DEVELOPMENT AND TESTING OF THE ILC MARX MODULATOR*

G.E. Leyh, Nevada Lightning Laboratory
Brisbane, CA 94005, U.S.A.

Abstract

Construction of the SLAC/ILC 'Reference Design' Marx Modulator is complete and testing is currently underway at SLAC. This modulator design is oil-free, air-cooled, and capable of delivering 120kV, 140A, 1400usec pulses at a rate of 5Hz. Total energy per pulse is 23,500 joules. Projected efficiency is greater than 96%.

The Marx modulator design employs a stack of sixteen 12kV Marx modules that generate high-voltage output pulses directly from a 12kV input supply voltage. This direct switching eliminates the requirement for a massive transformer and reduces the capacitor bank size by more than a factor of four, yielding a considerably cheaper and more compact mechanical solution.

Advantages of the ILC Marx design include higher efficiency, smaller physical size, and a modular architecture that provides greater reliability and cost-effective PC board-level integration.

INTRODUCTION

The International Linear Collider [ILC] will require 576 klystron stations, each delivering 10MW pulses of RF at a rate of 5Hz. Each 10MW L-band klystron will require a 120kV, 140A, 23.5kJ drive pulse, 1400usec in duration. This unusually long pulse length requirement would adversely impact the size and cost of a transformer-driven modulator design, providing a strong incentive to research alternative topologies that avoid power magnetics.

The ILC Marx Reference Design circumvents the need for a transformer through direct solid-state switching of capacitors, arranged in a Marx configuration. The reference design prototype also employs direct air-cooling of the power components, allowing the entire modulator to operate without high-voltage insulating oils.

DESIGN OVERVIEW

The baseline design for the ILC Marx modulator employs sixteen 12kV 'main' cells and one 12kV 'vernier' regulator module, consisting of sixteen internally arranged 900V Marx cells used for fine regulation of the output pulse. In normal operation, fourteen of the sixteen main cells are active, with two cells parked as spares. The parked cell locations continuously rotate, ensuring even wear of all the cells.

The sixteen 900V Marx cells within the vernier module can produce a total voltage well above 12kV, and typically switch at a higher rate than the main 12kV cells. The vernier module smoothes out the coarse effects of the main cells and regulates the 120kV output pulse using a feed-forward algorithm to level the output pulse.

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Core Structure

Figure 1 shows the assembled modulator and control system, with the personnel safety cage, shorting crossbars, and high-voltage output divider (blue) in place. The modulator structure consists of a backing framework, a cantilevered backbone beam and a modulator backplane. The steel backing framework supports the cantilevered backbone, and two 19" control racks are built directly into the backing frame.

The cantilevered backbone consists of a box beam made from G-10, measuring 88cm high by 10cm wide. This beam supports all sixteen of the 12kV Marx cells and the modulator backplane. The beam is cantilevered in order to eliminate the need for structural support members at the 120kV end of the modulator. In this way, all of the structural elements are completely surrounded by the equipotential ring elements of the Marx cells, insuring that their surfaces see minimal electric fields.

Figure 1. The ILC Marx Modulator in Testing Area.

The cantilevered beam also provides several other functions. The hollow interior of the beam serves as an air plenum, delivering forced-air to the cells through apertures located in the side panels as shown Figure 2. The beam also provides a passageway for fiber-optic cables and a shielded exit path for the HV output cable.

The modulator backplane mounted to the bottom edge of the cantilevered beam supports the Marx cells and provides the connectivity between them. This backplane consists of three large PC boards with sockets at each cell location as shown in Figure 2.

The PC-board approach for the backplane eliminates much of the hand-wiring and custom mechanical assembly of a standard modulator design, streamlining the assembly and QC processes and resulting in considerable manufacturing cost savings.

Cell Design

The Marx cell uses a highly modular design approach, consisting of two main PC boards that support the all modular components of the cell. The two main boards mount to a Delrin support frame, which is connected to the aluminum equipotential ring that surrounds the cell. The equipotential ring, besides providing critical E-field shielding and mechanical rigidity, presents a well defined attachment point for robotic service equipment.

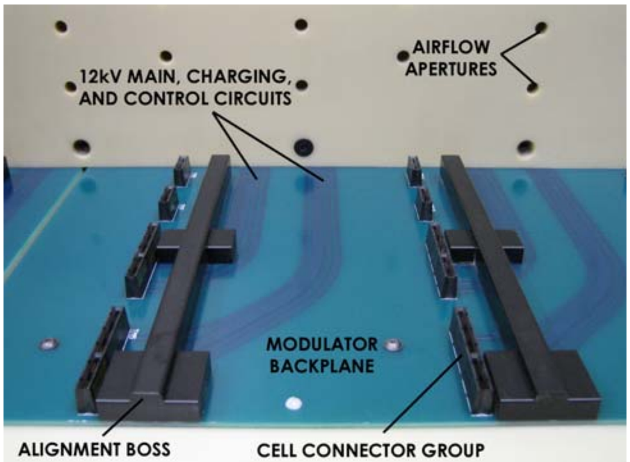

Figure 2. The Modulator Backplane.

Figure 3 shows a Marx cell mounted into position on the modulator backplane. The charging and firing IGBT switches are at (A) and (B), respectively. Each switch consists of five identical 3.2kV IGBT modules, providing a total switch capability of 16kV. Each module features intrinsic over-voltage protection and timing stabilization circuitry. The switch is designed to operate with one shorted module at nominal 12kV operation.

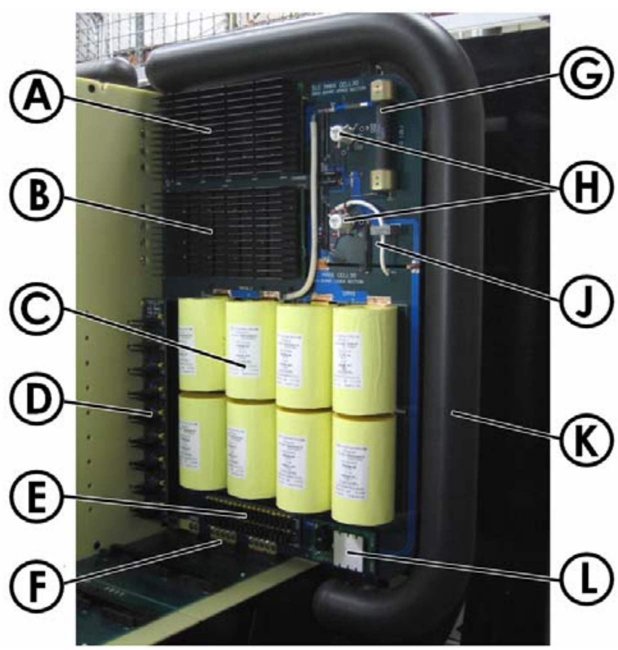

Figure 3. The 12kV Marx Cell.

Each switch module is independently removable. The modules plug directly into the Marx cell as shown, and are held in place by two socket-head screws.

The energy storage bank (C) consists of eight 96uF, 3kV capacitors arranged in series-parallel to obtain a total bank value of 48uF at 12kV. Accelerated life testing of these individual capacitors at twice the rated voltage predicts a service life of approximately 10e9 shots.

Both the charging diode module (D) and the cell-freewheel diode module (E) consist of eighteen 1200V diodes in series. The cell-freewheel module actually contains two diode stacks; the main freewheel diode and the 375V control voltage blocking diode. The charging diodes at (D) are mounted to heatsinks and cooled by the forced-air apertures on the cantilever beam.

The control power module (L) converts the unregulated 375VDC control power to a regulated 24VDC for local use by the vacuum relays and the control module. The converter must accept input voltages ranging from 150V to 375V depending on its position in the Marx stack, owing to the forward voltage drop of the HV diodes.

The local cell control module can monitor critical points and determine the status of the cell using the charging current monitor and HV dividers at (J).

In the event of a cell failure, the vacuum relays at (H) de-energize, isolating the cell from the 12kV charging line and discharging its local energy storage capacitor through the 12kJ discharge resistor at (G). The relays also shunt the main current path through the cell when de-energized, allowing the modulator to continue normal operation.

The equipotential rings for each cell at (K) form a continuous shield around the Marx cell components. Ansoft Maxwell 3D calculated the surface electric field contours on this equipotential ring system at 120kV operation. Figure 4 shows the results.

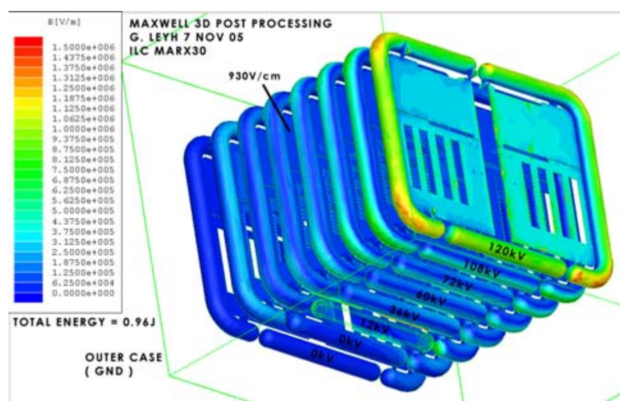

Figure 4. Surface electric fields at 120kV.

Short straight segments of aluminum pipe with rounded ends mounted underneath the modulator backplane form a smooth continuation of the equipotential rings on the Marx cells. These short segments can be seen in the model in Figure 4. In addition to providing electric field continuity, these pipes also act as the horizontal beam members that support the modulator backplane, and the Marx cells.

TESTING AND EVALUATION

We began initial tests of the completed modulator frame using 2 cells, producing 24kV pulses into the 150kW test load. We then added cells two at a time, verifying operation at each stage before advancing further. Most of the observed problems involved fast electric fields between the cells, interfering with the cell control circuitry and IGBT optocouplers. We addressed these problems with a combination of firmware changes, electrostatic shielding add-ons and component substitutions. The most difficult problem encountered appeared around 80kV, at which point the IGBTs would begin to switch erratically, often resulting in a critical fault. We determined the cause to be a fast electric field between the di/dt limiting inductor and nearby photocouplers controlling the firing IGBTs on each cell, as shown in Figure 5. Changing the photocouplers to a higher voltage version and adding a copper shielding housing around each photocoupler solved this problem.

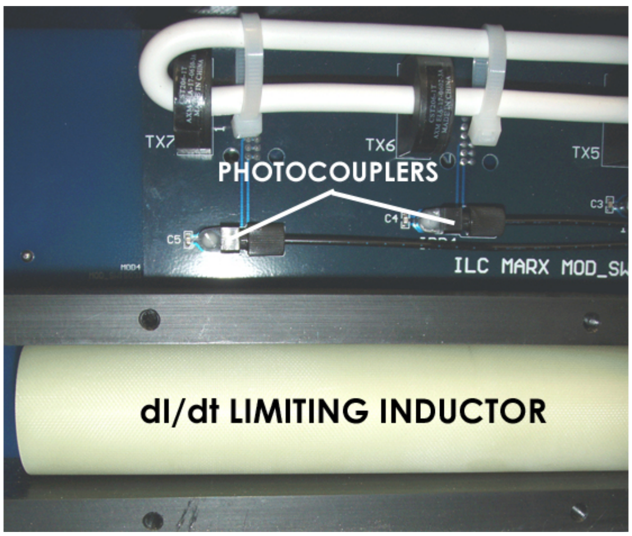

Figure 5. Positions of Optocouplers and Inductor.

Operation at 120kV

Figure 6 shows the Marx modulator output voltage and current waveforms while producing 120kV, 100usec output pulses into the 150kW test load. The green trace is the output voltage at -20kV per division, the violet trace is output current at -50A per division.

As can be seen in these waveforms, a total of twelve cells are engaged in generating the pulse, with their timing intentionally staggered into 6usec steps in order to control the current surges launched into the capacitance of the output coaxial cable. The current surges when each cell fires can be seen in the lower current trace.

These surges are small compared with the main 140A current, and therefore shouldn't present a problem during normal operation. In addition, the output cable for this test is about 75ft in length, which is likely much longer than would be used for an actual klystron installation.

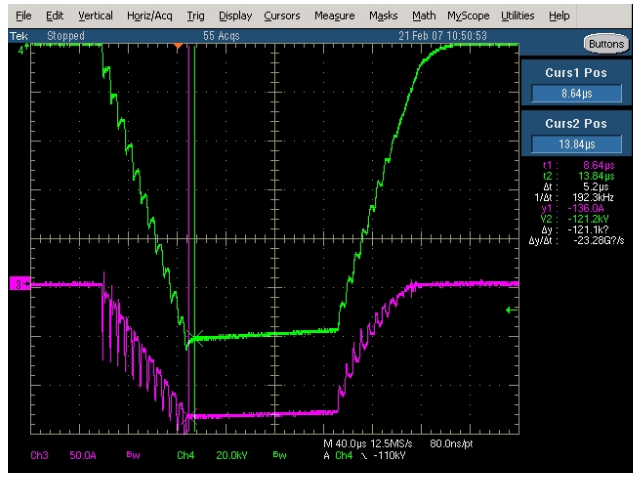

Figure 6. Marx at 120kV, Short Pulse Operation.

In order to produce the full 1400usec pulse length the Marx modulator must delay-fire several cells at regular intervals during the pulse, to compensate for long-term capacitor voltage droop. Figure 7 shows the modulator generating a full 1400usec pulse at 120kV by delay firing two of the cells, producing a coarse-leveled pulse with a 12kV sawtooth on top of the 120kV waveform.

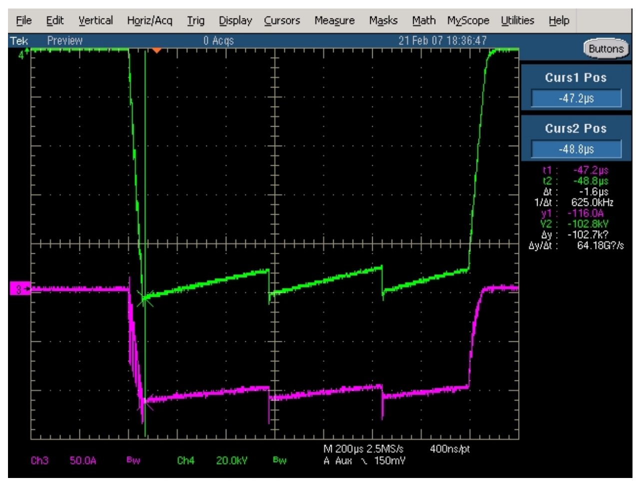

Figure 7. Marx at 120kV, Long Pulse Operation.

The 12kV vernier cell (currently in development) will compensate for this 12kV sawtooth component and fine regulate the output amplitude to the +/- 0.5% tolerance using a feed-forward algorithm.

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