Technical Notes

The Effect of a Magnetic Field on Wake Potential Structures

N. D'ANGELO AND R. L. MERLINO

Abstract—**Potential profiles in the wake of a body in a plasma flow are presented for several values of a flow-aligned magnetic field. A transition from a potential "well" to a potential "hill" is found when the electron gyroradius becomes smaller than the size of the body transverse to the flow.**

I. Introduction

The interaction of a plasma flow with a metallic body has been studied for many years, both experimentally and theoretically [1]-[7]. An understanding of the wake structure that results from this interaction is of particular importance in the case of spacecrafts orbiting at speeds of several kilometers per second through the earth's ionosphere [8]. In the frame of reference of the spacecraft, the plasma flow is generally supersonic, with a plasma flow speed v many times the ion-acoustic speed C_s, but much smaller than the electron thermal speed $v_{e,th}$, i.e., $C_s \ll v \ll v_{e,th}$. This is also the case in most laboratory studies of plasma flow-body interaction. These experiments have concentrated mainly on the structure of the density depletion in the wake and the subsequent plasma expansion into the wake. The effect of a magnetic field on the flow-body interaction has received only limited attention in the laboratory [4], [9], [10].

In this note we report preliminary results, also obtained in the laboratory, and limited entirely to the effect that a magnetic field of variable strength has on the plasma potential structure in the near wake of a metallic object. A full two-dimensional set of data including densities, potentials, and possibly distribution functions should become available when a new larger and much-improved device, now under construction, will be installed in our laboratory.

The (flow-aligned) magnetic field in our experiments could be varied continuously, allowing us to examine two different situations, namely a) the case in which both electrons and ions are unmagnetized, with the electron gyroradius ρ_e and the ion gyroradius ρ_i both larger than the size L of the body transverse to the flow; and b) the case in which the ions are unmagnetized ($\rho_i > L$), while the electrons are magnetized ($\rho_e < L$ or even $\rho_e \ll L$). The latter situation ($\rho_e \ll L \lesssim \rho_i$) occurs, e.g., when a spacecraft of $\sim$1-m size orbits in the earth's F region or above. Our study may also be relevant to the question of the charging of manned maneuvering units (MMU's) in the Shuttle wake [11]. Of course, our results would be strictly applicable only when the spacecraft motion is nearly B-field aligned, a situation that occurs at times for spacecraft in polar orbits.

II. Experimental Setup

Fig. 1 is a schematic drawing of the experimental setup that we have used for this study, a double-plasma (DP) device with a longitudinal magnetic field with strength up to $\sim$100 G. The "driver"

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The authors are with the Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242.

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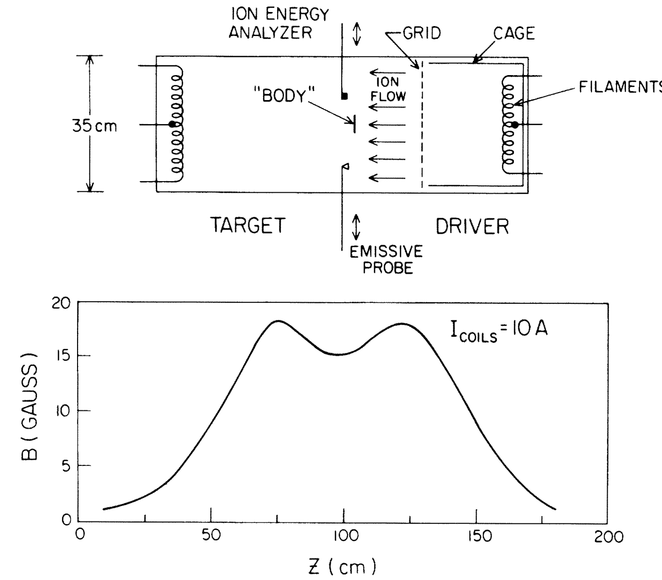

Fig. 1. Schematic of the experimental setup. The profile of the axial magnetic field for a coil current of 10 A is also shown, on the same scale.

chamber (discharge voltage = −50 V) and the "target" chamber are separated by a grid biased at −62 V. When the "cage" is biased positive, an ion beam (of variable energy, 0-50 V) can be injected from the driver into the target. Electrons in the target chamber are provided in the present experiment by the hot filaments of the target, biased at −15 V relative to the target walls. This bias is not large enough to produce a discharge in the target chamber. The main function of the target filaments is to provide enough electrons to neutralize the ion flow from the driver and keep the potential of the target at some fixed value below the driver potential, so that an ion beam can actually be injected. This mode of operation is different from the usual one for a DP device. It allows us to have a flowing plasma in the target, with a density that can be much larger than the density of the (nonflowing) background plasma. The density of the flowing plasma is typically in the range 10^8–10^9 cm^{-3} ($T_e \simeq 1-4$ eV, $T_i \approx 0.2$ eV), with a neutral gas (argon) pressure of $\sim 3 \times 10^{-5}$ torr. At this gas pressure the mean-free path for $A^+ - A$ charge exchange is on the order of meters, but even so, most of the background plasma in the target chamber is still provided by charge exchange of the A^+ beam ions with the neutral gas background.

The "body" (or obstacle) that interacts with the plasma flow is a 3-cm diameter 0.8-mm thick tantalum disk located on the axis of the device and oriented normal to the plasma flow. The disk can be biased at any potential and was usually kept at a voltage near the plasma potential in the target. Measurements on the ion beam and the plasma background were performed by means of an ion-energy analyzer. The potential measurements were made using an emissive probe, which consisted of a 0.025-mm diameter tungsten wire of $\sim$5 mm length, although only the center $\sim$1 mm portion of it was actually hot enough to emit. The dc heating current was set sufficiently high so that the probe floating potential saturated at a value very close to the actual space potential [12]. At this value of the heating current, the voltage drop across the 5-mm length of the wire was $\lesssim$ 1 V. The floating potential was then measured with a very high input impedance ($> 10^{12}$ Ω) voltmeter. For the set of

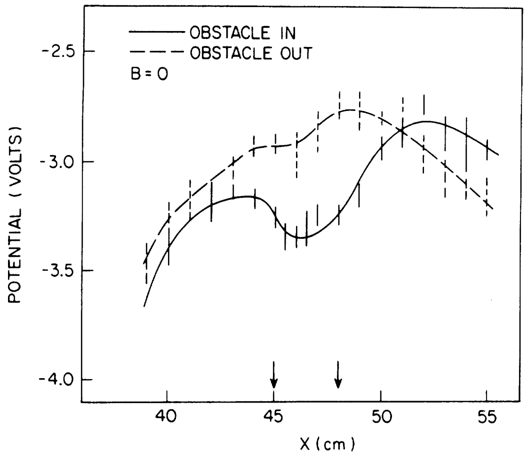

Fig. 2. Potential profile (full line) in the body wake in a direction transverse to the ion flow. $B = 0$ G. The vertical arrows indicate the edges of the body. The dashed line was obtained with the body removed.

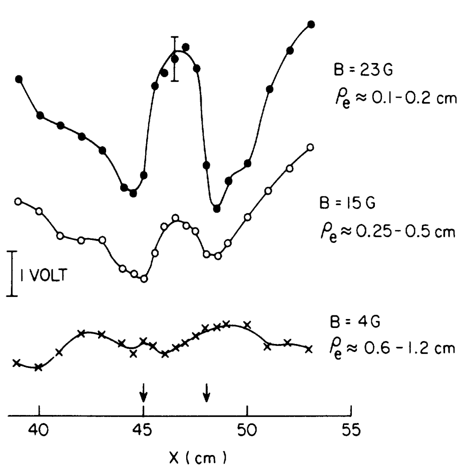

Fig. 3. Potential profiles in the body wake in a direction transverse to the ion flow, for several magnetic field strengths. The corresponding electron gyroradii are also shown. In each case the ion gyroradius is much larger than the transverse body dimension. The vertical arrows indicate the edges of the body. For clarity, the plots are displaced vertically.

measurements reported here, the emissive probe could be moved only radially, at a fixed distance of ~4.5 cm downstream from the disk. Thus the present measurements should complement those of Kawaguchi and Tanaka [4], for example, where a Langmuir probe could be moved only axially, downstream from a metallic object.

III. Experimental Results

We describe here the results on the potential behind the disk, obtained with the emissive probe. Fig. 2 shows a radial scan of the potential, ~4.5 cm downstream from the disk, with $B = 0$ G (full line). For comparison, the potential scan obtained with the disk removed is shown by the dashed line. The radial positions corresponding to the two edges of the disk in a radial scan through the disk center are indicated by vertical arrows. In this case the ion-beam energy was ~ 18 eV. Evidently, the presence of the disk generates a potential "well" ~0.5 V deep.

Fig. 3 shows radial scans of the potential, also ~4.5 cm downstream from the disk, at three different values of the magnetic field at the "body," namely 23, 15, and 4 G. With an electron temperature in the range 1-4 eV, the electron gyroradii at these three values of the magnetic field have the values indicated next to each of the three plots. In all three cases the gyroradii of 0.2-eV thermal ions are considerably larger than the disk diameter. For Fig. 3 the ion-beam energy was approximately 7 eV. Clearly, at $B = 23$ G, the electrons are magnetized, but the ions are only slightly affected by the magnetic field over distances comparable to the disk diameter. As the magnetic field is decreased to 15 G and then to 4 G, the electrons become progressively less magnetized. When the electrons are strongly magnetized, there is a potential "hill" behind the disk, as also observed by Nosachev and Skvortsov [9] in a Q-machine plasma, at a much higher magnetic field strength. When ρ_e becomes comparable to the disk radius, we begin to observe a transition to the potential "well" of Fig. 2.

The behavior of the potential for the two cases of magnetized and unmagnetized electrons can be explained as follows (see also [13]). When the electrons are unmagnetized, they can easily flow into the near wake, since their thermal speed is large compared to the plasma flow speed. The opposite, of course, is true for the ions since $v \gg C_s$. This results in a potential minimum in the wake. When the electrons are magnetized (and the ions are not), only ions can reach the disk near wake, thus producing a potential maximum.

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