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HIGH SPEED SWITCHING IN GASES*

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INTRODUCTION

A fast, efficient and reliable switch is the basic ingredient of a pulse power accelerator. Two switches have been proposed so far: the solid state switch, and the vacuum photodiode switch. The solid state version has been tested to some extent, albeit at low (few kilovolts) level, with risetime around 10 ps in the radial line transformer configuration.[1] The vacuum photodiode is being investigated by Fisher and Rao at Brookhaven National Laboratory.[2] Common to both switches is the need of a short laser pulse; near infrared for the solid state switch, and ultraviolet for the vacuum photodiode switch. Another common feature is the poor energy gain of these switches: the gain being the ratio between the electrical energy switched and the laser energy needed to drive the switch. For the solid state switch, calculations and experimental data[1] show that the energy gain cannot exceed a value between 5 and 10. For the vacuum photodiode, the situation is somewhat similar, unless very high quantum efficiency, rugged photocathodes can be found. A closing switch also can be used to produce short pulses of RF at frequencies related to its closing time, using a well-known device called the frozen wave generator.[3] For a risetime of the order of 30 ps, one could produce several Gigawatts of RF at Xband at very low cost.

AVALANCHE GROWTH CALCULATIONS

The calculation of the avalanche growth in gas has been attempted by many authors, with various degree of success. In particular, the calculations have centered the attention on complex breakdown phenomena related to high power switching, for conditions that span from very low gas pressures (below atmospheric, as in the case of thyratrons) to values of the order of a few atmospheres. Our interest is to obtain extremely high rate of rise of the current; as a consequence, we must look at the breakdown conditions in a region of

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electric field/pressure, pressure and initial electron distribution different from those typical of a conventional spark gap. In a conventional spark gap the main current is carried by a rapidly expanding, hot channel which has an inductance capable of limiting the rate of rise of the current. This limitation is removed to some extent by rail gap switches, where the inductance of the gap due to the hot thin channel is reduced by having many channels in parallel.

If the geometrical inductance of the spark and of the electrode structure is made negligible, the next limit to a fast current rise is the resistive phase of the spark itself.

The initial phase of breakdown is universally assumed to be an electron avalanche, developing under the influence of an applied electric field. The growth rate is given by:

$$N(t) = N_o e^{\alpha v t} \tag{1}$$

Where α is the first Townsend coefficient, v the electron drift velocity, t the time, N_o the initial number of electrons present in the field region at the time $t = 0$.

The avalanche does not grow indefinitely: when the internal electric field cancels approximately the external field, the avalanche speed changes, and so does the propagation mechanism. It is said that the avalanche has reached the streamer phase. Typical number of electrons in an avalanche at the streamer transition is of the order of 10^8 ($\alpha v t = 20$).

The avalanche growth time can be reduced by increasing gas pressure, and maintaining constant the value of E/p. In fact, the value of α/p is constant for constant E/p (hopefully up to very high pressure); and the electron drift velocity also scales as E/p. Some experimental data on α/p and drift velocity as a function of E/p are shown in Figs. 1 and 2. Since the avalanche growth time is $1/\alpha v$ [from Eq. (1)], it follows that one can increase the speed by increasing the gas density and the electric field (Fig. 3).

However, as will be shown later, one single avalanche is not capable of producing a large current. Typically, if the electron drift velocity is 10^7 cm/sec, an avalanche containing 10^8 electrons will produce a current of 8 ma in a gap 200 microns wide. Many avalanches in parallel, *i.e.*, developing simultaneously in the same gap, will produce a large current, with a rate of rise related to the avalanche growth time. In other words, as observed by Dickey,[4] if the number of initial avalanches is large, the current due to the electrons moving in the

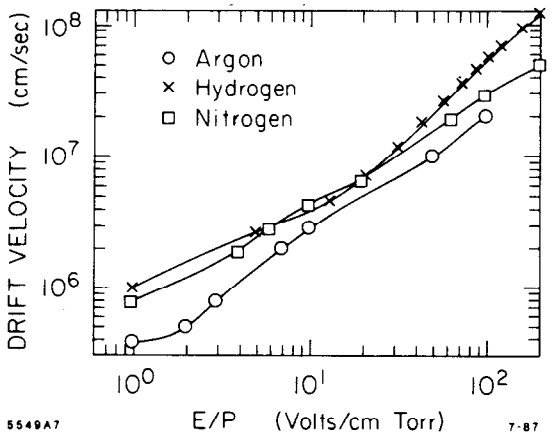

Figure 1: Electron drift velocity for different gases, as a function of E/p (electric field/pressure).

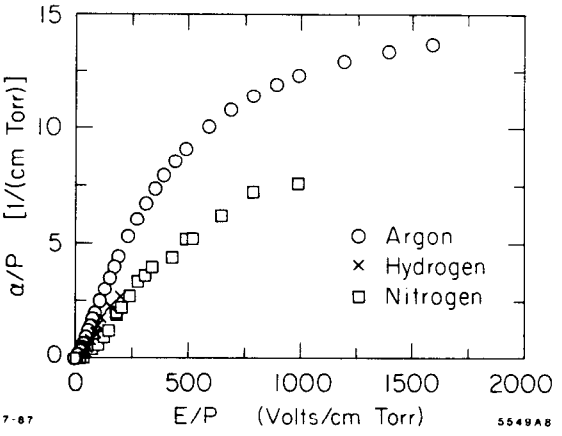

Figure 2: α/p, ratio of first Townsend coefficient/gas pressure, as a function of E/p.

gap at their drift speed will be sufficient to collapse the voltage applied to the gap, without waiting for the streamers to coalesce in a spark and connect the anode to the cathode. Notice also that if the avalanche growth is as fast as a few picoseconds, avalanches a few millimeters apart will be "transit time isolated" from each other.

There is some experimental evidence that each individual electron develops a separate avalanche even when the initial electrons are very close to each other.[5] The authors in this reference report the observation that when the number of electrons starting the avalanche is large, the breakdown proceeds uniformly in the gas, without the formation of filamentary discharges.

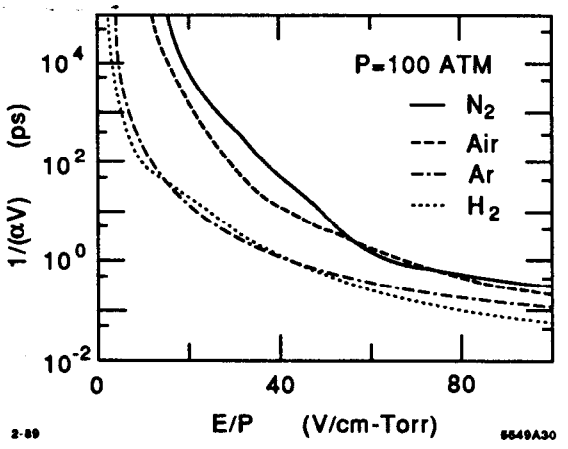

Figure 3: $1/\alpha v$, or time constant for avalanche growth, for different gases (Air, Nitrogen, Hydrogen, Argon), at a pressure of 100 Atm.

Some evidence about speed of growth of the current comes from gas avalanche counters.[7] In these counters, the ionization left in an appropriate mixture of high pressure gases by a charged particle grows under the influence of the applied electric field, generating a very fast pulse.

Although the pulse has not been observed at the bandwidth necessary to observe a few hundred picoseconds risetime (these pulses could not propagate along the counter's structure), one can infer the speed of the output from the timing jitter of the counter.

The other evidence comes from work done by Fletcher,[6] and quoted by Dickey.[4] The latter author points out that the fast risetime observed in a highly overvoltaged gap by Fletcher can be explained quantitatively with a simple equation:

$$C \frac{dV}{dt} = -\frac{qN_o v}{g} e^{\int \alpha v dt} + \frac{V - V_0}{R} \tag{2}$$

where qN_o is the charge of N_o electrons initially released in the gas (by a picosecond ultraviolet laser, for example, focused into the switch gap volume); α and v are experimental data;[9] V_o is the voltage applied to the switch; and R is the impedance in series with the switch. The value of the capacity C of the switch is estimated as two flat paralled electrodes separated by a gap g.

This equation can be solved numerically; some predicted waveforms for different gases are shown in Fig. 4.

The numerical solutions of Eq. (2) were compared with the calculations reported by Mayhall[8] for Air as avalanching gas. The results are in Fig. 5. The agreement between the two calculations is remarkably good. The conditions are identical for both simulations, except that we scaled the value of α in our code by a constant factor of .67. The two-dimensional code of Mayhall does not use explicitly the parameter α, but the cross sections are extracted from the value of α (among other "ingredients") measured experimentally. If one reconstructs the value of α as a function of E/p from the two dimensional code, one obtains a value of α systematically smaller than the measured value by about 30%. In conclusion, if the function α (E/p) is the same in both codes, the resulting waveforms are identical.

Equation (2) makes the implicit assumption that the value for α is a function of E/p, as given by measurements. This assumption, albeit correct in most cases, should be modified to take into account the following effect: when an electron avalanche grows to a large density, a modified value of α has to be used, since there is a finite probability that any electron in the

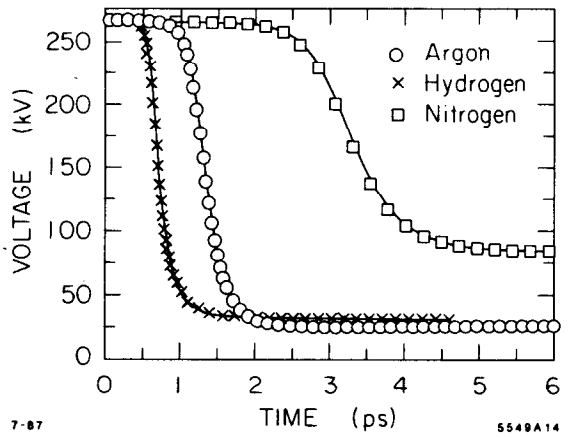

Figure 4: Voltage waveform from numerical integration of Eq. (2). The conditions are E/p = 100, Volts/cm Torr, 100-micron gap, 10^8 initial electrons, 350 Atm pressure.

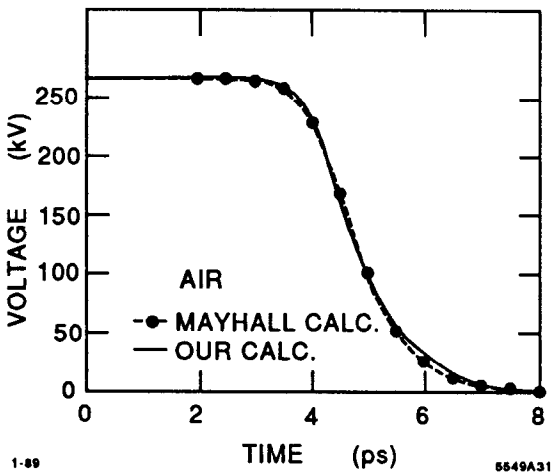

Figure 5: Waveforms as calculated with Eq. (2) and by Mayhall with a two-dimensional avalanche simulation code.

avalanche may collide with a molecule (or atom) that has been already ionized by a previous impact. This free charge density effect is not present in the conventional measurements of α, because the density of free electrons in these electron swarms is very small. To estimate the density of the avalanche we have assumed that the diffusion velocity (transverse to the electric field) is $1/n$ of the electron drift velocity, where n is a small number greater than one. This may or may not be a good assumption, because the local electric field is already distorted by the avalanche charge distribution. Certainly n cannot be smaller than one. The ratio R of ionized to nonionized atoms in the avalanche volume is given by:

$$R = \frac{n^2 e^{\alpha v t}}{N_a p v^3 t^3} \tag{3}$$

where p is the operating pressure of the switch and $N_a p$ is the number of molecules per unit volume. Inserting some numbers, we find that R is of the order of .5 for a value of t given by:

$$R = \frac{n^2 e^{\alpha v t}}{N_a p v^3 t^3} \quad , \qquad Ar \text{ at } 100 \text{ Atm } E/p = 100$$

$$
\begin{aligned}
v &= 4 \times 10^7 \text{ cm/sec} \\
\alpha &\sim 2.5 \times 10^5 \text{ cm}^{-1} \\
\alpha v &\sim 10^{13} \text{ sec}^{-1} \\
n &= 2 \\
N_a &= 2.68 \times 10^{19} \\
R &= .5 \quad , \qquad \text{for} \quad t = 1.9 \times 10^{-12} \text{ sec} \quad .
\end{aligned}
$$

Therefore, sometime during the avalanche growth process it becomes necessary to consider the fact that the effective α must be changed.

This effect has been taken into account in our calculations as follows:

Consider an infinitesimal time Δt, during which the avalanche traverses a volume ΔV, containing k gas molecules. The number of ionization events produced by a single electron in the avalanche during this time is $\alpha v \Delta t$. For a low density avalanche (low density means that the number of nonionized molecules is large compared to the ionized fraction), the increment of ionized molecules will be $\Delta N = N \alpha v \Delta t$. To consider the case where N approaches k, we look at each electron in the avalanche sequentially, and reduce the probability of ionization by the reduction of gas molecules from previous ionization:

$$
\Delta N = \sum_{i=1}^{N} \alpha v \Delta t \ (1 - \alpha v \Delta t / k)^{i-1} \quad . \tag{4}
$$

Summing this series:

$$
\Delta N = k[1 - (1 - \alpha v \Delta t / k)^N] \quad . \tag{5}
$$

Since the ionization from a single electron does not approach the total number of gas molecules, or $\alpha \cdot v \cdot \Delta t << k$:

$$
\Delta N = k[1 - e^{-N \alpha v \Delta t / k}] \quad . \tag{6}
$$

Let R be the number of ionization events expected without taking into account the finite number of gas molecules available, divided by the total number of gas molecule available,

or:

$$R = N\alpha v\Delta t/k \quad ; \tag{7}$$

then:

$$\Delta N = k[1 - e^{-R}] \quad . \tag{8}$$

Therefore, the reduction factor, *i.e.*, the actual ionizations divided by the expected (uncorrected) number is:

$$r = \frac{\Delta N}{N\alpha v\Delta t} \tag{9}$$

then the factor r is given by:

$$r = \frac{1 - e^{-R}}{R} \tag{10}$$

describing the reduction in avalanche growth due to density corrections. This factor has been included in the numerical calculation of Eq. (2).

As expected, there are substantial differences between the numerical solutions of Eq. (2), with and without density corrections, when the value of R [Eq. (3)] is sufficiently large.

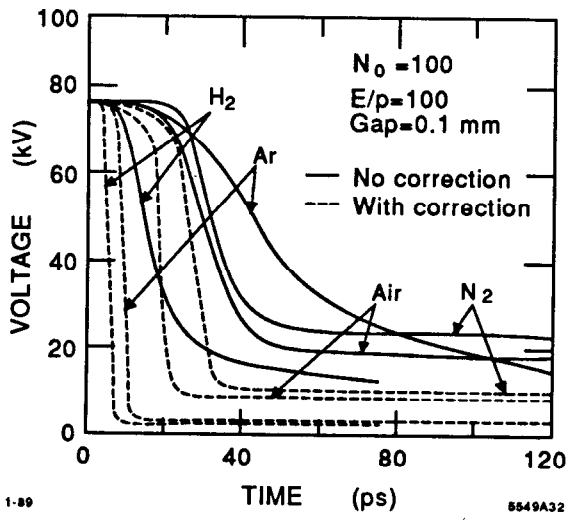

Figure 6: Effect of density correction on calculated waveforms.

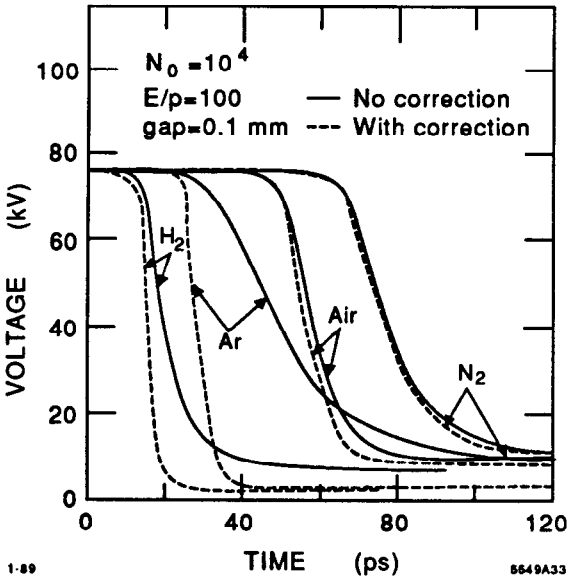

Figure 7: Same as Fig. 6, increasing the number of initial electrons by 100.

Some typical results are in Figs. 6 and 7. The waveforms are predicted for H_2, Air, Ar, N_2, for E/p = 100 V/cm Torr, at a pressure of 100 Atm. The two figures differ in the number of initial electrons released in the 100-micron gap at the time $t = 0$. Argon seems to be the gas that suffers the most from the reduction of α, since its drift velocity is low. Hydrogen would seem the gas of choice, but it appears untractable because of the very short formation time. Nitrogen appears promising because of the long formation time and rather fast risetime.

The effect modeled by Eq. (10) may or may not be a good representation of the true avalanche dynamics: many other complicated effects should be considered, one being the field enhancement at the head of a dense avalanche.

COMPARISON WITH EXPERIMENTAL DATA

We have compared the solutions of Eq. (2) to the waveforms recorded by Fletcher,[6] using the values of drift velocity and α/p as reported in Ref. 9. We find the agreement between the calculations and the measurements particularly good, considering the uncertainties in the calculations due to errors in the measurements of α/p and v_{drift}, and the uncertainties due to our digitization of Fletcher's waveforms. It is important to notice that there are no free parameters to be adjusted to obtain such agreement. The calculated waveforms and the Fletcher "drawings" are shown in Figs. 8 through 12. The calculated waveforms do not include the risetime of the recording apparatus (cables, oscilloscope, attenuators). From Refs. 10 and 11, we guess the risetime of the recording system to be of the order of 70 ps. This system, called the micro-oscillograph, was designed and built in 1945, and it had the same bandwidth as the fastest Tektronix scope available today. The micro-oscillograph did achieve such short risetime by trading speed for vertical sensitivity.

If this risetime is added in quadrature to the calculated waveforms, the agreement does improve, since our calculations show a systematically faster pulse. Finally, it is important to point out that not only the risetime, but also the delay (otherwise known as the avalanche formation time) agrees quite well with Fletcher experimental data, using the initial number of electrons as reported in Ref. 6 ($\sim$ 100 electrons).

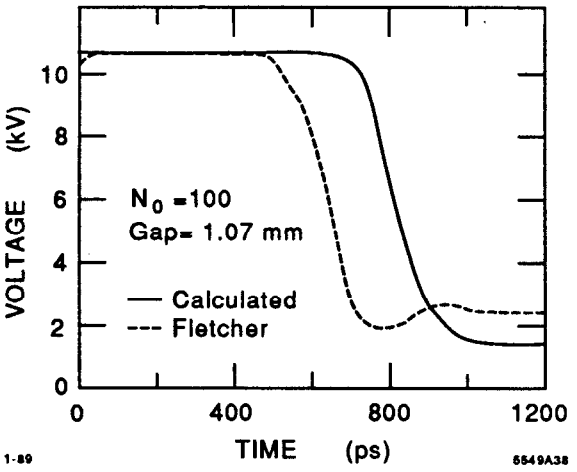

*Figure 8.**

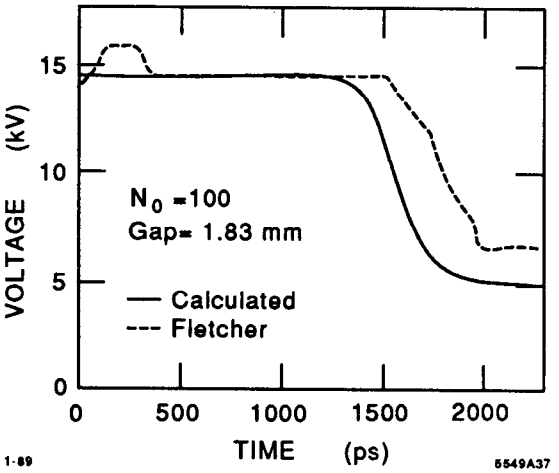

*Figure 9.**

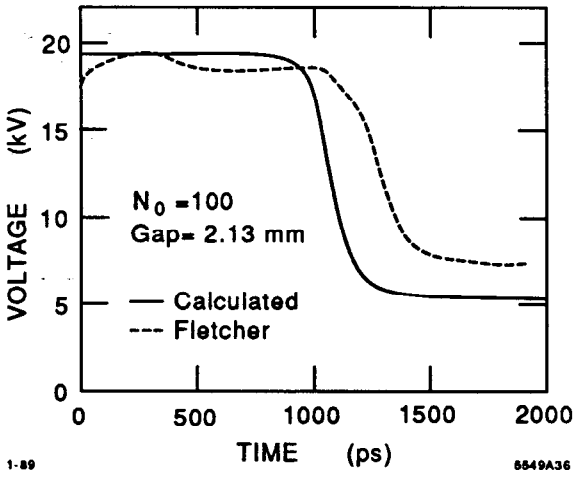

*Figure 10.**

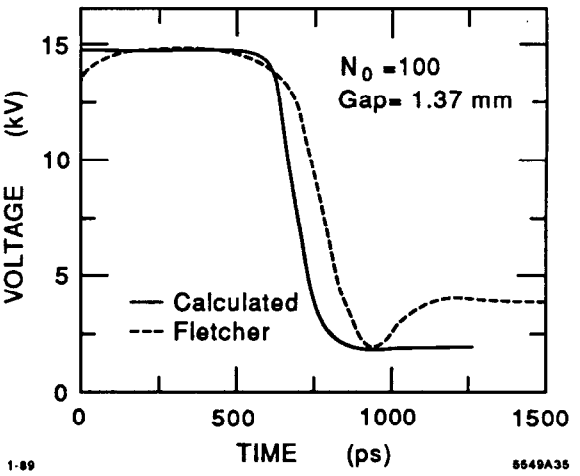

*Figure 11.**

* *Figures 8–12: Comparison between calculated waveforms and Fletcher's oscillographic recordings. The dashed traces are obtained by digitizing the* Physical Review *figures*[3] *enlarged* ~ 10 *times the original.*

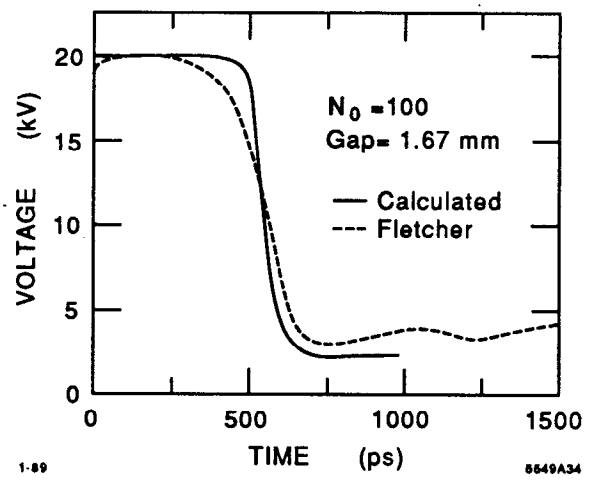

Figure 12. (See caption, previous page.)

LASER TRIGGER

The switch will be triggered by injecting free electrons in the high pressure gap; this can be achieved by illuminating the gas with a picosecond duration ultraviolet ($\lambda \approx 250$ nm) laser pulse. This wavelength can be obtained either with an excimer (KrF), or by quadrupling a dye or an equivalent laser emitting around 1000 nm. Shorter wavelengths may improve the ionization efficiency, but they are more difficult to transport, and not readily produced by "conventional" laser arrangements. An estimate of the energy needed to trigger the switch can be obtained from the value of the cross section for three photon ionization reported in Ref. 12, for Xe gas. We assume that 2 Atm of Xe is added to the gas of choice; the laser light will be focused on a line 10 λ wide, for a depth of 50 λ ($\lambda \cong 250$ nm), for a length of 1 cm. Under these conditions, a power density of 2×10^8 W/cm^2 (corresponding to 5×10^{-8} Joules in 1 ps) will produce 10^4 electrons. As mentioned before, ionization occurs when three photons are absorbed by the same Xe atom; hence, the electron yield varies with the third power of the number of photons/unit area $\times$ time. Therefore, for a laser energy of 2.5×10^{-8} Joules (3×10^{10} photons), the electron yield still will be 10^3, sufficient to trigger the switch. The electrical energy controlled by the switch is of the order of 4×10^{-3} Joules (100 KV on 50 Ω for 20 ps), or 10^5 times larger than the laser energy required to trigger: for an accelerator using 100 KJoules of electrical energy/pulse, the laser control will be of the order of a few Joules, considering the inevitable losses in handling the laser beam.

Other "seed" gases may have a much higher cross section for ionization, and an ionization potential requiring only two photons. Two possible candidates are NO, with an ionization potential of 9.5 ev; and C_7H_8, toluene, with an ionization potential of 8.5 ev. The ionization rate for these two gases is larger than that in Xe by a factor of 10^5 (at equal laser power density). If they can be used, they will be introduced in the switch gas in miniscule, almost undetectable, amounts, and further reduce the amount of laser energy needed to trigger.

EXPERIMENTAL PROGRAM

The main uncertainty in the switch performance comes from the possibility (or impossibility) to withstand high electric fields without breakdown, for a short time. Since any breakdown in this regime is initiated by field emitted electrons at the cathode, we plan to take particular care in the design of the switch electrodes. First, we will use materials that are known for their low field emission; second, the cathode's surface electric field will be made as small as possible. Switch lifetime and reliability, together with recovery properties, must await the experimental test.

A general purpose, high-pressure vessel with quartz windows (to inject UV laser light and to observe the switch breakdown) has been constructed. The vessel has two high voltage coaxial feed-throughs to bring voltage to the switch(es) and to observe the sharpened output. The high voltage is provided by a small Marx generator, appropriately shaped to generate subnanosecond risetime and short pulse duration.

The vessel can be "easily" opened, so that different switch geometries can be studied. The system has been pressure tested to 1000 Bar.

The fastest diagnostic available to us is a 60 ps risetime scope. We are prepared to measure the switching time with an electrooptical modulator in conjunction with a streak camera, if the risetime of the switch appears comparable to 60 ps.

The first measurements will determine how high an electric field can be supported across the switch under study, as a function of different gases, pressure, electrode geometries, gap width, *etc.* We are confident that we can predict the risetime of the switch, once E/p and p at breakdown are known. If some promising combination of gas, gas pressure, electrode material and geometry can be found, we will proceed to synchronize the high voltage pulse and the UV laser to actually trigger the switch.

CONCLUSIONS

A simple calculation predicts extremely high rate of rise for the current in a switch working in a high pressure gas, triggered by some electrons released by a very short pulse laser. The energy required to drive this switch is much smaller than the energy needed to drive the other two candidates (the solid state semiconductor and the photocathode). Our calculations agree very well with a more complex, fluid in cell code (see Mayhall, these

proceedings). The agreement with Fletcher's experimental data also is excellent. Although Eq. (2) cannot predict the actual development of an electromagnetic wave, it allows us to look at different gases with a modest use of computer time.

REFERENCES

1. C. Bamber *et al., Particle Accelerators,* Vol. 28 (1988) p. 255–263.
2. J. Fisher *et al., Proceedings of the 4th Workshop on Pulse Power Techniques,* Erice, Italy, March 4–9, 1988, to be published by Plenum Press.
3. J. M. Proud, Jr. *et al., IEEE Trans. Microwave Theory Tech.,* Vol. MIT–26 (1978) p. 137–140.
4. F. R. Dickey, Jr., *Journal of Applied Physics,* Vol. 23, No. 12 (1952) p. 1336–1339.
5. G. A. Mesyats *et al., Sov. Phys. Usp.* 29 (1) (1986) p. 57–69.
6. R. C. Fletcher, *Phys. Rev.* 76, No. 10 (1949).
7. W. B. Atwood, *Proceedings of Summer Institute on Particle Physics,* SLAC Report #239, p. 287–307 and references therein.
8. D. Mayhall, *Proceedings of the 4th Workshop on Pulse Power Techniques,* Plenum Press, to be published.
9. L. B. Loeb, *Basic Processes of Gaseous Electronics,* University of California Press, (1961) p. 719.
10. G. M. Lee, *Proceedings I.R.E.* 34, 121W (1946).
11. R. C. Fletcher, *Rev. Sci. Instr.,* Vol. 20, No. 12 (December 1949).
12. M. D. Perry *et al., Phys. Rev. A,* Vol. 38, No. 6 (September 1988).