Solid State Marx Modulators for Emerging Applications

Mark Kemp- 9/12/2012

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Presentation Overview

- General modulator characteristics and where advancement is needed
- The solid-state Marx modulator topology
- Some recent implementations
- The SLAC P2 Marx
- Potential application of the topology to emerging applications

Desired Characteristics of Next-Generation Modulators

Low Cost	Easily Maintained	High Availability	Superior Pulse Quality

Desired Characteristics of Next-Generation Modulators

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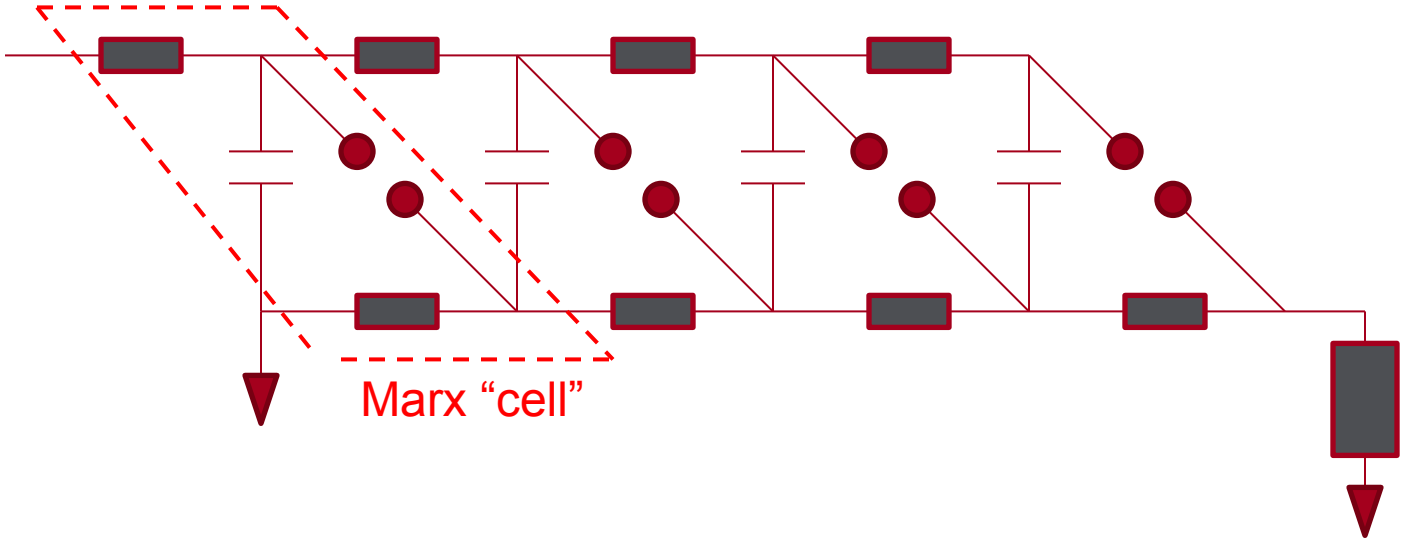
How does a Marx Modulator Achieve these characteristics?

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

The Marx Modulator Topology



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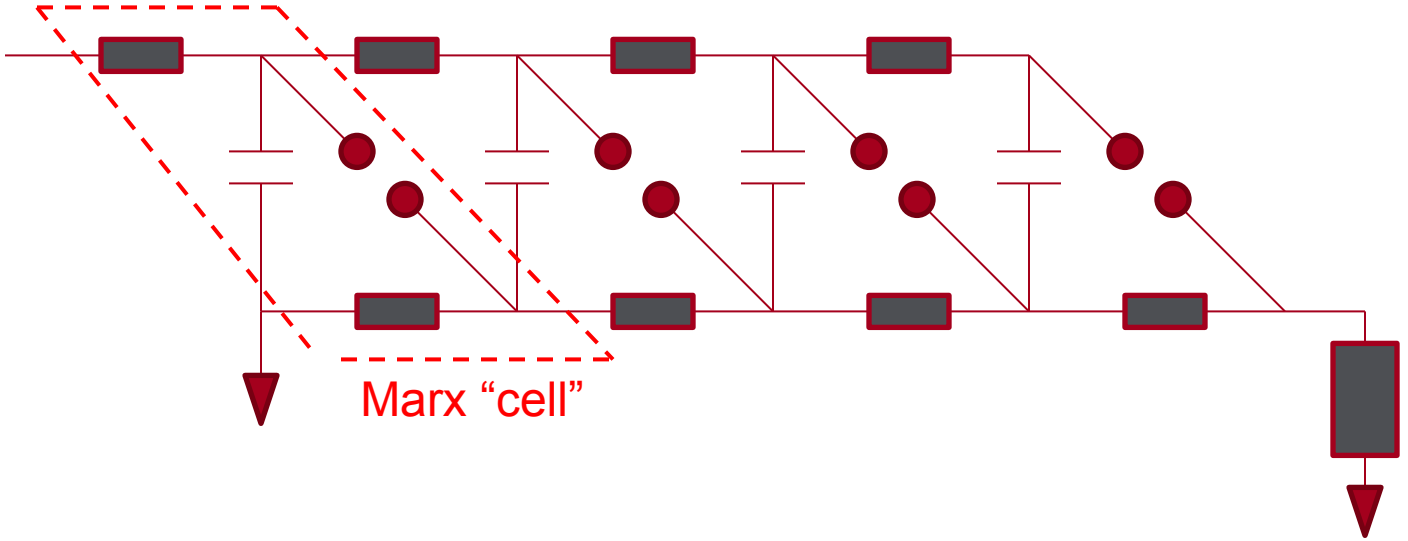

What characteristic may a cell have during the pulse?

- As implemented above, an RC decay
- Chopped output pulse
- Flat pulse
- Ramping pulse

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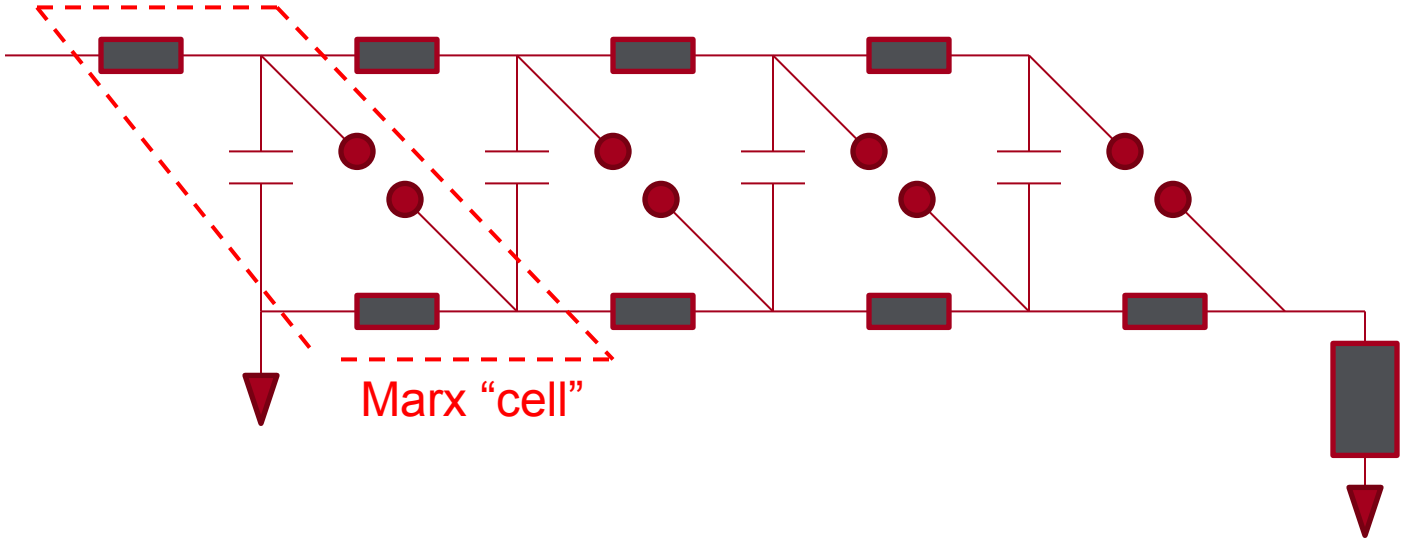

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- Chopped output pulse
- Flat pulse
- Ramping pulse

The best option depends on the application

The Marx Modulator Topology

- 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***

Some Embodiments of the Technology

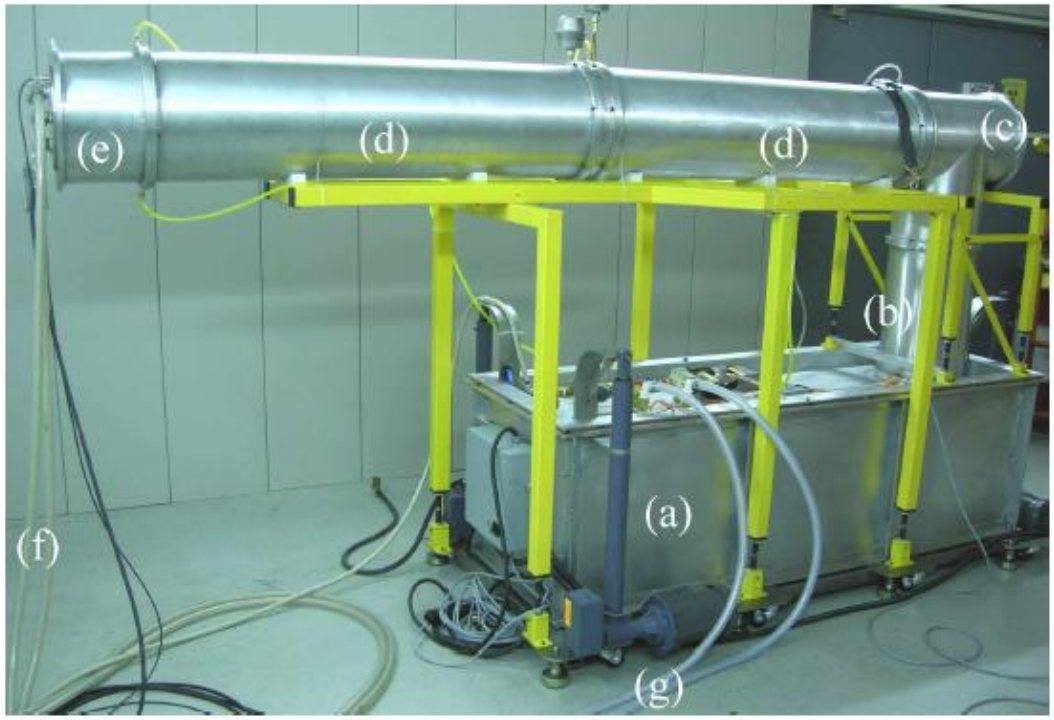
DTI ILC Marx Modulator

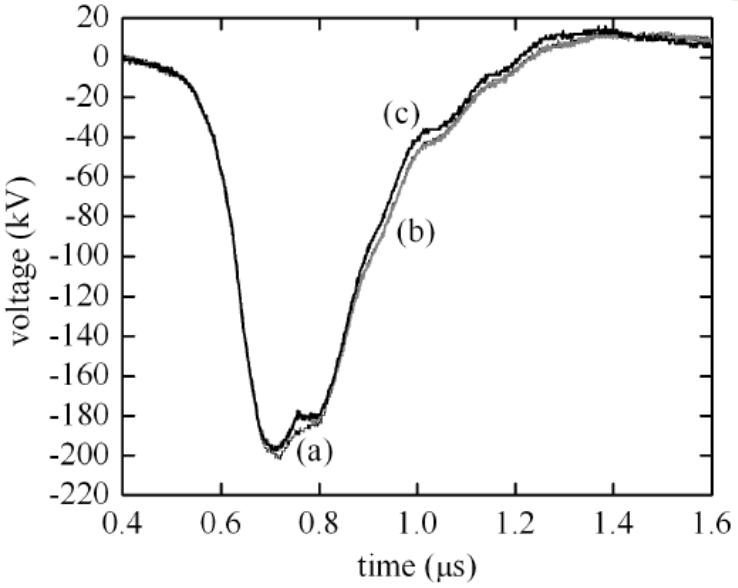
- Cells have RC droop
- Staggered turn-on produces overall flat output pulse

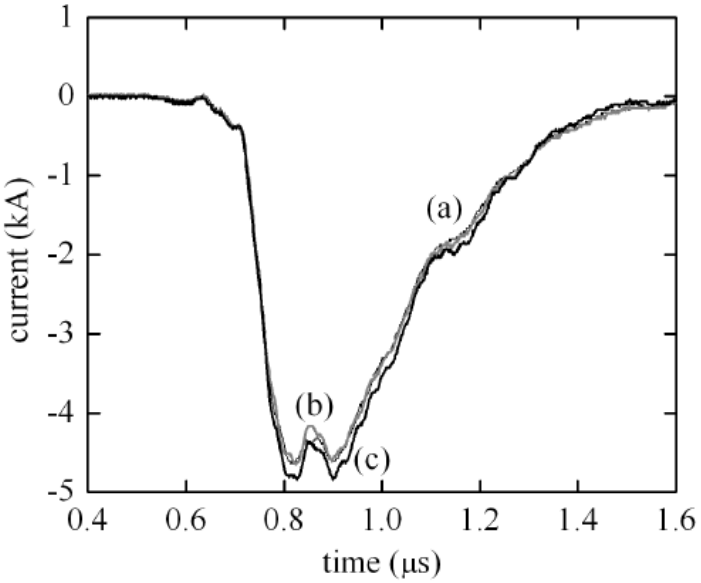
SLAC P1 Marx Modulator

- -120 kV, 140 A, 1.6 ms, 5 Hz

Some Embodiments of the Technology





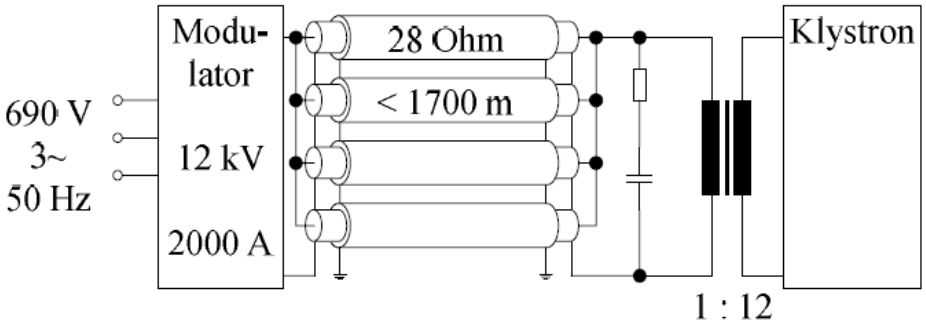


NRL Marx Modulator for KrF Laser

- -200 kV, -5 kA, 300 ns, 10 Hz pulses

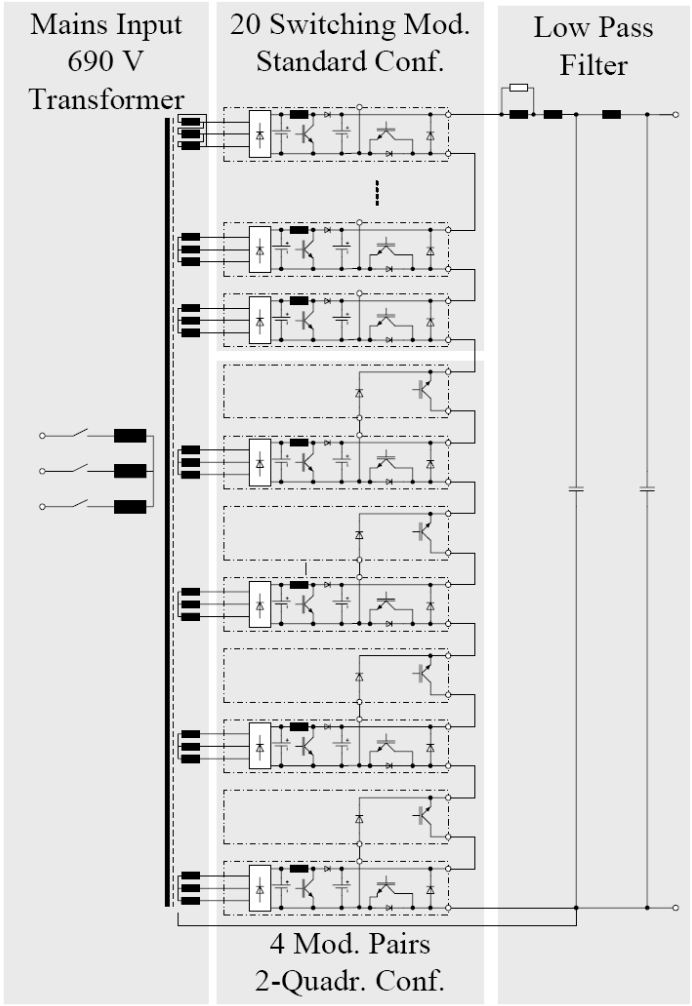
F. Hegeler, et al., "A Durable Gigawatt Class Solid State Pulsed Power System, Trans. Plasma Sci. 2011.

Some Embodiments of the Technology



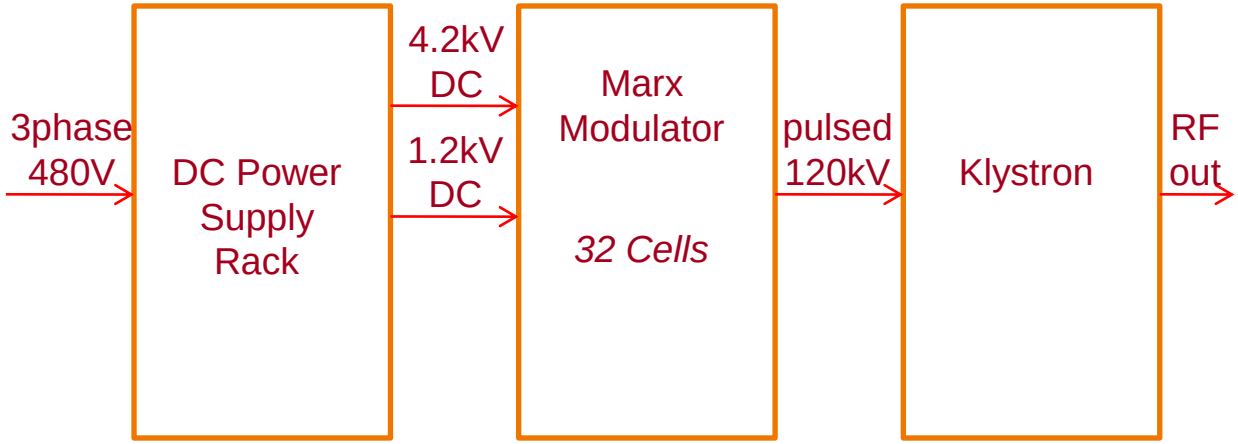
Thompson "Pulse Step" Modulator

- Used in several accelerators. Shown here is XFEL configuration
- Cells have chopped-pulse output and are interleaved and filtered
- "Power supply" is integrated into modulator architecture
- Operation into a pulse transformer



H. Leich, *et al*, "Towards a Modulator for the XFEL RF Stations" LINAC 2010, THP061

The SLAC P2 Marx



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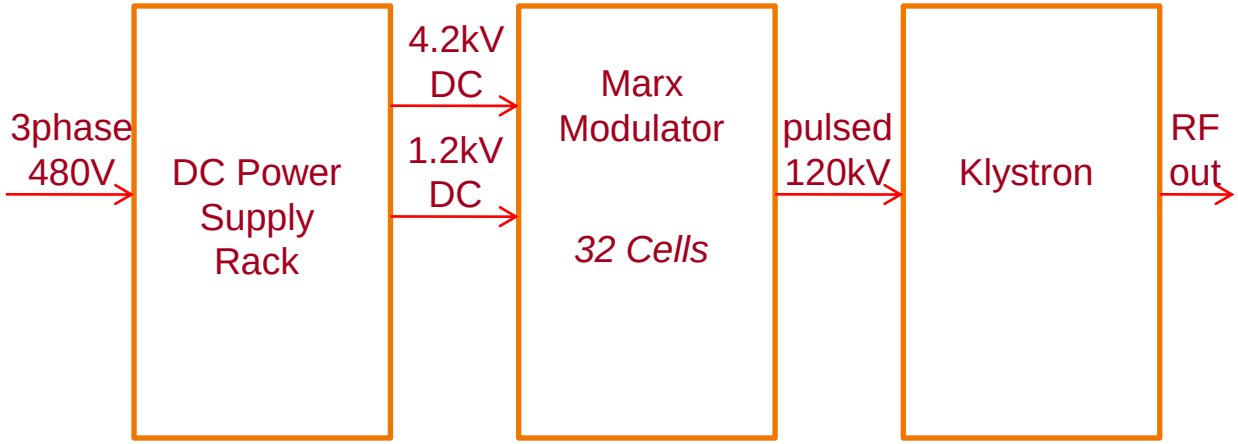
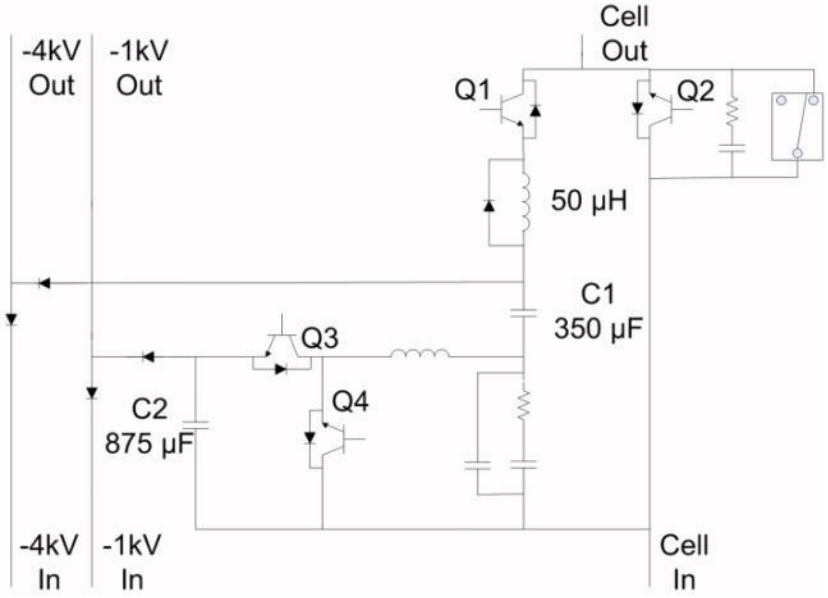
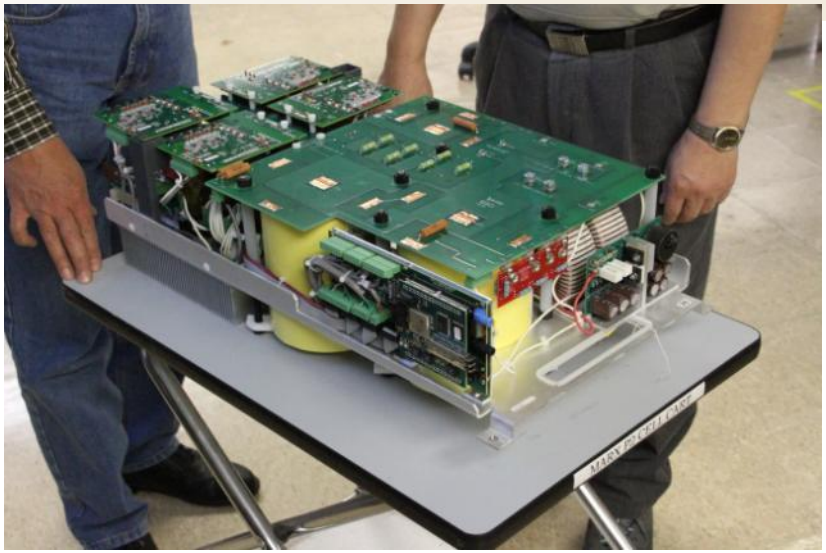




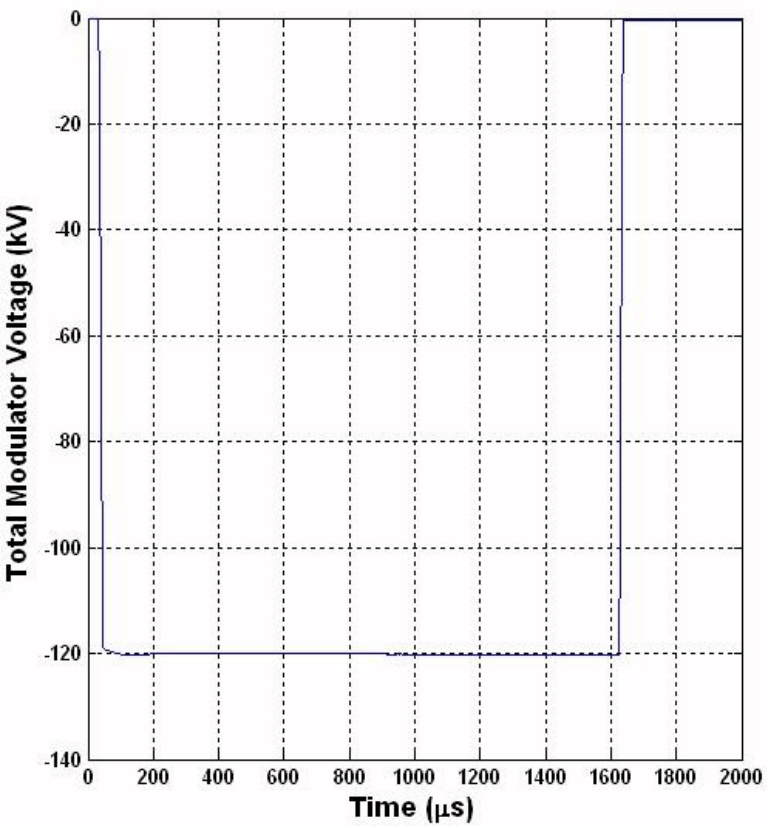
- Each Marx cell produces a flat-top: a “buck” converter is in series with the main cell capacitor
- The modulator regulation is closed-loop
- N+2 redundancy

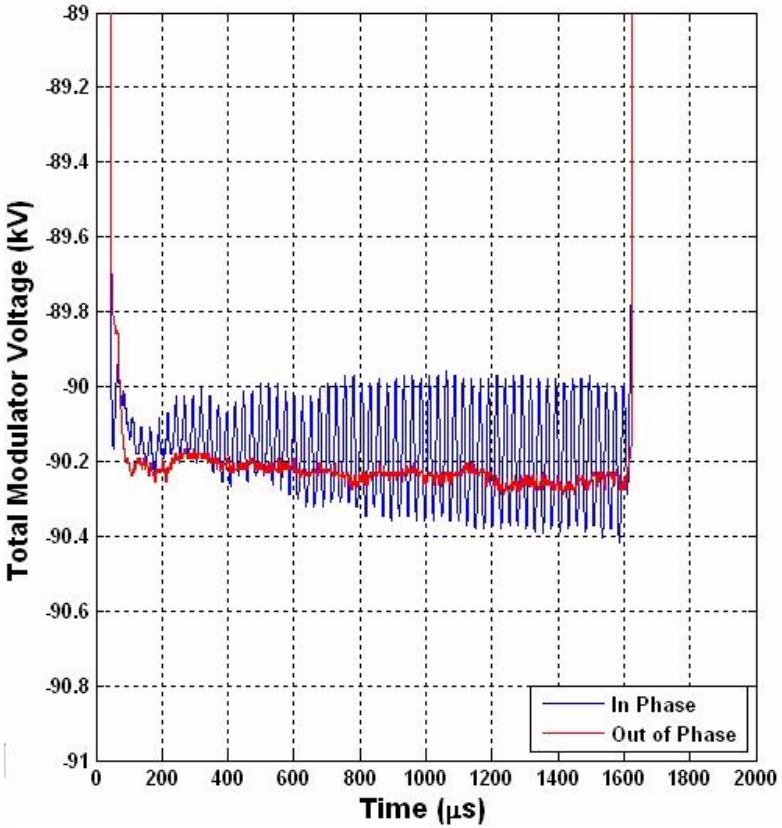
SLAC P2 Marx Photographs



SLAC P2 Marx Performance

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

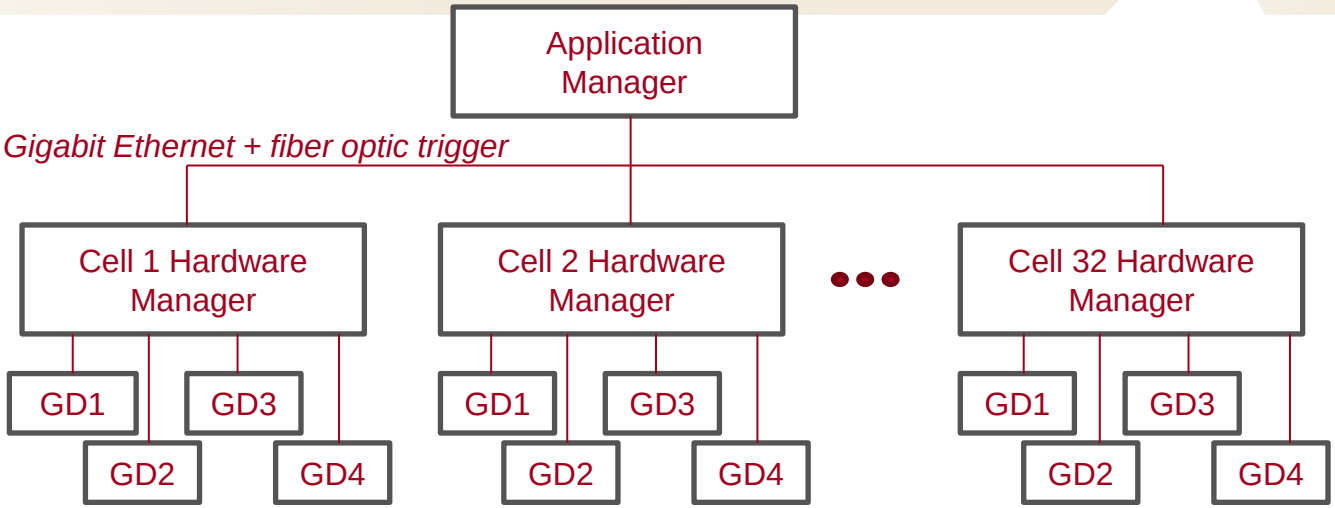




SLAC P2 Marx: Simple Maintenance

- 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



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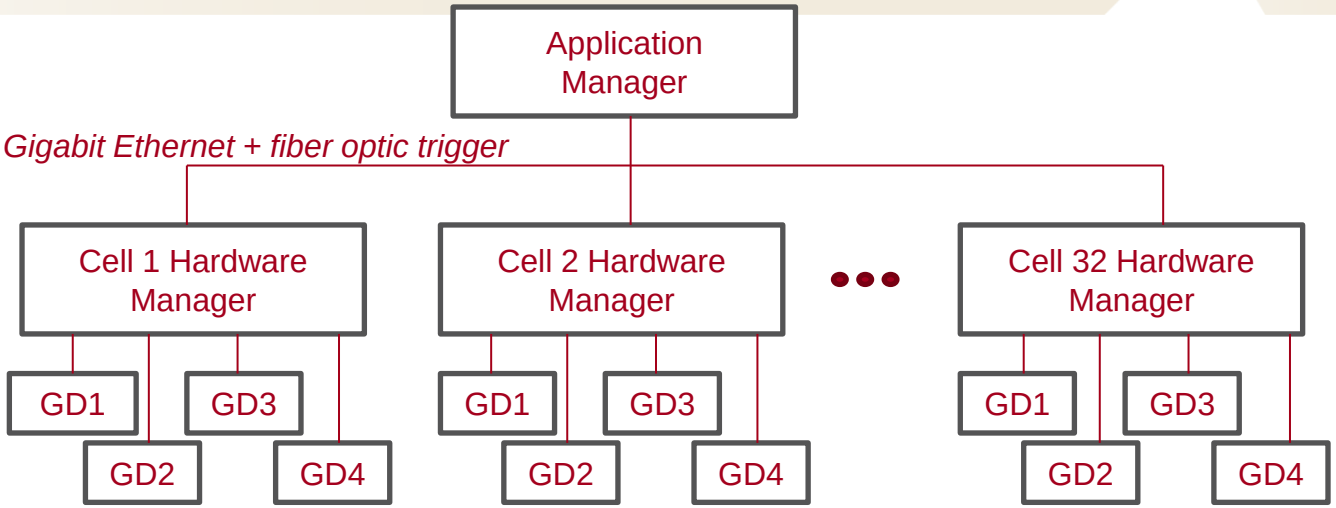
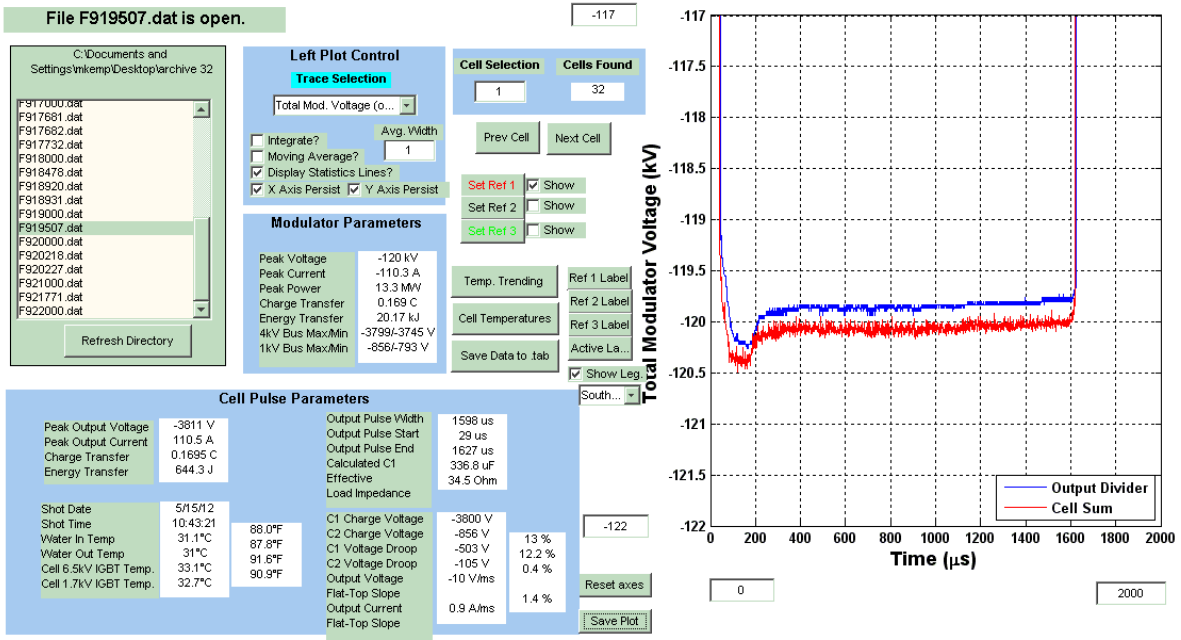


- 256, 12-bit, 1 MS/s, 2.1ms-long waveforms are captured each shot



Scaling of the Technology to Emerging Applications

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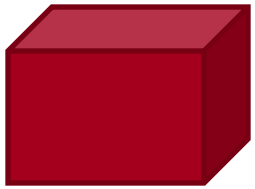
- The ILC P2 Marx building block has:
  - A maximum voltage (4kV)
  - A maximum peak current (200A)
    - Can increase by changing switches
  - A maximum average power
    - Can increase by changing cooling
  - A maximum energy transfer per pulse
    - Can increase by increasing cell capacitance



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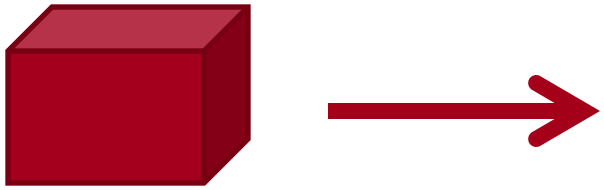

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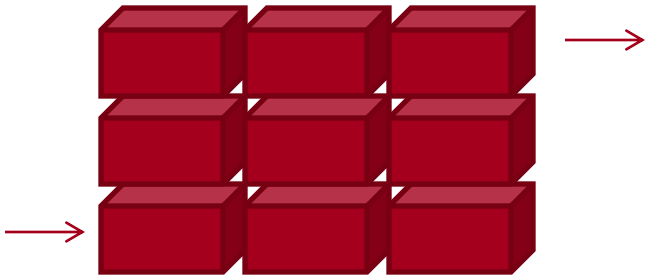

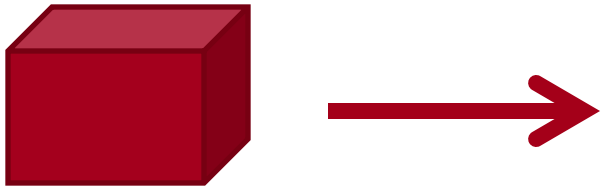

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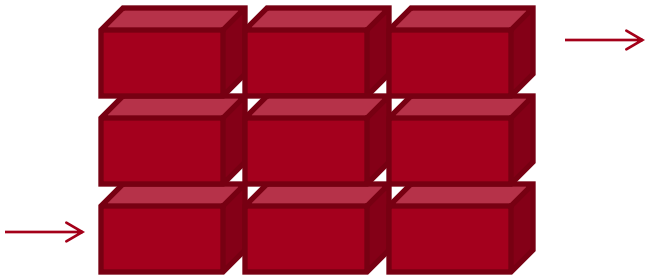

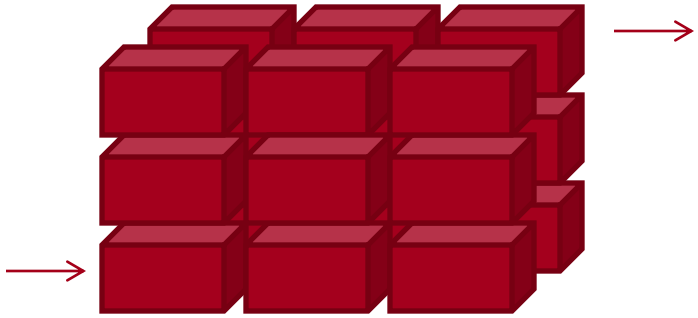

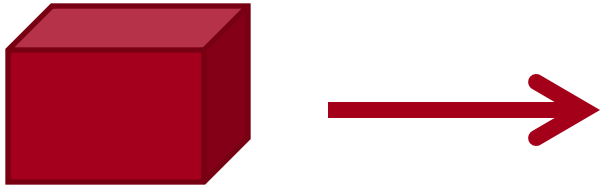

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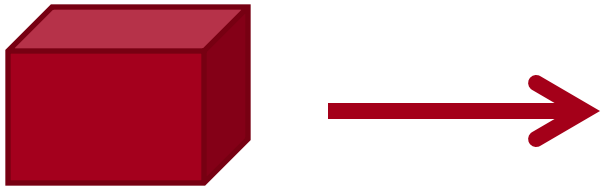

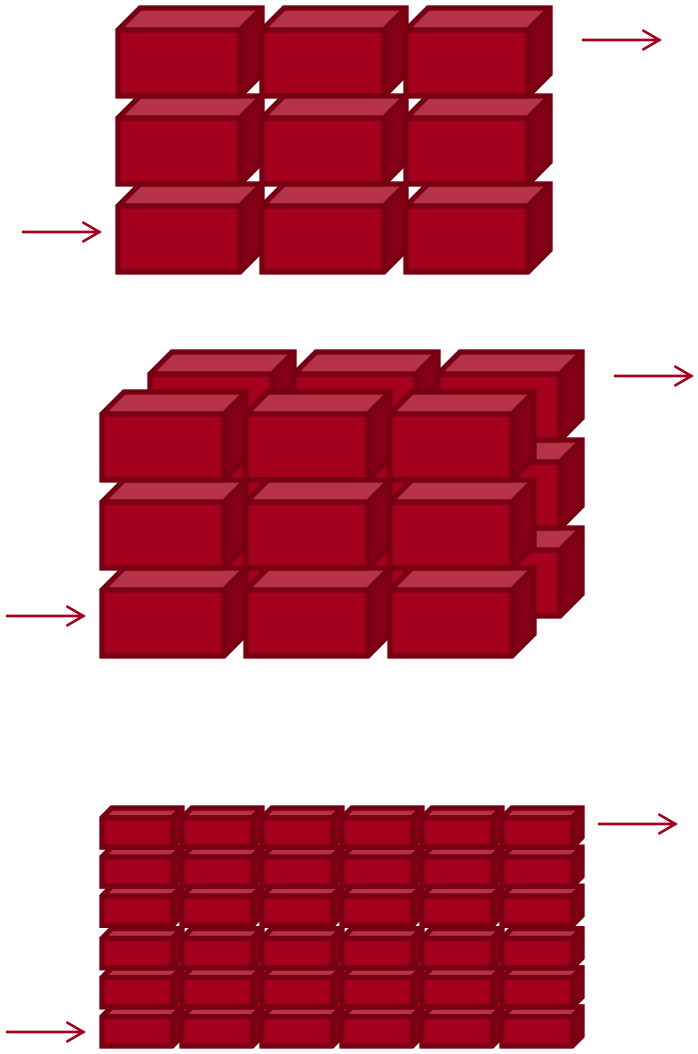

SLAC P2 Marx Scaled to ESS Klystron Modulator

- Assume 4.8MW, 14 Hz, 3.4ms pulse
- Assume same cell structure, same cell operating voltage, and N+2 redundancy

	# of Cells	Max Single Cell Loss	DC to Pulse Efficiency
ILC P2 Marx	32	410 W	95.0%
80kV ESS Marx	23	780 W	95.8%
113 kV ESS Marx	31	610 W	95.5%

CLIC Drive Beam Klystron Modulator

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- Challenging for efficiency and pulse-to-pulse reproducibility

Pulse Voltage	150 kV
Pulse Current	160 A
Pulse Width	140 μs
Reproducibility	10-50ppm
AC-Pulse Eff.	90%
Pulse Rep. Freq.	50 Hz

D. Aguglia, *et al*, "Klystron Modulator Technology Challenges for the Compact Linear Collider" Pulsed Power Conference, 2011.

CLIC Drive Beam Klystron Modulator

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•To address the pulse-to-pulse reproducibility specification, take advantage of in-cell diagnostics and control loops

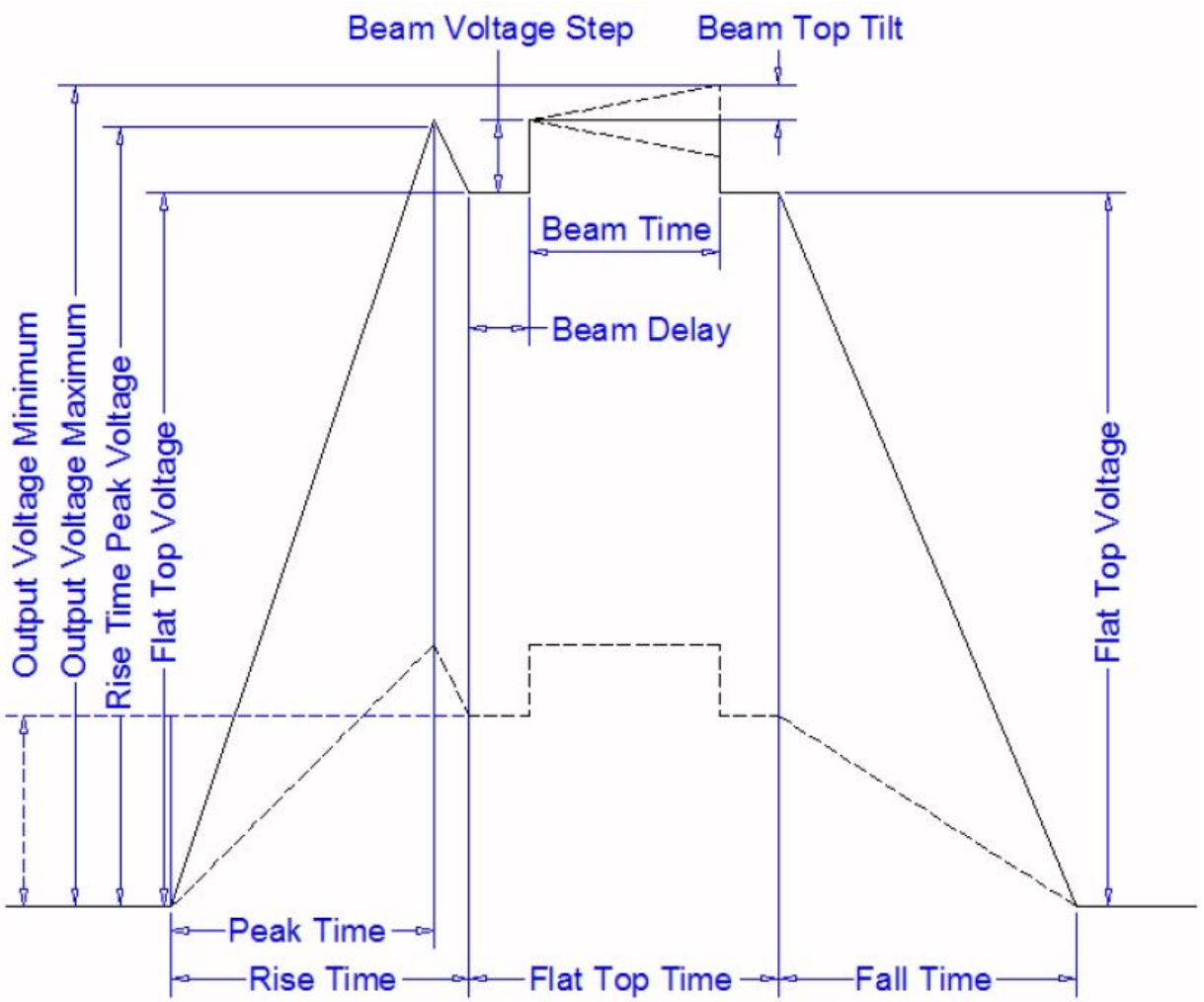
•*For example:*

- •A 12-bit diagnostic on the output can only hope to achieve $1/2^{12}$ precision
- •However, regulating on each of the n cells improves this number to $1/(n)^{0.5}/2^{12}$

- •*Precision can be improved from 244 ppm to 40 ppm*

D. Aguglia, *et al*, "Klystron Modulator Technology Challenges for the Compact Linear Collider" Pulsed Power Conference, 2011.

Fermi 201 MHz Linac Triode Modulator



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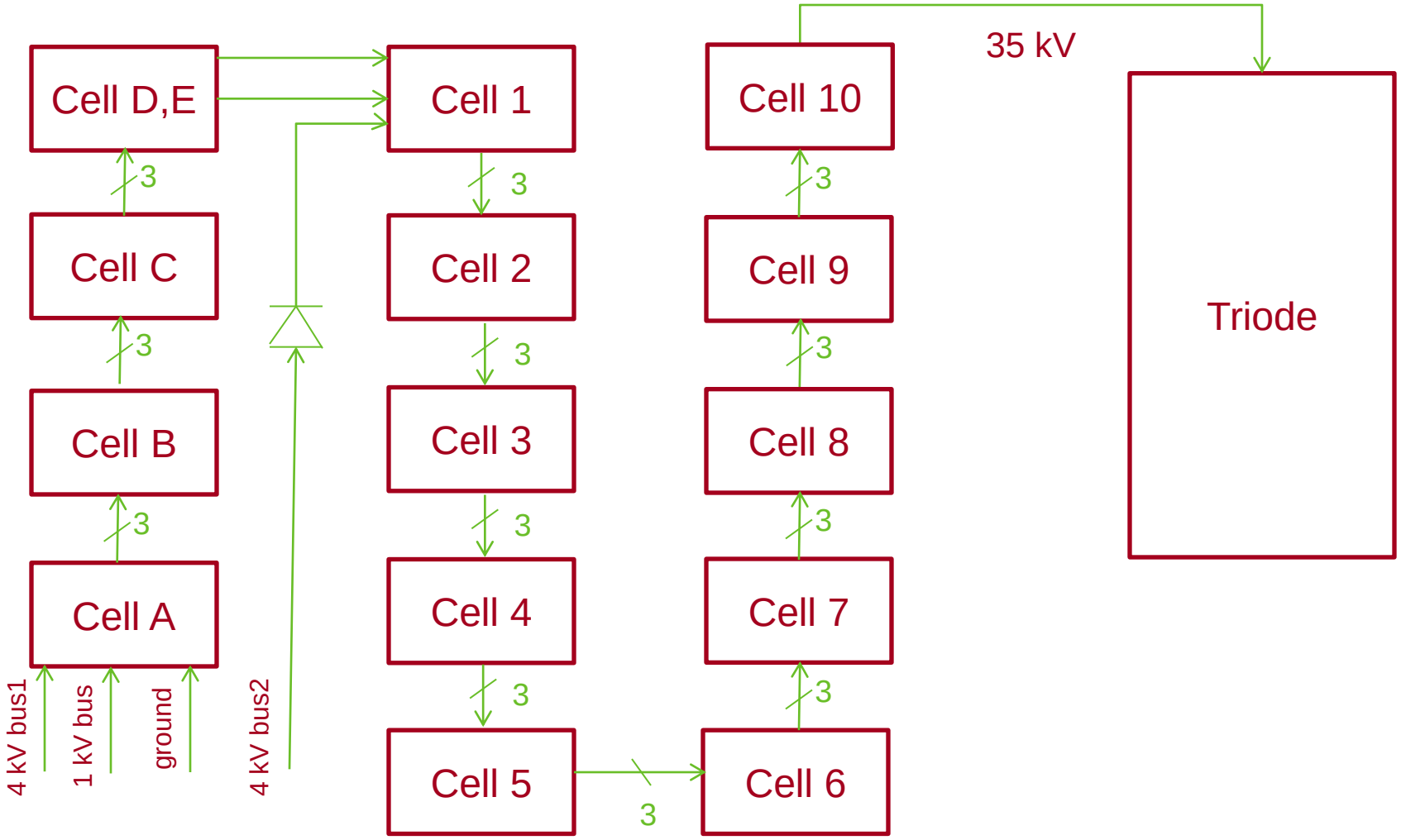

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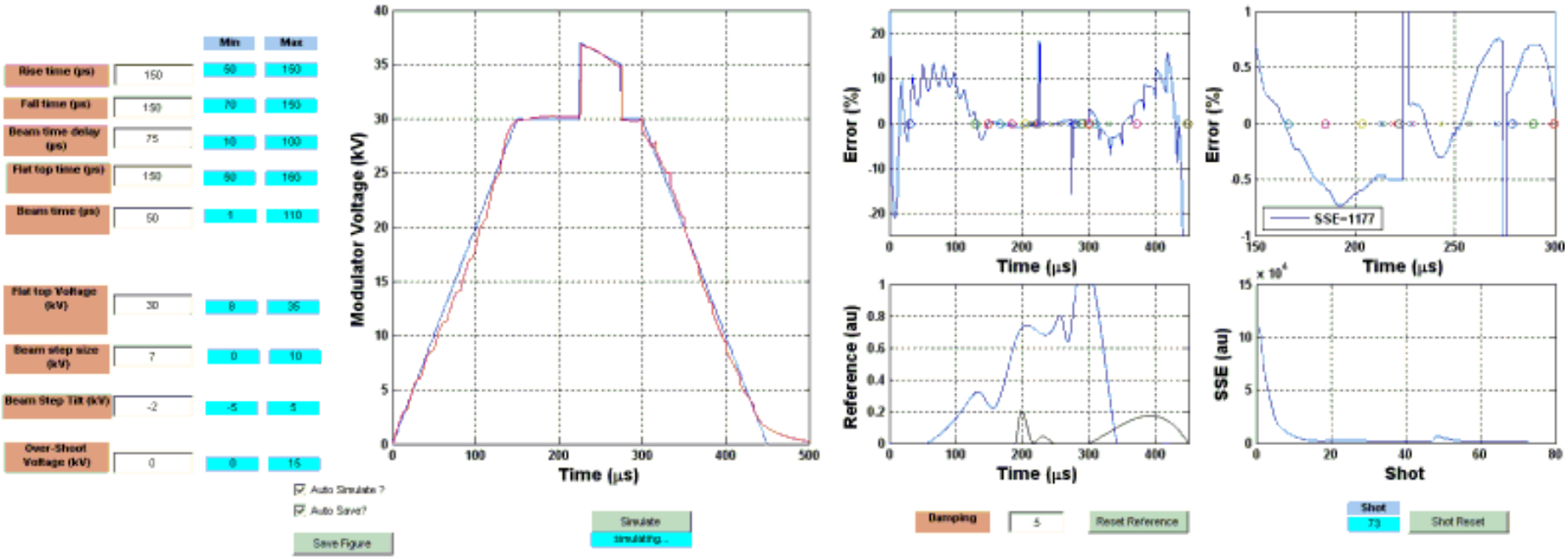

Summary

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- Solid state Marx modulators have characteristics which make them attractive for emerging applications

- Focus is on producing high availability, superior pulse quality, and an easily maintained system

- Modular topology with low-voltage subunits allows traditional power electronics techniques to be utilized

THANK YOU!