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ATOMIC ENERGY ESTABLISHMENT

PLASMA PHYSICS AND ACCELERATORS DEPARTMENT

CO-AXIAL ELECTRODES GUN CHARACTERISTICS

By

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NUCLEAR INFORMATION DEPARTMENT

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ABSTRACT

A coaxial electrodes gun is constructed with inner electrode diameter of 3.2 cm.; outer electrode diameter of 6.6 cm. and length of 25 cm. it is connected to a condenser bank which delivers 4 K. joule stored energy. The maximum power of the discharge is equal to 4.5×10^4 K. watt; for 5 kV charging voltage. The inductance showed two main peak values of 0.257 μH and 0.27 μ H. Theoretical calculations using one-dimension-single fluid model is used, which shows that the maximum acceleration is at 0.5 μ sec., and the gas breakdown takes place at the gun breech; at the start of the discharge, will leave the gun after 1.625 μ sec, also the drift velocity, the force and the magnetic field are given. The measured results show quite reasonable agreement with the calculations for most of the results, and the position of the plasma sheath inside the gun slightly deviated from the theoretical calculations due to viscosity and wall interaction, as well as other parameters which did not be take into consideration. The plasma current density of the sheath has its maximum value at $Z \approx 18$ cm, the plasma will leave the coaxial source after 1.5 μ sec. from the start of the discharge, which confirms with the theoretical model. Resistance of the gas between the electrodes, changes with time according to the particle injected from this source, and the maximum efficiency of the installation for charging voltage 5kV and pressure 80 μ Hg is at $\simeq$ 10 μ sec. and 20.5 μ sec.

INTRODUCTION

Co-axial gun, has been originally studied by Marshall (1960)[1]. The current distribution of the plasma sheath has been measured by Philip J. Hart (1962)[2] and showed that nearthetime when peak velocity is attained, the first shock wave splits into two pulses; and loops currents are formed, as the current near the base of the electrodes reverses its direction. J. Marshall and I. Henins (1966)[3] measured the axial current jet from the muzzle of the gun which was investigated, with a Rogovsky loop. Loops and other probes probably disturb the gun plasma at positions downstreams from the tip. It is believed, however, that effects on currents and potentials at the tips are small. Tsagas, N.F.(1977)[4] made a good analysis, and measured the sheath movement which had been solved theoretically and then compared experimentally by N.F. Tsagas, G.L.R. Mair, A.E. Prinn (1978)[5]. In our study, we measured the sheath velocity inside the coaxial gun and compared the results with numerical calculations of a single fluid-one dimension model in order to facilitate the problem.

1.1 <u>One Dimensional Single Flow Model</u>

In order to represent the plasma flow characteristics Klein (1970)[6], N.F. Tsagas, G.L.R. Mair, A.E. prinn (1978) and several authors tried to solve the problem analytically or numerically. In our case we assumed that the discharge starts at the breech and a sheath of thickness equals to the mean free path is formed in a short time compared with other physical processes. Micro and macro instabilities, diffusion, charge separation are not take into account and the discharge is symmetric, considering no presence of plasma interaction with the walls.

Using conservation law, the conservation law of momentum is given by

$$\frac{\partial}{\partial t}\int_V \Big(\sum_{+,-}\pi_i + G_i\Big)\, d\tau + \int_{\Sigma} \Big(\sum_{+,-}\pi_{ij} + T_{ij}\Big)\cdot d\sigma_j = 0$$

where

π_i	is the momentum vector
π_{ij}	is the momentum transfer tensor
G	is the momentum of the electromagnetic field
T_{ij}	is the stress tensor
V	is the volume bounded by the surface Σ
t	is the time
$d\sigma_j$	is the surface element
$d\tau$	is the volume element

Subscripts + and - refering to the ions and electrons respectively. The conservation law of energy is given by:

$$\frac{\partial}{\partial t}\int_V \Big(\sum_{+,-}\mathcal{E}_P + \mathcal{E}_F\Big)\, d\tau + \int_{\Sigma} \Big(\sum_{+,-} Q_j + S_j\Big)\, d\sigma_j = 0$$

where

$\mathcal{E}_P$	is the kinetic energy
$\vec{Q}$	is the heat flow vector per unit volume
$\vec{S}$	is the poynting flow vector

$\mathcal{E}_F$ is the energy density of the electro-magnetic fild.

The continuity equation is given by:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial X_j}(NV_j) = 0$$

where

- N is the particle density
- V is the mean velocity
- x is the co-ordinate x

The equation of motion of the n^{th} particle is given by:

$$m_n \ddot{\vec{r}}_n = e_n \left[\vec{E}(\vec{r}_n) + \frac{1}{c}\left(\vec{V}_n \times \vec{B}(\vec{r}_n)\right)\right]$$

$\vec{E}$ and $\vec{B}$ denote the electric and magnetic fields, C denotes the speed of light

The magnetic induction between co-axial electrodes

$$B = 2I\left[\ln\left(\frac{b}{a}\right)\right] Z/\text{cross section area (gauss)}$$

where

- I is the discharge current (abs. unit)
- b is the outer electrode radius (cm)
- a is the inner electrode radius (cm)
- z is the length of the coaxial electrodes (cm)

Thermal electron - electron collisions

$$\lambda_{ee} = 23 - \ln \left(n_e^{1/2} \; T_e^{-3/2} \right)$$

Electron - ion collisions

$$\lambda_{ei} = \lambda_{ei} = 23 - \ln \left(n_e^{1/2} \; Z \; T_e^{-3/2} \right)$$

Mixed ion - ion collisions (one type)

$$\lambda_{ii} = 23 - \ln \left[\frac{z^2}{T} \left(\frac{2n z^2}{T} \right)^{1/2} \right]$$

$$= 23 - \ln \left[\frac{\sqrt{2n} \; Z^3}{T^{3/2}} \right]$$

where:

n is the density of ions.

z is the charge of ions

T is the temperature of ions.

The value of acceleration, drift velocity, force, magnetic field, and distance Z from the above laws, are calculated numerically and are plotted in Fig. (1A). Kinetic energy (w) VS number of particles N, kinetic energgy VS $\frac{dN}{dw}$, and kinetic energy VS $d(\frac{dN}{dw})/dw$ in Fig. (1B) are also plotted.

2. EXPERIMENTAL ARRANGEMENT

Fig.(2) shows a cross-section of the coaxial electrodes, both are connected directly to each other with teflon insulating ring in - between. The stored energy from a capacitor bank is supplied to the electrodes in the form of pulsed discharge. The operation of such a condenser bank is controlled by the use of trigatron spark gap switch. The details of the construction and operation characteristics is given by M.M. ABD El Aal (1977)[7].

3. DIAGNOSTIC TECHNIQUES

The discharge current, was measured by a pick up loop (Rogovsky coil), the discharge voltage was obtained by a potential divider while axial and radial currents are measured by miniature Rogovsky coil.

A- Current Measurement

A Rogovsky coil is used to measure the discharge current, the output of the coil is shunted by an ohmic resistor which is very small compared with inductive resistance of the coil. Copper wire was used (601turn) and the shunted ohmic resistance $= 0.6\ \Omega$.

The coil sensitivity S is:

$$S \simeq 1002 \text{ A/volt},$$

for charging voltage $= 5$ kV, the coil output peak voltage measured on the oscilloscope is $\simeq 29$ volt, and hence the current of the discharge is:

$$I \simeq 30 \text{ kA}$$

The calculated current for such experimental arrangement is given by:

$I = \frac{2\pi CV}{\tau} \simeq 48$ kA (for the case in hand)

The difference between the calculated value and the measured one is due to the ohmic resistance of the circuit as well as an expected variation of the capacitance of the condenser bank during the discharge.

B <u>Voltage Measurement</u>

Resistor dividers are used to measure the discharge voltage. In our measurements the potential divider ratio was 1 : 800. The measured voltage between the two coaxial electrodes during the discharge has a peak value of $\simeq$ 2kV.

The power flow variation with discharge time is shown in Fig. (3), the power curve shows that the power flows from the discharge circuit increases with time from the beginning of the discharge, and have the maximum peak value at $t \simeq 4.5 \mu$ sec, then reaches zero at $t \simeq 9 \mu$sec. Maximum power $\simeq 4.5 \times 10^4$ K. watt

The average energy liberated in the discharge/ particle as a function of time is shown in Fig.(4), these values calculated from the formula:

$$W_t = \int_0^t IV \, dt$$

The total energy liberated in the discharge for the first half cycle $\simeq$ 0.173 k.j

The relation between the inductance and the time of the discharge is shown in Fig.(5), in this Fig. two maximum peaks are existing. The inductance L of the gas volume could be calculated from the formula:

$$L_t = \frac{\int_0^t V\,dt}{I_t}$$

By neglecting the ohmic resistance, the value of inductance at the two peaks is $L = 0.257\,\mu H$ and $0.27\,\mu H$ respectively.

Fig. (6) shows the relation between $\ln/\left(\frac{I - I_o}{I_o}\right)/$ and discharge time, the slope of this curve gives directly the value $/\frac{R}{L}/$

$$I \quad I_o \left(1 - e^{-\frac{Rt}{L}}\right)$$

where

I_o = Maximum discharge current

I = discharge current obtained at mid point at each of two branches of the half cycle.

From this curve, it is clear that there are two peaks at $\simeq 8\,\mu$sec. and $26\,\mu$sec. The variation of $/\frac{R}{L}/$ with discharge time is shown in Fig. (7). Fig.(8) shows the relation between $\frac{Rt}{L}$ and discharge time. It is obvious that $\frac{Rt}{L}$ is maximum at $t \simeq 10\,\mu$ sec. and $20.5\,\mu$ sec. It is obvious that there exist two peaks at $t \simeq 10 \mu$sec, 20.5μsec. Fig. (9) shows the relation between the gas volume resistance (approximately) and time of discharge, by multiplying $(-\frac{R}{L}-)$ x (L). At $t = 3$ to 6.5μsec., the resistance has a constant value equal to $\simeq 1 \times 10^{-3} \Omega$; while at time $t \simeq 9.5 \mu$sec. and 21μsec., resistance shows a maximum values equal to 0.036Ω and 0.03Ω respectively.

A miniature Rogovsky coil is used to measure the axial and radial current along the coaxial electrodes. Fig. (10) shows the relation between I_z, I_r and distance Z at different times for charging voltage 5 kV and pressure 80μHg, at $t = 0.5, 1$, 1.25μsec, the maximum axial current exists at $Z = 18$ cm. At $t = 1.5 \mu$sec. the maximum axial current exists at $Z = 25$ cm. For the radial current measured at $t = 0.5, 1, 1.25$ μ sec. and $Z = 21.5$ cm, the direction of the current is reversed; but at $t = 1.5 \mu$sec. the current has only one direction. Fig. (11) shows the relation between the axial current and the distance Z, its obvious that the maximum current at $Z = 25$ cm. for most values of time of discharge. Fig.(12) shows the relation between radial current and distance Z.

4. DISCUSSION AND CONCLUSION

In a coaxial electrodes gun, the discharge current is 30 kA, for charging voltage of 5 kV. Maximum power $\simeq$ 4.5×10^4 K. watt, total energy liberated in the discharge $\simeq$ 0.4 K. joule, maximumm inductance experimentally equals to $\simeq 0.27 \mu$H and maximum resistance $\simeq 0.036 \Omega$.

Theoretical model showed that the gas travel from breech to the muzzle in 1.625 μsec. which coincide with the experimental work at which the gas start to leave the source at 1.5 μsec. Such small deviation from the theoretical calculations is due to viscosity and wall interaction. The discharge voltage shows an oscillation at $t = 1.5 \mu$ sec. of frequency $f \simeq 700$ kH_z.

The parameters of the discharge showed that the maximum inductance takes place at a time which corresponds to the focusing time $\sim$ (10 and 20.5 μ sec.) . The energy flow shows maximum at $t \simeq 5, 13, 19, 24$ and 34 μ sec., which does not represent the maximum drift velocity, since the gas motion does not follow the current.

The current density fron is not clear due to its inclination between the two electrodes. Fig. (10) shows that the peak axial current density at Z $\rightarrow$ 18 cm (most of the time before focusing) which occur at $t = 1.5 \mu$ sec. The expansion of the results after that time showed that the gas does not totally leave the source (which is clear from the inductance and resistance curves). The plasma resistance increases sharply after the first half cycle, but due to the loss of the most energy in heating and ionizing the gas, and there is still enough particles which might proceed the second discharge and focusing at the second half cycle. This is clear from current density variation curves Fig. (11,12).

Since the plasma travels the distance between the breech and muzzle at 1.625 μsec. So their is no overlapping of the first half cycle on the sheath formed and the result is clear as if it is a single pulse discharge. Formation of second sheath in the same half cycle was not observed.

This study shows that we can achieve high efficiency of the co-axial gun by synchronizing the discharge current, discharge period, type of gas, gas density and the gun dimensions.

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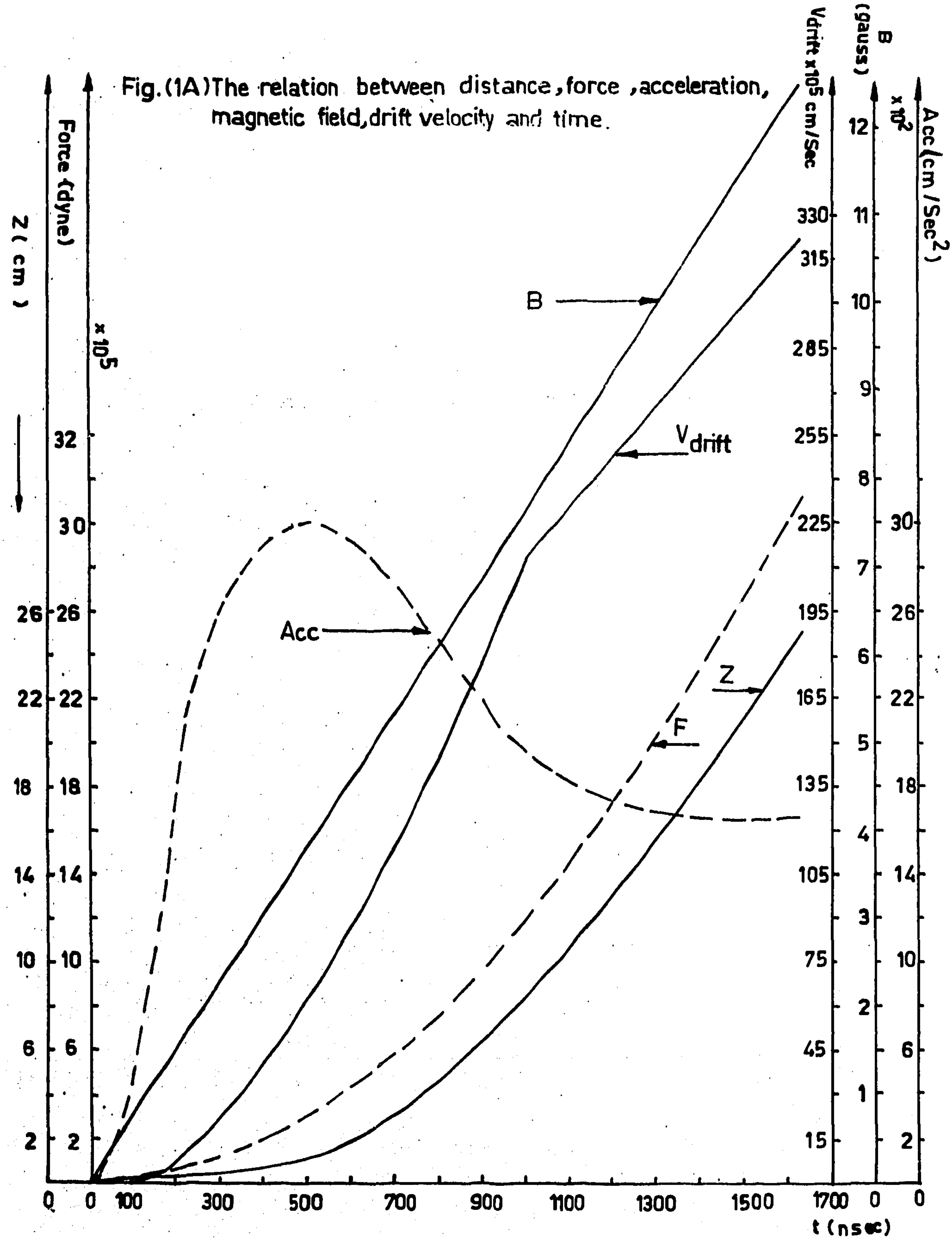
Fig.(1A)The relation between distance, force, acceleration, magnetic field, drift velocity and time.



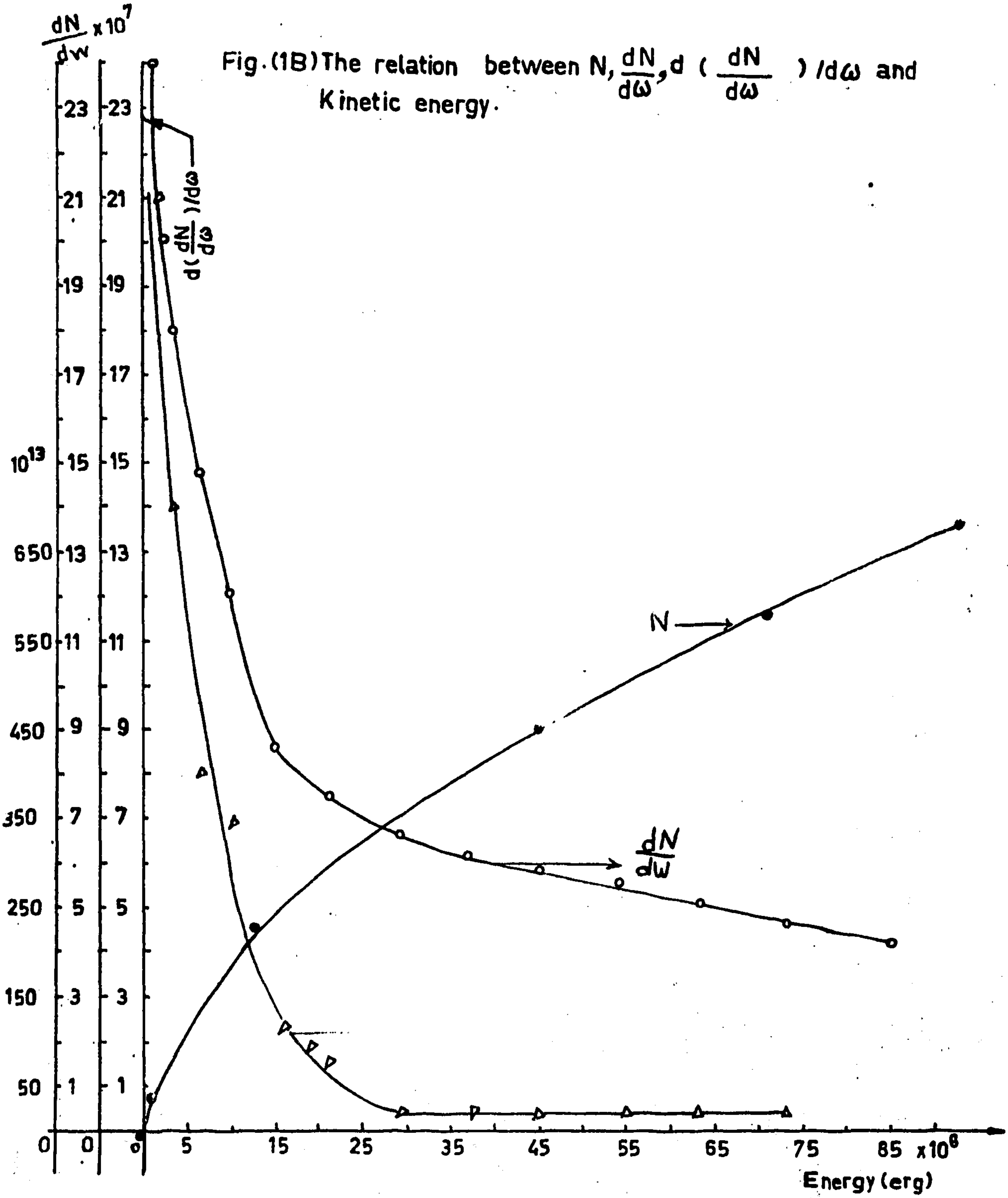


Fig.(1B) The relation between N, $\frac{dN}{d\omega}$, d ($\frac{dN}{d\omega}$) /dω and Kinetic energy.

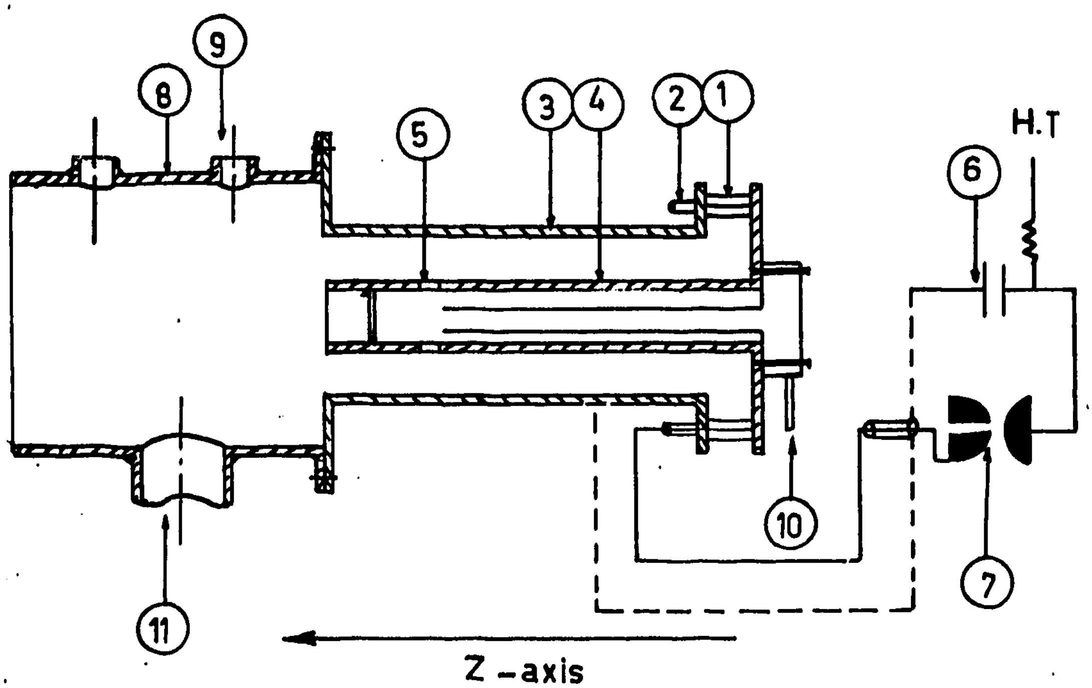


Fig. (2) THE CROSS SECTION IN THE CO- AXIAL ELECTRODES.

1-Inter-electrodes insulator. 2-Discharge cables.
3-Outer electrode (Cathode). 4-Inner electrode (Anode).
5-Circutar hole gas outlet. 6-Condenser bank.
7-Spark gap. 8-Expansien Chamber.
9-Vacuum measuring Connection 10-Gas inlet.
11-Pumping Connection.

- Fig. (3) Power flow in the discharge chamber.

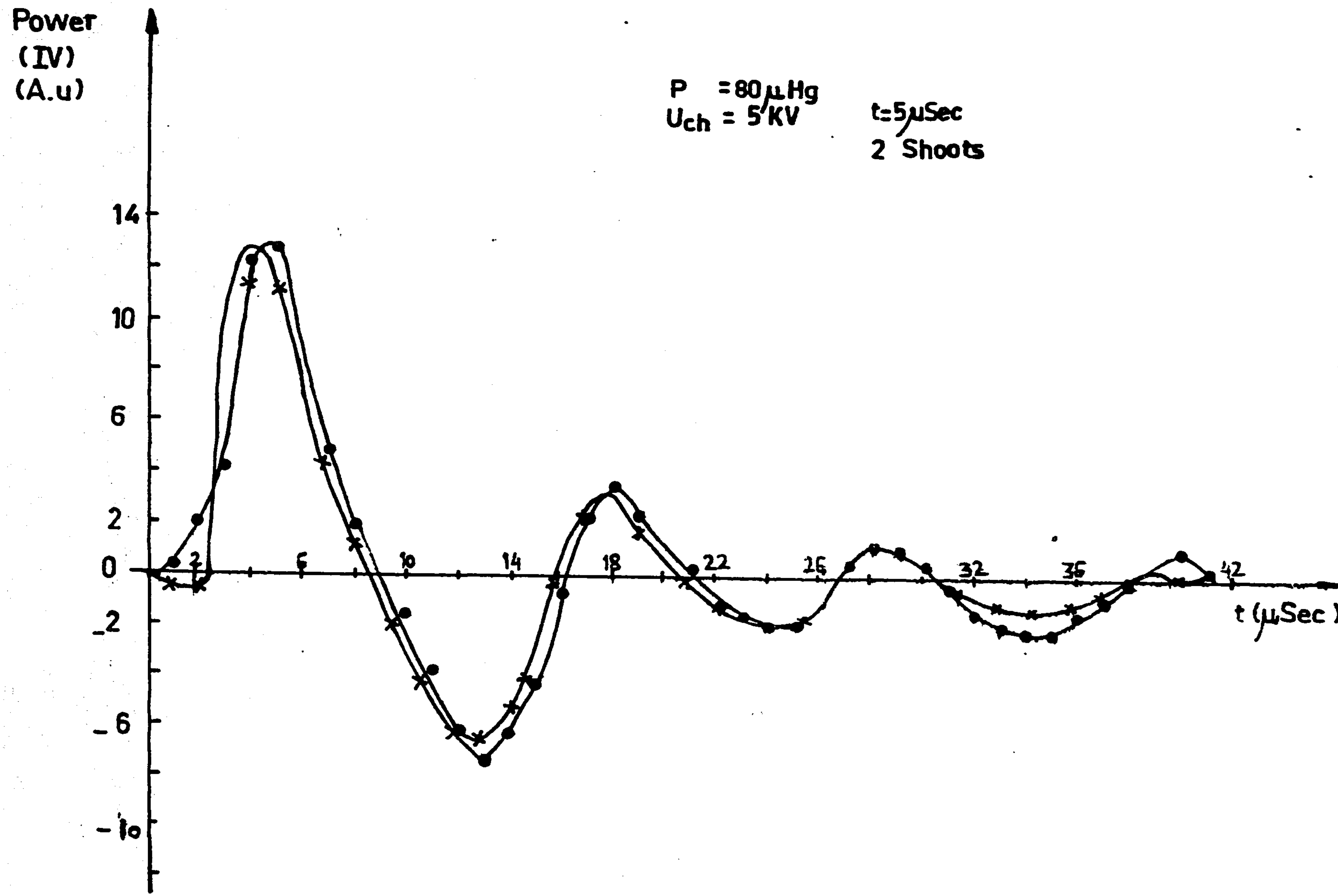


Fig.(4) Energy, put into the discharge as a function of time of discharge..

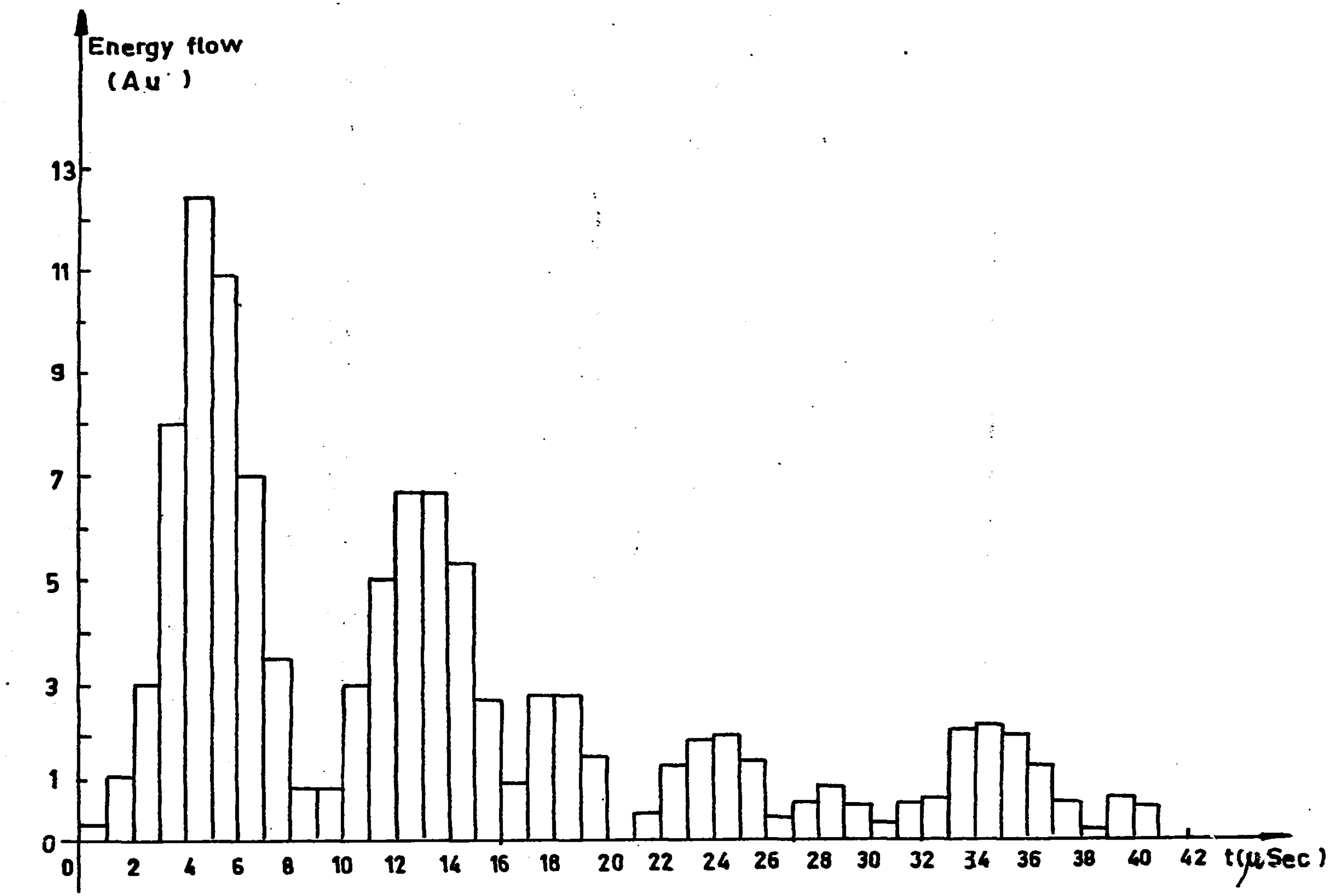


Fig.(5) Inductance of the gas volume as a function of time of discharge.

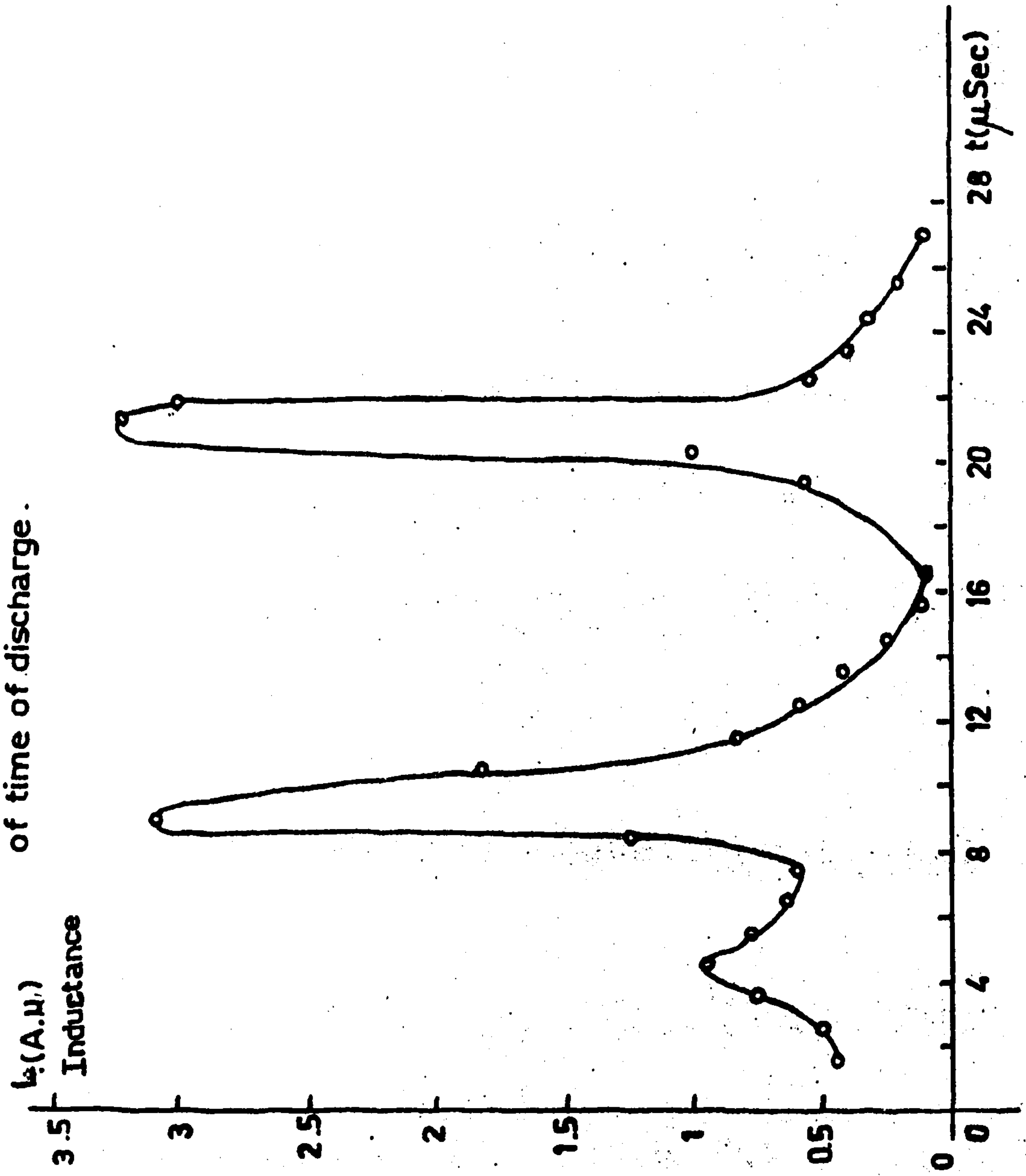


Fig.(6)The relation between $\ln\left|\frac{I_o - I}{I_o}\right|$ and time of discharge.

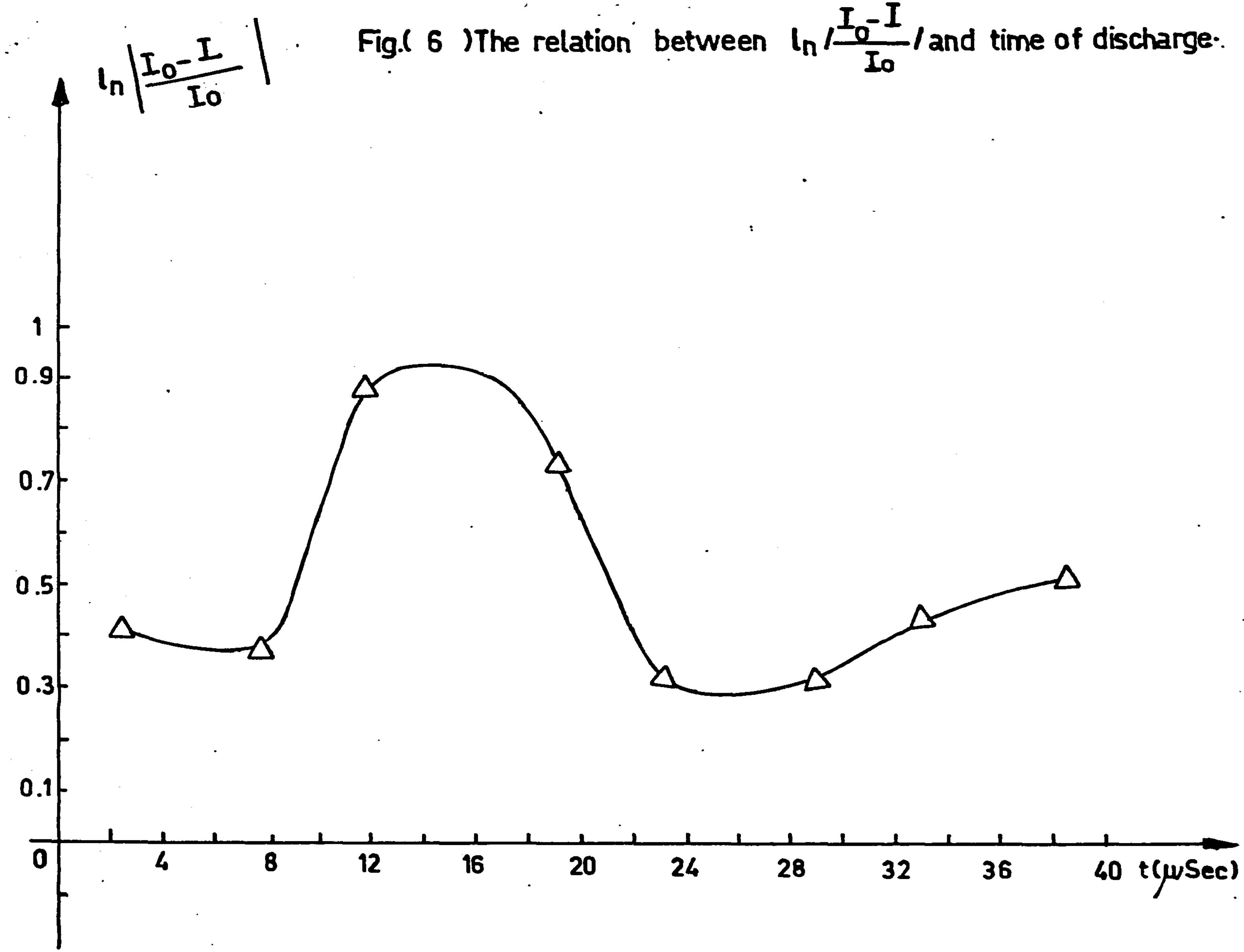


Fig (7) The relation between $\left|\frac{R}{L}\right|$ and time of discharge.

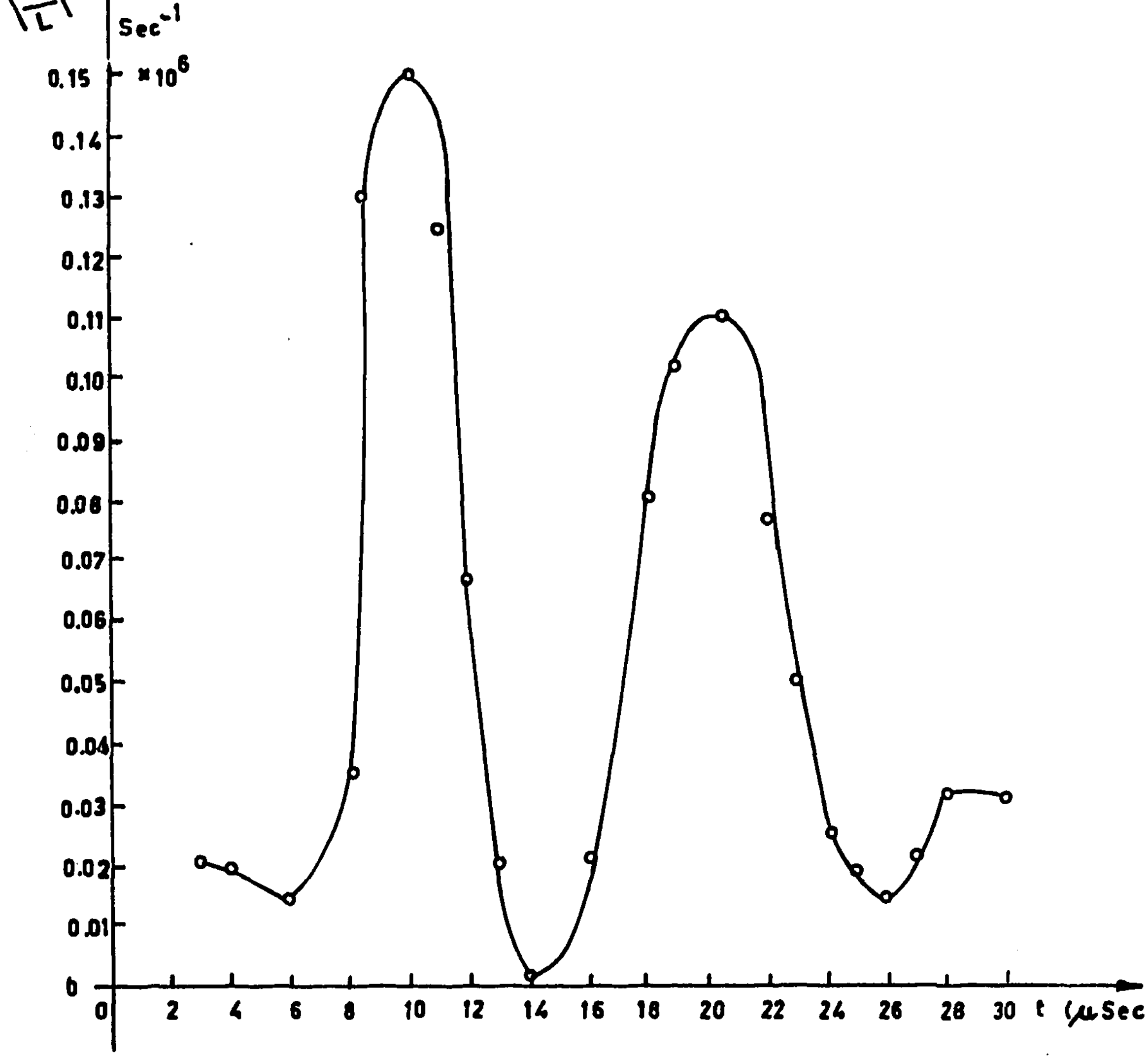


Fig. (8) The relation between $(\left|\frac{R}{L}\right| t)$ and time of discharge.

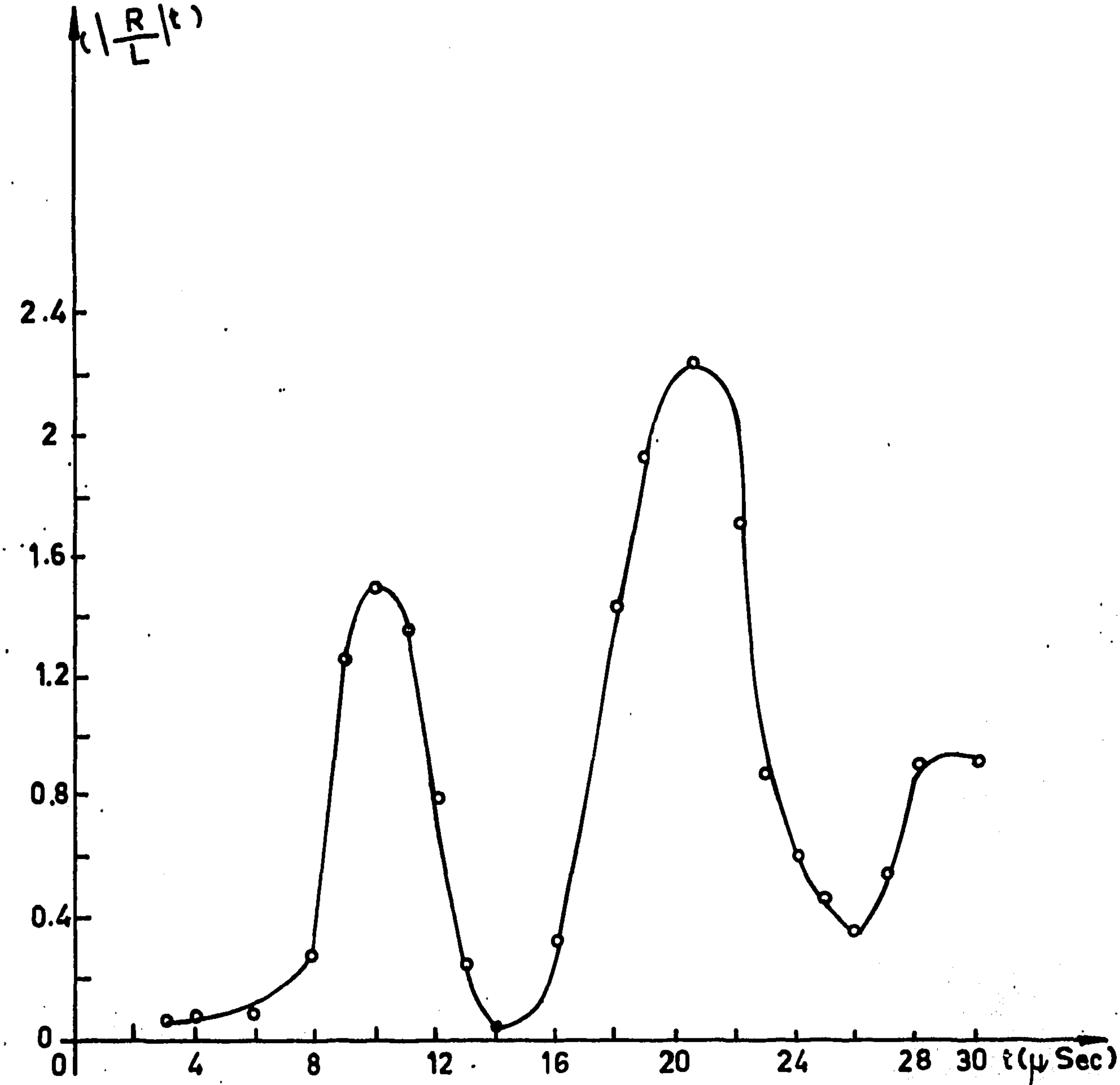
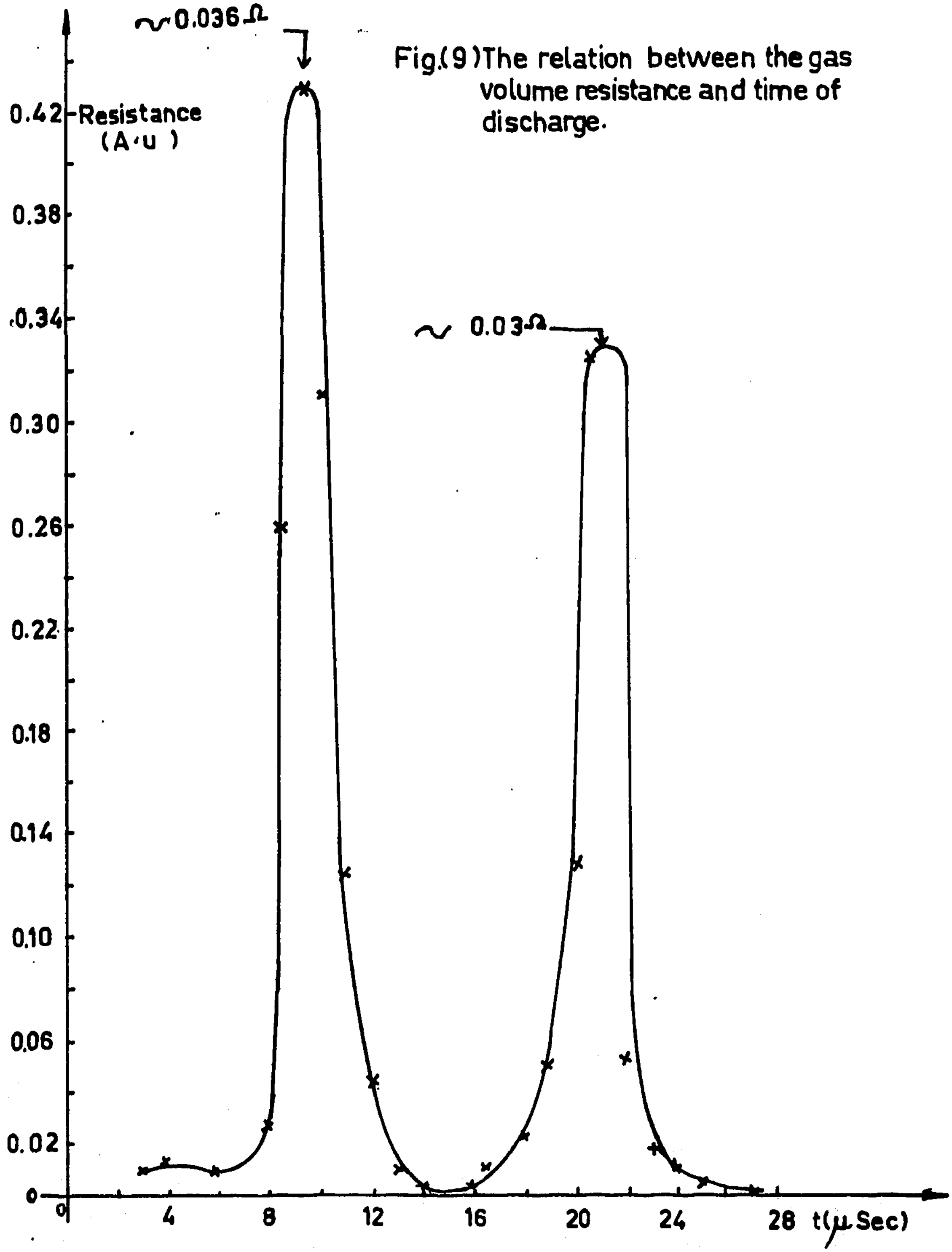


Fig.(9)The relation between the gas volume resistance and time of discharge.



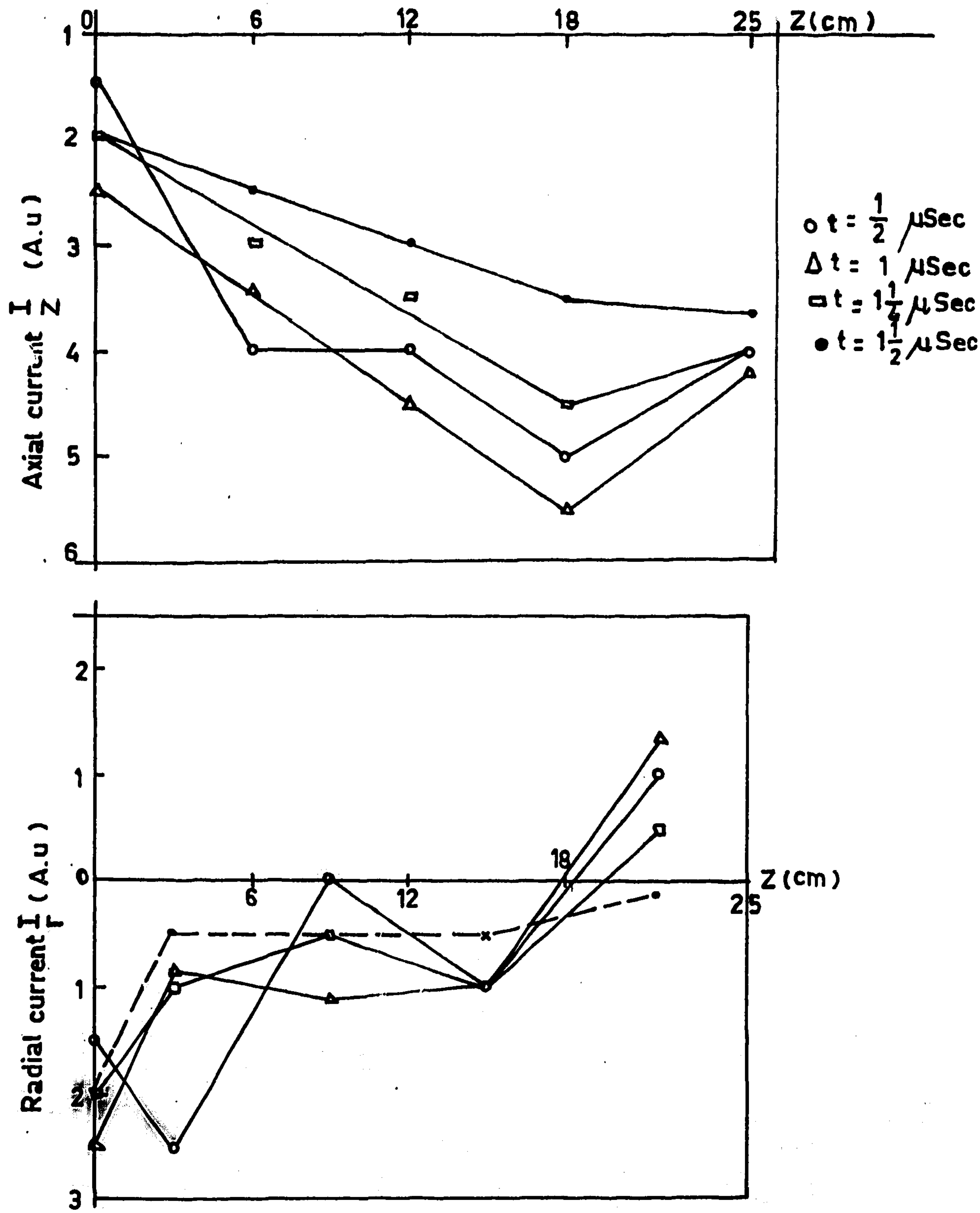


Fig.(10)The relation between axial current, radial current and axial distance Z at different time.

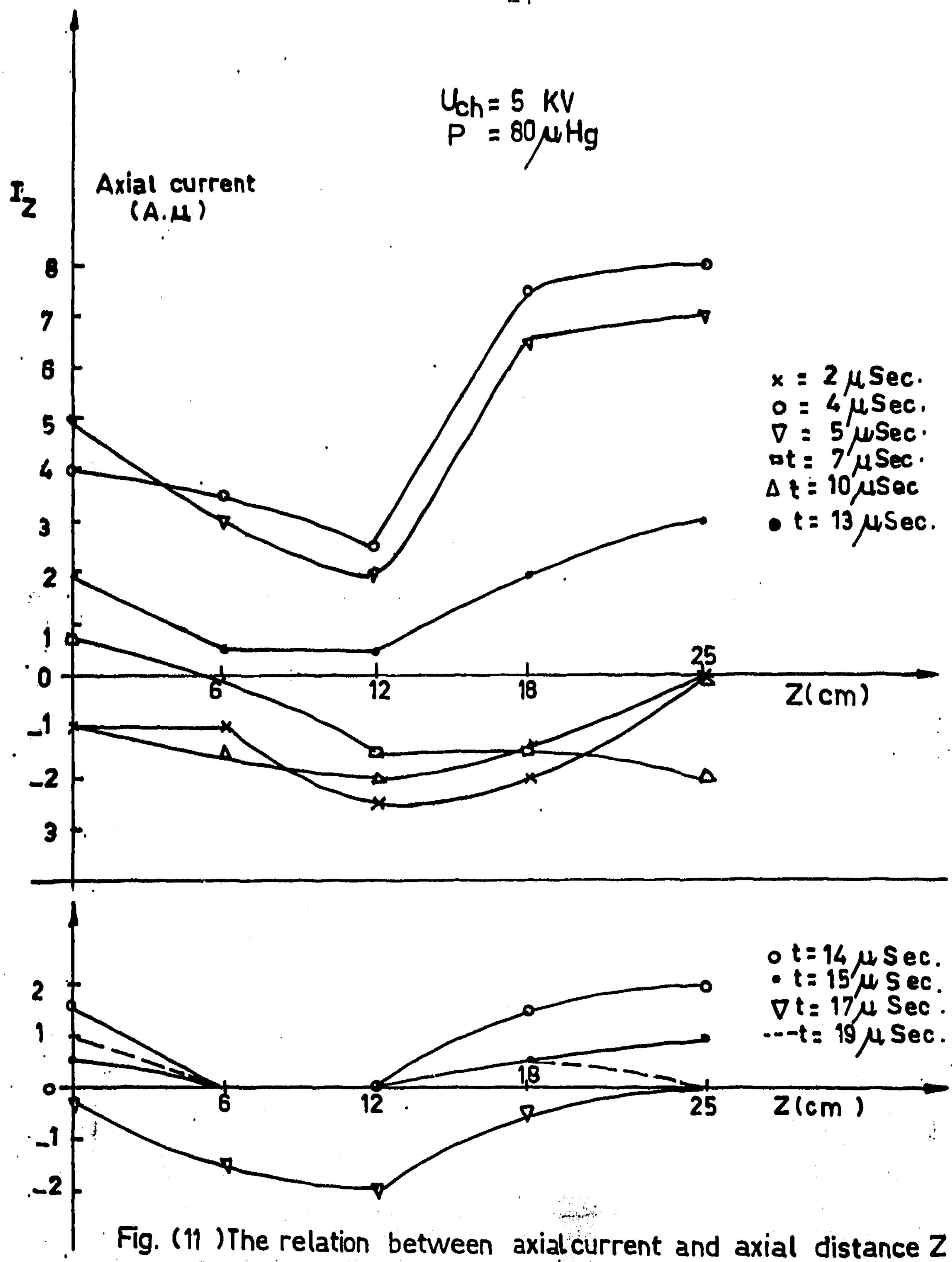


Fig. (11)The relation between axial current and axial distance Z at different time.

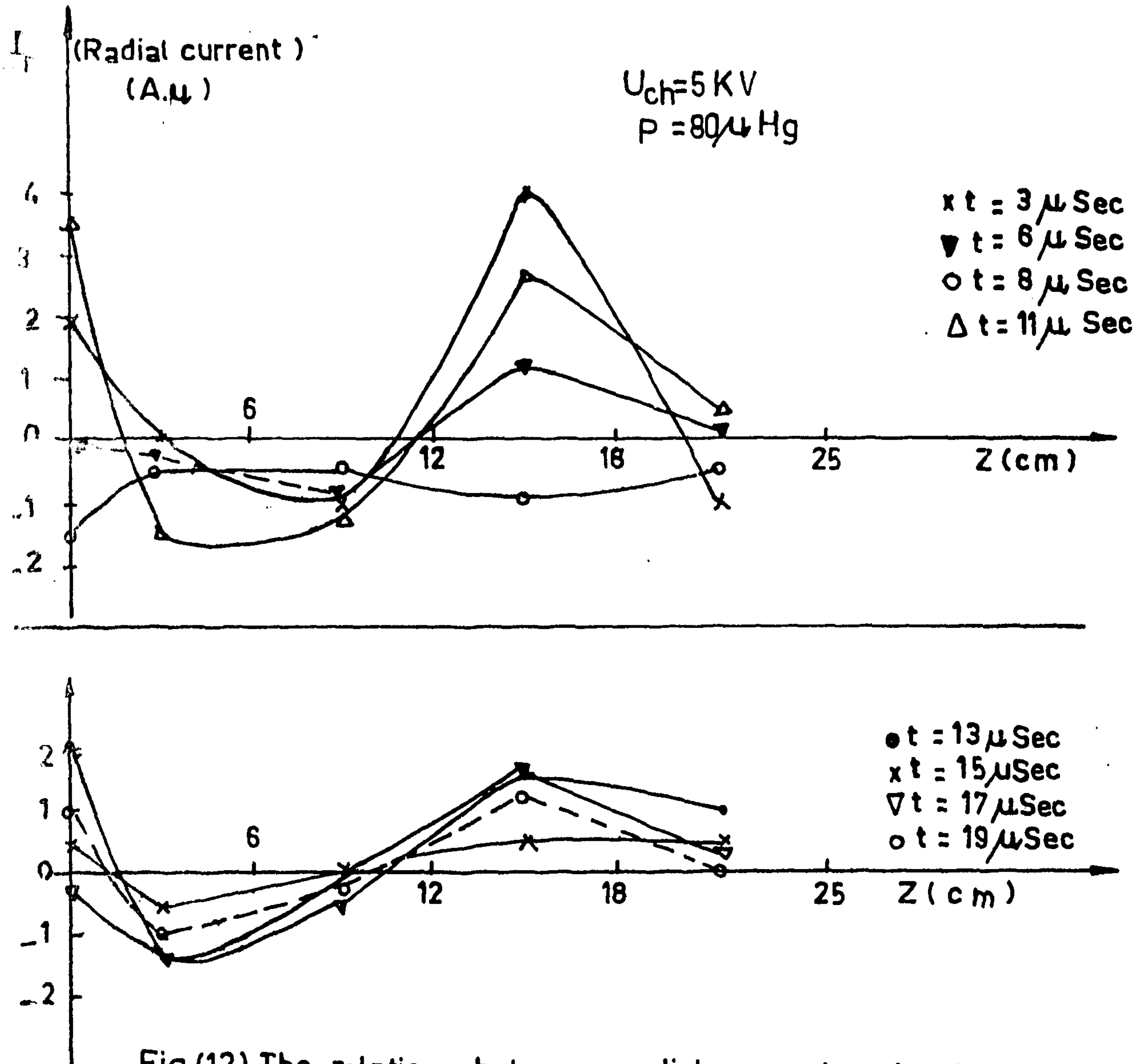


Fig.(12) The relation between radial current and axial distance Z at different time.