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Double-Layer-Relevant Laboratory Results

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***Abstract*—Over the past few years, many double-layer-relevant laboratory experiments have been carried out at the University of Wisconsin. Laboratory stair-step double layers, which resemble *three* or more weak double layers joined in series, have been produced without ionization for the first time. Double-layer floating potential fluctuations have been investigated and progress has been made in developing a novel technique for measuring electron energy distribution functions in low-density double layers (i.e., $\lambda_D \gg$ probe dimensions). A new inductive plasma source has been developed. With this source, magnetized double layers can be routinely produced. These magnetized double layers are often weak stair-step double layers that are oblique to the magnetic field. Laboratory data of emitting probe characteristics taken in tenuous plasmas have helped to quantify space-charge-enhanced plasma gradient induced error in double-layer electric field measurements made by satellite double probes. Also, magnetic sheaths have been experimentally studied and compared with theory.**

I. INTRODUCTION

ALTHOUGH it has long been thought that double layers (DL's) may be responsible for the acceleration of charged particles associated with the aurora borealis, it is still not clear whether it is strong double layers (SDL's), i.e., DL's with $e\Delta\phi \gg 10T_e$, where $\Delta\phi$ is the potential drop across the double layer and T_e is the plasma electron temperature, or weak double layers (WDL's), i.e., DL's with $e\Delta\phi \leq 10T_e$, that are primarily responsible for auroral particle acceleration. Temerin *et al.* [1] found that probes on board the S3-3 polar-orbiting satellite observed many WDL's, between altitudes of 6000 and 8000 km, aligned with and moving along the magnetic field. They proposed that a series of these DL's might account for a large portion of the parallel potential drop that accelerates auroral particles along field lines. More recently, but again from S3-3 data, Mozer [2], [3] has found evidence of field-aligned SDL's and has suggested that SDL's may be primarily responsible for auroral particle acceleration.

Analysis of Viking data by Boström *et al.* [4]–[6] revealed a predominance of WDL's in regions of relatively weak overall potential drop, i.e., less than 1 keV as inferred from particle data. Mozer [3] has noted in his analysis of S3-3 data that when S3-3 was in regions of strong overall potential drop (roughly as much as 10 keV or more as inferred from particle data) its data were dominated by SDL's and that when S3-3 was in regions of weak overall potential drop its data were dominated by WDL's. Although Viking has flown in both these types of regions, the analysis of Viking data to date has been concentrated on those regions of weak overall potential drop [6]. It may be that in regions of weak overall potential drop WDL's are primarily responsible for charged particle acceleration while in regions of strong potential drop it is SDL's that are primarily responsible [3], [6].

Our group has been experimentally addressing DL issues for the last decade at the University of Wisconsin, and before that at the University of Iowa. This laboratory work has included both SDL's [7]–[11] and WDL's [12]–[22]. More specifically, this work includes the first laboratory observations of ion-acoustic-type DL's [18], slow ion acoustic DL's [20], two-step DL's [16], very weak DL's (i.e. $\Delta\phi \simeq T_e$) [18], DL's with no external electric field applied [13], currentless DL's [20], stair-step DL's [21], magnetized stair-step DL's [22], SDL's in a triple plasma device [7], WDL's in a triple plasma device [12], and U-shaped DL's in a magnetic field in a triple plasma device [8]. It should be noted that all our DL's have been produced in triple plasma devices [9] and that with the exception of the DL's described in [10], [18], and [20], these DL's have been stationary. For a review of many of these, as well as other DL experiments, the reader is referred to Hershkowitz [23].

II. STAIR-STEP DOUBLE LAYERS

Chan and Hershkowitz [16] were the first to show that it is possible to obtain laboratory two-step DL's (which resemble two single WDL's joined in series) without ionization occurring in the DL's. An example of a two-step DL, measured by Bailey, is shown in Fig. 1. Chan and Hershkowitz [16] argued that two-step DL's can be produced when the ratio λ_D/L, where λ_D is the Debye length and L is the length of the chamber in which the DL's are produced, is made to be less than approximately 1×10^{-2}. In their experiment, they achieved this both by increasing the plasma density and by increasing L. However, subsequent efforts in which both the plasma density and the device length were further increased failed to produce stair-step DL's with three or more single DL's joined in series.

Bailey and Hershkowitz [21] were the first to achieve, without ionization, laboratory stair-step DL's with three or more single WDL's joined in series. These stair-step DL's were achieved by careful control of the boundary conditions and appeared to be a new class of laboratory DL's that were intermediate between anomalous resistivity [24] and

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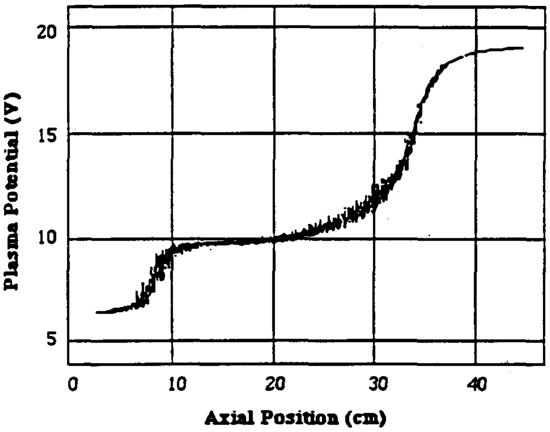


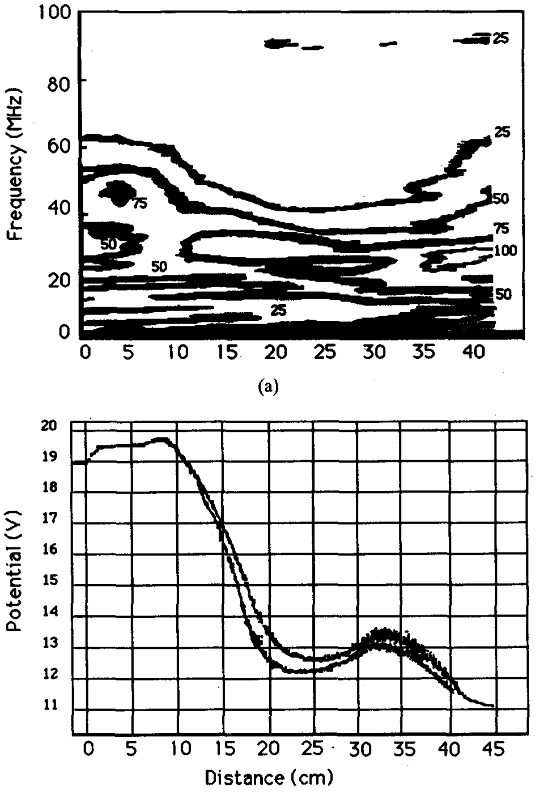
Fig. 1. Plasma potential (volts) versus axial position (cm) of a two-step DL.

conventional BGK [25], [26] DL's. The stair-case DL's also appeared to depend on turbulence for their existence. As an extension of this work, Forest and Kaufman studied the high-frequency floating potential fluctuations, as measured by a capacitive probe [27], associated with these and other DL's. An example of their data is shown in Fig. 2. Some qualitative correspondence between the high-frequency floating potential fluctuations and DL's was found. For example, in Fig. 2(a) there is a peak in fluctuation amplitude at a frequency of approximately 45 MHz on the high-potential side of the DL shown in Fig. 2(b) and another peak at a frequency of approximately 25 MHz on the low-potential side of that DL.

In an effort to determine whether high-frequency fluctuations associated with DL's caused thermalization of electron beams created by DL's, Kaufman, Forest, and Lee attempted (unsuccessfully) to measure the electron distribution functions of stair-step DL's. Standard, for our laboratory, 7-mm-diameter Langmuir probes were found to function poorly in the DL's which were investigated. In particular, probe $I-V$ (current versus voltage) characteristics did not show knees, which are a basic feature of probe $I-V$ characteristics.

It was first thought that the absence of knees was due to probe surface contamination. A pulsed probe technique developed by Szuszczewicz and Holmes [28] (also see Holmes and Szuszczewicz [29]) was employed. This technique can considerably reduce surface-contamination-induced distortion of probe $I-V$ characteristics. However, it should be noted that with this technique a nonzero, constant contact potential difference between the voltage applied to a probe and the voltage on the surface (which interacts with the plasma) of that probe can exist. Therefore, plasma potential cannot be inferred from data obtained by this technique. This was not a concern for Kaufman and Lee, however, as they were able to measure plasma potential with emissive probes. Some typical data taken by Kaufman and Lee with the pulsed probe technique are shown in Fig. 3. As is evident from the data, a knee still could not be found.

In a second attempt to obtain probe characteristics with knees, guarded Langmuir probes were employed. In the double layers which Kaufman and Lee investigated, $n \sim 10^6$ cm^{-3} and $T_e \simeq 2$ eV, which means that λ_D was approximately 1/3 of the probe diameter. In low-density plasmas where λ_D is comparable to the probe diameter, the sheaths of even planar probes become spherical, and the $I-V$ characteristics of probes with spherical sheaths have no knees [30]. When plasma density becomes low, the fringing fields of a guarded probe's sheath should fall mainly on its guard; i.e., for decreasing density, the effective area of the probe should remain roughly constant while the effective collecting area of its guard increases. Insulating material is used to electrically isolate the probe and its guard. The guard and probe are kept at the same voltage by separate power supplies so that the guard's current does not add to the probe's current.

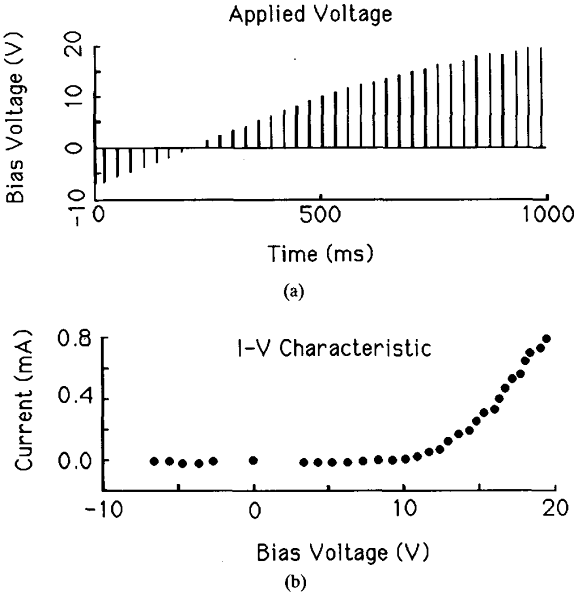


(a)

(b)

Fig. 2. Capacitive probe measurements of the high-frequency floating potential fluctuations associated with a DL. (a) Equiamplitude contours (marked in dB) in the frequency (MHz), distance (cm) domain. (b) Plasma potential (volts) versus distance (cm) of the corresponding DL.

The qualitative design of the first guarded probe employed by Kaufman and Lee is shown in Fig. 4(a). Characteristics from this probe still showed no knee. The guarded probe shown qualitatively in Fig. 4(b) was then tried and yielded $I-V$ characteristics with knees. It is believed that the important difference between the guarded probes shown in parts (a) and (b) of Figs. 4 is that insulating surfaces are exposed to the plasma for the probe shown in Fig. 4(a) but not the probe shown in Fig. 4(b). Insulating surfaces are known to charge negative with respect to the plasma potential; they charge toward the floating potential. In low-density plasmas, sheaths



(a)

(b)

Fig. 3. Data from a probe in a plasma when the voltage applied to the probe was pulsed. (a) Pulsed bias voltage (volts) applied to a probe versus time (ms). (b) The corresponding probe current (milliamps) versus bias voltage (volts), also referred to as the probe's $I-V$ characteristic, using the pulsed probe technique.

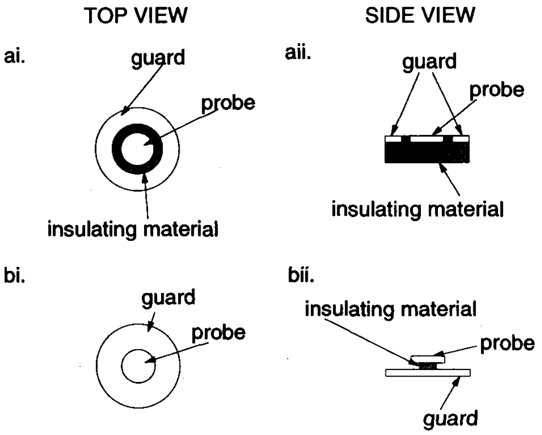


Fig. 4. Schematics of the guarded probes used by Kaufman and Lee. The thicknesses in the side views are exaggerated for clarity. The first design tried is shown in (a) and the second in (b).

can become quite large; and it is believed that the probe shown in Fig. 4(a), and perhaps its guard as well, were in the sheath of the insulating material.

Fig. 5 depicts a "witch's hat". One might think of the witch's hat as a guarded probe with a large guard that is bent into a "hat" over the probe. Again, the hat and probe are biased with different power supplies so that the hat's current does not add to the probe's current. However, with the witch's hat, the hat is biased to the local plasma potential (as determined by an emissive probe) rather than the probe's voltage. If the hat is successful in containing the probe's sheath within it, then there is no sheath between the hat and the plasma. Under such conditions, the effective collecting area of the probe is just the area of the opening in the top of the hat.

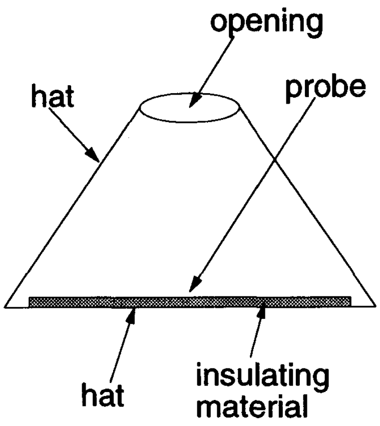


Fig. 5. Schematic of the witch's hat.

Probe characteristics with knees were obtained with the witch's hat and the knees were at the same probe bias voltage as the knees obtained with the guarded probe. However, the electron energy distribution functions measured by the two probes were not the same; the effective electron temperatures measured by the witch's hat were greater than those measured with the guarded probe. Furthermore, the voltage bias at which the knees occurred did not change as the probe was moved axially through the double layer chamber. Subsequent emissive probe measurements showed that double layers were destroyed when either the witch's hat or the guarded probe was used. At this point, the effort to measure the electron energy distribution functions associated with double layers was abandoned.

III. Double Layers Oblique to an Applied Magnetic Field

In the laboratory, constraints are imposed on the production of DL's by the plasma sources that are used. Consequently, there has been much work in our laboratory regarding plasma source development [7], [31]–[41]. In particular, in the past, plasma source limitations have restricted our efforts to investigate DL's which are oblique to externally applied magnetic fields. There has been interest in such DL's, among other reasons, because when Temerin *et al.* [1] suggested that auroral particle acceleration might be due a series of WDL's aligned with the magnetic field, they also suggested that these WDL's might be two-dimensional in structure.

Most of our double layers are obtained in the absence of applied magnetic field. Our plasmas are usually produced with hot, electron-emitting, thoriated tungsten filaments. When a magnetic field is applied, the emitted electrons tend to be confined to those field lines which intersect the discrete filaments. Hence, in the presence of an applied magnetic field, our filament discharges tend to be noisy and have large spatial variations perpendicular to the applied magnetic field [8], [23]. Despite these problems, Coakley *et al.* [8] did manage to produce DL's in a magnetic field of about 40 gauss.

For the reasons discussed above, it is difficult when using filament sources to obtain DL's in magnetic fields. Q machines have been used to generate DL's in magnetic fields. However, with regard to studying WDL's that are oblique to the magnetic field, Q machines have the disadvantage that $T_e = T_i \simeq 0.2$ eV, which means that it is not possible to produce ion-acoustic-type WDL's with Q machine plasmas.

Intrator *et al.* [22] have developed an inductive source that produces relatively quiet and spatially uniform plasmas with T_e (~ 3 eV) $\gg$ T_i (~ 0.1 eV) in magnetic fields of up to 360 g. To produce WDL's oblique to applied magnetic fields, Intrator *et al.* [22] used two such inductive sources in the two source chambers of the triple plasma device double layer investigator-II (DOLI-II), which has been described elsewhere by Intrator *et al.* [42].

With argon as the working gas, plasma was produced with two loop antennas. One antenna was powered with RF at 13.56 MHz and the other antenna was powered with RF at approximately 10 MHz. In the target chamber, where the DL's were produced, the plasma density was approximately 5×10^9 cm^{-3} when an external field of 360 g was applied.

One interesting feature of this type of inductive source is that the plasma potentials in both the sources and the target oscillate at the RF input power frequencies. The RF frequencies employed are great enough that ions and the emissive probes used to measure the plasma potential cannot respond to plasma potential fluctuations at the RF frequency. On the other hand, the electrons have enough mobility that they can respond to plasma potential fluctuations at the RF frequency. Hence, during part of the RF cycle of each source, electron beams traveling parallel to the magnetic field can exist while during the other part of the RF cycle antiparallel electron beams can exist. This is similar to the situation implied by satellite data analyzed by Hultqvist *et al.* [43], which suggested the simultaneous (to within the time resolution of their diagnostics) existence of upward moving, magnetic-field-aligned electron and ion beams.

Stair-step DL's were produced by Intrator *et al.* [22] with up to four (or possibly more) WDL's in series, oblique to the magnetic field. The average perpendicular scale length of DL's produced by Intrator *et al.* [22] was found to be dependent on the magnetic field and roughly proportional to the inverse of the magnetic field strength (or ion gyroradius). The corresponding average parallel scale length was found to be only marginally dependent on magnetic field.

Fig. 6 is an example of data taken by Intrator *et al.* [22] and shows two-dimensional equipotential contours taken in the target chamber when a 180 g field was applied. In Fig. 6, DL's are those regions in which the equipotential contours are closely spaced. Note that if the potential shown in Fig. 6 had only been measured along a line (similar to satellite data, which are only measured along the satellite's path) instead of in two dimensions, then the number of DL's that would have been measured would have depended on the line of measurement. For example, if the data had been measured along the line segment between the points $(r, z) = (6, -20)$ and $(-6, 30)$, only one DL (the DL in the region near $(5, -10)$) would have been measured. On the other hand, if the data had been measured along the line segment between $(0, -40)$ and $(6, 20)$, then three DL's (one near the point $(0.5, -30)$, another near $(2, -12)$, and the last near $(5, 14)$) would have been measured. For more details regarding this experiment, the reader is referred to Intrator *et al.* [22].

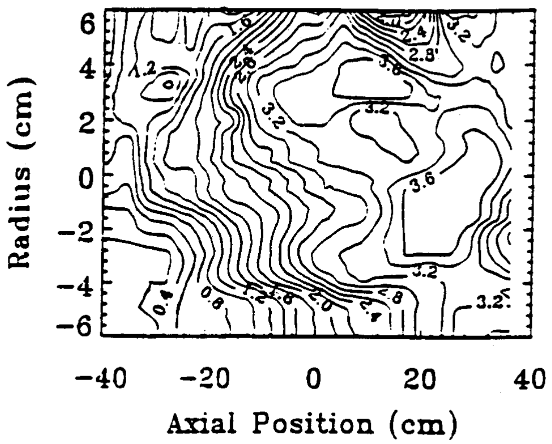


Fig. 6. Equipotential contours (in volts) in the radius (cm), axial position (cm) domain. The applied magnetic field was 180 g and in the axial direction.

IV. SPACE-CHARGE-ENHANCED PLASMA GRADIENT ERROR

While plasma sources place limits on the laboratory DL's that we can produce, plasma diagnostics place limits on the accuracy with which we can measure DL's. We use probes (collecting, emitting, capacitive, etc.) extensively in our laboratory; therefore, in addition to plasma source development, we have done much work on the development of these probes and the techniques with which to use them [44]–[57]. For a review of these and other probe-related works, the reader is referred to Hershkowitz and Cho [58], Hershkowitz *et al.* [59], and Hershkowitz [60].

As part of our laboratory's probe-related effort, Diebold *et al.* [56] measured (thermionically) emitting probe characteristics in tenuous laboratory plasmas with densities very roughly in the range of 10^3 cm^{-3} to 10^5 cm^{-3} ($T_e \simeq 1-2$ eV). The data from these laboratory measurements helped Diebold *et al.* [56] in their efforts to quantify the "space-charge-enhanced, plasma gradient induced error (PGIE)" as it relates to photoemitting, current biased satellite double probe measurements of magnetospheric double-layer electric fields.

As example of such measurements, consider double probe measurements made by Viking of WDL's. Boström *et al.* [4] have reported Viking data in which small-scale (~ 100 m, compared with the 80 m distance between the two probes of the Viking double probe), large-amplitude ($|\Delta n|/n \leq 50\%$), negative-potential ($|\Delta\phi| \leq 2$ V) solitary waves moved upwards along the magnetic field. These structures, which resembled ion holes, often had a net potential drop (≤ 1 V) in the upward direction and were interpreted to be WDL's. It is under conditions such as these, when there can be a relatively large difference in the plasma conditions at the two

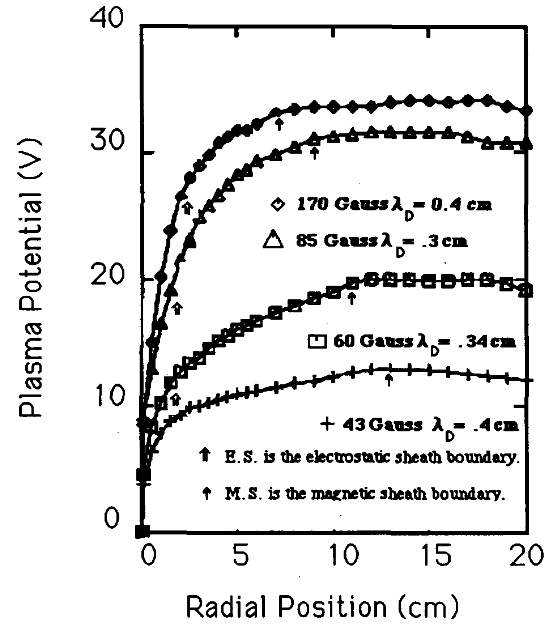


Fig. 7. Plasma potential (volts) versus radial position (cm) of the sheaths near a planar electrode in a He plasma for various applied magnetic fields and plasma conditions. The angle ψ between the applied magnetic fields and the normal to the planar electrode was 60°. The solid arrows indicate the beginning of the magnetic presheath and the open arrows indicate the beginning of the electrostatic sheath.

probes of a double probe, that one might expect space-charge-enhanced PGIE. Furthermore, if space-charge-enhanced PGIE were significant, one would expect it to cause an error that is qualitatively similar to the measurements reported by Boström *et al.* [4].

Diebold *et al.* [56] were able to quantify space-charge-enhanced PGIE. They found that, for the data reported by Boström *et al.* [4], space-charge-enhanced PGIE was not significant. For more details concerning this work, as well as an explanation of what space-charge-enhanced PGIE is and the quantitative expressions describing it, the reader is referred to [56].

V. MAGNETIC SHEATHS

In our laboratory, we have studied many nonneutral plasma phenomena which are not commonly referred to as DL's. Our investigations of plasma wakes [61], [62], plasma expansions [63], [64], and the virtual cathodes near electron-emitting cathodes in plasmas [65] have found potential steps associated with two adjacent regions of net electrical charge, one region of net electrons and one region of net ions. In this sense, these investigations also have been studies of DL's. On the other hand, the sheaths of nonemitting objects [66]–[68] are regions of net ions only; there are no regions of net electrons adjacent to sheaths.

Kim *et al.* [69] measured the sheath potential structure of an nonemitting object in the presence of an oblique magnetic field. In their experiment, up to 500 W (at 13.56 MHz) was inductively coupled into He plasmas in the presence of a maximum applied magnetic field of 170 g. Plasma densities were in the 10^7 cm^{-3} range, electron temperature was approximately 5 to 8 eV, and ion temperature was ≤ 0.5 eV.

The sheath of the electrode was found by Kim *et al.* [69] to consist of the usual electrostatic sheath (which scaled with the electron Debye length) *and* a magnetic presheath. Fig. 7 shows data taken by Kim *et al.* [69]. The arrows indicate the beginning of the magnetic presheath (solid arrows) and the beginning of the electrostatic presheath (open arrows).

In rough agreement with a theory by Chodura [70], the magnetic presheath length was found to be approximately proportional to the ion gyroradius (or the inverse of the magnetic field), the ion acoustic sound speed (i.e., $C_s = (T_e/M_i)^{1/2}$ rather than $v_{i,th} = (T_i/M_i)^{1/2}$), and $\sin\psi$, where ψ is the angle between the magnetic field direction and the normal to the planar electrode. In addition to fusion devices with large magnetic fields nearly parallel to their walls, this work may be relevant to satellites and satellite probes in magnetic fields.

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Photographs and biographies of the authors were not available at the time of publication.