PLASMA SWITCHES

Switches are common components in electric circuits that are familiar to our everyday experience. In applications for which intense bursts of energy are required, switching becomes a technical challenge. It is in these cases that plasma switches are typically employed. Reliable plasma switches are essential components in pulsed power systems. Hold-off voltages of these switches range from kilovolts (kV) to megavolts (MV), and conduction currents vary from amperes to mega-amperes (MA). A simple multiplication of the current and voltage rating indicates that some of the largest devices transfer power in excess of terawatts (TW). For comparison, a large electric power plant generates on the order of 1 gigawatt (GW) of continuous power.

Pulsed power technology is used in many applications such as lasers, radar, X-ray generators, particle accelerators, pollution control, material surface treatments, and nuclear weapons effects simulators. A pulsed power system consists of an energy store, which is charged slowly at low power (i.e., charging time constants between milliseconds and minutes) and then is quickly discharged within nanoseconds (ns) to milliseconds (ms) into a load (Fig. 1). The switch accomplishes the rapid transition from the charging to the discharging stage.

Switches are categorized into two major groups: opening and closing switches. Capacitive energy storage systems need closing switches (S_c), whereas inductive energy storage systems require opening switches (S_o), as shown in Fig. 2. The capacitor is charged with a source voltage V_s through a charging resistor; R_{charge}, [Fig. 2(a)]. Power amplification is given by the ratio of load current to charging current. For inductive energy storage systems, the increase of the inductor voltage during the rapid opening of the switch, S_o, results in power amplification at the load, Z_{load} [Fig. 2(b)]. Reliable and repetitive closing switches have been developed successfully, and thus the capacitive energy storage system is being used extensively. Fast, reliable, and repetitive opening switches present a greater technological challenge. While there is little physical impediment to the operation of a closing switch, an opening switch must work against inductance (manifested as a tendency to increase voltage in order to maintain current) that tends to oppose the opening of the switch. Recently, research has been directed toward opening switches because the energy storage density of typical inductors is 2 to 3 orders of magnitude greater than that of capacitors. Table 1 gives a list of the most common opening and closing switches.

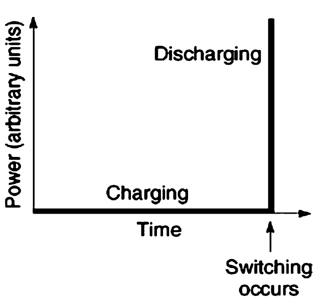

Figure 1. Pulsed power systems are charged slowly and discharged rapidly, which achieves high output power amplitudes.

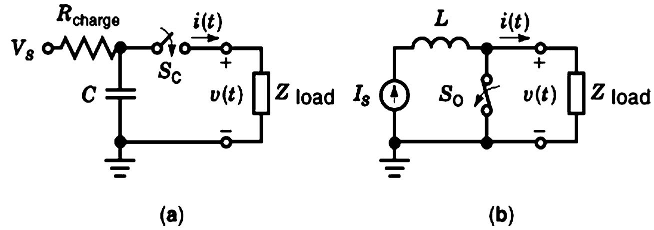

Figure 2. (a) Capacitive energy storage system with a closing switch and (b) inductive energy storage system with an opening switch.

This article describes plasma switches, such as plasma arc switches (gas spark gaps and surface discharge switches), diffuse discharge switches, and low-pressure switches (plasma opening switches, plasma flow switches, thyratrons, tacitrons, crossatrons, pseudospark switches, and ignitrons).

GENERAL SWITCH PARAMETERS

The following parameters are used to characterize most switches.

Hold-off Voltage. Maximum blocking voltage of switch in the "open" state. Exceeding the hold-off voltage causes an electrical breakdown in the switch, in most cases, owing to field emission at the electrodes and/or ionization of a background gas and rapid formation of a conducting plasma (see article on ***Conduction and breakdown in gases*** Conduction and breakdown in gases).

Peak Conduction Current. Maximum switch current in the "closed" state. The switch impedance in the open state, the load impedance, and hold-off voltage limits the peak charge voltage, and hence the peak current in a capacitive energy store system. The switch impedance in the closed state limits peak current in both the capacitive and inductive energy storage systems.

Current Rise (dI/dt). Rate at which the conduction current can be applied without device damage, or in some cases, the value of current rise limited by switch or circuit configuration.

Voltage Rise (dV/dt). Rate at which a voltage can be applied during the open state without causing switch closure. (applies to opening switch)

Forward Voltage Drop. Voltage drop of the switch during the on state. It is found by multiplying the switch impedance in the closed state with the conduction current.

Closing Delay Time. Time between the triggering of a switch and the beginning of the conduction state. It often relates to a plasma drift time for closing the electrode gap or a gas ionization time.

Opening Delay Time. Time between triggering a control grid of the switch and the termination of the conduction current.

Table 1. Some of the Most Common Opening and Closing Switches in Pulsed Power Systems

Closing Switches	Opening Switches
Crossatron switches	Chemically exploding switches
Exploding foil dielectric switches	Crossatron switches
Ignitrons	Diffuse discharge opening switches
Krytrons	Electrically exploding fuses and foils
Mechanical switches	Mechanical switches
Photoconductive switches	Plasma (erosion) opening switches
Pseudospark switches	Plasma flow switches
Spark gaps	Solid-state switches
Solid-state switches	Vacuum switches
Surface-discharge switches	
Tacitrons	
Thyratrons	
Vacuum switches	

Recovery Time. Time between the end of the conduction current and the point at which a voltage with a certain *dV/dt* can be applied without breakdown. In most cases, it is the recombination time of the gap plasma.

Pulse Repetition Rate. The rate at which the switch can be "closed" and/or "opened" without degradation of switch characteristics. The usual units are pulses per second (pps) or hertz (Hz).

Jitter. Variation in the opening or closing delay times.

Switch Lifetime. Number of "shots" (switching operations) or amount of time during which the switch operates within its normal specification. Electrode or grid erosion, mechanical failure, and insulator degradation, are typical factors that limit switch lifetime.

GAS SPARK GAPS

Gas sparks gaps are plasma arc switches that are widely employed in pulsed power technology. They are closing switches that are conceptually simple and easily manufactured. Voltage and current parameters are scalable, with hold-off voltages varying from kilovolts to gavolts and conduction currents ranging from amperes to megaamperes. They operate to the right of the so-called Paschen minimum (see article on ***Conduction and Breakdown in Gases***), at pressures of 10^5 Pa to 10^6 Pa. Dry air, and sulfur hexafluoride (SF_6) are the most common insulating gases in spark gaps. The hold-off voltage of a spark gap depends on the electrode geometry and material, gap spacing, gas pressure, gas species, and the applied pulse duration. Rough surfaces on electrodes tend to lower the breakdown strength due to microscopic field enhancements (i.e., the electric field at a tip of the rough surface is significantly higher than the average surface field). To decrease macroscopic field enhancements, the radius of the electrodes should be larger than the gap distance. At high electric fields, materials with a low work function tend to give a lower breakdown voltage due to a reduced field emission threshold. The product of electrode gap spacing and gas pressure is roughly a constant function of the electric breakdown field strength (see ***Conduction and Breakdown in Gases***); at constant electrode gap spacing, the hold-off voltage increases with gas pressure and vice versa. The insulating gas in the spark gap has a notable effect on the breakdown strength. With SF_6, an electronegative gas with excellent arc-quenching capacity, the breakdown strength is 2.5 to 2.8 times that of air; a 10% SF_6−90% N_2 mixture has twice the strength of pure N_2. The dc breakdown field in dry air at atmospheric pressure (10^5 Pa) is about 30 kV/cm for parallel plate electrodes. In addition, the hold-off voltage can be larger than that calculated for a Townsend dc breakdown (see article on CONDUCTION AND BREAKDOWN IN GASES) if the applied pulse duration is less than the ionization time.

The spark gap closes if the applied voltage exceeds the self-breakdown voltage of the gap or if the gap is triggered. Ionization of the gas and the formation of an arc discharge in the plasma close the switch. Triggering of gas-filled gaps is generally achieved by one of the following methods: field distortion, arc initiation (trigatron), laser triggering, electron-beam triggering, UV irradiation, or any other means of initiating ionization. For good switching performance, the gap voltage should be above 60% of the self-breakdown voltage by choosing the appropriate gap spacing and gas pressure. Voltage trigger generators should have a low internal impedance, fast voltage rise times, and an open-circuit voltage that is several times greater than the self-breakdown of the igniter gap. A field distortion spark gap is presented in Fig. 3. The trigger electrode is located on an equipotential line in the gap, thus, maximizing the hold-off voltage. A trigger pulse initiates breakdown between one electrode and the trigger plate, causing practically the full gap voltage to appear across the other half of the gap, initiating a Townsend breakdown. The trigger electrode may be located halfway into the electrode gap, or closer to the cathode. Although trigger voltage requirements are reduced with shorter trigger electrode–cathode distances, closing delay times are often increased. Figure 4(a) shows the trigatron arrangement. An arc discharge is formed between the trigger electrode and one of the main electrodes, which initiates breakdown both by providing seed electrons for ionization and UV light for gas volume photoionization. Reliable triggering can be achieved with lower trigger voltage amplitudes compared to the field distortion spark gaps, but the trigatron has a lower hold-off voltage due to field enhancements at the trigger pin–cathode interface. Lasers can be used to achieve very accurate triggering of megavolt spark gaps as shown

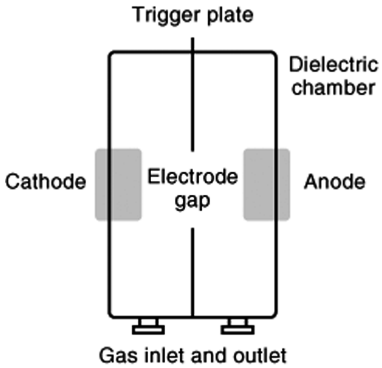

Figure 3. A field distortion spark gap with interchangeable anode and cathode. The electrode gap holds off the applied voltage between the anode and cathode until a breakdown is initiated by energizing the trigger plate, which distorts the electric field in the gap.

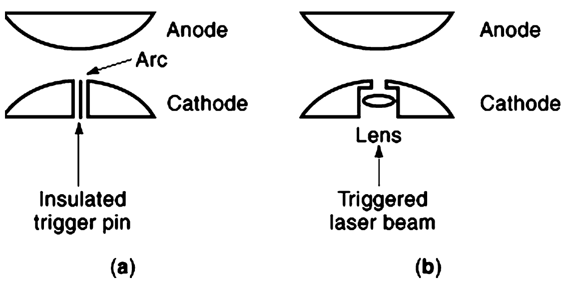

Figure 4. Configuration of (a) a trigatron and (b) a laser-beam-triggered spark gap.

in Fig. 4(b). When the anode is irradiated by energetic photons, the gap is closed by streamer propagation (see article on ***Conduction and Breakdown in Gases***), which is 10 to 100 times faster than breakdowns obtained from Townsend avalanche formation. Rail-gap switches (i.e., electrodes are much longer than they are wide) are usually UV laser triggered along the axis of the electrode rail, and its switch inductance is lower due to a parallel multichannel discharge.

Spark gaps have low conduction losses with forward voltage drops ranging from 100 V to a few kV, depending on the configuration. In small, high-pressure, coaxial gaps, closing times of less than 1 ns have been achieved; for large gaps, delay times of 10 ns to 100 ns are common. The recovery time in sealed spark gaps is a few milliseconds. Increasing the gas pressure improves the recovery rate, However, gas flushing is required for extended repetition rate operation, which provides cooling of the switch electrodes and gas as well as removes debris from the electrode gap. Repetition rates of up to 100 Hz are typical; higher rates of up to 10 kHz can be obtained with proper electrode configuration, cooling, and gas flushing. Jitter ranges from as low as 25 ps for UV-irradiated gaps to as low as 1 ns for trigatrons and field distortion spark gaps. The switch lifetime is mainly limited by electrode erosion, which is affected by the conduction current rise time and amplitude, pulse duration, repetition rate, electrode material, gas type, electrode temperature, and other factors that contribute to erosion. Charge transfers of more than 100 C per shot have been demonstrated with a total switch lifetime in excess of a megacoulomb; smaller spark gaps typically conduct total charges of tens of kilocoulombs over the lifetime of the switch. Copper, brass, stainless steel, aluminum, tungsten, graphite, molybdenum, and alloys (for example elkonite, which is a mixture of tungsten and copper) are commonly used as electrode material, with tungsten having one of the highest erosion resistances. For further information on electric field enhancements, spark gaps, and gas breakdowns see Refs. 1, 6.

Applications. The spark gap is the most common pulsed power closing switch. It is used in capacitive pulse generators, as a peaking gap to sharpen the voltage rise times, and in prototype pulsed power systems.

SURFACE DISCHARGE SWTCHES

The surface discharge switch also falls in the category of plasma arc switches. It is a simple high-current closing switch used with low-impedance loads. A schematic of this switch is shown in Fig. 5. It consists of two electrodes on a dielectric surface and a trigger electrode in the electrode gap, which is generally on or above the insulator surface. The position of the anode and cathode is determined by the polarity of the applied high voltage (*HV*), and either gas or vacuum surrounds the switch. Typical gap dimensions are 1 cm to 40 cm in width (anode-to-cathode separation) and 1 cm to 50 cm in length. In a gas environment, the surface breakdown proceeds in several stages. First, after a voltage pulse has been applied to the trigger electrode, the capacitance of the electrode gap is charged. The trigger pulse should have a fast voltage rise of about 10^{12} V/s to assure multiple arc channel formation, and a high open-circuit voltage is essential, similar to trigger requirements for spark gaps. Electrons are then field emitted from the cathode-dielectric-gas (or vacuum) triple point and accelerated by the applied electric field. They ionize the gas in the electrode gap, and plasma spreads with a speed of 10^5 cm/s to 10^8 cm/s, depending on the gas type and pressure, towards the anode. An exponential rise of the breakdown current is seen in the third stage, which is characteristic of a Townsend-like breakdown, and in the final stage, the conduction current flows through the plasma (switch closure). For vacuum surroundings, some of the field-emitted electrons, with energies between 30 eV to 2 kV, hit the dielectric surface and generate secondary electrons. A positive surface charge is generated, which leads to a saturated surface current on the order of tens of milliamperes. Gas, which had been absorbed on the insulator surface, is released by electron impact and drifts away from the surface at its thermal velocity. A gas layer with a thickness of less than 1 mm and pressures on the order of 10^4 Pa is formed above the dielectric and is ionized by high-energy electrons. In vacuum, plasma velocities of 10^6 cm/s to 2×10^7 cm/s have been reported. In both gas and vacuum surroundings, the discharge arc is located on the dielectric surface due to geometric field enhancements (i.e., the relative permittivity ε_r of the dielectric is larger

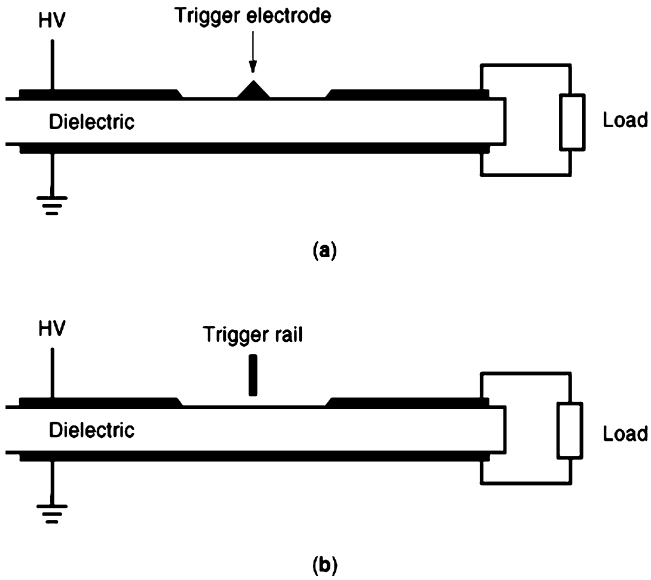

Figure 5. Cross section of a surface discharge switch with trigger: (a) trigger electrode on surface, and (b) trigger rail above dielectric surface.

than that of the surrounding medium). A surface discharge switch without a trigger electrode usually operates as a peaking gap.

The desired hold-off switch voltage determines the minimum thickness of the dielectric with its bulk breakdown strength. For fast conductmion current rise times, a high switch capacitance with a low inductance is necessary; thus, the dielectric should be thin and multiple, parallel arc channels should form during switch closure. Gap length, gas type and pressure, insulator properties, surface roughness, and electrode configuration determine the hold-off voltage of surface discharge switches. Single-gap switches usually withstand less than 100 kV. Conduction currents depend on the number of simultaneous arc channels formed during a discharge. Currents of up to a few megaamperes have been achieved for large gaps, with tens of arc channels generated by trigger voltage rises of more than 10^{12} V/s. Pulse durations of a few microseconds to milliseconds, maximum current rises of 10^{11} A/s to 10^{12} A/s, closing delay times of 100 ns, and jitters of a few nanoseconds are typical for surface discharge switches. Repetition rates of 0.1 Hz for megaampere currents to 100 Hz for kiloampere conduction currents with gas-purge velocities of 10 m/s are possible. Recovery times vary from a few to tens of milliseconds in gases and hundreds of microseconds to a few milliseconds for the vacuum case. Usually, the dielectric material determines the lifetime of the switch. In high current applications, some areas of the dielectric surface are metallized with electrode material. Therefore, erosion of the dielectric is necessary to clean the insulator surface. However, material loss will eventually cause dielectric bulk breakdowns. Lifetimes range from 10^3 shots to 10^6 shots, depending on the conduction current amplitude, pulse width, cooling, and other factors that impact electrode and dielectric erosion. Reference 7 provides more information on surface discharge switches.

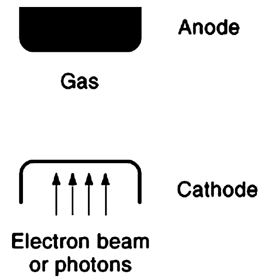

Figure 6. Electrode configuration of a diffuse discharge switch. The switch is closed as long as the applied electron beam or photons ionize the gas between the electrodes.

Applications. Surface discharge switches can be used for capacitive, megaampere, pulsed power systems with low-impedance loads.

DIFFUSE DISCHARGE OPENING SWITCH

The operating principle of an externally controlled diffuse discharge opening switch is given in Fig. 6. It consists of an electrode gap and a high-energy electron beam, a UV source, or laser radiation that ionizes the gas mixture in the electrode gap during the closing state of the switch. Plasma between the electrodes conducts the current and the electric field strength to gas density ratio (*E*/*N*) or electric field strength to gas pressure ratio (*E*/*p*) is kept in a range in which ionization by discharge electrons is negligible. When the external ionization source is turned off, electron attachment and recombination processes in the gas mixture cause the conductivity to decrease and the switch opens. To increase switch performance, the gas should have a large electron mobility and small attachment and recombination rate coefficients during the conduction state (at low *E*/*N* ratios).

In the opening stage at high field strengths, a low electron drift velocity, large electron attachment and recombination coefficients, high breakdown strength, and self-healing gas mixtures (gas-mixture compositions that do not change in time) are desired. Typically, methane (CH_4) and/or argon (Ar) are used as buffer gases, which do not have electron attachment at low *E*/*N* ratios, and are mixed with an electron attacher gas such as freon (C_2F_6) or perfluoropropane (C_3F_8). Optically enhanced attachment by laser radiation can also be used to decrease switch opening times because certain gases have a substantially larger electron attachment cross section in their excited state. Pulsed hold-off voltages of up to 300 kV, with peak conduction currents of up to 10 kA, and conduction current densities of 10 A/cm^2 to 30 A/cm^2 have been reported.

Electrode gap distances of a few millimeters to tens of centimeters, electrode diameters of 2 cm to 30 cm, and gas pressures of 10^5 Pa to 10^6 Pa are common switch parameters. Conduction times are limited by the external ionization source and range from 0.5 μs to 5 μs. Operation as a closing switch is possible, but short conduction times restrict its application. Opening times of 50 ns to 3 μs have been measured, depending on the gas type, gas pressure, and the use of optically enhanced electron attachment

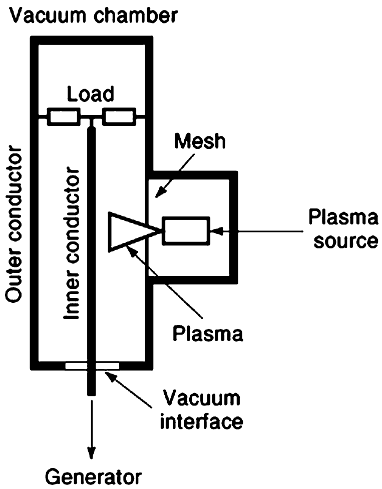

Figure 7. Simple coaxial geometry plasma opening switch. Plasma streams through the mesh and electrically shorts the inner and outer conductors.

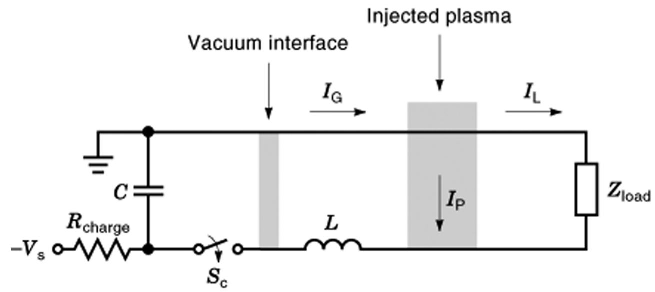

Figure 8. Circuit schematic of an inductive pulsed power system with a plasma opening switch. After the switch S_c closes, the generator current I_G flows through the plasma. The load current I_L is initially zero ($I_G = I_P$).

methods, and repetition rates of up to 1 kHz are possible. Further information on of diffuse discharge switches is given in Refs. 48 and 9.

Applications. The diffuse discharge switch was studied as an opening switch for inductive pulsed power systems in the 1970s and 1980s, but little information exists on practical applications.

PLASMA OPENING SWITCHES

Plasma opening switches (*POS*) and plasma erosion opening switches (*PEOS*) have been studied extensively as repetitive opening switches for compact, energy-dense, inductive storage generators since the 1970s. Figures 7 and 8 give the coaxial geometry of a simple *POS* and a schematic of a pulsed power system with a *POS*, respectively. A plasma source, which consists of a flashboard, plasma gun, or laser-illuminated target, is triggered and emits plasma that drifts through a mesh and electrically shorts the inner and outer conductors. Initially, the generator current I_G charges the circuit inductance without passing through the load; thus the plasma current I_P equals I_G.

The fast opening of the switch occurs due to a "plasma thinning" mechanism that locally decreases the plasma density near the inner conductor, and a load current begins to flow. The plasma opening mechanisms are not fully understood. It is postulated that magnetic pressure, erosion, or combinations of both mechanisms generate a plasma-free region near the inner electrode. The magnetic pressure, $B^2/2\mu_0$, is derived from the Poynting vector, $\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{B}/\mu_0$,

$$\boldsymbol{S} = \frac{\eta}{\mu_0}\boldsymbol{J} \times \boldsymbol{E} + \left(v_\perp - \frac{J_\perp}{n_e e}\right)\frac{B^2}{2\mu_0} \tag{1}$$

where η is the plasma resistivity, μ_0 is the permeability of free space, $\boldsymbol{J}$ is the current density, $\boldsymbol{B}$ is the magnetic flux density, $\boldsymbol{v}_\perp$ is the electron velocity perpendicular to the magnetic field, $\boldsymbol{J}_\perp$ is the current density perpendicular to the magnetic field, n_e is the plasma electron density, and e is the electron charge. This magnetic pressure displaces the plasma on the generator side, resulting in a low-density region that generates an axial current density [see Fig. 9(a)]. The radial $\boldsymbol{J} \times \boldsymbol{B}$ force [see Fig. 9(b)] or plasma erosion opens the plasma gap, and load current begins to flow. Based on the erosion model, the *PEOS* opens if the amplitude of the plasma current I_p reaches the maximum allowed current I_{max} due to the space-charge limit[see Fig. 10(a)

$$I_{max} = 2\pi r l\sqrt{\frac{m_i}{Zm_e}}Zen_i v_d \tag{2}$$

and

$$\frac{I_i}{I_e} = \sqrt{\frac{Zm_e}{m_i}} \tag{3}$$

where r is the radius of the inner conductor, l is the length of the plasma channel, m_i is ion mass, m_e is the electron mass, Z is the ion charge state, n_i is the plasma ion density, v_d is the ion drift speed, I_i is the ion current, and I_e is the electron current. For C^{2-+} plasmas, the I_e/I_i ratio is about 100. When the generator current exceeds I_{max}, ions are removed from the plasma faster than they are replaced, and the ion current is determined by

$$I_i = 2\pi r l Zen_i\left(v_d + \frac{dD}{dt}\right) \tag{4}$$

where D is the plasma gap spacing. In the enhanced erosion phase [see Fig. 10(b)], a magnetic field is generated by the initial load current, which significantly increases the plasma gap opening rate. The final magnetic insulation phase occurs when the plasma gap is larger than an electron gyroradius, as shown in Fig. 10(c).

Typical dimensions of plasma opening switches are an inner electrode radius of 3 mm to 10 cm, an outer electrode radius of 2 cm to 20 cm, and a plasma channel length of 2 cm to 15 cm. Equation (2) indicates that the maximum conduction current increases with switch size. The *POS* permits switch powers of megawatts to tens of terawatts, with hold-off voltages ranging from kilovolts to a few megavolts, conduction currents of kiloamperes to megaamperes,

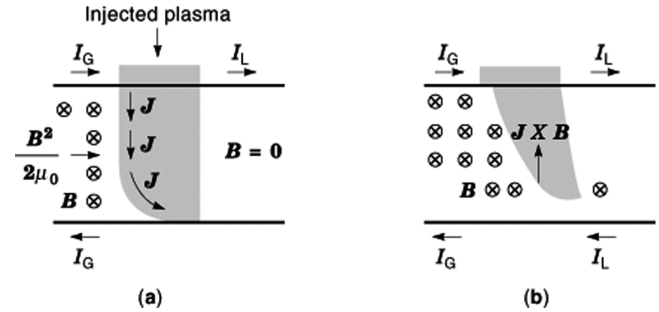

Figure 9. Magnetic pressure opening mechanism of a plasma opening switch. (a) Plasma displacement by magnetic pressure, and (b) gap opening. As the gap opens, current flows through the load.

very low forward voltages, and opening times of 10 ns to 100 ns. The closing stage conduction time is limited to the range of 50 ns to 1 μs, depending on the applied current rise time and plasma characteristics, and the switch jitter relies on the reproducibility of the plasma parameters. Repetition rates are seldom published since they are often not limited by the *POS*, but rather by the recharging time of the generator or other factors. See Refs. 8 and 10–13 for additional information.

Application. Plasma opening switches are used in inductive energy storage systems with low impedance loads, which produce high-current electron beams or high-power radiation (Z pinch).

PLASMA FLOW SWITCHES

The plasma flow switch (*PFS*) technique employs a vacuum discharge through a plasma armature that stores magnetic energy for several microseconds and rapidly transfers current and energy to a load when the armature exits the inductive store structure. A schematic of the *PFS* operation is presented in Fig. 11. Prior to switching, the *PFS* consists of a vacuum electrode gap, a wire array, barrier foil, and a load, as shown in Fig. 11(a). With the application of a megaampere current, a plasma armature is created by electrical explosion of the wire array and its impact on a plastic barrier foil. The total mass of the plasma ranges between 50 mg and 200 mg, and the plasma armature is accelerated by $\boldsymbol{J} \times \boldsymbol{B}$ forces to velocities of up to 70 km/s [see Fig. 11(b)]. Current flows through the load when the plasma armature reaches the plasma dump as shown in Fig. 11(c). The electrode gap is on the order of 3 cm, and plasma is accelerated over a length of 6 cm. Conduction times of 3 μs to 4 μs are typical for these plasma accelerating lengths.

A cylindrical design of the *PFS* decreases the circuit inductance compared to a planar design, which makes short current rise times possible. The electrode gap is reduced by the plasma dump, which decreases the circuit resistance during load current conduction. The hold-off voltage is on the order of 100 kV,. The advantage of the PFS over the spark gap is the capability for, peak conduction currents of a few megaamperes, producing switching powers of up to 1 TW. Opening times of hundreds of nanoseconds and load current rises of 3×10^{13} A/s have been measured, indicating a factor-of-10 enhancement in current rise by the plasma flow switch. The *PFS* is a single-shot device due to the total destruction of the wire array and barrier foil. See Refs. 10, 14, and 15 for additional information.

Application. The *PFS* has been used to study high-power radiation loads (Z pinch by metal foil implosion).

THYRATRONS

The thyratron is a low-pressure plasma-closing switch that is generally filled with hydrogen. A schematic of a simple single-gap hydrogen thyratron is given in Fig. 12. In the opened stage of the thyratron, prior to triggering, the control grid usually has the same potential as the cathode. It shields the anode so that very little or no electric field from the anode penetrates to the cathode. A grid baffle prohibits a direct path from the cathode to the anode, which prevents spurious triggering. The auxiliary grid limits the cathode current and maintains a low-amplitude dc current discharge during the opening stage of the switch. The use of both the baffle and the auxiliary grid increases the hold-off voltage of the thyratron. To reduce the trigger voltage requirements, the distance between the control grid and the cathode times the pressure of the hydrogen gas is close to the Paschen minimum. The hydrogen gas pressure, controlled by a hydride reservoir, is on the order of 70 Pa. In hot-cathode thyratrons, the metal oxide or tungsten cathode is heated to 700° to 1200°C, depending on the cathode material, providing thermionic electron emission. Current densities of 30 A/cm^2 for metal oxide and 100 A/cm^2 to 150 A/cm^2 for impregnated tungsten cathodes are typical for modern thyratron cathodes with microsecond pulses.

The hold-off voltage of the switch (40 kV to 50 kV) is limited by electrical breakdown in vacuum between the control grid and the anode. Gas breakdown during the opening stage of the switch is unlikely since the control grid–anode distance (top gap) is less than one electron mean free path. To close the switch, the control grid is triggered with a voltage of about 1 kV above the cathode potential; i.e., the trigger voltage depends on the gas pressure and the control grid–cathode gap (bottom gap). A discharge is formed between the control grid and the cathode, hydrogen gas is partially ionized in the bottom gap, and the resulting plasma drifts into the top gap. High electric fields in the top gap cause a rapid ionization of the gas, which forms a highly conductive plasma. The potential of the control grid changes to that of the anode, and a secondary ionization of the hydrogen gas takes place in the bottom gap. The plasma shorts both the top and the bottom gaps, and the voltage drop during this closing stage is roughly 100 V. In this stage, the switch current density in the anode gap is larger than the emitted cathode current density since the high electric field pulls the emitted electrons through the auxiliary grid towards the anode. This grid area must be large enough to ensure that the current density does not exceed approximately 1.5 kA/cm^2; otherwise, plasma instabilities may occur, which could significantly increase the closing resistance and thereby the voltage drop of the switch. Once the top gap is filled with plasma, the switch

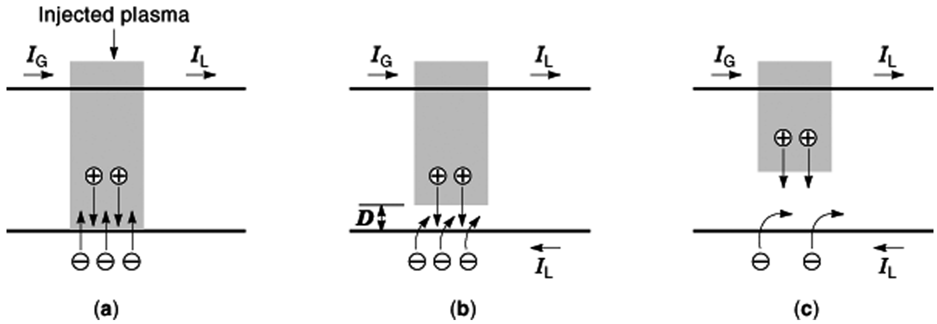

Figure 10. Erosion opening mechanism of a plasma opening switch or plasma erosion opening switch. (a) Initial erosion phase, (b) enhanced erosion phase, and (c) magnetic insulation phase.

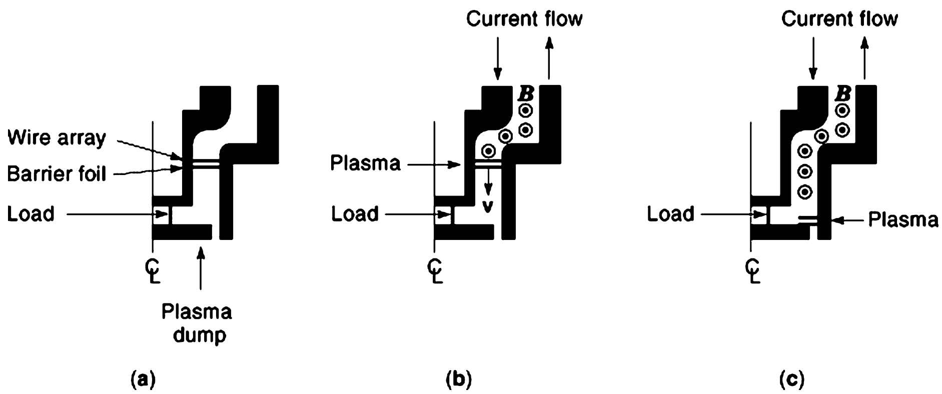

Figure 11. Schematic of the plasma flow switch opening process. (a) Initial stage, (b) plasma flow stage, and (c) opening stage. Plasma drifts down the vacuum gap, which allows current to flow through the load.

cannot be turned off until the switch current decreases to zero and sufficient time (up to a few tens of microseconds) is given for the recombination of the conducting plasma. The control grid potential strongly affects the recovery time. A negative grid bias of 50 V accelerates the plasma recombination process by a factor of 5 compared to the case with no grid bias.

The thyratron conducts peak currents of tens of kiloamperes for a few tens of microseconds. The advantage of this switch is its high repetition rate. At high currents (kA), the thyratron is capable of operating at a few hundred Hz, while at lower currents (tens of amps) the repetition rate is as high as 100 kHz. High current rises of 10^{11} A/s to 10^{12} A/s have been achieved. The cathode predominantly limits the life of the switch, usually 10,000 h for metal oxide and 30,000 h for impregnated tungsten cathodes. The main disadvantage is the delay time, that is, time between the triggering of the control grid and the closing of the thyratron, due to the plasma that must form a conduction path between the cathode and the anode. Delay times of 20 ns to 30 ns are typical among modern, hot-cathode thyratrons with an associated jitter of 1 ns to 10 ns.

The back-lighted thyratron (*BLT*) is a different class of thyratrons. The cathode of the BLT is radiated by intense UV light, which generates photoelectron emission. These electrons drift into the anode–cathode gap and initiate a glow discharge, from which current densities of up to 10 kA/cm^2 over a 1 cm^2 cathode area have been reported. This design does not require a cathode heater or grids, that is,

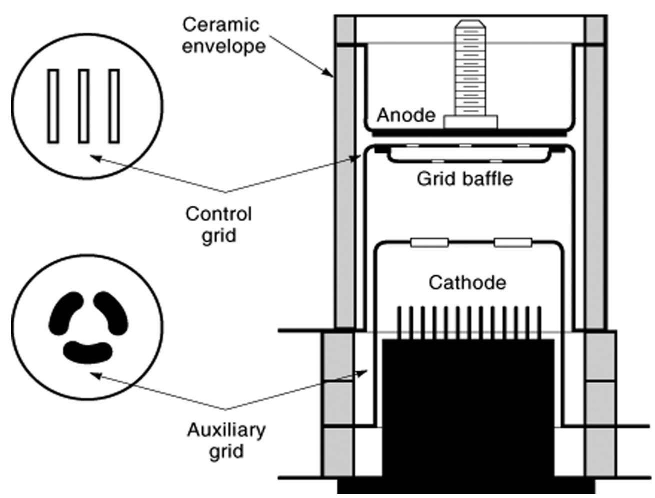

Figure 12. Simplified cross section of a modern, single-stage, high-power, hot-cathode, hydrogen thyratron. The small gap between the anode and the control grid makes ionization of the hydrogen gas unlikely. Plasma is formed always in the auxiliary grid/cathode gap.

the switch is triggered by laser light. Advantages of this switch are cold cathodes, higher peak switching currents, lower voltage drops, and a simpler and smaller switch design. Disadvantages are longer delay times (200 ns to 300 ns) and the need for a laser–UV trigger system. The design of BLTs is similar to that of pseudospark switches. More facts on thyratrons can be found in Refs. 2 and 16–19.

Application. Thyratrons are used in pulsed, high-power gas lasers and radar modulators. Low power thyratrons have been phased out and replaced with thyristors (a solid-state semiconductor device).

TACITRONS

The tacitron is a hydrogen gas triode that can be used as an opening or closing switch. While the construction of his device is very similar to that of a hydrogen thyratron, the tacitron has smaller grid apertures, with a diameter of 0.5 mm and a lower gas pressure of 0.7 Pa to 4 Pa. The initial ionization in the tube is limited to the control-grid–anode region, so that complete grid control of the tube is possible. Tacitrons components include an anode, control grid, hot cathode, and heated reservoir (usually titanium or tantalum hydride) for gas-pressure control. Russian hydrogen tacitrons have peak ratings of a few megawatts, with hold-off voltages of up to 12 kV, conduction currents of a few hundred amperes, and peak pulse repetition rates up to 200 kHz. The grid-driven commutation causes the tacitron to absorb more energy than an externally commutated thyratron of equivalent power, since the tacitron must interrupt the full conduction (or discharge) current while the thyratron ceases to conduct near zero current. Thus, the design of the tacitron control grid is more massive and includes cooling. The typical flow rate for cooling water is 5 L/min for the control grid and 10 L/min for the anode. The recovery time is faster than an equivalent thyratron, no more than a few hundred nanoseconds, but the forward voltage drop during the closing stage is typically a few tens of volts higher than a thyratron.

Since the 1970s, cesium (Cs) and cesium–barium (Ba) mixtures have been investigated for use in tacitrons instead of hydrogen. Cesium has the lowest first ionization potential of any element (only 3.89 eV versus 13.6 eV for hydrogen, 10.5 eV for mercury, and 12.1 eV for xenon), and multistep ionization takes place through a resonant state (metastable states) of the Cs atom. The use of cesium reduces the voltage drop by more than one order of magnitude compared to hydrogen tacitrons and allows the possibility of using this plasma switch as a low-loss dc inverter in high-temperature or high-radiation environments.

The disadvantage of cesium is its mass; cesium ions have less mobility than hydrogen ions, causing Ca–Ba tacitrons to have larger turn-on and turn-off times. Russian Cs tacitron prototypes had low forward voltage drops of 1.75 V to 2.75 V, hold-off voltages of 50 V, and modulation frequencies of up to 1 kHz. The major limitation of the Cs vapor tacitron is its low emission current density of <1 A/cm^2.

By adding small amounts of Ba vapor ($<2\%$), the emission current of a Cs–Ba vapor tacitron is increased by more than one order of magnitude. At the present time, the Cs–Ba tacitron is still very much an experimental device.

Figure 13 shows a simplified cross section of a Cs–Ba tacitron. It does not require any water cooling since peak power ratings are on the order of kilowatts. Cs and Ba vapor pressures are controlled by heating a pure source

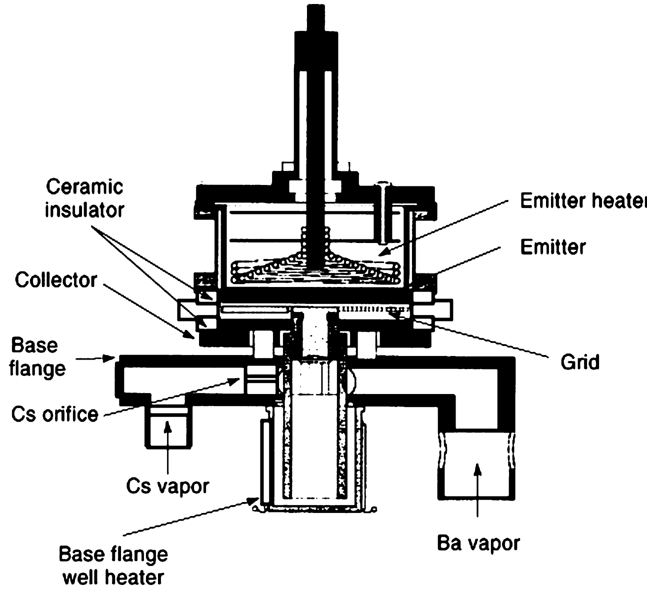

Figure 13. Cross section of a planar, high-current, demountable Cs–Ba tacitron. The Cs plasma has a low ionization energy, which results in a low voltage drop during the closing stage.

rather than storing them in a chemically bound form as with the metal hydride reservoirs used in commercial hydrogen tubes. The cathode (emitter) is heated to temperatures of 1100° to 1300°C and the 1 mm thick molybdenum grid with a transparency of 35% is placed between the molybdenum cathode and molybdenum anode (collector). It has complete grid control of the tube conduction like the hydrogen tacitron, but a very low forward voltage drop of 1.3 V to 3 V. Reverse voltages or hold-off voltages of 100 V to 200 V have been demonstrated in laboratory devices that lack grid baffles. Peak conduction current densities range from 10 A/cm^2 to 30 A/cm^2 and current rise times are on the order of 10 μs.

The modulation frequency depends on the conduction current and plasma density—higher plasma densities require higher current densities in order to deplete ions from the plasma during conduction. Ion depletion reduces the turn-off time and thereby increases the maximum attainable modulation frequency. Modulation frequencies of 10 kHz have been obtained with an average current density of 5 A/cm^2; at lower frequencies the current density can be increased. The control grid is triggered with a voltage of 10 V to 50 V and a current density of 2 A/cm^2. The grid turn-on delay time is 10 μs, the turn-off delay varies from 0.1 μs to 3 μs, and current rises of 10^7 A/s have been measured. See Refs. 20–22 for additonal information.

Application. Hydrogen tacitrons are used in cyclotron accelerators, copper vapor lasers, and microsecond pulse generators.

CROSSATRONS

Cross-field tubes work to the left of the Paschen minimum breakdown region at low hydrogen pressures (2 Pa to 7 Pa); consequently field emission or vacuum breakdown

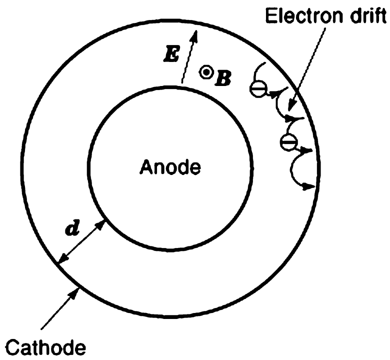

Figure 14. Cross section of a simple, grid-free cross-field tube. Electrons drift in cycloidal orbits, which increases the ionization probability of the fill gas.

phenomena limit the hold-off voltage. A cross section of a simple, grid-free cross-field tube is shown in Fig. 14. The electrode spacing d is less than one electron mean free path, and thus a glow discharge cannot be sustained. With the application of a magnetic field normal to the electric field, electrons travel in cycloidal $\boldsymbol{E} \times \boldsymbol{B}$ orbits around the cylindrical anode. This increases the collisional probability for ionization of hydrogen due to the greater electron path length; plasma is formed in the electrode gap, which drifts toward the anode, and the switch closes. Removal of the magnetic field will result in recombination of the conducting plasma. Therefore, the cross-field tube is an opening switch as well as a closing switch.

The crossatron is a cross-field tube with additional grids. Figure 15 shows a crossatron modular switch configuration. The cylindrical symmetric crossatron uses rare-earth (SmCo) permanent magnets attached outside of the switch to generate the $\boldsymbol{E} \times \boldsymbol{B}$ electron drift for efficient ionization of the helium or hydrogen background gas. The cathode material is typically molybdenum or chrome. The stainless-steel source grid is continuously biased at 500 V to 700 V to sustain the plasma between the cathode and the source grid. This decreases the turn-on jitter of the switch and maintains a low-power discharge (about 4 W) to the cathode during the stand-by mode and between high-voltage pulses.

The control grid (*CG*) is pulsed above the 200 V plasma potential, usually at 600 V to 5 kV. Plasma streams through the 50% to 80% transparent grid, with apertures of 0.5 mm to 2 mm towards the anode, and closes the switch. Lowering the control-grid potential to the cathode voltage turns off the switch; the plasma recombines in the CG–anode region, and the full anode voltage appears across the *CG*–anode vacuum gap. Crossatrons typically range from 6 cm to 15 cm in diameter and 7 cm to 30 cm in length. The cathode does not require any heating, and the gas pressure in the switch is controlled by an internal Zr–Al reservoir. Hold-off voltages up to 120 kV have been achieved, with peak conduction currents of 2.5 kA, time average currents of 5 A, current rises of 5×10^{10} A/s, and forward voltage drops of 200 V to 500 V. Other parameters are modulation frequencies of 1 kHz to 1 MHz, opening delay times of 100 ns to 300 ns, closing delay times of 50 ns to 150 ns, a recovery time of less than 1 μs, a switching jitter of 1 ns to 10 ns,

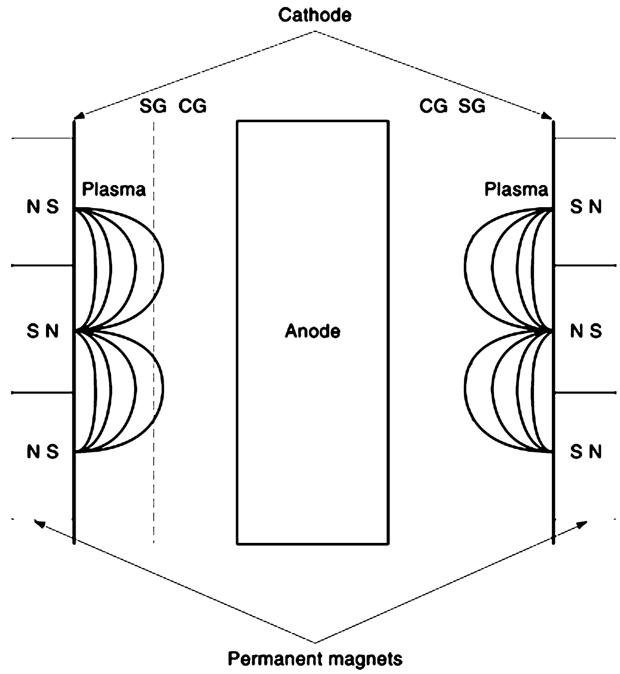

Figure 15. Crossatron modular switch configuration with source grid (*SG*) and control grid (*CG*). The source grid is used to sustain the plasma, whereas plasma streams towards the anode only if the control grid is triggered at a voltage above the plasma potential.

and a switch lifetime of greater than 2×10^{10} shots. See Refs. 8 and 23 for additional information.

Applications. Crossatrons have been used in ground-based radar modulators and lasers, and they have been proposed as inverter switches in mobile power conditioning systems.

PSEUDOSPARK SWITCHES

The pseudospark switch (*PSS*) is a low-pressure discharge device that operates in a glow discharge mode. Figure 16 gives a schematic cross section of a pseudospark discharge closing switch. It includes a hollow cathode and anode, trigger, and preionization electrodes (shown for a glow-discharge trigger configuration), and a blocking grid (optional). Characteristic features of the *PSS* are two parallel plane electrodes with a central hole, separated by a dielectric insulating ring.

Switch closure is initiated by triggering (1) a surface flashover in the cathode hole, in the hollow cathode, or behind the cathode cage, (2) a glow discharge in the back of the hollow cathode, or (3) UV photons on the back side of the cathode. Hydrogen or deuterium gas at pressures between 10 Pa and 100 Pa is ionized and plasma streams through the cathode hole and electrically shorts the electrode gap. In the glow-discharge trigger configuration, the preionization grid is dc biased at − 2 kV, with a current of 100 μA, whereas the trigger electrode receives a 3 kV to 5 kV positive voltage pulse. The surface flashover trigger configuration is similar to a surface discharge switch with a shorted load and without trigger electrode (compare to Fig. 5). Typical electrode gaps are 3 mm to 5 mm and

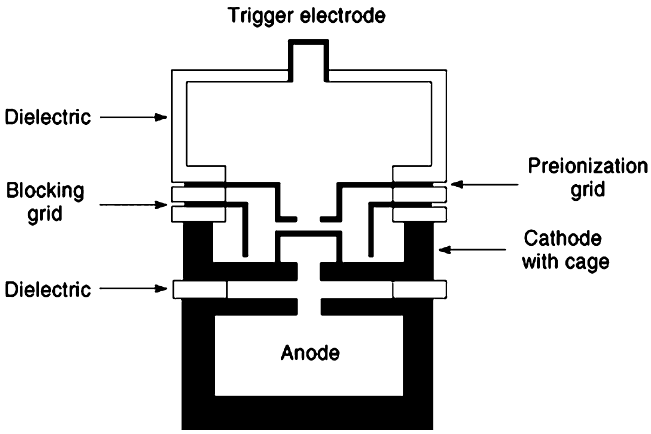

Figure 16. Pseudospark switch configuration. Plasma is generated inside the hollow cathode, drifts into the cathode–anode gap, and closes the switch.

electrode holes are 3 mm in diameter. The *PSS* opens only after the conduction current amplitude decreases to zero and the plasma in the electrode gap recombines. Short recovery times are achieved by applying a 300 V pulse to the blocking electrode after cessation of conduction, which increases the ion mobility and thus decreases the recombination time of the plasma. Hold-off voltages are limited to 35 kV for a single electrode gap, with peak conduction current amplitudes ranging from hundreds of amperes to hundreds of kiloamperes. A multielectrode gap *PSS* has higher hold-off voltages, up to 70 kV for a three-electrode *PSS*. Trigger electrodes are often mounted behind the hollow cathode to protect them from erosion by the main discharge. Disadvantages of this setup are a switch jitter of tens of nanoseconds and closing delay times of 100 ns to 500 ns. Conduction pulse lengths are on the order of a few microseconds, with plasma densities of 5×10^{16} cm^{-3} to 10^{17} cm^{-3} generated in the conduction gap. Pulse length and conduction current increase with larger electrode apertures since more plasma drifts in the electrode gap region; on the other hand, the rate of current rise decreases.

Repetition rates depend upon the conduction current amplitude and 1 Hz, 1 kHz, and 5 kHz have been achieved for 5 GW, 200 MW, and tens of megawatts switching powers, respectively. The switch lifetime is limited by electrode erosion around the cathode aperture. Maximum charge transfers of several 10^5 C over the lifetime of the switch are possible, but electrode erosion increases significantly when conduction currents exceed 50 kA, resulting in lifetimes of 10^5 shots to 10^6 shots for gigawatt devices and 10^9 shots for hundreds of megawatt switches. More details on pseudospark switches are given in Refs. 2 and 24–27.

Applications. Pseudospark switches are used in pulsed gas discharge lasers, X-ray microscope systems, and in pulsed power systems for CERN's Large Hadron Collider (*LHC*) project.

IGNITRONS

Although the ignitron can be categorized as a liquid-metal cathode vacuum switch, it is described briefly since the final conduction phase occurs through plasma. A schematic of an ignitron is given in Fig. 17. A simple ignitron consists of a liquid cathode, mercury (Hg), which, in principle, allows massive coulomb transfer without destructive effects. It is a low-pressure device, and vacuum surrounds the 10 cm to 20 cm wide electrode gap during the opening stage. Switch closure is achieved by applying a trigger pulse of 2 kV to 4 kV to the ignitor. An arc is formed between the ignitor and the cathode, some mercury is vaporized and plasma is emitted, pressure increases in the electrode gap, and a glow discharge initiates, which further develops into an arc between the anode and cathode. The switch opens at zero current, the plasma recombines, and mercury condenses at the walls of the ignitron and returns to the cathode pool.

A control grid may be added [see Fig. 17(b)] to achieve precision in closure time. During opening, the grid is held at zero (or negative) potential relative to the cathode. Thereupon, the switch will close only after the ignitor has been triggered and a positive pulse has been applied to the control grid. A gradient grid is placed less than one mean free path from the control grid, thereby preventing breakdown prior to triggering the ignitor. The shield grid helps prevent spurious breakdowns and decreases the voltage requirements of the control grid. While the splash baffle blocks mercury from being sprayed directly onto the molybdenum anode and insulators, it may reduce the hold-off voltage of the switch due to field enhancement. Maximum hold-off voltages are on the order of 50 kV, in addition to conduction current amplitudes of 1 kA to 500 kA and time average currents of approximately 10 A. The ignitron has a low forward voltage drop of 10 V to 100 V, closing delay times

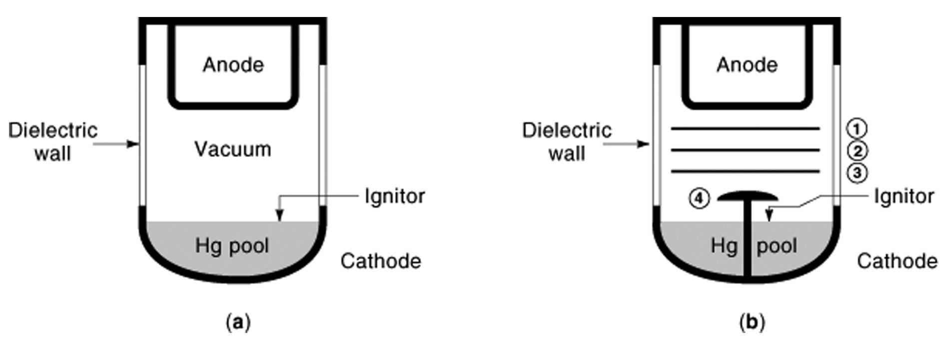

Figure 17. Basic ignitron configurations: (a) simple ignitron and (b) ignitron with (1) gradient grid, (2) control grid, (3) shield grid, and (4) splash baffle. These particular ignitrons are unidirectional switches.

between 50 ns to 300 ns, and jitters as low as 10 ns. Simple ignitrons are operated at repetition rates of less than 1 Hz, while gridded ignitrons operate up to a few 100 Hz. The ignitor usually limits the lifetime. Metallic sputtering may shorten the trigger gap, or erosion at the ignitor tip may increase the trigger gap. Lifetimes of 10^8 shots at 1 kA and 1000 shots at hundreds of kiloamperes have been obtained with microsecond pulses. References 2 and 28, 29 provide additional data on ignitrons.

Application. The ignitron is used as a reliable, almost maintenance-free, closing switch in low-repetition-rate pulse power system with kiloampere load currents.

We presented an overview of a variety of plasma switches that are used in pulsed power applications. Future trends in this area include more compact switches with longer lifetimes. Research is continuing in this field, and the latest advances are found in journals and conference proceedings that are provided in the reading list. The following encyclopedia articles provide additional background information: CATHODES, CONDUCTION AND BREAKDOWN IN GASES, FIELD EMISSION, FIELD IONIZATION, GASEOUS INSULATION, VACUUM INSULATION, AND VACUUM SWITCHES.

BIBLIOGRAPHY

1. R. E. Friedrich, (ed.) *Application of Power Circuit Breakers*, New York: IEEE, 1975.
2. G. Schaefer, A. Guenther, M. Kristiansen (eds.), *Gas Discharge Closing Switches*, New York: Plenum, 1990.
3. S. C. Brown, *Basic Data of Plasma Physics*, New York: Technology Press of MIT and Wiley, 1959.
4. M. A. Gundersen, Gas-phase pulsed power switches, *IEEE Trans. Plasma Sci.*, **19**: 1123–1131, 1991.
5. L. Liebing, Motion and Structure of a plasma produced in a rail spark gap, *Phys. of Fluids*, **6**: 1035–1036, 1963.
6. R. S. Taylor and K. E. Leopold, UV radiation-triggered rail-gap switches, *Review Sci. Instrum.*, **5**: 52–63, 1984.
7. R. E. Reinovsky, Surface-discharge switches for high-performance closing applications, *IEEE Trans. Plasma Sci.*, **32**: 1765–1777, 2004.
8. A. Guenther, M. Kristiansen, T. Martin, (eds.) *Opening Switches*, New York: Plenum, 1987.
9. K. H. Schoenbach, G. Schaefer, M. Kristiansen, H. Krompholz, H. C. Harjes, and D. Skaggs, An electron-beam controlled diffuse discharge switch, *J. Appl. Phys.*, **57**: 1618–1622, 1985.
10. G. Cooperstein, P. F. Ottinger (eds.), Special issue on fast opening vacuum switches, *IEEE Trans. Plasma Sci.*, **PS–15**: 629–780, 1987.
11. B. V. Weber, R. J. Commisso, P. J. Goodrich, J. M. Grossmann, D. D. Hinshelwood, J. C. Kellogg, and P. F. Ottinger, Investigation of plasma opening switch conduction and opening mechanisms, *IEEE Trans. Plasma Sci.*, **19**: 757–766, 1991.
12. M. E. Savage, D. B. Seidel, and C. W. Mendel Jr., Design of a command-triggered plasma opening switch for terawatt applications, *IEEE Trans. Plasma Sci.*, **28**: 1533–1539, 2000.
13. J. W. Schumer, S. B. Swanekamp, P. F. Ottinger, R. J. Commisso, B. V. Weber, D. N. Smithe, and L. D. Ludeking, MHD-to-PIC transition for modeling of conduction and opening in a plasma opening switch, *IEEE Trans. Plasma Sci.*, **29**: 479–493, 2001.
14. R. L. Bowers, A. E. Greene, D. L. Peterson, N. F. Roderick, R. R. Bartsch, J. C. Cochrane, and H. Kruse, Initiation and assembly of the plasma in a plasma flow switch, *IEEE Trans. Plasma Sci.*, **24**: 510–522, 1996.
15. R. L. Bowers, J. H. Brownell, A. E. Greene, D. L. Peterson, N. F. Roderick, and P. J. Turchi, Effects of Plasma Surface Layers on the Efficiency of Plasma Flow Switching, *IEEE Trans. Plasma Sci.*, **26**: 1420–1436, 1998.
16. W. J. Sarjeant R. E. Dollinger, *High-Power Electronics*, Blue Ridge Summit: TAB, 1989.
17. B. M. Penetrante and E. E. Kunhardt, Kinetics of hydrogen thyratron plasmas during the conduction phase, *J. Appl. Phys.*, **59**: 3383–3396, 1986.
18. W. Hartmann, V. Dominic, G. F. Kirtman, and M. A. Gundersen, An analysis of the anomalous high-current cathode emission in pseudospark and back-of-the-cathode lighted thyratron switches, *J. Appl. Phys.*, **65**: 4388–4395, 1989.
19. G. Kirkman-Amemiya and M. A. Gundersen, High current back lighted thyratron switch, *Appl. Phys. Lett.*, **60**: 316–318, 1992.
20. E. O. Johnson, J. Olmstead, W. M. Webster, The tacitron, a low noise thyratron capable of current interruption by grid action, *Proc. IRE*, **42**: 1350–1362, 1954.
21. C. Murray, B. Wernsman, M. S. El-Genk, and V. Kaibyshev, Ignition and extinguishing characteristics of Cs-Ba tacitron, *J. Appl. Phys.*, **72**: 4556–4565, 1992.
22. B. Wernsman and M. S. El-Genk, Experimental investigation of current modulation in a planar Cs-Ba tacitron, *IEEE Trans. Plasma Sci.*, **23**: 196–203, 1995.
23. D. M. Goebel, Cold-cathode, pulsed-power plasma discharge switch, *Rev. Sci. Instrum.*, **67**: 3136–3148, 1996.
24. K. Frank M. A. Gundersen (eds.), Special issue on physics and application of pseudospark discharges, *IEEE Trans. Plasma Sci.*, **23**: 209–392, 1995.
25. M. Gundersen and G. Schaefer, *Physics and Applications of Pseudosparks*, NATO ASI Series, Plenum Press, New York, 1990.
26. K. Frank, O. Almen, P. Bickel, J. Christiansen, A. Gortler, W. Hartmann, C. Kozlik, A. Linsenmeyer, H. Loscher, F. Peter, A. Schwandner, and R. Stark, Pseudospark switches for high repetition rates and high current applications, *Proc. IEEE*, **80**: 958–970, 1992.
27. Y. D. Korolev and K. Frank, Discharge formation processes and glow-to-arc transition in pseudospark switch, *IEEE Trans. Plasma Sci.*, **27**: 1525–1537, 1999.
28. J. Slepian and A. H. Toepfer, Cathode spot fixation and mercury pool temperatures in an ignitron, *J. Appl. Phys.*, **9**: 483–484, 1938.
29. D. L. Loree, M. G. Giesselmann, M. Kristiansen, A. P. Shulski, and R. Kihara, Recent advances in high-power ignitron development, *IEEE Trans. Electron Devices*, **38**: 720–725, 1991.

Reading List

J. D. Cobine, *Gaseous Conductors: Theory and Engineering Applications*, New York: Dover, 1958.

Yu. D. Korolev G. A. Mesyats, *Physics of Pulsed Breakdown in Gases*, Yekaterinburg: URO-Press, 1998.

L. Latham, (ed.) *High Voltage Vacuum Insulation*, New York: Academic, 1995.

T. H. Martin A. H. Guenther (eds.), *J. C. Martin on Pulsed Power*, New York: Plenum, 1996.

IEEE Conference Record of the Power Modulator Symposium (biannual, even years).

Proceedings of the IEEE International Pulsed Power Conference (biannual, odd years).

Proceedings of the International Conference on High Power Particle Beams (biannual, even years).

Special Issue on Pulsed Power Science and Technology, *IEEE Trans. Plasma Sci.* (biannual, even years).

Special Issue on Vacuum Discharge Plasmas, *IEEE Trans. Plasma Sci.* (biannual, odd years).

FRANK HEGELER
Commonwealth Technologies, Inc./Naval Research Laboratory, Washington, DC