Lev Tsendin: Impact on Gas Discharge Physics

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Agenda

Fundamentals of Electron Kinetics in LTP
• The Concept of Total Energy
• Kinetic Equations for Different Electron Groups

Applications to Glow Discharges:
• Positive Column
• Anode Region
• Cathode Region
• Striations

Analytical Approaches to Plasma Discharge Problems
• Oscillations in Townsend DBD
• Ionization Fronts
Scientific Carrier

The formation of L.D.Tsendin as a scientist was far from simple. He graduated from the Department of Theoretical Physics and was a post-graduate student of Prof. G.F.Drukarev – a known expert in quantum collision theory.

After graduate school, L.D.Tsendin taught for several years at the Forestry Academy and Shipbuilding Institute.

At the end of 60's he came in contact with Prof. Yu.M.Kagan at Leningrad University. In parallel with teaching, Tsendin began studying theoretical problems in gas discharge plasma, and received his Ph.D. for studies of ionization waves in DC discharges.

A new stage in scientific carrier of L.D.Tsendin was associated with his transition to the Polytechnic University of St.Petersburg, where he worked until his death.
**Fluid vs Kinetics**

**Fluid**

Particles are described by five quantities:

1. Density
2. Mean directed velocity
3. Temperature,

They depend on 4 scalar arguments – 3 spatial coordinates and time.

**Kinetic**

The only quantity is the Velocity Distribution Function (VDF) – the particle density in phase space

\[ f(v, r, t) \]

It depends on 7 scalar arguments – 3 spatial coordinates, 3 velocity components and time.

“The development of modern physics of gas discharges requires more thorough and more precise (first of all kinetic) description. Without using the new kinetic approach, it is impossible to understand mechanisms of many phenomena”
Electron Kinetics in Gas Discharges

Due to low mass, electrons lose a small fraction of their energy in elastic collisions with neutral gas particles:

\[ \frac{\partial f}{\partial t} + \mathbf{v} \nabla f + \frac{e\mathbf{E}}{m} \frac{\partial f}{\partial \mathbf{v}} = S \]

Lorentz models for elastic collisions of electrons with neutrals:

Isotropic scattering

\[ S_B = \nu \int_{S^2} [f(\Omega') - f(\Omega)] d\Omega' \]

Small angle scattering

\[ S_C = \nu \Delta \Omega f \]

Lorentz collision operators modify the direction of electron velocity but conserve its modulus or kinetic energy.

Total energy is an approximate invariant of electron motion in a weakly ionized gas under effects of electric fields.
Slow Electrons

Inelastic collisions are rare compared to elastic collisions for the majority of electrons in gas discharges – Electron Velocity Distribution Function is nearly isotropic in velocity space.

Collisional plasma: $L \gg \lambda$

$$f(v, r) = f_0(v, r) + \frac{v}{v} \cdot f_1(v, r)$$

trapped and free electrons

Joule heating

$$f_1 = -\frac{v}{v} \nabla f_0 + \frac{eE}{mv} \frac{\partial f_0}{\partial v}$$

During its life time, each electron must generate (on average) one electron-ion pair.

Near-collisionless plasma: $L \sim \lambda$

$$f(v, r) = f_0(\varepsilon) + f_1(v, r)$$

trapped and free electrons

collisionless heating

$$f_1 = -\frac{v}{v} \nabla f_0 + \frac{eE}{m} \frac{\partial f_0}{\partial v}$$
Total energy formulation

\[ \frac{\partial f_0}{\partial t} - \frac{\partial \varphi}{\partial t} \frac{\partial f_0}{\partial \varepsilon} + \frac{1}{v} \left[ \nabla \cdot (vD_r \nabla f_0) + \frac{\partial}{\partial \varepsilon} \left( V_\varepsilon f_0 + D_\varepsilon \frac{\partial f_0}{\partial \varepsilon} \right) \right] = S \]

Spatial derivatives are calculated at constant **total** energy

Boundary conditions specified at surface

\[ \varepsilon = \frac{mv^2}{2} + e\varphi(\mathbf{r}, t) \]

\[ \varepsilon = e\varphi(\mathbf{r}, t) \]

“Electrons, like people, are fertile and infertile: high-energy electrons are fertile and able to reproduce” – L. Tsendin

The energy relaxation length:

- EEDF body
  \[ \lambda_\varepsilon = \lambda \sqrt{\frac{v\varepsilon}{V_\varepsilon}} \sim \lambda \sqrt{\frac{M}{m}} >> \lambda \]

- EEDF tail
  \[ \lambda_\varepsilon = \lambda \sqrt{v/v^*} > \lambda \]
Fast Runaway Electrons

Runaway electrons appear
- cathode regions of DC discharges
- pulsed discharges of dense gases
- strong electric field near streamer tips
- runaway breakdown in atmosphere

Runaway criteria

\[
\frac{dp}{dt} = eE - \frac{p}{p} F(p)
\]

\(\mu\) is the cosine of the angle between the electric field and the momentum vector

\[
\frac{dp}{dt} = eE\mu - F(p)
\]

\[
\frac{d\mu}{dt} = \frac{eE(1 - \mu^2)}{p}
\]

Scattering moves electrons across characteristics
Kinetic Equation for Fast Electrons

\[
\frac{\partial f}{\partial t} + v \nabla f + a \nabla_v f = S
\]

\[
S = v \Delta_\Omega f + \frac{\partial}{\partial \mathbf{p}} \left( \frac{\mathbf{p}}{P} F(w) f \right) + I
\]

Small angle scattering is described as a diffusion over angle

Energy loss in collisions is described as quasi-continuum retarding force

“Fast electron is like Don Juan, it does not distinguish between free and bound electrons, as Don Juan does not distinguish between married and unmarried women” – L Tsendin

Generation of secondary electrons by impact ionization

\[
I = \delta(v) \int_0^\infty v' \Phi(v') f dv'
\]

\[
\Phi(w) = \frac{F(w)}{\varepsilon_0}
\]

Analytical Solution for Fast Electrons

Strongly anisotropic EDFs are typical to runaway electrons

Analytical solution with neglect of scattering

\[ \frac{\partial f}{\partial t} + v \frac{\partial f}{\partial x} - \frac{eE(x,t)}{m} \frac{\partial f}{\partial v} - \frac{\partial}{\partial v} \frac{F(u)}{m} = I(x, v, t) \]

Assuming \( F(w) = F_0 = \text{const} \)

and using total energy, we obtained

\[
f(\varepsilon) = \frac{m\Gamma}{e\phi_c} \left( \delta(\varepsilon - 1) + \frac{\alpha \phi_c}{E(x_0(\varepsilon))} \exp(\alpha x_0(\varepsilon)) \right)
\]

\( \Gamma \) is the electron flux from the cathode

\[ \alpha = \frac{NL_0}{\varepsilon_0} \]
allgemeine übersicht (general overview)

In the general case, the rates of scattering and energy loss depend on electron energy and gas type.

In domain $a$, both the EVDF body and its tail are almost isotropic. The electron motion is a random walk, which corresponds to diffusion in energy. In domain $b$, the energy loss in inelastic collisions can be treated as quasi-elastic. In domain $c$, the EVDF body is isotropic, but the tail highly anisotropic. In domain $d$, both the EVDF body and the tail are strongly anisotropic, with a needle-like EVDF along the electric field. Domain $e$ corresponds to electron runaway.

Selection of specific models depends on gas type, electron energy, the value of the electric field, and angular dependences of inelastic collision cross-sections.

EDF formation in external electric fields for arbitrary ratios of scattering and deceleration

Participants of the NATO Workshop “Electron Kinetics and Applications of Glow Discharges, St Petersburg, Russia (1997)
Jim Lawler, Lev Tsendin, and Yuri Golubovsky during the NATO Workshop, St Petersburg, Russia (1997)
Positive Column of DC discharges

- Separate axial electric field and radial ambipolar field
- Include radial field into total energy

\[
\frac{1}{r} \frac{\partial}{\partial r} r \Phi_r + \frac{\partial}{\partial \varepsilon} \Gamma_{\varepsilon} = \sum_k \left[ \nu_k^* w^{1/2} f_0 - \nu_k^* (w + \varepsilon_k)(w + \varepsilon_k)^{1/2} f_0 (w + \varepsilon_k) \right]
\]

Two limiting cases:
- local: $\lambda_\varepsilon << R, \quad f_0 = n_e (r) F_0 (w)$
- BHT: $\lambda_\varepsilon >> R, \quad f_0 (\varepsilon)$

Generalized Boltzmann relation

\[
f_0 (w, r) = f_0^{(0)} [\varepsilon = w - e\phi (r)].
\]
Positive Column of DC discharges

Intermediate case is the most interesting and unexplored

\[ \frac{1}{r} \frac{\partial}{\partial r} r \Phi_r + \frac{\partial}{\partial \varepsilon} \Gamma_\varepsilon = S \]

Streamlines of the phase flow vector \((\Phi_r, \Gamma_\varepsilon)\)

for Argon (a) and Oxygen (b) at \(p = 6\) Torr and \(R = 1\) cm

Radial distribution of excitation rates for Ar at different pressures

Ambipolar electric field can heat up electrons!

E.A. Bogdanov & A.A. Kudryavtsev, Technical Physics 54 (2009) 810

Nitrogen \(p = 0.15\) Torr, \(R = 1.6\) cm
Positive Column: Free Flight Regime & Langmuir Paradox

Maxwellian EEDF observed in positive column of low-pressure DC discharges is one of the most mystifying phenomena in the physics of gas discharge plasmas.

Langmuir first observed this phenomenon in the 1920s, and returned repeatedly to this paradoxical discrepancy between experiment and an estimate that seemed based on physically obvious considerations.

Since inter-electron collisions are rare under “Langmuir-paradox” conditions, various mechanisms for Maxwellization of the electrons have been discussed in the literature but no satisfactory explanation of the observed effects has yet been obtained.

Tsendin suggested that the Langmuir paradox is not related to some unknown mechanism for Maxwellization, but to the physical features of the formation of the EEDF under these conditions (loss cone).

Model calculations of the EEDF in the positive column of low-pressure glow discharges showed possibility of approximating it by an exponential with a single slope over a wide range of energies, i.e. a combination of already known mechanisms operating in low-pressure discharges can create EEDF that are close to Maxwellian.

A.A. Kudryavtsev and L. D. Tsendin, Mechanisms for formation of the electron distribution function in the positive column of discharges under Langmuir-paradox conditions, TECHNICAL PHYSICS 44 (1999) 1290
Anatoly Kudryavtsev, Vladimir Kolobov and Lev Tsendin at St. Petersburg State Polytechnical University
Cathode Region: Electron Groups

Kinetic Theory of the Cathode Region in DC Glow Discharges

The Sign of Anode Potential Fall

For large currents – negative potential fall. For low currents – the sign of potential fall changes from negative to positive with increasing gas pressure.

The value of anode fall is about ionization potential, and is much lower than cathode fall: Electron and ion currents in the anode sheath change by $b_i/b_e$, whereas in the cathode sheath by $\ln(1+1/\gamma)$.

Negative fall corresponds to a double layer and trapping of electrons in the potential well, similar to the cathode region.

Positive fall correspond to anode glow and anode dark space.

Electron kinetics is the “missing link,” to construct a consistent theory of phenomena in the anode region.


Theory of anode region:

Schematic potential profile in the anode region. Electrons move in horizontal planes with conservation of total energy.
Anode region of DC Glow Discharges

An extended region of visually uniform spatially-inhomogeneous plasma was uncovered by the theory and confirmed experimentally.

Analytical solution (a) and measured (b) EEDF at various distances from the anode (labels in cm). EEDF is depleted by slow electrons at $\sim \lambda_e \gg R$.

Theory of Striations in Rare Gases

- Theory of hydrodynamic waves in diffuse positive column for low pressures and high currents
- Theory of kinetic resonances and analytical model of kinetic striations
- Theory of 2D striations in constricted positive column (jointly with Golubovskii & Kolobov)

Kinetic Resonances in Spatially Periodic Electric Fields

A spatially periodic electric field with a potential difference in its period, slightly exceeding $\varepsilon_1$ (by a fraction of $k$), acts on the EEDF as a klystron with respect to energy, spanning differential fluxes to resonant trajectories. Any EEDF injected into such a field contracts near resonant trajectories into a delta-shaped distribution.

Tsendin obtained an equation for differential flux and analyzed formation of resonant trajectories for S- and P-striations.

Later, Winkler and Golubovskii with coworkers solved numerically 1D kinetic equation for given spatially modulated field. R-striations were attributed to $p=3/2$ resonance and confirmed in experiments.

A self-consistent theory of S-, P-, and R-striations is still lacking. It is also not clear whether striations corresponding to other values of $p$ are actually possible.

Robert Arslanbekov, Vladimir Kolobov and Lev Tsendin at CFDRC, Huntsville, AL, 2005
Analytical Approaches to Glow Discharge Problems

Current Pulses in Dielectric Barrier Discharges

Low-frequency Townsend regime:

\[ \tau = \frac{L}{E_{br} b_i} \ll \frac{2\pi}{\omega} \]

An analytic model of a uniform DBD has been proposed.

This equation describes the motion of a particle in a system with a driving force and alternating friction. Using this analogy, the nature of current pulses was revealed, expressions for maximal and minimal electric fields and the oscillation frequency derived, and scaling laws were obtained.

Comparison with Experiments

He, 760 Torr, L=0.3 cm, d=0.23 cm, \( \varepsilon = 7.63 \), \( \gamma = 0.01 \).


Summary

• L.D. Tsendin did pioneering work on nonlocal electron kinetics, the theory of ionization waves and high-frequency discharges, the theory of near-electrode regions, the theory of Langmuir of probes in the diffusion regime, etc. His ideas fell on fertile ground, and began flourishing thanks to both theoreticians and experimentalists. Along with theoretical publications, numerous experiments appeared in which predictions of the kinetic theory were tested and applied to a variety of objects.

• Scientific style of articles written by L.D. Tsendin, highly saturated with new ideas in combination with brevity of presentation, required a very thorough job of readers studying them. Not every specialist could appreciate the depth of the ideas embodied in these works.

• Problems of understanding Tsendin’s works have been partially resolved with the publication of several reviews and the book "Physics of the glow discharge," (in Russian) which appeared in recent years.
Summary

• L.D. Tsendin was one of the most prominent figures working in the field of gas discharge physics, possessing a distinctive and unusual thinking, the ability to penetrate into the essence of the physical mechanisms of very complex phenomena. He liked to uncover hidden nature of things and hated “white noise” produced by some authors.

• L.D. had a colorful personality. Some of his favorite phrases:
  This is Marxism.
  What I told you three times is true.
  An average soviet electron …
  ……………..

• He left behind a dedicated group of followers converted into his “nonlocal religion” and willing to further develop his ideas and methods.
Co-authors and Followers

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“Almost all of my students are extramarital” – L.D. Tsendin