Guest Editorial

Fast Opening Vacuum Switches for High-Power Inductive Energy Storage

THE USE of inductive energy storage techniques for pulsed power has a number of advantages over conventional capacitive techniques with regard to cost and size. The key to the development of inductive systems is the advancement of opening switch technology which, at the terawatt level, invariably involves plasma science. Research efforts in this area have recently provided new and exciting results. The most important results involve very fast opening (~ 10–100 ns) vacuum switches, because they can be used immediately to upgrade existing pulsed power generators by adding a vacuum-inductive-storage pulse-compression stage for power and voltage multiplication. In the longer term, these new switches, when used in parallel with an additional slower stage of vacuum switching (~ 0.1–1-μs opening time), could usher in a new generation of inexpensive compact single-shot or repetitively-pulsed, high-power accelerators. Many applications of this new pulsed power technology are envisioned in areas such as inertial confinement fusion, X-ray lasers and lithography, neutron radiography, and directed energy weapons.

Recognizing the immediate importance and interest in this area of research, the IEEE TRANSACTIONS ON PLASMA SCIENCE has devoted this Special Issue to fast opening vacuum switches. The goal of this Special Issue is to provide a comprehensive review of the state of the art in this area with emphasis on applications to inductive storage pulsed power generators. By limiting this Special Issue to fast opening vacuum switches capable of operating at high power, we have not included much of the slow opening switch research which applies primarily to kinetic energy weapon systems where the output pulse duration requirements are in the 100-μs range and longer. From among the switches that do fall within these guidelines, this issue includes papers on plasma erosion opening switches (PEOS's), ion beam opening switches (IBOS's), plasma flow switches (PFS's), and other novel vacuum opening switches. There are both experimental and theoretical contributed papers describing original research, and invited papers giving up-to-date overviews of major research efforts. These invited papers include most of the ongoing international efforts in this research area.

Although the operation of all the switches included in this issue involves complex plasma physics phenomena, earlier research has usually considered the opening switch to be an engineering problem. This, we believe, is the reason that little progress has been made in the development of *high-power* inductive storage since inductive storage was first considered 30 or 40 years ago. Examples of the plasma physics phenomena which can occur at different stages of operation in such systems include plasma–wall interactions, electrode sheaths, energetic particle emission from the electrodes, complex mechanisms for electron current conduction across strong magnetic fields (in many cases at low plasma densities, where Coulomb collisions would be negligible), magnetic insulation of electron flows, plasma microinstabilities and associated anomalous resistivity, and plasma hydrodynamics. Plasma physics theoretical tools which can be applied to these problems include kinetic (Vlasov) and fluid analytic treatments, 2.5-dimensional electromagnetic particle-in-cell (PIC) codes, and various fluid and hybrid codes. Only in the past few years have these sophisticated plasma physics theoretical tools and understanding been successfully applied to the problem of opening switch operation. The detailed understanding arising from this theoretical research, coupled with recent plasma diagnostic measurements, has provided many of the breakthroughs in opening switch operation and will provide those yet to come.

A tutorial comparing inductive and capacitive energy storage systems is now presented in order to identify the advantages of inductive systems over conventional capacitive storage systems. The key role that fast opening vacuum switches play in inductive systems will also be made clear.

A simple capacitive energy storage system is shown in Fig. 1(a), where a high-voltage low-current primary energy source charges a capacitor of capacitance C. When the peak voltage V is reached, a closing switch connects the capacitor to the resistive load R_L. The characteristic output duration is $R_L C$, and the peak current is about V/R_L. The primary energy source is high impedance and can be treated as an open circuit after the switch is closed. For such a system, the primary charging voltage is transferred to the load, and the current is multiplied by the ratio of the charging time to the output-pulse duration. It appears that a high-power short-duration output pulse could be obtained simply by using a low-resistance output load. Unfortunately, parasitic inductance limits the output-pulse rise time to L/R_L for small R_L, where L is the total parasitic inductance $L_C + L_L$ of the capacitive energy store, the output closing switch, and the load.

For the simple inductive store system shown in Fig. 1(b), a high-current low-voltage primary energy source "current charges" an inductor (i.e., drives current through an inductor which stores magnetic field energy). When the peak current I is reached, an opening switch opens, connecting the inductor to the resistive load R_L. If the load inductance L_L is very much smaller than the storage inductance L, then the characteristic output-pulse duration is L/R_L, and the peak voltage is about IR_L. Here, the primary energy source is low impedance and can be treated as a short circuit after the switch is opened. For such a system, the primary charging current is transferred

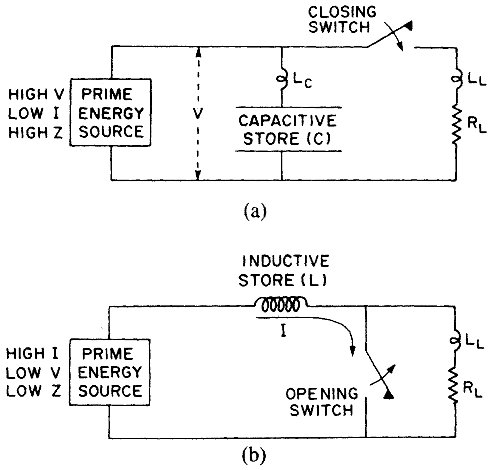

Fig. 1. (a) Simple capacitive energy storage system with a closing switch. (b) Simple inductive energy storage system with an opening switch.

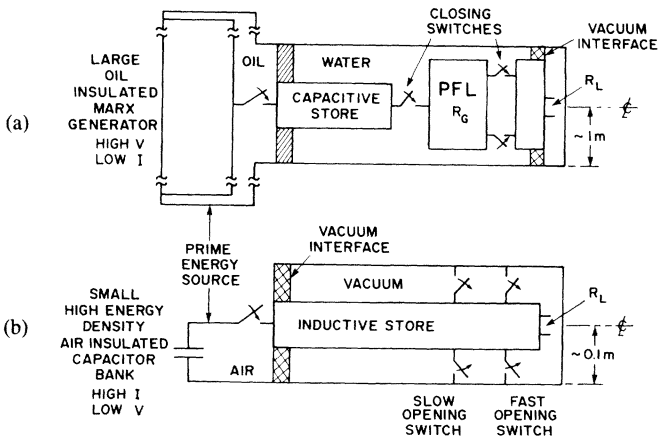

Fig. 2. (a) Typical staged capacitive system with successive lower inductance stages in series with closing switches. (b) An ideal staged inductive system with two successive stages of faster opening switches in parallel.

to the load, and the voltage is multiplied by the ratio of the charging time to the output-pulse duration. It appears in this case that a high-power short-duration output pulse could be obtained simply by using a high-resistance output load. Unfortunately, the output-pulse rise time and voltage are limited here by the opening time and the voltage hold-off capability of the opening switch. Generally, all that can be expected for a single opening switch is about a factor of 10 for the ratio of switch conduction time (charging time) to opening time (output-pulse duration).

One of the major advantages of inductive systems over capacitive systems is the very high energy densities obtainable with inductors. Capacitive energy densities are limited by voltage breakdown of materials, whereas inductive energy densities are limited by mechanical strengths of materials. The energy density in an inductor can be several orders of magnitude larger than the energy density in a capacitor, though present research on advanced capacitors is narrowing this difference. When a vacuum inductor is used, the size of the system can be further reduced because any electron flow generated from the cathode surfaces is at low voltage and can easily be magnetically insulated during both charging and discharging. Additional advantages of vacuum-inductive systems will be presented below when staging is discussed.

Capacitive and inductive systems, which are more realistic than the simple systems shown in Fig. 1, use the concept of staging in order to achieve high-power short-duration pulses. The rise-time-limiting problem of finite parasitic inductance in capacitive systems is solved by using several successive stages, each with lower inductance, connected in series by closing switches to multiply current and power. A typical capacitive system is conceptually illustrated in Fig. 2(a). A very large high-voltage low-current oil-insulated Marx generator, consisting of many capacitors charged in parallel and discharged in series, charges a water capacitor in several microseconds, typically through a triggered gas closing switch. Deionized water makes an excellent high-energy-density dielectric storage medium for pulses of short duration. The water capacitor, which is much lower inductance than the Marx generator, then charges an even lower inductance water-dielectric pulse-forming-line (PFL) section in a few hundred nanoseconds through a moderate-inductance closing switch. This section acts like a simple capacitor during the charging time, but acts like a low-impedance PFL during its less-than-100-ns discharge time through a low-inductance multichannel closing switch. Voltage into a matched load is a square wave with amplitude of half the PFL voltage. Voltage (with the exception of the last stage) and energy are preserved, and current and power are multiplied, by the successive stages of pulse shortening.

The finite switch-opening-time problem in inductive systems is solved by using several successive stages of opening switches in parallel. Each stage is capable of conducting current during the longer opening time of the previous stage and then opening in a shorter time in order to multiply voltage and power. An ideal staged inductive system is conceptually illustrated in Fig. 2(b). A high-current (>1 MA) low-voltage (≤ 100 kV) source, such as a compact air-insulated low-voltage capacitor bank, current charges a vacuum inductor through the first-stage long-conduction-time switch. A shorter conduction time, faster opening switch is used to provide the final stage of pulse compression and voltage multiplication. The inductance between the two opening switches and the inductance between the final opening switch and the load should both be minimized in order to maximize the energy delivered to the load. In the ideal case, the inductor acts like a simple lumped-circuit element during the long charging time, but acts like a short current-charged PFL during discharge into the load. The current into a load whose resistance is matched to the vacuum impedance of the inductor is a square wave with amplitude of half the charging current. Current (with the exception of the last stage) and energy are preserved, and voltage and power are multiplied, by the successive stages of faster opening switches.

There are several potential advantages to an inductive storage system over a capacitive system. While both typically have first-stage capacitive storage, the lower voltage bank of the inductive system is inherently significantly more compact, lighter, and less expensive. The vacuum inductive store has similar size, weight, and cost advantages over the dielectric capacitive store. These advantages increase with the elimination of the storage tanks and associated hardware required for water and oil. In addition, the voltage across the most critical component in these systems, the vacuum interface, is significantly reduced in an inductive system. In the capacitive system, the full output voltage appears across the vacuum interface during the entire charging time of the final stage. In an inductive system, the vacuum insulator only sees the low charging voltage, not the high output voltage. In addition, the critical vacuum interface is physically removed from the load in an inductive system, and thus less affected by ultraviolet radiation and load debris. Even if the vacuum insulator were to flash over when the final switch opens in an inductive system, most of the energy would have already been transferred to the vacuum inductor and thus would be available to drive the load. The staged vacuum inductive system conceptually illustrated in Fig. 2(b) has not yet been attempted; however, recent advances in opening switch technology may make this possible in the near future.

Up to the present, much of the research on vacuum opening switches (and most of the PEOS papers reported on in this Special Issue) has involved the addition of a final vacuum-inductive pulse-compression stage to the output of a conventional (≤ 100-ns output pulse duration) high-power capacitive generator in order to achieve voltage and power multiplication over that attainable with an ideal matched load. In most of the capacitive pulsed power generators in use today (such as illustrated in Fig. 2(a)), voltage hold-off limitations across the vacuum interface dictate large spacings which, in turn, create large inductances between the coaxial-waterline output and the vacuum-diode load. This inductance is generally the limiting factor in obtaining fast output-pulse rise times (< 10 ns) at high output powers. By employing this inductance and an additional vacuum inductance terminated with a fast opening vacuum switch (in parallel with the load), it has been possible to obtain shorter duration, faster rise-time output pulses with significant power and voltage multiplication. Because the vacuum inductor at the opening switch location can have a radius small compared to the waterline and comparable to that of a typical load, the parasitic inductance between the switch and the load can be very much smaller than the equivalent parasitic inductance in the unmodified capacitive system. Thus, the output-pulse rise time is primarily limited by the switch opening time. For most plasma opening switches, this opening time can be very fast and the voltage hold-off can be very high because both involve self-magnetic insulation of the electron flow in a gap formed in the plasma.

The electrical circuit for such a hybrid system is schematically illustrated in Fig. 3. A capacitive generator with open-circuit voltage V_G and characteristic output impedance R_G current charges an inductor through a fast opening vacuum switch opening in the closed state. The peak electrical energy stored in the inductor can be greater than 80 percent of the energy available in the output pulse of the generator. When the current in the inductor reaches its peak, the switch opens and discharges the inductor current through the load impedance R_L. Assuming no energy loss, $R_L > R_G$, and that the storage inductance L is very much greater than the parasitic load inductance L_L, the power and voltage are multiplied by R_L/R_G (i.e., $V_L/V_G = R_L/R_G$). This results because the characteristic charging time is L/R_G, while the discharge time is L/R_L. Even if the vacuum interface flashes over and becomes a short circuit, the energy already stored in the inductor will be delivered to the load.

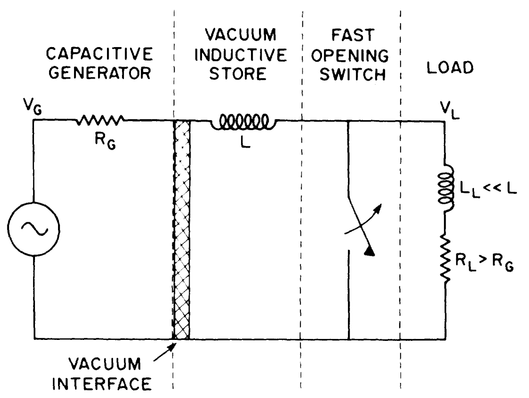

Fig. 3. Conceptual circuit diagram of conventional capacitive generator with an inductive-store pulse-compression final stage.

Recent laboratory research for developing purely inductive systems has mostly concentrated on the development of the fast opening vacuum switches that are required. For opening switches that conduct for greater than 100 ns, it is possible to design a switch testbed that eliminates the capacitive pulse-line generator by directly current charging an inductor with a fast-rise-time low-inductance high-voltage Marx capacitor bank. A slower rise-time low-voltage capacitor bank could also be used in conjunction with a slow opening switch, such as a fuse operating outside the vacuum, in order to generate the required fast-rise-time high-voltage pulse. Experiments discussed in this issue have been performed with both the PEOS and the PFS operating in this manner. In general, the PEOS conduction time has been less than 1 μs in order to avoid excessive $\boldsymbol{J} \times \boldsymbol{B}$ driven plasma motion, while the PFS specifically utilizes this magnetically driven hydrodynamic motion of the plasma to achieve long conduction times (~ 10 μs). The PFS is thus better suited for use as the first stage opening switch illustrated in Fig. 2(b), and the PEOS is better suited for use as the final stage opening switch.

Most of the papers in this Special Issue cover some aspect of either the PEOS or the PFS. In some papers, the PEOS is referred to as a plasma opening switch (POS). There are eight experimental and six theoretical papers on the topic of PEOS research. Many of these are invited papers with one each from the United States (Weber *et* *al.*), West Germany (Bluhm *et al.*), Japan (Miyamoto *et al.*), and France (Bruno *et al.*), and three from the Soviet Union (Mesyats *et al.*, Arbuzov *et al.*, and Bystritskii *et al.*). Two of these papers (Mesyats *et al.* and Weber *et al.*) cover aspects of long-conduction-time ($\sim 1\ \mu s$) PEOS research. There are three papers describing PFS research including one invited review paper (Turchi *et al.*), and one invited experimental paper (Degnan *et al.*). Finally, there is one invited paper (Humphries) on other novel types of vacuum opening switches including the grid-controlled plasma switch and the scanned-electron-beam switch.

The PEOS experimental research has been carried out for both short- (< 100 ns) and long- ($\sim 1\ \mu s$) conduction-time operation. The paper by Weber *et al.* provides historical review of PEOS research starting with the key experiment of Mendel *et al.* in 1977 (see [1] in Weber *et al.*) and sets the stage for the remaining PEOS papers. This paper also reviews most of the pioneering research at the Naval Research Laboratory (NRL) using a short-conduction-time PEOS culminating with the recent achievement of power and voltage multiplication of greater than a factor of 2 (to 3.5 TW and 4.6 MV with less than a 10-ns rise time from the 1.5-TW, 1.7-MV Gamble II generator). The paper by Mesyats *et al.* reviews the pioneering experiments at the Institute of High Current Electronics at Tomsk with long-conduction-time plasma opening switches. This group was the first to report successful long-conduction-time operation of plasma opening switches into high-power diode loads. In these experiments, a high-voltage Marx capacitor bank directly current charges a vacuum inductor with either a plasma-filled diode operating as both the opening switch and the load, or a PEOS connected between the output of the inductor and the load. An impedance rate of rise of $\sim 10^9$ Ω/s to final values of 10–20 Ω was achieved. Weber *et al.* also report on long-conduction-time PEOS experiments where a 0.25-TW, 100-ns output pulse has been produced from a low-voltage (40 kV) fuse-enhanced capacitor bank.

The remaining papers reporting on experimental PEOS research involve short-conduction-time operation. Detailed measurements using a broad range of switch geometries, currents, voltages, and diode impedance behaviors are reported in the paper by Bluhm *et al.* on generators of 0.1 and 1.5 TW. Peak power multiplications of 2 have been achieved. They found that low-density plasma-filled diodes with rising impedance characteristics coupled best to the PEOS, and, in some circumstances, high-density plasma-filled diodes could be operated in a manner similar to the PEOS. In the paper by Miyamoto *et al.*, the effects of plasma injection velocity and direction were studied experimentally with an "inverse-pinch" electron beam diode. This group was the first to report significant voltage multiplication at very high voltages (from 2 to 6 MV). PEOS coupling to ion diodes as a function of plasma density, velocity, electrode geometry, load impedance, and the presence of either externally or self-generated magnetic fields are presented in the paper by Arbuzov *et al.* Power multiplications of 3 were obtained under conditions similar to those observed by the other groups but with the addition of a self-generated magnetic field in the region of the PEOS by using a helical cathode coil. PEOS experiments at the terawatt level are reported by Bruno *et al.* and are compared to theory. The results are extended to predict efficient production of a 14-MeV neutron burst from an imploding *Z*-pinch plasma using this technology. A novel parallel diode geometry is reported by Isakov *et al.* where the first pulse from a double-pulse generator produces a plasma in the first diode, which then acts as a PEOS to achieve power multiplication of the second pulse in the second diode.

Most PEOS models predict faster opening time with a high-velocity low-density plasma. The IBOS discussed by Greenly *et al.* replaces the switch plasma with a charge-neutral ion beam (100–300 kV, ≤ 120 A/cm^2) to test this prediction. Opening times as fast as 4 ns were observed. A standard Mendel gun plasma source was also used in the same geometry, and the resulting switch behavior is compared to the IBOS results. The observed similarities and differences are compared to theoretical predictions.

There are controversies in the theoretical interpretation of how the PEOS works which are inevitable in a fast growing field of research involving complex plasma physics phenomena. The PEOS papers included in this issue illuminate, but do not yet eliminate, these controversies. The theory of PEOS operation has generally been approached by dividing the problem into two parts: the physics of current conduction during the closed state and the physics of opening. In the closed state, current can be conducted in the plasma across the strong self-magnetic field by either $\boldsymbol{E} \times \boldsymbol{B}$ electron drift, as discussed in the papers by Mosher *et al.* and Grossmann *et al.*, or by anomalous collisions, as discussed in the papers by Mason *et al.*, Payne *et al.*, and Grossmann *et al.* It is found that the presence of anomalous collisions is required to explain the broad current channels observed experimentally. Mosher *et al.* suggest that proper treatment of the electron pressure will provide diamagnetic drifts which will also broaden the theoretically predicted current channel.

Experimental observations of current conduction are consistent with models of electron dynamics that couple to the electrode boundary conditions through space-charge-limited (SCL) sheaths. This sets the problem apart from electrodeless systems such as the theta pinch. The model described in the papers by Weber *et al.* and Bystritskii *et al.* proposes that the flux of ions injected into the cathode sheath from the plasma determines the conduction current under bipolar SCL flow conditions. Since $J_i/J_e \sim (m_e/m_i)^{1/2}$ for bipolar SCL flow, the model predicts that the full switch current is controlled by the much smaller ion current. In two-dimensional fluid code simulations, SCL flow can be modeled by forcing the normal electric field to zero at the cathode as in the paper by Mason *et al.* In one-dimensional fluid treatments, where the electrodes are not treated, Grossmann *et al.* and Mosher *et al.* model the effects of the cathode boundary condition by limiting the current density in the plasma to the local SCL value. They also provide a prescription for determining the energy of the electrons injected into the plasma in terms of the calculated plasma potential.

Although PIC codes include kinetic effects and can treat emission physics more easily than fluid codes, they are limited by computational constraints to treating only the lower density regime of switch plasmas ($<10^{13}$ cm^{-3}). The considerable effort in PIC code simulations of the PEOS is not represented in this Special Issue, though it is alluded to, for example, in the paper by Weber *et al.* Fluid codes have been used to investigate the hydrodynamics and current conduction processes in the PEOS in the higher density ($\geq 10^{13}$ cm^{-3}) regime. The paper by Payne *et al.* presents work using an MHD code, and the paper by Mason *et al.* presents work using an implicit multiple-fluid code. Both codes include anomalous resistivity models. Unlike MHD codes, the multiple-fluid approach allows for modeling of opening phenomena where space-charge separation is important. One drawback of present fluid code modeling in comparison to PIC simulation is the cold-electron-fluid approximation used to close the set of moment equations. Mosher *et al.* discuss the need to include pressure tensor terms to improve high-energy electron modeling.

Two mechanisms for opening have been proposed for the PEOS: the erosion mechanism and the magnetic pressure mechanism. In both cases, the PEOS is fully open when a gap has been created that is large enough to magnetically insulate the electron flow. The NRL model for opening, as described in the paper by Weber *et al.*, involves erosion and enhanced erosion. Erosion opens a gap by depleting the plasma above the cathode when the current density exceeds that allowed by bipolar SCL flow. Enhanced erosion opens this gap rapidly when the self-magnetic field alters the electron space-charge distribution and thus enhances the ion current as in an intense ion diode. The magnetic pressure mechanism was first proposed by Mendel and is discussed in the papers by Miyamoto *et al.* and Mason *et al.* In this model, a radial $\boldsymbol{J} \times \boldsymbol{B}$ force opens the gap. This mechanism will be most effective if the surface currents shield the interior of the plasma from high fields. This mechanism appears to be at odds with measurements reported by Weber *et al.* which show large magnetic fields in the interior of the PEOS plasma.

Circuit modeling of the PEOS has provided a tool for reproducing existing experimental results and for predicting PEOS performance in proposed experiments. Examples of this type of work are found in the papers by Bystritskii *et al.*, Weber *et al.*, Bluhm *et al.*, and Miyamoto *et al.* Results indicate that PEOS performance improves when the plasma source timing is adjusted to create a lower density, higher drift velocity plasma. The physics of how the plasma is ejected off of a flashboard plasma source is discussed in the paper by Colombant and Weber.

Although experiments at long conduction time have been carried out, the theory of microsecond-conduction-time PEOS operation has not been as well developed as the 100-ns-conduction-time theory and is not represented in this Special Issue.

Pioneering experimental and theoretical research utilizing the PFS to produce a pulse for driving plasma liner implosions and high-energy ion flows is reviewed in the paper by Turchi *et al.* The PFS uses the nonlinear and nonuniform dynamics of a plasma discharge in vacuum to accumulate magnetic energy in times of several microseconds and then release this energy to a load in times of a few hundred nanoseconds. Experiments involving capacitor banks with stored energies of up to 6 MJ, currents greater than 10 MA, and peak voltages over 0.5 MV are described. Theoretical efforts include simple slug dynamics coupled to a lumped-circuit analysis, magnetoacoustic flow in one and two dimensions, and two-dimensional magnetohydrodynamic code calculations. Based on this work, Turchi *et al.* provide a theoretical picture of PFS operation. At the onset of the power pluse, a discharge is initiated in an arrangement of foils and/or wires which are connected across the electrodes of a cylindrical vacuum line. The resulting plasma is accelerated by the increasing magnetic pressure as the current rises. The mass is chosen so that the bulk of the plasma is expelled off the end of the center conductor and out of the load region at the time of peak current. A low-density trailing plasma carries the accumulated magnetic energy radially inward to the load. The PFS is particularly well suited for coupling to imploding plasma loads. Coupling to a vacuum diode or a final stage vacuum opening switch is presently under investigation.

Experiments using the SHIVA Star capacitor with a vacuum inductive store and PFS to drive cylindrical foil implosions are discussed in the paper by Degnan *et al.* With 5-MJ stored energy, liner implosions driven by a 9-MA, 0.2-μs rise-time pulse result in an isotropic equivalent 2.7-TW, 0.5-MJ X-ray yield when the linear kinetic energy stagnates on the axis of symmetry. A companion paper by Buff *et al.* describes the successful simulation of these results with the two-dimensional MHD code, MACH2, and confirms the theoretical picture of PFS operation presented by Turchi *et al.*

The final paper in this Special Issue by Humphries reports on two novel vacuum opening switches under investigation at the University of New Mexico. Unlike the single-shot, high-power, high-current plasma opening switches previously described, both of these switches are directed to moderate current (~ 10 kA) and high repetition rates. The grid-controlled plasma flow switch is designed to operate in the megahertz range, and 20-ns opening times have already been observed in proof-of-principle experiments. The scanned-electron-beam switch utilizes electric field deflection to direct the power of a sheet electron beam alternately between two inverse diodes connected to output transmission lines. Theoretical studies suggest that 100-MHz rates are feasible in gigawatt devices.

There are a number of research efforts on fast opening vacuum switches that are not represented in this Special Issue. In the area of PEOS (or POS) research, the large research effort at Sandia National Laboratories (SNL) is not represented. SNL is developing a PEOS in order to double the voltage and power of their PBFA II accelerator to 30 MV and 150 TW for application to light-ion-beam inertial-confinement fusion. This work has just been reported in a paper by Stinnett *et al.* in the October 1987 Special Issue of the IEEE TRANSACTIONS ON PLASMA SCIENCE devoted to vacuum discharge plasmas. A significant experimental effort by Mendel *et al.* of SNL to develop a new plasma opening switch uses externally and/or self-generating magnetic fields to "toggle" the switch from the conduction state to the opening state. Also, several recent theoretical research efforts supporting the SNL PEOS program are not reported here. Finally, other major experimental and theoretical research efforts on fast opening vacuum switches that are not represented in this Special Issue include research on the reflex-diode switch, the imploding plasma switch, the plasma-filled diode switch, and the PEOS at Physics International Laboratories Inc., with theoretical support from Berkeley Research Associates (BRA), research on both the PEOS and the imploding plasma switch at Maxwell Laboratories Inc., with theoretical support from System Science and Software Inc., and research on the density-controlled plasma opening switch at Pulse Sciences Inc., with theoretical support from BRA.

The impressive results from the recent worldwide research efforts that are included in this Special Issue attest to the experimental and theoretical advances that have been made in the area of fast opening vacuum switch research primarily as a result of applying the latest tools of plasma science. It is also evident that future research in this area will lead to the development of a new generation of high-power accelerators with exciting applications in many areas again involving plasma science.

We would like to thank the many authors and referees who have generously contributed much time and energy to this Special Issue on Fast Opening Vacuum Switches. We especially want to thank our colleagues at NRL and, in particular, D. D. Hinshelwood for helping in this valuable endeavor. We would also like to acknowledge M. Mague and L. Conroy for assisting us in generating and maintaining all the necessary paperwork.

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