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STATEMENT OF CURRENT CAPABILITIES IN FLASH X-RAY TECHNOLOGY

Author: Matt Lara

Applied Physical Electronics L.C. was founded in 1998 as a pulsed power company specializing in the design, construction, and application of compact Marx generators based upon the wave-erection principle pioneered by David Platts of LANL [1]. Because of their compact form-factor, fast rise-time, low-jitter and relatively low source impedance, this style of Marx generator has become very popular as a source for flash x-ray diodes. Over the past 25 years, APELC has matured the design of these Marx generators into robust, low-maintenance, commercially available sources. Paired with APELC accessories, such as power and control racks, diagnostics, and calibration loads, these Marx generators are available as user-friendly, turn-key systems.

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APELC MARX GENERATORS FOR FLASH X-RAY

APELC's line of Marx Generators are capable of sourcing soft to hard x-ray diodes with energies ranging from 5keV to >2MeV. A sampling of these generators is provided below:

1. MG15-3C-940PF

The MG15-3C-940PF is APELC's workhorse Marx Generator. The compact, coaxial package and 50 Ohm source impedance have made it ideal for multiple applications including high-power RF, triggering of larger pulsed power systems, and flash x-ray. The extremely low system jitter when paired with APELC's trigger generator make the MG15 an ideal source for applications requiring tight timing. Examples include combined environment testing, flash x-ray of ballistics events, and even multi-pulse radiography - as discussed in subsequent sections. Physical and electrical specifications are provided below:

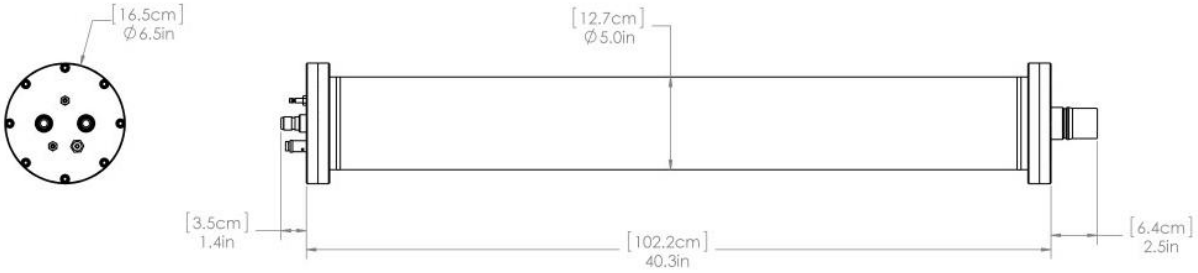

Figure 1 MG15-3C-940PF physical dimensions

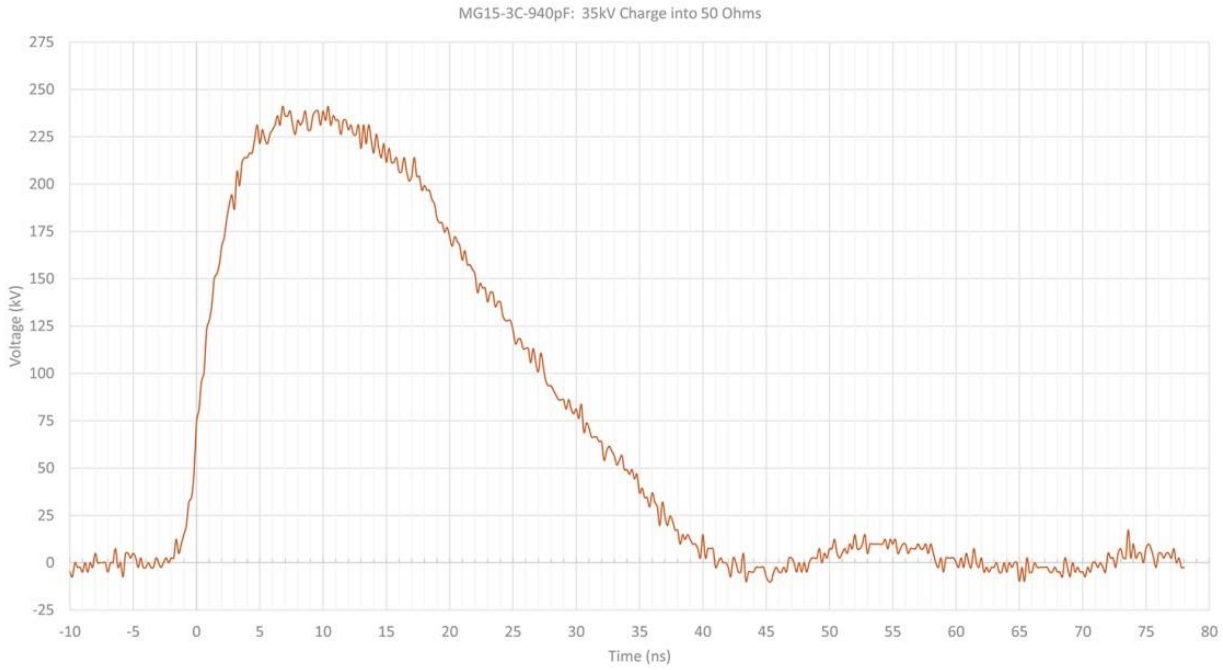

Figure 2 MG15-3C-940PF output into 50 ohms at 35kV charge

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PARAMETER	DESCRIPTION	VALUE	UNIT
N	Number of Marx Generator stages	15	–
E_{pulse}	Maximum Marx energy per pulse	33	J
P_{max}	Peak power to a matched load	1.7	GW
V_{ch}	Marx maximum charge voltage	40	kV
V_E	Peak Erected voltage	600	kV
C_{stage}	Capacitance per Marx stage	2.8	nF
C_E	Erected capacitance	188	pF
L_e	Series Inductance	510	nH
Z_m	Marx Impedance	52	Ohm
L	Marx Generator Length	31	In.
D	Marx Generator Diameter	5	In.

2. MG40-3C-2700PF

The MG40-3C-2700PF was initially based upon the “Super Saver” Marx pioneered by David Platts of LANL [1]. The Super Saver has been used for decades as a compact source for flash x-ray systems at LANL and other national labs. The APELC MG40 has matured this design to increase lifetime, decrease jitter and add our quick-disconnect output connector as an option to attach an x-ray diode remotely via coaxial cable. The 70 ohm impedance of the MG40, and ~40 ns pulse-width make it ideally suited for sourcing most flash x-ray diodes. Moreover, the peak voltage of 800kV into a matched load and 1:5 dynamic range make it capable of driving diodes with end-point energies from 150 keV to >500 keV. Specifications for the MG40-3C-2700PF are provided below.

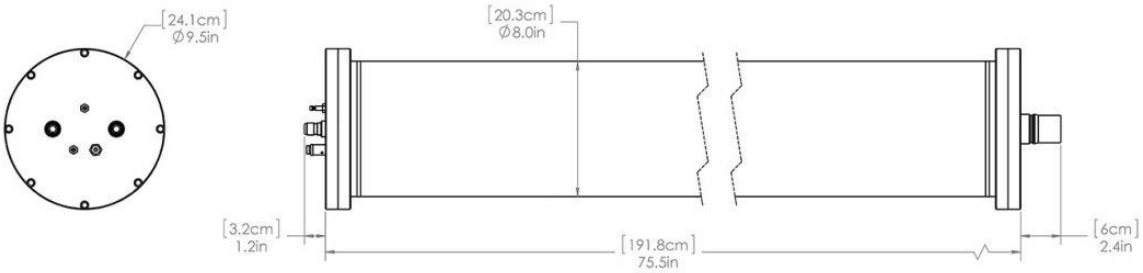

Figure 3 MG40-3C-2700PF physical dimensions

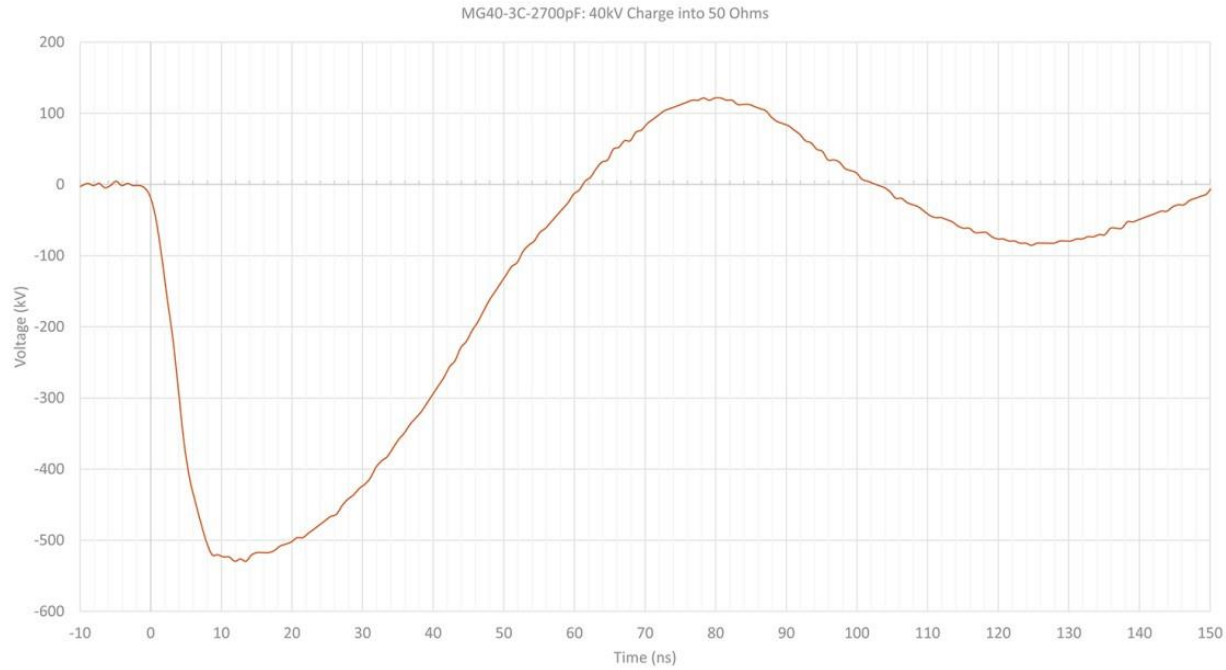

Figure 4 MG40-3C-2700PF output into 50 Ohms at 40kV charge

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PARAMETER	DESCRIPTION	VALUE	UNIT
N	Number of Marx Generator stages	40	–
E_{pulse}	Maximum Marx energy per pulse	260	J
P_{max}	Peak power to a matched load	9	GW
V_{ch}	Marx maximum charge voltage	40	kV
V_E	Peak Erected voltage	1600	kV
C_{stage}	Capacitance per Marx stage	8.1	nF
C_E	Erected capacitance	200	pF
L_e	Series Inductance	1	uH
Z_m	Marx Impedance	70	Ohm
L	Marx Generator Length	72	In.
D	Marx Generator Diameter	8.5	In.

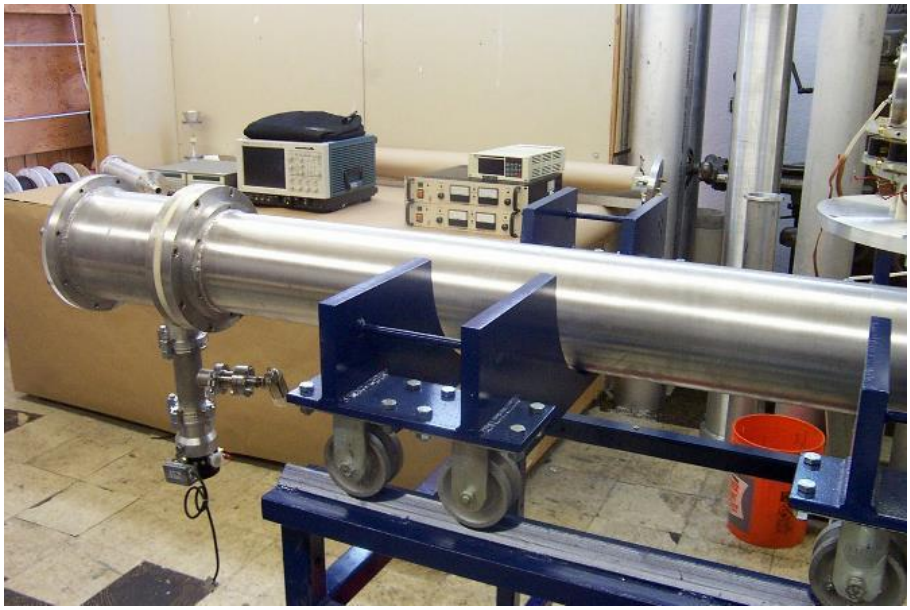

Figure 5 Example of the MG40-3C-2700PF Marx Generator with an attached X-ray diode

3. Larger APELC Marx systems for >1 MV.

APELC designs and manufacturers larger, more energetic Marx generator systems that are capable of driving systems with voltages well above 1 MV. One example of this is the MG83-1C-150NF. APELC's MG83-1C-150NF Marx Generator was built for the world's largest vertical electromagnetic pulse (EMP) simulator located at the Patuxent River Naval Air Station (NAVAIR).

This generator uniquely brings a wide-charging voltage range of 8 kV – 50 kV, which results in an open-circuit voltage of 660 kV – 4 MV. With a matched 70 Ω load resistance, a maximum peak power of 230 GW is delivered with a pulse energy of 14.45 kJ. A rise-time of approximately 180 ns has been measured into a matched load.

This generator also features unique spark gap switch blocks, in sets of 6 switches, which aid in the wide operating range made possible by the line-of-sight UV optical coupling within the individual blocks. The Marx circuit is insulated with transformer oil, and the spark gaps are insulated with pressurized dry breathable air. With APELC's custom transfer and peaking circuits, rise-times as fast as 1.2 ns have been measured. Specifications for the MG83-1C-150NF are provided below:

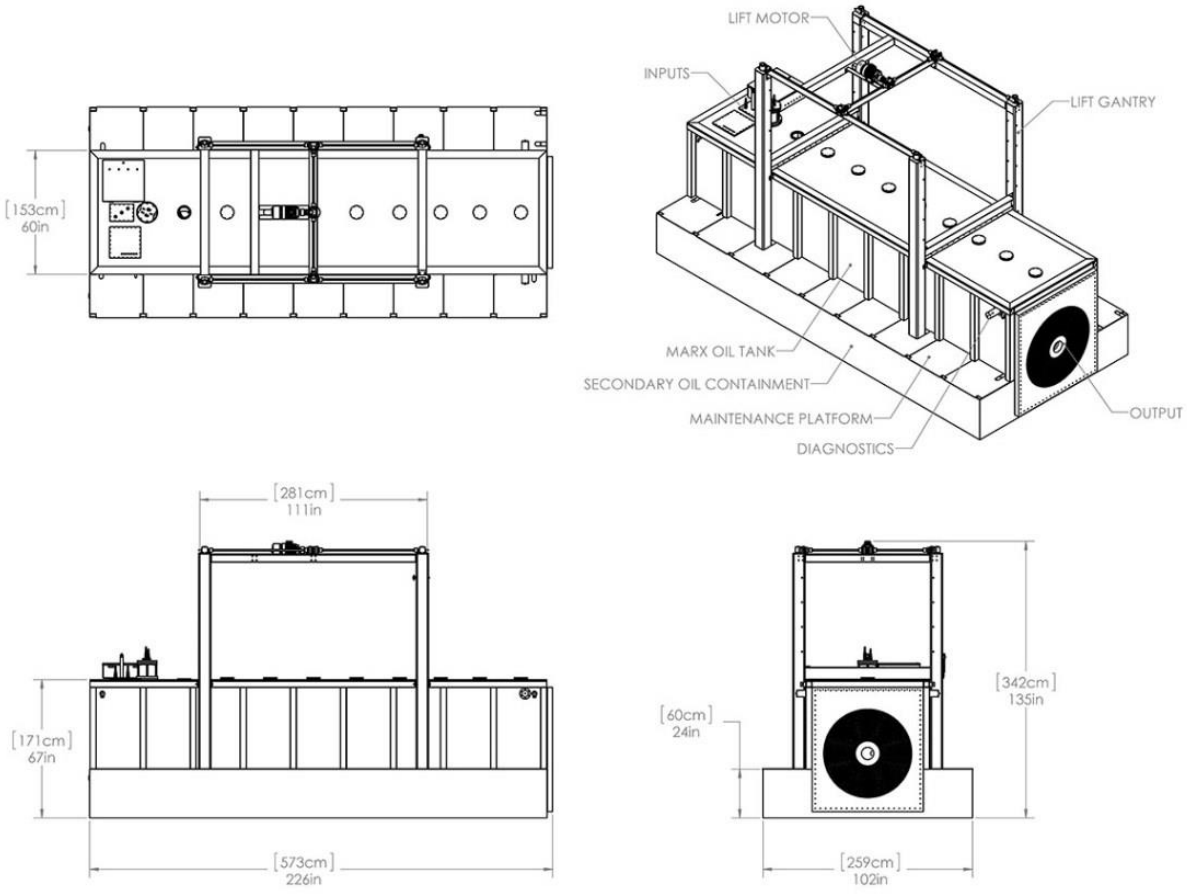

Figure 6 MG83-1C-150NF physical dimensions

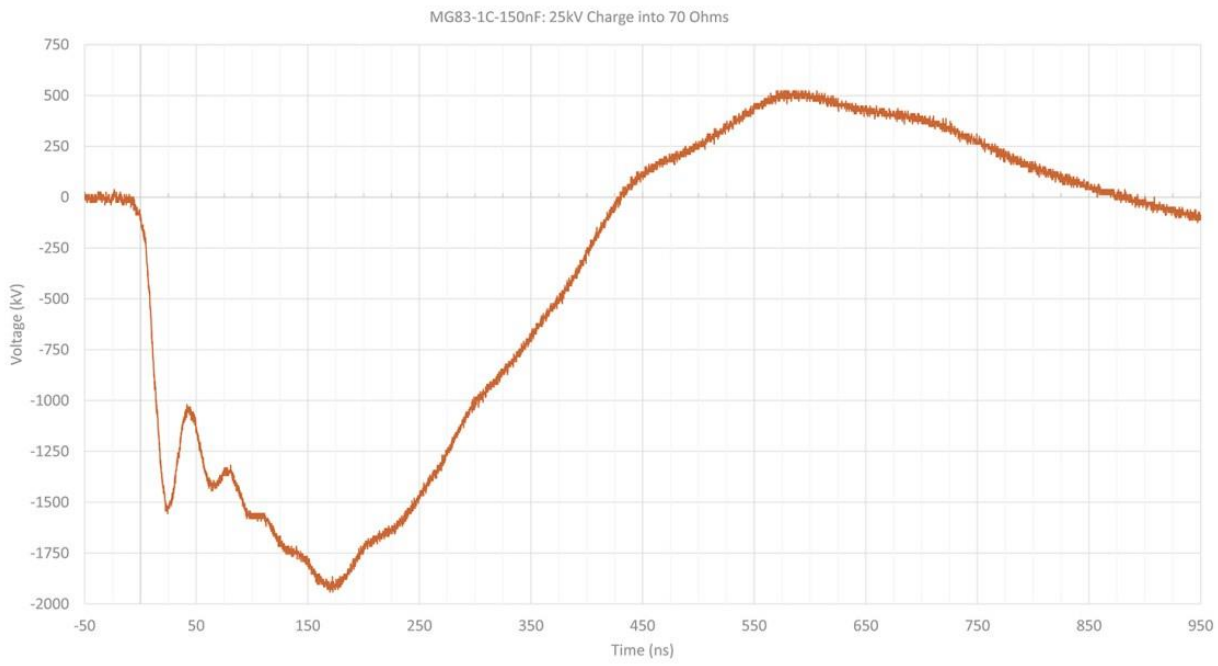

Figure 7 MG83-1C-150NF output into 70 Ohms at 25kV charge

PARAMETER	DESCRIPTION	VALUE	UNIT
N	Number of Marx Generator stages	83	–
E_{pulse}	Maximum Marx energy per pulse	14.45	kJ
P_{max}	Peak power to a matched load	230	GW
V_{ch}	Marx maximum charge voltage	50	kV
V_E	Peak Erected voltage	4	MV
C_{stage}	Capacitance per Marx stage	150	nF
C_E	Erected capacitance	1.81	nF
L_e	Series Inductance	8	µH
Z_m	Marx Impedance	70	Ohm
L	Marx Generator Length	18	ft
H	Housing height	65	in
W	Marx width	59	in

4. APELC PFN and Custom Marx Generators

In applications requiring a constant end-point energy across the pulse-duration, APELC provides multiple pulse-forming network (PFN) based solutions. These include external PFN circuits, pulse forming lines, and compact PFN Marx generators. One example of this is the MG24-20C-2700PF-PFN Marx generator. This Marx uses an integrated PFN topology within the Marx generator circuit to provide a rectangular pulse directly from the Marx generator, with no need for external pulse forming hardware. The MG24 is capable of driving up to 420 kV onto 100 ohms with a flat-top pulse (<10% ripple) across the 260ns FWHM duration of the pulse. The 70ns rise-time shown in the figure is limited by an internal output inductor that was used to suppress over-shoot. If a faster rise-time is required, this inductance can be significantly reduced. Specifications for the MG24-20C-2700PF-PFN are provide below:

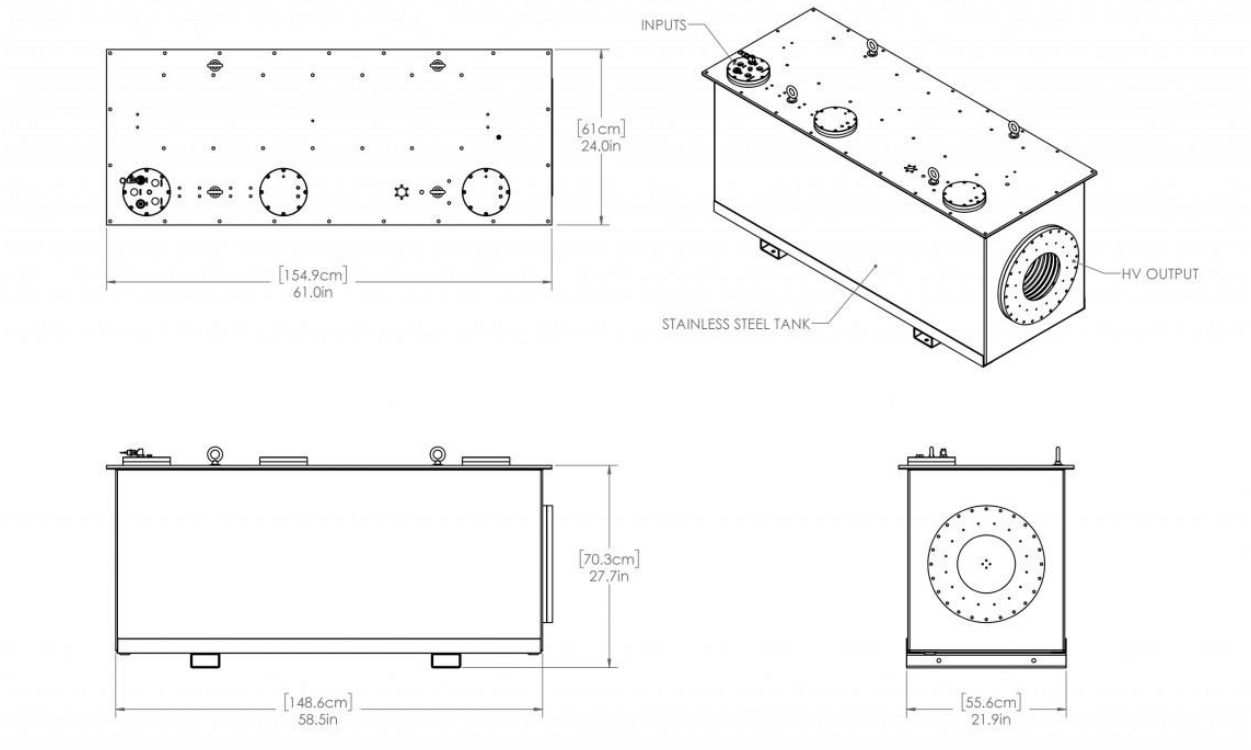

Figure 8 MG24-20C-2700PF-PFN physical dimensions

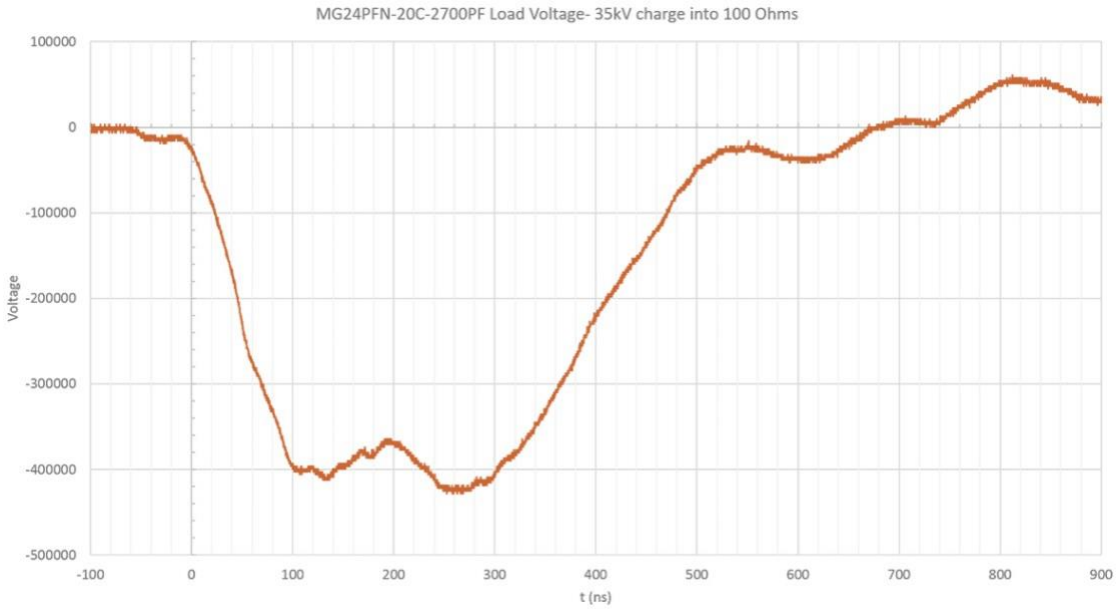

Figure 9 MG24-20C-2700PF-PFN output into 100 ohms at 35kV charge

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PARAMETER	DESCRIPTION	VALUE	UNIT
V_{erect}	Erected voltage (min – max)	120 – 800	kV
N	Number of Marx Generator stages	24	–
V_{ch}	Charge voltage (min – max)	5 – 30	kV
Z_{PFN}	Stage PFN impedance (approximate)	4	Ohm
C_{basis}	Basis capacitor	2700	pF
Z_{source}	Impedance of the Marx generator	100	Ohm
Z_{load}	Typical load impedance[1]	100 – 200	Ohm
T_{PW}	Approximate pulse width (3 dB points)	260	ns
T_{rise}	Approximate rise time (10 – 90%)	70	ns
E_{pulse}	Energy per pulse at min charge	20	J
	Energy per pulse at max charge	580	J
P_{max}	Maximum peak power	1.78	GW

APELC Efforts Toward Multi-Pulse Flash Radiography

In 2000, APELC developed a system for UWB Radar applications that was capable of driving 10 high-voltage pulses onto a single 50 Ohm cable with <50ns between pulsed. Because of the multiple Marx generators arrayed around a common tapered transmission line, this system became known as the "Gatling Marx Generator System" [2]. The Gatling system took advantage of APELC's low-jitter Marx generators in combination with a unique tapered transmission line design to combine pulses from multiple Marx generators into a single load. This topology was presented to researchers familiar with flash x-ray and identified as a strong potential candidate for multi-pulse radiography.

The following data was taken from the original 10-pulse Gatling system detailed in the 2001 publication.

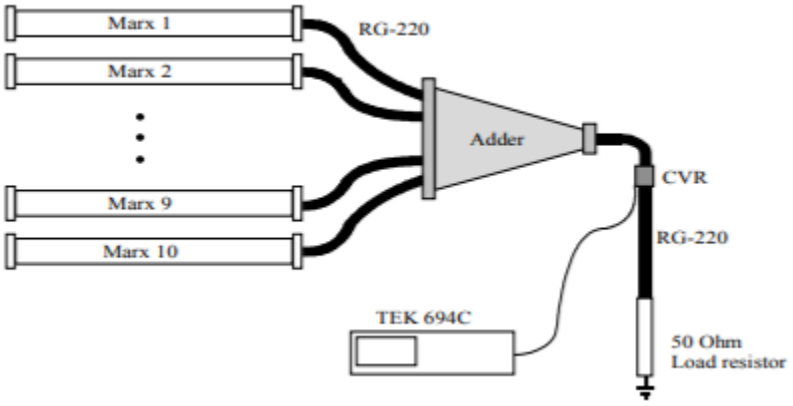


Figure 10 Experimental arrangement from APELC 10-pulse adder/Gatling system

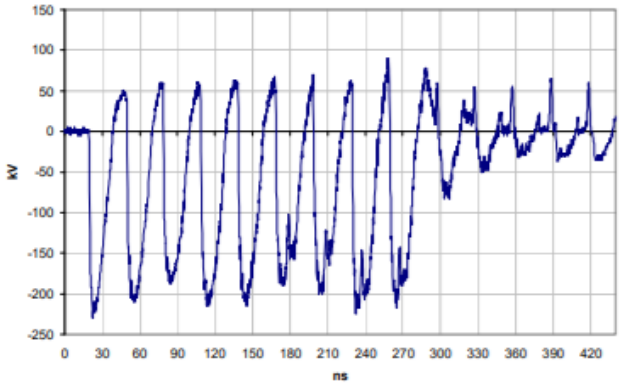


Figure 11 9-pulse output waveform from the 10-pulse system (one generator was not being used)

Most recently, in a collaborative effort with the Naval Research Labs (NRL) and Mission Support and Test Services (MSTS), APELC has developed a pulsed power system for delivering up to 3, 300kV pulses into a single 60 ohm coaxial cable with digitally adjustable pulse separation as low as 50ns. A quick disconnect system allows change-over of the load from a resistive load for Marx and probe calibration, to a flash X-ray head. In order to address the radiography component of this system, APELC is beginning to work with NRL under a CRADA to develop a single-anode X-ray diode capable of delivering multiple pulses with the goal of 200ns pulse separation. Presently, APELC and NRL are looking for funding to put toward the CRADA in order to move multi-pulse diode development forward. MSTS has published some of their preliminary results in a report to NNSA.

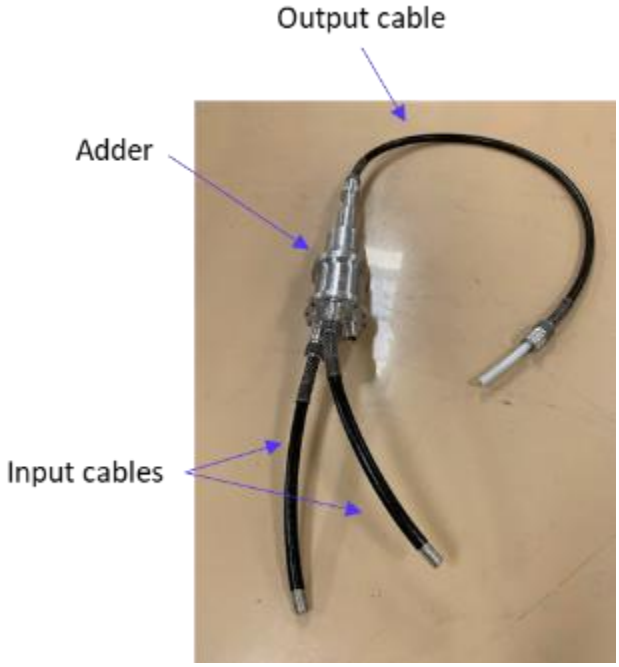


Figure 12 3-pulse "adder" for APELC Gatling system- 2 input cable shown

APELC Quick Disconnect Connectors

APELC has designed and manufactured a unique line of quick-disconnect connectors for high-voltage coaxial cable. These connectors are extremely well-suited for flash x-ray systems because they allow the Marx generator load/cabling to be easily removed. This will aid in quick-turn maintenance of x-ray diodes, as well has verification of the pulser output by replacing the x-ray diode with a calibrated resistive load and CVR. A brief synopsis of these connectors is provided below.

The APELC quick disconnect connector set for DS-2077 and DS-2236 cable (QDM-2077-1 and QDF-2077-1) terminate the DS-2077 and DS-2236 series cables and provide up to 350 kV voltage hold-off for <100ns FWHM pulses. The male side of the connector resides at atmosphere, whereas the female-side

provides an o-ring seal for use in either pressurized environments up to 200 psi or transformer oil. Both the center and outer conductors of the connector make electrical contact through a Bal Seal® spring contact. By varying the length of the connector and the number of Bal Seal® contacts, a wide range of voltage and current specifications can be met with this connector depending on customer requirements. Additionally, custom current and voltage (d-dot and b-dot) probes can be added at customer request.

APELC has developed two different versions of this connector:

1.) **QDM-2077-1-AL/QDF-2077-1-AL**: The original aluminum version of the APELC Quick-disconnect connector for 2077-1. The body of the connector is made from aluminum and can be treated with an Alodine coating for corrosion resistance upon customer request.

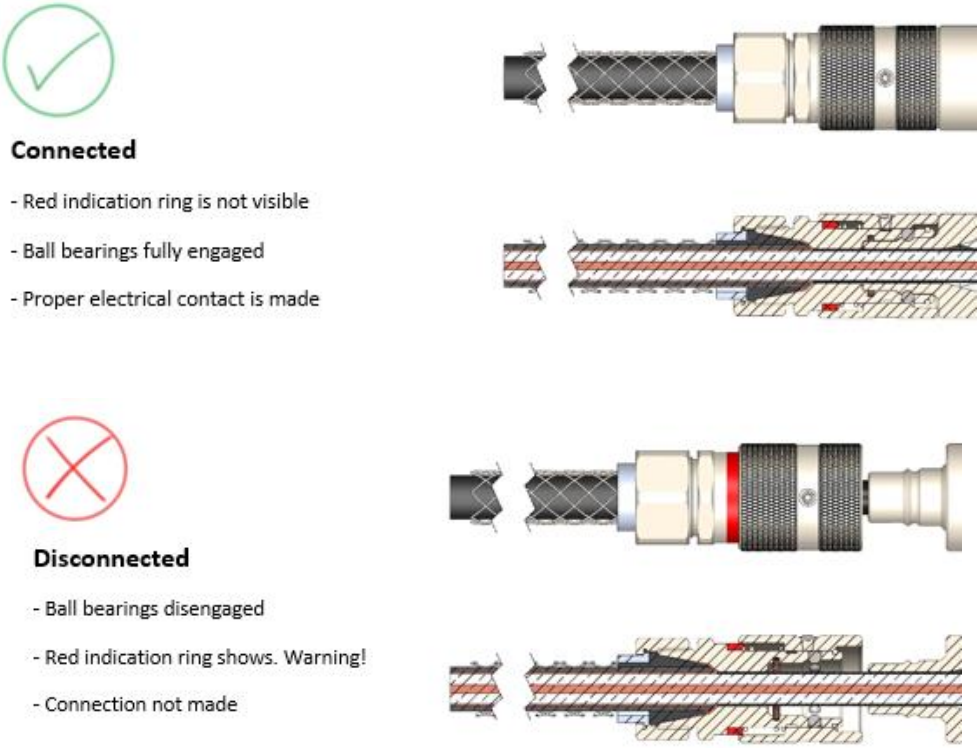
2.) **QDM-2077-1-BR/QDF-2077-1-BR**: The updated brass version of the APELC quick-disconnect connector for 2077-1. The body of the connector is made from brass and nickel plated for corrosion resistance. This version of the connector also includes APELC High-Visibility Fail-Safe Indication as described below.

Figure 13 QDM-2077-1-AL and QDF-2077-1-AL APELC Quick-Disconnect Connector set for 2077-1 (connected)

Figure 14 QDM-2077-1-AL and QDF-2077-1-AL APELC Quick-Disconnect Connector set for 2077-1 (disconnected)

APELC High-Visibility Fail-Safe Indication:

The APELC QDM-2077-1-BR provides a fail-safe method of connection, whereby a bright-red anodized ring is exposed when the connector is not fully engaged. The ring is only covered when the connector is fully engaged. The connection set is designed such that no in-between state of connection is possible.



QDM-2077-1-BR FEATURED HIGHLIGHTS:

- High visibility engagement indication ring: Red = disconnected
- Integrated locking set screw requiring Allen key to unlock (optional)

- Integrated strain relief
- High conductivity Bal Seal® electrical contacts for ground and center conductor

- Beryllium free contacts
- Tactile feedback of center conductor engagement prior to mechanical grasp

- Graded termination of the ground conductor for reduction of field-enhancements

APELC Manufacturing Capability

APELC is an IS09001:2015 certified CNC manufacturer with an extensive line of CNC capabilities. We have the ability to do rapid prototyping as well as production level machining, and can test all finished products for both electrical and mechanical accuracy. A listing of our CNC capabilities is shown below:

CAPABILITIES

Milling – Turning – Boring – Threading – Grooving – Facing – Tapers – Chamfers – 3D Surf Milling – Drilling – Reaming – Tapping – Thread Milling – 4th Axis cutting – Custom Engraving – Knurling – Sawing – Live Tooling – Dual Spindle – Mill Turn – 3D Printing – Waterjet cutting

MATERIALS

Aluminum – Brass – Bronze – Copper Tungsten – Copper – Carbon – Stainless – Inconel – Plastics – Monel – Hastelloy – ABS – Acetal – Polycarbonate – Polypropylene – Cast Iron – Phenolic – Titanium – Damascus – Alloy – Chromoly – Wood – Fiberglass – Graphite – Ceramic – Teflon – Nylon

Figure 15 APELC CNC Machine Shop

Figure 16 APELC Quality control and inspection area

REFERENCES

[1] D. Platts, M. P. Hockaday, D. Beck, W. Coulter and R. C. Smith, "Compact flash X-ray units," *Digest of Technical Papers. Tenth IEEE International Pulsed Power Conference*, 1995, pp. 892-896 vol.2, doi: 10.1109/PPC.1995.599725.

[2] Mayes, J. R., et al. "The Gatling Marx generator system." *PPPS-2001 Pulsed Power Plasma Science 2001. 28th IEEE International Conference on Plasma Science and 13th IEEE International Pulsed Power Conference. Digest of Papers (Cat. No. 01CH37251)*. Vol. 1. IEEE, 2001.