White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
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• Statistical mechanics of plasmas	S

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	"X"
Oral	X
Poster	
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Title:	**Formation of Electron Energy Distribution and Gas Discharge Structure in near-collisionless and dynamic regimes**
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

An anomalous short relaxation length of the cathode beam and the existence of the Maxwellian electron energy distribution function (EEDF) in the positive column of a dc arc discharge at low gas pressure were found by Langmuir [1,2] and have been known in the literature as the Langmuir paradox.

Under the condition of the Langmuir paradox, when the electron mean free path λ exceeds the tube radius, R (pR $\leq$ 20 mTorr·cm), the relaxation length of the electron cathode beam (of a few mm) appeared to be about 3-4 orders of magnitude less than the estimated collisional relaxation length. This part of the paradox was resolved by Merrill and Webb [3] by discovering the plasma-beam instability. They have found strong microwave oscillations with frequencies close to the local plasma frequency in the beam relaxation zone. Those oscillations transformed the cathode electron beam to the dispersed spectrum electron swarm.

Langmuir's conclusion about Maxwellian EEDF was based on the fact that the measured electron part of the probe I/V characteristic, $I_e(V)$ on a semi-log scale $\ln[I_e(V)]$ could fit a single straight line for elastic ($\varepsilon < \varepsilon^*$) and non-elastic ($\varepsilon > \varepsilon^*$) electron energy ranges. Here, ε^* is the excitation energy. Langmuir's observation becomes surprising after taking into account fast losses of high energy electrons in the processes of electron excitation, ionization and escape to the wall of the tube. However, numerous experiments performed in course of several decades after the paradox was formulated confirmed Langmuir's finding.

So far, none of many hypotheses put forward to explain the paradox proved to be credible [4,5]. Despite considerable advancement in understanding many of the plasma kinetic and electrodynamic phenomena in gas discharge plasmas and their successful modeling, the existence of Maxwellian EEDF in the positive column of dc linear discharges at low gas pressure has remained a mystery.

Recent experiments [6] with positive column of a dc discharge in the Tonks-Langmuir regime, (the experimental setup is shown in Fig.1 revealed strongly non-Maxwellian and non-isotropic EEDF. The non-Maxwellian EEDF shown in Figure 2 were obtained using recently developed instrument with high energy resolution and wide dynamic range.

These experimental data obtained over wide range of discharge currents and gas pressure are in strong disagreement with all previous EEDF measurements, latest of which was done about a half century ago. These data also challenge the most rigorous EEDF calculation existing today at the condition of Langmuir paradox [7] which show Druyvestein-shaped distribution. Spatial periodicity of the EEDF in the quiescent discharge [6] and similar temporal periodicity of the moving striations observed in the same set-up [8] may find its explanation in strongly non-Maxwellian and non-isotropic EEDF originated due to non-local electron heating in an axially non-uniform electric field caused by the discharge stratification. Non-Maxwellian EEDFs found in our experiment in argon gas cast doubts on the very existence of Langmuir paradox and call for farther experiments and calculations.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The challenge of the present problem requires synergetic study (experimental, theoretical and numerical) of two poorly understood and apparently coupled problems: striations and the EEDF formation and their interplay in low-pressure near-collisionless discharge plasma.

This implies reexamining experimental evidences of the Langmuir Paradox by measuring EEDF (its symmetrical and directional parts) over wide range of the gas pressure and discharge current for different positions and orientations of cylindrical and flat probes. Theoretical and modeling efforts supplementing these experiments should involve EEDF calculation in the positive column at low gas pressure. This would require comprehensive analysis of EEDF accounting for finite anisotropy, the loss cone and, possibly, the particle-wave interaction.

Carrying such program out would require:

a) Developing the probe technique (experimental equipment and processing routine) for diagnostics of EEDFs in strongly non-equilibrium and non-isotropic plasmas where traditional Druyvesteyn method is not applicable.

b) Creating the comprehensive database of the plasma parameters and discharge structure along standing and moving striation with purpose of understanding their effect on EEDF.
c) Theoretical and numerical efforts to model and understand interplay between EEDF and striation structure and comparison with experimental observations.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Successful accomplishment of the program outlined above would resolve a century old problem of the Langmuir paradox. But more important, it would advance development of new diagnostic techniques, and refine theoretical approach and numerical code involving the plasma kinetics, which is needed for analyses of complicated highly non-uniform, non-equilibrium plasma and non-isotropic dc and rf plasma systems. Progress in this area would impact the plasma materials processing, fusion and space plasmas.

References

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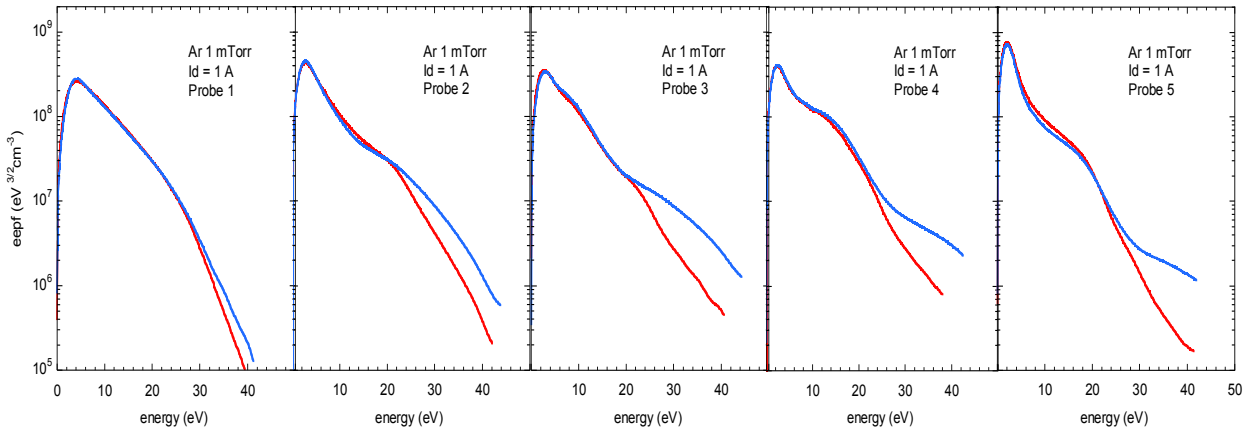

Fig. 1 – EEPF evolution along the positive column of Ar DC discharge. Red and blue correspond to radially and axially oriented cylindrical probe. The distance between the probes is 20 cm.