

# Solid-State Modulators For The International Linear Collider\*

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**Abstract-**This paper describes DTI's ongoing development of solid-state, transformerless modulators for the International Linear Collider (ILC), including Marx Bank (Figure 1) and hard switch (Figure 7) modulator configurations. As these designs are built and tested, the overall ILC program will be in an excellent position to select a design for construction to minimize the overall ILC life cycle cost.

## I. INTRODUCTION

Funded by the U.S. Department of Energy SBIR program, Diversified Technologies, Inc. (DTI) is developing two solid-state modulator designs for the International Linear Collider (ILC). This paper will discuss design tradeoffs, energy storage requirements and alternatives, and the construction and test status of both modulators.

The ILC klystrons are expected to be similar to the Tesla klystrons, with the final design in the range of 110–150 kV, 120–166 A, and 1.5 ms pulses of  $\pm 0.5\%$  flatness. The defining characteristic of the ILC klystron modulators is the relatively long (1.5 ms) pulse width, which requires 25 kJ delivered every pulse, and the resultant large stored energy required to deliver this energy without significant cathode voltage droop.

## II. COMMON CONSIDERATIONS

Stored energy capacitors are normally a minor design consideration in any of these variants of hard-switch modulators. The brute force approach to any of the three modulator architectures (transformer coupled, Marx, hard switch), however, must use an energy storage bank on the order of 1.5 MJ to keep the droop within a 1% range. DTI's efforts in ILC modulator design have, therefore, been focused on variants of droop correction circuitry – trading off increased modulator complexity against reduction in the size of the energy storage bank. Two architectures, an incrementally correcting Marx switch, and an actively bounced hard switch, appear to be easily configured for such corrections.

For each of these architectures, the goal was to reduce the size of the energy storage bank drastically without materially increasing the cost or complexity of the modulator. A goal of under 100 kJ stored energy was targeted, as an energy storage bank of this size has both cost and volume of the same order as the solid state switch. Hence, further reductions yield diminishing returns. The tenfold reduction in energy storage

will result in a “raw droop” of over 12 kV (10x that acceptable) which must be removed.

The cost (in size, dollars, and reliability) of supplementary systems used to reduce the energy storage bank must be weighed against the benefits. The high voltage solid-state switches for either architecture are extremely robust and well proven in both commercial and military use – a significant dent in this performance is not acceptable.

## III. INCREMENTALLY CORRECTED MARX MODULATOR

A Marx Bank Modulator is an array of capacitors charged in parallel (at low voltage), then switched in series to form a high voltage discharge (Figure 2). This has the advantage of using DC power at a voltage much lower than that delivered to

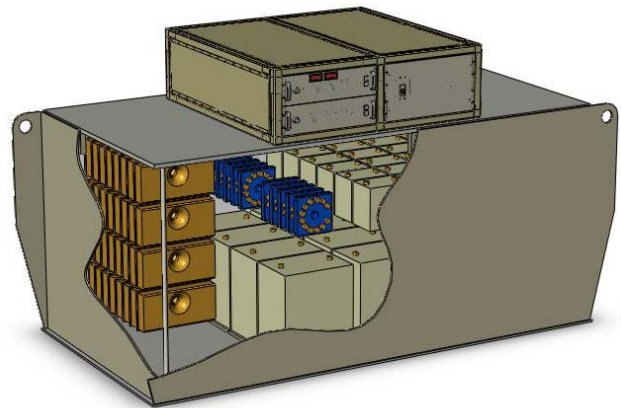


Figure 1. Conceptual drawing of an ILC Marx Modulator, nominally delivering 125 kV, 140 A, 1.5 ms, 5 Hz – from a raw 3-phase 13.8 kV input.

the load. In fact there is no DC present at load voltage anywhere in the system.

A solid state Marx modulator uses IGBTs or FETs which can open under load, thus the capacitor stack becomes a filter/storage bank analogous to that of a solid state hard switch modulator.

The Marx architecture is a convenient way of using devices with intrinsic limits of a few kV to erect very large pulses. Unfortunately, the cost and efficiency of the system suffer if the unit voltage is too low. The repeated overhead at each stage, and the ohmic losses of the higher current recharge,

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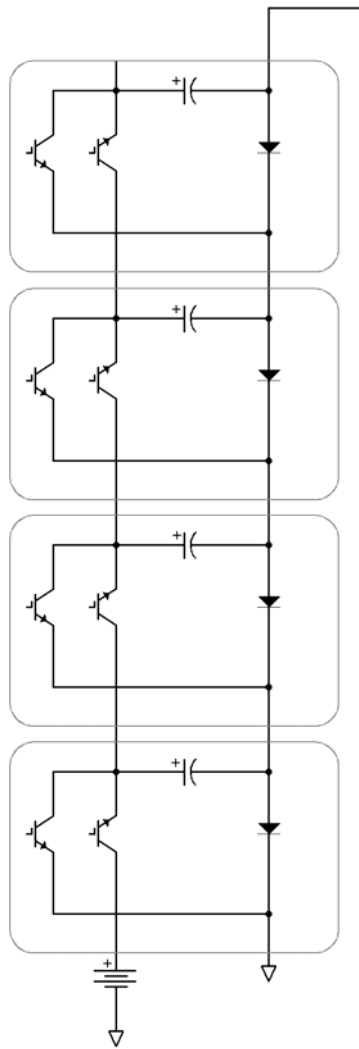


Figure 2. Four-stage solid-state Marx bank modulator (with switched recharge).

make this option unattractive for voltages beyond 40-60 kV. Using DTI's series IGBT technology to assemble single modules of higher unit voltage avoids this issue. This significantly affects the size, number, and complexity of the switching modules, and allows for greater optimization of the complete design.

Recharge of the capacitors in parallel during the interpulse period can be accomplished by one of several means:

- A chain of resistors is the simplest recharge scheme, but is limited to only very low duty cycle and power,
- A diode / inductor network allows average current to recharge while blocking HV discharge during the pulse, but is limited to low duty cycle and short pulse,
- A common-mode choke scheme recharges faster and thus works at higher duty cycle, but is still limited to short pulse,
- A second bank of switches can be used for arbitrary duty cycle and power, but at higher cost and complexity.

Optimizing this configuration for size, cost, and complexity gives an interesting hybrid design – where we have a small number of “core” modules to deliver the base pulse efficiently, and a larger number of “corrector” modules at much lower voltage to finely ratchet the flattop and correct out the droop. (See Figure 3 and Figure 4). The use of the higher voltage core modules allows the recharge current to be kept low, and keeps the capacitor packaging efficient – these modules will be about 7.5 kV each. The corrector modules must have lower voltage authority to correct the droop within the flattop specifications – hence they operate at about 1 kV. Cost modeling confirms our 100 kJ target as being optimal. A smaller bank requires too much correction hardware, while a larger bank is too large and more expensive.

The choice of ~10 kV for prime input power yields one further bonus. By rectifying raw 13.8 kV mains and stepping

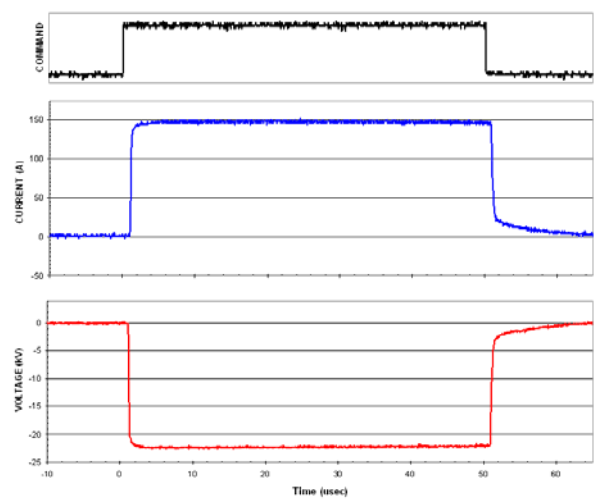


Figure 3. Prototype Marx pulses, with three 7.5 kV Marx modules, delivers a full voltage (21.5 kV) and current (150 A) 50 μsec duration pulse.

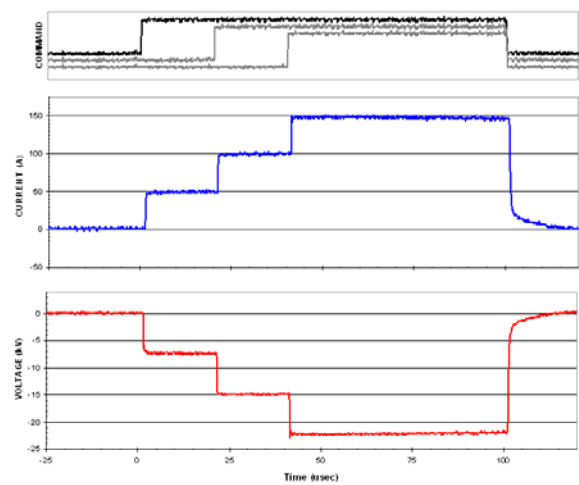


Figure 4. Prototype ILC Marx, using three modules, each precharged to 7.5 kV, is pulsed into a resistor with staggered start delays on the modules, demonstrating the diode bypass for droop correction. Trigger signals are show at the top, I and V are shown in the next two traces.

down to the operating voltage with a solid state buck regulator, we can greatly reduce the cost and size of the DC input section and the need for separate DC power supplies. A second solid-state buck regulator will be used to step down the ~10 kV core voltage to the ~1 kV corrector voltage at the junction between these sections.

Recent efforts at DTI have proven both the Marx operation at full module voltage and current, as well as the ability to control the flattop droop by arbitrarily switching in additional modules.

#### IV. ILC HARD SWITCH

A 150 kV solid-state hard switch design employs an innovative energy storage system. The hard switch represents, in many ways, the simplest modulator design, consisting of only a capacitor and a full-voltage switch. Unfortunately,

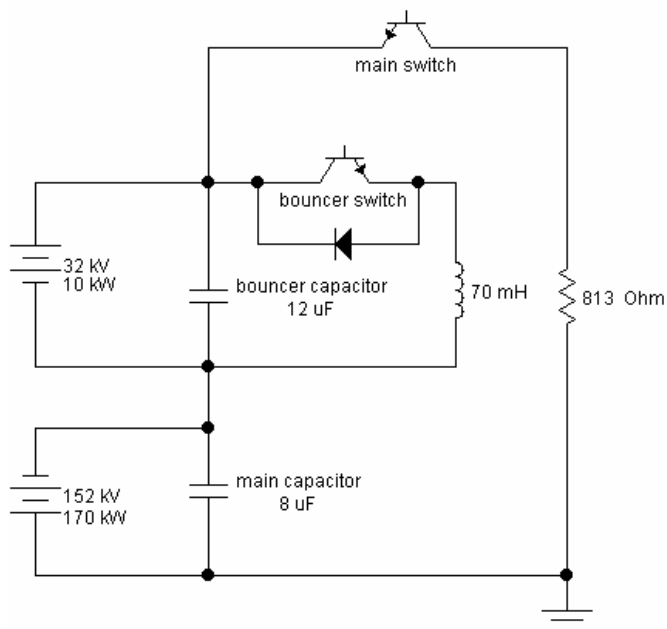


Figure 5. Hard-switch circuit, including bouncer to give flat pulse.

meeting the droop requirements with a conventional storage capacitor requires an extremely large capacitor – approximately 180 uF at 150 kV. This is, perhaps, feasible to build, as larger capacitor banks do exist. It is very large, and would not only be expensive, but would place a large facility burden on the ILC, making it unfeasible for ILC consideration.

A resonant bouncer, as shown in Figure 5, provides the desired pulse flattop to meet the ILC specifications, at significantly reduced size and capacitor requirements. The main capacitor and bouncer provide 25 kJ over the ILC's 1.5 millisecond pulse at very tight voltage regulation. The switch is rated to handle the full voltage and current of the load, including fault currents. In this circuit, the bouncer capacitor produces an increasing voltage that compensates for the droop on the main capacitor. Initially the main and bouncer capacitors are charged, but to opposite polarities. The bouncer switch is then closed, and the bouncer capacitor voltage becomes less negative. When the bouncer voltage is increasing linearly (at 2 ms in the figure) the main switch is closed,

producing the output pulse (waveforms are shown in Figure 6). At the end of the pulse, the main switch is opened. Finally, the

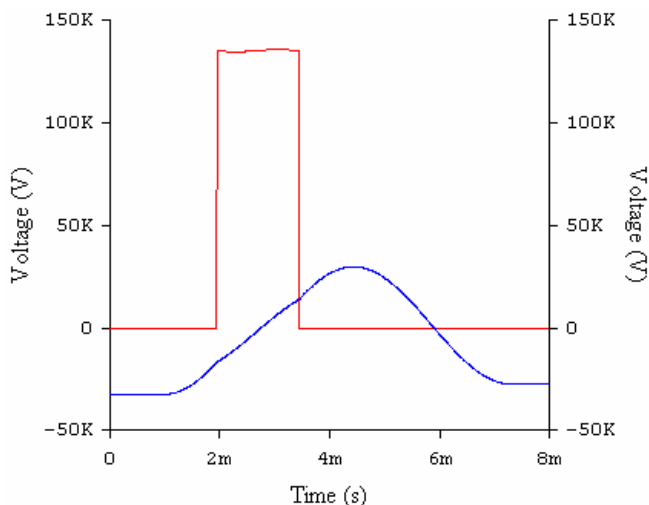


Figure 6. Voltages in bouncer circuit. Upper trace, output voltage; lower trace, voltage across bouncer capacitor.

voltage in the bouncer rings back, recharging the bouncer capacitor. The ILC pulse requirements call for constant pulsewidth, load perveance, and duty cycle are ideally suited to this type of resonant circuit.

Under two SBIRs from the Department of Energy, DTI is currently building a full scale hard switch modulator for ILC class klystrons (Figure 7). This system has four main components: a ~150 kV DC power supply, a ~35 kV DC power supply to charge the bouncer, the modulator tank (back right in the figure), and the capacitor tank. While the modulator could have been built in a single tank, the

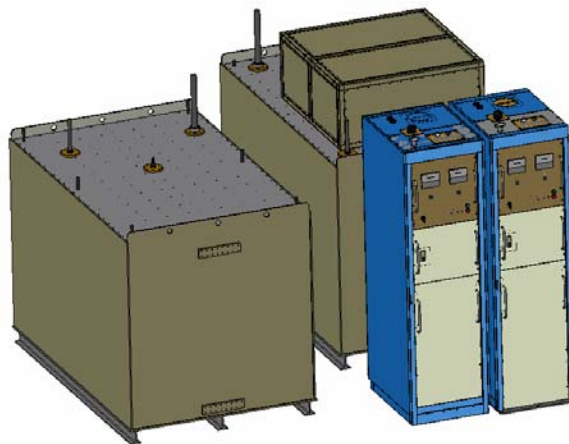


Figure 7. ILC Hard Switch configuration

modulator and capacitor tanks were split in this design to allow easier transportation and handling. Controls for the modulator are located in 19" drawers above the modulator tank. This design allows the equipment to be operated at low

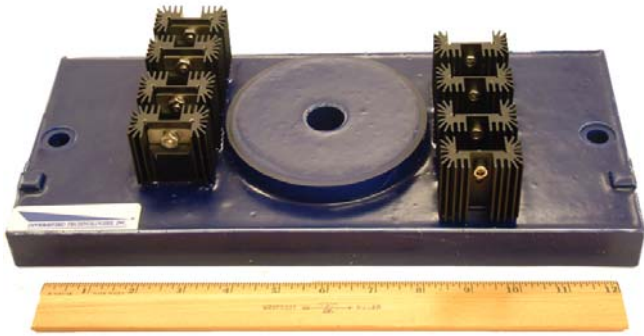


Figure 8. 20 kV, 150+ A, switch module.

voltage outside of the oil tank for assembly and testing, without the need to disconnect any wiring.

The hard switch itself is built using Powerex QIS4506001 IGBTs, which were jointly developed by DTI and Powerex, specifically for pulse power applications in a previous DOE SBIR. Figure 8 shows a switch module, similar to that used in the ILC hard switch, which uses eight of these IGBTs in series in a 20 kV module. These modules, in turn, are connected in series to build the full hard switch.

Given the switch module size, it is clearly not the hard switch itself that drives the overall size of the hard switch modulator. Rather, it is the passive components, primarily the capacitors and the bouncer inductor, which require the volume shown in the mechanical layout. In comparison, however, the total floor space required by the

hard switch modulator is estimated to be only 25% of that required in the baseline FermiLab/DESY design.

## V. SUMMARY AND CONCLUSIONS

The work performed by DTI in developing these alternative modulator design for the ILC clearly shows that a transformerless system is not only possible, but has significant size and cost advantages over a transformer-coupled system.

Current plans call for the ILC Hard Switch modulator to be completed in late summer 2006, and delivered to SLAC in the fall for assessment and use as a klystron test stand. The ILC Marx will move from the design phase into full scale development in 2006, with delivery to a laboratory selected by DOE in late 2007.

The cost estimates for a hard switch with bouncer are similar to those for a similarly specified incremental Marx switch because the primary cost drivers (the switch IGBTs, gate drive infrastructure, and energy storage capacitors) are nearly identical for both systems. In both cases, our estimates show that these transformerless designs will be 30 – 50% less expensive in production than the published figures for the baseline FermiLab / DESY design. In part, this is due to the elimination of the pulse transformer itself, but it is also attributable to the smaller, simplified designs made possible using high voltage, solid-state switching.

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