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Hypersonic Wake Structure Observed with Electrostatic Probes

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ABSTRACT

Wakes of 9.5-mm diameter non-ablating spheres fired at speeds of about 5.5 km/sec into air and into N_2 at a pressure of 40 Torr have been observed with electrostatic probes. Ionization is observed, immediately after passage of the pellet, over a region approximately 4 cm in diameter. After 0.1 msec (60 body diameters downstream), the ionized region grows at a rate in agreement with schlieren observations of turbulent wakes. Somewhat after 1 msec, the electron concentration in a 5-cm diameter core dips precipitously, followed by large subsequent fluctuations for N_2 but staying very small for air. Regions of the wake at greater radial distances continue to contain electrons and to grow, and experience the precipitous dip further downstream. No corresponding sudden reduction in positive ion concentration is observed, implying that the electron loss is by attachment. The data are not yet sufficient to describe the structure of the electron-deficient core.

HYPERSONIC WAKE STRUCTURE OBSERVED WITH ELECTROSTATIC PROBES

I. INTRODUCTION

In the Lincoln Laboratory Re-entry Simulating Range, light-gas guns fire projectiles at hypersonic velocities into chambers containing gases of known composition and pressure. These projectiles and their wakes are observed by UHF cavities,[1] spectroscopic techniques,[2] schlieren photography,[3] and electrostatic probes. Evolution of the probe technique has been reported in the Lincoln Laboratory Project PRESS Semiannual Technical Summaries starting in 1964 and will not be repeated here. Previously reported probe results are compatible with cavity and schlieren measurements. The wake structure observed in the experiment now under way is of enough interest that it is felt worthwhile to present a preliminary report, even though many aspects remain to be studied and only a qualitative explanation has been developed.

II. EQUIPMENT

Figure 1 shows the type of probe used. The collecting electrode is a 0.12-mm diameter gold-plated cylinder exposed for 0.1 to 0.2 mm. It is supported in Teflon within a 0.5-mm diameter gold-plated hollow cylinder that serves as a current return path, collecting charges of opposite sign in order that the plasma remains neutral. Gold plating is used to facilitate cleaning of the probes before each shot and to minimize probe surface contact potential difference. The probes are placed radially in a plane perpendicular to the pellet path and are supported in a brass holder which carries transparent reticles that are photographed with the passing pellet by spark photography in order to determine the exact trajectory of the pellet relative to the probes. Figure 2 gives the positions thus determined for two shots.

Currents collected by the probes are fed to bipolar "logarithmic" amplifiers whose outputs are displayed on oscilloscopes with various sweep rates. The amplifiers have approximately a logarithmic response between 2×10^{-5} amp (saturation level) and 5×10^{-9} amp with linear gain for smaller signals. Their gain is frequency-independent from 0 to 100 kHz and is useful to 300 kHz. During each shot, exponentially decaying calibration current pulses are inserted just before the pellet arrives at the probe station. The calibration currents decay by a factor of ten during each 100 μsec, giving triangular waveforms at the amplifier outputs.

For the shots reported here, one probe is biased two volts negative and the others two volts positive with respect to the return electrodes, which are held at the potential of the experimental chamber.

III. THEORETICAL CONSIDERATIONS

In the regime of this experiment, the Debye length (0.05 mm to 0.5 mm) and electron mean-free path (10^{-2} mm) are comparable to the probe radius. The ion mean-free path (10^{-3} mm) is much less than the probe dimensions so that there are many ion-neutral collisions within a Debye length; therefore, the traditional Langmuir probe theory[4] does not apply. Treatments taking into account collisions[5] are not applicable here because the plasma is in motion with a velocity greater than the drift velocity that would be expected for an ion placed in the electric field of the probe. The fluid dynamic boundary layer thickness is comparable to the ion mean-free path and much smaller than the Debye length. Published analyses for probes in moving media[6] treat the collisionless case.

Comparison[7] with UHF cavity measurements indicates that the average current to a positively biased probe is proportional to the average electron density. Schlieren photographs containing probes[8] have shown that probe current onset coincides with schlieren observation of wake arrival at the probe.

In the absence of a detailed theory to relate electron or ion density to probe current, this preliminary discussion will be confined to the properties of the probe current, with only qualitative reference to the ionization properties of the medium itself. Comparisons with cavity and schlieren measurements justify confidence that probe results can yield quantitative information about electron densities, which will be treated in subsequent presentations of the results.

IV. EXPERIMENTAL OBSERVATIONS

Figures 3 and 4 show the collected currents for the shots in Figures 2a and 2b, respectively. These are typical of the currents observed in 28 shots at a pressure of 40 Torr. The probes are numbered as in Figure 2, and their currents are presented in numerical order from top to bottom. Probes close to the pellet path collect current immediately after passage of the pellet, while those further away begin collection at a later time determined by wake growth. The triangular waveforms at the beginning of the 20-msec sweeps are due to the calibration currents. In both air and N_2 at a pressure of 40 Torr, the average electron current decays exponentially during the early wake but dips sharply between 600 and 800 body diameters after pellet passage if the probe offset diameter (twice the distance from the probe tip to the trajectory axis) is less than 5 cm. For larger probe offset diameter, the dip comes later. For a particular shot, the spread in dip times for different probes at the same offset may be as large as the over-all spread. Following the dip, electron currents from N_2 wakes "recover" to values comparable to those expected from extrapolation of the currents before the dip and exhibit large discontinuities, indicating well-defined boundaries of electron-rich regions lasting for many msec. The high-frequency part of a Fourier spectrum would be greatly influenced by these boundaries, and the spectrum should not be interpreted as that of a stationary process. In air wakes the electron current following the dip usually remains below the detection capability of the equipment, although it sometimes recovers to a value less than for N_2. In the cases where there is recovery, the current then decays more rapidly than in N_2 but otherwise exhibits the same qualitative behavior.

Positive ion currents collected by negatively biased probes are from 4 percent to 40 percent of the electron currents to positive probes in comparable positions for early parts of the wake. Positive ion currents do not exhibit a dip similar to the electron current dip.

In Figure 5 the time of first probe current and the time of the sharp dip are presented as functions of probe offset diameter. The diagonal line represents growth as the one-third power of time in agreement with schlieren observations.[3] The triangles show the outer and inner edges of the schlieren-observed "scallops" (see below) for some of the same shots. Along the left margin are shown bands corresponding to measurement in body diameters of elapsed time since pellet passage. These are bands rather than discrete lines because of the spread in velocities of the pellets here reported. The "prompt current" indicator shows the 4-cm diameter region in which probes receive current immediately. It is dashed at its left end since there it represents probes passing less than 2 mm from the pellet surface, and no observations have been made in that region.

Figure 6 presents the data in a somewhat different manner with both probe offset diameter and time after pellet passage measured in units of pellet diameter. The coordinate axes have been interchanged to conform with the practice of turbulent wake studies. The outer turbulent wake boundary is indicated by the diagonal dashed line. Regions of observed electron current collection are to the right and below the solid line labeled "First Current." The shaded area outlines the region in which the precipitous dip in electron current is observed. The light horizontal dashed lines represent the positions of probes 3 and 4 of Figure 4, whose currents are presented to the same time scale in the upper portion of the figure. Short-term fluctuations have been omitted from these typical current waveforms. The difference between electron current behaviors from air and N_2 is indicated.

Figure 7 gives wake outlines at various times after pellet passage, taken from schlieren photographs for some of the shots reported here. Schlieren photographs for air and for N_2 are indistinguishable. Since the schlieren is at a different station than the present probe experiment, it is not possible to correlate probe current observations with specific portions of the schlieren pictures. As the wake expands and moves forward, the probe enters it in a path determined by the probe position and the wake dynamics. Frequently the probe enters a "scallop" at the edge, then passes through a wake-free region before entering the main body of the wake. Probe 1 in Figure 3 and probe 4 in Figure 4 show this effect.

There have not yet been extensive measurements on the effects of changes in various parameters, but the following trends are indicated by preliminary observations. Dry air at 10 Torr and 20 Torr shows similar characteristics, although the dip is often not so deep and the current recovery is frequently greater than at 40 Torr. There is an indication that the dip may be more pronounced just after the experimental chamber has undergone a thorough cleaning, but not enough data have been collected to allow a positive assertion in this regard. If the probe positive bias is increased at lower pressures, the dip appears to be less pronounced; but this effect has not been investigated at 40 Torr.

V. DISCUSSION

UHF cavity observation of hypersonic wakes[1] has demonstrated that electron concentrations averaged over the wake cross section in air and in N_2 are comparable for the first few msec, but the electron density in air then falls much more rapidly than in N_2. This has been attributed primarily to attachment of electrons to oxygen in the air as it cools. The reduction in electron density now observed in the wake core thus suggests that the central portion of the wake cools more rapidly than the outer regions. Such cooling has been indicated by spectroscopic studies of similar wakes.[2]

At 1.5 msec following pellet passage when the electron-deficient inner region is completely established, it has a diameter of about 5 cm. At this same time the total wake diameter is 9 cm. Absence of electrons in the core may therefore be equivalent to nearly 30 percent reduction in the total number of free electrons. UHF cavity measurements of electron line density have been examined for comparison with this observation. The precision of cavity measurements is such that a 30 percent drop in electron line density should be observable. The line density often has fluctuations of this magnitude, but their timing is not consistent with probe results, often occurring at times less than 1 msec. Further investigation of details of the electron density distribution is required to resolve this apparent discrepancy.

From the preliminary results reported here, the following wake description may be deduced. Probes placed within a few body radii of the trajectory of a sphere exhibit a current, due to shock-heated gas (the "inviscid" wake), that decays exponentially without appreciable fluctuation until the turbulent wake grows to the probe position. There then follows a period of slight current fluctuations as long as the diameter of the turbulent wake is smaller than that of the inviscid wake. Large amplitude fluctuations appear as soon as the turbulent wake begins to engulf cold (thus electron-free) outside air.

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Gratitude is expressed to Dr. W. G. Clay, who directs operation of the light-gas gun and associated pellet velocity- and position-measuring equipment. Helpful discussions with Dr. R. S. Cooper and Dr. W. M. Kornegay are acknowledged. Dr. Kornegay has kindly given access to UHF cavity data for purposes of comparison. Mr. J. R. Theriault has been very helpful in development and construction of the probes, as well as in the collection of probe data.

RER:JH/jls

14 November 1966

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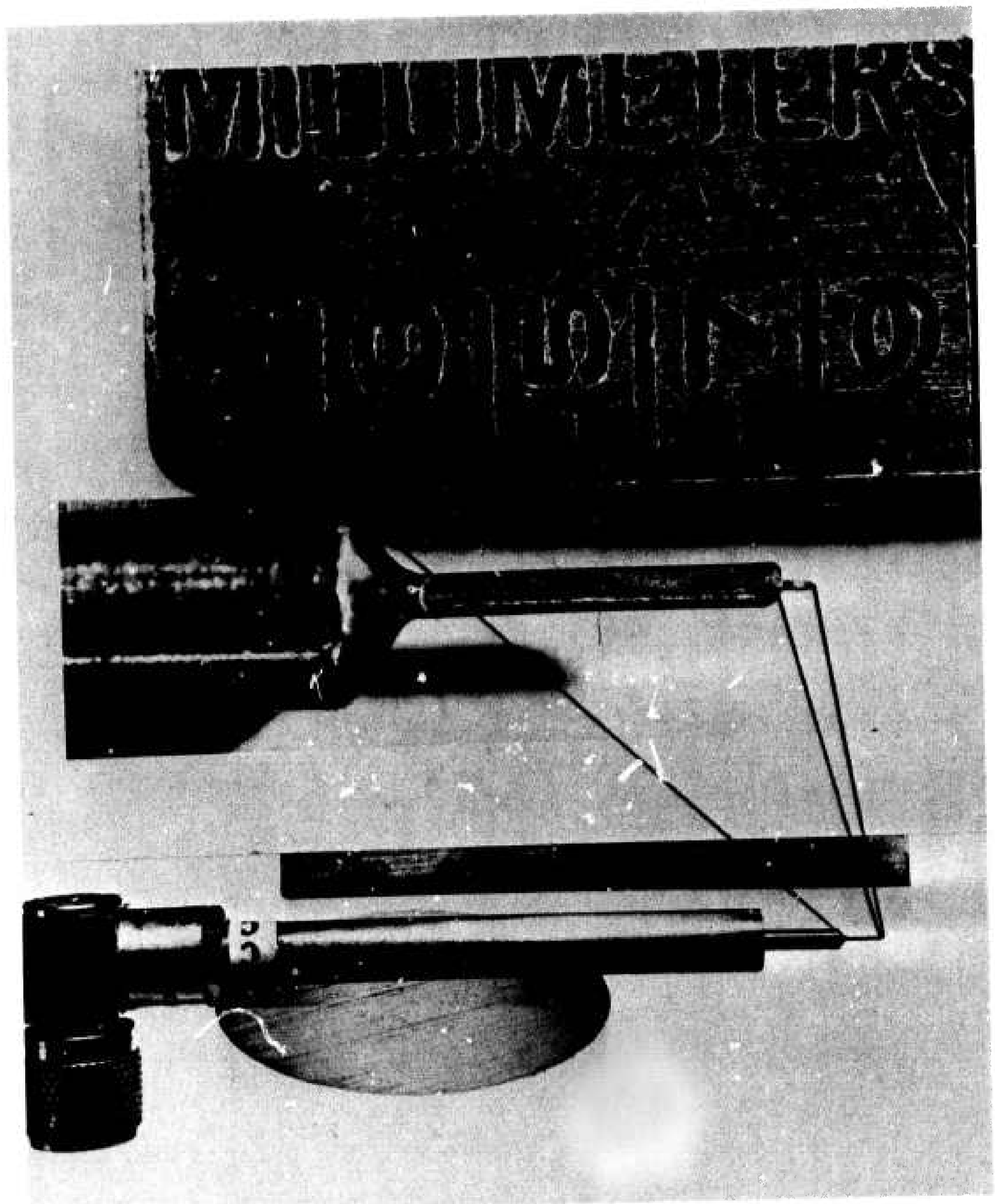
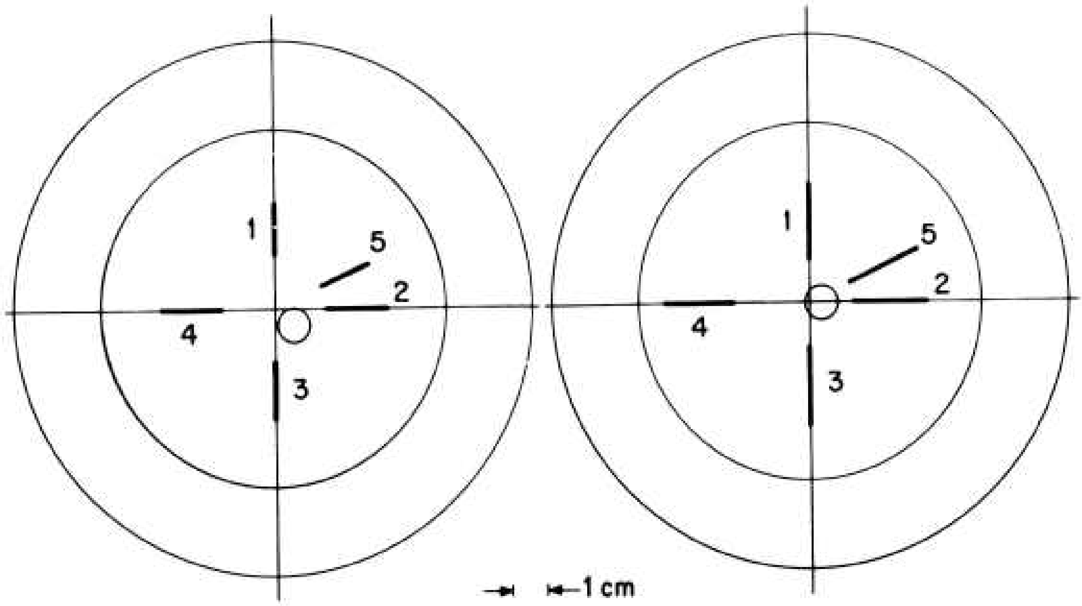


Fig. 1. Electrostatic double probe. All exposed metal parts are gold plated for ease of cleaning and minimizing of contact potential differences.



2(a) 2(b)

Fig. 2. Pellet position relative to probes for two specific shots. 2a.) Shot No. 1193, 40 Torr dry air. 2b.) Shot No. 1207, 40 Torr N_2.

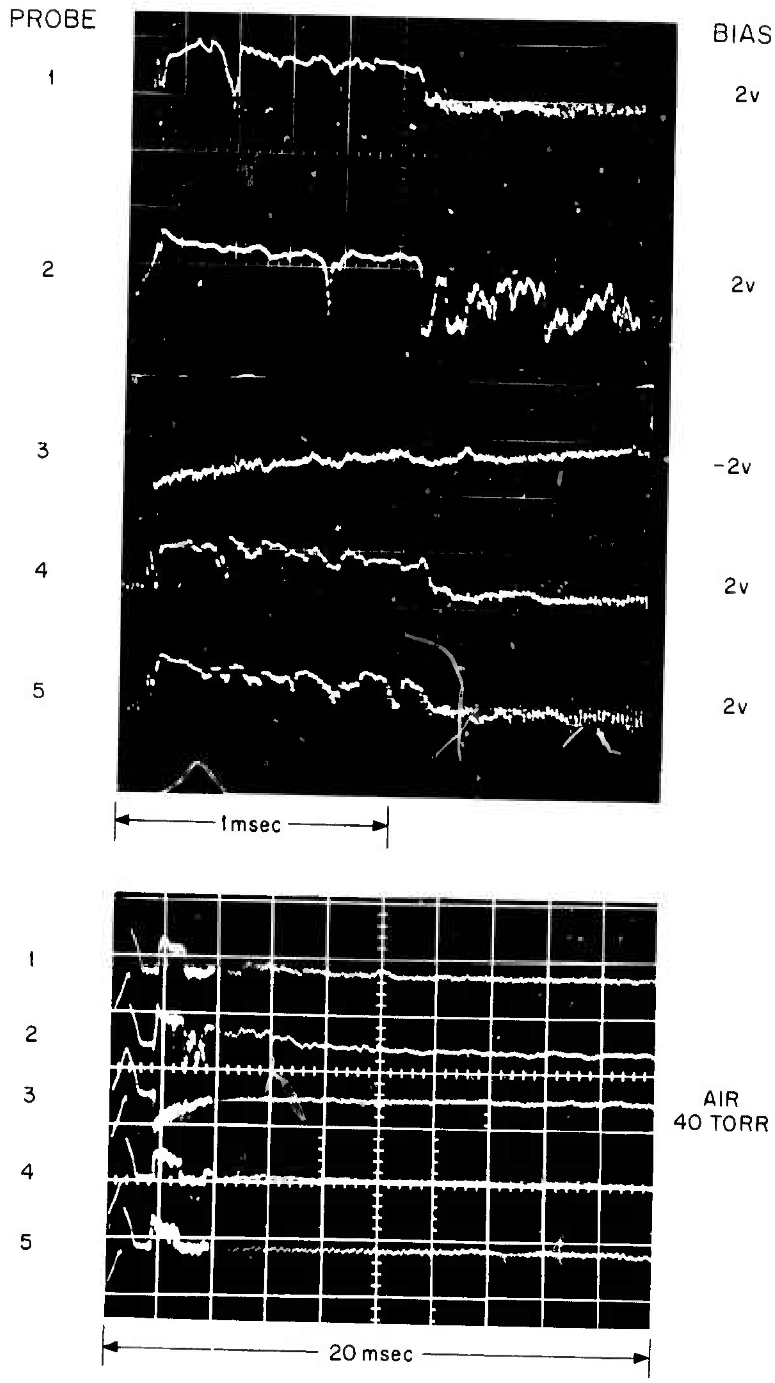


Fig. 3. Probe currents for shot No. 1193. Upper traces 0.2 msec/div. Lower traces 2.0 msec/div. Trace numbers correspond to probe numbers in Figure 2a.

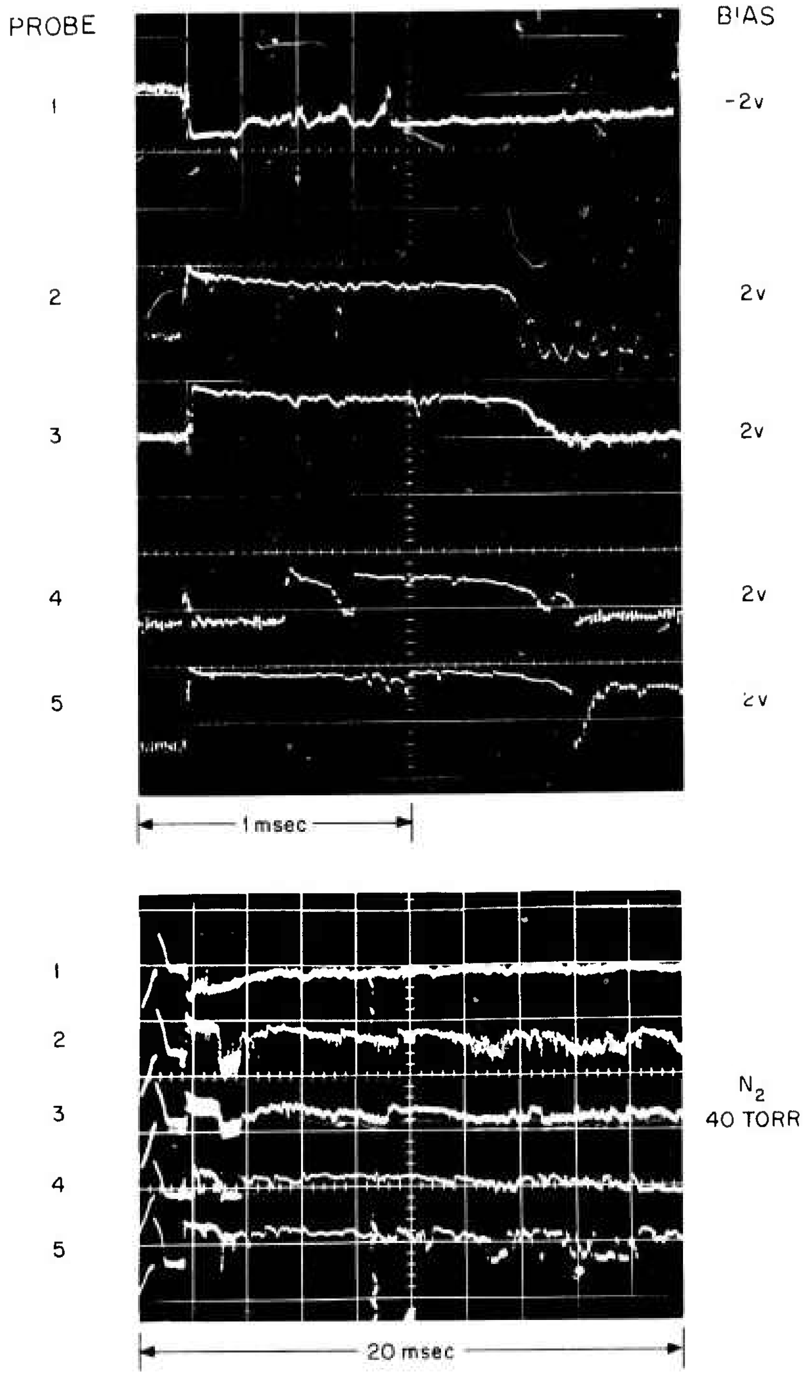


Fig. 4. Probe currents for shot No. 1207. Upper traces 0.2 msec/div. Lower traces 2.0 msec/div.

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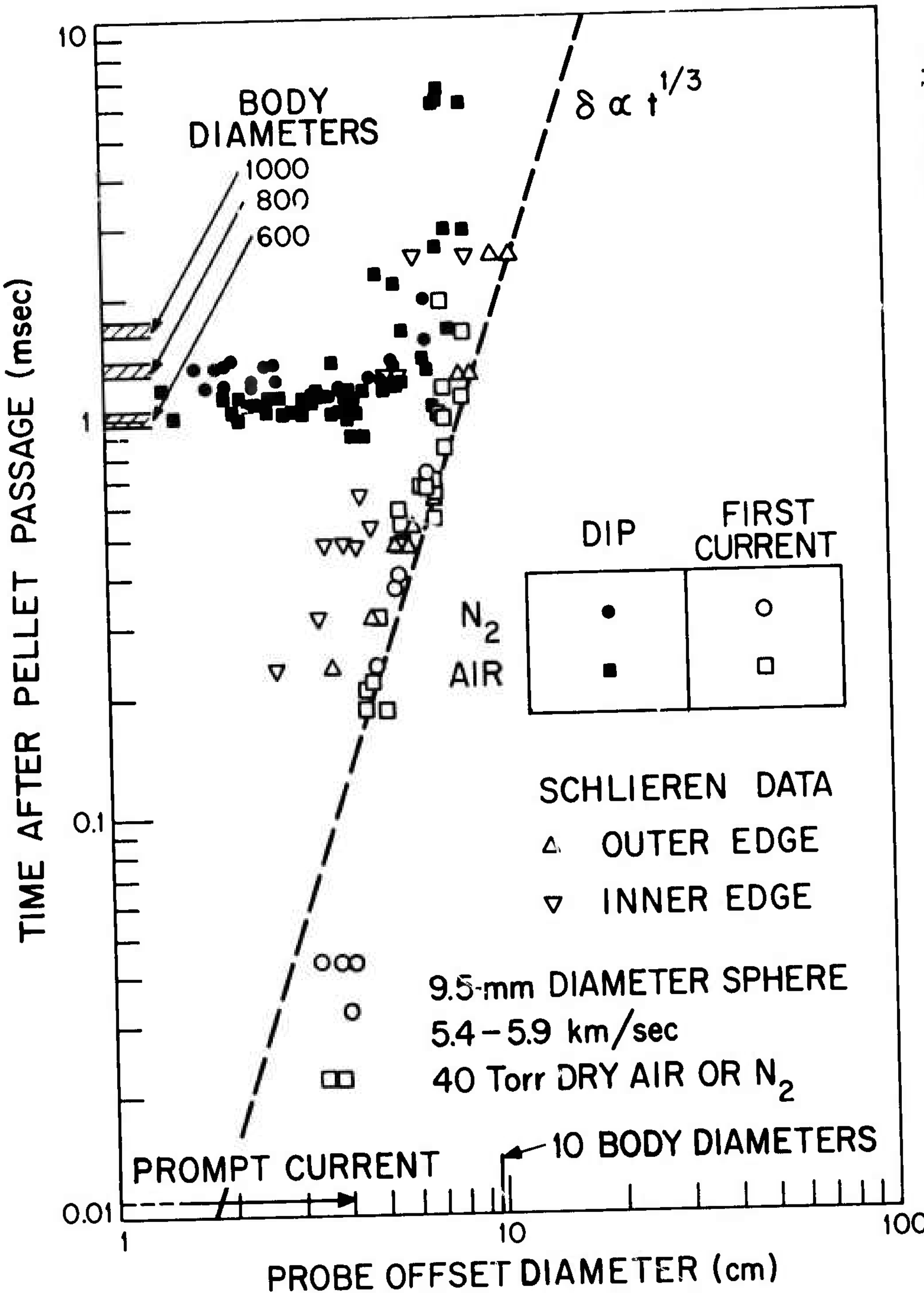

Fig. 5. Time of first probe current and time of the sharp dip as functions of probe offset diameter. The diagonal line represents growth as the one-third power of time and originates on a circle of pellet diameter passing the probes coincident with the rear of the pellet. Bands at left margin indicate distance behind pellet in body diameters.

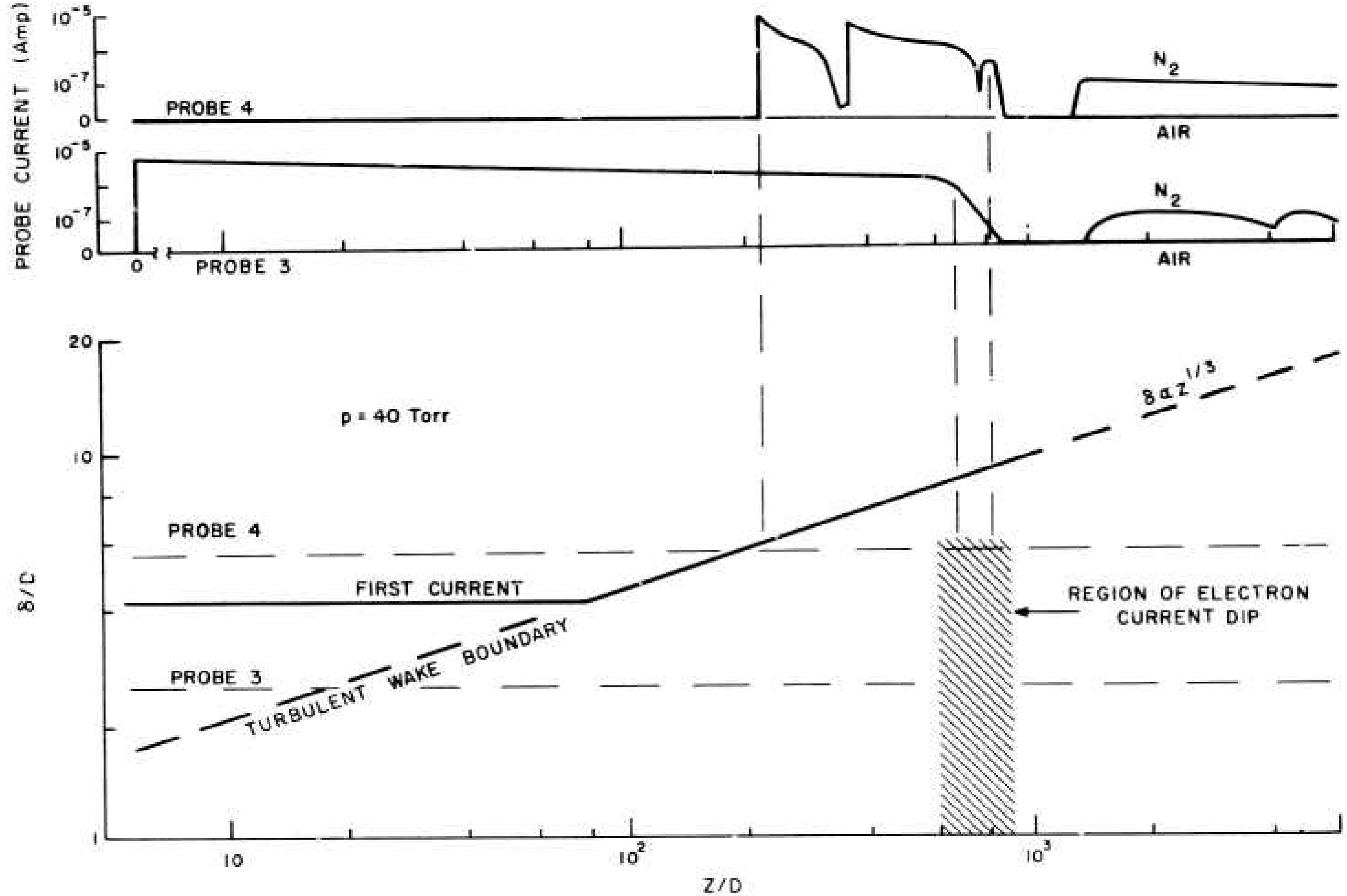

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Fig. 6. Summary of data presented in Figure 5. Z is distance behind the pellet, δ is probe offset diameter, and D is sphere diameter. The two upper curves are representations to the same logarithmic distance scale of typical probe electron currents, with short-term fluctuations omitted.

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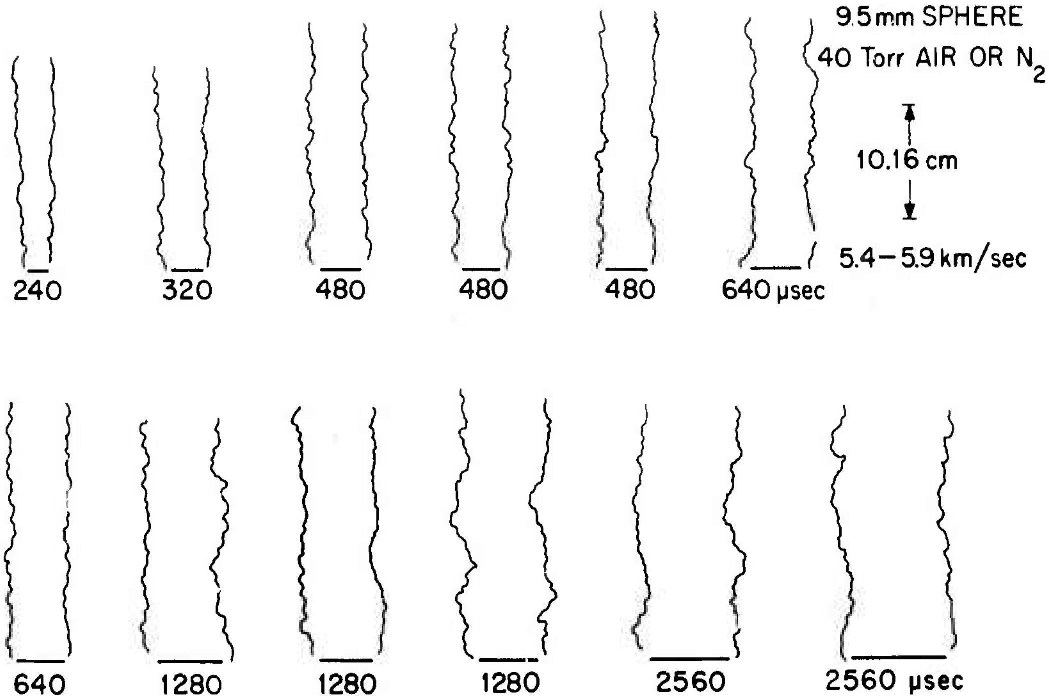

Fig. 7. Wake outlines at various times after pellet passage--from schlieren photographs.

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