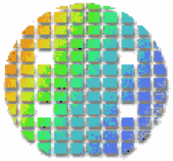
NIST

High-Voltage, High-Frequency Devices for Solid State Power Substation and Grid Power Converters

Allen R. Hefner
Semiconductor Electronics Division
National Institute of Standards and Technology
Gaithersburg, MD 20899
hefner@nist.gov

The devices discussed in this paper were produced by Cree/Powerex. NIST does not necessarily recommend or endorse the devices as the best available for the purpose.



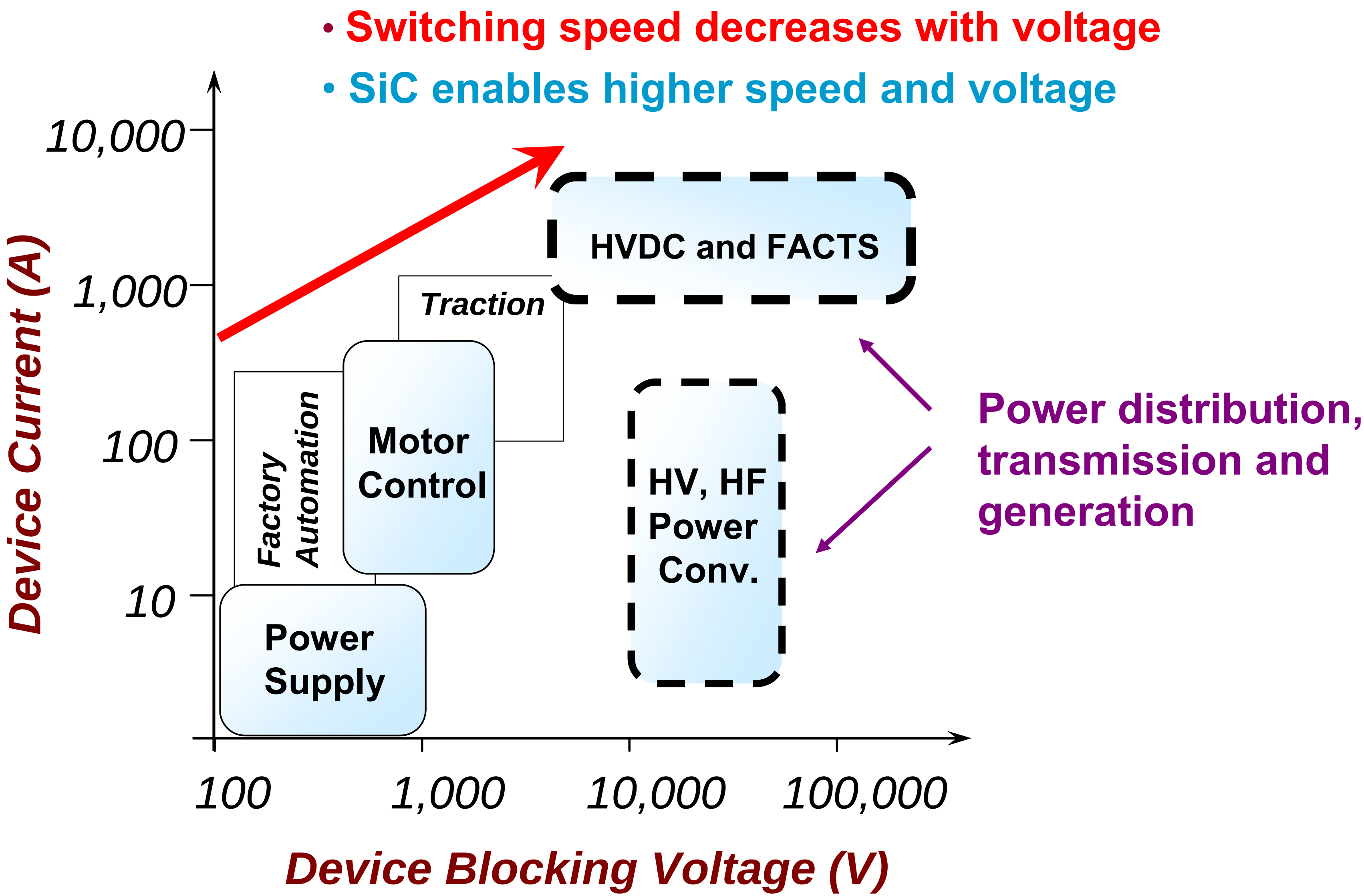
Outline

- HV-HF SiC Power Devices
- DARPA HPE Program Overview
  - Goal: Solid State Power Substation (SSPS)
  - Status: 10 kV, 100 A, 20 kHz power modules
- Component Modeling and Circuit Simulation
- Impact on Grid-Connected Power Converters

HV-HF Power Conversion

- **Switch-mode power conversion and conditioning:**
  - **advantages: efficiency, control, functionality, size and weight**
  - **semiconductors from: 100 V, ~MHz to 6 kV, ~100 Hz**
- **New semiconductor devices extend application range:**
  - **1990's: Silicon IGBTs**
    - **higher power levels for motor control and traction**
  - **Emerging: SiC Schottky diodes and MOSFETs**
    - **higher speed for power supplies and motor control**
  - **Future: HV-HF SiC MOSFET, PiN diode, Schottky, and IGBT**
    - **enable 15-kV, 20-kHz switch-mode power conversion**

Switch-Mode Power Applications



SiC Power Devices

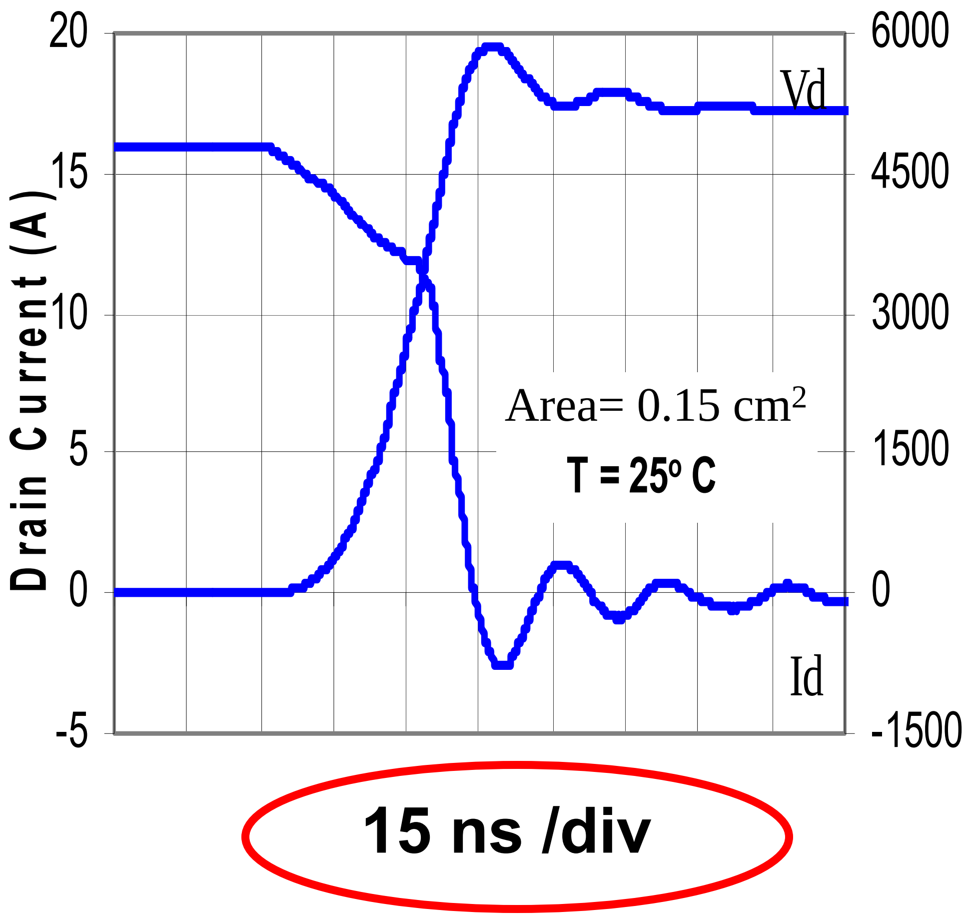
SiC wide bandgap material enables better electrical and thermal performance than Si power devices

Semi-Conductor Material	Energy Bandgap (eV)	Breakdown Electric Field (V/cm)	Thermal Conductivity (W/m·K)	Saturated Electron Drift Velocity (cm/sec)
4H-SiC	**3.26**	**$2.2 \cdot 10^6$**	**380**	**$2.0 \cdot 10^7$**
Si	1.12	**$2.5 \cdot 10^5$**	150	$1.0 \cdot 10^7$

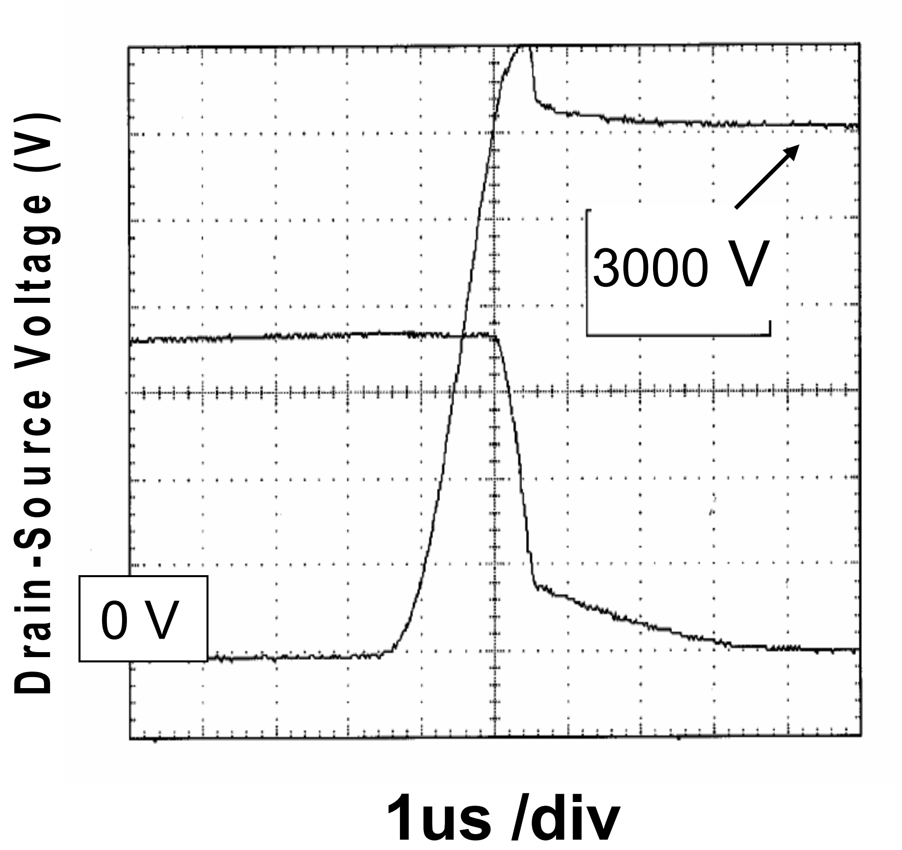
- **Handles higher temperature:** larger bandgap
- **Higher voltage, current and speed:** larger breakdown field
- **Fault tolerance, Pulsed:** intrinsic-temperature, saturation-velocity and thermal-conductivity

DARPA HPE MOSFET:
High Speed at High Voltage

SiC MOSFET: 10 kV, 30 ns

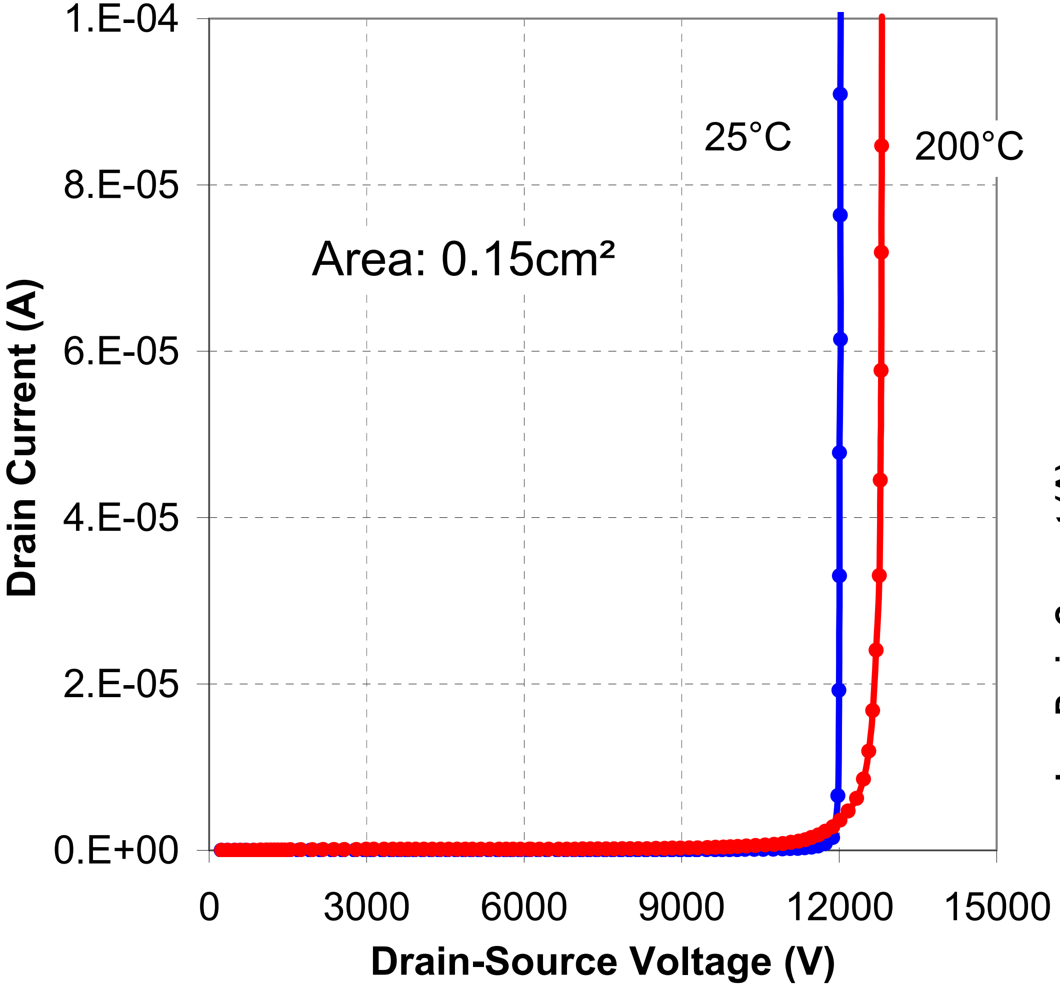


Silicon IGBT: 4.5 kV, 2us



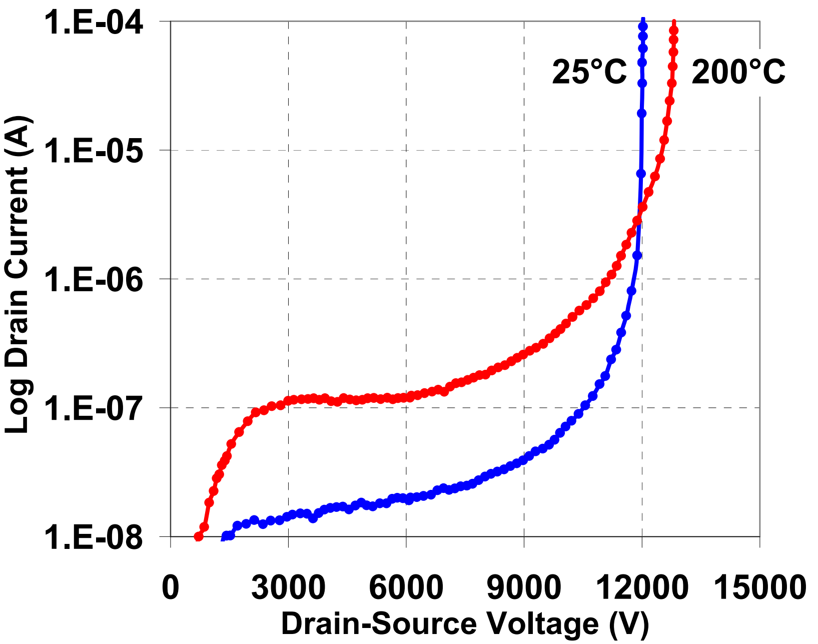
MOSFET Voltage Capability

Voltage Capability > 12 kV



Low Channel Leakage for Vg ≤ 0, T ≤ 200° C

Increased Threshold Voltage

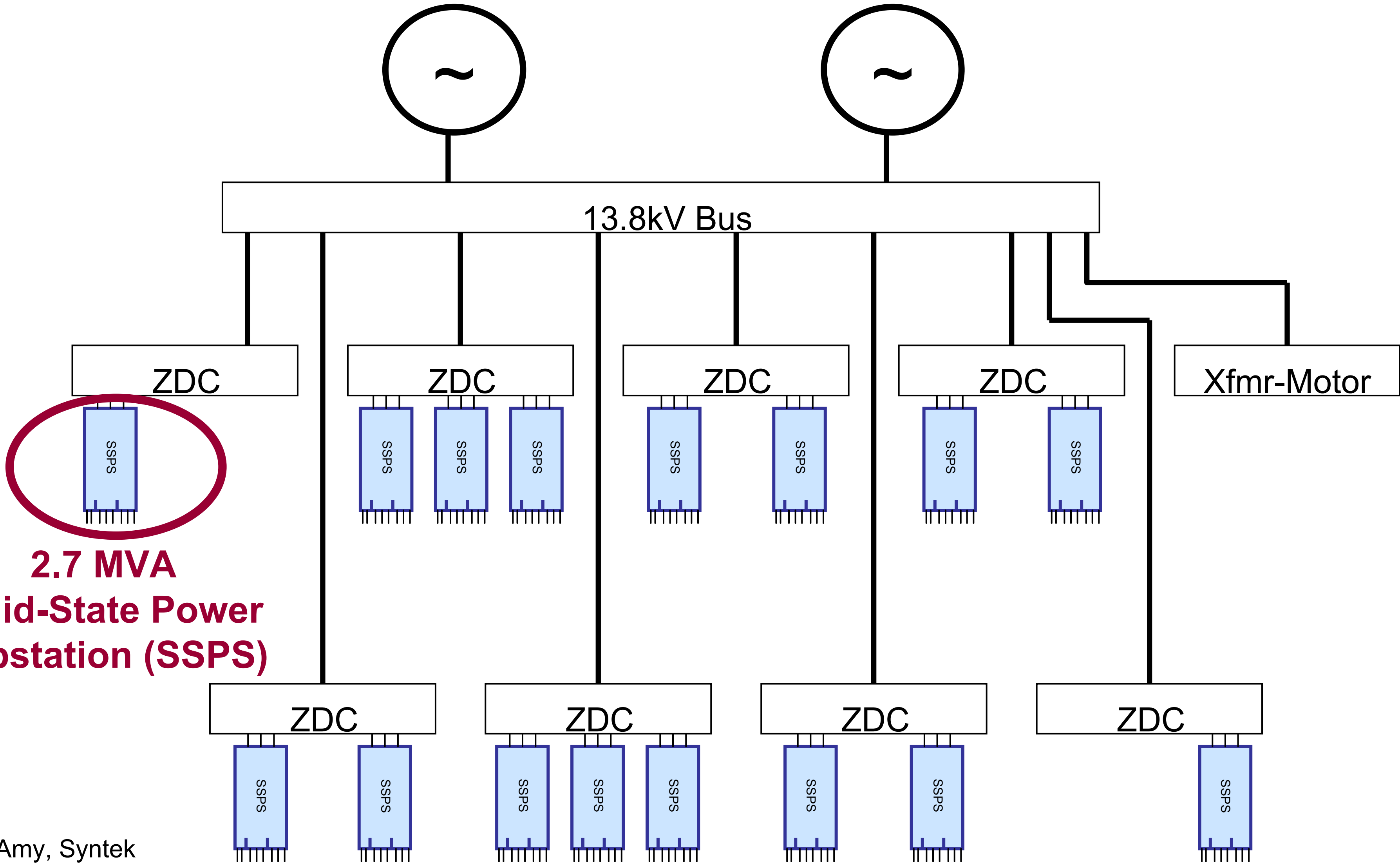


Outline

- HV-HF SiC Power Devices
- DARPA HPE Program Overview
  - Goal: Solid State Power Substation (SSPS)
  - Status: 10 kV, 100 A, 20 kHz power modules
- Component Modeling and Circuit Simulation
- Impact on Grid-Connected Power Converters

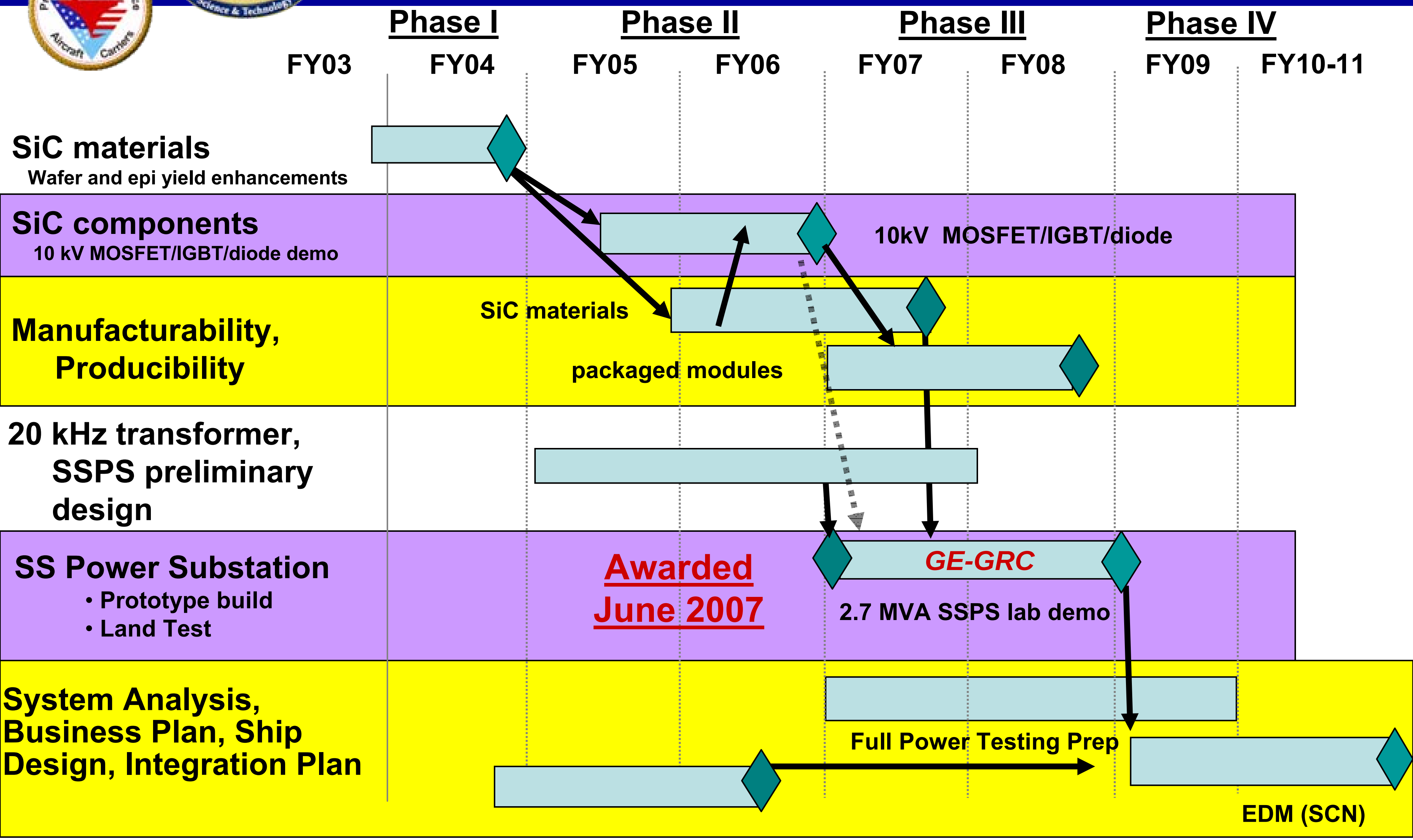
HPE Program Application

CVN21 Aircraft Carrier Zonal Distribution System



John Amy, Syntek

HPE Program Timeline



DARPA HPE SiC Devices

- **HV-HF SiC power devices:**

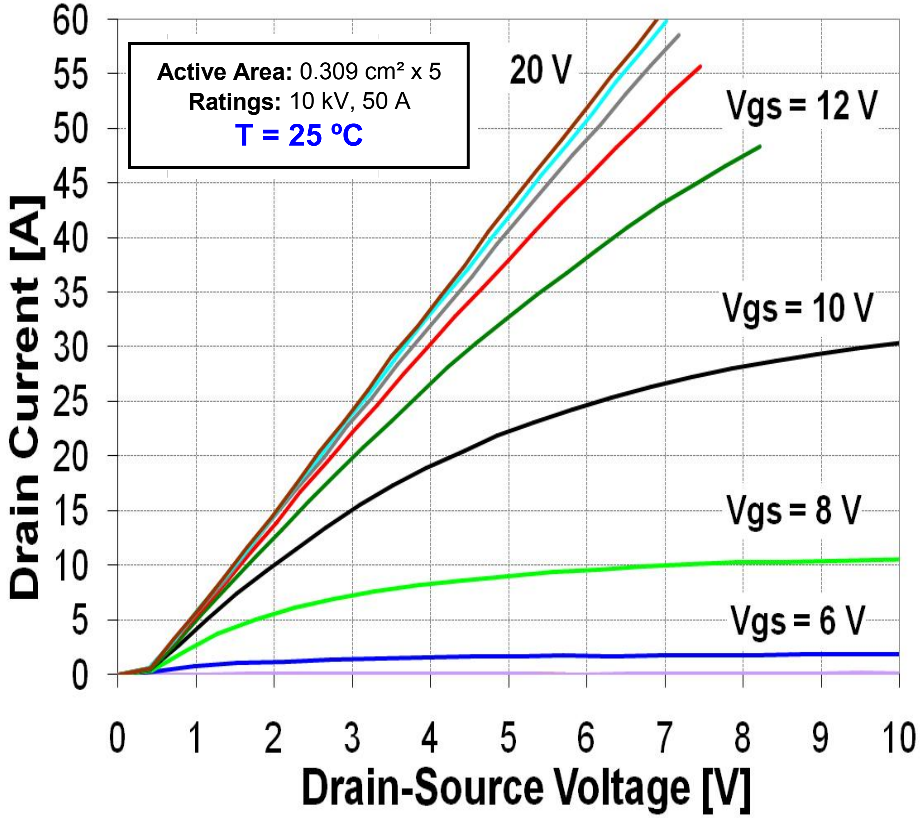
  "game changer" enabling SSPS

- **HPE Phase II device and module goals:**

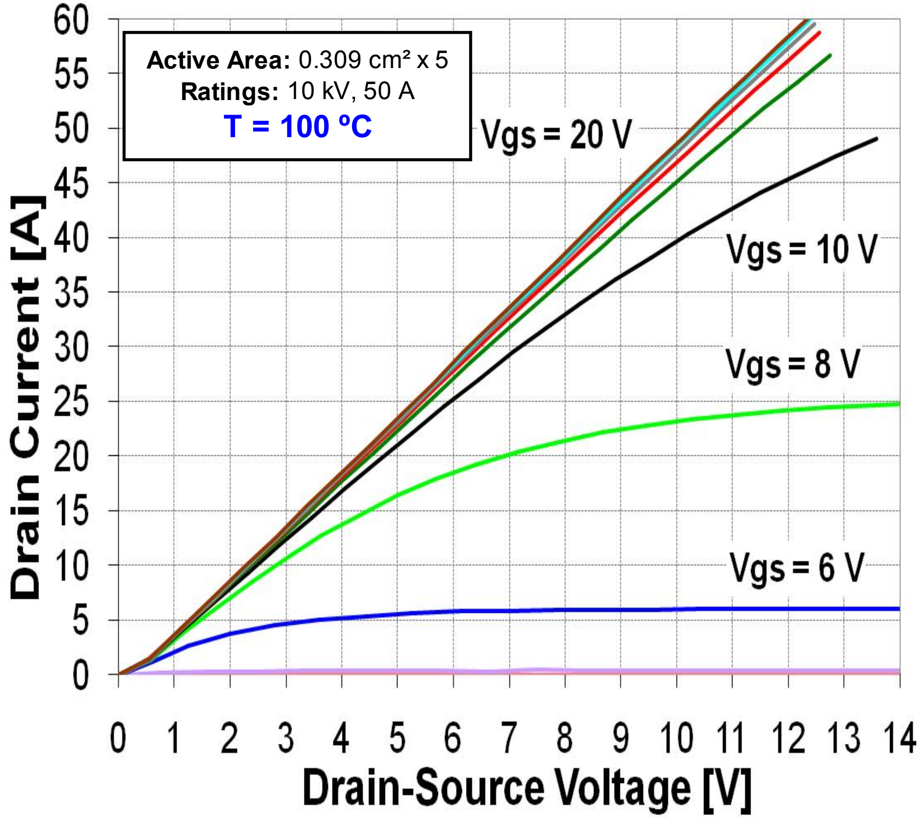
DARPA High Power Electronics Proposed Device Development				
	PiN, *(JBS)* (single die)	**MOSFET** (single die)	*IGBT** *(single die)*	**Half Bridge Module**
BV (V)	**10 kV**	**10 kV**	*15 kV**	**10 – 15 kV**
Ion (A)	**45 A** *(18 A)*	**18 A**	*25 A*	**110 A**
Tj (°C)	**200 C**	**200 C**	*200 C*	*200 C*
Fsw (Hz)	**20 kHz**	**20 kHz**	*20 kHz*	**20 kHz**

Measured Output Characteristics for 50 A, 10 kV SiC MOSFET Module

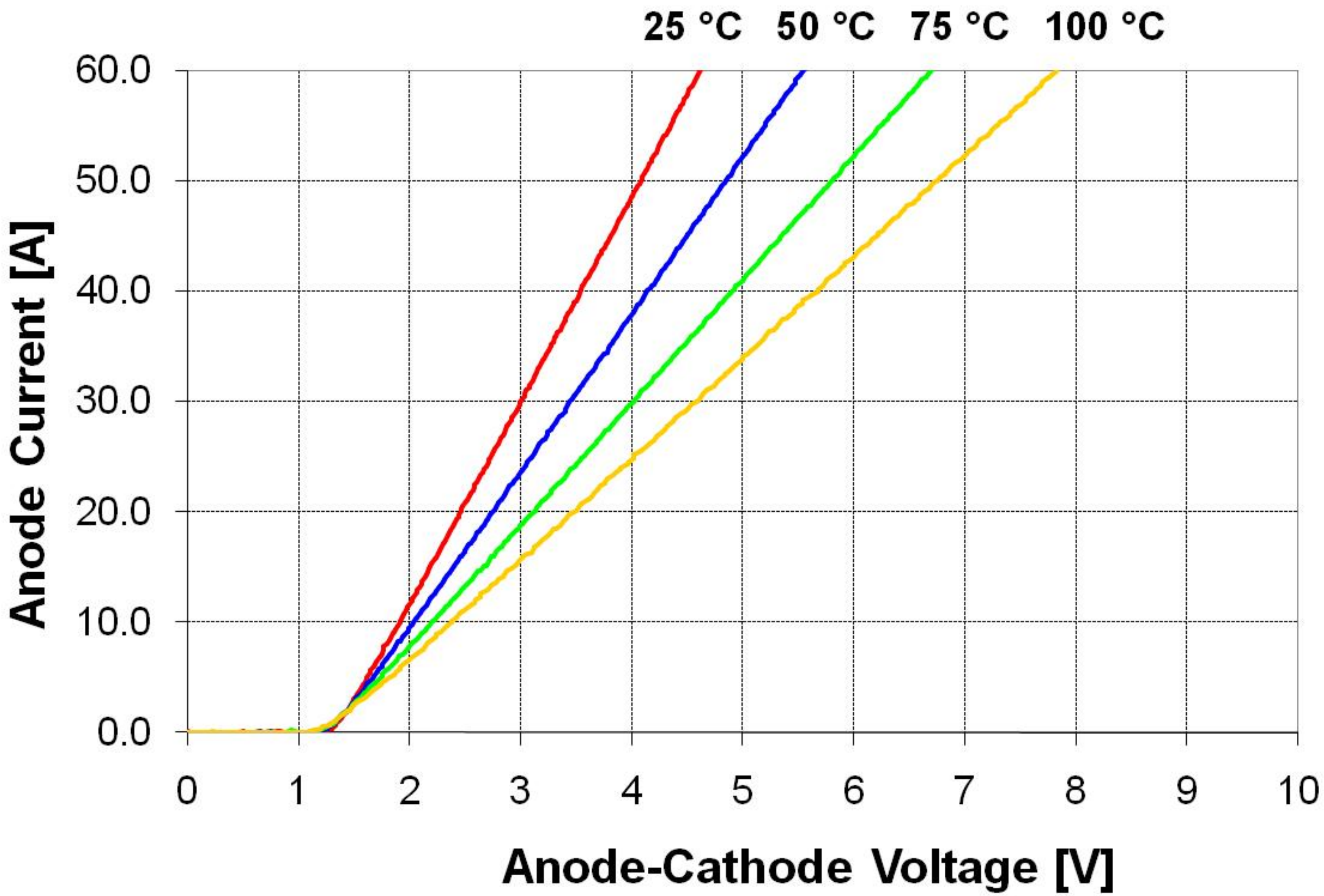
25 °C



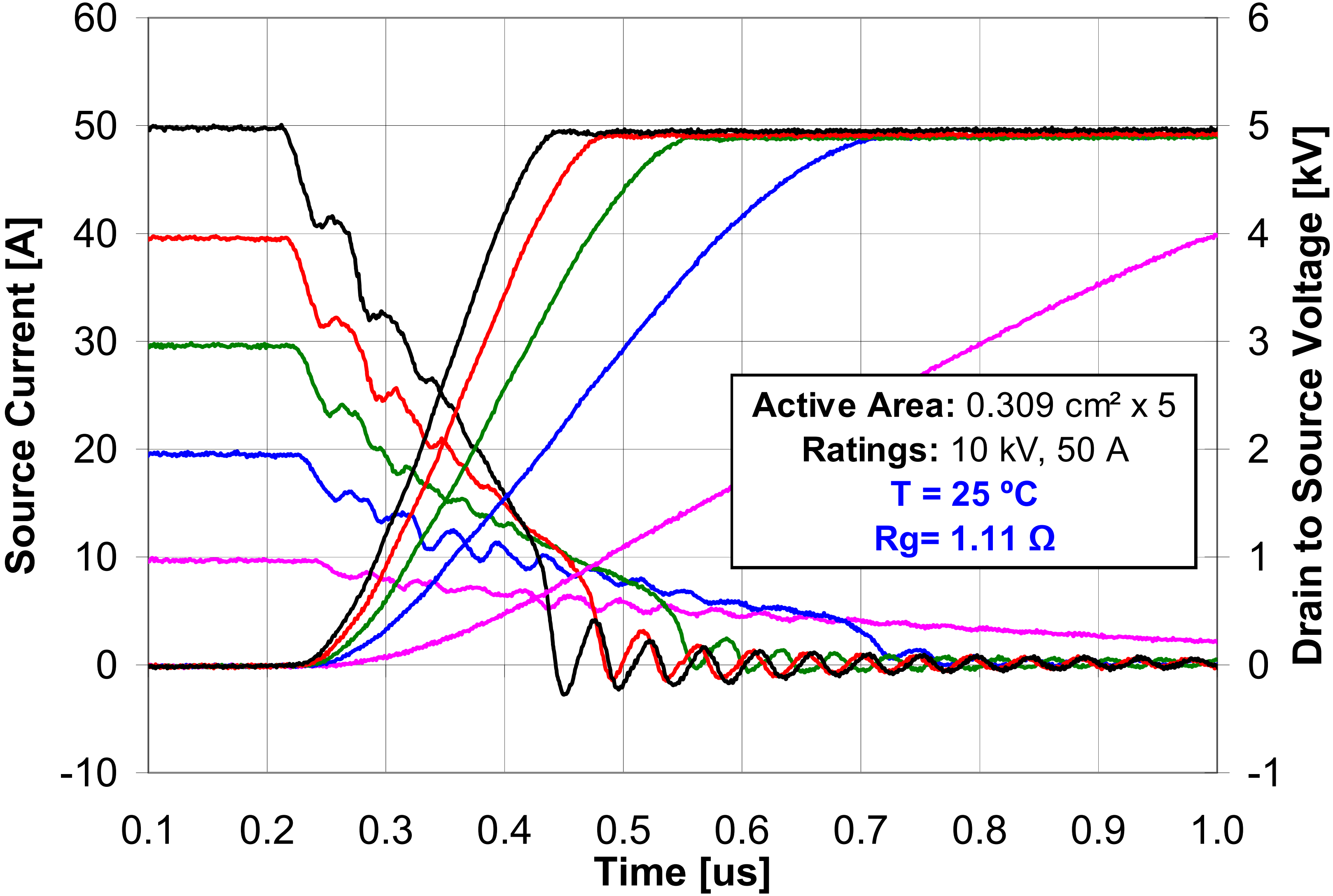
100 °C



Measured SiC JBS Diode Characteristics for 50 A, 10 kV Half-Bridge Module



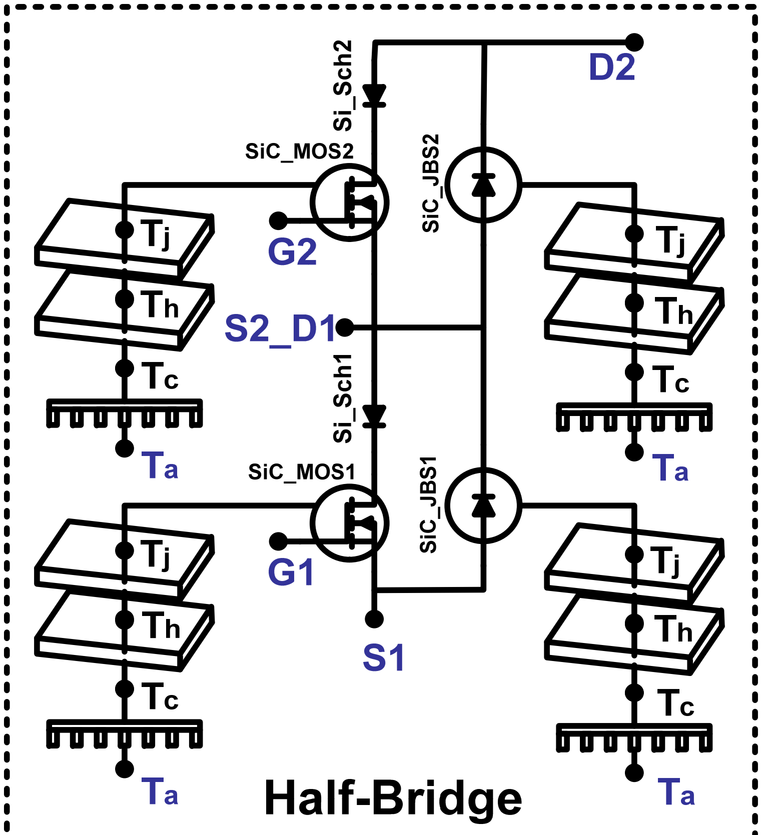
Inductive Load Turn-Off for 50 A, 10 kV Half-Bridge Module



Outline

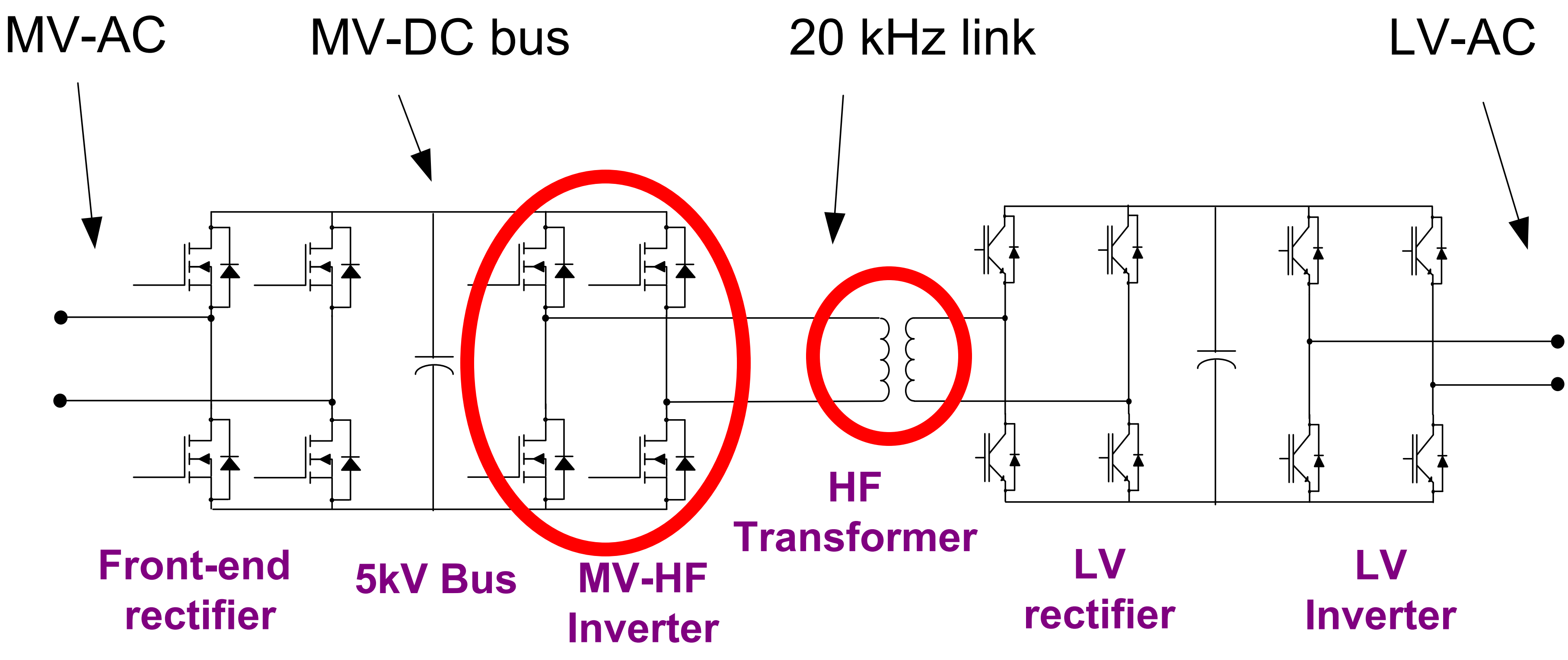
- HV-HF SiC Power Devices
- DARPA HPE Program Overview
  - Goal: Solid State Power Substation (SSPS)
  - Status: 10 kV, 100 A, 20 kHz power modules
- Component Modeling and Circuit Simulation
- Impact on Grid-Connected Power Converters

SiC MOSFET/JBS Half-Bridge Module Model and Circuit Simulation



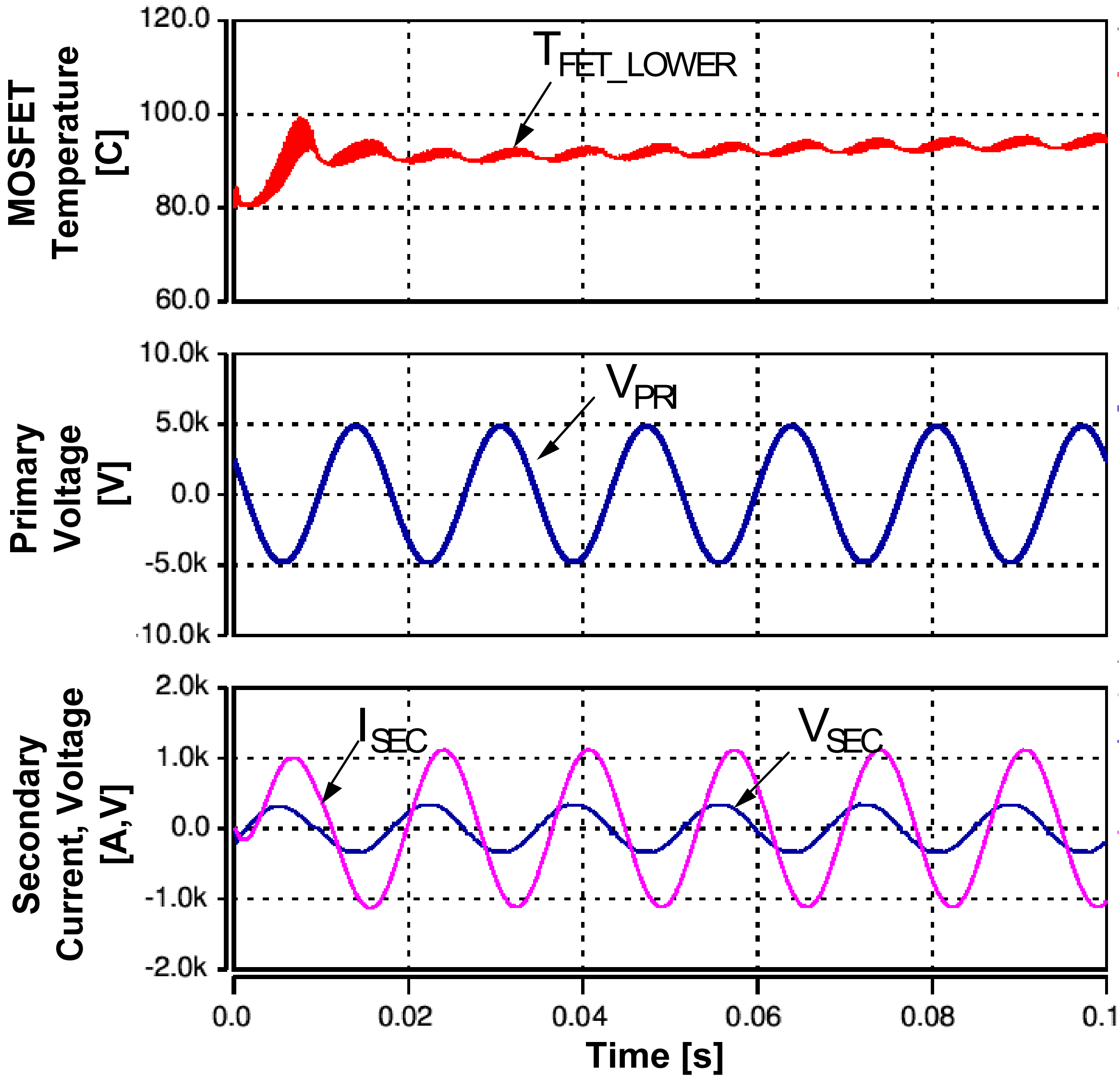
- **Model being used to perform simulations necessary to:**
  - optimize module parameters
  - determine gate drive requirements
  - SSPS system integration
  - impact on grid power converters
- **Half-bridge module model:**
  - 10 kV SiC power MOSFETs
  - 10 kV SiC JBS for anti-parallel diodes
  - low-voltage Si Schottky diodes
  - voltage isolation and cooling stack
- **Validated models scaled to 100 A, 10 kV half bridge module**

Representative SSPS Topology



This configuration would require twelve blocks to implement a three-phase 2.75 MVA, 13.8 kV to 465 V SSPS.

Electro-Thermal SSPS Simulation



- Optimized module with AMOSFET = 3 cm^2 and AJBS = 2 cm^2
- Worst case coolant temperature of 80 ºC
- Rated load at 0.8 power factor lagging
- MOSFET temperature rises by 20 ºC to 100 ºC at start-up

Outline

- HV-HF SiC Power Devices
- DARPA HPE Program Overview
  - Goal: Solid State Power Substation (SSPS)
  - Status: 10 kV, 100 A, 20 kHz power modules
- Component Modeling and Circuit Simulation
- Impact on Grid-Connected Power Converters

Impact on Grid Power Converters

Objective:

- **High-Megawatt Power Conditioning Systems (PCS) are required to convert:**
  - **from power produced by Fuel Cells (FC) in future power plants**
  - **to very high voltage and power required for delivery to the grid**

Motivation:

- **DoE SECA cost goals:**
  - **FC generator plant $400/kW**
  - **including $40-100/kW for PCS**
- **Today's PCS cost *(Fuel Cell Energy Inc.)*:**
  - **FC generator plant $3,000/kW**
  - **including $260/kW for power converter (to 18 kV AC)**

http://www.netl.doe.gov/publications/proceedings/07/SECA_Workshop/index.html

300 MW PCS

~700 V DC

Approx. 500 Fuel Cells

~700 V DC

Semiconductors
Packaging and Interconnects
HF transformers
Filter Inductors and Capacitors
Cooling System
60 Hz Transformer up to 18 kV
Breakers and Switchgear

18 kV AC → 300 kV AC

$40-$100 / kW

Ripple < 2%
Stack Voltage Range
~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion

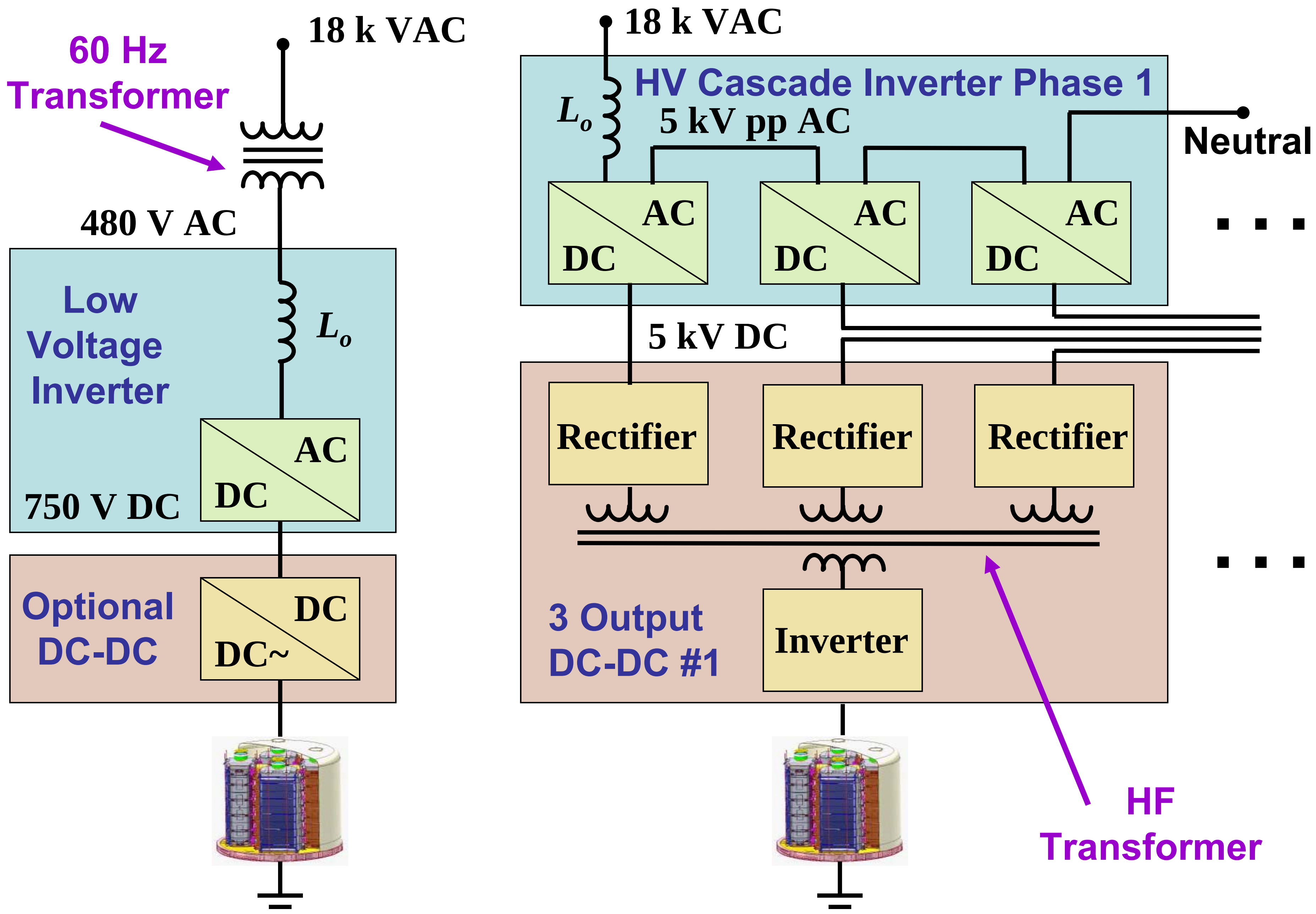
Advanced Technology Cost

- Future, high-volume costs: 5 to 10 years, 1 GW/yr
- Advanced Technology Goals and Cost Break Points
  - 1.2 kV Schottky diodes: $0.2/A
  - 12 kV Schottky diodes: $1/A
  - 12 kV Half-bridge SiC-MOSFET/SiC-Schottky: $10/A
  - 15 kV SiC-PiN: $0.4/A
  - 15 kV SiC-IGBT/SiC-PiN Module: $3.3/A
  - Nano-crystalline transformer: $2/kW
  - Power Electronics DC-DC, DC-AC: 150 % overhead
  - 60Hz Transformer and Switchgear: 50 % overhead

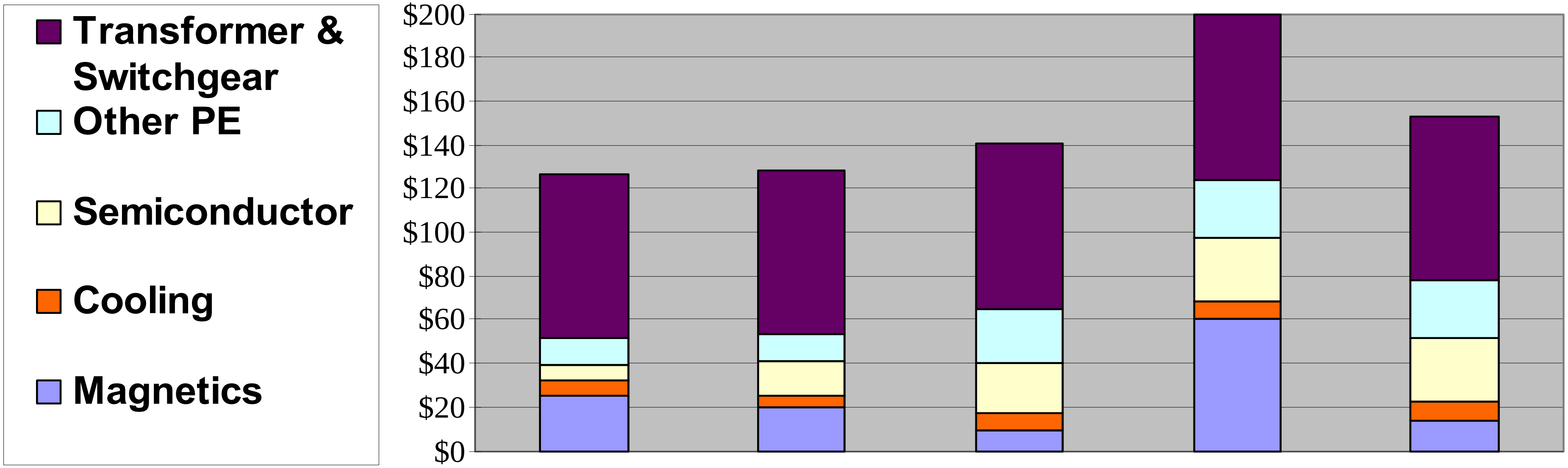
Power Converter Architectures

- **Low-Voltage Inverters (460 V AC):**
  - Require high inverter current for each FC module
  - and large number of Inverters for 300 MW Plant
- **Medium-Voltage Inverters (4160 V AC):**
  - Lower inverter current for each FC module
  - Combine multiple FCs with single high power inverter
- **High-Voltage Inverters (18 kV AC):**
  - Replaces 60 Hz transformer with isolation from HF transformer
  - Cascade enables: 18 kV AC inverter by series connection, and interleaved switching decreases losses and filter requirement

HF Transformer versus 60 Hz Transformer



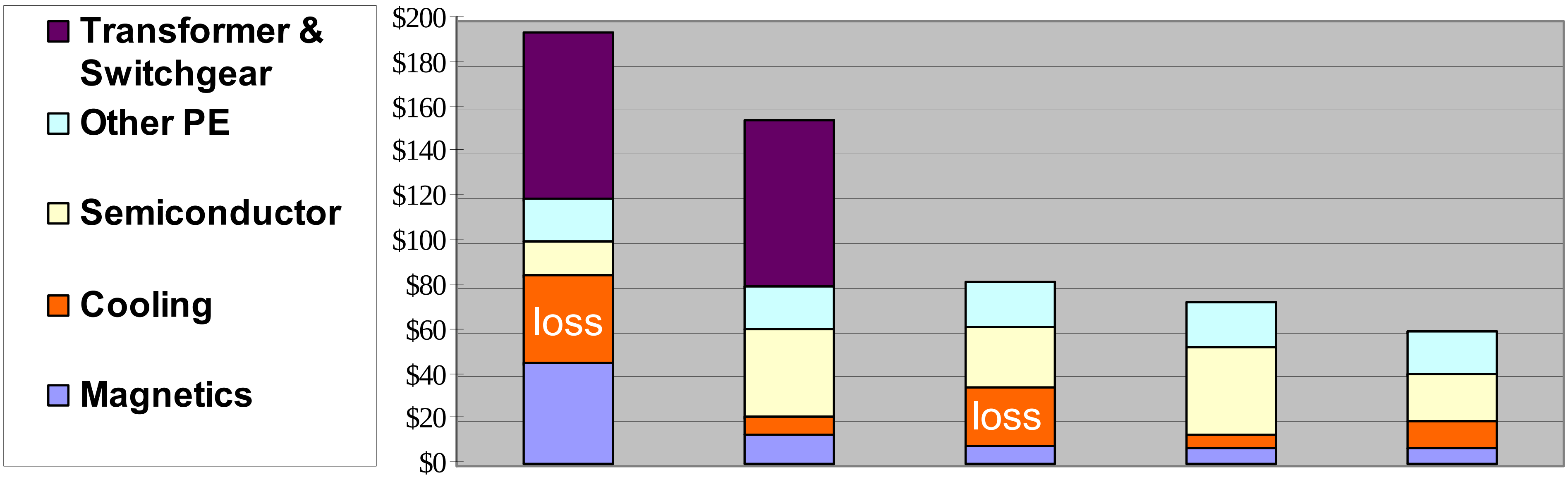
Estimated $/kW: LV Inverter



Inverter Voltage	Low	Low	Low	Low	Low
Converter Stages	One	One	Two	Two	Two
LV-SiC Schottky		yes	yes	yes	yes
HF Transformer				Ferrite	Nano
60 Hz Transformer	yes	yes	yes	yes	yes

Risk Level:	Low	Moderate	Considerable	High

Estimated $/kW: MV & HV Inverter



Inverter Voltage	**Medium**	**Medium**	**High**	**High**	**High**
HV-SiC Diode		**Schottky**	**Schottky**	**Schottky**	**PiN**
HV-SiC Switch		**MOSFET**		**MOSFET**	**IGBT**
HF Transformer	**Nano**	**Nano**	**Nano**	**Nano**	**Nano**
60 Hz Transformer	**yes**	**yes**			

Risk Level: **Low** | **Moderate** | **Considerable** | **High**

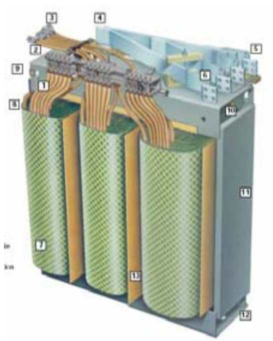
Conclusion

- **HV-HF switch-mode power conversion:**
  - SiC material enables HV-HF devices
  - efficiency, control, functionality, size and weight,… cost
- **DARPA HPE SiC devices reduce weight for CVN21**
  - Phase II is developing 100 A, 10 kV SiC power modules
  - Phase III goal is 13.8 kV 2.7 MVA Solid State Power Substation
- **Circuit simulation used to**
  - Optimize SiC module and system
  - Evaluate impact of new technology on grid power converters
- **SECA goal of $40-$100 / kW for the fuel cell plant**
  - High-Voltage grid-connected inverter may reduce cost
  - Requires HV-HF SiC devices and HF power transformer

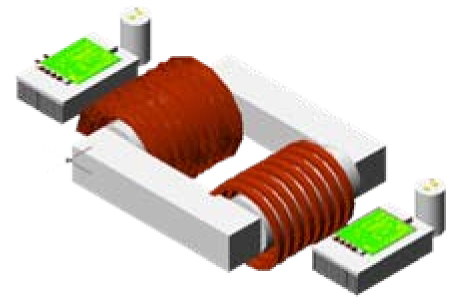
SiC Benefits and Requirements

Voltage and Current Range				
BV (kV)	0.3 – 1.2 kV	2 – 6 kV	10 – 15 kV	20 – 40 kV
Ion (A)	1 - 500 A	50 – 3000 A	3 – 1000 A	200 A
Si Speed	20ns PiN	<1k - 15kHz	---	---
SiC Speed	0ns Schottky	> 20 kHz	50ns, 20 kHz	> 1 kHz
SiC Benefits	Efficiency *High Temp HT Coolant	Efficiency Control	Control Functionality Weight	Control Functionality Part Count
SiC Barrier	Cost *HT Package *MOS mobility/ oxide reliability	Cost Large Area/ Full-wafer- device	Vf degradation HV-HF package Yield High Volume	HV substrate Vf degradation Series Package

HPE Phase III Goal



Low Frequency Conventional Transformer (analog)
- 2.7MVA
- 13.8kV/450V (Δ/Y) 60Hz
- **6 tons/each**
- **10 m³/each**
- **fixed, single output**



Estimated SiC-based Solid State Power Substation (digital)
- 2.7 MVA
- 13.8kV/465V (Δ/Y) 20 kHz
- **1.7 tons/each**
- **2.7 m³/each**
- **multiple taps/outputs**

***BENEFITS*:**
- **Reduction of weight and volume**
- **Precise voltage regulation to isolate voltage spikes, voltage dips**
- **Unity Power Factor (20% increase in power)**
- **Fast fault detection, protection, and potential removal of circuit breakers**