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On the physics of electron transfer (drift) in the substance: about the reason of “abnormal” fast transfer of electrons in the plasma of tokamak and at known Bohm’s diffusion

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Abstract. An analysis of the problem of so-called "abnormal" fast transfer of electrons in tokamak plasma, which turned out much faster than the result of accepted calculation, is given. Such transfer of hot electrons leads to unexpectedly fast destruction of the inner tokamak wall with ejection of its matter in plasma volume, what violates a condition of plasma confinement for controlled thermonuclear fusion. It is shown, taking into account real physics of electron drift in the gas (plasma) and using the conservation law for momentum of electron transfer (drift), that the drift velocity of elastically scattered electrons should be significantly greater than that of accepted calculation. The reason is that the relaxation time of the momentum of electron transfer, to which the electron drift velocity is proportional, is significantly greater (from 16 up to 4 times) than the electron free path time. Therefore, generally accepted replacement of the relaxation time, which is unknown a priori, by the electron free path time, leads to significant (16 times for thermal electrons) underestimation of electron drift velocity (mobility). This result means, that transfer of elastically (and isotropically) scattered electrons in the gas phase should be so fast, and corresponds to multiplying coefficient (16), introduced by D. Bohm to explain the observed by him "abnormal" fast diffusion of electrons.

1. Introduction

It is known that transfer of electron beams in tokamak plasma occurs much faster (in ~10 times) than expected result of accepted calculation, and therefore it was called as “anomalous” transfer of electrons. Such fast transfer of electrons leads to unexpectedly rapid destruction of inner wall of tokamak chamber by hot electrons and to ejection of wall matter in tokamak plasma, what violates adjusted plasma properties desired for realization of controlled thermonuclear fusion. This circumstance created a complicated problem of wall protection from hot electron beams, for solution of which considerable expensive efforts are used. For successful realization of controlled fusion it is necessary to reveal the cause of “anomalous” electron transfer in order to establish possible methods to suppress this damage by fast transfer of hot electrons. It is important, particularly, for implementation of controlled thermonuclear fusion within effected in France well-known ITER (International Thermonuclear Experimental Reactor) project, which is based on tokamak for plasma confinement at controlled fusion.

Paper gives theoretical explanation of the problem of “anomalous” (unexpectedly fast) transfer of electrons with the use of earlier developed, statistically correct theory of electron transfer and heating.
in the gas under electric field force [1-3]. This theory, which results are well confirmed by known experimental date [4-6], takes into account for the first time real physics of forced transfer (drift) of electrons in the gas phase and is based on the fundamental conservation laws of momentum and energy. Using the law of momentum conservation for transfer impulse of drifting electrons it is shown that electron drift velocity (and mobility) in gas phase for elastically scattered electrons should be much faster (from 16 to 4 times) than the value of accepted calculation [7].

Really, the reason of the problem of “anomalous” fast electron transfer is rather simple. At calculation of electron drift velocity, the value of which is proportional to relaxation time of electron transfer impulse (according to the main concepts of physics), it is generally accepted to substitute this time, which is not known a priory, by electron free path time, which may be calculated using known cross sections of electron scattering. Developed theory [1-3] gives that relaxation time of electron transfer impulse for elastically (and isotropically because of comparatively very small electron mass) scattered electrons is significantly larger (from 16 to 4 times) than the electron free path time [7]. This result directly follows from accomplished analyses [5, 6] of specific features of the field dependence of electron drift velocity in dense rear gases which was accurately established in [4]. As clear, such substitution should lead to corresponding significant underestimation of the value of electron drift velocity. Another important result of the theory is that an appreciable decrease of the difference between these two times (from 16 to 4) occurs at heating of drifting electrons (above their thermal energy coursed by substance temperature) due to their forced transfer under the force of the strong electric field.

Such wrong substitution of relaxation time of electron transfer impulse by the time of electron free path is generally substantiated by isotropic scattering of all drifting electrons during one free path time. As supposed, at such scattering also an isotropy (and full dissipation) of electron transfer impulse takes place at every one free path time. However, this substantiation is not correct, since at that no difference is made between electron transfer impulses and their thermal (isotropic) impulses, which don’t contribute to the directed transfer of drifting electrons. To explain electron “anomalous” transfer it is important at first to separate the electron transfer impulses from their thermal impulses, and then apply to the electron transfer impulse the law of momentum conservation. At that, namely the fact of isotropic scattering of drifting electrons (because of their small mass with respect to the mass of substance particles) gives that the relaxation time of electron transfer impulse is significantly larger (namely, from 16 to 4 times) than the time of electron free path [7]. It is worth to mark, that sometimes it is assumed that the relaxation of electron transfer impulse may takes more than one possibly two or three) times of electron free path. Nevertheless, at calculation of electron drift velocity only one time of electron free path is always used instead of relaxation time of electron transfer impulse.

Therefore, obtained theoretic result means that the so-called “anomalously” fast electron transfer in tokamaks (and at known Bohm’s diffusion) is a consequence of significant underestimation of electron drift velocity at accepted calculation, and observed fast electron transfer really must be so unexpectedly fast. Such result of simple statistically correct theory is well confirmed by theoretical analysis [5, 6] of known experimental data for electron drift velocity in dense rare gases [4]. This result, obtained due to taking into account the appearance of statistically average value of transfer impulse of drifting electrons and due to the use of momentum conservation law for this transfer impulse, shows that for correct explanation of observed physical processes it is always necessary take into account their real physics and use for their explanation known fundamental laws of physics. Known three conservation laws of classical physics and principles of quantum mechanics with the value of Planck’s constant, as was recently shown [9], have their materialistic substantiation, since all they are determined by observed features of cosmic microwave background radiation produced by dark matter thermal seesaw motion at temperature 2.7K.

2. **Real physics of electron drift in a gas under a constant weak and strong electric field**

Understanding of the physics of electron transfer (drift) in the gas substance (including plasma) under the action of an electric field is important for the correct calculation of the electron drift velocity ($V_d$),
which is experimentally measured and which reveals real properties of the process of electron transfer. As clear, calculation of \( V_d \) dependence on the electric field should be based on the conservation law for the electron transfer impulse \( P_e=mv_{dr} \), where \( m \) is the mass of the electron, since namely this impulse is formed under the action of the electric field strength \( (E) \) [1-3]. Taking into account this basic physical property of the process of electron transfer (drift) in the substance is necessary for correct calculation of \( V_d(E) \) since by comparing the result of this calculation with the experimental data for \( V_d(E) \) dependence it is possible to reveal real properties of the electron transfer (drift) in the substance. The application of this approach to the calculation of \( V_d(E) \) for the case of dense gas of rear atoms [5, 6] is given in the paper, what let revealed the physical reason of the so-called "anomalous" fast electron transfer, which is observed in the tokamak plasma and at well known Bohm’s diffusion.

Thus, the correct consideration of the physics of the process of electron transfer in a gaseous medium allows one to establish a quantitative relationship between the relaxation time \( (\tau_{rel}) \) of the electron transfer pulse \( P_e = mV_d \) with the time of their free path \( (\tau) \): \( \tau_{rel} = Z \tau \) [5, 6, 7], where number \( Z \) must be larger than 1. It should be emphasized that the quantitative relationship between \( \tau_e \) and \( \tau \) is logical, since the relaxation (dissipation) of \( P_e \) occurs only at the scattering of electrons in the substance with frequency, which is determined by the value of \( \tau \).

This numerical connection (between \( \tau_e \) and \( \tau \)) has a fundamental importance for the correct calculation of \( V_d \). The value of \( V_d \), according to the conservation law for the transfer impulse \( P_e=mv_{dr} \), is proportional to \( \tau_e \), namely, \( V_d = eE \tau_{rel} / m \), where \( e \) is the electron charge, \( [1-3] \). Indeed, since the rate of growth of the impulse \( P_e \) is equal to the force acting on the electron \( eE \), and the rate of dissipation (relaxation) of \( P_e \) is generally determined through its relaxation time as \( P_e/\tau_{rel} \), then the equality of these velocities at the stationary drift of electrons gives this simple expression for \( V_d \) value: \( V_d = eE \tau_{rel} / m \). However, the value of \( \tau_e \) is not known a priori, because it is determined by different processes of dissipation of momentum and energy of the electron during its scattering, but the value of \( \tau \) can be usually calculated from known scattering cross sections of electron. Historically (from the works of Drude and Lorentz at the end of the 19th century) it is simply supposed that the relaxation time of \( P_e \) may be replaced by the value of the electron free path time. Thus it is assumed that \( \tau_e = \tau \), that is \( Z = 1 \).

However, as can be shown by applying the conservation law to the transfer impulse \( P_e=mv_{dr} \), the number \( Z = \tau_e / \tau \) for elastically (and isotropically) scattered electrons varies from 16 to 4, and the decrease of the Z value in this interval occurs with the increasing of the energy of the forced heating of the drifting electrons with increasing of \( E \) [3]. So, for correct calculation of \( V_d \) on the basis of simply determined value of \( \tau \), it is necessary establish the true value of \( Z \). For calculation of \( Z \) value, it should be taken into account that the stationary electron transfer impulse is \( P_e = mV_d = eE \tau_{rel} = eE \tau \), and the increase of \( P_e \) in the direction of the field force action for each time \( \tau \) is \( eE \tau \). It is clear that in order to ensure the stationarity of electron transfer, it is necessary that for the time \( \tau \), during which all the drifting electrons are scattered isotropically, the same value of \( eE \tau \) must be scattered against the action of the field strength, that is must be scattered \( Z \) part of \( P_e = eE \tau \). The correct calculation of the part of \( P_e = eE \tau \) that is scattered against the action of the field, as presented in [7], gives that in the limit of a weak electric field, when the contribution of electron thermal velocities is significant, \( Z = 16 \), and in the limit of a strong electric field, when the contribution of thermal velocities of electrons is negligible, \( Z = 4 \). This theoretical result is fully confirmed by the known experimental data for the specific \( V_d(E) \) dependence in dense inert gases, the most qualitative of which is given in the work done in the MEPiL [4]. The developed statistically correct ideas about the properties of forced transfer and heating of electrons in a gas [1-3] for the first time let to explain the specific effects observed for condensed inert gases: saturation (reaching a limiting value) of \( V_d \) in the limit of large \( E \) and a multiple increase of \( V_d \) at small additions of molecular impurities [5, 6].

Thus, revealed significant underestimation of generally calculated value of \( V_d \) (at assumption that \( \tau_e = \tau \)) let logically explain the so-called "anomalous" fast electron transfer, observed both in the tokamak plasma, and at known Bohm’s diffusion. By the way, D. Bohm, to explain observed unexpectedly rapid transverse transfer of thermal electrons (in crossed electric and magnetic fields), received the enlarging factor namely 16, which is known as the Bohm’s coefficient. It should be noted
that such correction factor was obtained by D. Bohm by introducing an idea of chaotic motion of drifting electrons due to their magnetodynamics behavior. However, as clear, the use of this representation is unnecessary, because the isotropy of elastic scattering of drifting electrons (each time \( \tau \)) really means their totally chaotic motion.

3. **Statistically correct calculation of the value of electron drift velocity in the gas substance**

Let’s consider a drift of assembly of electrons (with mass \( m \)) under a constant electric field \( (E) \) in the gas of atoms (with mass \( M \gg m \)). Observed (by electron current measurement) stationary drift velocity \( (V_d) \) of this electron assembly means an appearance (due to electric field force) of directed transfer impulse \( P_E=mvV_d \), which value is statistically average over all drifting electrons. In order to correctly calculate \( V_d \) value it is necessary to apply the momentum conservation law to this appeared transfer impulse \( P_E=mvV_d \). At that it should be taken into account that a growth rate of \( P_E \) is equal to electric field force \( eE \), acting on each electron with its electric charge \( e \), and a dissipation rate of \( P_E \) is equal to \( P_E/dt_\tau_p \), where \( \tau_p \) is relaxation time of \( P_E \) (according to accepted concepts of physics).

Then, at stationary electron drift, when growth and dissipation rates of \( P_E \) are equal, follows simple equation:

\[
eE - \frac{P_E}{\tau_p} = 0. \tag{1}
\]

From equation (1), which is dynamic balance for transfer impulse \( P_E=mvV_d \), follows well known expression for \( V_d \):

\[ V_d = \frac{eE}{me} \tau_p, \tag{2} \]

and also the expression for electron mobility (\( \mu \)):

\[ \mu = \frac{V_d}{E} = \frac{e}{m} \tau_p. \tag{3} \]

As clear from equations (2) and (3), both \( V_d \) and \( \mu \) are proportional to \( \tau_p \) value, which should be found in each particular case for correct calculation of \( V_d \) and \( \mu \) values. Usually the value of \( \tau_p \) is not known a priori, since \( \tau_p \) value is defined by scattering (dissipation) mechanism of drifting electrons. Unfortunately, it has been long ago accepted (more than a century ago) to substitute desired \( \tau_p \) value by the value of electron free path time \( \tau \), which may be easily calculated from known cross-sections of electron scattering in the substance. Thus, it is generally accepted to assume that \( V_d=eEt/m \) (and \( \mu=e\tau p/m \)). However, this substitution for the case of elastically (and isotropically) scattered electrons leads to significant underestimation of \( V_d \) (and \( \mu \)) values, since in this case the \( \tau_p \) value is much larger (from 16 to 4 times) than \( \tau \) value. As was shown [7], this result follows from correct application of momentum conservation law to the electron transfer impulse \( P_E=mvV_d \), what is well confirmed by known experimental date for \( V_d(E) \) dependences in dense rare gases [1-3].

It is reasonable to think, that \( \tau_p \) should be equal to several values of \( \tau \), since dissipation (relaxation) of transfer impulse \( P_E \) may occurs only at electron scattering, whose statistically mean frequency is determined by \( \tau \). Thus, there should be quantitative relation between \( \tau_p \) and \( \tau \) values, i.e. it should be \( \tau_p = Z\tau \), where \( Z \) is a number larger than 1. Then, according to equation (2), for value of \( V_d \) follows such expression:

\[ V_d = \frac{eEZ\tau}{m}. \tag{4} \]

Equation (4) gives that the stationary drift impulse of electrons should be equal to:

\[ P_E = mV_d = eEZ\tau. \tag{5} \]
In order to correctly calculate $V_d$ value it is necessary establish $Z$ value since the value of $\tau$ may be calculated. To obtain the value of $Z$, it is important to take into account real physics of stationary drift of elastically scattered electrons, i.e. to understand why constant value of $V_d$ is achieved at applied constant $E$. For that it is convenient to consider transfer of electron assembly during one electron free path time $\tau$, for which all drifting electrons should be scattered for certain. As clear, this scattering of electron assembly is isotropic since drifting electrons will be scattered on the atoms uniformly (in all directions). During time $\tau$ a statistically mean increase of $P_\beta=mv_d=eEZ\tau$ (in direction of $E$ action) is equal to $eEr$. For stationary electron drift it must be so that a backscattered (against direction of $E$ action) part of $P_\beta=mv_d=eEZ\tau$ during time $\tau$ must also be equal to $eEr$. According to equation (5) this backscattered part must be equal to $Z^4$ part of stationary electron drift impulse $P_\beta=eEZ\tau$. Thus, in order to obtain desired $Z$ value it is necessary reveal what part of impulse $P_\beta=eEZ\tau$ is backscattered for the time $\tau$. This part, which may be revealed by spatial analysis of $P_E$ scattering [7], must be equal to $Z^4$, what gives desired value of $Z$.

At spatial analysis of backscattered part of $P_E$ it is necessary take into account the presence for drifting electrons of their thermal (isotropic) impulses, which introduce no contribution to $P_E$, but strongly affect its backscattered part, changing significantly $Z$ value. Such spatial analysis of backscattered part of $P_E$ was done for two limiting cases of $E$ values [7]. For small $E$ and small $P_E$, when drifting electrons are nearly thermal, it was obtained that $Z=16$. This value corresponds well to known Bohm coefficient 16, introduced by him to explain observed "anomalous" fast diffusion of thermal electrons in the gas of argon under crossed magnetic and electric fields. As was noted above, to explain "anomalous" fast electron diffusion, D. Bohm have used an idea (magnetohydrodynamic) of chaotic motion of electrons, what is true, but not necessary since the motion of drifting electrons in the gas substance is chaotic in principle due to isotropic scattering of drifting electrons (for each time $\tau$ in arbitrary directions). For large $E$ values, when drifting electrons are strongly heated above their thermal energy and so their thermal impulses may be neglected, it was obtained that $Z=4$ [7]. This result for large $E$ values, when only transfer impulse $P_E$ is scattered, may be substantiated very simply. As known, at isotropic scattering of some flow an exactly $\frac{1}{4}$ part of this flow is scattered in any direction, therefore in this case namely $\frac{1}{4}$ part of $P_E$ will be backscattered, and consequently it means that in this case $Z=4$. As was shown [5,6], these theoretically obtained limiting values for $Z$ and diminution of $Z$ value from 16 to 4 at increasing $E$ are entirely confirmed by known experimental data for electron drift velocity in dense rare gases.

4. Conclusions

The use of statistically correct theory, based on the law of momentum conservation for transfer impulse of drifting electrons $P_E=mv_d=eEZ\tau$, shows that the problem of "anomalous" fast transfer of electrons in tokamak plasma (and at known Bohm’s diffusion) is caused by significant (from 16 to 4 times) underestimation of electron drift velocity (and mobility) at its accepted calculation, when it is believed that $Z=1$.

The law of momentum conservation for transfer impulse $P_E$ gives that drift velocity (and mobility) of electrons in gas phase must be so fast really. Therefore, to suppress the damage of tokamak chamber by “anomalously” fast transfer of hot electrons, what disturbs conditions of controlled fusion realization, it is reasonable to increase inner diameter of tokamak chamber according to really fast electron mobility.

The damage of inner wall of tokamak chamber by fast transfer of hot electrons may be significantly suppressed due to additional heating of drifting electrons (above thermal energy of tokamak plasma) by additional electric field. As gives developed theory [1-3], such overheating lets diminish the “anomalous” fast transfer of electrons by several times (up to 4 times). As known, this possibility, revealed due to practical activities, is used already for suppression of “anomalous” transfer of hot electrons in tokamak (and stellarator) chambers.

It is important to take into account the established real properties of the forced transfer of electrons under the electric field (numerical relationship $P_\beta=Z\tau$) at investigation of substance (plasma) electron
parameters based on measuring of electron conductivity. In particular, this allows correctly calculate the concentration of conduction electrons (based on the measured value of electron conductivity) on the base of true expression for $V_\phi$,calculated with relationship $\tau_e=Z\tau$, without leading to significant (in $Z$ times) overestimation of electron concentration because of the generally accepted use of wrong relationship $\tau_e=\tau$.

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