Formation of Electrostatic Potential Barrier between Different Plasmas

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A potential depression is formed between two magnetized plasmas with different electron temperatures and ion species in the absence of electric current passing through them. The depression is deep enough to reflect both groups of electrons, reducing thermal contact between the plasmas. By addition of a magnetic bump to a uniform magnetic field, the potential dip is localized around the mirror point. A dependence of the phenomenon on neutral-gas pressure is also clarified.

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There has been an increasing interest in electrostatic potential formations along a magnetic field in conjunction with auroral particles[1] in space plasma and plasma confinement in open-ended fusion devices.[2] In a tandem-mirror system where a fusion plasma is expected to be confined in a central cell between end-plug mirror cells,[2] it is of crucial importance to know how to form a necessary potential configuration. In the TMX and Phaedrus experiments, the end loss of central-cell ions was reduced by the tandem potential.[3] To improve the reactor picture, however, there are advantages to having hot electrons in the end plugs.[4] As a possibility for maintaining two plasmas with different electron temperatures in two spatially separated regions, it has been proposed to form a potential depression between the two regions, which isolates the two groups of electrons from each other, acting as a thermal barrier.[4] As far as the auroral-particle acceleration is concerned, it is important to know the potential configuration in a contact region between a hot magnetospheric plasma and a cold ionospheric plasma.[5]

Here a potential depression is experimentally demonstrated to be formed between two plasmas with different electron temperatures and ion species. The result is obtained in the absence of any externally applied potential difference between (and electric current through) the plasmas. In this sense, the phenomenon is related to electric double layers without current in plasmas,[6] which cannot be realized in the works[7,8] on double layers with external voltage and/or current sources.

Two different plasmas are produced, respectively, at two ends in a straight 15.7-cm-diam stainless-steel vacuum chamber, as shown in Fig. 1. A Q-machine plasma[8] with density N_1 ($\lesssim 3\times10^9$ cm^{-3}), electron and ion temperatures T_{e10} and T_{i10} ($\lesssim T_{e10} \simeq 0.2$ eV), is produced by contact ionization of potassium atoms at a hot tantalum plate [source 1 (S_1)] under the electron-rich condition. The other plasma with density N_2 (10^8–10^9 cm^{-3}) is produced by an argon-gas discharge between mesh anode A and oxide cathode K [source 2 (S_2)] (the maintaining voltage between A and K is around 15 V). The separation between S_1 and S_2 is 200–300 cm. The argon gas is fed near K by keeping the gas pressure near S_2 in the range 1.5×10^{-4}–1.5×10^{-3} Torr. A differential pumping yields the pressure of 4.0×10^{-5}–8.0×10^{-4} Torr in the experimental region. The electron temperature of the discharge plasma, T_{e20} ($\simeq 2.0$ eV), is larger than T_{e10} by an order of magnitude, although the ion temperature T_{i20} is nearly equal to T_{i10}. The two plasmas of about 3.5 cm in diameter diffuse along a strong magnetic field B (1–4 kG) in opposite directions. Their plasma pressures near the sources are defined by $P_{10} = N_1 T_{10}$ $[= N_1(T_{e10} + T_{i10})]$ and $P_{20} = N_2 T_{20}$ $[= N_2(T_{e20} + T_{i20})]$ while their local pressures are defined by $P_1 = n_1 T_1$ $[= n_1(T_{e1} + T_{i1})]$ and $P_2 = n_2 T_2$ $[= n_2(T_{e2} + T_{i2})]$, respectively. A is grounded electrically together with the vacuum

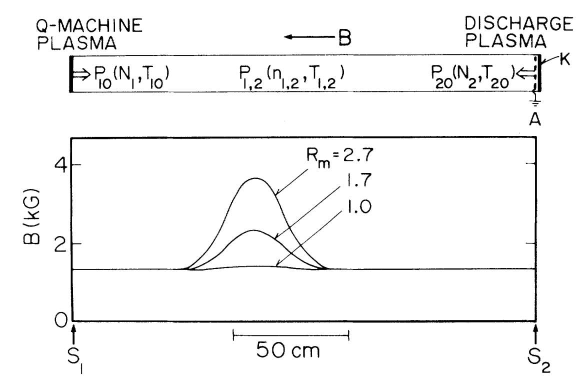

FIG. 1. Schematic of experimental device with two different plasma sources (S_1, S_2) and magnetic-field configuration B.

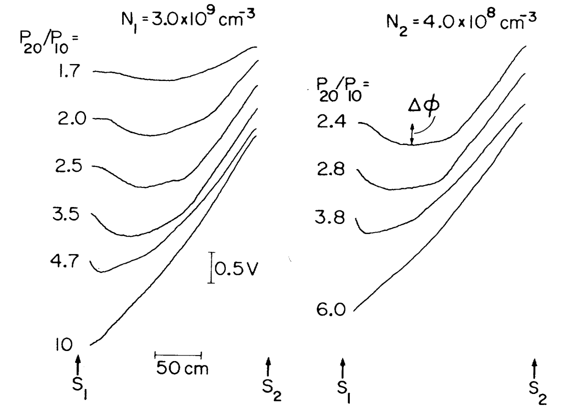

FIG. 2. Potential distributions along the plasma column for various ratios of the plasma pressures, P_{20}/P_{10}, at the sources with N_1 or N_2 kept constant under the uniform magnetic field. The argon-gas pressure is 2×10^{-4} Torr in the experimental region (8×10^{-4} Torr near S_2). The curves are shifted vertically one after another (the potential near S_2 is almost independent of P_{20}/P_{10}).

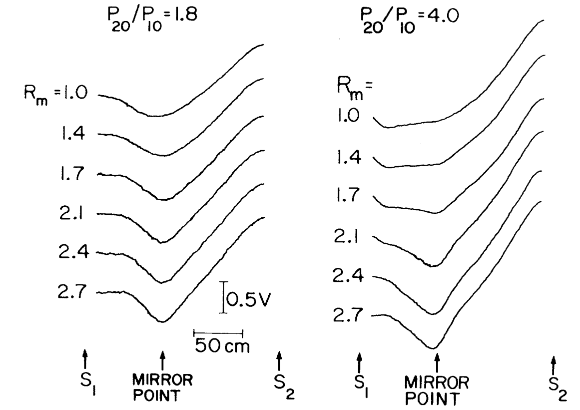

FIG. 3. Potential distributions in the presence of the magnetic bump with mirror ratio R_m at typical plasma-pressure ratios $P_{20}/P_{10}=1.8$ and 4.0. The argon-gas pressure is 2×10^{-4} Torr (8×10^{-4} Torr near S_2).

chamber to fix the potential of the discharge plasma. S_1 is kept at floating potential (there is no externally applied potential difference between S_1 and S_2). There is no net electric current along the plasma column. A local magnetic bump with mirror ratio R_m ($\lesssim 3.0$) can be produced between S_1 and S_2, as shown also in Fig. 1. The ion Larmor radius ($\lesssim 0.3$ cm) is much smaller than the plasma radius. The collision mean free paths between charged particles are longer than 50 cm. According to Brown's data book,[9] the mean free path of electrons is in the range 60–1200 cm while that of ions with neutral particles (including charge-exchange collisions) is in the range 10–200 cm under our conditions. The plasma potential φ is determined by axially movable emissive probes (spatial resolution $\simeq 1$ mm) and is checked by the Langmuir probe method.

First of all, measurements are performed on φ along the uniform magnetic field ($R_m=1$). When we have only the discharge plasma (S_1 is not heated), a monotonic decrease of φ towards S_1 is observed, as expected from ambipolar diffusion along the magnetic field. When S_1 is heated hot enough for plasma production, however, we can recognize an increase of φ near S_1. With an increase of plasma supply from S_1, a spatial region of this potential increase spreads towards S_2 and there appears a broad potential minimum along the plasma column. The position of this potential dip is controlled by changing the pressure ratio P_{20}/P_{10}, as presented in Fig. 2. The dip shifts towards S_1 when N_2 is increased with N_1 kept constant. The shift towards S_1 is also observed when N_1 is decreased with N_2 kept constant. The results imply that there might be a plasma-pressure balance between the two plasmas at the position where the negative dip is formed. By operation of only S_1 (S_2), the local plasma pressure P_1 (P_2) is measured at the position where the potential minimum could be observed under the operation of both S_1 and S_2. The measurements show that P_2/P_1 is approximately unity around the dip position. The depression depth is on the order of T_{e1}/e which is large enough to reflect most electrons supplied from S_1.

When a local magnetic bump is added to the uniform field, a potential change due to the magnetic mirror is observed near the mirror point even in the case of the monotonic potential variation under the uniform magnetic field. This change is enhanced under the condition where the broad negative dip is produced at $R_m=1$, as demonstrated in Fig. 3. With an increase in R_m, the potential dip becomes sharp and shifts towards the mirror point, showing an increase of the depression depth. The maximum depth, however, is $(1-3)T_{e1}/e$ in our range of R_m at any value of P_{20}/P_{10}.

In Fig. 4, a dependence of the potential shape on the argon-gas pressure is shown at $R_m=2.7$. As the pressure is decreased, the potential slope becomes small in the discharge plasma and the potential drop is much localized around the potential depression, resulting in a more remark-

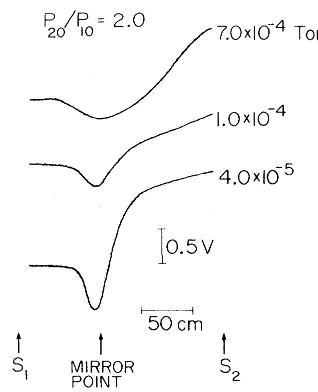

FIG. 4. Potential distributions at argon-gas pressures of 7×10^{-4} (9.5×10^{-4}), 1.0×10^{-4} (3.0×10^{-4}), and 4.0×10^{-5} (1.5×10^{-4}) Torr in the experimental region. The pressures near S_2 are given by the values in the parentheses. $R_m = 2.7$.

able feature of the phenomenon. At the pressure of 4.0×10^{-5} Torr, the ion collision mean path is about 200 cm, and thus the collisional effects can be neglected. The measured shape of the potential profile reminds us of the double layers with the potential dip on the low-potential tail.

As described above, the potential of the plasma supplied from S_1 is not fixed externally, but is determined by a contact with the plasma supplied from S_2, yielding the potential profile with the potential depression between the two plasmas. The phenomenon is enhanced at such a gas pressure where the collisions are neglected and there is no appreciable generation of fluctuations causing anomalous resistivity. Thus, Hultqvist's theory[5] for thermoelectric effect cannot be applied to this experiment. Under our potential configuration, both groups of electrons supplied from S_1 and S_2 are reflected by the potential decreasing towards the potential dip except for a small amount of high-energy tail electrons. Ions supplied from S_1 are reflected by the potential slope between the dip position and S_2. On the other hand, ions supplied from S_2 can pass through the potential dip towards S_1. The electric current due to these ions is compensated by the electric current due to the high-energy tail electrons, resulting in no net electric current passing through the plasma column. In fact, the tail electrons with energy of 4 eV are observed to pass through the dip towards S_1. Since the density is less than 1% of the bulk electrons in the discharge plasma, the energy transport [$\propto$ density $\times$(energy)$^{3/2}$] due to the tail electrons is negligibly small ($\lesssim 4\%$). The plasma density decreases towards the potential dip and the minimum appears at the same position as φ. The electron temperature increases slightly towards S_2, but an abrupt change is observed around the potential dip. The measured relation between the density and potential profiles is found to be consistent within an error of 20% with the prediction based on the Boltzmann relation.[10] In the presence of the magnetic bump, we must take into account the ion deceleration and reflection due to the magnetic mirror, which give rise to a change of the plasma density, resulting in the modification of the plasma potential. The density at the position of the maximum magnetic field is observed to decrease with an increase in R_m, being consistent with the localization of the potential depression at the magnetic bump.

In conclusion, the potential depression separates the two spatial regions with higher potential of the order of the corresponding electron temperature and isolates the two groups of electrons from each other, reducing thermal contact between the two plasmas. In the thermal-barrier variation of the tandem mirror,[4] this kind of thermal barrier has been expected to be formed by sloshing charged particles in a magnetic well.[11] Although our thermal barrier is localized at the mirror throat, the experiment shows an essential feature of thermal-barrier formation between two different plasmas. The result should correspond to a kind of the Bernstein-Greene-Kruskal solutions[12] of the Vlasov-Poisson equations including effects of magnetic mirror. Finally, it is to be noted that the potential depression observed is closely related to the negative potential dip formed on the low-potential tail of double layers.[8]

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