Compact Flash X-ray Systems for Radiographic Applications

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ABSTRACT

Compact Marx generators based on the wave-erection principle are ideal drivers for flash x-ray systems. Traditional Marx generator design techniques lead to slow rising voltage pulses, marked by high impedances, large temporal jitter values and inefficient transfer of energy. As a result, larger pulse generators are fabricated to overcome these shortcomings, which results in excessive volumes and weights. Applied Physical Electronics, L.C. has been developing Marx generators for many years based on the wave-erection principle. As a result, generators with relatively low source impedances, high impulse voltages and compact geometries are making their way into use as portable flash x-ray drivers. More recently, APELC is extending their compact designs into complete flash x-ray systems, including the diode load. This paper discusses two generator systems that have been developed, basic diode geometries that will be incorporated, and a new novel system designed to generate up to an x-ray energy of 3.2 MeV.

Keywords: Marx generator, flash x-ray, penetrative radiography, compact Marx geometry

1. INTRODUCTION

Compact Marx generators have been employed for many years as trigger generators for larger systems and intermediate sources for high voltage pulses designed to pulse-charge pulse-forming lines. These generators are typically designed with pulse characteristics of more than 200 kV in peak voltage, more than 10 ns rise times, 10 ns rms jitter and pulse widths on the order of 10 ns. However, these systems grow in volume with increases in their erected voltages, since more Marx stages leads to higher source impedances and lower load voltage efficiencies. Recent efforts with compact Marx generators have brought faster rise times, higher peak voltages, and increased load voltage efficiencies, making them good presents two compact generators, namely a 600 kV generator and a 1.6 MV generator. Each generator has been designed with integrated, battery power ancillary components for autonomous operation. In addition to the generators, several x-ray diode configurations are discussed, all based on the rod-pinch geometry. Completing this paper is a discussion on the development of a dual-polarity Marx generator configuration sourcing a rod-pinch geometry for a 3.2 MeV x-ray source.

2. BACKGROUND AND DESIGN

2.1 The Wave Erection Generator

Traditional and antiquated Marx generator designs simply fabricate the circuit based on the fundamental Marx circuit concept—i.e. charging a bank of parallel capacitors via resistors and then switching the capacitors into a series configuration via interconnecting spark gap switches for a voltage multiplication. This simple design leads to slow voltage rise times and relatively low load voltage efficiencies.

Newer design methodologies include a good ground plane and the consideration of the associated stray components. As shown in Figure 1, the complete Marx generator model with a ground plane includes the stray-to-ground capacitance at each stage, the series inductance due conductive materials and the switch physics, and the stage-

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to-stage capacitance. Designing the stray elements into the overall design can lead to a "wave erection", in which an electromagnetic wave efficiently propagates the Marx circuit as the switches sequentially close. As a result, ultra fast rise times and high load voltage efficiencies can result. [2]

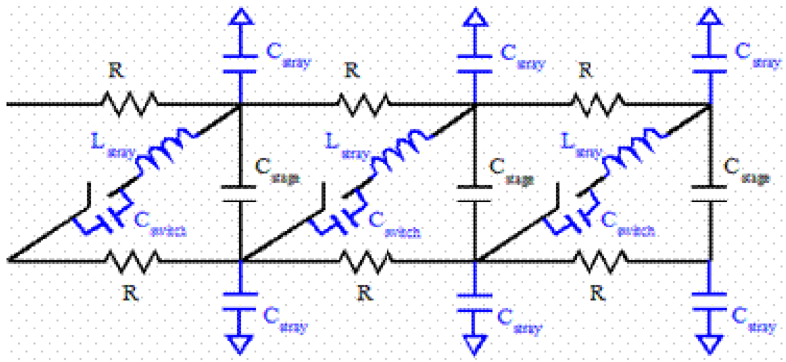

Figure 1. The wave-erection Marx generator topology.

APELC has developed a wide variety of Marx generators based on this topology, from handheld solid state circuits designed for the direct generation of RF, to large pallet-sized generators designed for sourcing low impedance vacuum diode loads. This paper discusses two APELC Marx generators specifically designed for sourcing x-ray diodes.

3. MARX GENERATOR/DIODE SYSTEMS

3.1 An Ultra Compact 600 kV Impulse System

A 15-stage Marx generator [3] has been designed for delivering low pulsed energies with relatively high pulsed voltages and is dimensionally illustrated by Figure 2. This generator uses three 940 pF TDK doorknob capacitors per stage, with charge voltages ranging from 10 – 40 kV. As a result, pulsed voltages from 150 kV to 300 kV result in a matched 50 Ω load, with an erected voltage of up to 600 kV. Table 1 provides the electrical specifications for this generator.

The generator is housed in an aluminum tube, measuring 5 inches in diameter and 30 inches in length. Inside this tube is an acrylic liner, insulating the Marx circuit from the ground plane. The vessel is then pressurized with a pressurized, dry and breathable air source for achieving high voltage holdoff with the spark gap switches. Table 2 provides the physical parameters for this generator.

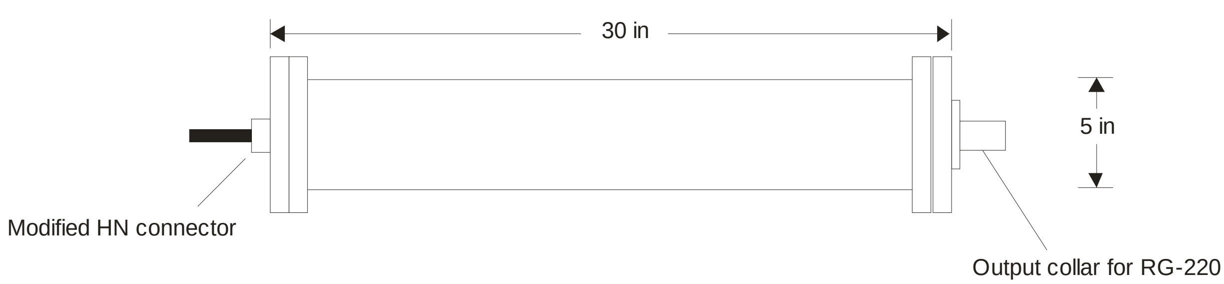

Figure 2. A dimensional view of the APELC 600 kV Marx generator.

Table 1. Electrical characteristics of APELC's 600 kV Marx generator.

Parameter	Description	Value	Unit
V_{open}	Open circuit voltage	600	kV
V_{ch}	Maximum charge voltage	40	kV
N	Number of stages	15	--
N_{cap}	Number of capacitors per stage	3	--
C_{stage}	Capacitance per stage	2.82	nF
C_{marx}	Erected capacitance	188	pF
L_{marx}	Erected series inductance	526	nH
Z_{marx}	Marx impedance	53	Ohm
EFF_{volt}	Voltage efficiency into 50 Ohm load	48	%
P_{power}	Peak power	950	MW
E_{marx}	Energy stored in Marx	33	J
T_{ch}^{*}	Time to charge	2	ms
T_{RR}^{*}	Maximum repetition rate	200	Hz
P_{ave}^{*}	Average power	4000	J/s

* Based on the use of a 4 kJ/s benchtop power supply

Table 2. Physical characteristics of APELC's 600 kV Marx generator

Parameter	Description	Value	Unit
L_{marx}	Marx length	30	in
D_{marx}	Marx diameter	5	in
L_{ps}	Power supply length	12	in
D_{ps}	Power supply diameter	9.5	in
Wt	System weight	30	lbs

Figure 3 provides a sample waveform from the 600 kV generator driving a 50 Ω resistive load fitted with a Current View Resistor (CVR). This waveform has been smoothed to reduce the reflection noise evident in the trailing edge, which is caused by the excessive load inductance. Figure 4 provides a sample acquired from the power supply monitor and is provided to illustrate the fast charging capabilities of the generator.

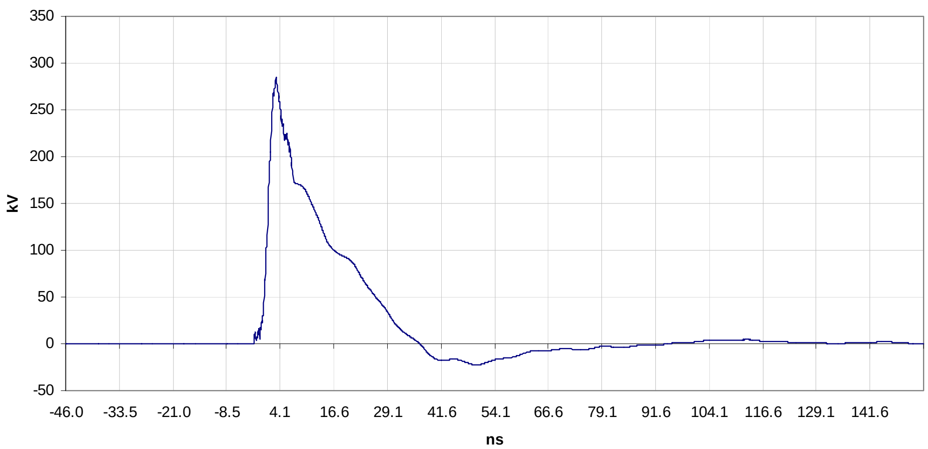

Figure 3. A sample output waveform with the 600 kV Marx generator driving a 50 Ω load.

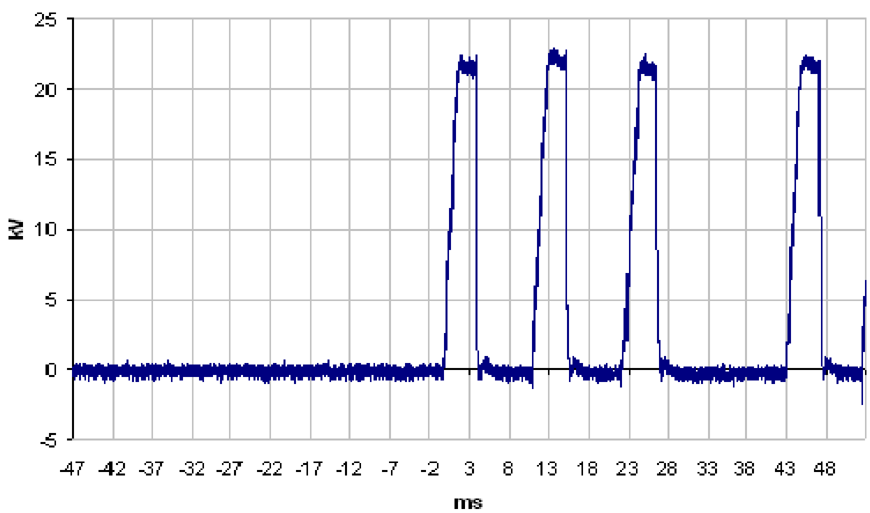

Figure 4. A sample waveform of the charge voltage monitor.

3.2 A Compact 1.6 MV Impulse System

The APELC MV generator [4] effort stems from the SuperSaver Marx generator developed by David Platts of Los Alamos National Laboratory [5]. APELC has taken Platts' design and moved it into a more modular geometry with minimal changes in the housing dimensions (approximately ½ inch was added to the housing diameter).

The completed design employs three TDK UHV-6A (30 kV, 2.7 nF) capacitors per stage, with a dimensional illustration shown in Figure 5. The capacitors are mounted to an ABS insulator that also fixes the brass electrodes and provides electrical interconnects. The Marx stages, once fixed together, compactly slide inside the insulating medium, which is fabricated with nylon (or epoxy for higher dielectric strengths). The liner has an internal diameter of 5 ½ inches and an outside diameter of 7 ½ inches. The liner is encased in an aluminum pipe that has a wall thickness of ¼ inches.

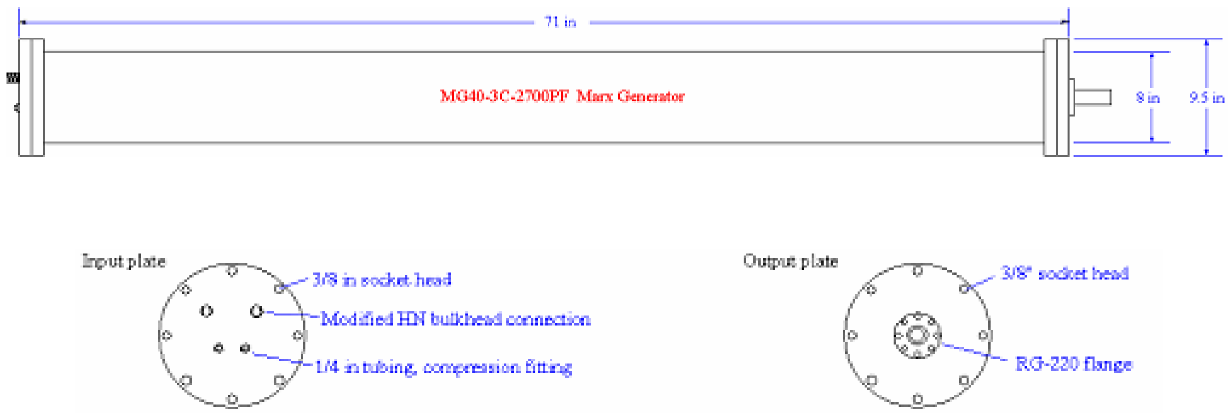

Figure 5. A dimensional view of the APELC MV Marx generator

Table 3. Electrical characteristics of the APELC MV Marx generator.

Parameter	Description	Value	Unit
V_{open}	Open circuit voltage	1.6	MV
V_{ch}	Maximum charge voltage	40	kV
N_{cap}	Number of stages	40	
C_{stage}	Number of capacitors per stage	3	
C_{marx}	Capacitance per stage	8.1	nF
L_{marx}	Erected series inductance	1	μH
Z_{marx}	Marx impedance	70	Ω
η_{volt}	Voltage efficiency into a 50 Ohm load	42	%
P_{peak}	Peak power (matched load)	15	GW
E_{marx}	Energy stored in Marx (maximum)	260	J
T_{ch}	time to charge	25	ms
T_{RR}	Maximum repetition rate	30	Hz
P_{ave}	Average power	10	kJ/s

Table 4. Physical characteristics of the APELC MV Marx generator

Parameter	Description	Value	Unit
L_{marx}	Marx length	72	in
D_{marx}	Marx diameter	8	in
L_{ps}	Power supply length	12	in
D_{ps}	Power supply diameter	8	in
Wt	System weight	250	lbs

A sample waveform from this generator is provided in Figure 6. In this case, the generator is configured to drive a 50 Ω cable that has been fitted with a 30 mΩ CVR. The charge voltage on the generator is set to 45 kV, representing a 50% increase over the voltage rating of the capacitors. The resulting waveform shows a 2 – 3 ns voltage risetime, achieving an approximate 800 kV amplitude.

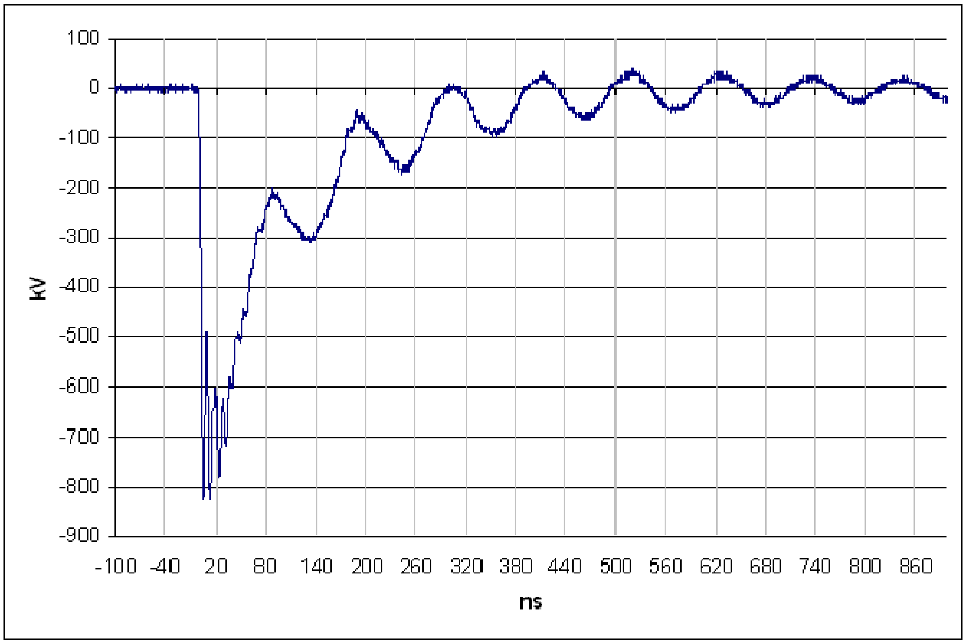

Figure 6. A sample output waveform from APELC's MV Marx generator driving a 50 Ohm coaxial cable.

3.3 Integrated Power and Control

To better support field applications such as flash radiography, APELC has been developing integrate ancillary component modules, which integrates prime battery packs, compact dc/dc converters, voltage-controlled pressure regulation, high voltage triggering and the user interface. As illustrated in Figure 7, the ancillary component module mounts directly to the Marx generator. The front panel control allows the user to select the operating charge voltage and vessel pressure, locally charge and fire the system via push buttons, or via a fiber-optically connected command box. Current efforts are focused toward incorporating imbedded controllers so as to provide the user with a LabView interface that will be fiber-optically connected to the generator.

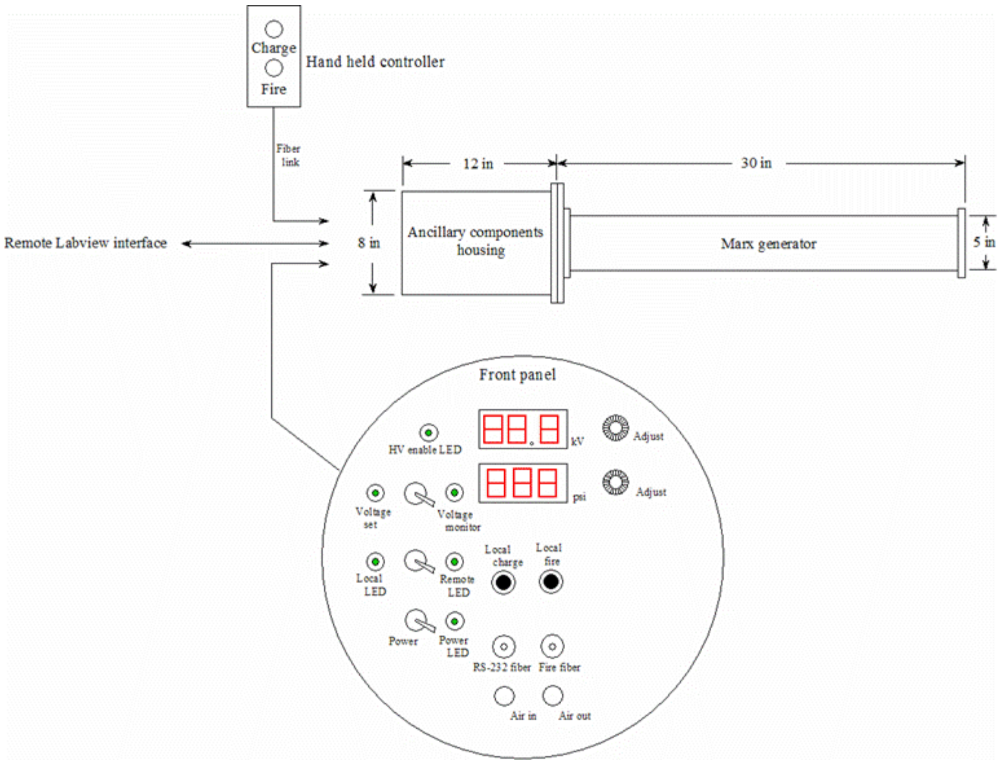

Figure 7. An illustration of the integrated ancillary component module

3.4 Diode pinch geometries

The rod pinch diode is established as a flash x-ray source for penetrative radiography. For a negative polarity voltage pulse from the Marx generator, the anode is formed by the center rod which protrudes through the cathode ring as shown in figure 8. The electron beam from the cathode self-insulates in the initial phase of operation to prevent electrons from traveling in a radial manner to the anode, to create a pinching effect where the electrons impacting the rod tip. Critical design parameters that determine performance include the rod length, diameter, and material. The anode is the limiting factor in the design due to its short lifetime—the impact of the high-energy electrons causes the rod to undergo a rapid hydrodynamic expansion which fatigues the material after several shots. The cathode aperture diameter and thickness also determine diode performance to a lesser degree. To enhance electron yield, the inner surface of the cathode is threaded to increase field enhancements. Figure 8 shows a schematic of the rod pinch geometry as discussed in technical reports [6,7,8].

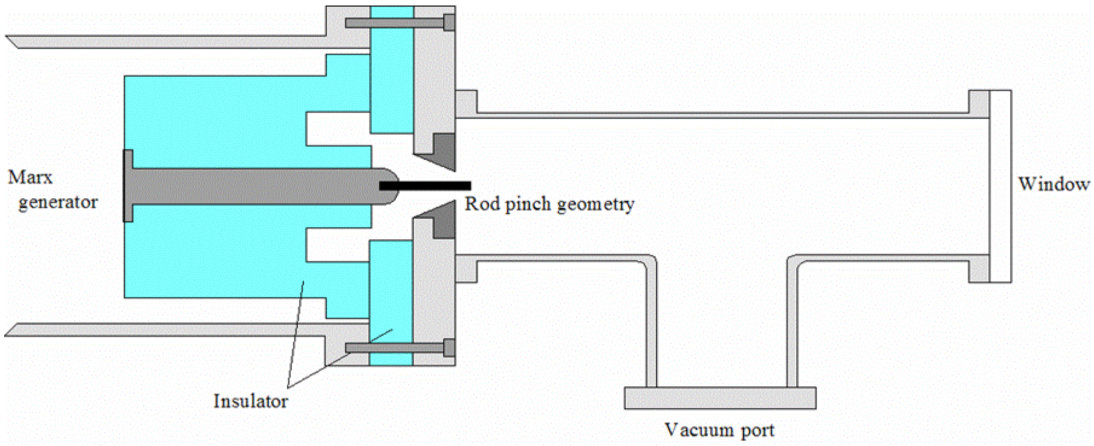

Figure 8. The basic rod-pinch geometry as directly mounted to a Marx generator.

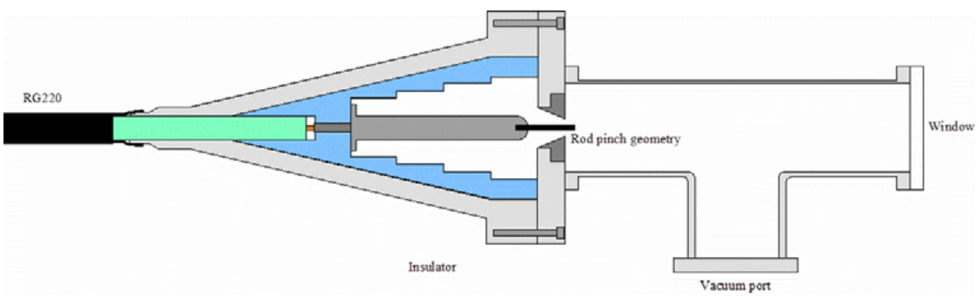

Figure 9. The rod-pinch diode connected to a Marx generator via coaxial cable.

Figure 9 illustrates an APELC modification on the rod-pinch geometry in which the diode is coupled to the generator via RG220 to enable a wider travel range for the system. This development represents a compact flash x-ray system with increased mobility for ease of use in the field.

4. ENHANCED HIGH-ENERGY MARX/DIODE DESIGN

Higher electron energies aimed at producing higher energy x-ray sources typically requires larger Marx generators. As a result more stages are added to the generator to achieve higher voltages. Unfortunately, as more stages are added to the Marx circuit, the impedance increases with the additional series inductance and the erected Marx capacitance. To circumvent the impedance problem, the stage capacitance is typically increased, which in turn affects the series inductance due to the increase in the vessel's diameter and volume.

APELC has recently developed a dual polarity Marx generator system based on its 1.6 MV Marx generator. In essence, two generator charged with opposite polarity charge are simultaneously triggered by a common trigger source. With a low temporal jitter, a voltage differential of 3.2 MV can be realized between the outputs of the two generators, as indicated in Figure 10. We note that each Marx is configured with an ancillary component module; however the generators share a common and external thyratron-based trigger source. Figure 11 provides sample waveforms measured from the output from each Marx generator. The waveforms are produced from an inline CVR mounted to each coaxial cable and digitized with a Tektronix TDS6604 oscilloscope. The excessive ringing is due to the loads' inability to withstand the 1.6 MV pulse and reflections result.

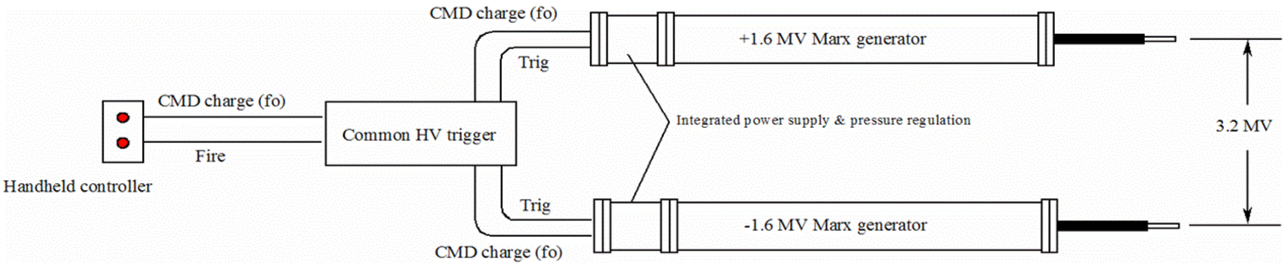

Figure 10. APELC's 3.2 MV Marx generator system.

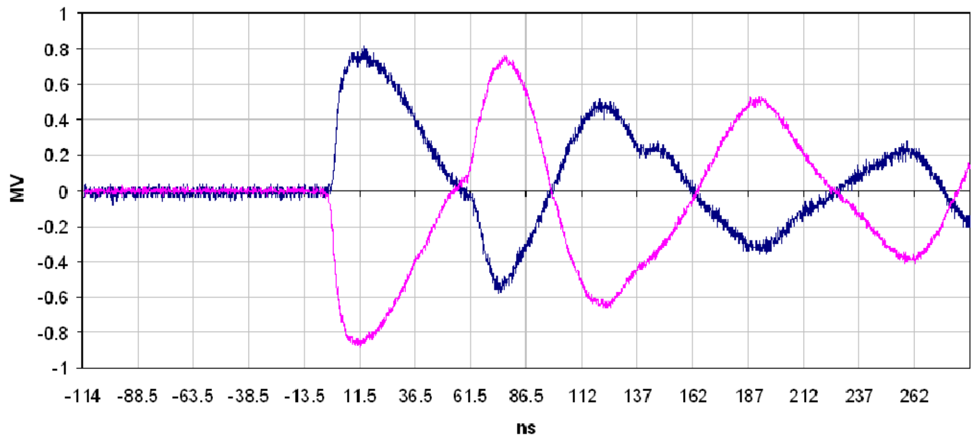

Figure 11. Output waveforms from the dual polarity MV Marx system.

Current APELC efforts with the dual polarity system are focused in the application of the high voltage differential, and namely toward the generation of more energetic x-rays. As illustrated in Figure 12, a floating rod pinch diode geometry is in development, wherein the positive polarity Marx generator pulse-charges the housing and the negative polarity Marx generator pulse-charges the cathode. This system promises are ultra-compact 3.2 MeV source that brings the flexibility of a cable-based load.

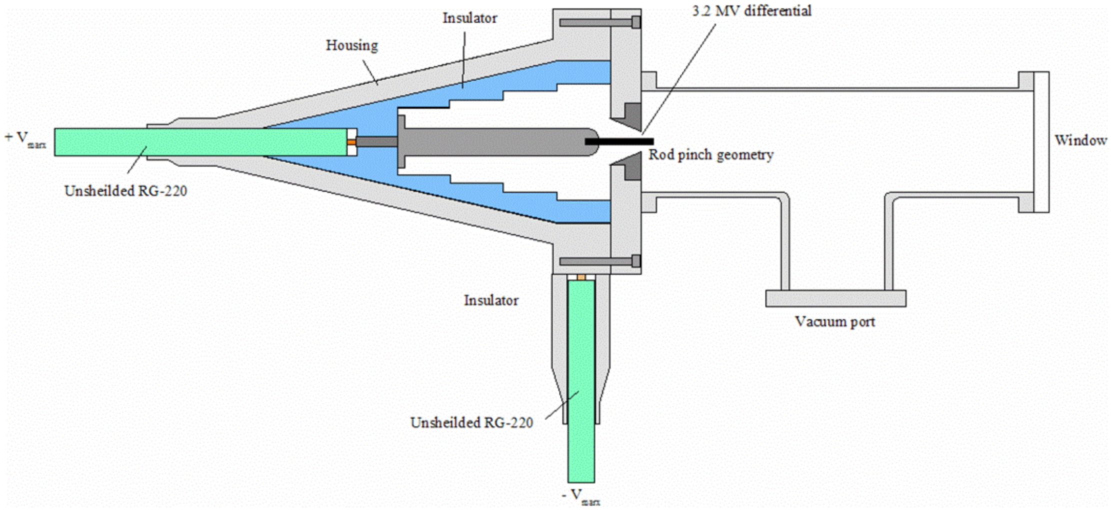

Figure 12. Dual polarity rod pinch diode geometry.

CONCLUSION

We have presented two experimental flash x-ray systems and a third system that is in current development. These efforts have achieved generators with relatively low source impedances, high impulse voltages and compact geometries ideally suited for portable flash x-ray drivers.

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