The Ten-Year Evolution of a High-Power Magnet Driver

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EAGLE HARBOR TECHNOLOGIES

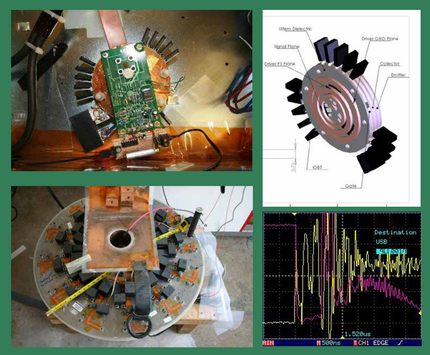
2007 — 2008 — 2009 — 2010 — 2011 — 2012 — 2013

SBIR Phase I

SBIR Phase II

pre-Phase I SBIR

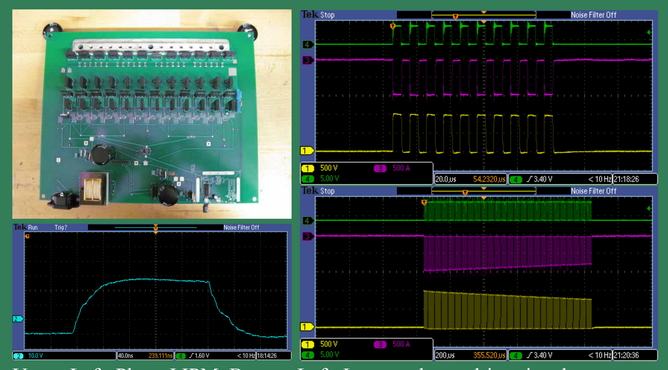
IGBT switching power supplies were in use at the Advanced Propulsion Laboratory (APL) and the Redmond Plasma Physics Laboratory (PPPL). These were research power systems that lacked robust operation at high peak power levels and high-frequency operation capabilities. There was significant room for improvement in snubber design, PCB-use, and gate drive.



Upper: Photo (left) and mechanical drawing (right) of helicon power system at APL. Lower left: STX power supply from PPPL. Lower Right: Gate drive signal from APL helicon power system.

DOE Phase I SBIR

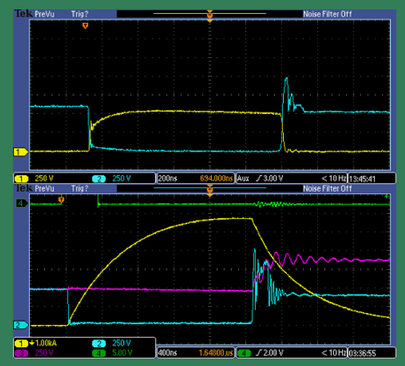
Initial Integrated Power Module (IPM) is developed as a pulsed, megawatt-class integrated solid-state switch. Key focus was on developing a high power gate drive for clean, reliable switching of high current. At the time, 100 kHz at these power levels was high frequency. Switches were operated in series (not shown).



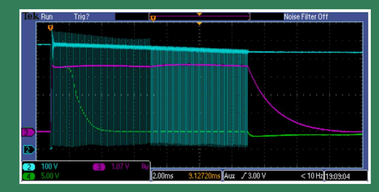
Upper Left: Phase I IPM. Bottom Left: Improved gate drive signal. Right: Module operating at 100 kHz. Top: 10 pulses showing 1 kA output current (CH3) at 1 kV (CH1) operating voltage. Bottom: 1 ms operation.

DOE Phase II SBIR

Several iterations of IPM were produced to optimize design for a module that would be useful for fusion science and other applications. Focused on improved reliability, high current switching, series stacking (not shown), resitive and inductive load driving.



Top: Resistive load 600 V and 6 kA for 1 µs with 50 ns rise. Bottom: Crowbarred inductive load 500 V and 6 kA 2 µs.



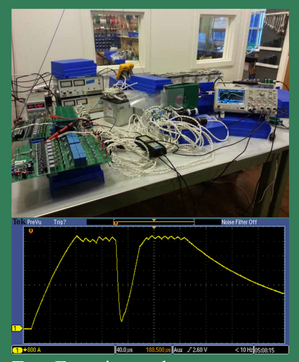
High current PWM at 100 kHz: 580 V, 2.9 kA for 12 ms. V_{ce} (blue), current from droop-free integrator (magenta), current from Pearson (green).

Above: Phase II Module - higher power density, faster gate drive and lower inductance. Left: IPMs operated in parallel to switch 40 kA.

2013 — 2014 — 2015 — 2016 — 2017 — 2018 — 2019

Winter 2013

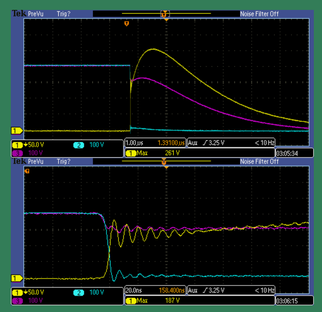
IPM allows unique waveforms in inductive magnets. 5 kA was PWMed at 100 kHz. A second switch rapidly removes current from inductor before current is restored.



Top: Experimental setup. Bottom: 5 kA current waveform in inductor.

Summer 2014

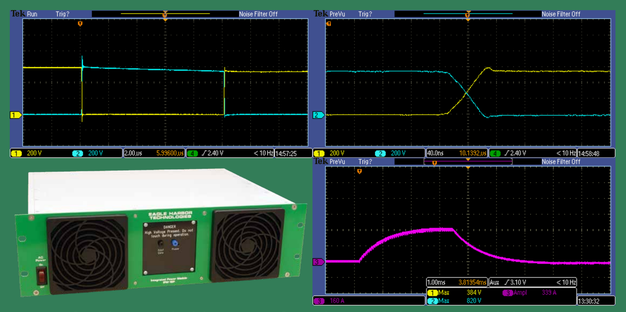
Short-circuit testing IPM into low-inductance 25 mΩ load to generate 10 kA current pulse for customer application. Closing switch only.



High current (10 kA) pulse on two timescales. Output voltage (yellow), Vce (blue). and capacitor voltage (magenta).

Summer 2016

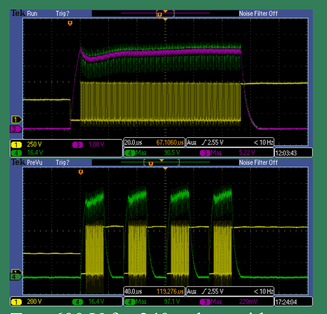
The IPM is redesigned for a commercial customer to incorporate air cooling for continuous operation. The specs are 500 A at 30 kHz and 50% duty cycle (air cooled) for driving a crowbarred inductive load (electromagnets). Reduced output capacitance and latest gate drive improves waveforms. Package is more user friendly.



Top Left: Clean switching waveform into 1 Ω load. Top Right: Same waveform showing fast voltage and current rise time (< 40 ns). Bottom Left: EHT IPM Bottom Right: Current waveform. IPM driving a 85 µH inductor at 350 V and 340 A with a PWM drive frequency of 30 kHz.

Autumn 2016

IPM is used for high current arc modulation.



Top: 600 V for 240 pulses with a pulse width of 350 ns producing flat top currents of 2.0 kA (left) and 1.1 kA. Bottom: 600 V with a pulse width of 375 ns for 240 pulses producing flat top currents of 2.0 kA. Four bursts at 17 kHz. Traces shown are V_{cc} (yellow), current probe (pink), and shunt resistor (green).

Conclusion

With support of a DOE FES SBIR, EHT developed a high-frequency solid-state switching module has been commercialized into fusion science and other markets. The technology created under this SBIR has led to other grant and commercial opportunities, which enabled the development of new solid-state switching systems, like the nanosecond pulser, inductive adder, and full-bridge driver. These systems are being commercialized in new markets. Most recently, this switching technology form the core of a Ćuk converter for the Pegasus Toroidal Experiment at the University of Wisconsin - Madison.

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