HIGH FREQUENCY PROBE MEASUREMENTS AND LOCAL BEAM-PLASMA INTERACTION NEAR DOUBLE LAYER

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The spatial distributions of high and low frequency fields were measured on the anode side of double layer. Measurements show that double layer is composed of a central region with a very sharp potential gradient surrounded by regions where ions and electrons entering the layer are accelerated. Low frequency field, which appears due to double layer motion and potential drop fluctuations in the layer, has a sharp maximum in the double layer region. The high frequency field has a broad maximum around the electron plasma frequency and it is localized in the anode plasma. Its maximum is displaced from the double layer to the high potential side, where electron beam is formed.

Distribution functions measured with the help of improved pair probe method showed that electron energy distribution is consisted of two parts: thermalized trapped electrons and beam part, which is formed passing through the double layer. Though electron beam rapidly losses its energy exciting high frequency field in the anode plasma, it does not become completely thermalized and preserves its directed character up to the anode surface.

Keywords: Double layer, Beam-Plasma interaction, High frequency field, Anode plasma.

1. INTRODUCTION

In number laboratory experiments the properties of double layer (DL) have been investigated in magnetized as well as in unmagnetized plasma [1.2.3]. However, little is known about the excitation of waves and fluctuations at a DL. In addition to possible instabilities associated with the spatial inhomogenity at the layer, interaction is expected between the surrounding plasma and the particle beams that are formed as the result of acceleration. Interesting questions are whether such interactions may lead to a strong modification of the DL structure, whether the electron beam breaks up and becomes completely thermalized within the anode plasma, and what fraction of the beam energy is converted to hf energy and ultimately radiated.

If the beam were completely thermalized the anode current would have the character of a random current, reduced by a Boltzmann factor corresponding to the potential minimum near the anode. The average depth of the fluctuating potential minimum is about 4V [1]. Probe measurements in the anode plasma indicate the electron temperature about 2 eV and density $3.10^{-15}m^{-3}$. A plasma with this density and temperature could only supply an anode current of a fourth or less of the actual current. The conclusion is that the electron beam does not become completely thermalized. The majority of the beam electrons make a single transit through the anode plasma to the anode.

In this paper results of experimental investigation of a DL in a magnetized plasma column on the anode side of the layer are reported. The spatial distributions and other important properties of the fluctuating electric field are presented for the high and low frequency waves. Electron energy distribution function have been studied with the help of improved pair probe method. Measurements show that the DL is composed of a central region with a very sharp potential gradient, surrounded by regions where ions and electrons entering the layer are accelerated. Though electron beam mainly losses its energy exciting hf field in the anode plasma, it preserves its directed character up to the anode surface.

2. THE DL FORMATION

The plasma column, which is confined by a homogeneous axial magnetic field, is obtained between the hollow electrode with inner diameter of 1.5 cm and the anode. The plasma source is a DC arc discharge between the mercury pool cathode and hollow electrode. The mercury vapor pressure in the vacuum chamber is kept at 0.1 mTor, which is about one order of magnitude smaller than the pressure in the plasma source.

The electron mean free path is much longer than the plasma column whereas the ion mean free path for charge exchange is estimated to 6 cm. In the current-free column the following parameter values are typical. The axial electric field is weak about 1 V/m and directed towards the anode. The electrons have a Maxwellian distribution with a temperature of about 2 eV. The ion energy can be estimated to be of the order of 0.1 eV. For the weak magnetic fields considered here, the ion gyro radius is larger than the column diameter, and a radial field confines the ions. The electron number density is of the order of $3\ 10^{15}\ m^{-3}$. This is also the typical electron number density on the low potential side of the formed DL.

When a sufficiently large electron current is drawn to the anode, an anode sheath depleted of ions is formed. The electrons in this sheath form a negative space charge and the anode potential rises to the value necessary to draw the actual electron current to the anode. When the potential difference between the anode and plasma exceeds the ionization potential of the gas, ionization begins in a thin sheath close to the anode, and electric field at the anode surface is expected to be reduced due to the space charge of the ions. When the current is further increased, the region with steep potential gradient moves further away from the anode and forms a DL. The layer can be placed at any desired distance from the anode by varying the anode current. The DL separates the cathode plasma from the anode plasma [4].

Number of axially and radial movable Langmuir probes have been used for potential, density and electron temperature determinations. The bandwidth of these probes is limited to about 200 kHz because of their rather large capacitance's to ground (100 pF).

Special methods have been used to overcome the difficulties caused by the fluctuations in the plasma, and to compensate for the inevitable disturbance of the plasma caused by the presence of the probes. A sampling technique has been used to select moments when the layer position and the potential drop over the layer assume fixed values.

The cathode plasma is quiescent but the potential of the anode plasma fluctuates almost coherently with the fluctuating potential drop across the double layer. Within the anode plasma the signals were found to be almost identical, independent of the probe positions, and the small delays between the probe potential fluctuations are consistent with propagation velocities of the order of the thermal electron velocity (10^6m/s) or larger.

Measurements of the spatial distributions for various frequencies confirm that the low frequency field assumes its maximum values in a region at the double layer, where it typically is an order of magnitude larger than in the surrounding plasmas. This is shown in figure 1a for a frequency of 50 kHz (bandwidth 8 kHz), and single- humped distributions like this one were found for frequencies larger than some tens of kHz. This suggests that the fluctuations in the layer profile are the dominating source for the electric field at these frequencies and that the axial layer motion manifests itself only in the width of the hump, which is a rough measure of the amplitude in the motion.

The radial electric field is directed inward in the cathode plasma but directed outward in the anode plasma. The equipotential lines, which are transverse to the magnetic field at the symmetry axis, tend to become parallel with the magnetic field at the plasma boundary. There is a radial expansion of the plasma column towards the anode. Most of this expansion seems to occur in a region at the DL.

The cathode plasma, which is maintained by the plasma source, provides the layer with reflected ions and free electrons, and random electron flux at the potential minimum ($x \approx x_0$, figure 1) determines the electron flux towards the layer and the discharge current.

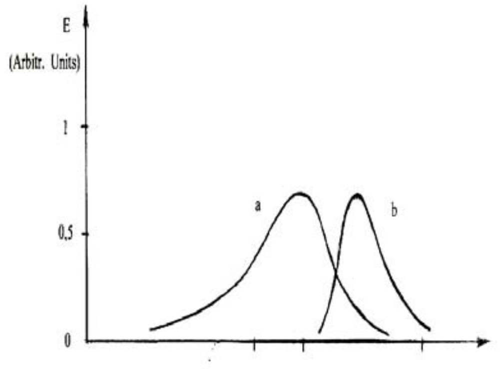

Fig.1. a) The spatial distribution of low frequency field for a frequency 50 kHz (bandwidth 8 kHz).
b) The spatial distribution of high frequency field, measured by a twin probe for a frequency of 500 MHz (bandwidth 3 MHz).

The acceleration of these electrons in the layer increases the probability of impact ionization by several orders of magnitude, and this process is the only source for positive ions in the anode plasma. The potential in the anode plasma assumes a flat maximum so that a potential well is formed for the electrons. Probe measurements show that the depth of the well, which is determined by the potential minimum in front of the anode, is at least 4 V, but it may be deeper. Although the electron mean free path is much longer than the length of the plasma column, elastic and inelastic collisions between electrons and atoms can accordingly build up a trapped electron population, which gives reflected electrons at the layer. Thus both free and reflected ions and electrons are present at the layer.

It can also be argued that the DL is strong, that is, the particle energies gained by accelerating in the layer (18 V) are much larger than the energies of the particles when they enter the layer. Electrons in the cathode plasma are Maxwellian-distributed with a temperature of 2eV. Accordingly the distribution function of the electrons, that enter the layer at the potential minimum, can be approximated by a half-Maxwellian distribution with this temperature. The fast ions, that have been accelerated in the DL, are lost in the cathode plasma by charge transfer collisions. The energy of ions moving towards the layer in the cathode plasma is therefore determined mainly by the mean free path for charge transfer collisions and the weak axial field there, which is directed towards the layer for $x<x_0$. The average energy can be estimated to be about 0-5 eV. In the anode plasma the initial energy of the ions, when they are formed by impact ionization, is negligible, and the maximum ion energy is limited by the passed potential difference. The energy of the trapped electrons in the anode plasma is limited by the depth of the potential well there; that is, the potential difference between this point and the point at the potential minimum in front of the anode.

3. HIGH FREQUENCY FIELDS AND BEAM – PLASMA INTERACTION

The electron distribution function on the high potential side of the double layer may be strongly modified due to beam-plasma interaction. A first evidence of this interaction is a high frequency field with frequencies of the order of the plasma frequency. The conditions on the high potential side of the DL are similar to those prevailing in front of the cathode sheath in hot-cathode, low pressure discharges, and in that case a large number of investigations of the high frequency field and the energy dispersion of electron beam have been presented [5]. Here the high frequency field existence on the high potential side of the DL and its properties with earlier investigations were demonstrated. Accordingly the same group of problems appearing in beam-plasma interaction should also be of importance for the understanding of a DL phenomenon.

Specially developed twin probes were used in the measurements for the following reasons. A single coaxial cable with the inner conductor as a probe tip would measure the difference between the potential of the tip and badly defined potential of the outer conductor, because this has usually to be grounded at some point several wavelengths from the plasma volume. In particular, this potential would depend on the way in which the cable enters the plasma, and correlation measurements with two probes would become erroneous. The twin probe consists of two thin parallel cables with the inner conductor protruding 2 mm into the plasma. The outer conductors are carefully joined near the probe tips, and therefore have a common potential. This unknown potential is eliminated by forming the difference of the signals in a hybrid tee. All cables are carefully terminated in the receiving end to avoid standing waves. The HF power is measured with a spectrum analyzer with 3 MHz HF bandwidth and 3 Hz LF bandwidth. All measurements are thus time-averages over periods that are long compared with the periods of the low frequency fluctuations.

The spatial distribution of the power level associated with the HF field, measured by a twin probe, is shown in figure 1b for a frequency of 500 MHz. It is a single hump in the anode plasma with a remarkably sharp maximum displaced about 100 Debye lengths from the DL. Similar distributions were found for frequencies between 300 and 700 MHz.

The power spectrum, shown in figure 1b, has a maximum in the vicinity of the plasma frequency. However, since the diagram represents time-averaged values, any possible fine structure is probably wiped out by the low frequency fluctuations. Errors due to the frequency-dependent coupling between the probe and the plasma also distort such diagrams.

Improved sampling and signal averaging technique has allowed refined probe measurements. Pairs of thin rod-shaped probes (Ø 0.2mm, ℓ =5mm), one rod parallel to the beam, the other transverse, have been used. The parallel probe exhibits only its small end surface to a parallel flow while the perpendicular one shows a hulf – cylindrical. Total areas of two probes were equal and currents of thermal electrons of both probes should be identical. Difference of currents $J_\perp - J_{II}$ provides a rough method to distinguish beam electrons. Thus $\frac{d}{dV}(J_\perp - J_{II})$ represents directed part of electron energy distribution function. In fig 2 is shown $\frac{d}{dV}(J_\perp - J_{II})$ versus V measured at different distances of DL. To eliminate hysteresis the curve 2a is measured in both direction of change of ramping potential. Near the DL (fig 2a) $\frac{d}{dV}(J_\perp - J_{II})$ shows a sharp peak according to the beam electrons accelerated in DL. This is an unstable situation and leads to hf – generation. Further downstream this peak diminishes and gradually disappears, though directed character of distribution function preserves in the course of whole anode plasmas.

Pair collisions cannot explain the strong energy exchange, obtained from the comparison of curves a, b, c, d in fig 2, as the mean free path of electrons is much longer than the plasma column length. The rapid loss of energy of electrons, accelerated through the DL can be explained by the conversion of this energy to the *hf* field generation. These oscillations having noise character with the wide spectrum exists in the measured curves. It should be noted that in this method the errors connected with the plasma potential oscillations eliminated since potentials of both probes change identically.

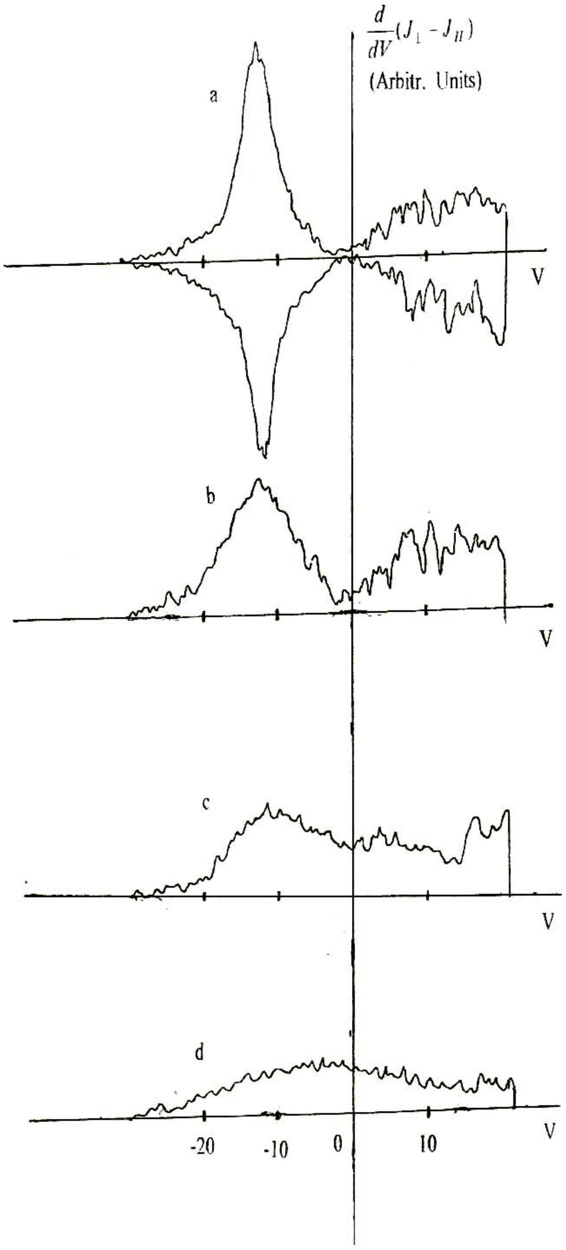

Fig.2. Measured $\frac{d}{dV}(J_\perp - J_{II})$ at different distances from the DL: a) 0,5 cm; b) 2 cm; c) 6 cm; d) 12 cm.

4. CONCLUSIONS

The double layer investigated is associated with low frequency and high frequency field fluctuations. Low frequency field is partly due to an axial layer motion back and forth and partly due to potential fluctuations in the layer. It has a sharp maximum in the double layer region. The high frequency field, which has a broad maximum around the electron plasma frequency, is also sharply localized in space. It has its maximum displaced from the double layer on the high potential side where an electron beam is formed. It is associated with axially propagating waves with a phase velocity that is nearly constant over a wide range of frequencies and rather smaller than the electron beam velocity.

Electron energy distribution is consisted of sum of thermalized trapped part and beam part, which is formed passing through the double layer. The measurements performed with the help of twin probes showed that beam electrons rapidly loss their energy exciting high frequency field. If the beam were completely thermalized, plasma with actual density and temperate could not supply an anode current. Consequently though electron beam mainly losses its energy exciting *hf* field in the anode plasma, it does not become completely thermalized and preserves its directed character up to the anode surface. The majority of the beam electrons make a single transit through the anode plasma to the anode.

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İKİQAT TƏBƏQƏ YAXINLIĞINDA YÜKSƏK TEZLİKLİ ZOND ÖLÇMƏLƏRİ VƏ DƏSTƏ-PLAZMA QARŞILIQLI TƏSİRİ

Plazmada ikiqat elektrik təbəqəsindən anod tərəfdə yüksək- və alçaq tezlikli elektrik sahələrinin intensivliklərinin fəzada paylanması ölçülmüşdür. Ölçmələr göstərdi ki, ikiqat təbəqə potensialın çox kəskin dəyişdiyi mərkəzi hissədən və onu əhatə edən, elektron və ionların ilkin sürətləndiyi, ətraf oblastlardan təşkil olunub. Alçaq tezlikli sahənin amplitudu ikiqat təbəqə oblastında kəskin maksimuma malikdir. Bu sahə əsasən ikiqat təbəqənin bütövlükdə fluktuasiya xarakterli hərəkəti və potensialın profilinin dəyişməsi ilə əlaqədardır. Yüksək tezlikli sahə plazmanın elektron tezliyi yaxınlığında geniş maksimuma malikdir və ikiqat təbəqədən yüksək potensial tərəfdə, elektron dəstəsinin formalaşdığı oblastda, lokallaşmışdır.

Paylanma funksiyasının təkmilləşmiş iki zond üsulu ilə ölçülməsi göstərdi ki, elektronların enerciyə görə paylanma funksiyası iki hissədən təşkil olunub:

1. Demək olar ki, izotrop paylanmış istilik elektronlarına uyğun hissə; 2. İkiqat təbəqədən keçərkən sürətlənərək dəstə təşkil edən istiqamətlənmiş hissə. Elektron dəstəsinin anod plazmasında yüksək tezlikli rəqslər həyəjanlaşdırması hesabına öz enercisini sürətlə itirməsinə baxmayaraq paylanma funksiyası tam izotrop olmur, və özünün istiqamətlənmiş xarakterini bütün anod plazması boyunja saxlayır.

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ВЫСОКОЧАСТОТНЫЕ ЗОНДОВЫЕ ИЗМЕРЕНИЯ И ЛОКАЛЬНОЕ ПУЧКОВО-ПЛАЗМЕННОЕ ВЗАИМОДЕЙСТВИЕ ВБЛИЗИ ДВОЙНОГО СЛОЯ

Измерены пространственные распределения высоко- и низкочастотных полей на анодной стороне от двойного электрического слоя. Измерения показали, что двойной слой состоит из центральной части с очень резким скачком потенциала, окруженной областями в которых электроны и ионы предварительно ускоряются. Амплитуда низкочастотного поля, возникающего в результате продольных флуктуационных перемещений двойного слоя и изменений профиля потенциала, имеет резкий максимум в области слоев. Высокочастотное поле имеет широк ий максимум вблизи электронной плазменной частоты и локализовано в анодной плазме. Его максимум несколько смещен от двойного слоя в сторону высокого потенциала, где формируется электронный пучок.

Измерения функции распределения усовершенствованным методом двух зондов показали, что функция распределения электронов состоит из двух частей: 1. Соответствующая запертым тепловым электронам и 2. Пучковой части, формирующейся при прохождении пролетных электронов через двойной слой. Хотя электронный пучок быстро теряет энергию в анодной плазме на возбуждение высокочастотного поля, распределение электронов полностью не термализуется, и сохраняет направленный характер вплоть до поверхности анода.

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