High voltage pulse generators and spark gap for gaseous discharge control*

A.A. Huerta†, E. Bautista†,
L.J. Villegas† and M. Villagrán
Laboratorio de Optica Aplicada, Centro de Instrumentos, UNAM
Apartado postal 70–186, 04510 México, D.F., México
Recibido el 15 de julio de 1994; aceptado el 13 de marzo de 1995

Abstract. High voltage trigger pulses are required for initiating conduction in triggered spark gaps, xenon flashtubes, or to provide an ignition type pulse for other special devices requiring a high impedance voltage source. This work describes the design, construction and operation of three prototypes: two high-voltage pulse generators and a spark-gap. For the first generator the FWHM was 28.9 μs with an amplitude of 20.8 kV at frequencies of 1–12 Hz. For the second generator, the amplitude varied between 20–40 kV with a FWHM of 750 ns and rise-times of 820 ns at a frequency of 0.3–18 Hz. The spark gap driven by these generators works at voltages of up to 20 kV. In our case the generators and the spark-gap were used to control laser gaseous discharges.

Resumen. Para controlar llaves rápidas (*spark gaps*), lámparas de xenon o para proveer de pulsos de disparo de aparatos que requieran de una fuente de alto voltaje se utilizan generadores de pulsos de alta tensión. En este trabajo se presenta el diseño, construcción, caracterización y operación de tres prototipos: dos generadores de pulsos de alta tensión, uno electromecánico, otro totalmente electrónico, y una llave rápida. Con el primero se han obtenido pulsos de 20.8 kV con anchos medios de 28.9 μs a frecuencias de 1–12 Hz. Con el segundo se lograron pulsos de amplitud variable de 20 a 40 kV con anchos medios de 750 ns y tiempos de subida de 820 ns a frecuencias de 0.3–18 Hz. La llave rápida controlada con estos generadores trabaja con tensiones de hasta 20 kV. Los generadores, junto con el *spark-gap*, fueron utilizados para el control de láseres de descarga gaseosa.

PACS: 84.70.+p; 85.20.–t

1. Introduction

High-voltage pulses are required to control a spark-gap trigger in discharge circuits such as lasers and flash lamps. These are generally produced by high-current devices, such as thyratrons [1], or low-current electronic devices, such as SCRs (silicon controlled rectifiers) [2]. The appropriate switch is chosen according to these requirements. In all cases, the desirable pulse characteristics are minimum delay, jitter and rise time.

Synchronization of two or more pulses within a period of several hundred nanoseconds are required for various fields of investigation on lasers. For example, commercial Nitrogen and Excimer lasers, used to pump amplifying stages, have characteristic delay times of 1 μs

---

*Work supported by CONACYT # 1648/A9209, and DGAPA/UNAM # D0103592/IN103692.
†Students of the "Láseres y Optoelectrónica" course at Departamento de Física, Facultad de Ciencias, UNAM.

between the electrical signal applied to the pulse generating circuit and the production of the desired laser pulse. Also used for the same objectives, are circuits with avalanche transistors to reduce delay time to 680 ns and jitter time to 0.8 ns [3].

In our experiments of laser induced fluorescence or photoacoustic signals, in which gaseous lasers such as N_2 [4,5] are used as sources, a precise control of the discharge shot is necessary, since it is related to the laser rate frequency and its emission time. The pulses are also used to trigger oscilloscopes, lock-in amplifiers and to synchronize a pulse delay generator which controls an optical multichannel analyzer for time-resolved laser spectroscopy experiments.

Since these pulse generators are commonly used in pulsed discharge circuits in N_2, excimer or flash lamp dye lasers and many other applications, pulse generators that efficiently control spark-gaps have been implemented at a lower cost than thyratrons. Modules that produce these types of pulses exist in the foreign market [6,7] but at a high cost. This work describes the construction, characterization and operation of two low-cost modules (approximately at a fourth of its commercial cost), with advantages over the commercial ones. One pulse generator is electromechanically driven and the other is electronically driven and, together with the spark gap, both types are efficient and economical in controlling gaseous discharge of lasers.

2. Description and operation of the devices

2.1. Electromechanical module

The easiest and most economical way to generate high voltage pulses is by using a car ignition system, based on feeding low voltage from the battery to the coil where it is converted to a high voltage. This high voltage pulse is powerful enough to jump the spark plug gap at the spark gap, as we shall explain further on.

In our design, we used a modification of a high energy ignition system, consisting of a pulse-triggered, transistor-controlled, inductive discharge system, in which a control module and magnetic pick-up replace the contact points of a conventional car ignition system.

Figure 1 shows a scheme of the electromechanical pulse generating circuit, which is made up of three basic parts:

a) The electronic part consists of a 5 V regulated source, an oscillating circuit (variable between 1–12 Hz) and a transistor.

b) The high-voltage control component includes a battery, an electronic ignitor and a car coil.

c) A magnetic interrupter.

The circuit works as follows: The 5 V source feeds the oscillating circuit (CI2) which, through transistor (Q1), stimulates the magnetic switch closing the high voltage circuit to the frequency of the oscillator. The magnetic switch acts as an interface between the electronic component and the high-voltage control component, isolating them to prevent possible damage. The car electronic ignitor delivers 300 V pulses to the coil which produces pulses of an amplitude above 20 kV at its secondary.

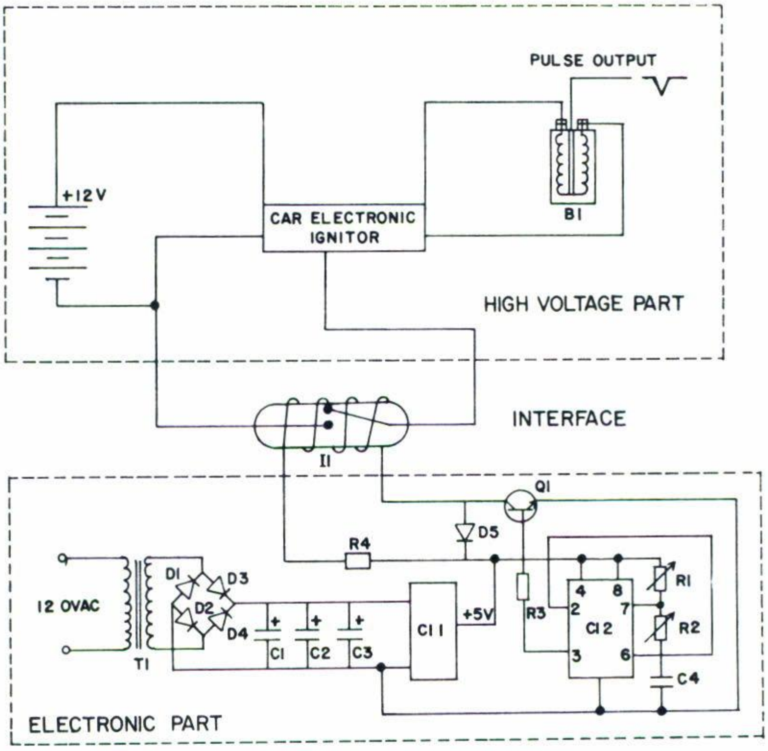

FIGURE 1. Electromechanical pulse generating circuit. C1–C3: 1000 μF–25 V; C4: 10 μF–16 V; B1: 9224771008 Bosch; R1–R2: 50 kΩ max; R3: 1 kΩ; $R4$: 120 $k\Omega$; CI1: 7805; CI2: LM555; D1–D4: 1N4007; D5: 127M; I: electronic ignitor Segura 2001; Q1: EM7001; I1: DRG-2-425; T1: 12 V–1 A.

Figure 2 shows a typical pulse measured with a Tektronix P6015 high-voltage probe on a storage digital oscilloscope, Tektronix TDS 540 with 500 MHz bandwidth and Table I shows its characteristics.

As Fig. 1 shows, this circuit is very simple and economical to build, with high amplitude (28.5 kV) and short fall time (1.1 μs) appropriate for triggering gaseous discharges like N_2 lasers, but, due to the other characteristics of the resulting pulse, (FWHM: 28.9 μs; jitter: 122 ns and delay time: 744 μs) it is not recommended for synchronizing to other experiments.

2.2. Electronic module

Generally, electronic pulse generators operate with a DC power source that charges a capacitor, which is then discharged, by means of an electronic switch, into a pulse transformer.

In our case, the pulse transformer has a voltage step-up ratio of 73 to 1, and can produce output amplitudes of up to 40 kV. The primary of the pulse transformer is mostly inductive, so as to produce a large output pulse; a current of large magnitude must flow through the primary in a short time. This is accomplished by charging a capacitor to a voltage between 300 V and 600 V.

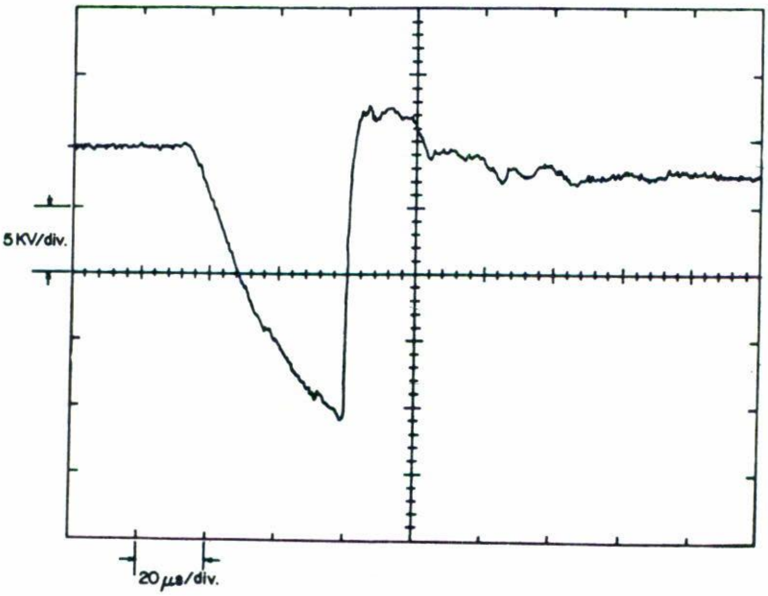

FIGURE 2. Typical output pulse of the electromechanical pulse generator working at 12 Hz without spark gap.

TABLE I. Electromechanical pulse generator characteristics.

Characteristic	Condition	Value
Amplitude [kV]	WSG	20.8
	W/o SG	28.5
Trigger rate [Hz]	Mx	12
	Mn	1
FWHM [μs]	W/o SG	126
	WSG	28.9
Rise Time [μs]	WSG	34
Fall Time [μs]	WSG	1.1
Jitter [ns]	WSG	122
Delay Time [μs]	WSG or W/o SG	744
Power [W]	115 Vac, 50 cps	20
Size [cm]	23 × 60 × 22	
Weight [Kg]	16	

Abbreviations. WSP: operating with a spark-gap; W/o SG: operating without spark-gap; Mx: maximum; Mn: minimum.

The proposed electronic circuit (see Fig. 3) is fed by 110 V AC, which is quadrupled (T1–T2), rectified and filtered (CR1–CR4 and C1–C2), charging a capacitor (C3) to a voltage between 285–571 V.

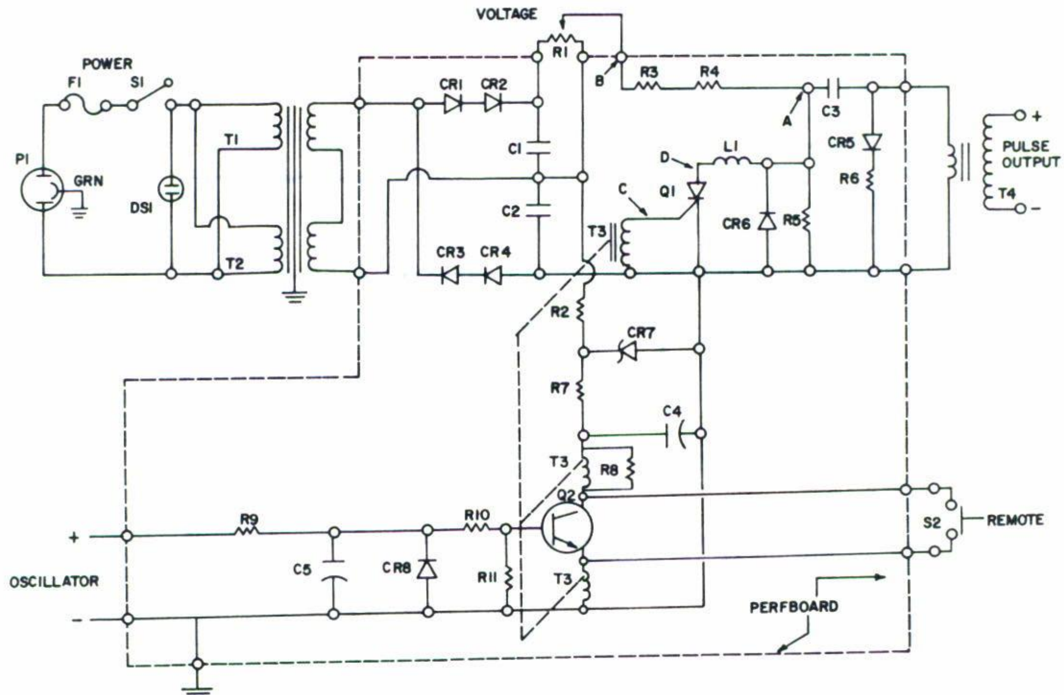

FIGURE 3. Schematic diagram of the electronic trigger module. C1–C2: 12 μF–450 V; C3: 0.27 μF–1 KV; C4: 22 nF; C5: 1 nF–1 KV; L1: 2 μH; CR1–CR6 and CR8: 1N4007; CR7: 19 V–1 W; DS1: Neon lamp; S1–S2 switches; T1–T2: 1:1 15 VA; T3: EG&G TR–1646; T4: EG&G TR–1700; R1: 100 KΩ–2 W; R2: 150 KΩ–2 W; R3–R4: 68 KΩ–2 W; R5: 560 KΩ–2 W; R6: 10 KΩ–2 W; R7: 47 KΩ–1 W; R8–R9: 1 KΩ–1 W; R10–R11: 1.5 KΩ–1 W; Q1: SCR NTE 5448; Q2: ECG 123 AP–5PK.

Since the primary of the pulse transformer is mostly inductive, rapid discharge to C3 towards the pulse transformer with a SCR (Q1) is necessary to produce output pulses of high amplitude and short rise time. To do this, Q1 is excited by a current pulse coming from a 1:1 transformer (T3), generated by a current flow regulated by a zener diode (CR7) and motivated either by a transistor (Q2) or a switch (S2). In this way, discharge can be produced in two different manners, namely:

a) Manually, with a push-button control (S2) from the front panel; or

b) Externally, a remote jack is supplied if the user wishes to trigger the unit from a remote location, and an oscillator input (BNC connector) for triggering by a square-wave generator. The oscillator input is compatible with TTL systems. It should be noted that the external activation signal should have an amplitude of 4.5–7 V. We also provide a variable frequency square-wave oscillator inside the electronic module (not shown in Fig. 3) to eliminate the need for an external oscillator.

In the steady state, the voltage at node A is eighty percent of the voltage at potentiometer wiper B. This voltage drop is provided by the R3–R4–R5 attenuator, and is necessary to obtain an output of 40 kV or less. The voltage at node A charges C3 (which

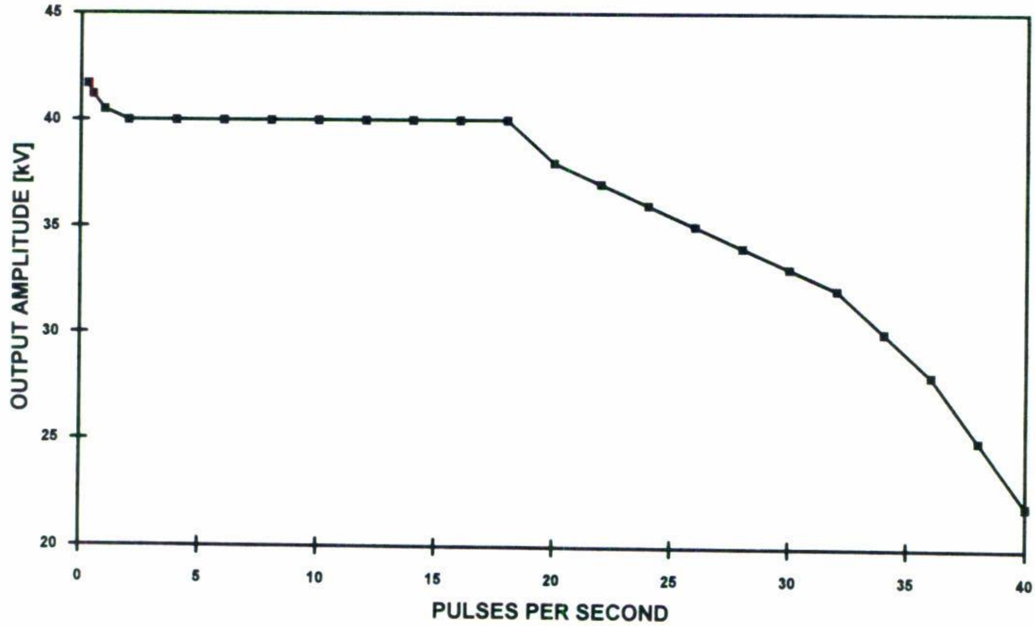

FIGURE 4. Output voltage versus repetition rate of the electronic trigger module.

stores energy in it to produce the output pulse) and biases the SCR properly. CR6 is provided to protect the SCR trigger from negative voltages at node A.

After Q2 is triggered, the voltage at point C becomes high enough to turn the SCR on. This drops the voltage at D to nearly zero, essentially putting the C3–L1 series combination across the primary of T4, the output pulse transformer. The energy stored in C3 in steady state is then transferred to T4 in the form of a high current pulse. With the voltage divider (R1), the output pulse amplitude can vary over a range of 20–40 kV.

Diode CR5 provides a path for the charging current of C3 to flow to ground; R6 limits the current through CR5. L1 prevents current overshoots from flowing through Q1, which can damage it. This inductor also appears in series with the pulse output transformer upon triggering, which reduces the output of the module.

The rise time of the output of the SCR switch can be estimated as $t_r \cong (L1C3)^{1/2} =$ 500 ns. This rise time will inevitably be slowed down by the sluggish nature of the pulse transformer, but should produce an output rise time near 1 μs (820 ns in our case).

The output voltage versus repetition rate of the module is shown in Fig. 4 and drops at an increased pulse rate because of limitations in the charging rate of C3.

Figure 5 shows a typical output pulse of the circuit, measured with the same instruments as the electromechanical module. Table II shows its characteristics, of which the most important is an amplitude eight times higher than the most recently reported [8].

The output waveform indicates a rise time of 820 ns, almost twice the desired input rise time. This longer rise time is due to the inductive sluggishness inherent to the pulse transformer. However, the result is a trigger with a rise time less than that of commercially available triggers (2 μs). The ringing frequency and damping time are inherent in commercially produced modules also, since the same type of pulse transformer is often used.

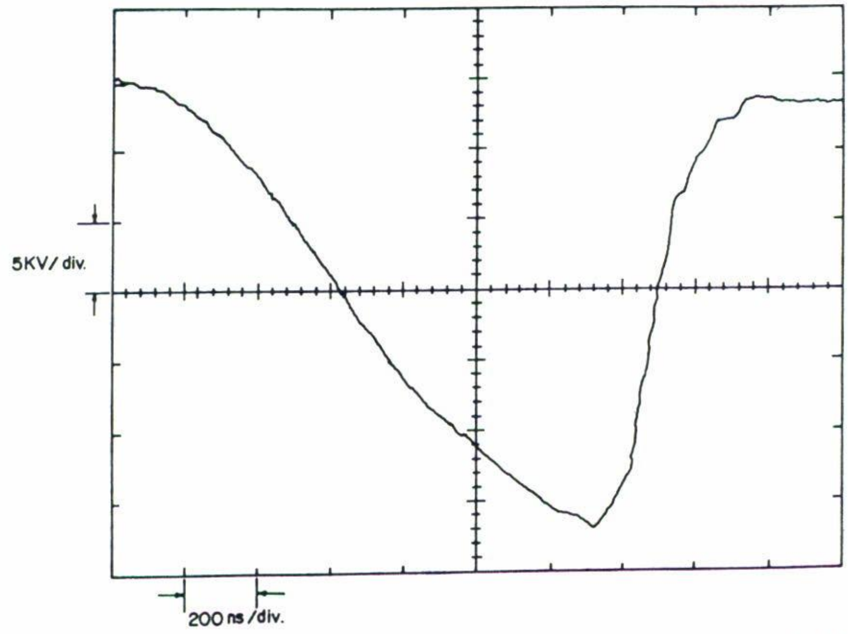

FIGURE 5. **32 kV output pulse of the electronic pulse generator, working at 20 Hz with a FWHM** of 750 ns.

The output is provided by thread terminals inside the case which can be accessed by removing the rear panel. The output may be taken positively or negatively. The user can shield the output from noise by connecting the inner conductor of coaxial cable to either the positive or negative terminal and by connecting the other terminal and the braided shield to the case, since it is grounded through the power line. The case ground is also provided for user safety.

As we mentioned, the applications of the module include triggered spark gaps and flash-tube triggering. The positive output terminal is normally connected to the trigger probe of triggered spark gaps or the trigger wire of sparking electrode for flashtubes. The negative terminal is connected to the adjacent main electrode or ground. When the unit is used to pulse a device, such as a triggered spark gap where the trigger probe and adjacent main electrode assembly are above the ground, the module must be connected as shown in Fig. 6.

It is necessary to use a series capacitance in each output lead. A capacitance of 100 to 500 pF rated for 30 kV provides the required dc isolation, preventing a discharge from the energy source (being switched by the gap) through the secondary circuit of the pulse transformer inside the module.

As a general rule, short connecting cables should be used whenever possible to achieve optimum rise time and pulse amplitude. The capacitance in coaxial cable and inductance in long leads tends to diminish the normal output characteristics.

2.3. Spark gap

The spark gap serves as a very fast switch, with the ability of suddenly short circuiting one storage capacitor, and capable of delivering several kA of current. There are two types

TABLE II. Electronic pulse generator characteristics.

Characteristic	Condition	Value
Amplitude [kV]	MxA at MnF	40
	MnA at MxF	25
Trigger rate [Hz]	Normal	0.3–18
	Mx	40
FWHM [ns]	MxA, WSG, MnF	750
Rise Time [ns]	MxA, WSG, MnF	820
Fall Time [ns]	MxA, WSG, MnF	260
Jitter [ns]	MxA, WSG, MxF	60
Delay Time [μs]	MxA, W/o SG, MxF	1.46
Power [W]	115 Vac, 50 cps	40
Size [cm]	21 × 22 × 14	
Weight [Kg]	7	

Abbreviations. WSP: operating with a spark-gap; W/o SG: operating without spark-gap; Mx: maximum; Mn: minimum; F: frequency; A: amplitude.

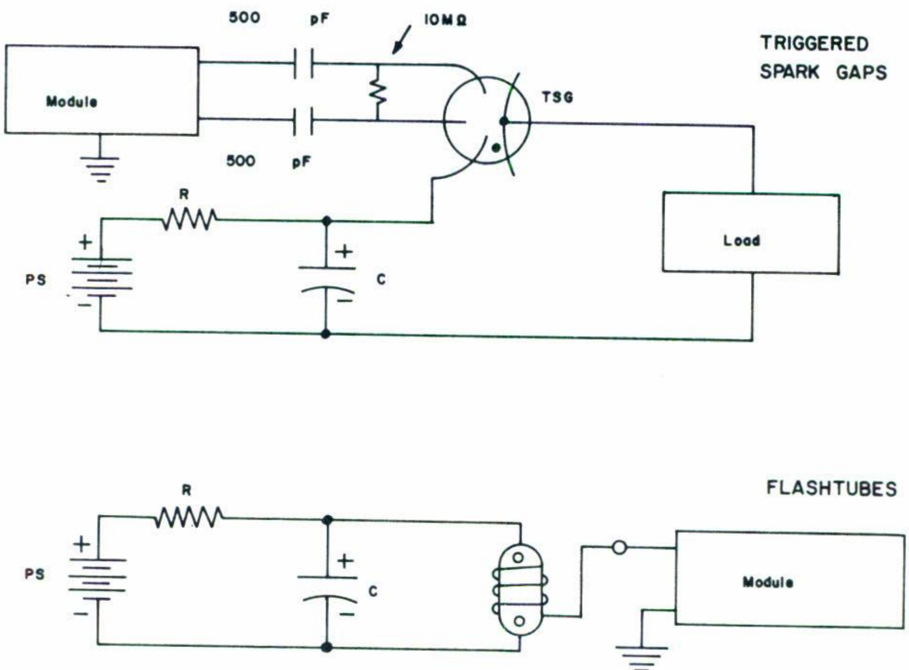

FIGURE 6. Connections for triggering systems above ground.

of spark gap switches: free-running [9] and triggered types [8,10–12]; both are cheap and can handle more power than thyratron tubes, with low losses and low inductances [13].

The standard applications for triggered spark gaps fall into two broad categories: (a) as a series switch, the spark gap delivers energy to a load in single shot or repetitive pulsing applications like gas lasers, spark discharges, flash lamps, Marx generators, Kerr or Pockels cells; and (b) as a protective device, where the gap is used to crowbar energy storage circuit components such as power supply filter capacitors, pulse forming networks, shunt protection for RF tubes and other circuitry.

Many triggered spark gap designs already exist [8–13], but they are generally complicated to reproduce due to the different materials used in their manufacturing and their diverse characteristics, according to specific applications. Our design has the advantage of being versatile, efficient, economical and very easy to build, and has characteristics similar to other reported or commercial spark gaps.

The proposed spark-gap, shown schematically in Fig. 7, consists of three electrodes and works as follows: the high-voltage trigger pulse from the generator is connected to a car spark plug which ends in a ground electrode made of stainless steel in a hemispherical shape with a small hole ($\phi \sim 1$ mm) at the center. The high voltage electrode is made of the same material and shape to avoid an increase in the electric field in any preferential zone: this allows for a uniform wearing down of the surface and improves the repetitivity of the sparks. More complicated designs for the shape of the electrodes [14] were tested with the same results as for the hemispherical shape.

The chamber, sealed with o-rings, was built with transparent acrylic to permit viewing of the discharge, observing the separation of the electrodes, and it is easily disassembled for cleaning since, because the electrodes are metallic, the insulator walls are metallized after 10^5–10^6 pulses. In order to increase the surface of the chamber without modifying the inductance, the internal surfaces are slotted to obtain a longer pathway for the wall discharge, thereby increasing the duration of the spark gap without having to disassemble it for cleaning. As the spark gap becomes dirty, shot-to-shot trigger jitter will start to increase. Typical lifetime of the sparking points is generally one million shots. Cleaning frequency depends on operation, but in any case, after long periods of disuse, the electrodes should be removed and cleaned before the spark gap is brought back to firing voltage.

The breakdown voltage (with no trigger voltage applied) is mechanically regulated by the separation of the electrodes and was tested between 1–20 kV which is the maximum voltage that our source can deliver; however, the design is prepared for a voltage of up to 30 kV. If it were necessary to use voltages above 20 kV, pure SF_6 or N_2 mixtures can be flown through the chamber. It should be added that, for voltages above 20 kV, it is advisable to build the chamber with materials of dielectric constants larger than that of acrylic (Teflon™ or Delron™), and that the whole circuit be submerged in insulating oil.

If the application of the spark gap requires low inductance with good pulse repetitivity, minimum delay and jitter, as in the excitation circuits for N_2 lasers, the breakdown voltage should be controlled by pressure [15]. Thus, the separation of the electrodes can be reduced, reducing inductance to some μH for small-size spark gaps. The flow and pressure conditions depend on the desired application.

This spark-gap has been successfully used with the circuits mentioned above to control the discharge of a N_2 laser with a capacitive charge transfer excitation circuit [4] at a voltage of 10 kV. In these lasers we tried to reduce the inductance of the whole circuit in order to efficiently deliver the energy stored in the charging capacitor to the laser discharge. The spark gap has a dynamic range of about 5 kV at any given air or Nitrogen

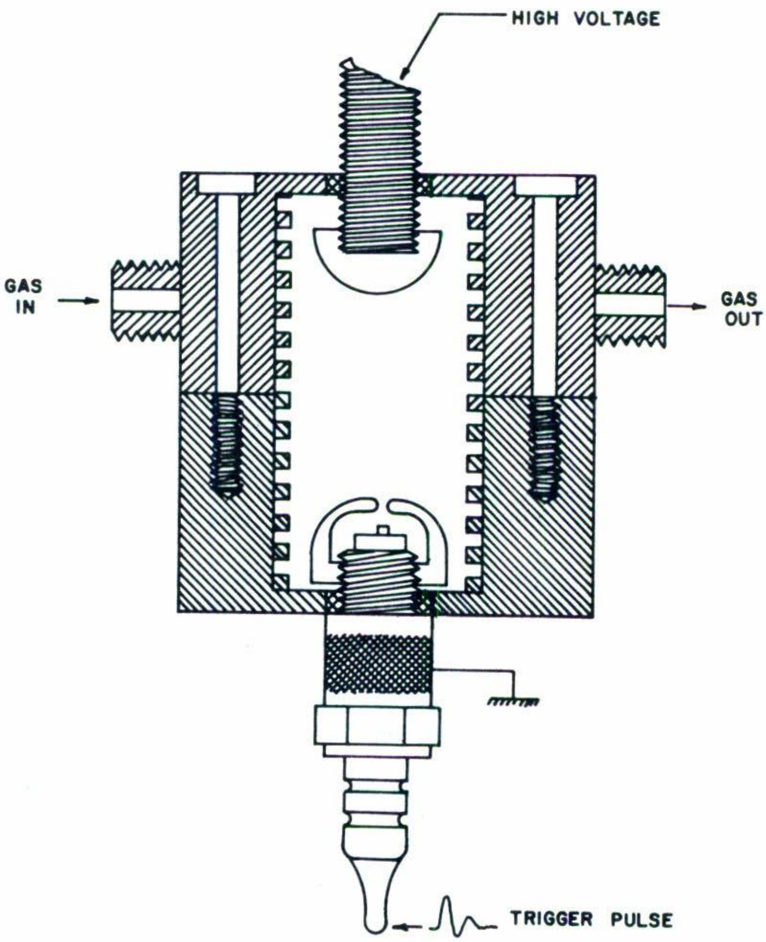

FIGURE 7. Cross section of the triggered spark gap with a chamber volume of 141 cm^3. The working voltage can be controlled from 1 kV to 30 kV by changing pressure or the separation of the electrodes.

pressure. This means that the operation range can be changed by increasing the pressure that exists between the sparking points. With no pressure, the range is typically 8 kV to 20 kV. Below approximately 8 kV the laser does not fire, and above approximately 20 kV it will self-fire. The operating range increases by adding pressure to the gap. Typically 50 kPa of air or Nitrogen will allow operation in the 10–14 kV range. Note that excessive air pressure will increase jitter problems; *i.e.*, variations in synchronization of laser output and input pulse times.

The spark gap triggering N_2 lasers [4,5] was compared to the commercial EG&G spark gap Model GP-46B [16] triggered by the electronic module, showing the same characteristics: maximum delay time of 30 ns at 70% static breakdown voltage (SBV) and 300 ns at 40% SBV, with the advantage that we can change the SBV mechanically.

Tables I and II show the measured characteristics of the controllers working with an open circuit, without spark gap (W/o SG) and with the spark gap (WSG).

3. CONCLUSIONS

Two high voltage pulse generators were built, namely, an electromechanical one with a FWHM of 28.9 μs and amplitude of 20.8 kV, and an electronic one with FWHM of 750 ns, which is 2.5 times better than commercially available modules, and variable amplitude between 20–40 kV, both with variable frequency. In addition, a spark gap to control voltages of up to 20 kV was built and tested by triggering N_2 lasers. While these instruments were used to control N_2 lasers [4,5] they can be used for a wide range of applications.

REFERENCES

1. I. Santa, L. Koznna, B. Racz and M.R. Gorbal, *J. Phys. E: Sci. Instrum.* **17** (1984) 368.
2. G. Mechterscheimer, R. Kohler, T. Lasser and R. Meyer, *J. Phys. E: Sci. Instrum.* **19** (1986) 466.
3. J. Jethwa, E.E. Marinero and A. Muller, *Rev. Sci. Instrum.* **52** (1981) 989.
4. J. de la Rosa, R. Linares, M. Villagrán y J. Garduño, *Acta Mex. de Ciencia y Tecnología* **41** (1993) 17.
5. M. Villagrán, M. Argote y C. Dominguez-Tagle. *Rev. Mex. Fís.* **40** (1994) 935.
6. EG&G Electro-Optics, "TM-11A Trigger Module", *Operation Manual* B-4542 (1979).
7. *M 1000 N_2 Laser Operating Instruction Manual*, Lambda Physik GmbH, Gottingen, West Germany (1980).
8. H. Golnabi and H. Samini, *Rev. Sci. Instrum.* **65** (1994) 3030.
9. T. Baby, T. Ramachandran, K. Sathianandan and V.P.N. Nampoori, *Optics & Laser Technology* **42** (1992) 329.
10. J.W. Keto, T.D. Raymond and S.T. Walsh *Rev. Sci. Instrum.* **51** (1980) 42.
11. H. Golnabi, *Rev. Sci. Instrum.* **63** (1992) 5804.
12. J.I. Levatter and Shao Chi Lin, *Appl. Phys. Lett.* **25** (1974) 703.
13. A.J. Schwab and F.W. Hollinger, *IEEE J. Quantum Electron.* **12** (1976) 183.
14. E.A. Stappaerts, *Appl. Phys. Lett.* **40** (1982) 1018.
15. F. Pashen, *Weid. Ann.* **37** (1889) 69.
16. EG&G Electronic Components "Ceramic-metal triggered spark gaps", Data sheet G6000E-5 (1989) 5.