Neutral Beam Power System for Fast Grid Modulation

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EAGLE HARBOR TECHNOLOGIES

Introduction

Neutral beam injection (NBI) is an important tool for plasma heating, current drive and a diagnostic at fusion science experiments around the United States. Producing power systems that can respond rapidly (10 µs) at high voltage (10 to 100 kV) for beam acceleration or high currents (~ 1 to 5 kA) for control of the ion source is non-trivial. Currently, there are no vendors in the United States for NBI power systems. Eagle Harbor Technologies (EHT), Inc. is developing new solid-state switching power systems for NBI that takes advantage of the latest developments in solid-state switching. EHT has developed a series resonant converter that can be scaled to the power required for NBI at small-scale validation platform experiments. This power system can modulate the injection beam current during a plasma shot, which can lead to improved control over the plasma. Additionally, these modern solid-state supplies can be made smaller and lower cost that previous generations of NBI power systems. We will present the Phase I testing results, including demonstration of current modulation on a neutral beam system.

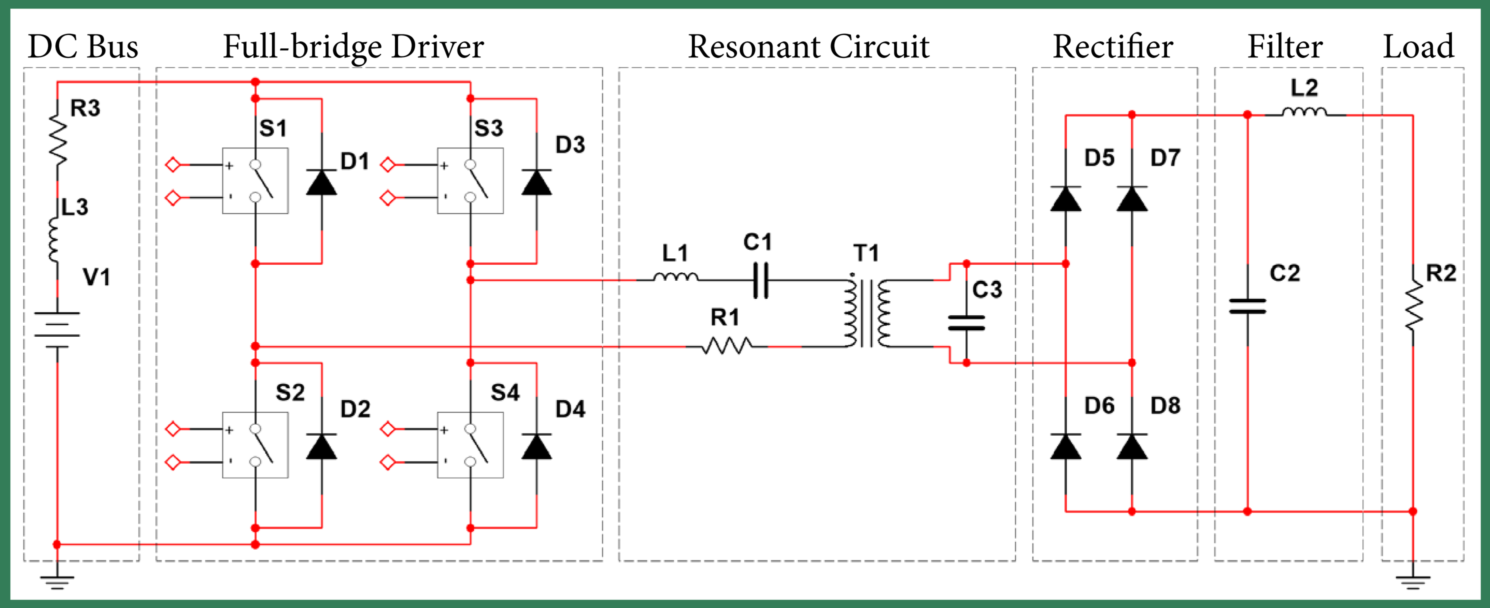
Neutral Beam Modulation

Neutral beam modulation experiments have been conducted at TEXTOR, MAST, and DIII-D. At TEXTOR, the NBI system apperature was modulated, while MAST modulated the current source. Recently, DIII-D published results modulating the grid voltage (slew 20 kV/s). The effects included beam torquing, instability supression, increased ion confinement time and improbed control of fast ion losses. This new EHT NBI power system can be used to modulate the NBI voltages on even faster timescales.

- Pace, et al. "Control of power, torque, and instability drive using in-shot variable neutral beam energy in tokamaks" Nucl. Fusion 57 (2017) 01400
- Pawley, et al. "Advanced control of neutral beam injected power in DIII-D," Fusion Eng. Des. (2017)

Circuit Modeling

EHT conducted initially SPICE modeling to optimize the system efficiency, resonant components, switching frequency, and output stages. Modeling was used to identify potential fault conditions in the event that the grids short. The grid driver must be shut off within 3 µs of the grid fault.

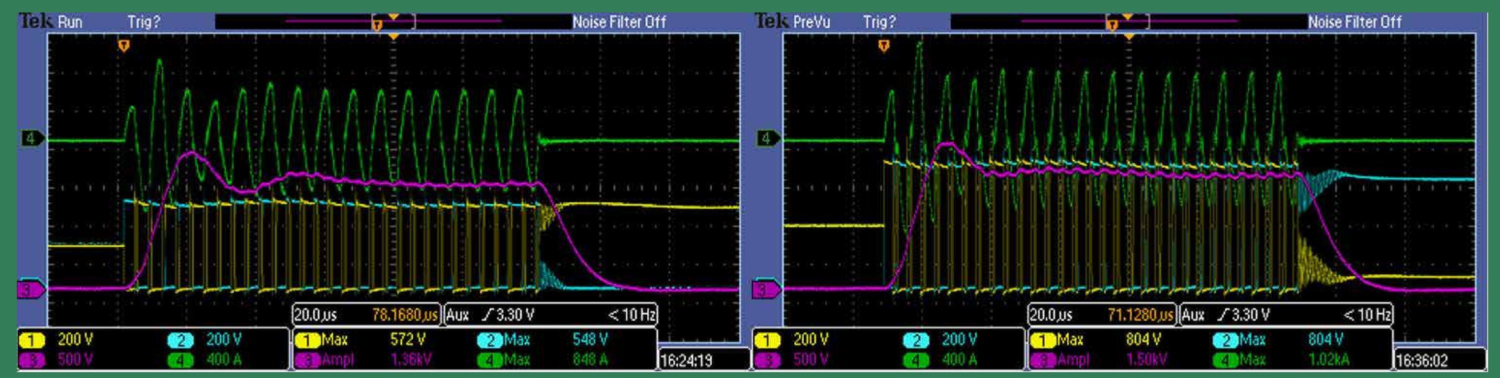


Simplified Multisim circuit model.

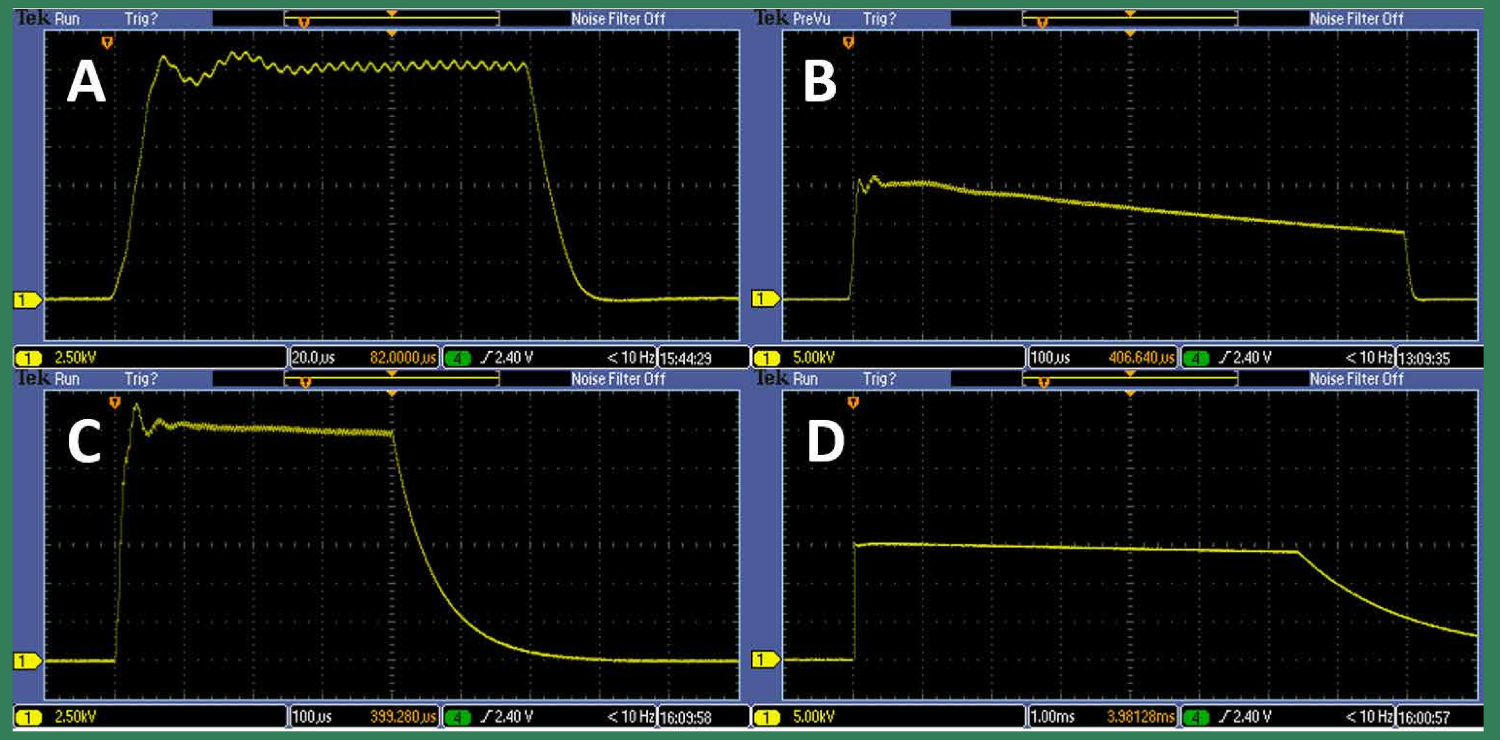
Testing at EHT Facility

EHT conducted initial short-duration testing of NBI power system into a dummy load at the EHT facility with output modulation. The two different images have different charge voltages and different duty cycle in order to achieve the same output voltage. It can be seen that the lower duty cycle (right image) results in a more triangular circulating current profile and as expected this produces greater ripple on the output.

The first two waveforms (A and B) are with the nominal 375 Ω dummy load. The droop in shot B is quite severe and is a function of our limited energy storage. Shot C is a 400 µs shot into a 4.4 kΩ dummy load. Shot D is 7.5 ms into a 100 kΩ load. The rise time to full output voltage was between 10-20 µs and is dependent on the inductance to the load.



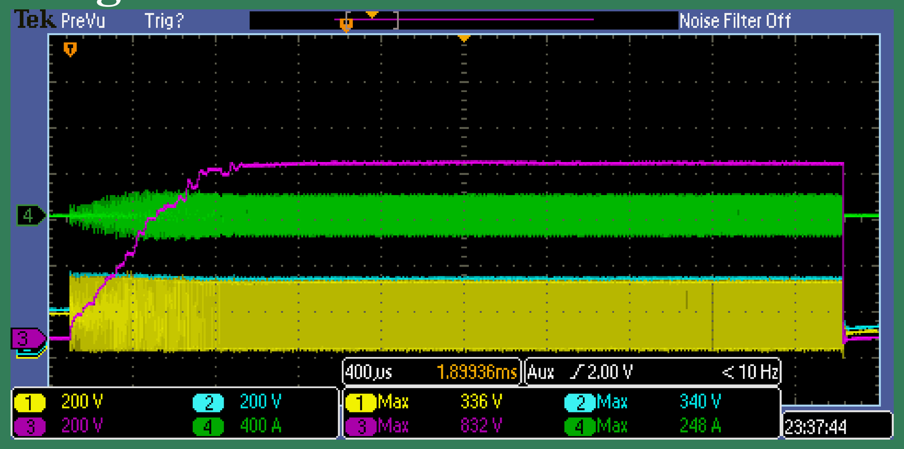
Characteristic waveforms showing 10 kV output into 375 Ω. Left is a shot with a charge voltage of 450 V and a duty cycle of 75% and right has an increased charge voltage of 650 V and a lowered duty cycle of 60%. Ch1 and 2 (yellow and blue) are the voltages across the switch. Ch 3 (magenta) is the output voltage measured by a 1:7 voltage divider. Ch 4 (green) is the circulating current out of the SPAs.



15 kV pulses with varying shot lengths and loads. A: 375 Ω and 120 µs, B: 375 Ω and 800 µs, C: 4.4 kΩ and 400 µs, D: 100 kΩ and 7.5 ms.

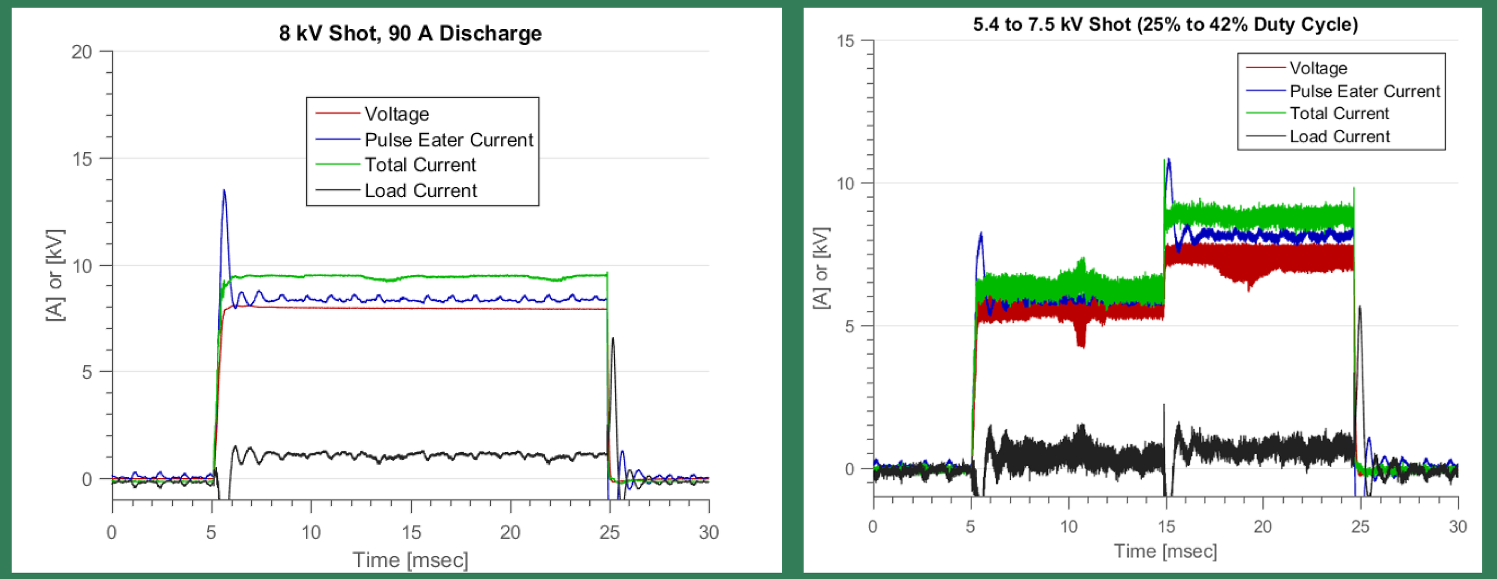
Long Duration Resistor Testing

EHT tested the NBI driver with a large capacitor bank into a dummy load at a user facility. The figure shows a 10 kV, 20 ms pulse (purple, 1:11 divider). Ch1(yellow) and ch2 (blue) are the voltage across the switch and ch4 (green) is the circulating current.



Testing at User Facility

EHT tested the NBI driver at a fusion science experiment with a large capacitor bank into NBI grid system. The system was tested with constant output voltage and voltage modulation. The output of the EHT NBI driver had a slew rate of 0.5 kV/µs, which is significantly faster than other experiments.



Operation with neutral beam grids Left: 8 kV shot showing ~1 A of beam current through the acceleration grid. Right: Dynamic control of voltage output of the NBI system at the user's facility during plasma shots (right).

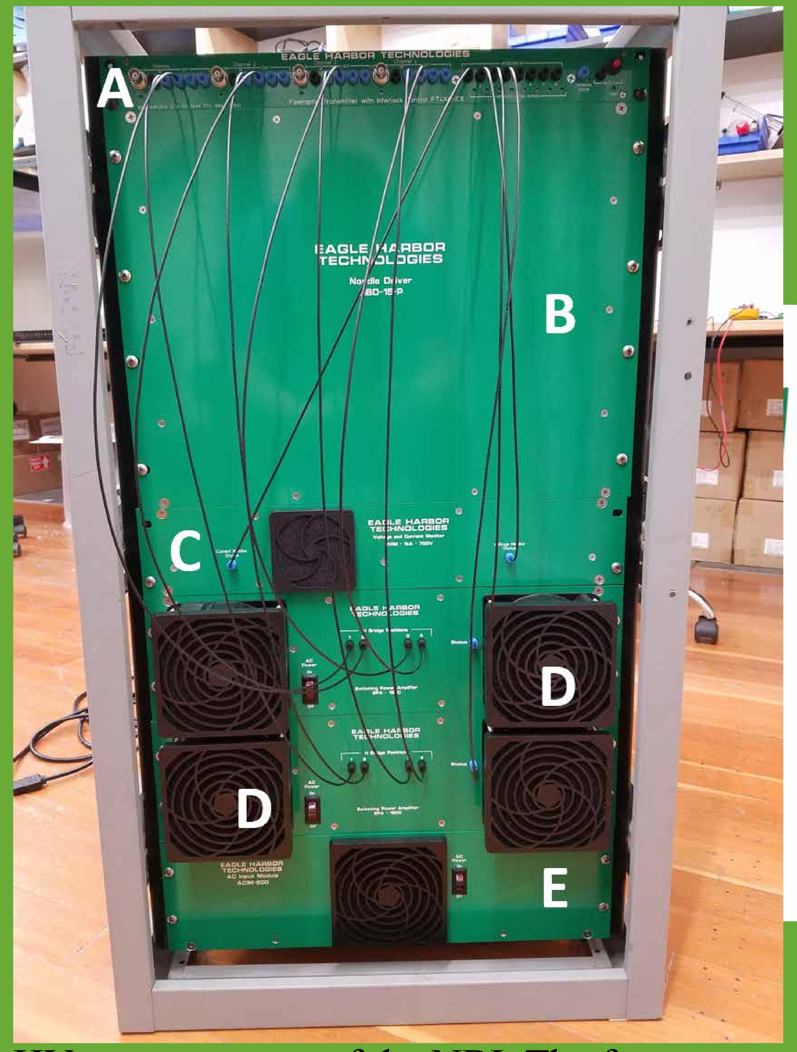
Conclusion

EHT has built an neutral beam grid power system with the following specs.

- Charge Voltage: 0 – 700 V
- Output Voltage: 0 – 15 kV
- Output Current: 0 – 40 A
- Switch Frequency: 125 kHz
- Pulse Width: 8 µs – 100 ms
- Shot Frequency: 1/min
- Control: External Fiber
- Short Tolerant: Overcurrent requires shut down in 3 µs

EHT is currently seeking funding for the next generation system that could be tested at the Lithium Tokamak Experiment.

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



HV power system of the NBI. The front panels of A: FT4x4, B: step-up output module, C: HVIM fault monitor, D: two SPAs running in parallel, and E: the ACIM.

Acknowledgment

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