Silicon-carbide (SiC) MOSFET-based full-bridge for fusion science applications

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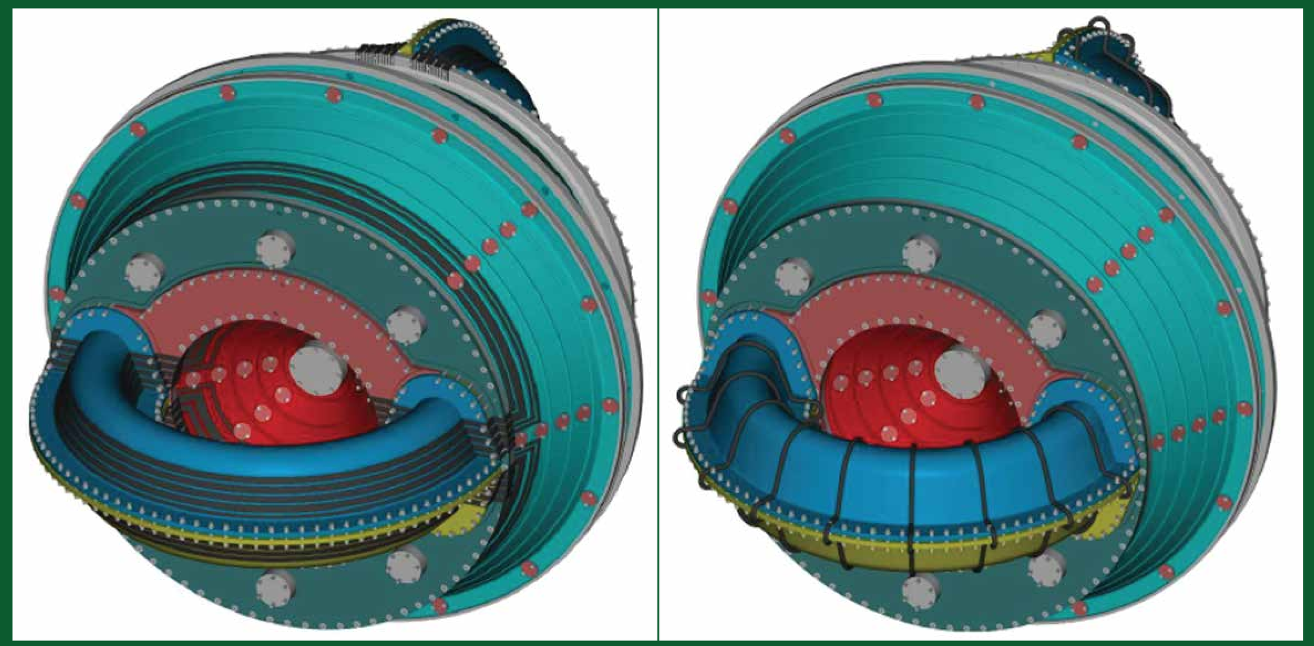
Introduction:

A current challenge facing the fusion energy community is the ability to generate increased pulsed power levels at low cost and in a robust manner. During the past decade, the state of the art in power semiconductors has advanced significantly. The introduction of silicon carbide (SiC) semiconductor devices provides advantages of fast, high-temperature and/or high-voltage devices. In 2011, Cree, Inc. introduced the first 1200 V SiC metal–oxide–semiconductor field-effect transistor (MOSFET) into the commercial market. Since the initial introduction, other MOSFET manufacturers, including ST Microelectronics, Microsemi, and POWEREX, have introduced a SiC line of MOSFETs. In order to meet the needs of the fusion science community and advance the state-of-the-art in switching power supplies and pulsers, Eagle Harbor Technologies, Inc. (EHT) is developing a full-bridge pulser, which takes advantage of SiC MOSFETs. This full-bridge can be operated CW or in pulsed applications and will be tested on the HIT experiment at the University of Washington.

Motivation and HIT Experiment:

The flux and voltage circuits of the three helicity injectors on HIT-SI3 utilizes old switching power amplifiers (SPAs). Each SPA can reliably operate at 1500 A at 900-1000 V for pulse lengths of up to 10 ms. Each SPA includes fast capacitors, IGBT drivers, fiber optic triggers, fiber-isolated fault protection, and associated power supply. The frequency ranges from 5.8 kHz up to 68.5 kHz, which is approaching the limit of the IGBTs in the SPA. The voltage and flux circuits require 14 and 6 SPAs, respectively.



The HIT-SI chamber and injectors showing the voltage coil (left) and the flux coil (right).

Left: The front and back of the SPA modules currently used at HIT. Right: Inside the SPA module showing the capacitors, IGBTs, and driver boards.

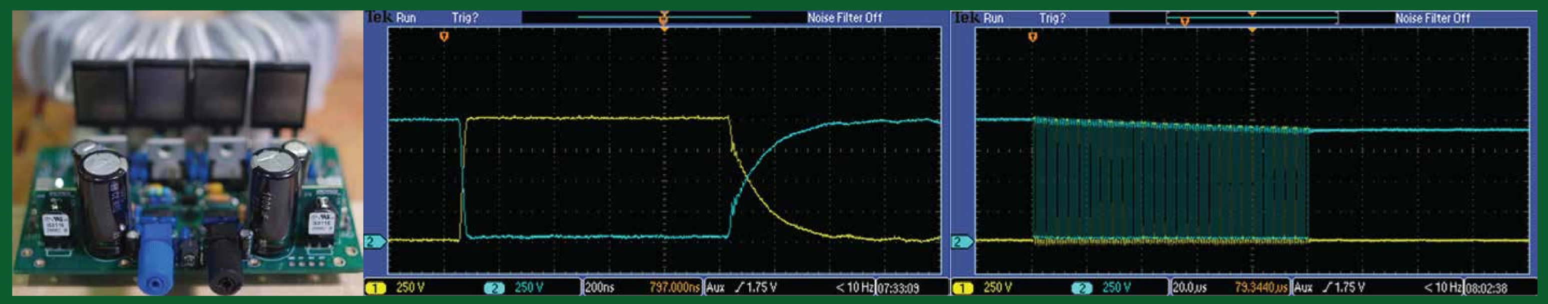
Why SiC MOSFETs?

In 2011, Cree, Inc. introduced the first 1200 V SiC MOSFET into the commercial market. They offer the following advantages over Si MOSFETs and IGBTs:

- Minimized conduction losses produce a forward drop (V_F) of <2 V at 20 A.
- Reduced switching losses compared with silicon MOSFETs and IGBTs.
- Lower capacitance due to high current density and small die size.
- Operation at 2-5 times the switching frequencies than IGBTs.
- Lowest gate drive energy (Q_G <100 nC) across the recommended input voltage range.
- Lower operating temperatures due to higher component efficiency.
- Ultra-low leakage current (<1 µA).

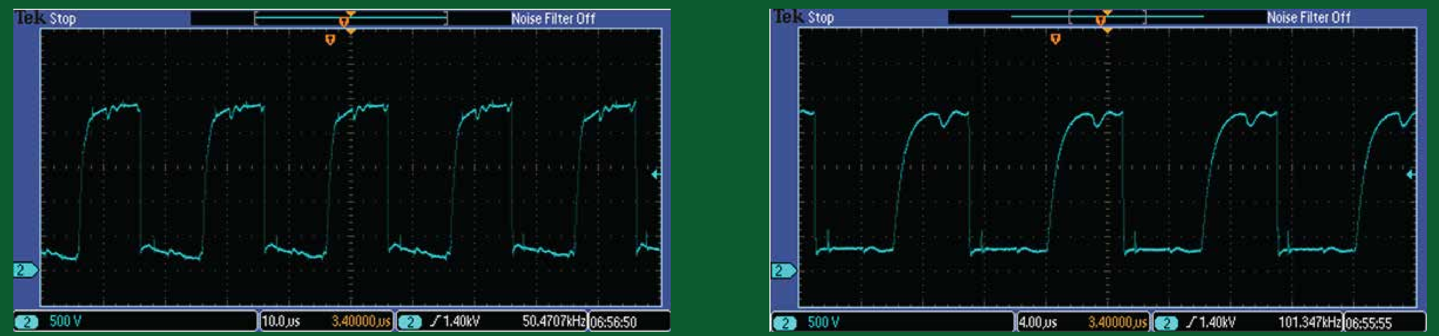
SiC Device Test Stand:

Part of the Phase I program is to characterize discrete SiC MOSFETs and compare their performance to the IGBTs that are currently used in EHT designs. Important characteristics include switching and conduction losses, switching time, current handling capability (surge and continuous).

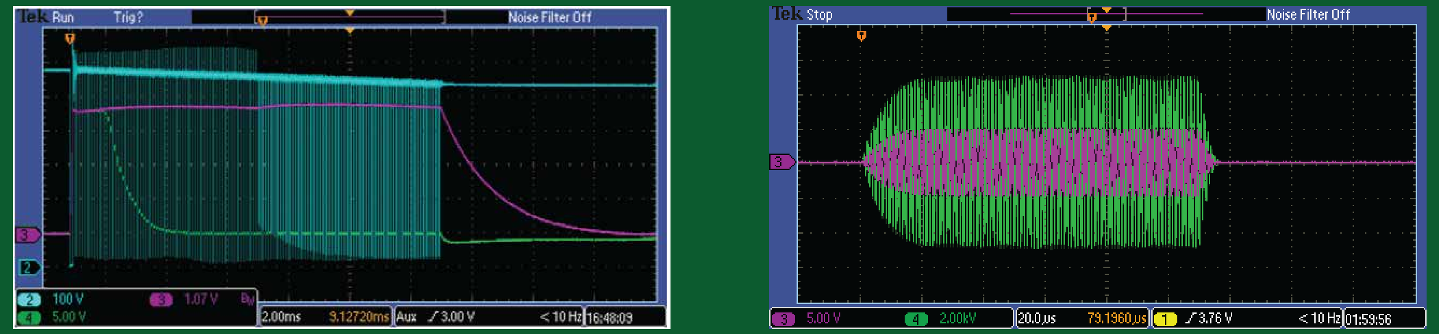


Left: Test stand to characterize IGBTs and SiC MOSFETs. MOSFET switching (CH1 (yellow): V_{load} and CH2 (blue): V_{DS}). Middle: Single 1 µs pulse switching 40 A/device at 1 kV. Right: 100 pulses at 1 MHz switching with 50% duty cycle 40 A/device at 1 kV. The voltage drop by the end of the 100 pulses is due to energy being drained from the capacitor

Other Full-Bridge Applications:



Isolated 2.5 kV into 2 kΩ at 50 kHz (Left) and 100 kHz (Right) from a full-bridge.



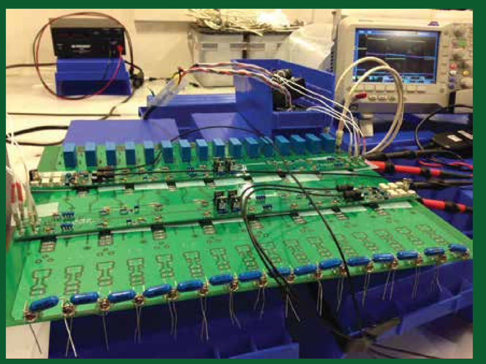
Left: 40 kA, 100 kHz PWM power supply for precision magnet waveform control.
Right: Current and voltage in a resonant tank circuit driven by a full-bridge.

Acknowledgments:

This work was supported by the U.S. Department of Energy (DE-SC0011907). EHT would like to thank the HIT group at the University of Washington for discussion related to full-bridge applications on their experiment.

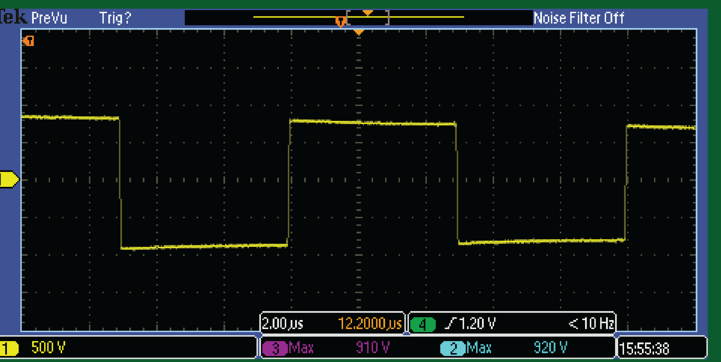
Full-Bridge Circuit Board Testing:

EHT has conducted full-bridge testing into a variety of resistive and inductive loads to demonstrate high power switching. In addition, this was testing with a transformer to increase the output pulse voltage and provide output isolation. In the near future, the full-bridge will be tested into a tank circuit, which is directly relevant for the HIT application.

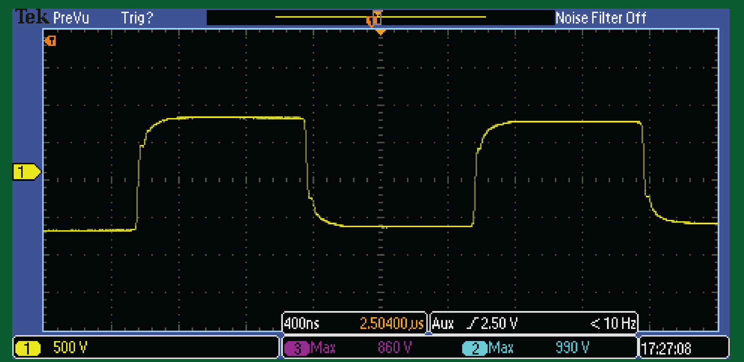


Full-bridge test setup.

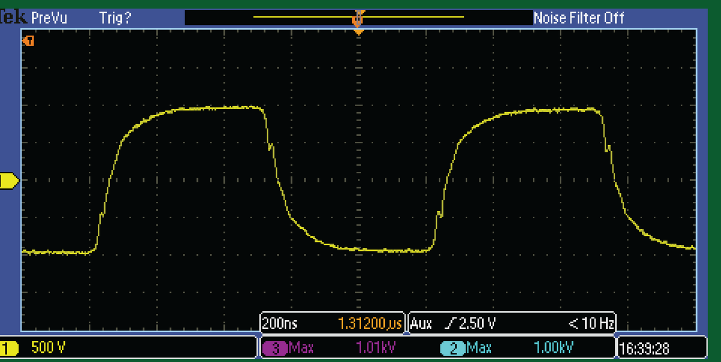
1.8 kV_{pk-pk} at 100 kHz PRF into 2.9 kA.



1.8 kV_{pk-pk} at 100 kHz PRF into 720 A.



1.5 kV_{pk-pk} at 500 kHz PRF into 8.0 kA



2.0 kV_{pk-pk} at 1 MHz PRF into 3.2 kA.

Conclusions

EHT is developing a full-bridge pulser capable of driving resistive, inductive, and tank circuit loads with the following characteristics:

- Output voltage: 2.0 kV_{pk-pk}
- Variable PRF over 1 MHz
- Variable duty cycle
- Output current (1 ms): 10 kA_{pk-pk}
- Output current (10 ms): 4 kA_{pk-pk}
- Output current (CW): 400 A_{pk-pk}

First generation EHT full-bridge pulser.

Future pulsers will incorporate enhanced thermal management, optional transformer for high voltage pulses,improved user interface, and fault detection/mitigation. These pulsers have applications within the fusion community for driving antennas and tank circuits as well as industrial applications such as semiconductor etching and deposition. Additional work during this program will include a quantitative comparison of SiC MOSFETs and the IGBTs used in EHT designs.

Further Information:

For more information on the SiC full-bridge or other switching power supplies please visit our website (http://www.eagleharbortech.com) or email me.