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Preface to Special Topic: Electron kinetic effects in low temperature plasmas

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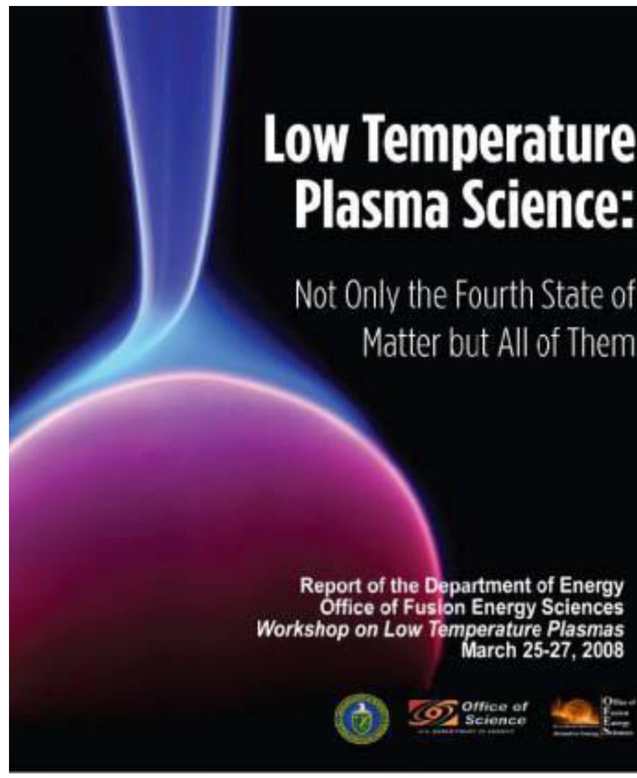
Low temperature plasmas (LTPs) are widely used in applications and are strongly affected by the presence of neutral species—chemistry adds enormous complexity to the plasma environment. Electron energies in such plasmas are of order a few electron volts with sufficient population of electrons with energies above the threshold energies of the excited states of neutral atoms and molecules. The power transfer from electrons to these atoms and molecules produces activated species (e.g., radicals, excited states, and photons). Due to the low degree of ionization, the mean energy of electrons and ions in such plasma considerably exceeds the temperature of the neutral species. This provides a unique set of conditions wherein plasma species can efficiently react with adjacent surfaces resulting in their beneficial modification. With such properties, low temperature plasmas are widely used in technological processes, ranging from manufacturing of semiconductor chips, solar and plasma-display panels, to the treatment of organic and bio-objects.[1]

Low temperature plasmas are characterized by a high degree of non-equilibrium. Electrons and ions are not in thermodynamic equilibrium and both are not in equilibrium with the neutral species. And they are not in equilibrium within their own ensemble, thus, demonstrating a significant departure from a Maxwellian distribution.

This unique property of LTPs is at the foundation of its ubiquitous use in numerous applications, as it was outlined in 2008 Report on Scientific Directions for Low Temperature Plasma sponsored by the Department of Energy.[1] This topic generated continued strong interest in the plasma community as evidenced by a series of scientific workshops:

- Workshop at the 64th Annual Gaseous Electronics Conference, 2011 "Control of Distribution Functions in Low Temperature Plasmas" organized by Igor D. Kaganovich, Yevgeny Raitses, David Graves, and Gottlieb Oehrlein, in Salt Lake City, Utah (http://meetings.aps.org/Meeting/GEC11/SessionIndex2/?SessionEventID=158302).
- Workshops at the 62nd Annual Gaseous Electronics Conference, 2009, "Role of Electron Kinetics, Swarms" organized by Zoran Petrovic (http://meetings.aps.org/Meeting/GEC09/SessionIndex2/?SessionEventID=108579).
- "General Kinetic Models" organized by Mirko Vukovic (http://meetings.aps.org/Meeting/GEC09/SessionIndex2/?SessionEventID=110525).
- Workshop on "Nonlocal, Collisionless Electron Transport in Plasmas", 2005 in Princeton NJ, organized by Igor D. Kaganovich, Yevgeny Raitses, and Samuel Cohen.



Proceedings of this workshop were published in a Special Issue of IEEE Transactions of Science.[2]
- The NATO Advanced Research Workshop on "Electron Kinetics and Applications of Glow Discharges," held in St. Petersburg, Russia, on May 19–23, 1997. Proceedings of this workshop were published in the book "Electron kinetics and applications of glow discharges", edited by Uwe Kortshagen and Lev D. Tsendin.[3]

This Special Topic Section was triggered by the premature death of the pioneer and leader of this field, Professor Lev D. Tsendin, and can be viewed as a tribute to his contributions to the field.

Photographs of Lev D. Tsendin visiting Germany and USA in the 1990s showing his enthusiasm for laugh and cakes.

Lev Tsendin made major contribution to the development of nonlocal electron kinetics for studying gas discharge phenomena.[4] He was one of the first to realize that LTPs with non-Maxwellian Electron Energy Distribution Function (EEDF) can be adequately treated by considering the EEDF

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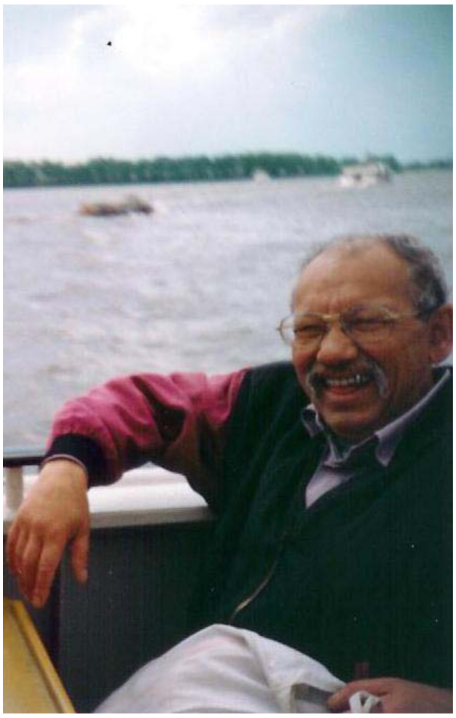

as a function of the total electron energy (kinetic + potential), which is an (approximate) invariant of the electron motion in a non-uniform plasma in a non-uniform electromagnetic field. Tsendin showed that in many cases the nonlocal approach allows solving semi-analytically the Boltzmann equation for the EEDF.

This method was first proposed by Bernstein and Holstein[5] and then was independently rediscovered by Tsendin.[4] Bernstein and Holstein applied the method to the positive column and concluded that—"the principal effect of the space charge field is an enhancement of the tail of the distribution function, with a consequent increase in specific ionization. The magnitude of the latter effect, however, is found to be much too small to account for the large ionization rates required in steady state discharges—." In contrast to Bernstein and Holstein, Tsendin realized the potential of the method and applied it with great success to a variety of discharge problems: the cathode and anode regions of dc discharges, radio frequency discharges, and ionization waves (striations); see, for example, his recent reviews[6] and books.[7] Tsendin identified different mechanisms of striations in DC discharges of rare gases and developed a kinetic theory of electron bunching and kinetic resonances. Kolobov wrote an excellent review of Tsendin's contributions to the kinetic theory of gas discharges in this special issue of *Physics of Plasmas*.[8] The paper by Golubovskii *et al.*, in this issue, reviews the latest developments of Tsendin's ideas about kinetic resonances and stratification of glow discharges.

The next logical step in the development of electron kinetics was not only explaining the observed kinetic phenomena but using this accumulated knowledge to explore ways of actively crafting EEDFs to achieve required effects. This research is the focus of DOE funded Center for Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems.[9] The complex dependence of different chemical reactions on electron energy places an extraordinary premium on optimally shaping EEDFs to influence the rate of interaction of a particular process. The ability to control the efficiency of the interaction of charged particles with their environment (gas atoms and molecules, or surfaces) depends on the ability to craft and control charged particles and photons distribution functions. Advancing LTP science requires the ability to control and to shape charged particles and photons distribution functions for beneficial treatment of surfaces, which is a challenging task considering the diversity and complexity of the variety of discharge conditions.

This Special Topic Section contains papers that demonstrate how this strong non-equilibrium in the velocity and energy distributions of its charged constituents affects plasma self-organization and how it can be utilized in applications. The Review paper by Godyak summarizes methods of EEDF control in gas discharge plasmas.[10] Papers[11,12] consider ways to control EEDFs making use of an auxiliary electrode in dc discharge. The authors of Refs. 13 and 14 investigate kinetic effects on physical mechanisms of self-organization in gas discharges of the Townsend type. The effects of magnetic fields on plasma self-organization are studied in Refs. 10, 15, and 16. The effects of plasma

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chemistry, negative ions in combination with nonlocal electron kinetic effects are investigated in Refs. 17–20 for different plasma producing gases. Geometric effects of antenna size on electron kinetics in inductively coupled plasmas are discussed in Refs. 10 and 21. These are just few examples in the diverse field of kinetic, nonlocal effects on plasma self-organization in gas discharges.

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