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6. AUTHOR(S) Shamiloglu, E., Barker, R.J., Gundersen, M., and Neuber, A.A.			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Southern California 3737 Watt Way – PHE 512 Los Angeles, CA 90089-0271		8. PERFORMING ORGANIZATION REPORT NUMBER	
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# Scanning the Technology

## Modern Pulsed Power: Charlie Martin and Beyond

EDL SCHAMILOGLU, FELLOW, IEEE, ROBERT J. BARKER, FELLOW, IEEE,  
MARTIN GUNDERSEN, FELLOW, IEEE, AND ANDREAS A. NEUBER, SENIOR MEMBER, IEEE

*In this introduction to the Special Issue on pulsed power and its applications, background information is provided for the non-specialist to better understand the many challenges in designing pulsed power systems, and the wide diversity of applications that are now emerging. The approach to providing a tutorial on pulsed power technology is to make available to the reader the paper written by J. C. Martin which appeared in a Special Section of the PROCEEDINGS OF THE IEEE on pulsed power technology in June 1992. That paper is supplemented in this introduction with additional information that complements many of the invited papers composing this Special Issue.*

**Keywords**—Bioelectrics, explosive pulsed power, high-power microwave, intense beams, plasma pinches, pulsed power, radiography, ultrawideband microwaves.

### I. INTRODUCTION

Modern pulsed power has its genesis in the pioneering work of the late John Christopher Martin and his colleagues at the Atomic Weapons Establishment, Aldermaston, U.K., in the 1960s [1]. “Charlie,” as he was known to the community, was a hydrodynamicist who was frustrated by his inability to purchase an adequate X-ray radiography source to image the dynamic phenomena he was interested in. As a result, he pursued a new generation of radiography sources that were based on high-power Marx generators, coupled with low-impedance transmission lines, and cold cathode single-stage accelerating gaps. Thus was the birth of modern pulsed power.

Pulsed power science and technology rapidly disseminated to the United States, former Soviet Union and the present-day Russia, Europe, and Asia. Pulsed power refers to the technology whereby energy is accumulated over a

relatively long period and then compressed in a short period to deliver very large power pulses to a given load. In this regard, pulsed power is an enabling technology; that is, its development has been spawned by some application (the “load”) that requires a very large power pulse for a relatively short period. Typical loads historically have included charged particle beam diodes, imploding plasmas, and other primarily defense-related applications; today, however, the loads can be biological samples, water from municipal drinking supplies, or effluents from combustion processes, among other environmental and biomedical applications. In short, pulsed power has evolved to not only play an important role in defense, including homeland defense, but has evolved to become an important technology in the environmental and biomedical arenas as well.

One of the reasons that pulsed power has emerged to become an important technology in the defense and nondefense sectors alike is that compactness and portability have increasingly become attributes of pulsed power systems. This is attractive to the defense sector, since the move to “all-electric” vehicles (for the army, navy, and air force alike) motivates the need for electrically driven (directed energy) weaponry. In the nondefense arena, compact pulsed power systems are more attractive to any practical application.

For some applications, it is desirable (and necessary) to achieve reliable repetitive operation of pulsed power systems. Early examples of repetitive pulsed power systems employed thyratron switches [3], described in more detail below. Extension of single-shot technology to applications requiring 100 Hz or higher repetition rates requires extraordinary innovation in order to achieve systems with long lifetime and good reliability.

In order to better grasp the breadth of pulsed power activities, we are motivated by the “mouse-to-elephant” curve in biology, shown in Fig. 1. The fact that all mammals (on this log–log plot) fall about a fairly straight line whose slope is power per unit mass should not be surprising, since mammals are made from similar matter, consume carbon-based food supplies, and breathe oxygen. Fig. 2 presents a plot of peak output power as a function of size (volume) for a wide

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E. Schamiloglu is with the University of New Mexico, Albuquerque, NM 87131-0001 USA (e-mail: edl@ece.unm.edu).

R. J. Barker is with the Air Force Office of Scientific Research, Arlington, VA 22203-1954 USA (e-mail: robert.barker@afosr.af.mil).

M. Gundersen is with the University of Southern California, Los Angeles, CA 90089-0271 USA (e-mail: mag@usc.edu).

A. A. Neuber is with the Center for Pulsed Power and Power Electronics, Texas Tech University, Lubbock, TX 79409-3102 USA (e-mail: andreas.neuber@ttu.edu).

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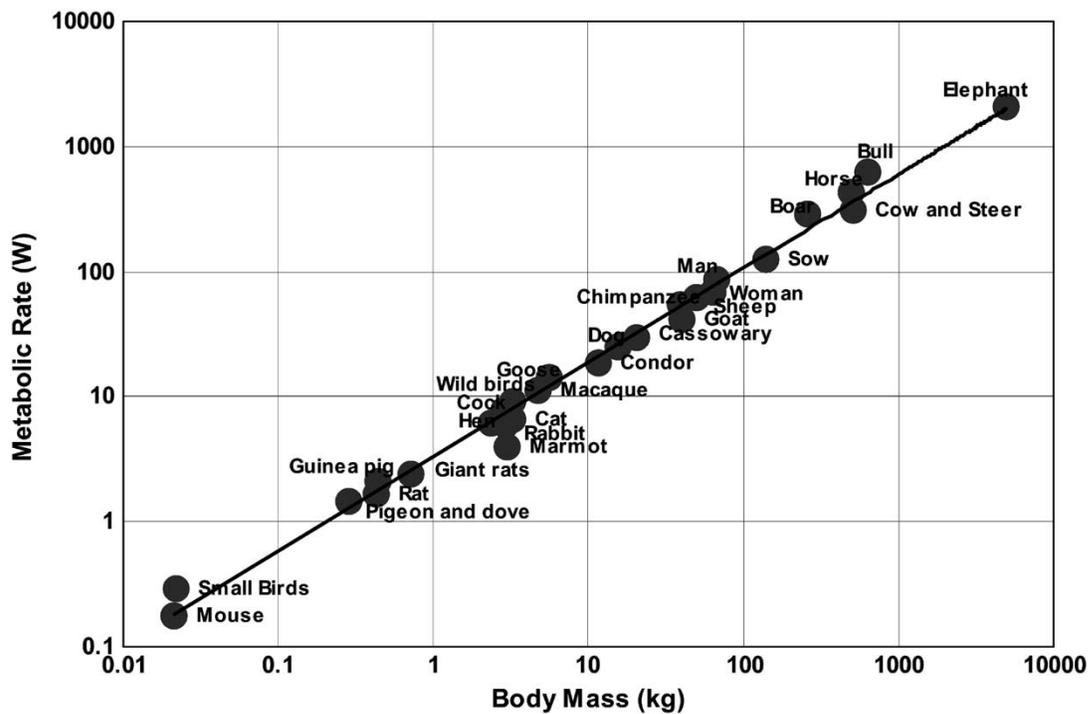


Fig. 1. The mouse-to-elephant curve in biology.

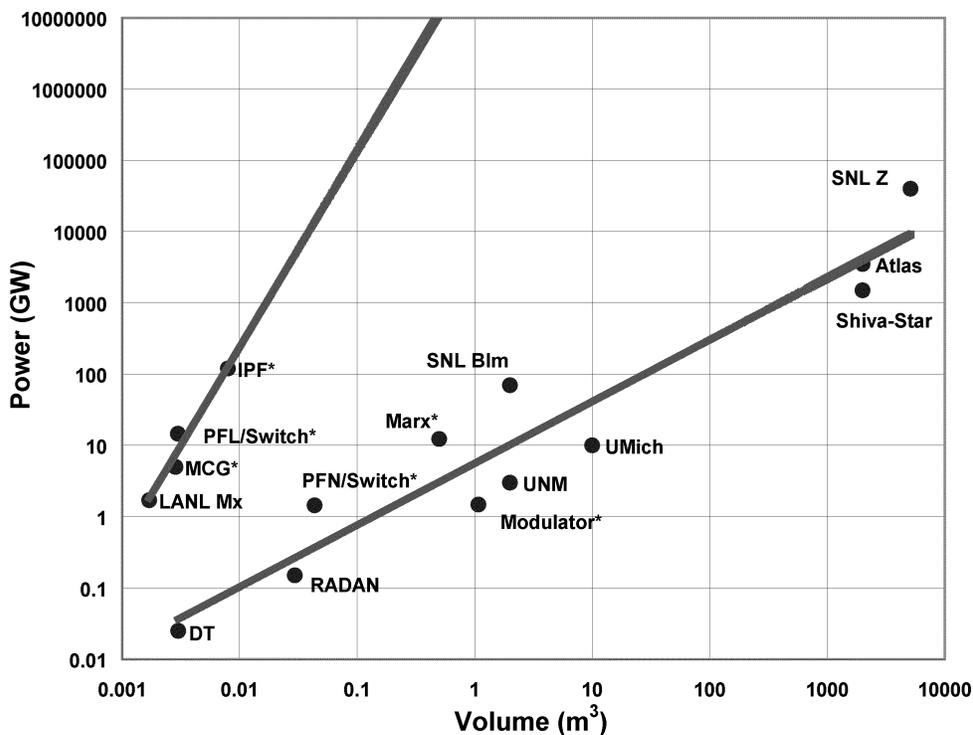


Fig. 2. The analogy of the mouse-to-elephant curve in pulsed power. The line with the faster rising slope comprises systems either driven by explosives or that use state-of-the-art high energy density components. The line with the lower slope represents more traditional pulsed power systems found in the laboratory. (Parameters for the sources denoted with an asterisk were obtained from [2].)

variety of pulsed power systems. This is an analogy of the mouse-to-elephant curve where the “mouse” is a compact hand-held pulsed power system developed at Los Alamos National Laboratory, Los Alamos, NM [4], and the “elephant”

phant” is the “Z” accelerator at Sandia National Laboratories, Albuquerque, NM, used for high energy density physics research [5], [6]. Since most pulsed power systems are made using similar materials, the power density uniting these sys-

**Table 1**  
Summary of Typical Various Pulsed Power Requirements for Given Applications

Application	Electrical Energy	Pulse Length	Peak Power/Pulse	Burst Avg. Power
High Energy Density Plasma Physics	20 MJ	100 ns	>10's TW	N/A
Intense Electron Beam Radiography	200 kJ	70 ns	< 1 TW	N/A
High Power Microwave (Narrowband)	10 kJ	100 ns	100 GW	100 kW
High Power Microwave (Ultra-Wideband)	10 J	1 ns	10 GW	10 kW
Ion Beam Modification of Materials	< 10 kJ	100 ns	30 GW	Small
Bioelectrics	0.1 mJ – few J	10 – 100's ns	10 kW – 100 MW	< mW - few W

tems describes a straight line, the line with the lower slope in Fig. 2. The challenge of future pulsed power systems, in this regard, is to develop and incorporate novel materials that would then increase the power density of future pulsed power systems. The line with the faster rising slope illustrates such systems, ranging from inherently efficient explosively driven pulsed power systems to those manufactured using newer higher energy density components.

## II. EXAMPLES OF PARAMETERS OF PULSED POWER SYSTEMS

The largest pulsed power systems are those used in the laboratory to study high energy density plasma physics and equations of state. They routinely generate in excess of tens of terawatts of electrical power. These include the Sandia National Laboratories' "Z" accelerator and its planned upgrades [5], [6], and the Los Alamos National Laboratory's Atlas machine [6] (which is now located at the Nevada test site). These large systems are intended to produce a single high-power pulse, and then would require some maintenance before being able to produce another pulse. The resultant shot rate on these large machines is typically about a single pulse per day.

Contrast this with high-power microwave sources, as another example, where some of their pulsed power accelerators can deliver 100-ns electrical pulses with tens of gigawatts of power and can be repetitively pulsed in burst mode with repetition rates as large as 1 kHz. These systems can operate for many shot cycles with minimal maintenance.

Table 1 summarizes the parameters of pulsed power systems used in some typical applications.

## III. ADDITIONAL SUPPLEMENTARY INFORMATION

The 1992 paper by J. C. Martin [1] should be read first.<sup>1</sup> Additional technical information is provided here that is not covered in the Martin paper, but nevertheless would be valuable to better understand some of the papers appearing in this Special Issue.

<sup>1</sup>[Online] Available: <http://www.ieee.org/organizations/pubs/proceedings>

### A. Pulsed Power Switching

In this section, we review some basic features of pulsed power switches. It is convenient to distinguish between gas-phase and solid-state switches, partly because the applications in pulsed power to some extent, although not totally, divide accordingly. Some of the work in pulsed power engineering at this time is directed toward distinguishing which switch is most appropriate for a given application and in responding to and applying new developments in both types. At this time, although there are exceptions for certain applications, those applications requiring high hold-off voltage and high current with fast switching time tend to require gas-phase switches. Solid-state switches such as thyristors are also used, but because of limitations in turn-on time, and requirements for multiple switches for high hold-off voltage, are still somewhat restricted in terms of application.

1) *Gas-Phase Switches*: Gas-phase switches primarily include spark gaps, thyratrons, and the pseudospark switches. These have advantages including the gas, or plasma (ionized gas), is very forgiving to a one-time over-current or overvoltage. The switch will still work; its lifetime merely will have been reduced. This is in sharp contrast to solid-state switches, where just the one-time formation of an arc is catastrophic. The plasma allows transport of very high currents along with high hold-off voltage, and switching times can be very fast. The power dissipation in these switches is relatively low, attributed to the conductivity of the plasma that is formed in the gas. Plasma properties vary, however, and a distinction may be made between a spark gap, typically operated at high pressure ( $\geq 1$  atmosphere), in an "arc" mode, and a thyratron and/or pseudospark, which normally operate at pressures below 1 torr, and in a glow discharge mode.

*Gas spark gaps*: Gas spark gaps have been used under a very wide range of single-pulse (or few-pulse) conditions, and operate with varying lifetimes at very high voltages and currents with very fast switching times. The primary limitation is in lifetime and repeatability, this because the type of arc formation at high current tends to be erosive, thus altering electrode characteristics. Gases include N<sub>2</sub>, air, H<sub>2</sub>, SF<sub>6</sub>, and

liquids such as water and liquid nitrogen. Voltages in excess of 1 MV and total charge >100 Coulombs have been obtained for important applications, such as Z-pinch for high energy density plasma physics research. Commercial spark gaps rated for 50–75 kA are available.

Triggering is achieved by techniques that include over-volting the main gap, introducing a plasma by auxiliary electrodes, or introducing UV through an overvolted auxiliary electrode. Radiation initiates breakdown through generation of charge by photoemission. Such optical triggering can be enhanced by using a laser. The closure time can be very fast:  $\leq 5$  ns. Most large pulsed power machines currently operating under single pulse mode utilize a spark gap switch.

*Thyratrons:* The original idea of a thyratron was conceived and patented by Langmuir [7], [8]. The general idea might be construed to include what is now known as an ignitron, which is a mercury cathode that conducts with a plasma of mercury vapor (and is capable of very high current operation). Development of a thyratron with high hold-off voltage was an enabling technology for repetitive pulsed power applications, such as radar modulators, and resulted from innovations by Germeshausen [9]. The thyratron for repetitive pulsed power applications (radar, pulsed lasers, and linear accelerators) is typically operated with H<sub>2</sub>, or H<sub>2</sub> with D<sub>2</sub>, although occasionally other gases are also used. Pressures are typically of the order 0.5 torr. The hold-off voltage can be very high, up to 100 kV for specialized tubes. Peak currents range to a few kA, much less than what commercial spark gaps are capable of handling; however, pulse-to-pulse repeatability is very good for millions of pulses. Thyratron lifetimes can be a billion shots in applications within specifications. The thyratron has the important advantage of a relatively low forward drop compared with vacuum tubes, due to space charge neutralization by the plasma in the tube, which can be critical for repetitive high peak power switching.

*Pseudosparks and back-lighted thyratrons:* The commercially less widespread pseudospark (electrically triggered) and back-lighted thyratron (BLT—optically triggered pseudospark) are similar to the thyratron in that the plasma is formed in a gas that is initially at pressures  $\approx 0.1$  to 0.5 torr. They differ in the operation of the cathode. For both the thyratron and the pseudospark, the limitation in current capability is found in the cathode, not in the plasma. Among the goals in developing the pseudospark was to achieve higher peak current, and this has been demonstrated.

The pseudospark cathode, or “superemissive” cathode, operates in a distinctly different mode from the externally heated thyratron oxide cathode. The superemissive cathode, which produces current from an area that is approximately 1 cm<sup>2</sup> of the order 10 000 A/cm<sup>2</sup>, vastly in excess of conventional thermionic cathodes, achieves this through a two-step self-heating process. In the first step, a hollow cathode discharge is formed, leading to a self-heating (resulting from the field and plasma) of a thin cathode surface layer. This cathode layer reaches emission that is extraordinarily high through a combination of field emission and thermionic emission [10].

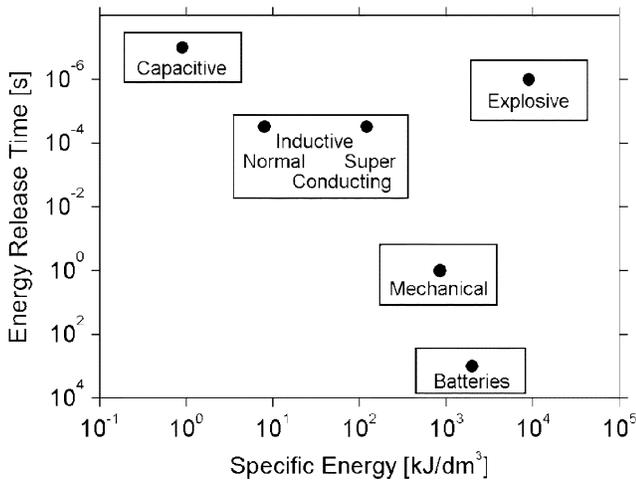
**Table 2**  
Summary of Various Switch Parameters in Pulsed Power Applications

Switch (selected for pulsed power, approx. max)	Hold-off Voltage (kV)	Peak Current (kA)	Forward Drop (V)
Spark Gap	100	10 to >1000	20
Thyratron	30	1 - 10	150
Pseudospark	35	5 - 100	200
Thyristor	1-5	1 to 50	2
IGBT	1	1	3
MOSFET	1	0.1	V <sub>DS</sub>
Vacuum Tube	200	0.25	Child-Langmuir

Pseudospark and BLT switches have been operated with hold off voltages in excess of 50 kV for a single gap, and 100 kV for two and three gaps. Peak currents for a typical switch are of the order 5–10 kA, although specialized versions conducting up to 200 kA have been reported. Switching times, that is, the time from approximately 10% to 90% of peak current, are of the order 25 ns in properly designed circuits, about a factor of two faster than a typical fast thyratron. Some versions of thyratrons apparently incorporate pseudospark emission characteristics in the design of concentric grid structures, leading to a combination of self-heated and externally heated cathode structures and operation. Pseudosparks are very robust to current reversal, and are reported to operate for switched charge lifetimes of the order 100 to 400 kC.

2) *Solid-State Switches for Pulsed Power:* Although unable to handle the parameters of large pulsed power systems, solid-state switches are nevertheless finding increasing applications in compact pulsed power systems. Principal solid-state pulsed power switches include the thyristor, gate-turn-off thyristor (GTO), insulated gate bipolar transistor (IGBT), and metal–oxide–semiconductor field-effect transistor (MOSFET). (See a recent Special Issue of the PROCEEDINGS OF THE IEEE for more detailed information on advances in power electronics [11].) These switches have the advantages that when operated within specifications will live very long and have reduced house-keeping requirements, but that when high voltage, high current, and fast rise rates are needed have some severe limitations not yet overcome for practical applications. Table 2 summarizes parameters of typical switches used in pulsed power applications.

a) *Thyristors for pulsed power:* Thyristors rely on triggering that results in an avalanche breakdown to form a solid-state plasma allowing high current conduction, and in this way are analogous to thyratrons (removing the gate voltage will not turn the device off). Thyristors, and



**Fig. 3.** Approximate specific energy and energy release time for diverse types of energy storage. (The explosive energy storage does not include the efficiency of transforming mechanical into electrical energy.)

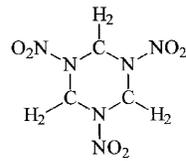
particularly GTOs, can hold off several kilovolts and switch hundreds of amperes. The rate of current rise is limited by the diffusion time in silicon, and failure mode is associated with the formation of a constricted arc accompanied by irreversible damage to the semiconductor. Although materials with higher mobility than silicon have been studied, other inherent material issues have thus far limited development for pulsed power. Applications for thyristors can be well correlated with pulse length—for example, major accelerator facilities requiring switching devices tend to use thyristors if the pulse lengths are many microseconds or longer, and thyratrons if the pulse lengths are a few microseconds or shorter.

*b) Other gated solid-state switches:* The MOSFET and IGBT are faster devices and turn off upon removal of the gate voltage, but have reduced current handling capability. Both are undergoing continued development and finding applications in systems where other switches have dominated. The IGBT, in particular, has been finding applications as a replacement module for thyratron switches.

Of interest are also new materials for various of these devices, such as SiC-based vertical MOSFET designs, which show promise for fast current rise and high hold-off voltage.

### B. Explosively Driven Pulsed Power

Storage of energy and fast release is the prerequisite for any pulsed power system. Traditionally, capacitive and inductive storage have found most widespread use enabling extremely fast energy release, as indicated in Fig. 3. Mechanical energy storage systems have a higher specific energy (stored energy per volume or weight) but are slower in their energy release. Any reactive chemicals such as simple gasoline (when mixed with oxygen) have many orders of magnitude higher specific energy compared with capacitive, inductive, or mechanical energy storage. However, the comparatively slow reaction (maximum flame front velocity of



Component	Percent (weight)
RDX	91.0
Di(2-ethylhexyl) sebacate	5.3
Polyisobutylene	2.1
20-weight motor oil	1.6

**Fig. 4.** Molecular structure of RDX and detailed C-4 composition.

a premixed  $H_2$ - $O_2$  flame is  $\sim 10$  m/s) of chemical fuels forbids their direct use in a pulsed power energy storage and release system. High explosives (HEs) that carry fuel and oxidizer within each molecule (see Fig. 4) are the only group of chemicals that provide reaction times in the microsecond regime. A typical HE, such as RDX, Cyclo-1,3,5-trimethylene-2,4,6-trinitamine, has a detonation speed in excess of 8 km/s or 8 mm/ $\mu$ s. Composition 4, C-4, with RDX as major constituent (91% by weight) is widely used for demolition, mining, and military applications. Other components of C-4 are mainly plasticizers, also including 1.6% motor oil (cf. Fig. 4). Its fast reaction time makes HE a prime candidate for the direct conversion of chemically stored energy into pulsed power.

The basic idea for efficiently transferring the chemical energy of the HE into electrical power is footed on the same principle that makes any standard electrical power generator work. A varying magnetic flux in an area enclosed by conductors induces a voltage in the conductors that will drive an electric current depending on the load connected to the generator. While the standard generator utilizes a rotating magnetic field to produce the needed flux variation, the typical explosive generator compresses the flux by explosively deforming conductors enclosing and trapping the initial magnetic flux. This conductor deformation occurs during several microseconds to several tens of microseconds, depending on the overall size of the generator. A simple estimate for the runtime of an explosive generator is its size divided by the detonation velocity of the HE used. For instance, a generator with 30-cm length will operate for about 40  $\mu$ s if C-4 with  $\sim 8$  mm/ $\mu$ s is used. Other ideas for generating pulsed power explosively rely on shock-demagnetizing permanent magnets, “squeezing” ferroelectric or piezoelectric materials, and implosive flux compression utilizing semiconductive materials.

It should be noted in this context that the peak pressure produced by the detonation of C-4 is about 20–30 GPa. This pressure is several orders of magnitude greater than the tensile yield strength of any metal. As an example, aluminum 6061, which is often used in explosive generators, has a yield strength of 400 MPa. Hence, the metal will yield to the explosive pressure and deform easily on the microsecond time scale.

The benefits of explosive driven pulsed power are clear: roughly a factor of 10 larger specific energy than capacitors with similar discharge characteristics, possible stand-alone systems without requirement for power supply and other prime power, and long shelf life. Hence, explosive pulsed power has been receiving considerable interest for use as

part of a system for high-power microwave generation or for oil well exploration and as a driver for basic physics experiments, among a variety of military applications.

Additional information on explosively driven pulsed power can be found in [12] and [13].

### C. Further Reading

In addition to the classic references cited in the reference list of [1], the interested reader can find additional references online, including textbooks that discuss specific aspects of pulsed power for specific applications [14], [15] and a pulsed power formulary [16].

Another important area within a broader context of pulsed power that is beyond the scope of this Special Issue has to do with megajoule, megaampere systems with current rise times on the order of  $dI/dt > 1 \text{ kA}/\mu\text{s}$  for railguns and other electromagnetic launch systems. The reader is referred to [17] for additional information.

The premier conference sponsored by the IEEE Nuclear and Plasma Sciences Society's Pulsed Power Science and Technology Committee [18] is the biennial IEEE International Pulsed Power Conference, which also publishes conference papers in a proceedings. The next conference will be in Monterey, CA, in June 2005. The IEEE Technically Cosponsored Power Modulator Symposium has been a conference that had traditionally focused more on aspects pertaining to repetitive pulsed power. This conference also publishes a Technical Digest.

The IEEE TRANSACTIONS ON PLASMA SCIENCE has been publishing a biennial special issue devoted to pulsed power science and technology since 1997, partly derived from papers presented at the preceding IEEE International Pulsed Power Conference. The next Special Issue will be published in October 2004.

Finally, it would be a disservice not to mention the passing of J. C. "Charlie" Martin in 1999. He was a "totally unforgettable character who left no person who met him unchanged."<sup>2</sup> The 12th IEEE International Pulsed Power Conference held a tribute to Charlie, and his biography and tributes from colleagues were published in [19]. Additional technical publications by Charlie were compiled in [20].

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**Edil Schamiloğlu** (Fellow, IEEE) received the B.S. and M.S. degrees from the School of Engineering and Applied Science, Columbia University, New York, in 1979 and 1981, respectively, and the Ph.D. degree in applied physics (minor in mathematics) from Cornell University, Ithaca, NY, in 1988.

He was appointed Assistant Professor of Electrical and Computer Engineering at the University of New Mexico (UNM) in 1988. He is currently Professor of Electrical and Computer Engineering and directs the Pulsed Power, Beams, and Microwaves Laboratory at UNM. He lectured at the U.S. Particle Accelerator School, Harvard University, Cambridge, MA, in 1990 and at the Massachusetts Institute of Technology, Cambridge, in 1997. He coedited *Advances in High Power Microwave Sources and Technologies* (Piscataway, NJ: IEEE, 2001) (with R. J. Barker) and he is coauthoring *High Power Microwaves*, 2nd Ed. (Bristol, U.K.: Inst. of Physics, 2004) (with J. Benford and J. Swegle). He has authored or coauthored 53 refereed journal papers, 100 reviewed conference papers, and one patent. His research interests are in the physics and technology of charged particle beam generation and propagation, high-power microwave sources, plasma physics and diagnostics, electromagnetic wave propagation, and pulsed power.

Dr. Schamiloğlu has received the Sandia National Laboratories Research Excellence Award as part of the Delphi/Minerva team in 1991, the UNM School of Engineering Research Excellence Award twice (junior faculty in 1992 and senior faculty in 2001), and the titles of UNM Regents' Lecturer (1996) and Gardner-Zemke Professor (2000). He is an Associate Editor of the IEEE TRANSACTIONS ON PLASMA SCIENCE and has served on a National Academies Panel on Directed Energy Testing.



**Robert J. Barker** (Fellow, IEEE) received the B.S. degree in physics from Stevens Institute of Technology, Hoboken, NJ, in 1971 and the Ph.D. degree in applied physics from Stanford University, Stanford, CA, in 1978.

He was previously with the U.S. Naval Research Laboratory, Washington, D.C., and the Mission Research Corporation, Washington, D.C., where he worked on improvements to and applications of both the two-dimensional MAGIC and three-dimensional SOS plasma

simulation codes. He is currently Program Manager for electroenergetic physics at the U.S. Air Force Office of Scientific Research (AFOSR), Arlington, VA. He coedited *Advances in High Power Microwave Sources and Technologies* (Piscataway, NJ: IEEE, 2001) (with E. Schamiloglu) and is currently coediting two new books. The first is an Institute of Physics Press book on nonequilibrium air plasmas, coedited with K. Becker, K. Schoenbach, and U. Kogelschatz; the second is an IEEE Press book on microwave vacuum electronics, coedited with N. Luhmann, J. Booske, and G. Nusinovich. He is sole inventor on two patents. His current interests include microwave/millimeter-wave generation, pulsed power, medical/biological effects, electromagnetic/electrothermal launchers, air plasmas, charged particle beam generation and propagation, explosive power generation, and computational physics.

Dr. Barker is a member of the American Physical Society. He was elected Fellow of the Air Force Research Laboratory in 1998. He has served in various capacities on the organizing committees of numerous international conferences, including cochairing the IEEE Joint Pulsed Power Plasma Science (PPPS) Conference in 2001.



**Martin A. Gundersen** (Fellow, IEEE) received the B.A. degree from the University of California, Berkeley, in 1965 and the Ph.D. degree from the University of Southern California (USC), Los Angeles, in 1972.

From 1998 to 2003, he was Chair of the Department of Electrical Engineering-Electrophysics and Cochair for Electrical Engineering at USC. He is currently Professor of Electrical Engineering, Physics and Astronomy, and Materials Science at USC. He has also been Visiting Professor at UCLA (1986–1987), Visiting Scientist at MIT (1986–1987 and 1989), Visiting Scientist, C.E.R.N. (1987), Visiting Associate at Caltech (1993–1994), and Visiting Professor of Physics at the Naval Postgraduate School (2003–2004), and has worked a little in movies. He has published approximately 240 technical papers, given approximately 250 invited and contributed presentations, and holds several patents. His main research interests are in applied physics, and include pulsed power science and technology, applied plasma physics, lasers, transient plasma devices, applications of pulsed power to biology, and science and entertainment.

Dr. Gundersen is a Fellow of the Optical Society of America. He received the Germeshausen Award of the IEEE Power Modulator Symposium (2000). He was Director, NATO Advanced Research Workshop (on Pseudosparks, 1989), Technical Program Chairman, IEEE Power Modulator Symposium (1990 and 1998) and High Voltage Workshop (2000), and is ExCom Chair for the Power Modulator Conference (2002 and 2004).



**Andreas A. Neuber** (Senior Member, IEEE) was born in Aschaffenburg, Germany. He received the Dipl.-Phys. and Ph.D., ME, degrees from the Darmstadt University of Technology, Darmstadt, Germany, in 1990 and 1996, respectively.

From 1990 through 1996, he was with the Institute of Energy and Power Plant Technology, Darmstadt University of Technology, in the area of nonlinear laser spectroscopy and chemical reaction kinetics in combustion. In 1996, he joined Texas Tech University, Lubbock, and is currently

Associate Professor in Electrical and Computer Engineering. He has published 100 journal and conference proceedings papers. His current research interests are high-power microwaves, unipolar surface flashover physics, and explosive-driven pulsed power.

Dr. Neuber has served in various capacities on the organizing committees of numerous international conferences, including Technical Program Co-Chair of the 2002 Power Modulator Conference and Technical Program Chair of the 2003 IEEE International Pulsed Power Conference. He is a Co-Guest Editor of the 2005 IEEE TRANSACTIONS ON PLASMA SCIENCE Special Issue on Power Modulators and Repetitive Pulsed Power, and he has served as an external readiness review panel member for the U.S. Department of Energy.