DIFFUSION MODEL OF THE CONDUCTION IN THE IONIZATION ZONE
OF THE CLOSED ELECTRON DRIFT ACCELERATOR

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Abstract

In this paper proposed is the diffusion model describing the current transfer in the
closed drift electron accelerator (CDA) from the acceleration layer to the anode. It is shown
that the intensive electron transfer crosswise the magnetic field in the ionization zone in a
CDA channel may be satisfactorily explained on the basis of mechanisms of diffusion and
heat conduction.

Developed is the related diffusion model for plasma motion in the ionization zone, on
the basis of this model the numerical calculations of a set of transfer differential equations
are performed, obtained are the distributions of the main plasma parameters:
concentrations of atoms and charged particles, velocities of electrons and ions, electrons
temperature.

Nomenclature

- longitudinal coordinate;
- the longitudinal electric and radial magnetic field;
- the densities of electrons and total longitudinal current;
- the conductivity crosswise a magnetic field;
- the concentration and temperature of electrons;
- the concentration and velocity of atoms;
- the Larmor radius of an electron;
- the time of electron collisions with atoms and ions;
- the ionization velocity of atoms;
- the ion price including the ionization potential and the radiation losses;
- the velocities of ions and electrons along the channel;
- the ion mass;
- the plasma potential;
- the nearwall potential in plasma;
- the channel width;
- characterizes a ion flow to channel walls.

Introduction

As a rule, there is no difference between zones of ionization and acceleration in the
closed electron drift accelerator (CDA). The abbreviation LIA (layer of ionization and
acceleration) testifies to it. However, our experience reveals that in the majority of cases
(when considering conduction, oscillations, electron distribution function), the processes in
these zones proceed variously, therefore, these zones should be distinguished in the
contemporary CDA's (of T-100, T-160 type) [1, 2]. The most effective operation of an
accelerator is apparently achieved in the case, when the ionization processes are mainly
completed by the origin of the acceleration zone.

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In the experiments, a great variety of versions of electric field \( E \) behavior in the ionization zone \([3]\) was observed, but the value of field remained enough small \( E \leq 10 \, \text{V/cm} \), with so regimes of accelerator operation in which the field changes its direction. This suggests that the electron conduction in the ionization zone must be defined by not classic volume conduction \( j_e = \sigma E \), but other mechanisms.

The "nearwall" conduction that is described in the enough large number of papers \([4]\) is quite inadequate to explain an electron current in the ionization zone because of smallness of a total electron flow reaching the walls what, in turn, is determined by a high nearwall potential \( \phi_w \approx 6T \) \([5]\). The mechanism of electron conduction caused by oscillations and instabilities in plasma is possible. But this problem needs separate and more detailed consideration. It turns out that a small gradient of a charged particle concentration \((\sim 10^{12} \, \text{cm}^{-2}/\text{cm})\) is quite sufficient to explain the electron condition in the ionization zone. At the same time, it is clear that the gradient in the ionization zone is necessary to take place, since neutral atoms come out from anode, and all of them are practically ionized by the beginning of the acceleration layer.

Set of equations for atoms and electrons

In the present paper, the diffusion mechanism for description of electrons transfer from the acceleration layer to anode is proposed. The discharge model the basis of which is the classic collision conduction in the \( E \perp H \) fields is proposed in \([5]\).

However, some inaccuracies are allowed for in it, which have resulted in conclusions rather far from reality, for instance: electron pressure gradient was not taken into account, the model was applied to the whole region of the acceleration channel whereas in the region of the section (magnetic field maximum) the classic conduction is obviously inadequate to explain an electron current.

Assuming that the mechanisms of diffusion conduction and heat conduction are decisive in the ionization zone, one can write an appropriate set of equations for electrons and atoms. It incorporates continuity equations for atoms and electrons in terms of ionization and losses on the walls and electron energy equation. Instead of motion equations, used are the assumptions as to constancy of atoms velocities \( V = \text{const} \) and diffusion model of transfer for electron velocity \( \nu = -\frac{r^2}{2} + (j - nV)k^2 / b \)

Then, in one-dimensional approximation, a set has the form:

\[
\begin{align*}
V_{n'} &= -n_n \beta + (j - nV)k^2 / b, \\
(nV)' &= n_n \beta - (j - nV)k^2 / b; \\
(3 / 2)(nVT)' &= n_n \beta E, - (j - nV)(k^2 / b)\psi + \left[ (nT)'/j \right] \\
&+ \left[ (nT)'/j \right].
\end{align*}
\]

Note that the choice of atoms and electrons but not atoms and ions, as the governing components, is of fundamental importance. The motion of ions and atoms was considered in \([7]\), in doing so, the electric field was through as postulated (for example, from experimental measurements). But such an approach proves to be of small efficiency, since we obtain simply the accelerated motion of ions and the uniform motion of atoms in terms of ionization processes going in parallel. The motion of just electrons (not ions) is considered to be primary and governing in the ionization zone according to the model proposed in this paper, as the electrons are less mobile, than ions, crosswise a magnetic field.

As electrons move to the anode under the effect of concentration gradient, they generate a current. At the same time, the charge separation generating an electric field \( E(z) \) comes into existence. This field adjusts automatically by itself to electron current \( j_e(z) \), so
that the total current \( j \) will be constant at each section (the case in point is the stationary regime without current oscillations in volume). At such approach, when considering the motion exactly electrons, there is no necessity to introduce the field \( E(z) \) as an additional parameter. It may be defined from the dependencies \( j_e(z) \) and \( n(z) \), found already.

\[
V_i(z) = (j - j_e)/en;
E(z) = \frac{m}{e} V_i \frac{dV_i}{dz}.
\]

Solution of a set of equations and review of results

The proposed set of equations (1) for atoms and electrons in one-dimensional statement reduces to Cauchy problem for a set of ordinary differential equations and allows numerical integration. It is more convenient to carry out the numerical integration along electron motion direction (to anode), then initial data are prescribed at the boundary of ionization and acceleration layers. When specifying the initial data, we proceed from the following assumptions. The ion concentration and velocity at the channel exit are calculated rather exactly by the known flow and thrust. Under the assumption that to the origin of the acceleration layer the whole mass flow involves practically ions which are already sped up \( \sim 10eV \), the ion concentration at the origin of the acceleration layer is easily found (from the flow equality). The initial temperature (energy) of electrons is determined by a drift velocity in the acceleration zone rather exactly. It is reasonable to specify the gradients of concentration and temperature as close to zero, as the concentration and temperature of electrons reach the peak value at the boundary of ionization and acceleration layers. The choice of the initial atom concentration is somewhat arbitrary. But in return, their concentration at the end of the layer, i.e. at the anode, is known exactly.

It is easily calculated by a mass flow under the assumption that the velocity of atom ejection from the anode is determined by its temperature. Through variation of initial values of atom concentrations we select that value which, from the calculations, gives the value closest to the true one near anode. Actual practice of calculations has revealed the efficiency of such a method.

Obtained are the longitudinal distributions of the most important plasma parameters in the ionization zone: concentrations of atoms and charged particles, velocities of electrons and ions, temperature of electrons. The typical results of the performed calculations are shown in Fig. 1-3. Let us note the following main peculiarities for plasma parameters change in the ionization zone that were obtained from solution of a set of equations (1), based on the diffusion model of electron conduction.

The behavior of concentrations of neutral and charged particles is of certain interest. Whereas ion concentration drops 1.5-2 times, atom concentration may increase tens times as terms of this fact one can use the atom balance equation for evaluation of ionization layer length

\[
V_a \frac{dn_a}{dz} = -n_a n \beta(T).
\]

The substitution of mean values for concentration \( n \) and ionization velocity \( \beta(T) \) and integration give:

\[
n_a(z) = n_{ao} \cdot \exp \left( \frac{n \beta}{V_a} z \right) = n_{eo} \exp \left( \frac{z}{z_{ion}} \right).
\]

Here \( z_{ion} = V_a / n \beta \) - the typical length of ionization where the neutral concentration increases "e" times.
Fig. 1

Fig. 2

Fig. 3
At \( V = 10 \) cm, \( Z = 10 \text{ cm} \), \( = 1.8 \text{ cm} \) which represents the facts well.

Depending on initial data, the calculated plots of spatial intensity versus longitudinal coordinate may have a rather complicated form with local maxima and minima or may be simply a smoothly changing function which correlates with its unusual behavior in the experiments.

**Conclusion**

It is shown that intensive transfer of electrons crosswise the magnetic field in the ionization zone of CDA may be explained through the diffusion mechanism.

Numerical solution of the set of equations based on the diffusion model has permitted the receipt of longitudinal distributions of main plasma parameters: concentrations, velocities and temperature.

Apart from the fact that the set of equations (1) proposed in this paper and based on the diffusion mechanism of electrons motion permits the numerical calculation of stationary plasma parameters in the ionization zone, it may be also used as initial for research of low frequency ionization oscillation emergence.

**References**