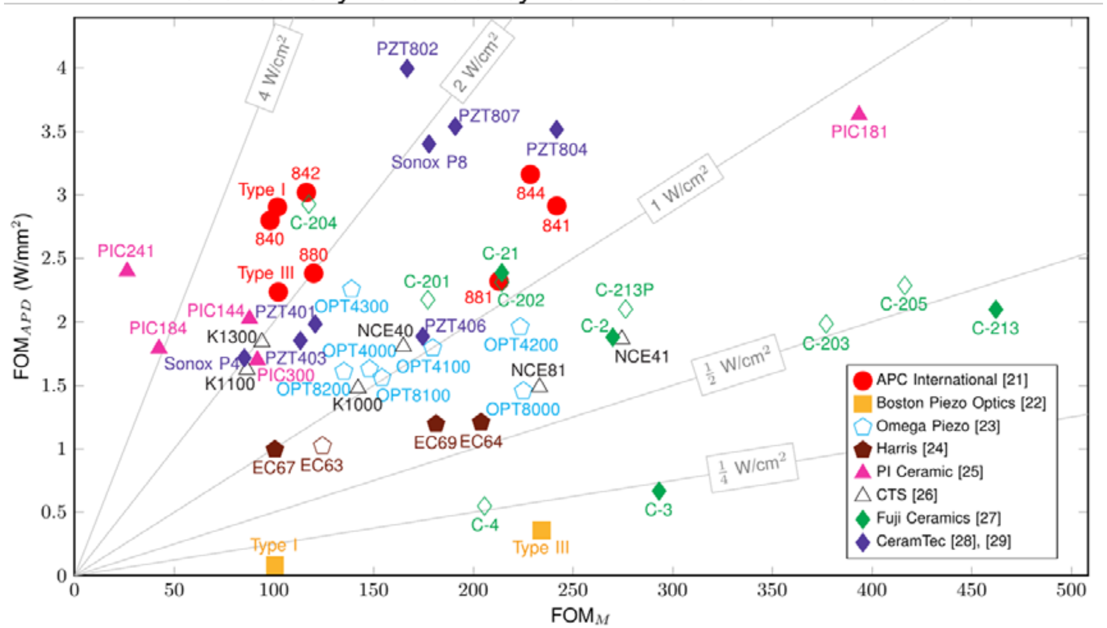
R. Yang et. al. "A Low-Loss Inductor Structure and Design Guidelines for High-Frequency Applications," *IEEE Transactions on Power Electronics*, 2019.

Piezoelectric Power Conversion

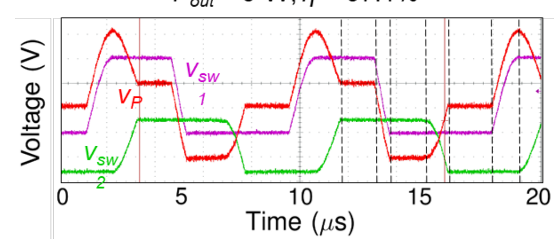
- ***Piezoelectric-based power converters*: store energy mechanically rather than magnetically**
  - **Potential for very high power density, better scaling to small size**
  - **Perreault / Lang collaboration with Texas Instruments**
- **Topologies, operating sequences, controls**
- **Investigation of materials and figures of merit**
- **Integration and high-power-density designs**



Power density vs. efficiency FOMs for 50 hard PZT materials



Experiment for V_{in} = 100 V, V_{out} = 40 V, P_{out} = 6 W, η = 97.1%



$$FOM_M = \left(\frac{P_{loss}}{P_{out}}\right)_{min}^{-1} = 4k_{33}^2 Q_m \frac{\pi + \gamma_o}{\pi^2 \gamma_o^2}$$

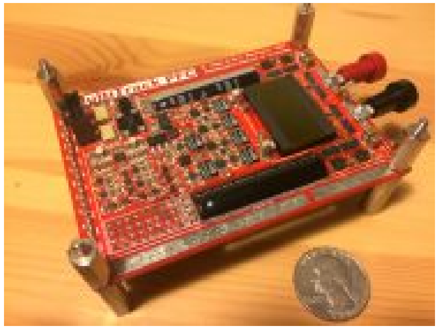
$$FOM_{APD} = \left(\frac{P_{out}}{A}\right)_{max} = \frac{I_{Lmaxo}^2}{4\pi^2 \varepsilon f_o}$$

J. D. Boles, et. al. "Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators," *IEEE Transactions on Power Electronics*, Jan. 2021.
J. D. Boles, et. al. "Evaluating piezoelectric materials for power conversion," *Proc. IEEE Workshop on Control and Modeling for Power Electronics*, Nov. 2020.

Applications

- **Power electronics technology to benefit specific applications**
  - **Design, manufacturing, control**
- **Target major system-level improvements**
  - **Efficiency, performance, functionality**
- **Many application areas**
  - **Electrified transportation**
  - **Computation and communications**
  - **Renewables**
  - **RF systems**

Hybrid magnetic switched-capacitor converter for low-voltage power delivery

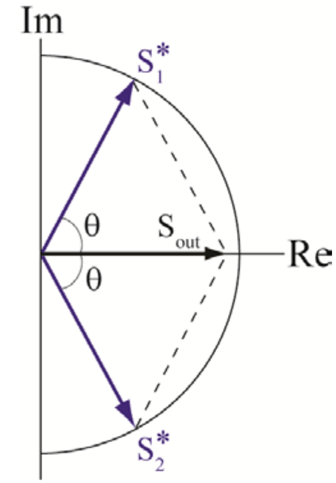


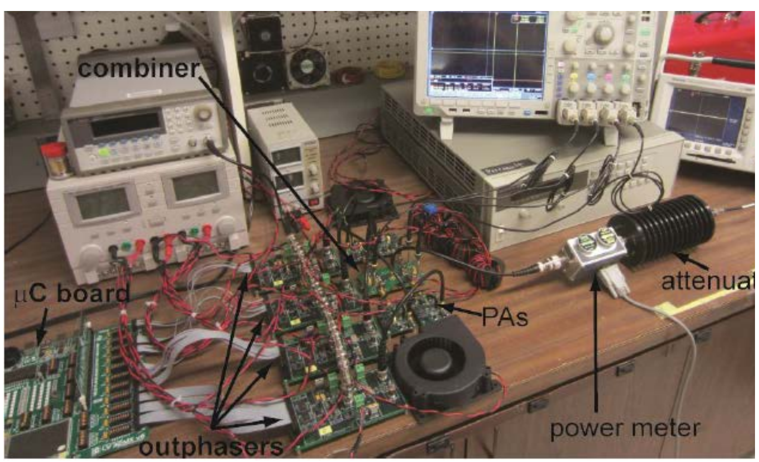
Multitrack HF PFC power supply, 50 W/in^3

Switched-mode rf matching network (1.5 kW @ 13.56 MHz)

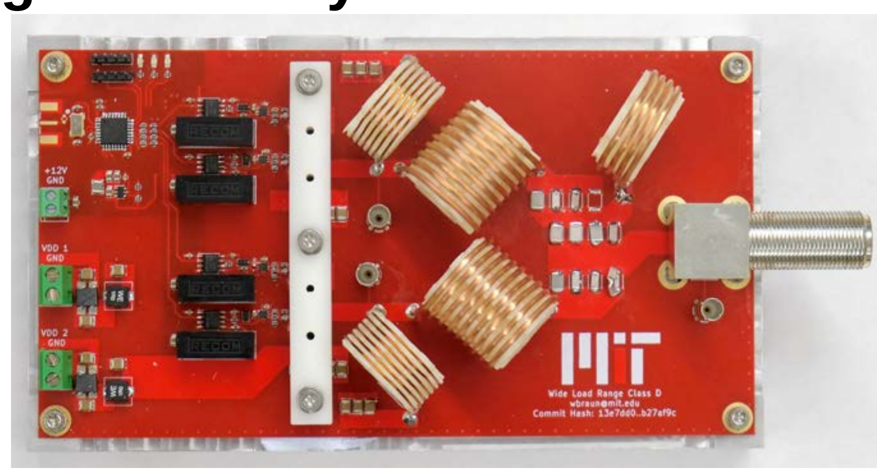
High Efficiency RF Power Amplification

- **Radio-frequency (RF) power amplifiers / inverters find use in a diverse range of applications**
- **A need is to better achieve (simultaneously)**
  - **Efficiency, Linearity, Bandwidth, Load Range**
- **We apply switched-mode techniques for efficient RF power conversion with linear control**
  - **Outphasing control for linear power amplification**
  - **Design of switched-mode RF inverters / power amplifiers**
- **Target wide load ranges at high efficiency**





27.12 MHz 100 W RF Inverter System



13.56 MHz 1 kW High-Frequency Variable Load Inverter (HFVLI) (MIT 2018). Suitable for directly driving a wide range of load impedances (e.g., for plasmas, wireless power transfer,…)