# STATUS OF GENESIS A 5 MA PROGRAMMABLE PULSED POWER DRIVER*

**S.F. Glover[1ξ], F.E. White[2], P.J. Foster[4], D.J. Lucero[2], L.X. Schneider[1], K.W. Reed[1], G.E. Pena[1], J.-P. Davis[1], C.A. Hall[1], R.J. Hickman[1], K.C. Hodge[2], R.W. Lemke[1], J.M. Lehr[1], D.H. McDaniel[1], J. G. Puissant[2], J.M. Rudys[1], M.E. Sceiford[1], S.J. Tullar[2], D.M. Van De Valde[3],**

[1]*Sandia National Laboratories, Albuquerque, NM 87185 USA*
[2]*Ktech Corporation, Albuquerque, NM. 87123 USA*
[3]*EG&G, Albuquerque, NM 87107 USA*
[4]*Defense Nuclear Facilities Safety Board, Washington, DC 20004 USA*



*Abstract*

Genesis is a compact pulsed power platform designed by Sandia National Laboratories to generate precision shaped multi-MA current waves with a risetime of 200-500 ns. In this system, two hundred and forty, 200 kV, 60 kA modules are selectively triggered to produce 350 kbar of magnetic pressure in a stripline load for dynamic materials properties research. This new capability incorporates the use of solid dielectrics to reduce system inductance and size, programmable current shaping, and gas switches that must perform over a large range of operating conditions. Research has continued on this technology base with a focus on demonstrating the integrated performance of key concepts into a Genesis-like prototype called Protogen. Protogen measures approximately 1.4 m by 1.4 m and is designed to hold twelve Genesis modules. A fixed inductance load will allow rep-rate operation for component reliability and system lifetime experiments at the extreme electric field operating conditions.

## I. INTRODUCTION

The use of pulsed power systems to generate magnetically driven isentropic compression in materials has generated a wealth of data on the properties of materials under dynamic shock loading [1][2]. This technique relies on current shaping to produce magnetic pressures that follow the material's isentrope while avoiding the formation of shock waves in the target material. The Z machine at Sandia National Laboratories (SNL) has demonstrated shaped current pulses for Isentropic Compression Experiments (ICE) through the staged triggering of 9 sets of pulse forming lines [3]. On smaller platforms, SNL's Veloce pulser has demonstrated shaped current pulses up to 3 MA, with a risetime of ~300 ns using two independently controlled trigger points [4].

The goal of the Genesis project is to extend the efficiency and flexibility of magnetic compression drivers to enable higher fidelity dynamic materials experiments on highly compact platforms up to 500 kbar. The Genesis project has focused on two main objectives; reduce the size of the driver platform and enable user programmable current shaping at multi-MA current levels [5] [6].

A significant portion of the initial stored energy in a driver for low inductance loads is lost to the driver's internal system inductance. Minimizing the internal driver inductance reduces the initial stored energy and operating voltage requirements. Genesis is a modular current adder, employing simple two-stage Marx generators configured in parallel to drive a low inductance disk transmission line. Genesis uses solid-dielectrics from the energy storage components to the stripline load. The solid dielectric system allows operation at extremely high electric fields which leads to modest operating voltage requirements for a multi-MA driver. This leads to a more compact foot print compared to conventional pulsed power technologies such as Linear Transformer Drivers (LTDs), which were optimized for voltage addition not current addition. Genetic optimization of module trigger timing enable high fidelity pulse shaping and is also used to minimize system peak voltages and voltage variation across the disk transmission line created by the temporal triggering of tightly coupled pulse forming modules.

A demonstration of Genesis concepts is being conducted in a small scale system call Protogen. Protogen is designed to include up to 12 high current Genesis modules connected into a plate structure containing all the features of a full scale Genesis system. These features include pre-constructed plate wedges, seam technology to bond wedge section together in configuration allowing maintenance, ports which allow low inductance module connections to the transmission line plate, and end seals to eliminate corona at the plate edges.

This paper presents the status of Genesis research and the details of the Protogen demonstration test bed.

## II. GENESIS

A SolidWorks [7] model of the assembled Genesis system is shown in Figure 1. This picture includes 240, 200 kV, 60 kA modules connected in parallel to a disk

* Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
ξ email: sfglove@sandia.gov

transmission base and support structure. Module charging and trigger cables are not shown for clarity.

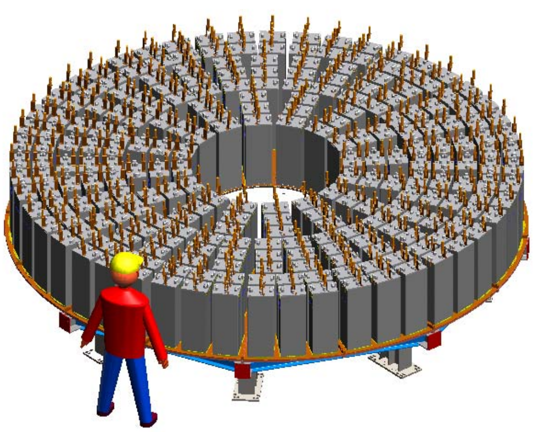

**Figure 1**. Solidworks model of the programmable 5 MA Genesis systems for dynamic materials experiments.

Genesis consists of two main components; a solid dielectric insulated disk transmission line and plug-in high current modules Figure 2. A stripline load assembly connects to an interface port in the center of the machine. Precision load current waveforms are achieved through temporal triggering of the high current modules. The 240 module Genesis design will produce waveforms up to 5 MA peak current which develops peak magnetic pressures of 250-350 kbar in a 20 mm wide, 1.75 nH strip line load.

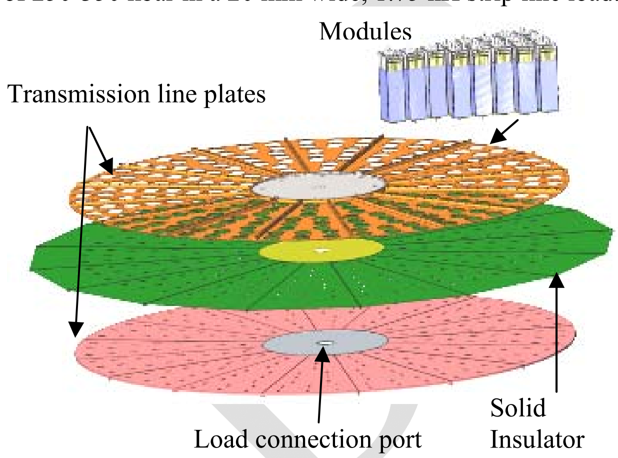


**Figure 2**. Genesis system components including high voltage modules and a solid dielectric insulated disk transmission line structure.

The design of a stripline load that connects to a port in the center of the disk structure maintains solid dielectric insulation from the base of the modules through the stripline. The use of all solid dielectrics enables an extremely low inductance path from the pulse forming components to the load. This also establishes tight coupling between the driver's pulse forming components and the dynamic impedance stripline load. The impact of the time varying stripline load on the performance capabilities of Genesis is discussed in reference [8].

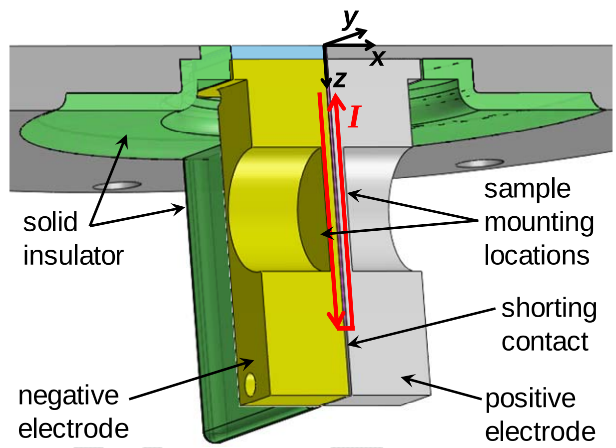


**Figure 3**. Isometric view from bottom of stripline load with counter-bores for mounting samples. CHANGE

The development of the Genesis architecture required a significant materials and process development program. This included identification and validation of high voltage dielectric materials, concepts for forming and using materials and electrode coatings. The ability to construct Genesis or other pulsed power machines using this approach requires the availability of high quality large area dielectric sheets to insulate between the large transmission line plates. A method for joining the single sheet dielectrics in a disk wedge to form larger areas has been developed and successfully tested in 10 inch diameter test fixtures. This joining concept creates a seam at the edge of the sheets that allows for the repair / replacement of one sheet without impacting the performance of the others. This capability will allow for a section of a larger system to be repaired without complete system disassembly. Another critical feature of Genesis is the high voltage seal at the edge of the disk plates to eliminate damaging corona and a high reliability port for module plug into the disk plate system. Critical solid dielectric materials and concepts needed for low inductance solid dielectric systems are being demonstrated on a multimodule prototype discussed in Section III.

Extending the lifetime of the solid dielectrics and bonding/sealing concepts used in Genesis became the primary focus of development and experiments over the past two years. Accelerated lifetime testing on various system materials was performed. Data collected to date indicates that the disk dielectric system should have a lifetime of 1300 to 4150 shots at a 5% probability of failure with a 95% confidence interval at worst case field levels during Genesis operation. Figure 4 includes testing data from multiple candidate concepts. Additional testing and analysis of a refined assembly process will be completed in the next several months.

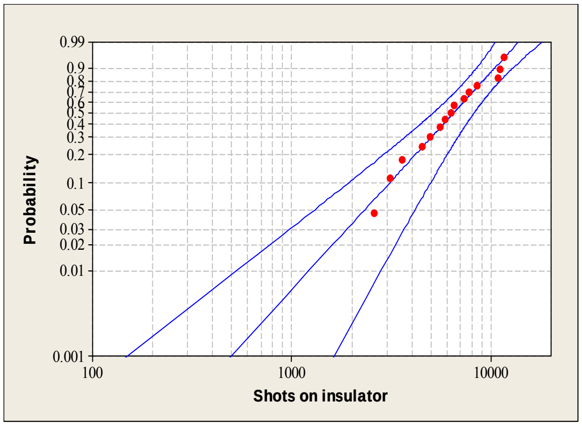


**Figure 4**. Transmission line dielectric system probability of failure.

The interface between the transmission line plates and the modules impact the system impedance and modularity. This is designed to be a plug in interface with dielectric seams that can hold off the voltages across the transmission line plates and contacts that can conduct 80 kA in a low impedance geometry. Modules include an outer housing, cabling, and gas lines. Each module contains two 80 nF capacitors, a High Current Electronics Institute (HCEI) switch [9] [10] [11], trigger resistor, and charge resistors as depicted in Figure 5.

The capacitors and switch are arranged in the form of a two stage Marx Generator (brick) that can be charged to ±100 kV. One capacitor is connected electrically to the bottom of the module, the other to an electrode that protrudes out the bottom of the module. This electrode penetrates the solid insulator between the transmission line plates to make electrical connection to the bottom transmission line plate. The latest version of the module has been tested to greater than 20,000 shots without failure of the plug in interface, resistors, or capacitors.

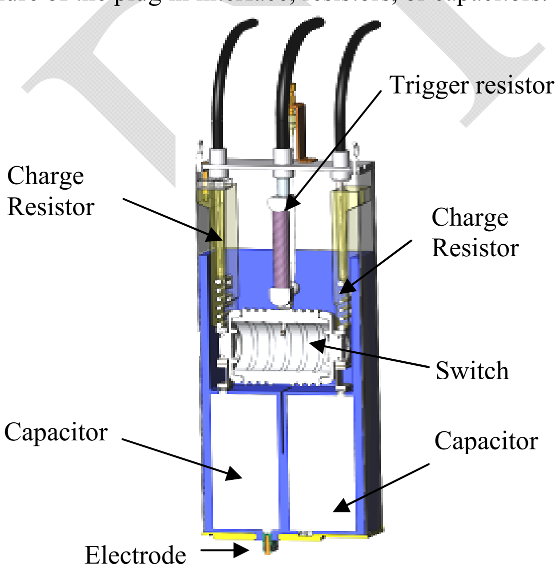


**Figure 5**. Module cutaway. Blue region is solid dielectric.

Switch lifetime at 80 kA has been demonstrated to be in the range of 4000 to 14000 (why such a wide range???) shots at maximum current. In addition to lifetime requirements, Genesis must operate with low jitter over a broad range of conditions. Performance of the switch has been demonstrated at sufficiently low jitter down to 45% of self break [12] [13].

Capacitor testing to date has resulted in 20,000+ shots at 80 kA in a module without failure. Testing of capacitors in a separate test fixture has demonstrated lifetimes ranging from 2000 to 7000 shots at ± 100 kV charge and a worst case 80 kA discharges. Switch and capacitor data will continue to be collected on the prototype demonstration system described in Section III.

State equation based modeling has been used to predict Genesis performance and component operating conditions. This circuit model of the system was created in MATLAB [14] with a comparison to a second model, created by L3 Communication [15]. Examples of this modeling technique and the triggering approaches have been demonstrated in hardware for a similar geometry [16]. Modeling continues to evolve as hardware is being built and better parameter estimates are determined. Expanded data sets and enhanced models are the focus of the prototype system discussed in the following sections.

## III. PROTOGEN SYSTEM

The concepts, materials and processes developed during Genesis R&D will be tested in a smaller scale prototype named *Protogen*. This testbed was designed to evaluate and characterize all critical system features including pre-constructed disk transmission wedges, disk wedge bonding techniques, disk end seals, module connection ports, high current modules and a Genesis class control and triggering system. The Protogen testbed is shown in Figure 6. Protogen was designed to hold up to twelve modules, however, only eight modules have been initially installed with the remaining four inside positions populated with fixed impedance loads to enable repetitive operation at peak Genesis electric levels in the solid dielectric system. A comparison between critical aspects of Genesis and Protogen are provided in Table 1.

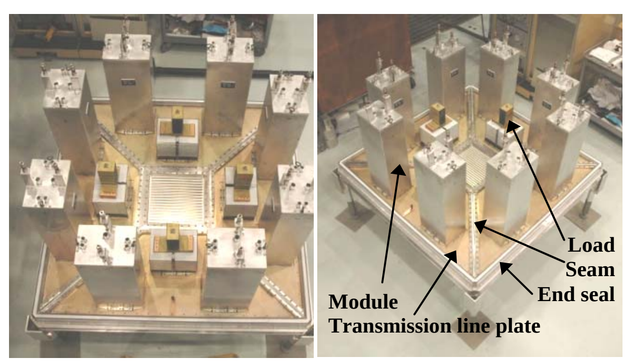


**Figure 6**. Protogen multimodule testbed. CHANGE PIC

**Table 1**. Genesis and 8 module Protogen comparison.

| | Genesis[2,3] | Protogen[1] | Ratio (%) |
|---|---|---|---|
| **Modules** | **240** | **8** | **5.0** |
| **Dielectric area** | **12.9 m** | **1.3 m** | **10.2** |
| **Seam length** | **41.2 m** | **4.7 m** | **11.4** |
| **End seal length** | **15.4 m** | **5.8 m** | **37.3** |
| **Peak module current** | **80 kA** | **xx kA** | **xx** |
| Peak load current | 4 MA | 222 kA | **5.5** |
| **Peak transmission line voltage** | **110 kV** | **100 kV** | **1.0** |

[1] Installation of twelve modules and a Genesis load would enable a peak load current of 878 kA[2] to be reached.
[2] Simulated currents.
[3] Operating point for 1200 shot lifetime.

The Protogen load, shown in Figure 7, was chosen to allow operation at Genesis transmission line plate voltage levels and for repetitive operation. For these reasons the impedance and physical dimensions of the Protogen load are significantly larger than a Genesis load. Each load is designed to be 1.5 Ω, 160 nH, and install in the same port as the high current modules.

Dielectrics between the Protogen transmission line plates are assembled using the same materials and processed defined for Genesis. This allows testing of larger area prototypic techniques for the first time in an integrated configuration at larger scale. Testing of seams prior to this experiment was conducted on small fixtures that allowed rapid prototyping to identify optimal materials and techniques.

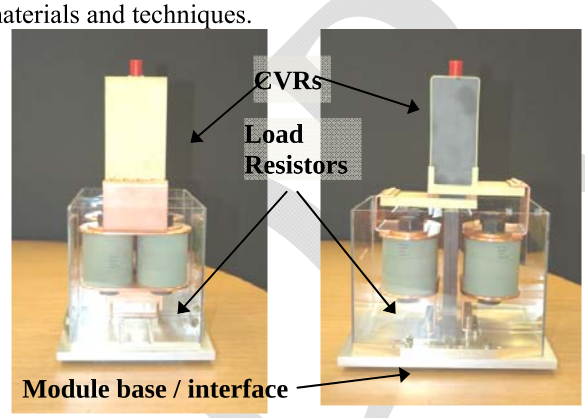


**Figure 7**. Protogen load for repetitive operation.

The module interfaces implemented in Protogen are identical to the Genesis design. With the installation of eight modules and four loads a total of twelve of these interfaces will be tested simultaneously. Testing of these interfaces will occur at Genesis-level electric field stresses but at lower peak current due to the larger load impedance required to test at the Genesis-level transmission line voltages. Where possible, data from Protogen experiments will be folded back into the relevant existing data base to decrease the spread of confidence intervals in the Weibull analysis.

As Protogen experiments are conducted, additional performance and reliably data will be collected on the module, switch, and capacitors.

## IV. PROTOGEN CIRCUIT MODEL

Performance of Protogen is predicted with a lumped element state equation based circuit model. This model uses the same modeling elements as the Genesis model described in reference [5]. The Protogen circuit diagram is overlaid on top view of Protogen in Figure 8.

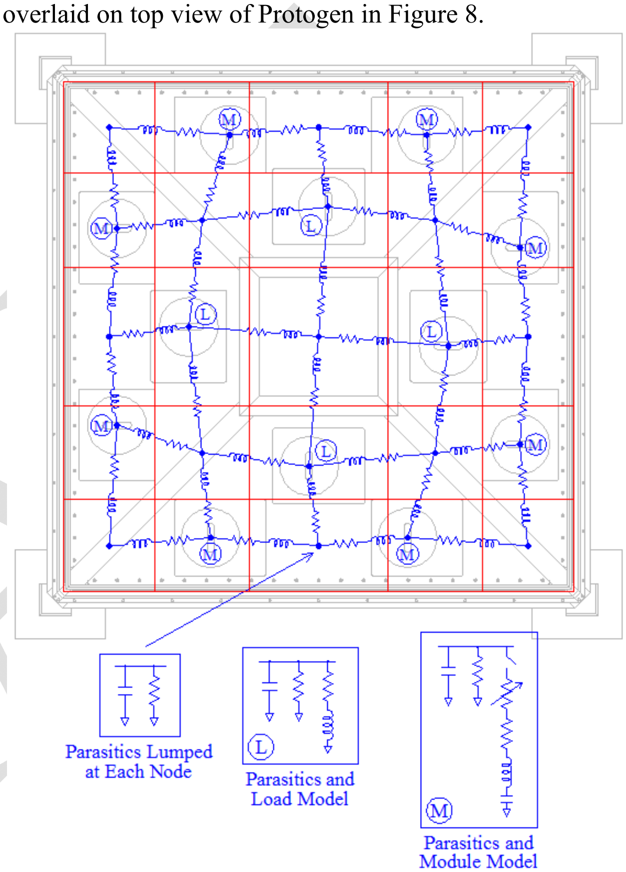


**Figure 8**. Protogen Circuit Model layout with submodels at the nodes, module and load locations.

A simplified transmission line model was used to simulate current flow along the plates, while the parasitics through the dielectric are lumped at the nodes. Loads are represented by RL circuits and the modules by RLC circuits located at the nodes indicated in Figure 8. Within each module, a time varying resistance is used to capture the dynamic behavior of the high voltage switch.

The switch model [17], which is an extension of the spark channel work in [18], uses a time varying resistance to describe the energy loss in each switch. In this model the radius of the spark channel, , is a function of the current flowing through the channel as defined by

, (1)

where $I$ is the magnitude of the current in the channel, $\rho_o$ is the gas density, $\sigma$ is the conductivity of the gas, and $\xi$ is set to a constant value of 4.5 as defined in [17]. The radius of a single channel is then used to calculate the resistance of a channel as

$$R_{channel} = \frac{L_{cm}}{\sigma \, \pi \, a^2} \tag{2}$$

where $L_{cm}$ is the channel length. From $R_{channel}$ the total HCEI switch resistance is calculated as

$$R_{switch} = \frac{R_{channel}}{(n_{channels})^{1/3}} \tag{3}$$

where $n_{channels}$ is the total number of channels formed.

All of the parameters in the switch model are predefined except for the number of channels. To determine the how many channels form over a range of operating conditions, self break data from an HCEI switch (modified for Genesis) was used. This data was collected from a switch installed in a brick configuration but external to a module. A Genetic Optimization (GO) routine [19] was used to determine the fixed R, L, and C in the circuit in addition to the $n_{channels}$ for the switch model. Parameters were fitted to all six waveforms simultaneously with the fixed R, L, and C forced to be identical for all waveform (Figure 9). Table 2 contains the operating conditions and the number of channels estimated by the GO. It is expected that there is a certain probability for any given channel to form therefore the number of channels formed each time the switch is operated is expected to be a stochastic. Repeating the above experiment six times at the operating conditions for shot 149 resulted in a mean of 2.4 channels with a standard deviation of 0.4. The effect of this range of channel values on simulated currents is a standard deviation of 0.36 kA with an average peak current of 71.96 kA.

Research by Woodworth [11] supports these results. In his publication, the six spark gaps of the HCEI switch (referred to as the Russian switch) are identified along with the switch operation. This includes the method in which the number of channels can vary from gap to gap, and how the conductivity of each channel is not necessarily identical.

Figures 22 – 24 in [11], indicate how the effective number of channels across the entire switch would not necessarily be an integer value. Moreover, it is unlikely that the number, conductivity, and location of the channels formed will remain constant from shot to shot, making $n_{channels}$ change in a manner difficult to predict. Additional triggered data will be collected in Protogen to further the ability to predict the HCEI switch behavior.

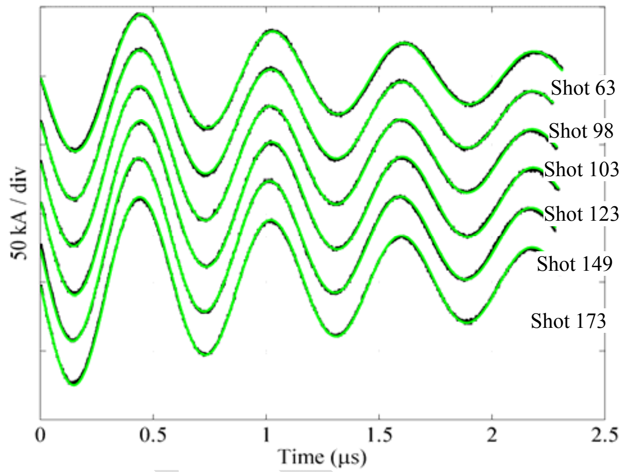


**Figure 9**. Six simulated currents (green) fit to six measured currents (black). See Table 2.

**Table 2.** Estimated number of channels at different operating conditions.

| Shot Number | Voltage (kV) | Switch Pressure (psig) | $n_{channels}$ |
|---|---|---|---|
| 63 | 148 | 9.0 | 2.5 |
| 98 | 159 | 11.0 | 2.6 |
| 103 | 168 | 12.5 | 4.0 |
| 123 | 182 | 15.0 | 4.1 |
| 149 | 191 | 16.5 | 3.9 |
| 173 | 196 | 18.0 | 4.8 |

Impact to the Protogen simulation from including the non-ideal switch model is evident in Figure 10. In this plot results are provided with and without the time varying switch resistance.

The initial capacitor charge voltages (190 kV) and the trigger times were the same for both simulations. The simulation with the time varying resistance had the switch pressure set at 16.5 psig and the number of channels to 2.4. It was found that the non-ideal switch model reduced the peak load currents and the transmission line voltages by 7.7% and 9.9% respectively. The rise time and damping of the waveforms were affected as well.

Modeling and simulation techniques will continue to evolve as new data becomes available from the Protogen experiments. In addition new triggered switch data will be collected to refine the HCEI switch model. Modeling advances with Protogen will further our ability to design and predict the performance of other Genesis-like systems.

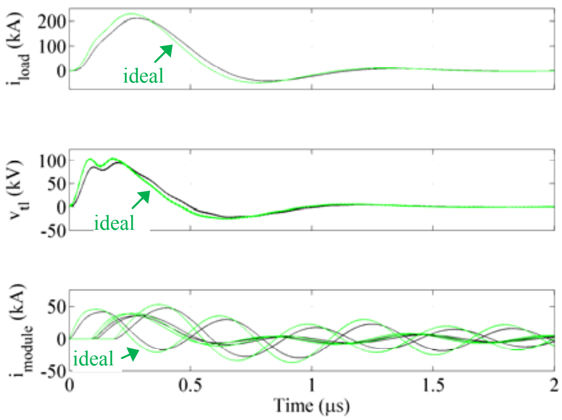


**Figure 10**. Protogen Ideal Switch (green) vs. non-ideal switch model (black).

## V. CONCLUSION

Critical solid dielectric system concepts, materials, and construction processes have been developed for the Genesis system. Advanced pulse shaping techniques have been developed and analyzed and the basic performance of Genesis components has been demonstrated. Advanced switch characterization continues to improve the capability of Genesis modeling to predict system performance.

The focus of Genesis R&D now turns to a demonstration of these concepts on a scaled testbed called Protogen. Protogen will allow system level reliability studies and a comparison of Genesis modeling techniques to hardware system performance. Protogen can be used to effectively demonstrate all the concepts required for a Genesis-class system or other systems requiring precision control of multi-MA current into low inductance loads.

The goal of the Genesis system was to offer extreme user flexibility in a compact platform. If reduced operational flexibility is required, Genesis concepts can be used to develop lower complexity, highly efficient multi-MA driver platforms.

## VI. ACKNOWLEDGEMENTS

The authors would like to thank: H.D. Anderson, H.L. Brown, M.L. Horry, M.D. Knudson, M.J. Madlener, G. Neau, V. Romero, S.D. Sudhoff, and R. White for their support, insight, and valuable discussions regarding this project. The authors also gratefully acknowledge valuable contributions from their colleagues at Sandia National Laboratories, Ktech Corporation, EG&G, L-3 Communications, and Purdue University.

## VII. REFERENCES


[1] C. A. Hall, "Isentropic compression experiments on the Sandia Z accelerator," Physics of Plasmas, Vol. 7, No. 5, May 2000, pp. 2069-2075.

[2] J.P. Davis, et al., "Magnetically driven isentropic compression to multimegabar pressures using shaped current pulses on the Z accelerator," Physics of Plasmas, vol. 12, no. 5, 2005.

[3] J.-P. Davis, C. Deeney, M. D. Knudson, R. W. Lemke, T. D. Pionton, and D. E. Bliss, "Magnetically driven isentropic compression to multimegabar pressures using shaped current pulses on the Z accelerator," *Phys. Plasmas*, vol. 12, no. 5, p. 056 310, May 2005.

[4] T. Ao, et al., "A compact strip-line pulsed power generator for isentropic compression experiments," Review of Scientific Instruments, 79, 013903, 2008.

[5] S.F. Glover, et al., "Genesis: A 5 MA programmable pulsed power driver for isentropic compression experiments," *IEEE Transactions on Plasma Science*, Vol. 38, No. 1, October, 2010, pp. 2620-2626.

[6] S. F. Glover, F. E. White, K. W. Reed, and M. J. Harden, "Genetic optimization for pulsed power system configuration," *IEEE Trans. Plasma Sci.*, vol. 37, no. 2, pp. 339–346, Feb. 2009.

[7] SolidWorks 3D CAD Software, Dassault Systèms SolidWorks Corp., 300 Baker Avenue, Concord, MA 01742, USA, www.solidworks.com.

[8] S.F. Glover, et al., "Impact of Time Varying Loads on the Programmable Pulsed Power Driver Called Genesis," 18th IEEE International Pulsed Power Conference, June 2011.

[9] B.M. Kovalchuk, et al. "Multi gap switch for Marx generators," Pulsed Power Plasma Science Conference, June, 2001, pp. 1739-1742.

[10] M.G. Mazarakis, et al., "High current, 0.5 MA, fast, 100ns linear transformer driver experiments," Physical Review Special Topics – Accelerators and Beams, 12, 050401 2009. .

[11] J. R. Woodworth, et al., "Low-inductance gas switches for linear transformer drivers," Physical Review Special Topics – Accelerators and Beams 12, 060401, 2009.

[12] S.F. Glover, et al., "Pulsed and DC charged PCSS based trigger generators," *IEEE Transactions on Plasma Science*, Vol. 38, No. 1, October, 2010, pp. 2701-2707.

[13] Jane Lehr, et al., "Evaluation of Spark Gap Switches Operated at Low Percent of Self Break Voltage," 17th IEEE Pulsed Power Conference, June 2009.

[14] MATLAB The Language of Technical Computing, The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098 USA, info@mathworks.com.

[15] G. Neau, L3 Communications, 4855 Ruffner St., Suite A, San Diego, CA 92111.

[16] S.F. Glover, et al., "Genetic optimization for pulsed power system configuration," IEEE Transactions on Plasma Science, Vol. 37, No. 2, February 2009, pp. 339-346.

[17] T. H. Martin, et al., "Energy Losses in Switches," Pulsed Power Conference, June 1993, Digest of Technical Papers, Ninth IEEE International, pp. 463-470.

[18] S. I. Braginskii, "Theory of the Development of a Spark Channel,'' JETP, Vol. 34 (7), No. 6, pp. 1068, December 1958.

[19] S.D. Sudhoff and Y. Lee, "Energy Systems Analysis Consortium (ESAC) Genetic Optimization System Engineering Tool, v. 2.2 Manual," School of Electrical and Computer Engineering., Purdue Univ., West Lafayette, IN., 47907. sudhoff@ecn.purdue.edu