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The electrical Discharge Characteristics of the 3.5 KJ Electrothermal Plasma Gun Experiment

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ABSTRACT

In order to better understand the operating characteristics of an electrothermal plasma gun and its design, a variety of operation characteristics including (the length of the capillary, applied voltage, diameter of the capillary tube, circuit inductance) were investigated to determine performance effects and viability in a real system. An Electrothermal Plasma Gun (ETG) is composed of a capillary discharge tube made of Teflon operated with simple RLC circuit. The device called Electrothermal Gun (ETG) which is composed of 4 capacitors (70 µF, 10 kV, 1.3 µH) connected in parallel to a plasma source by means of one high power plane transmission line by mean of a switch triggered by negative pulse 360/385 V. For the present studies a simple RLC was chosen, which allowed the circuit parameters to be easily measure d. The electrothermal discharge characteristics of the plasma gun operated in open air, So that at atmospheric pressure the main parameters were measured. The gun voltage and discharge current are measured with voltage divider and Rogowiski coil respectively. From the results recorded we found that, the current lagged the voltage i-e the plasma source has an inductive reactivity. Moreover, the current value was changed by changing the circuit parameters, including the discharge voltage and circuit inductance, and the wire properties such as the length and diameter. The maximum gun current ranged between (5 - 50 KA) according to the charging voltage of capacitors between (1-7KV), a typical discharge times are on the orde r of 125 µS.

Keywords:** Electrothermal Gun/ Capillary Discharge/ Wire Exploding.**

INTRODUCTION

A- Capillary Tube as an Electrothermal Gun

A capillary discharge (CD) is a pulsed, ablative electrothermal gun, capable of efficiently producing high density plasma. These devices are characterized by their high aspect ratio. An arc is established in the center of the capillary, which results in ablated wall material that constitutes the high density plasma. Usually, the Source of the plasma gun is an electrical confined discharge, taking place between the tow electrodes with an ablative capillary built from different materials. Furthermore, the plasma ignition is an efficient tool to optimize the gun operation (1).

Experiments using capillary discharge plasma in the electrothermal chemical gun are under investigation for different experimental measurements. However, the study of the plasma parameters, physical processes and effects of the capillary plasma cannot be done easily in the electrothermal plasma gun devices. Therefore, experimental studying on the capillary discharge have been started separately to get the optimization design of the capillary plasma discharge tube as shown in figure 2 which illustrate the simple schematic diagram of the capillary plasma tube. During an experimental work many of the plasma parameters and gun discharge properties are measured. These parameters are the current trace dependence on (charging capacitor voltage, capillary length and circuit inductance). Moreover, the plasma produced from the capillary discharge in an ET gun is in the pressure of atmospheres. Electromagnetic launch devices are used for acceleration of projectiles to hypervelocity include rail guns, coil guns and electrothermal guns. An electrothermal gun facility was assembled and studied for investigation of the physical phenomena in an initial state of the capillary discharge [(2)]. It has been reported that reduction of the capillary diameter leads to an increase in the energy applied to the plasma source because the plasma resistance increases with decreasing capillary diameter and hence, results in an increase of the input energy into the capillary plasma [(3)].

Currently, Preliminary tests and measurements have been done by discharging the capillary injector in open air and the results have been recorded. These results will be helpful for designing an accurate experimental setup and performing measurements. These basic studies on the capillary Plasma is required to study further their interactions with propellants in chamber and sample treatments.

The present work focuses on quantifying and studying the basic parameters of the capillary like, gun discharge current, gun discharge voltage for different capillary length (L) and exploding wire. The property of the exploding wire seems to be very complicated compared to the capillary discharge which shows consistent properties providing more simple results to investigate the best processes of the ET gun operation. The physical phenomena in an initial state of the capillary discharge are discussed with a view toward achieving the best operating conditions for the electrothermal gun.

B- Capillary Discharge Description

Capillary discharges can produce high-density, high-temperature pulsed plasmas [(4)]. They typically consist of a long capillary of a nonconductive material, usually high density Polyethylene (HDPE), in this experiment we are used a Teflon tube with electrodes at both ends of the capillary as shown in Figure (1) which illustrate the basic processes occurs in the capillary plasma discharge including ablation processes, radiation processes and energy transfers. The anode is typically inserted into one end of the capillary while the cathode is a hollow cylinder on the opposite end of the capillary, although the reverse polarity also works.

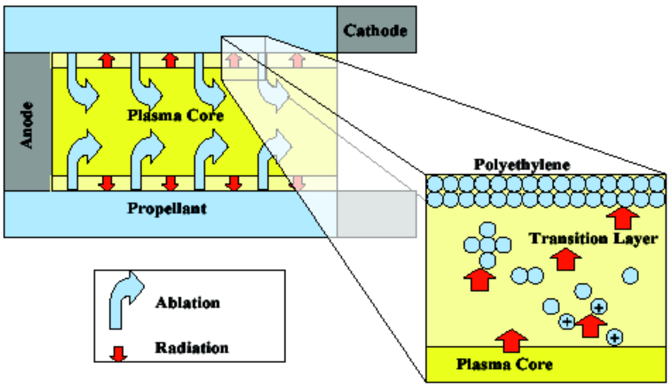


Figure (1): Capillary Discharge Ablation Process [4].

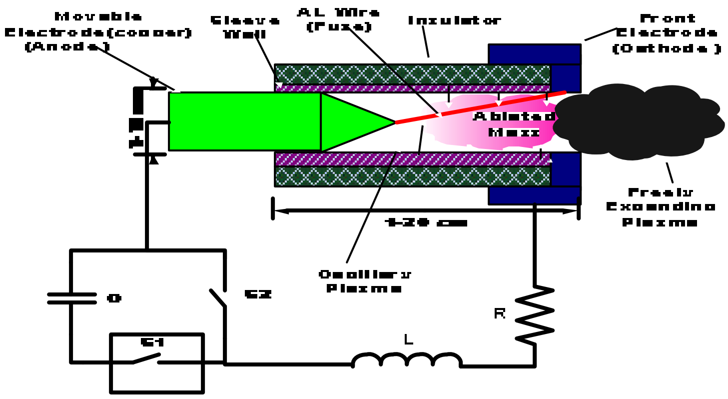
Capillary discharges are ignited by creating predischarge plasma throughout the capillary using an ignition source, typically an exploding wire ignition system as shown in Figure (2). A capacitive electrical energy source is connected across the electrodes. Once a conductive path has been created between the electrodes, current will begin flowing between them and the plasma will be heated by Joule heating.

The heated plasma along the axis radiates, ablating material in the wall. The ablated material becomes dissociated and ionized during its transit through a thin (typically several µm) transition layer, adding mass to the capillary discharge. Many workers have previously reported experimental or theoretical treatments of ETC plasmas [5].

EXPERIMNTAL SET-UP

In order to better understand the operating characteristics of a capillary discharge and its design we started this experiment in the open air separately to understand the physical processes of the discharge and to improve the capillary design. The diameter of the wire is less than 1 mm and has a (1-20 cm) long of copper and aluminum wires which were held vertically in air, or vertically within a capillary between two electrodes. In general, Electrothermal- Chemical (ETC) propulsion was considered to be an attractive technology to control the pressure generated by chemical propellant in a combustion chamber [6].

A schematic diagram of the experimental arrangement and its principle is shown in Figure (2). The experiment consists of ET source section (plasma gun), transmission line, capacitor bank, and associated diagnostics. The capacitor is connected to the cathode of the gun via a transmission line and a spark gap switch. The anode of the gun is inserted in the center of the capillary tube. The electrical energy of the capacitor is discharged through the gun upon closure of the switch. The plasma gun is typically operated in air. A high electrical current vaporizes an aluminum wire in a small tube and generates hot plasma by joule heating. Moreover, the plasma source is generated by the rapid discharge of 3.5 *kJ* of electrical energy into a Teflon (Lexan) capillary. This energy is stored in a 70 *µF* capacitor charged to a maximum of 10 *kV*. The capacitor was discharged with a wire load through a spark gap switch and inductance *L*. In the experiment, inductance *L* could be changed into eight values from 1.3 to 80 *µ*H as shown in table (3). The capillary is (3*mm*-*8mm)* in diameter, (10 *mm* - *200 mm)* long, and is open at one end only. The discharge is initiated with a thin copper or aluminum fuse wires (less than 1 *mm*), ablation and ionization of material from the capillary surface sustains the discharge. The wire explodes at more or less 20 µs and provides the initial plasma used to ignite the main discharge and the energy transferred in to the wire is calculated by experimental waveforms of current and voltage. The wire itself was previously treated to heat up uniformly, and upon reaching boiling, immediately vaporized. The anode is made of copper and the cathode is made of aluminum. The aluminum wire is enclosed in a cylindrical tube, and has contact to two electrodes.



The discharge voltage across the capillary was measured as a function of time using a high voltage probe (BK-PR-28A). The discharge current trace was measured using a Rogowiski coil and the signal was integrated with respect to time to get the total current in the plasma circuit during the discharge. When the capacitor discharges through the gun, an arc is formed between the cathode and anode of the source section. Photons from this arc ablate the interior of the 'Lexan' sleeve. The ablated material is Joule heated, forming a high-density low-temperature plasma. Pressure gradients force the plasma out through the 3 mm diameter opening of the cathode barrel, where the plasma is free to expand into the open air. The current signal and voltage are recorded on Tektronix TDS Oscilloscope model (2014-100 MHZ-1Gs/S).

RESULTS AND DISCUSSION

A - Current and Voltage Measurements of the capillary

The most easily measured, most accurate, and most repeatable measurements made during the course of this work were the current flowing through the capillary discharge and the voltage difference across the capillary discharge [7]. During each firing, the variations of the discharge current $I_{dis}(t)$ and of the discharge voltage $V_{dis}(t)$ across the electrodes are recorded. Figure (3) is a plot of the typical discharge voltage and current traces obtained during a discharge with a capacitor voltage of 5 kV .The peak current through the plasma is approximately 37 kA for a storage energy of ˜ 0.9 kJ, and the periodic discharge duration time is approximately (more or less 120 µs).. The figure shows the current and the voltage across the capillary. When the discharge is triggered (by closing the switch), the voltage across the capillary increases rapidly until the wire exploded, After the pulse voltage produced by the melting and vaporization of the thin copper wire, the voltage increases slowly in the time ranged for about 5 to 10 µs .The voltage became constant during around 10 µs and decreases thereafter. For unconfined wire explosions in air, the voltage spike is followed by a voltage plateau, which has been sustained for experimental purposes by the discharge.

A trigger pulse supplied to the initiates the breakdown in the spark gap, which results in an arc in the source region. The plasma extinguishes before the capacitor fully discharges. Thus the energy supplied to the plasma, is the difference between the energy stored in the capacitor before and after a shot.

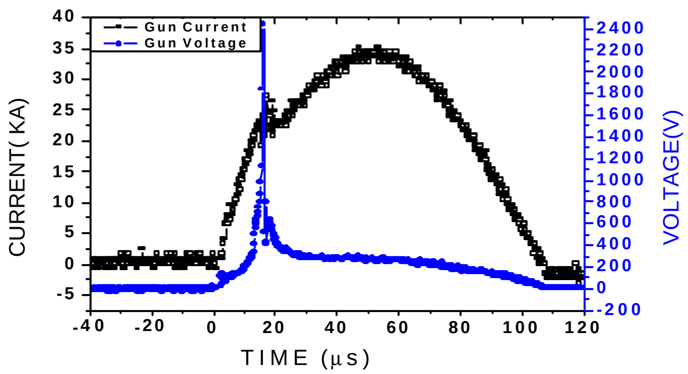


Figure (3): Typical Discharge Voltage and Current Traces.

Figure (3) illustrates an example of a typical discharge current and voltage trace for the conditions of charging voltage 5 KV, Capacitance = 70µF, diameter = 4mm, length = 5 cm. of additional capacitor modules, with material ablated from the electrodes acting as a mass source for the maintenance of the plasma. The magnitude of the voltage plateau is in the range of (20-100 µS).

In atmospheric pressure a clear signature of the wire explosion is evident (the current sharply drops and increases again shortly afterwards). Figure (4) shows the drop in the current shape which is known as the "wire-burst." The wire fragmentation is accompanied by a small inflection in the current profile.

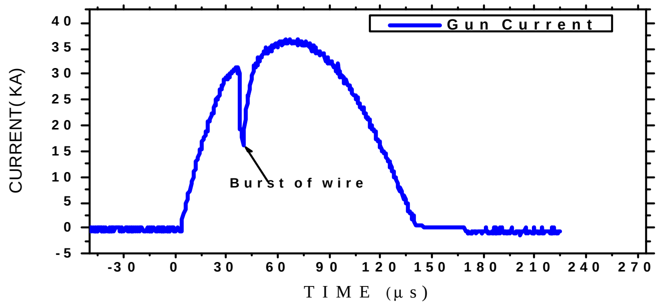


Figure 4: Current signals of exploding wire in atmospheric pressure of the gun at 5 KV.

Moreover, the discharge current trace shows a clear double peak structure as shown in Figure (5). The first peak is due to the ignition wire explosion and the second peak represents the main discharge. In brief, the current approximates to a half sine wave, although the current decays approximately gradually with time.

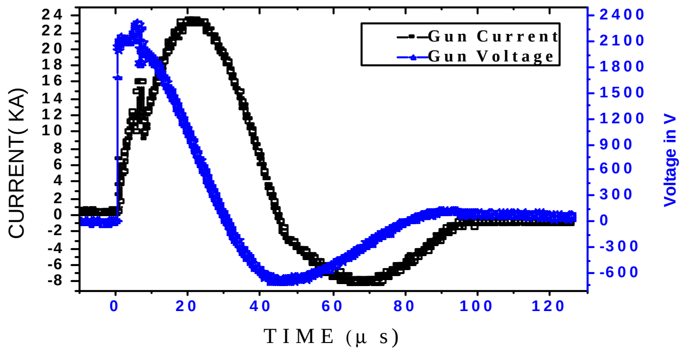


Figure (5): discharge current and voltage of the gun.

Figure (5) shows the measured discharge current and voltage as a function of time. The difference between Figure (3) and Figure (5) is the position of measurements. Figure (3) the voltage and current diagnostic systems are placed on the capillary it self, but in Figure (5) the voltage and current diagnostic systems are placed on the capacitor after the switch , so that the coil inductance appear a quit difference on the signal waveforms of the voltage and current. The small notch in the curves indicates to the point which the wire connected between the two electrode are exploded. It should be noted that the capillary plasma resistance is calculated from measurements of the discharge current and voltage. In addition, the spike in the voltage trace has been identified as being related to fragmentation of, and plasma development around the wire, and begins shortly after the melt phase. The rapid rise and descent in voltage is seen to be due to changes in plasma resistance, as the current over this period is constant. In details, the wire was electrically exploded.

The residual capacitor voltage through the gun is determined by measuring the initial and final capacitor voltages. Measurement of the static capacitor voltage is made with a dc voltage divider. The discharge voltage is the capacitor voltage at which the spark gap switch is closed and initiating the discharge.

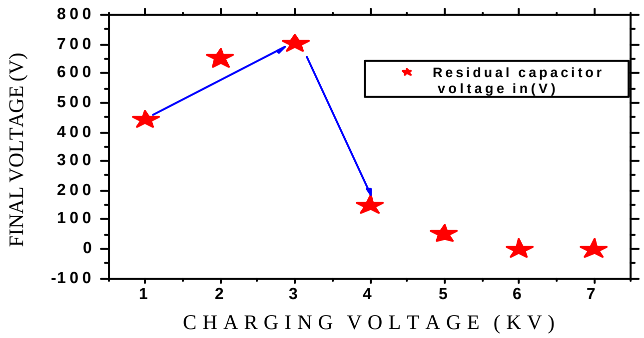


Figure (6): final capacitor voltage versus charging capacitor voltage.

Figure (6) shows the residual capacitor voltage versus charging capacitor voltage which the residual can be defines as the difference between the initial capacitor voltage and the discharge voltage, or the energy left on the capacitor after the discharge. It can be seen in the figure that the magnitude of the residual voltage initially increases with increasing initial voltage, and then begins to decrease at charging voltages higher than 3 kV. Moreover, the gun is not typically operated at the very low energies. Charging voltages are often in excess of 3 kV

B- Current Trace Dependence on charging Capacitor Voltage

Figure (7) shows the experimentally measured discharge current for seven different charging capacitor voltages at the conditions listed in table (1). There is a clear increase in maximum of discharge current with increasing charging capacitor voltage.

No. of Shots	Charging Voltage (KV)	Max. Current (KA)	Energy (J)
3	1	9	35
3	2	12.4	140
3	3	19	315
3	4	27.2	560
3	5	36.4	875
3	6	44	1260
3	7	49	1715

Table (1): the max. Current and energy measured versus charging capacitor voltage.

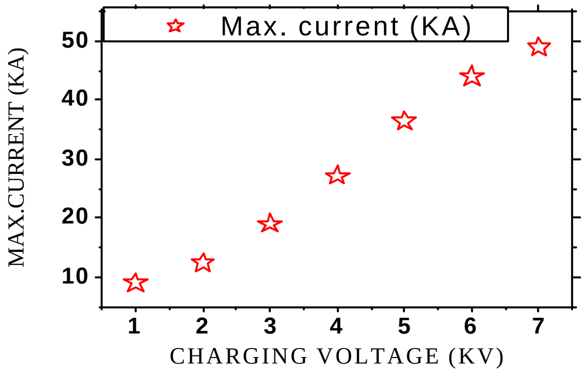


Figure (7): the maximum current versus the charging capacitor voltage.

C- Current Trace Dependence on Capillary Length

Figure (8) shows the experimentally measured discharge current traces for different Teflon capillary lengths at the conditions listed in table (2) at charging voltage 5KV. The discharge lengths in the capillary can be varied by inserting a copper or aluminum wires of 1 mm diameter inside it. At shorter capillary lengths higher main discharge peak current levels are achieved primarily because the path length between the electrodes is shorter which reduces the resistance. In this case we repeat the shot for five times and we take the average value of them.

No. of Shots	Length (cm)	Charging voltage (KV)	Max. Currents (kA)
5	1	5	36.3
5	3	5	17.2
5	8	5	13.13
5	10	5	11

Table (2): the value of currents measured with different capillary lengths.

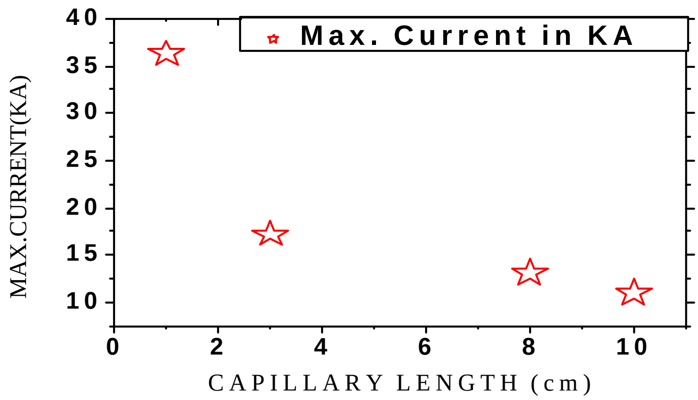


Figure (8) the maximum current versus the Capillary tube length.

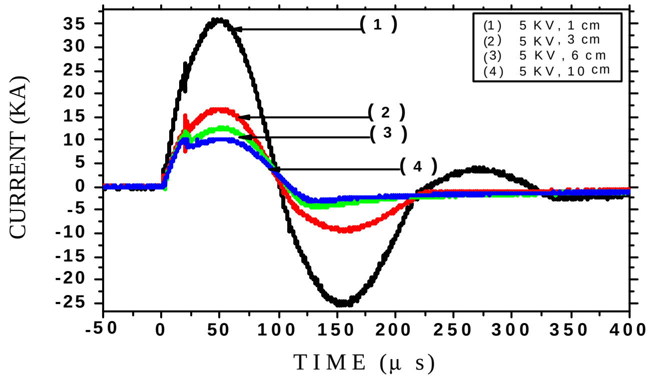


Figure (9): Plots of the measured electrical discharge current through the capillary hole versus the time t in μs for several different values of the Capillary length.

D- Current Trace Dependence on Circuit Inductance

Figure (10) shows the experimentally measured discharge current traces for various numbers of inductors in series and the discharge conditions listed in table (3). As expected an increase in inductance causes a decrease in the peak current and an increase in the periodic time of the discharge current signal. Different conditions/faults like normal discharge, no breakdown in capillary, breakdown at capillary entrance flange, breakdown before capacitor were created. The current initiated in capillary discharge system is damped sinusoidal in nature and frequency of this sinusoid is determined by the parameters of the discharge signal, inductance, capacitance and resistance. Different type of faults cause change in these parameters, thereby resulting into change in frequency of current and voltage for normal discharge capillary column was shorted by a copper and aluminum wires. Under normal discharge, the breakdown takes place inside the capillary and the current flows from the capacitor, switch and the capillary. Since the periodic time of discharge signal is longer, the inductance will be higher and the frequency will be lower.

No.of Shots	Charging Voltage (KV)	Circuit Inductance(μH)	Max. Current (KA)	Periodic time (μS)
5	5	1.3	36.6	101.1
5	5	10	16	227
5	5	20	9	312
5	5	30	7	363
5	5	45	5.1	410
5	5	60	3.5	480
5	5	70	2.8	550
5	5	80	2.1	600

Table 3: The max. Current and periodic time versus the circuit inductance at V_{CH}=5KV data measurements.

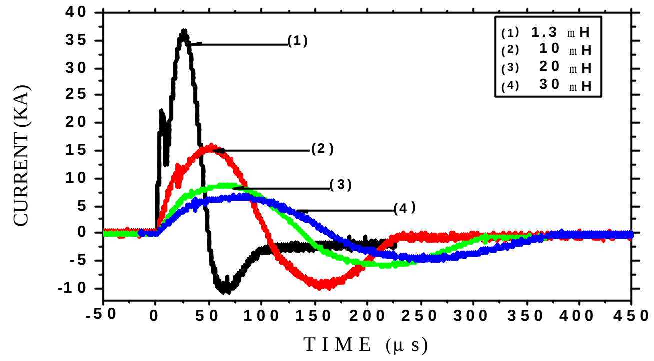


Figure (10): Current Trace Dependence on Circuit Inductance.

As can be seen from Figure (10) the periodic time of the current pulses and its amplitude are controlled by the inductance of coils in the electrical circuits.

E- Current Trace Dependence on Capillary Diameter

The inner diameters of the cylindrical capillary is varied from 4 to 8 mm and the length is constant at 40 mm. Figures (11)and (12) show the waveforms of the discharge current and the voltage across the capillary respectively for capillary diameters of 4, 6 and 8 mm.

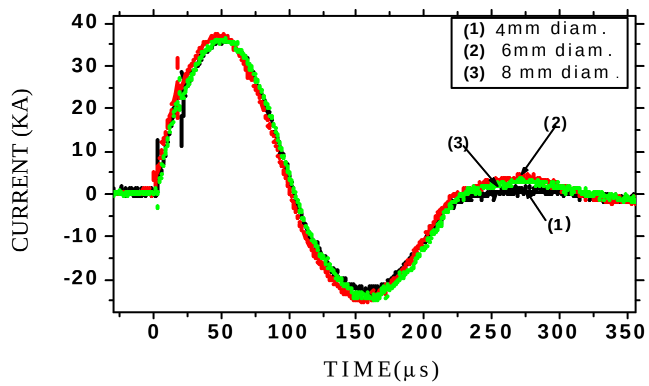


Figure (11): Waveforms of the discharge current for capillary diameters of 4, 6 and 8 mm.

The experimental results show that the voltage increase with reduction of the capillary diameters and the current dose not change much since it is determined by the circuit capacitance and inductance. Thus, the capillary plasma resistance increases with decreasing of capillary diameters.

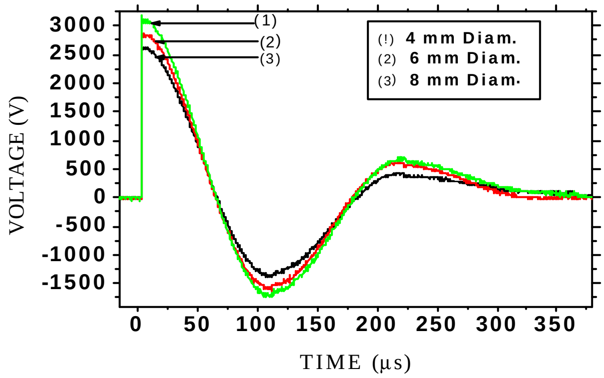


Figure (12): Waveforms of the discharge voltage for capillary diameters of 4, 6 and 8 mm.

E- Ablations Effects of The capillary Wall Material.

In order to understand the basic characterization of the Capillary discharge, it can be seen that the capillary discharges maintain a resistive arc through a narrow insulating capillary by the continual ablation of the capillary wall material or by injected mass. They are typically ignited by shunting current through a fine copper or aluminum wire strung between the anode and cathode. The wire explodes in more or less 15 µs according to the circuit inductance and provides the initial plasma used to ignite the main discharge.

One phenomenon that was observed during gun ignition tests, when more than one firing was taken on a tube, as can be seen from Figure (11), the first discharge was always different than subsequent ones when we use a tube for the first time. A good example of this is shown in Figure (11), in which the current profile is plotted. Here 4 shots were taken on the same capillary tube. The first discharge had noticeably higher currents and longer discharge times.

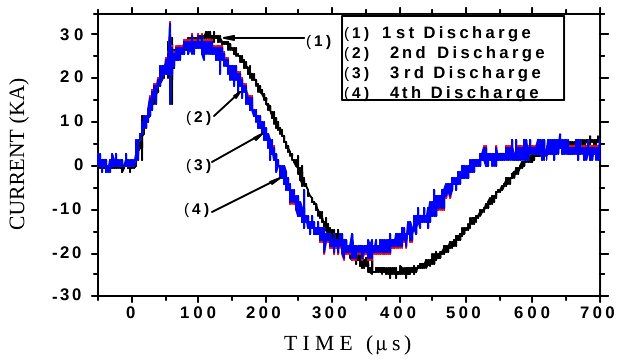


Figure (11):.Four consecutive fires on a 4 cm capillary at 5 KV.

The change in the surface properties will be affect on the peak of current and periodic time of the signal recorded. After the first discharge occurs the material surface is significantly different. This different due to the ablation effects can be seen as a black capillary. It is not as smooth, roughened from the boiling and evaporation that occurs during the ablation process. There is also soot that coats the surface from the previous discharges.

SUMMARY

Several series of experiments have been undertaken to understand the operation and characteristics of electrothermal gun. Capillary plasma discharged in open air was investigated. Furthermore, an improvement of the characteristics of the capillary plasma generator system and some experimental work has been outlined. In general, the operation of an electrothermal gun is strongly related to capillary discharges. In this part of work we concentrate on the operation of the electrothermal gun with different capillary length and diameter in open air. In this paper voltage and current during discharge process were measured and discussed which are made with voltage divider and Rogowiski coil respectively. With the increase in the circuit inductance the peak current decrease. With the increase in the capillary length the peak current decrease. With the increase in the initial voltage discharge the peak current increase also. The experimental results show that the voltage increase with reduction of the capillary diameters and the current dose not change much since it is determined by the circuit capacitance and inductance. The maximum gun current ranged between 5 and 50 KA**,** and was shown different peaks of current measurements with different of (initial voltage discharge, capillary length, coil inductance) of the system. The gun was operated in open air at discharge energies between 0.5– 3.5 kJ. Typical discharge durations were on the order of 125 µs**.**

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