Development Status of the ILC Marx Modulator

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ILC08

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SLAC NATIONAL ACCELERATOR LABORATORY

Power Conversion
Solutions for Challenging Problems

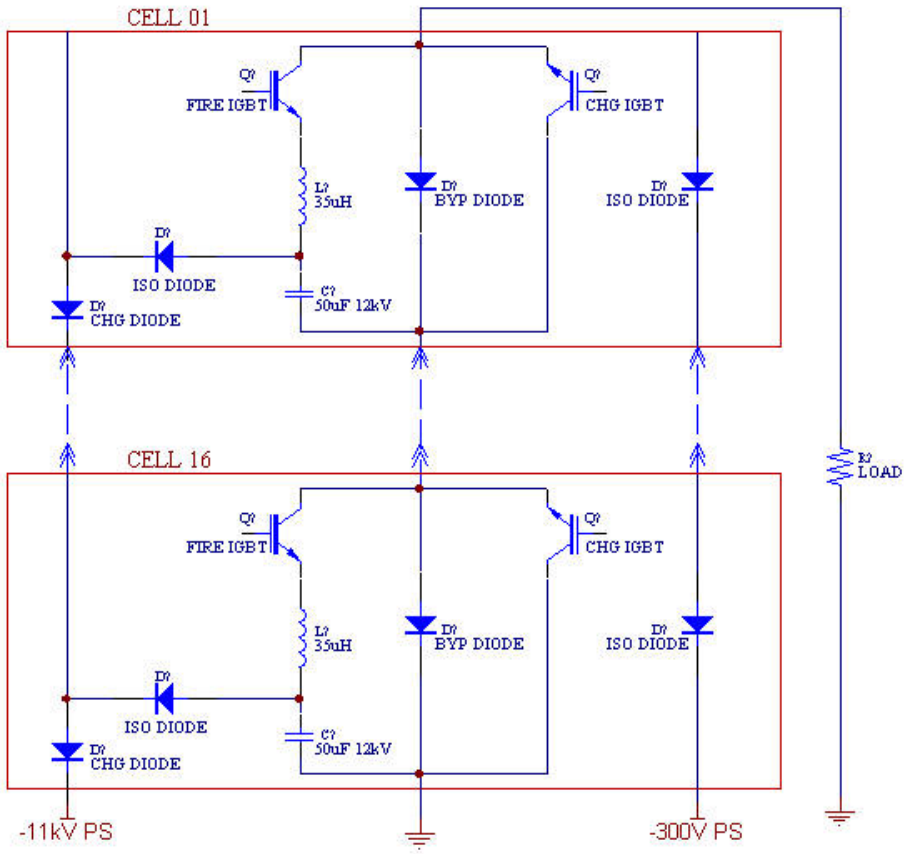
Development Program for Marx-based ILC Klystron Modulator

- SLAC 1st Generation Prototype (P1)
  - Preparing for Life Testing
  - Fine Regulation of Output (±0.5%)
- DOE Small Business Innovative Research (SBIR) Projects (HEP - L.K. Len)
  - Three Phase I Grants (9 month, $100k)
  - Two Phase II Grants (2+ years, $750k+)
- SLAC 2nd Generation Prototype (P2)
  - Conceptual Design

P1-Marx Status

- Developmental Testing in B015 Completed
  - Operational Testing
    - Full voltage (120 kV), current (140 A) and pulse length (1.6 mS) with coarse flattening
    - Full PRF (5 Hz)
    - Near full power (135 kW), load limit ~100 kW, HVPS limit ~120 kW
    - Several shifts without intervention
  - Arc-down Testing (Simulated Klystron Arc)
  - Integrated into “Sealed” Enclosure
- Install in L-Band Test Station in ESB for Extended Life Tests
  - Marx Control System Upgrades: EPICS interface
  - L-band Test Stand Interlocks and Control
- Improve Output Voltage Regulation to ±0.5%
  - Vernier Regulator

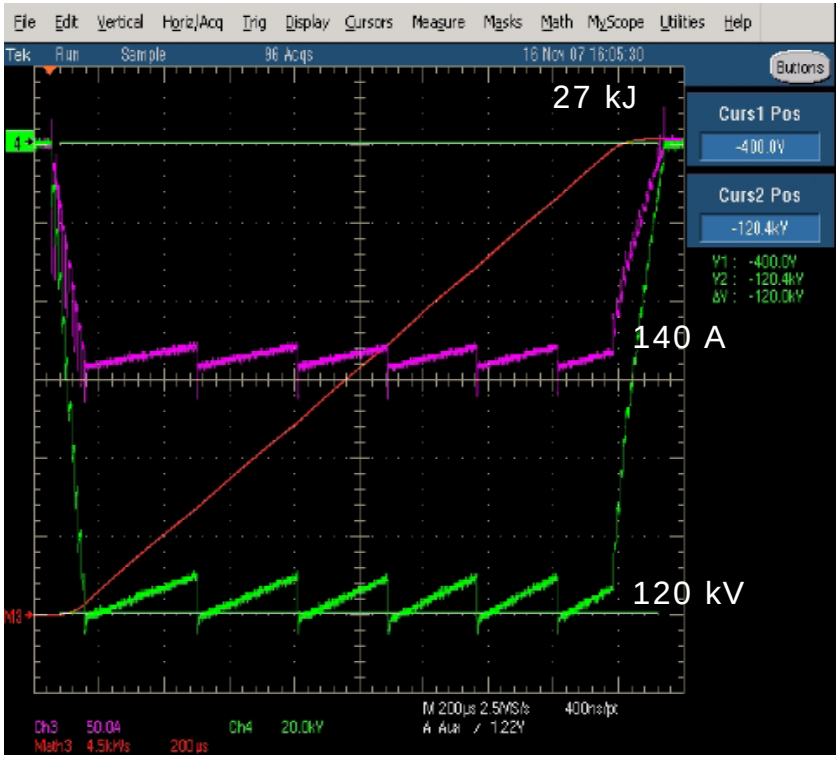
Simplified P1-Marx Circuit



- Marx Topology: Charge Cells in Parallel, Discharge in Series
- 11kV per Cell
- 16 Cells
  - 11 prompt cells → 120 kV
  - 5 delay cells, compensates capacitor droop
- Cell High Voltage Switches
  - Array of 4.5kV, 60A IGBTs 3 parallel X 5 series
  - Fire switches erect Marx
  - Charge switches provide current return path for main charging supply (-11 kV) and auxiliary power (-300 V)
- Diode Strings Provide Isolation Between Cells When Marx Erects
  - 18 series 1200 V, 60A, Ultrafast Soft Recovery Type
  - Parallel Resistors and MOVs to balance & protect against over-voltage
- Inductors Limit Fault dI/dt

P1-Marx Cell
Front & Rear Views

P1-Marx: Normal Operational Testing

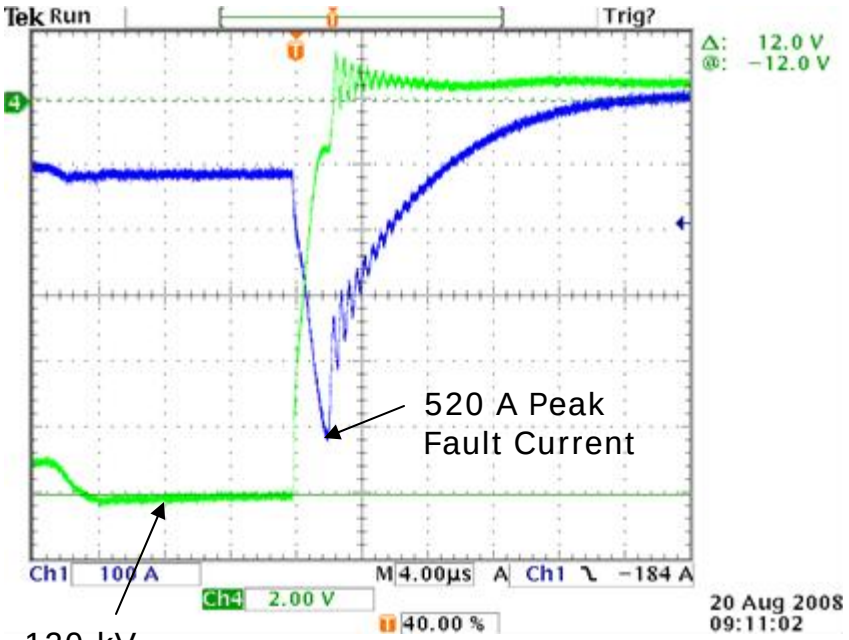


- Coarse Pulse Flattening
  - 16 Cells: 11 prompt, 5 delayed
  - 0.86 kΩ water load
- Efficiency Measurement
  - Total power efficiency: 97%
  - Usable (RF) efficiency: 92%

P1- Marx Fault Testing: Load Arc

16 Cell Arc-Down Test:
Voltage & Current Waveforms

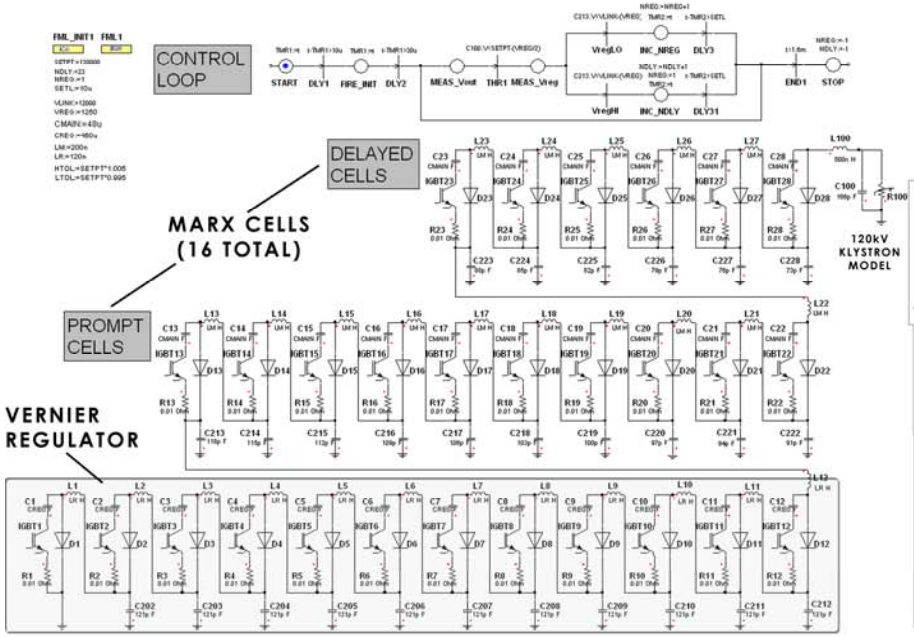
16 Cell Arc-Down Test:
Arc Detail

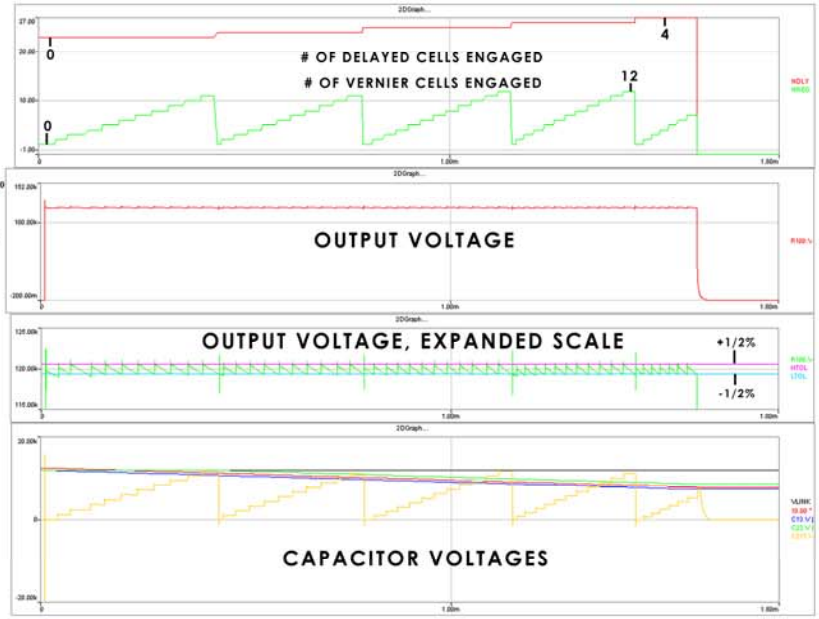


P1-Marx Installed in "Sealed" Enclosure

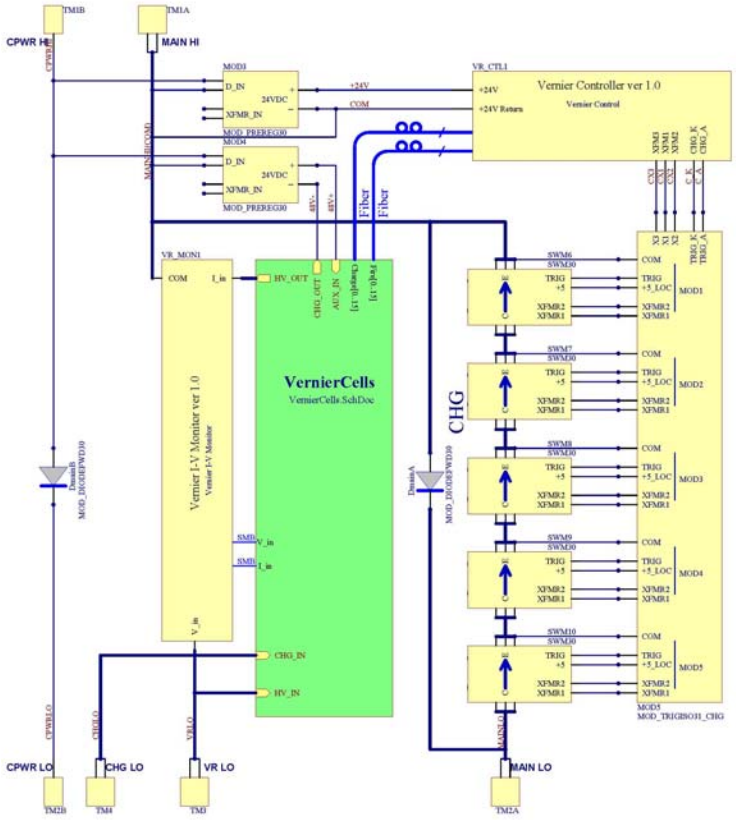
Installing P1-Marx in ESB

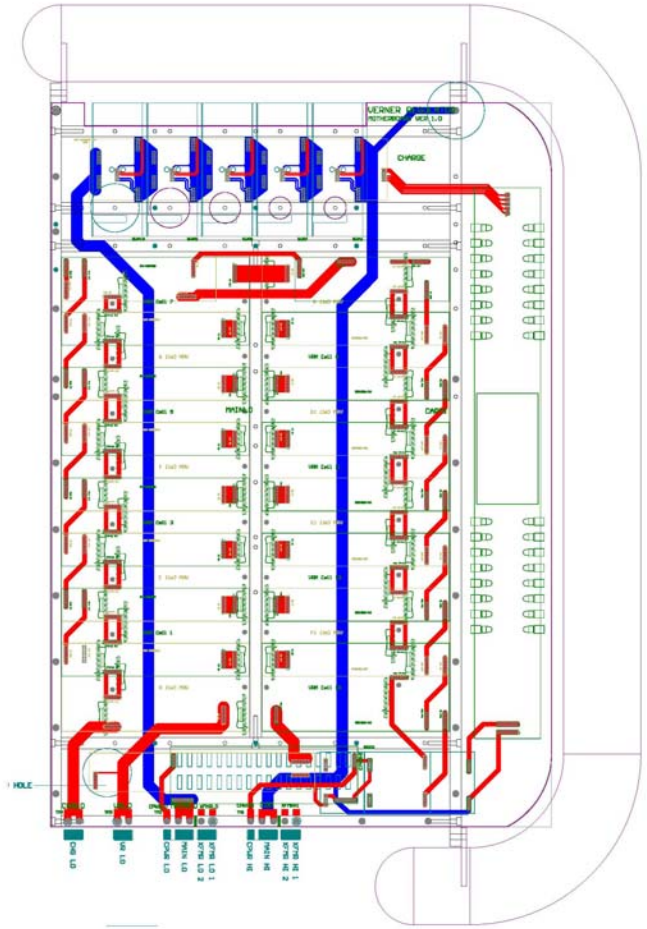
P1-Marx Voltage Regulation



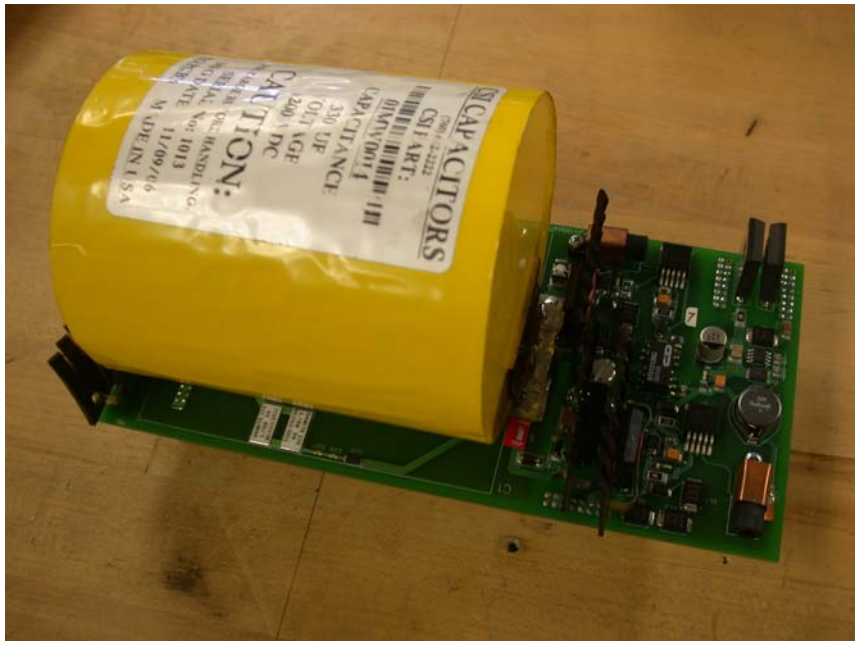


P1-Marx Vernier Regulator Board





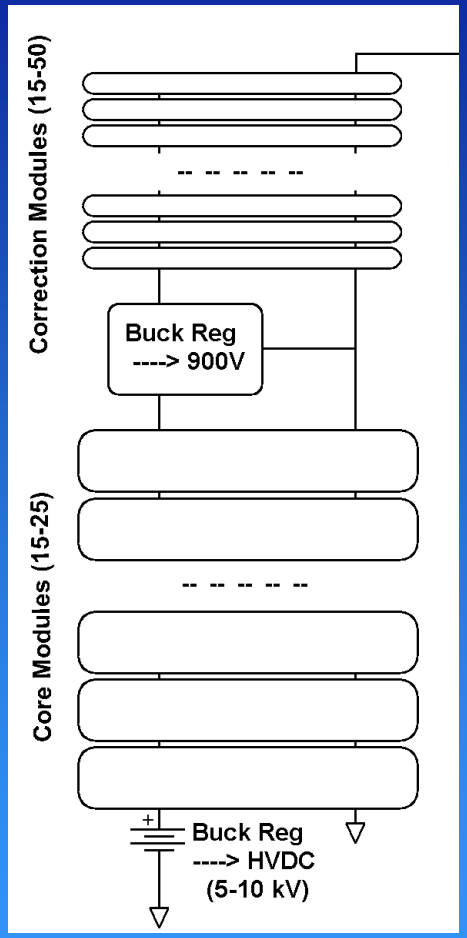
Vernier Regulator Marx Cell



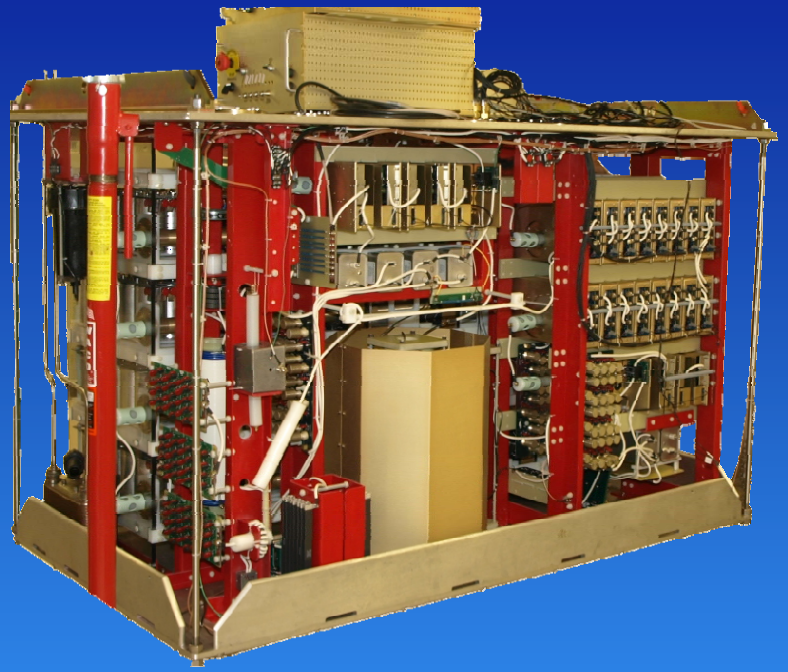
SBIR Contributions

- Two Phase-II Programs
  - Diversified Technologies, Inc.
  - ISA Corporation
- Both Programs in Third Year
  - Significant Development Completed
  - Supplemental Funding Provided to Increase Probability of Successful Completion
- Finished Systems to be Delivered to SLAC
  - Independent Testing and Evaluation
  - Additional Modulators to Support SLAC HLRF Effort

DTI Marx Modulator for ILC (DOE SBIR)



- **Specs: 120-150 kV, 120-150 A, 1.5 ms, 5 Hz**
- **Marx Topology used to beat cap droop**
  - **Initially erect pulse with optimized Marx, using twenty modules at 6.0 kV each**
  - **Maintain flattop by sequencing in additional modules: sixteen at 900 V each**

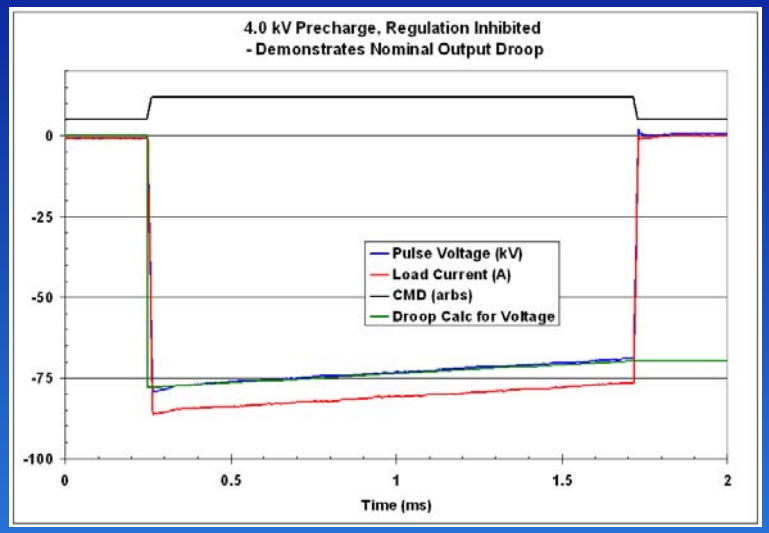


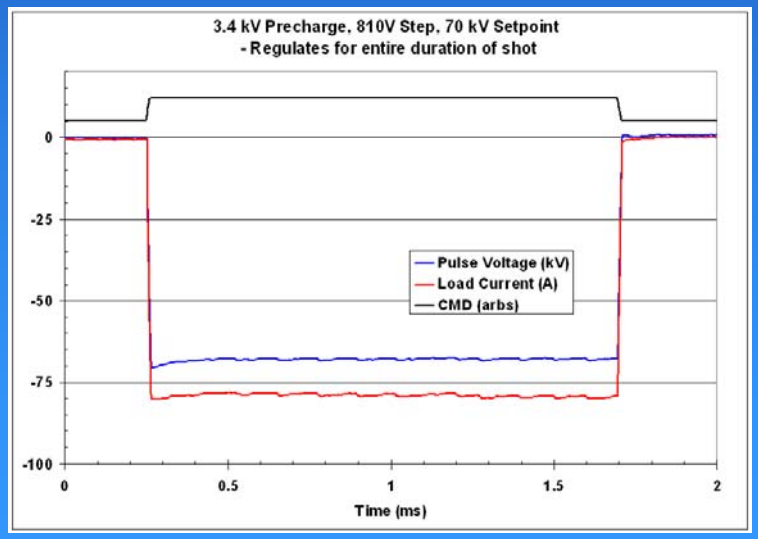
- **Total system: 170 kJ to deliver 30 kJ pulse - +/- 0.5%**
  - **electrolytic capacitors used for lower volume**
  - **N+1 redundancy on caps and switches, with internal diags**
- **Internal Buck Regulator at prime input voltage (6 kV)**
  - **no external power supply, runs off unregulated DC**

DTI Marx Modulator for ILC (DOE SBIR)

- **Results:**
  - **20 Cores at ~ half voltage**
  - **load = 900 Ω**
  - **upper: no regulation**
  - **lower: regulate at 70 kV**

- **Status (fall '08):**
  - **tested to >80% voltage**
  - **all systems operational**
  - **noise chatter present above half voltage, needs better snubbing**
  - **system to be completed & delivered to SLAC in '09**

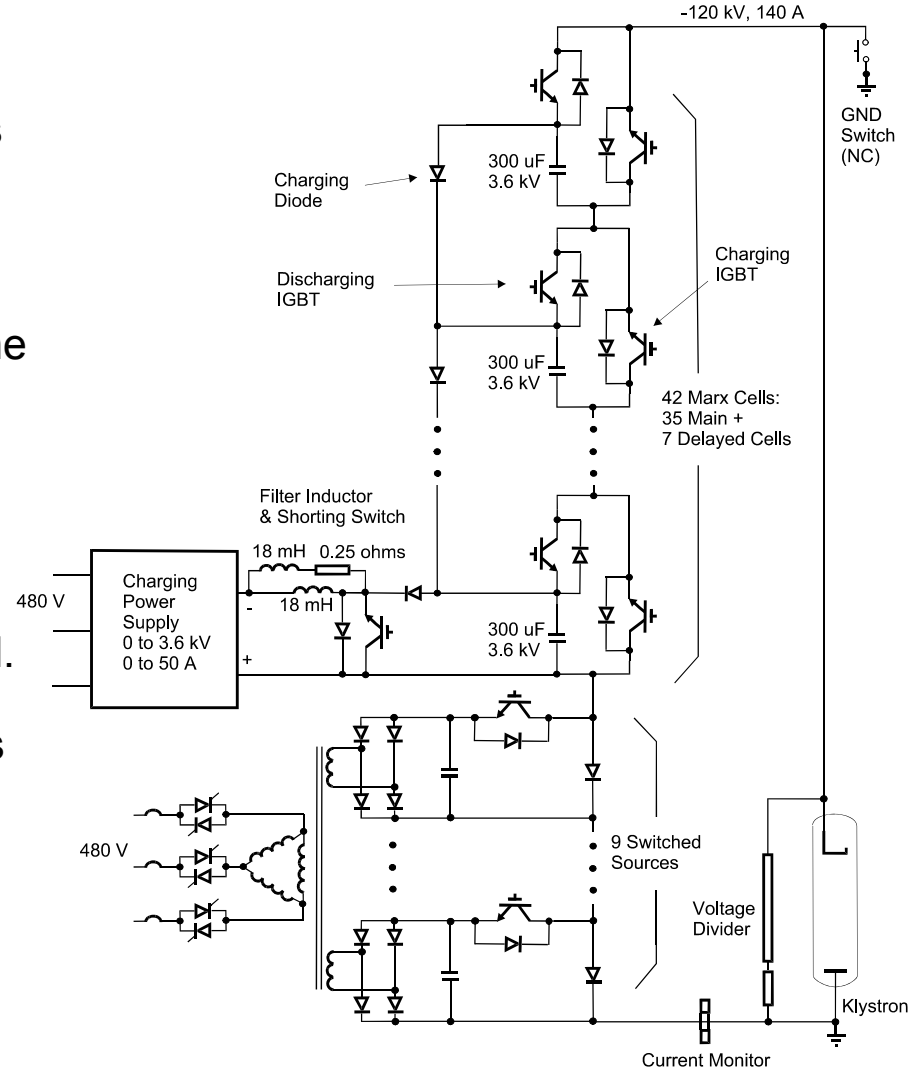




Technical Overview

DOE SBIR Grant No. DE-FG02-05ER84364, “Marx Based Modulator for ILC and Industry,” ISA Corporation, Dan Shimer, Principal Investigator

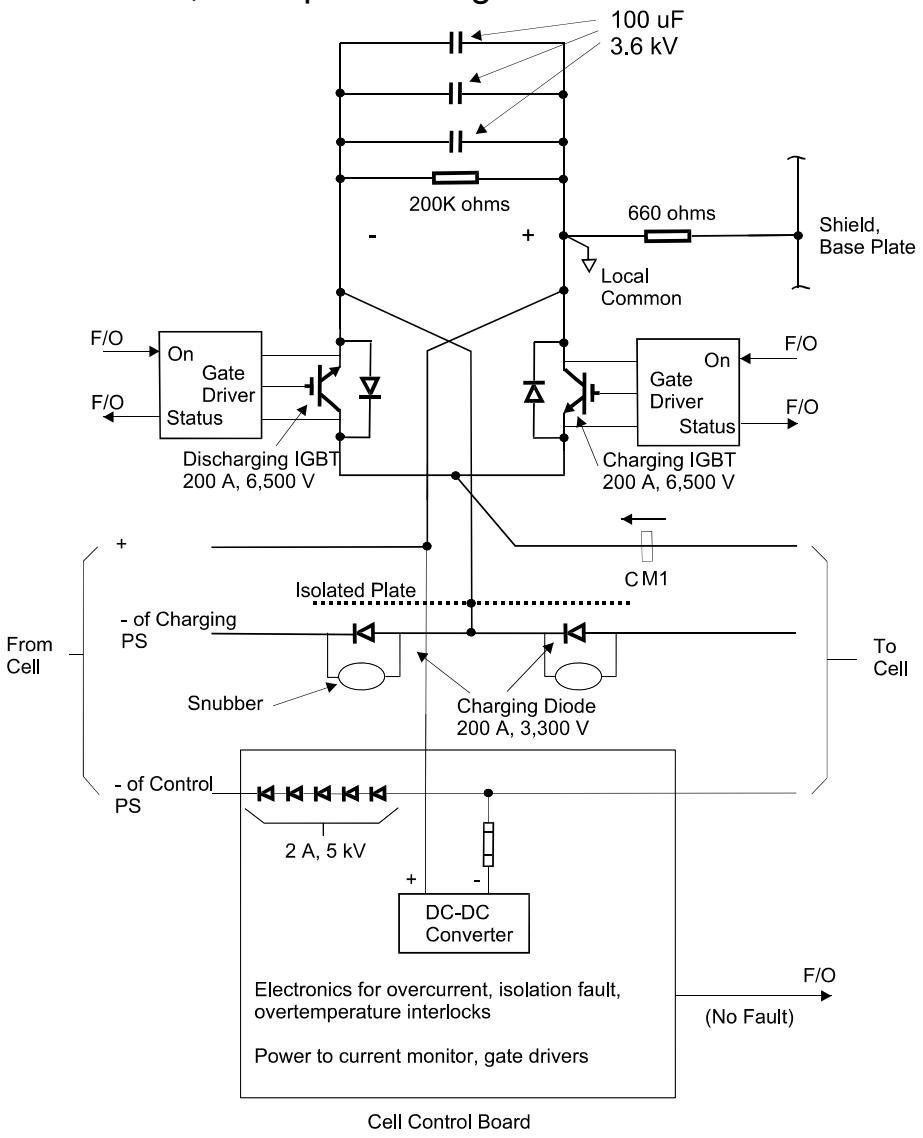
- Pulse train at -120 kV, 140 A, 1.7 ms wide, 5 Hz repetition frequency, +/- 0.5 % flatness
- 42 Marx cells – 35 main and 7 delayed for droop compensation. Voltage droop is 27.8 kV (23 %) in the main section during pulse.
- 9 Switched Sources of 0 to -500 V each in series for reduction of 3.5 kV (2.9 %) ripple during pulse.
- Charging supply consists of transformer-rectifier and two choppers at 1 kHz for voltage control.
- Commercially available IGBT modules, drivers, and diode modules are used.
- Air insulated, water cooled, no oil



Marx Cell

DOE SBIR Grant No. DE-FG02-05ER84364, “Marx Based Modulator for ILC and Industry,” ISA Corporation, Dan Shimer, Principal Investigator

- ABB 400 A, 6,500 V IGBT modules used – 200 A units not yet available.
- IGBT drivers from CT Concept.
- Diodes are series-connected 3,300 V diode modules from Powerex.
- Capacitors are dry, self-healing from NWL, type ER.
- Control interface is through fiber optics.
- Interlocks in each cell protect against a shorted IGBT, control power fault, over current, local ground fault, and over temperature. A fault shuts down the entire modulator.



Status

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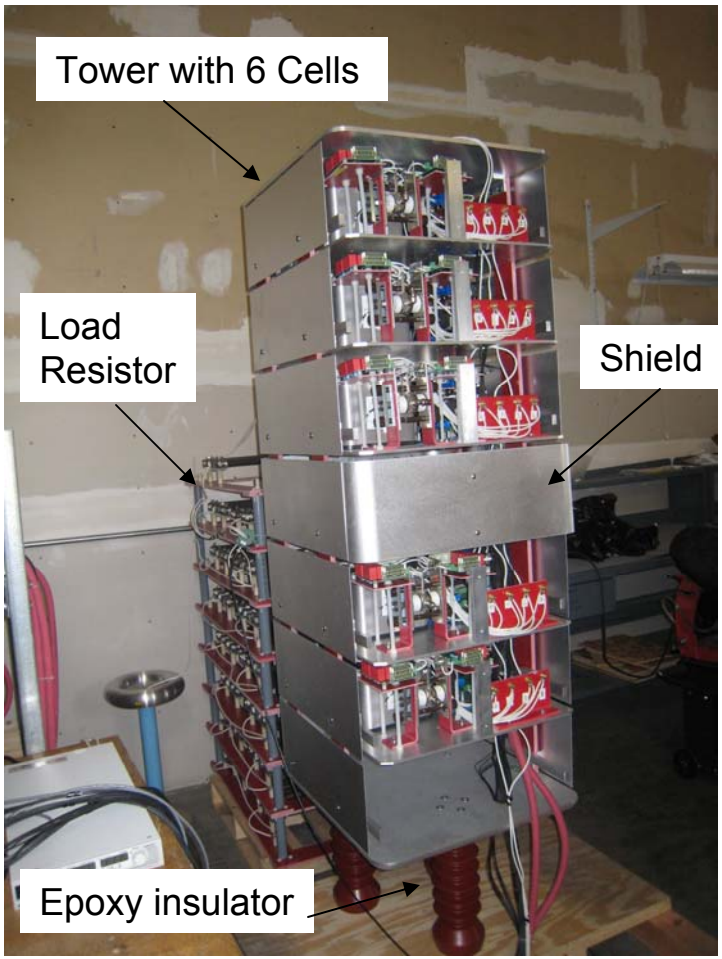
- Low power testing of the charging supply and 6-cell tower occurred in January, 2008
- Full power testing of original 6 cell tower will be completed in January, 2009.
- Present activity is concentrating on redesign of the cell to make it smaller using Powerex diode modules instead of Westcode hockey puck type. A prototype will be built and tested by end of February, 2009.
- All IGBTs to be received in May, 2009.
- Final assembly and subsystem testing will occur in May, June, and July, 2009.
- Full modulator testing at partial power (< 30 kW) will occur in August and September, 2009. Average power limited by facility and resistive load.



SLAC P2-Marx

- Revise Footprint: Compatible with RDR Tunnel Layout
- Build on Expanded Knowledge Base
  - P1-Prototype
    - Improve reliability of “power block”
    - Single IGBT/diode cells: no electrostatic arrays
    - Increase “on cell” diagnostics
    - Simplify voltage regulation
  - SBIRs
  - New PSD Staff
- Improve “Manufacturability”

P2-Marx Power Block Evaluation

- Energy Storage Capacitor
  - High Ohms/square Metalized High Crystalline Polypropylene (HCPP)
    - Proven technology for HV capacitors
    - Long life
    - High energy density
  - Design for 20% Voltage Droop
    - Shallow cost optimum: 20 – 40% droop
    - Small droop simplifies compensation

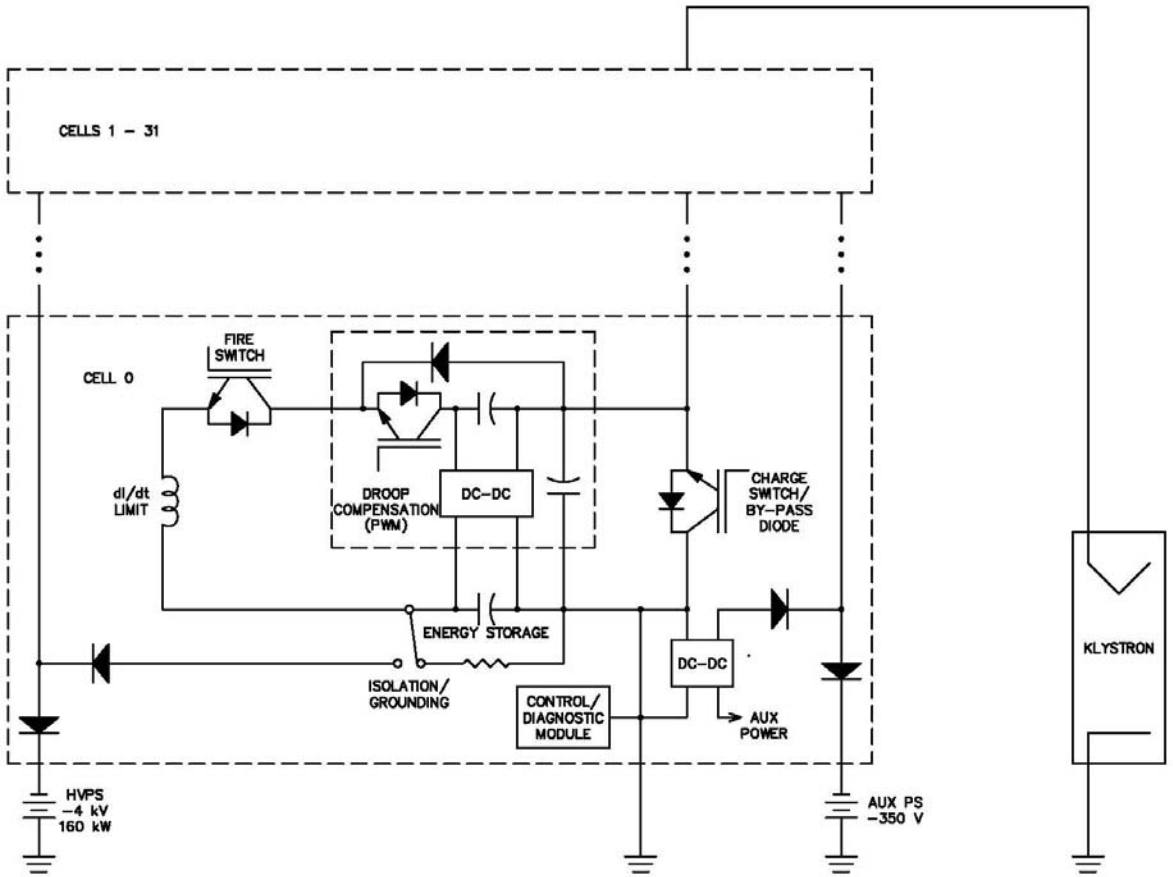
P2-Marx Power Block Evaluation

- 6.5 kV IGBT
  - Highest Voltage Commercial IGBT
  - Smallest Commercial Package is 200 A, but Anticipate 2 X 100 A (Ideal for Marx) in Future
  - Reliability Analysis (10^5 hr) to Establish Operating Voltage: 3.8 kV
    - Insulation capability (partial discharge)
    - Cosmic ray withstand
    - Thermal cycling

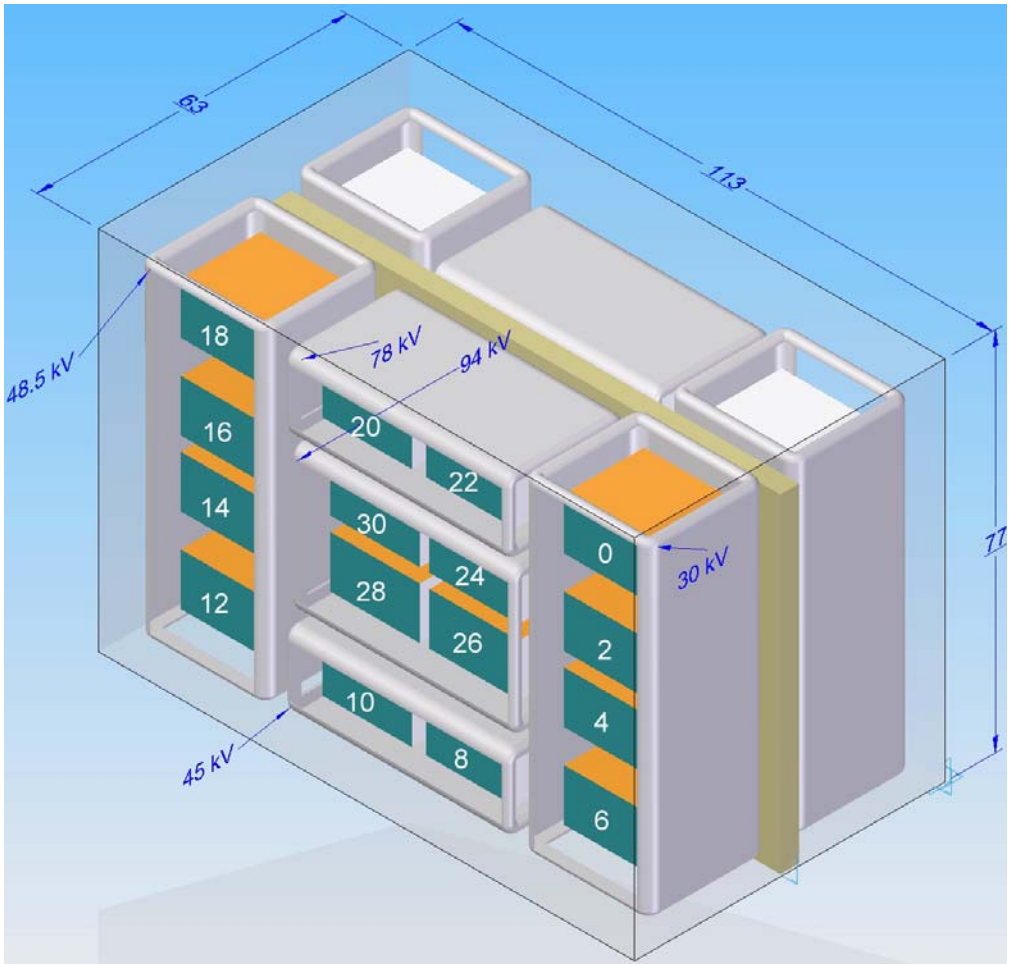
P2-Marx Conceptual Design

- 32 Cells
  - 3.75 kV Nominal Cell Voltage (Reliability)
  - 4 kV Max Cell Voltage (Redundancy) Isolate Failed Cells (2 Max)
  - 350 µF Cell Capacitance
  - On-cell Droop Compensation (Preliminary)
    - Simplifies control
    - Maximizes redundancy
    - PWM or Vernier
  - Air Cooling/Insulating: No Oil/Water Only in 2ndary Heat Exchanger
- Independent Charging Supplies
  - Optimize Power Level
  - Better Control Over Line Transients
- FPGA-based Diagnostic/Control Module

P2-Marx Conceptual Design



P2-Marx Conceptual Design



Marx Program Status Summary

- SLAC P1-Marx
  - Developmental Testing: Complete
  - Initial ESB Operation: 11/08
  - Integration into L-Band Station: Early ’09
  - Output Regulation (±0.5%): 3/09
- SBIRs
  - Complete ’09
  - Hardware to SLAC: FY10
- SLAC P2-Marx
  - Initial Design/Components Ordered: 12/09
  - 1st Cell Assembly & Testing: FY09-Q2&3
  - Multi-Cell Testing: FY09-Q4
  - Final Design/Components Ordered: FY10-Q1
  - Cell Assembly: FY10-Q2
  - Modulator Testing: FY10-Q3&Q4

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