SAND2019-4157PE

Component Testing, Co-Optimization, and Trade-Space Evaluation

Jason Neely, PI, Integrated Electric Drive

Sandia National Laboratories

June 11, 2019

DOE Vehicle Technologies Program

2019 Annual Merit Review and Peer Evaluation Meeting

Project ID: elt223

Overview

Timeline

- Start – FY19
- End – FY21
- 25% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY19: $ $250k

Goals/Barriers

- Drive System Power Density = 33 kW/L
  - Power Electronics Density = 100 kW/L
  - Motor/Generator Density = 50 kW/L
- Power target > 100 kW (~1.2kV/100 A)
- Cost target for drive system ($6/kW)
- Operational life of drive system = 300k miles
- Design constraints include
  - Thermal limits
  - Transistor / Diode reliability
  - Capacitor reliability

Partners

- Scott Sudhoff, Steve Pekarek – Purdue University
- Jon Wierer – Lehigh University
- Woongie Sung – State University of New York (SUNY)
- Project lead: Sandia Labs, Team Members: Jack Flicker, Greg Pickrell, Todd Monson, Bob Kaplar

LEHIGH UNIVERSITY

PURDUE UNIVERSITY

SUNY Poly Albany Campus

Relevance and Objectives

Objectives

- Evaluate reliability/performance of state-of-the-art SiC power devices and identify gaps.
- Develop advanced test-bed to evaluate low-TRL components developed in consortium.
  - Identify performance measures corresponding to consortium design targets
  - Develop metrics for performance/reliability of power electronics and electric motors
- Evaluate state-of-the-art/baseline traction drive system
  - Identify co-optimized designs
  - Evaluate parameter sensitivities and identify target specifications

Impact

- Component testing and in-circuit demonstrations are essential to rapid iterative design and optimization of components
- The Electric Traction Drive ties together Power Electronics, Motor, Control Systems, and the Road; co-optimization of subsystems is required to meet system objectives
- These efforts support research that is enabling advanced future Electric Traction Drive vehicles, which contributes directly to clean energy transportation

Approach – Component Testing

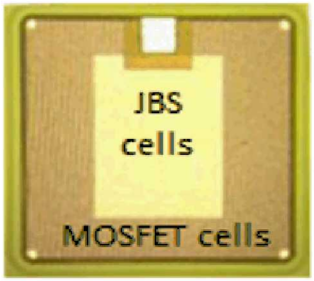
Objective: Evaluate state-of-the-art SiC power devices and identify gaps. Initiate design-for-reliability studies aimed at fabrication of devices specific to automotive environments.

- **Ensure that next-gen WBG devices are of sufficient performance, reliability and price to achieve system level DOE goals by 2025**
  - 10x better reliability than Si IGBTs
  - Cost < 2cents per A (1200V/100A device)

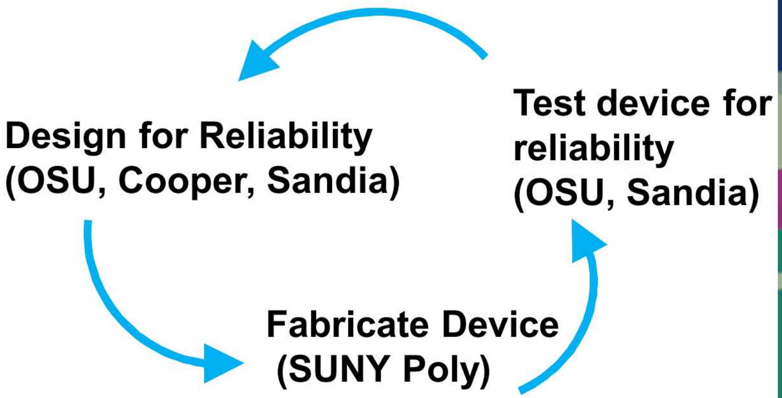
- **Research on Fundamental cost/reliability/performance problems**
  - Room Temperature Implant to reduce processing cost by 30%
  - Reduction of Basal Plane Dislocations during High Temperature oxidation
  - Increase inversion layer mobility

- **Comprehensive reliability study of commercially available devices to uncover failures**
  - threshold voltage instability
  - inadequate short circuit time
  - gate oxide failures due to gate voltage overshoot
  - high junction temperature
  - body diode instability

MOSFETs Integrated with JBS diodes



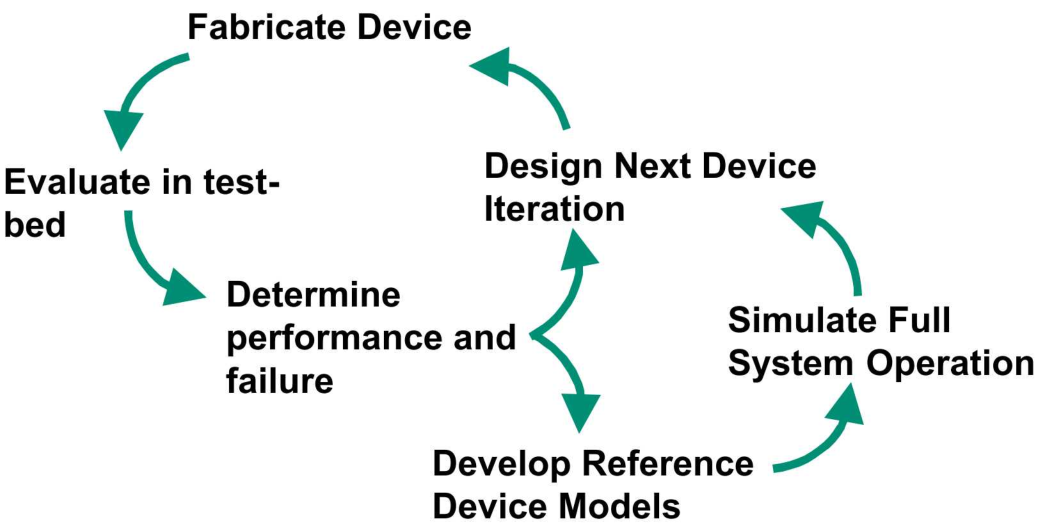
*SUNY-Poly and the Power Electronics Manufacturing Consortium (PEMC) in Albany



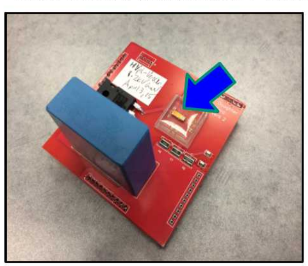
Approach – Component Testing

Objective: Based on survey of existing capabilities, optimize an advanced test-bed to evaluate low-TRL components developed in the consortium. This test-bed will replicate realistic device use profiles present in the final consortium-level vehicle inverter.

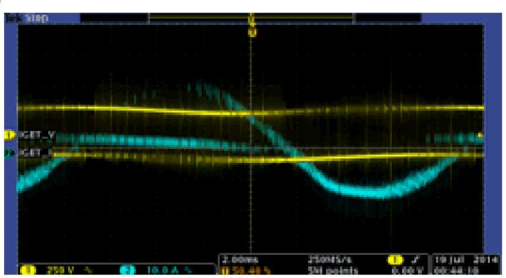
- Need rapid prototyping for R&D devices before incorporation into full power module
- Design and construction of custom test assemblies
- Data on performance and reliability (failure modes, mechanisms) used as input in future generations of components
- Realistically emulate operations and stressors that exist in end-use application (vehicle drivetrain)
    - can be scaled in parameters (voltage, current, temperature, etc.) to suit intermediate maturity devices



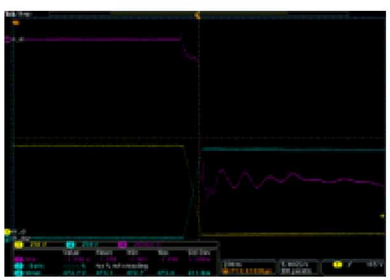
*Sandia National Laboratories



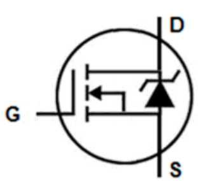
R&D device incorporation into daughter circuit



Operation in switching circuit



High fidelity switching behavior



Compact model development

Approach – Co-Optimization & Trade-space Evaluation

Objective: Identify performance measures corresponding to the consortium design targets. Develop plan for evaluating performance and reliability of power electronics and electric motors.

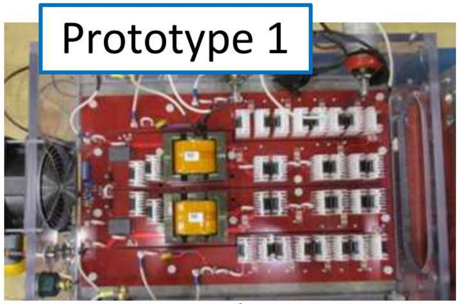
- DOE Targets must be mapped to performance criteria that can be measured and validated in a laboratory environment
  - Integrated electric drive peak power capability must be evaluated in a manner consistent with vehicle operation
  - Establish a range of 300,000 miles
    - 13,456 miles/year average [1] => 22.3 years reliability
    - Approximately 20,000 start-stops
    - Process approximately 102 MWh [2] over lifetime
    - Weighted efficiency measure
  - Operation in environmental extremes
    - Humidity, Temperature, …
- Sandia testbeds and Sandia-developed models + standard profiles will demonstrate performance
- Performance criteria will be encoded into constraints and performance measures for system optimization

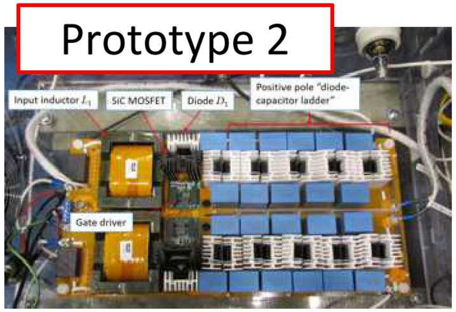
[1] URL: https://www.fhwa.dot.gov/ohim/onh00/bar8.htm
[2] URL: https://afdc.energy.gov/fuels/electricity_charging_home.html

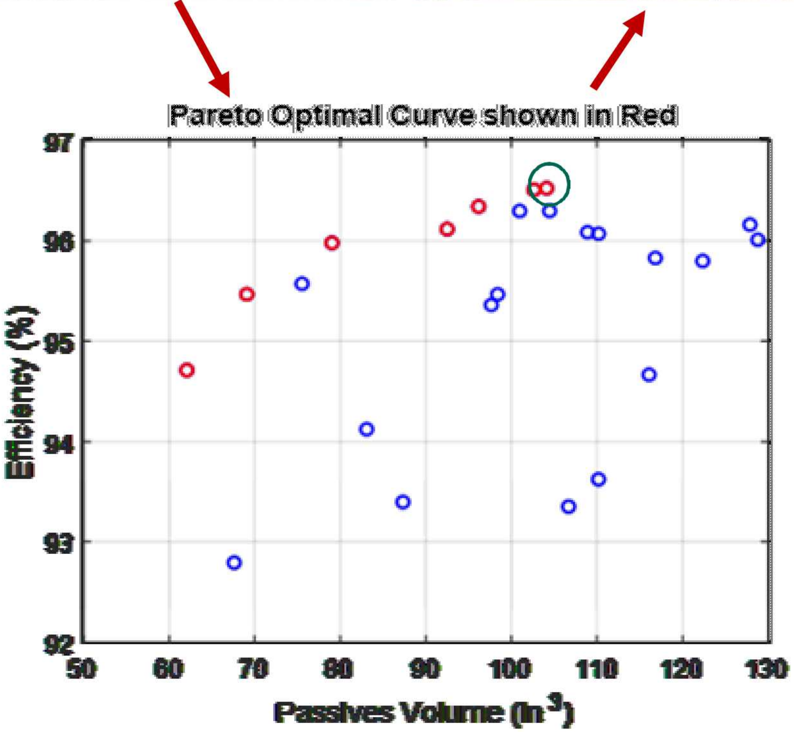
Approach – Co-Optimization & Trade-space Evaluation

Design Codes and Iterative Hardware Evolution Occur Together

- Pilot designs are built and evaluated
- Component and prototype test data are used to develop calibrated simulation models
- Design optimization identifies a set of Pareto Optimal solutions
- Select designs are constructed and tested
- The process repeats until targets are met
- Optimization results also identify parameter sensitivities







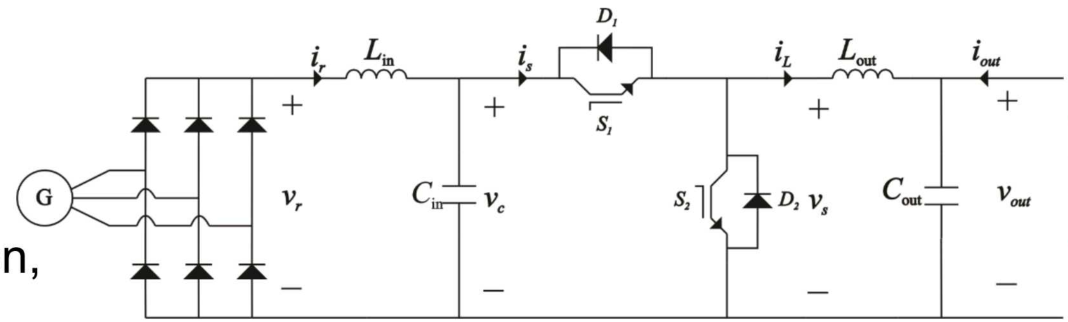
Previous work with ARPA-E to develop high-performance power electronics: coupled hardware iteration with model validation and simulation-based optimization

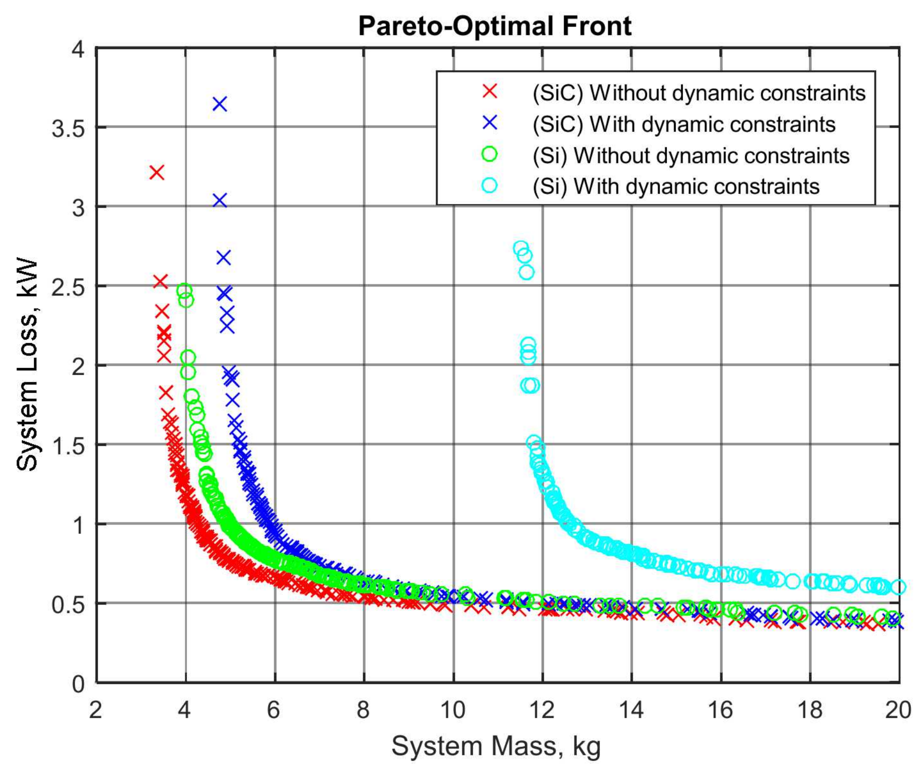
J. Stewart *et al*., "Design and evaluation of hybrid switched capacitor converters for high voltage, high power density applications," *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, San Antonio, TX, 2018, pp. 105-112.

Approach – Co-Optimization & Trade-space Evaluation

Design Codes can be Formulated to Co-Optimize Motor and Drive

- Validated high-fidelity models are developed for the motor and power electronic components
- To facilitate system-level optimization, reduced-order metamodels are generated where appropriate
- Models include feedback controls, and objectives include required dynamic performance
- Purdue-developed *Genetic Optimization System Engineering Toolbox* (GOSET) may be used to identify designs, simultaneously solving for motor and electric drive parameters





B. Zhang, S. Sudhoff, S. Pekarek and J. Neely, "Optimization of a wide bandgap based generation system," *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, Arlington, VA, 2017, pp. 620-628.

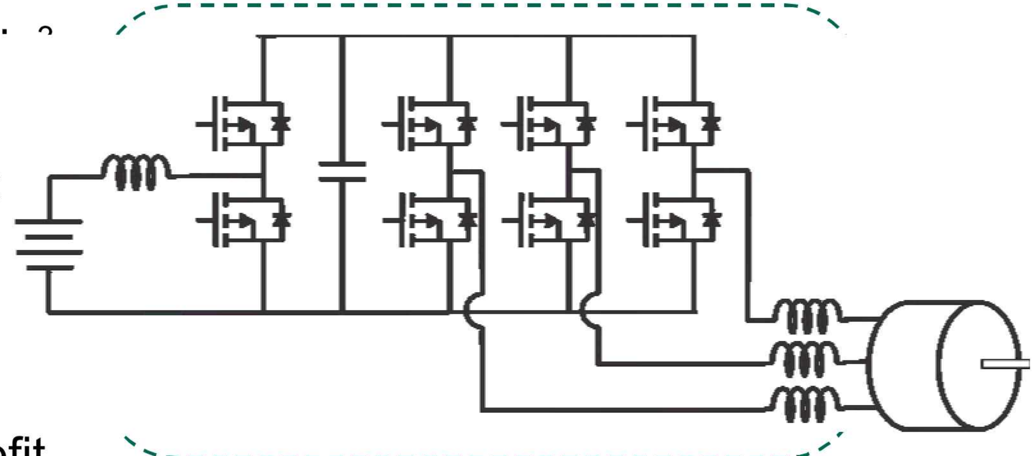
B. Zhang *et al.*, "Prediction of Pareto-optimal performance improvements in a power conversion system using GaN devices," *2017 IEEE 5th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Albuquerque, NM, 2017, pp. 80-86.

FY19 Milestones

	Milestone	Date	Status
1.2	Survey today’s state-of-the-art SiC power devices to determine what device types are most suitable for application to consortium goals, and what existing technology gaps are.	3/2019	In Progress
1.4	Design and fabricate advanced component test-bed capable of evaluating advanced semiconductor, magnetic, and dielectric devices, specific to the needs of consortium-level inverter design.	9/2019	On Track
3.1	Identify system attributes, including materials, device types, candidate circuit topologies, and motor topologies, necessary to meet consortium targets.	3/2019	In Progress
3.2	Generate Pareto-Optimal fronts required to determine the ultimate power density achievable for various materials and components	9/2019	On Track
-	Go / No Go: Topology Down-Select	9/2019	On Track

Technical Accomplishments and Progress – Co-Optimization & Trade-space Evaluation

- Target volume for 100 kW Drive is 60 (<1 Liter)
- Competing architectures are identifiec for the motor drive
- Modular form factor resembles conventional assemblies
- Flat Integrated Form Factor may benefit from the energy density and temperature resilience of ceramic capacitors



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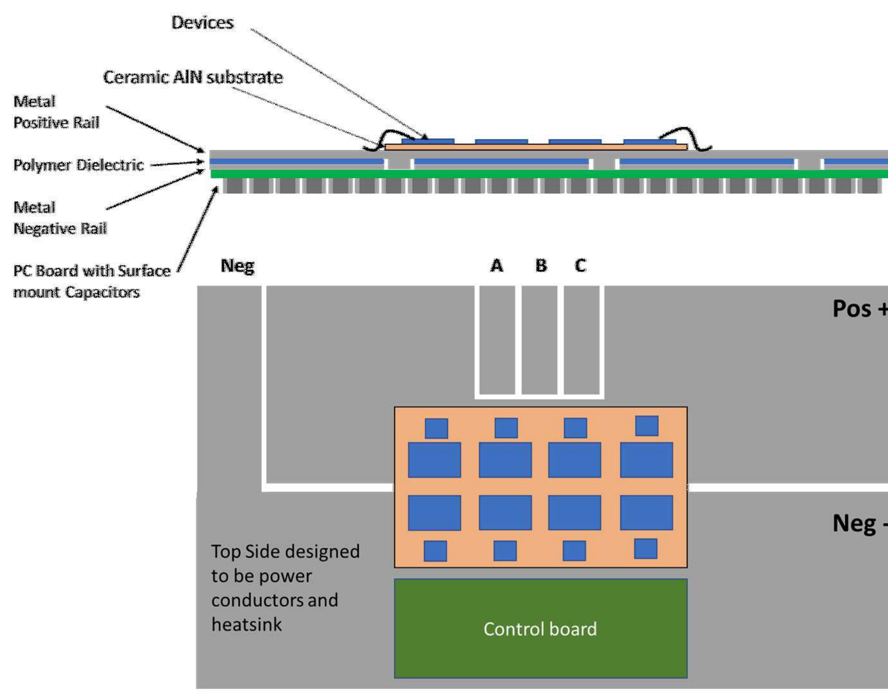
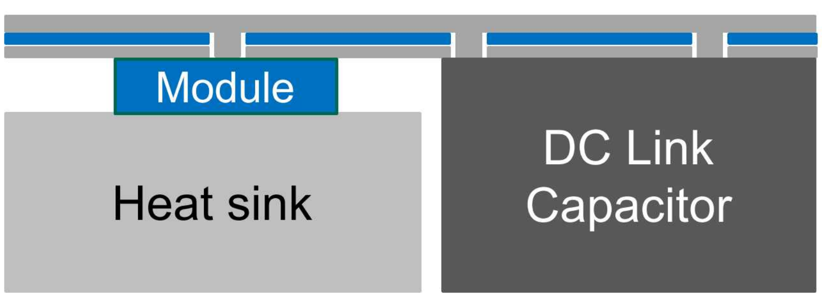
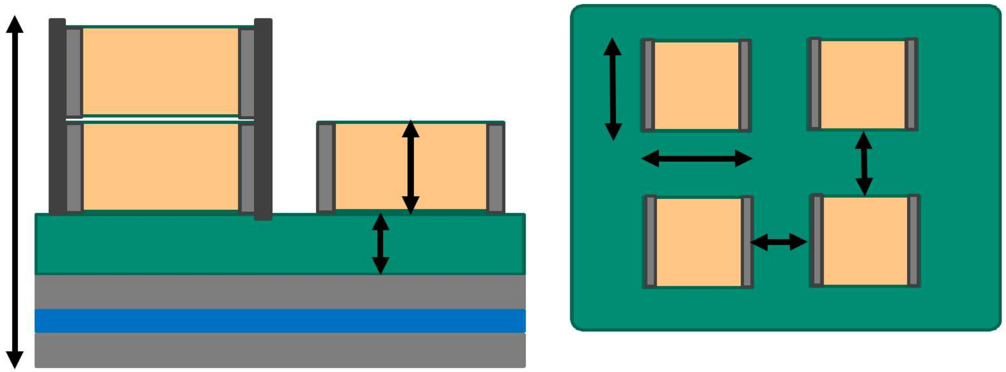


Modular Form Factor

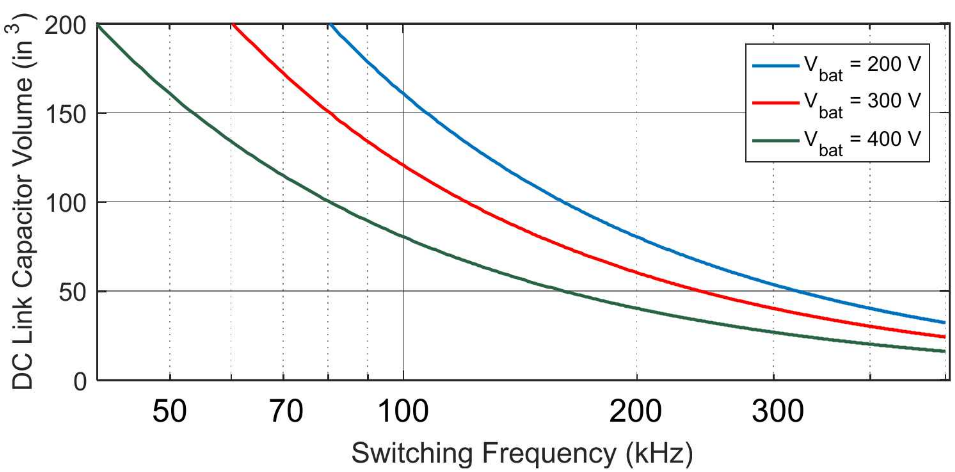


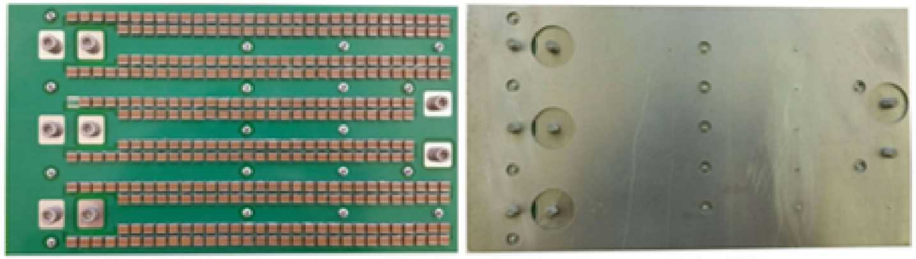
Technical Accomplishments and Progress – Co-Optimization & Trade-space Evaluation

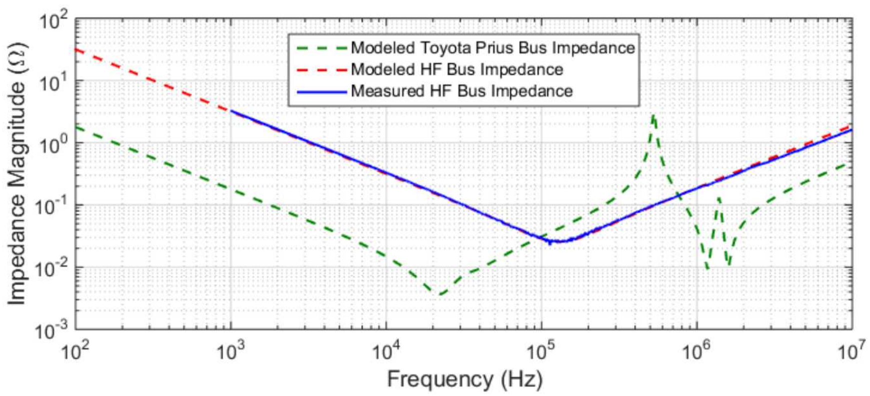
- Geometric models are being developed to estimate component volume relative to operational characteristics
- Designs combining high frequency switching, high battery voltage, and ceramic capacitors show promise to achieve power density goals



Flat Integrated Form Factor







J. Stewart, J. Neely, J. Delhotal and J. Flicker, "DC link bus design for high frequency, high temperature converters," *2017 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Tampa, FL, 2017, pp. 809-815.

Responses to Previous Year Reviewers' Comments

- Sandia's first year on this program
- No previous comments

Collaboration

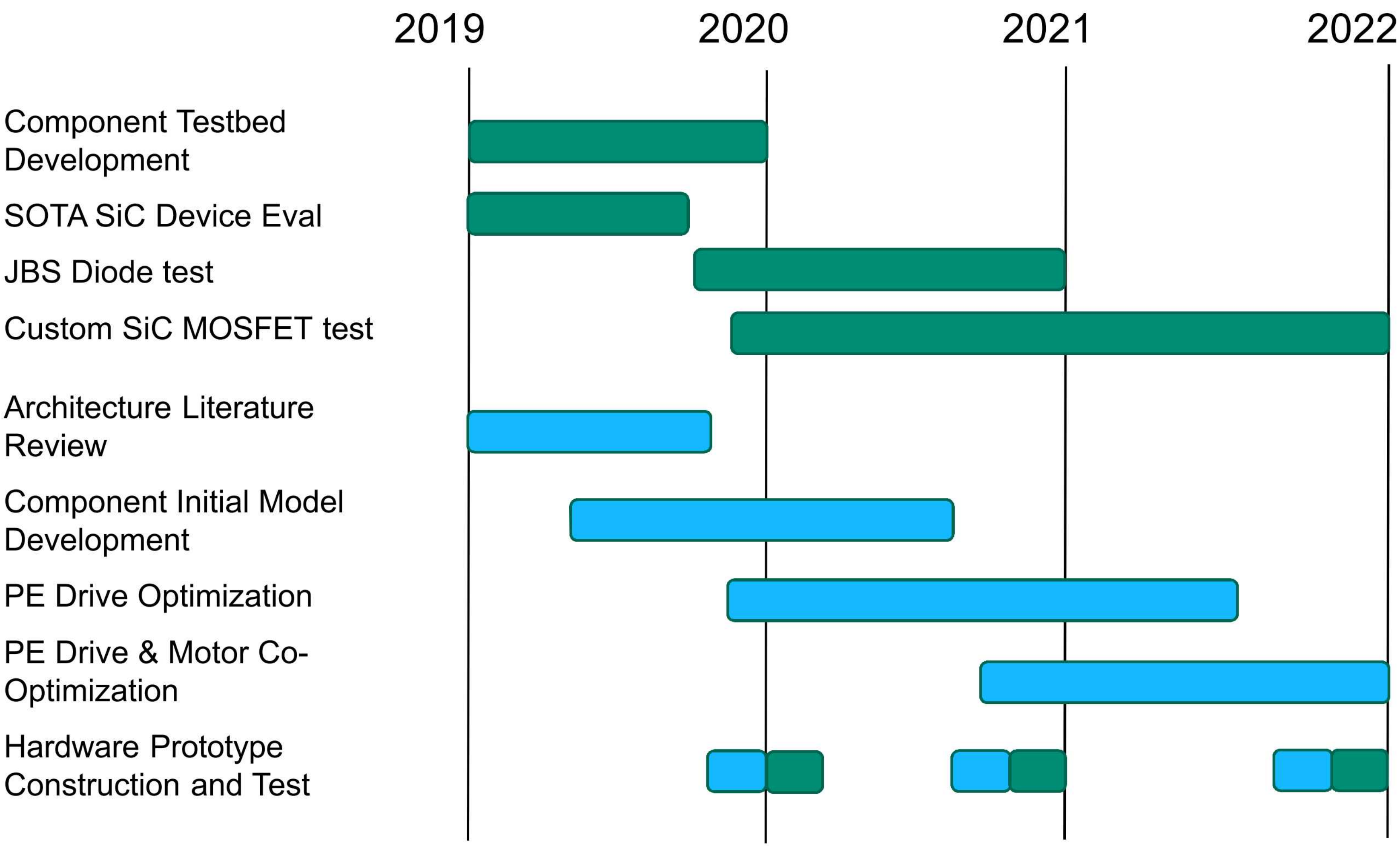
SUNY Poly
Albany Campus

Purdue University/Sonrisa Research, Inc. (Scott Sudhoff) – Working with Sandia to co-optimize motor and drive

Lehigh University (Jon Wierer) – Working with Sandia for design/simulation/modeling of GaN JBS diodes.

State University of New York (SUNY) (Woongie Sung) – Fabricating SiC JBS diode integrated with MOSFETs

Proposed Future Research



Summary

- Project Objectives are identified to support wide bandgap device development through testing and modeling as well as to identify designs through co-optimization of power electronics and machine

- Testing will be done using a custom designed device / component testbed, currently under development.
  - Verify device electrical performance
  - Demonstrate device operation in relevant circuits
  - Develop device models
  - Compute device reliability estimates

- Co-optimization will rely both on design codes and hardware synthesis and test.
  - Design codes will first be developed to optimize candidate power electronic and motor designs separately; these will then be merged to co-optimize these two components
  - Each year, hardware prototypes will be developed to verify designs and recalibrate models
  - Sandia is working closely with Purdue; Purdue is focusing on the machine optimization

Reviewer-Only Slides

Publications and Presentations

New program start.

Critical Assumptions and Issues

- Assumptions
  - Power density targets are based on the combined volume of all power electronic modules and machines (whether there be one centralized drive with motor or 4 in-wheel drives with motors) needed to achieve total power
  - DOE targets pertaining to reliability can be established using limited laboratory testing that is scaled using reliability models.