Advanced Topology - Marx Modulators

Pulsed Power Engineering
Michigan State University
February 3 – 7, 2025

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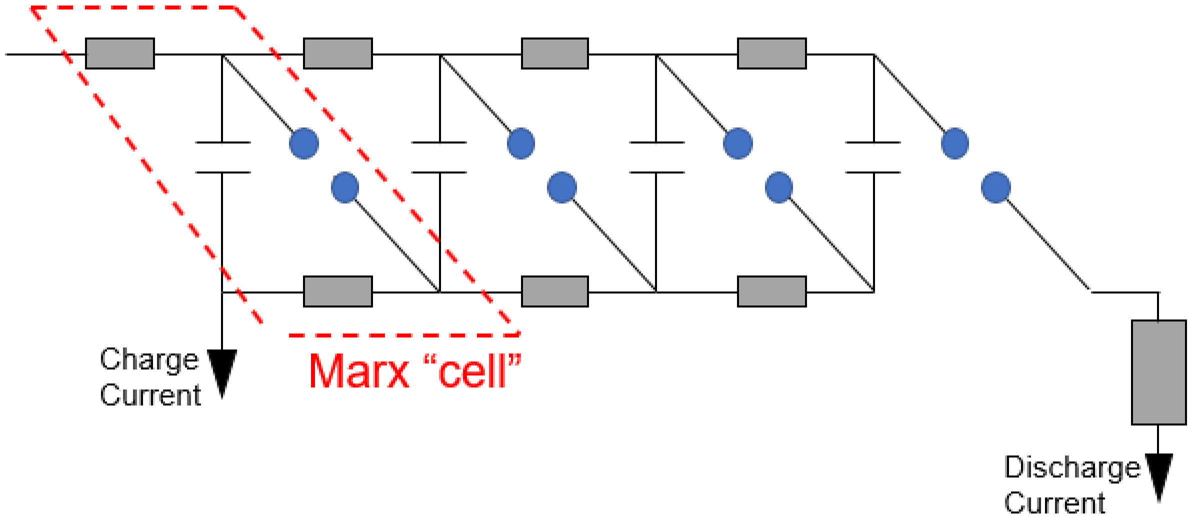
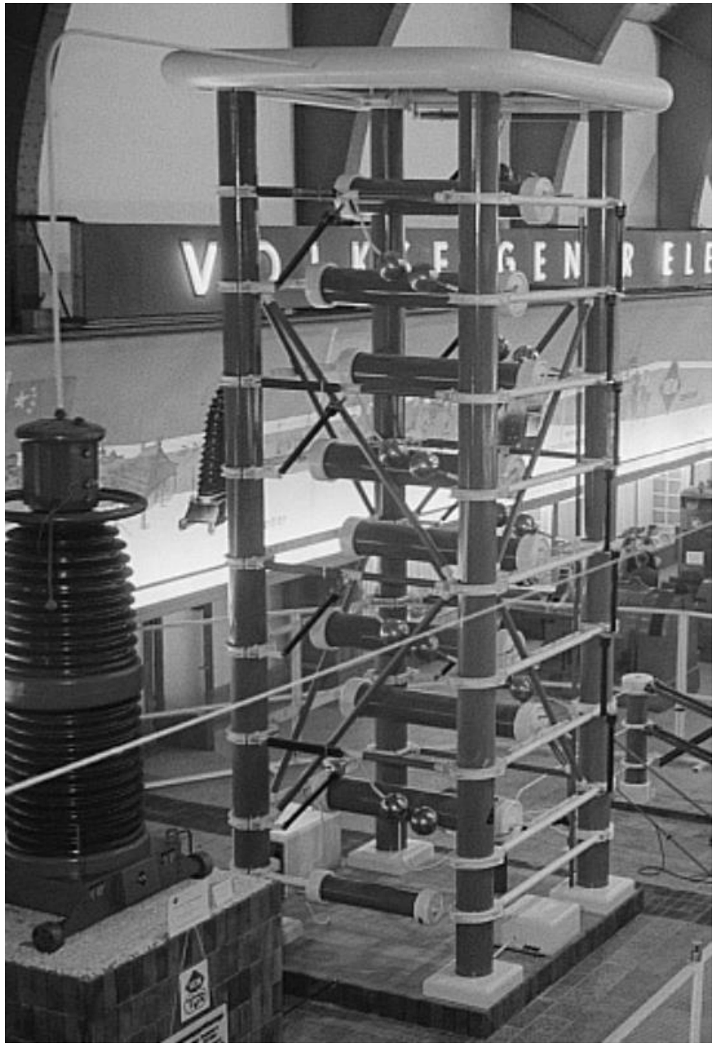
Basic Marx Generator

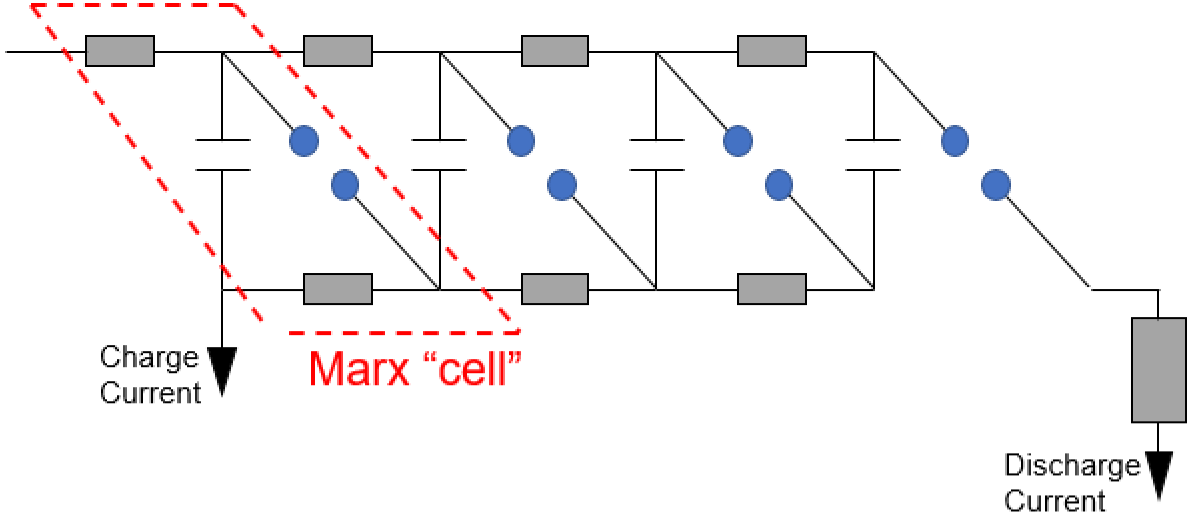
- Concept first proposed by Erwin Marx in 1925
  - Charge capacitors in parallel
    - Maximum voltage: V
    - Total capacitance: C*N
  - Discharge them in series
    - Maximum voltage: N*V
    - Total capacitance: C/N



- 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

Basic Marx Generator



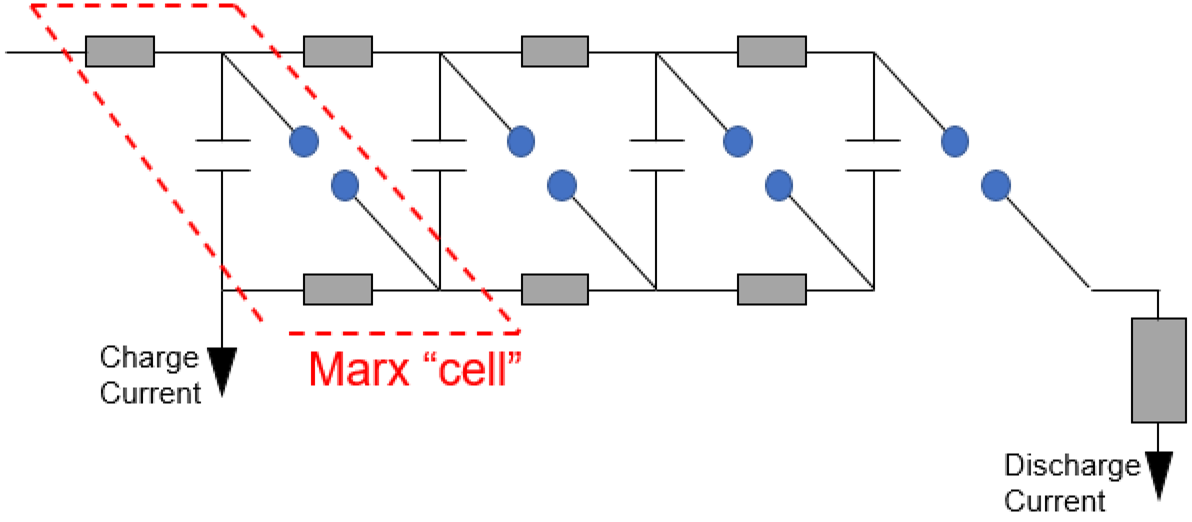


- Historically, switched with spark gaps. Triggering the first spark gap leads the other spark gaps to self commutate.

Autumn Exhibition of State-Owned Electrical Engineering Enterprises (VEM) at Leipzig, East Germany, September 1954 Deutsche Fotothek

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



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

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

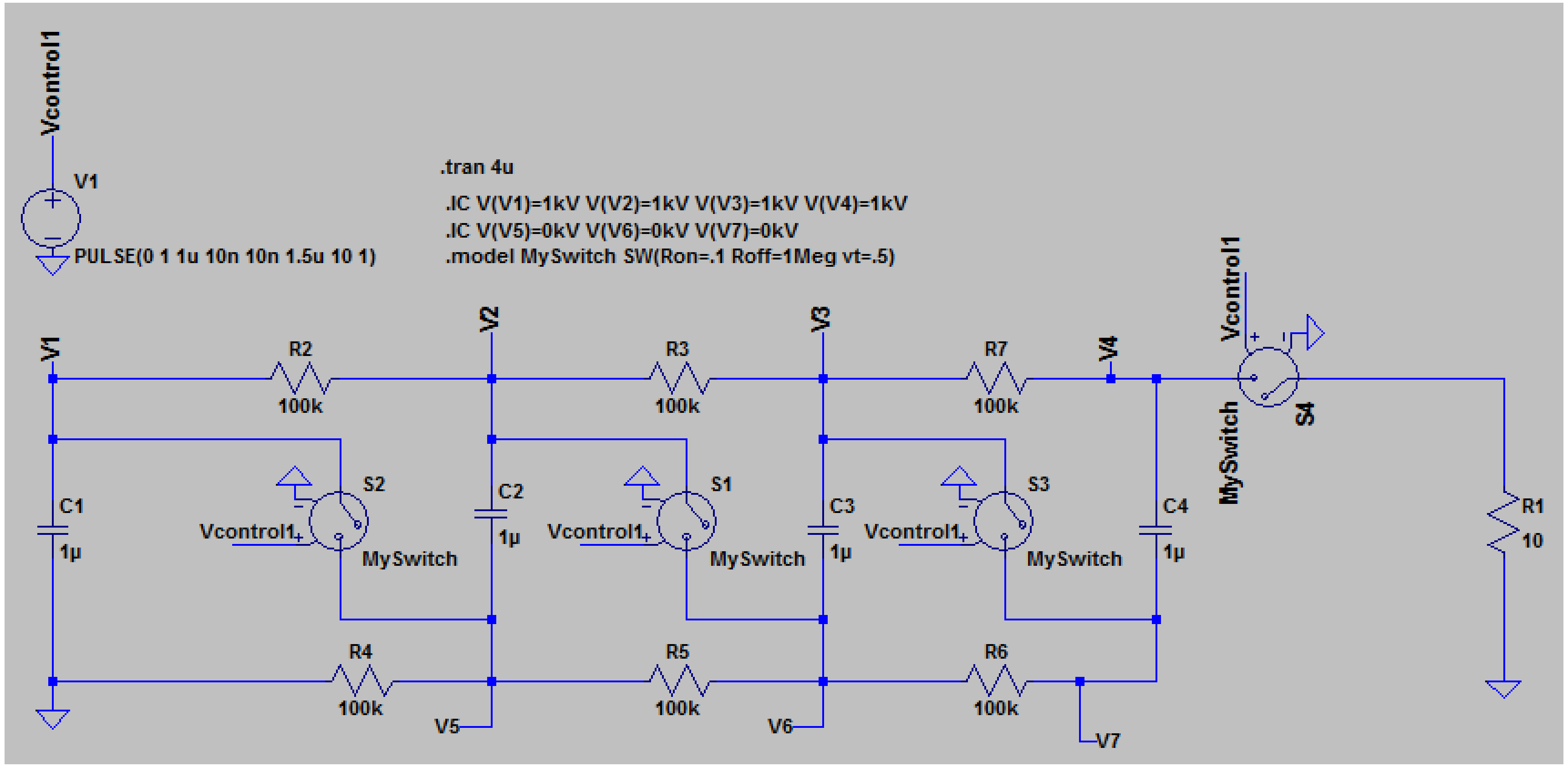
Basic Marx Generator

- 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

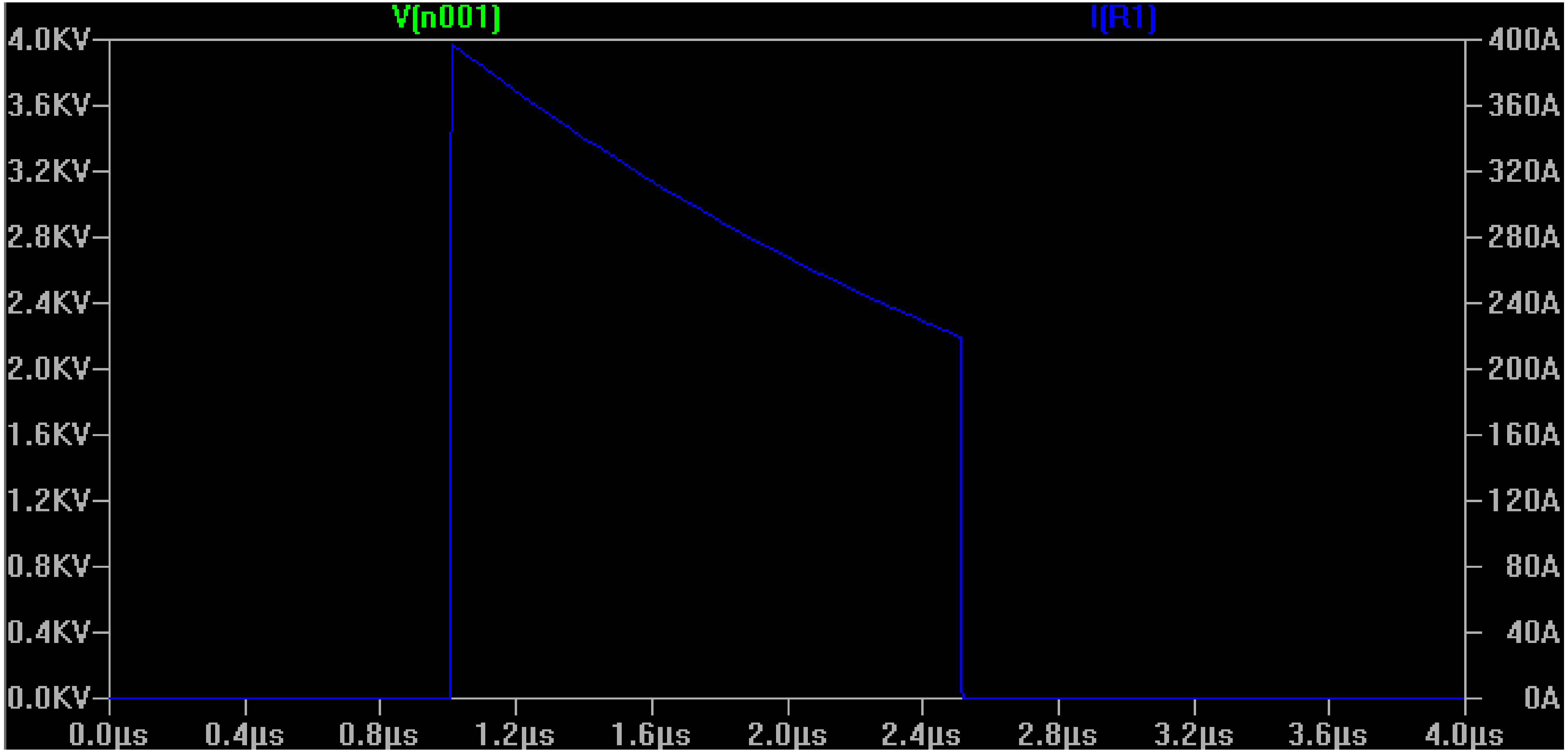
Marx-parasitics

- •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



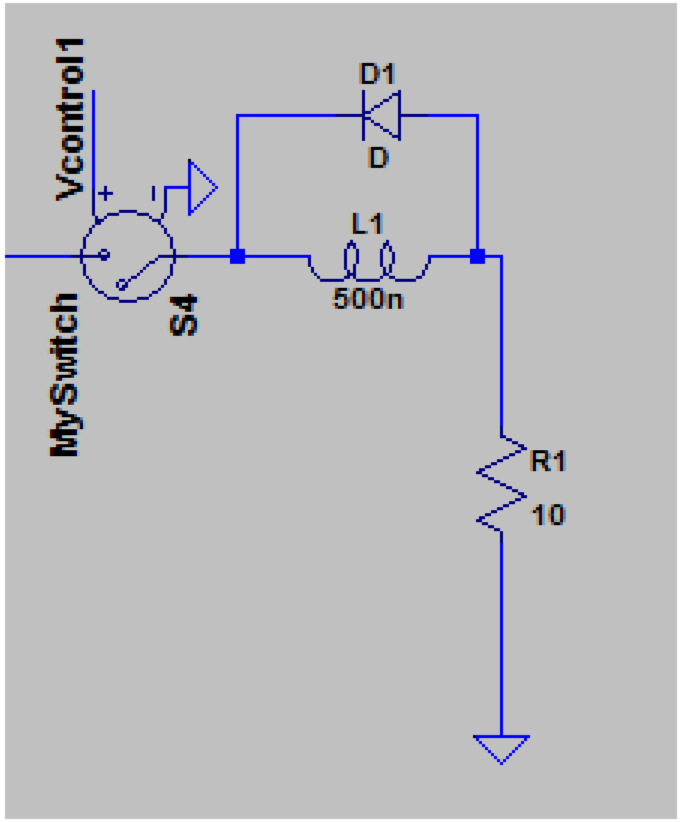
Marx-parasitics

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



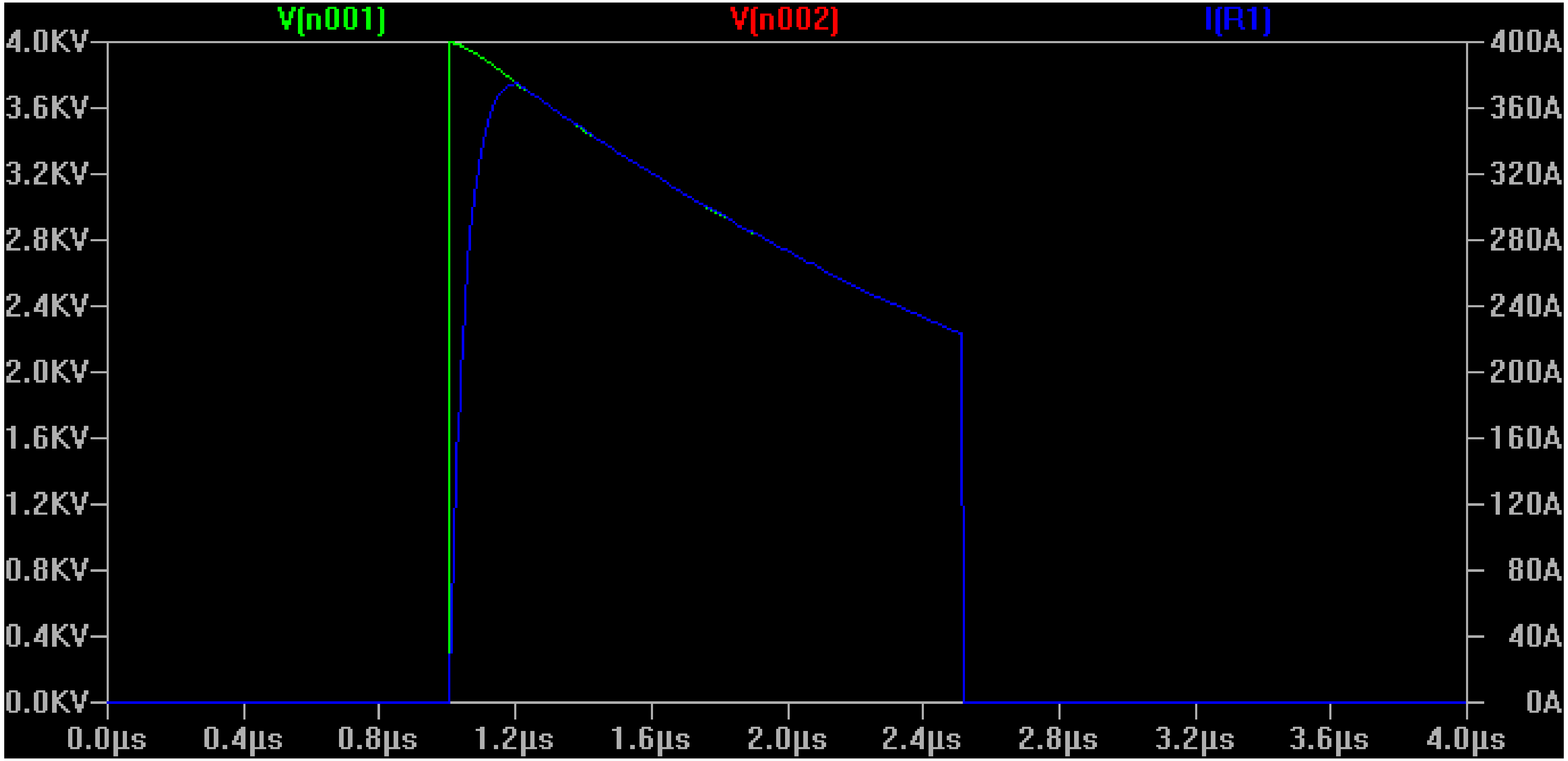
Marx-parasitics

- 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



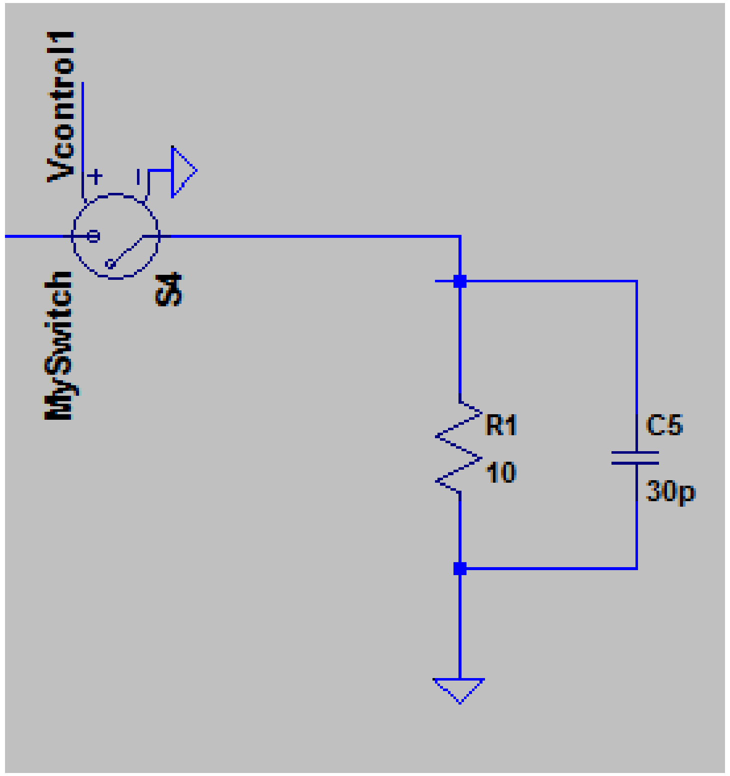
Marx-parasitics

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



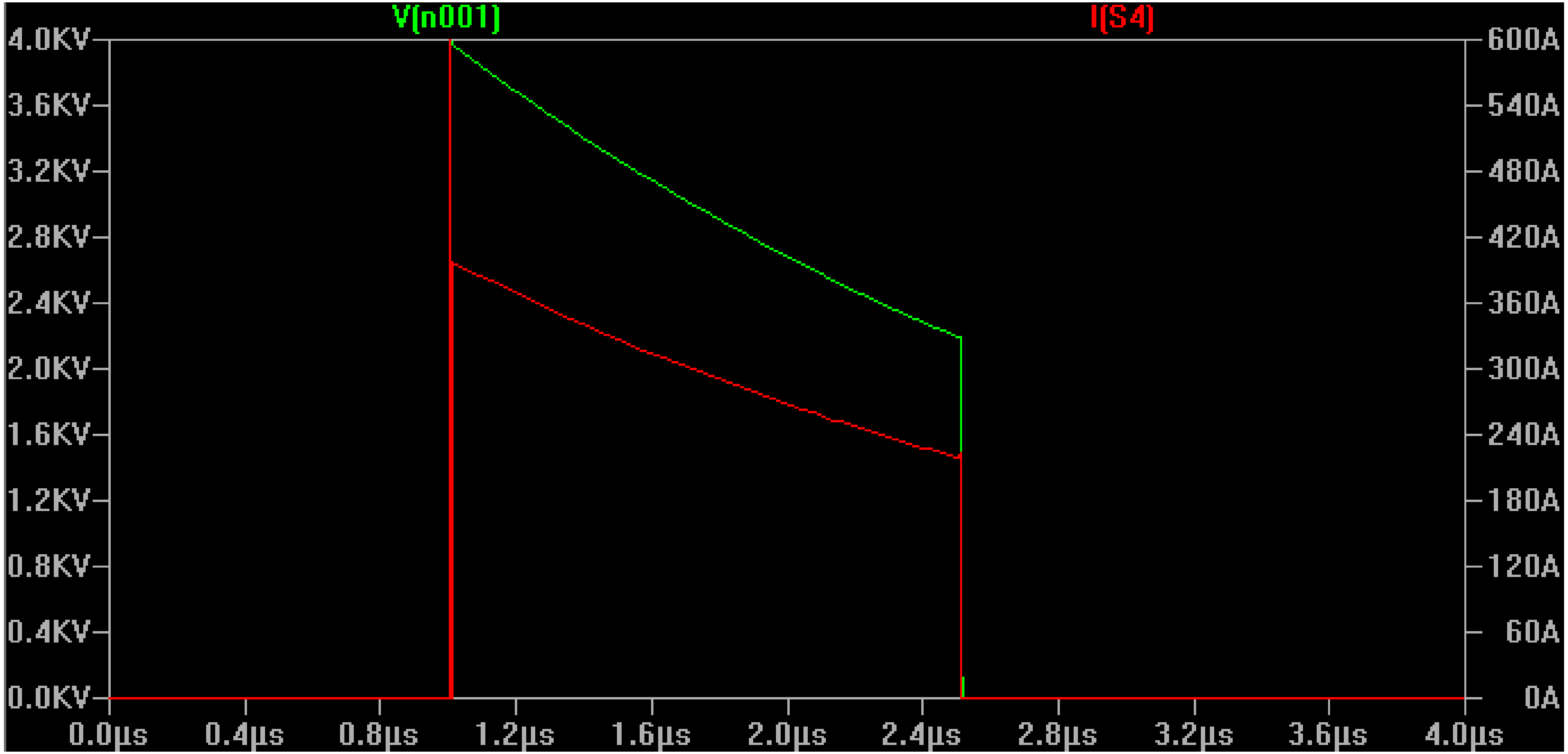
Marx-parasitics

- 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

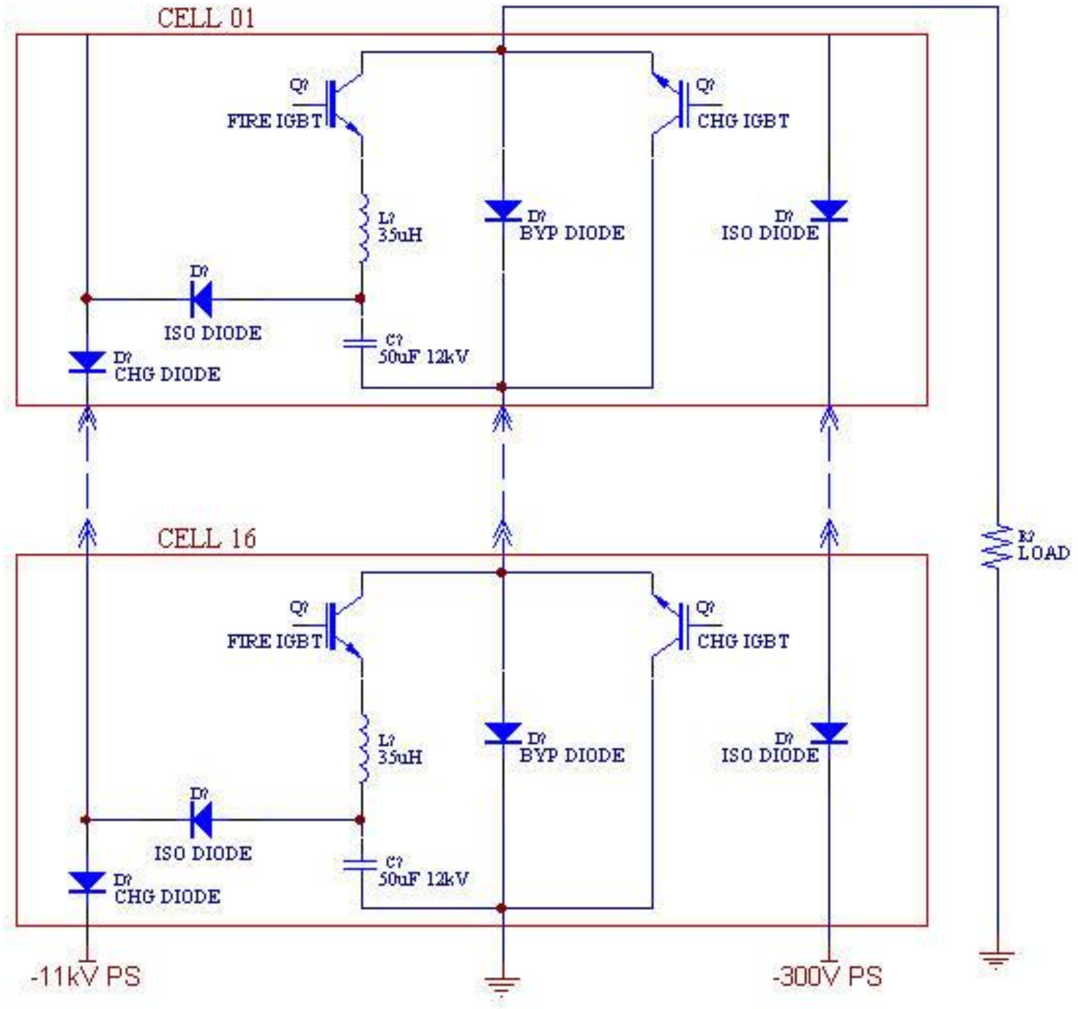
- Modularity
  - Building blocks can be arranged in different configurations for different applications
  - Many inexpensive components
- Electrostatic Adding
  - Pulse transformer not necessary
- Independent Module Control
  - Reconfiguration possible
- Low-Voltage Sub-Units
  - ***Conventional power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

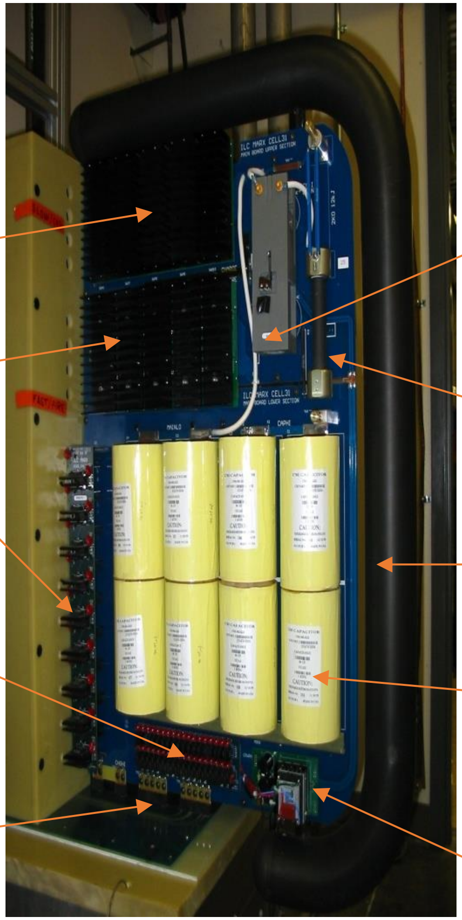
Simplified Schematic of ILC-Marx P1-Prototype



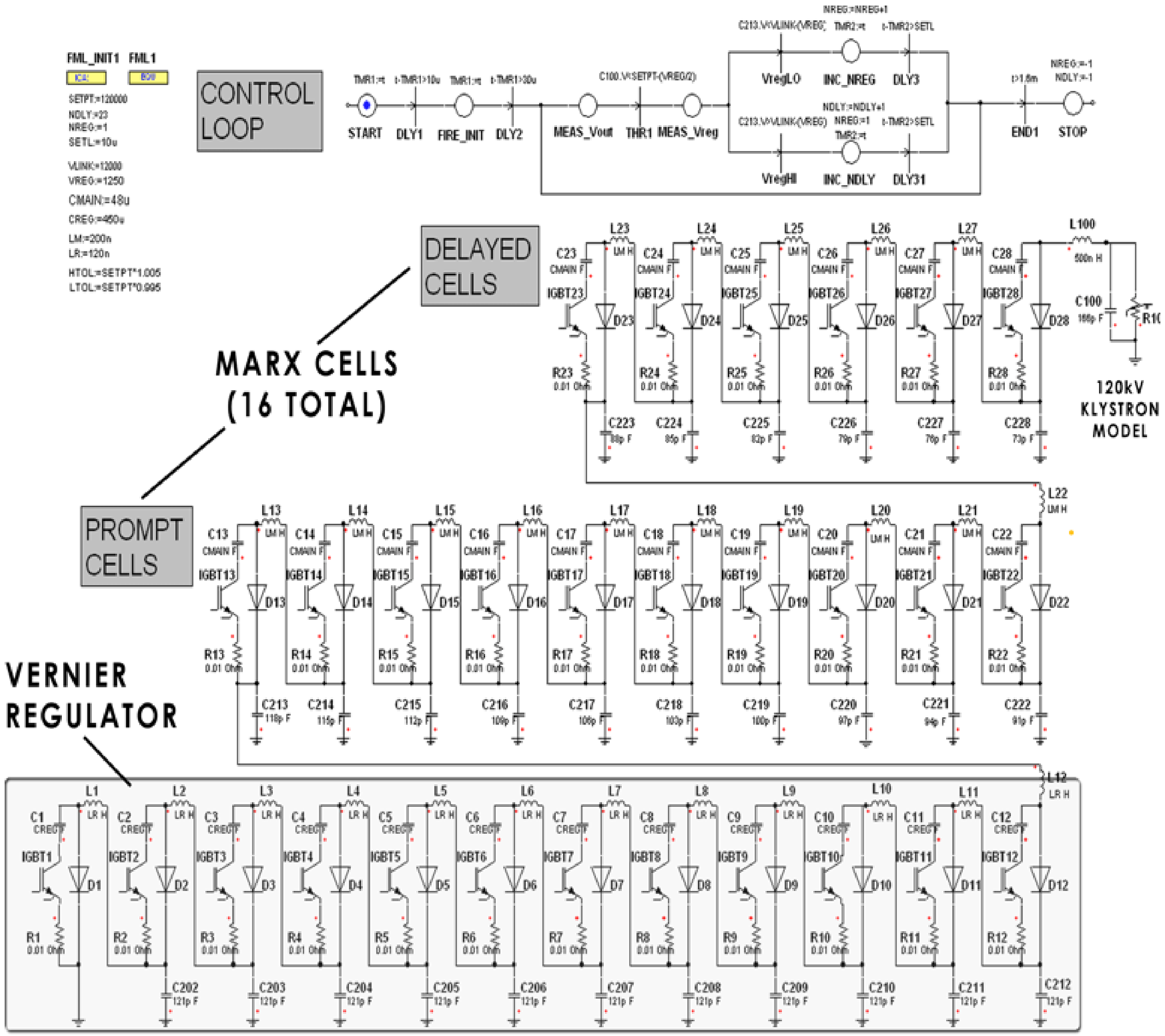
- 11kV per Cell
- 16 Cells
  - 11 prompt cells → 120 kV
  - 5 delay cells, compensates capacitor droop
- Cell High Voltage Switches
  - Array of 4.5kV, 60A IGBTs 3 parallel X 5 series
  - Fire switches erect Marx
  - Charge switches provide current return path for main charging supply (-11 kV) and auxiliary 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

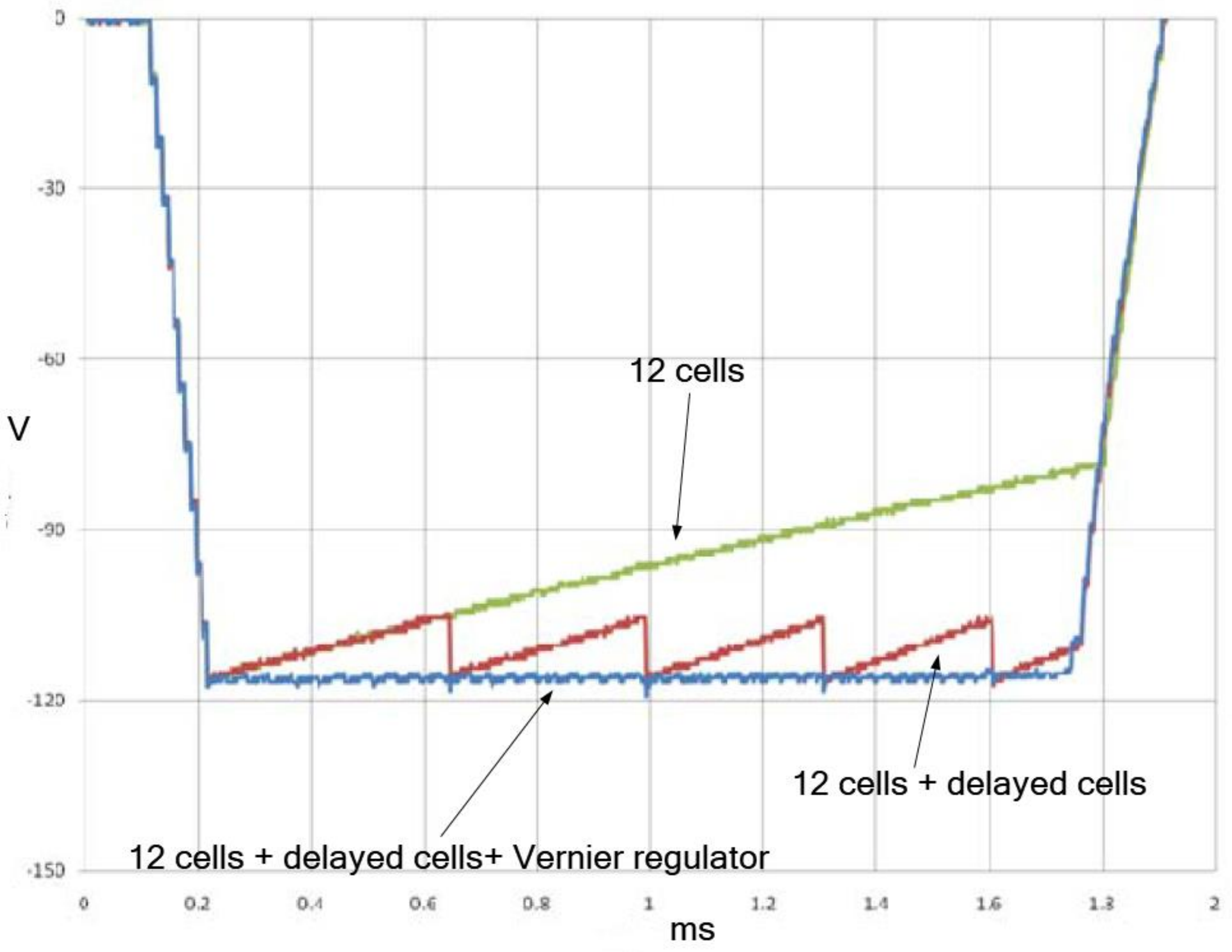
P1-Marx Installed in “Sealed” Enclosure

P1-Marx Cell Front & Rear Views

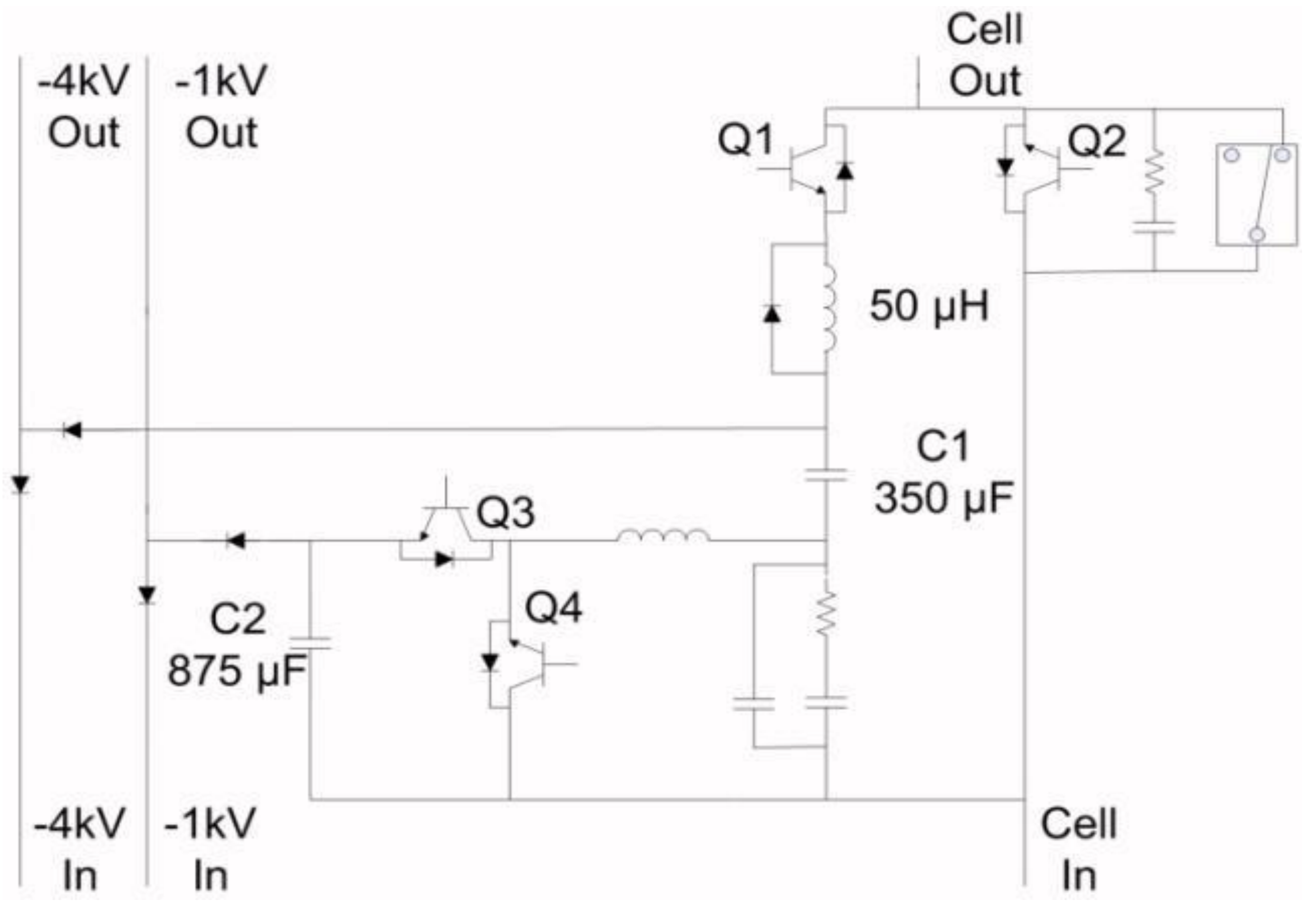


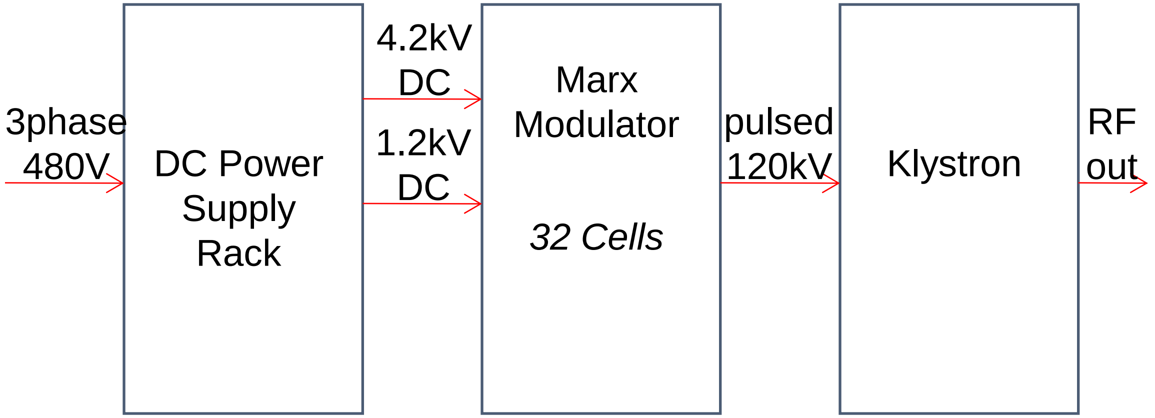
P1-Marx Voltage Regulation





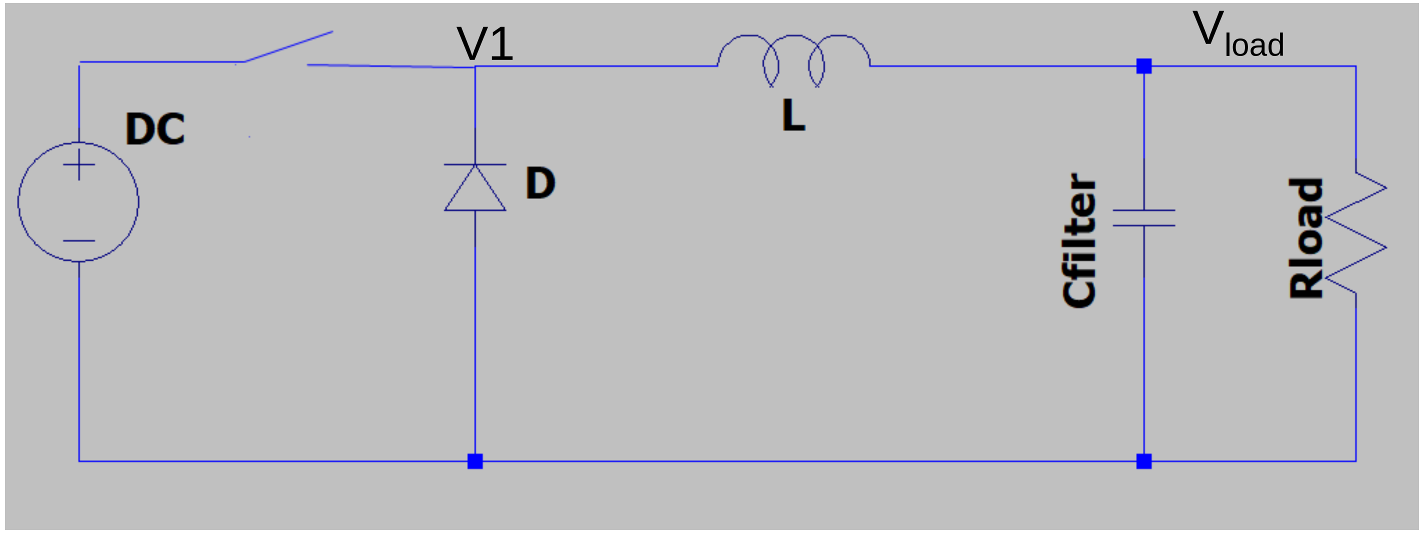
The SLAC P2 Marx

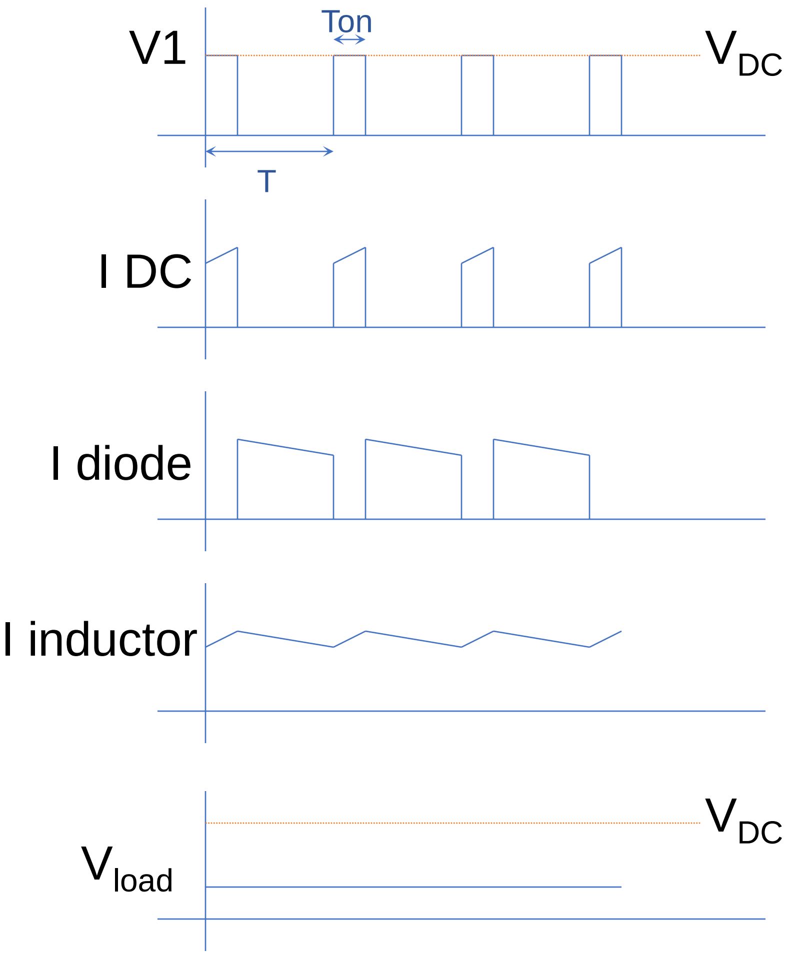




- Each Marx cell produces a flat-top: a “buck” converter is in series with the main cell capacitor
- The modulator regulation is closed-loop
- N+2 redundancy

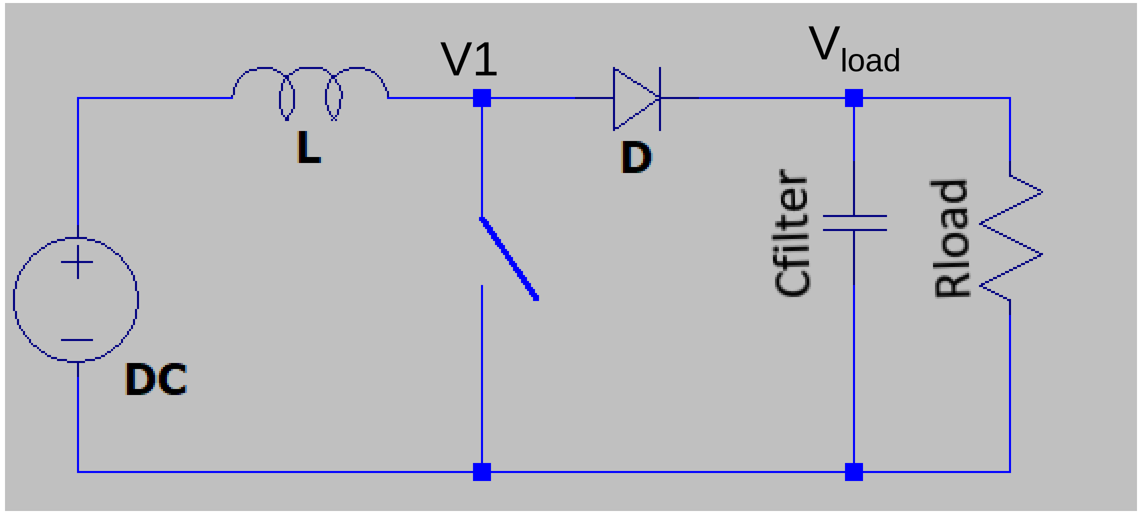
Buck Regulator

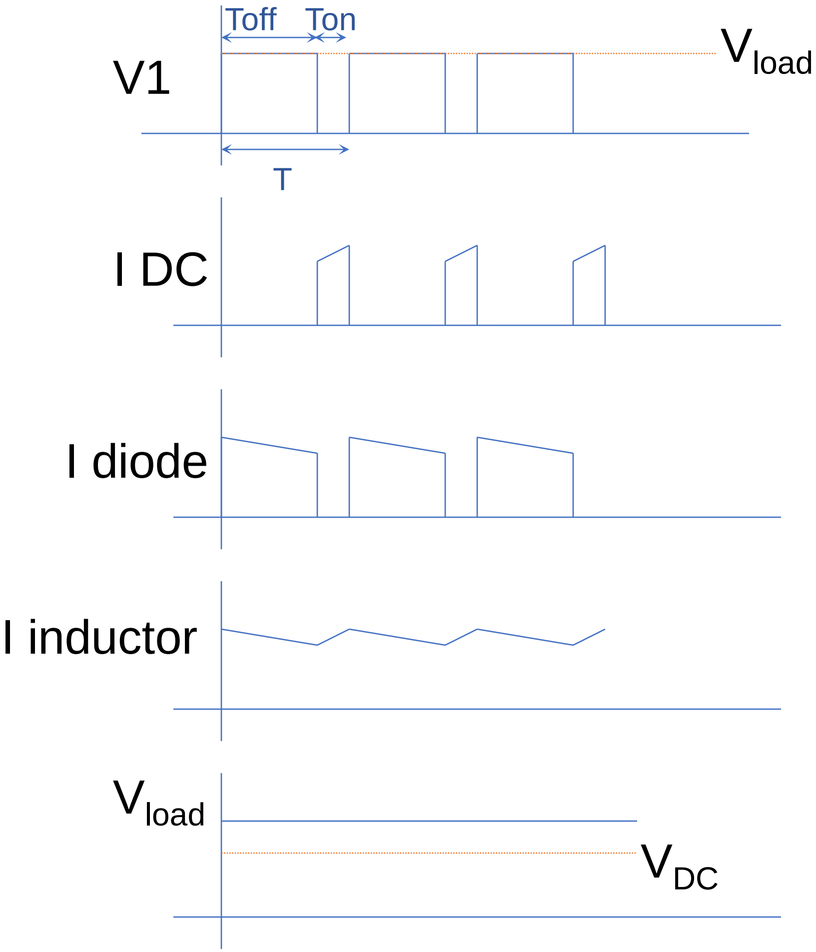




$V_{1ave} - V_{load} = 0$
With good filtering V_{load} is constant
$(T_{on}/T) * V_{DC} – V_{load} = 0$
$V_{load} = D * V_{DC}$

Boost Regulator





V_{DC} - $V1_{ave}$ = 0

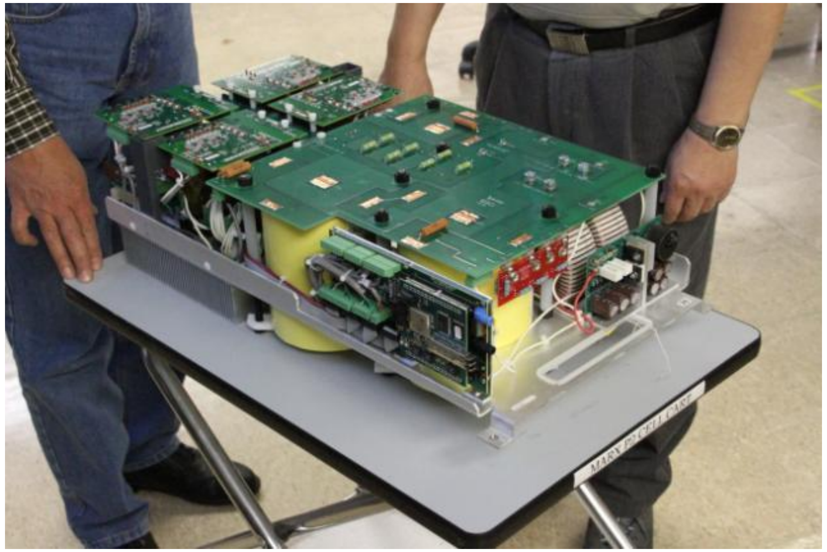
With good filtering V_{load} is constant

$V_{DC} - (T_{off}/T) * V_{load} = 0$

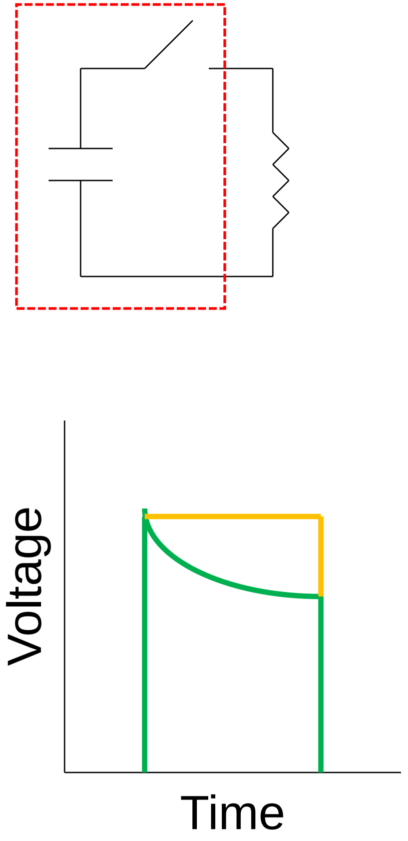
$T_{off}/T = 1-D$

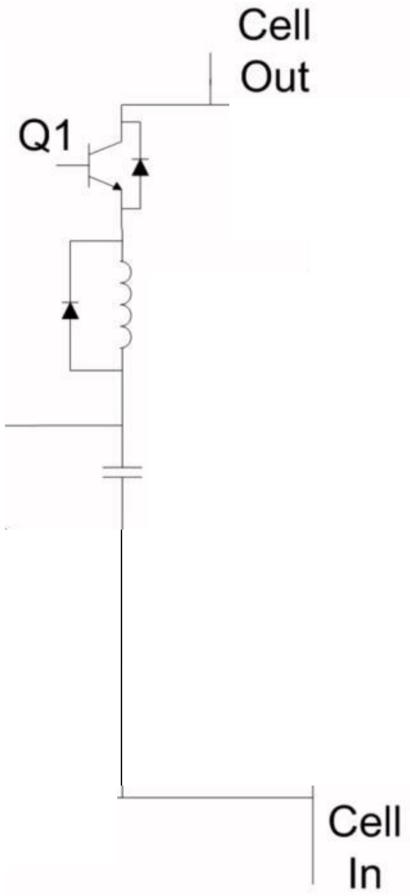
$V_{load} = V_{DC}/(1-D)$

SLAC P2 Marx Photographs

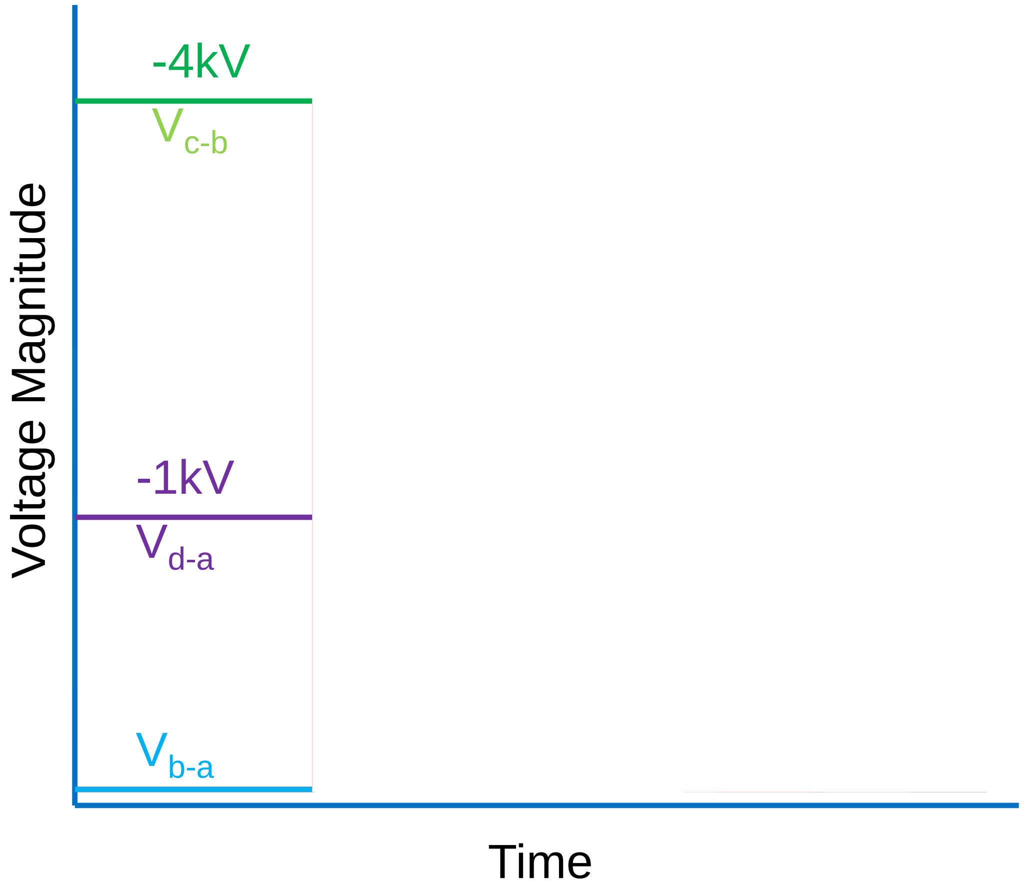


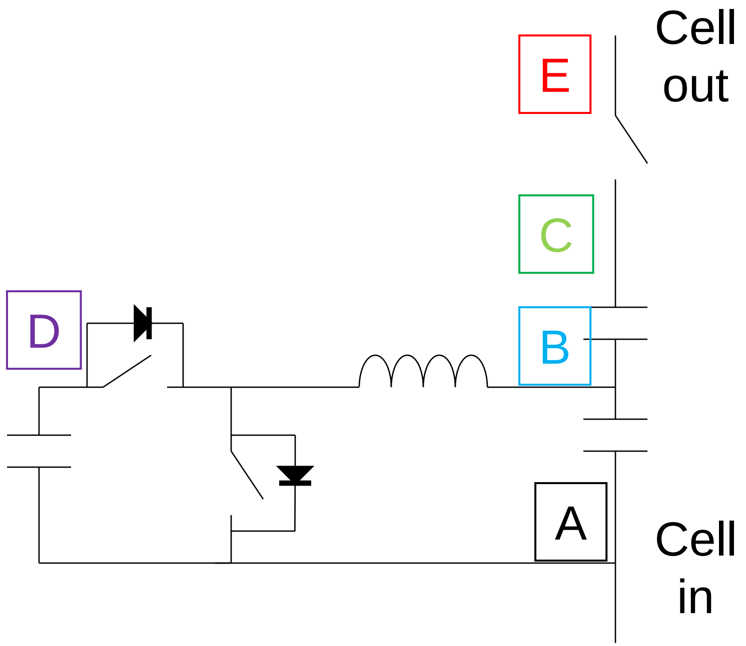
SLAC P2 Marx Cell Schematic





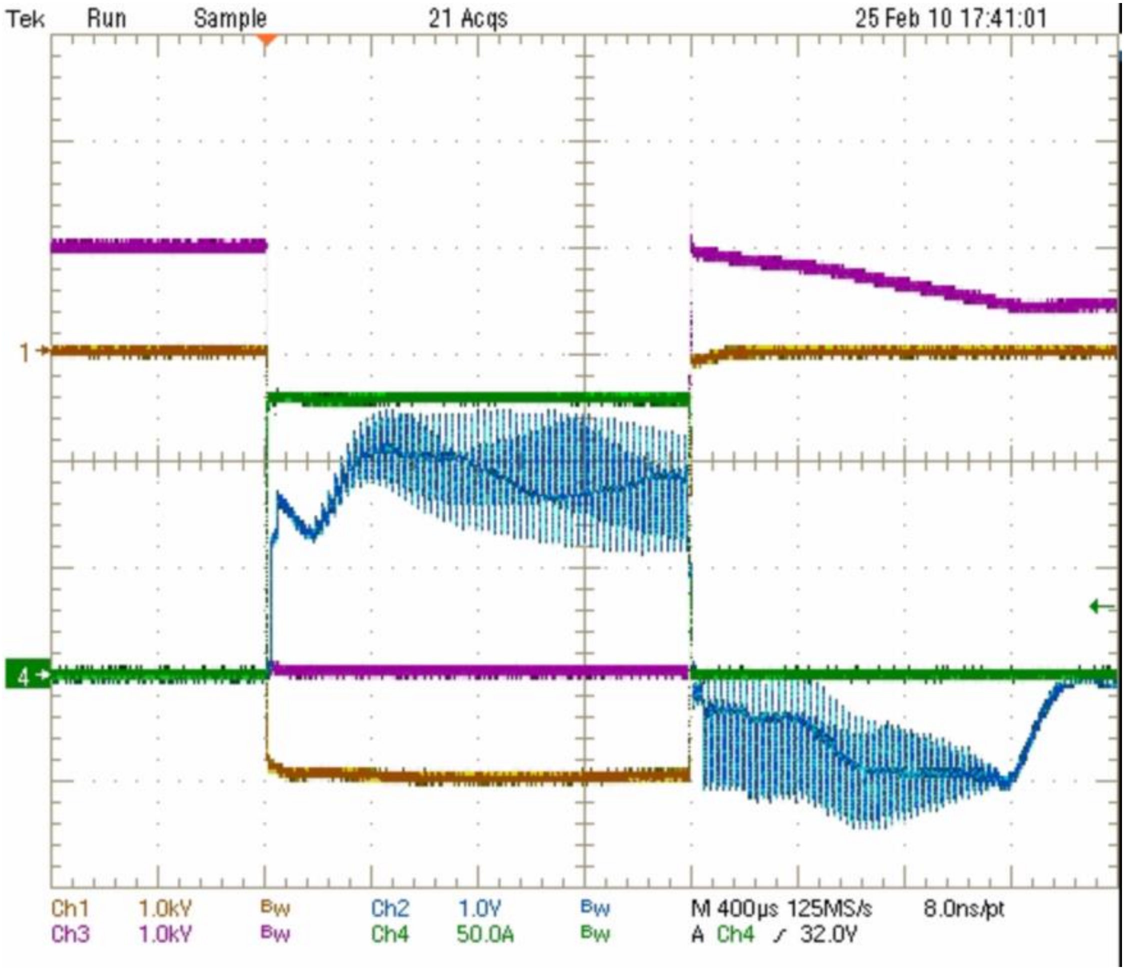
Correction Scheme





(negative bus voltage)

Correction Scheme

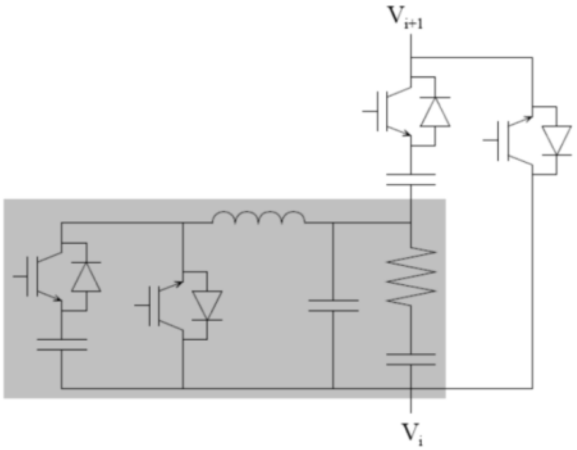


Cell Output Current

Cell Output Voltage

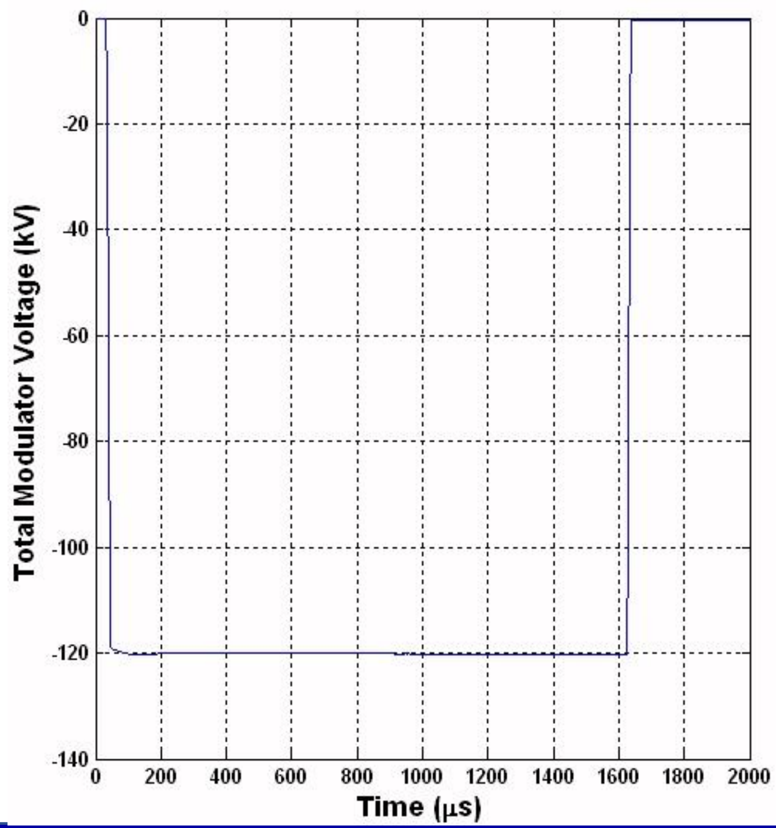
Main IGBT V_{ce}

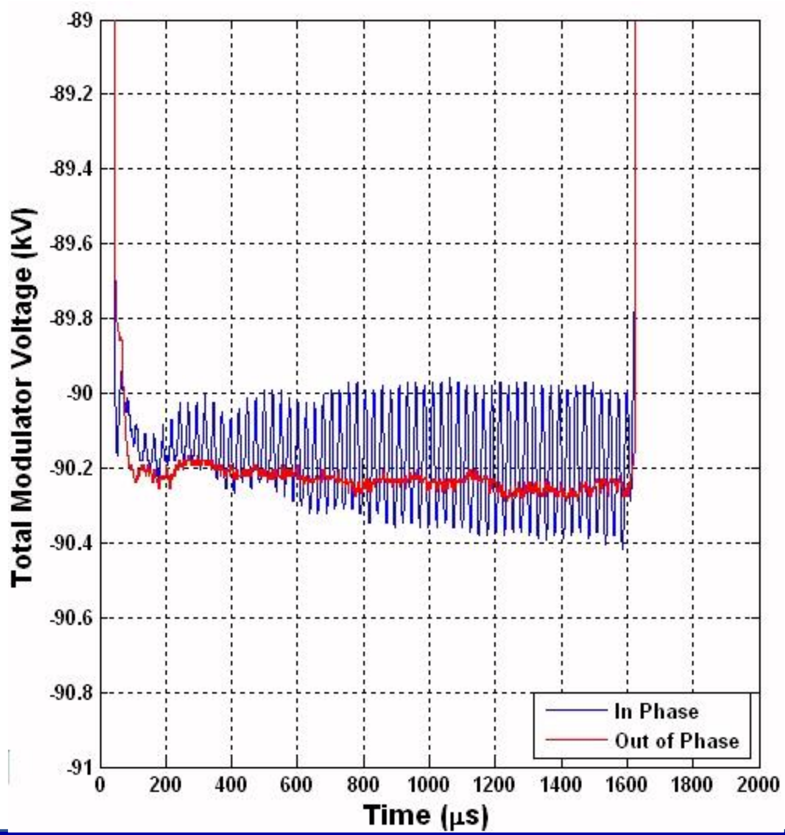
PWM Inductor Current



SLAC P2 Marx Performance

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

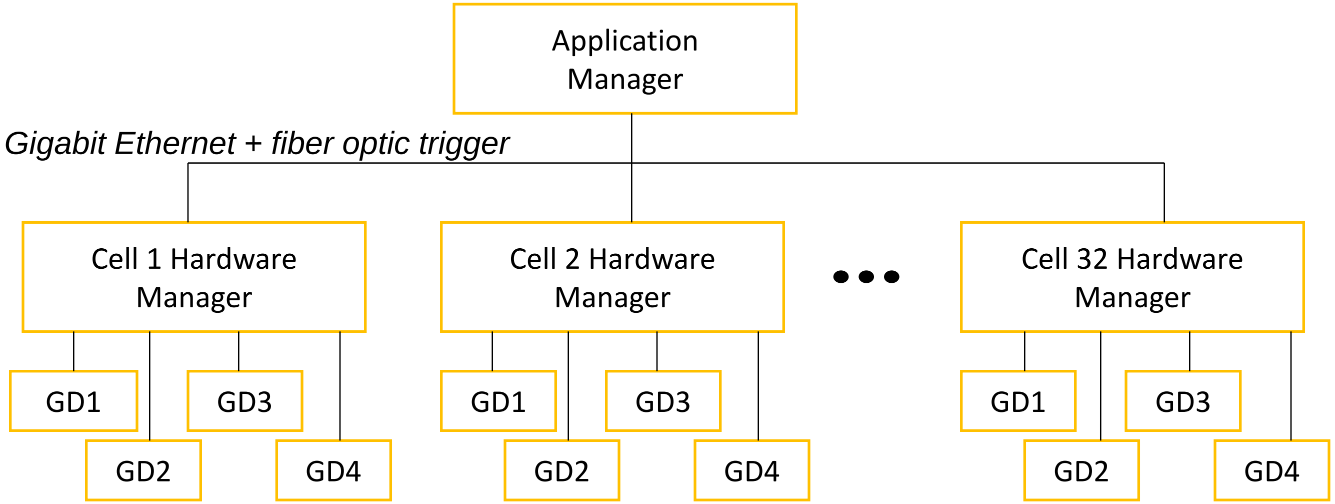




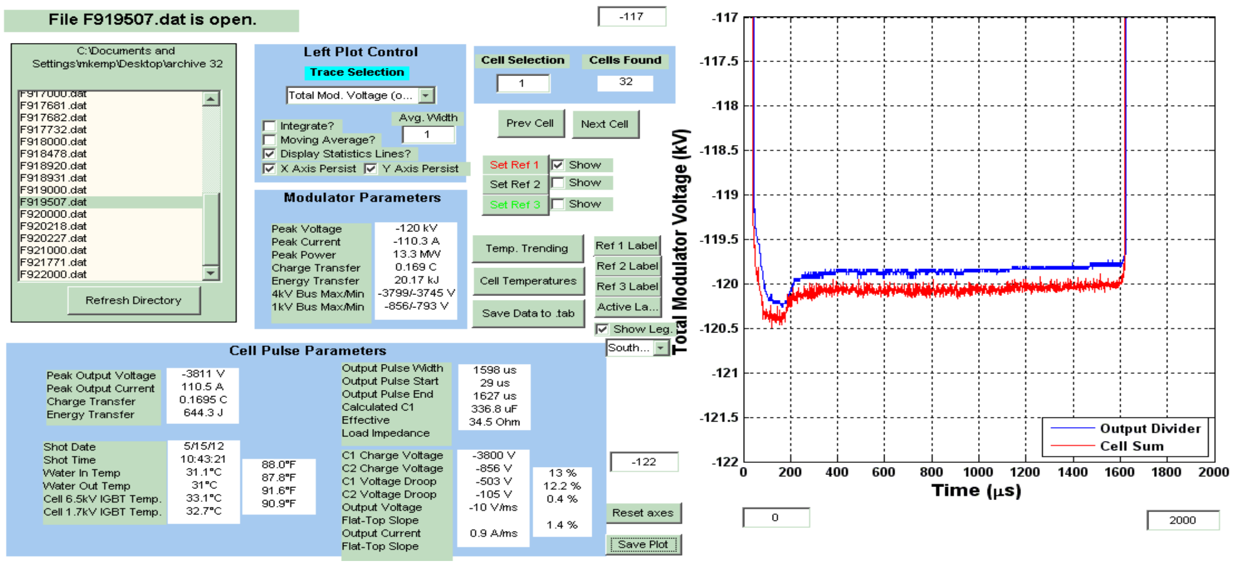
SLAC P2 Marx: Simple Maintenance

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

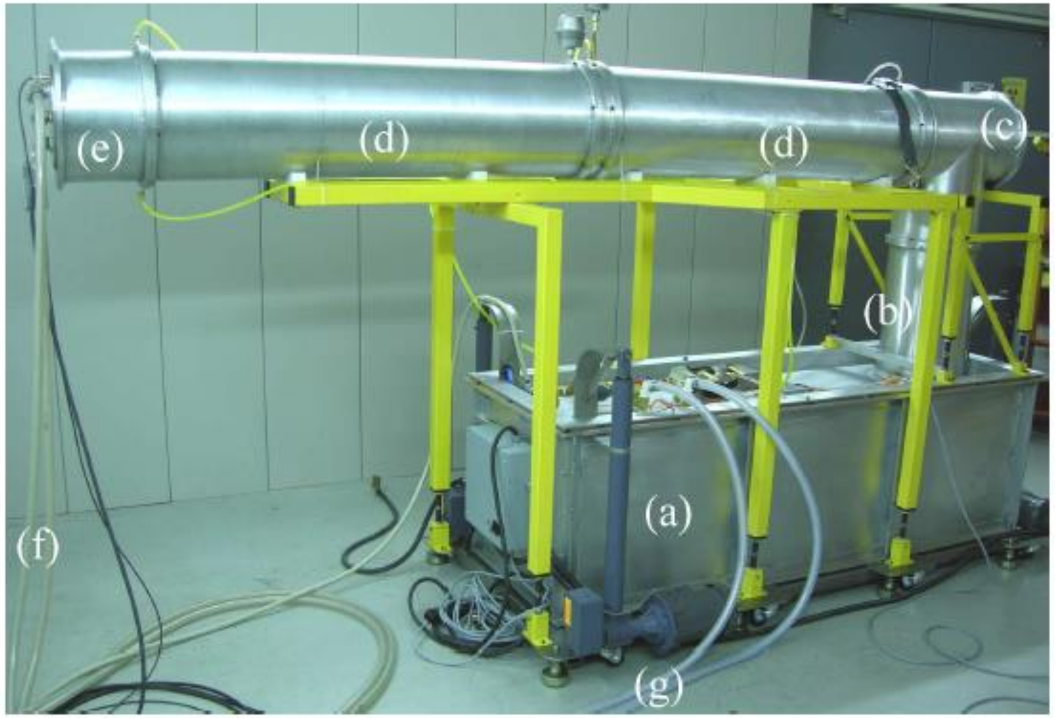
SLAC P2 Marx Control System

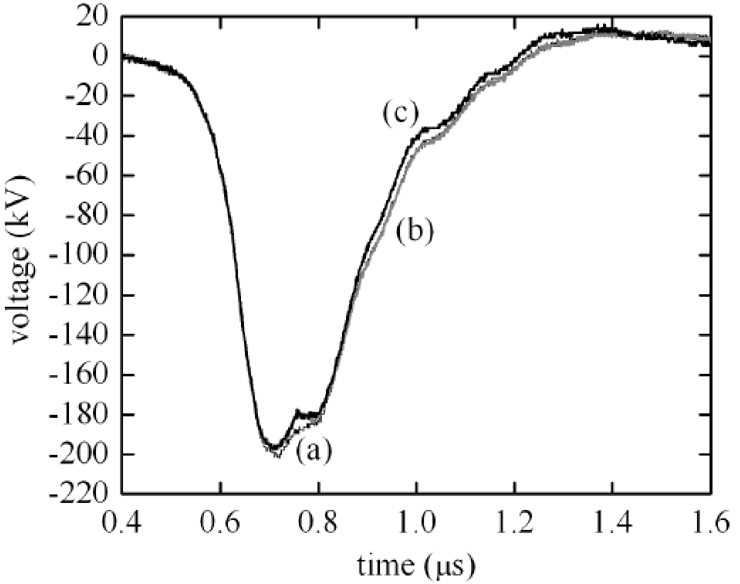


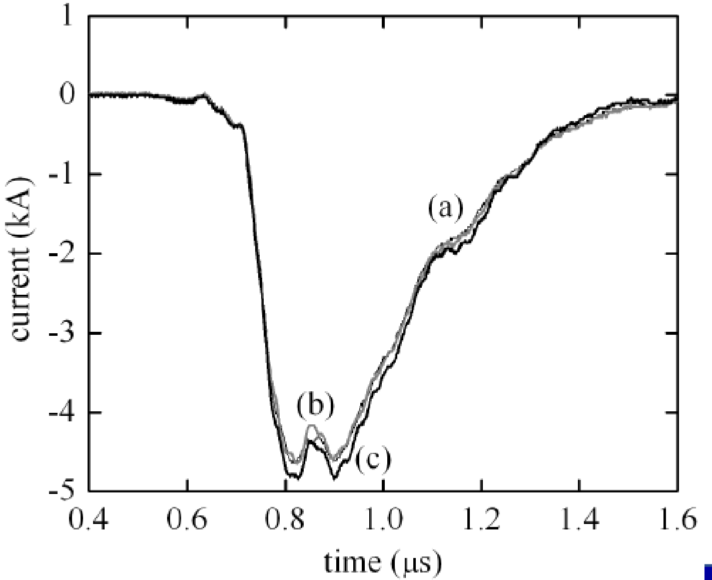
- 256, 12-bit, 1 MS/s, 2.1ms-long waveforms are captured each shot



Some Embodiments of the Technology





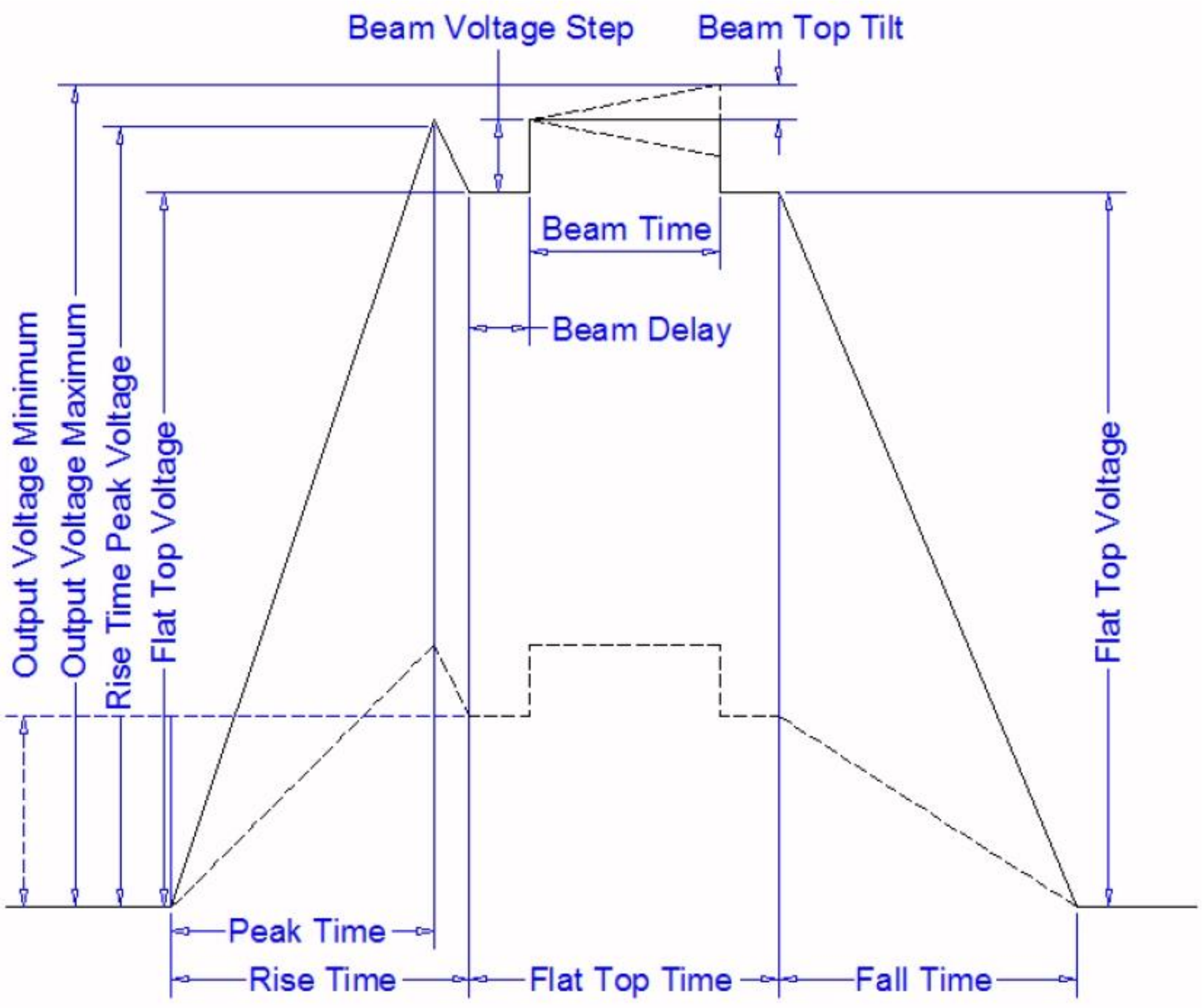


NRL Marx Modulator for KrF Laser

- -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 Modulator Paper Study



Fermi Designed/Built Modulator For This Load [1]

FNAL Linac Marx Topology

41 Main Marx Cells (900 V)

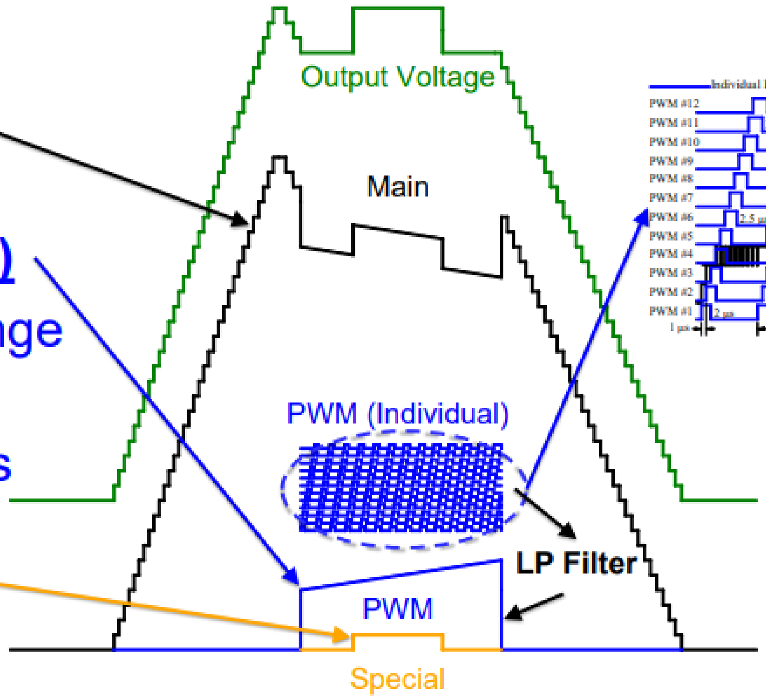
- Create the rising and falling edges
- Limits cavity reflected power back to tube

12 Pulse Width Modulation Cells (900 V)

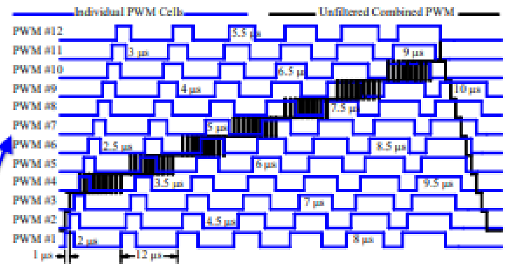
- Interleaved & filtered regulator w/ 7 kV range
- Flatten capacitive droop & regulate flattop voltage via feedback & learning algorithms

1 Special Cell (0 to 900 V)

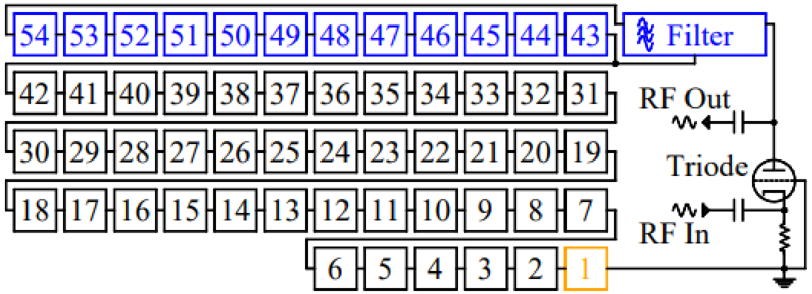
- Independently adjustable charging PS
- Enables fractional beam voltage step size



Marx Waveform Breakdown



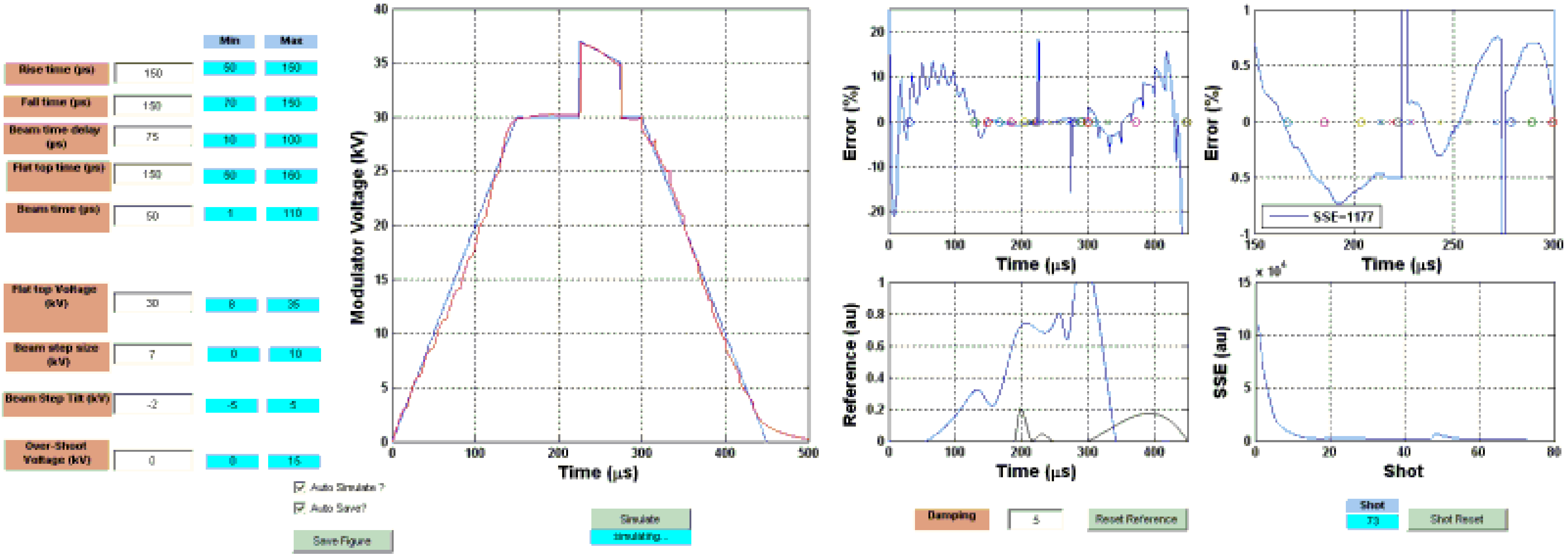
PWM Interleaving



[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.

Fermi Designed/Built Modulator

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