Solid State Induction Modulator Replacement for the Conventional SLAC 5045 Klystron Modulator

R.L. Cassel, J.E. Delamare, M.N. Nguyen, G.C. Pappas, SLAC*
Stanford Linear Accelerator Center

Abstract

The Next Linear Collider accelerator is developing a high efficiency, highly reliable, and low cost pulsed-power modulator to drive the NLC 500KV, 230A X band klystrons. To demonstrate the feasibility and effectiveness of the proposed induction modulator, a 10 section Solid State Induction Modulator has been assembled to drive a single 5045 klystrons in the SLAC linac. The Induction Modulator replaces the existing modulators PFN/thyratron and drives the klystron using its existing conventional pulse transformer. The status of the proposed thousand-megawatt NLC Solid State induction modulator will be discussed, and the results of the 5045 klystron modulator test.

1.0 Modulator Design consideration

The Next Linear Collider accelerator proposal at SLAC has selected the Solid State Induction Modulator approach for its X band klystrons because of its high efficiency, highly reliable, and low cost. The major difficulty with the conventional PFN type modulator use at SLAC for the Next Linear Collider (NLC) is the efficiency of the modulator for short pulse operation. The leakage inductance for the pulse transformer and the stray inductance of the switching circuit inherently limit the rise and fall time of the klystron voltage waveform. To reach the efficiency goals of > 75% for the modulator for the NLC it is necessary to have a rise and fall time of the klystron voltage pulse of less than 200 nsec. It is extremely difficult to obtain a fast rise time and high efficiency with a PFN modulator.

1.1 NLC modulator program

The NLC solid state induction modulator R&D program is divided into three Stages.

1) A model using 10 cores and a standard pulse transformer to drive a SLAC 5045 klystron, which is discussed in this paper.
2) Full modulator core stacks of 76 cores with one turn secondary to drive water load to one-third voltage.
3) Full core stack 80 cores with three turns to drive full 500 kV into water load and then full current into 4 each 5045 klystrons at full repetition rate for a full load testing.

1.2 Proposed Modulator

The modulator topology selected for the NLC modulator is similar to an induction accelerator. It consists of a large number of single turn induction cores each driven by its own solid state switch. Due to the inherent low inductance of such a structure the secondary will have three turns. The resulting total leakage inductance at the secondary is extremely low (<20 μhy). The major part of the leakage induction is in the multiple primary side connections and drivers.

To obtain 500 kV for 3 usec (1.5 volt seconds per turns) with a transformer, a three turns secondary required a large magnetic core cross sectional area. The cores selected are metglas 2605SA1. With the cores pulsed reset; each core is operated at 0.0065 volt-seconds with a saturation level of 0.008 volt-seconds. To drive the core without using a matched PFN requires a switch that can not only turn on fast at high power levels but also turn off. Switching devices now exist in the form of IGBT (Isolated Gate Bipolar Transistors). IGBT are now available from several manufactures which can switch on and off with a dI/dT of >15,000 Amps per microsecond to power levels of >6 megawatts per device. Higher voltage devices capable of switch > 10 megawatts are under development. The use of three turn secondary fractional turn transformer combined with two high current IGBT allows for the driving of 8 klystrons with one modulator or approximately 1000 megawatts of power for 3 μsec see Figure 1.

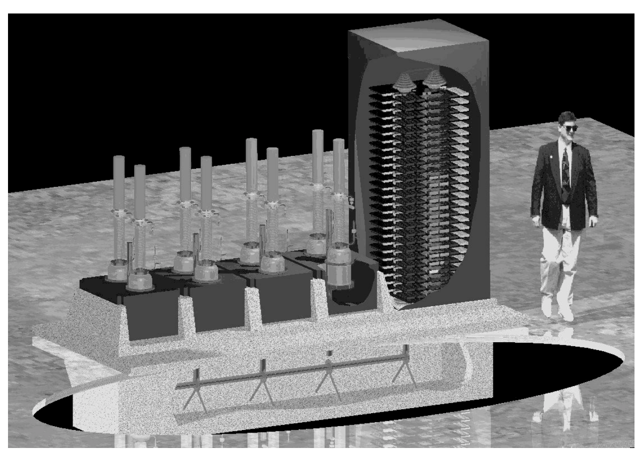

Figure 1. Induction Modulator Artistic Rendition

1.3 Induction Modulator Specification

• Number of NLC klystron	8 EACH
• Operating pulse voltage	500 kV
• Operating pulsed current	2120 AMPS
• Repetition rate	120 Hz
• Voltage regulation flat top‘	<±1.0 %
• Rise /Fall time	<200 ηsec
• Pulse duration flat top	3.0 μsec
• Energy Efficiency	>75%
• Number of secondary turns	3
• Number of fractional turns	80
• Number of core stacks	2
• Voltage per core	2.2 kV
• Current per core	2.3 kA
• Total leakage inductance	<20μH
• Secondary stray capacitance	<400 ρF

1.4 Transformer design

The induction transformer consists of 80 individual AlliedSignal 2605SA1 Metglas core wound and insulated by National-Arnold Magnetics and epoxy impregnated by Stangenes Industries into a aluminium case design and fabricated by SLAC’s Collaborators at LNL & Bechtel Nevada. The case has and inside diameter of 6.5” and an overall height of 2.13”. Each core case has O-ring groves to allow for an oil seal when the cores are stacks. Each of the cores can be operated at 2.2 kV for 3 μSec. or 0.0066 volt-Seconds with a loss of less than 0.6 Joules per pulse or 72 watts at 120 PPS. A water-cooling coil internal to the case will maintain the core temperature to less than 45 degrees C (Figure 2).

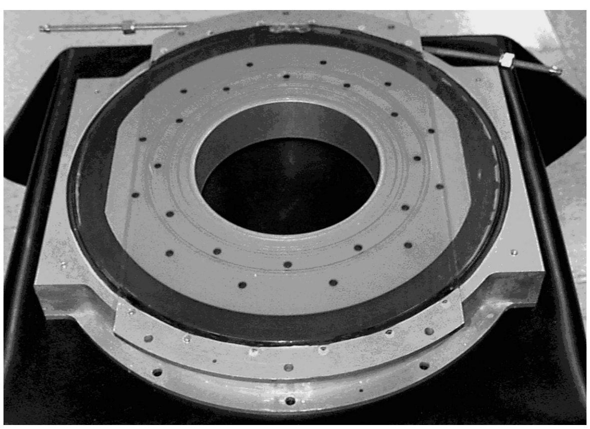

Figure 2. Metglas Core in case

1.5 Solid State Drive

The Core driver is simple consisting of a IGBT, a DC charge capacitor in series with the IGBT driving the individual magnetic core. A capacitor with fast diode is used across the core to absorb the reflected energy from stray inductance under normal and fault conditions as well as the current if the one of IGBT is turned on later or off earlier then the other IGBTs. A pulse reset of the core is used to insure that the core is totally reset before the next pulse. The energy storage capacitor is charged through the transformer core. Figure 3.

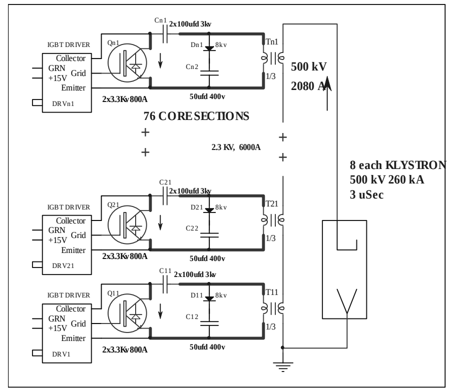

Figure 3. IGBT Drive circuit

We have tested several different IGBTs for turn on and turn off characteristics. The EUPEC FZ800R33KF1 was chosen because it has the he best turn on and turn off times. Figure 4.

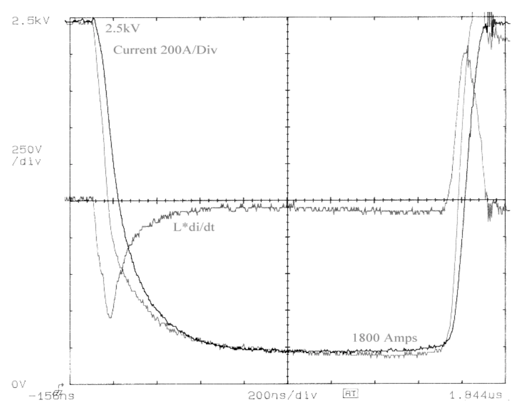

Figure 4. EUPEC FZ800R33KF1 Pulse

The modulator consists of two driver boards with one 3.3 kV IGBT per board. The driver boards are PC Board in air and arranged so that they can be plugged into the transformer core with the IGBT cooled by the core case or easy replacement. Figure 5.

Figure 5. PC Board Core Driver circuit

1.6 Model of Induction modulator

To obtain early experience with the solid state induction modulator driving a klystron load, a model program has be developed to utilise the Induction modulator to drive one of the existing SLAC 5045 Klystrons. A stack of 10 each modulator cores driving and the existing 5045 klystron 15/1 pulse transformer would allow early testing of the induction modulator design concept. Operation the 10 core stack at 20kv and 4400 amps well drive the Klystron to 288 kV 315 A. Figure 7, Figure 8.

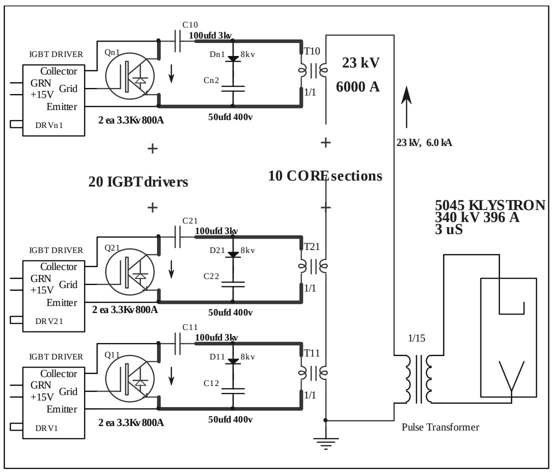

Figure 7. Model Modulator Schematic

1.7 Model Induction Modulator Specification

- Number of 5045 Klystrons — 1each
- Operating pulsed voltage — 340 kV
- Operating Pulsed Current — 400 Amps
- Repetition rate — 120 Hz
- Pulse duration flat top — 3.0 µsec
- Number of secondary turns — 1
- Number of fractional turns — 10
- Number of IGBT drivers — 20

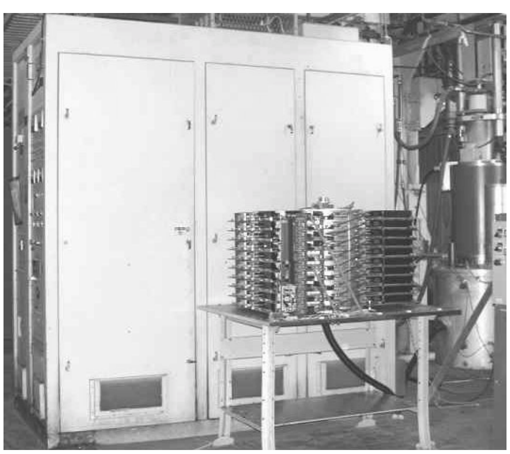

Figure 8. Table Top Induction Modulator

The model has operated to demonstrated that the concept was workable Preliminary results are shown in Figure 9.

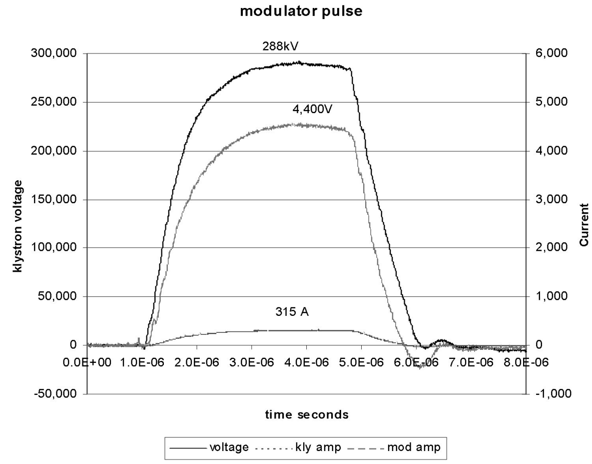

Figure 9. Model Preliminary Waveform

Testing of the model modulator have just started at low repetition rate. The rise time is dominated by the pulse transformer and long cable to the klystron. The pulse length is determined by the voltage seconds of the core stack.

1.8 Induction modulator additional advantages

There are several addition advantages of the Solid State induction modulator over the conventional modulator. All of the very high voltage parts of the modulator are inside the transformer core. The core drivers are at ground potential with only the IGBT collector and capacitor at moderate voltages of 2 to 4 kV. The addition of more driver cells then are required, results in redundancy so that an individual driver or core could fault without effecting the overall operation of the modulator. The pulse duration is only determined by the volt-seconds in the core so that a shorter pulse can be obtained by timing for conditioning of the klystron/accelerator or if operated at a lower voltage a longer pulse is available. Although there is a high number count of parts the overall availability and maintainability should be much higher than a PFN with thyratron

1.9 Conclusions

The ten-stack model of the induction modulator address's many of the issues of the full NLC solid state induction modulator when operated into a klystron load. The model will test the performance of the modulator under klystron non-linear load conditions including fault protection under klystron arc condition.
The modulator is a collaboration of SLAC, LLNL and Bechtel Nevada to produce a fully functional modulator.

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