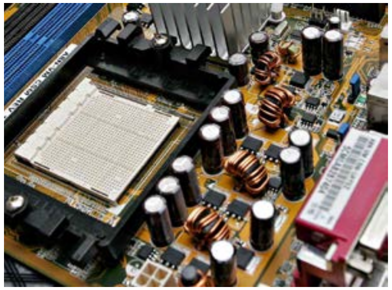
# Power Electronics Challenges

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

**Efficient Lighting (LED driver)**

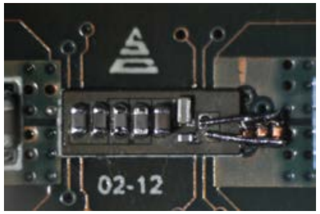


**Computers (Power Supply)**

**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)**

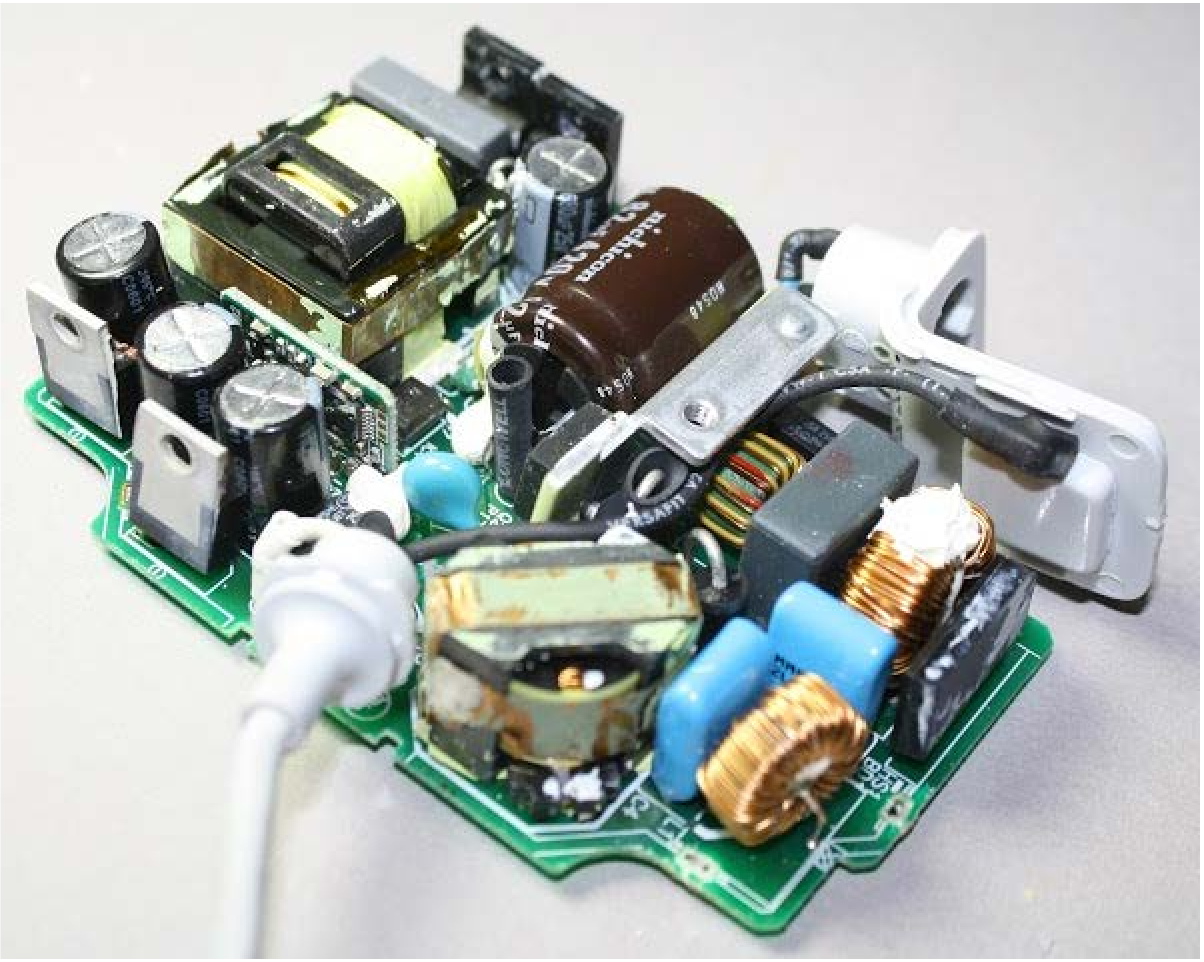



**Mobile Devices (Power management)**

***Develop and apply technologies for improved power conversion***

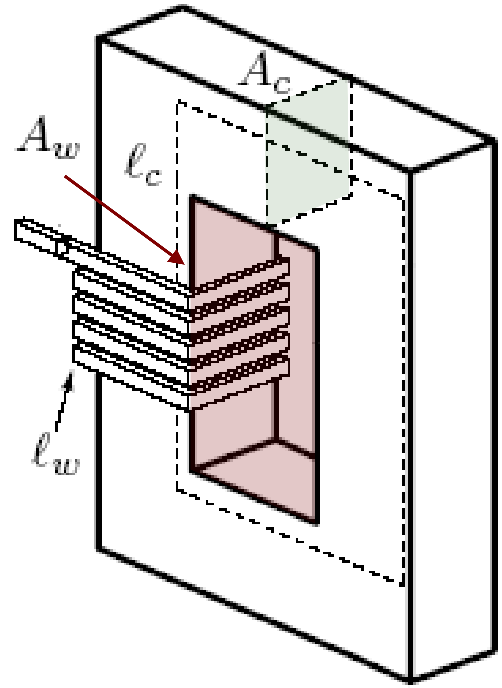
# Passive Components Dominate

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



# Miniaturizing Magnetics is Difficult

- **Scaling laws work *against* miniaturization of power magnetics**
  - **Simplified case: power handling (VA) of a fixed-frequency inductor**
    - **Flux density $B_0$ limited by core loss**
    - **Current density $J_0$ limited by winding loss**
- **If we scale dimensions by factor ε**
  - **Areas scale as $\varepsilon^2$**
  - **Volumes scale as $\varepsilon^3$**
  - **Power handling as $\varepsilon^4$, *faster* than volume**
- **Power *density* scales as ε**
  - **Gets worse at smaller size!**




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

**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**

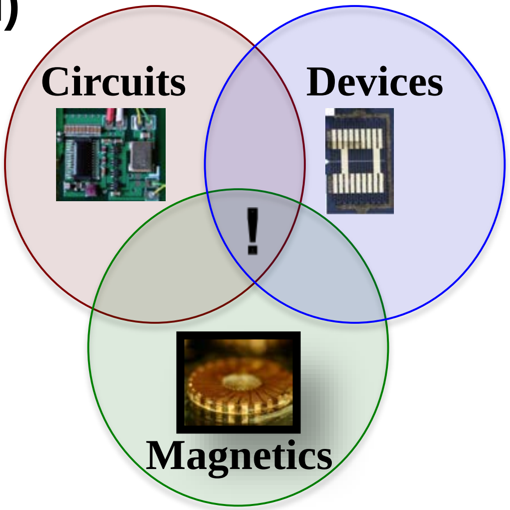
# Opportunities for Advances

- **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**

# 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**

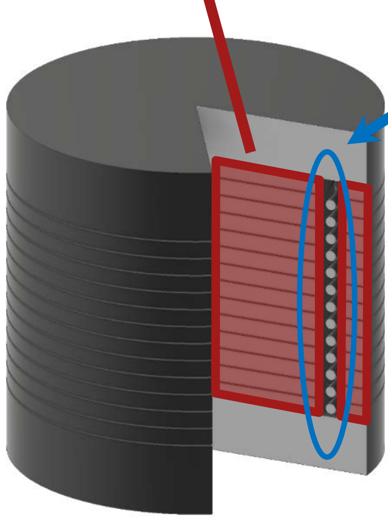


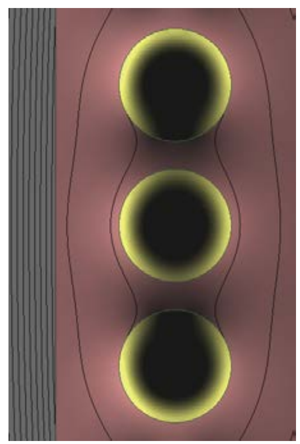
# HF Magnetics Example: Low-loss inductors

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

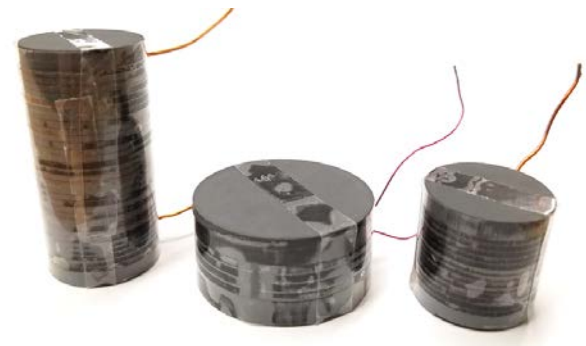
quasi-distributed gaps

double-sided conduction (balanced H fields)





**Approach scalable to a wide range of applications**



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

***Twice* the Q of conventional inductors with the same magnetic materials**

**(Yang, TPEL'21)**

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

# High-Power HF Self-Shielded Inductor

- **500 nH, 13.56 MHz Inductor @ 80 $A_{ac}$ / 3400 $V_{ac}$**

**Outer core and Inner core** | **Winding** | **Endcaps** | **Inductor with Outer Shield**

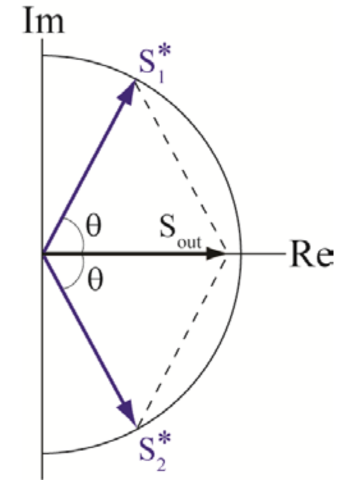
**Inner core + outer core top view**

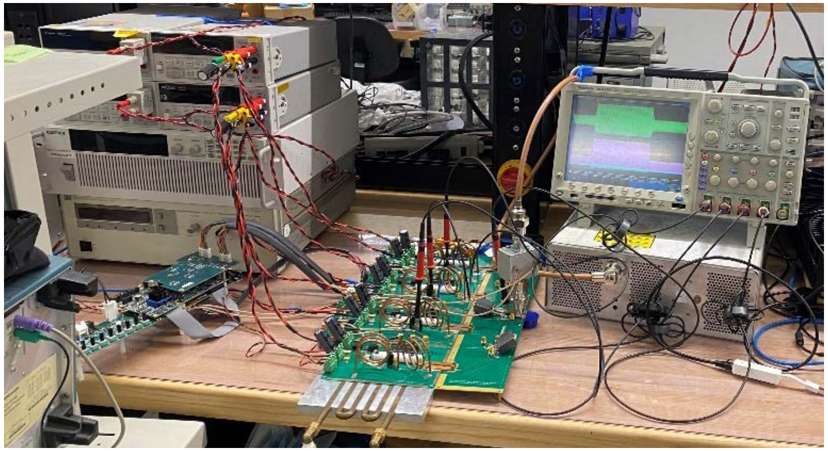
- **Cored inductor for use in high-power rf applications (PAs, TMNs)**
- **Smaller, more efficient than coreless solenoids, and shielded!**
- **Prototype demonstrated with Q~850+ up to 80 A, 13.56 MHz**

Mansi Joisher, MIT 2023

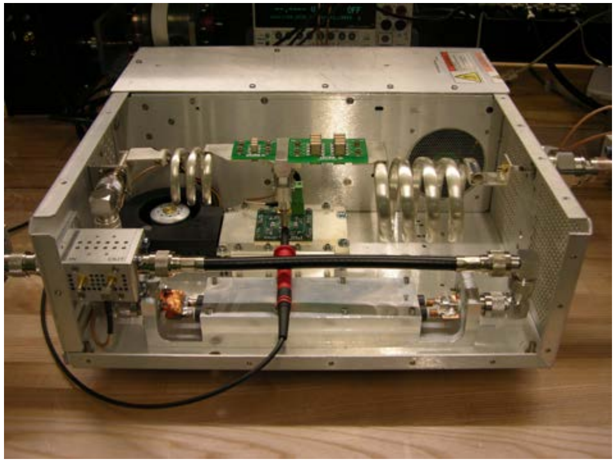
# High Efficiency RF Power Systems

- 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 power and load impedance ranges at high efficiency



5 kW, 13.56 MHz Wide-Range Inverter

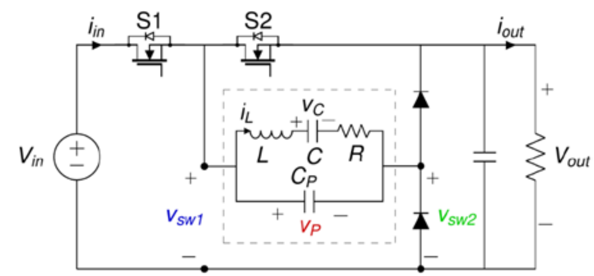


Switched-mode rf matching network (1.5 kW @ 13.56 MHz)

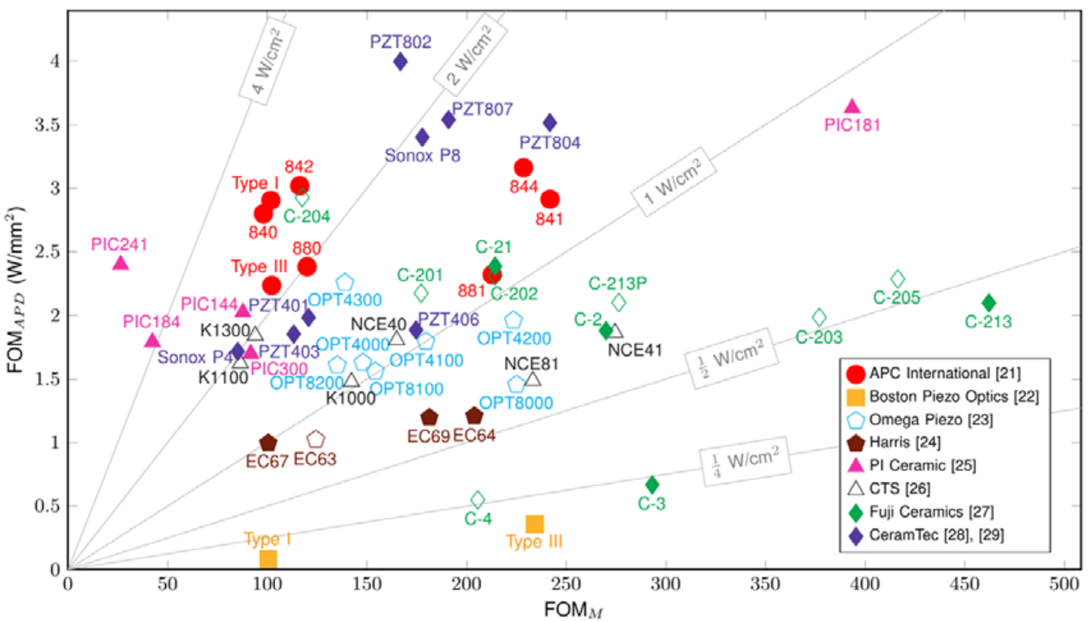
# Piezoelectric Power Conversion

- ***Piezoelectric-based power converters*: store energy mechanically rather than magnetically**
  - **Potential for very high power density, better scaling to small size**

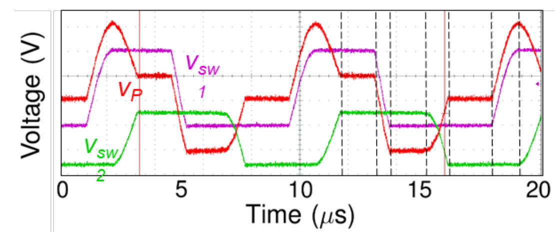
- **Topologies, operating sequences, controls**
- **Investigation of materials and devices**
- **Packaging, integration and high-power-density designs**




Power density vs. efficiency FOMs for 50 hard PZT materials




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




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

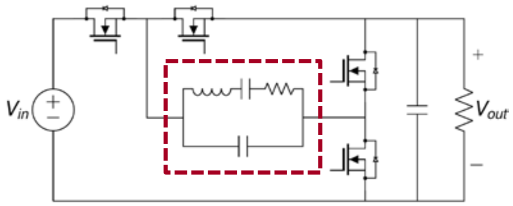
$$FOM_{APD} = \left(\frac{P_{out}}{A}\right)_{max} = \frac{I_{Lmaxo}^2}{4\pi^2 \varepsilon f_o}$$


J. D. Boles, et. al. "Enumeration and Analysis of DC-DC Converter Implementations Based on Piezoelectric Resonators," *IEEE Transactions on Power Electronics*, Jan. 2021.

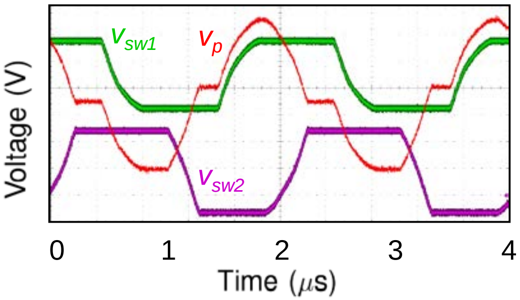
J. D. Boles, et. al. "Evaluating Piezoelectric Materials and Vibration Modes for Power Conversion," ," *IEEE Transactions on Power Electronics*, Mar. 2022.

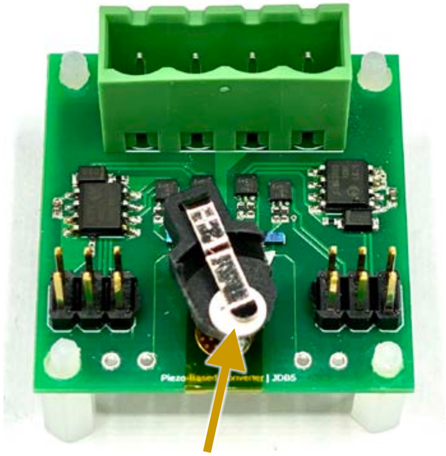
# High-Performance Design Example

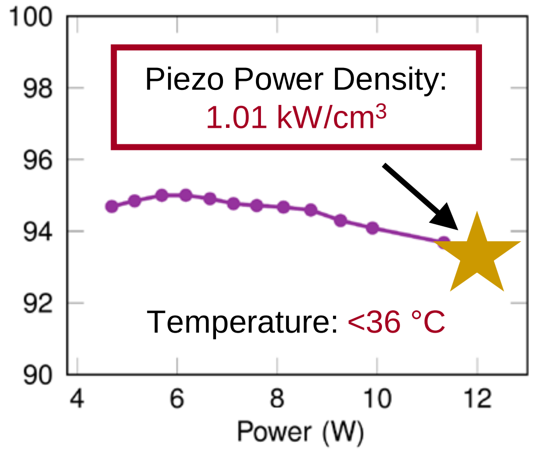
- **Achieves high performance with high power density**
  - **Step-down dc/dc converter at ~ 500 kHz**
  - **PR power handling > 1 kW/cm³ at low ΔT**




$V_{in}$ = 275 V, $V_{out}$ = 150 V, $P_{out}$ = 12 W, 493 kHz




J. D. Boles et al., "Towards High Power Density with Piezoelectric-Resonator-Based DC-DC Converters," *IEEE Trans. Power Electron (to appear)*.

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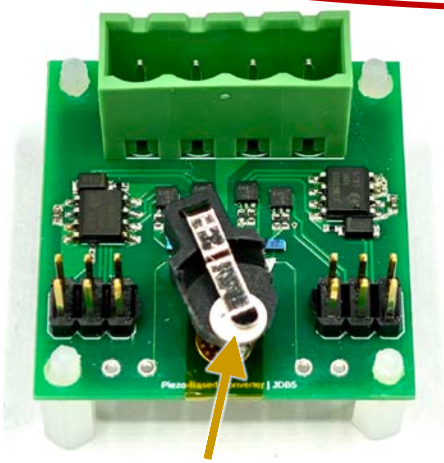
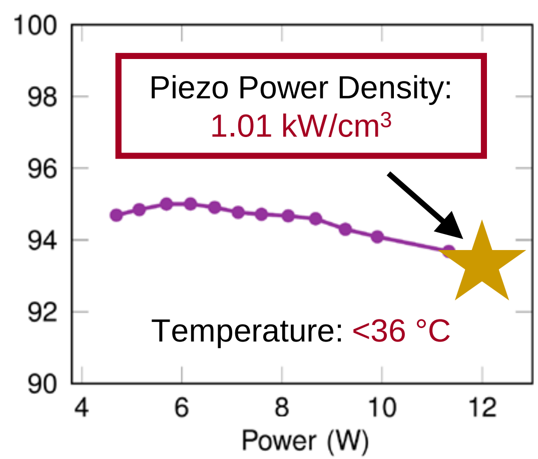
***Today's talk by Amanda Jackson is an example of this research direction***

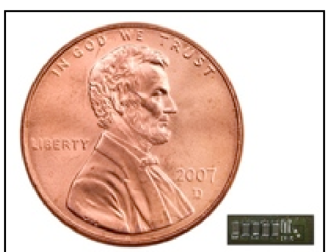


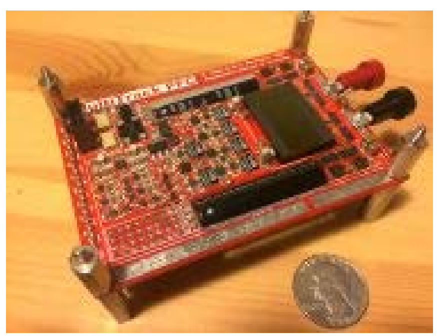

J. D. Boles et al., "Towards High Power Density with Piezoelectric-Resonator-Based DC-DC Converters," *IEEE Trans. Power Electron (to appear).*

# Applications

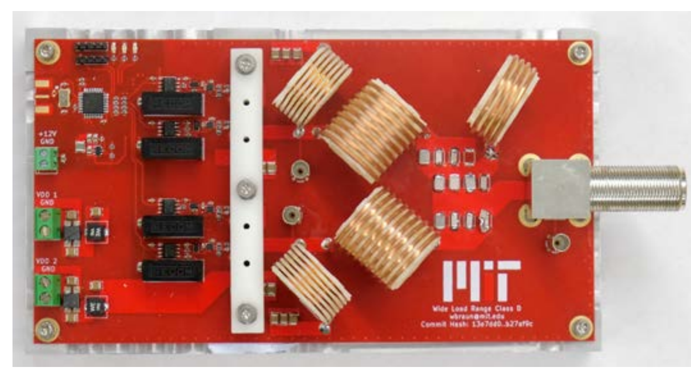
- **Power electronics technology to benefit specific applications**
  - **Design, manufacturing, control**
- **Target major system-level improvements**
  - **Efficiency, performance, functionality**
- **Many application areas**
  - **Electrified transportation**
  - **Computation and communications**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




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



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



**13.56 MHz 1 kW High-Frequency Variable Load Inverter (HFVLI)**