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HIGH-POWER PSEUDOSPARK AND BLT SWITCHES

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Abstract

A review of recent developments in a new group of high-power hollow-electrode switches, including the pseudospark and the backlighted thyratron (BLT), is presented. Experiments demonstrate that for several key high-power switching performance factors the pseudospark and BLT switches are superior to either high-pressure spark gap switches or thyratrons or, in some cases, both. High performance has been demonstrated in peak current (>100 kA), current rate of rise ($>10^{12}$ A/s), switching precision, trigger efficiency, current reversal (100 percent), and recovery time. Several electrical and optical trigger methods have been demonstrated and are described. Pseudosparks and BLT's have also been tested as switches for different types of gas lasers including copper vapor, N_2, and excimer laser

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1. INTRODUCTION

This paper reviews the research and development of the pseudospark [1]-[5], [7] and the backlighted thyratron (BLT) [6]-[8], which are new thyratron-type switches. The BLT is an optically triggered version of the pseudospark. These switches operate with a low-pressure glow discharge, *not an arc,* and achieve high stand-off voltage by operating on the left branch of the Paschen curve, analogous to high-power hydrogen thyratrons. They are typically comprised of two parallel-plane electrodes each with a central hole. The switches are triggered either by injection of charge carriers or by photoemission. A distinction is made between the electrically triggered pseudospark switch which, following the original authors [2], is referred to as a pseudospark, and the optically triggered version of the pseudospark which is referred to as a "backlighted" thyratron, or BLT [6].

"Improved" high-power switches have one or more improved characteristics such as peak current, current rate of rise, stand-off voltage, modularity, repetition rate, lifetime, and energy dissipation at high power. In general, it is difficult to characterise improvements in a simple way because improvement in one area often results in degradation of another. The switches described here, the BLT and the pseudospark, have demonstrated *simultaneous* improvements of these characteristics, and are thus important candidates for a variety of applications.

The pseudospark was first proposed and studied at the University of Erlangen (Erlangen, West Germany) for use as an ion and electron beam source [2]. Initial experiments using a 40-gap device filled with 100-Pa hydrogen and an accelerating voltage of 100 kV produced a 70-keV electron beam with a current density of 10^6 A/cm^2. In collaboration with a group from CERN, the pseudospark was further developed as a fast high-power switch [3]. The discharge was initiated by a surface flashover-type trigger at the central hole of the cathode. This method of triggering gave a jitter of about 1 ns but was the limiting factor in switch lifetime.

The multichannel pseudospark [7], a switch of pseudospark geometry with several discharge channels instead of one central hole, has been studied at the German French Research Institute, Saint-Louis, France. A ten-channel switch operating at a voltage of 10 kV and a pressure of 10-Pa argon switched 14 kA with a dI/dt of 1.7×10^{12} A/s. A switch with only two channels operating at the same voltage and pressure carried 7.5 kA and exhibited a dI/dt of 7.5×10^{11} A/s. The triggering scheme used is called "charge injection" and is somewhat more complicated than other pseudospark triggering methods [4].

Proton-antiproton collider experiments at CERN required focusing of very high current antiproton beams with a linear charged particle lens. A 400-kA pulse generator utilising four pseudospark switches was developed for this purpose. More than 100 kA of current was carried by each of the pseudospark switches used in the plasma lens circuitry.

There has been one study of microwave emission from pseudosparks by a group at The Institute for Angew. Physik, TH Darmstadt, West Germany [9]. This group studied the time evolution and angular distribution of the emission from a five-gap pseudospark discharge. The microwave pulses observed had a half-width of 2 ns with maximum intensity in the J band (5.3-8.2 GHz).

The group at the university of Southern California (USC) has used pseudospark electrodes to develop a group of "back of the cathode light triggered" thyratrons (BLT's) [6]. The BLT can be triggered by several optical methods, and small-single-gap devices have achieved peak currents of >50 kA and a circuit-limited dI/dt of 4×10^{11} A/s.

2. *PRINCIPLE OF OPERATION*

Figure 1 illustrates the scheme of the discharge geometry. Two parallel-plane electrodes with holes on a common axis are separated by an insulator ring at a distance d (d normally some millimeters). With gas pressures of typically 10 Pa, working range of this geometry is on the left-hand branch of the Paschen curve. At breakdown, the longest possible path is preferred, producing an axial discharge. The applied voltage can be >100 kV with multigap devices. Figure 1 shows the pseudospark discharge in a single-gap as well as in a multigap pseudospark chamber.

Time-resolved optical spectroscopy of the pseudospark discharge and measurements of delay and jitter lead to the following simple model of the temporal development of breakdown, described briefly in [3]. The pseudospark starts on axis according to the generalised Townsend scheme.

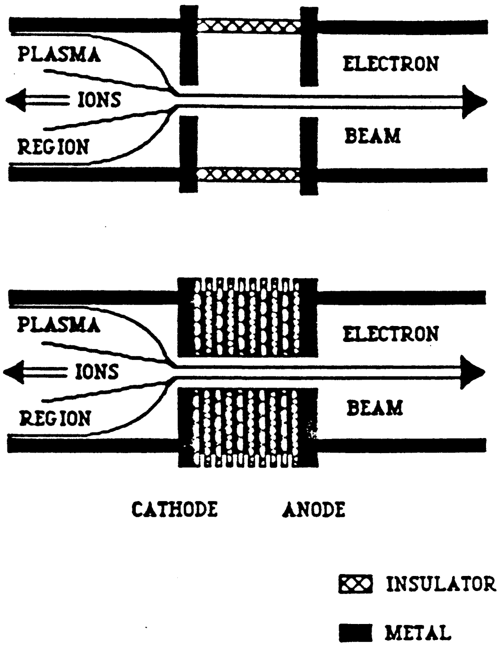


Fig. 1 - *Schematic of single-gap (top) and multigap (bottom) pseudospark chambers, showing the discharge geometry.*

As soon as the positive space charge which is caused by this high-voltage predischarge reaches a critical value near the cathode hole, the discharge plasma extends axially into the hollow cathode with a velocity of about 10^6 m/s due to an ionisation wave. This leads to a very fast current rise because within the hollow cathode the yield of secondary electrons and the efficiency of electron-impact ionisation are increased. The increased ionisation efficiency is a direct result of the "pendel electrons" [10]. These electrons reflect back and forth between the cathode sheaths of the hollow cathode and effectively ionise the plasma. Secondary emission is also increased because the cathode sheaths tend to be thinner in hollow electrodes, causing a greater ion velocity at the cathode surface. These hollow-cathode effects [11]-[14] imply that only few electrons are needed in the cathode backspace to initiate breakdown. Because of this, and the special geometry, triggering by several methods is possible.

Pseudospark triggering methods include a dielectric surface flashover and a pulsed, low-current discharge. The manner in which these triggering methods initiate closure of the switch is discussed in later sections. A third electrical triggering method has been demonstrated using an electron beam injected into the hollow cathode. The BLT discharge is initiated by photoemission of electrons produced by unfocused UV radiation incident on the interior of the hollow cathode. The UV light may be directed into the switch from a laser, a flashlamp, or a spark, or by coupling the light into a fiber-optic cable. The process of photoemission which initiates triggering is currently unclear. It is believed that the dielectric window allowing optical access to the hollow cathode plays a role. This window, or fiber as the case may be, is exposed to the plasma and accumulates a surface charge. Electrons are then emitted when UV light illuminated this dielectric surface.

3. *TRIGGER METHODS AND RESULTS*

3.1 "Charge Injection" Trigger

This trigger method was developed by G. Mechtersheimer at ISL, Saint-Louis, France [4]. An example is shown in Fig. 2. This method is based on a pulsed low-current gas discharge behind the rear cathode surface and allows repetition rates up to 100 kHz. The main switch is separated from the trigger module by a cylindrical cage forming the hollow cathode. This cage screens the trigger section from the main discharge thus providing a practically unlimited lifetime, greater than 10^{10} discharges of the trigger module. The cage is also necessary for the fast current rise.

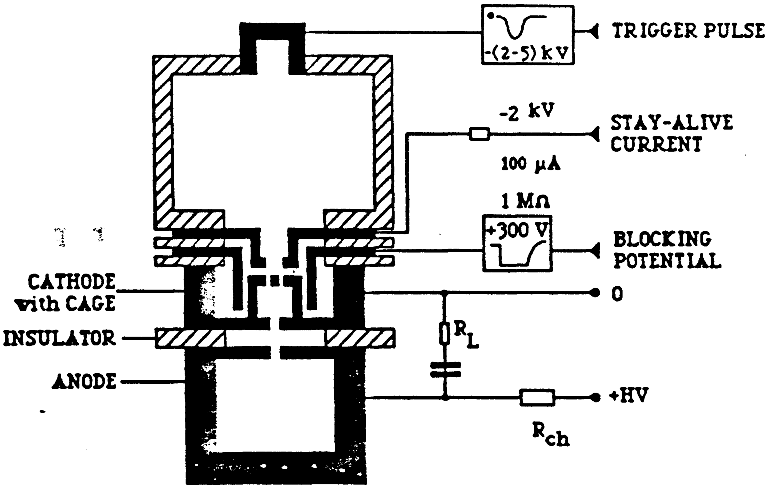


Fig. 2 - *Experimental pseudospark switch design for pulsed glow discharge triggering, and electrical circuit. To trigger the switch, the blocking potential of several hundred volts is driven to zero, and a negative high-voltage pulse of 2-5 kV in amplitude and several microseconds duration is simultaneously applied to the trigger electrode*

A positive voltage of up to 300 V, applied to the electrode surrounding the cage, influences the hollow cathode of the main switch through holes on the side of the cage. This prevents the buildup of a positive space charge in the hollow cathode and suppresses undesired statistical prefiring of the main switch.

A low current glow discharge ($I_{dc} < 1$ mA keep-alive current) provides preionisation inside the trigger section. For triggering, a pulsed gas discharge (maximum current < 1 A) is generated by applying a negative pulse of several kilovolts to the trigger electrode. At the same time the blocking potential is switched to zero, thus enabling the charge carriers penetrating through small holes in the top of the cage to initiate closure. Reapplication of the blocking potential thereafter accelerates recombination of the switch plasma. Within a few microseconds, depending on the parameters of the preceding discharge, high voltage can be applied again to the switch. The power necessary for triggering the pseudospark switch is relatively small, requiring about 200 mW for d.c. preionisation and less than 0.2 mJ/pulse for switching the trigger and auxiliary electrodes. The pseudospark switch has been shown to work with various gases in a pressure range of 10-100 Pa. Anode triggering is also possible, although over smaller ranges of pressures and voltages.

The delay between the application of the trigger pulse and the onset of voltage breakdown of the main switch is governed by a 2-stage process:

1) The onset of the trigger discharge is characterised by a step rise of the trigger current and is *independent* of the high voltage applied to the main switch. The buildup time of the trigger discharge strongly depends on the geometry of the trigger section, the pressure, the preionisation current, and the trigger pulse characteristics. The best data are achieved for preionisation currents which are characteristic of the transition from a normal to an abnormal glow discharge. Figure 3 shows the delay as a function of the preionisation current. The best result was a delay of 150 ns at a trigger pulse amplitude of 7 kV.

2) From the onset of the trigger discharge there is a delay before the buildup of the positive space charge in the hollow cathode of the pseudospark chamber. Normally the main discharge is formed within 10-50 ns.

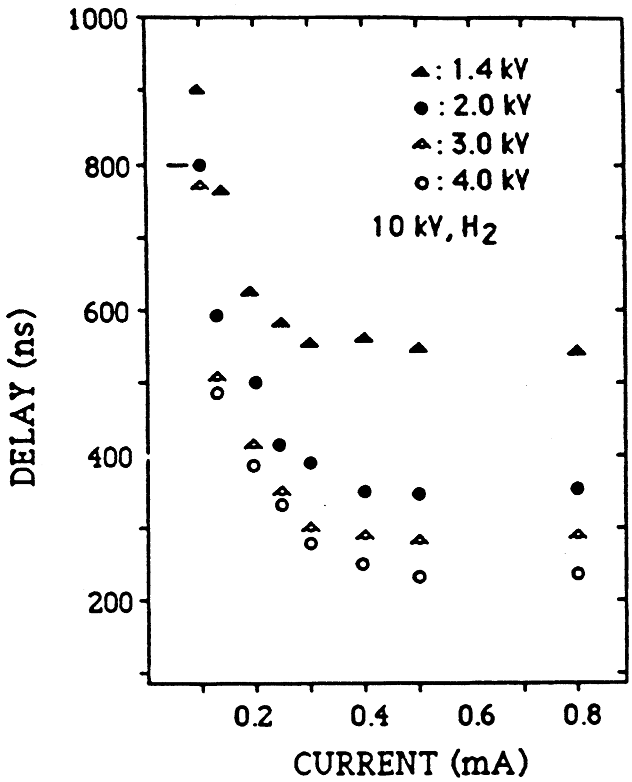


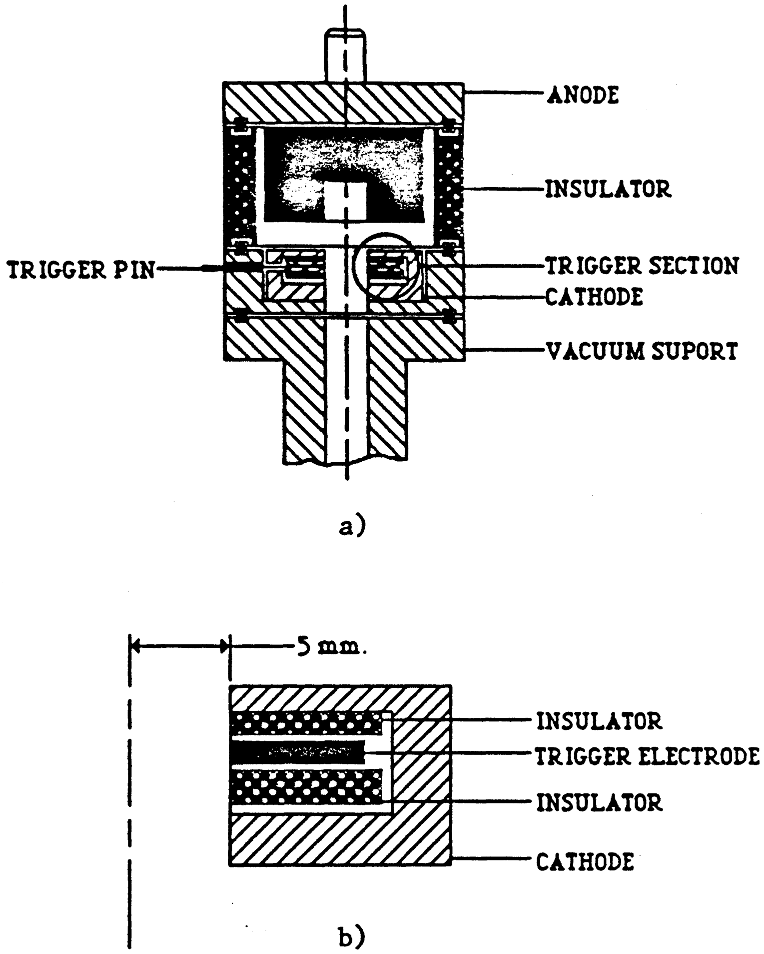
Fig. 3

Delay of the pulsed-glow discharge triggered pseudospark as a function of the preionisation current, for different trigger pulse amplitudes.

Single channel pseudospark switches have been designed for medium voltages and currents of typically less than 20 kV and 10 kA. The switches work at high repetition rates of up to 100 kHz and fast current rise rates of up to 5×10^{11} A/s with a jitter of about 1 ns. These switching capabilities are considerably improved by multichannel pseudospark switches with as many as 19 discharge channels linearly arranged on common cathode and anode plates [5]. Triggering is again provided by a pulsed low-current gas discharge. The inductance of the completely closed switch is less than 0.5 nH. The current rise rate, limited by the resistive breakdown time, is increased to 2.4×10^{12} A/s at a voltage of 10 kV

3.2 Surface Discharge Trigger

Preliminary studies of this triggering scheme were done at CERN, and the results were first described [3]. Subsequent work at Erlangen includes the following. The surface discharge trigger is integrated into the hollow cathode of the main switch by embedding a trigger electrode between two thin insulator discs. A high-voltage pulse (U_{pulse} = 3kV, t_{Rise} < 10 ns) is applied to this electrode (Fig. 4). The insulating discs in these investigations were organic materials like Mylar and



TRIGGER SECTION

Fig. 4 - Schema of the slide-spark-triggered pseudospark switch (a), and enlargement of the trigger section (b). The discharge is ignited by applying a high-voltage pulse (of typically 2 kV) to the trigger electrode, causing the surface of the thinner insulator to flash over.

Kapton (both manufactured by DuPont), which lose their surface dielectric strength through treatment with long-term high-voltage pulses because of a burned-in, low-impedance trace of carbon ("conditioning") [15]. If long-term pulses are used for triggering the trace of carbon is reproduced, and lifetimes of 10^8 or more discharges can be reached. Later on, however, delay and jitter degrade as a result of the continuous erosion of the insulator. Using short-trigger pulse lengths of less than 100 ns, the lifetime of the surface discharge trigger is limited to 10^5 discharges due to the reduction of the carbon trace. Subsequently, the trigger must be "conditioned" again.

The process of triggering may occur as follows: the sliding spark produces a dense gas cloud and a high number of free electrons and VUV photons, which can ionise the gas effectively. A plasma develops, which rapidly expands into the hollow cathode of the switch. The starting electrons, necessary for the buildup of the positive space charge, are thus produced in the region of high electric fields. This mechanism results in a short delay between the trigger and the pseudospark discharge, as well as very small jitter. Typical values are 30 ns and 0.8 ns, respectively. These values are independent of the power of the spark, in contrast to triggered vacuum gaps. The pulse energy sufficient for fast triggering is below 0.4 mJ.

The following results were obtained at switch voltages smaller than 20 kV and currents up to 4 kA. The location of the trigger discharge inside the hollow cathode could be set at four different positions, 1, 3, 5, 7 mm, referred to the cathode surface facing the anode. Figure 5 demonstrates the dependence of delay and jitter on the normalised pressure p/p(Br), where p(Br) is the pressure for self-breakdown in hydrogen at a given voltage. The trigger position was fixed at 3 mm for this figure. The delay increases with decreasing pressure and with decreasing gap voltages. The jitter, on the other hand, is nearly constant in the normalised pressure interval of p/p(Br) = 0.55 to 0.95. Below this, however, it grows rapidly. With growing electrode spacing the delay increases as well, while the jitter stays almost constant. The quantitative behaviour of these functions is independent of the working gas: in nitrogen the delay is approximately 15% smaller than in hydrogen, whereas the jitter is nearly identical. If the distance from the trigger discharge to the cathode surface is increased, a rise in delay and jitter is observed. Between 1- and 3-mm distance delay and jitter change only slightly, whereas beyond 5 mm a rapid increase is found. This is an important result, because the lifetime of the carbon trace in the 1- and 3-mm positions is significantly different: 40 000 and 150 000 discharges, respectively.

The pseudospark can be triggered at the cathode and at the anode. The delay at the anode is longer by a factor of 4. In summary, the basic advantages of the surface discharge trigger are its short delay and small jitter. It is a simple construction which needs no power in standby mode, and also requires no additional blocking and control electrodes with corresponding circuitry. Its main disadvantages are reduced lifetime and the production of carbon and gaseous products. These problems may be solved by suitable trigger insulators.

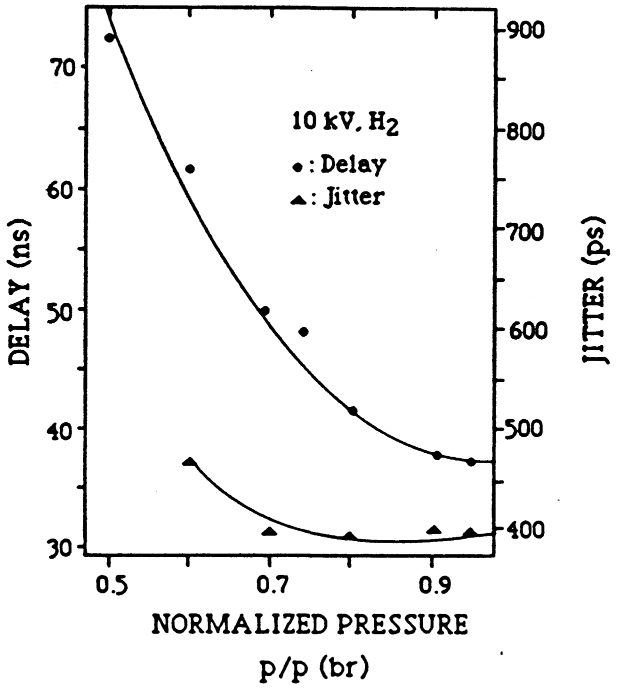


Fig. 5 - *Delay and jitter of the slide-spark triggered pseudospark as a function of the pressure p at a voltage of 10 kV (p(Br) is the pressure of self-breakdown at 10 kV).*

3.3 Optical Trigger

High-power laser-initiated switches, such as laser-triggered spark gaps, have been under development for more than 20 years [16]. The laser triggering mechanism normally requires a focused laser which produces a plasma, electrode damage, and electrode erosion at the laser focus [16]. Photoemission has also been investigated for high-pressure spark gap triggering [17], but with little success. The BLT differs from these other devices in that unfocused light initiates the discharge through photoemission, rather than through the formation of a plasma at the surface of the cathode. This is ordinarily not possible with a high-current switch, as it has not been possible to fabricate devices that have both photosensitive cathodes and have the cathode in a region where either the laser or arcing produce permanent cathode damage.

The BLT is similar to the pseudospark [6], but differs in that the conductive phase is initiated by light. The light is incident on the back of the cathode. Typical operating parameters are 10-50-Pa H_2 or He, 3-mm electrodes separation, and a few millijoules of UV radiation. Over 35-kV stand off has been obtained, with circuit-limited dI/dt ~ 4×10^{11} A/s. Optical triggering has been demonstrated by 1) by using an unfocused laser (XeCl at 308 nm and KrCl at 222 nm) directly incident on the back of the cathode, 2) by a flash lamp [8], 3) by radiation from a spark generated in air, and 4) by coupling laser radiation into the BLT cathode area through an optical fiber [7].

The compact structure of the anode and cathode, as well as the pseudospark and BLT results, suggest that extremely high dI/dt should be possible. A two-gap construction achieved stand-off voltages in excess of 60 kV. It should be straightforward to connect several BLT's in parallel in order to lower the inductance and increase peak current capability. Because several switches can be triggered by the same laser, pulse-to-pulse jitter should be minimal. Switch-to-switch jitter, however, is not known for this configuration.

3.4 Flashlamp Trigger

Characterisation of the laser-triggered switch revealed that only a few millijoules of light energy was required to initiate the discharge, prompting the design of a switch using a UV flashlamp. The flashlamp-switched BLT has significantly improved power gain and is a simpler device than the laser-triggered BLT. This version has operated at hold-off voltages of more than 37 kV, peak currents of more than 37 kA in 2-μs pulses, and at a repetition rate of 100 Hz. This repetition rate was limited by available power supplies and not the switch. The power gain, measured as the ratio of switched energy to trigger energy, was ~1400. High repetition rates should be achievable, partially because energy loading restrictions will be somewhat relaxed as a result of the simpler structure. A UV flashbulb (EG&G FX265) was used as the trigger light source. The bulb has an electrical-to-light-energy conversion of about 14% with up to 39% of the light energy below 300-nm wavelength. It is mounted directly behind the hollow cathode such that the window of the bulb is also the window of the switch. This allows the maximum coupling of light into the hollow cathode. With an improved trigger and discharge circuit for the flashlamp, the rise time of the light pulse was reduced to 35 ns, resulting in a delay of 260 ns and a jitter of 22 ns [8]. Streak-camera recordings at different wavelengths show that, as pointed out above, the discharge is a homogeneous dense glow located in the vicinity of the electrode holes, rather than a spark or arc.

3.5 Fiber Optic Trigger

It is also possible to use a fiber-optic waveguide to deliver the UV light pulse to the cathode. Advantages of using an external light source for triggering include complete electrical isolation, serviceability of this trigger separate from the switch, and ease of triggering multiple gaps/switches simultaneously. At a wavelength of 308 nm (XeCl excimer laser), consistent triggering was found with as little as 1.5 mJ of energy incident in a 15-ns pulse. The pressure was 15-26-Pa H_2, the switch was operated at repetition rates of 1 to 10 Hz with voltages up to 25 kV and pulse durations of 1.5 μs. The peak current reached about 4 kA with a dI/dt of 3×10^{10} A/s. The circuit was not designed to test the switch for high peak currents and dI/dt's; consequently, these numbers are rather modest.

The best jitter and delay times to date are 0.8-ns FWHM and 78 ns, respectively, operating at a pressure of 27 Pa of H_2, 10-kV anode charging voltage, 4.4 mJ/308 nm light from the fiber, and molybdenum electrodes. A serious concern for this device is the metallisation of the glass walls adjacent to the electrodes and of the fiber due to evaporation of the electrode material around the holes. We have operated the ıtch at 15 kV (50 J/pulse) for 1×10^5 shots with nickel electrodes and more than 2×10^5 shots with molybdenum electrodes. At the end of these runs, the switch often flashed over at the metallised glass surface near the electrodes and the output power from the fiber had significantly decreased (Fig. 6).

The number of photoelectrons generated by the UV light pulse from the fiber has been directly measured using a collection electrode within the hollow cathode. From 5×10^8 to 2×10^9 photoelectrons were measured for light-pulse energies ranging from 1.5 to 6 mJ at 308 nm. This corresponds to a quantum efficiency of about 10^{-7}, which is reasonable since the work function of the electrodes (about 4.25 eV for molybdenum and 5 eV for nickel) is slightly greater than the energy per photon (4.025 eV at 308 nm). Comparable results were achieved using only 10 µJ of laser light at 222-nm incident on the rear cathode surface. The corresponding quantum efficiency is almost a factor of 700 larger than that at 308 nm.

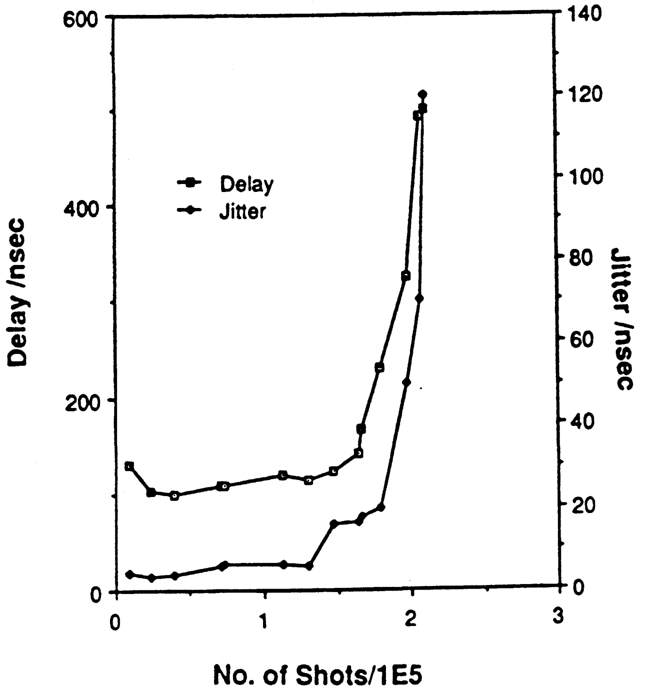


Fig. 6

Jitter and delay of an excimer laser/fiber optic triggered BLT as a function of the number of discharges at 15 kV, 50 J/shot, and 8 kA, at a hydrogen filling pressure of 16 Pa. The initial laser pulse energy at the back of the cathode of 4.4 mJ at a wavelength of 308 nm decreased strongly at the end of the test when the fiber was covered by an absorbing metallic layer. This decrease in light energy causes the rapid increase of delay and jitter.

4. *APPLICATIONS*

Prototypes have been tested in different types of gas lasers which are normally driven by hydrogen thyratrons or high-pressure spark gaps. A charge-injection-triggered pseudospark replaced a hydrogen thyratron in a discharge-heated longitudinal copper vapor lasers [4]. Peak currents of 400-1500 A in 60-100 ns pulses have been achieved at repetition rates up to 30 kHz for switch voltages between 9 and 15 kV.

A pseudospark triggered by a surface discharge was used as a switch for a TEA-N_2 laser [18]. The current rise time of 16 ns was primarily determined by the discharge circuit. At a voltage of 15 kV and a maximum current of 8 kA, the shortest switch turn-on delay amounted to 30 ns, including the delay of the electronic control device. The overall jitter of the laser is less than 1.3 ns at a minimal laser delay of 63 ns. A current reversal of 100% can be tolerated without damage. This method of triggering requires a small, very fast and reliable control device. For this purpose, a seven-stage Marx-type pulse generator, which consisted of selected avalanche transistors, was developed [19].

A flashlamp-triggered BLT was tested as a replacement for a thyratron in a commercially available XeCl excimer laser. The magnetic "assists" in the pulse circuit were removed and the laser performed at least as well as with the thyratron and magnetic circuitry.

Four pseudosparks in parallel have been used at CERN to operate a prototype plasma lens [20], [21]. The pulse generator powering the plasma lens consisted of four parallel, specially designed pseudosparks switching four 25-μF capacitor banks charged to a voltage of 16 kV. Peak currents exceeded 400 kA, e.g., more than 100 kA per switch, with a dI/dt of 6×10^{11} A/s. The pulse length was 15 μs with a 45% reverse current. These switches operated at helium pressures of 1-5 Pa and repetition rates below 1 Hz. They have switched 3.5 kJ/shot for more than 400 000 shots and are capable of 100% current reversal. The amount of charge transferred per shot is greater than 0.4 C.

6. *CONCLUSIONS*

Using a pseudospark switch triggered by a surface discharge, it is possible to initiate switching with time delays of less than 40 ns and jitters smaller than 1 ns. These results are valid for voltages up to 20 kV and currents of 10 kA. The rate of current rise $dI/dt = 5 \times 10^{11}$ A/s is partly restricted by the discharge circuit. Comparable performance has been demonstrated with the BLT, which also has the special attraction that it can be electrically isolated. The experimental work done up to now demonstrates that these switches not only can perform as well as existing thyratrons, but also possess some of the important advantages of the high-pressure spark gap, including high peak current and high rate of current rise. Pseudosparks can also achieve very high repetition rates and long lifetimes using the "charge injection" trigger. Long lifetimes are also expected for other triggering methods because of the cold-cathode operation.

In summary, these switches operate in a glow-discharge mode without electrode degradation from arcing. they utilise a cold cathode and under varying operating conditions have switched over 100 kA, demonstrated over 2×10^{12} A/s dI/dt, and achieved subnanosecond jitter. Table I presents a direct comparison between thyratrons and these hollow-cathode devices. These switches are the result of basic research programs. The anomalously high (» hot cathode) current densities (40 000 A/cm^2, » normal thyratron plasmas), obtained in a non-arcing mode and with a simple structure, strongly encourage further basic study of plasma devices. The physics of the cathode emission and high current density require study, and further device applications should be sought.

Table I

Principal points of comparison between hot-cathode thyratrons and hollow-electrode high-power switches

Parameter	Hot Cathode	Hollow Electrode
Conduction medium	Glow	Glow
Gas medium	H_2	H_2, He, N_2, Ar
Peak current	-10 kA	>100 kA
Cathode	Thermionic	Cold
dI/dt (A/s)	2×10^{11}	$>10^{12}$
Reverse current	10%	100%

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