Phase I Summary: Neutral Beam Injector Grid Power System

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

EAGLE HARBOR TECHNOLOGIES

Introduction

Neutral beam injection (NBI) is important in fusion science experiments for plasma heating, current drive and diagnostics. Currently, there limited vendors for these systems, and there are no vendors in the United States, which is a potential challenge for the development of private fusion for defense applications. Eagle Harbor Technologies (EHT), Inc. has completed a Phase I program to develop a new power system for NBI that utilizes the state of the art in solid-state switching. EHT has developed a resonant converter that can be scaled to the power levels required for NBI at small-scale validation platform experiments like the Lithium Tokamak Experiment at Princeton Plasma Physics Laboratory. This power system can be used to modulate the NBI voltages over the course of a plasma shot, which can lead to improved control over the plasma. EHT will present initial modeling used to design this system as well as experimental data showing power system operation at 15 kV and 40 A for 10 ms into a test load. Additionally, testing results from a neutral beam system will also be presented.

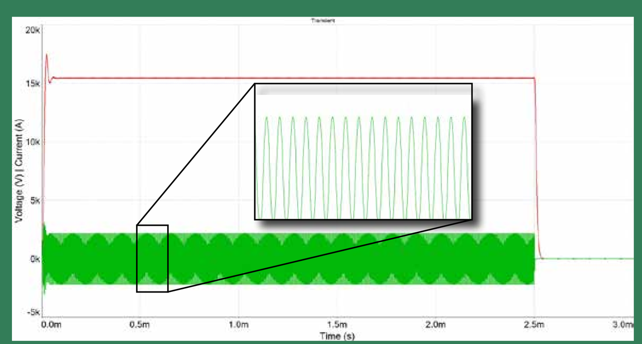
Neutral Beam Modulation

Neutral beam modulation experiments have been conducted at TEXTOR, MAST, and DIII-D. At TEXTOR, the NBI system aperture 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 suppression, increased ion confinement time and improved control of fast ion losses. This new EHT NBI power system can be used to modulate the NBI voltages on even faster timescales.

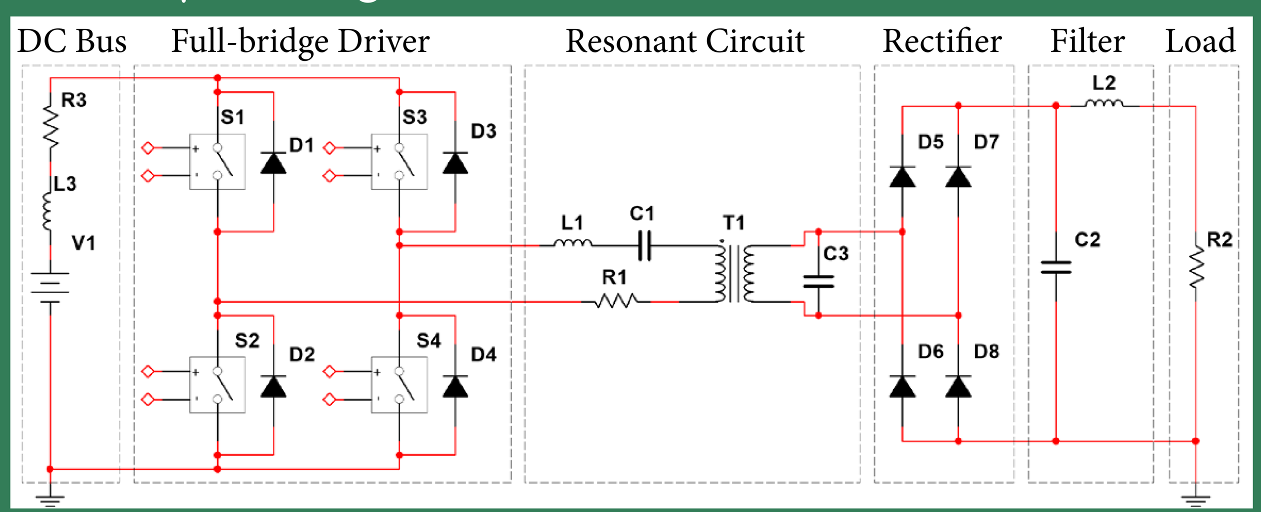
- Pace, et al. "Control of power, torque, and instability drive using in-shot variable neutral beam energy in tokamaks" Nucl. Fusion 57 (2017) 01400
- Pawley, et al. "Advanced control of neutral beam injected power in DIII-D," Fusion Eng. Des. (2017)

Circuit Modeling

EHT conducted initially circuit modeling using National Instruments Multisim 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.



Left: Load voltage (red) and oscillating current (green) during normal operation. Initial voltage spike can be eliminated by lowering the switching duty cycle during startup.

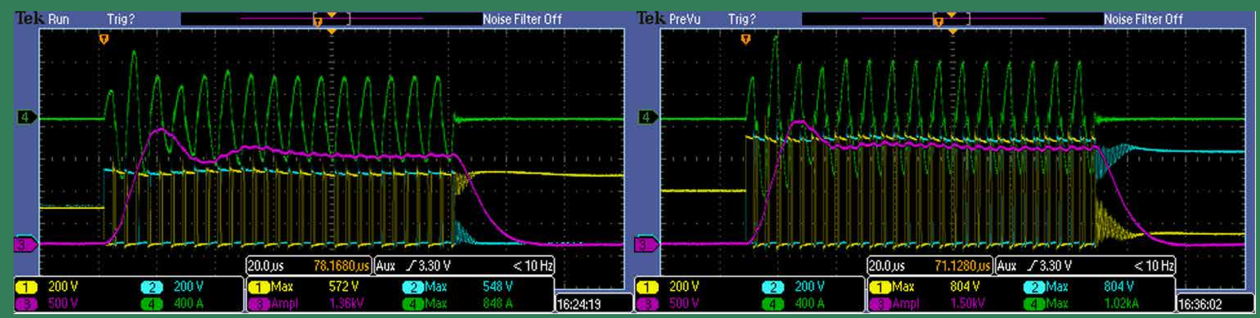


Simplified Multisim circuit model.

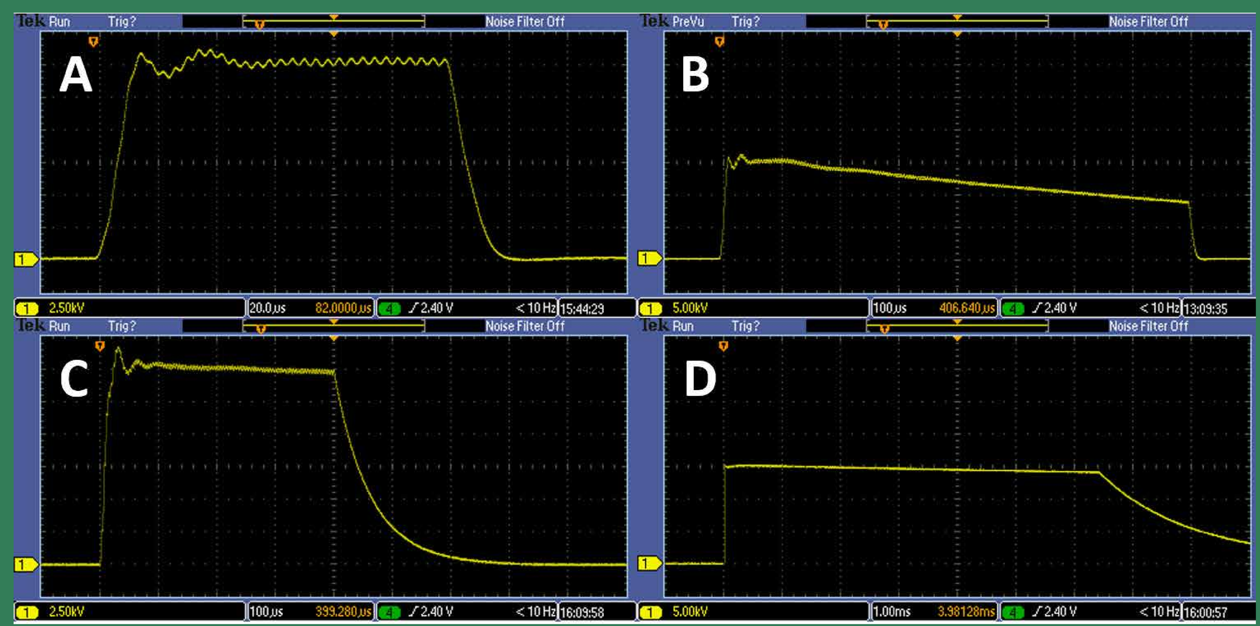
Testing at EHT Facility

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.



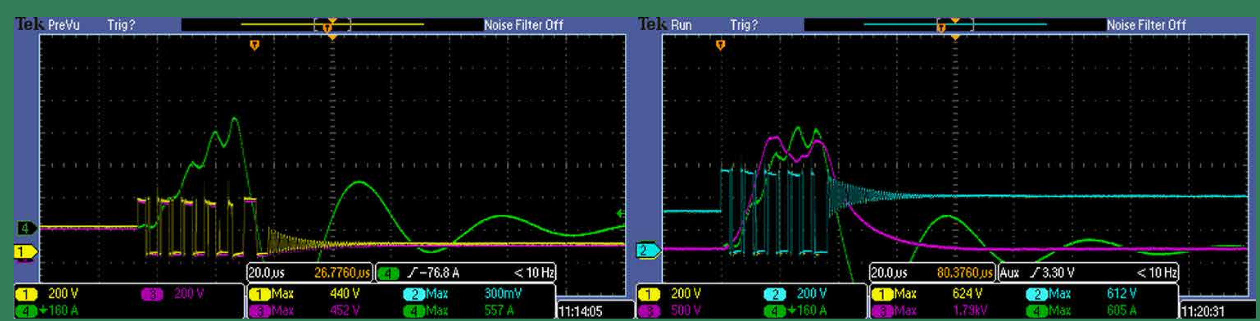
Characteristic waveforms showing 10 kV output into 375 Ω. Left is a shot with a charge voltage of 450 V and a duty cycle of 75% and right has an increased charge voltage of 650 V and a lowered duty cycle of 60%. Ch1 and 2 (yellow and blue) are the voltages across the switch. Ch 3 (magenta) is the output 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.

Overcurrent Monitor Testing

EHT demonstrated overcurrent monitoring, which will protect the NBI supply in the event of an arc between grids.



Overcurrent trip resulting in the HVIM and interlock of the FT4x4 to shut down the supply quickly to mitigate any damage that may occur. Left: NBI supply shorted. Right: 100 Ω load. Ch1 (yellow) and ch2 (blue) voltage across the switches, ch3 (magenta) output voltage, ch4 (green) output current of the NBI supply.

Acknowledgment

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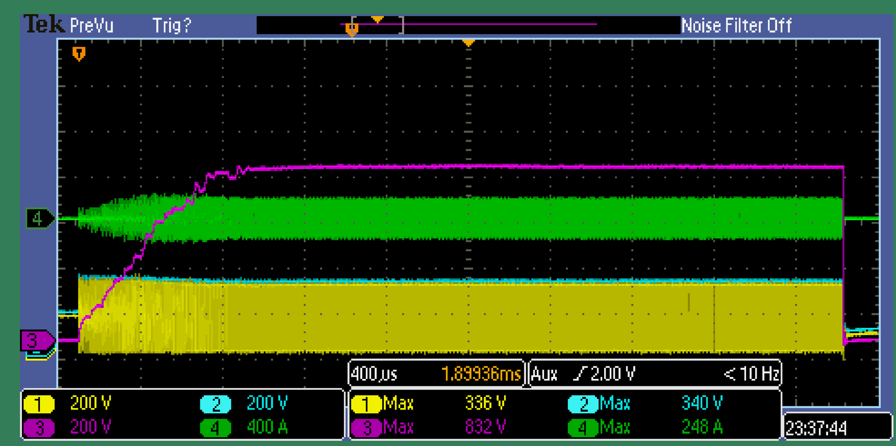
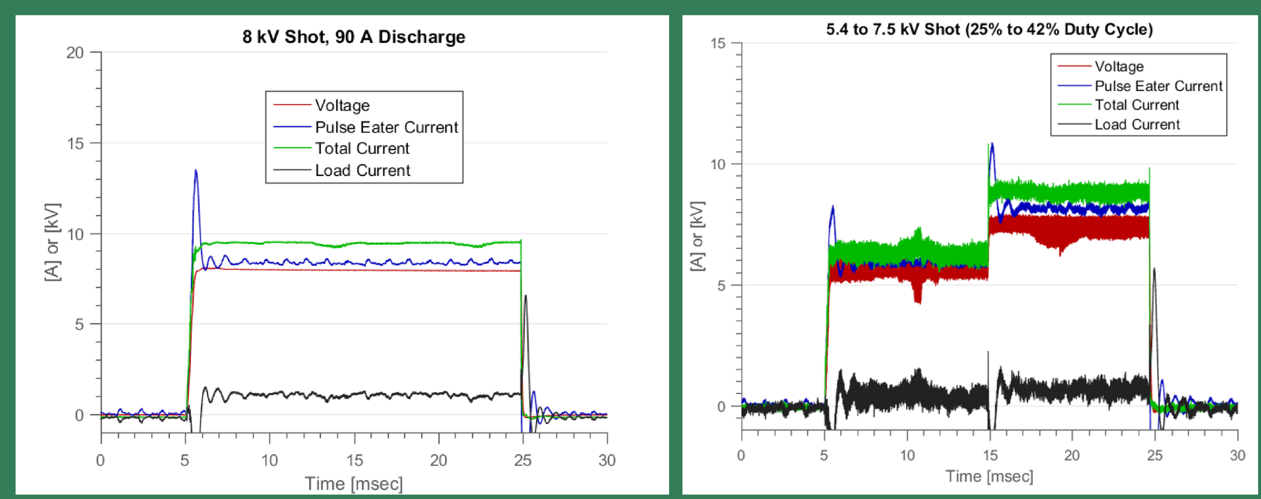
Testing at User Facility

EHT tested the NBI driver at a fusion science experiment with a large capacitor bank into both a dummy load and 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.



Long duration testing with dummy load. 20 ms pulse with 10 kV output (purple, 1:11 divider). Ch1(yellow) and ch2 (blue) are the voltage across the switch and ch4 (green) is the circulating current.

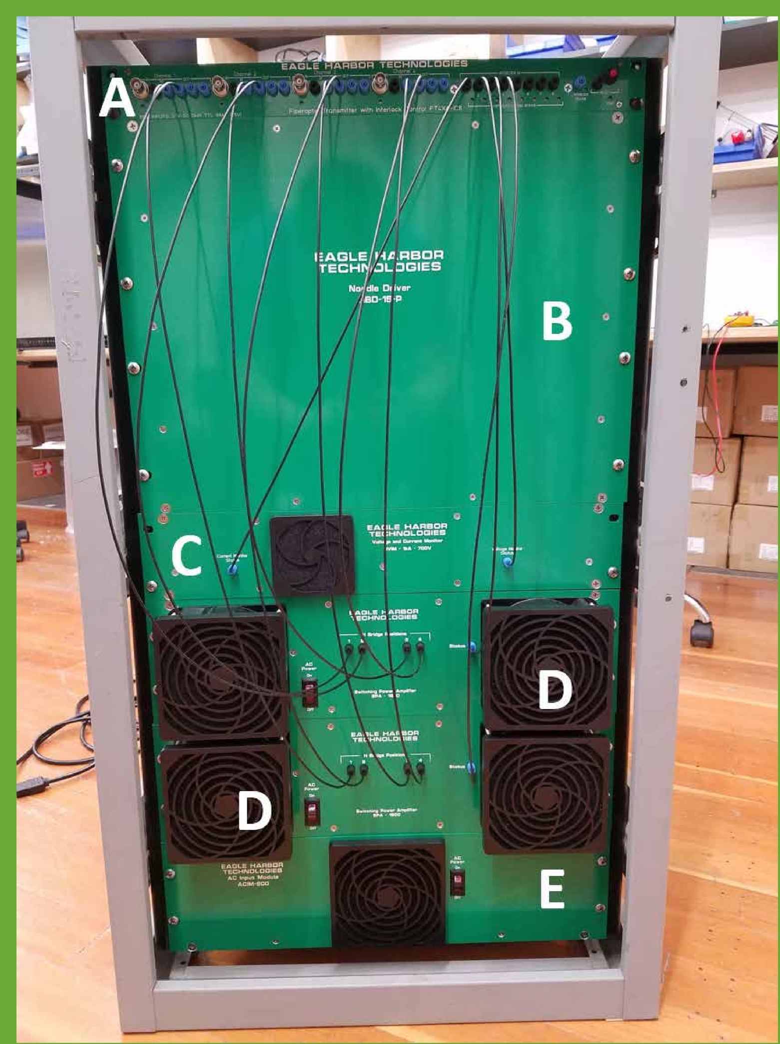


Operation with neutral beam grids Left: 8 kV shot showing ~1 A of beam current through the acceleration grid. Right: Dynamic control of voltage output of the NBI system at the user's facility during plasma shots (right)..

Conclusion

EHT has built an initial 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



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.

Future work includes increasing the output voltage to over 20 kV and measuring the efficiency.

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