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DEVELOPMENT STATUS OF THE ILC MARX MODULATOR

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***Abstract*-The ILC Marx Modulator is under development as a lower cost alternative to the "Baseline Conceptual Design" (BCD) klystron modulator. Construction of a prototype Marx is complete and testing is underway at SLAC.**

The Marx employs solid state elements, IGBTs and diodes, to control the charge, discharge and isolation of the modules. The prototype is based on a stack of sixteen modules, each initially charged to ~11 kV, which are arranged in a Marx topology. Initially, eleven modules combine to produce the 120 kV output pulse. The remaining modules are switched in after appropriate delays to compensate for the voltage droop that results from the discharge of the energy storage capacitors. Additional elements will further regulate the output voltage to ±0.5%.

The Marx presents several advantages over the conventional klystron modulator designs. It is physically smaller; there is no pulse transformer (quite massive at these parameters) and the energy storage capacitor bank is quite small, owing to the active droop compensation. It is oil-free; voltage hold-off is achieved using air insulation. It is air cooled; the secondary air-water heat exchanger is physically isolated from the electronic components.

This paper outlines the current developmental status of the prototype Marx. It presents a detailed electrical and mechanical description of the modulator and operational test results. It will discuss electrical efficiency measurements, fault testing, and output voltage regulation.

INTRODUCTION

The International Linear Collider (ILC) will require 576 RF stations. Each 10 MW L-band klystron will require a modulator capable of; 120 kV, 140 A, 1.6 ms (27 kJ) at 5 Hz repetition rate. The existing BCD is a transformer-based topology. The large size, weight, and cost of this transformer, owing to the long pulse length, have motivated research into alternative topologies that do not employ power magnetics.

The ILC Marx [1] modulator uses solid-state switches and isolation elements to connect capacitors in parallel while charging but in series during discharge to generate the required high voltage output without the use of a transformer.

DESIGN OVERVIEW

The topology is illustrated in Fig. 1. A diode string provides a path for charging the 50 μF capacitor of each of the 16 Marx cells to 11 kV and isolation between the cells during erection. Likewise, a second diode string provides a path for auxiliary power to each cell. A charge switch in each cell provides a common return path for both power sources.

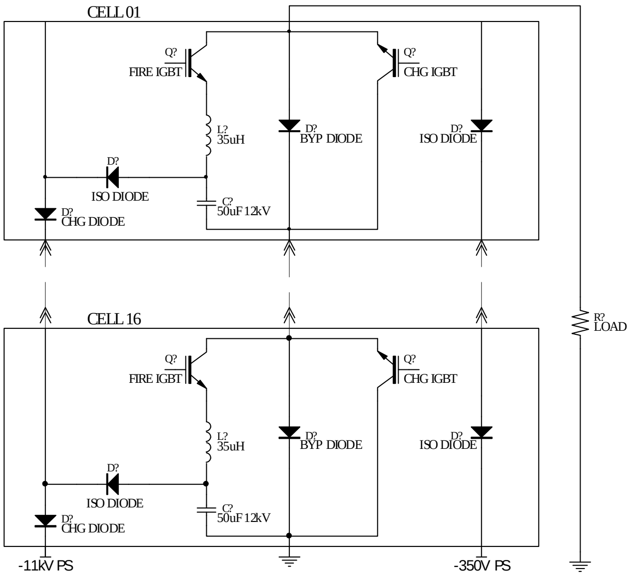

Fig. 1. Simplified schematic diagram of the ILC Marx.

Closure of a fire switch will produce a -11 kV output pulse from the cell; closure of additional switches will increase the output by -11 kV for each cell that is fired. The by-pass diode provides a conduction path to the load through the cells that have not been fired. The series inductor limits dI/dt of the output current.

Eleven cells are triggered to produce the required output voltage. As the energy storage capacitors discharge, the output voltage drops. Once it has decreased by 11 kV, in ~0.35 ms, an additional cell is triggered to bring the output back to 120 kV. This proceeds sequentially through the remaining five cells to provide coarse, ±5%, pulse flattening.

The output will be further regulated to ±0.5% by a second Marx, the vernier regulator, in series with the main Marx. The topology of the vernier is similar to the main Marx, however each of the 16 cells is charged to 1.2 kV. These are fired sequentially to generate a stair-step waveform, which is added to the main Marx to maintain a constant output voltage.

Marx Structure

Fig. 2 is a photo of the partially assembled modulator, 12 cells installed, housed in the personnel protection cage. A steel structure supports the modulator components and the

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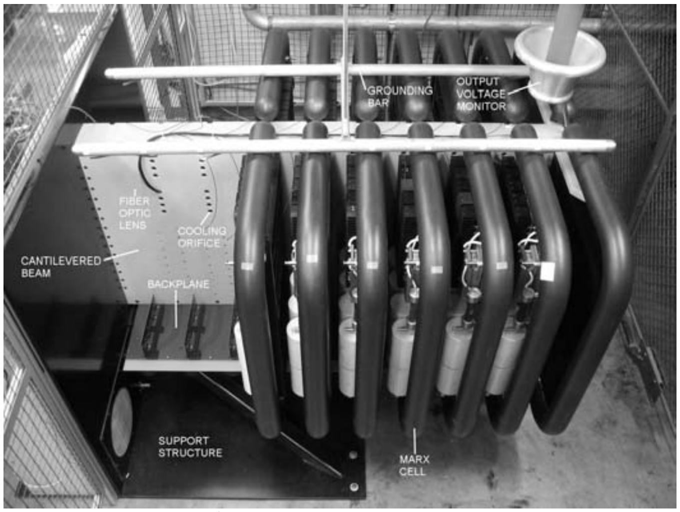

Fig. 2. Photo of the ILC Marx in the developmental test cage.

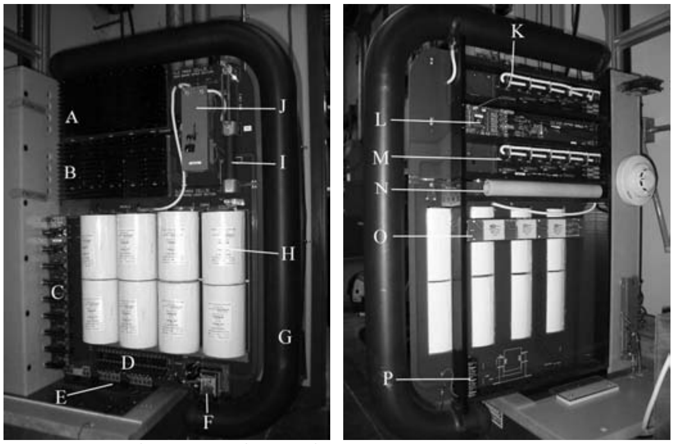

Fig. 3. Photo of Marx cell, front (left) and rear (right), noting major elements. A: Charge IGBT module, B: Fire IGBT module, C: Charge diode, D: By-pass diode, E: Backplane connector group, F: Auxiliary power dc-dc converters, G: Equipotential ring, H: Energy storage capacitor, I: Discharge resistor, J: Discharge relay, K: Isolation board for charge switch, L: Control board, M: Isolation board for fire switch, N: Series inductor, O: Charge isolation diode, P: Auxiliary power storage capacitor

control system (not visible, outside the cage in the front of the support structure). The hollow, cantilevered beam supports the individual Marx cells, forms the duct to direct the forced air coolant, and houses the permanent fiber optic cables (the visible fibers were a temporary installation). It also supports a PCB backplane that provides the electrical interconnections between cells. When a cell is installed, it hangs from the beam, plugs into connectors on the backplane, and aligns the fiber optic lenses with those in the beam to transmit and receive optical control and diagnostic information. A grounding bar is lowered from supports above the modulator to ground out all cells for personnel protection during servicing. A high voltage divider is used to monitor the modulator output.

The design is intended to simplify maintenance. A cell is removed by lifting it off the backplane and a replacement cell is then set in place; there is no wiring to remove or install. Ambient air provides high voltage insulation. When developmental testing is complete, the modulator will be housed in a sealed enclosure; 0.35 m spacing between the cell structure and enclosure walls is sufficient insulation for the Marx voltage.

Marx Cell Design

The Marx is a fundamentally modular topology, with inherent cost and maintenance advantages. The ILC Marx design fully exploits this trait. A Marx cell, shown in Fig. 3, consists of a PCB motherboard on which connectorized, modular components are mounted. The motherboard is supported by a backing frame that also supports the equipotential ring that surrounds the cell. The energy storage capacitor, capacitor discharge relay and resistor, and series inductor are permanently mounted on the motherboard; all other major components are modular.

The charge and fire switches are each an array of IGBTs, five modules connected in series. Each module uses three parallel IGBTs that are controlled by a common driver. During transient conditions, the voltage distribution between the series switches will be non-uniform. To protect the IGBTs from damage, over-voltage protection is incorporated into each switch module. The isolation boards translate auxiliary power and control signals from the reference potential to the emitter potential of each switch module. The control board, auxiliary power, and equipotential ring are referenced to the cell output potential.

The diodes; charge, charge isolation, by-pass, and auxiliary (on the same PCB as the by-pass) are each an array of eighteen series 1200 V ultra-fast devices with a parallel MOV to assure uniform voltage distribution.

A CPLD on the control board sequences the firing of the charge and fire switches; the charge switch is gated off 10 μs before the fire switch is gated on and then back on 10 μs after the fire switch is gated off. The delays eliminate the shoot-through condition that would occur if both switches were on simultaneously. Both switches are monitored for an over current condition, which if detected remove the gate pulse from the switch.

Control System

The Marx employs a FPGA-based control system. A diagnostic module, with a jumper configurable address, is attached to the control card in each cell. Communication to the system ground station is over 60 Mb/s fiber optic data lines using point-to-point serial protocol. In the ground station, a FPGA communicates with a ColdFire processor, which provides the system's RTEMS-based EPICS IOC. The EPICS database contains the timing information, entered by the operator, and status and diagnostic information communicated from the Marx cells.

The diagnostic module passes timing information to the control board CPLD to coordinate the timing of the Marx cells. The diagnostic module also has four analog input channels to monitor voltages and currents on the Marx cell. The channels are monitored at 20 kS/s with a resolution of 16 bits. A fast transient recorder can also be triggered to capture each of the channels at 30 MS/s with an 8-bit resolution into a 2 kS buffer.

TEST RESULTS

Individual modules are extensively tested for quality control purposes. Over-voltage testing of switch modules, shown in Fig. 4, exemplifies this testing regiment. Switch modules are tested with a high inductance load, which at turn-off causes the switch voltage to increase until clamped by the over-voltage protection circuit. In the Fig. 4 data, the switch was closing against 2 kV and 140 A. Without the over-voltage protection circuit limiting the IGBT voltage to 3.7 kV, the inductive voltage would have greatly exceeded the 4.5 kV breakdown voltage of the switch.

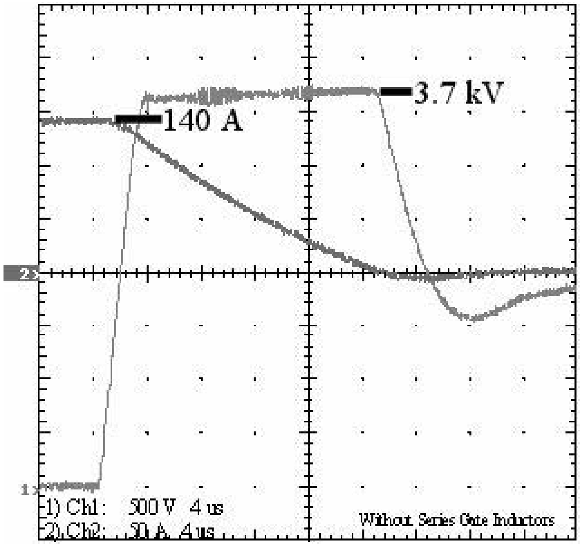

Fig. 4. Switch module over-voltage test results, Ch1 is switch voltage, Ch2 is current.

Qualified modules are assembled into Marx cells, which are individually tested to 12 kV and 150 A. Cells are tested under normal operating conditions and short-circuit conditions to evaluate the effectiveness of the over-current protection circuitry. An example of the latter is shown in Fig. 5. The initial load conditions are 12 kV and 140 A. After the load is shorted, the voltage collapses and the current rapidly rises. Once the current exceeds the threshold of 180 A, the fire switches are gated off, and after a turn-off delay of ~1.4 µs the current decreases from a peak of 600 A. The maximum dI/dt, 300 A/µs, corresponds to 11 kV across the series inductor.

Once cells have been qualified, they are assembled into the Marx. The vernier regulator is still under development, so the modulator is run with only coarse pulse flattening at present. Infrastructure issues currently prevent operation at full power, so the modulator is run at either the full 1.6 ms pulse width and reduced PRF or at 5 Hz and reduced pulse width. The former is illustrated in Fig. 6. The turn on, and off, of the cells is staggered to reduce the peak current into the long cable that connects the modulator to the load in the test configuration. In the ILC implementation the cable would be eliminated, as could be the triggering delays, shortening the rise and fall times.

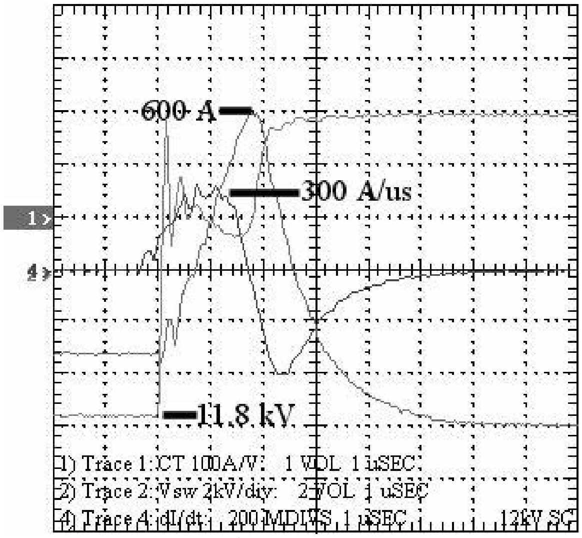

Fig 5. Over-current testing of an individual Marx cell, Ch1 is load current, Ch2 is load voltage, Ch4 is dI/dt.

The next phase of modulator testing will focus on fault tolerance, primarily arc-down testing of the output to simulate klystron breakdown. In addition to the single test results shown above, testing has been successfully completed with a 2-cell configuration and preliminary results have been obtained with a 4-cell configuration, as shown in Fig. 7. The voltage is monitored at the output and mid-point of the Marx along with the modulator current. With initial load conditions of 32 kV and 40 A, the load was shorted and the peak current rose to 450 A. At present, the cells individually detect and react to the over-current condition. System over-current detection will be added to the controls to provide a back-up. Detailed examination of the voltage waveforms indicates good voltage sharing between cells under this transient condition. These measurements will be extended to full voltage in the 4-cell configuration and then to 8, 12, and 16-cell configurations.

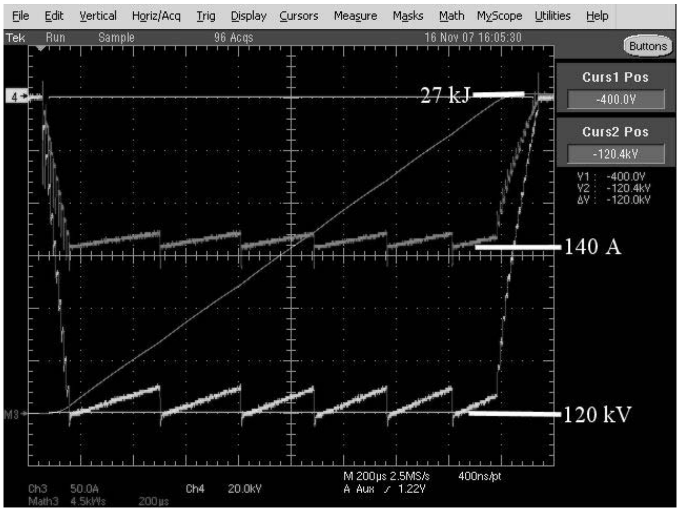

Fig. 6. Marx output with coarse flattening, Ch3 is load current, Ch4 is load voltage, and Math3 is load power.

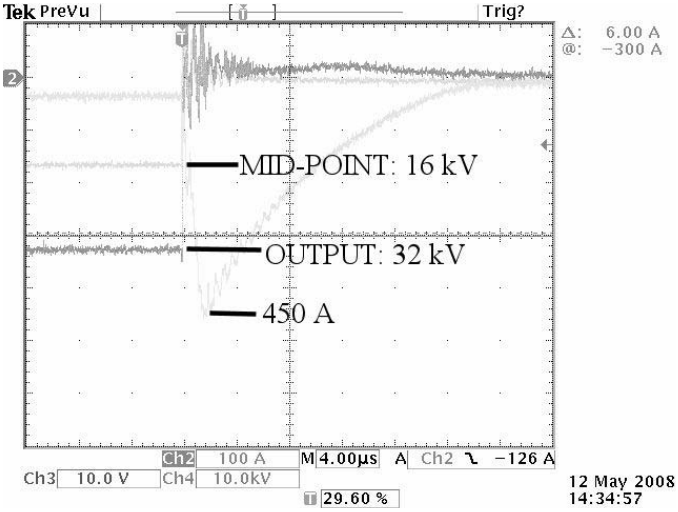

Fig. 7. Four-cell arc-down test; Ch4 is Marx output voltage, Ch3 is Marx midpoint voltage, and Ch2 is Marx current.

The efficiency of the modulator has been estimated from measurement of the input power and energy delivered to the test load. The measurement accuracy is 1%. At an input power of 25.4 kW, 24.7 kW were delivered to the load, of which 23.5 kW were in the flattop portion of the pulse. This corresponds to an efficiency of 92% in the flattop (97% overall), which will be improved when the rise and fall times are shortened, as discussed previously.

The ILC Marx developmental testing is nearing completion. Following additional high average power operation and arc-down testing, it will be installed in a new L-band test facility at SLAC to undergo extensive life testing during FY09.

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