

# Basic research on pulsed power for narrowband high power microwave sources

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## ABSTRACT

Relativistic, intense beam-driven High Power Microwave (HPM) sources emerged as consequence of the development of pulsed power. In this context, pulsed power refers to components of a system following the prime power source, and before the load, which is typically an electron beam diode. Progress in fielding HPM sources on mobile platforms requires developing more compact pulsed power drivers. The Air Force Office of Scientific Research is sponsoring, using resources allocated by DDR&E, a Multidisciplinary University Research Initiative (MURI) program to study basic phenomena and processes that can lead to the design of more compact pulsed power systems. The University of New Mexico is leading a consortium, uniting researchers at Old Dominion University and the University of Nevada-Reno, to study basic phenomena relating to breakdown in solid and liquid dielectrics, high dielectric constant ceramics for use in compact, folded Blumlein transmission lines, gas switches, thermal management in compact pulsed power systems, among other topics. This paper describes the research activities on this program that are being performed in the initial year.

**Keywords:** pulsed power, high power microwaves, dielectric breakdown, high energy density storage, gas switches, thermal management

## 1. INTRODUCTION

Future DoD weapons systems such as High Power Microwaves (HPM's) [1], Directed Energy Lasers (DEL's), as well as other advanced concepts will require compact, portable pulsed power systems in order to find a practical embodiment. As an example, present-day HPM sources are largely laboratory curiosities because the capacitive storage-based pulsed power systems that are required to energize them occupy a large volume and have a large mass. To-date very little basic research funding has supported the fundamental studies that would be required to achieve the output of typical capacitive storage-based pulsed power systems in more compact and lightweight packages. This is primarily because most of the research has focused on the development of the sources (such as the HPM tubes themselves), and large-scale laboratory scale facilities provided a flexible environment to develop, test, and diagnose various source concepts. A block diagram of an HPM system is depicted in Figure 1.

Capacitive storage-based pulsed power systems are commonly used as HPM source drivers, since the requirements on such drivers include maintaining a constant impedance (typically of the order of 10-100  $\Omega$ ) at 100-1000 kV voltages for time scales on the order of 100's ns. Capacitive energy storage-based systems are well-suited for this requirement. Such a system is depicted in Figure 2. The primary energy source (or "prime power") in the laboratory is the electrical transformer. In the field, this could be turbines on an aircraft or a diesel generator on the ground or on board a ship. We are not concerned with prime power in this program. Rather, we focus on the capacitive energy store and pulse forming sections, since these

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occupy the greatest volume and the largest mass in the system. Furthermore, we will consider issues pertaining to attaching a load to portable pulsed power systems.

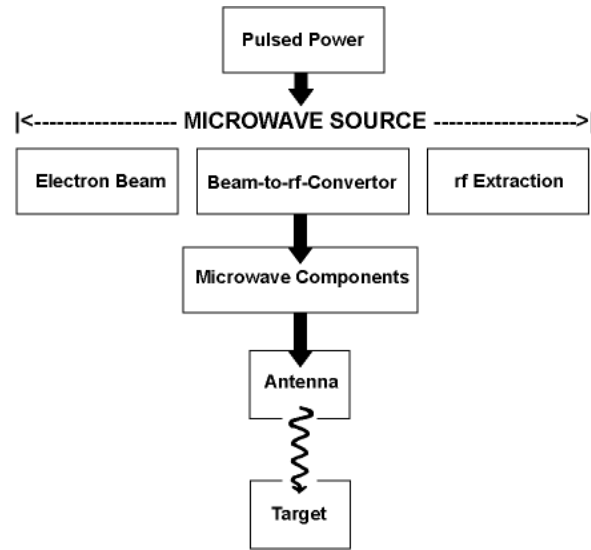


Figure 1. A block diagram depicting an HPM system. Pulsed power is used to energize the electron beam diode. The microwave source itself comprises the electron beam, the beam-to-rf convertor (typically termed the interaction space), and the rf extractor. Once rf is extracted from the interaction space, components are used to couple the rf to an antenna, which ultimately radiates the energy towards some target. (Figure originally appeared in [1], used with the permission of the authors.)

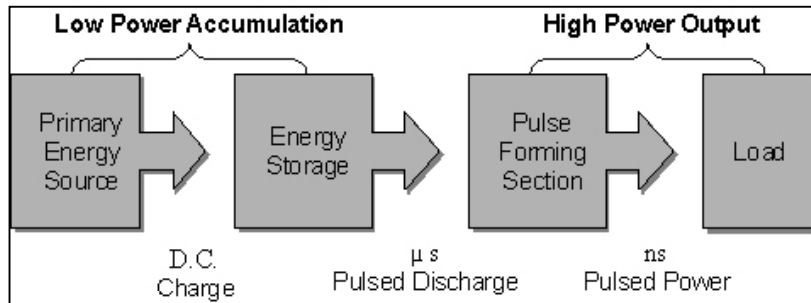


Figure 2. A capacitive storage-based pulsed power system. The prime power charges a capacitor bank on a long time scale. This output is then conditioned to meet the needs of the load. The load of interest is an HPM source.

The research topics that we are focusing on during the first year of this program can be broadly categorized into the following areas: breakdown in solid, liquid, and high-pressure gaseous dielectrics; electromagnetic calculations of fields in tailored high dielectric constant ceramics; and high power pulse forming line and gas switch studies. Although much of our focus is on compact pulsed power systems for HPM drivers, aspects of our program (such as breakdown in high pressure gaseous dielectrics) also address problems that are relevant to high power sources of ultra-wideband microwaves, where the pulsed power technology seeks to generate the largest time-rate-of-change of voltage  $dV/dt$  for a given antenna aperture height [2]. The remainder of this paper describes the pulsers that are of interest to this research program, as well as the activities in terms of breakdown studies and other aspects of pulsed power cited earlier.

## 2. BACKGROUND ON PULSERS OF INTEREST

Although research into breakdown in solid, liquid, and gaseous dielectrics has been ongoing since the early days of studies involving high voltage [3], recent interest has been motivated by specific challenges faced by researchers in the course of developing a particular pulser for some application. In the context of this research program, the particular pulsers that are being investigated include a compact folded Blumlein transmission line (whose continued development requires better understanding of liquid breakdown and of high dielectric constant ceramics) and a high-pressure gas switch for ultra-wideband generation. We first provide some background on these pulsers, and then discuss the breakdown issues in the context of those pulsers.

### 2.1 Compact folded Blumlein pulse-shaping driver

Researchers at Sandia National Laboratories have been developing a 600 kV, 50 ns, 5 Ω compact pulse-shaping drive that is significantly lighter than comparable coaxial water transmission line systems. Studies by Alexander *et al.* [4] demonstrated that propylene carbonate-impregnated Kapton™ sheets are attractive for constructing high average field striplines that can be folded into a compact geometry. Such a compact source can be used to drive low impedance HPM sources (such as a Vircator, MILO, or Radial Accelerator, see [1]) on a portable platform.

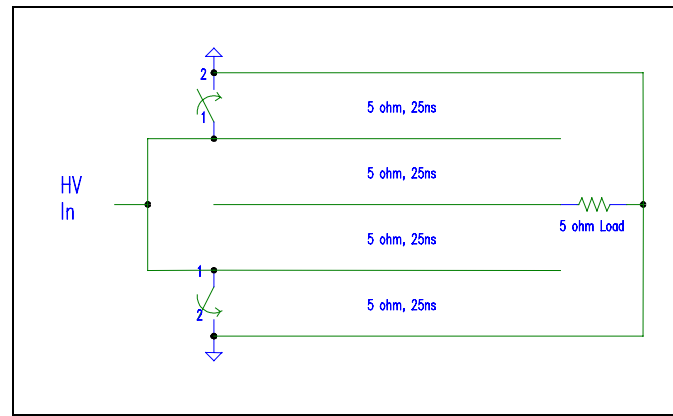


Figure 3. Electrical schematic of the pulse-shaping section of a 600 kV compact capacitive energy storage pulsed power driver. (Figure originally appeared in [4], used with the permission of the authors.)

The pulser used to charge the pulse-shaping section indicated in Figure 3 is a 6-stage bipolar charged Marx system. The capacitors in the Marx are 0.2 μF, 100 kV cans and the switches used are Maxwell™ midplane-triggered pancake spark gaps. The pulse shaping section comprises the Blumlein transmission line (Figure 3) and the Blumlein switch (triggered rail gap switch). The purpose of this pulser was to demonstrate its output in terms of the voltage waveform and pulse duration can be repeatedly achieved in a single-shot system. The extension to a repetitively-pulsed system was to follow. The Blumlein transmission line section utilized 10" wide copper strips with 2" Kapton™ margins in a 48" line that was folded into a 15" long unit. The dimensions were selected to achieve the design line impedance utilizing

$$Z \approx \frac{377 * d}{w * \sqrt{\epsilon_r}} \Omega, \quad (1)$$

where  $d$  is the thickness of the dielectric and  $w$  is the width of the line (assuming  $d/w < 0.1$ ).

In order to achieve the output parameters in this pulser, considerable electrical stress is placed on the liquid dielectric, propylene carbonate [5,6]. In fact, after many shots of testing were taken, fine bubbles were being generated in the propylene carbonate, well in advance of any visible corona or breakdown [4]. The

bubbles were generated at electric fields greater than 1.0 MV/cm, even though expectations were that breakdown would not be a problem until the 1.4 MV/cm field level was approached. Attempts at utilizing salts diluted in the propylene carbonate to adjust the electrical conductivity of the liquid dielectric did not greatly alter the situation. This observation motivates interest in studies of liquid breakdown.

Although this pulser is compact, it is widely recognized that high energy density dielectrics can further decrease the volume of such systems and this is what motivates our interest in breakdown in solids.

## 2.2 High pressure switch for ultra-wideband transmitter applications

Oil switches will be studied in the context of a high voltage switch to generate the requisite  $dV/dt$  to couple to an ultra-wideband antenna. Oil was chosen to avoid the engineering problems of high pressure gases and the subsequent difficulties in maintaining clean optics for the propagating fields. For high repetition rates, gas switches may be preferable; however, hydrogen at near liquid densities is needed to achieve results comparable to liquid switches [7]. Earlier work with oil switches in Hertzian generators [8] yielded sub-nanosecond switch closure times that were more than 10 times faster than that predicted by the traditional scaling laws of Martin [9]. Unlike traditional pulsed power systems where the generator is separate from the load or antenna, in the Hertzian generator the radiation emanates directly from the switch region and is guided by a conically symmetric antenna structure and subsequent optics. This procedure can eliminate dispersion, mode conversion, and high frequency losses inherent in other geometries. It also allows the remote measurement of the spark gap voltage versus time through a precise measurement of the radiated fields [8, 10, 11].

Pulsers that are being developed in the context of the discussion of the previous paragraph motivate the interest in both high pressure liquid and gaseous dielectric breakdown studies. It should be noted that the nature of the liquid breakdown in this application, compared to the folded Blumlein application, is likely to be different because of the differences in peak voltage, rise time, fall time, and full-width-half-maximum (FWHM) pulse duration.

## 3. BREAKDOWN IN SOLID, LIQUID, AND HIGH-PRESSURE GASEOUS DIELECTRICS

### 3.1 Breakdown in solids

The particular aspect of breakdown in solids that is of interest to this consortium is breakdown in high dielectric constant ceramics [12, 13]. High dielectric constant ceramics are being developed for a wide variety of applications in electrical engineering, including as a dielectric for high energy density capacitors [14]. Although the dielectric constant of electronic ceramics typically range from a low value of 2.2 for pure  $\text{SiO}_2$  up to 30,000 for relaxor ferroelectrics, the parameters of interest to the Blumlein pulse-shaping driver application include high dielectric constant ( $\epsilon_r > 100$ ) and high breakdown strength ( $>400$  kV/cm).

The energy density  $\gamma$  (in  $\text{J/m}^3$ ) of a ceramic under the influence of an applied electric field is given by

$$\gamma = \epsilon_0 \epsilon_r E^2/2 \quad (2)$$

where  $\epsilon_0$  is the permittivity of free space and  $E$  is the applied electric field. Typical candidate materials that are being studied in this regard are  $\text{TiO}_2$  and  $\text{BaTiO}_3$ .

The development of high dielectric constant ceramics is led by the ceramists, who are concerned with the microstructure and processing techniques used in fabricating samples. The researchers in [12, 13] included both ceramists and pulsed power engineers. The University of New Mexico (UNM) has begun an experimental and computational effort to study high dielectric constant ceramics for use in transmission lines [15]. The experimental program utilizes a simple DC breakdown set-up using a variety of electrode geometries and materials. The experimental set-up was developed by Sandia National Laboratories and is located on-site in the laboratory facility utilized for the Blumlein pulser studies [16]. Some ceramic material is available for investigation, fabricated under the auspices of the earlier Sandia collaboration [12, 13]. Continued interaction with ceramists from the University of Missouri-Rolla is anticipated.

The computational studies seek to address electrical breakdown along the edges of the Blumlein transmission line. Line, degradation of the dielectric material, and longevity of the composites are but some of the key limitations faced at present. In order to achieve a better understanding of the ceramic material under charging and discharging conditions, electromagnetic calculations are performed using HFSS™ (Agilent/Ansoft) to provide guidance for improved designs of substrate material and their integration with conductors. Although one of the goals of the ceramic development program is to achieve material with an electric field breakdown strength exceeding 400 kV/cm, only a fraction of this electric field has been successfully sustained [17]. Further improvement will rely on a combination of careful tailoring of the dielectric constant distribution, based on the results of electromagnetic calculations, coupled with advances in fabrication technique.

### 3.2 Breakdown in liquids

The energy density in a pulse forming network (PFN) is determined by the product of dielectric constant  $\epsilon_r$  of the liquid and the square of the maximum electric field  $E$  that can be applied without causing breakdown. In gases  $\epsilon_r$  is 1 and the breakdown voltage of *e.g.*, air at atmospheric pressure is 30 kV/cm. Liquids have higher values of  $\epsilon_r$  and hold-off voltage, and should therefore allow to reduce the size of pulsed power generators. Liquids have been explored for use as an energy storage and switch medium since the 1970s [18]. Most of the research in this field has focused on water and oil. Whereas water has a much higher dielectric constant compared to oil, 81 compared to 3, the resistivity of oil ( $10^{15} - 10^{20} \Omega\text{-cm}$ ) exceeds that of water (purified water:  $2 - 3 \times 10^7 \Omega\text{-cm}$ ) by many orders of magnitude. The dielectric strength has been quoted as  $3 \times 10^5$  V/cm and  $1.5 \times 10^5$  V/cm, respectively for oil and water [19]. However, short-time breakdown fields on the order of MV/cm (uniform fields) or several tens of MV/cm at the tip of needles have been reported [20]. Mixtures of water with ethylene glycol [19] have demonstrated that by using additives it is possible to increase the resistivity of water considerably without reducing the dielectric constant. In spite of all these efforts, “High power liquid dielectric switches, ... , remain to this day developmental,” as I. Vitkovitsky stated in 1987 [21]. This is to our knowledge still true today, and holds also for the use of liquids for energy storage.

For the use of dielectric liquids as electrical insulation, low losses (low conductivity even at high electric fields) and high dielectric strength are important. If used, in addition, as medium for electrostatic energy storage, the dielectric constant,  $\epsilon$ , becomes important. It should be as high as possible, since the attainable energy density, expressed by Eq. (2), requires the maximum electric field intensity that can be applied without causing electrical breakdown. Polar liquids, such as water or nitrobenzene, are liquids with high dielectric constants. For water as a prototype of a polar dielectric liquid  $\epsilon_r$  is about 80 up to frequencies of several GHz. There are liquids with even higher dielectric constant, such as N-Methylformamide with an  $\epsilon_r$  of 189.

The optimum candidates for electrostatic energy storage are liquids with:

1. asymmetric molecules with polar functional groups (yielding a large permanent dipole moment)
2. molecules which involve strong  $sp^3$  hybridized bonding (yielding a resistance to both dielectric breakdown and to electron/hole injection)
3. molecules which act as poor acids and poor bases (yielding a resistance to autoionization).

Propylene carbonate,  $C_4H_6O_3$  is one of the candidate liquid dielectrics of interest that satisfies these three criteria. Furthermore, since the folded Blumlein pulser being developed at Sandia National Laboratories utilizing this liquid, we will focus some of our attention on this dielectric.

Researchers at Old Dominion University (ODU) have been studying liquid breakdown for numerous years. Among their findings (in the context of liquid dielectrics used in switches) is that electrical breakdown of liquids, which needs to be prevented if the fluid is used for energy storage, needs to be stimulated if the fluid is used as a high voltage switch. Breakdown is generally assumed to be related to “bubble” formation at the electrodes, an effect that they had observed experimentally (see Figure 4). The bubbles could either be generated by ionization and current growth in the liquid phase, and subsequent heating of the liquid when the avalanche has reached a critical size. They could also be generated thermally, and avalanches will be generated in preexisting bubbles [22]. The first process requires, according to Gosse [23], electric fields greater than  $2 \times 10^6$  V/cm, fields that are likely to occur at microtips. However, the increased current

density at such microtips might also lead to the thermal generation of bubbles. This is similar to the bubbles observed in the propylene carbonate utilized in the folded Blumlein pulser.

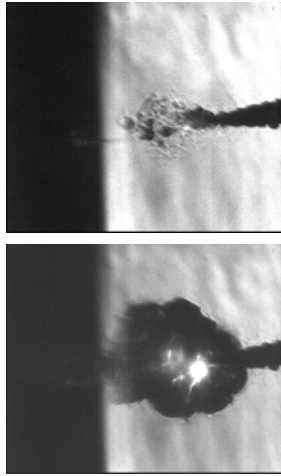


Figure 4. Photographs of prebreakdown phenomena in tap water between a tip and plate. The gap is  $100\ \mu\text{m}$  and the applied voltage is 2 kV. The exposure time is 10 ns. The first photograph (top) shows the gap at  $27\ \mu\text{s}$  after pulse application. Micro-bubbles are formed at the tip. Ten microseconds later (lower photograph) plasma formation is observed at the location of the air micro-bubbles, and shockwaves are emitted from the plasma centers.

Recent work at ODU has focused on liquid breakdown in sub-millimeter gaps. They have focused in the first phase of a project on energy storage and breakdown in liquids on water as a baseline dielectric and have studied the electrical characteristics of water at high electrical stress, up to values of 1 MV/cm between sphere-plane electrodes with gaps in the submillimeter range. In addition they have begun to explore the recovery phase of water switches. The experimental studies are correlated with modeling. A percolative approach, which successfully predicts fractal structures, was used to model breakdown.

The current-electric field ( $I$ - $E$ ) characteristics of water under electrical stress were measured up to 1 MV/cm. It shows a distinct increase in differential conductance with increasing electric field, an effect, which may be attributed to proton hopping [24]. The electrical breakdown, with highest values of almost 1 MV/cm between a 1.5 mm diameter sphere and a plane, is preceded by a phase of slightly increased current, indicating streamer development. The rate of current rise during breakdown exceeds  $10^{11}\ \text{A/s}$ . At average electric fields of 400 kV/cm in distilled water,  $100\ \mu\text{m}$  wide striations have been observed which emerge from the surface of the spherical electrode, and propagate toward the plane electrode with the velocity of approximately  $20\ \text{mm}/\mu\text{s}$ . The striations seem to play a major role in streamer initiation, as indicated by the observation that early breakdown is related to geometrical distortions of the striations. The recovery time of the water gap was measured for static and flowing water. A considerable decrease in recovery time was measured with water flowing through the gap, compared to the static case. The data from these studies indicate that flowing the water promises to allow the operation of water switches at repetition rates exceeding 1 kHz [25].

This basic research in liquid breakdown will continue and other liquids (*viz.* propylene carbonate) will be studied using the existing experimental set-ups.

### 3.3 Breakdown in gases

A variety of data have been collected recently exploring sub-nanosecond breakdown in liquids and gases [26]. These data involved the measurement of the outwardly propagating electromagnetic fields in a quasi-conical test fixture fed by a self-triggered spark at the apex of the cone. All measurements were performed

sufficiently far from the breakdown region in order to protect the diagnostic equipment and avoid altering the properties of the arc. In order to ascertain the physics of switch closure, simulation capabilities are needed to relate the electromagnetic fields at the point of measurement to the voltage and current behavior of the switch at the breakdown region.

In this collaborative work between the University of Strathclyde, Sandia National Laboratories, and the University of New Mexico, the means to analyze the data in a manner discussed in the previous paragraph are being developed. The large database was generated at Strathclyde, and the data is being analyzed at Sandia and UNM. In the UNM work [27] two new time-domain tools that will model this problem in two dimensions are being developed. The first is a finite-element, time-domain model. This model can handle material properties that vary spatially in radius and polar angle. The mesh is composed of adaptively sized linear, tetrahedral elements. The second tool is a time-domain integral equation (TDIE) technique that models the surface currents alone, again reducing the computational domain to two dimensions. The drawback of the TDIE method is that the Green's function must be known; in other words, arbitrary material properties cannot be modeled.

At present these simulation tools are being developed and will be applied to the experimental database. The ultimate goals of this research is to better understand liquid and gaseous dielectric breakdown in the short pulse, fast rise time regime.

#### **4. HIGH POWER PULSE FORMING LINES AND GAS SWITCHES**

Researchers at the University of Nevada-Reno have initiated a program to study tapered transmission lines. A tapered transmission line [28, 29] has an impedance that slowly varies spatially from source end to load end. The use of a tapered transmission line yields a nearly ideal transformer for frequencies above the transmission-line cutoff frequency, which is related to the variation in impedance along the transmission line and the phase velocity of the transmission-line medium. A common use of a tapered line is matching impedances at high frequencies. For example, an impedance match [30] from  $1.2 \Omega$  to  $50 \Omega$  over a frequency band of 700 MHz to 1.4 GHz is achieved with a dielectric-filled ( $\epsilon_r = 9.9$ ) exponential transmission line with a length of 9 cm and a transmission line cutoff frequency of 318 MHz. For a cutoff frequency of 1 MHz, the dielectric filled transmission line would increase in length to 28 m. Use of a material with high permeability and high permittivity significantly reduces the transmission-line wavelength, and thereby reduces the physical length of the tapered transmission line and extends the use of tapered transmission lines to lower frequencies. Transmission line topologies, range of impedance transformation, transformer ratios, high-permeability high-permittivity materials, reduction in phase velocity, and power handling are being studied as part of this program [31].

In terms of gas switches, the folded Blumlein work discussed earlier [4] utilizes a single triggered rail gap switch as the Blumlein switch. (In earlier experiments three parallel-triggered small gap trigatron switches were also used.) The rail gap switch offers the advantage of being low inductance, thereby assuring a fast rise time. However, the lifetime of this switch is not very good and material erosion is a problem. Improved Blumlein switch performance will be required for the next phase of development of this compact pulser. This aspect of the problem is being studied at UNM.

#### **5. CONCLUSIONS**

A consortium of three universities has been established to perform basic research on compact pulsed power. The initial year of research has focused on breakdown in solid, liquid, and gaseous dielectrics, as well as the development of pulsed power components, such as tapered transmission lines and gas switches. Additional topics to be addressed in the future include material erosion in gas switches, experimental studies of fast breakdown in pressurized dielectrics, boundary effects at liquid/conductor interfaces, additional modeling of liquid breakdown, the development of slow wave PFNs for liquid dielectrics, the development of compact, high voltage power supplies, and thermal management in pulsed power systems.

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