Microwave Interferometer Measurements of the Electron Density Distribution behind Shock Fronts and Discharge Plasmas*

Mikrowellen-interferometrische Messungen der räumlichen Elektronendichteverteilung hinter Stoßfronten und Entladungsplasmen

W. Makios

IPP 3/25 Dezember 1965

INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

Microwave Interferometer Measurements of the Electron Density Distribution behind Shock Fronts and Discharge Plasmas*

Mikrowellen-interferometrische Messungen der räumlichen Elektronendichteverteilung hinter Stoßfronten und Entladungsplasmen

W. Makios

IPP 3/25 Dezember 1965

---

* Dieses Manuskript ist der Text eines Vortrages, gehalten am 8.9.65 beim 26th Meeting of the Propulsion and Energetic Panel der AGARD in Pisa.

Es gibt gleichzeitig in erweiterter Form den Inhalt eines Vortrags wieder, der im Rahmen der 7th International Conference on Phenomena in Ionized Gases 1965, in Belgrad am 23.8.65 gehalten wurde.

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Institut für Plasmaphysik GmbH und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

AGARD Conference Proceedings Series No.8

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

FUNDAMENTAL STUDIES OF IONS AND PLASMAS

Edited by

H.Dean Wilsted

Manager, Applied Research
Allison Division, General Motors Corporation
Indianapolis, Indiana

Published in Two Volumes

VOLUME II

Proceedings of a Specialists' Meeting, sponsored by the AGARD Propulsion and Energetics Panel, held at the University of Pisa, Pisa, Italy, 6-10 September 1965

MICROWAVE INTERFEROMETER MEASUREMENTS OF THE ELECTRON DENSITY DISTRIBUTION BEHIND SHOCK FRONTS AND DISCHARGE PLASMAS

by

Wassilios Makios

Institut für Plasmaphysik,*
Garching bei München,
Germany

---

*This work has been undertaken as part of the joint research program of the Institut für Plasmaphysik and Euratom

SUMMARY

Previously, various investigators have shown that in electromagnetically driven shock waves the luminous front is generated from parts of the discharge plasma, in front of which the shock front is propagating. In order to measure the electron density distribution behind the shock front, microwave transmission interferometric measurements have been made. The space resolution achieved with horn antennae and focusing lenses was unsatisfactory, because the distance between the shock front and the discharge plasma is of the order of a few wavelengths. With the use of Lecher wires instead of horn antennas, a space resolution of about half a wavelength was obtained.

RESUME

Divers chercheurs ont montré par des études précédents que, dans le cas des ondes de choc entaînées par des moyens électro-magnétiques, le front lumineux provient de parties du plasma de décharge devant lequel se propage le front de choc. Pour mesurer la répartition de la densité électronique derrière le front de choc, on a effectué des mesures interférentielles de la transmission des micro-ondes. La séparation spatiale obtenue à l'aide d'antennes en cornet et de lentilles de focalisation s'est avérée pen satisfaisante en raison du fait que la distance séparant le front de choc et le plasma de décharge est de l'ordre de quelques longueurs d'ondes. L'utilisation de fils Lecher au lieu d'antennes en cornet a permis d'obtenir une séparation spatiale d'environ une demi-longuer d'onde.

NOTATION

c	velocity of light, $\simeq 3 \times 10^{10}$ cm sec^{-1}
d	thickness of plasma sheath, cm
E	signal voltage
k	constant
M	Mach number
n	particle density
p	pressure, mmHg
t	time, μsec
U	potential
v	velocity, cm μsec^{-1}
x	distance behind shock front, cm
ν	collision frequency, sec^{-1}
ϕ	phase position
ω	measuring frequency, radians sec^{-1}

Subscripts

o	initial conditions
e	electron

MICROWAVE INTERFEROMETER MEASUREMENTS OF THE ELECTRON DENSITY DISTRIBUTION BEHIND SHOCK FRONTS AND DISCHARGE PLASMAS

Wassilios Makios

1. INTRODUCTION

Shock waves of higher Mach numbers which occur in conventional diaphragm tubes can be produced electromagnetically. In 1953 Fowler devised a T-shaped shock tube, which was improved by Kolb in 1956. Figure 1 shows the schematic construction of such a tube. The electric energy of a capacitor is discharged in a very short time through a gap and this produces a high temperature plasma. The plasma then expands into the long branch of the tube, preceded by a shock wave. In the magnetic field of the backstrip the plasma undergoes additional acceleration. The shock wave is driven only during the short discharge time of the capacitor, after which it runs free. It thus takes the form of a blast wave. In the front of the blast wave the Rankine-Hugoniot equations should describe the variables of state of the plasma. Discrepancies[1] between experimental data and these theoretical calculations were at one time attributed to precursor effects and later to relaxation phenomena. Meanwhile, Brinkschulte[2] has succeeded in showing that, in the case of electromagnetically driven blast waves in hydrogen up to Mach number 20, that is, in the region of dissociation, the values of the variables of the state in the front are correctly predicted by theory. He and Cormack[3] have also shown that the shock front is not luminous, and that the luminous phenomena observed are caused by the discharge plasma which follows at some distance behind the blast wave front. The luminosity then gives the position of the shock front, but the variables of state are no longer given by the Rankine-Hugoniot equation since, as demonstrated by Cormack[3], there is energy transfer from behind to the front. Whereas the shock wave is plane and reproducible, all phenomena affected by the discharge plasma are extremely irreproducible.

Besides the density jump in the shock front itself, Brinkschulte[2] investigated the density distribution of the heavy particles (molecules and atoms) behind the front. He was able to show that the density distribution agrees with that given by a special theory of blast waves, namely the homology theory according to von Weizsäcker and his co-workers[4,5]. This theory reproduces correctly the velocity time-dependence as well.

Electron density and electron temperature in the front, on the other hand, were not expected to be represented by the Rankine-Hugoniot equations in conjunction with the Saha equation, since relaxation effects delay the onset of equilibrium. This paper reports on work done in order to complete the picture in this respect. The main question was: does a jump in electron density as well as in neutral density occur in the non-luminous shock front and, if so, how high is it?

First, I shall review briefly the measurements we have made in which 4 mm microwaves were reflected at the shock front, and then I shall describe in more detail the experiments we have done to determine the electron density behind the shock front using microwave signals transmitted through the shock front. The electron densities investigated were in the range of 10^{13} cm^{-3} while the cut-off density for 4 mm microwaves is 6×10^{13} cm^{-3}.

2. REFLECTION MEASUREMENTS[6]

An extremely simple microwave reflection interferometer was used to determine the velocity of the ionization front in hydrogen (initial pressure range 1 mmHg $< p_0 <$ 10 mmHg) by using the Doppler effect.

Figure 2 shows the interferometer used. The wave produced in the klystron passes through a uniline and is emitted in the shock tube from a suitably designed horn (see also Figure 1). When part of the energy is reflected by an ionization front, the reflected wave interferes with the incident one. At a suitable point between the uniline and the horn a small silver wire is introduced as an "antenna" into the wave guide. This wire transmits the interference signal to a transverse wave guide which is tuned with a movable short on either side. A crystal diode at one end picks up the interference signal, that is the Doppler signal.

We have established that, in the region of relatively low velocities (5 < Mach number < 8) the electron density in the shock front in hydrogen is lower than 10^{13} cm^{-3}. Reflection of the microwaves does not occur until they reach the luminous plasma, which follows the shock front at some distance and in which higher electron densities are encountered. Streak camera photographs prove that the Doppler signals give the velocity of this luminous front.

In the next range of velocities (8 < Mach number < 12), the Doppler signals consist of *beats* (Fig.3). The two frequencies contained therein also correspond to two velocities. The lower velocity again agrees with that determined with streak photographs for the luminous front. The higher velocity corresponds to that of the shock front measured by Brinkschulte[2] with a Mach-Zehnder interferometer. A discontinuity in the electron density causes reflection; therefore both the luminous front and the shock front should be associated with zones where the electron density is discontinuous. The shock front, however, still remains partially permeable. There are reasons for estimating that the shock front reflects 10% - 30% of the incident energy. With this estimation, the electron density in the shock front can be calculated to within a factor of 2 (even when a wide range is allowed for the electron collision frequency). These calculations give electron densities of 2×10^{13} cm^{-3} to 4×10^{13} cm^{-3}.

At even higher velocities the Doppler signals again give only one velocity, namely, that of the shock front.

3. TRANSMISSION MEASUREMENTS

Once we saw that we could measure electron densities in shock fronts with a 4 mm reflection apparatus, we decided to try to obtain information on the electron density distribution behind the shock front using transmission measurements.

The first tests were conducted with an ordinary interferometer circuit (sketched in Figure 4). The shock tube was positioned between the horn antennae. Teflon lenses were used to focus the microwave energy in the shock tube. The spatial resolution attained was 2 to 3 wavelengths (approximately 1 cm). Although this resolution is good for microwave conditions, few conclusions could be drawn from the measurements since the distance between shock front and discharge plasma is of the same order of magnitude.

However, we were able to devise a *new* interferometer system to improve the space resolution to *one half* a wavelength (2 mm). The main part of this system consisted of a Lecher wire system suspended across the plasma path perpendicular to the shock tube axis. The enhanced resolution arises since the greater part of the microwave energy is concentrated in a very narrow region between the wires. The transition from wave guide to Lecher system was made by means of a so-called finline[7] (Fig. 5). The Lecher wires are made of 0.1 mm diameter copper wires. The distance between them is 2 mm. The characteristic impedance of the Lecher system is then equal to that of the wave guide. Ideal matching was achieved and the energy losses in the system were very small. Because of the very thin wires no perturbations of the plasma were observed.

The transmission interferometer with the Lecher wires used is shown in Figure 6. The wires run transversely through the shock tube and are galvanically decoupled from the other parts of the interferometer. By means of a selfmade variable coupler the energy coming from the klystron may be distributed to the measuring and reference paths so that no energy is lost in the reference circuit. The two waves are superimposed on the detector (which has a quadratic characteristic). The initial phase setting is determined by the phase shifter.

Signal voltages as indicated in Figure 7 can now be expected. The measuring wave amplitude is superimposed on the amplitude of the reference wave. Depending on the phase of the two waves in relation to one another, voltages between U_1 and U_2 can be observed. As the electron density between the Lecher wires increases, the phase of the measuring wave changes, and thus the amplitude of the total signal changes as well. If damping also occurs as the collision frequency increases, the amplitude of the measuring wave becomes smaller. This process may continue until the cut-off density is reached.

The transmission measurements in hydrogen were made in the same pressure and velocity range as the reflection measurements ($8 <$ Mach number < 12 and $1 \text{ mmHg} < p_0 < 10 \text{ mmHg}$). Figure 8 shows a typical oscillogram from this test series. The top signal is a multiplier signal for recording the arrival of the luminous discharge plasma at the location of the wires. The middle one is the microwave signal and the lower one is the same microwave signal with a greater time resolution. Following a precursor signal, the phase returns to its initial position. Before the luminous front of the discharge plasma reaches the wires, the electron density (in the shock front) rises suddenly. Within 0.1 μsec the damping becomes so great that no further information retrieval is possible, even though we have an extremely high spatial resolution.

With argon, on the other hand, the behaviour of the ionization behind the shock front is determined by *relaxation phenomena*, and we can extract information about the electron density distribution behind the shock front.

Three oscillograms at various Mach numbers are shown in Figure 9. Clearly recognizable are the initial phase settings, the phase shift in the measuring branch due to the rising of the electron density, and the damping due to the non-zero collision frequency. The electron density may be calculated from the phase shift, and the electron collision frequency may be calculated from the damping.

The measurements in argon were carried out in the same pressure and velocity ranges as those in hydrogen. They were also made at the same distance from the electrodes (50 cm).

The oscillograms enable (even in presence of damping) a determination of the electron density from the phase variation as a function of time:

$$n_e(t) = \frac{c}{k}\left\{2\omega\frac{\phi(t)}{d} - c\left(\frac{\phi(t)}{d}\right)^2\right\} . \qquad (1)$$

Using the velocity time-dependence found from the homology theory[4,5],

$$v = \text{constant} \times t^{-k} , \qquad (2)$$

where $k = 0.4$ = homology exponent , it is then possible to represent n_e as a function of the distance x behind the shock front. Figure 10 shows $n_e(x)$ (the Mach number of the shock wave when it passes the Lecher wires or equivalently the capacitor charging voltage was chosen as the parameter for this picture). At $M = 6$ the electron density is very low at 10 cm behind the shock front, and then it increases quickly until it reaches the cut-off density (6×10^{13} cm^{-3}) at approximately 15 cm. As the shock front velocity increases, the relaxation zone becomes smaller and smaller. At $M = 11$ the cut-off density occurs as little as 3 cm behind the front and for $M = 15$ this distance is only 0.8 cm.

In the case of argon the electron density behind the front then shows quite a different behaviour than would be expected for the atoms according to Brinkschulte's[2] investigation.

n_e was calculated using an approximation which is valid only for $\nu/\omega < 0.2$. It is thus necessary to check whether the collision frequency ν stays sufficiently small.

In order to determine ν , the transmission coefficient of a plane wave in a homogeneous plasma sheath of a given thickness was calculated as a function of n_e and ν . By equating the measured amplitudes (see Figure 11) with those calculated (with allowance made for the initial phase setting) it was then possible to determine

ν or ν/ω. These are also represented as a function of x behind the shock front (Fig. 12). The ν have a similar trend for all shock front velocities. In the measuring range ν/ω always remain below 0.16, and so the condition for determining n_e is fulfilled. Theoretical estimates generally result in even smaller values.

All graphs show characteristic troughs. The number of test values, however, is still not sufficient to determine exactly the dependence of the collision frequency ν as a function of the distance x behind the shock front. The region in which ν probably lies was therefore represented by hatching only.

4. RECOMBINATION OF THE PLASMA

Of course the recombination of the electrons and ions is observed with the interferometer. Figure 13 shows a recombination signal in argon which reproduces the familiar trend. The recombination time of 6×10^{13} cm^{-3} to 10^{12} cm^{-3} agrees with calculations.

5. CONCLUSIONS AND DISCUSSION

The investigations reported here have proved that a transmission microwave interferometer with the Lecher wire system vastly improved the spatial resolution over that of a conventional microwave interferometer using horns and lenses. With this interferometer local measurements of the electron density and the electron collision frequency with a spatial resolution of 1/2 wavelength are possible. No perturbations of the plasma due to the Lecher wires were observed optically. The wires do not appear to effect the measurements.

It appears that, as the waves are guided along the wires, they are more plane than when focused with horns and lenses. In this connection it may be pointed out that a single-wire system (metallic or dielectric) is unsuitable for such measurements, since then the energy is not concentrated in such a small region.

The electron density n_e and the collision frequency ν behind the shock front were measured. From these measurements the relaxation behaviour of the electrons could be followed. Comparison with measurements on diaphragm tube shock waves in argon make it possible to show whether the radiation of the discharge plasma affects the relaxation time. From the collision frequency ν it is possible to determine the electron temperature T_e when, in addition to the electron density n_e, the density of the argon atoms n_{Ar} behind the shock front is known. n_{Ar} can be calculated from the homology theory.

REFERENCES

1. McLean, E.A. et al. — Physics of Fluids, Vol.3, 1960, p.843.
2. Brinkschulte, H., Muntenbruch, H. — Zeitschrift für Naturforschung, Vol.20a, 1965, p.196.
3. Cormack, G.D. — Zeitschrift für Naturforschung, Vol.19a, 1964, p.934.
4. v. Weizsäcker, C.F. — Zeitschrift für Naturforschung, Vol.9a, 1954, p.269.
5. v. Hoerner, S. — Fortschritte der Physik, Vol.6, 1958, pp.375-425.
6. Makios, W., Muntenbruch, H. — Zeitschrift für Naturforschung, (in print).
7. Robertson, S.D. — IRE Transactions on Microwave Theory and Techniques, 1956, p.263.

The discussion on this paper follows on page 438

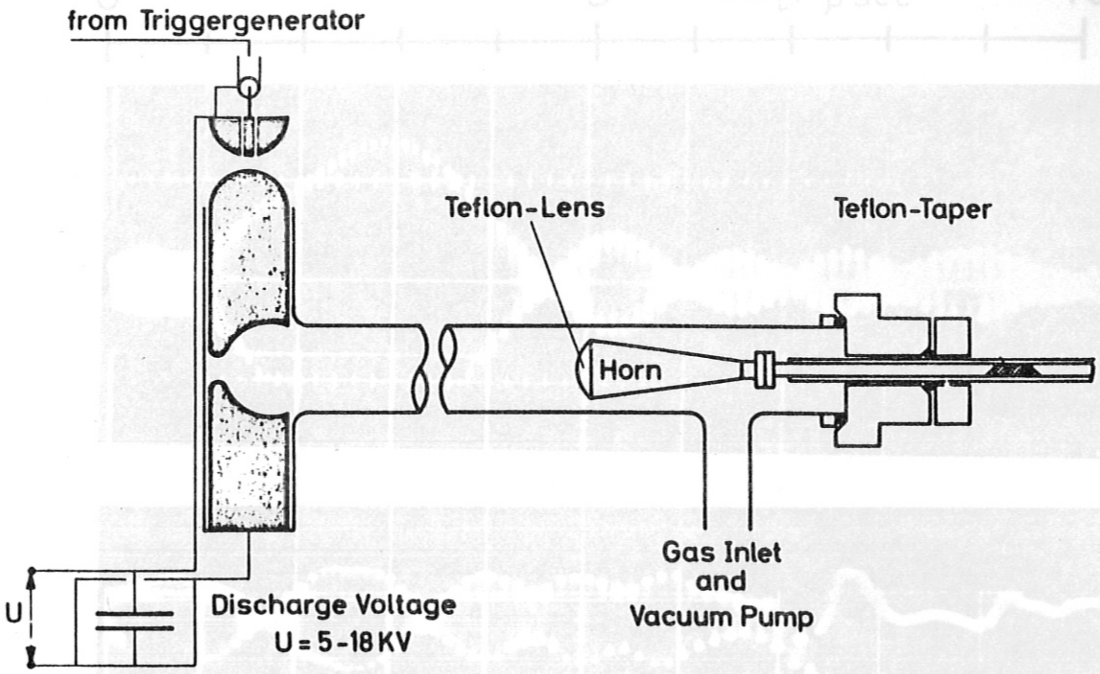


Fig. 1 T-shaped shock tube with horn antenna for reflection measurements

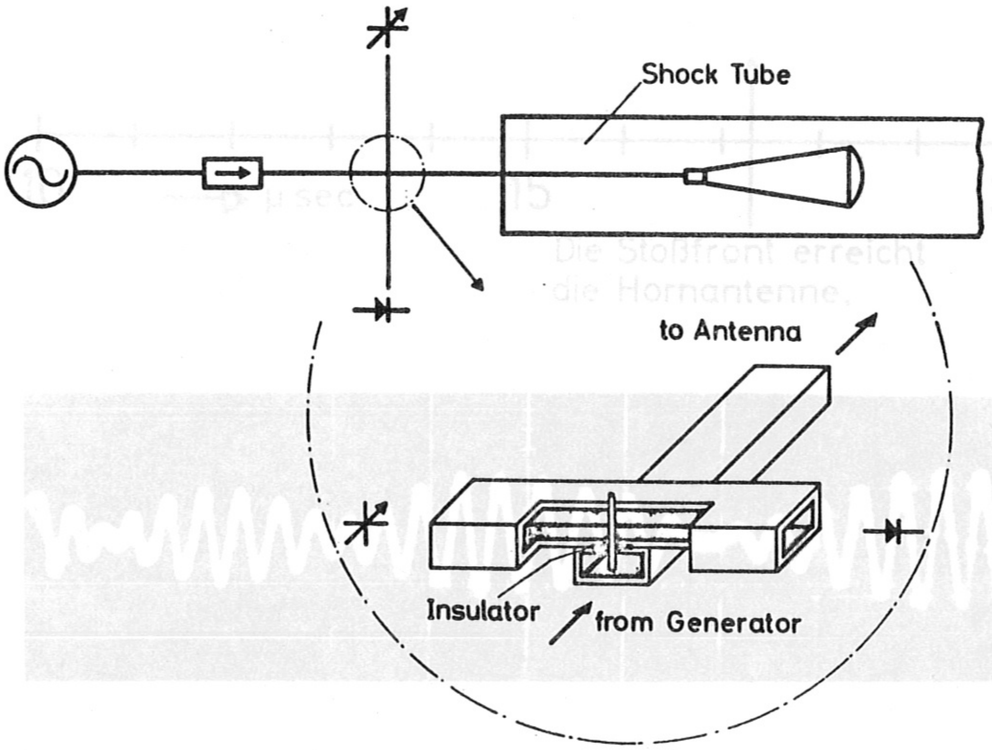


Fig. 2 4 mm microwave interferometer for reflection measurements

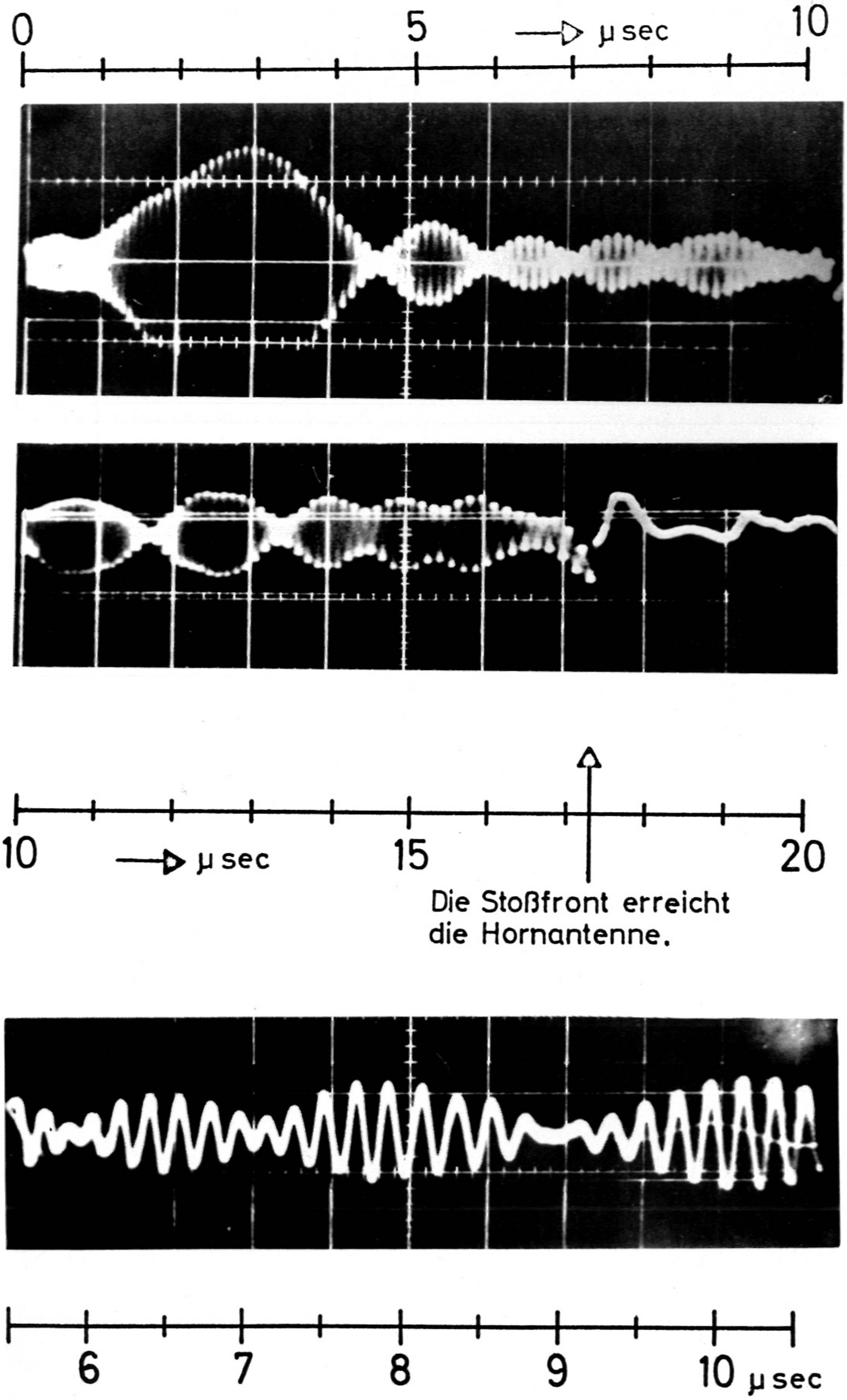


Fig.3 Reflection Doppler signals with *beats* (hydrogen; $p_0 = 2$ mmHg).
Two frequencies ω, Ω can be seen.
($\omega + \Omega \hat{=} v_{\text{shock front}}$, $\omega - \Omega \hat{=} v_{\text{luminous front}}$)

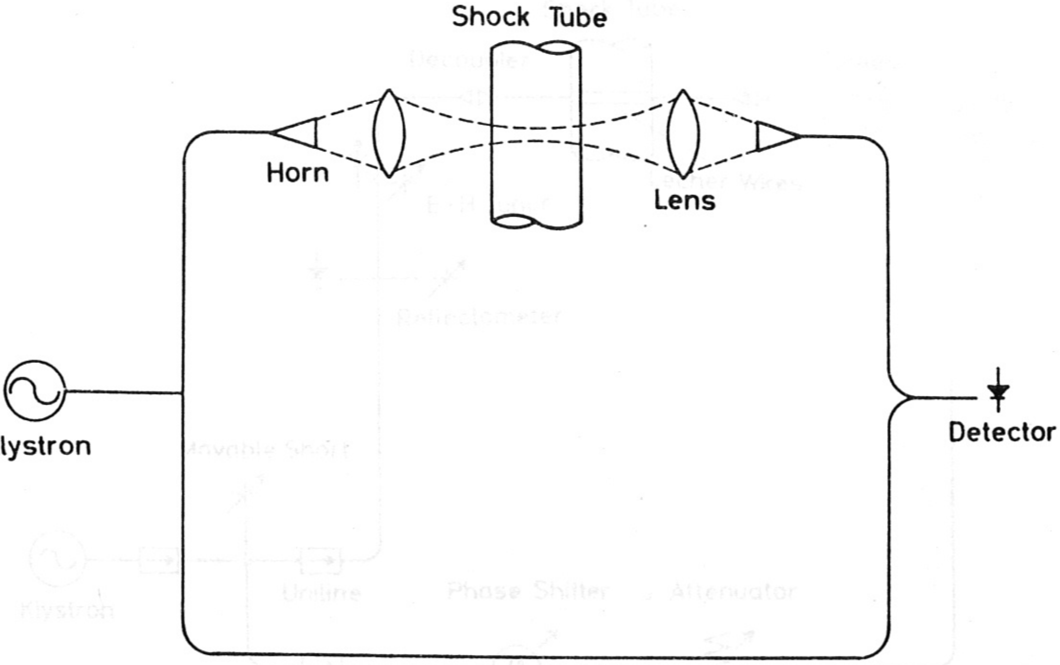


Fig. 4 Principle of the ordinary 4 mm transmission interferometer with horns and lenses

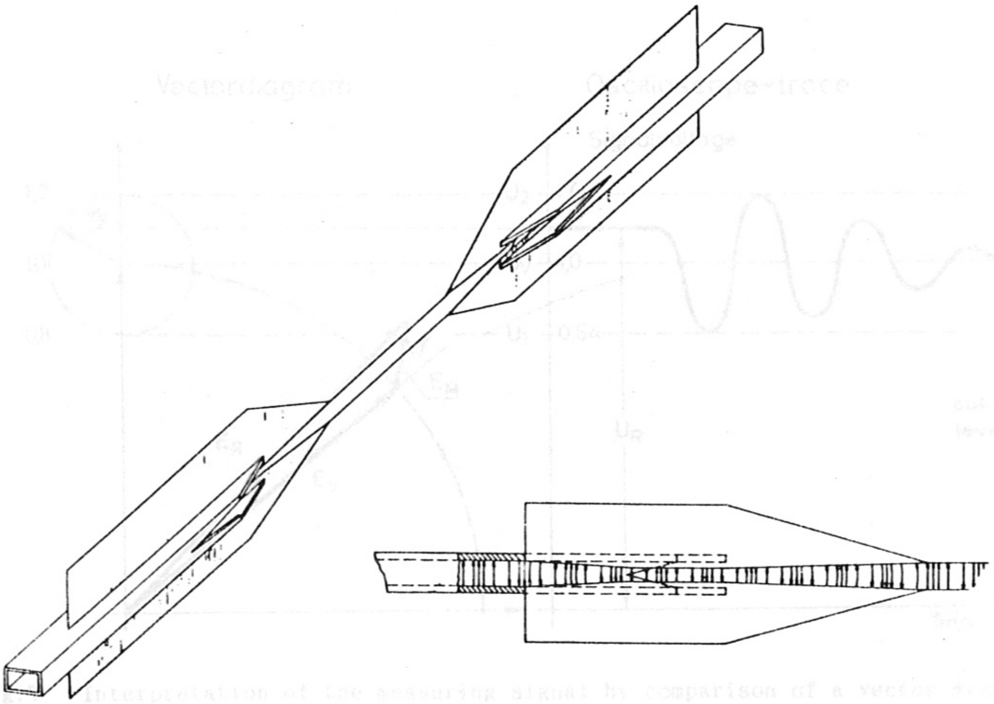


Fig. 5 Matching the wave guide to the Lecher system with finlines

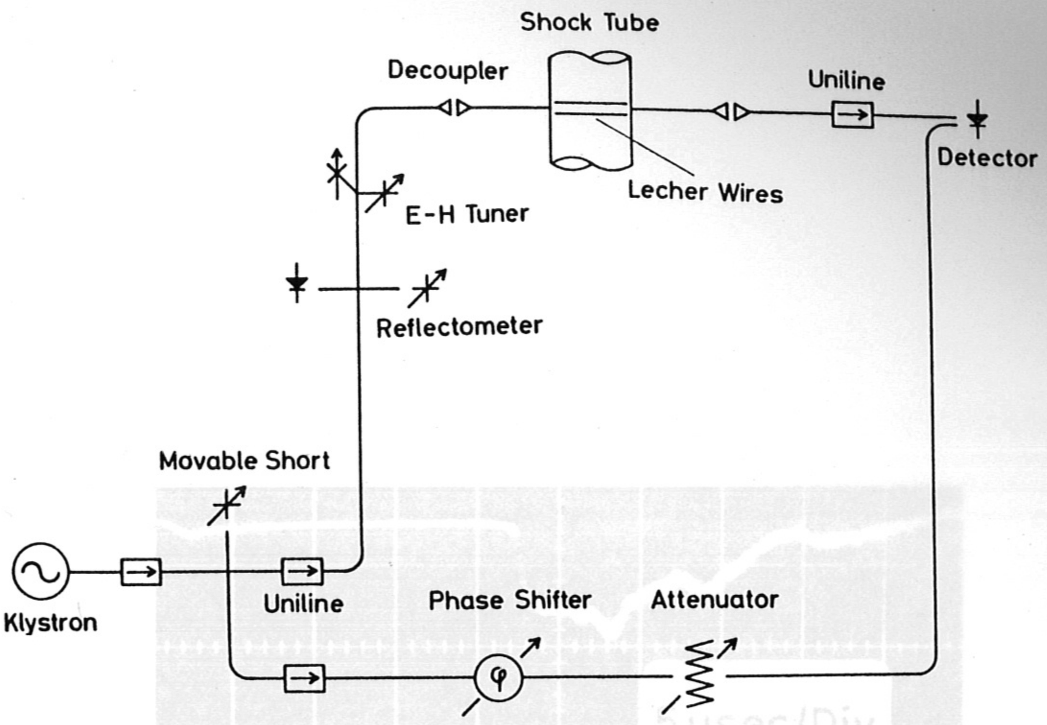


Fig.6 4 mm transmission interferometer with Lecher wires running transversely through the shock tube

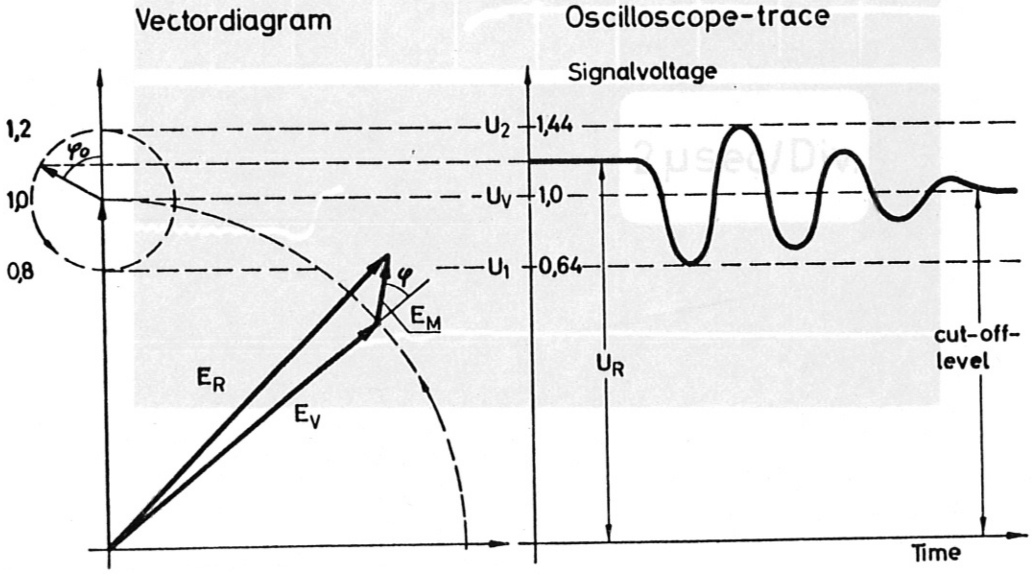


Fig.7 Interpretation of the measuring signal by comparison of a vector diagram and an oscillogram. The numerical values express a ratio $E_V : E_M = 1 : 0.2$. (The suffixes V = reference path , M = measuring path and R = resulting signal)

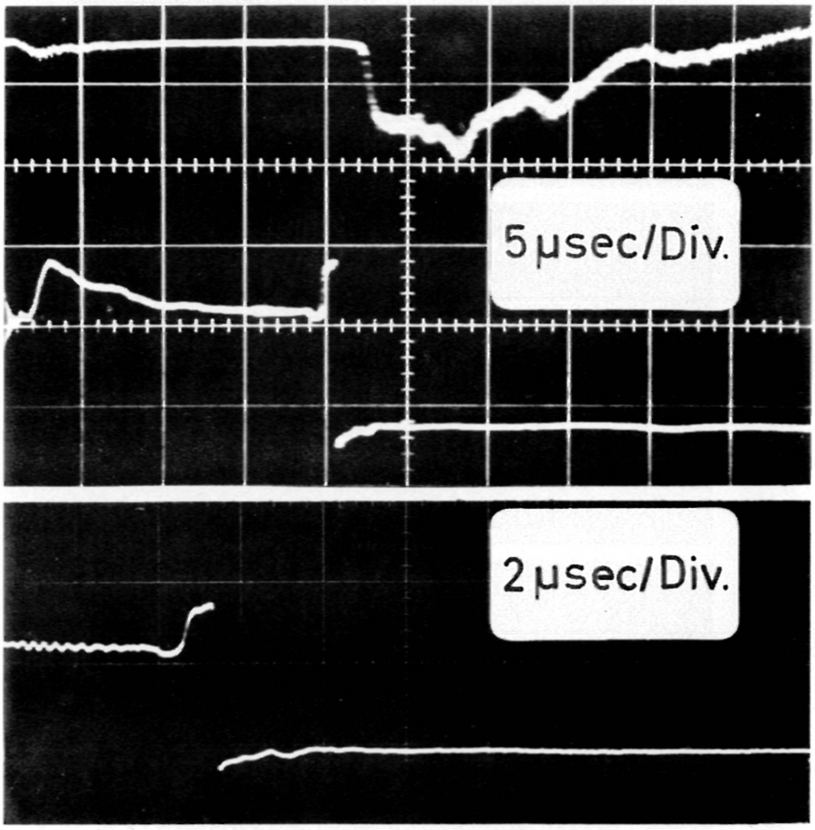


Fig.8 Multiplier and microwave transmission signals for hydrogen

$p_0 = 2$ mmHg; $U_0 = 8$ kV
$v = 1.45$ cm/μsec $\hat{=}$ $M = 11$
$\Delta t = 0.1\ \mu$sec $\hat{=}$ $\Delta x = 1.45$ mm
$n_e = 1.2 \times 10^{13}$ cm^{-3}; $\nu = 2.2 \times 10^{11}$ sec^{-1}

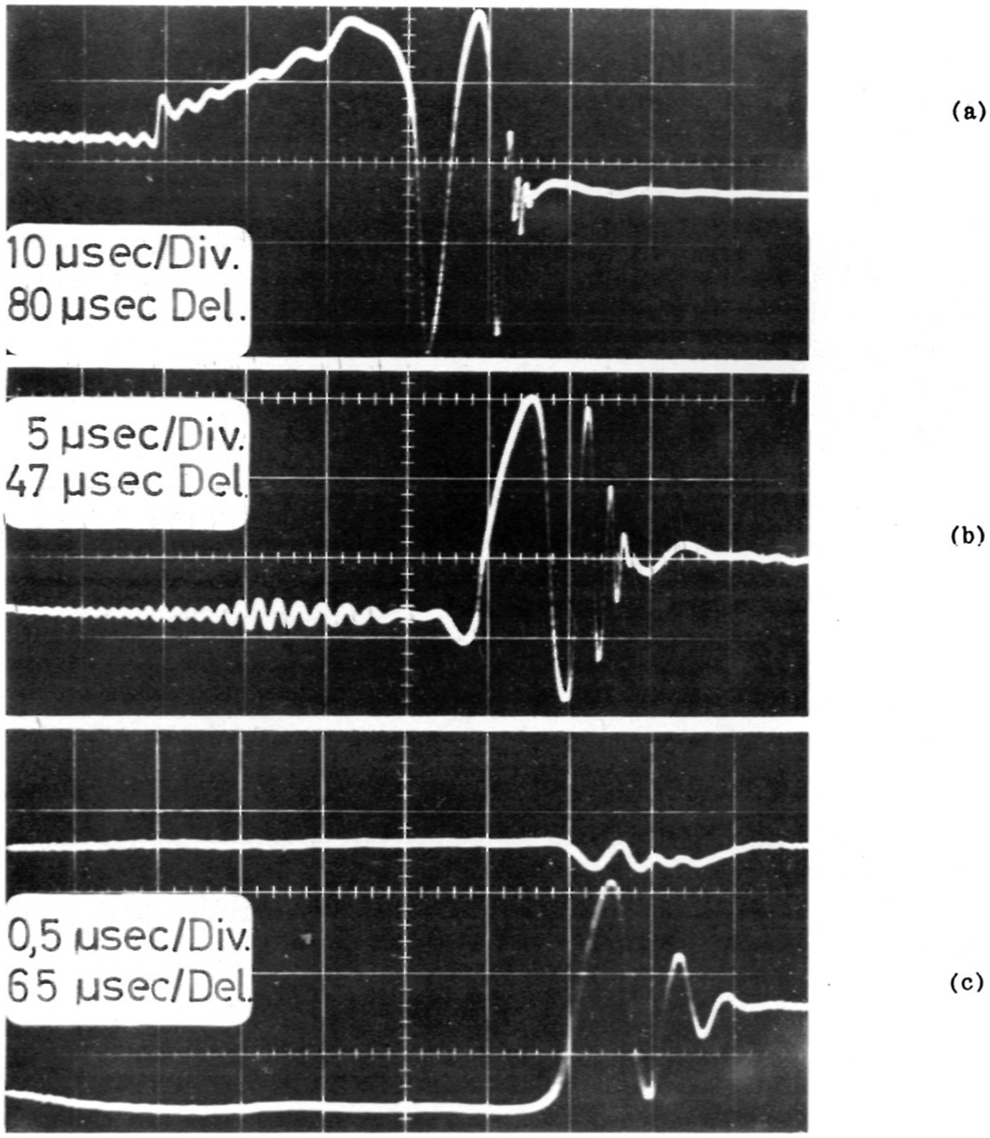


Fig. 9 Transmission signals in argon (p_0 = 2 mmHg) for three different Mach numbers; (a) M = 6, (b) M = 11, and (c) M = 15

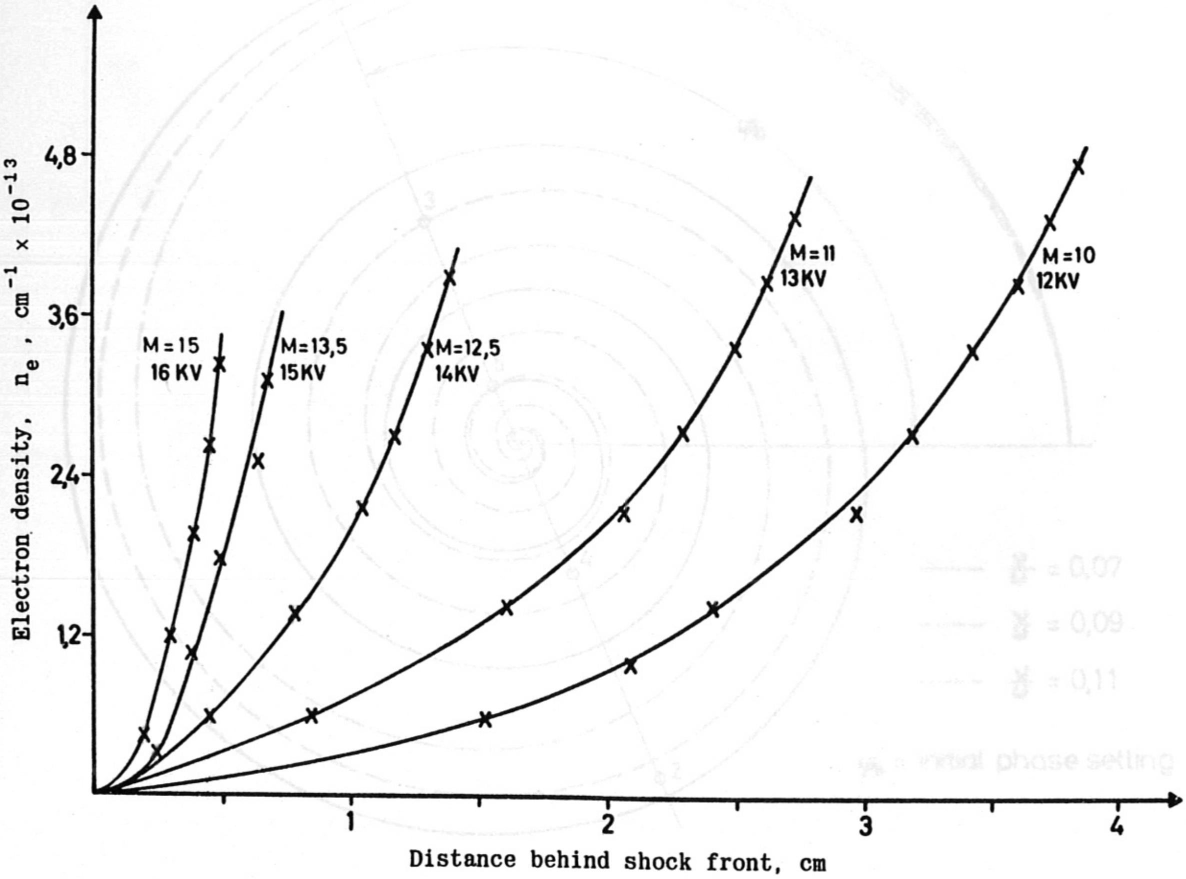


Fig. 10 Electron density rise as a function of the distance x behind the shock front (the Mach number, or equivalently the charging voltage of the capacitor, is used as a parameter)

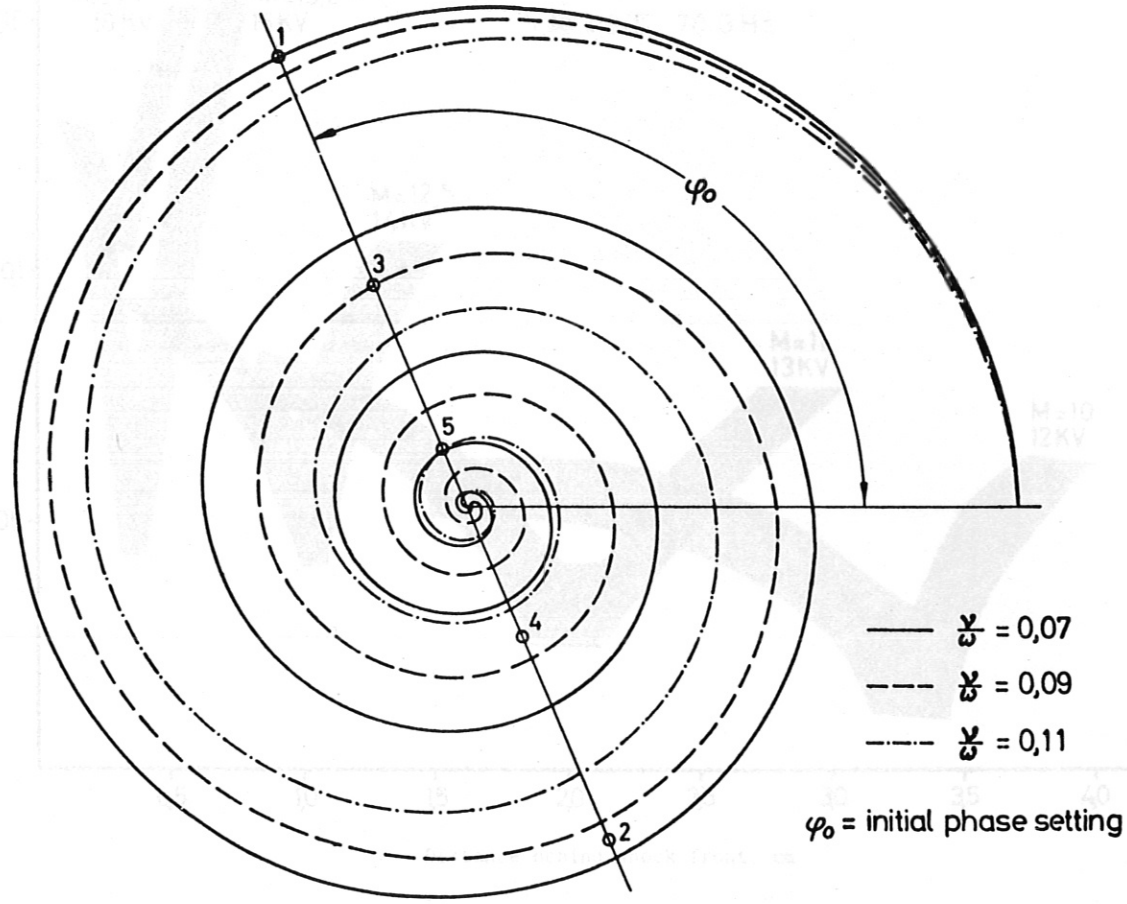


Fig.11 Transmission coefficient of a plane wave (4 mm) in a homogeneous plasma sheath (thickness = 3 cm) as a function of n_e. Parameter is the electron collision frequency ν/ω. The points 1 to 5 are taken from the extrema of the interference pattern (Fig.7). A ν/ω-value can be determined from each extremum

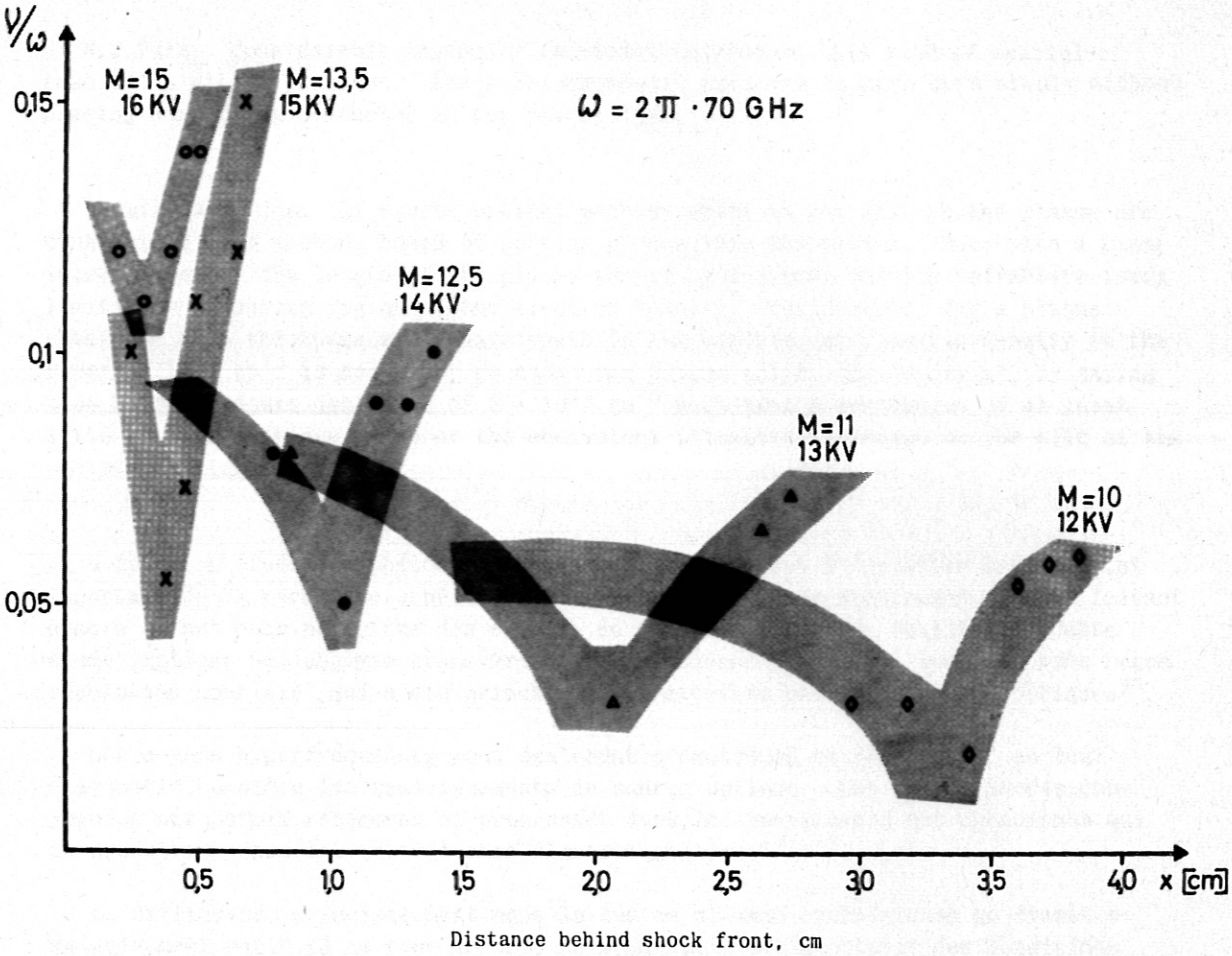


Fig.12 Electron collision frequency as a function of the distance x behind the shock front. Parameter is the Mach number of equivalently the charging voltage of the capacitor

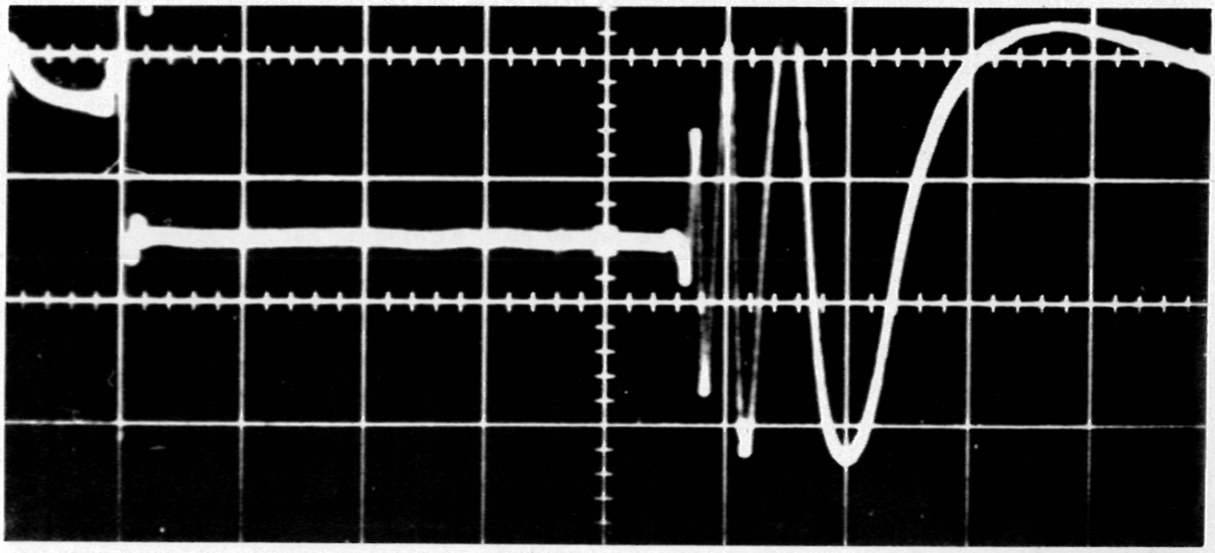


Fig.13 Recombination signal in argon. Time resolution 100 μsec/cm

DISCUSSION

H.J.Pain: Considerable ingenuity is needed to produce this kind of spatial resolution with microwaves. Laser interprometry achieves it much more simply without placing conducting obstacles in the plasma flow.

Wassilios Makios: Of course optical methods which do not disturb the plasma are much better than methods based on putting probes into the plasma. But, with a Laser interferometer, the length of the plasma passed by the beam and its refractive index limits the measuring region of the electron density. For example, for a plasma sheath of 3 cm thickness and a wavelength in the visible, an electron density in the order of 10^{17} cm^{-3} is necessary to cause one fringe shift. Dr Verdeyen*, by saying that he can measure densities of 2×10^{13} cm^{-3} must have a resolution of at least 1/100 to 1/1000 fringe width or the equivalent intensity variation on the slit of the photomultipliers.

M.Laug: L'étude des phénomènes d'ionisation précédant l'équilibre est un point important de la recherche expérimentale sur les plasmas, de nombreuses données faisant encore défaut pour permettre des calculs de composition en non-équilibre. Cette étude implique une analyse transversale de la colonne de plasma, avec une très bonne résolution spatiale, qui a été principalement atteinte par des méthodes optiques[A1].

Les moyens hyperfréquences sont également prometteurs et répandus[A2], et leur diagnostic complète les renseignements de source optique. Les deux méthodes conjuguées ont permis récemment de progresser dans la connaissance des phénomènes qui se produisent dans les tubes à choc électromagnétiques[A1,A3].

La difficulté, principalement dans le cas de plasmas cylindriques de diamètre relativement petit (3 cm pour le tube de M.Makios), est d'obtenir des conditions expérimentales conduisant à un traitement mathématique simple et sûr, à savoir pratiquement l'approximation de l'onde plane traversant une lame de plasma (en tenant compte éventuellement des réflexions multiples dans le plasma, et même dans le diélectrique qui le contient[A4]). Pour que cette approximation soit applicable à une colonne de plasma, et que simultanément la résolution spatiale soit bonne, il faut que le faisceau soit mince dans deux directions du plan d'onde (perpendiculairement et parallèlement à l'axe du tube à choc). Or les deux conditions (onde plane, faisceau mince) sont assez contradictiores avec les antennes classiques:

(i) Un cornet ne donne une onde à peu près plane que s'il est placé loin du plasma et si son ouverture est grande: le faisceau est alors large.

(ii) L'emploi de réflecteurs paraboliques our de lentilles planes-hyperboliques accentue les propriétés d'un cornet de grande ouverture.

(iii) Les meilleurs résultats semblent avoir été obtenus avec deux lentilles (une émettrice, une réceptrice) ayant toutes deux un foyer sur l'axe du plasma. En effet, l'onde est presque plane dans la tache focale de diamètre:

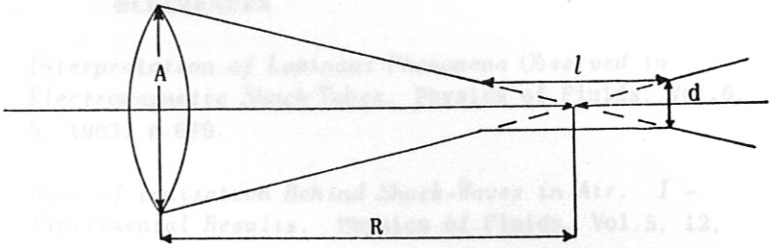
---

* Editor did not receive comments of Dr Verdeyen

$$d = \frac{R}{A}\lambda$$

et de longeur

$$l = \left(\frac{R}{A}\right)^2 \lambda \ .$$



(R distance focale, A diamètre, de la lentille émettrice)[A5].

Cependant il n'existe pas de faisceau non guidé de diamètre inférieur à λ . De plus pratiquement si $\lambda = 4$ mm , pour avoir une onde presque plane dans toute la traversée d'un tube de diamètre 3 cm, il faudra prendre $R/A = 3$. Le faisceau aura alors une largeur de 3λ , soit 12 mm, au mieux. Par ailleurs, l'onde n'est plane qu'en première approximation.

Seules les ondes guidées laissent espérer une amélioration. Mais les guides fermés doivent être traversés par le tube à choc: la largeur du faisceau est donc supérieure au diamètre du tube et le traitement mathématique fait appel à des approximations (théorie des petites perturbations). La résolution spatiale ne peut guère descendre au-dessous du centimètre[A6].

L'idée de M.Makios, qui consiste à utiliser comme guide une ligne bifilaire, semble être la seule qui permette d'obtenir une onde plane TEM concentrée dans un faisceau mince, en laissant le libre passage à l'écoulement, et de se prêter au même traitement mathématique qu'en espace libre. Les avantages obtenus me paraissent compenser largement les risques de perturbation du plasma par les fils, risques que l'auteur a d'ailleurs réfutés.

Son procédé doit permettre d'étendre le champ des connaissances actuelles sur les relaxations d'ionisation: jusqu'ici, elles n'ont guère été étudiées qu'à basse pression, de manière que les distances de relaxation soient supérieures aux résolutions spatiales possibles (par exemple à 20 microns Hg dans l'air[A2]).

Questions:

(i) Etant responsable de recherches sur les plasmas aérodynamiques, j'utilise habituellement l'air comme gaz de travail. Je pense étudier les relaxations dans l'air à 10^{-2} mmHg (pour fixer les idées). La densité électronique serait alors d'environ 10^{11} électrons/cm^3 (derrière un choc à Mach 14). Le diagnostic pourrait alors impliquer des fréquences assez basses (gamme des 3 cm). M.Makios pense-t-il que sa technique de la ligne de Lecher soit également applicable? Suit-elle la même loi de similitude que les antennes classiques, (résolution proportionnelle à λ)? Sinon, quelle résolution pourrait-on en attendre?

(ii) Que pense M.Makios de l'utilisation d'une tube à choc électromagnétique: pour la recherche fondamentale en physique des gaz? Pour ses applications à l'accélération d'un gaz (propulsion)?

REFERENCES

A1. Cloupeau, M. *Interpretation of Luminous Phenomena Observed in Electromagnetic Shock Tubes.* Physics of Fluids, Vol.6, 5, 1963, p.679.

A2. Lin, S.C. et al. *Rate of Ionization Behind Shock-Waves in Air. I - Experimental Results.* Physics of Fluids, Vol.5, 12, 1962, p.1633.

A3. Thornton, J.A. *Electrical and Electronic Shock Tubes.* 5th Biennul Congress on Gas Mechanics, Northwestern University, Evanston, Illinois, 14-16 August 1963 (AIAA Memo 63-368).

A4. Bachynski, M.P. Graf, K.A. *Electromagnetic Properties of Finite Plasmas.* RCA Rev. XXV, 1, 1964, p.3.

A5. Papoular, R. Balazard, J. *Applications des Ondes Hyperfréquences et Infra-Rouges à l'Etude des Plasmas.* Monographie Dunod, Paris, 1965.

A6. Davison, C.W. Farvis, W.E.J. *Microwave Studies of a Pulsed Glow Discharge.* Physical Review, Vol.127, 6, 1962, p.1858.

Wassilios Makios: I would like to answer the questions of my reviewer M.Laug.

(i) Of course one can apply the Lecher wires system with a larger wavelength than 4 mm. I have not done it myself but I think it is easier from the technical point of view to construct the finline transition for waveguides of higher wavelength; the only condition one has to apply is that the characteristic impedance of the waveguide has to be the same as that of the Lecher wires, i.e.

$$Z_{H_{10}} = Z_{\text{Lecher}} = 120 \log_e (2a/d) ,$$

where d = diameter of the wires
a = distance between the wires .

So you can easily see that for the wanted resolution you can calculate the thickness and the distance of the wires.

For better phase-shift measurements you also have to pay attention that the diameter of the tube is at least some wavelengths of the applied frequency. The same law of similarity for the classical antennas is of course valid in our case.

(ii) For the second question I could say that in a conventional shock tube the variables of the state behind the shock front are constant and well known, neglecting relaxation effects so one can use the conventional diaphragm tube as a tool for the measurements of fundamental physical values. Of course relaxation effects and sheath effects are not so well known so far and make the situation a little more difficult as I have sketched before.

In a T-tube or other electromagnetic shock tubes, on the other hand, the situation is much more complex because of the non-steady and instationary shock wave, that means that the variable of state behind the front change with the distance from the front. So the fundamental problem is to find a theory describing those shocks. We were able to show that shock waves generated in a T-tube are of a special type of blast waves, namely those described by the homology theory given by V.Weiszäcker and his co-workers. Brinkschulte, in our Institute, has shown that the measured density distribution of the heavy particles behind the front is in accordance with this theory. So one can hope that it is possible to use such a tube for fundamental investigations of gases.

As for the propulsion applications, of course one can apply the electromagnetically accelerating tubes but in that case the tube acts as a plasma gun and not as a shock tube. As shock waves of the blast-wave type appear in explosions, for example, in those of an atomic bomb, one can have a very important tool in the laboratory to examine the reaction of blast waves on obstacles. Up to now such studies have been made in conventional shock tubes, which have conditions behind the shock front different from those behind blast waves.

R.P.Hagerty: The three papers, "Plasma Energy Transfer to a Surface With and Without Electric Current" by E.R.G.Eckert and E.Pfender, "Diagnosis of a Plasma Beam Extracted from an Electron-Bombardment Ion Source" by W.A.Clayden and C.V.Hurdle and this report, falling under the heading of "Plasma Diagnostics", dealt with somewhat disparate areas of this field.

The first reviewed the results of experimental studies of the heat transfer from a hot, dense plasma, produced by an electric arc, to the solid electrode surfaces and discussed energy transfer to a surface first in the absence of and then with electrical current flow to the surface. Simple energy transfer models enabling qualitative description of the phenomena observed experimentally were proposed and discussed.

The second described a plasma beam facility enabling simulation and study in the laboratory of the phenomena of interaction between a body moving at high speed in the ionosphere and the ambient charged particles.

The third described measurement by microwave transmission interferometric technique of the electron density behind a shock front propagating in front of an electromagnetically driven shock wave. The use of Lecher wires instead of horn antennas enabled attainment of the required space resolution.

In its particular area, each of these papers made a contribution of significance to workers in that area and worthwhile periods of discussion were generated.

This report is to be treated as strictly confidential.

The 'Institut für Plasmaphysik' holds the exclusive rights of publication, mimeographing, propagation and translation into foreign languages of the original text, inclusive of the drawings, wholly or partially; also of excerpts or résumees, as well as of the technical or scientific contents of this report. Exceptions to these restrictions require written permission.

Furthermore, the 'Institut für Plasmaphysik' reserves the right of exclusive exploitation of the information contained in this report, for the purpose of obtaining protective industrial rights, particularly patent and utility patent rights at home and abroad. Actions of exploitation taken on the basis of the knowledge gained from this report cannot be regarded as grounds for obtaining the right of prior use ('Vorbenutzungsrecht') according to article 7 paragraph 1, first sentence of the German Patent Law. The reader is referred to article 5 of the Patent Law. For reasons stipulated by the Patent Law, the report must not be exhibited in public libraries, or lent out indiscriminately.

The Institute does not guarantee that the information given in this report is free from protective rights, such as patent rights, utility patent rights or trade-mark rights.

No guarantee is given in respect of the accuracy, completeness or usefulness of the information contained in this report. Thus, no liability can be accepted for damage resulting from use of the information, or of the apparatus, methods and procedures described.