Development of a Marx Modulator for FNAL Linac

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FERMILAB-POSTER-19-116-AD

Modulator Requirements

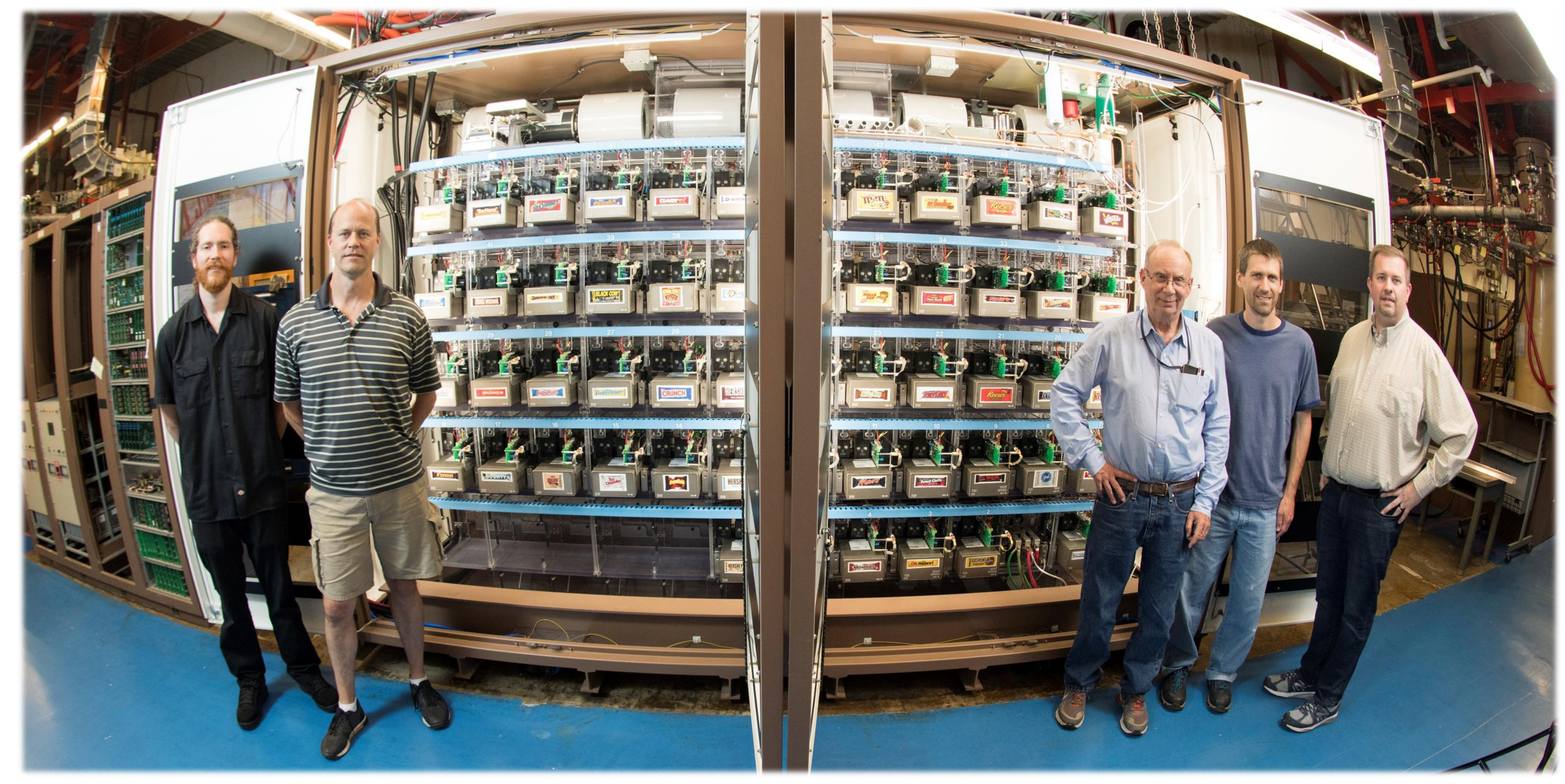
- Solid-state Technology
- Superior Reliability & Efficiency
- Variable Waveform Shape
- Modulator sets accelerating gradient
- Cavity filling & beam compensation
- Learning & feedback control

Modulator Design Challenges

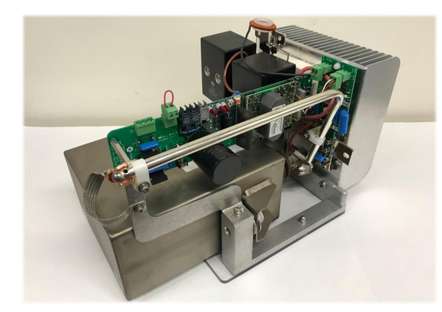
- High beam step slew rate ($\partial V/\partial t$)
- Protect Marx cells against tube sparks
- Limit spark energy delivered to tube

Design Specifications

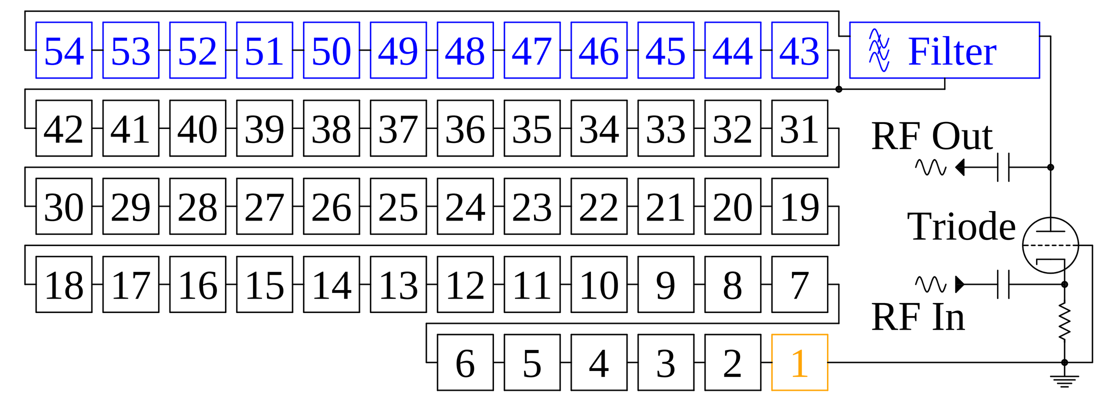
Peak Voltage:	35 kV
Peak Current:	375 A
Repetition:	15 Hz
Pulse Width:	460 μs
Step Size:	< 1500 V
Beam Step:	15 kV/μs
Rise Time:	50-150 μs
Fall Time:	70-150 μs
Beam Tilt:	± 5 kV
Regulation:	± 25 V
Spark Energy:	< 2 Joules



FNAL Linac Marx Modulator "The Candy Vending Machine"



Individual Marx Cell



Marx Cell Modulator Layout

FNAL Linac Marx Topology

41 Main Marx Cells (900 V)

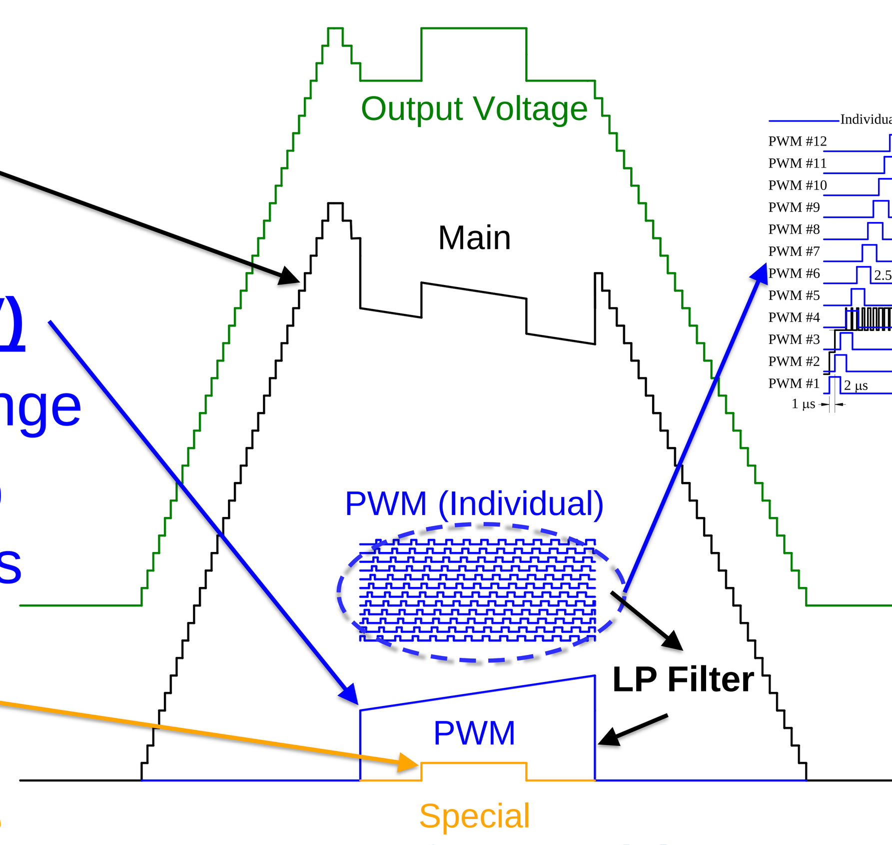
- Create the rising and falling edges
- Limits cavity reflected power back to tube

12 Pulse Width Modulation Cells (900 V)

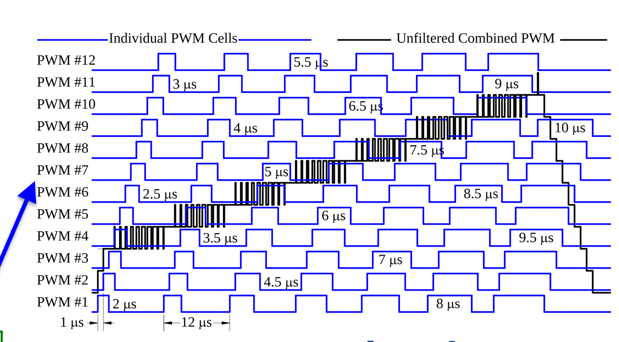
- Interleaved & filtered regulator w/ 7 kV range
- Flatten capacitive droop & regulate flattop voltage via feedback & learning algorithms

1 Special Cell (0 to 900 V)

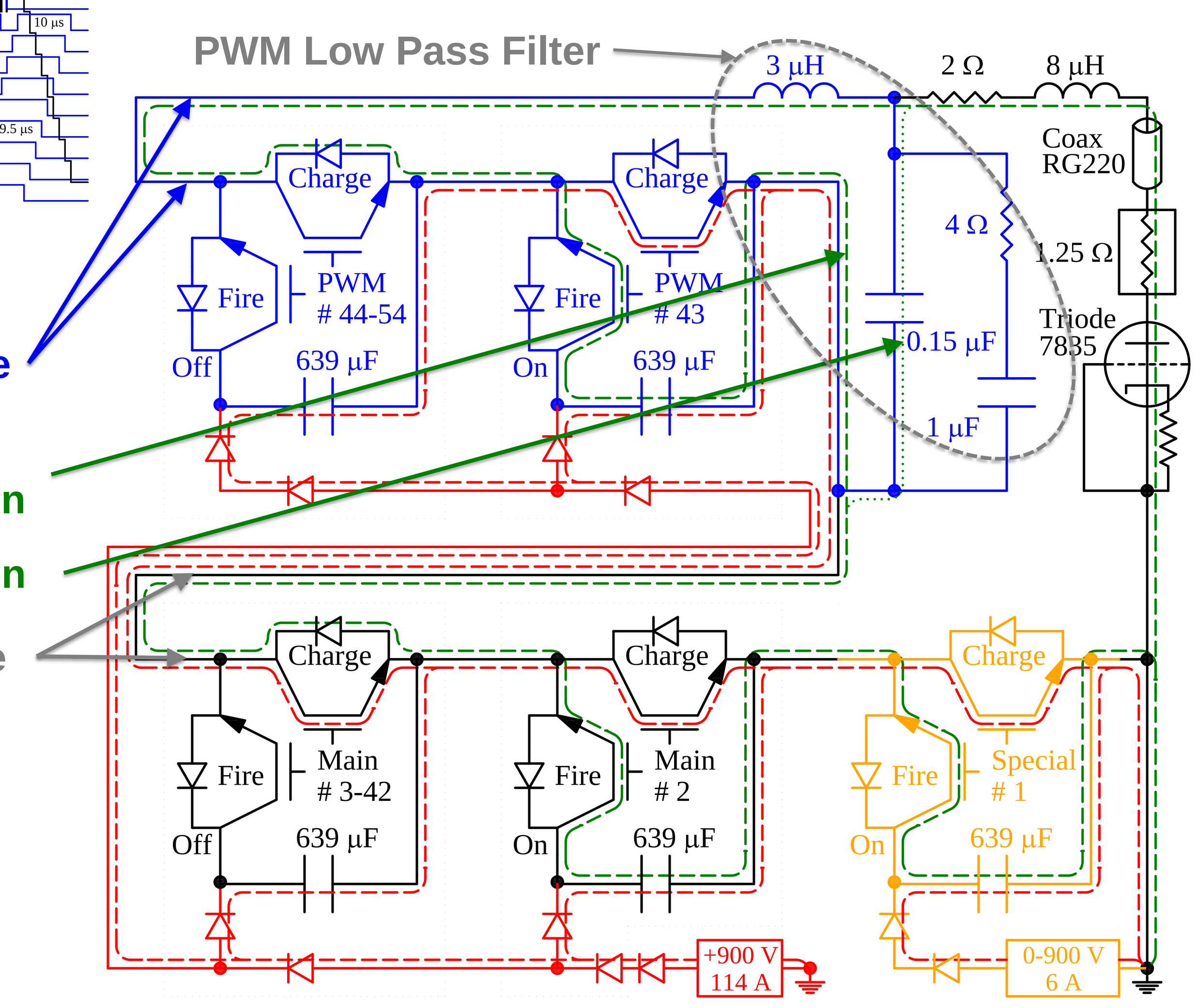
- Independently adjustable charging PS
- Enables fractional beam voltage step size



Marx Waveform Breakdown



PWM Interleaving

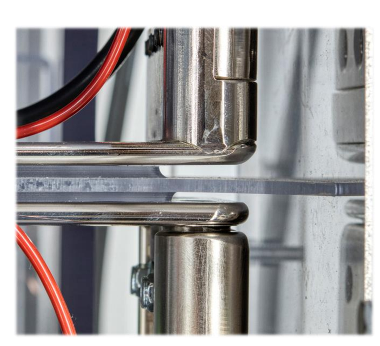


Simplified 5 Cell Marx Modulator Schematic

(Charging Current Path in Red, Firing Path in Green)

Modulator Control System

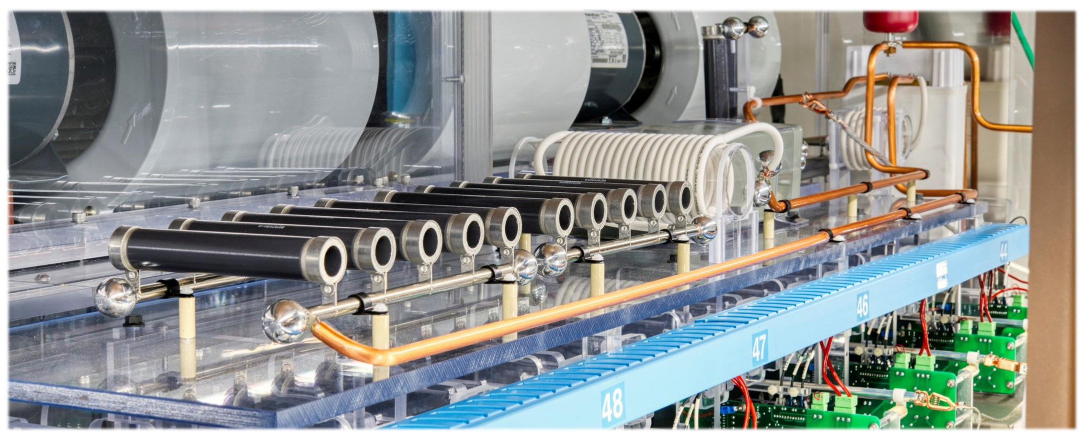
- 162 Fiber-optic Cables (Fire, Charge, & Status)
- Analog Readbacks (Gradient, Voltage & Current)
- Programable Logic Controller with Touch Screen
- Local accelerator controls network Integration
- FPGA Altera Cyclone V System-on-Chip
- Compare Gradient with gradient reference to calculate feedforward & feedback correction
- Feedback is summed with the learned correction & sent to the PWM cells with a 30 kHz
- Regulates flattop gradient to < 0.1%



Stripline Endplates

Rogowski Coil

Row of Marx Cells



Pulse Width Modulation Filter

Operational Results

- Gradient Flatness ↑ by factor of 2
- Slew Rate ↑ from 2 kV/μs to 15 kV/μs
- Pulse-to-pulse stability < 0.1%
- Power Efficiency, Uptime, & Tube Life ↑

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Conclusion

- Solid-state Marx modulator designed to replace previous hard-tube modulator
- Marx topologies can use traditional power electronics due to lower voltage cells and require less overall capacitance than traditional solid-state designs
- Solid state Marx Modulator have superior reliability, decreased physical size, lower component cost, lower operational costs, & increased efficiency
- Modulator simultaneously has high slew rate capabilities, can achieve low flattop ripple specifications, all while minimizing energy delivered into a tube spark
- Simultaneously performs waveform learning & real-time feedback
- Capable of creating any desired arbitrary wave shape

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.