Development of a Marx Modulator for FNAL Linac

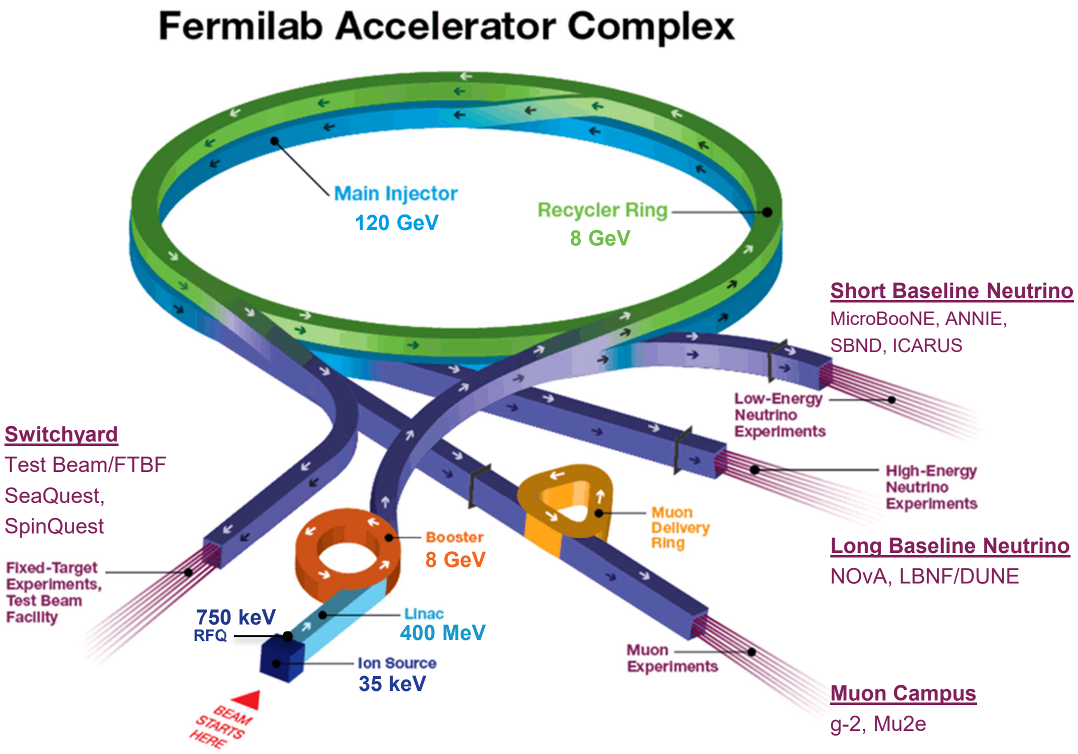
Trevor A. Butler, NAPAC 2019

4 September 2019

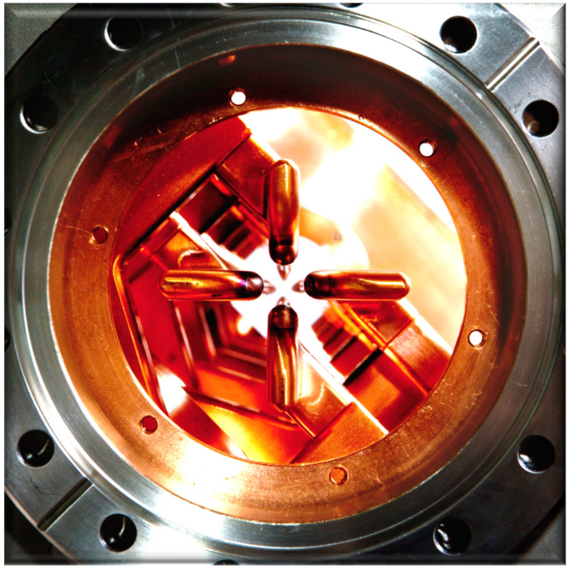
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Agenda

1. FNAL Linac Accelerator
2. Modulator Specifications
3. Marx Modulator Topology
4. FNAL Marx Modulator Design
5. Operational Results
6. Conclusion



FNAL Linac Accelerator



<u>Radio Frequency Quadrupole (2012)</u>
201.2406 MHz (35 – 750 keV)
1 RFQ, 175 kW Tetrode
H- Magnetron Ion Source

<u>Alvarez Drift Tube Linac (1970)</u>
201.2406 MHz (0.75 – 116 MeV)
5 tanks, 5 MW Power Triode
Hard-Tube → Marx Modulator

<u>Side Coupled Linac (1992)</u>
804.9624 MHz (116 – 400 MeV)
7 modules, 12 MW Klystron
Pulse Forming Network Modulator

Fermilab

FNAL Linac Modulator Specifications

Modulator: Converts AC Mains to pulse the anode of RF Tube

Previous Hard-Tube Modulator

- Energy storage capacitor bank
- Three parallel electron tubes
- Analog feedback control
- Discontinued vacuum tubes

Hard-Tube Modulator & Triode Tube

Variable Waveform Shape Requirement

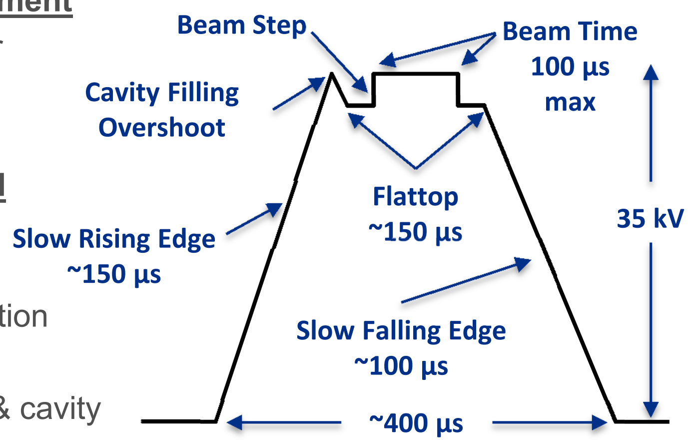
- Modulator Voltage sets RF Power
- RF Drive for phasing only
- Cavity filling & beam loading

Waveform Learning / Feed-forward

- Long term drift of tube & cavity
- Take previous gradient error from ideal & apply to next pulse correction

Waveform Real-time Feedback

- Pulse-to-pulse variations in tube & cavity
- Gradient error correction within the pulse



Variable Modulator Waveform

New Design Specifications

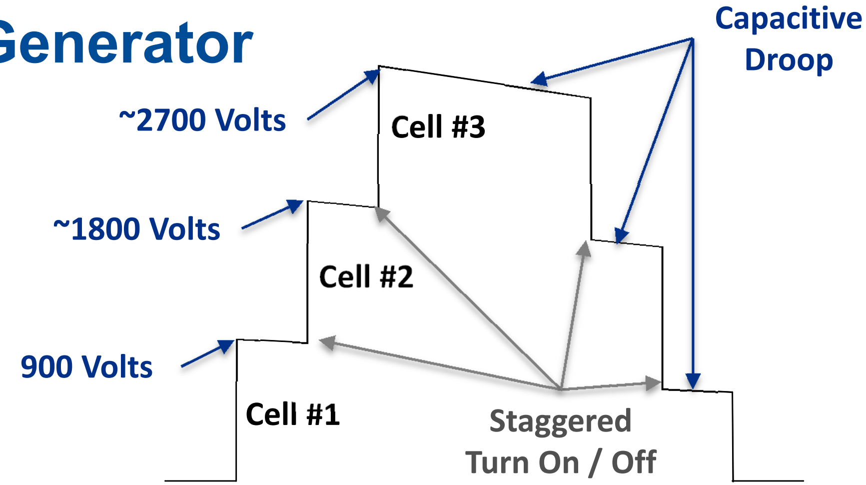
Solid-state Technology

- Superior reliability & efficiency
- Small size & lower operational cost

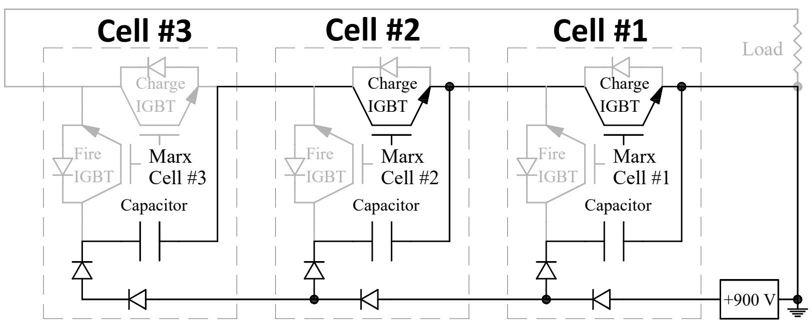
Peak Voltage:	***35 kV***
Peak Current:	***375 A***
Repetition:	15 Hz
Pulse Width:	460 µs
Step Size:	< 1500 V
Beam Step:	**15 kV/µs**
Rise Time:	50 – 150 µs
Fall Time:	70 – 150 µs
Beam Tilt:	± 5 kV
Regulation:	**± 25 V**
Spark Energy:	**< 2 Joules**

Modulator Design Choice → Marx Generator

- **Solution → Replace a high powered (linear, high power dissipation) "amplifier" with switch-mode (non-linear, low power dissipation) technology**
- Create a high voltage pulse by stacking many lower voltage "Marx" capacitor cells in series
- Marx cells charged in parallel between pulses
- Marx cells fired in series to create the desired pulse
  - Output voltage droops as capacitors discharge
  - Capacitor size determines percentage of droop

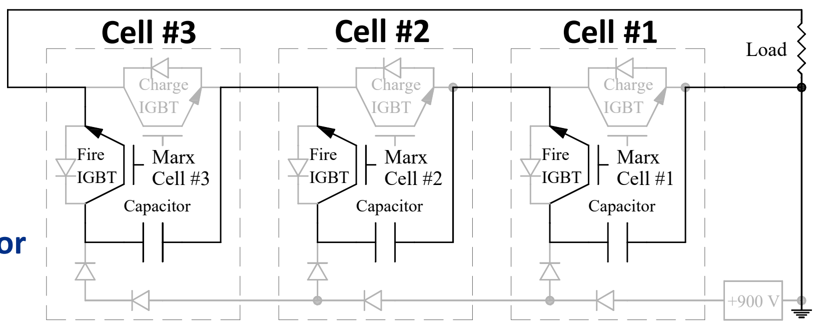


Simple 3 Cell Staggered Marx Modulator Waveform



Charged in Parallel

Simple 3 Cell Marx Modulator



Fired Sequentially in Series

FNAL Linac Marx Topology

Requirements of Solid-state Linac Marx Modulator

- Compensate for capacitive voltage droop
- Regulated smooth flattop with feedback (± 25 V)
- Fast beam step slew rate (> 15 kV/μs)
- Slow rising & falling edges (minimize reflected cavity power)

Solution → Create 3 Groups of Marx cells*

41 Main Cells (900 V) → Black

- Create the overall rising and falling edges
- Enabled 900 V incremental beam voltage steps
- Steps small enough to limit accelerating cavity reflected power to acceptable levels for the RF power tube

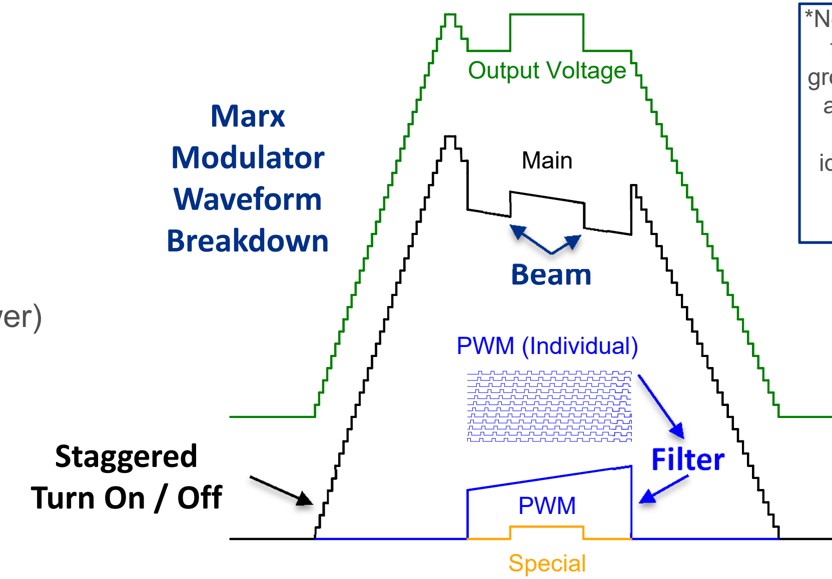
12 Pulse Width Modulation Cells (900 V) → Blue

- Interleaved & filtered PWM regulator with 7 kV range
- Flatten capacitive droop & regulate flattop voltage via feedback & learning control algorithms

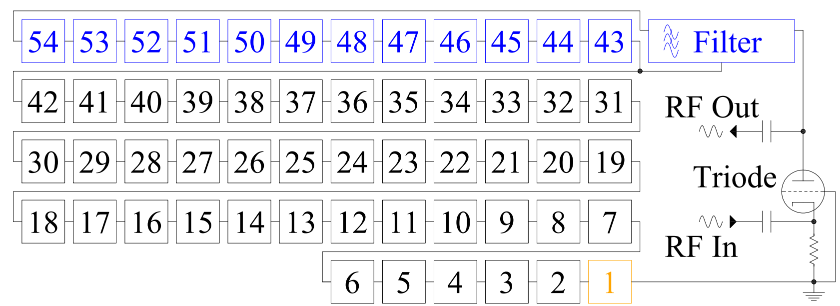
1 Special Cell (0 to 900 V) → Orange

- Independently adjustable charging power supply
- Enables fractional voltage beam step size

Marx Modulator Waveform Breakdown



*Note: Although there are 3 groups of cells, all individual cells are identical, just utilized differently.



Marx Cell Modulator Layout

FNAL Linac Marx Modulator

12 Cells Wide

Set by amount of voltage droop and beam tilt (~7 kV)

5 Cell High

Maximum height for technician serviceability

Open Cell Construction

Larger components shield smaller components

Forced Air cooling

Cool IGBT's & diodes

Polycarbonate Frame

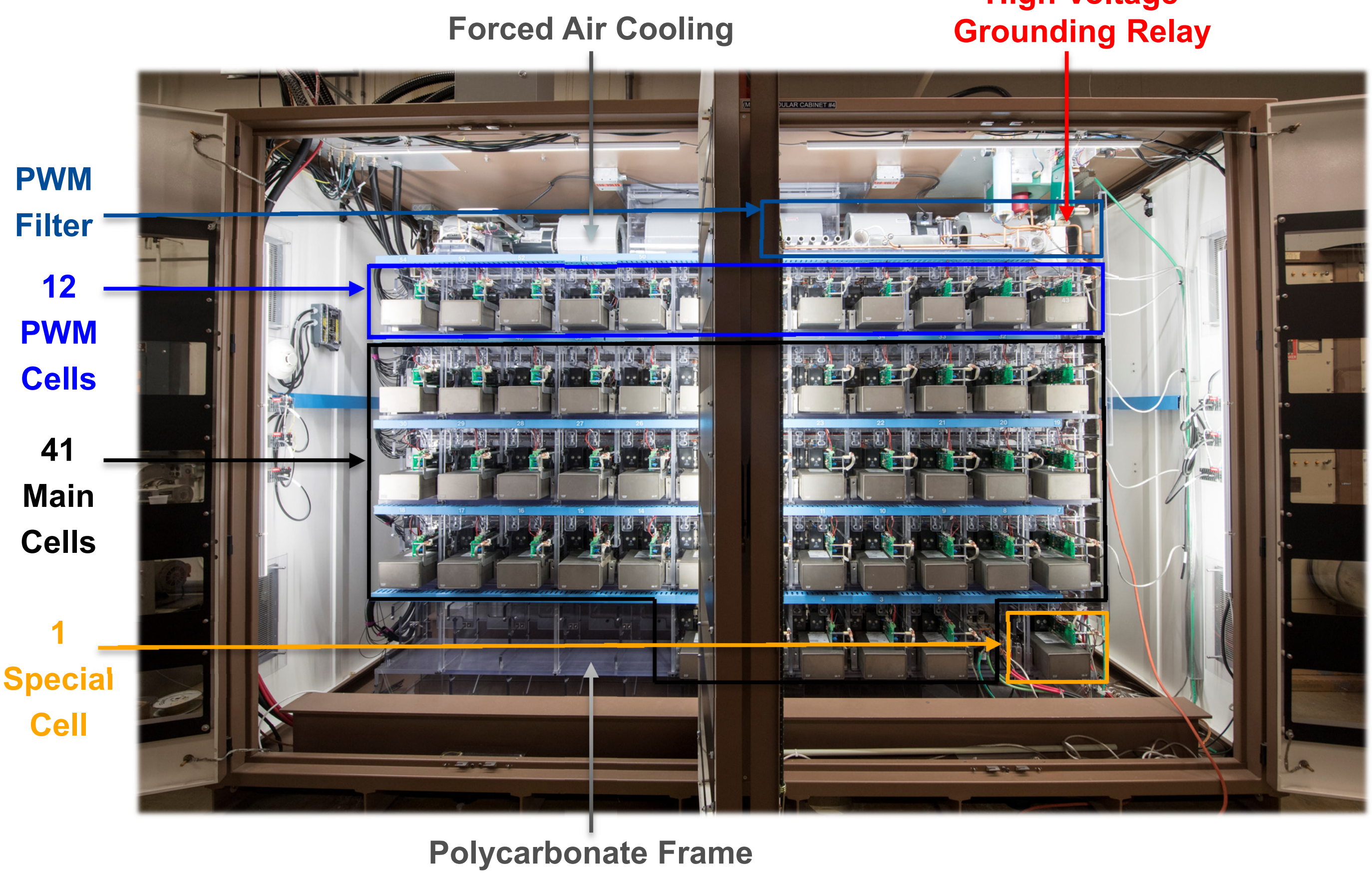
High voltage standoff

Corona mitigation

2D Cell Layout

Cells interconnected by parallel plate stripline

Done to minimize modulator inductance



FNAL Marx Generator Simplified Schematic (5 Cells)

Marx Cell Energy Storage Capacitors

- **Power Film Capacitor (639 μF, 1.8 kV)**
- 2 Parallel Snubber Capacitors* (5.6 μF, 1.5 kV)

Marx Cell Charge/Fire Solid-state Switches

- **Insulated-gate bipolar transistor (IGBT)**
- Half-bridge configuration (1.7 kV, 600 A)

Marx Cell Charging Path → RED

- Cells charged during 66.2 ms between pules (99.5% of 15 Hz)
- Fast recovery charging diodes (120 A, 1.8 kV)
- **Each cell charged thought previous cell's charging IGBT**
- Sequential activation of charging switch's during startup

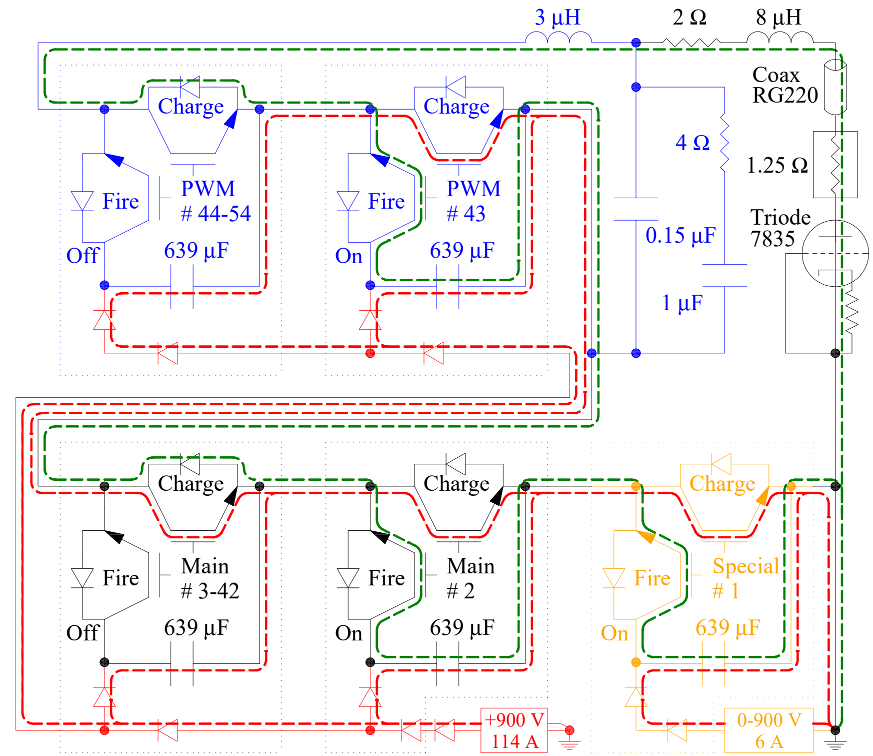
Marx Cell Firing → GREEN

- Cells firing during 460 μs pulse width (0.5% of 15 Hz)
- Exclusive Or (XOR) interlock separates charging & firing

Marx Cell Gate Controls Circuity*

- **Convert Fiber-optic commands to IGBT gate pulses**
- Sense IGBT desaturation to keep switch in safe operating area

Cells interconnected by parallel plate stripline (< 10 μH)
Cells charged by capacitor charging PS (120 Amps, 900 Volts)



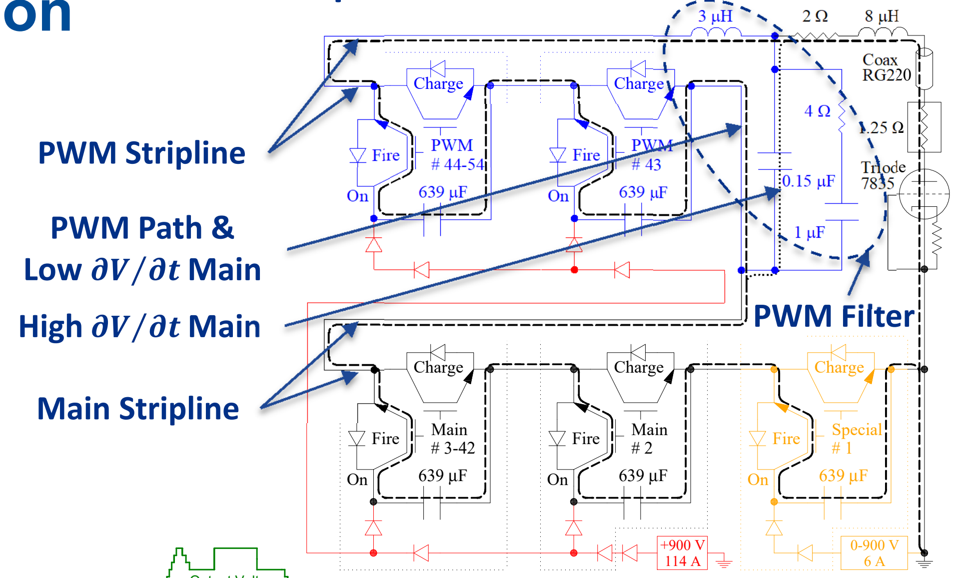
Simplified 5 Cell Marx Modulator Schematic

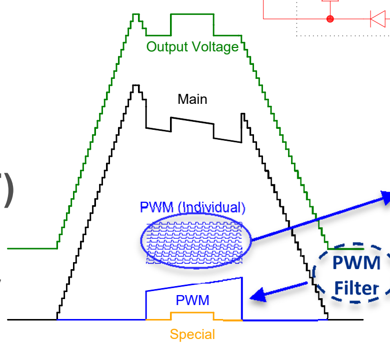
* Note that these components are not shown on schematic

Modulator Pulse Width Modulation

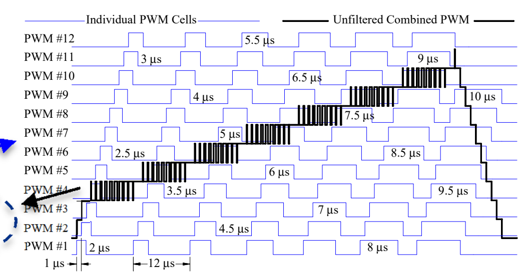
- ***Multi-function PWM Cells***
  - Capacitive droop correction (Feedforward)
  - Flattop slope (Learning)
  - Beam slope / tilt (Beam Learning)
  - Pulse-to-pulse corrections (Feedback)
- Pulse Width Modulation Specifications
  - 12 PWM Cells, run at 83.3 kHz (12 μs period)
  - **PWM frequency: 1 MHz (1 μs interleaving)**
  - Duty Factor (16.7% to 83.3% → 2 μs to 10 μs)
  - 8 Cells (~7kV) of Voltage Range (2 min. to 10 max.)
- Switching losses limit operation to flattop
- **Higher frequencies filtered by 2nd order 100 kHz "Praeg" low-pass filter** **(damped & undamped capacitors)**
- **Undamped Praeg low-pass filter capacitor (0.15 μF) passes fast slew rate ($\partial V/\partial t$) of main cells**
- PWM cells must be located on top row to prevent filter components from disrupting cell charging

Simplified 5 Cell Modulator Schematic





Marx Waveform Breakdown



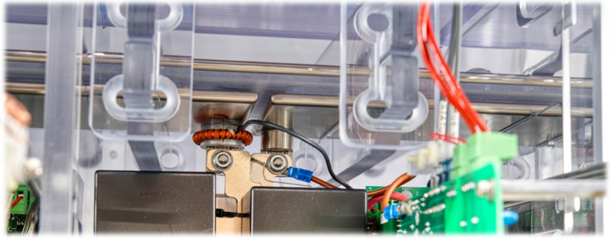
PWM Interleaving

Modulator Design Challenges

- **Achieve high beam step slew rate ($\partial V/\partial t$) specification**
  - Modulator inductance must be < 10 μH
  - Cells are connected in series via parallel plate stripline
  - Low inductance construction within individual Marx cells
- **Protect Marx cell against effects of tube sparks**
  - ***Limit short circuit current and time***
  - 3 kA/μs current rise into spark (assuming 10 μH & 30 kV)
  - Controls not fast enough to turn off switches before overcurrent
  - IGBT's must be individually self-protecting
- **Limit spark energy to < 2 Joules**
  - Minimize stored energy in Pulse Width Modulation low-pass filter
  - Add energy absorbing resistors on output of the modulator
  - Protect against Marx cell firing IGBT failing to turn off

Marx Modulator design involves making tradeoffs between many factors to create a production design

Low Inductance Stripline Endplates

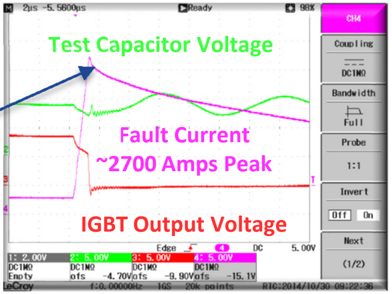


Low Inductance Marx Cell Connection

Pulse Width Modulation Low-Pass Filter

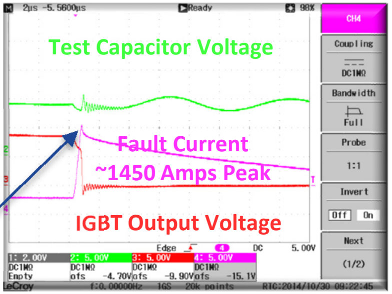
Modulator Spark Fault Current Limiting

- **Commercial IGBT Gating Circuit**
  - Sense desaturation & turns off the gate in a controlled manner to keep device within the safe operating area & avoid destructive turn-off spikes
  - **Limits the peak short circuit current to < 3 kA peak**
- ***Rogowski coil is added to output of each cell***
  - Rogowski coil is a high speed, low inductance helical coil of wire with no metal core, wrapped around output of Marx Cell, with voltage induced proportional to $\partial I/\partial t$
- ***Limits spark fault current by triggering a gate voltage clamp***
  - High $\partial I/\partial t$ output pulse triggers circuit to clamp the IGBT gate command voltage to 12 volts to minimize the Miller effect
- **The combined effect of these reduces the modulator short circuit current to < 1.5 kA peak**
  - Limits peak $\boldsymbol{\partial V/\partial t}$ to less than ½ of snubber cap max rating during sparks



Short Circuit Test (No Coil)

Marx Cell Row



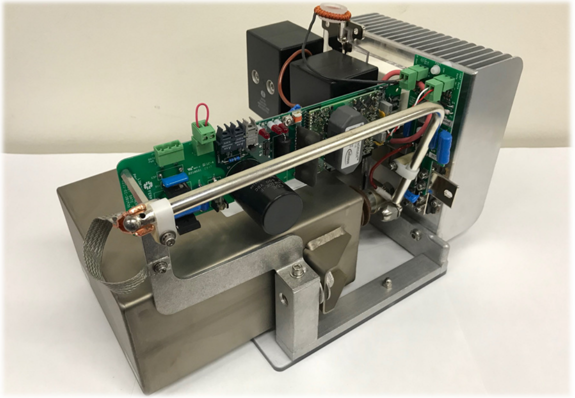
Short Circuit Test (with Coil)

Rogowski Coil

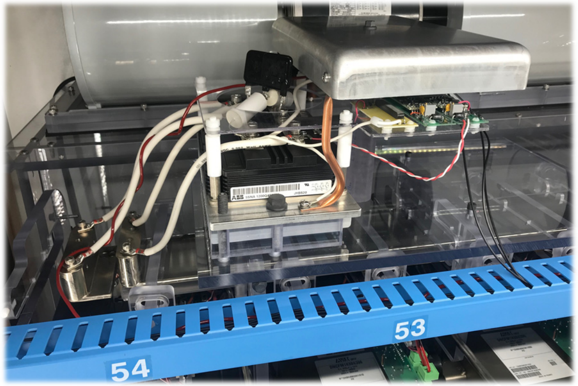
Fermilab

Modulator Spark Energy Reduction

- **RF Power Vacuum Tube limited to < 2 Joules**
- Short Circuit Current (< 1 Joule of stored energy)
  - Limited to 1.5 kA maximum current
  - Limited to 8 μs maximum turn-off time
  - Assuming 50 volt spark, below tube spark energy limit
- Undamped filter (5 Joules of stored energy)
  - **2-ohm resistor added in series with output to absorb this energy**
- Coaxial RG220 Transmission Line (~ 2 Joules of stored energy)
  - **1.25-ohm resistor added at end of the cable to absorb this energy**
- Marx Cell Main Storage Capacitor (300 Joules of stored energy)
  - Special 'ZOV' cell was added at the output of the PWM group of cells
  - 4.5 kV, 1.2 kA IGBT paralleled with a 1.5 kV zinc oxide varistor
  - IBGT Conducts during normal operation, then opens during a spark
  - **The ZOV then blocks the voltage of up to two failed Marx cells if they have failed to turn off due to a shorted cell firing IGBT**



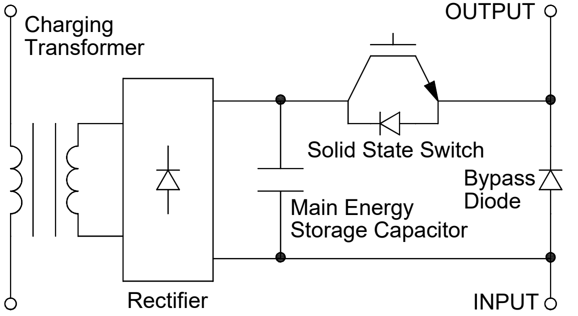
Individual Marx Cell



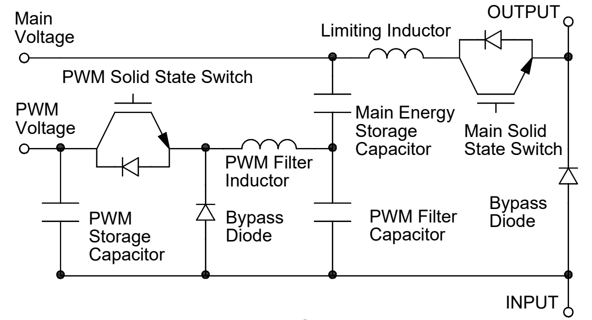
Marx Modulator ZOV Cell

Modulator Designs Considered

- **Other Marx style switch-mode modulators evaluated**
  - Industrial Design → Extensively modify solid-state AM broadcasting transformer coupled modulator (625 V/cell)
  - Accelerator Option → Modified version of the SLAC P2 Marx originally designed for ILC (4 kV/cell), which was not originally designed for real-time feedback control
- *No off-the-shelf designs available that meet all specifications without substantial development or modification costs*
- **<u>FNAL Electrical Engineering Group Design (900 V/cell)</u>**
  - Based around challenging specifications
  - Broad local modulator design experience at FNAL
  - Simultaneous testing, installation, & modification capability
  - Previously developed algorithms for learning & feedback control



Basic Transformer Coupled Cell

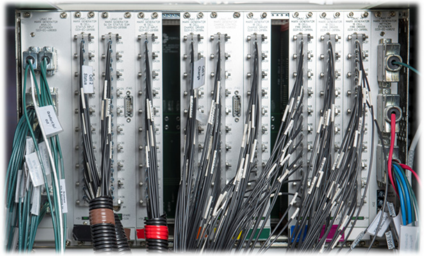


Dual Main/PWM Cell

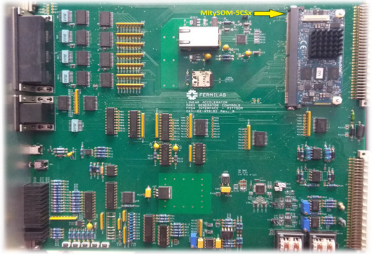
Fermilab

Modulator Control System

- **162 Fiber-optic cables (fire, charge, & status)**
- Analog readbacks (gradient, voltage & current)
- Programable logic controller with touch screen control
- Integrated into local accelerator controls network
- Controlled by a field-programmable gate array (FPGA)
  - **Altera Cyclone V MitySOM-5CSx System-on-Modules**
  - ARM Cortex-A9 CPU Hard Processor System @ 925 MHz
  - On-board power supplies, flash storage, & memory
  - Linux OS on HPS Core (15 Hz interrupts & application)
- <u>Feedforward & Feedback Controls System</u>
  - Generates reference gradient ramping curve
  - Calculates the voltage required to create curve
  - ***Compare gradient with reference to calculate both a fast feedback correction & a cycle-by-cycle learned correction***
  - Fast gradient error feedback is summed with the learned correction & sent through to the PWM cells (30 kHz BW)
- ***Control system regulates flattop gradient to < 0.1%!***

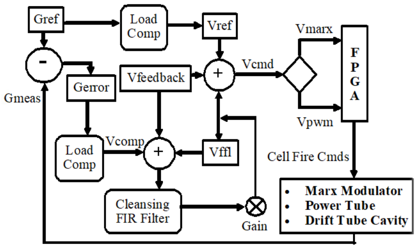


Fiber-optic Control System



FPGA Controller

Touch Screen Interface

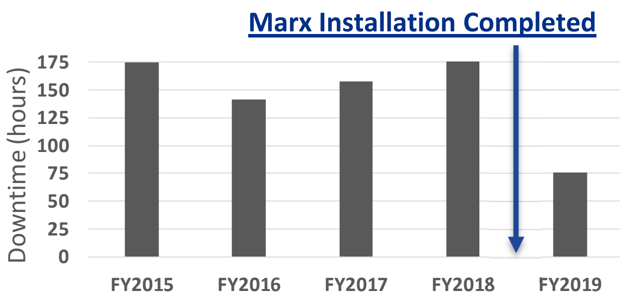


Feedforward Learning

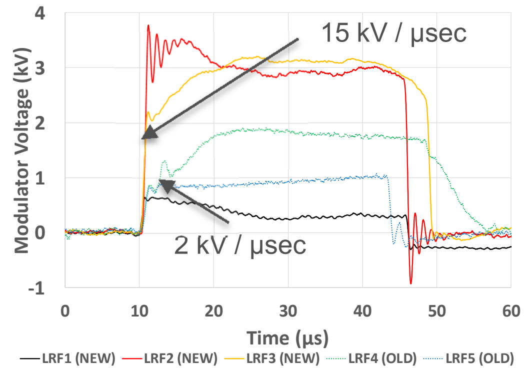
Fermilab

Operational Results

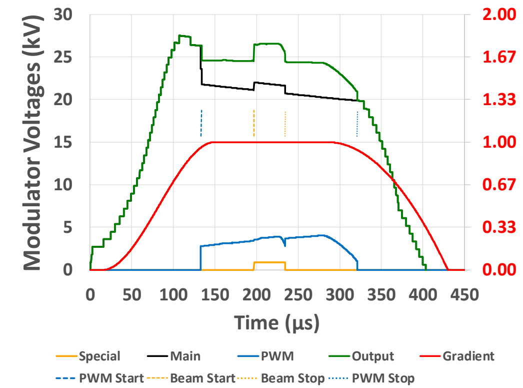
- Installed modulators in staggered stages due to shutdown time constraints
- **Noticed substantial improvements in waveform shape & quality**
  - Increased slew rate from 2 kV/μs to 15 kV/μs
  - Increased gradient flatness by factor of 2
  - Achieved better than 0.1% pulse to pulse gradient stability with learning & feedback
- Increased RF power triode lifetime
- Improved power efficiency & uptime



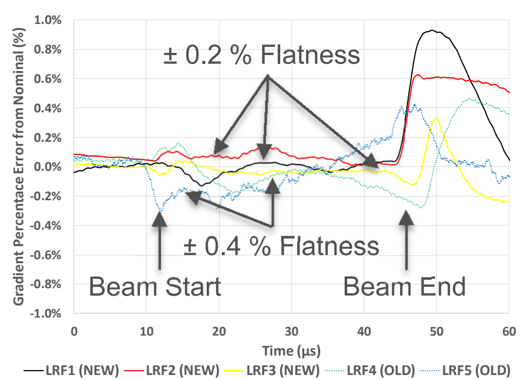
Linac RF Related Yearly Downtime



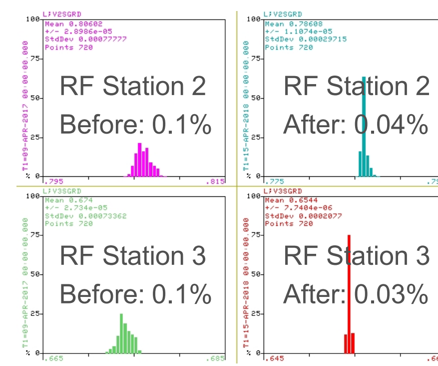
Slew Rate Comparison



Operational Modulator Waveforms



Gradient Flatness Comparison



Gradient Stability Comparison

Conclusion

- ***Solid-state Marx modulator designed to replace hard-tube design***
  – Marx topologies can use traditional power electronics due to lower voltage cells and require less overall capacitance than traditional solid-state designs
  – Superior reliability, decreased physical size, lower component cost, lower operational costs, & increased efficiency

- **FNAL Marx Modulator topology different from other Solid-state designs**
  – Flat Long Pulse (SLAC ILC) → Internal PWM to each cell to compensate for droop
  – Variable Long Pulse (FNAL) → External filtered PWM for some cells (low speed) & other cells unfiltered with no PWM (high speed)
  – Modulator topology capable of creating any desired arbitrary wave shape by performing waveform learning & real-time feedback
  – *Modulator simultaneously has high slew rate capabilities, can achieve low flattop ripple specifications, all while minimizing energy delivered into a tube spark*

- Started by building a 3, 9, & 28 cell prototypes before building 54 cell design
- Successfully updated all 5 modulators by FY 2018 during yearly shutdowns
- Marx Modulator was the final project of the Proton Improvement Plan
- **Proton Source uptime as a result of all PIP upgrades ↑ from 87% to 93%**

FNAL Linac Marx Modulator

Thanks! Any Questions?