High Voltage, Fast-Switching Module for Active Control of Magnetic Fields and Edge Plasma Currents

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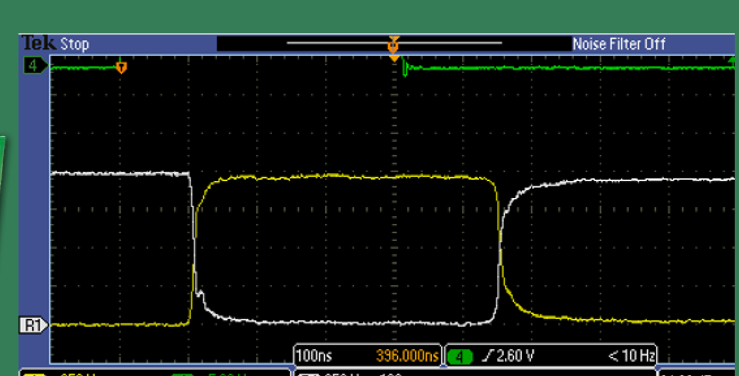
EAGLE HARBOR TECHNOLOGIES

Introduction

Fast, reliable, real-time control of plasma is critical to the success of magnetic fusion science. High voltage and current supplies are needed to mitigate instabilities in all experiments as well as disruption events in large scale tokamaks for steady-state operation. Silicon carbide (SiC) MOSFETs offer many advantages over IGBTs including lower drive energy requirements, lower conduction and switching losses, and higher switching frequency capabilities; however, these devices are limited to 1.2-1.7 kV devices. As fusion enters the long-pulse and burning plasma eras, efficiency of power switching will be important. Eagle Harbor Technologies (EHT), Inc. developing a high voltage SiC MOSFET module that operates at 10 kV. This switch module utilizes EHT gate drive technology, which has demonstrated the ability to increase SiC MOSFET switching efficiency. The module will allow more rapid development of high voltage switching power supplies at lower cost necessary for the next generation of fast plasma feedback and control. EHT is partnering with the High Beta Tokamak group at Columbia to develop detailed high voltage module specifications, to ensure that the final product meets the needs of the fusion science community.

Integrated Power Module

The Integrated Power Module (IPM) is complete IGBT switch solution originally designed for magnet control. The EHT IPM includes fiber optically isolated gate drive, solid-state switches, freewheeling diodes, fast capacitors, snubbers (optional), and crowbar diodes (optional). This rack-mount unit is easily integrated with customer DC supplies, capacitors, and loads.



Left: New EHT Integrated Power Module. Right: Switching profile of Integrated Power Module for 370 A at 1 kV at 1.25 MHz. R1 shows V_{ce}. Ch1 shows V_{load}.

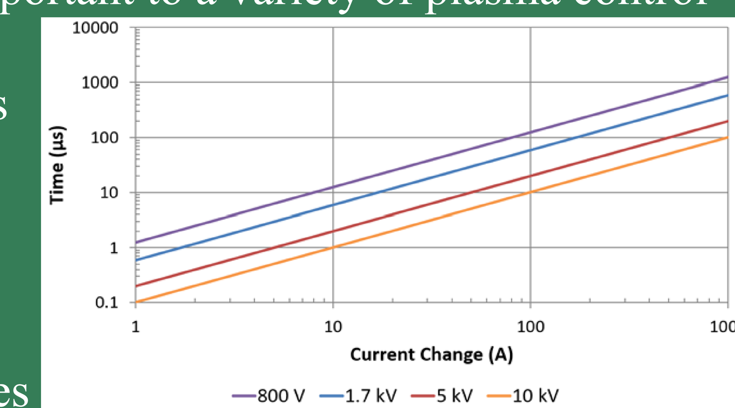
These units have been used to drive magnetic field coils both in and outside of the fusion science community:

- Pulsed magnet driver example: 2.5 kA at 100 kHz and 50% duty cycle for 10 ms
- Continuous magnet current: 500 A at 30 kHz and 50% duty cycle

The EHT IPM uses off-the-shelf discrete components, which simplifies builds and reduces costs. This allows us to take advantage of new advances in components, including IGBTs, without having to redesign the board. As designed today, the IPM has a absolute maximum voltage of 1200 V with a recommended maximum operating voltage of 800 V, which is suitable for many applications.

High Voltage for Fast Magnet Control

Fast changes in magnetic field are important to a variety of plasma control schemes. In order to enable faster magnet field changes, higher voltages are required. Quickly changing large current in coils requires voltages above 1200 V. High voltage IGBTs are available on the market today; however, SiC MOSFETs with voltages above 1200 V are not.



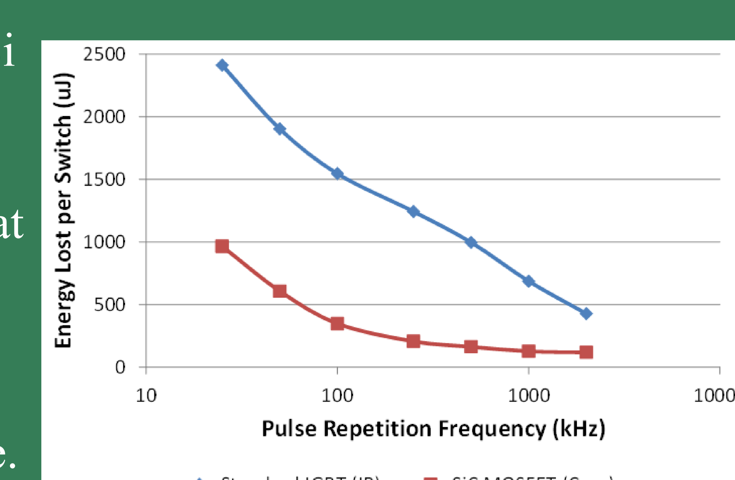
The time required to change the current in a coil with a 1 mH inductance.

Manufacturer	Style	Part Number	Blocking Voltage (V)	Current Rating (A)
Mitsubishi Electric	Brick	CM1500HC-66R	3300	1500
Mitsubishi Electric	Brick	CM1200HC-90R	4500	1200
Mitsubishi Electric	Brick	CM750HG-130R	6500	750
IXYS	Discrete	IXA40I4000KN	4000	80
IXYS	Discrete	IXGH10N300	3000	18
IXYS	Discrete	IXGK75N250	2500	170

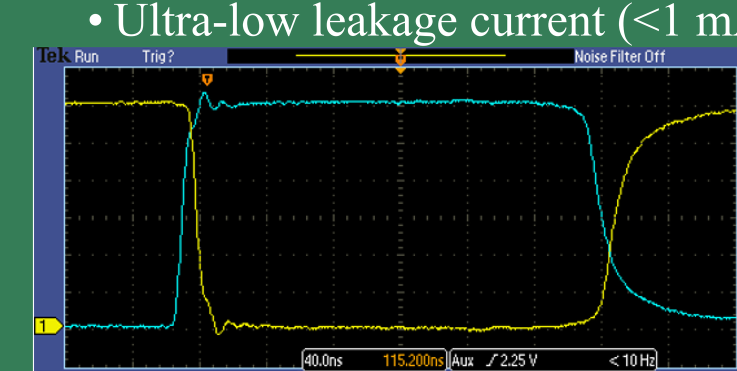
Manufacturer	Device	Part Number	Blocking Voltage (V)	Current Rating (A)
Cree	SiC MOSFET	C2M0025120D	1200	60
Cree	SiC MOSFET	C2M1000170J	1700	3.6
GeneSiC	SJT	GA50JT17-247	1700	100
GeneSiC	SJT	GA50JT12-247	1200	100
Infineon	SiC JFET	IJW120R070T1	1200	35
Microsemi	SiC MOSFET	APTMC120AM08CD3AG	1200	200
Rohm Semiconductor	SiC MOSFET	SCH2080KE	1200	40
Rohm Semiconductor	SiC MOSFET	SCT2H12NZ	1700	3.7
STMicroelectronics	SiC MOSFET	SCT30N120	1200	45
POWEREX	SiC MOSFET	FMF1200DX1-24A	1200	1200

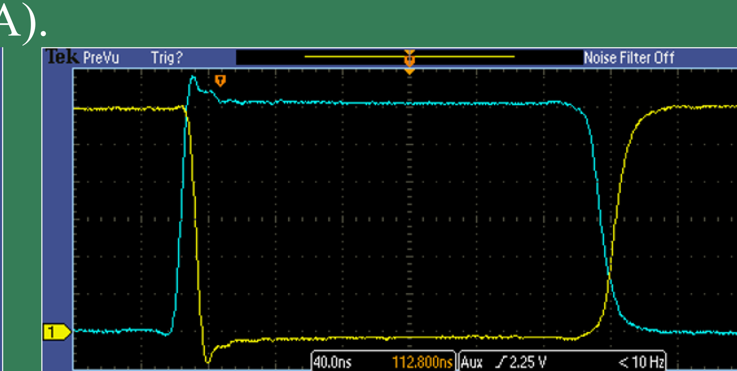
Why SiC MOSFETs?

Advantages of SIC MOSFETs over Si MOSFETs and IGBTs:



- Minimized conduction losses produce a forward drop of <2 V at 20 A.
- Reduced switching losses
- 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 (QG <100 nC) across the recommended input voltage range.
- Lower operating temperatures due to higher component efficiency.
- Ultra-low leakage current (<1 mA).





Oscilloscope traces showing rise and fall switching characteristics for both IGBTs (Left) and SiC MOSFETs (Right). Faster rise times are noted with the SiC MOSFETs.

Development Plan for HV SiC MOSFET Module

The primary goal of the Phase I program is to develop a proof-of-concept (POC) fast, high voltage switch module to eliminate the complexity of developing high voltage power systems while taking advantage of the efficiency gains of SiC MOSFETs. This module will be able to switch at 10 kV at 500 kHz for 10 ms. The ultimate current carrying capability will depend on the SiC MOSFET devices selected, but the target is ~100 A. The HBT-EP group at Columbia University will play a critical role in setting up the design specifications during the initial design phase to ensure that the final module meets the needs of the Validation Platform Experiments.

1. Design High Voltage Switch Module
   a. Develop HV switch module specifications document
   b. Perform SPICE modeling of HV switch module
   c. Select electronic components for HV switch module
   d. Design HV switch module circuit board

2. Build and Test High Voltage Switch Module
   a. Procure electronic components
   b. Assemble HV switch modules
   c. Bench test HV switch module to show high power operation

3. Demonstrate Parallel Operation
   a. Build test setup for parallel operation
   b. Test multiple modules operating in parallel
   c. Conduct fault tolerance and jitter testing

4. Prepare for Demonstration at HBT-EP During Phase II
   a. Develop preliminary design for Phase II HV switch module
   b. Consult with Columbia HBT-EP for Phase II system design

Conclusion

As fusion enters the long-pulse and burning plasma eras, overall efficiency of power switching will become important. Currently, HV IGBTs allow for fast switching of large currents; however, future experiments will need to take advantage of the latest gains in power electronics and therefore require high voltage SiC MOSFETs. There are currently no HV SiC MOSFETs on the market today. To meet the needs of future experiments, Eagle Harbor Technologies is developing a high voltage SiC MOSFET module that will allow for faster changes in large current in electromagnets. These units will allow for faster feedback and control of magnetic systems, thereby allow for greater plasma control.

Acknowledgment

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