50 kV Klystron Driver for Fusion Science Applications

J.R. Prager*; A. Henson; K. E. Miller; T. M. Ziemba; S. Wilson
*prager@eagleharbortech.com

EAGLE HARBOR TECHNOLOGIES

Introduction

Eagle Harbor Technologies, Inc. (EHT) is developing a new, solid-state klystron driver for use in fusion science applications. EHT is using high-frequency SiC MOSFET-based full bridges, previously developed with the support of the DOE SBIR program. These full bridges drive a resonant circuit that allows for zero current switching, reducing the stress on the solid-state switches. The high frequency operation allows for a more compact system, which can be placed closer to the klystrons. The Phase I program focused on a demonstration of 50 kV operation with low output voltage ripple (< 1%) and minimizing stored energy in the output filter (< 2 J). During a klystron fault, this energy is deposited into the klystron. Minimizing the stored energy is a more robust, passive solution that allows for the removal of additional switching components to protect the klystron. EHT will present the Phase I results. In a potential Phase II program, EHT would build and deliver a 50 kV, 600 kW klystron driver to MIT for testing.

Next-generation Klystron Driver Requirements

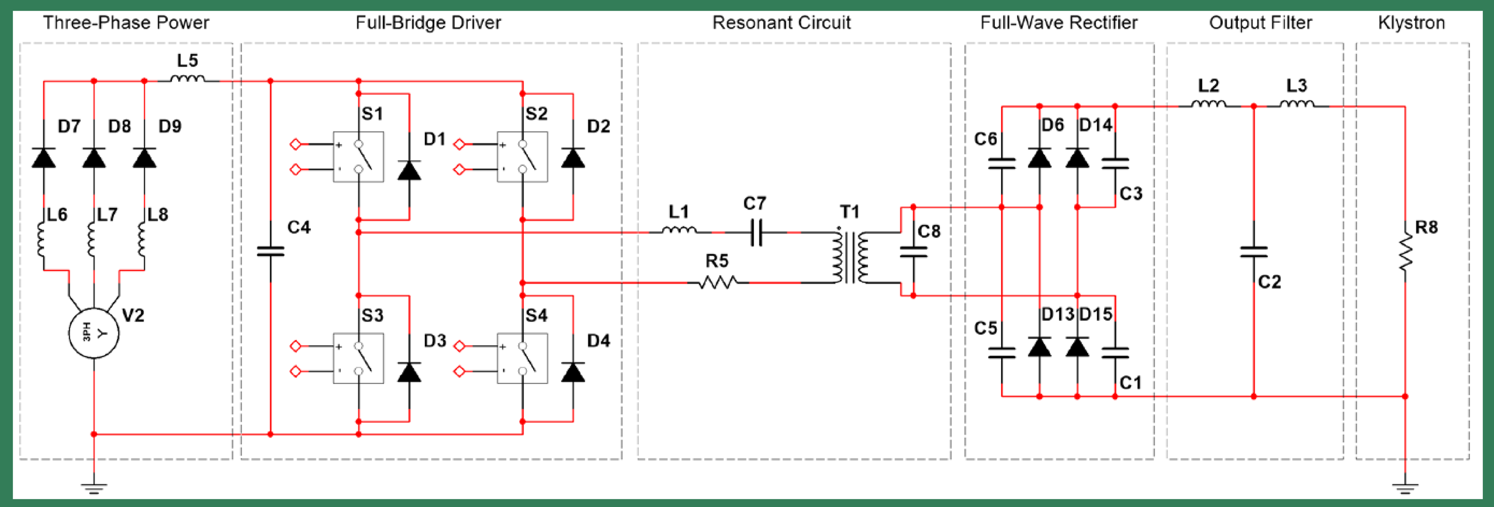
The MIT CPI klystrons were driven with a high voltage power supply that produced 50 kV pulses for up to five seconds. The system was large, about the size of two shipping containers stacked, which had to be located far from the klystrons. The energy stored in this inductance must be managed during a klystron fault, adding system complexity.

The next-generation klystron driver should have the following specifications for operating the MIT CPI klystrons at DIII-D:

- Output voltage: 50 kV (ripple < 1%)
- Output current: 12 A/klystron
- Rise time: 600 µs (faster is better)
- Pulse length: 10 s every 10 min
- Fault mitigation: < 1 J deposited with fall time < 30 µs
- Compact design located in close proximity to klystrons

Circuit Modeling

A series-resonant converter with fast response times could be developed to produce the next-generation klystron driver. This system would convert rectified three-phase power to produce the 50 kV/12 A pulse needed to drive the klystron.



Simplified Multisim circuit model. Actual circuit model included stray components.

Single Device Testing

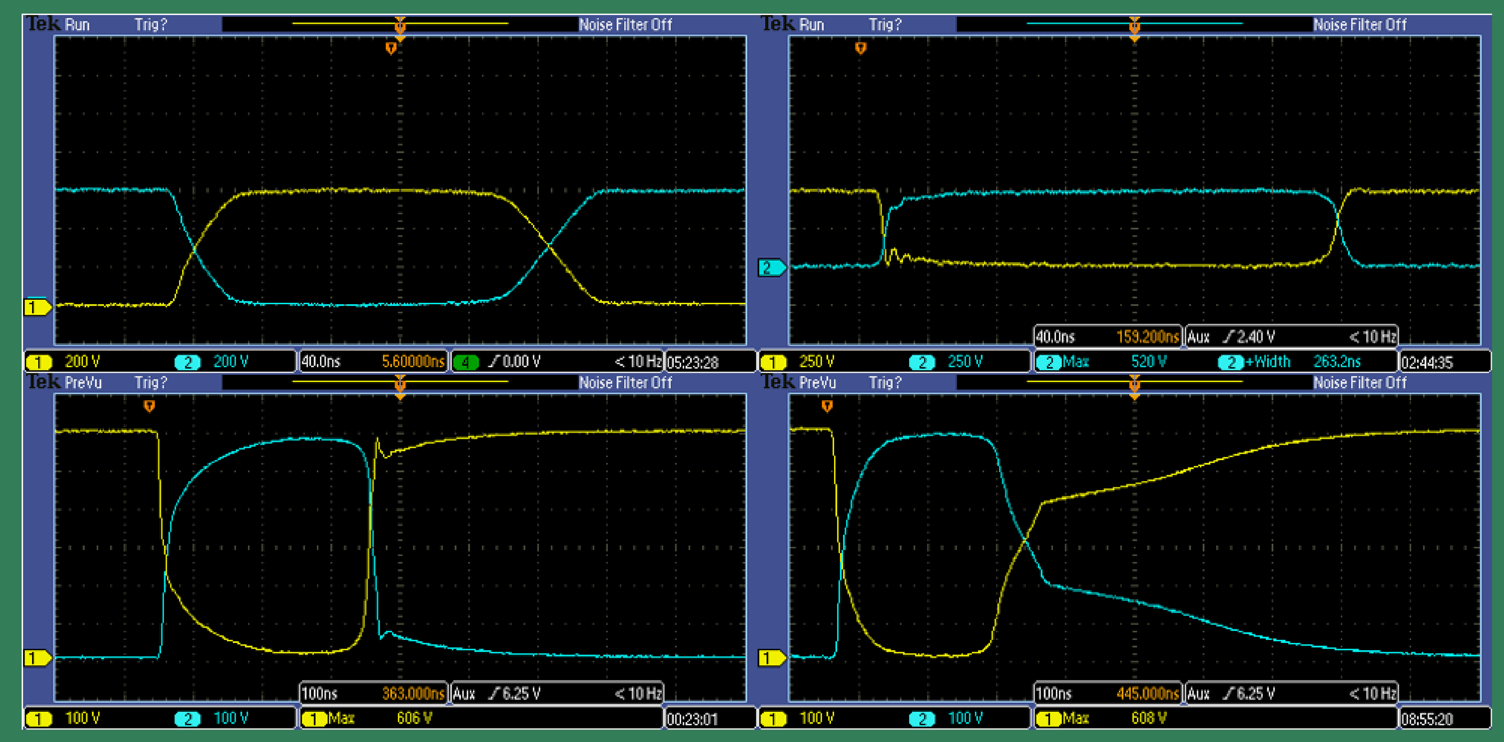
This testing was to determine the best suited switch for operation in the klystron topology. EHT evaluates switch rise and fall times into resistive loads, high-frequency robustness, and short-circuit capability. Our standard IGBT does not contain a body diode, so this test was used to compare devices with body diodes to our standard switch.

- Standard IGBT is black
- APT25GR120BD15 (75A) is blue
- FGH12040WD-F155 (40A) is red
- STGWA40N120KD (80A) is green

# of Pulses \ Frequency	200 k	500 k	1 M	2 M
1 k	✓✓✓✓	✓✓✓	✓✓✓	✓✓
2 k	✓✓✓✓	✓✓✓	✓✓✓	✓✓
5 k	✓✓✓✗	✓✓✓	✓✓✓	✓✓
10 k	✓	✓✓✓	✓✓✗	✓✓
20 k			✓✓	✓✓
50 k				✓✓
100 k				

# of Pulses \ Frequency	200 k	500 k	1 M	2 M
1 k	✓✓✓✗	✓✓	✓✓	✓✓
2 k	✓✓✗	✓✓	✓✓	✓✓
5 k	✓✓	✓✓	✓✓	✓✓
10 k		✓✓	✓✓	✓✗
20 k			✓✓	✓
50 k				✗
100 k				

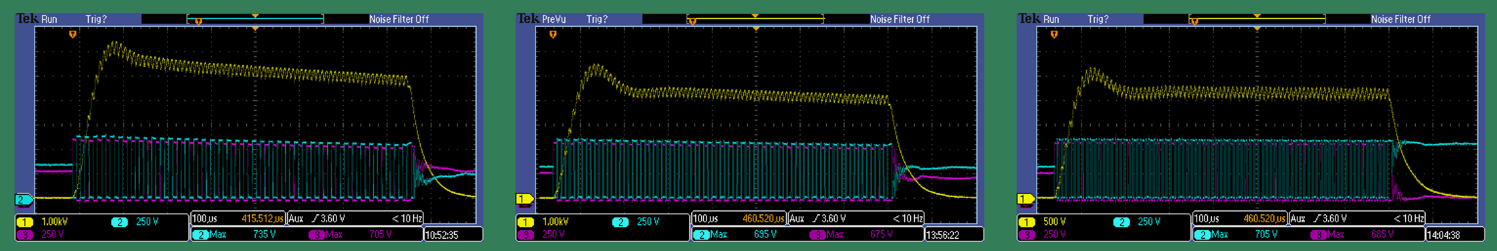
Parameter space of device testing for 30 A (top) and 80 A (bottom). Check means device passed; X means device failed.



Switching waveforms at 600 V and 20 A with 10 Ω gate resistor. Top left: Standard. Top Right: APT25GR120BD15. Bottom Left: FGH12040WD-F155. Bottom Right: STGWA40N120KD.

Single Board Resonant Testing

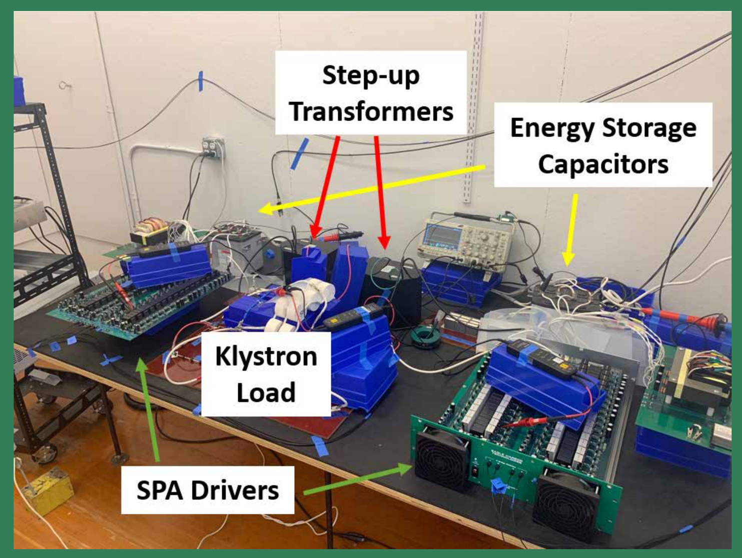
EHT tested each unit at up to 50 kV and 3 A with a 16.7 kΩ resistive load, a charge voltage of 640 V, shot length of 800 µs, and varying duty cycles. This ripple on a single board is about 5% with more than 10 J stored. The output voltage droop is the result of insufficient energy storage. A controller or pre-programmed triggering waveform adjust the duty cycle in real time. This can be used to adjust the rise time, eliminate the overshoot, or compensate for energy storage droop and increased losses due to component heating.



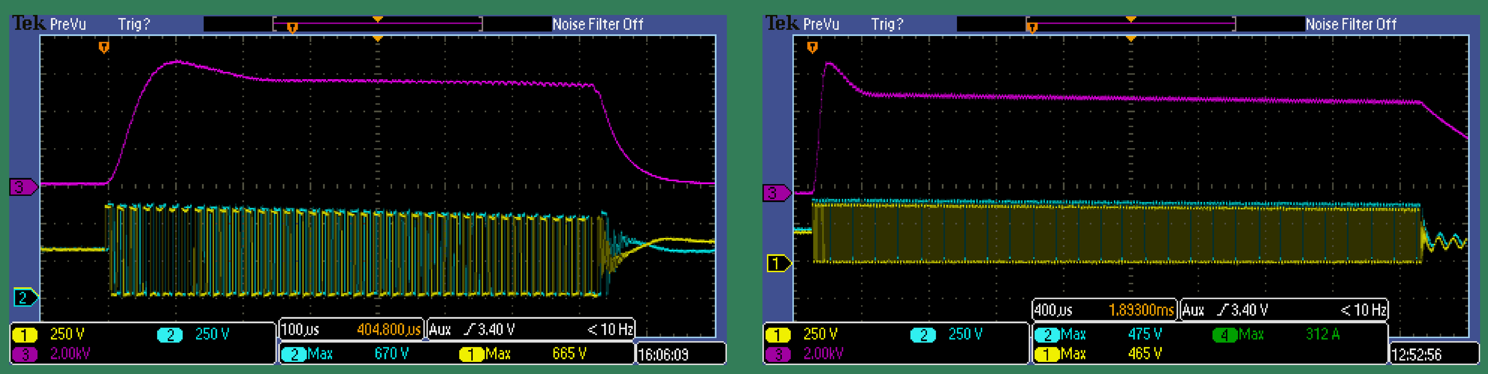
Yellow: output voltage. Blue: VCE for switch position 1. Purple: VCE for switch 3. Left: 50 kV at 84%. Middle: 40 kV at 74%. Right: 23 kV at 50%.

Multiple Boards in Parallel

Multiple full-bridge PCBs were tested in parallel operating out of phase: a charge voltage of 640 V, duty cycle of 84%, and output voltage of 50 kV. This test demonstrated an output voltage ripple of 1.1%. Since the only filter element was a capacitance of 4 nF and the output voltage was 50 kV, the energy stored in this element was only 5 J. The ripple, stored energy, and pulse fall time will be further reduced with additional PCBs in parallel. This will be demonstrated with the full 600-kW system build in a potential Phase II program.



Multi-board klystron test setup.



Purple: output voltage. Yellow and Blue: VCE of full-bridge positions 3 and 2. Left: 50 kV, 6 A output for 700 µs. Right: 50 kV, 270 mA output for 3.6 ms.

Conclusion

EHT's Phase I SBIR develop of the next-generation klystron drive is complete. EHT's design relies on state-of-the-art solid-state switching to build a more compact robust klystron driver. This design will operate multiple full bridges in parallel, but out of phase. This technique can reduce the output ripple to below 1% and the stored energy to less than 1 J.

Switch testing has identified a modern IGBT with body diode that can be used in the full bridge. EHT has built resonant full bridges that were tested in isolation and parallel operation to demonstrate low ripple, low stored energy, and scaling to a full system.

In a potential Phase II program, EHT will operate multiple full-bridges in parallel, test faults conditions, and integrate a controller. Finally, EHT would test a single 50 kV, 600 kW klystron driver at MIT with the CPI klystrons. At the end of a potential Phase II program, EHT would have a klystron driver design that could be commercialized.

For more information: http://www.eagleharbortech.com/

Acknowledgment

This work was funded by a DOE SBIR (DE-SC0018687).