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George C. Ishiekwene

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EVOLUTION OF SPARK PLASMA USING NITROGEN LASER SHADOWGRAPHY SYSTEM

George C. Ishiekwene[1]
International Centre for Theoretical Physics, Trieste, Italy.

ABSTRACT

A simple, low cost, home built high power nitrogen laser is used as the light source for a shadowgraphy system. A series of shadowgrams depicting the temporal growth of a spark plasma discharge is obtained. The results could be useful in plasma diagnostic studies.

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[1] Permanent Address: Department of Physics, College of Science and Technology, University of Liberia, Monrovia, Liberia.

Introduction

Shadowgraphy has been widely used to visualize shock waves and turbulence in aerodynamic studies. More recently, with the advent of laser light sources, time resolution of the order of nanosecond has been achieved. Particularly, the Nitrogen laser which is very simple to construct can be utilised in diagnostic methods of nanosecond shadowgraphy. This opens up a method to study the dynamics of usually transient experimental set-ups by providing quickly a comprehensive picture which would otherwise be difficult to obtain using other methods such as streak photography and magnetic mappings [1].

This paper demonstrates the ease and usefulness of the shadowgraphic techniques through an analysis of the entire system design and also presents a series of shadowgrams depicting the temporal development of a plasma discharge. These results could be useful in plasma diagnostics.

Design of Shadowgraph System

The shadowgraphic set-up consists of subsystems which include a nitrogen laser, a beam expander (magnifier), an external spark gap, an imaging system (telescope), and a camera.

The Nitrogen Laser

The laser consists of a channel, two parallel plate storage capacitors C_1 and C_2 and a spark gap. The laser channel is connected electrically to the capacitors by two brass electrodes which extend from the middle of the channel. A resistor R is connected across the laser channel to both sides of the electrodes in order to have both capacitors C_1 and C_2 initially charged to the same voltage when the high voltage is supplied. A schematic diagram of the nitrogen laser is shown in Fig. 1. Other components of the construction include a unit for triggering the spark gap discharge and a high voltage power supply for charging the capacitors.

Nitrogen gas at atmospheric pressure is pumped into the laser channel and evacuated through the middle and the ends of the channel. When the spark gap is triggered, it causes a spark discharge thereby grounding the laser electrode connected to capacitor C_2, and an instantaneous high voltage develops at the other electrode connected to capacitor C_1. For fast triggering, the criterion is to have low inductance in the switching circuit and this is achieved by usage of the flat plate capacitors [2]. The charging voltage to the system is provided by a 35 kV variable charger. The nitrogen laser is known to operate best around 10 to 25 kV.

The Beam Expander

The design of the beam expander is shown in Fig. 2. The criteria for the design is as follows [1]:

a) input lens diameter $D_1 \geq d$, the laser beam diameter so that the full beam may be used;

b) distance between lenses is adjusted to equal $f_1 + f_2$ the sum of their focal lengths, where f_1 = focal length of input lens and f_2 = focal length of output lens; and,

c) the full diameter of output lens for maximum system aperture is used when

$$\frac{D_2}{d} = \frac{f_2}{f_1} \tag{1}$$

The laser beam is about 1 cm and with the use of quartz lenses having typical dimensions of $D_1 = 25.4$ mm, $D_2 = 50.8$mm and $f_2 = 101.6$mm, D_2 is almost fully utilized.

The External Spark Gap

The external spark gap is developed with a swinging cascade configuration. The Swinging Cascade Spark Gap (SCSG) is essentially a three electrode device forming two gaps in series. The central (or trigger) electrode is positioned asymmetrically between the main electrodes. The ratio of the gap is 3:2 (4 1/2 mm to 3mm), with the gap near the high voltage main electrode being larger. The total gap length is such that there is no self triggering at the operating voltage.

Fast operation is achieved by applying a large negative voltage pulse ~ -17 kV with a small rise time to the trigger electrode thus swinging its potential negative until the HV (larger) gap breaks down [3]. This connects the HV to the trigger electrode whose potential swings positive past its initial value thus appying a high voltage across the second (smaller) gap which breaks down because of the very large overvoltage. With an operating voltage of $\sim$ 15 kV and well rounded electrodes, the spark gap is triggered via an isolating capacitor ($\sim$ 100 pF, 1m length of UR67 cable) from a 340 V SCR pulse stepped up by a 1:17 pulse transformer. Figure 3a shows the schematic circuit diagram of a typical SCSG and in Fig. 3b the variation of gap voltages during operation.

The Imaging System

The imaging system consists of an imaging lens D_s with focal length f_s, a pinhole to reduce the plasma light, a band pass filter centered at 340 nm having a bandwidth at FWHM of 12 nm and an objective lens D_0 with focal length f_0. The layout of the system is shown in Fig. 4.

The event to be shadowgraphed is placed x distance from the imaging lens. The parallel laser beam from the beam expander focuses at distance f_s on the other side of the lens. A pinhole (diameter $\sim$ 1 mm) is placed at the focal point.

In this system, lenses with $D_s = 51mm$, $f_s = 30$cm, $D_0 = 51$mm, $f_0 = 10$cm are used. The pinhole is placed at 30 cm from the imaging lens and $x \sim 40$cm.

For the case of a highly luminous event, such as a spark plasma, in which the light from the event is still sufficiently strong to be of the same order as the laser light the pinhole serves a very important function. It reduces the plasma light falling on the film whilst not stopping the laser light if the pinhole is bigger than the focused laser beam diameter at the stop.

If the plasma event produces light of intensity I, then the light collected by lens D_s is $I(D_s^2/4x^2)$. This light is focused by D_s onto the film. At the pinhole, this light beam has diameter R given by

$$R = D_s \frac{f_s}{x} \tag{2}$$

Hence, of the total light intensity I, the light intensity getting through the stop of diameter S is

$$I' = \left(\frac{S}{R}\right)^2 \times I\frac{D_s^2}{4x^2} \tag{3}$$

which after substituting for R from equation 2 and simplifying yields $(I/4)(S/f_s)^2$.

Thus the pinhole reduces the light collected at the film from $(I/4)(D_s/x)^2$ to the stopped value $(I/4)(S/f_s)^2$.

The stop reduction ratio SR is therefore given by

$$\frac{I}{4}\left(\frac{S}{f_s}\right)^2 \Big/ \frac{I}{4}\left(\frac{D_s}{x}\right)^2$$

or

$$SR = \left(\frac{S}{D_s}\right)^2 \times \left(\frac{x}{f_s}\right)^2 \tag{4}$$

In this arrangement S = 1mm, D_s = 51mm, x = 40cm and f_s = 30cm; hence $SR = 7 \times 10^{-4}$.

The Camera

Polaroid 660 film is used for recording.

Experimental Setup

The experimental setup is shown in Fig. 5. The system comprises primarily of a laser shadowgraphy setup which has already been described in some detail and an external spark gap operated at 17 kV. The other major component of this system is the electronic timing sequence. The time sequence consists of silicon controlled rectifier (SCR) trigger unit used as the master trigger unit to generate a pulse of approximately 10 V peak and correlate the time sequence of the nitrogen laser and the external spark gap. This pulse triggers the high voltage SCR's (HVSCR) which then produce a voltage pulse of about 340 kV peak. The HVSCR output trigger pulse appears across the primary of the pulse transformers wound with transformation ratio of up to 50 times. The transformers then give an output pulse of 17.0 kV peak which is used to operate the nitrogen laser. This high voltage output pulse delivered from the secondary of the transformer also causes the external spark gap to fire thereby inducing a high voltage plasma discharge across the gap. In this type of experiment, it is found that the nitrogen laser fires about 1 μs before the formation of the spark when the whole system is triggered [4]. Thus, a delay unit is connected in the line circuit of the nitrogen laser in order to synchronize the laser flash and the various pulses of the plasma discharge from the external spark gap. The shadowgraph image is recorded using a camera.

Results

Figure 6 shows a series of shadowgrams depicting the temporal growth of the spark plasma [5]. In these pictures, it is seen that there is a sharply defined front which is the shock front moving outward axially as well a radially (axial means from left to right and radial means from down to up). At $t \leq 0.2\mu s$, the shape of the spark plasma is elongated in the axial direction. At $0.84\mu s \leq t \leq 7.6\mu s$, the growth in both axial and radial directions becomes more pronounce. Moreover, examination of the shadowgraphs also reveals an interesting phenomena. There is a well defined intersection of the shock fronts at $5.0\mu s < t \leq 7.6\mu s$ with no indication of reflected shock waves. These shadowgraphs can be used in diagnostic studies to obtain a velocity profile for the expansion of the spark plasma.

Conclusion

This work has demonstrated that the shadowgraph may be built as a very simple system which could be applied to produce very quick and authoritative results.

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Figure Captions

Fig. 1. Equivalent circuit of nitrogen laser.

Fig. 2. Design of beam expander.

Fig. 3a. Circuit diagram of a swinging cascade spark gap.

Fig. 3b. Voltage waveform for a swinging cascade spark gap charged to 10kV, gap setting and bias ratio 3:2 and triggered by a negative pulse.

Fig. 4. Layout of imaging system.

Fig. 5. Block diagram of nitrogen laser shadowgraphy system.

Fig. 6. Composite shadowgraph showing the temporal growth of a spark plasma.

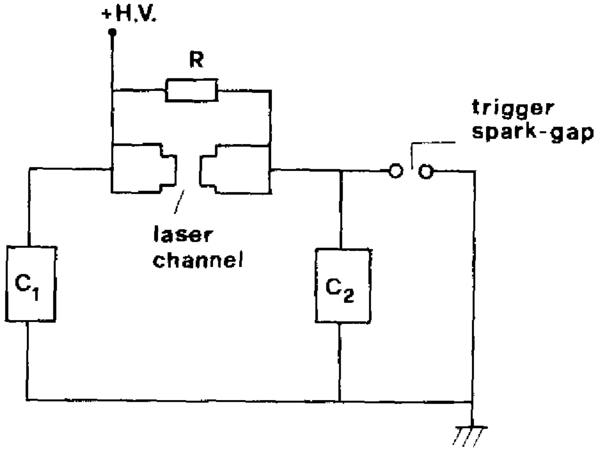

Fig.1

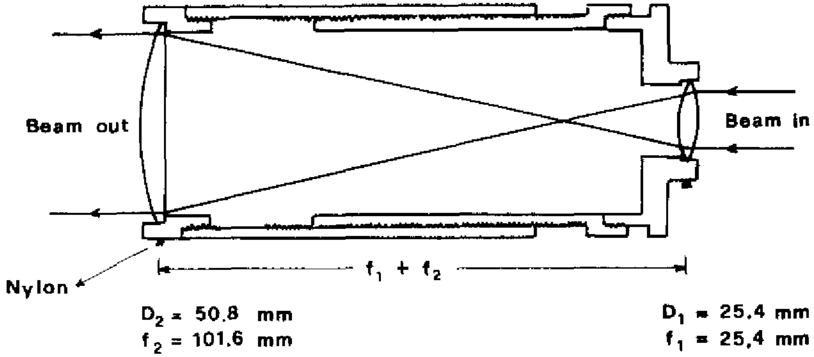
Beam out
Beam in
Nylon
$f_1 + f_2$
D_2 = 50.8 mm
f_2 = 101.6 mm
D_1 = 25.4 mm
f_1 = 25.4 mm

Fig.2

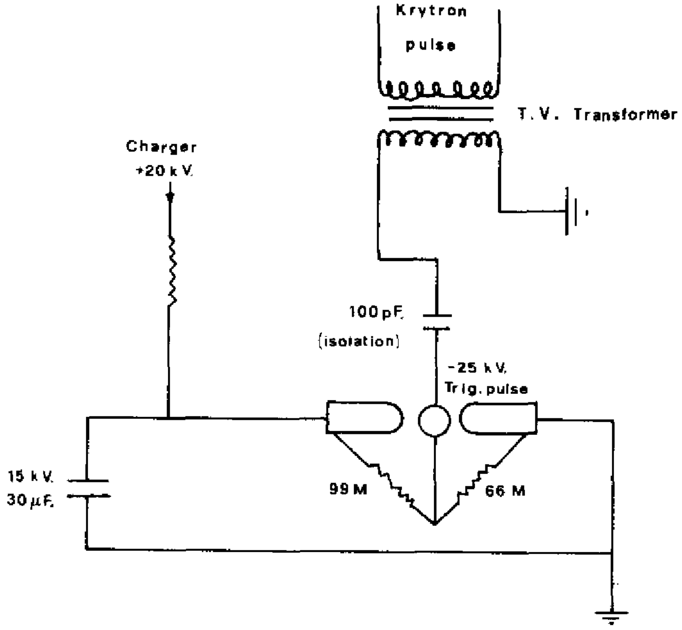
Krytron pulse
T.V. Transformer
Charger +20 kV.
100 pF. (isolation)
-25 kV. Trig. pulse
15 kV. 30 μF.
99 M
66 M

Fig.3a

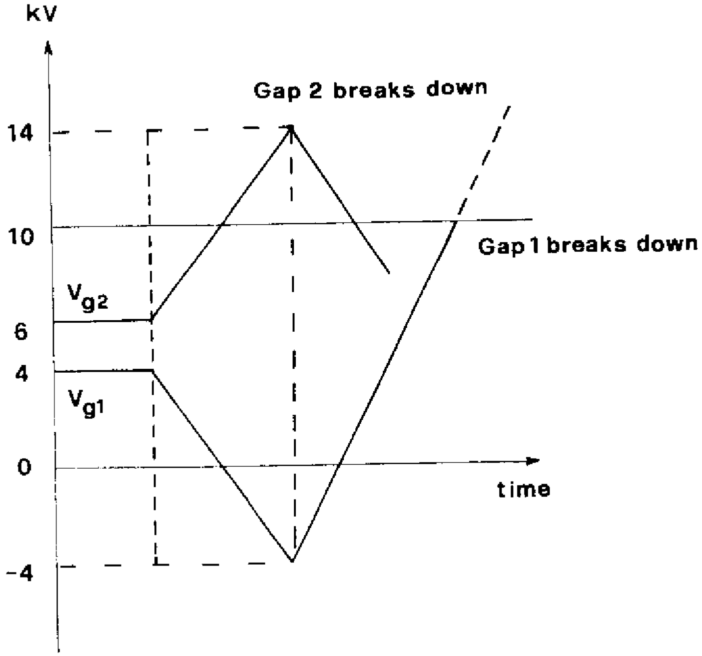
kV
Gap 2 breaks down
14
10
Gap 1 breaks down
V_{g2}
6
4
V_{g1}
0
time
-4

Fig.3b

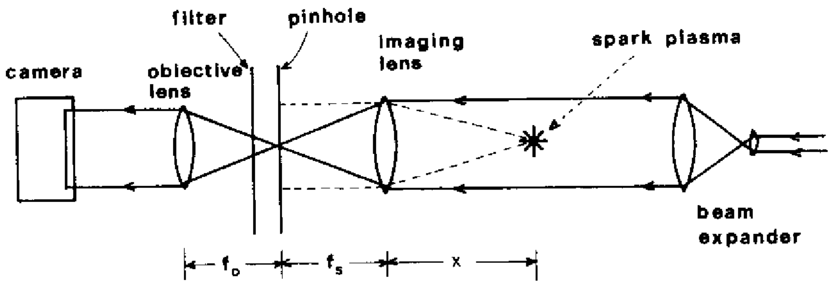
filter
pinhole
imaging lens
spark plasma
camera
objective lens
beam expander
f_o
f_s
x

Fig.4

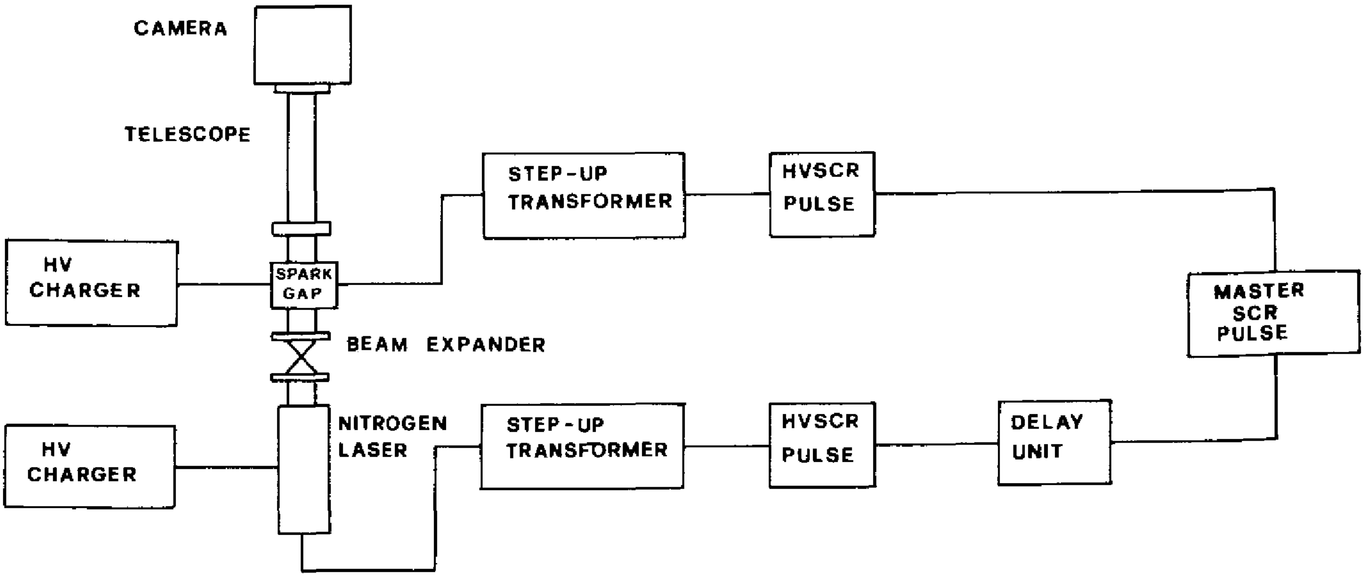
CAMERA
TELESCOPE
HV CHARGER
SPARK GAP
BEAM EXPANDER
HV CHARGER
NITROGEN LASER
STEP-UP TRANSFORMER
HVSCR PULSE
MASTER SCR PULSE
STEP-UP TRANSFORMER
HVSCR PULSE
DELAY UNIT

Fig.5

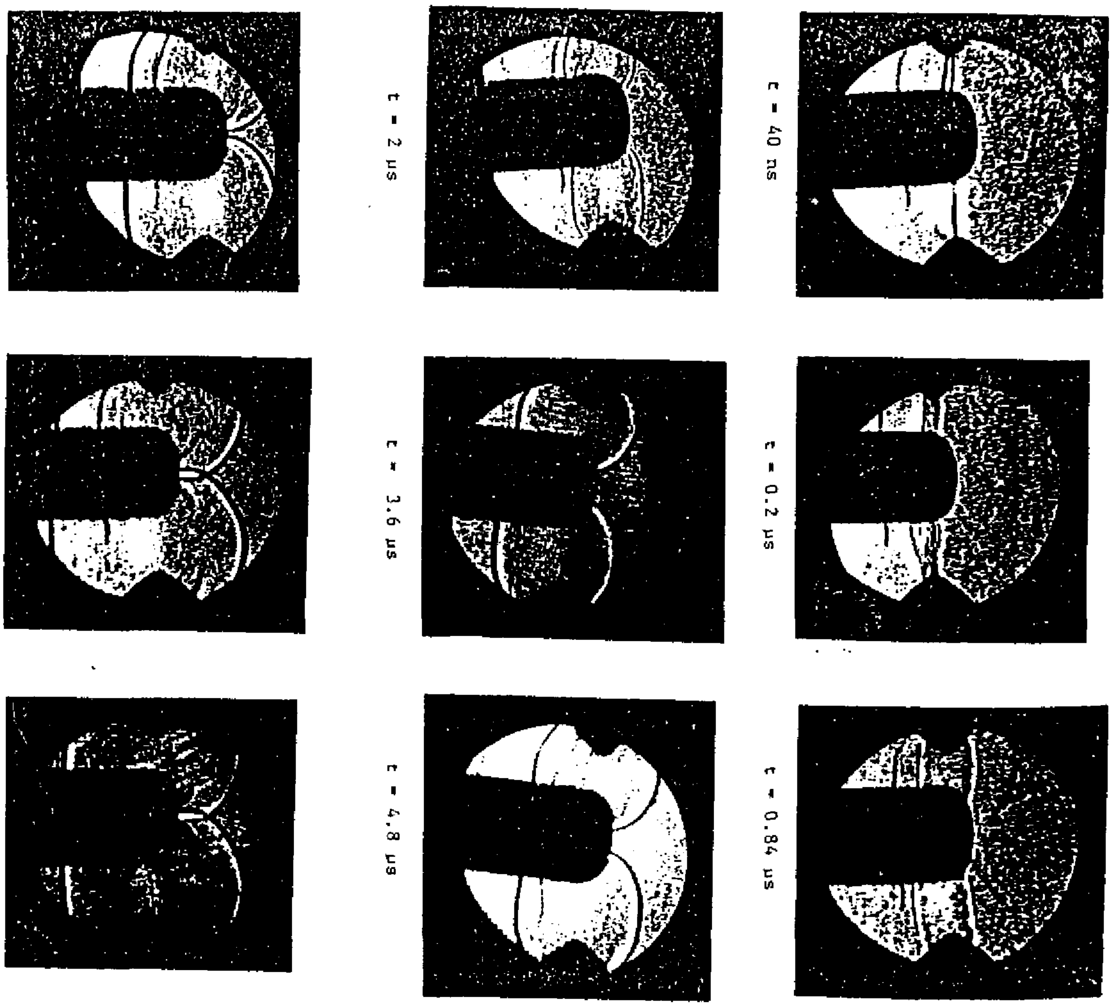
t = 5 µs
t = 2 µs
t = 40 ns
t = 7 µs
t = 3.6 µs
t = 0.2 µs
t = 7.6 µs
t = 4.8 µs
t = 0.84 µs

Fig.6