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DEVELOPMENT OF A MARX MODULATOR FOR FNAL LINAC*

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Abstract

A Marx-topology modulator has been designed and developed at the Fermi National Accelerator Laboratory under the Proton Improvement Plan (PIP). This modulator replaces the previous triode hard-tube design, increasing reliability, lowering operational costs, and maintaining waveform accuracy. The Marx modulator supplies the anode of the 7835 VHF power triode tube with a 35 kV, 375 Amp, 460 µs pulse at 15 Hz. It consists of 54 individual Marx cells, each containing a 639 µF capacitor charged to 900 Volts, combined in series with IGBT switches to create the desired output waveform. This requires variable rise and fall times, flattening of capacitive droop, and feedforward beam loading compensation. All five 201.25 MHz RF systems have been upgraded to Marx modulators to ensure continued operation of the linear accelerator.

INTRODUCTION

The specification and design of a new anode modulator for the 7835 triode [1] have culminated in the development and installation of a new design, shown in Fig. 1. This new modulator uses the solid-state Marx generator technique of charging individual cells, each consisting of main storage and control power capacitors, in parallel via a charging switch in each cell, and then, after the charging cycle has completed, erecting the high voltage output by turning on separate firing switches in each cell. The modulator output amplitude is controlled by the voltage of the main storage capacitors in each cell and the number of cells fired at a time. This modulator is distinguished by the addition of a multi-cell interleaved pulse width modulation (PWM) regulator that sits on top of the main cells. The main cells run the voltage up to the flattop and back down while the PWM cells flatten and regulate the voltage during the flattop.

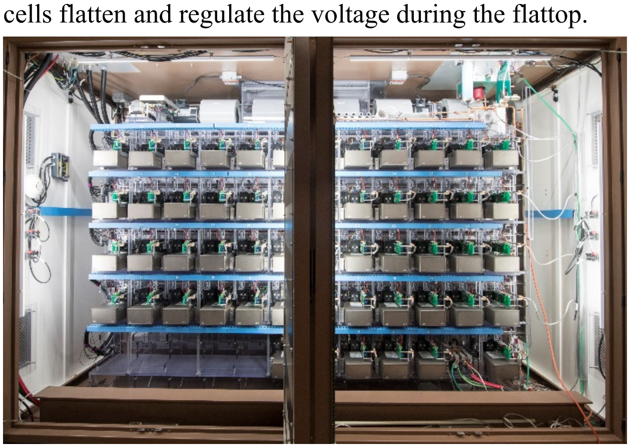

Figure 1: Photograph of the Marx modulator.

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MARX MODULATOR DESIGN

Marx modulator topologies can be used to create any desired waveform since each cell can be independently fired. However, the fixed step size and undesired capacitive voltage sag of each cell creates a challenge in designing a modulator that has a smooth flattop plus the desired slow rising and falling edges as well as the high dV/dt beam step slew rate needed to match the rising edge of the incoming beam. To overcome the limitations of the standard Marx topology, this modulator design was broken up into three groups as shown in Fig. 2, consisting of 41 Main cells, shown in black, which are used to create the overall rising and falling edges of the modulator pulse, 12 PWM cells, shown in blue, which are filtered to reduce the ripple created from the PWM process and used to compensate for capacitive droop along with providing the beam top tilt, and one special cell, shown in orange, that uses an adjustable voltage charging power supply to create a voltage step of any desired value to match various beam intensities.

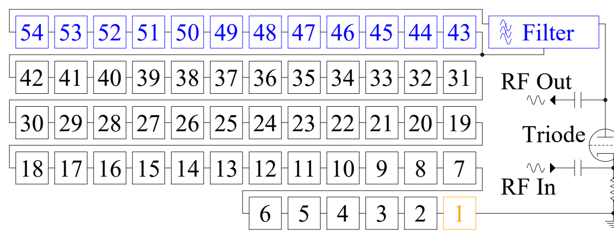

Figure 2: Marx modulator cell layout.

Marx Cell Design and Operation

The selection of the voltage per cell is critical in determining the cost, performance, and reliability of any Marx design. With the desire to reduce the power reflected from the accelerating cavity back to the tube, the operation of 900 V per cell was selected. The main storage capacitor is a 639 µF, 1.8 kV power film capacitor, which limits voltage sag to < 15%. Dual 5.6 µF snubber capacitors are added to reduced transients across the main storage capacitor. The solid-state insulated-gate bipolar transistors (IGBT) half-bridge configuration switches have a collector-to-emitter rating of 1.7 kV and peak collector current rating of 600 A, providing the overhead required for reliable operation.

The Marx cells main storage capacitors are charged by nineteen 6 A, 1 kV capacitor charging power supplies fed through 120 A, 1.8 kV fast recovery diodes to the Marx cells. To power the gate control circuitry, each cell also receives 300 V through a separate power supply. The gate circuity uses the same charging IGBT's as the main capacitors but use a different set of charging diodes. The cell outputs are interconnected by parallel plate stripline, used to limit the Marx inductance to 10 µH. The high voltage wiring for the capacitor charging and gate power supply are

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routed in parallel with the stripline to avoid magnetic inductive transients present when pulsing. A photograph of a Marx cell row and stripline are shown in Fig. 3.

Figure 3: Photograph of a Marx cell row and stripline.

The Marx cells are configured to operate in two modes, either in charging mode or firing mode. Hardware interlock circuity ensures that the charge and fire IGBT's can't be simultaneously activated, preventing a short that would destroy the Marx cell. All 54 cells are charged during the 66.2 millisecond delay between pulses. A simplified schematic of the Marx Modulator is shown in Fig. 4, with the charging path shown in red and firing path shown in green.

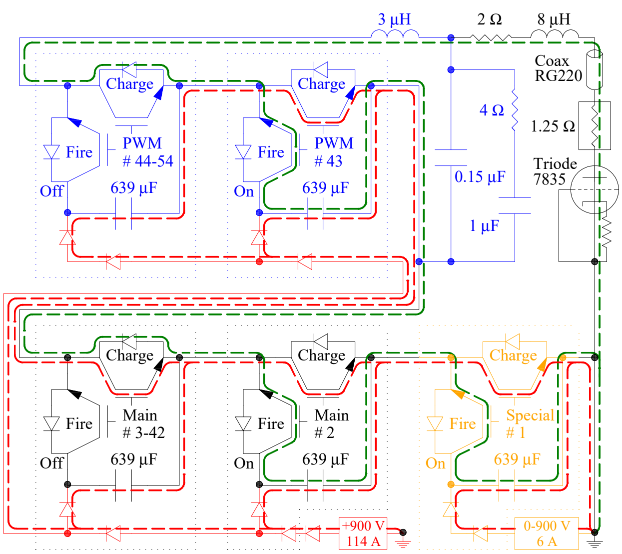

Figure 4: Simplified 5 cell Marx modulator schematic.

In the firing mode, each cell can independently turn on or off to create the desired voltage waveform. In other Marx modulators, these cells are often all turned on simultaneously, but in this modulator application, they are staggered on and off to enable the slow rising and falling edges needed to limit reverse power. The firing path, shown in green in Fig. 4, has cells 1, 2, & 43 turned on. In these cells, the output current will pass through the main storage capacitor, thereby adding the capacitor voltage to the output of the modulator. If a cell is off, such as cells 3-42 & 44-54 in Fig. 4, the output current will pass through the freewheeling diode of the charging IGBT, reducing the voltage by one diode drop. The waveforms for the three groups of cells in a full 54 cell production modulator, along with output voltage summation of the groups, the gradient waveform, and the PWM and beam timing are shown in Fig. 5.

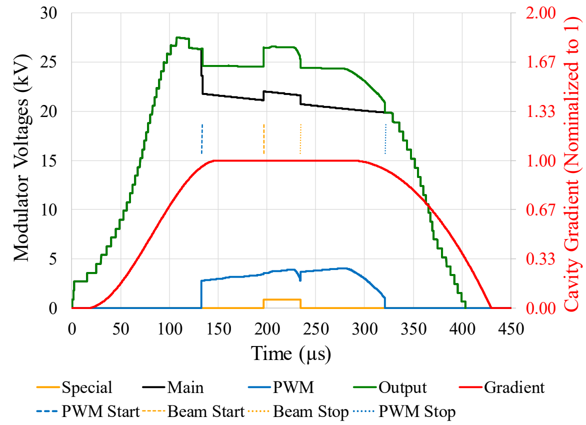

Figure 5: Typical waveforms for the Marx modulator.

The main Marx cells are only turned on or off during the rising or falling edges of the pulse. After the rising edge, the number of main Marx cells on is locked and only the PWM cells are used for regulation during flattop. The exception is during beam time, when the special cell, and possibly some main cells, are used to create the high slew rate beam step. The PWM cells are only activated during the gradient flattop section to limit switching losses and must be placed above the other cells so that the low-pass filter components don't disrupt the diode charging chains.

The twelve PWM cells are operated on a 12 µs period, with 2 µs minimum on and minimum off times. The 1 µs interleaving between cells creates a predominate ripple at 1 MHz, as shown in the unfiltered, ramped waveform in Fig. 6, which is then attenuated by a 2nd order 100 kHz low-pass filter applied across output of the group of PWM cells. This filter still allows the high slew rate beam step to pass through the undamped filter capacitor directly to the output. The PWM cells are used to create the fast feedback required to compensate for pulse to pulse tube instabilities, along with the waveform learning algorithm corrections to account for long term tube drift.

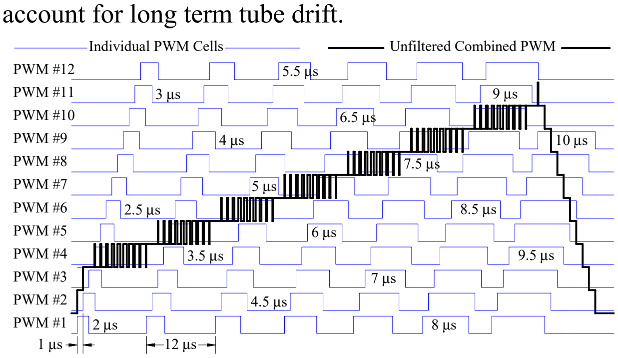

Figure 6: Ramped PWM waveform with commands.

Marx Modulator High Speed Design

The required 15 kV/µs beam step makes the response to load sparks quite challenging. At 30 kV output voltage, assuming approximately 10 µH of parallel plate stripline inductance, the dI/dt into a spark will be 3 kA/µs. Since the controls are not fast enough to detect a spark and turn off the IGBT's before they overcurrent, each Marx cell must be self-protecting. To do this, commercial gating circuits

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are used which sense IGBT desaturation and turn off the gate in a controlled manner to keep the devices within their safe operating area and avoid destructive turn-off spikes. This gate driver circuit limits the peak short circuit current to 3 kA. To reduce this further, a dI/dt sensing Rogowski coil is added on the output of each cell to quickly detect the spark signature and trigger a circuit that clamps the gate voltage to 12 V. The combined effect of these two circuits reduces the short circuit current to 1.5 kA, which is beneficial to the load and the cell circuitry, thus limiting the peak dV/dt across the snubber capacitors. To mitigate the consequences of high-speed spark transients travelling through the Marx structure, a lumped 8 µH coil was added to the output, putting the modulator past the 10 µH inductance budget, but after operational running, this was not a concern since the beam step rise time was fast enough.

Marx Modulator Spark Energy

The 7835 tube needs to be limited to a low 2 Joules of energy delivered during tube sparks. The 1.5 kA short circuit current limit and 8 µs turn-off time keep the energy well below this value, but the undamped filter cap may contain up to 5 Joules, so a 2 Ω resistor was added in series with the output to absorb this energy. Another 1.25 Ω resistor was added at the end of the RG220 coaxial output cable to absorb the cable stored energy during a tube spark.

An important part of the commissioning of each modulator is the spark test, in which a spark gap is triggered on the output. A concern was noted of the possibility of a firing IGBT failing short during a spark and dumping up to 300 Joules, the energy stored in each main storage capacitor, destructively into the 7835 tube. To mitigate this, a special 'ZOV' cell was added at the output of the PWM group of cells, consisting of a 4.5 kV, 1.2 kA IGBT paralleled with a 1.5 kV zinc oxide varistor. This IGBT conducts during normal operation but is opened during a spark. The ZOV then blocks the voltage of up to two failed Marx cells.

Marx Modulator High Voltage Design

The generation of corona was a concern due to high voltage operation in air. To mitigate this concern, the Marx cells are attached to a custom designed self-extinguishing polycarbonate frame, which from experience, has a high corona inception voltage due to its homogeneous structure. After corona testing a section of cells, it was found that the smooth surfaces of the stripline, main storage capacitors, and rounded heatsinks provided good shielding for the smaller components, such as the firing boards, enabling the components of each cell to be exposed. Without the need for a metal case surrounding each cell, the IGBT's and diodes can easily be air cooled from the fans installed above the cells, which force air past the rounded heatsinks.

Marx Modulator Control System

The custom designed control system uses 162 individual fiber-optic cables to control the fire, charge and readback status of all 54 cells, along with reading the analog gradient, voltage, and other signals used for regulation and interlock control. A programmable logic controller is used for interlock control, to communicate with a touch screen for local control, and to interface with the accelerator controls network for remote operation. The field programmable gate array used is an Altera Cyclone V, based on the MitySOM-5CSx, to control all fiber-optic, analog, and interface cards, along with providing the memory and central processing unit. The control system generates a reference curve for the ramping up of the cavity gradient, holding it constant for flattop, then ramping it back down. The system calculates the voltage required to create this gradient ramp and controls the various Marx cells via fiber-optic firing commands to create the voltage, and then compares the measured gradient with the reference to calculate both a fast feedback correction and a cycle-by-cycle learned correction to regulate the flattop gradient to < 0.1%.

The learning system is based on the algorithm used in the Fermilab Main Injector power supply system, where the power supply voltage drives the magnet current with a known gain and time constant. In this application, since the RF output power of the tube tracks the voltage applied, the algorithm uses the 7835 tube gain and the 35 µs accelerating cavity filling time constant. Both control systems make use of digital finite impulse response filters to roll off the response signals without introducing phase shifts that limit bandwidth. Fast feedback of the gradient error is summed with the learned correction and sent through to the PWM cells, which have a usable bandwidth of about 30 kHz.

CONCLUSION

The PIP Marx Modulator upgrade was implemented to address the required accelerator upgrades needed to increase proton flux without increasing activation level, to ensure viable operation, and increase overall reliability of the proton source [2]. Since upgrading all 5 systems, increases in tube lifetimes have been noticed, along with a decrease in downtime, and an increase in gradient stability in both pulse-to-pulse basis and flatness across the pulse.

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