THE ILC MARX MODULATOR DEVELOPMENT PROGRAM AT SLAC *

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Abstract

The International Linear Collider [ILC] baseline design requires 576 L-band klystron stations, each supplying 10MW peak RF power to the accelerating structures. Each klystron requires a modulator capable of delivering 120kV, 140A 1.6ms pulses, at 5Hz.

Solid-state Marx modulator topologies are rapidly becoming feasible with the advent of PC-board-level 4500V IGBTs, fast single junction HV diodes, high density capacitors, and sophisticated modeling software.

Making full use of recent technology advances, the ILC Marx Modulator program at SLAC plans to pursue a 120kV solid-state Marx design, which appears to offer significantly higher efficiency, availability, and cost savings than existing modulator options.

I. INTRODUCTION

In the last 5 years several groups [1] [2] [3] [4] [5] [6] have presented operational solid-state Marx modulator designs. Richter-Sand et al [2] have demonstrated a 30 cell, 30kV 400A Marx bank operating at 7.5kW average power. Casey et al [3] have demonstrated a 5 cell, 50kV design, with edge speeds better than 100nS at 24kV and 210A output. Leyh [4] demonstrated one 12-cell section of a 500kV design, producing 18kV at 550A with 150nS edge speeds. Kirbie et al [5] are currently developing a 46kV, 160A 5uS modulator with advanced waveform synthesis capability. The ILC Marx Modulator program plans to further these efforts towards a 120kV design, capable of generating 140A, 1.6ms pulses at 5Hz.

II. CHALLENGES

A. Cell Isolation

In contrast to the Marx designs outlined above, the ILC Marx modulator must support very long pulses (1.6ms). This precludes the use of inductive cell isolators, requiring active schemes with solid-state switches and diodes to safely isolate the DC charging path before the bank fires. The isolating switches must also be capable of passing the full 130kW input power, with minimal losses.

B. High-Voltage Cell Switches

Higher operating cell voltages require lower charging currents, therefore offering substantially higher modulator efficiency. For the ILC Marx design, the optimal cell voltage is approximately 12kV. However, this voltage is many times beyond the capacity of the highest voltage commercial IGBTs, requiring a custom high-voltage switch design that employs several IGBTs in series. This switch design must provide low losses, fast response times (<1us) and low cost (<$3k). The switch assembly must use a modular, unencapsulated format to reduce total cell extraction weight and improve serviceability.

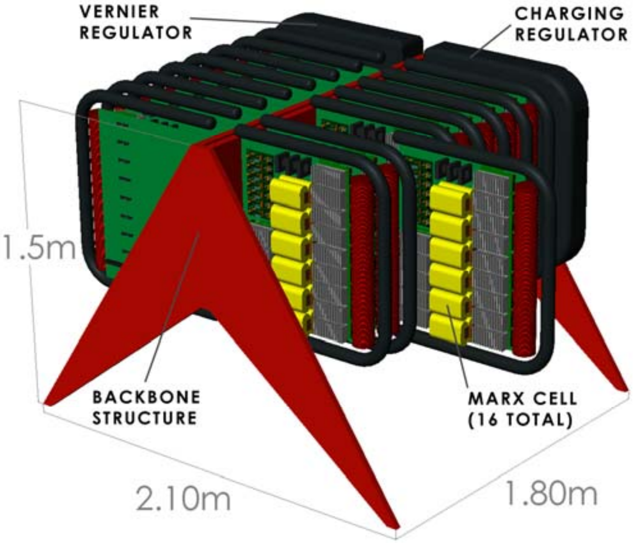

Figure 1. ILC Marx Modulator Mechanical Layout.

C. Feed-forward Control System

The low-level klystron RF controls use feed-forward techniques to compensate for vibration and other noise sources in the accelerator housing. The modulator can significantly enhance the RF feed-forward performance by using feed-forward as well, as this provides greater pulse-to-pulse waveform stability. For a feed-forward control system to work effectively in a Marx bank, there must be a deterministic relation between any cell switching event and its effect on the output waveform. In contrast, a modulator design with a heavily filtered output would mask the switching effects of individual cells, making feed-forward calculations difficult or impossible.

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III. BENEFITS

A. Efficiency

The lower operating currents and simple switching requirements of a Marx bank yield considerably higher modulator efficiencies. Marx cell switches handle the relatively low (140A) klystron current directly, compared to transformer-based modulators with primary switch currents in the thousands of amperes.

Marx modulator switching losses are also lower since each Marx cell cycles only once per pulse, as opposed to high-frequency resonant converter modulators.

Calculated ILC Marx modulator efficiencies are in the 96-98% range, based on actual measurements of switch power dissipation at 12ADC for the charging switches and 150A, 1.6ms pulsed for the main switches.

B. Oil-free Design

The high efficiency of the Marx Bank permits air-cooling instead of oil immersion. This simplifies maintenance in underground installations, reduces mean repair times, and avoids complex oil regulatory issues.

C. Construction Costs

The highly modular PC board-level integration of the ILC Marx design streamlines assembly and QC processes. The obviation of oil containment issues greatly simplifies external enclosure and support utility requirements.

D. Machine Availability

The Marx modulator can operate around failed cells, significantly reducing the risk from single-point failures. The modular nature of the Marx bank simplifies diagnosis and component replacement, reducing mean repair times.

E. Physical Size

The Marx design requires roughly 1/3 the space of existing transformer-based long pulse modulators. This directly impacts civil engineering costs for the ILC tunnels and underground structures.

IV. DESIGN

The baseline design for the ILC Marx modulator employs sixteen 12kV ‘main’ cells and sixteen 1.2kV ‘vernier’ cells used for fine regulation of the output pulse. In normal operation, fourteen of the main cells are active, with two cells parked as spares. The parked cell locations continuously rotate, ensuring even wear time and confirming operational status for all components.

All sixteen of the vernier cells are active during normal operation, although the modulator can operate normally with as few as thirteen vernier cells. Figure 1 illustrates the mechanical arrangement for the central modulator backbone, main Marx cells, charging regulator module, and the vernier regulator module.

A. Marx Cell

The schematic in Figure 2 outlines the basic cell design and interconnections between cells. The IGBT charging switches to the right remain closed most of the time, providing constant-power charging current to the cells. The charging switches open only during an actual output pulse, isolating the cells from the DC charging source. The main IGBT switches then close in a pre-determined sequence to generate the desired output pulse waveform. At the end of the pulse all main switches open, allowing the charging switches to close once again and resume charging the cell capacitors.

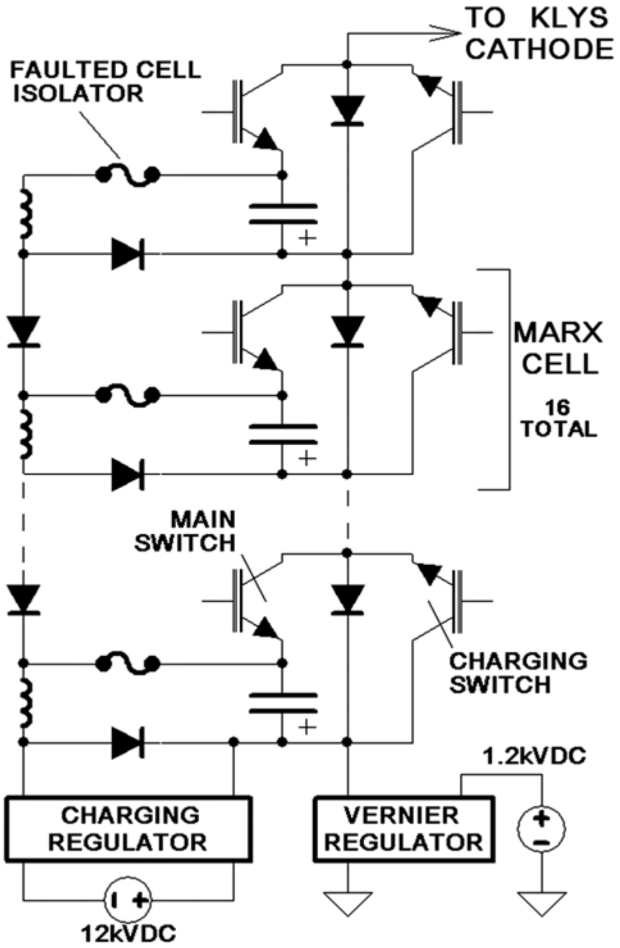

Figure 2. Cell Stack Schematic Diagram.

The charging regulator shown in Figure 2 consists of five independent buck regulator modules in parallel, providing N+1 redundancy, 5x effective ripple frequency, and finer top-off regulation accuracy. The RMS current handled by the regulator is only 12A at 12kV.

The sixteen 1.2kV vernier regulator cells reside on two PC boards, housed together in a single module approximately the same size as a single Marx cell. The vernier regulator provides the fine resolution needed for maintaining the output pulse wave shape, and processes about 5% of the total modulator output power.

All of the components in the Marx Cell are designed for PC board integration, and are arranged onto planar cell assemblies as shown in Figure 3. A mechanical docking system attaches the cell to the modulator backbone, which can be latched and released using a hand operated grappler or by automated means such as overhead robotic service platforms in the equipment tunnel.

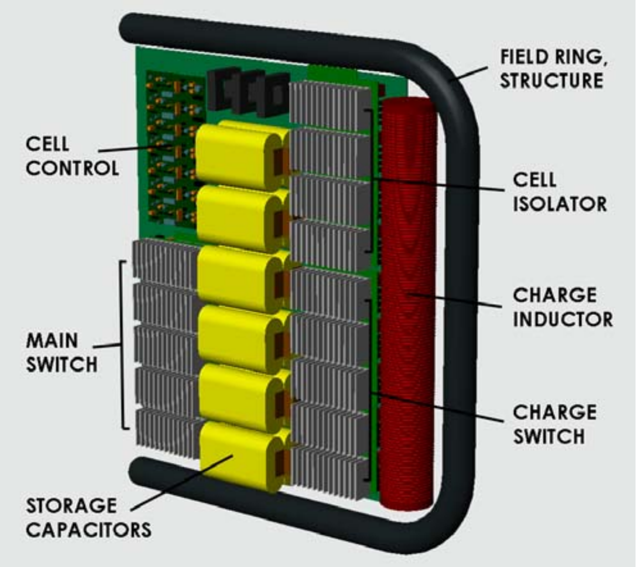

Figure 3. ILC Marx Cell Mechanical Layout.

The central backbone beam supporting the 16 Marx cells serves several functions. Aside from being the main structural member, the backbone provides connectivity between the cells through the docking sockets supporting each Marx cell assembly. The hollow interior of the backbone beam provides passage for fiber-optic control cables, acts as a transport duct for the forced-air cooling, and contains a controlled-gradient termination scheme for the output pulse cable to the klystron.

V. PROGRESS

A. 12kV Switch Performance Testing

The custom 12kV IGBT switch represents one of the largest single-item technical risks for this project; therefore the first prototyping effort is to construct a full 12kV switch assembly and characterize its performance.

Figure 4 shows the first prototype switch assembly on the test bench. The switch consists of five identical IGBT modules, each capable of supporting up to 3.7kV for a total switch holdoff capability of 18kV. Each module has intrinsic over-voltage protection, and timing stabilization circuitry. The switch is designed to operate with one shorted module at nominal 12kV operation. Each switch module is independently removable. The modules mount directly to the Marx cell as shown in Figure 3, in the Main Switch, Charge Switch, and Cell Isolator positions shown.

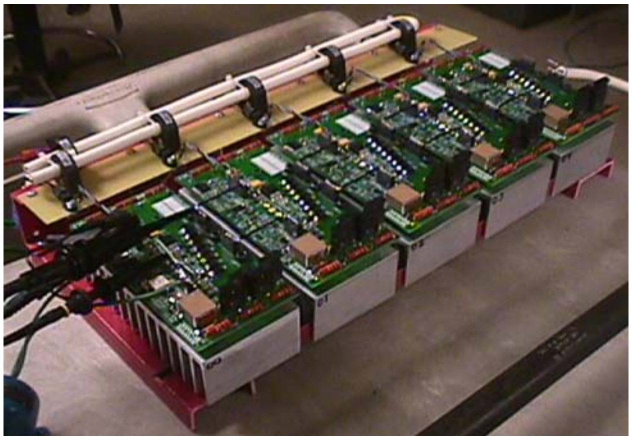

Figure 4. 12kV Switch Assembly.

Tests of the switch assembly included power dissipation at 12ADC and 150A/1.6ms/5Hz pulsed, and transient response to various overvoltage fault conditions. Figure 5 shows the dynamic performance at 12kV and 180A, with a 20kHz firing rate.

With the heatsinks in still air, the 150A/1.6ms/5Hz current load test produced a heatsink temperature rise of 4degC after 45 minutes. A continuous 12ADC current load resulted in a heatsink temperature rise of 21degC.

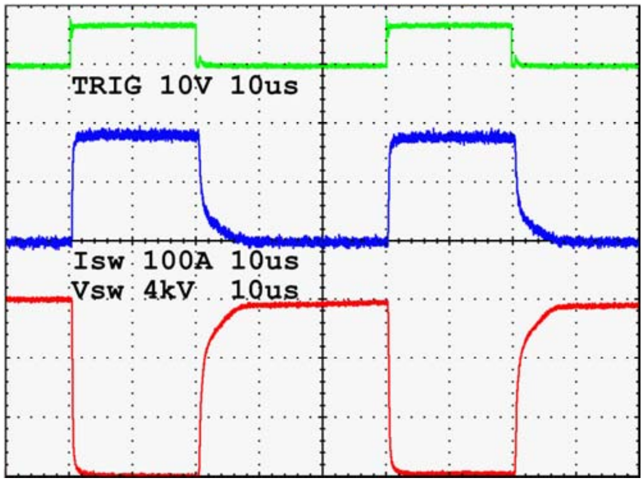

Figure 5. Dynamic Switch Performance at 20kHz.

Timing errors between switch modules can result in transient overvolting of modules that turn on late, or turn off early. A fast overvoltage protection circuit in each module fires the IGBT, if its Vce exceeds about 3700V. This circuit operates along with an RCD snubber to keep Vce excursions well below the IGBT Vces of 4500V.

To test the response of the overvoltage protection feature, a large inductor was placed in the load circuit, which forced current to flow in the module for several usec after the module tried to turn off. The induced fault is an order of magnitude longer than the largest expected timing error. Figure 6 shows the resultant test waveform.

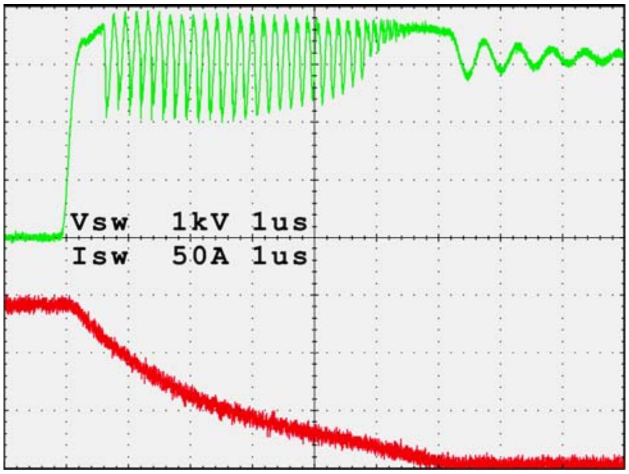

Figure 6. Overvoltage Protection Response.

The bottom waveform shows a current of 140A when the IGBT turns off. The collector voltage quickly rises to the snubber voltage at about 3.2kV, where the dV/dt slows to the rate set by the snubber. The voltage continues rising at the slower rate towards the trip point, where the IGBT fires. The protection circuit repeatedly fires the IGBT, limiting the collector voltage as the inductor current falls to zero. Once the overvoltage fault clears, the protection circuit releases the IGBT, allowing it to fully turn off. For this test, the module operated in this fault mode at 20Hz for one hour without ill effect.

B. Effects of Fast Electric Fields

When the Marx bank fires, cells at the top of the stack will experience fast external electric field movements as their voltages to ground suddenly change by up to 120kV. There will also be fast dE/dt movements between neighboring cells, and within the cells between various cell components. These fast dE/dt values can produce significant current transients on exposed cell components and disrupt unshielded control circuitry within the cell.

Computer simulation tools that solve electric fields on 3D structures performed an extensive survey of the Marx bank geometry for potential dE/dt hotspots. The highest dE/dt found in the simulations resided between the collector heatsinks on the switch modules (Figure 4) and the nearby PC board that controls the module. With a clearance of only 0.9cm, the dE/dt to the control board is about 20,800 V/cm-us. For comparison, the dE/dt between the outer field ring of the top cell (at 120kV) and the grounded metal enclosure is only 8,000 V/cm-us.

In first tests of the prototype 12kV switch module, the dE/dt from the heatsink would falsely re-trigger the gate control circuit at a Vce of about 1500V. This represents a dE/dt of about 10,400 V/cm-us. The rising voltage edge on the heatsink at turn-off induced the re-triggering by coupling capacitively to several high impedance (~10Kohm) nodes in the trigger circuitry. A circuit re-design reduced the impedance of all logic nodes to below 300 ohms, eliminating the problem. One of the next highest dE/dt regions is between the cell control board (Figure 3) and the backplane of the adjacent cell, at 12,200 V/cm-us. Because of the open area around the board, however, this control board can be easily shielded, and will be enclosed in a standard shielding enclosure.

VI. CONCLUSIONS

Initial 12kV switch tests indicate that the switch meets basic performance criteria for the ILC Marx modulator. However, testing of short-circuit fault scenarios needs to be completed before freezing the switch design.

Based on actual measurements of 12kV switch conduction losses under both DC and pulsed current conditions, the air-cooled approach for the Marx cells appears to be feasible. Calculated modulator efficiency based on loss measurements is in the range of 96 - 98%.

The next development step is to test a full Marx cell, followed by a ‘short stack’ of at least four cells.

Further test results will be presented at the PPC2005 conference poster session and in future papers.

VII. ACKNOWLEDGEMENTS

Piotr Blum, SLAC, for providing superb mechanical CAD work and for the design and construction of the 12kV prime power supply.

VIII. REFERENCES

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