Radio Frequency Plasma Generation without 50 Ohm Matching

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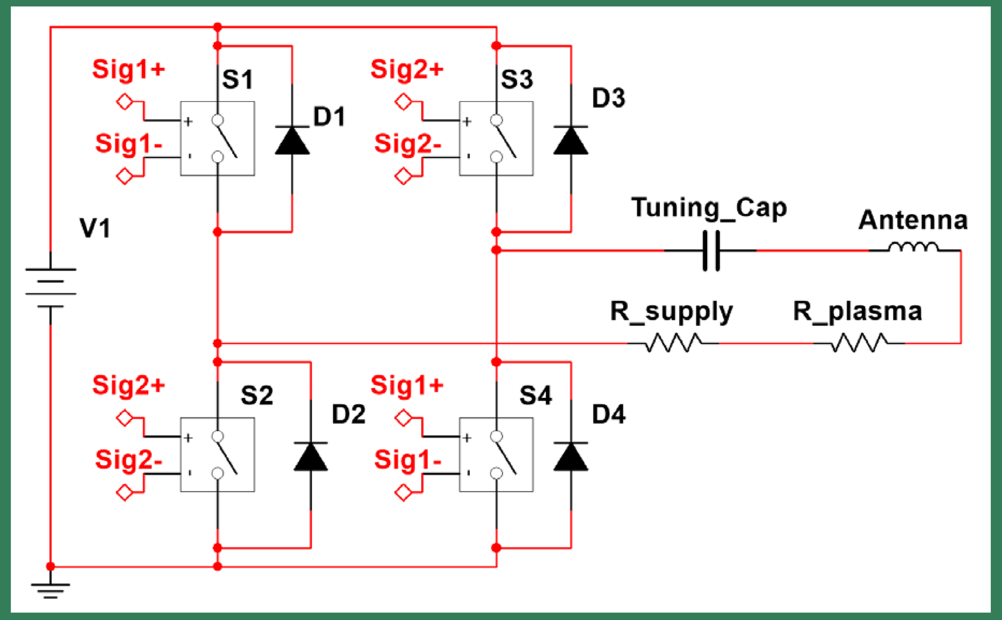
EAGLE HARBOR TECHNOLOGIES

Introduction

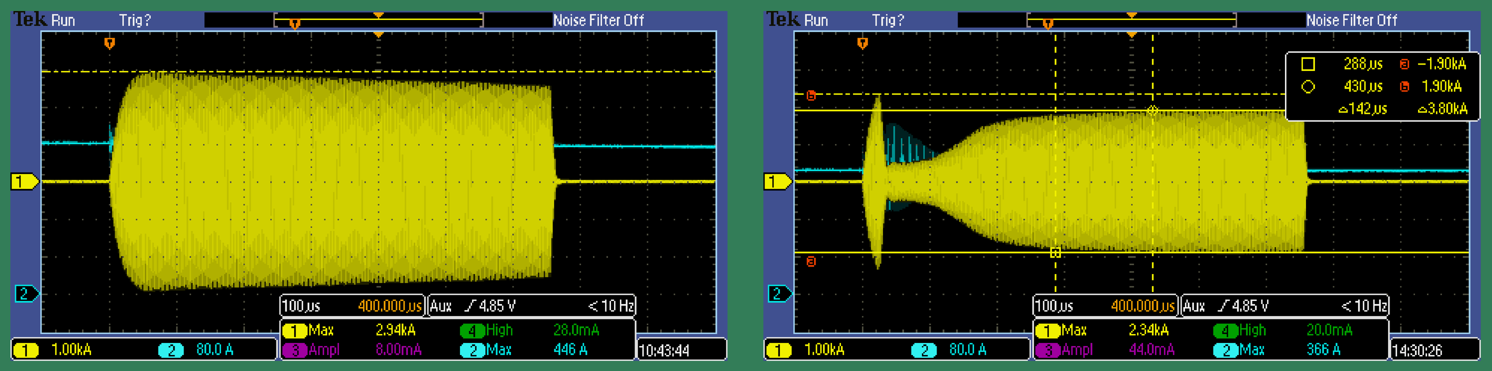
Eagle Harbor Technologies (EHT), Inc. is developing radio-frequency (RF) solid-state switching power supplies without the need for a 50-ohm matching network. The ability to remove the 50-ohm matching network from RF plasma generation systems significantly simplifies the design while allowing for a faster response time to changing plasma conductions. This system takes advantage of EHT's previously developed full-bridge circuit and uses that to drive a resonant load. These systems can be designed to operate from 100 kHz to tens of megahertz. This power system has applications in semiconductor processing, fusion energy science, material science, and basic plasma physics. EHT will present circuit modeling, diagrams, and waveforms.

High-Power RF Generator

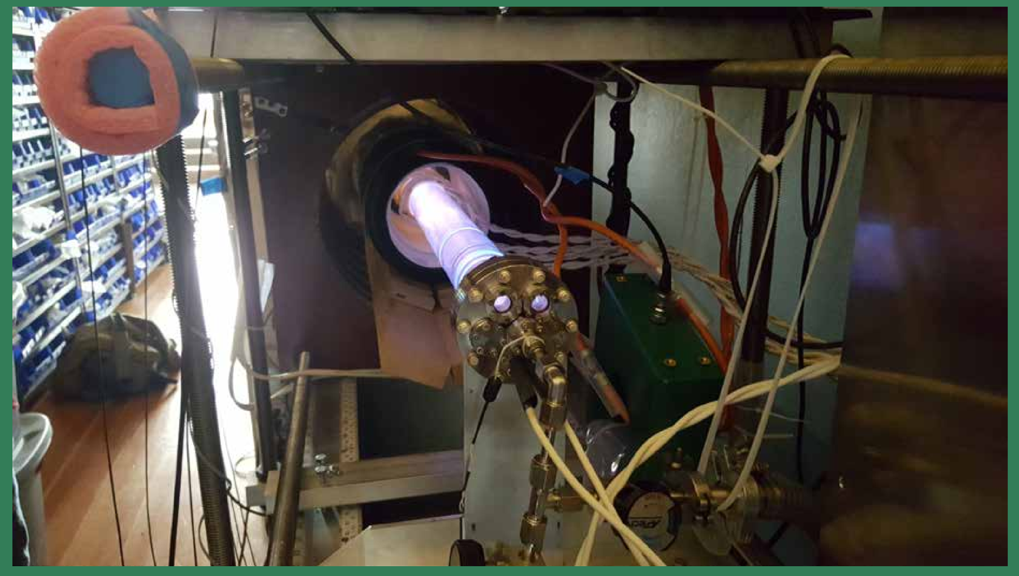
EHT has developed a SiC MOSFET-based full bridge to drive capacitive, inductive, and helicon plasma sources. The helicon antenna is part of an RLC circuit that is driven the full bridge at its resonant frequency (up to 1 MHz), which allows large currents to be generated in the antenna. This system can be pulsed for a single RF cycle or RF burst widths up to 10 ms while delivering more than 250 kW to the plasma. This power system was developed with support of a DOE SBIR.



Full bridge driving an RLC circuit.



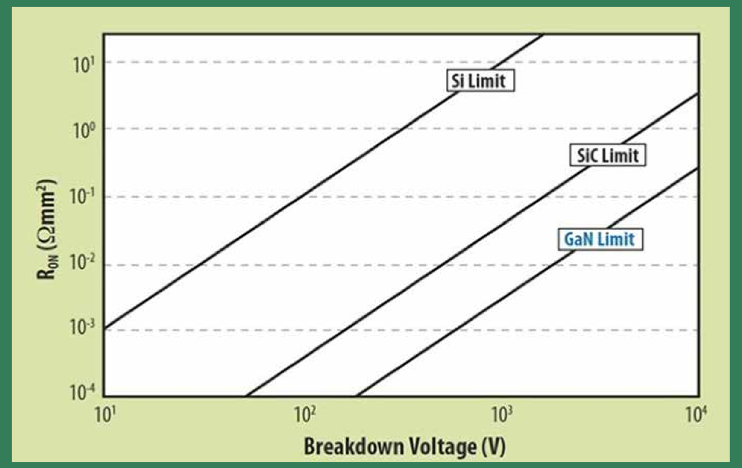
Antenna current for a vacuum shot (left) and plasma shot (right). The flat top current is 2.94 kA and 1.9 kA for the vacuum and plasma shots, respectively.



Inductive plasma produced by High-Power RF Generator.

Gallium Nitride Field Effect Transistors

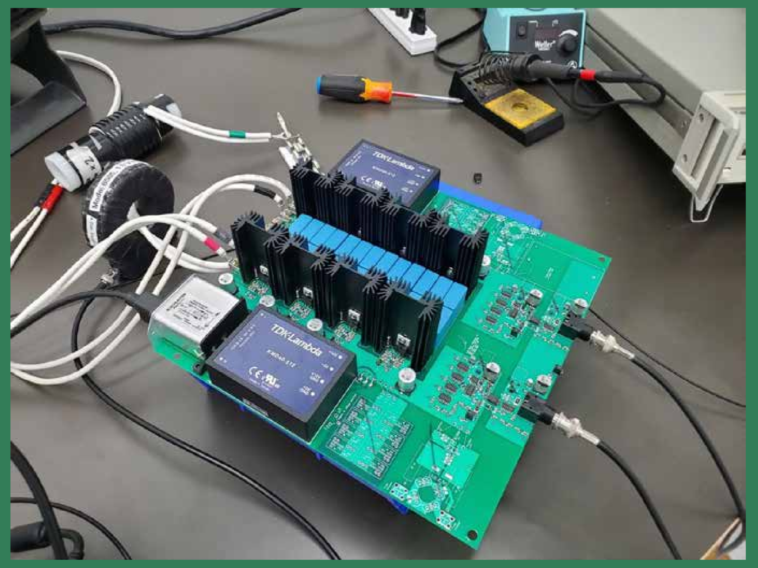
Gallium nitride (GaN) high electron mobility transistor (HEMTs) are now vying to improve the power electronics market. Smaller sized devices can be made from GaN for the same on-resistance and breakdown voltage. Additionally, GaN HEMTs have lower gate drive power requirements compared to similar Si-based devices. GaN switches also are more easily operated in parallel than SiC MOSFETs. There are 650 V devices that can switch up to 100 MHz on the market today, with 1200 V devices expected in 2020.



Theoretical limits of on-state resistance for Si, SiC, and GaN devices.(S. Davis "The Great Semi Debate: SiC or GaN?" *Power Electronics*, February 2019)

Matchless RF Generator with GaN HEMTs

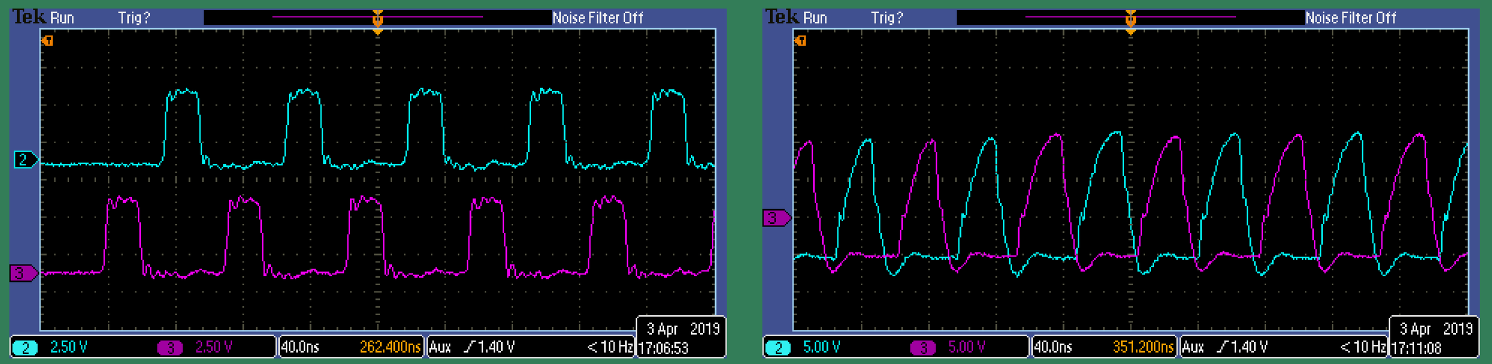
EHT has used GaN HEMTs to build a full bridge to drive RLC resonant circuits at even higher frequency than was possible with SiC MOSFETs. The initial PCB was designed for low average power operation (500 W), but the peak power was much higher (25 kW). Future designs will use more GaN HEMTs in parallel to increase the average and peak power levels.



EHT half-bridge with GaN HEMTs driving a series resonant circuit.

The GaN HEMT full bridge had the following specifications:

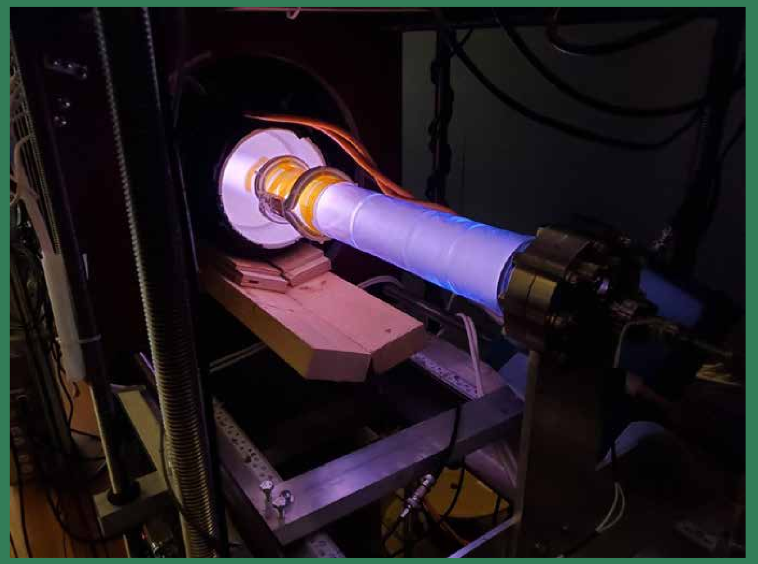
- **Frequency:** Up to 15 MHz
- **Output Voltage:** ±200 V (burst) or ±75 (continuous)
- **Current:** Up to 60A
- **Duty Cycle:** 0-100%
- **Q:** Up to 80, load dependent
- **Load:** Inductive or resonant.
- **Power Isolation:** External AC Transformer, on-board rectifier
- **Switches:** 650V GAN HEMTs from Transphorm
- **Triggering:** BNC inputs, with digital isolators to couple the signal for high side switching



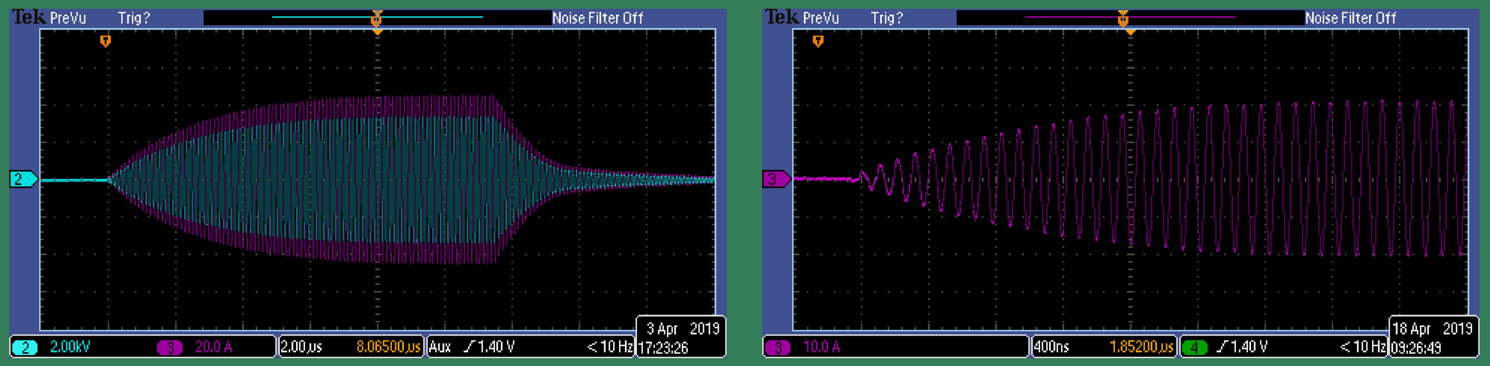
Left: Input signal from BNC inputs for the two channels. Right: Gate signal at input to the GaN HEMTs.

Plasma Waveforms

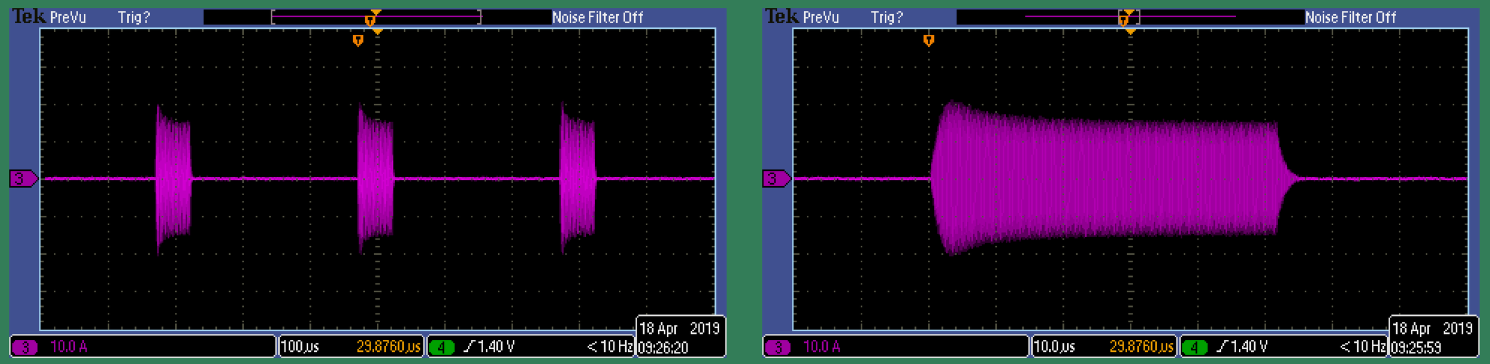
The matchless RF generator was used to drive an inductive antenna. The chamber pressure was ~100 mtorr and the working gas was hydrogen. The RF burst width can be precisely controlled down from a few microseconds to continuous. The RF bursts can be repeated at high burst repetition frequency. The RF burst width, burst repetition frequency, and antenna current can be adjusted in real time. This system was operated at RF frequencies up to 15 MHz, including the standard 13.56 MHz.



Hydrogen plasma produced with matchless RF generator driving an inductive antenna.



Antenna current without plasma at 13.56 MHz. Left: 12 μs burst 45 A of current in the antenna. Right: Expanded timescale showing the rise of the RF burst.



Antenna current with plasma production at 13.56 MHz. Left: 50 μs burst with 300 μs burst repetition frequency. Right: Expanded timescale of a single RF burst.

Conclusion

EHT has designed, built, and tested two matchless RF systems for plasma production. The first system used SiC MOSFETs and could operate at up to 1 MHz for short bursts at high peak power (1 MW).

The second system uses GaN HEMTs, which allow RF up to 15 MHz. This system can be integrated with high-speed DAQ and controller. The burst width, burst repetition frequency, and output current can be adjusted to control the plasma in real time. This precision control is only possible with the elimination of the 50 Ohm matching network that is typically used in these applications.

Future work will investigate focus on a kilowatt-class GaN-based RF generator and the integration of a real-time controller.

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