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DOUBLE LAYERS IN THE LABORATORY AND ABOVE THE AURORA

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Abstract

Recent laboratory double layer experiments have simulated, much better than before, the conditions prevailing on auroral field lines at high altitudes. In particular, magnetic fields strong enough to magnetize the electrons (but not quite the ions) have been used. Particle and wave spectra have been measured. Wave-particle interaction has been shown to play a minor role in the only case that has been quantitatively analyzed. The three-dimensional potential distribution has been mapped. The particle budget requires the radial electric field to be outward in the no magnetic field case but inward with magnetic field, in agreement with what is observed above the aurora.

1. Introduction

Laboratory studies and computer simulations can often contribute greatly to our understanding of plasma processes in space (cf. e.g. Block, 1976). This is eminently true for the double layer phenomenon. The existence of double layers (henceforth abbreviated DL in this paper) would not even have been suggested, had they not been observed earlier in the laboratory.

It is, however, well known that a proper scaling between laboratory and space is difficult and sometimes almost impossible. The early DL experiments suffered from several deficiencies, the most important being:

(1) the chamber walls may have played an important role in the laboratory,

(2) the short Debye lengths in the laboratory made it virtually impossible to study the interior properties of the DL in sufficient detail to discriminate between monotonic and non-monotonic potential variations, to localize excitation of waves, or to measure particle velocity distributions at different locations within the DL,

(3) the laboratory plasmas were unmagnetized,

(4) the three-dimensional (3-D) particle flow and potential distribution were not measured,

(5) no detailed particle and momentum flow analysis was made,

(6) the role of wave-particle interaction was not established although many workers have reported wave emissions,

(7) no attempts were made to inject, on both sides of the DL, particles with velocity distributions that realistically reproduce those injected e.g. below and above DL on auroral geomagnetic field lines.

Recent improvements on the six first points listed above will be discussed here, mainly from the point of view of theoretical understanding of the DL phenomenon, per se. Discussion of (7) above on particle velocity distributions is deferred to the second half of the paper, devoted to comparisons with auroral DL.

2. Experimental Improvements in the Laboratory

Wall effects

In the earliest experiments DL were observed at a position where the discharge tube cross section changed more or less abruptly (Crawford and Freeston, 1963 ; Schönhuber, 1963; Andersson *et al.*, 1969). A probable explanation for the existence of a DL at such a position is that the plasma properties depend on the tube cross section. In a narrow tube the rate of ionization has to be higher to cover the greater particle losses to the walls. That implies a higher electron temperature. A matching of two plasmas with different temperatures can most easily be done by means of a weak DL with a potential drop of the order of kT_e/e. No critical minimum current density is required for the existence of this kind of DL.

Unstable, very fast growing DL, where the potential drop can rise to 100 kV or more in a fraction of a millisecond and then collapse, have been shown to be due to a sudden rarefaction of the plasma density at a certain point (Torvén, 1968). Normally the plasma density is maintained by ionization. If, however, the current is so strong that it nearly equals the random electron current, a small decrease in the rate of ionization, due to e.g. an increased adsorption of neutral particles on the walls, will lead to a rarefaction instability and a DL (Carlqvist, 1972; Raadu and Carlqvist, 1979). The subsequent heating will then release gas from the walls with a DL collapse as a result.

The importance of wall effects is obvious in the above examples. Torvén and Babić (1975) showed, however, that a relatively stable DL can be formed in a plasma tube with uniform cross section provided the current density exceeds a critical value corresponding to an electron drift speed about equal to the electron thermal speed. Still, the tube was narrow (2 cm diameter and 100 cm long) so wall effects could not be excluded. Later experiments in larger plasma chambers and/or axial magnetic fields have considerably reduced the influence of the walls. Other detailed studies to be discussed below have also shown that the walls do not play a decisive role.

Interior DL potential profile

In a large plasma chamber particle losses to the walls play a relatively minor role, due to the decreased area to volume ratio. Hence a more tenuous plasma with correspondingly longer Debye length can be produced. A DL will therefore be thicker, thus facilitating investigation of its interior. In this way DL in plasmas with Debye lengths of the order of millimeters (Quon and Wong, 1976; Coakley et al., 1978) or centimeters (Baker et al., 1980) have been studied and the potential variation within them have been found to be monotonic. Torvén and Lindberg (1980) were able to show the same in a plasma with only 0.4 mm Debye length, by feeding the signals from two narrowly space probes to the x- and y-inputs of an oscilloscope. The measured electric fields, potential drops and DL widths as related to Debye length and electron temperature agree reasonably well with theory and computer simulations in all these experiments.

Magnetized layers

The first indication of a DL in a longitudinal magnetic field was made by Lutsenko et al. (1975). However, their experiment was pulsed and the potentials measured with capacitive probes outside the tube. The first measurements with in situ (emissive) probes were made independently by Coakley et al. (1979) and Torvén and Andersson (1979), and later by Baker et al. (1980). Thus, it is now established beyond doubt that magnetized layers can exist under the same general conditions as unmagnetized ones. However, only the electrons have been well magnetized, while the ion gyro radii could not at all, or (Baker et al., 1980) only marginally be made smaller than the plasma column radius.

Some characteristics of DL could be demonstrated more easily in a magnetic field, due to the better beam confinement (Baker et al., 1980), as will be discussed below.

Attempts to magnetize the ions are very desirable and should be tried in the near future.

Two- and three-dimensional potential distribution

To understand the formation and stability of DL it is essential to consider the 2-D and 3-D potential distribution. With a few exceptions (Swift, 1976; Kan et al., 1979; Wagner et al., 1980) self-consistent theories have only been one-dimensional. Unfortunately, the few 3-D theories are not applicable to the laboratory experiments since they all assume magnetized ions as well as electrons. Even so, the laboratory measurements of 3-D potential distributions in non-magnetized and weakly magnetized DL plasmas (Coakley et al., 1979; Torvén and Lindberg, 1980; Baker et al., 1980) represent a considerable progress. Fig. 1 shows the potential distributions measured by Baker et al. (1980), who discuss their results qualitatively in terms of particle production, focussing and losses due to the radial electric field. In the no magnetic field case the radial electric field must be directed outward to maintain quasi-neutrality by confining the electrons (cf. Fig. 1a). With magnetized electrons (Fig. 1b) ion losses must be reduced at the high potential side of the layer, so the radial electric field is partly reversed. Note how the magnetization tends to make the potential distribution similar to that observed above the aurora.

Particle and momentum flow

Since the need for parallel electric fields was recognized, different mechanisms for production of such fields have been proposed. (For a reference see Block and Fälthammar, 1976.)
The essential difference between them is the different processes balancing the momentum gain from the electric field for the majority of the electrons. For normal resistivity it is binary collisions, for anomalous resistivity wave-particle interaction, and for DL it is particle inertia. As is discussed in the following section, wave emissions have been observed from most or all DL. It is, therefore, very important to quantitatively evaluate the relative roles of the three above mentioned processes.

The presence of a well-defined electron beam on the high potential side has been demonstrated by Crawford and Freeston (1963), Andersson et al. (1969), Andersson (1977), Coakley et al. (1978) and Baker et al. (1980). An approximate analysis by Baker et al. (1980) for the simpler case of magnetized electrons, allowing an essentially one-dimensional treatment, showed that inertia balances at least 50% of the momentum input from the electric field, binary collisions about 25%, and wave-particle interaction at most 25%. Beam divergence, which was not measured, could have shifted some of the 25% wave-particle interaction to inertia. Figure 2 shows the electron flux spectra upon which the above numbers are based. There is a clear beam population already on the low potential side of the layer. It is due to a strong potential drop in a sheath at the negative grid where plasma is injected. It can be seen that most of the momentum loss is suffered by this beam, which indicates some beam plasma interaction, but on the other hand beam divergence could account for some of the apparent degradation, since the magnetic field confinement is least efficient for the most energetic electrons.

Role of wave-particle interaction

The above mentioned analysis of Baker et al. at least puts an upper limit (< 25%) on the role of wave-particle interaction, i.e. anomalous resistivity, for the momentum balance. We do not know of any other similar quantitative analysis, but the electron beams observed on the high potential side in several DL experiments (for references, see the preceeding section) strongly indicate that wave-particle interaction in any case does not play a major role.

Torvén and Lindberg (1980) observe low frequency fluctuations (~50 kHz << electron gyro frequency but >> ion gyro frequency at B = 50 gauss, cf. Fig. 3) generated and spatially concentrated within the layer due to rather regular fluctuations in DL potential position. On the high potential side the electron beam is observed to generate a wave spectrum (100 - 1000 MHz) with maximum intensity at the plasma frequency (500 MHz). These waves propagate away from the DL with a nearly frequency independent phase velocity that is 10 - 20% less than the electron beam velocity. They are damped out within a few hundred Debye lengths from the DL without strongly degrading the beam. Apparently, the electron velocity distribution requires only a slight modification to make its wave-inducing power negligible.

More detailed wave measurements in laboratory DL are urgently needed.

3. Comparisons with Auroral Double Layers

There are both similarities and differences between the laboratory and space conditions that have to be taken into consideration when discussing the chances for DL formation above the aurora. We shall here discuss the following aspects of the problem:

(1) the need for plasma sources on both sides of the DL,
(2) a minimum electron drift velocity on the low potential side (Bohm condition),
(3) particle velocity distribution before and after passage through the DL.

(4) wave-emissions,
(5) magnetic field,
(6) potential distribution.

Plasma sources

Quon and Wong (1976), Torvén and Babič (1975) and Torvén and Lindberg (1980) have used a plasma source only on the low potential side of the DL. Torvén and Lindberg show that in their device ionization by the energetic electrons acts as a plasma source on the high potential side. The same mechanism may also work in Quon and Wong's double plasma device. In any case, it is very tricky to obtain a double layer with only one plasma source, but difficult to avoid it with two plasma sources at different potentials. In space there is a vast plasma source in the ionosphere, and the magnetospheric convection supplies plasma from the magnetotail to the auroral field lines, while simultaneously generating the necessary potential difference.

Critical electron drift velocity

It is well known from theories and computer simulation that formation and conservation of a DL requires that the electrons entering the DL on the low potential side have a minimum drift velocity of the order of the thermal electron velocity (see e.g. Block, 1972, 1978; Goertz and Joyce, 1975; Singh, 1980). This was also demonstrated experimentally by Baker et al. (1980). It is called the Bohm criterion (Bohm, 1949).

The exact value for the critical drift velocity depends on the particle velocity distributions on both sides of the layer. Kan and Lee (1980) show that it can be made arbitrarily small if sufficiently many trapped electrons with energies up to the DL potential drop exist on the high potential side. These electrons supply the necessary negative charge upon reflection near the negative DL boundary.

Due to the loss cone there is always a net downward drift velocity on geomagnetic field lines. Electron absorption at 130 km altitude causes a net downward drift velocity equal to the thermal velocity of an initially isotropic distribution just below 300 km, i.e. where Albert and Lindstrom (1970) claimed to have demonstrated the existence of three ~100 V DL. Any upward parallel electric field will enhance the chances for DL formation in two ways: both drift velocity and the energetic trapped population due to back-scattering will be enhanced. The latter effect will decrease the critical drift velocity (Kan and Lee, 1980). Hence, one DL could conceivably induce formation of an additional DL at higher potential, and so on. In other words, the available circuit voltage may well be shared by several layers in series (Block, 1972, cf. also the following section).

Lennartsson (1977) has considered this mechanism in rather great detail and proposed that the basic mechanism for production of parallel electric fields above the aurora is the magnetic mirror mechanism, but that when a current flows it is hardly possible to meet the quasi-neutrality condition everywhere. Hence, at least one DL must be formed somewhere. The mere existence of a magnetic mirror induced parallel field induces formation of one or more DL.

Particle velocity distributions

In the laboratory experiments made so far, no particular efforts have been made to realistically simulate the ionospheric and magnetospheric velocity distributions. In particular, no one has tried to inject a hot "plasma-sheet-like" plasma on the low potential side and a cool "ionosphere-like" plasma and energetic backscattered electrons on the high potential side. Even so, similarities have arisen, more or less by chance, as is discussed below.

The experiment by Baker et al. (1980) happens to provide an interesting example of another aspect, however. Fig. 2 shows the axial potential distribution in one of their layers along with the electron flux spectra before and after acceleration in the DL. The pronounced beam before acceleration is due to the sheath near the negative grid through which electrons (and ions) are injected. This is of course not realistic if we wish to simulate the normal plasma sheet. However, it is somewhat more similar to an already accelerated plasma sheet population. It has, in fact, been accelerated at the negative grid in the sheath, which from this point of view may be considered as another DL or any kind of parallel potential drop. Still, there are differences in the velocity distributions. As explained by Baker et al., the waterbag population at energies below that of the beam is due to ionization by the beam electrons between the sheath and the DL. Ionization is negligible thousands of km above the aurora. However, as will be explained in the section on potential distributions below, plasma may be injected below the highest, initially formed DL (corresponding to the sheath), and that plasma may act in the same way as the ionization in the laboratory, to create a potential plateau as a "platform" for the next DL. If that is correct, the experiment by Baker et al. supports the idea that there may be several layers in series on auroral field lines.

The plasmas injected on the low potential side in the experiments by Coakley et al. (1978) and Torvén and Lindberg (1980) were essentially Maxwellian, and in that respect they certainly simulate the plasma sheet rather well.

On the high potential side double-peaked spectra similar to auroral precipitation spectra have been observed in some experiments (Anderson et al., 1969; Coakley et al., 1978; Baker et al., 1980). The low energy peak, which is produced by local ionization and (in the case of Coakley et al. and Baker et al.) by a plasma source, may nevertheless contribute to the space charge in a way similar to the backscattered electrons seen in the auroral precipitation.

More experiments with different velocity distributions, separately controlled for injected electrons and ions on both sides of the DL are very desirable. Methods for backscattering or reflection of particles should also be used, e.g. magnetic mirrors.

Wave-emissions

As pointed out in an earlier section wave-particle interaction does not play a major role in the momentum balance, which determines the strength of the electric field. Whether that is true also in the auroral DL is a matter of controversy. No doubt, the beams produced by the DL must generate waves which are observed both in the laboratory and in space.

The experiment of Torvén and Lindberg (1980) provides a good example for comparisons. As shown in Fig. 3, the electron beam generates waves around the plasma frequency of 500 MHz in a spatially small region on the high potential side. The corresponding frequency spectrum covers about a decade in frequency. Phase velocity measurements showed that the power flow is from the electron beam to the waves. Nevertheless, the waves are damped out long before the beam, i.e. a plateau in the electron velocity distribution below the beam velocity is probably formed, such that wave generation ceases.

The VLF-emissions observed on auroral field lines may be of a similar nature provided the electron density at auroral DL is very low (< 10 cm^{-3}) as is indicated by the S3-3 results (Mozer et al., 1979). However, they are not damped out as quickly. The reason for the damping and associated strong spatial confinement in the laboratory may be the limited radial extent of the plasma.

The ion cyclotron waves observed on S3-3 have no counterpart in the experiments since the ions are not magnetized. The 50 kHz fluctuations seen by Torvén and Lindberg in the DL region but not outside may be associated with trapped ionosonic waves that cause fluctuations in the DL potential and position.

Wave measurements in large plasma chambers, even without magnetized ions, are urgently needed, to see how the damping of different kinds of waves depends on radial density gradients.

Finally we note that the laboratory experiments do not indicate any necessity for waves to maintain a DL, but that waves are inevitably produced as a secondary effect. Neither does the theory of DL or of any BGK (Bernstein, Greene, Kruskal, 1959) equilibrium potential structures require that, although the stability is not yet understood. The laboratory DL experiments indicate that, at least under many circumstances, a constant non-fluctuating supply of charges is sufficient for stability. However, in space a great variability in charged particle supply must be expected, and hence it would indeed be surprising to find non-fluctuating DL there.

Magnetic field

From the above discussion we have seen that the too weak magnetic field is perhaps the most important deficiency of the experiments. Without a magnetic field

(1) the particle beams are not well confined,
(2) cyclotron waves cannot be excited,
(3) the three-dimensional potential distribution must differ from that around auroral DL (cf. next section),

(4) magnetic mirror effects, important for the backscattering and trapping of energetic electrons that can contribute to the DL space charge balance, cannot be reproduced at all or must be replaced by other types of mirrors, e.g. electrostatic, which may influence the DL in other undesirable ways.

To produce strong magnetic fields in large plasma chambers is expensive. We may therefore have to wait a long time before DL with both magnetized ions and large radial extent can be studied.

Potential distribution

As has been already discussed, great progress has been made in the laboratory experiments to measure the 3-D potential distribution. In general, the radial field in laboratory discharges depends on the particle budget. The ion and electron losses in the radial direction differ by orders of magnitude, unless a radial electric field suppresses the dominant one and enhances the other. In the no magnetic field case the electron losses dominate, giving outward directed field as observed e.g. by Baker et al. (1980). With magnetized electrons, regardless of ion magnetization or not, the ion losses dominate and an inward electric field is necessary. Of course, the axial supply and losses have to be accounted for in order to determine the exact "turning pint" (cf. discussion in Baker et al., 1980).

This view is confirmed both by Baker et al. (1980) as is seen in Fig. 1, and by the observed fields in space. In the ionosphere radial particle losses are of course of no importance since the plasma is essentially infinitely extended in the radial (horizontal) direction. However, inward directed electric fields usually prevail anyhow, because of current continuity with the upward directed Birkeland current.

Not only the losses but also the supply of particles depends on the potential distribution. This aspect deserves some further discussion, since some erroneous arguments against parallel field acceleration have been put forward, namely

(1) all particles in a precipitation spectrum must have been accelerated through the entire potential drop,

(2) no net acceleration can occur since the particles cannot reach the high potential level without climbing the hill along the perpendicular electric field at high altitude.

The first argument presupposes no particle supply within the acceleration region. The second argument forgets that the particle supply is mainly along equipotentials, all of which can reach out to the solar wind. Besides, all generators lift up particles from low to high potential energy. There must be a generator in the circuit.

Figure 4 shows how it works. $\bar{E} \times \bar{B}$-drifting electrons in region 1 will fall through the entire parallel potential drop when they arrive above the arc. Electrons on equipotential surfaces in region 2, at altitudes corresponding to approximately the shaded area, will precipitate through part of the potential drop. The key is the indentations on the surfaces. Note that this also leads to a weaker ionospheric electric field within the arc than outside.

There must not necessarily be a perpendicular electric field reversal at the parallel field in the middle of the precipitation region. Displacement of the equipotentials sideways as shown in Fig. 5 also gives a similar effect with one or possibly two shocks with the same, rather than reversed perpendicular field, as sometimes observed on S3-3. Also in this case, a weakened southward or northward electric field will result in the arc.

A realistic model must also include an electric field component along the arc, since supply of particles at one end only would not suffice. It is easy to modify the potential distribution of Figures 4 and 5 accordingly, but difficult to make a good drawing of it.

4. Summary

Considerable progress in the understanding of DL has been achieved through recent laboratory studies. Many properties expected on auroral field lines have been reproduced:

(1) Two plasma sources at different potentials (ionosphere and magnetosphere) usually leads to formation of DL.

(2) A critical electron drift velocity is required on the low potential side. The loss cone will automatically lead to some finite drift velocity which can be enhanced by magnetic mirror induced fields. The critical drift requirement can be partly relaxed by backscattered or mirroring energetic electrons.

(3) The particle velocity distributions in the laboratory differ in some respects from those observed in space, but the electron

distributions after acceleration are rather similar to auroral precipitation spectra. Ionization processes play a role in the laboratory, but that may have similar effects on the charge distribution and precipitation spectra as the injection of plasma within the acceleration region, which must occur in space.

(4) Waves do not play an essential role (or no role at all) in maintaining a layer, as shown by a momentum balance analysis of electron flow spectra in the laboratory. Waves are, however, generated by the electron beam on the high potential side, but they do not destroy the beam. A broad wave spectrum, centered at the plasma frequency, is observed in the laboratory and may correspond to VLF emissions from the acceleration region above auroras.

(5) Experimental DL with magnetized electrons but not ions have been studied in the laboratory. They are formed under the same conditions as DL with zero magnetic field. Since the ions are unmagnetized, no ion cyclotron waves are found, in contrast to what is seen on the S3-3 satellite. The magnetized DL results lend themselves more easily to demonstration of true DL properties than those of non-magnetized DL in the laboratory.

(6) The 3-D potential distribution with U-shaped equipotentials, oriented as is observed above auroras, can only be produced in the laboratory with a magnetic field. The reason is understood to be associated with the particle budget. To balance perpendicular losses of electrons and ions, the electric field must be directed towards the center with, but away without a magnetic field.

The potentialities for further improvements in laboratory simulation of auroral DL are great. Good but incomplete wave measurements have been made in one experiment. Other experimenters have measured some particle spectra, but again with incomplete coverage. Stronger magnetic fields to magnetize the ions may be made within the near future but perhaps not in very large plasma chambers. More efforts should be made to separately control the velocity distributions of the different species, in order to better simulate plasma sheet and ionospheric plasmas, and to improve our understanding of the dependence of DL properties on the velocity distributions.

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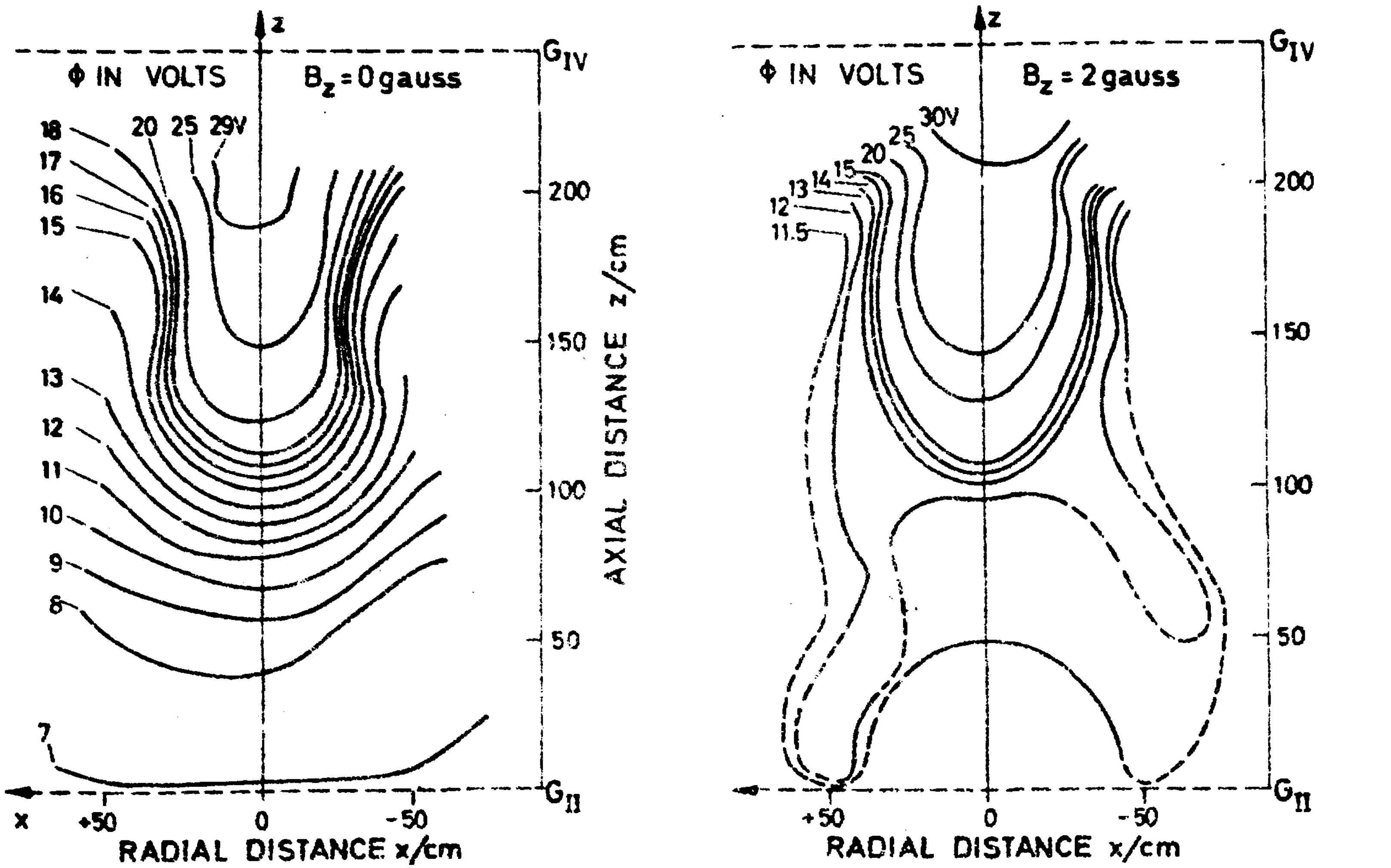

Fig. 1 Two-dimensional potential distributions in experiments by Baker et al. (1981): to the left with zero magnetic field and to the right with B = 2 gauss. Note that mostly the radial component is away from the central z-axis, thus reducing electron losses to the zero volt chamber walls. However, with 2 gauss field the radial E-field can partly turn towards the central axis.

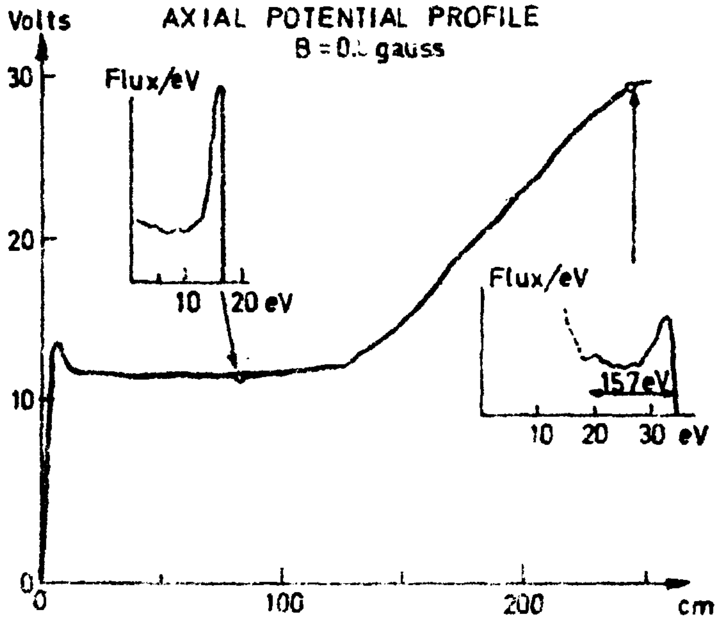

Fig. 2 Axial potential profile and energy distributions measured at indicated positions for the electron flux towards the positive plasma source before and after passage through the DL (Baker et al., 1981). The potential energy difference between the two spectra is 17.5 eV. The full curve part of the "After-spectrum" (17.5 - 34 eV) carries a momentum flux that is ~5.7 nN/m^2 larger than the "Before-spectrum"). Theoretically it should carry ~11.4 nN/m^2 more. Half of the missing 5.7 nN/m^2 can be attributed to binary collisions. The other half is shared in an unknown proportion between beam divergence and wave particle interaction. The dashed part of the "After--spectrum" is due to ionizing collisions within the DL. The ionization potential of Argon is 15.7 eV. The beam peak in the low potential spectrum is due to the sheath potential drop which in space may be equivalent to a DL at higher altitude. The DL at 130 - 250 cm thus proves that an already accelerated beam can induce a second DL.

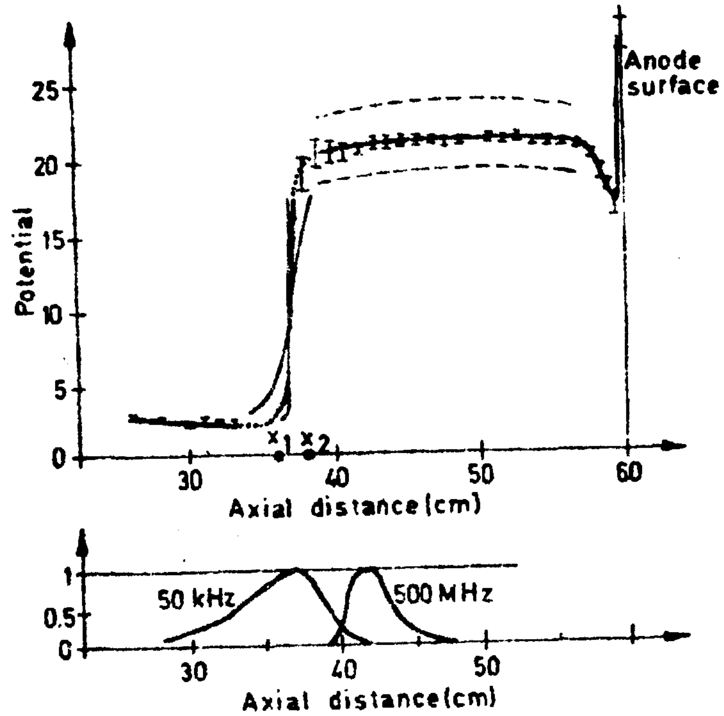

Fig. 3 Axial potential profile at the symmetry axis (upper diagram) with B = 50 gauss, in an experiment by Torvén and Lindberg (1980). The DL is situated between x_1 and x_2. The high potential level fluctuates between the two dashed levels, implying varying steepness of the potential curve within the DL, as indicated. This fluctuation, together with fluctuations back and forth in the x--direction with an amplitude of about the layer thickness, gives rise to a low frequency (50 kHz, bandwidth 8 kHz) spectrum with spatial distribution as shown by the left curve in the lower diagram. On the high potential side the electron beam generates waves propagating towards the anode, but damped out at 50 cm (500 MHz curve with spectrum extending from about 100 to 1000 MHz). However, the beam is essentially conserved up to the anode.

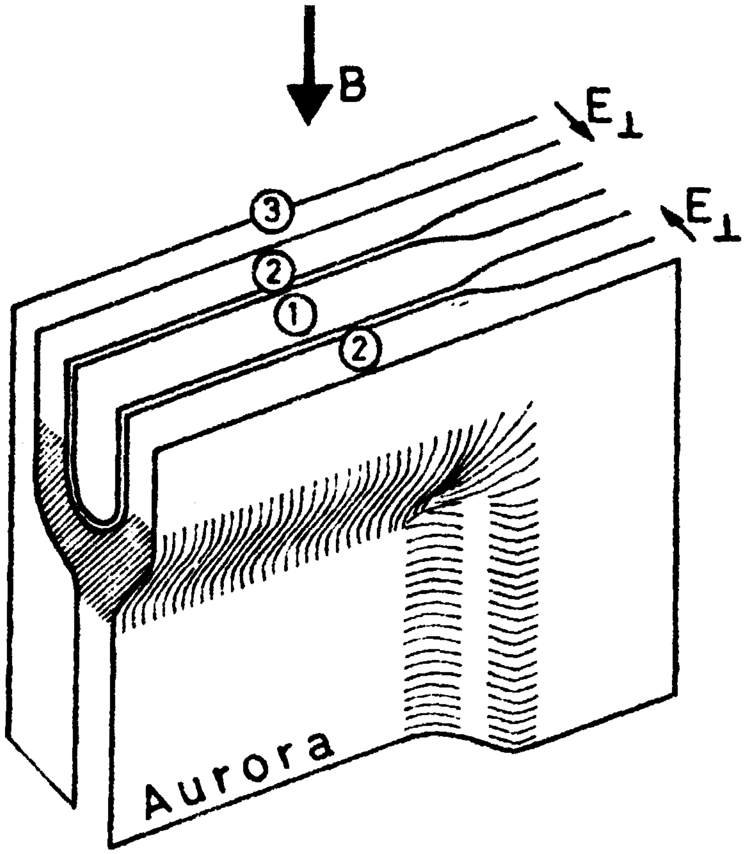

Fig. 4 Suggested equipotential surfaces above an auroral arc at a perpendicular electric field reversal. Electrons injected in region (1) will fall through the entir^ DL potential drop. Electrons drifting along surfaces in regions (2) at shaded altitudes will fall through part of the drop. Electrons on surface (3) will not see any parallel E-field.

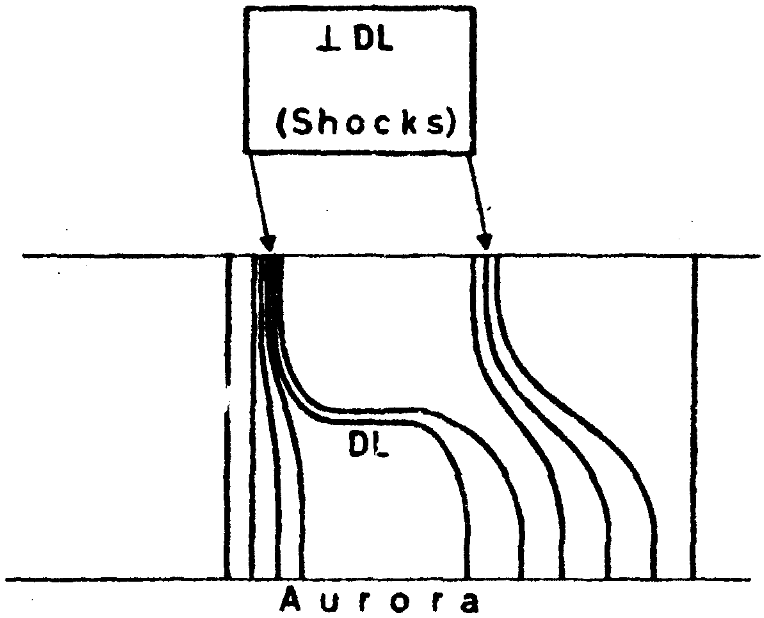

Fig. 5 Equipotential surfaces above an aurora with no perpendicular electric field reversal. Also in this case can electrons be injected sideways within the DL corresponding to the electrons formed through ionization in the experiment of Baker et al. (1981). C . Figure 2.

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DOUBLE LAYERS IN THE LABORATORY AND ABOVE THE AURORA

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Recent laboratory double layer experiments have simulated, much, better than before, the conditions prevailing on auroral field lines at high altitudes. In particular, magnetic fields strong enough to magnetize the electrons (but not quite the ions) have been used. Particle and wave spectra have been measured. Wave-particle interaction has been shown to play a minor role in the only case that has been quantitatively analyzed. The three-dimensional potential distribution has been mapped. The particle budget requires the radial electric field to be outward in the no magnetic field case but inward with magnetic field, in agreement with what is observed above the aurora.

Key words: Aurora, Double layer, Laboratory experiments, Magnetic field, Momentum flow, Particle velocity spectrum, Three-dimensional potential distribution, Wave-particle interaction.