ENERGY BALANCE AND ROLE OF WALLS IN ACDE

*V.I. Baranov, Yu.S. Nazarenko, V.A. Petrosov**,
A.I. Vasin, Yu.M. Yashnov

Keldysh Research Center
Moscow, Russia

Abstract

In the paper the new ideas were developed, which brighten up some vague places in understanding of the processes in plasma of the ACDE acceleration channel. The energy balance of electrons and near wall processes were investigated and the close link between them was shown. It is established that the electrons temperature is essentially anisotropic and its value depends on the secondary emission properties of the channel walls. The formula for the electrons collisions with walls was obtained and the latter take essential part in the full electrons conductivity in the acceleration zone. The mechanism of the acceleration zone formation was shown.

Nomenclature

- U - discharge voltage;
- M, m - ion and electron mass;
- E_{1i} - energy cost of ion;
- I - full axial current;
- G - mass flow;
- n - density of charged particles;
- V, T - axial velocity and temperature of electrons;
- ν_{ee} - frequency of electron;
- Ω - Larmour frequency of electrons;
- ε_1 - first threshold of electrons reproduction on a wall;
- ν_w - frequency of electrons collisions with walls;
- $V_{e\parallel}$, $V_{i\parallel}$ - average velocities of electrons and ions along magnetic field;
- E, B - electric and magnetic fields;
- φ_w - near wall potential;
- $T_\perp$, $T_\parallel$ - temperature components along and across magnetic field;
- b - distance between walls of the channel;
- T_i - ion temperature;
- V_{Dr} - electron drift velocity;
- ν - total frequency of electrons collisions;
- ν_1, ν_2 - frequencies of elastic and nonelastic collisions;
- e - electron charge;
- c - velocity of light;
- L - length of acceleration zone.

Introduction

In the paper the questions concerned mainly to an electron energy balance in accelerators with closed electron drift and an extended zone of acceleration (ACDE) are investigated. The knowledge of properties of an electron component is very important, as just it determines the main parameters of plasma in the channel of an accelerator. Dynamics of electrons was investigated in many articles[1-3], nevertheless lot of questions is not decided yet. For example, until now there are no methods of account or estimation of electron temperature T, its value is taken usually only from experimental measurements.

As to energy of ions, in the first approximation it is possible to consider, that they simply increase directed velocity in a longitudinal electric field E, for what, properly, the accelerator is intended, and their temperature does not rise of above several units of eV, that makes a small part from their finite energy (~ 250 eV).

Energy Exchange Processes

Ions

Smallness of ion temperature can be simply explained if we take into account only ion heating because of collisions electrons and ions, as the large difference of masses between an ion M and electron m considerably magnifies the energy transmission time (in $[M/m]^{1/2}$ times). However, in plasma of ACDE the oscillations of different types always presents, in which ions can participate. Therefore the ions can be heated because of oscillations. Analytically to estimate this heating is not simply, but the answer to this question can be received from experiment. In the reports [4,5] with the help of spectroscopic measurements was shown, that temperature of ions at the exit from the acceleration zone does not exceed some units of eV.

Electrons in the acceleration zone

In the acceleration zone electrons, which are going from the cathode to the anode and ensuring neutrality of ion stream and also ionization of atoms, pass a potential difference ~ 250 V (that is almost discharge voltage U=300 V). As temperature of electrons in the channel ACDE obtained from measurements is at a level 20-30 eV, a natural

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question occurs - where electrons cast off others 220-230 eV of its energy? Such channels can be only three:

1) heating of ions;

2) ionization and radiation in spectral lines;

3) heating of the channel walls.

Let's analyze each of them. In view of a smallness of ion temperature it is possible to consider that energy exchange between electron and ions is small, that is the first channel is unessential. The ionization and radiation losses can be calculated if we know the ion cost. For Xenon the ion cost makes E_{1i} =25-30 eV (look [6]), obviously it includes also losses on radiation in linear spectrum. In the articles [1,7] it was supposed, that the average energy of ions at the exit of an accelerator was about 80-100 eV at a discharge voltage U ~ 220 B. In this case it is possible to say about the double (repeated) average ionization of each ion in the acceleration zone (that is, ionization then recombination and again ionization). The process of acceleration is not so effective, as the essential part again born ions passes only part of acceleration zone.

However, in modern type engines (for example, T-100, T-160 [8]) the average energy of ions is much higher ~ 250 eV and is commensurable with discharge voltage (U ~ 300 V), that is it is necessary to say already about single on the average ionization, as, practically, all ions pass a layer of acceleration from a beginning up to the end without recombination. Knowing of the full current I and the mass flow G let us to estimate the electron current, it usually makes from a half up to one third of the ion current. It means, that on one electron passed through the acceleration zone it is necessary from two up to three ions, which have taken off from an accelerator. In other words, on one electron it is necessary no more than three acts of ionization, that is, in the sum no more than 100 eV. Let's mark, that the ionization of plasma stream occurs mainly in the ionization zone before than ions come into acceleration zone, where the main falling of applied voltage is concentrated. The carry of energy necessary for ionization (~ 100eV), from a layer of acceleration in a zone of ionization can occur to mass stream of electrons (~ nVT) and by means of an electron thermal conduction (~ $T\nu_{ee}nT'/m\Omega^2$). Estimations and accounts show, that these streams are commensurable on the value. Then necessary minimum of temperature on boundary of zones of ionization and acceleration should be at a level ~ 50 eV. However measured in experiments electron temperature makes ~ 20-30 eV. How this mismatch disappeared we shall show some later. For now we shall mark most important in this moment result - without existence of significant downthrow of the electron energy immediately on walls of the channel it is impossible to explain rather low temperatures of electrons in ACDE, which are watched in experiments. Really, in the acceleration layer electrons take ~ 250 eV, and carry out in the ionization zone not more than ~ 100eV, that is other energy can be cast off only on walls, as the ions remain cold.

Thus, from three enough reliable experimental facts: 1. The electrons temperature is rather low (T < 50 eV); 2. the temperature of ions is insignificant (units of eV) in compare with discharge voltage (U ~ 300eV); 3. the average energy of directed motion of ions is close to discharge voltage - follows, that in modern ACDE such mode of operations are realized, at which in the acceleration zone the intensive downthrow of electrons energy on walls of the channel take place. As a consequence, it leads, certainly, to originating of the high electron conductivity because of the electrons collisions with walls, that is, to so-called near wall conductivity.

Near Wall Processes

Now we discuss more detail the interaction of electrons with walls. Let's estimate energy, which electrons cast off on walls in case of neglect by secondary electronic emission (SEE). In this case the stream of electrons on walls is equal to stream of ions. The stream of ions on walls we can estimate, at first, through temperature of ions. It approximately is less on two order than energy of directed motion of ions, that is, the velocity of ions in a direction to walls is less on the one order than axial directed velocity . And as width of the channel and length of a layer of acceleration are commensurable (~ 1 cm), approximately the one tenth part of full ions stream reaches the walls. The second way of an estimation of ion stream on walls, in which the total mass flow and mass blown from walls owing to erosion are compared gives the same result. As the ion current is in 2-3 times more than electron one, the stream of electrons on walls will make (20-30) % from axial electron stream through the acceleration layer. The losses of energy in electron collisions with walls are the sum of theirs temperature T = 50 eV (temperature of a wall is neglected) and cost of an ion E_{1i} = 25-30 eV, then on the average each electron will lose in the acceleration zone on walls no more than (0,2-0,3)·(50+30)=25 eV. Earlier we have received that this value should be much greater (~ 150 eV), this mismatch results in the necessity of taking into account the processes of SEE by consideration the near wall processes in the acceleration zone of ACDE.

As was shown in the paper [9], the dependence of the near wall potential φ_w from electrons temperature T for maxwellian distributions has threshold character, that is, poorly depends from T if T < ε_1, and sharply drops to zero if T $\rightarrow$ ε_1, where ε_1 - the first threshold of reproduction of electrons for a material of a wall. The similar behaviour of the near wall potential is watched for closer to reality non-maxwellian energy distributions of electrons (look [10]), this fact have been confirmed by the numerical accounts of the near wall potential for these distributions. The threshold dependence of the near wall potential from T results in that the substantial growth of electrons stream on a wall is possible only if T is close to the first threshold of reproduction of electrons $T \rightarrow \varepsilon_I$.

Electron Collisions Frequency With Walls

The numerous theoretical researches of near wall conductivity (look, for example, [2] and quoted there literature) have not reduced in real concrete results, in main, because of they were founded on incorrect source assumptions. For example, it was supposed, that the main role in near wall conductivity plays the electrons elastic collisions with walls, in reality, as we have shown above, - inelastic. The attempts to receive a unusual electrons distribution function, watched in experiments, using the scattering properties of the channel walls have not resulted in anything too. In the paper [10] we have shown, that this specific electrons distribution function arises owing to certain conditions in plasma volume (presence of the crossed magnetic and electric fields, rear density of plasma etc.), and the walls are necessary only as the reservoir for downthrow of electrons energy.

For taking into account the near wall conductivity in different estimations and accounts it is necessary to have the expression for the effective electrons collisions frequency with a wall ν_w. Let's receive this expression, basing on following rather transparent in physical sense formula

$$\nu_w = \frac{V_{eII}}{b}\exp(-\frac{\varphi_w}{T_{II}}) \tag{1}$$

here b - distance between walls of the channel, V_{eII} - the average velocity of electrons along a magnetic field B, φ_w - the near wall potential, T_{II} - the part of a kinetic electrons energy for motion along a field B. In (1) b/ V_{eII} - time of electron motion between walls, and the factor exp $(-\varphi_w/T_{II})$ takes into account collisions immediately with a wall, instead of with the near wall barrier. For the value φ_w we use expression, obtained in [9]

$$\frac{\varphi_w}{T_{II}} = \frac{1}{2}\ln(\frac{MT_{II}}{mT_i}) + \ln(1 - \frac{T_{II} + T_{\perp}}{\varepsilon_1}) \tag{2}$$

It is obtained for maxwellian electrons distribution, however, as we already have noted earlier, the true dependence φ_w from T_{II} has the same «threshold» character, therefore for the near wall potential it is possible to use expression (2). Taking into account the expressions (2) we receive from (1) the following result (we supposed here that $T < \varepsilon_I$)

$$\nu_w = \frac{V_{iII}}{b}\frac{1}{1 - T/\varepsilon_1} \tag{3}$$

where V_{iII} - the average velocity of ions in the direction to a wall. From (1), (3) we can immediately see, that depending on electrons temperature T, the collisions frequency with a wall ν_w can vary on ~ 3 orders: (at $T \ll \varepsilon_I$ $\nu_w \rightarrow V_{iII}/b$, and at $T \rightarrow \varepsilon_I$ $\nu_w \rightarrow V_{eII}/b$). Earlier we have shown, that in the acceleration zone of ACDE $T \rightarrow \varepsilon_I$, now we shall estimate how close T and ε_I are. For this purpose we shall attract in addition to (3) known expression for the electron velocity V along a field E when it moves in the crossed fields B, E

$$V = c\frac{E}{B}\frac{\nu}{\Omega} = V_{Dr}\frac{\nu}{\Omega} \tag{4}$$

where V_{Dr} - the drift velocity of electrons. Further it is natural to assume, that the electrons collisions with walls bring in the essential contribution to the total frequency of electrons collisions ν, that is, $\nu_w \approx \nu$. If we take into account already noted earlier facts, that the electron current makes usually (30-50)% from ion, and the ion current on walls is equal ~10% from a longitudinal ion current, from (3) and (4) we can obtain

$$1 - \frac{T}{\varepsilon_1} = \frac{1}{(3-5)}\frac{V_{Dr}}{b\Omega} \tag{5}$$

Substituting in (5) characteristic values $V_{Dr} = 2\cdot10^8$ cm/c, $\Omega = 2\cdot10^9$ c^{-1}, b = 1.5 cm, we obtain, that in modern ACDE temperature of electrons in the acceleration layer is rather close to ε_I - energy of the first threshold of electrons reproduction for a material of the channel wall, differing from it on units of percents.

Negative Near Wall Barrier For Electrons

It is curious, that at $T = \varepsilon_I$ the near wall conductivity can supply in some times greater longitudinal (axial) electron current (see expression (1)), than it takes place in a reality. This implies, that the value of an electron current is not limited, as they believed earlier, by only the resistance of the acceleration layer , where the transversal magnetic field has maximum, but is determined by the total resistance of the discharge interval.

So we have received, that temperature of electrons in a layer of acceleration is rather close to ε_I, the question arises whether it can exceed ε_I. Basically such situation can arise owing to inhomogeneous (in sense of secondary electronic emission) properties of walls of the channel.

If $T > \varepsilon_I$ the near wall barrier for electrons becomes negative, that is, it accelerates electrons in the direction to the wall. It is easy to see, that the transition of the value of the near wall potential φ_w through a zero point creates an unstable situation - more the energy of falling on the wall electrons, more of them leaves a wall and goes in plasma volume. That is, the positive charge of a wall will grow and accordingly the value of the negative barrier also will be magnified. However, this growth has upper limit - the temperature of electrons in plasma, that is, if the value of the barrier becomes more than T, then secondary electrons will have not energy for overcoming the barrier in the opposite direction. The real value of a barrier will be certainly less than T, as the share of inelastic collisions with a wall is rather significant than elastic.

Let's analyze how the presence of a zone with the negative near wall barrier for electrons will affect operation of an accelerator in whole. Even the small stain will sharply magnify the number of the electrons collisions with walls and accordingly the local longitudinal conductivity of plasma, and also heating of a wall in this place, and as a consequence the characteristics of the accelerator naturally will worsen.

We have not while direct experimental confirmations of existence in ACDE of modes with the negative near wall barrier for electrons, but the indirect data allow us with a large share of reliability to maintain, that such modes already have met during tests. The main reason of originating of such modes in practice is the presence of ions-of other materials in plasma and their concretion on walls of the acceleration channel. The ions concretion does not arise in that part of the channel, where the Xenon ion stream on walls has enough energy to bring down from a surface atoms of another materials, which came from volume. But, in these places, where energy of ions is smaller (beginning of a zone of acceleration and zone of ionization), surface films can occur, and as a result the secondary emission properties of a surface vary. In conditions without films when the emissive properties of walls are fixed, the temperature of electrons drops in accordance with their movement through a zone of ionization to the anode and accordingly the electrons collisions frequency with walls diminishes too. However, in case of originating such film, which diminishes the value ε_1, there can be an area with $T > \varepsilon_1$, and then the electrons stream on a wall is sharply magnified in some times.

The experiments with engines T-100 and T-160 have shown, that there were such modes of operation, at which on ceramics inside the channel the flashing ring originated, and the efficiency of acceleration is reduced. And, on the same modes of operation (identical powers and mass flows) in one vacuum chamber the flashing ring arose, and in another was not present. Note that vacuum chambers had various pumps, materials of walls, etc., it is natural therefore to assume that structure of dust substance in different cameras was various. It is very probably, that the flashing ring is just the area, where $T > \varepsilon_1$ and the mode with the negative near wall barrier for electrons is realized.

Thus, during the ACDE tests it is necessary to take into consideration, that dusting of walls of the acceleration channel originating because of a specific atmosphere in the vacuum chamber, can considerably distort the characteristics of an accelerator.

Anisotropy Of Electrons Temperature

During movement electrons in crossed fields E, B only component along E (or transversal to B) of electrons velocity grows. The transmission of energy in parallel to B component occurs after collisions with other corpuscles. The electron collisions frequencies with alternate corpuscles are less than a collision frequency with a wall, that means the presence of an anisotropy on energy for electrons $T_\perp > T_{II}$ in plasma. Realizing complexity of introduction of concept of temperature for non-maxwellian distribution functions we under term temperature shall mean the full kinetic electron energy $T = T_\perp + T_{II}$ (on the other hand if to consider, that temperature characterizes only random energy, it is possible to understand temperature as the total electron energy minus energy of directed motion, however it only question of a terminology, which does not influence an essence of matter). Distinction between longitudinal and transversal temperatures is especially strong at the end of the acceleration layer (that is, closer to the cathode), while in the beginning of the acceleration layer, where electrons quit from a strong field E, the anisotropy practically fades, as the collisions frequencies between alternate corpuscles become dominating compared with wall collisions.

Until now, as far as we know, temperature in ACDE was not considered as anisotropic. The importance of taking into account of the electron temperature anisotropy can be explained even on an example of measurement of the temperature by probes. If the surface of the plane probe is oriented along the wall of the channel, that takes place when the probe is built in a wall, only T_{II} is measured, which can be significant less than full temperature. If the surface of the probe is oriented towards to stream, the probe measures $T_\perp$ minus energy of the drift motion, which can be far from the total electron energy too. Now it is clear, that the mismatch between the predicted by theory energy (temperature) of electrons (~ 50 eV) and measured by probes (~ 20-30 eV) only seemed effect, it arises from incorrect treatment of probe measurements results, if the anisotropy of temperature is not taken into account.

Closed Set Of Plasma Dynamics Equations

The number of works was devoted to simulation of plasma flow in the ACDE channel, however, their results were not quite satisfactory, mainly because of the physical essence of occurring processes has been not opened yet. Therefore some accounts were partly based on measurement results (for example, in[11], where the field E was supposed as known), in others many simplifications were brought in and as a result in the solution the features, which are characteristic just for ACDE, were lost (look [12]).

It seemed, that the most full simulation was carried out in[13], however, at setting the task is missed the essential link - the interaction electrons with walls with taking into account the secondary electronic emission. In result the calculated characteristics were far from real, especially the distribution of the potential - the acceleration zone has turned out considerably more than real one.

In the present report it was possible to open and to understand many earlier vague details in a picture of main physical processes in ACDE plasma. In result there was a possibility to develop the self-consentaneous closed model of plasma acceleration in the channel. Here we have not possibility to describe in detail a set of equations, way of its solution, and also to carry out the detail analysis of results, it is a theme of separate work. Some results of accounts are published in [14]. It is most valuable for us that the results well coincide with real parameters in whole, and not only separately taken characteristics. It signifies, that the constructed model is adequate to real processes.

Creation Of The Acceleration Layer

The developed above new physical ideas about processes in the channel of ACDE allow to understand besides of others the mechanism of creation of the acceleration layer, that is, to explain rather unusual distribution of E field along the channel, which is characteristic for accelerators of this type. The fact that the magnetic field defines the form of electrical one was clear before. For example, it is obvious, that the surfaces of equal potential of the electric field should settle down along magnetic power lines (with accuracy up to the gradient of electron pressure), as electron can freely be transferred along magnetic power lines and fast will neutralize the potential difference, which has arisen along a power line. However, it was remained vague how we can find the characteristic length L of the acceleration layer, and how other parameters of plasma influence on this length.

The set of equations for determination of acceleration layer parameters can be constructed in the first approximation basing only on the equations of an electronic component of plasma: motion, continuity, energy [14]. In a stationary one-dimensional case (axes "x" in the direction of E field) this system has the following view:

$$V=\left[E+\frac{1}{\mathrm{en}}\frac{\mathrm{d}(nT)}{\mathrm{d}x}\right]\frac{c(\nu_1+\nu_2)}{B\Omega};$$
$$\frac{\mathrm{d}(nV)}{\mathrm{d}x}=0; \tag{6}$$
$$-\frac{\mathrm{d}(nVT)}{\mathrm{d}x}=n(eVT-\nu_2 T),$$

here ν_1 and ν_2 - accordingly, frequency of elastic and inelastic electrons collisions. The system becomes full with the condition $\int_{\mathrm{cathode}}^{\mathrm{anode}}\mathrm{E}\mathrm{d}x=\mathrm{U}$. From (6) immediately follows

$$\left\{eE+\frac{d(nT)}{ndx}\right\}\left\{eE+\frac{dT}{dx}\right\}= \tag{7}$$
$$=\frac{e}{c}B\Omega T\frac{\nu_1}{\nu_1+\nu_2}$$

Further using the experimental fact, that "T" and "n" have maxims inside of the acceleration channel, from (7) we can obtain the following approximation formula

$$E^2\cong B^2\frac{T_{\max}}{mc^2}\frac{\nu_2}{\nu_1+\nu_2} \tag{8}$$

From (8) follows, that the value of a field E and hence the length L of acceleration layer ($L\approx U/E$), are determined: by 1) value of a magnetic field, 2) mechanisms of a downthrow of electrons energy, which form their temperature, 3) ratio of the frequencies of inelastic and elastic electrons collisions. It is worth to emphasize, that the major factor, on which sufficient notice was not brought earlier, is the intensity of losses of energy by electrons, as just it is coupled to frequency of inelastic electrons collisions and determines their temperature. With other things being equal, the more ν_2, the more E and shorter the layer of acceleration, and this legitimacy is executed irrespective of the mechanism and place of losses of energy (in volume or on boundary of plasma).

The equations (7), (8) allow us on a qualitative level to explain changes of parameters of the acceleration layer in Hall thrusters during their historical development. In ACDE of a first generation[6] zones of acceleration occupied practically all length of the channel ($L\approx 10$ cm). An peculiarity of this model was a fixed magnetic field B, that resulted in a swing of intensive oscillations in plasma, that is we had $\nu_1 >> \nu_2$, and accordingly to the formula (8) weak fields $E\approx 20$ V/cm and extended zone of acceleration. In the seventieth they began to use B fields, which increase from the anode and have a maximum before cathode. The oscillations have considerably decreased ($\nu_1\geq\nu_2$), the fields E became more (E = 50-100 V/cm), and the acceleration zone shorter (L = 3 - 5cm). In further (80-s' - 90-s' years) they began to use other materials for walls of the ACDE channel, the electrons temperature in the channel and ν_2 magnified, accordingly the E field even more has grown(up to 200-300 V/cm) and length of the acceleration zone has decreased (L = 1 - 1,5cm).

Let's mark, that in TAL (thruster with the anode layer) the electrons temperature is much higher, since in them the downthrow of the electrons energy on walls is small, as, at first, the walls of the channel are manufactured of metal (ε_1 is large), secondly, wall, as a rule, are under a potential of the cathode. Therefore gradient of temperature T ' becomes comparable with the value of the electric field eE, but is directed opposite. Then from (7) follows, that with other things being equal (equality of B field, ν_1, ν_2) fields E in TAL should be more than in ACDE, and the layer of acceleration accordingly shorter, as it is watched in a reality.

Thus, we have established, that apart from the magnetic field just the power balance of electrons mainly determines parameters of the acceleration layer.

Conclusions

The balance of energy electrons in a layer of acceleration ACDE is considered and is shown, that the significant part of energy electrons, which they will type, moving in an electric field E, is given back in walls of the channel at the expense of direct collisions.

The expressions for electrons collisions frequency with the wall are obtained depending on the electrons temperature and the value of the first threshold of the electrons reproduction during secondary electron emission.

There is shown, that in ACDE temperature electrons in a layer of acceleration is close (on some percents less) to the value of the first threshold of reproduction electrons for a wall of the channel.

There is shown, that in a layer of acceleration the electrons temperature (energy) is anisotropic, that is, the average energy of the motion of electrons along the magnetic field T_{II} and across it $T_{\perp}$ can considerably differ ($T_{\perp} > T_{II}$), that it is necessary to take into account in calculations and at the experimental definition of temperature.

The extent of the acceleration layer and value of a field E in it is determined mainly by electronic component of plasma, namely by the intensity of a dissipation of electrons energy, which they have received from the field E of and then give back on walls or in volume.

The near wall conductivity plays an essential role in the acceleration layer, where the electrons temperature is close to the first threshold of the electrons reproduction on a wall, but during approaching to the anode its influence becomes insignificant, as temperature diminished.

If the emissive properties of walls of the acceleration channel are inhomogeneous, for example, owing to thin films of other materials, there can be zones with the negative near wall barrier for electrons (that is, electrons are accelerated toward the wall). Such situation results in change of the optimum operation mode of an accelerator (additional heat of walls, lowering of a general efficiency), and whenever possible it should be avoided.

The closed set of equations for plasma flow in the ACDE channel is obtained, which solution allows to receive distributions of the main parameters of plasma, including the field E along the acceleration axes without engaging of data, previously obtained from experimental measurements.

In whole the new ideas on the electrons dynamics and near wall processes in the acceleration channel of ACDE are presented, which considerably expands existing until now views on these questions.

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