Formation of Electron Energy Distribution and Gas Discharge Structure in near-collisionless and dynamic regimes, their diagnostics, modeling and control

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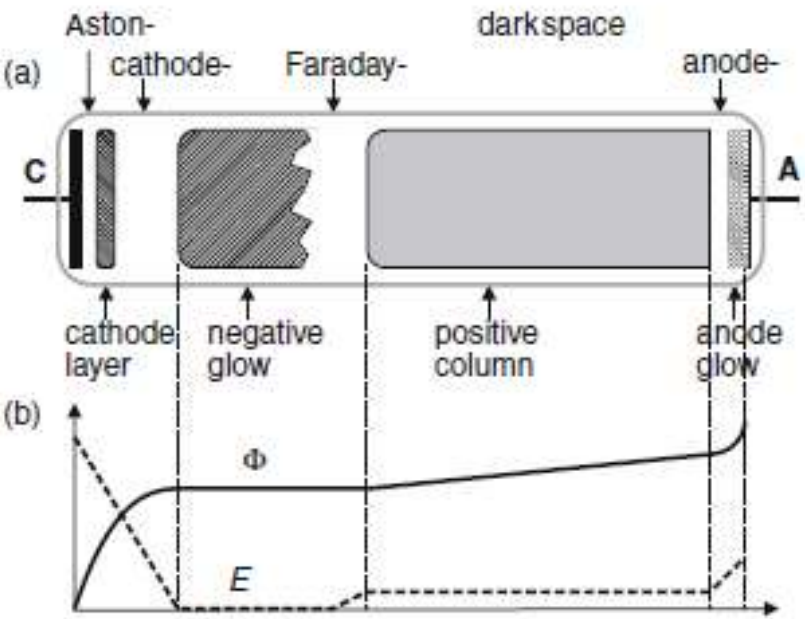
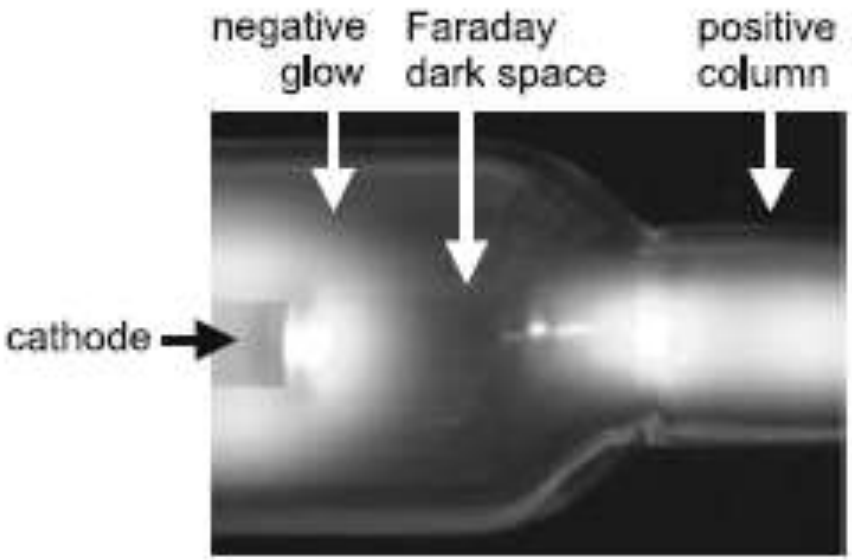
Classical self-organized structures in DC discharge

Example of electron kinetics non-locality





Object	*Feature*	*Mechanism*
• Stable positive column	1-D axially uniform structure	divI = 0 $E \sim N^{-1}$ Self stabilized uniformity
• Cathode plasma	Non-self-sustained cold plasma	Fast electron ioniz.
• Striations (mov. & stand.)	Strong N and T_e perturbations	Ionization instability

Striations are universal states of current-currying plasmas

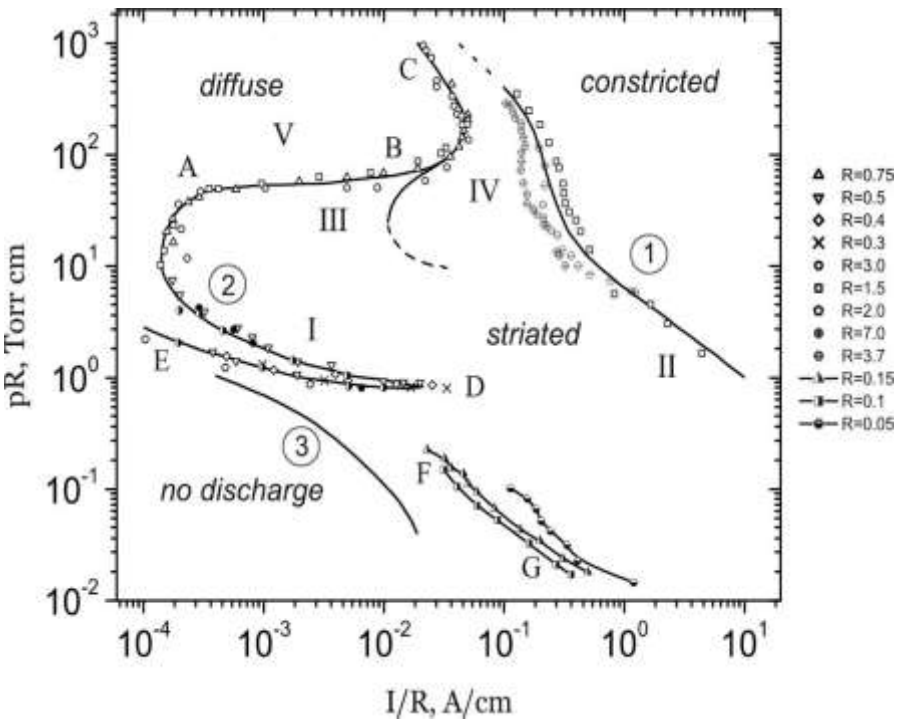
Striations have been observed in DC discharges at pressures 10^{-3}-10^{3} Torr and currents 10^{-4}-10 A in almost all gases

Striations are non-stationary, non-local, highly non-linear and multi-dimensional phenomena that present and ideal object for study of self-organization.

Stratification is closely coupled with EEDF. Kinetic, multi-dimensional approach has already proven its effectiveness.

There are almost no data on striations at near-collisionless regime (pR ~ 1-10 mTorr cm). This regime is of special interest in relation to the Langmuir paradox.

Striations in molecular and electronegative gases remain unexplored



Rich variety of different types of striations in rare gases: all types of striations in rare gases require kinetic models for electrons

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.

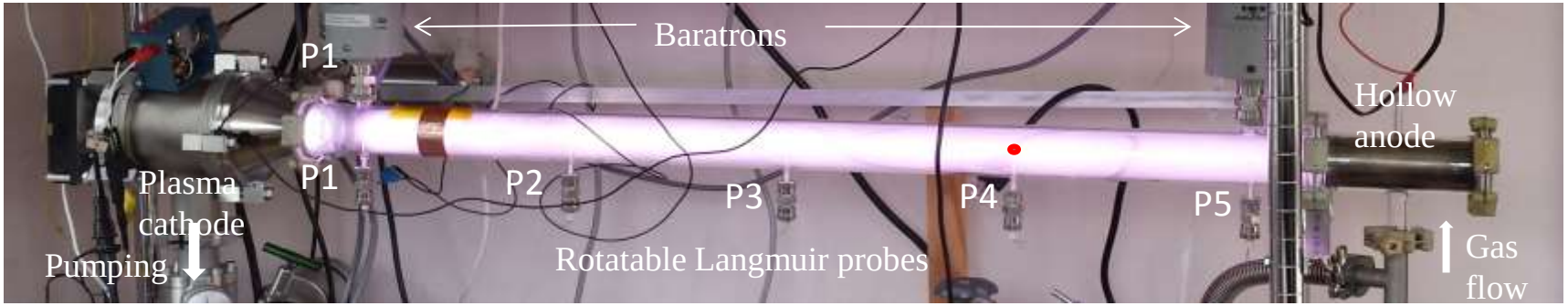
The first part of the paradox was resolved by Merrill and Webb a few years later (Phys. Rev. **55**, 1191, 1939). They observed plasma-beam instability near the cathode long before this instability was discovered by theoreticians. However, the existence of Maxwellian EEDF in the positive column of a 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.

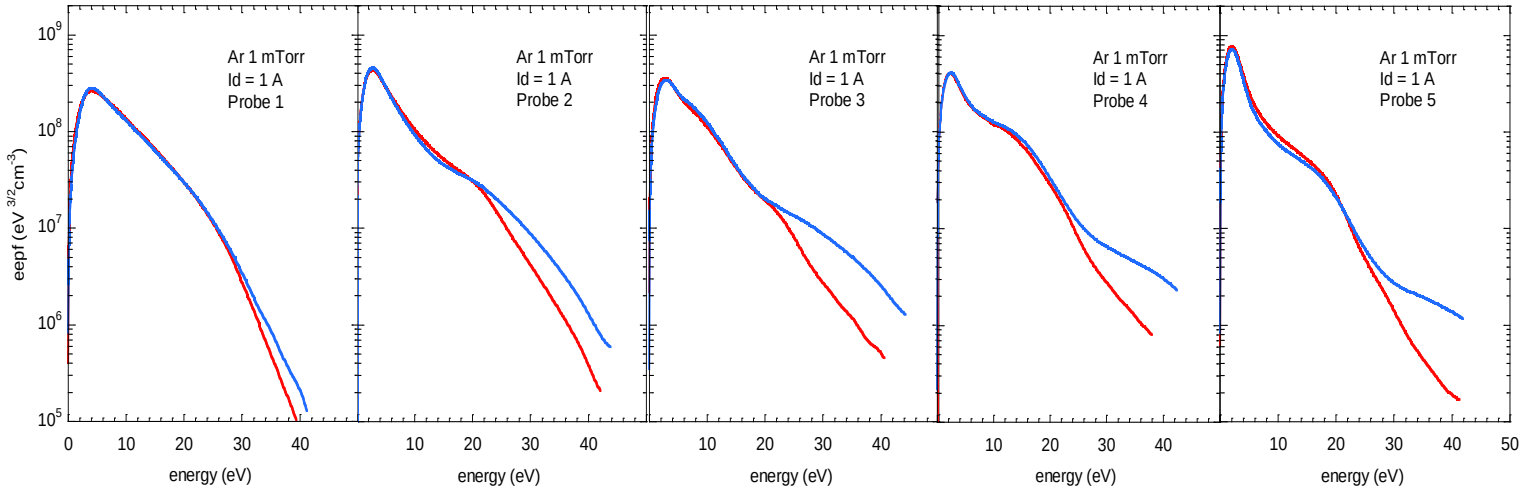
In the present stature, the Langmuir paradox splits in two questions:

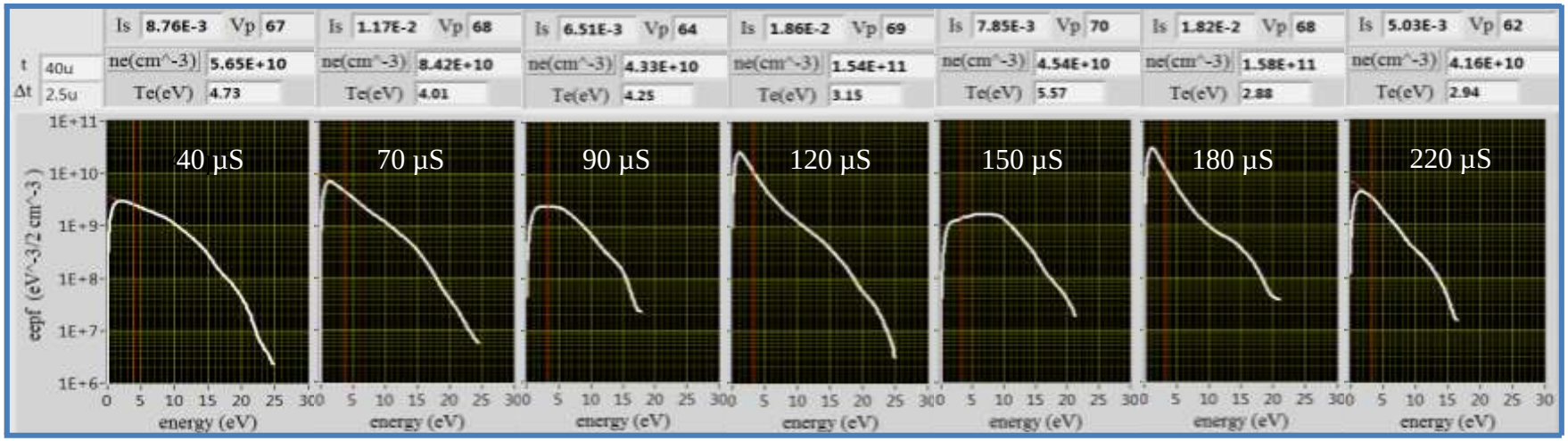
- First one - does the paradox really exist? Indeed, the data base on EEDF in low pressure positive column has been obtained decades ago, when EEDF measurement techniques were immature. Today's measurement equipment is much more sophisticated: high energy resolution and dynamic range, able to resolve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

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**, *PGPI, Russian Sci. Acad., 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 (last was obtained 50 years ego)


Baratrons
P1
P1
P2
P3
P4
P5
Hollow anode
Plasma cathode
Pumping
Rotatable Langmuir probes
Gas flow

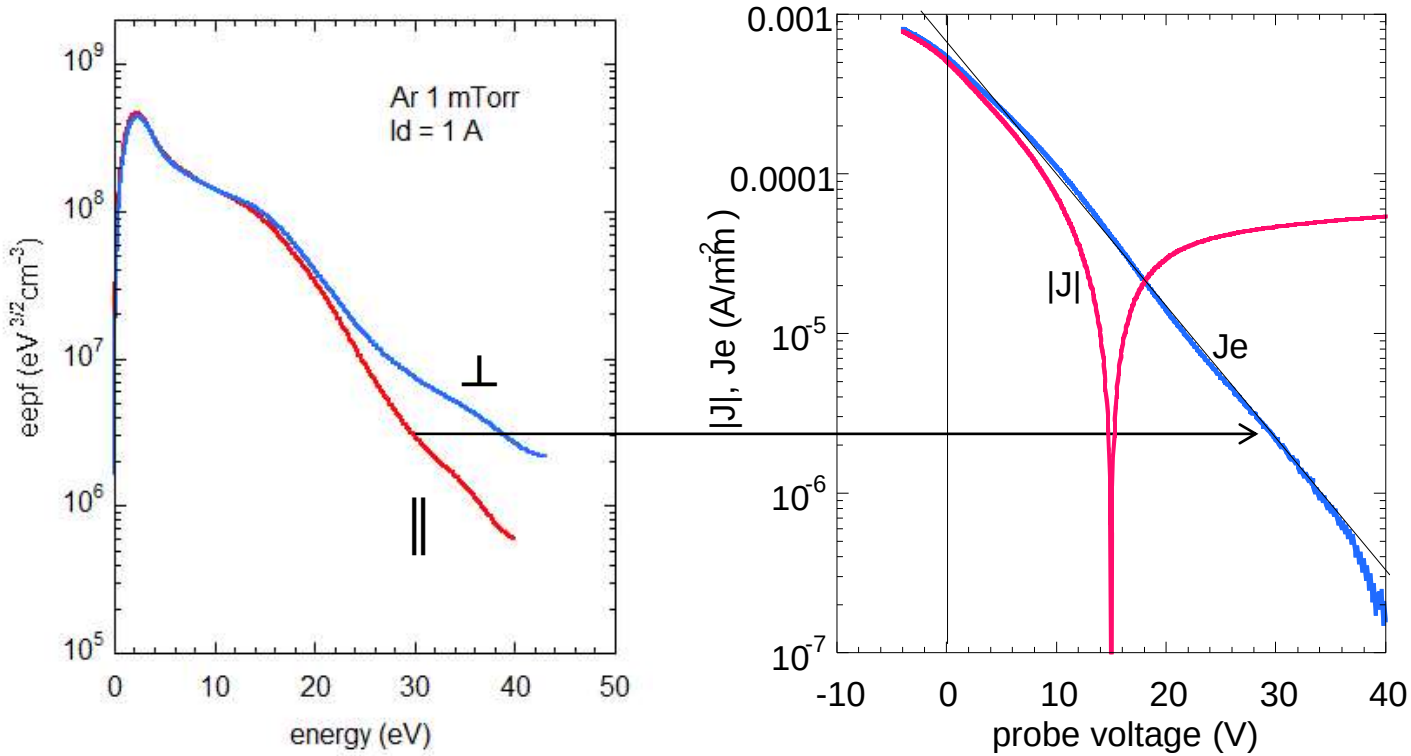

Ar 1 mTorr
Id = 1 A
Probe 1
Ar 1 mTorr
Id = 1 A
Probe 2
Ar 1 mTorr
Id = 1 A
Probe 3
Ar 1 mTorr
Id = 1 A
Probe 4
Ar 1 mTorr
Id = 1 A
Probe 5
eepf (eV^3/2cm^-3)
energy (eV)


Is 8.76E-3 Vp 67
ne(cm^-3) 5.65E+10
Te(eV) 4.73
Is 1.17E-2 Vp 68
ne(cm^-3) 8.42E+10
Te(eV) 4.01
Is 6.51E-3 Vp 64
ne(cm^-3) 4.33E+10
Te(eV) 4.25
Is 1.86E-2 Vp 69
ne(cm^-3) 1.54E+11
Te(eV) 3.15
Is 7.85E-3 Vp 70
ne(cm^-3) 4.54E+10
Te(eV) 5.57
Is 1.82E-2 Vp 68
ne(cm^-3) 1.58E+11
Te(eV) 2.88
Is 5.03E-3 Vp 62
ne(cm^-3) 4.16E+10
Te(eV) 2.94
t 40u
Δt 2.5u
40 µS
70 µS
90 µS
120 µS
150 µS
180 µS
220 µS
eepf (eV^-3/2 cm^-3)
energy (eV)

Where "Maxwellian" EEDF comes from?

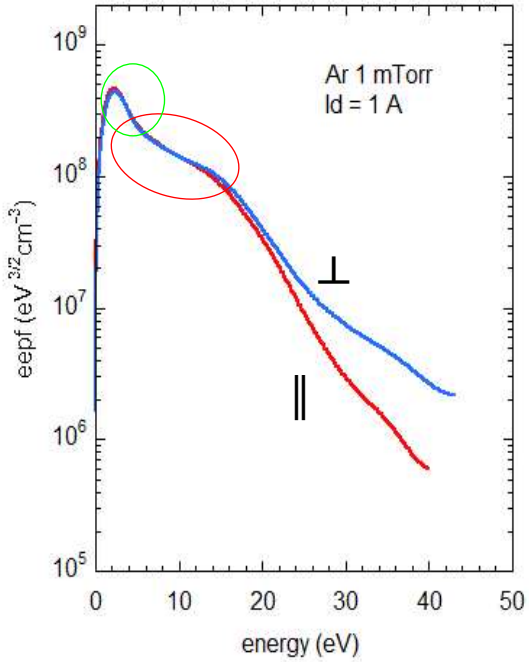
It is known for long time that, practically always, ln[I(V) – I(V)] can be fit with a straight line (expected for a Maxwellian EEDF).
Arbitrariness in the ion current approximation, and uncertainty in the plasma potential give plenty of opportunities to obtain an expected straight line for ln[I_e(V)].

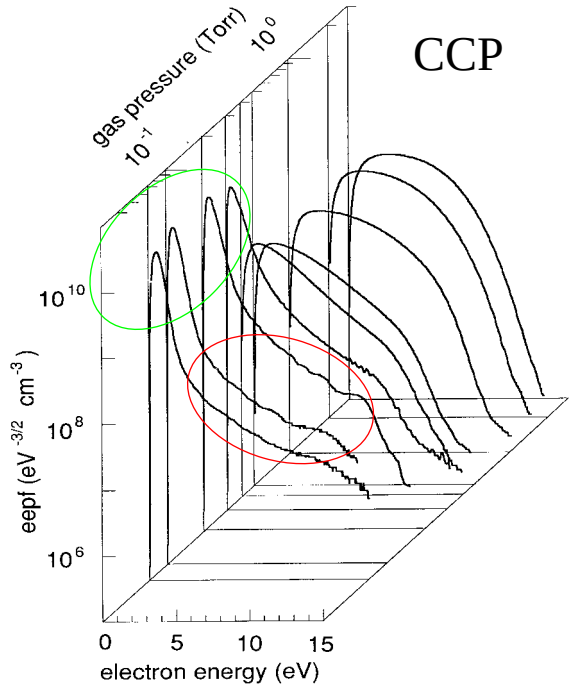
EEPF, I(V) and I_e(V) measured in Ar PC with the axially oriented probe

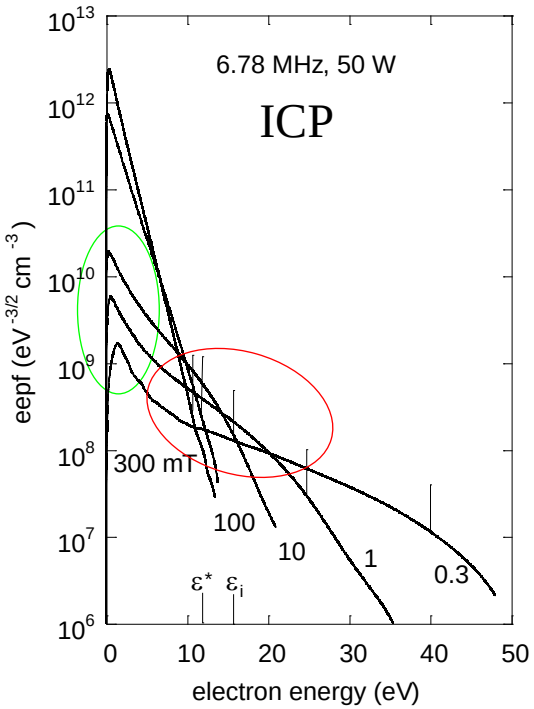


What is the nature of the low energy peak?

The low energy peak in EEPF is common in CCP and ICP at low gas pressure. It is a feature of non-local electron kinetics when low energy electrons are trapped and cannot reach the area of the heating field localization





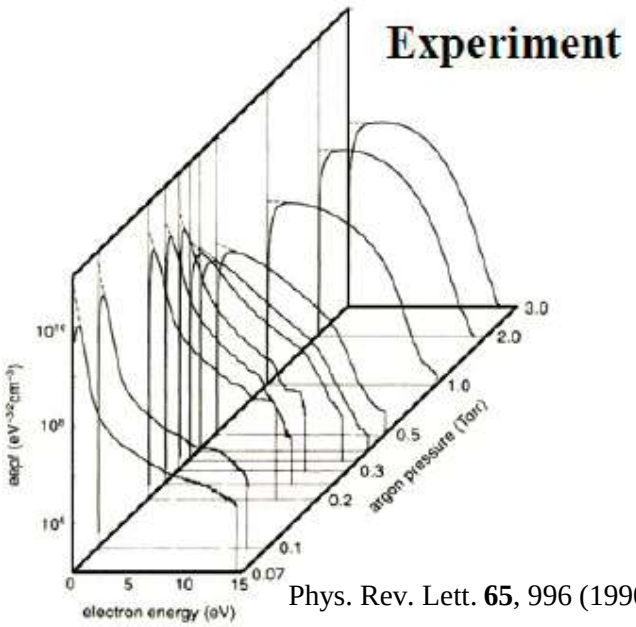


Electric field and trapping potential in stratified dc plasma are similar to those in CCP (rf sheath) and in ICP (skin layer). Low energy peak is due to electron trapping and is accompanied with enhanced number of high energy electrons

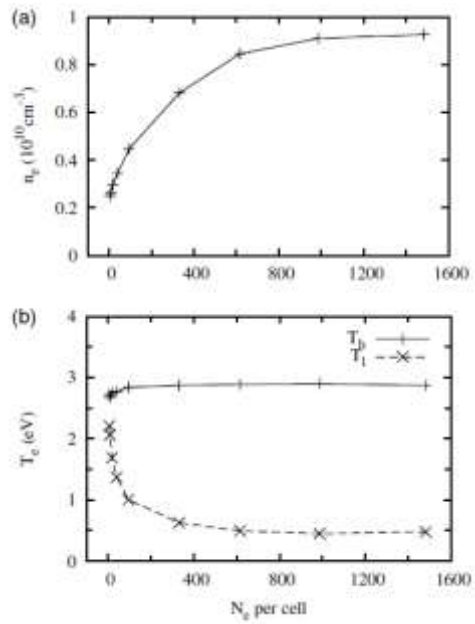
Application of a modern probe diagnostics technique to the old problem revealed some new understanding in dc plasma

- Strongly non-Maxwellian EEDF
- Essential EEDF anisotropy
- Plasma is not in equilibrium with discharge current
- Angle-resolved probe measurement is needed for anisotropic EEDF
- Self consistent 2-D kinetic modeling is missing to compare with experiment
- What about others widely used probe techniques?

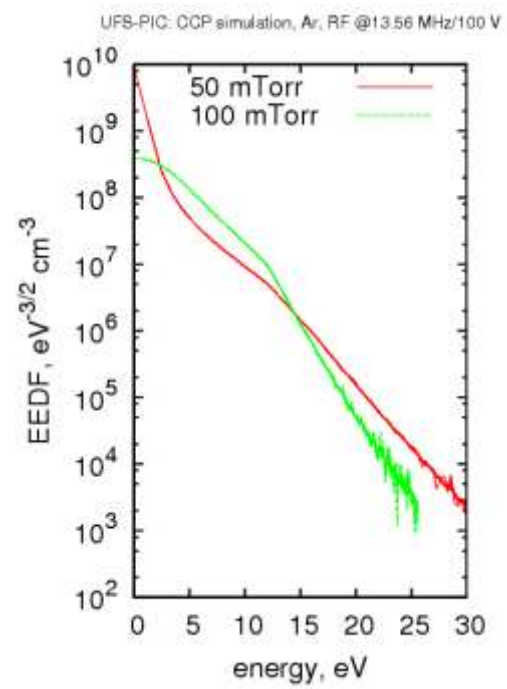
Simulations: Need for Hybrid Kinetic-Fluid Codes



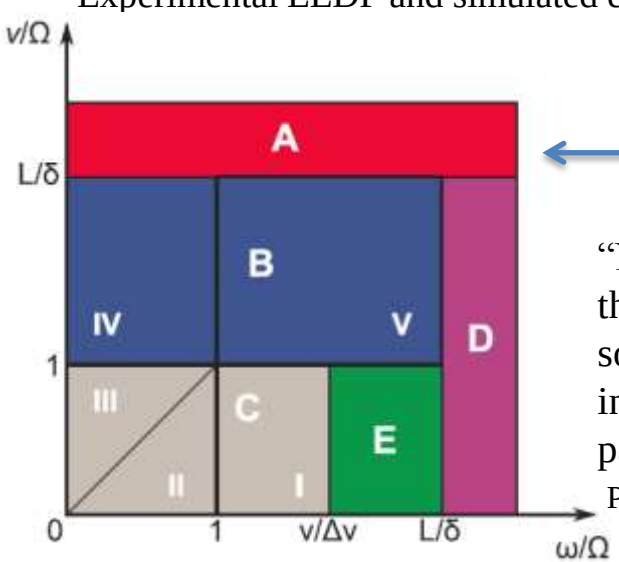
Phys. Rev. Lett. **65**, 996 (1990)



Experimental EEDF and simulated electron density (a) and temperatures
ɔer of super-particles in a cell



Results of PIC module in UFS with 2000 particles per cell



Electron heating regimes

"Numerical noise level in PIC codes can be as much as 10^4 times higher than Vlasov simulations. The noise can therefore be viewed as playing a somewhat similar role to that of particle collisions, and consequently introduces an artificial phase randomization and stochastization even if particle collisions are removed"

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Refining of "well established" diagnostic technique may lead to new finding

- Among variety techniques, the most accurate are considered those based on first principles and having minimal assumptions and limitations

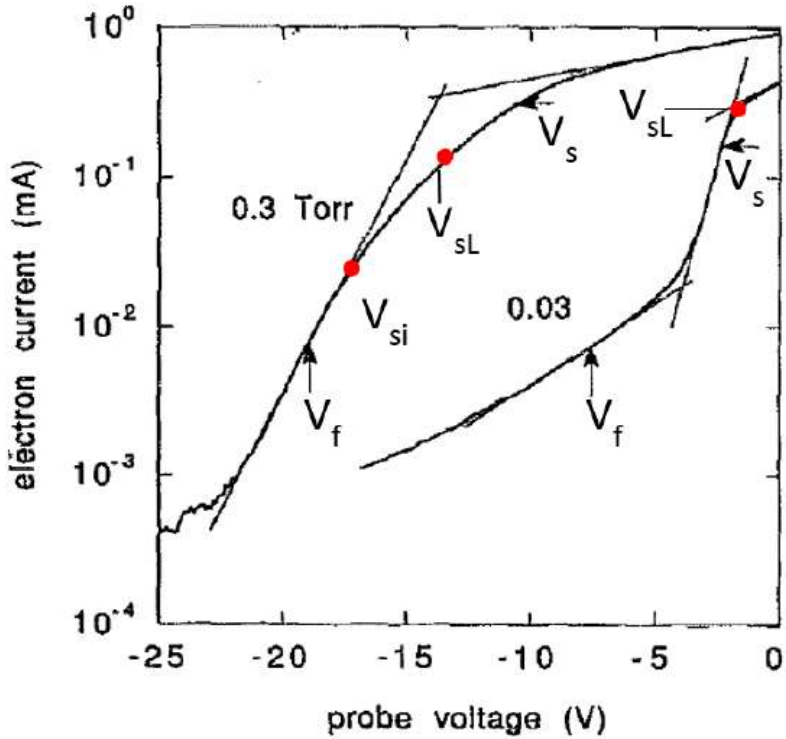
- Comparative analysis of numerous studies on plasma parameters inferred from different probe diagnostics revealed their essential inconsistency

- EEDF measured by Langmuir probe and cut-off probe measuring ω_{pe} are preferred. Both have sound foundation. The first is working in a wide range of condition. The second is immune to probe contamination and emission and is independent on EEDF. But, unfortunately, it works in very narrow condition band. Good for supporting the first one

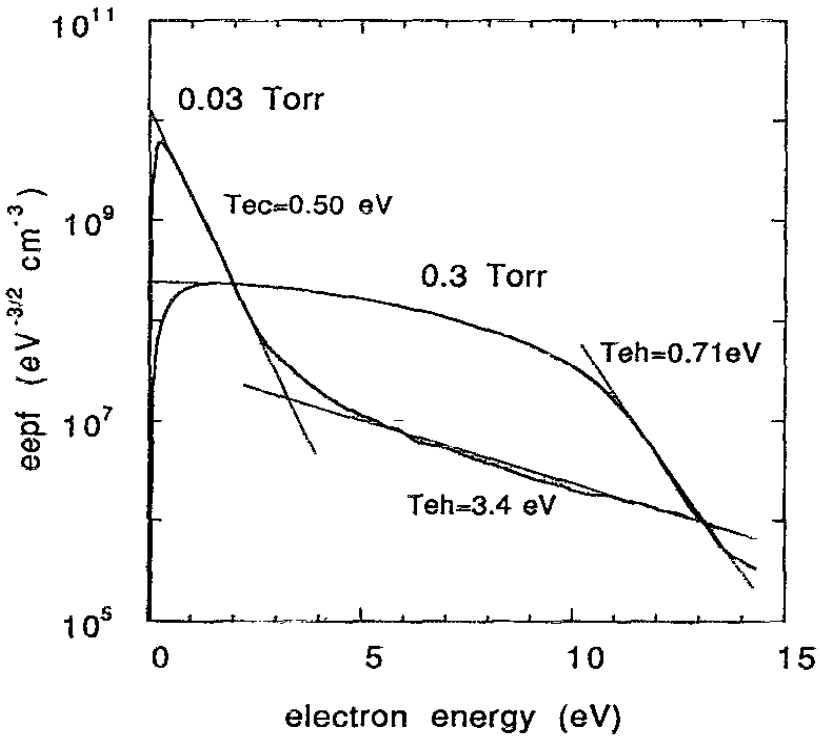
Langmuir (classical) probe diagnostics implies a Maxwellian EEDF that practically never occurs in practice

CCP 13.56 MHz

Langmuir procedure



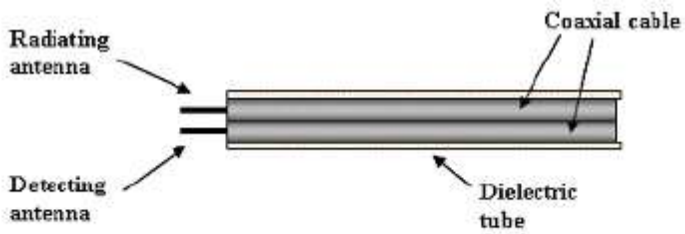
Druyvestein procedure

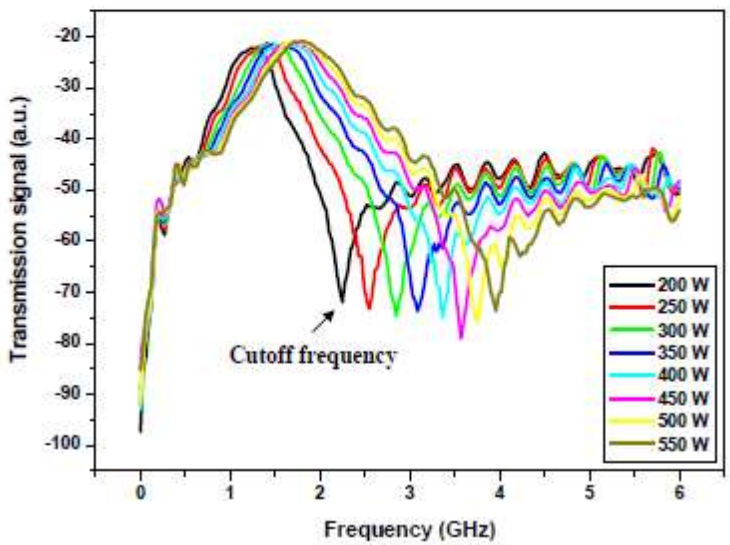


Deviation from Maxwellian EEDF for high energy electrons is well known, but strong non-equilibrium for bulk electrons, typical for low pressure DC and RF discharges makes Classical Langmuir probe inappropriate for such plasmas

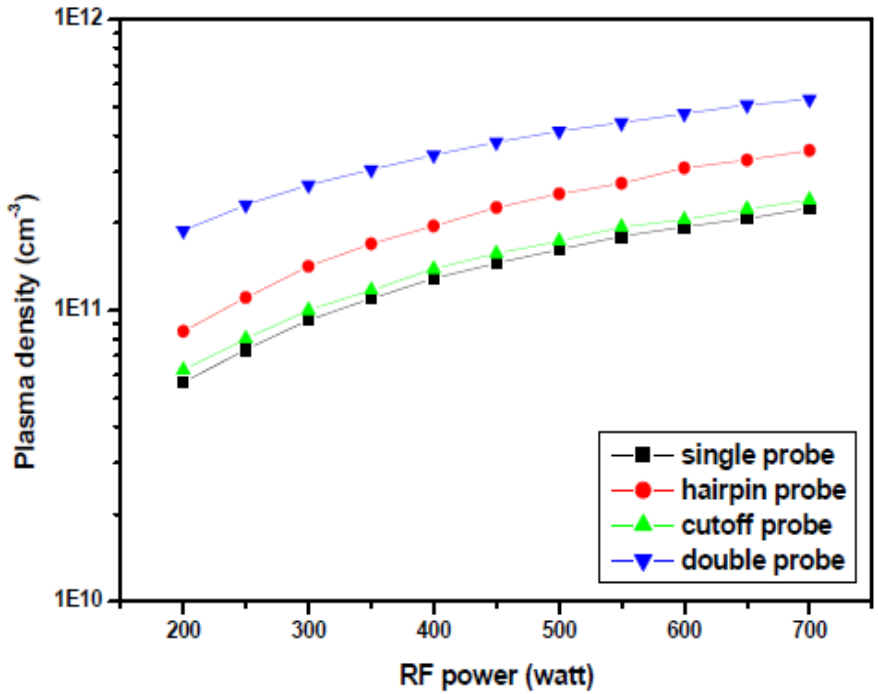
Cut-off probe (Proposed by Levitsky & Shashurin 50 years ago)

Complex plasma conductivity and transmission signal are minimal at $\omega = \omega_{ep}$





K. W. Ki & C. W. Chung, 2005



Unfortunately, the plasma resonance peak frequently is lost among multiple others

Plasma density N related to N_0 found by integration of the measured EEDF

First Author	Year of publication	Gas/pressure	Electron Part of I/V	Ion orbital theory	Ion radial Theory	Hairpin probe	Interfero-meter	Cut-off probe
Godyak	1993	Ar 0.03 Torr	**1.34**	**2.5**				
Godyak	1993	Ar 0.3 Torr	**0.38/0.07**	**3.3**				
Sudit	1994	He .04 Torr	**0.85**	**9 !!!**	**0.25**			
Piejak	2004	Ar 3-50 mT				**1.2-1.5**	**1.3-1.6**	
K W Ki	2005	Ar 7-22 mT		**2.6-3.2**		**1.5**		**1.05 !!!**
Iza	2006	Ar 1mTorr		**3**	**0.3**			
Iza	2006	Ar 10 mTorr		**4**	**0.45**			
Iza	2006	Ar 0.1 Torr		**2 !**	**0.14**			

All studies above show inapplicability of ion current theories for plasma diagnostics

The main problems are: non-Maxwellian EEDF, ion collisions, ambipolar field and violation of 1-D plasma structure around the probe. Will be reported at GEC 2015

Summary: How to advance the frontier ?

Synergetic studies (experimental, theoretical and numerical) of two poorly understood and apparently coupled problems: striations and the EEDF formation in near-collisionless discharge plasma.

- Reexamining experimental evidences of the Langmuir paradox by measuring EEDF (its symmetrical and directional parts) and understanding the nature of striation at low gas pressures.
- Theoretical and computational studies of the positive column accounting for radial and axial non-uniformity, EEDF anisotropy, the loss cone and, possibly, the particle-wave interactions.

- Successful completion of this program would resolve a century old problem of the Langmuir paradox and clarify fundamental mechanisms of plasma self-organization at the kinetic level.
- More important, it would advance development of new diagnostic techniques, promote development of theory and numerical algorithms for analyses of spatially non-uniform, non-equilibrium plasmas.
- Progress in this area would impact the plasma materials processing, fusion and space plasmas.

Summary: Advancing Probe diagnostics beyond Langmuir-Druyvestein routine (collisional, magnetized and anisotropic plasmas)

- There are no reliable and acceptable procedure to make EEDF measurements in collisional, magnetized and anisotropic plasmas.
- Development of reliable probe plasma diagnostics beyond traditional applications would brings possibility for accurate and convenient routine to many contemporary devices utilizing high-pressure and/or magnetized plasmas.
- Reliable diagnostics is the primary condition for value, impact and social benefit for any experiment.

The challenge for contemporary probe diagnostics consists of development and validation of robust procedures beyond of classical Langmuir and Druyvestein analysis. Unification of existing theories and models for collisional, anisotropic and magnetic field effects on probe characteristics, collecting comprehensive experimental data base and their comparison with other methods are the main goal of the proposed efforts.