EEDF in Argon Positive Column at Low Pressure

(Does Langmuir Paradox exist?)

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The Langmuir Paradox

An anomalously short relaxation length of the cathode beam and the existence of a Maxwellian electron energy distribution function (EEDF) in the positive column of a dc arc discharge at low gas pressure have mystified scientists for over 80 years. Discovered by Langmuir himself, today these phenomena are known as the Langmuir Paradox. Numerous experiments, performed in next decades, have confirmed the Langmuir's finding.

The first part of the paradox was resolved by Merrill and Webb a few years later (Phys. Rev. **55**, 1191, 1939). They observed plasma-beam instability near the cathode long before this instability was discovered by theoreticians. However, the existence of Maxwellian EEDF in the positive column of a dc linear discharge still remains a mystery in spite of the impressive theoretical and experimental achievements gained in last decades in the understanding of many plasma phenomena in low temperature plasmas.

In the present stature, the Langmuir paradox splits in two questions:

First one - does the paradox really exist? Indeed, the data base on EEDF in low pressure positive column has been obtained decades ago, when EEDF measurement techniques were immature. Today's measurement equipment is much more sophisticated: high energy resolution and dynamic range, able to resolve the low energy electrons, as well as electrons in the inelastic energy range. All this is a great motivation to revisit the EEDF data base.

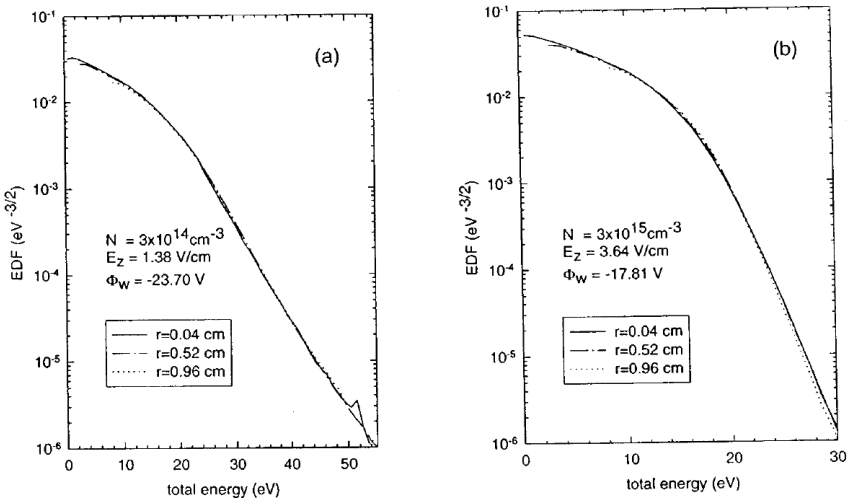
The second question is: what is the EEDF at such condition, and if the EEDF is Maxwellian - why?

Langmuir Paradox milestones

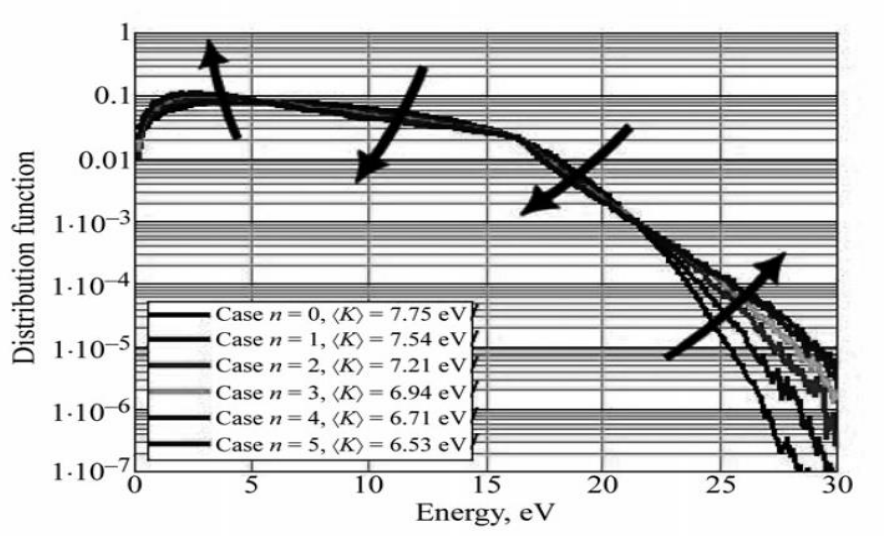
Author(s)	milestone	Reference
Langmuir	LP discovery and formulation	**1929**, Phys. Rev. **33**, 1995
Merrill and Webb	Plasma-Beam instability	**1939**, Phys. Rev. **55**, 119
Crawford, and Self	Latest review of LP	**1965**, *Int. J. Elec.* **18**, 569
Kagan	Latest exp. study & review	**1970**, *Gas Discharge Spectroscopy*
Rayment and Twiddy	Non-Maxwellian EEDF	**1968**, *Proc. Roy. Soc. A*, **304**, 87
Kudryavtsev & Tsendin	Non-local PC model	**1999**, *Tech. Phys*. **44**, 1290
Mayorov	EEDF in periodic E field	**2013**, *Bulletin of PGPI **40**, 258*

- Many hypothesis were put forward in an attempt to explain the paradox; neither of them were proved so far.
- In spite of the impressive achievements in today's modeling of complicated phenomena in RF discharges, the Langmuir Paradox remains a mystery
- A general perception among specialists about LP problem is the lack of reliable experimental data

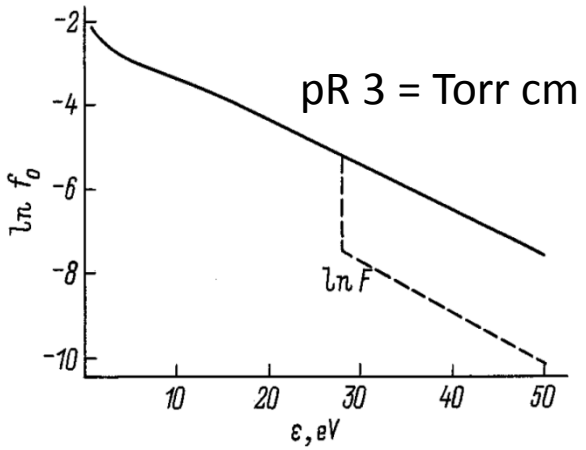
Modeling of EEDF in Ar PC

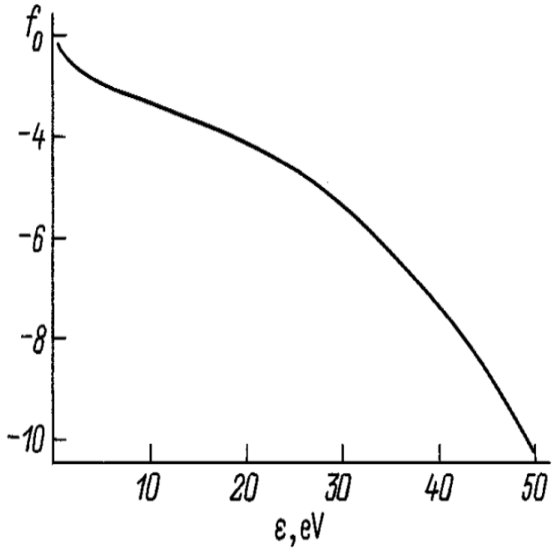


*Kortshagen et al, Phys. Rev. **E54**,6746,1996*



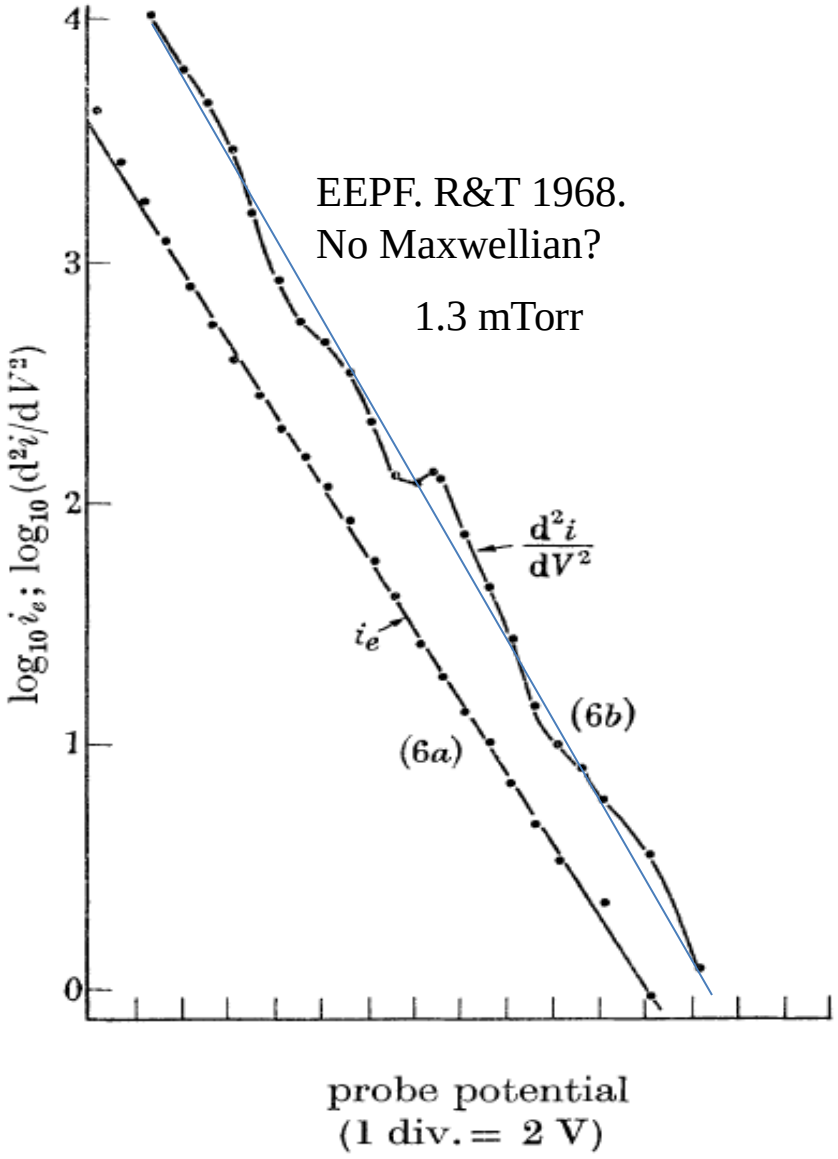
*Mayorov, Bulletin. of PGPI **40**, 258,2013*

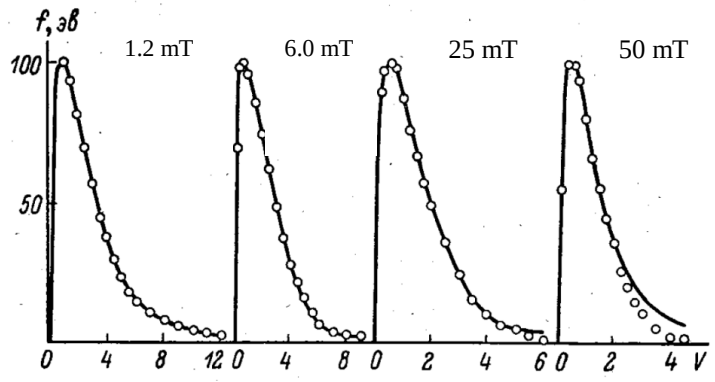




*Kudryavtsev & Tsendin, Tech. Phys. **44**,1290,1999*

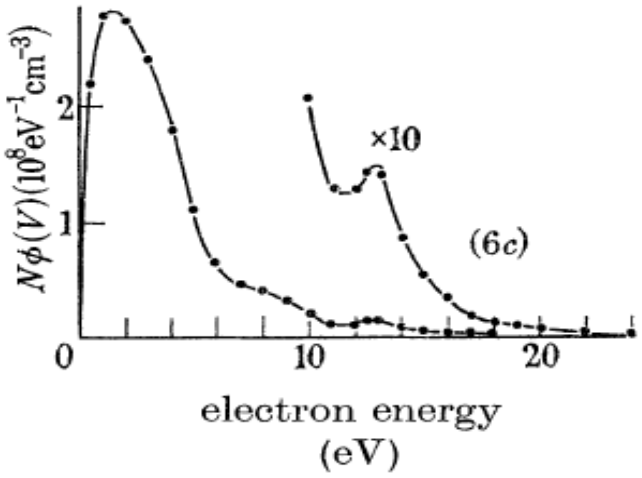
EEDF experiment in Hg PC





EEDF, $f \propto \varepsilon^{1/2}$(EEPF). Kagan, 1970. Maxwellian
No information about low energy electrons,
and to small dynamic range (no fast electrons)

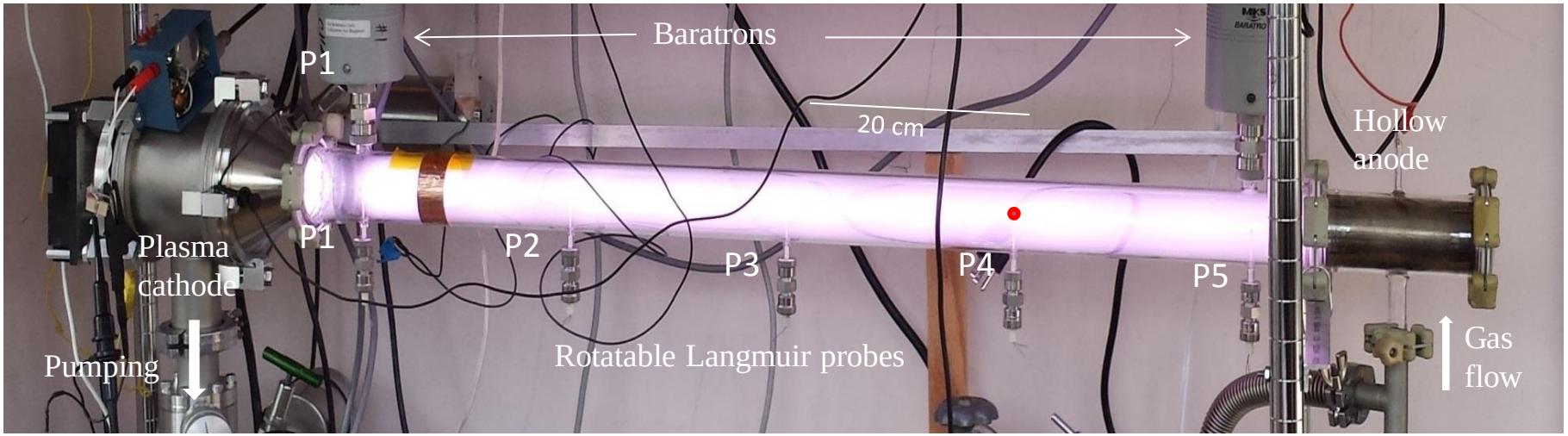
EEDF, $f \propto \varepsilon^{1/2}$EEPF. R&T. 1968. No Maxwellian



Existing experimental data base (half century old) has to be revisited taking advantage of progress in EEDF measurement technique

Experimental setup

R_{in}= 2.5 cm, total length -120 cm, PC length - 90 cm, $I_d \leq 3$ A, p_{Ar}=1-10 mTorr

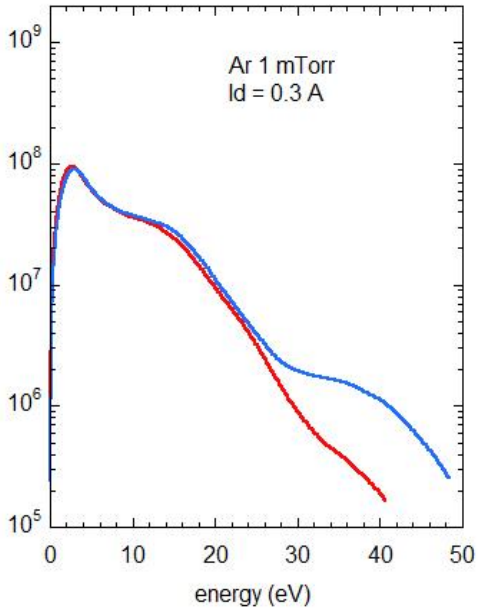


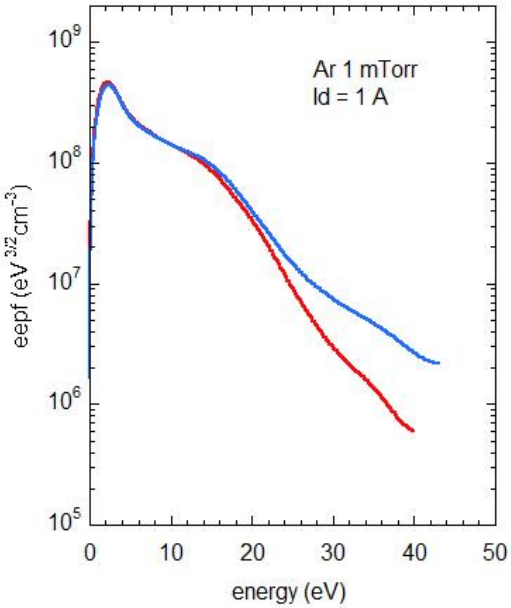
The measurements were performed with the latest version of Plasma Sensors probe station, MFPA having superior energy resolution and dynamic range

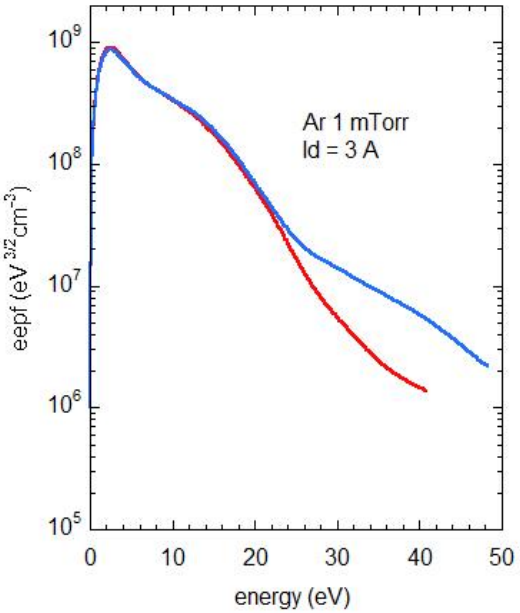
www.plasmasensors.com

EEPF at 65 cm, for 1 and 3 mTorr, and 0.3; 1.0 and 3.0 A

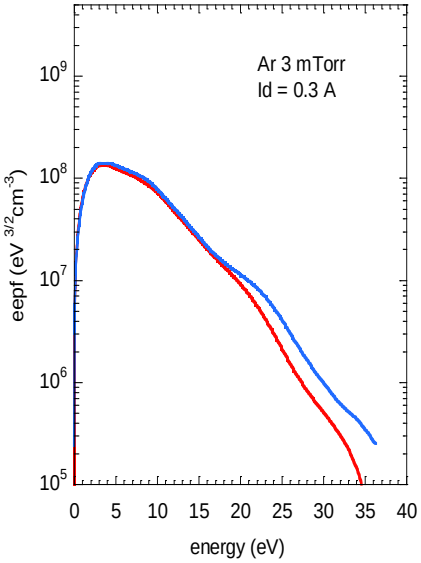
radial probe orientation — axial probe orientation

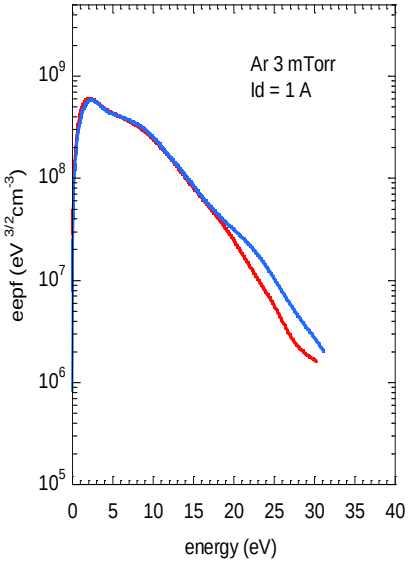


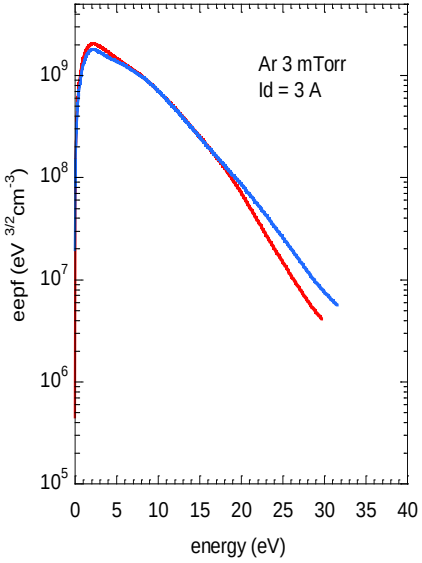




1 mTorr

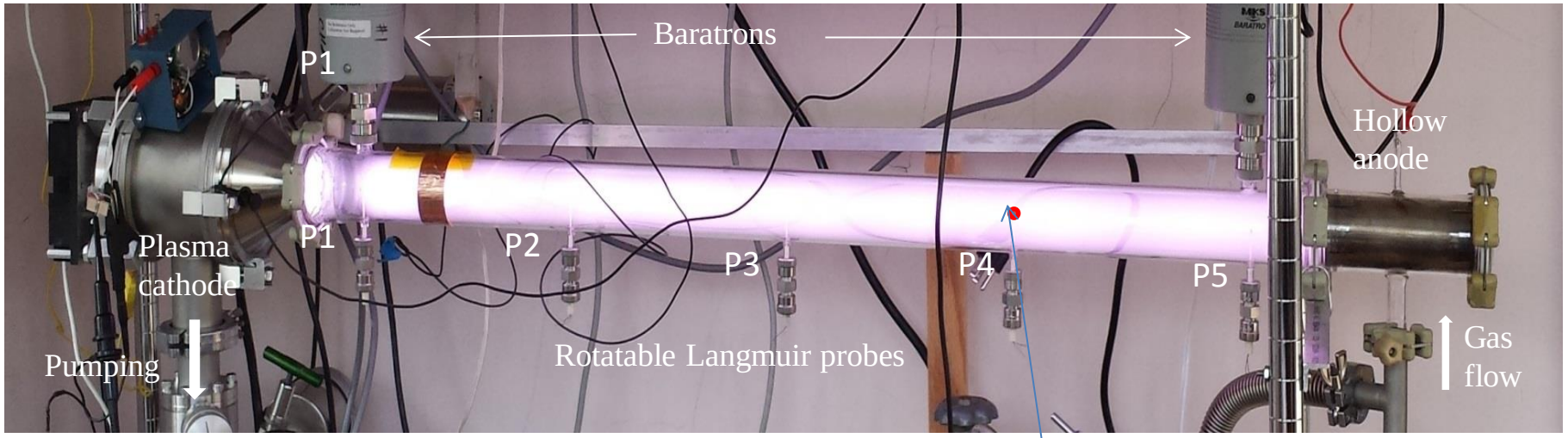


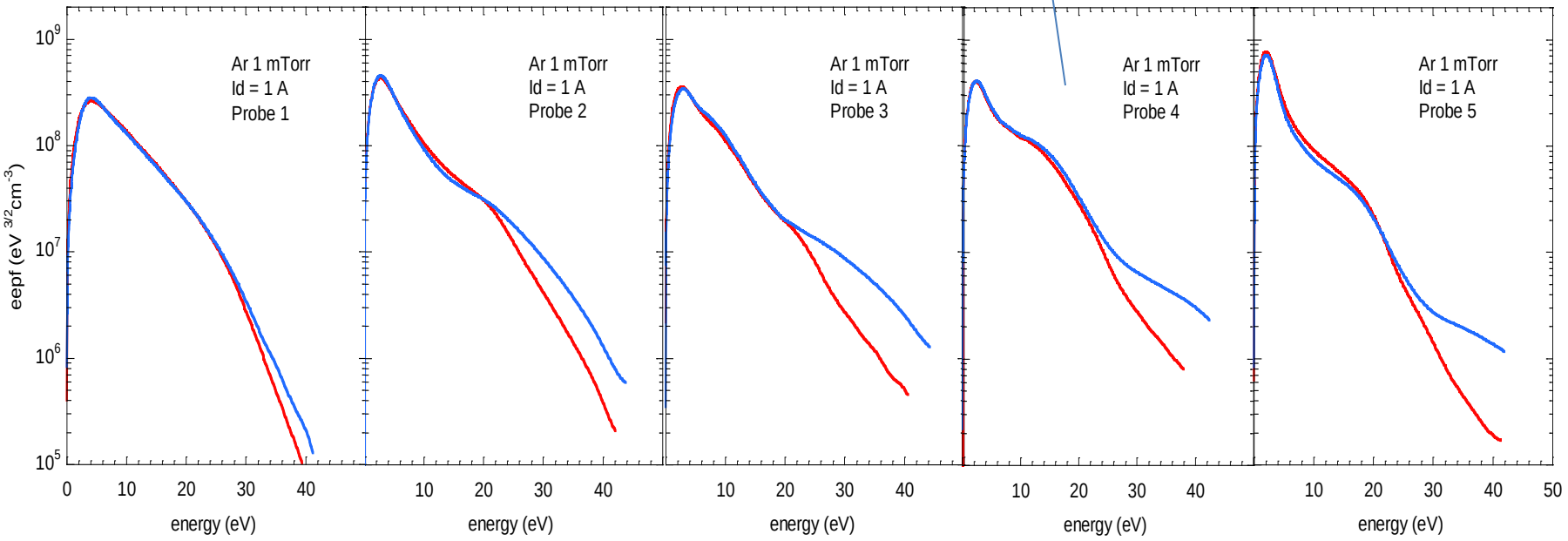




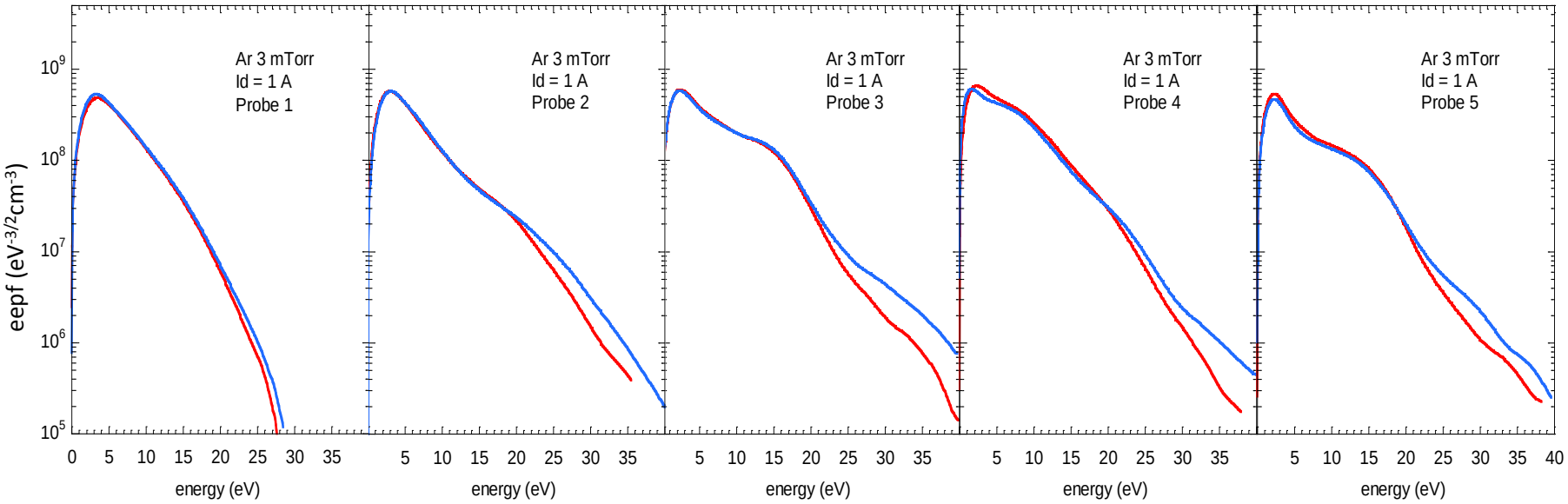
3 mTorr

EEDF measurement along the positive column, 1mTorr





EEDF measurement along the positive column, 3 mTorr

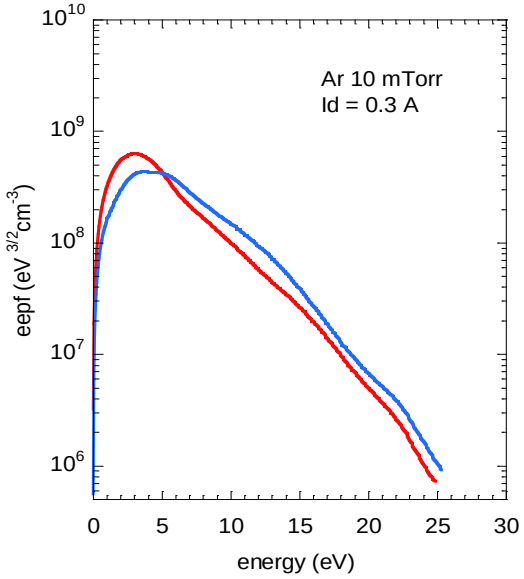


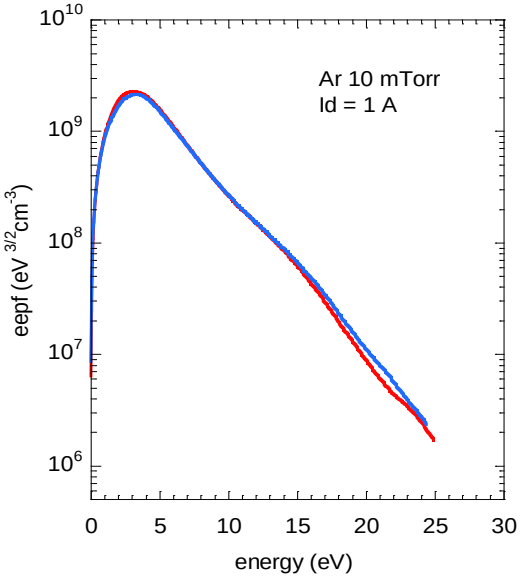
In the pressure range 1-10 mTorr there were no moving striations.
Some periodicity in the EEDF reflects a non-uniformity along the discharge, similar to a standing striation.

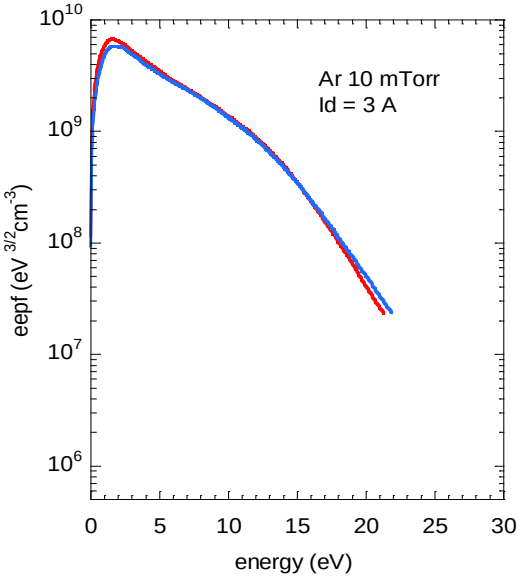
There is a strong deviation from Maxwellian EEDF

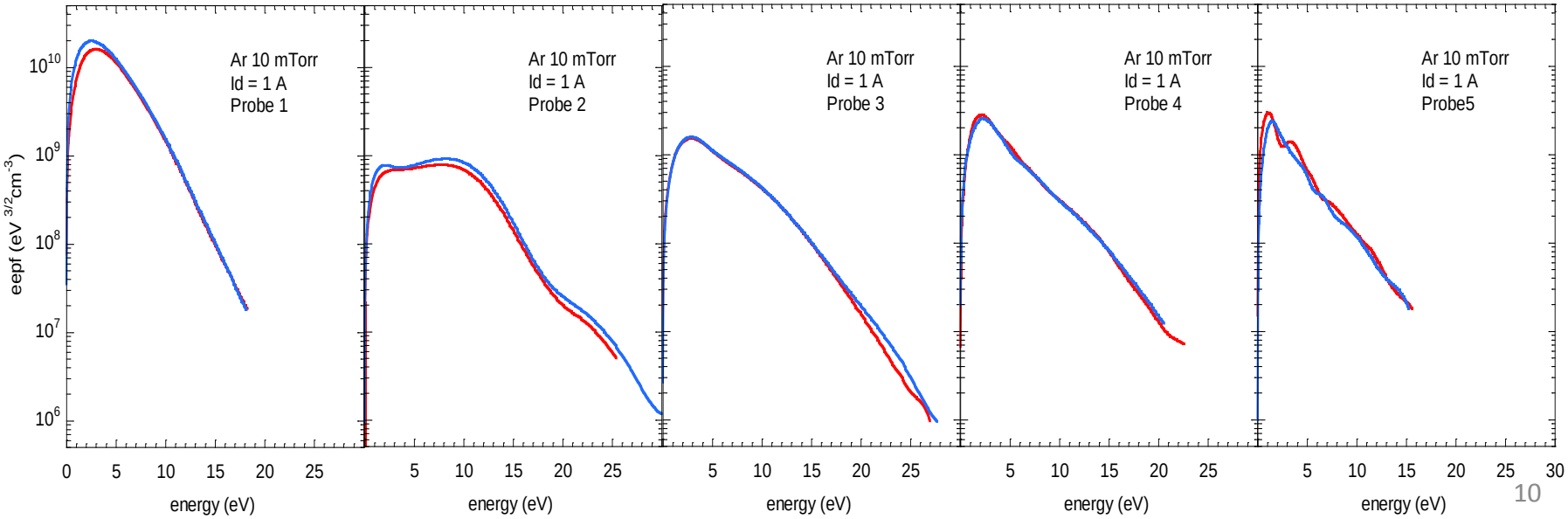
Similar non-Maxwellian EEDF and its axial non-uniformity was found in Hg positive column. *Godyak et al, GEC 2006*

Results for 10 mTorr at P4, and along the PC

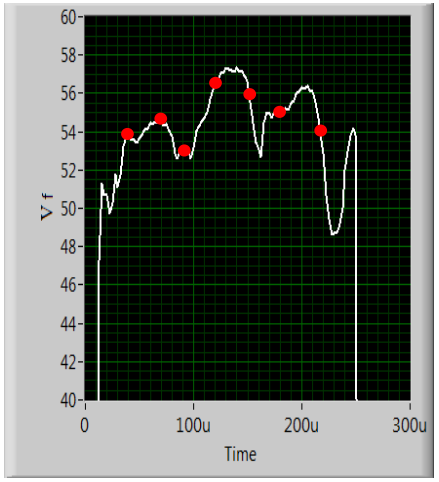








Time resolved EEDF in PC with moving striations



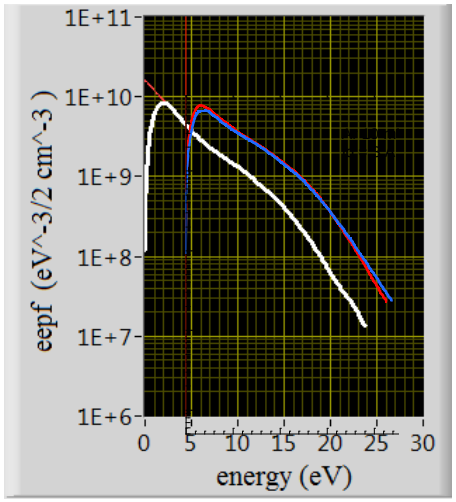
Ar, 10 mTorr, 1 A, 65 cm from the cathode

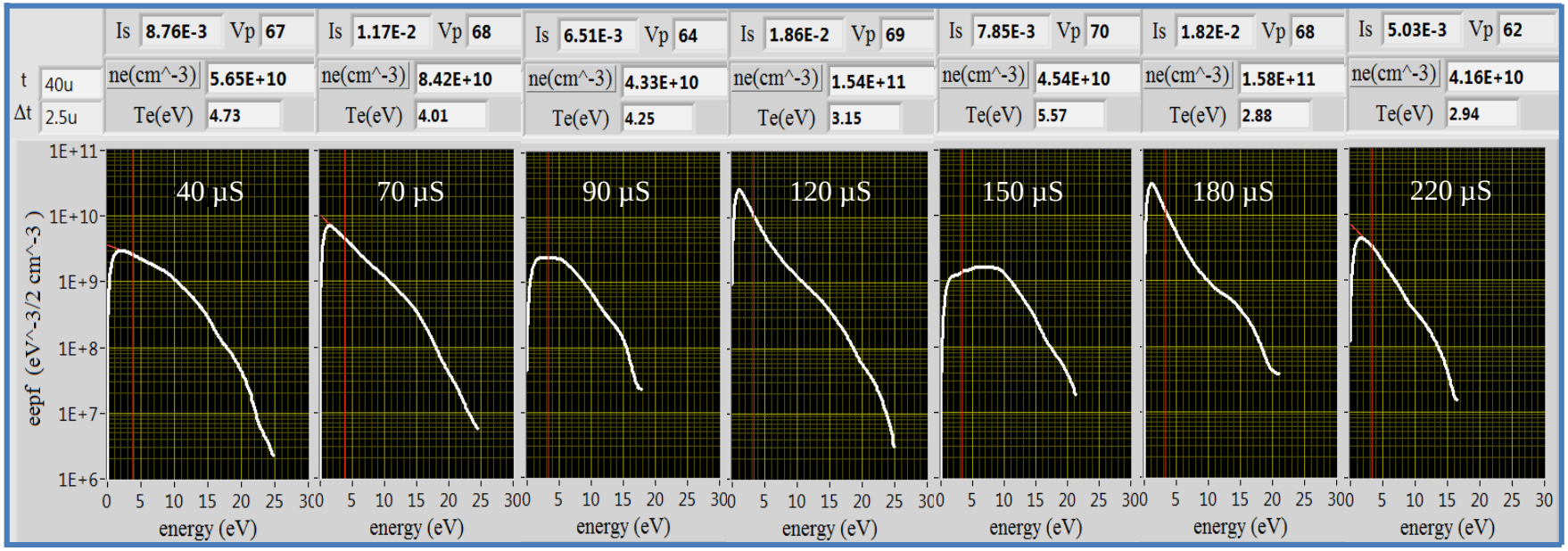
F ≈ 15 kHz, $\Delta V_p \approx 8$ V, $\frac{n_{max}}{n_{min}} \approx 4$, $\frac{T_{emax}}{T_{emin}} \approx 2$

Period 65 μS Time resolution 2.5 μS

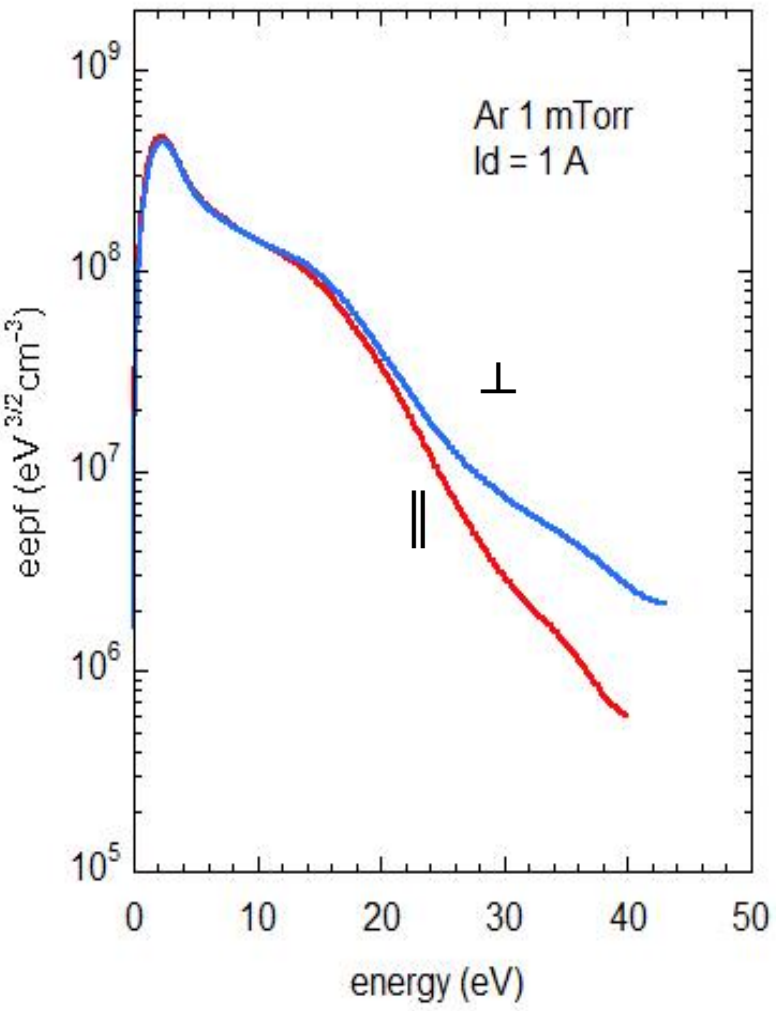
Time averaged EEPF in moving and in standing striations →

← Probe floating potential





What is the nature of the low energy peak?

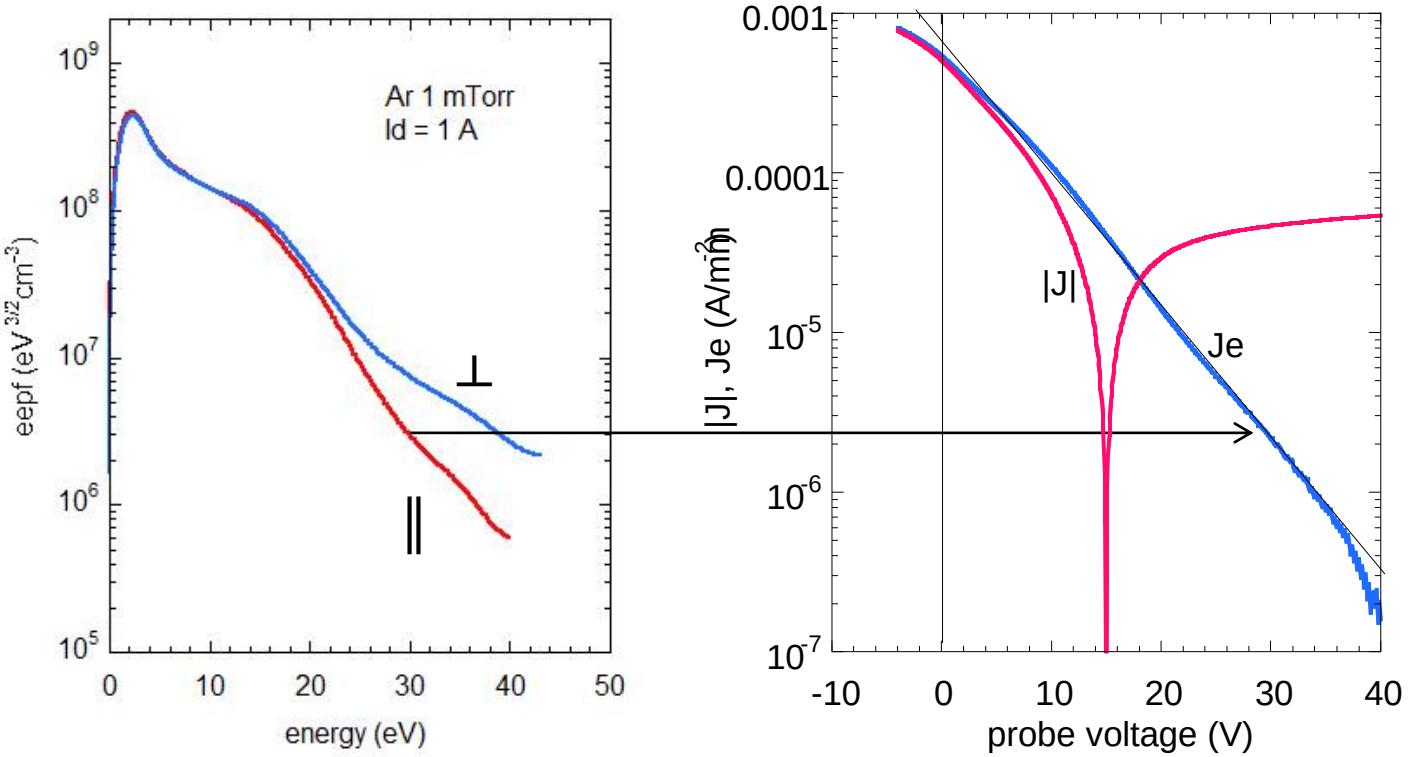


- The low energy peak in EEPF is common in CCP and ICP at low gas pressure. It is due to inability of slow electrons to reach the area of RF field localization. *Godyak & Piejak, PRL, **65**, 996, 1990*
- In stratified PC of dc discharge, the similar patterns of electron heating localization and potential profile occurs leading to the peak and high energy tail formation. *Mayorov, Bull. LPI, **40**,258, 2013*
- The peak may be result of electron energy drop due to ionization, shifting the remaining part of the EEDF tail to the low energy part of the EEDF. In this case, the slope of the low energy pat of the EEPF should repeat that for EEPF with $\varepsilon > \varepsilon^i$. *Kudryavtsev & Tsendin, Tech. Phys.* **44**, 1290, 1999

Where “Maxwellian” EEDF comes from?

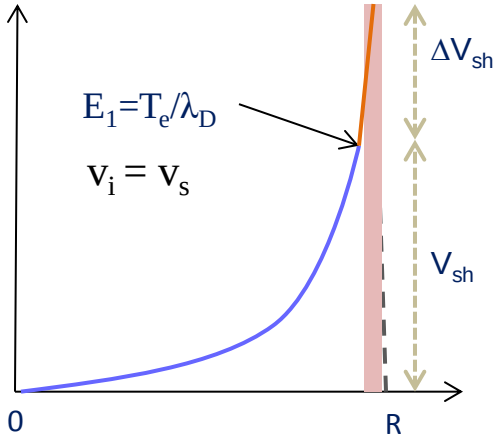
It is known for long time that, practically always, ln[I(V) – I(V)] can be fit with a straight line (expected for a Maxwellian EEDF).
Arbitrariness in the ion current approximation, and uncertainty in the plasma potential give plenty of opportunities to obtain an expected straight line for ln[I_e(V)].

EEPF, I(V) and I_e(V) measured in Ar PC with the axially oriented probe



One-dimensional numerical modeling

- 1D electron Boltzmann equation [1]
- 1D ion continuity equation [2]
- 1D excited states equation [2]
- Poisson equation [2]
- Equation for sheath potential jump [3]
- Eigenvalue for E_r determined at the plasma-sheath interface: $E_1=T_e/\lambda_D$ [4]



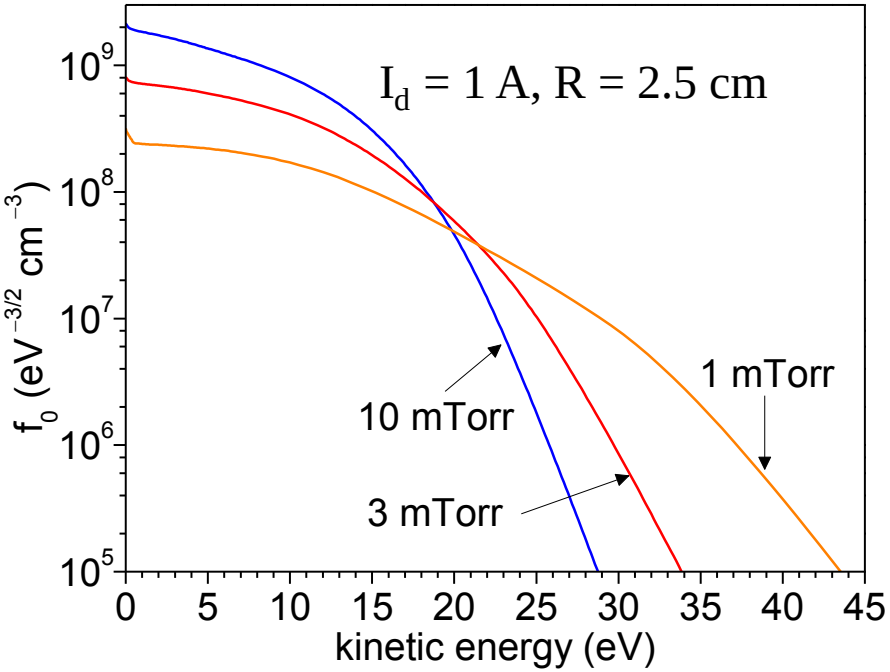
References

[1] D Uhrlandt and R Winkler, J. Phys. D: Appl. Phys. **29**, 115–120 (1996).

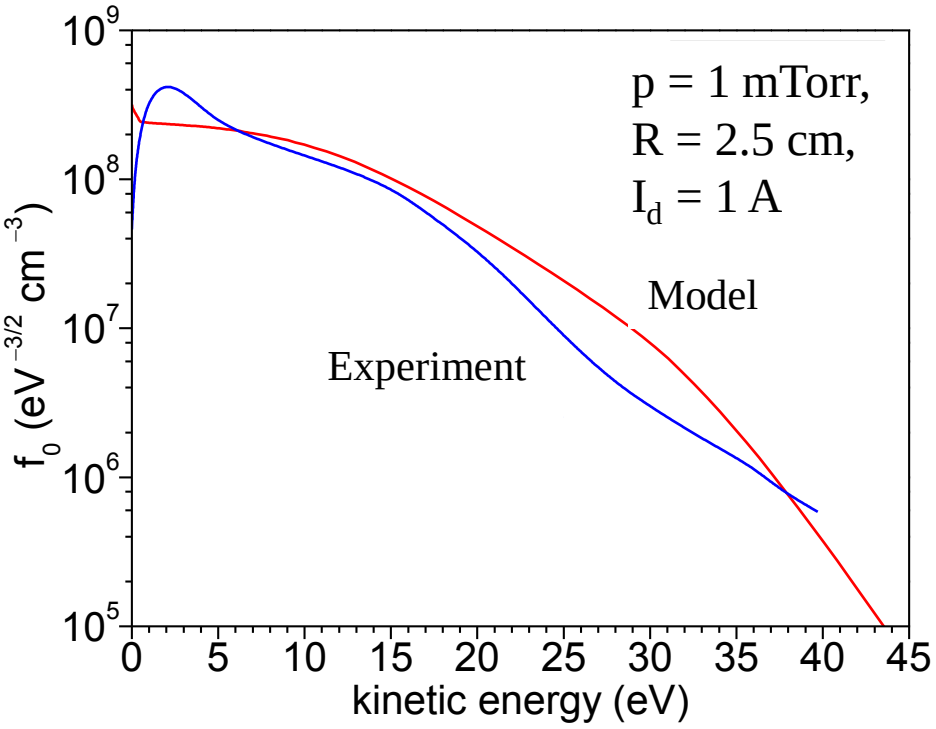
[2] M Schmidt, D Uhrlandt and R Winkler, J. Comp. Phys. **168**, 26–46 (2001).

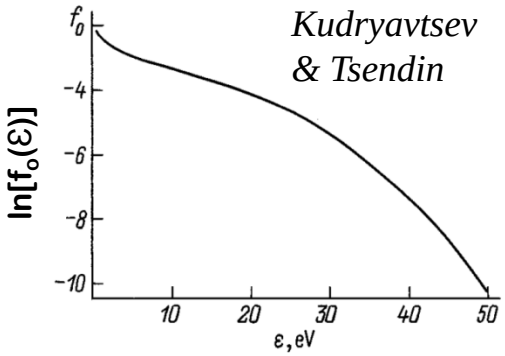
[3] C. Bush and U. Kortshagen, Phys. Rev. E **51**, 280-288 (1995).

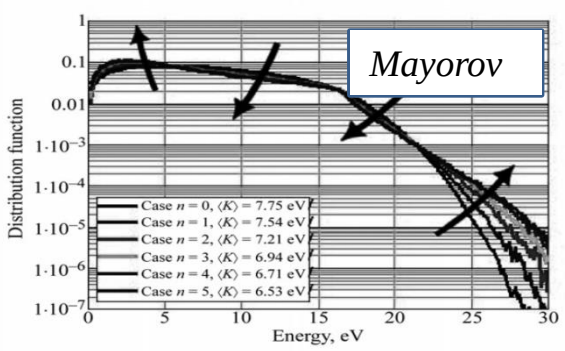
[4] V. Godyak, Phys. Lett. **89A**, 80 (1982).



One-dimensional numerical modeling: comparison to experiment







Experiment: E = 0.26 V/cm, T_e = 6.2 eV, N = $9.5 \cdot 10^9$ cm^{-3}

Model: E = 0.24 V/cm, T_e = 7.9 eV, N = $9.6 \cdot 10^9$ cm^{-3}

Our measurement, seems, supports the notions by these authors towards EEDF formation at low pressure positive column, governed by nonlocal electron kinetics and by non-uniform axial electric field due to discharge stratification

Conclusions

- Application of a modern probe diagnostics to the old problem
- Strongly non-Maxwellian EEDF
- Essential EEDF anisotropy
- Plasma is not in equilibrium with discharge current
- Found new features in EEDF are in agreement with qualitative predictions of non-local semi-analytical model by Kudryavtsev and Tsendin, and calculation EEDF in a space periodical electric field by Mayorov
- Angle-resolved probe measurement is needed for anisotropic EEDF
- Self consistent 2-D kinetic modeling is missing to compare with experiment

Acknowledgements

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