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LASER TRIGGERED GAS SWITCHES UTILIZING BEAM TRANSPORT THROUGH 1 MΩ-cm DEIONIZED WATER

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Abstract

We report on the successful attempts to trigger high voltage pressurized gas switches by utilizing beam transport through 1 MΩ-cm deionized water. The wavelength of the laser radiation was 532 nm.

We have investigated Nd: YAG laser triggering of a 6 MV, SF6 insulated gas switch for a range of laser and switch parameters. Laser wavelength of 532 nm with nominal pulse lengths of 10 ns full width half maximum (FWHM) were used to trigger the switch. The laser beam was transported through 67 cm-long cell of 1 MΩ-cm deionized water constructed with anti reflection UV grade fused silica windows. The laser beam was then focused to form a breakdown arc in the gas between switch electrodes. Less than 10 ns jitter in the operation of the switch was obtained for laser pulse energies of between 80-110 mJ. Breakdown arcs more than 35 mm-long were produced by using a 70 cm focusing optic.

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NOMENCLATURE

mJ	millijoule
DOE	Department of Energy
SNL	Sandia National Laboratories
LTGS	Laser Triggered Gas Switch
MV	Mega Volt
cm	centimeters
nm	nanometers
PFL	pulse forming line
APPRM	Advanced Pulsed Power Research Module
Z	the Z accelerator
ZR	Z refurbished
SATPro	System Assessment Test Program
SF_6	sulfur hexafluoride

1. INRTODUCTION AND BACKGROUND

Laser Triggered Gas Switches (LTGS) have become a corner stone of successful multi-module pulsed power accelerator operation. LTGS provide excellent reliability, low jitter, low prefire rate, low laser energy requirements, multi-channeling, and low inductance when switches are used in parallel [1]. Many pulsed power accelerators, including Sandia National Laboratories' Z-machine use LTGS because of the benefits discussed above. With the upgrade from Z to Z-refurbished (ZR) new laser triggering schemes are being investigated to mitigate some of the potential problems associated with the LTGS on the ZR accelerator.

The ZR LTGS is immersed in oil to inhibit breakdown of the grading structure. The switch is triggered by a laser pulse of 16-20 mJ of 266 nm radiation which provides a 1σ standard deviation in switch jitter ~ 2 ns. This laser radiation is delivered to the switch by traveling through a pressurized gas enclosure, referred to as the laser cross-over tube, from ground to the high potential inner electrode of the Pulse-Forming Line (PFL) as shown in Figure 1. The laser tube is a component of concern since the System Assessment Test Program (SATPro) showed electrical and mechanical failure.

A superior solution would be to eliminate the laser tube, crossing the highly stressed liquid (water) dielectric instead. By this means of laser triggering the laser energy would be transported through the water section of the PLF and then into the switch through optical windows and dielectric coated mirrors. To this end, experiments have begun to demonstrate that sufficient amounts of laser energy at 355 and 532 nm can be transmitted through water to operate a LTGS with jitter consistent with the ZR requirements.

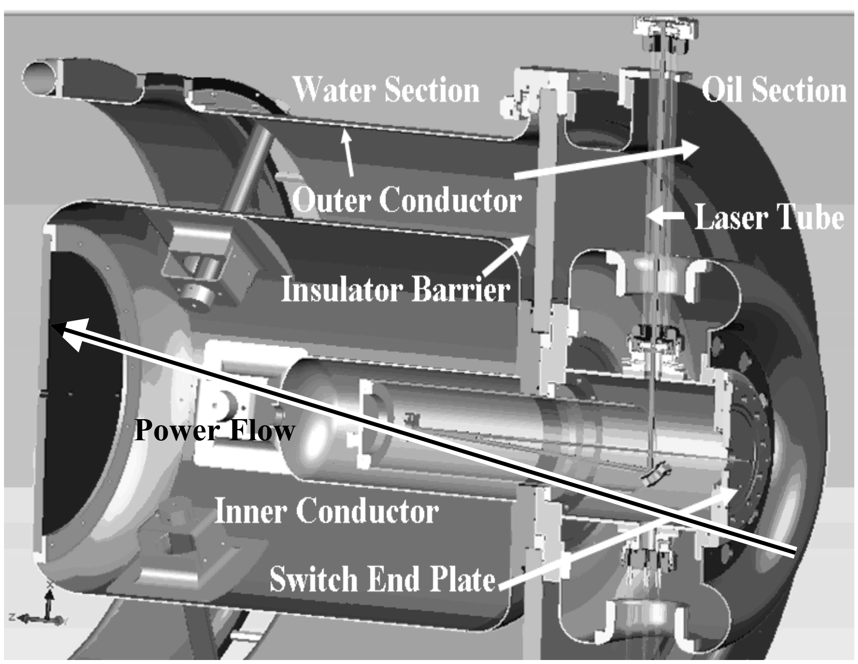

Figure 1. Cross section of PFL with laser cross over tube, switch end plate and laser beam path to switch.

This paper will focus on three main points. I. Showing that 355 and 532 nm laser radiation can be transmitted through water with minimal loss. II. Showing both of these wavelengths can breakdown SF_6 in a pressurized chamber after being passed through a 67 cm long water cell of 1 MΩ-cm deionized water. III. 532 nm laser radiation can be transported though water and used to trigger high voltage pressurized gas switches.

1.1. Laser Gas Interaction

When a high-power laser beam of intensity **I** interacts with a gas, electrons can be generated through two main mechanisms: direct multi-photon ionization (MPI) and electron impact ionization [2]. These electrons can ionize and breakdown the gas when their energy exceeds the ionization energy of that gas molecule. In the case of wavelengths shorter than 1 μm multi-photon ionization is expected to play an important role in this breakdown process.

According to published literature [3], the breakdown of SF_6 is a multi-photon ionization process requiring incident photon energy exceeding the ionization energy of 15.6eV. Table 1 shows the approximate number of photons required to ionize and breakdown SF_6 at the Nd: YAG fundamental wavelength and its harmonics.

1.2. Transmission of Laser Radiation through Water

In order to transport laser radiation through water and reemerge to form a breakdown arc in a pressurized SF_6 switch, light of the wavelength of the laser beam must propagate an appreciable distance through pure water [4]. The transport of laser radiation through water is inherently dependent upon the optical properties of absorption and scattering. According to published literature [5, 6], the optical properties of water are the least absorbent at 355 and 532 nm; wavelengths easily available with commercial lasers. Observe in Table I. the absorption of pure water versus wavelength at the Nd: YAG harmonics.

The relatively long 1/e absorption lengths of water at 355 and 532 nm suggest that laser beams at these wavelengths could be transported directly through water from the ground-side to the high voltage side of the PFL [4]. No gas-filled “laser crossover tubes” such as those currently used to transport 266 nm laser radiation would be needed [7].

Table I Wavelength information

λ (nm)	Energy per Photon (eV)	# of Photons for SF_6 Ionization	Absorption Coefficient α (cm^{-1})	e^{-1} Absorption Length (m)	Ref. For α
266	4.66	4	.02	0.5	Woodworth
355	3.49	5	$8.4x10^{-5}$	110	Buiteveld
532	2.33	7	$4.45x10^{-4}$	22	Buiteveld
1064	1.16	14	.12	0.08	Curcio

2. EXPERMENTAL EQUIPMENT

The laser used in these experiments was a New Wave Tempest Nd:YAG laser equipped with doubling and redoubling crystals to produce coherent radiation at 355 and 532 nm. A 3X beam expander located at the output of the laser was used to improve focusability and allowed the breakdown arc's location to be varied in the switch gap. Stainless steel conflat tubing and antireflection (AR) coated UV grade fused silica windows were used to create a 67cm long, 10 cm diameter cell of 1MΩ-cm deionized water.

Laser energy measurements were made by using a Molectron joule meter model # EM400. A Coherent laser energy sensor model # JLP25-2 was connected to the joule meter to provide measurement capabilities. All laser energy values were obtained by averaging 25 pulses. The 1σ standard deviation of the 25 pulses ranged from 0.6 to 1.2 mJ for all energy measurements.

The LTGS was tested in the Advanced Pulsed Power Research Module (APPRM). APPRM was originally constructed as a test bed for the development of pulsed power technologies and components that could be used in future generation high power facilities [8]. The test bed is comprised of a 56 stage, 2.2μF 100 kV Marx generator that charges a 5.5 Ω 20 nF water insulated Intermediate Storage Capacitor (ISC) to more than 7 MV in ~1.5 μs [8]. The switch is located at the output end of the ISC where it is connected to 5.5 Ω $CuSO_4$ resistive load [8].

The physical layout of the laser experiment is shown in Figure 2**.** The beam propagates through a water cell, passes through a splitting optic feeding photo diode for timing, and then is reflected by a dielectric coated mirror into a PVC tube entering the oil tank of APPRM. The beam enters into a submerged metal box that contains a 2^{nd} mirror used for axial alignment of the beam into the switch. The 2^{nd} mirror reflects the beam so that it passes through a focusing optic in a laser tube and focuses between the switch electrodes.

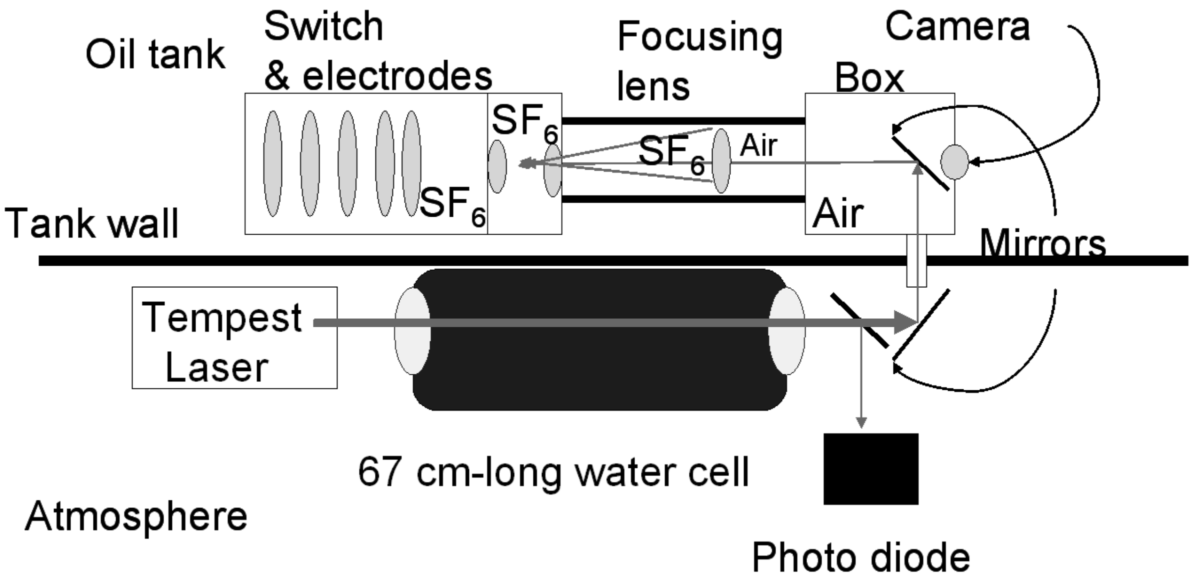

Figure 2. Diagram of beam transport path through water cell to the switch

3. EXPERIMENTS

3.1. Transmission and Breakdown Threshold

Initially a series of transmission and breakdown threshold experiments were performed with 355 and 532 nm laser radiation to determine if these wavelengths could be transmitted through the 67 cm water cell and reemerge in to a pressurized chamber to breakdown SF_6.

Energy transmission measurements at 355 and 532 nm through the 67 cm long water cell yielded 75% and 86 % transmission, respectively. These measurements do not include losses from window reflections which amount to ~7.0 %. Transmission measurements with window losses subtracted out result in ~ 93 % and 82 % transmission of incident laser energy for 532 and 355 nm, respectively.

The primary method for determining breakdown threshold was to gradually increase laser energy while maintaining gas pressure fixed until a visible spark was observed in the focal region [2]. Breakdown was observed as a visual spark and an audible "snapping" sound. Breakdown arcs were recorded by using a digital camera.

A time history measurement of the arc light emission was measured with a fast photomultiplier tube behind laser safety glasses and a neutral density filter. The rise time (10-90%) of the light emission from the spark formation was measured to be ~ 4-7 ns for both 355 and 532 nm light. The fast rise time and decay of the arc light indicate that the breakdown is a prompt process that should yield low-jitter triggering of switches [4].

The focal lengths of the optics used were 35, 50, 60, and 70 cm. Results showed that both 355 and 532 nm laser light could be passed through the water cell and breakdown SF_6 in a chamber pressurized to 5 psig. However, arc formation and length were limited by the focal length of the optic used and energy delivered to the pressurized chamber, which was measured after the focusing optic. Figure 3 shows arc formation at 355 nm formed with a 50 cm focusing optic produced with 27 mJ of energy.

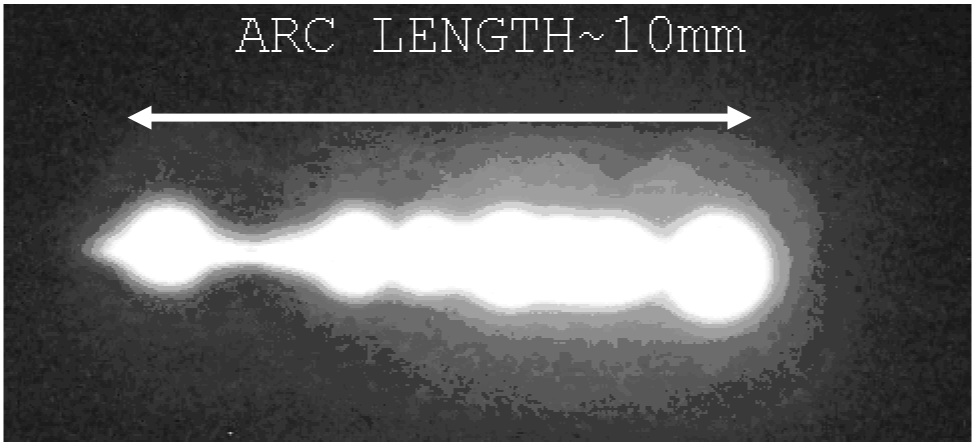

Figure 3: Breakdown arc formed with 27 mJ of 355 nm light by using a 50 cm focusing optic. Beam is transported through water cell and then focused in pressurized chamber of SF_6

3.2. Breakdown Threshold vs. Energy & Gas Pressure

In this section we present a series of breakdown thresholds experiments with 532 nm light that were conducted to determine how breakdown arcs would be affected in the switch by changing gas pressure and laser energy. The arc produced by 532 nm light was bright white in color and multiple arcs were created throughout the switch gap. i.e. the arc could be describes as a “string of pearls”. Figure 4 shows a breakdown arc in the switch gap created by 75 mJ of 532 nm light.

A Marshall CCD camera with focusing lens was mounted to view breakdown arcs in the switch from a radial position. The camera was connected to a frame grabber card “National Instruments PCI 1407 card” in a PC that triggered the laser on a 2 Hz cycle. Live video of spark formation was viewed on a PC monitor while gas pressure and laser energy where changed.

Test 1 consisted of maintaining laser energy at 90 mJ and increasing gas pressure from 5 to 42 psig. Observations showed arc formation and length were only slightly affected by increase in pressure. Visible sparks were produced over the entire range of gas pressures at constant laser energy of 90 mJ.

Test 2 kept gas pressure constant at 42 psig while decreasing laser energy from 90 mJ until arc formation disappeared. Arc size started to decrease at 50 mJ and continued to get smaller until it vanished between 5-10mJ.

Flowing gas in both tests has a turbulent affect on spark formation introducing large discontinuities in the arc but once pressure stabilized arcs were nearly continuous across the electrode gap.

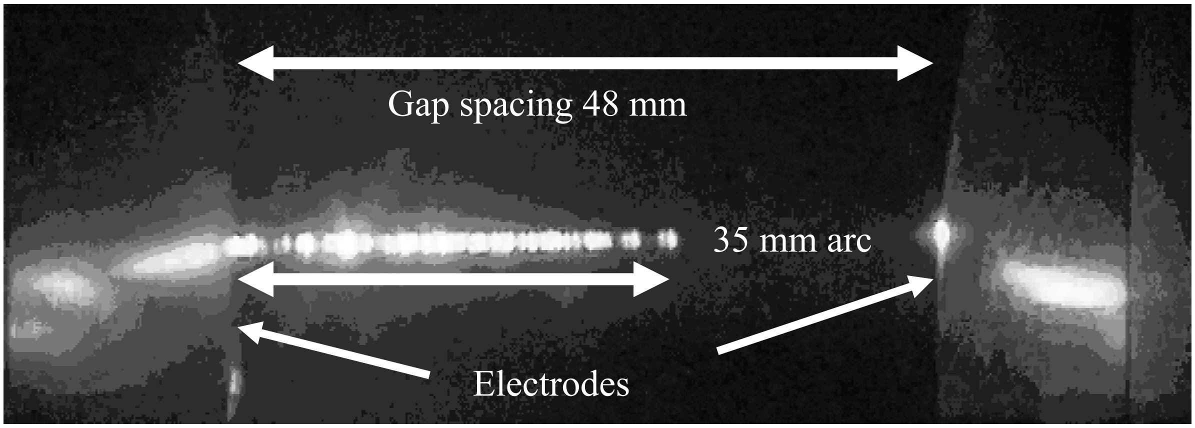

Figure 4. 35 mm-long breakdown arc formed with 75mJ of 532nm laser radiation passed through 67cm long water column and focused in to SF_6 gas switch pressurized to 5 psig through 70 cm focal length lens. Picture is taken through laser goggles that blocks 99% of green light.

3.3. Switch Testing

We investigated the performance of the switch for a variety of different conditions. We examined triggering for different operating voltages, gas pressures, and the trigger energy used to create breakdown arcs between switch electrodes. The switch was operated at 85 % of self break for all shots.

The runtime "delay time" of the switch is defined as the time difference between the arrival of the laser pulse and the start of current conduction in the switch. This measurement is based on measuring the arrival time of the laser pulse, measured with the photo diode, to voltage drop of the Intermediate Store Capacitor with a (V-dot) probe and correcting for the physical distance of 21 ns. Figure 5 shows a 4.75 MV output voltage waveform and the arrival of the laser trigger pulse for shot 1197. The laser energy used to trigger the switch was ~108 mJ and measured runtime was ~32.1 ns. Jitter is defined as the 1σ standard deviation of the runtimes of the switch.

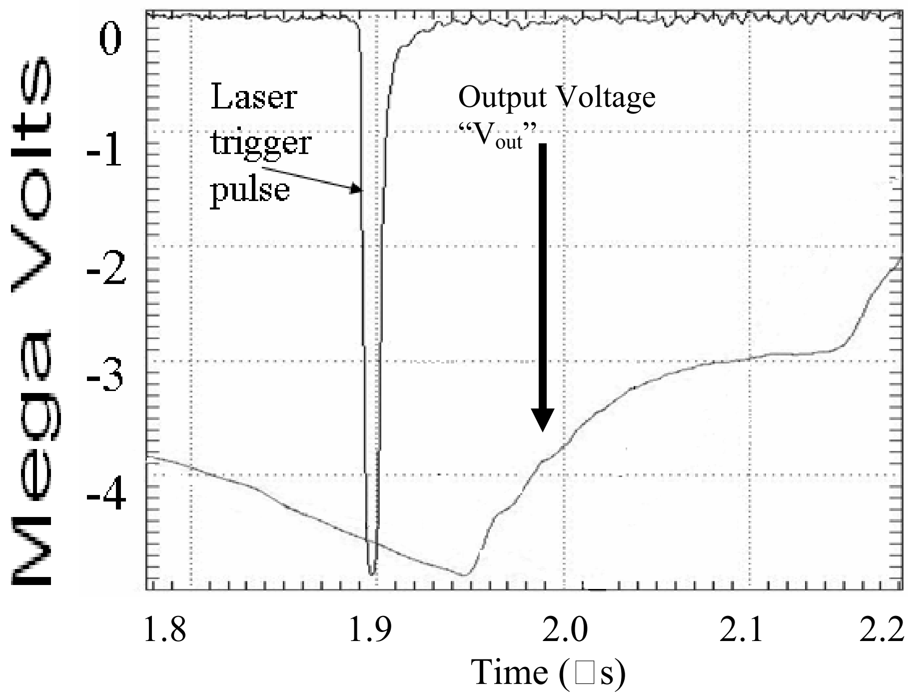

Figure 5. Voltage waveforms and laser trigger pulse for shot 1197. Runtime~32.1 ns

3.3.1. Data Set 1 Water Column in Laser path

Set A.
48 shots were conducted at the following parameters: switch voltage ~ 3.6 MV, gas pressure = 17 psig, and trigger energy ~ 80 mJ ± 3mJ. The average switch runtime was ~ 39.3 ns with 1σ jitter~9.43 ns.

Set B.
17 shots were conducted at the following operating parameters: switch voltage ~ 4.6 MV, gas pressure ~ 33 psig, and trigger energy ~ 110 mJ. The average runtime was ~38.2 ns with 1σ jitter ~9.0 ns.

3.3.2. Data Set 2 No water cell in laser path

Set C.
39 shots were conducted at the following operating parameters: switch voltage 3.6 MV, gas pressure = 17 psig, and trigger energy ~ 90 mJ. The average runtime ~ 32.9 ns and 1σ jitter ~ 4.24 ns.

Set D.
20 shots were conducted at the following operating parameters: 3.6 MV, gas pressure = 17 psig and trigger energy ~ 80±3 mJ. The average runtime was ~36.8 ns and 1 σ jitter~9.52 ns

A comparison of the data set A and D show that runtime and jitter are approximately the same with and without the water cell for trigger energies ~ 80 mJ, switch voltage ~3.6 MV and gas pressure ~17 psig. The shortest runtime and smallest jitter was obtained for data set C without the water cell with trigger energy ~ 90 mJ.

We used a similar Tempest Nd: YAG laser to conduct data set B. Pulse width was still 10 ns, but the maximum energy that could be delivered to the switch with the water cell in the beam's path was ~110 mJ. Increasing the trigger energy to 110mJ with the water tube in the laser path did not have the same affect as removing the water cell as in data set C where trigger energy was ~ 90 mJ. We have not resolved this issue yet and are looking at beam quality properties associated with each laser. In addition the beam quality could be affected by transmission through water. Attempts have be made to measure beam spot size at focus with and with out the water cell in the laser beam's path, but these tests were difficult to make on a pulsed laser and did not provide substantial information pertaining to spot size at focus.

4. SUMMARY AND CONCLUSION

1. Laser radiation at 355 and 532 nm can be transported through water with minimal losses and breakdown SF_6 in a pressurized chamber.
2. Switch jitter < 10 ns was measured for 80-110 mJ pulses of 532 nm laser radiation being delivered to the switch through 67 cm long water cell.
3. Runtime and jitter seem to be energy dependent but more shots are needed to come to a substantial conclusion.

We have examined laser triggering of 6 MV switches by transporting 532 nm laser radiation through an insulating medium of water. In these experiments we demonstrated less than 10 ns in switch jitter with 80-110 mJ of 532 nm laser radiation. These results represent a significant advance in the laser triggered switches in pulsed power accelerators because most accelerators use water as an insulating medium for operations. We would consider removing the gas filled laser cross over tubes on ZR if switch jitter could be reduced to < 2 ns by using 355 or 532 nm laser radiation.

4. References

1. G.J. Denison, et al. "Performance of the Hermes III Laser Triggered Gas Switch," in Proceedings of the 7th IEEE Pulsed Power Conference (1985), pp 579-582.

2. D. I and G. Weyl, "Laser-induced breakdown in nitrogen and the rare gases at 0.53μm and 0.35μm", J. Phys. D: Appl. Phys. 20 (1987) 1264.

3. J.R. Woodworth, P.J. Hargis, et al. "Laser triggering of a 500-kV gas filled switch: A parametric study) J. Appl. Phys. 56(5),1 Sept. 1984.

4. J.R. Woodworth, et al. Laser Triggered Water Switches, 14th IEEE Pulsed Power Conference,0-7803-7915-2 (2003).

5. H. Buitevld, et al. The optical Properties of pure water, SPIE proceedings on Ocean Optics XII, edited by J.S. Jaffe, 2258, pg.174, (1994).

6. J.A. Curico, et al. J. Opt. Soc. America, 41, pg. 302, (1951).

7. K.W. Struve, J.P. Corley, D.L. Johnson, H.C Harjes, D.H. McDaniel, R.W. Shoup, D.L Smith, W.A. Stager, E.A. Weinbrecht, Design Options for Pulsed Power Upgrade of the Z Accelerator, 13th IEEE Pulsed Power Coference,0-7803-7120-8, (2002).

8. J.P Corley, et al. Development/ Tests of 6-MV Triggered Gas Switches at SNL, 14th IEEE Pulsed Power Conference, 0-7803-7915-2 (2003).

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