

## NLC HYBRID SOLID STATE INDUCTION MODULATOR\*

R.L. Cassel, J.E. deLamare, M.N. Nguyen, G.C. Pappas @SLAC,  
E. Cook, J. Sullivan @ LLNL, C. Brooksby @ Bechtell Nevada

### Abstract

The Next Linear Collider accelerator proposal at SLAC requires a high efficiency, highly reliable, and low cost pulsed power modulator to drive the X band klystrons. The original NLC envisions a solid-state induction modulator design to drive up to 8 klystrons to 500kV for 3 $\mu$ s at 120 PPS with one modulator delivering greater than 1,000-megawatt pulse, at 500kW average. A change in RF compression techniques resulted in only two klystrons needed pulsing per modulator at a reduced pulse width of 1.6 $\mu$ s or approximately 250 megawatts of the pulsed power and 80kW of average powers. A prototype Design for Manufacturability (DFM) 8-pack modulator was under construction at the time of the change, so a redirection of modulator design was in order. To utilities the equipment, which had already be fabricated, a hybrid modulator was designed and constructed using the DFM induction modulator parts and a conventional pulse transformer. The construction and performance of this hybrid two-klystron Induction modulator will be discussed. In addition the next generation DFM induction modulator utilizing a ten-turn secondary and fractional turn primary transformer well be presented.

### PROTOTYPE MODULATOR

The prototype Solid State induction modulator for the NLC Klystron was original designed to drive eight X-band klystron in parallel requiring 500kV 2000A pulses for 3.2 $\mu$ s flat top at 120 PPS. [1] [2] The prototype was fabricated and tested in a water load to 500kV and into two 5045 klystron up to 420kV. The NLC program for the RF testing was modified requiring a change in the modulator to operate only four XL4 klystron at 400kV, 1300 Amps, 1.6 $\mu$ s flat top at 60Hz. (See figure 1)



Figure 1: "8-pack" Solid State modulator installation.

To better match the operating condition of the klystron the two parallel drivers were reduced to one driver operating at 2kV at 3600A.

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The stray capacitance to ground of the XL4 klystrons, was twice that of the X-band klystron resulting in a voltage overshoot of greater than 20%. This overshoot was eliminated by delaying the turning on of 18 of the 76 driver cells. (See figure 2)

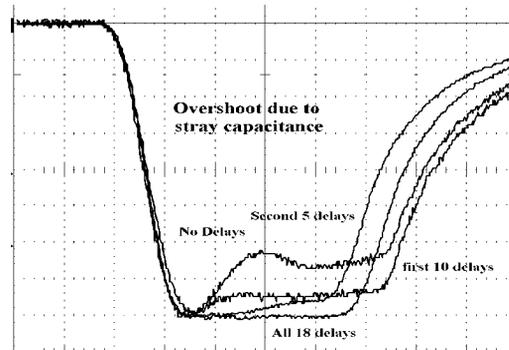


Figure 2: Overshoot correction by delaying triggers.

Delaying eliminated the overshoot without compromising the rise time and adjusted the flat top to a flatness of < 0.5%. (See figure 3)

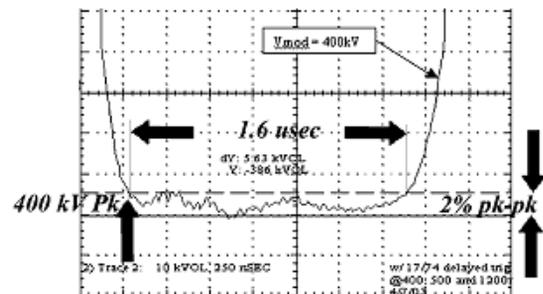


Figure 3: Pulse flat top regulation.

The prototype solid-state modulator has been operating at 60 Hz 24 hours a day for months >600hr with a minimum of intervention. Even with more than a thousand interruptions of operation for RF vacuum faults the modulator continues to operate.

### Klystron Arcs

There were numerous (>15) klystrons arc at different points along the flat top pulse with no discernable effect on either klystron of modulator. (See Figure 4) The klystron and modulator resumed operation after the klystron arcs with no klystron damage. From the measurements of the klystron arcs, it is clear that the joules and coulombs under which a klystron can recover from are considerably higher than previously predicted.

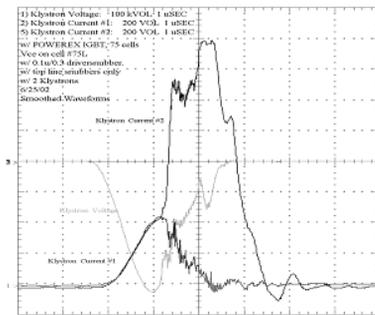


Figure 4: Klystron fault with induction modulator.

The prototype NLC solid-state induction modulator has proven itself an effective way to make a very high power pulsed modulator.

**DFM1 HYBRID MODULATOR**

The next stage in the Solid State induction modulator program was the development of a “Design for Manufacturability” (DFM) modulator. The ordinal design was for a modulator to drive 8 X-band PPM klystrons from one modulator to match the expected RF compression technique. The modulator had a three turn secondary with 46 cores using the available 6.5kV IGBT to deliver 500kV, 2000A, 3.2µS pulses.

*DFM Cores*

Each of the new DFM Metglas® cores was designed to support a 4kV pulse for 4.5µS with a one-turn primary. The cores were enclosed in a single turn stainless steel jacket, which serves as the electrical turn as well as holding the cores in place while allowing oil to flow pasted the core to prove the cooling. Two cores were used with an insulator between the cores to provide for the pulse voltage insulation. A outer cast aluminum case served to complete the grounded side of the single turn, supported the cores, and provided the oil seal. (See Figure 5) This outer casing has penetration for the electrical connection to a single turn in three locations. Two of the insulated connections are for the two IGBT driver and one for a bypass diode, used to carry the pulsed current if the IGBT drivers are delayed on turn on.

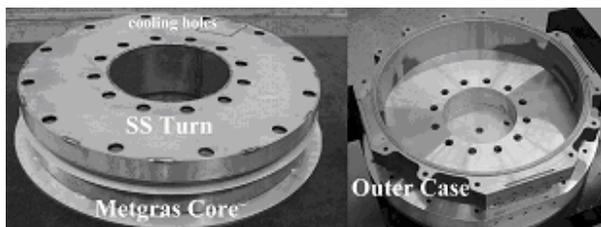


Figure 5: DFM Cores and outer Case.

*DFM Drivers*

The IGBT driver utilized two 37µfd 4.3kV pulsed capacitors in parallel. The capacitors are in series with a 6.5kV 600 Amp IGBT with specially design gate drive. The capacitors are change from an external source by way of a capacitor charging diode network with safety shorting

relay. The driver is a plug in, strip line PC, board with the heat sink for the IGBT bolted to the outer core casing for support and cooling from the core oil cooling system. (See figure 6)

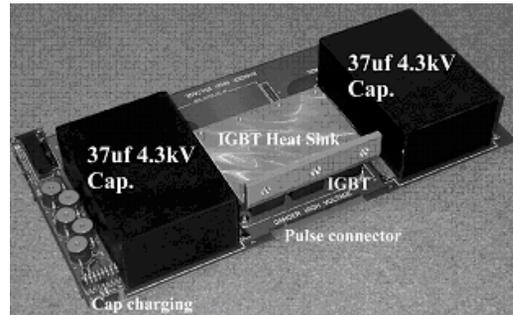


Figure 6: IGBT Driver Boards.

*DFM1 Hybrid Modulator*

The cores, cases and drivers were design and were in fabrication for the 8 klystron DFM modulator when the RF compression technique use to drive the accelerator structure was revised, reducing the modulator requirements to drive only 2 klystrons for 1.6µS.

A three turn secondary induction modulator is not economically the right design for driving 2 klystrons. A 10 to 12 Turn secondary winding is a better match to 2 klystron operation. With cores and cases already fabricated and not suitable for so many secondary turns the program was redirected into two parts

First, the DFM1 Hybrid modulator utilizing DFM fabricated parts with a single secondary turn driving a conventional 10 to 1 turn’s ratio pulse transformer, and second the DFM2 fractional turn modulator in which the secondary has 10 turns and the primary 15 cores with single turns or a 150/1 turns ratio transformer.

The DFM1 utilized 15 of the DFM cores and 30 drivers with a single secondary turn. The core and IGBT’s drivers were design to produce a 4kv 3.2µS pulse at 3kA per driver. With 15 cores and 30 drivers, the single turn primary could develop ~60kV at 6kA. With a 10 to 1 pulse transformer, the output could produce ~600kV at 600A maximum. . (See figure 7)

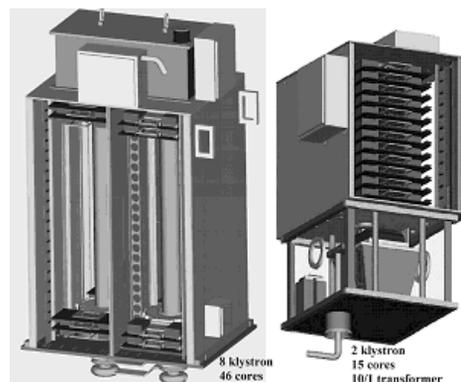


Figure 7: DFM and DFM1 Modulators.

### DFM1 Installation and Testing

The DFM1 was fabricated and installed on the prototype test stand and is under test into a 1kohm water load. The current balance, thermal properties and pulse performance were measured. (See Figure 8)

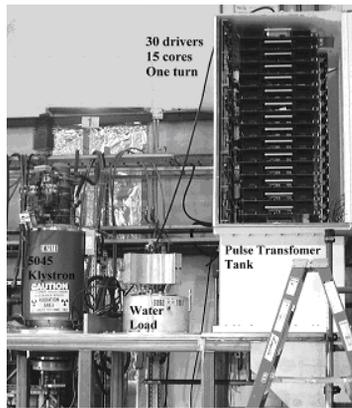


Figure 8: IGBT Driver Boards.

The use of an additional conventional designed pulse transformer, not only introduces more series inductance limiting the rise time of the voltage, but also the stray capacitance. As in the prototype modulator, the additional capacitance results in an overshoot of voltage. Delaying the turn on of 4 of the 15 cells corrects for the overshoot in voltage. The water load was driven to 500kV, 500A 1.6µS at 120Hz. (See figure 9)

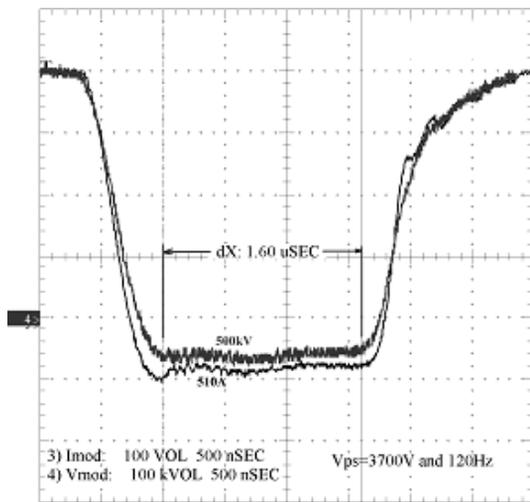


Figure 9: Waveform of DFM1 Modulators water load.

As expected the power loss and efficiency of the Hybrid modulator is not as low as would be desired ~65% It did should that the Hybrid design is a practical design.

### DFM2 MODULATOR

#### DFM2 Conceptual Design

The hybrid modulator, although it works, is not an optimal design for driving one or two klystrons, There are two transformers in series one for the induction one turn core and the second conventional pulse transformer which increase the cost weight, and limits the rise time of the pulse. It is much preferred to combine the two transformer into one transformer. This is done be increasing the core

size to accept a more conventional multi turn pulse transformer windings. (See figure 10)

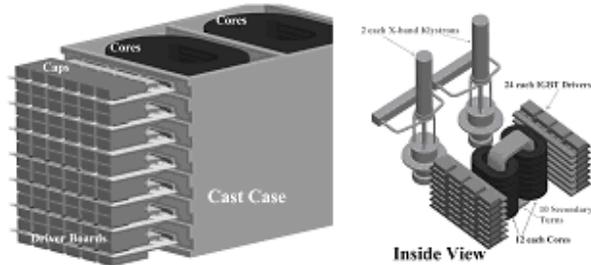


Figure 10: DFM2 conceptual design.

#### DFM2 IGBT Exploration

The present 6.5kV 600A IGBT modules require sophisticated gate drivers to allow for the fast turn on and protection against klystron arcs and insulation flashovers, due to the modules internal structure. As part of the DFM2 design we are exploring the used of smaller IGBT modules with integrated gate drives. A two chip IGBT package with integrated gate drives appears to work will reducing the protection problems. (See figure 11)



Figure 11: IGBT with gate drive 6.5kV.

### SUMMARY

The prototype solid-state induction modulator and DFM1 have demonstrated that the solid-state fractional turn approach to modulator is workable. They have the ability to controls the wave shape, pulse width and clear faults. In order to deduce the cost and increase the performance for a two-klystron driver a fractional turn primary multiple turn secondary DFM2 appears to have a better performance and reduce cost.

### REFERENCES

- [1] A solid state induction modulator for SLAC NLC Cassel, R.L.; Pappas, G.C.; Nguyen, M.N.; DeLamare, J.E.; Particle Accelerator Conference, 1999. Proceedings of the 1999 ,Volume: 3 , 27 arch-2 April 1999 Pages:1494 - 1496 vol.3
- [2] Three turn secondary for the prototype SLAC solid state induction modulator Cassel, R.L.; deLamare, J.E.; Nguyen, M.N.; Pappas, G.C.; Cook, E.; Sullivan, J.; Brooksby, C.; Power Modulator Symposium, 2002 and 2002 High-Voltage Workshop. Conference Record of the Twenty-Fifth International , 30 June-3 July 2002