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Transient processes in plasmas produced by surface waves

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Abstract. The rise time of a wave electric field τ_{HF} and the ionisation front velocity v_f are measured in a pulsed plasma produced by a surface wave. Different behaviours of τ_{HF} and v_f are observed when the pressure is varied. The passage from a collisional to a non-collisional mode may be identified, in accordance with the electronic mean free path estimated for the discharge. The variations of v_f and τ_{HF} with power corroborate this classification.

The electron density along the plasma column is also measured for different instants t_i from the beginning of the pulse. Thus the discharge stabilisation can be identified by its behaviour in analogy with the stationary plasma.

1. Introduction

The plasma produced by surface waves (PSW) has been a subject of great interest for the past few years (Moisan *et al* 1982, Moisan and Ricard 1977). Long plasma columns have been produced using a new wave-launching structure called Surfatron (Moisan *et al* 1979). The plasma produced in this way was quite stable along the axis of the tube containing the gas and the electron density was slightly varying along that axis. This plasma has a wide range of applications: ion source, spectral lamp, chemical plasma, laser, etc (Wilkinson and Tanaka 1955).

Two important reasons have recently led to the use of PSW in a pulsed mode. The first one is of a practical nature: it is that there is a possibility of obtaining higher powers using this mode rather than using plasmas produced by surface waves in the continuous mode. Under similar conditions of production more intense spectral lines and higher electron density are obtained with the pulse mode which leads to an important power saving (Paik and Creedon 1968). The second reason is that the pulse mode facilitates the study of the plasma creation and evolution to stablisation which is extremely important in many chemical plasma experiments (Taras *et al* 1982).

At present, there is no theoretical model that fully explains the temporal evolution of these plasmas throughout their creation. This lack may be due to the scarcity of experimental work on plasma transient processes. The purpose of this paper is to report an experimental study of the transient phenomena and their dependence on discharge parameters such as pressure and power.

2. Theoretical considerations

Plasmas produced by surface waves have a special charactistic: they are not just a simple disturbance of the wave but also what sustains it. Although from this point of view the propagation of a surface wave in the plasma created is a nonlinear phenomenon, the validity of the linear model of propagation in the case of plasmas near their stable state has been established (Zakrzewski *et al* 1977).

Expressions for the fields for a cylindrical Pyrex tube coated with a metallic and coaxial cover, where the discharge originates, can be found from the wave propagation equation in cylindrical coordinates (Chaker 1981). If the boundary conditions are imposed on the components of the fields at the surfaces between the different regions, the dispersion curve of the system is found (Nghiem *et al* 1981).

Figure 1 shows the electron density n versus the wavelength λ for our experimental arrangement.

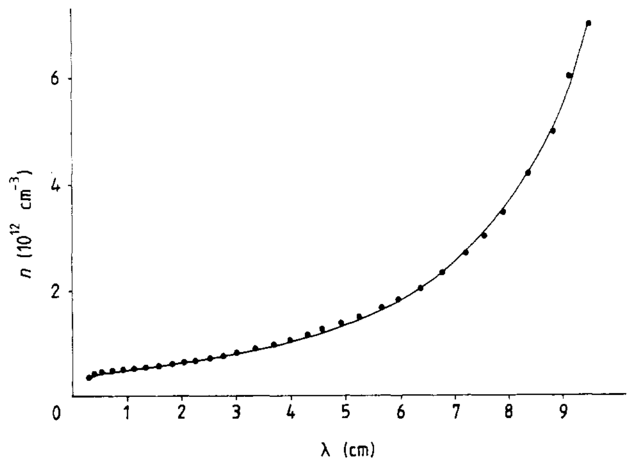

Figure 1. Phase diagram for variable n. Wave frequency $f = 2200$ MHz. Tube dimensions: $\varphi_{\text{in}} = 6$ mm, $\varphi_{\text{out}} = 9$ mm.

From the dispersion equation it is possible to conclude that the density n tends to the value n_c when $\lambda \rightarrow 0$:

$$n_c = 3.156 \times 10^{-10}\, \omega^2(1 + \varepsilon_v) \tag{1}$$

where ε_v is the relative permittivity of the glass that surrounds the plasma. Therefore wave propagation for density values under the critical electron density n_c is shown to be impossible.

2.1. *Longitudinal distribution of the electron density*

Although the effect of collisions was not considered when studying the dispersion curve (Chaker 1981), the evolution of the wave power along the plasma has to be calculated taking account of the wave attenuation α.

Glaude *et al* (1980), from the expressions for the power absorbed along the axis per unit length and the incident power, showed that the ratio between α and the effective collision frequency ν is a function of electron density only. In the case where the discharge is produced by the wave they have elaborated a theoretical model of the variation of n versus z under the hypothesis that the power absorbed per unit length is proportional to the number of electrons found in that interval. They obtained that the electron density, in the steady state, does not depend on the incident power and that the electron density variation with z is given by

$$\mathrm{d}n/\mathrm{d}z = -2\alpha n/[1 - (n/\alpha)\,\mathrm{d}\alpha/\mathrm{d}n]. \tag{2}$$

The numerical solution of the dispersion equation shows that the product αn rises smoothly when plotted as a function of z except at the end of the column where there is a sharp rise. They also found that the RHS of equation (2) becomes constant and n is a decreasing linear function of z (from the Surfatron) assuming that αn is nearly constant.

2.2. *Transient processes*

Ionisation is produced along the discharge tube during the time in which the plasma is created. The wavefront velocity depends on the ionisation time since the wave does not propagate in the absence of plasma and an ionisation front along the column can be observed. The ionisation-front velocity is much more smaller than the group velocity of the wave; this means that once the power is coupled by the Surfatron it is successively reflected at the end of the transient plasma created.

A model for the ionisation-front advance has been obtained by Bloyet *et al* (1981) by assuming that an instantaneous gradient of the electron density is produced in the boundary of the plasma leading to a gradient of $|\boldsymbol{E}|^2$. This gradient pushes the electrons forward in the plasma with an axial velocity given by

$$v_{\mathrm{e}} = \tfrac{1}{2}(e^2/m^2\omega^2)t_{\mathrm{c}}\nabla|E^2| \tag{3}$$

where t_{c} is the average time between two consecutive collisions of electrons with gas molecules and e and m are the electron charge and mass respectively.

In the present case for a pulsed power supply the ionisation front advances for the duration of the pulse and this process is repeated with the pulse frequency. The advance of the ionisation front limits the length L of the plasma produced; therefore for pulses with duration τ the length is

$$L = \int_0^\tau v_{\mathrm{f}}\,\mathrm{d}t. \tag{4}$$

Moreover the evolution of the surface wave in the transient period is characterised by the time interval τ_{NF} in which the electric field reaches the maximum amplitude corresponding to the stationary plasma.

Finally it is obvious that a study of the transient process would require the determination of the electron density. Therefore the magnitudes of v_{f}, τ_{HF} and $n(t)$ characterise the transient process and will be measured in our experiment in order to analyse the plasma creation mechanism.

3. Experimental methods and results

Figure 2 shows the experimental arrangement used in this work. A pulsed wave of frequency 210 MHz is coupled to the discharge tube through the Surfatron. The pulse

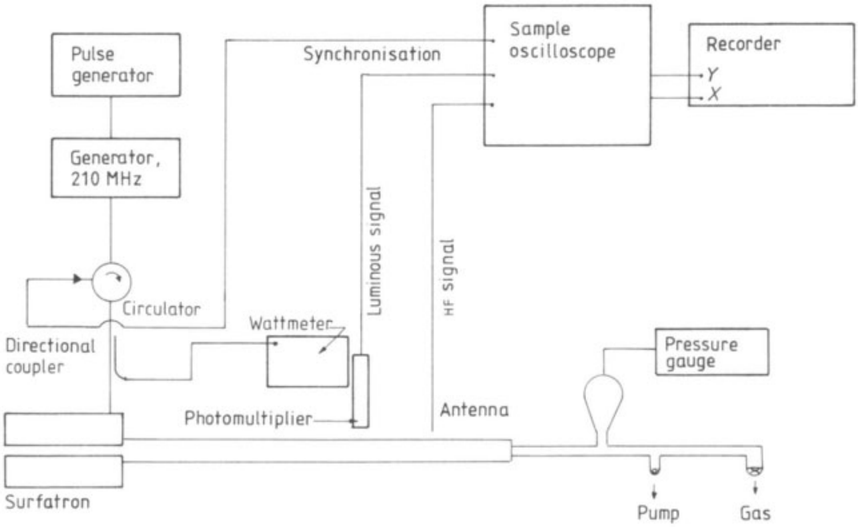

Figure 2. The apparatus for measurements of τ_{HF} and v_f.

width was varied, from 0.5 to 2 μs, and depended on the discharge pressure. The pulse frequency was 1 kHz and the wave peak power varied betwen 1 and 4 kW. The discharge tube was a Pyrex tube with $\varphi_{in} = 6$ mm, $\varphi_{out} = 9$ mm and length 1 m.

A circulator between the generator and the Surfatron prevented the unwanted reflections from reaching the generator. Part of the incident power was directed through a directional coupler to a wattmeter. The HF signal propagated along the tube was picked up through an antenna oriented perpendicular to the glass tube. A photomultiplier detected the luminous intensity emitted by the discharge. Both signals were sent to a sampling oscilloscope providing the necessary output for a recorder.

Figure 3 shows photographs of the HF signals displayed on the oscilloscope. It is possible to see how a certain time interval (tens of nanoseconds) is needed for the HF signal in order for it to reach its maximum amplitude. Once this maximum is established an amplitude modulation of the HF signal is observed. This is explained by the power reflected on the ionisation front. It is also observed that the rise time increases with increasing distance from the Surfatron, owing to the wave attenuation along the plasma.

The results obtained are detailed below.

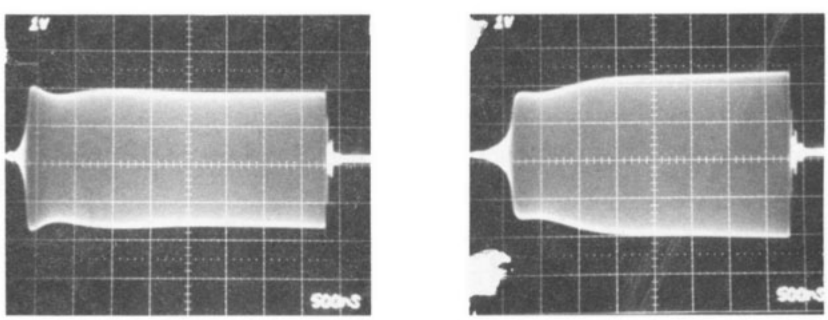

Figure 3. Photographs of the HF signal in an argon discharge at 0.2 Torr and 1 kW of wave peak power, for two distances from the Surfatron: (*a*) $z = 10$ cm; (*b*) $z = 20$ cm.

3.1. Measurement of the rise time τ_{HF}

Once the breakdown is established the wave amplitude grows until it reaches its maximum value. Then it is possible to define τ_{HF} as the time interval spent between the 10% and 90% of the maximum wave amplitude.

The experimental results are shown in figure 4. A minimum value for τ_{HF} versus pressure is observed. The position of this minimum is almost independent of the power of the wave, although it is different for different gases. As can be seen from figure 4, for the argon plasma, an increase in power corresponds to a decrease in τ_{HF} for pressures higher than 150 mT while it is smaller for pressures lower than 150 mT.

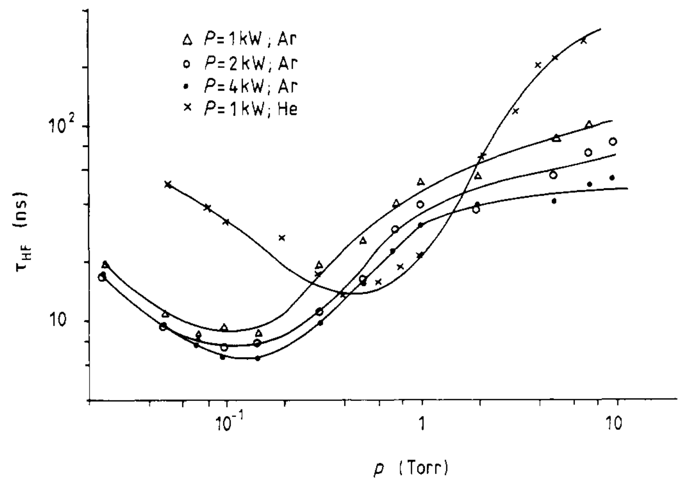

Figure 4. The variation of τ_{HF} with pressure p.

Under identical conditions of pressure and power, the values of τ_{HF} are higher in helium than in argon. This is due to the lower ionisation efficiency of the former (MacDonald 1966) and leads to a need for more time to obtain a suitable density for establishing the wave. The minimum of τ_{HF} may be explained by considering the electron mean free path l in the discharge. From the values of the effective collision frequency ν and the electron temperature T_{e} given by Chaker *et al* (1982) it is possible to conclude that l is about 0.15 cm for pressures of 150 mTorr in argon. In helium the mean free path l (MacDonald 1966) is 0.16 cm at 400 mTorr. Both values are within the range of the plasma tube radius.

Thus it is possible to explain the minimum of τ_{HF} as being due to the transition from the collisional ($l < R$) to the non-collisional ($l \geqslant R$) mode. In figure 4 this transition is observed to be a smooth one when $l \geqslant R$. Many of the electrons diffuse to the walls preventing the production of enough electron density for the wave to be established and thus explaining the increase in τ_{HF}.

3.2. Experimental results for the ionisation-front velocity v_f

The ionisation-front velocity v_{f} was obtained from the time delay Δt between the luminous signals observed in two different positions in the column separated by a distance $\Delta z = 2$ cm. The calculated velocity $v_f = \Delta z/\Delta t$ was assigned to the intermediate point. Figure 5 shows a record of the luminous signals corresponding to two positions of the photomultiplier $d = 9$ cm and $d = 11$ cm from the Surfatron. This figure also shows the way Δt is calculated.

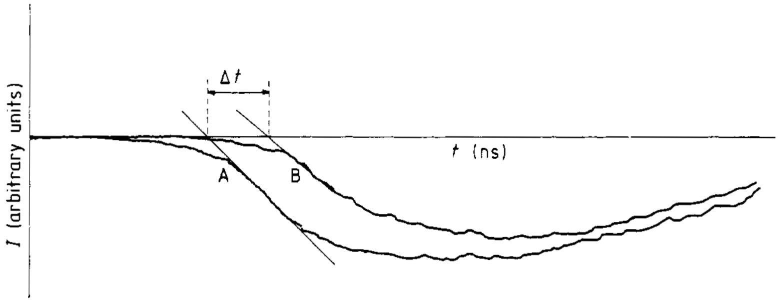

Figure 5. The measurement of Δt from luminous signals picked up at (A) 9 cm and (B) 11 cm from the Surfatron.

The results found for He and Ar for different pressure and power conditions are shown in figure 6. A maximum for v_f as a function of pressure is observed. This corresponds to the minimum of τ_{HF}, as expected from the definitions of the two magnitudes.

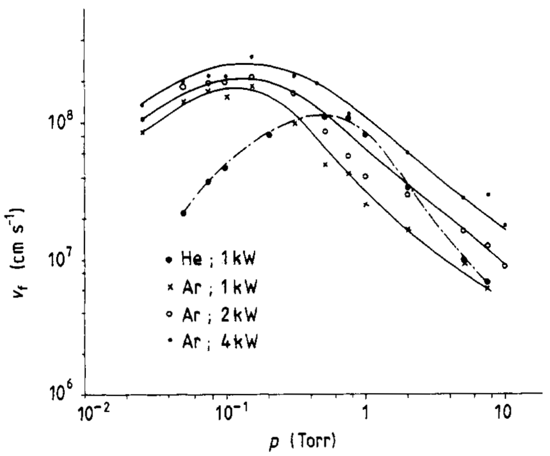

Figure 6. The variation of v_f with presure p.

Figures 7 and 8 show log v_f versus log P for the argon plasma. The dimensions of v_f and P are ms^{-1} and W respectively. The factor B in the relation

$$v_f = AP^B \tag{5}$$

is obtained from the slope of the straight lines represented in figures 7 and 8. A decrease of B with pressure is observed from the values shown in table 1. In the collisional mode a proportionality between v_f and P is obtained.

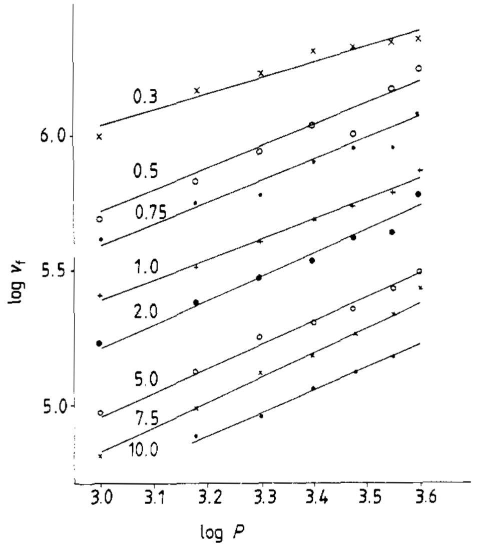

Figure 7. The variation of log v_f with log P for the collisional regime in an argon discharge, for various pressures given in the figure in Torr.

The measurements of velocity v_f for different positions along the column are shown in figure 9. The decrease observed for v_f is due to the attenuation of the wave along the plasma column, as the influence of the power upon v_f is important, as can be seen in figure 7. As pressure increases the attenuation of the wave becomes greater, speeding

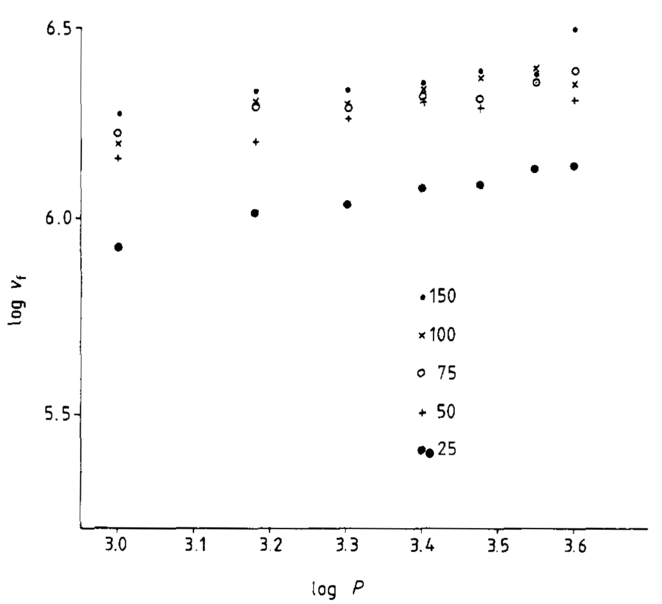

Figure 8. The variation of log v_f with log P for the non-collisional regime in argon discharge, for various pressures given in the key in mTorr.

Table 1. The variation of exponent B with pressure for different values of the peak power.

Pressure (Torr)	B	Peak power (kW)
10	0.87	1.5–4
7.5	1.04	1–4
5	0.82	1–4
2	0.85	1–4
1	0.73	1–4
0.75	0.7	1–4
0.5	0.89	1–4
0.3	0.58	1–4
0.15	0.28	1–4
0.1	0.27	1–4
0.075	0.18	1–4
0.050	0.30	1–4
0.025	0.34	1–4

the decrease of v_f. The results obtained for velocity v_f and its variation with pressure and power corroborate the distinction made before between collisional and non-collisional modes.

The variation with the power P in the first mode is consistent with the theoretical model (Bloyet *et al* 1981) which explains the advance of the front based on the ponderomotive force according to equation (3). The higher the power, the higher will be the acceleration experienced by the electrons in travelling towards the neutral gas, allowing the surface wave to be established after them. This happens along the entire column during the power pulse giving rise to a plasma column of length L as given by (4).

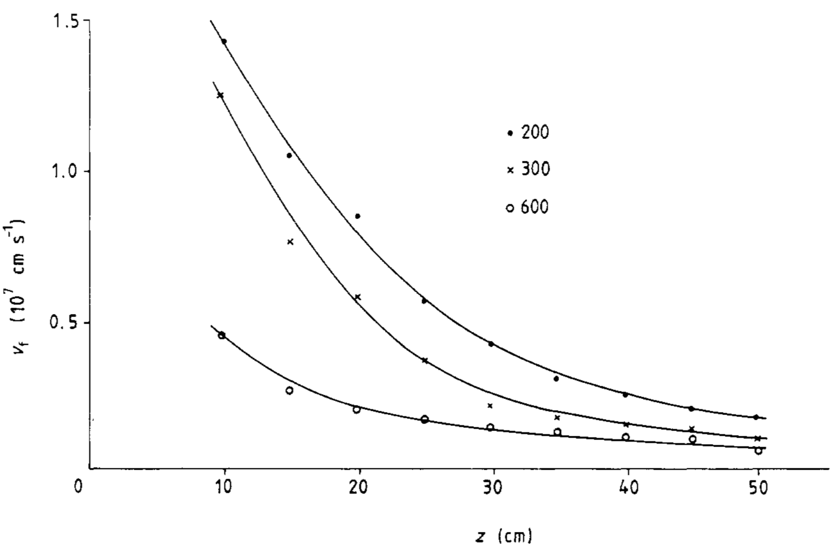

Figure 9. The ionisation-front velocity v_f as a function of distance z from the Surfatron for different pressures of argon discharge given in the key in mTorr.

In the non-collisional mode the above theoretical model is not suitable because of the electron losses in the tube walls.

3.3. Measurement of the electron density

3.3.1. Method of measurement. In order to determine the electron density n along the plasma column the wavelength of a signal propagated through the plasma was measured. The value of n is found from the phase curve of figure 1 and these measurements. The average wavelength λ was measured by an interferometric method where the product between the signals propagated in the plasma E_m and a reference signal at the same frequency and power level was obtained. Both signals are expressed analytically by

$$E_{\text{ref}} = E_0 \cos(\omega t - \psi_0) \tag{6}$$

$$E_{\text{m}} = E(r)\, \mathrm{e}^{-\alpha z} \cos(\omega t - \bar{\beta} z) \tag{7}$$

where $E(r)$ is the radial variation of the amplitude and $\bar{\beta} = 2\pi/\bar{\lambda}$.

The output of a mixer treating both signals is

$$A_1 = E(r) E_0\, \mathrm{e}^{-\alpha z} \tfrac{1}{2}[\cos(2\omega t - \bar{\beta} z \quad - \psi_0) + \cos(\bar{\beta} z - \psi_0)]. \tag{8}$$

That filtered by a LP filter becomes

$$A_0 \propto \cos(\bar{\beta} z - \psi_0). \tag{9}$$

The distance between a maximum z_1 and a minimum z_2 of (9) was considered to be $\bar{\lambda}/2$ and this average value of the wavelength $\bar{\lambda}$ is associated with the point z_m equidistant between z_1 and z_2. If should be noted that the value of $\bar{\lambda}$ is always less than the actual value of the wavelength in z_m (Chaker 1981), since for the positions z_1 and z_2 we have

$$\beta(z_2) z_2 - \beta(z_1) z_1 = \pi. \tag{10}$$

Multiplying equation (10) by $\lambda(z_m)$ leads to

$$(\lambda(z_m)/\lambda(z_2)) z_2 - (\lambda(z_m)/\lambda(z_1)) z_1 = \lambda(z_m)/2. \tag{11}$$

As the wavelength decreases along the column (as shown in figure 1), we have

$$\lambda(z_1) > \lambda(z_m) \tag{12}$$

$$\lambda(z_m) > \lambda(z_2). \tag{13}$$

Thus equations (11), (12) and (13) lead to

$$\lambda(z_m)/2 > z_2 - z_1 \Leftrightarrow \lambda(z_m) > \bar{\lambda}(z_m). \tag{14}$$

In order to minimise the intrinsic error associated with this mean value, a wave of 2200 MHz (measurement wave) was superimposed on the 210 MHz wave that produced the plasma, shortening the distance where the mean value is taken. However this implies that the measurement wave will only be propagated in the plasma up to a position z where the electron density is equal to the critical density for this frequency. Therefore this measurement wave will never reach the end of the plasma column.

The experimental arrangement for the measurement of $\bar{\lambda}(z)$ is shown in figure 10. The plasma production is carried out as above but with pulses of width 70 μs in order to allow for the stablisation process. The measurement wave was excited on a Surfaguide (Moisan *et al* 1976) in pulses of width 2 μs and picked up by a sliding antenna along

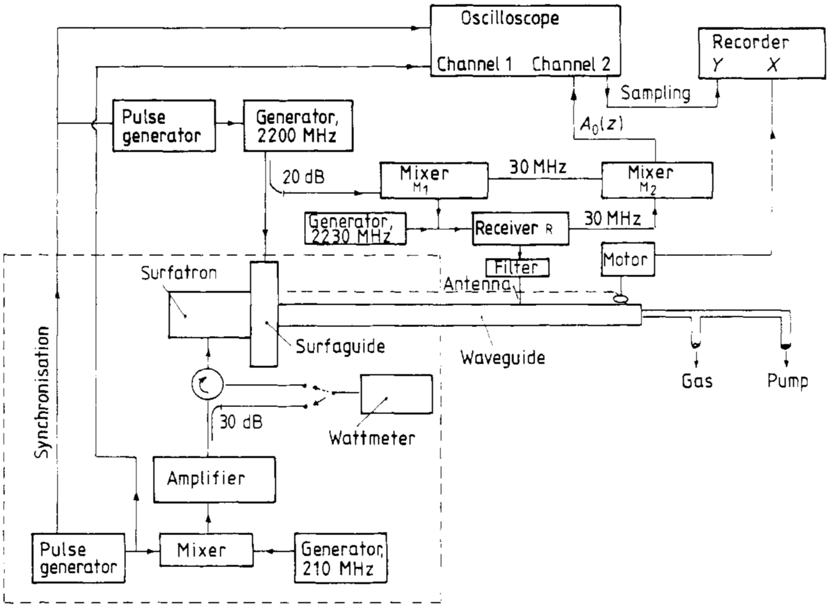

Figure 10. The apparatus for measurements of $\bar{\lambda}(z)$.

the slotted guide which encloses the plasma. In order not to disturb the plasma, a measurement wave of very low power (about 1 mW) was used.

The signal picked up, once it had been filtered and amplified, was mixed with the reference signal. As there was no amplifier available for 2200 MHz, a change of frequency to 30 MHz in the signals was necessary. This was carried out via the mixer M_1 and the receiver R. The signal so obtained at the output of the mixer M_2 is given by (9). This output was sent to a sampling oscilloscope and selection of the instant t_i, where measurements were taken, was made. This signal was used as the Y input of a recorder, the

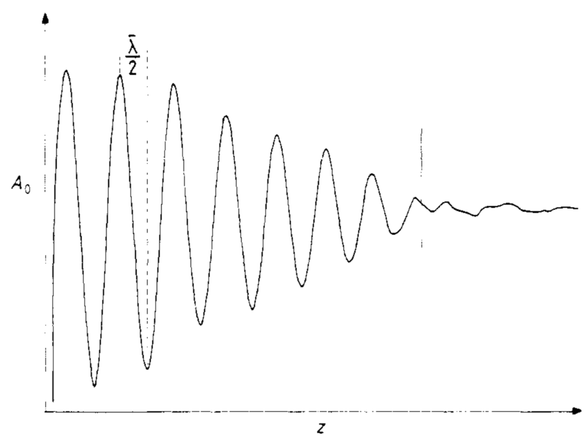

Figure 11. The determination of $\bar{\lambda}$ from the signal A_0 obtained in the recorder.

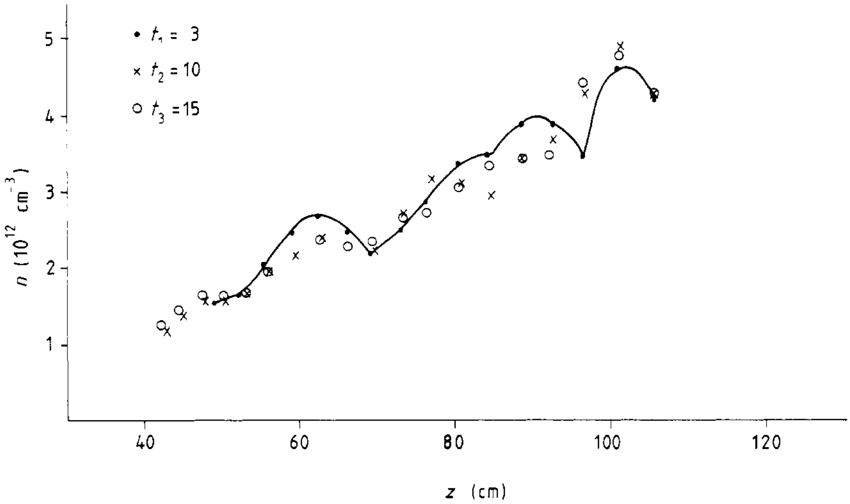

Figure 12. The measured electron density n as a function of distance z from the edge of the stationary plasma column for an argon discharge with $P = 400$ W and $p = 500$ mTorr at successive instants t_i given in the key in μs.

X input signal being a voltage proportional to the displacement of the antenna. Figure 11 shows a recording of the signal $A_0(z)$ for an instant t μs after the beginning of the pulse that created the discharge.

3.3.2. Experimental results for the electron density evolution. The measurements were taken along the plasma for instants t_i from 2 to 20 μs after the HF power was applied. Figures 12 and 13 show the axial evolution of the density for successive instants t_i.

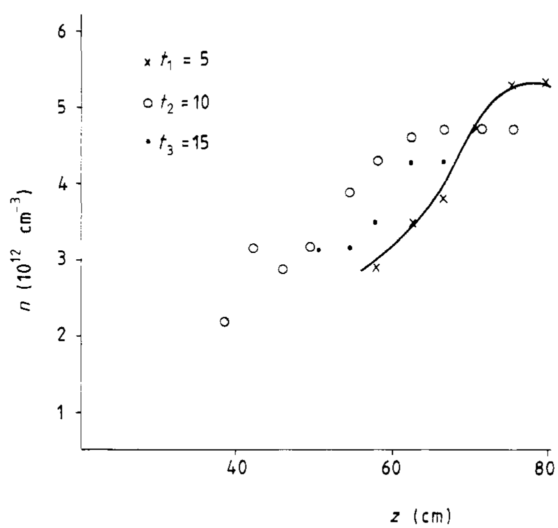

Figure 13. The measured electron density n as a function of position z from the edge of the stationary plasma column for an argon discharge with $P = 170$ W and $p = 1$ Torr at successive instants t_i given in the key in μs.

The maxima and minima in the axial evolution of the electron density become less pronounced as the time elapses. For each position z and for different values of t_i, the fluctuations of n show that the power reflected on the ionisation front plays an important role in the production of electron density when this front is near enough to position z. This is consistent with the modulation observed in the photograph of the HF signal taken prior to stabilisation.

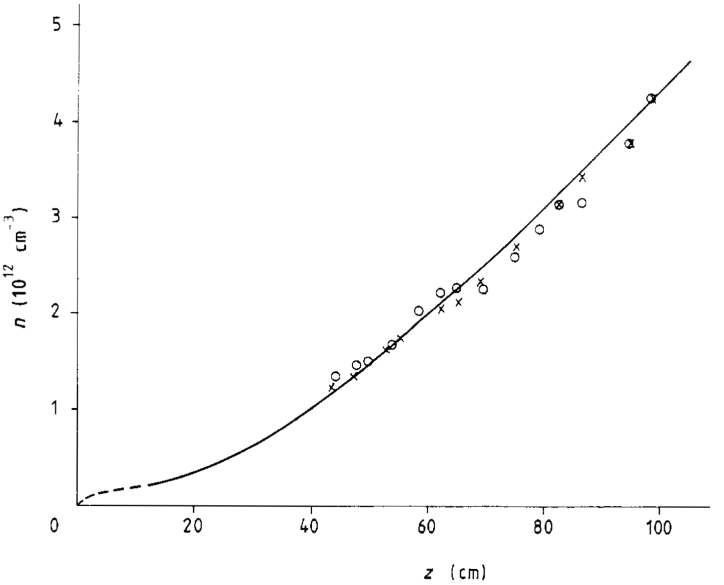

Figure 14. The theoretical axial distribution of the electron density in the stationary plasma (full curve) and measured axial distribution of the electron density after stabilisation (broken curve). Experimental conditions were as for figure 12. ○, t_1 = 15 μs. ×, t_2 = 20 μs.

Figures 14 and 15 show the experimental results for the electron density axial distribution for instants $t_i \geqslant 15$ μs as well as the theoretical calculation corresponding to the stationary plasma. It may be observed that experimental density values fit the curve corresponding to the stationary plasma; this means that after 15 μs the portion of plasma the measurement wave has gone through has already reached its stationary stage. The ionisation front for these time values is distant enough so that the reflected power does not alter the density values.

An estimation of the time elapsed before the stabilisation of the entire column is achieved may be made using the luminous intensity observed with an optic fibre for different instants t_i. Thus, it is possible to verify that after a time t_c the luminous intensity along the plasma axis is monotonically decreasing and the intensity peak, characteristic of the ionisation front and present for instants $t_i < t_c$, is no longer observed. The position of the front indicates the end of the instantaneous plasma whose length is given by equation (4). When this front advances towards the position in which the electron density reaches its critical value the wave is completely attenuated and the propagation stops. The final length of the plasma in its stationary stage is thus established. Under our experimental conditions the time it takes to reach this state is between 20 and 30 μs.

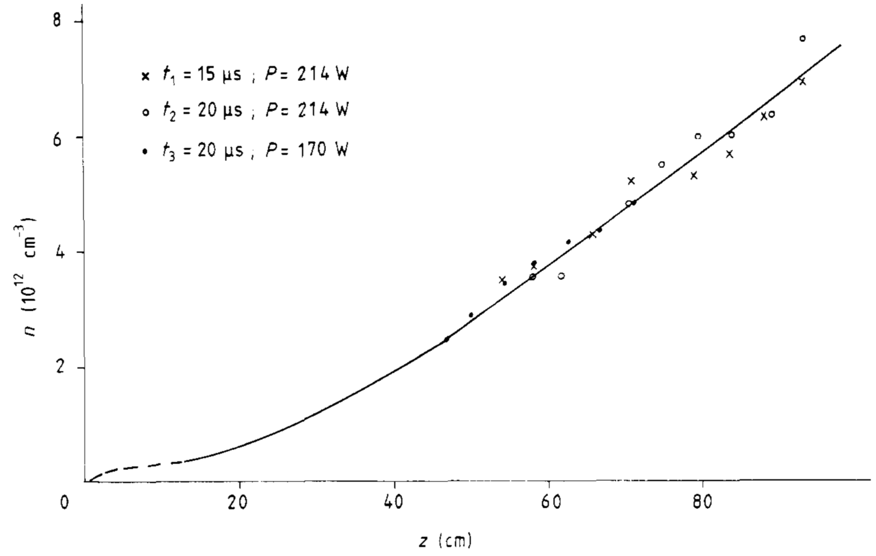

Figure 15. The theoretical axial distribution of the electron density in the stationary plasma (full curve) and measured axial distribution of the electron density after stabilisation (broken curve). Experimental conditions were as for figure 13.

From the instant t_c onwards the plasma is in a stationary state and its length is given by replacing τ by t_c in equation (4).

4. Conclusions

The measurement of ionisation-front velocity and rise time in pulsed plasmas produced by surface waves enabled us to separate a collisional and a non-collisional mode, which control the advance of the front and require different theoretical approaches. The dependence of v_f on the power corroborates the differentiation between the two modes and we may conclude that in the case of the collisional mode v_f depends linearly on the power.

As regards the electron density, we found a temporal evolution during the approach to stabilisation and a characteristic time in which this occurred. Therefore, it is possible to conclude that the transient period for a certain position is basically determined by the power reflected on the ionisation front that gives rise to the electron density fluctuations for times much greater than the rise time of the wave.

Finally, the observation of the luminous signal from the discharge allowed us to study how stabilisation extends to the whole plasma column.

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