Advanced Topology - Marx Modulators

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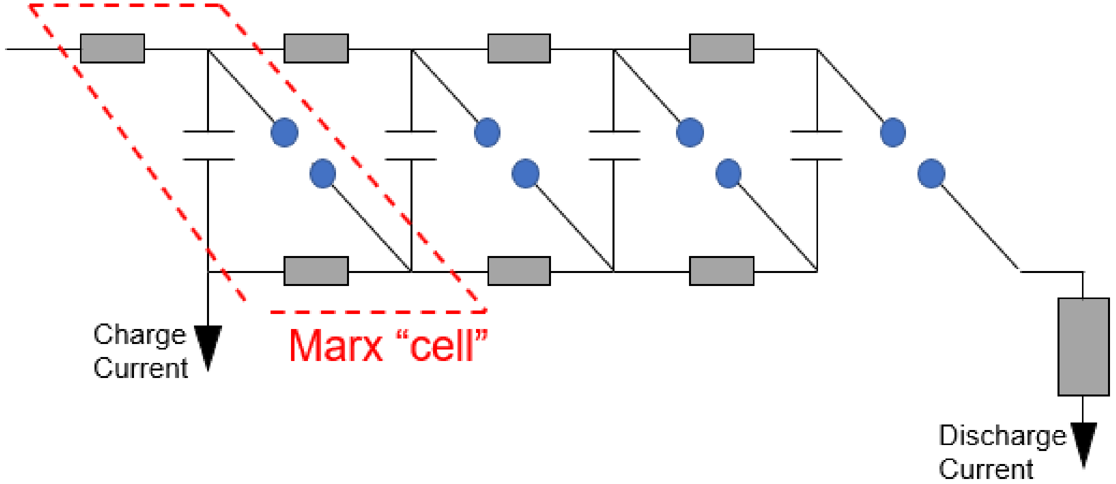
Basic Marx Generator

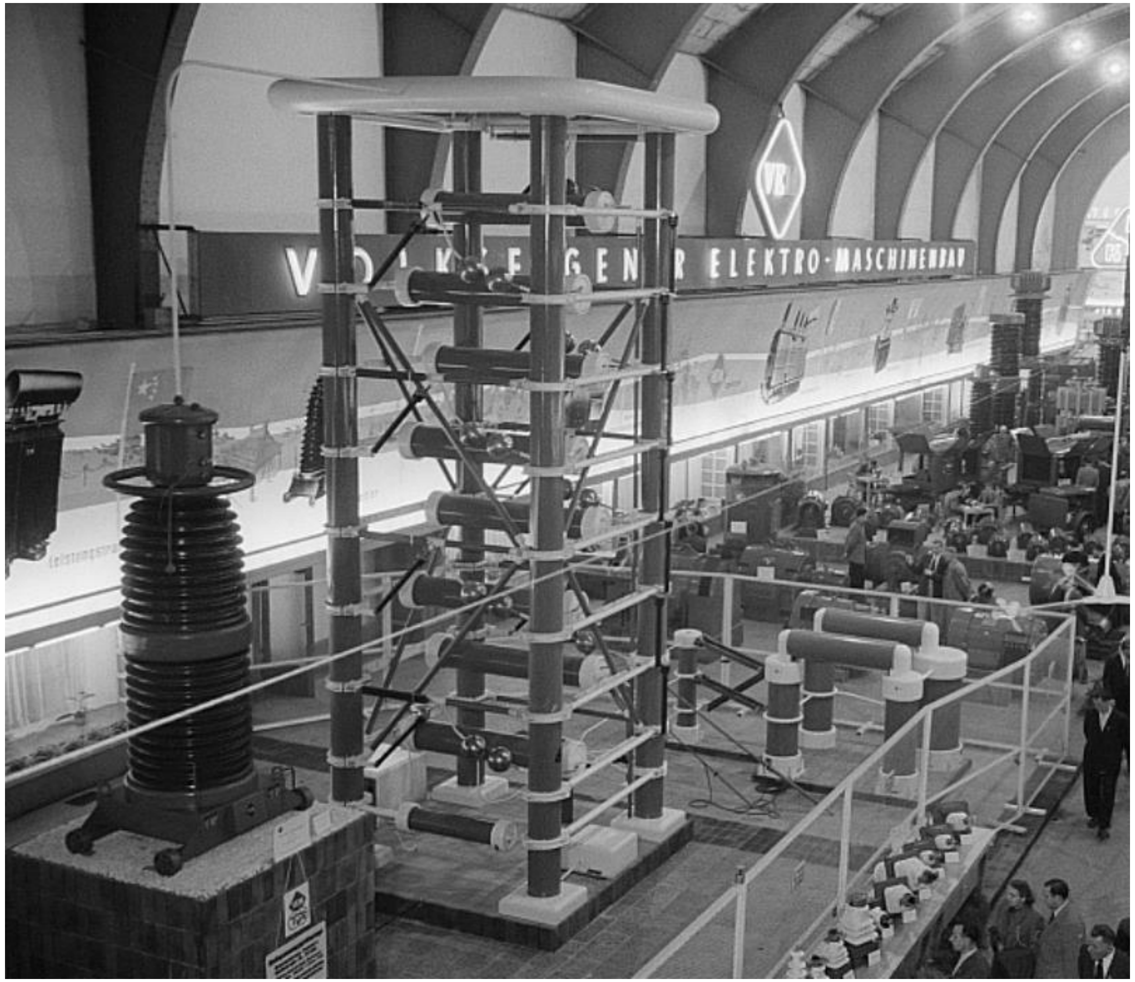
- Concept first proposed by Erwin Marx in 1925
  - Charge capacitors in parallel
    - Maximum voltage: V
    - Total capacitance: C*N
  - Discharge them in series
    - Maximum voltage: N*V
    - Total capacitance: C/N
- Applicable over wide range of parameters
  - Sub-μs < pulse length < multi-ms
  - ~0.1 MV < output voltage < over 10 MV
- Simplifies voltage insulation and reduces switch voltage by factor of N (up to ~100)
  - Relatively low voltage on long time scales (charging)
  - High voltage only present while being delivered to load



- Historically, switched with spark gaps. Triggering the first spark gap leads the other spark gaps to self commutate.

Basic Marx Generator

- Necessitates isolation elements between stages (R or L historically) that can hold off V
- Waveform subject to distortion
  - Reduced output voltage
  - Slow risetime
  - Impaired stage triggering
  - Due to parasitic circuit elements
    - Capacitance
      - Stage-to-stage
      - Stage-to-ground
    - Inductance
      - Switch
      - Capacitor
      - Leads/layout



Autumn exhibition of State-Owned Electrical Engineering Enterprises (VEM) at Leipzig, East Germany, 1954. Marx generator to test electric utility power transmission equipment. Deutsche Fotothek.

Basic Marx Generator

- Total output voltage
  - Without parasitics, output voltage is number of stages times the charging voltage
- Total energy storage
  - The total capacitance is the number of stages times the stage capacitance

$$E_{total} = \frac{1}{2} N_{stage} * C_{stage} * V_{charge}^2$$

  - Equivalently, the total energy is the series capacitance times the output voltage

$$E_{total} = \frac{1}{2} \frac{C_{stage}}{N_{stage}} * \left(V_{charge} * N_{stage}\right)^2$$

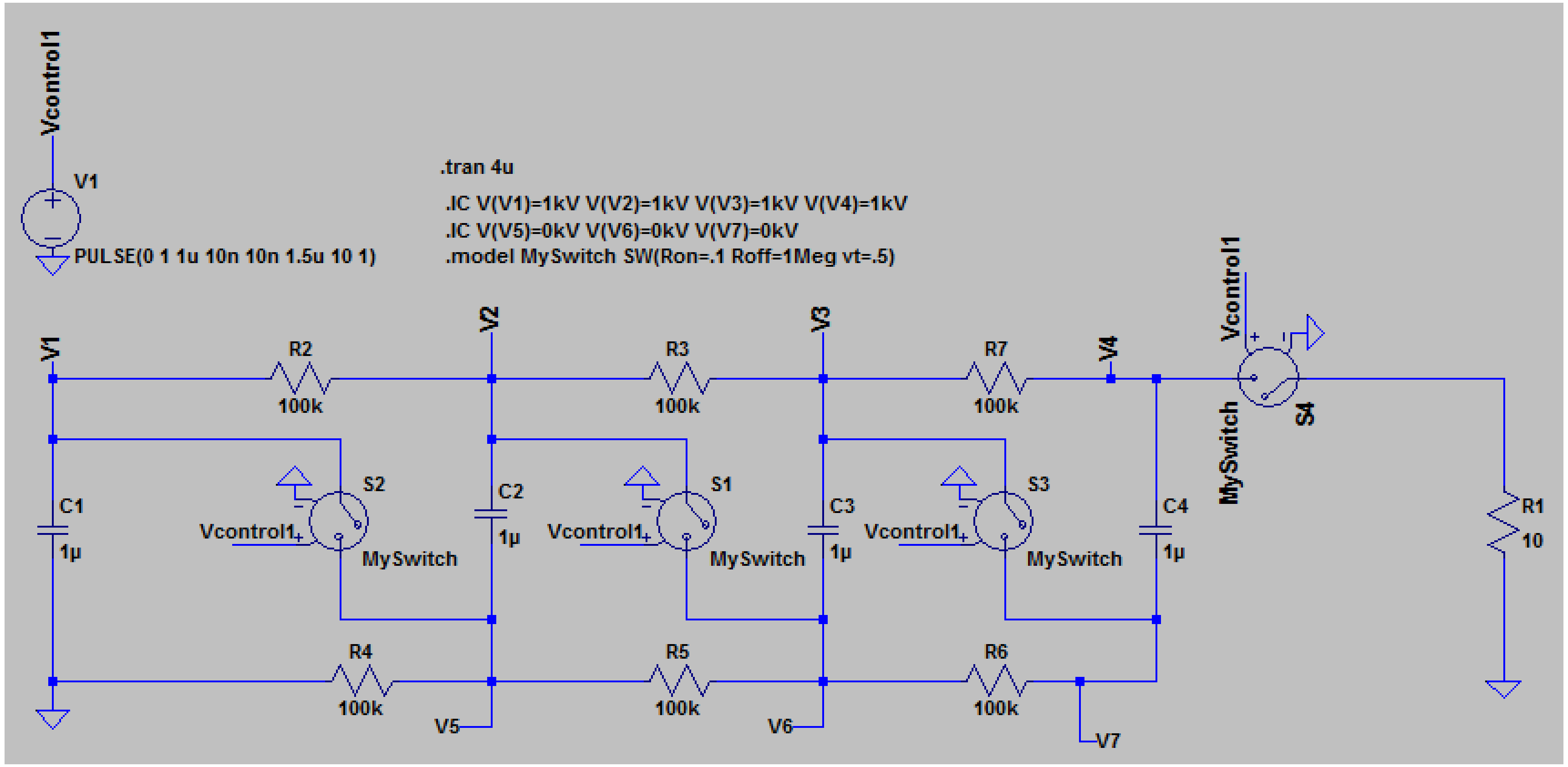
Basic Marx Generator

- The output shape depends on parasitics, the nature of the switch timing, and the load impedance. Most simply, the erected Marx is a capacitance discharging into a resistance

- For many accelerator applications, the output pulse must be truncated. Therefore, opening switches are required. These also prevent excess energy transfer to the load during a fault

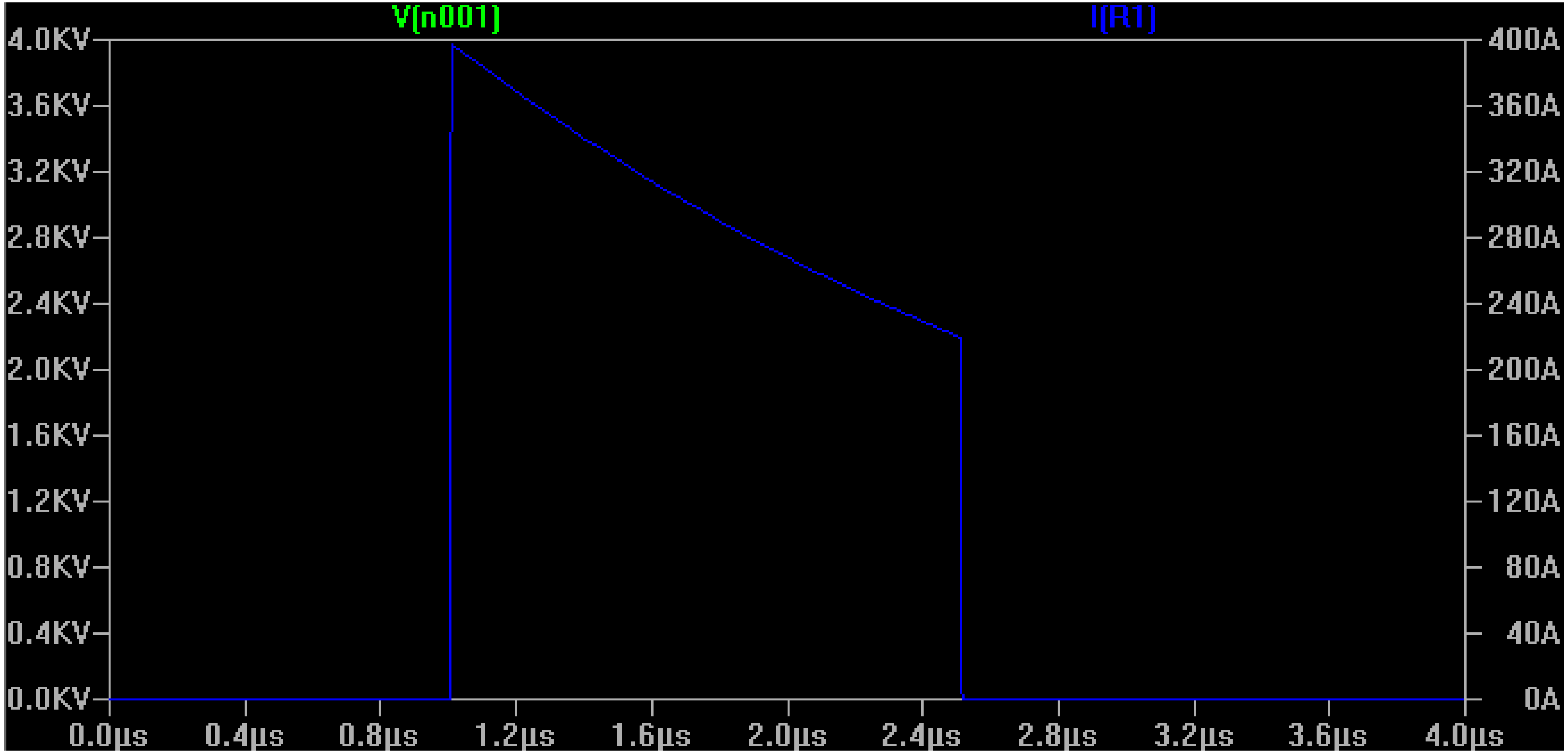
Marx-parasitics

- Start with a simulation of an “ideal” 4 stage Marx
- Each stage is 1 µF and charged to 1kV
- Load is a 10 Ohm resistor
- Switches turn on for 1.5 µs, then turn off



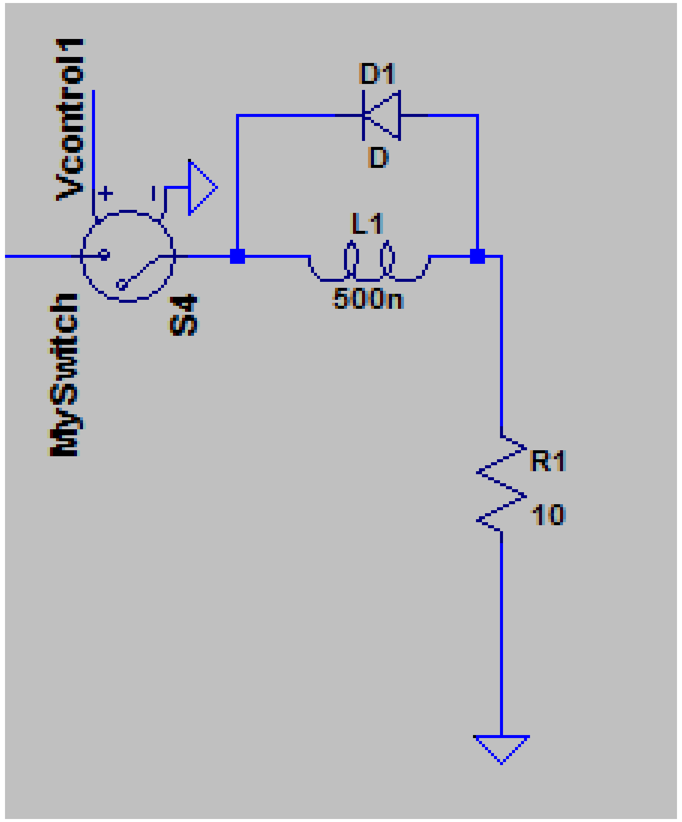
Marx-parasitics

- Voltage instantly rises to 4kV, then has an RC decay until the cells turn off



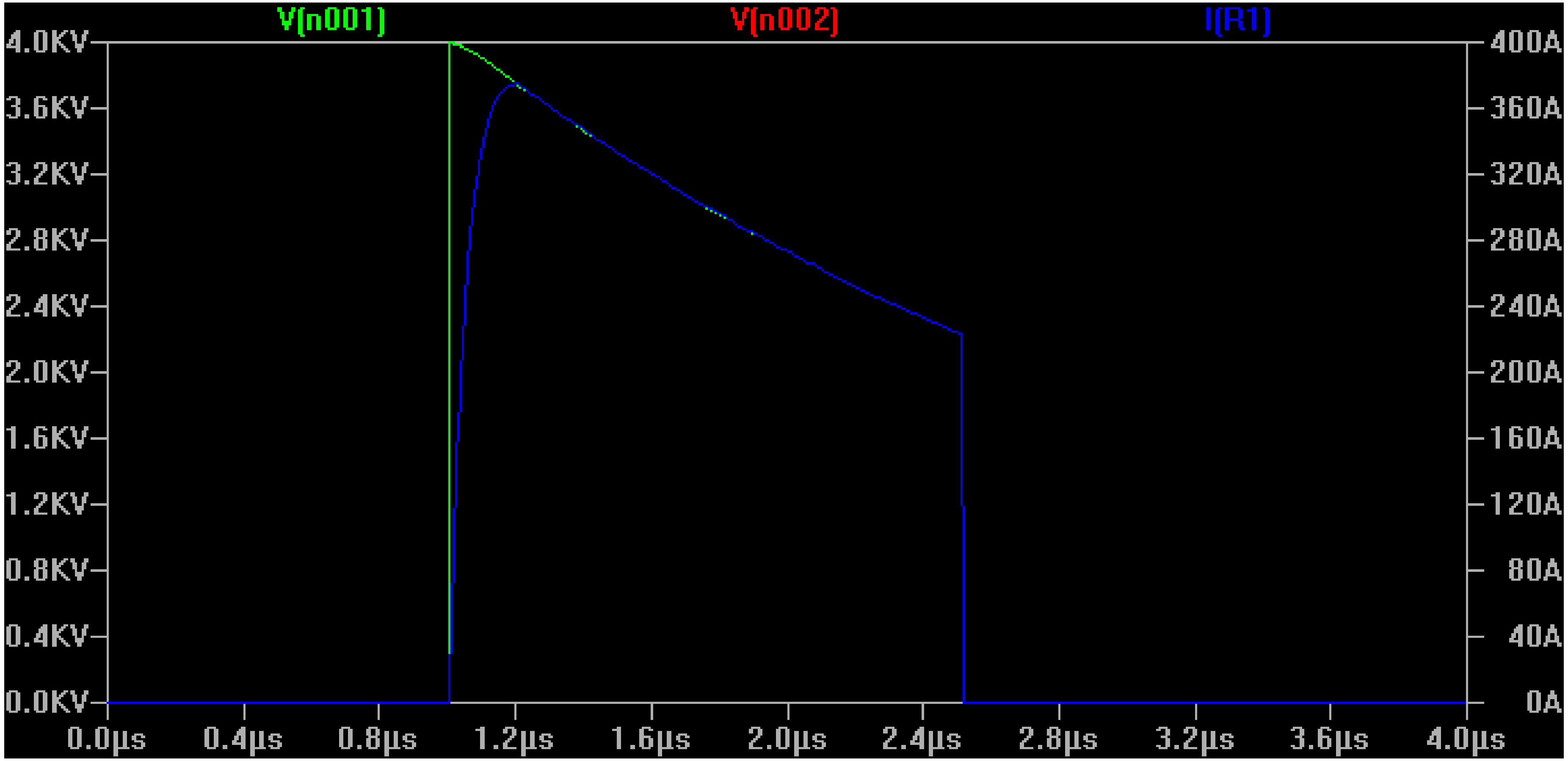
Marx-parasitics

- Add a 500 nH inductance to the load
  - This could simulate parasitic inductance or intentionally added inductance.
- Free-wheeling diode conducts the current during Marx turn-off
  - Without, there would be a large voltage spike from the inductance



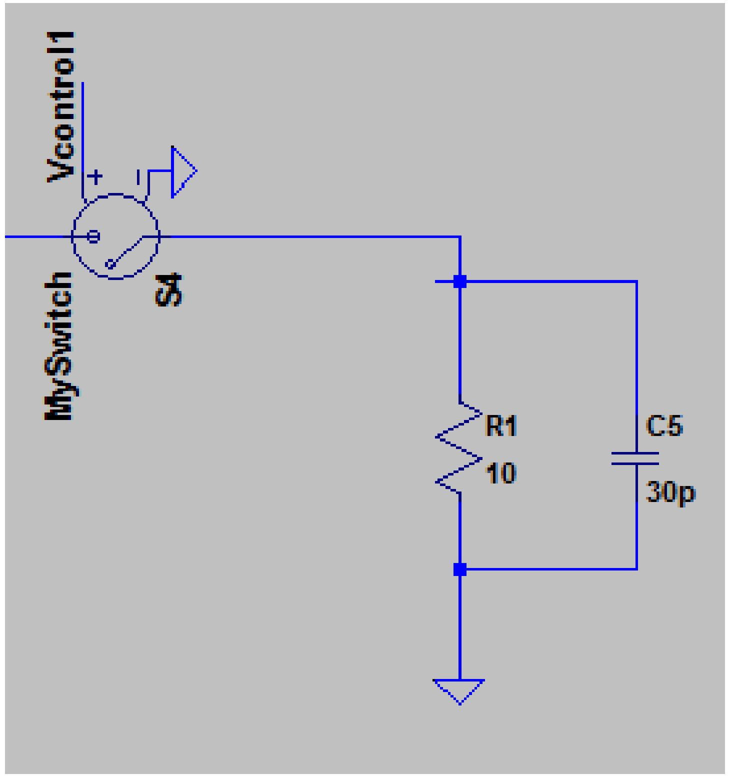
Marx-parasitics

- L/R risetime added to rising front of current waveform.



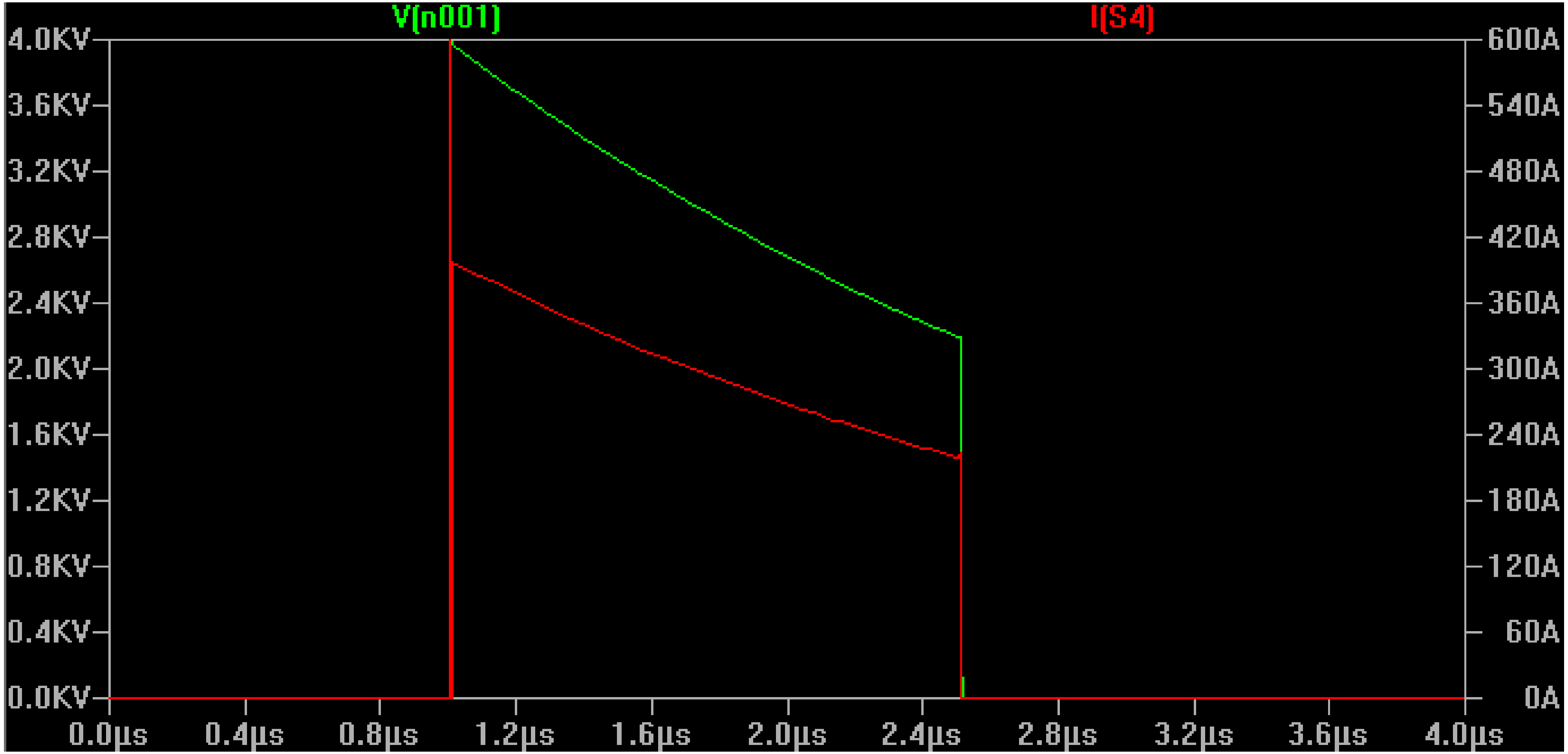
Marx-parasitics

- Add a 30 pF capacitance in parallel with the load to simulate parasitic capacitance.



Marx-parasitics

- Current spike as parasitic capacitance charges.



Desired Characteristics of Next-Generation Modulators

Low Cost	Easily Maintained	High Availability	Superior Pulse Quality
Efficient operation	Simple construction	High mean time between failures	Pulse to pulse repeatability
Commoditized components from multiple vendors	Easy-to-get-to parts	Low mean time to repair	Operation into multiple impedance loads
Low fabrication costs	Simple safety procedures	Redundant architecture	Exceptional flat-top

Desired Characteristics of Next-Generation Modulators

How does a Marx Modulator Achieve these characteristics?

Low Cost	Easily Maintained	High Availability	Superior Pulse Quality
Modularity			
Low-Voltage Sub-Units			
Electrostatic Adding			
Independent Module Control			

Desired Characteristics of Next-Generation Modulators

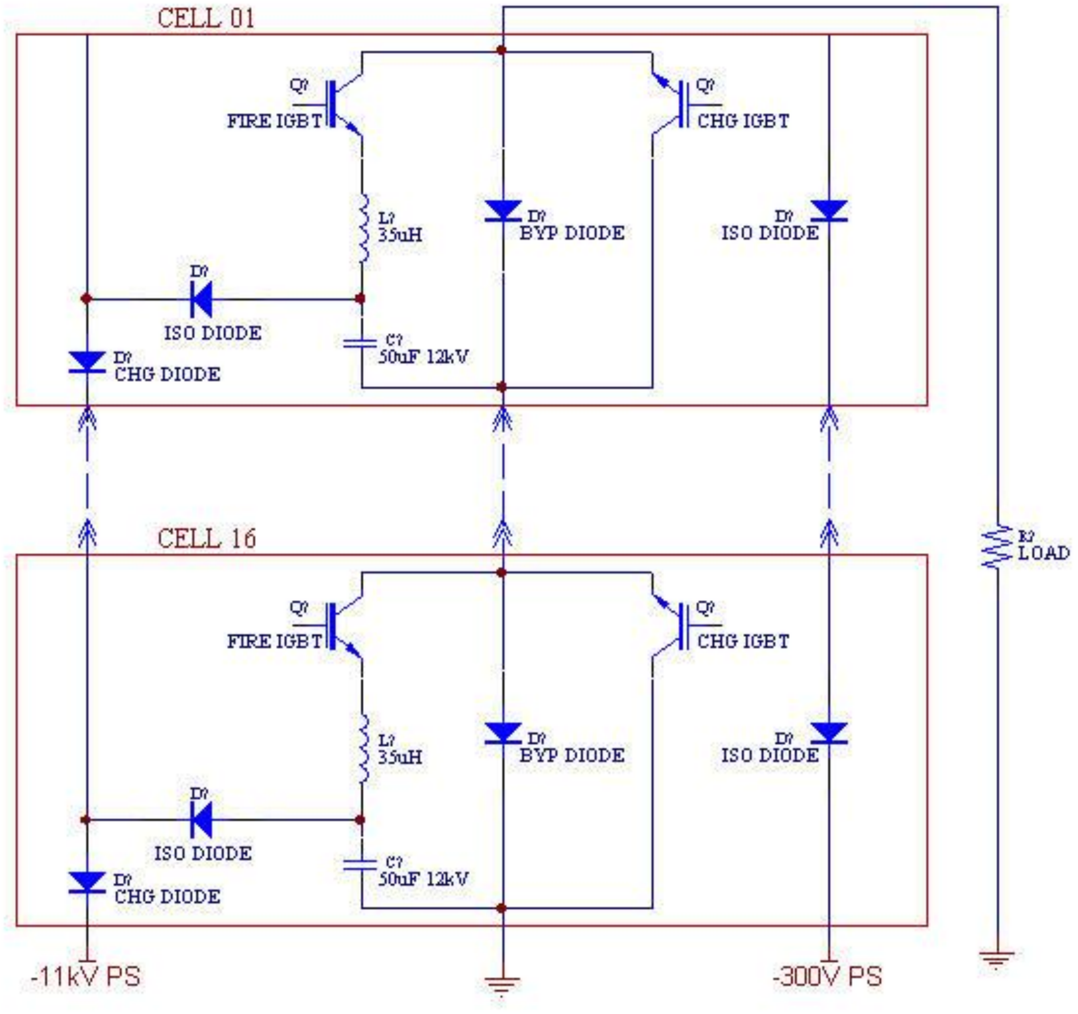
- Modularity
  - Building blocks can be arranged in different configurations for different applications
  - Many inexpensive components
- Electrostatic Adding
  - Pulse transformer not necessary
- Independent Module Control
  - Reconfiguration possible
- Low-Voltage Sub-Units
  - ***Conventional power electronic converter techniques can be employed***
  - ***Commoditized components***

Solid State Marx

- Use as a voltage multiplier to array solid state switches to klystron voltage requirements
  - Output ~0.1 MV
  - Cells ~few kV
  - Square output waveform
    - Hard switch (close/open) topology
    - Controlled switching of each cell
  - High average power
  - High PRF (> Hz)
  - Long life

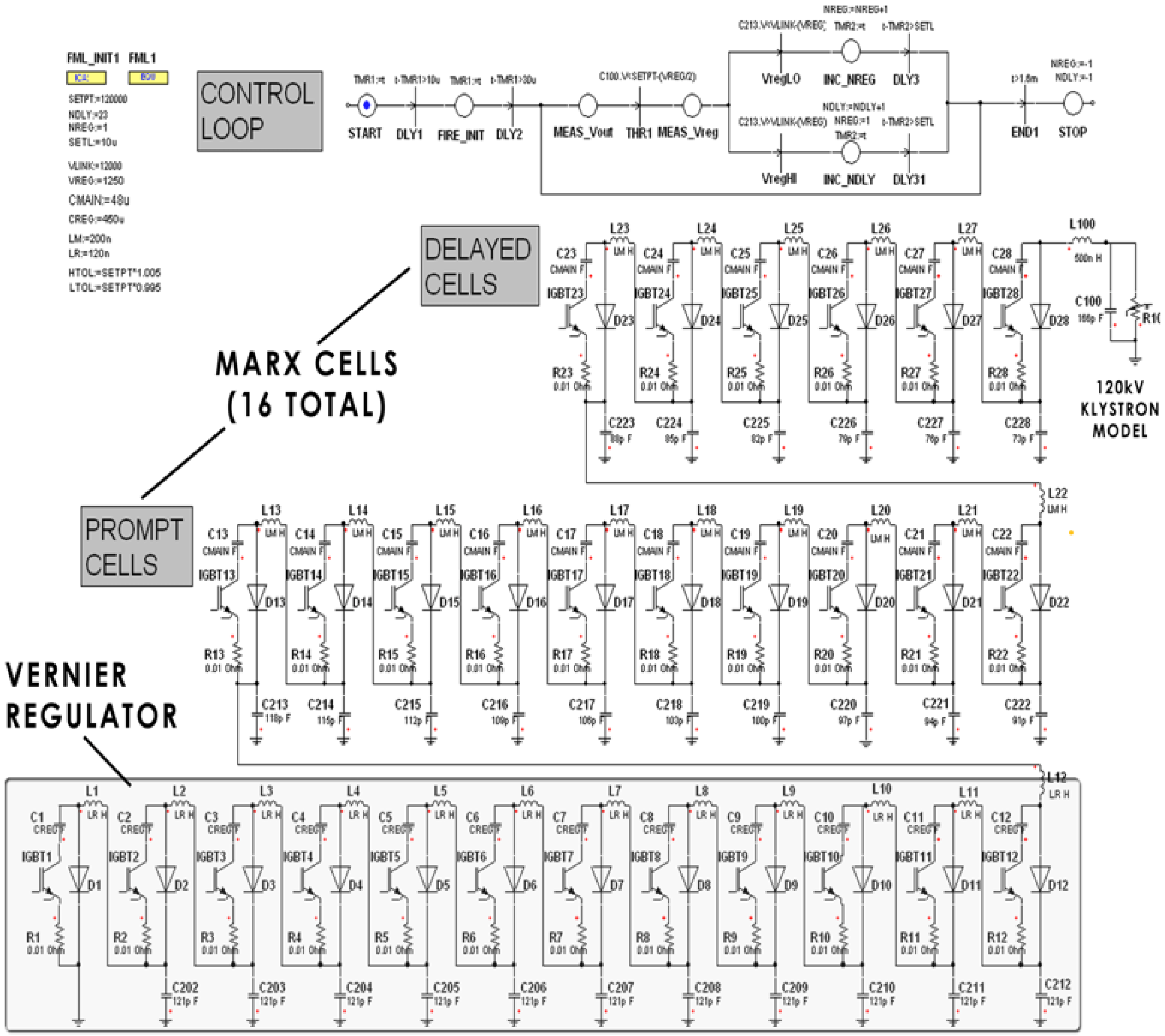
- Solid state charging/isolation elements
  - Low loss
  - Minimize recharge time

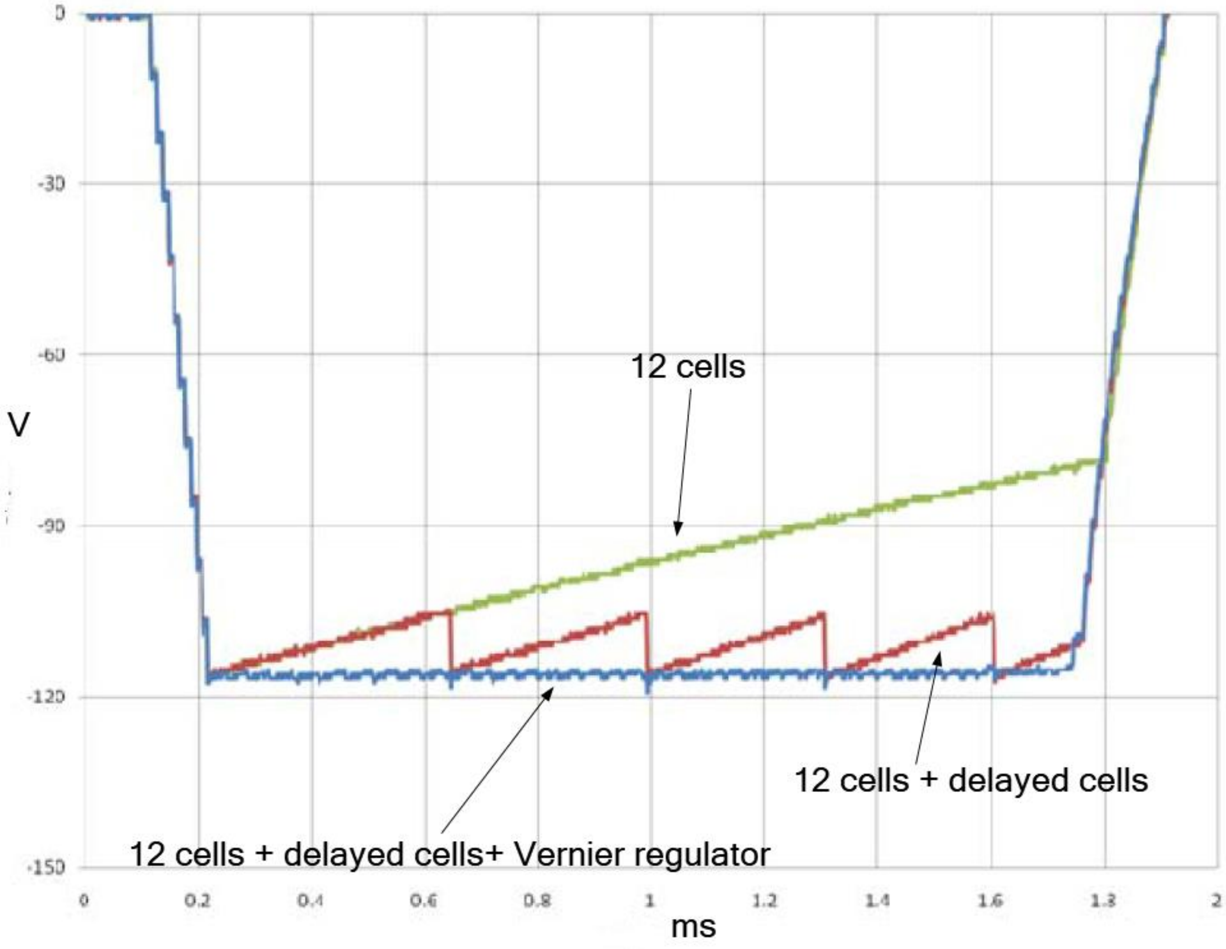
Simplified Schematic of ILC-Marx P1-Prototype



- 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

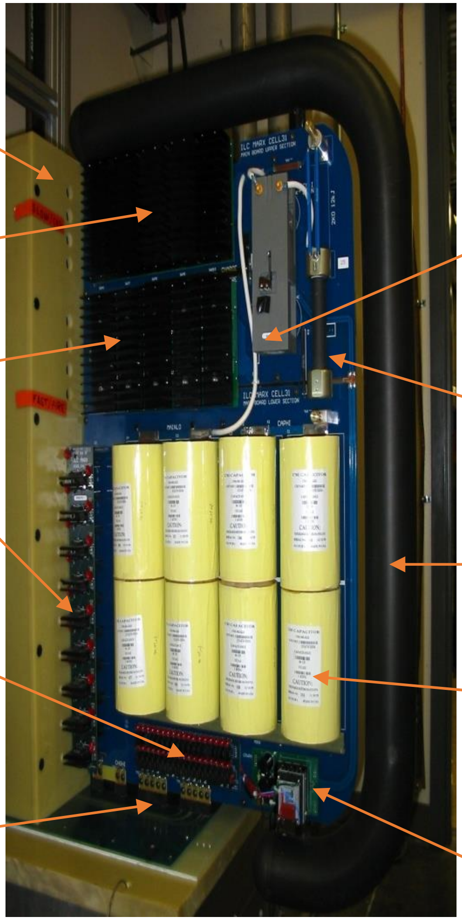
P1-Marx Voltage Regulation



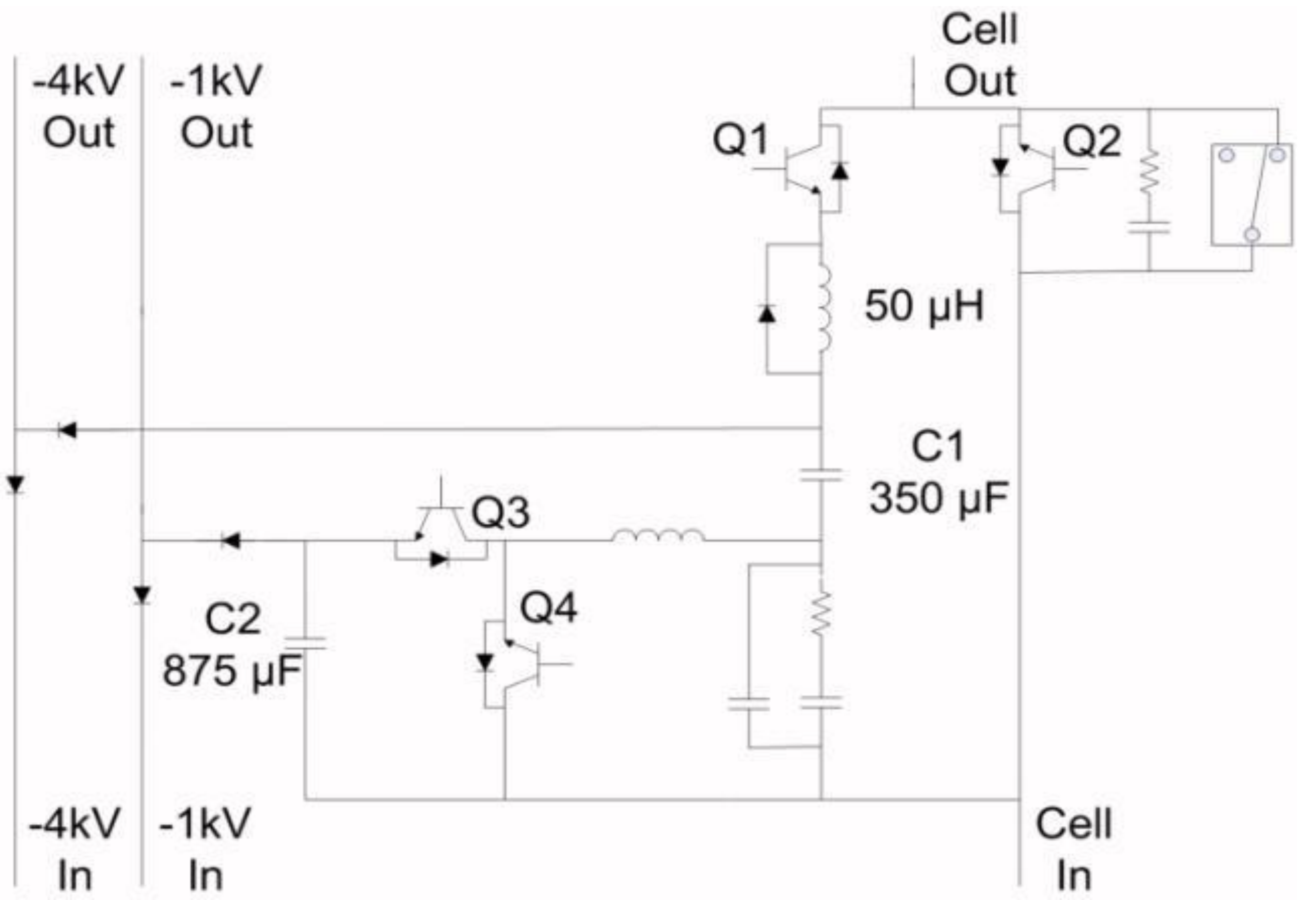


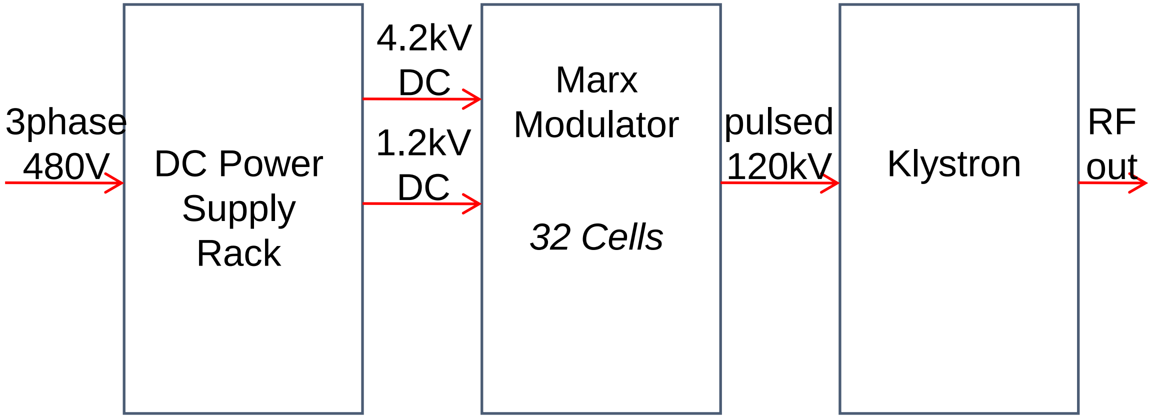
P1-Marx Installed in “Sealed” Enclosure

P1-Marx Cell Front & Rear Views



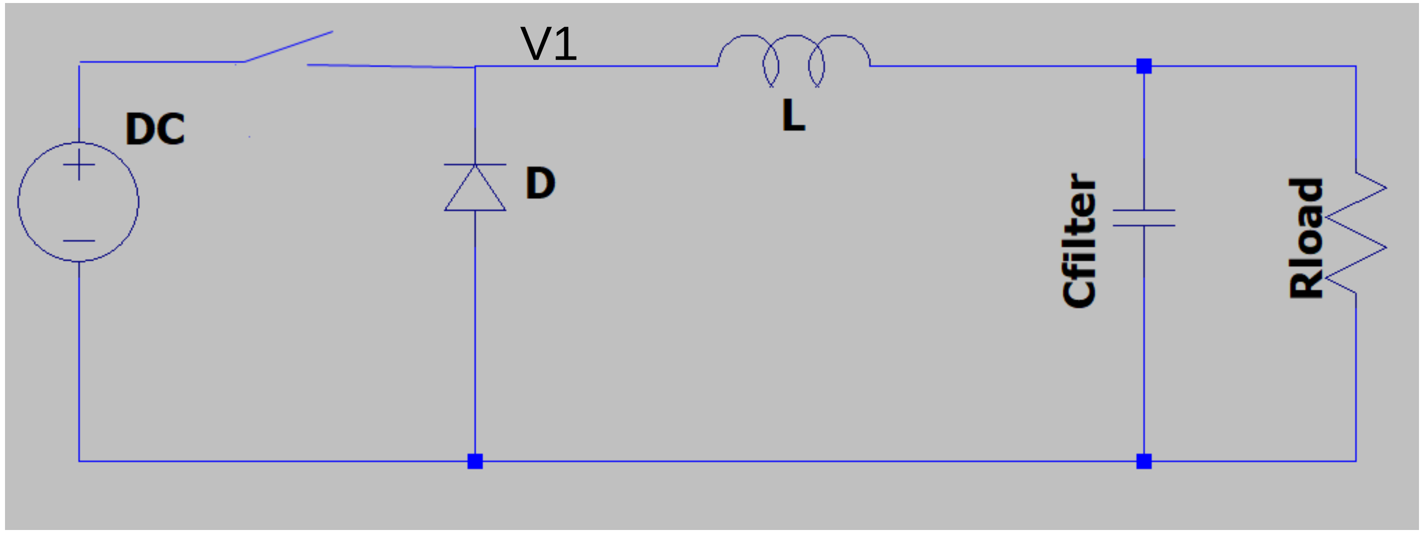
The SLAC P2 Marx

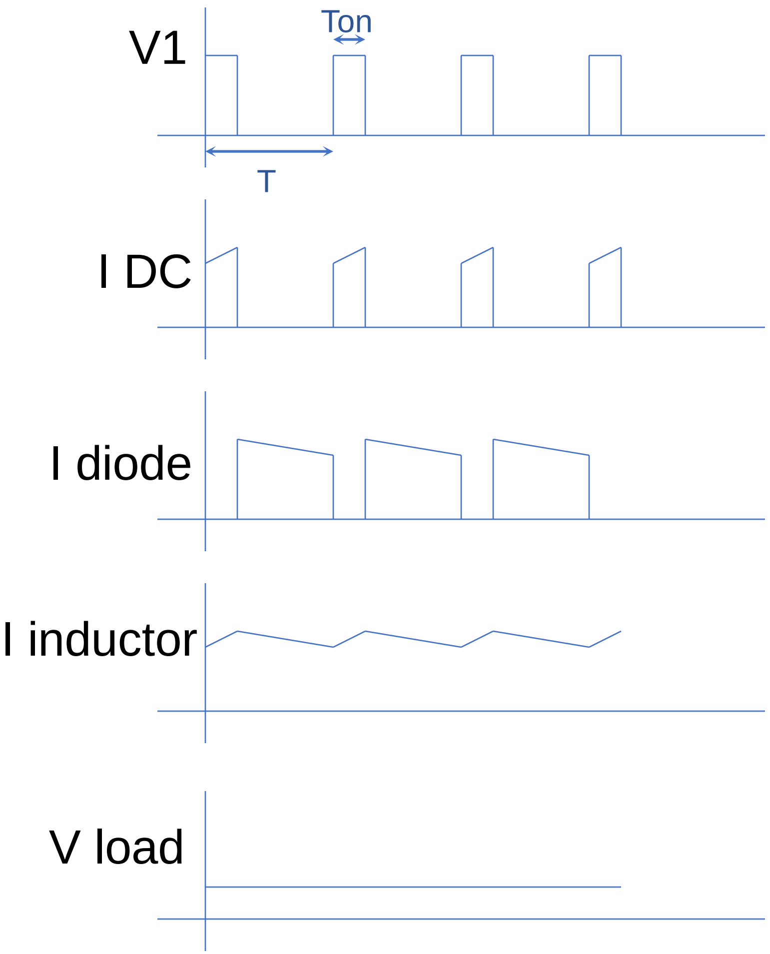




- Each Marx cell produces a flat-top: a “buck” converter is in series with the main cell capacitor
- The modulator regulation is closed-loop
- N+2 redundancy

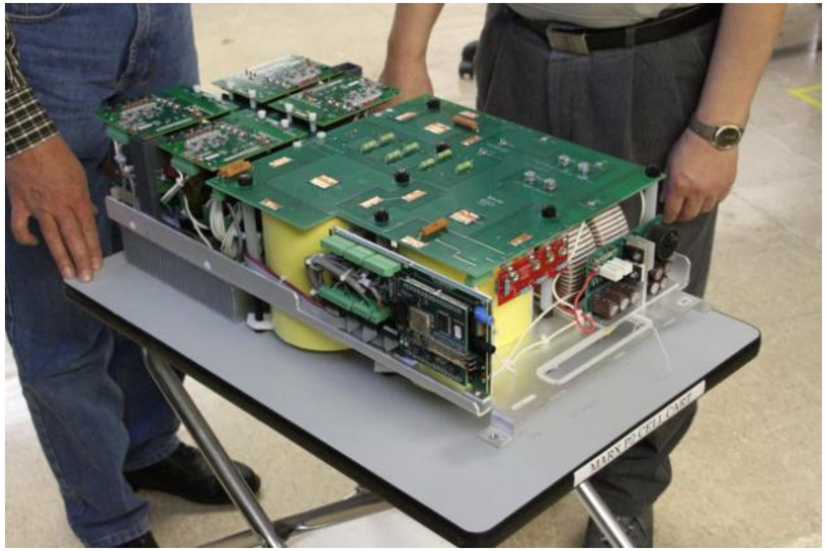
Buck Regulator



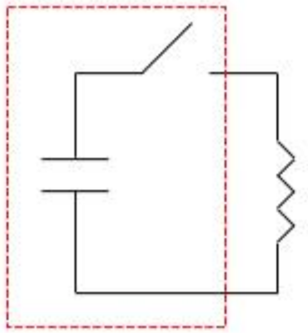


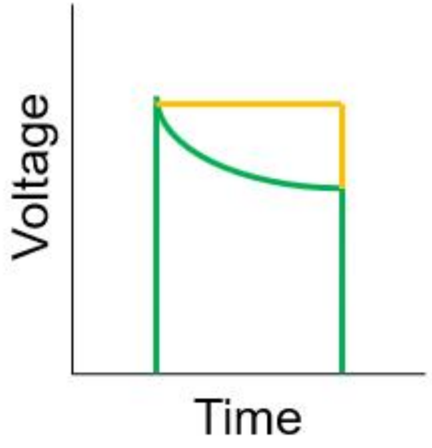
V load = Ton/T * Vdc

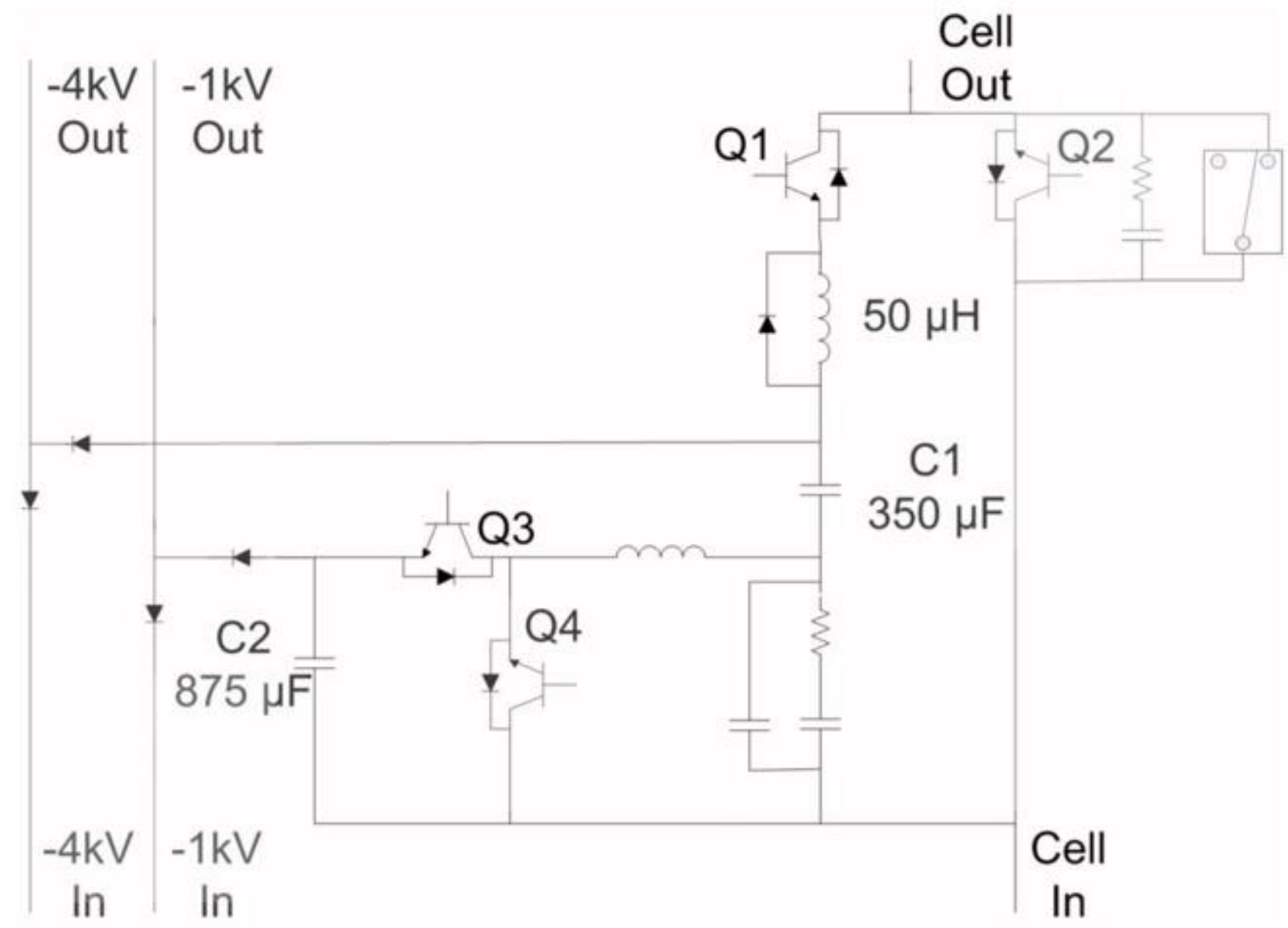
SLAC P2 Marx Photographs



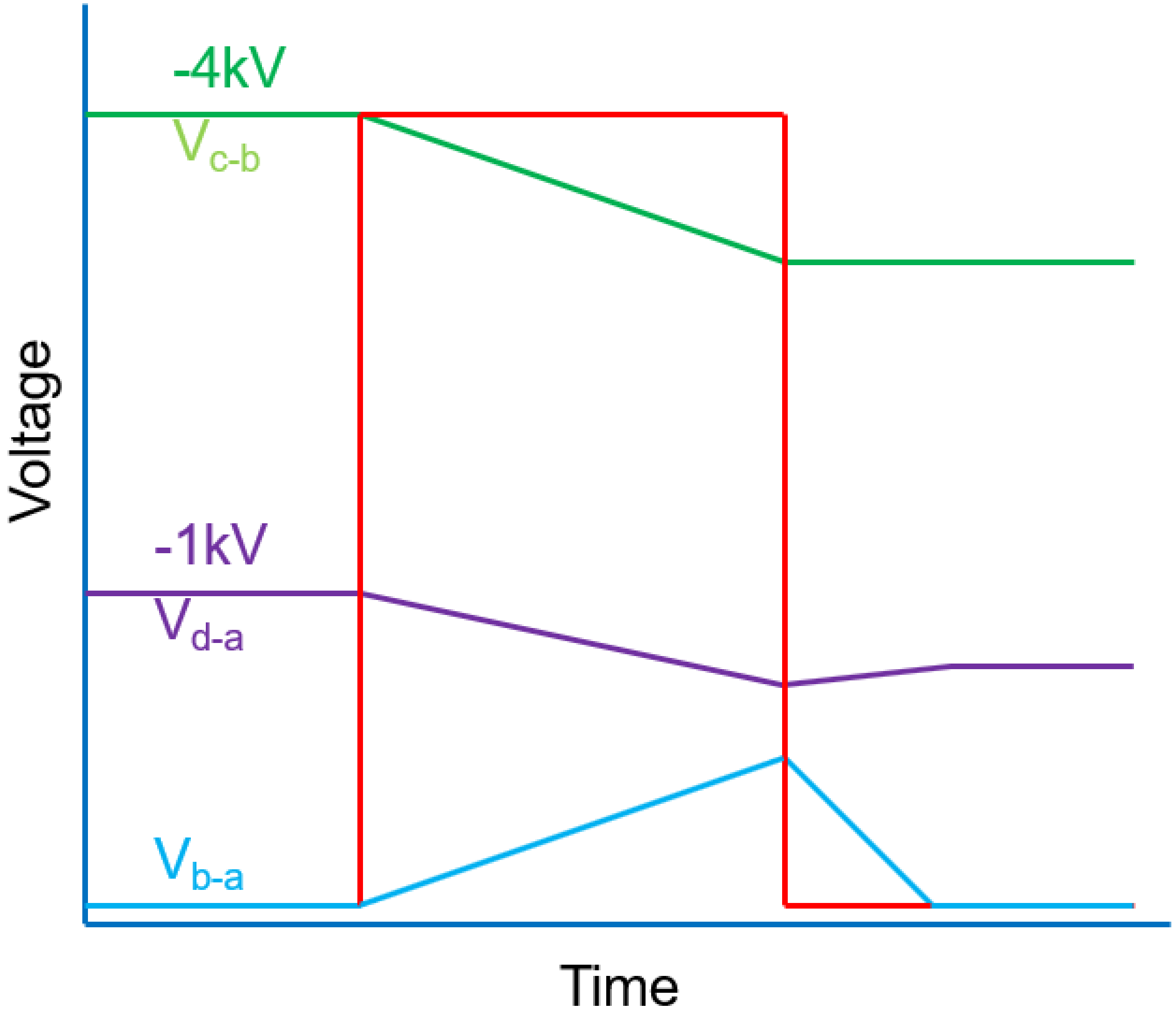
SLAC P2 Marx Cell Schematic

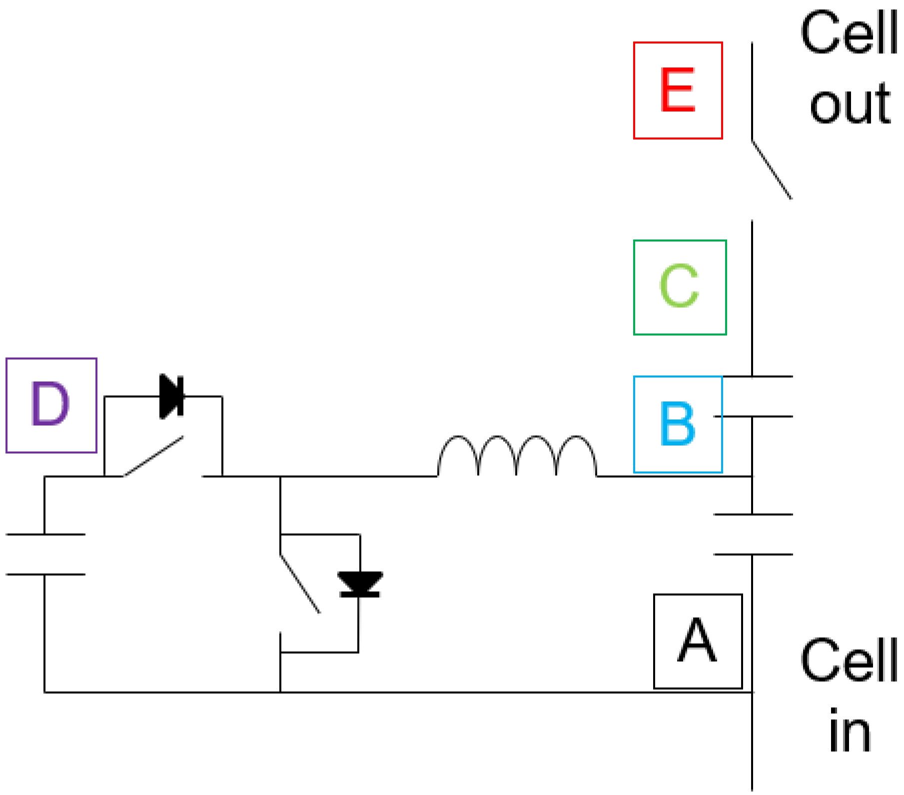






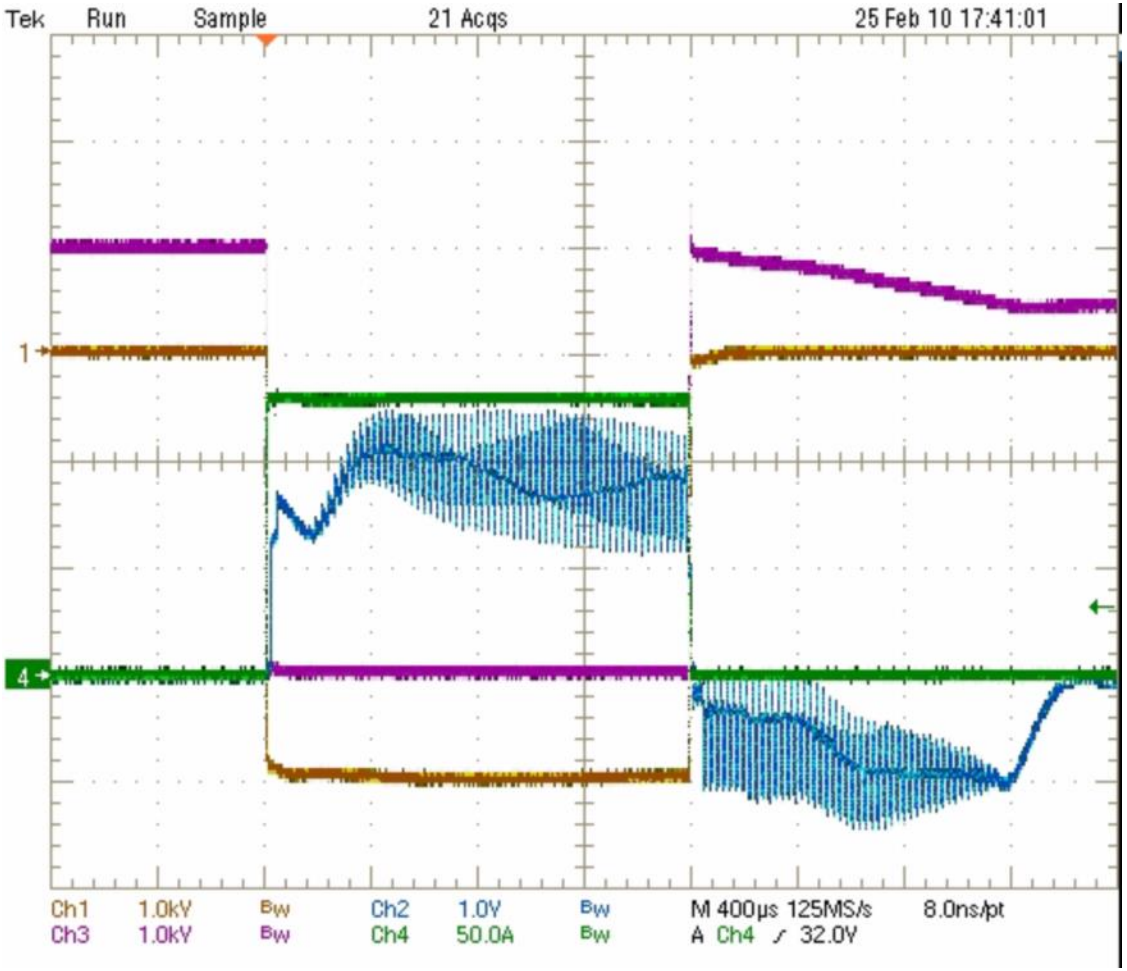
Correction Scheme





(negative bus voltage)

Correction Scheme

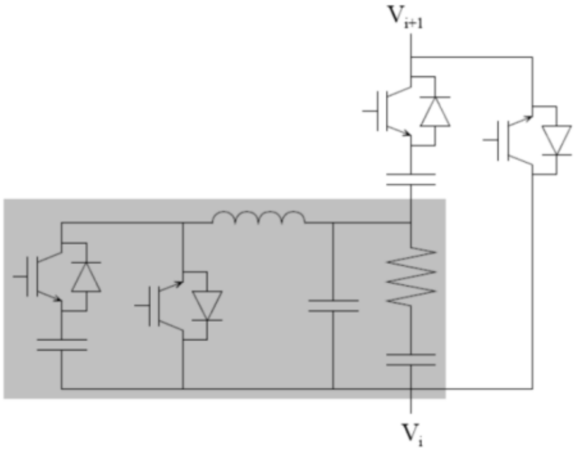


Cell Output Current

Cell Output Voltage

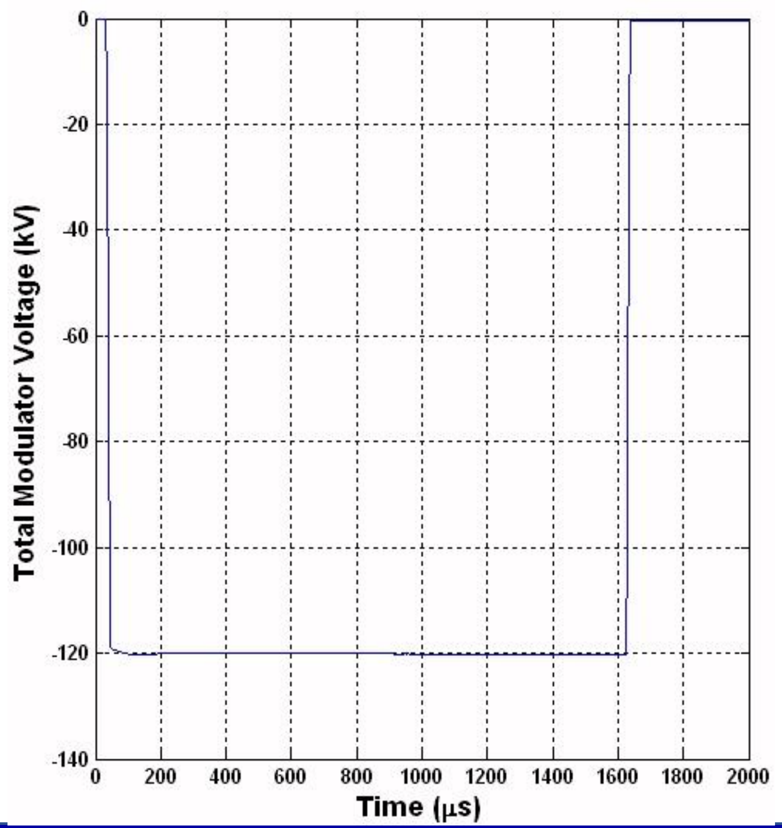
Main IGBT V_{ce}

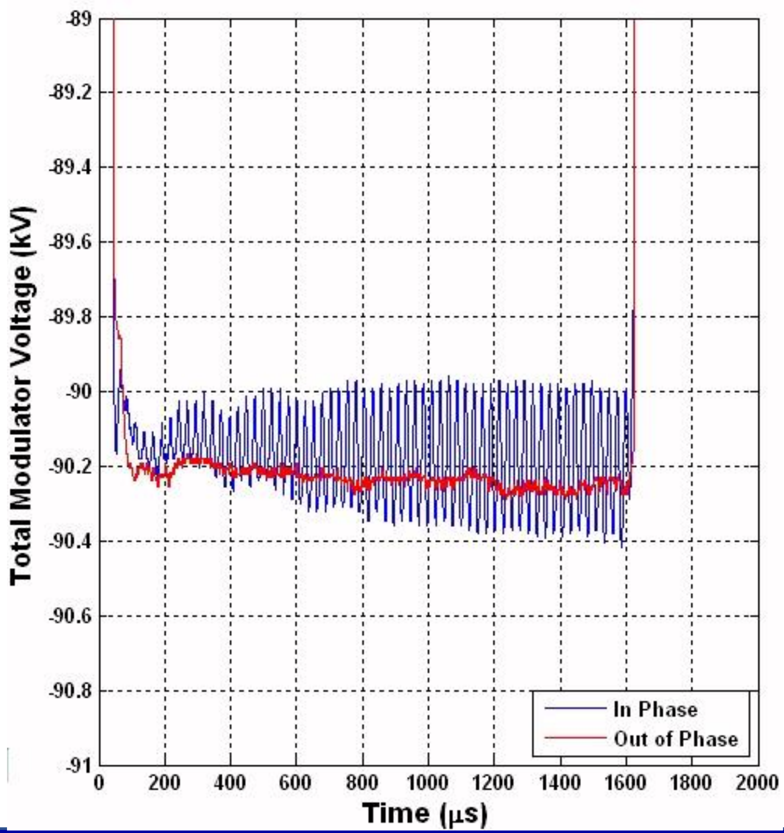
PWM Inductor Current



SLAC P2 Marx Performance

- Marx rise and fall times are ~10 µs
- A flat top has been demonstrated -> +/-0.05% over 1.6ms

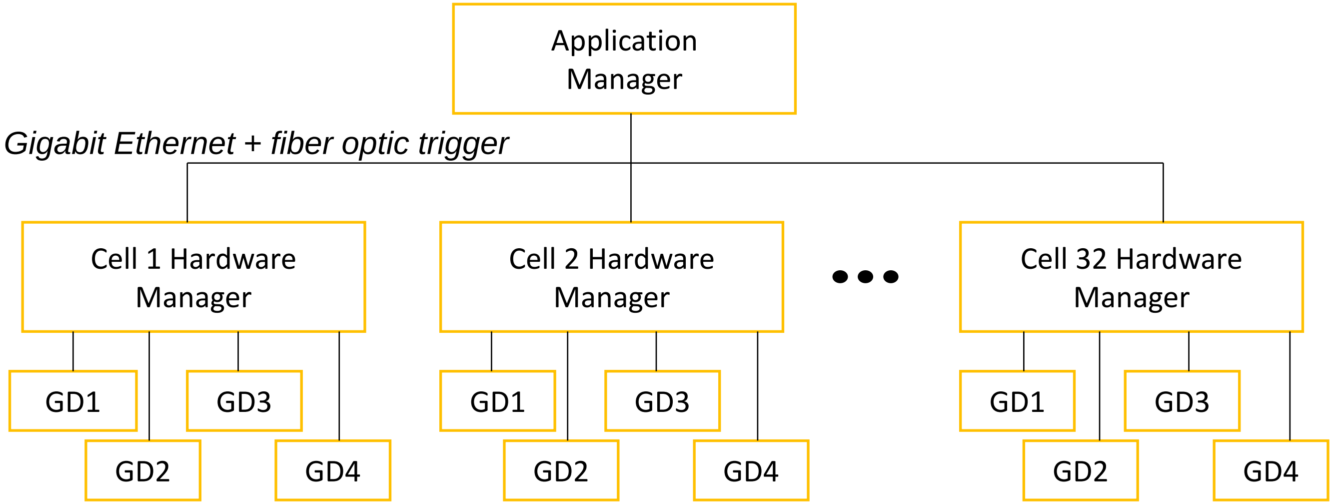




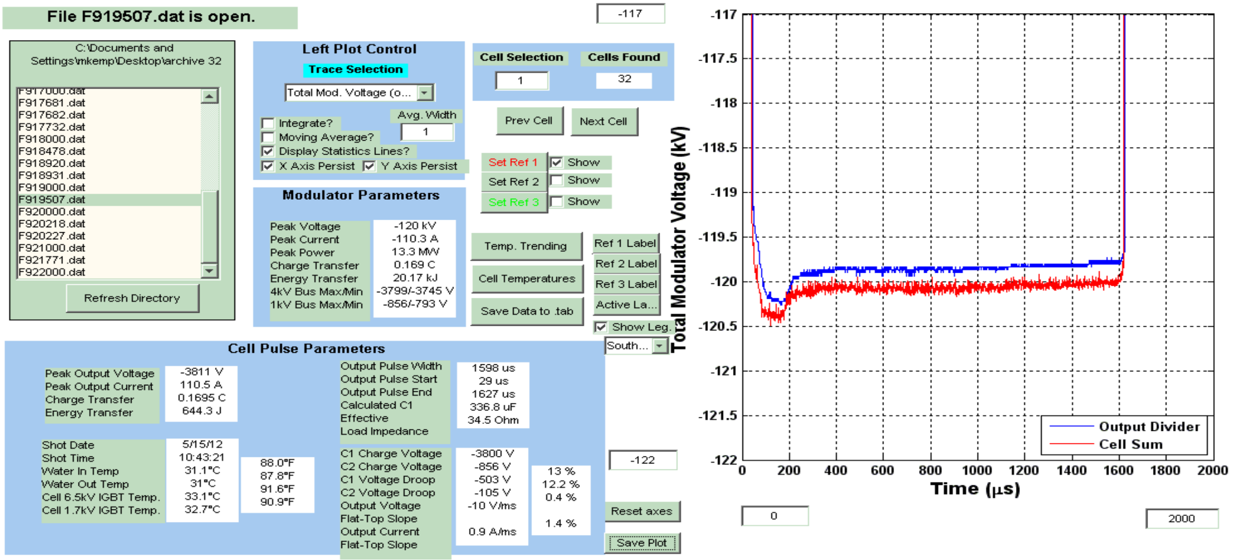
SLAC P2 Marx: Simple Maintenance

- A single cell can be changed in 2 minutes
- Maintenance is “back at the shop” rather than at the modulator -> low MTTR

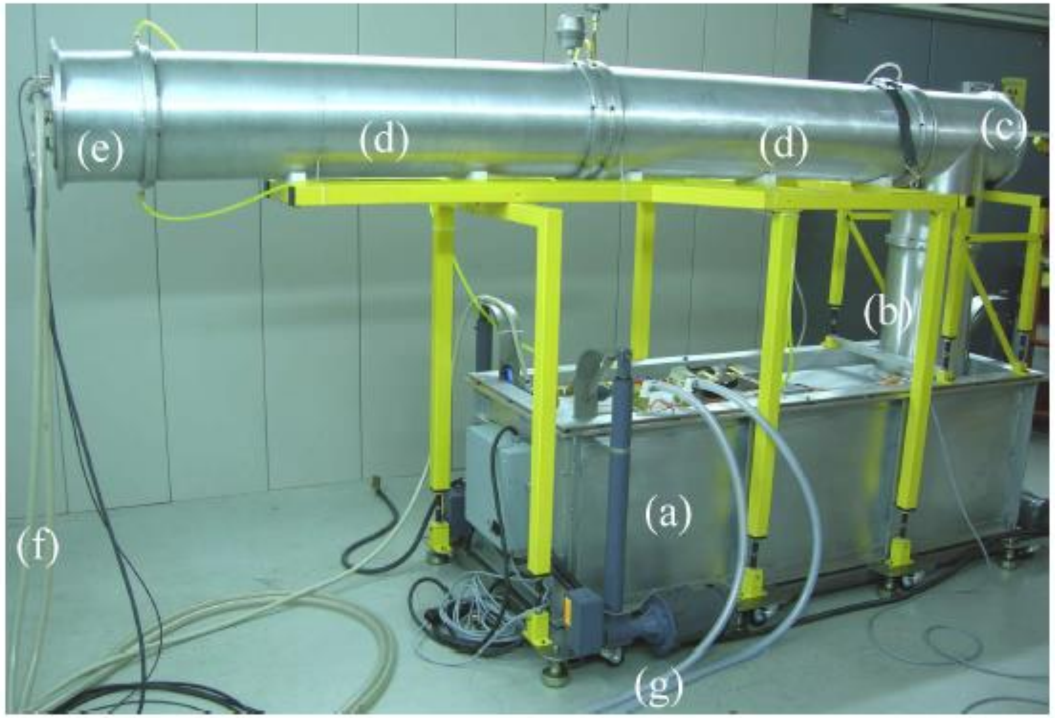
SLAC P2 Marx Control System

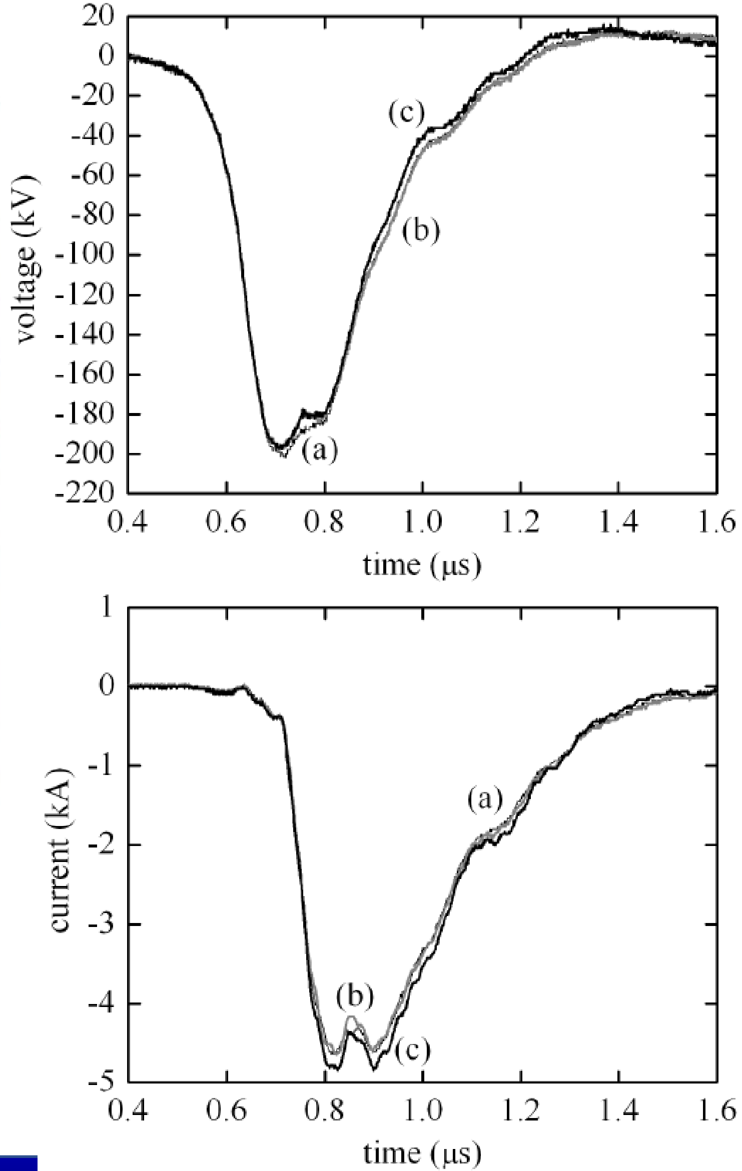


- 256, 12-bit, 1 MS/s, 2.1ms-long waveforms are captured each shot



Some Embodiments of the Technology



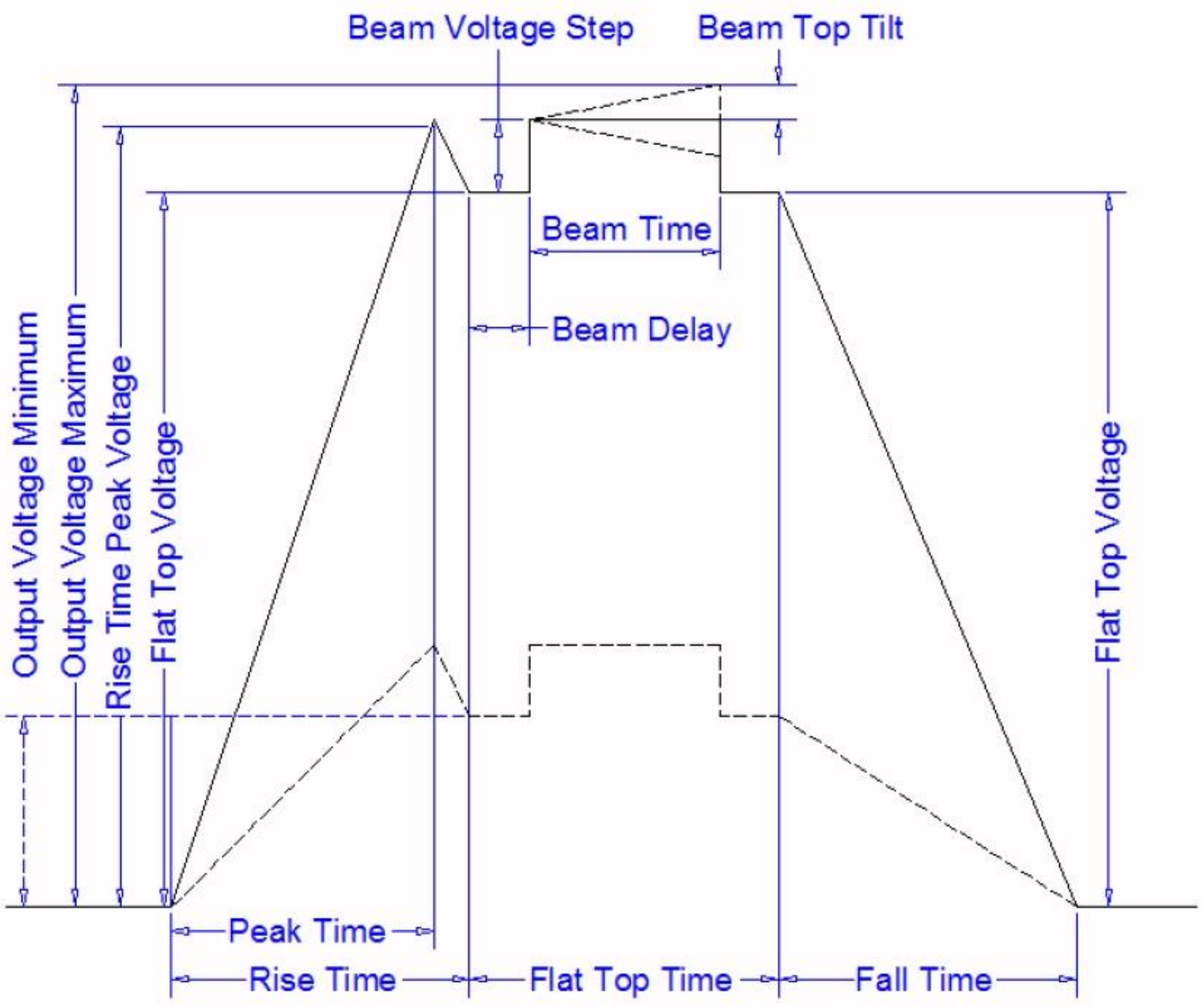


NRL Marx Modulator for KrF Laser

•-200 kV, -5 kA, 300 ns, 10 Hz pulses

F. Hegeler, et al., "A Durable Gigawatt Class Solid State Pulsed Power System, Trans. Plasma Sci. 2011.

201 MHz Linac Triode



Fermi Designed/Built Modulator For This Load [1]

FNAL Linac Marx Topology

41 Main Marx Cells (900 V)

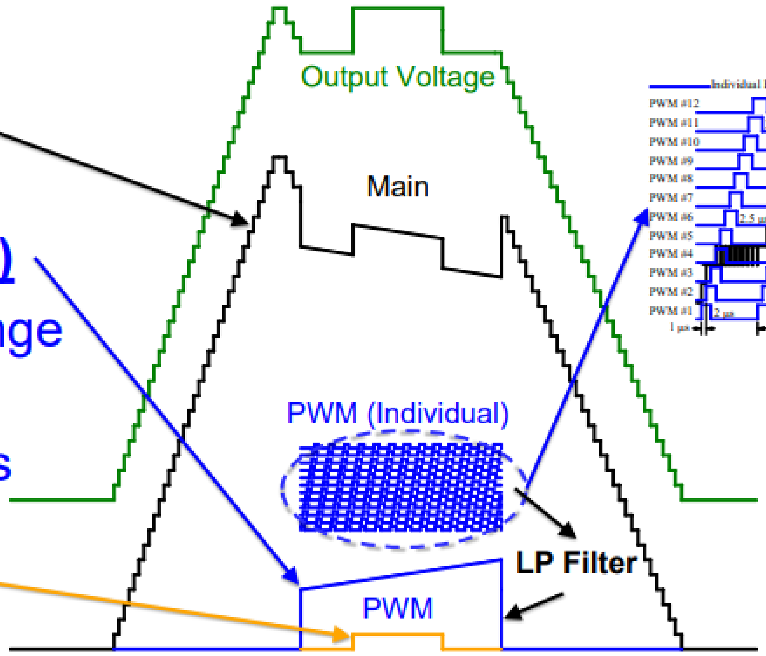
- Create the rising and falling edges
- Limits cavity reflected power back to tube

12 Pulse Width Modulation Cells (900 V)

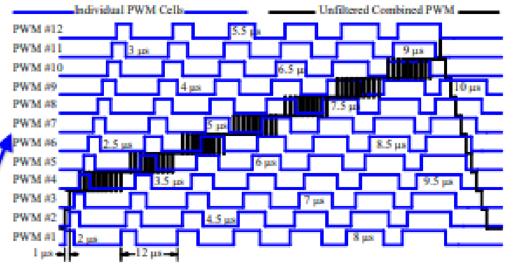
- Interleaved & filtered regulator w/ 7 kV range
- Flatten capacitive droop & regulate flattop voltage via feedback & learning algorithms

1 Special Cell (0 to 900 V)

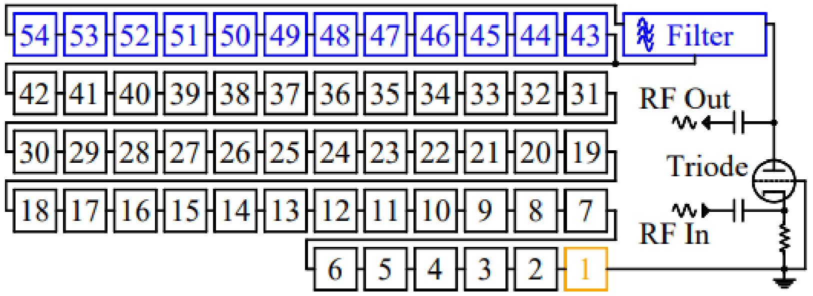
- Independently adjustable charging PS
- Enables fractional beam voltage step size



Marx Waveform Breakdown

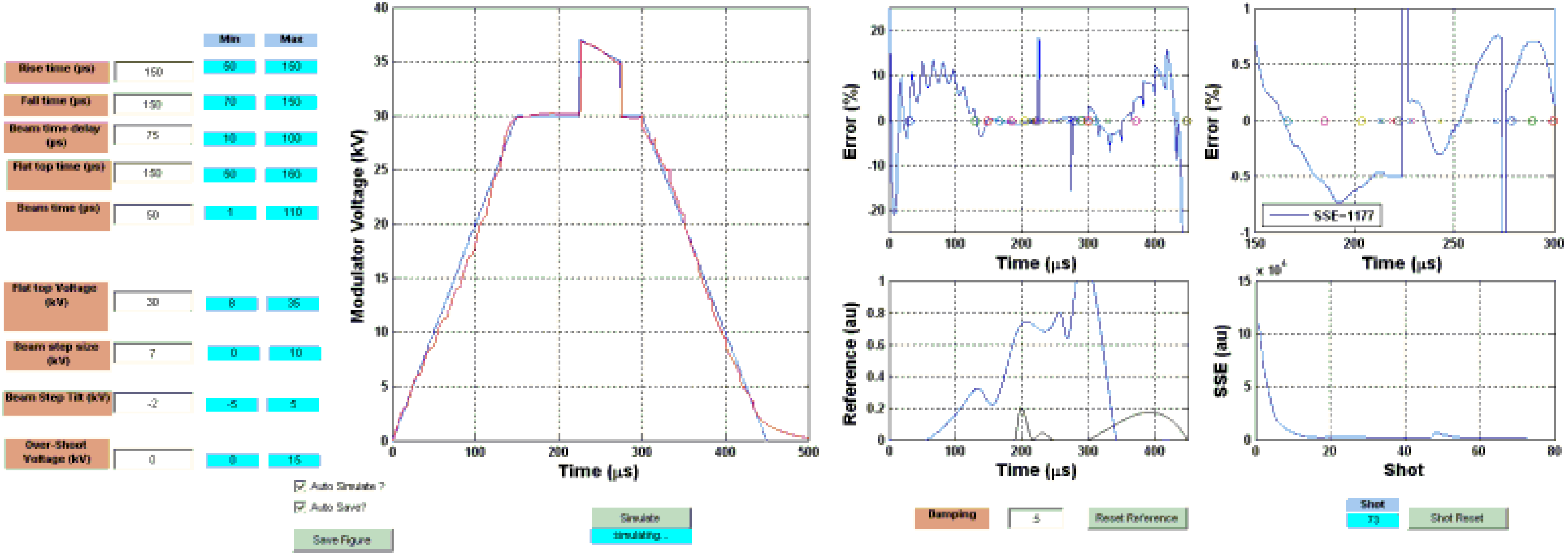


PWM Interleaving



[1] Development of a Marx Modulator for FNAL Linac Trevor A. Butler, F. G. Garcia, M. R. Kufer, K. S. Martin, H. Pfeffer, FNAL, Batavia, IL 60510, USA . Poster. NAPAC 2019.

201 MHz Linac Triode Modulator Early Paper Study (Feed Forward)



Scaling of the Technology to Emerging Applications

- The ILC P2 Marx building block has:
    - A maximum voltage (4kV)
    - A maximum peak current (200A)
        - Can increase by changing switches
    - A maximum average power
        - Can increase by changing cooling
    - A maximum energy transfer per pulse
        - Can increase by increasing cell capacitance