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KINETIC ASPECTS AND SOME APPLICATIONS OF DIFFUSE GAS DISCHARGES IN TURBULENT FLOWS

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Résumé.- L’équation cinétique pour une seule génération électronique (EG) à E/P bas dans les décharges diffuses turbulentes (TDD), et des évaluations sur les intervalles de temps caractéristiques pour E/P divers, sont obtenues. Les propriétés de TDD qui sont essentielles pour application plasma-chemique et laser sont discutées.

Abstract.—The kinetic equation for a single electron generation (EG) at low E/P in turbulent diffuse discharges (TDD) and estimates of characteristic time intervals for various E/P are obtained. TDD’ properties essential for plasma-chemical and laser applications are discussed.

Introduction

Recent study of diffuse discharges in the hydrodynamically turbulized gas speedily passing through the region with a high electric field strength E has shown that the turbulence causes deep changes of properties and parameters of the discharge and leads to large observable effects such as:¹ (i) A sharp increase of power consumption W and electric current I at prearcing mode up to $10^2$ to $10^7$ times of non-flow conditions without losing the discharge stability. (ii) A great enhancement of transport coefficients, e.g., of turbulent ambipolar diffusivity

$$D_{At} \approx \frac{Re}{Re^*} D_A = \frac{Re}{Re^*} \cdot \frac{\bar{e}_e}{\bar{e}_i} \cdot D_l,$$

where Re and $Re^*$ << Re are the Reynolds and the critical Reynolds numbers; $\bar{e}_e$ and $\bar{e}_i$ << $\bar{e}_e$ are the mean energies of electrons and ions, and e.g.,

$D_{At}$ can reach values $D_{At} \approx 10^5$ cm$^2$/s at $Re/Re^* \approx 3 \times 10^5$, $\bar{e}_e/\bar{e}_i \approx 10^2$ and $D_l \approx 0.2$ cm$^2$/s, and so on.

Turbulent diffuse discharges (TDD) are of substantial interest due to their possible applications to plasma chemistry, to turbulent gas discharge lasers (TGDLS), etc.¹ ². However, the TDD kinetics has been studied very little. In this paper we shall consider the kinetic aspects and a non-stationary stochastic model of unionized gas-to-plasma trans-
itions (GPT) under the influence of electric field $E(x_0, y_0, z_0, t)$ during a short residence time $\Delta t_a = L_a/v$ of the gas moving through the discharge zone with the mean velocity v, where $r_0 = (x_0, y_0, z_0)$ are coordinates in the unmoved coordinate system. The behaviour of the moving gas affected by $E$ during $\Delta t_a$ is similar to that of the unmoved gas affected by a short-term pulse of the electric field¹ ³. We shall consider this problem following the ideas suggested in ref. 3.

Some TDD properties essential for TDD applications are also discussed. The TDD kinetics represents an extension and a combination of the following phenomena whose study is far from being accomplished: (i) The hydrodynamics and physical chemical hydrodynamics of turbulent but unionized gases (see e.g., ref. 4-8). (ii) The hydrodynamics and kinetics of turbulent plasma jets (see e.g., refs. 9-11). (iii) The kinetics of discharge phenomena in non-flowing or laminar flowing gases affected by short term pulses of the electric field (see e.g., refs. 11-14). (iv) Phenomena in unmoved gases affected by non-uniform electric fields (see e.g., refs. 15-19). This is why one can hardly expect to solve the considered problems exactly. We shall resort, therefore, to the use of approximation analysis, similitude theory and

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approximate stochastic modeling of the processes in question, to obtain qualitative and semi-quantitative results for the main features of the problem and to come to some observable consequences. On this basis, we combine some qualitative and semi-quantitative results of theory of turbulence and gas discharges with a stochastic model of the charged particle behaviour to obtain expressions for the considered values.

Some Kinetic and Stochastic Characteristics of Turbulent Gas Discharges

Consider a turbulent unionized gas consistent of \( N = N_B + N_P \) different kinds of particles (per 1 cm\(^3\)) of mass \( M_B \) and concentration \( N_B = P/kT \) entering the discharge zone with mean velocity \( v \) at pressure \( P = \sum P_B \), temperature \( T \). This gas has random turbulent pulsations characterized by the smallest space scale \( L_0 \) and its corresponding frequency \( \omega_0 \) given by

\[
L_0 \approx \frac{R_e^*/R_e}{5/4}. \mathcal{L} \quad \text{and} \quad \omega_0 \approx \frac{(\Delta v/\mathcal{L})(R_e/R_e^*)}{3/4} \quad (1)
\]

\( \Delta v \approx \mathcal{v} \) and \( \omega_0 \) are the characteristic frequency and space scale of the turbulent pulsations, \( L_0 \) and \( \omega_0 \) are the characteristic frequency and space scale of the turbulence, e.g., the scale of the corona zone. For instance, if \( \Delta v \approx \mathcal{v} \approx 10^6 \text{ cm/s} \), \( \mathcal{L} \approx 4 \text{ cm} \), kinematic viscosity \( \gamma \approx 0.2 \text{ cm}^2/\text{s} \) and \( R_e^* \approx 50 \) one can obtain \( R_e \approx 2 \times 10^5 \), \( L_0 \approx 10^{-2} \text{ cm} \), \( \omega_0 \approx 10^6 \text{ s}^{-1} \). The gas entering the discharge has very low initial electron concentration \( n(0) = n_0(0) \cdot N \) associated with very small initial degree of gas ionization \( a(0) \approx 10^{-12} \) to \( 10^{-13} \) caused by cosmic rays, by natural radioactivity, etc. This gas speedily passing through the discharge zone with space scale \( L_a \) (e.g. corona zone) is affected by the electric field only during short time \( \Delta \tau_a \approx L_a/v \). The GPT can occur in the moving gas only if the GPT time \( \tau_a \approx n(0) \cdot N \). During \( \tau_a \) time-dependent electron concentration \( n(t) = a(t) \cdot N \) increases up to \( n(0) = n(a) \cdot N \) which satisfies the condition

\[
\rho_D(t) = \left[ \frac{\varepsilon(t)}{4\pi e^2 \cdot n(t)} \right]^\frac{1}{2} = \left[ \frac{\varepsilon(t)}{4\pi e^2 a(t) \cdot N} \right]^\frac{1}{2} \quad (3)
\]

Therefore the time-dependent Debye radius

\[
\rho_D(t) = \left[ \frac{\varepsilon(t)}{4\pi e^2 n(t)} \right]^\frac{1}{2} = \left[ \frac{\varepsilon(t)}{4\pi e^2 a(t) \cdot N} \right]^\frac{1}{2} \quad (4)
\]

rapidly decreases from the initial value \( \rho_D(0) \) up to \( \rho_D(\varepsilon(t)) \) where \( \varepsilon(t) \) is the mean electron energy at \( t \) determined by

\[
\varepsilon(t) = \int \varepsilon f(c,t) \cdot dc \quad \text{and} \quad \int f(c,t) \cdot dc = 1, \quad (5)
\]

\( f(c,t) \) is the electron energy distribution function, \( L_a \) is the space scale of the discharge zone where the GPT occurs, e.g. \( L_a \) is the scale of the turbulent corona zone on \( R_e/R_e^* \). If \( \varepsilon(t) > \Delta \tau_a \) the GPT has no time to occur. Time \( \varepsilon(t) \) depends on \( E/P \), on \( n(0)/N_0 \), etc. and can vary from one discharge to another, and even within the same discharge volume. To estimate \( \varepsilon(t) \) and compare it with \( \Delta \tau_a \) we introduce the following criteria for the low, moderate and high \( E/P \):

\[
\varepsilon(t) < W_0 = W \quad \text{or} \quad E/P < \frac{W_0}{kT}, \quad \sigma_{\text{max}} = \left( \frac{E}{P} \right)_b \quad (6)
\]

\[
\varepsilon(t) \lessgtr W_0 \quad \text{or} \quad E/P < \left( \frac{E}{P} \right)_b \quad (7)
\]

\[
\varepsilon(t) \gtrsim W_0 \quad \text{or} \quad E/P > \left( \frac{E}{P} \right)_b \quad (8)
\]

where \( \lambda_{\text{min}} = [N_\text{max}]^{-1} \), \( \sigma_{\text{max}} \) is the maximum total effective cross-section within the considered electron energy interval, e.g., within interval \([0,W_0]\) with \( W_0 \) being the threshold energy sufficient to start ionizations of gas particles with ionization potential \( W \). The effective total electron cross-section and the mean free path length are given by

\[
\lambda^{-1} = \Sigma \frac{1}{\mathcal{B}} = \Sigma \left( \frac{\sigma_B(\varepsilon)}{B} \right) \cdot N_B \quad ; \quad \sigma(\varepsilon) = N^{-1} \cdot \Sigma \left( \frac{\sigma_B(\varepsilon)}{B} \right) \cdot N_B \quad (9)
\]
\( \sigma_B^*(e) = \sigma_{B0e}^*(e) + \sigma_{B1}^*(e) + \Sigma \sigma_{B\alpha}^*(e) \); 

\( \sigma_B(e) \) is the total cross-section of electron collisions with particles of type B, that includes that of elastic, \( \sigma_{B0e}^* \) ionizing, \( \sigma_{B1}^* \), and exciting (of level \( \omega_\beta^* \)), \( \sigma_{B\alpha}^* \) collisions. Therefore, the applicability of low, moderate and high \( \varepsilon/E \) approximations to particular cases depends on characteristic ratio 

\[
\frac{(E/P)_b}{(P/P_0)^{\varepsilon}} = \frac{W_0}{K_{T0}} \frac{\sigma_{\text{max}}}{e},
\]

where \( T_0 = 273 \text{ K}, P_0 = PT/T \). For example, if \( \sigma_{\text{max}}^* = 2 \times 10^{-15} \text{ cm}^2 \) (e.g., in Ar at \( e \approx 12 \text{ eV} \)), \( T = 300 \text{ K} \) and \( W_0 = 1 \) to \( 20 \text{ eV} \) (e.g. in Ar, \( W_0^* \approx 16 \text{ eV} \)). One can obtain from (11): \( (E/P)_b \approx 65 \) to \( 1.3 \times 10^5 \text{ cm} \text{torr} \); and if \( P \approx 760 \) 
torr, one has \( E_b \approx 50 \) to \( 10^5 \text{ KV/cm} \). However, if \( \sigma_{\text{max}}^* \approx 3 \times 10^{-16} \text{ cm}^2 \) (e.g., \( \text{Ne at } e_l^* \approx 25 \text{ eV} \)) and other conditions equal, one has \( (E/P)_b \approx 9.5 \) to \( 190 \text{ V/cm} \) torr. Consider now a stochastic model of the GTP and related phenomena, following the approach suggested in ref. 3. 

1. The low \( \varepsilon/E \) approximation

Condition (6) means that every low energy electron (e.g., the initial one or the one that has lost its energy during an ionization collision) with energy \( \varepsilon_0 \) \(< W_0 \) at \( t_0 \) suffers as many as 

\[
\sigma^* \approx \sigma_{B0e}^* \left( \frac{e}{e_{0}} \right) \left( \frac{W_0}{W} \right)^{-1} \gg 1
\]

ionizing collisions with gas particles during time \( \Delta t = t_1 - t_0 \approx \tilde{\tau}_e \) before the electron gains energy \( \Delta \varepsilon = W_0 - \varepsilon_0 \approx W_0 \) sufficient for ionizations; after that the electron with energy \( \varepsilon \approx W_0 \) suffers \( \sigma/\sigma_{1}^* \) additional ionizing collisions during time \( \tilde{\tau}_e \approx \delta \varepsilon \tau_e^* \), before the first ionizing collision, where 

\[
\tilde{\omega}_e = \tilde{\tau}_e^* \sum_{\beta} \frac{\tilde{\omega}_\beta^*}{\sigma_{\beta\alpha}} \Delta \omega_{\beta}^* 
\]

is the mean energy lost per one ionizing electron-gas particle collision, \( \Delta \omega_{\beta}^* \) is the partial loss given by 

\[
\Delta \omega_{\beta}^* = \sigma_{\text{int}}^* \left( \sum_{\beta} \Delta \omega_{\beta}^* \sigma_{\beta\alpha}^* \varepsilon_{\beta}^* \right) ,
\]

\[
\tilde{\tau}_e^* = \sum_{\beta} \frac{\tilde{\omega}_\beta^*}{\sigma_{\beta\alpha}} \approx \frac{1}{\sigma_{\beta\alpha}}
\]

is the frequency of electron collisions with gas particles, \( \tilde{\omega}_\beta^* = \frac{2 \tilde{\omega}_\beta^*}{mW_\beta} \), \( \delta_{\beta\alpha} \approx 2mW_\beta^* \sigma_{1}^* \approx \Sigma \sigma_{\beta\alpha}^* \). 

The mean time between the two ionizing collisions 

\[
\Delta \tilde{\tau}_e = \Delta \tilde{\tau} + \tilde{\tau}_e \approx (\alpha + \delta \alpha) \tilde{\tau}_e
\]

can be treated as the lifetime of a single electron generation (EG) with \( n \approx \text{const} \). This EG is formed by the electrons of the previous EG and by the secondary ones created by ionizing collisions of the previous EG. Then the time \( g(g) \) of formation of 

\[
g = (\xi n) \ell - 1 \xi n(h/g) \ell (\ell)
\]

EGs can be estimated by 

\[
g(g) \approx g + \delta g \approx g(\alpha + \delta \alpha) \tilde{\tau}_e
\]

where \( \kappa \) is the average number of secondary electrons formed by one electron of a single EG during \( \delta \tilde{\tau}_e \), in many cases \( \kappa \approx 2 \). The energy distribution \( f(\varepsilon, \ell) \) of a single EG is 

\[
f(\varepsilon, \ell) = \int G(\varepsilon, \ell | \varepsilon_0, \ell_0) \cdot f(\varepsilon_0, \ell_0) d\varepsilon_0 \, ,
\]

where \( G(\varepsilon, \ell | \varepsilon_0, \ell_0) \) is the conditional probability of the electron transition from the state with energy \( \varepsilon_0 \) at \( \ell_0 \) into the one with \( \varepsilon \) at \( \ell \). \( G \) is determined by the Fokker-Plank equation in the energy space 

\[
\frac{\partial G}{\partial \ell} = \frac{2}{\varepsilon_0^2} (A \cdot G) - \frac{3}{\varepsilon_0^2} (B \cdot G)
\]

closely connected with the stochastic equation of electron motion 

\[
\frac{d\varepsilon}{dt} = e \varepsilon u_d - A_1 + g \varepsilon(t)
\]

where 

\[
A = e \varepsilon u_d - A_1, A_1 = \varepsilon \varepsilon_0 \d_\ell^2, u_d \approx \varepsilon m^{-1} e E \varepsilon_0^* \]

is the electron drift velocity, 

\[
g = B, B \approx (eE)^{D_{11}^D} D_{11}^D
\]

is the electron diffusivity along the field. If \( E/P \) is so low and
\( \alpha_0 \) is so high that \( \Delta \approx \alpha_0^{-1} \), one has \( D_{11} = D_{11} \) (see Eq. (1)). Equation (20) takes the part of the kinetic equation of a single EG at low \( E/P \). As is well-known this equation can be solved for some particular cases. For instance, when \( B \) and \( A \) can be replaced by averaged constant values \( B = \text{const} \) and \( A = \text{const} \), one can obtain

\[
G(t) = G_0 \cdot \exp \left( -\frac{(t-t_0)}{2B(t-t_0)} \right)^2 \tag{22}
\]

Equations (12)-(22) allow various conclusions and estimates; among them are the following:

(i) Systematic drift of \( \epsilon \) towards higher values is determined by \( \Delta \) depending on the gas nature, \( E \), etc., and \( \lambda_0 \) if \( E/P \) is not too small.

(ii) Values of \( \Delta \) and \( \lambda_0 \) are not too large when \( \Delta \) and \( E/P \) are not too low; (iii) \( n(\epsilon) \) and \( n(\epsilon) \) are exponential functions of time \( t \):

\[
n(\epsilon) = n(0) \exp \left( \frac{\epsilon \cdot t \cdot \ln \epsilon}{2 \Delta} \right) \tag{23}
\]

\[
\rho(\epsilon) = (\epsilon/n(0)) \cdot \exp \left( \frac{n(0) \cdot \ln \epsilon}{2 \Delta} \right) \tag{24}
\]

where \( \Delta \) depends on parameters of the process.

(iv) Rate coefficients of ionizations, excitations, reactions, radiation, etc., induced by electron impacts with cross-sections \( \sigma_R(\epsilon) \) at moment \( t \approx t(\epsilon) \) are

\[
K(t) = n(0) \int \frac{\sigma_R(\epsilon) \cdot f(\epsilon, t) \, d\epsilon}{2 \Delta} \tag{25}
\]

(v) The GPT time \( \tau(\epsilon) \) can be estimated from

\[
\tau(\epsilon) \approx n(0) \left[ \frac{\epsilon \cdot \sigma_R(\epsilon) \cdot f(\epsilon, t) \, d\epsilon}{2 \Delta} \right] \tag{26}
\]

If \( eE_0 \approx \Delta \approx \epsilon_e \), time \( \tau(\epsilon) \) can become greater than \( \lambda_0^{-1} \) and can even approach \( \lambda_0^{-1} \) if \( E/P \) is rather low. For instance at \( P \approx 760 \) torrs, \( T = 300K \), \( E = 10^3 \, V/cm \), \( \sigma(0) \approx 10^{-13} \)

\[
\sigma(0) \approx 3 \times 10^{-4}, \sigma_{max} \approx 2 \times 10^{-15} \, cm^2, \sigma \approx 10^{-15} \, cm^2,
\]

\[
k \approx 2 \text{ and } W_0 \approx 16 \, ev \text{ one can find } g \approx 32,
\]

\[
\tau \approx 3 \times 10^{-13} \, s,
\]

\[
a \approx 8 \times 10^{-4}(1 - \epsilon_e \Delta W_0/eU_0)\tag{27}
\]

\[
\delta(32) > 10^{-6}(1 - \epsilon_e \Delta W_0/eU_0)^{-1}
\]

2. At moderate and high \( E/P \) associated with conditions (7) and (8) electrons gain energy \( \Delta \approx W_0 \) during \( \Delta t \approx \tau \), or \( \Delta t < \tau \), and the single EG lifetime

\[
\lambda_0 \approx \lambda_0 + \delta \approx \lambda_0 \approx (\epsilon_e \Delta W_0/eU_0)^{-1}
\]

and \( \delta(\epsilon) \approx \lambda_0^{-1} \), are much shorter than those at low \( E/P \) and than \( \lambda_0^{-1} \) and \( \lambda_0 \). In this case calculations of \( f(\epsilon, t) \) differ from those at low \( E/P \) and require a special consideration, but \( \lambda_0 \) and \( \rho(\epsilon) \) can be easily estimated from Eq. (28).

For instance, at \( P \approx 760 \) torrs, \( T = 300K \), \( k \approx 2 \), \( E \approx 2 \times 10^5 \, V/cm \) (near corona electrode pins)

\[
\sigma \approx 10^{-16} \, cm^2 \text{, } (\sigma/e_0) = 30, \lambda_0 = 22 \, ev, \sigma_{max} = 3 \times 10^{-16} \, cm^2, n(0) \approx 10^{-13}, \text{ and } a(0) = 3 \times 10^{-4},
\]

\[
u \approx 3 \times 10^8 \, cm/s \text{ one can obtain } E/P = 260 \, V/cm \text{ torr}
\]

\[
\tau \approx 210 \, V/cm \, torr, \tau \approx 10^{-12} \, s, \Delta \approx 3 \times 10^{-11} \, s, \text{ and } a(30) = 3 \times 10^{-11} \, s. \text{ Therefore even during residence time } \Delta t \approx \Delta t \ll \Delta t \text{ in small regions with space scale } \Delta L \ll a \text{ (e.g., in small parts of the corona region in which field } E \text{ is approximately uniform,} \text{ many electron generations and a large amount of excitations of gas particles can be formed.}

Discussion and Conclusion - Remarks

The approach considered in the previous section can be applied to various TDDs. Consider for example, positive turbulent corona (PTC) at \( P \approx 1 \) at, described in ref. 1. The PTC differs very much from its counterpart in non-flow conditions, although the field \( E(r_0) \) is also non-uniform: very high near positive electrode.
pins (e.g., $E_a \approx 50 - 200$ kV/cm and $E_a/P \approx 70-250$ V/cm torr) and much lower in regions far removed from the pins (e.g., $E_a \approx 1-5$ kV/cm and $E_a \approx 1.5-6.6$ V/cm torr). Only part of the gas entering the discharge volume pass through the corona region and is affected by field $E_a$. However, intensive ionizations and excitations in this part of gas produce electrons, ions and promote intensive radiation which can form photoelectrons and ions in regions far removed from the pins (e.g., in simple gases Ar, H$_2$, He, etc.).

Turbulent pulsations directly involving ions and affecting electrons through Coulomb coupling:

(i) Affect much formation of the space discharge$^{1,2}$. (ii) Spread charged particles over the discharge zone and increase sharply cross section $S_c$ of conducting channel$^1$ and the volume $V_a = S_a L_a$ of the corona zone with relatively high electron concentration $n_e$ and $\varepsilon$ not too large, but sufficient for excitations of not very high levels, for pumping, for initiations of plasma chemical reactions, etc.$^2$; this volume can be enlarged by overlapping of such zones formed by neighbouring pins$^{1,2}$. (iii) Prevent from streamer formation and from break downs of the discharge at relatively high currents $I$ and power input $W$. (iv) Lead to much higher smoothness of the discharge in time and space, and causes a significant increase of effectively working electron area $E_t = n_p \cdot S_p$ associated with the corresponding growing up of the number, $n_p$, of simultaneously working pins and of working areas $S_p$ per pin. (v) Promote better cooling of electrodes (if they are heated) and lower heating of the gas passing through the discharge zone. The aforementioned properties can be used for initiation of plasma chemical reactions and for pumping of turbulent gas discharge lasers (TGDLS's) in relatively large active volumes.$^2$ A similar approach with some modifications can be applied to transverse TCs. Note that the kinetics of phenomena in near-electrode plasma layers (PLs) in hydrodynamically turbulent gas, caused by the secondary electrode emission, can be considered through the correspondingly modified approach used in ref. 21 for the treatment of processes in PLs in laminar flows.

Summarizing all the aforesaid one can make the following conclusions.

1. A gas portion entering the discharge volume is affected by the non-uniform time-dependent field $E(r,t)$ during a short time where $r = (x,y,z)$ are the space coordinates in the moving coordinate system accompanying the gas flow. This field can be a random function of time $t$ due to random turbulent pulsations even in the case when $E(r_0)$ does not depend on time.

2. A part of this gas is affected by the strong electric field $E_a$ near the pin electrodes, associated with high $E/N$, e.g., $E/N \approx 10^{-14}$ to $10^{-15}$ V cm$^{-2}$ at $N \approx 3 \times 10^{19}$ cm$^{-3}$ and $E \approx (3$ to $1) \times 10^5$ V/cm. In these short-term conditions the highly non-equilibrium and non-stationary electron energy distribution $f(\varepsilon,t)$ (which can be also anisotropic) "tune" into electronic excitations and ionizations of gas particles. For example, in He/N$_2$/CO$_2$ mixture with the molar ratio 3/2/1 the larger and larger amounts of power go into the ionizing process, beyond $E/N$ of about $2 \times 10^{-16}$ V cm$^{-2}$.$^{22}$ Intensive avalanche formation, the CPT, electronic excitations and radiation take place in this part of the discharge which serves as the internal ionizer promoting the discharge also in parts of its volume more removed from the electrode pins. Therefore, the turbulent
coronas can work without any external ionizer (electronic beam, etc.)

3. The discharge volume $V_R$ not too close to the electrode pins, enriched by electrons having not too high energy, can be used for pumping of lasing levels and as a plasma chemical reactor. For low $E/P$, the rate coefficients of these processes can be presented in the form, using Eqs. (22) and (25).

$$K \sim \frac{n}{(2nBt)^k} \int \left[\frac{(e^{-e_0/t} - 1)}{2^\beta - t}\right] \times f(e_0, t_0) de_0 de$$

where $K$ can depend on space coordinate and $t$ also through $n$, $A$, and $B$. Therefore, such a discharge with volumetric temperature and discharge stability control, with not small power input $W$ and current $I$ and with the relatively high active volume $V_R$ can be considered as a scalable device relying neither on walls nor low pressures for operation. In particular, for the aforementioned mixture $H_2N_2CO_2$ at $E/N$ of about $10^{-16} \text{ V cm}^2$ more energy enters the upper laser states than the lower, and inversions are possible. 22

4. The problem of the quality and optical homogeneity of the laser medium in the TDDs arises in connection with turbulent pulsations. This problem should be carefully elaborated. However, one can expect that fine-scale turbulence with small $A_0$ and high $Q_0$ and $Re/Re_*$ should be less severe than large-scale. Therefore, it can be expected that the increase of $Re/Re_*$ can promote not only the higher transport coefficients, power inputs $W$ and currents $I$ but also a higher degree of optical homogeneity of the laser medium.

5. The rapid CPTs in the hydrodynamically turbulized gas lead to the problem of interactions of the hydrodynamic turbulent pulsations with waves and fluctuation in the newly formed plasma. Our knowledge on this field is very poor and this problem deserves to be studied in detail.

6. We think that a special attention should be paid to the problem of the non-stationary non-equilibrium electron energy distributions at high $E/P$, when characteristic GPT time intervals are small and formation of high-energy runaway electrons is rather probable. These electrons can have an anisotropic non-stationary distribution function and the conventional approaches to its calculation are not very valid.

The sharp increase of power input and of the transport coefficients and other related phenomena described in ref. 1-3 and in this paper seems to show some interesting possibilities for applications of the TDDs and demonstrate the very multi-disciplinary character of this field. We are hopeful that the development of the TDD problem presented in this paper will stimulate further investigation of the non-stationary non-equilibrium kinetics of the TDDs.

References

3. Y.L. Khait, Abstracts XIV UPAP Int. Conf. on Statistical Physics, Edmonton Alberta, Canada (1980).
7. S. Corrsin, Phys. Fluids 1, 42 (1958); 7, 1156 (1964)