Comparative Analysis of Plasma Probe Diagnostics Techniques

V. A. Godyak[1] and B. M. Alexandrovich [2]

[1] Electrical Engineering and Computer Science Department, University of Michigan, Ann Arbor, Michigan, and RF Plasma Consulting, Brookline, Massachusetts 02446
[2] Plasma Sensors, Brookline MA 02446,

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Introduction

"There is no plasma diagnostics method other than probe diagnostics where the danger of incorrect measurements and erroneous interpretation of results are so great."

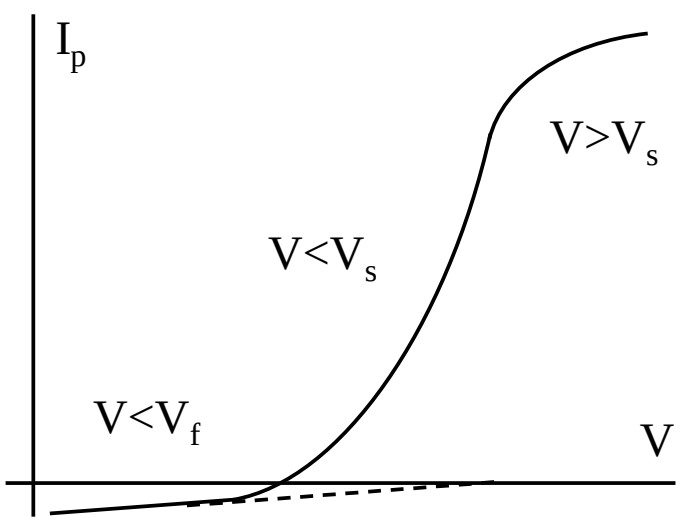
L. Schott, in ***Plasma Diagnostics***, editor
W. Lochte-Holtgreven, Amsterdam,1968

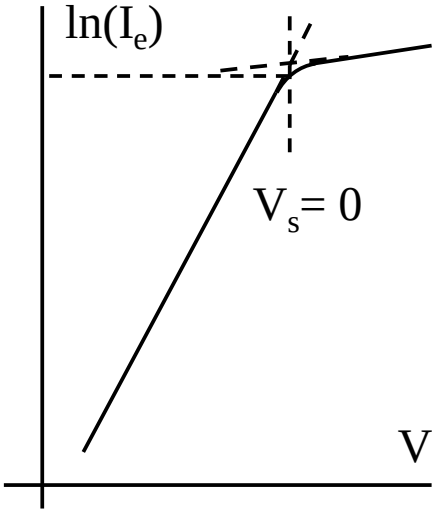
It was true then, it is even more true today, when plasmas are more complicated and the measurement techniques are more sophisticated

Comparison of plasma parameters obtained with different probe techniques (Langmuir, ion current and EEDF) is given in this talk for collisionless probes at B = 0

Electron part of the probe I/V

(Classical Langmuir technique)





Large probe gives a nice looking probe I/V, but prone to plasma perturbation

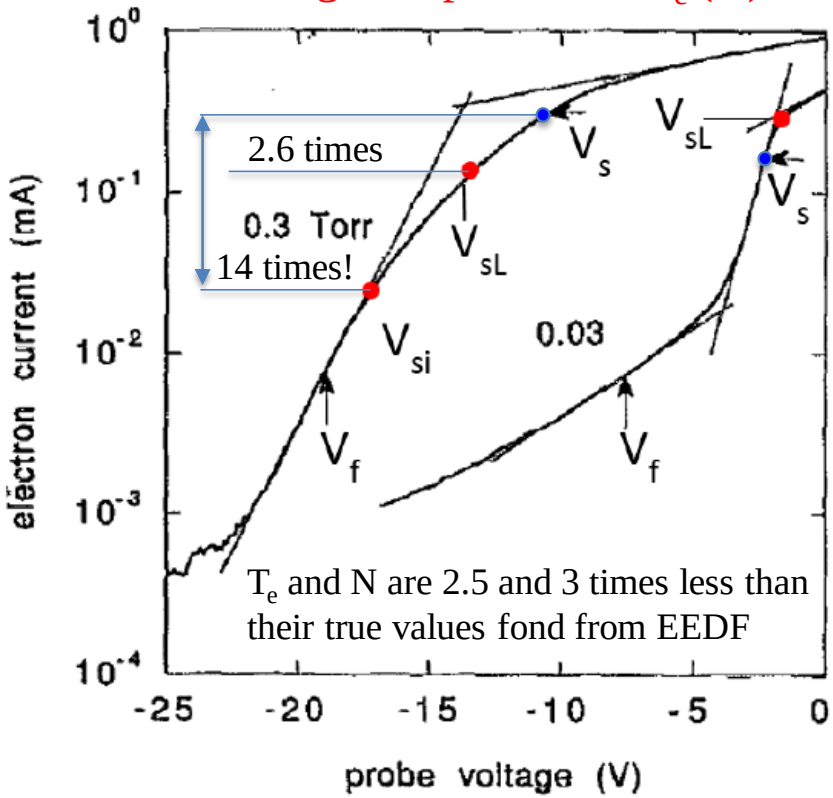
Main problems in using Langmuir procedure:

1. Assumption of Maxwellian EEDF $\longrightarrow$ errors in T_e and N
2. Uncertainty in plasma potential V $\longrightarrow$ error in N
3. Arbitrariness in the ion current approximation $\longrightarrow$ error in T_e for high energy electrons ($\varepsilon > |eV_f|$)

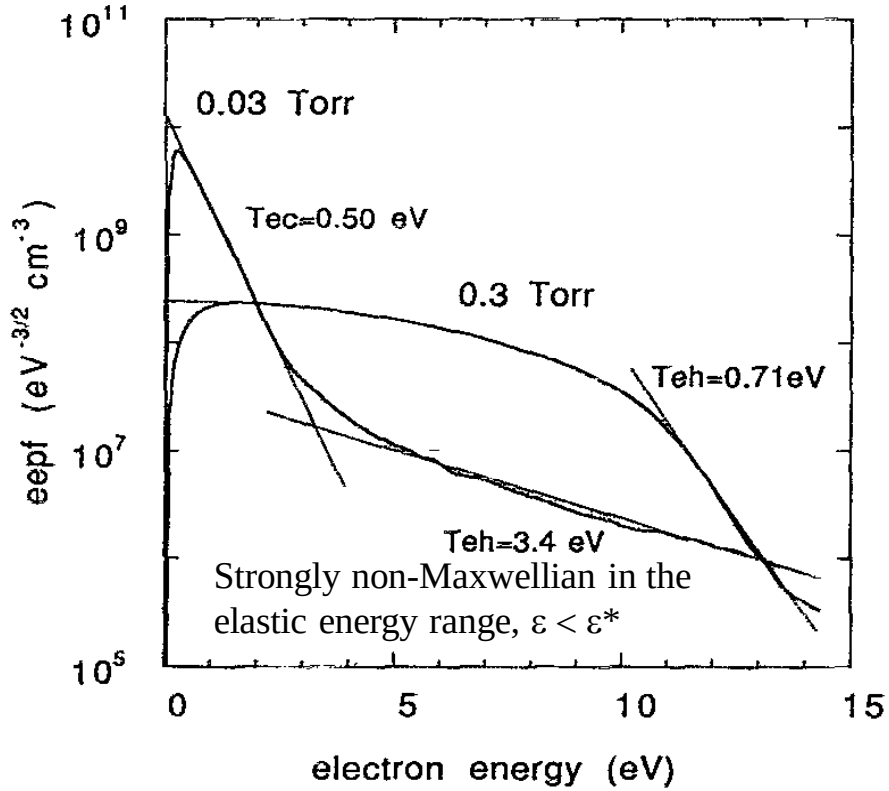
Probe characteristics and EEDFs in Argon CCP

Godyak et al, J. Appl. Phys. ***73****, 3677 (1993)*

Langmuir procedure, I_e (V)



Druyvestein procedure, f(ε)



Deviation from Maxwellian EEDF for high energy electrons ($\varepsilon > \varepsilon^*$, ε_i, ε_w) is typical for gas discharge plasmas. Strong non-equilibrium for bulk electrons ($\varepsilon < \varepsilon^*$, ε_i, ε_w) in DC and RF discharges in Ramsauer gases makes the <u>classical Langmuir procedure inadequate for diagnostics of such plasmas</u>

Plasma parameters for Ar CCP at 30 and 300 mTorr

30 mTorr (bi-Maxwellian)		300 mTorr (Druyvesteyn-like)	
Langmuir	EEDF	Langmuir	EEDF
T_e = 0.73 eV	T_e = 0.67eV	T_e = 1.37 !	T_e = 3.4 eV
$N=5.9\times10^9 cm^{-3}$	$N=4.4\times10^9 cm^{-3}$	$N=4.5\times10^9 cm^{-3}$	$N=2.9\times10^9 cm^{-3}$

The temperatures of cold and fast electrons in bi-Maxwellian plasma found from the Langmuir procedure and those found from the EEDF are different!

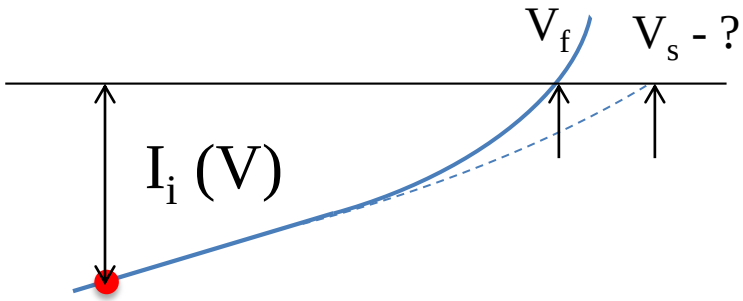
T_{ec} = 0.73 eV and T_{he} = 4.2 eV are found as $T_e^{-1} = d\ln I_e/dV$

T_{ec} = 0.50 eV and T_{he} = 3.4 eV are found as $T_e^{-1} = d\ln f_e/dV$

Inferring the plasma parameters from the ion part of the probe characteristic

$T_e = [d(I - I_i)/I_i dV]^{-1}$ @ $V = V_f$

N is found from one of theories: Radial, or Orbital motion, Kagan-Perrel or Laframboise.
Which one to use ?



$V_s - V_f = (½)T_e \ln(M/2\pi m)$ is only valid for Maxwellian EEDF and flat probes

Numerous studies showed that plasma parameters found from the ion part of the probe characteristic can be in error, up to an order of magnitude comparing to those found from the electron part of the probe characteristic! ↓ ↓ ↓ ↓ ↓

Warning!

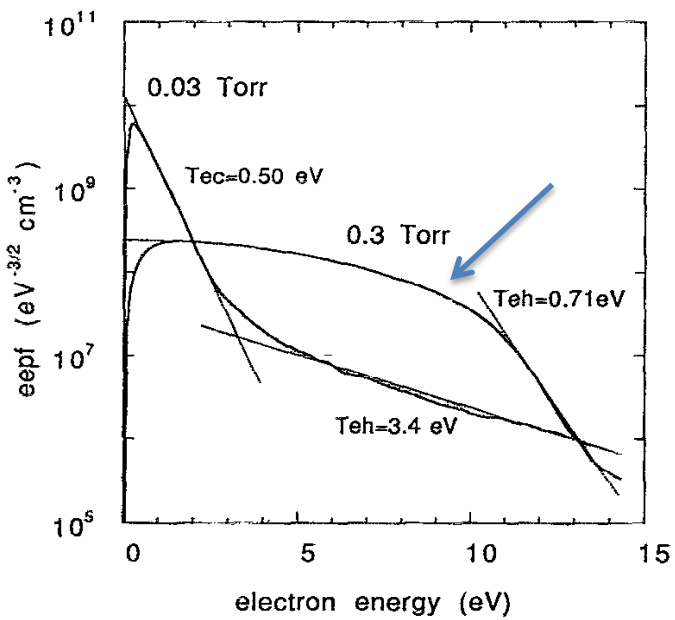
The inferred T_e is formed by the fast electrons of the EEDF, T_{eh}. The last could be larger, or less than T_{eeff} defined by the bulk electrons.

Possible reasons for "ion density" failure?

Unrealistic assumptions for $I_i(V)$ theories:

- Maxwellian EEDF,
- No ion collisions ($\lambda_i << \lambda_e$),
- One-dimensional probe models
- No ambipolar flow ($v_s \geq v_{amb} > v_{Ti}$)
- Uncertainty in V_s
- Unknown ion temperature

Non-Maxwellian EEDF



As shown by Vasil'eva *(High Temp. **12**, 409, 1974)*, I_i and $\lambda_D \sim [T_{es}]^{1/2}$, while $V_f \sim T_{eh}$, where T_{es} is the electron screen temperature waited by T_{ec}.

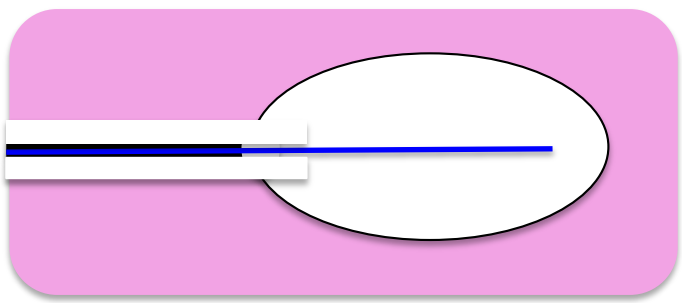
@ 0.3Torr, T_{es} = 15 eV, T_{eh} = 0.71 eV, and T_e= 3.4eV.

T_e at $V = V_f$ is an order of magnitude lower than T_{es} that defines the Bohm velocity, u_B and the sheath collecting area around the probe. Combination of these effects may result in order of magnitude error in N_i.

Ion collisions Generally, $\lambda_i << \lambda_e$, and collisional regime for ion onsets at much lower gas pressure than that for electrons. For the orbital ion theory:

$R_0 = a_p(eV/T_i)^{1/2} << \lambda_i$, @ $a_p = 0.05$ mm, $T_i = 0.03$ eV, V = 60 V, the collisionless regime in Ar gas occurs at p << 15 mTorr. I. e. OML theory is not applicable for the range of gas pressure where the theory usually used (p > 2-3 mTorr).

1-D not satisfied R_0 and S are comparable to the probe length; L = 5 mm



$I_i \sim V^{1/2}$ for cylinder. and $I_i \sim V$ for sphere - ???

$R_0 = 2.24$ mm and L/2 = 2.5 mm; they are equal, while applicability of the cylindrical model requires $R_0 << L/2$

Ambipolar drift In gas discharge plasmas, except of plasma center, $v_{Ti} < v_i < v_B = (T_e/M)^{1/2}$, while all ion current theories (used in probe Diagnostics) assume $v_i = 0$, or $v_i = v_{Ti}$. Ion directed motion can be accounted for, but the ion velocity number and its direction are *a priory* unknown.

Uncertainty and erroneous estimation of the plasma potential

EEDF measurement with probe I/V differentiation

Druyvestein (1931) showed that $d^2I_e/dV^2 \propto$ EEPF, $f(\varepsilon)$, while EEDF, $F(\varepsilon) \propto \varepsilon^{1/2}f(\varepsilon)$ gives plasma parameters and process rates

- Applicable to arbitrary isotropic $F(\varepsilon)$
- Applicability limitations are the same as for Langmuir probe
- Accurate V_s measurement and no ion current effect
- Plasma parameters, rate of e-collisional processes and transport coefficients can be readily found as integrals of the measured $F(\varepsilon)$
- Since low temperature plasmas as a rule are non-Maxwellian, the EEDF measurement is recommended as a reliable probe diagnostics for laboratory and processing plasmas

See recent review on EEDF measurement *Godyak and Demidov, J. Phys. D; Appl. Phys.* ***44****,233001, 2011*

Ratio of the measured plasma density to that 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 30 mT	1.34	2.5				
Godyak	1993	Ar 300 mT	0.38/0.07	3.3				
Sudit	1994	He 40 mT	0.85	9 !!!	0.25			
Piejak	2004	Ar 3-50 mT				1.2-1.5	1.3-1.6	
Ki	2005	Ar 7-22 mT		2.6-3.2		1.5		1.05
Iza	2006	Ar 1mT		3	0.3			
Iza	2006	Ar 10 mT		4	0.45			
Iza	2006	Ar 100 mT		2 !	0.14 !!!			

Godyak et al, J. Appl. Phys. ***73*** *3657, 1993*

Sudit and Woods, J. Appl. Phys. ***76,*** *4488, 1994*

Piejak et al, J. Appl. Phys. ***95****, 3785 (2004)*

Ki and Chung, Korean Phys. Soc. ***50****, 329, 2005*

Iza and Lee J. Vac. Sci. Technol. A ***24****, 1366, 2006*

Large data discrepancy found from ion and electron probe currents.

More reliable are data obtained with minimal number of assumption (EEDF and ω_{0e})

What makes a reliable EEDF measurement ?

- EEDF measurements yield meaningful results only when they contain accurate information about electrons in both elastic and inelastic energy range; ($\varepsilon < \varepsilon^* \rightarrow T_e$ & N) and ($\varepsilon > \varepsilon^* \rightarrow$ excitation & ionization). This requires high energy resolution ($\Delta\varepsilon < 0.5\ T_e$) and large dynamic range of the measurements, (50-70) db undistorted by noise.

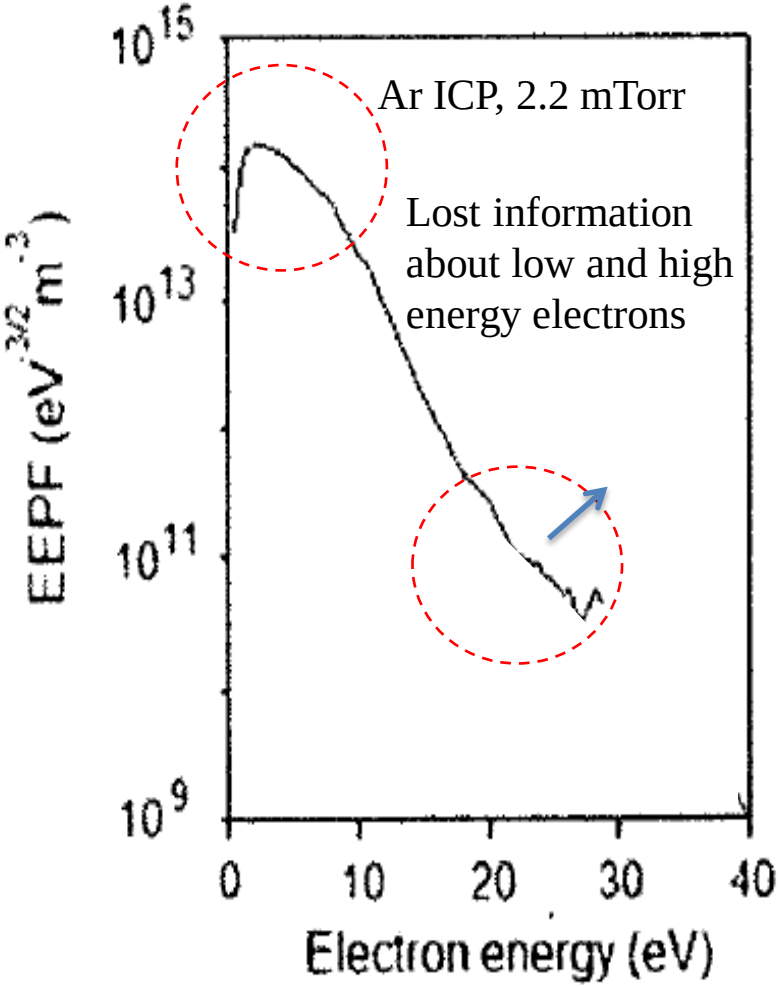
- Measurements in processing chambers have to be unaffected by the wide spectrum of RF and low frequency plasma potential and the probe and chamber surface contamination.

- Real time EEDF monitoring allows to notice impediments in measurements and mitigate them.

Majority of published EEDF data measured by self-made and commercial instruments are obviously distorted missing essential information. That indicates either lack of the probe diagnostics skills or the instrument deficiency, or frequently both.

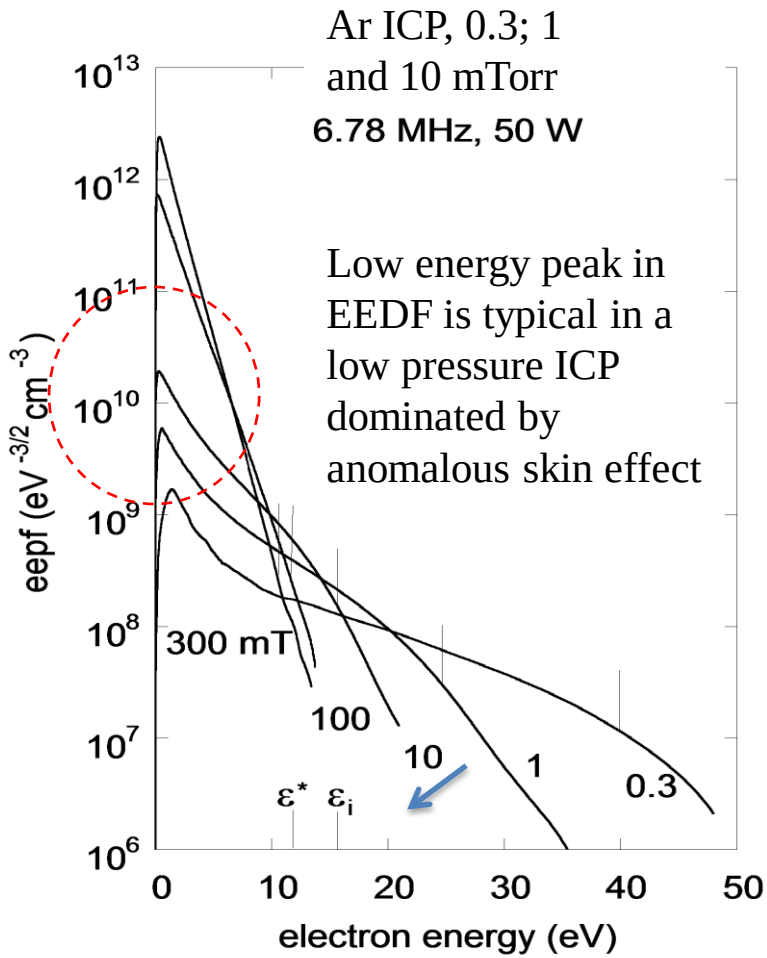
EEDF measured with different instruments in similar plasmas

Impedance ALP



Gahan et al, PSST ***17****, 035026 (2008)*

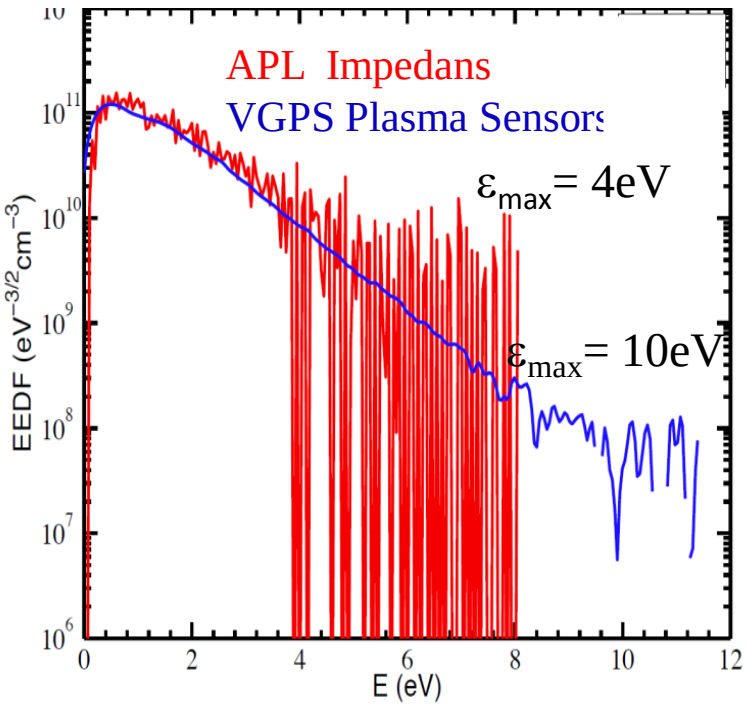
Plasma Sensors VGPS



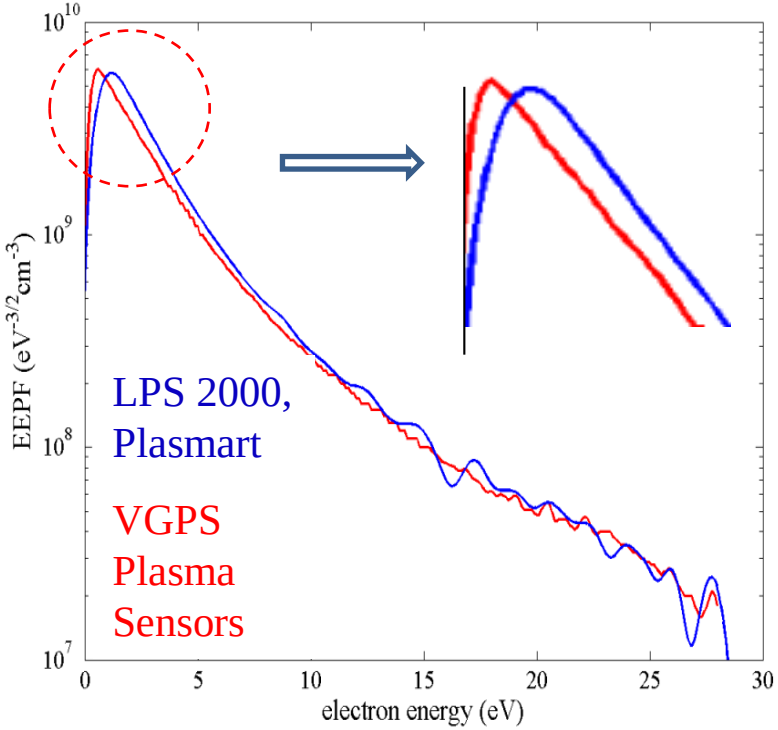
Godyak et al, PSST ***11****, 525 (2002)*

EEDF measurements in the same noisy plasma with different commercial instruments

(Dynamic range and energy and resolution)



PEGASES. Ar 10 mTorr, 100W.
Ecole Polytechnique, France



ICP with ferrite core. Ar 1.2 mTorr, 40 W
Tsinghua University, China

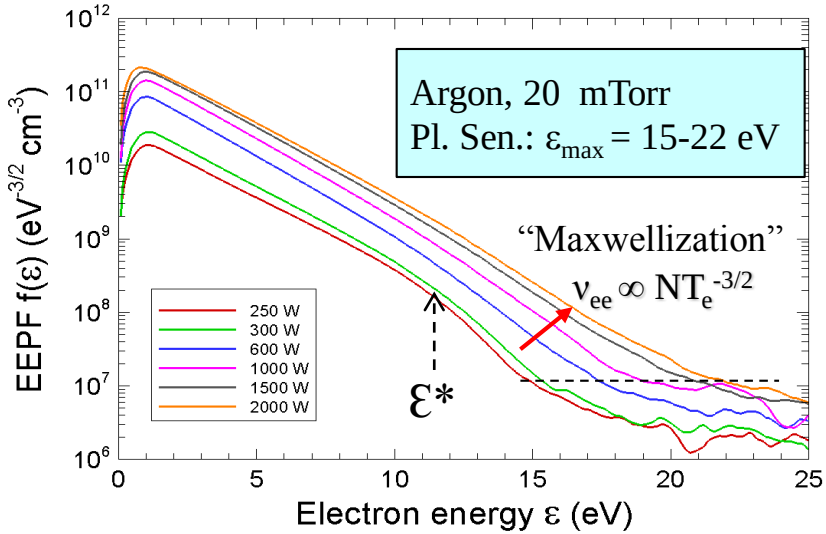
EEDF measurements in a commercial ICP reactor

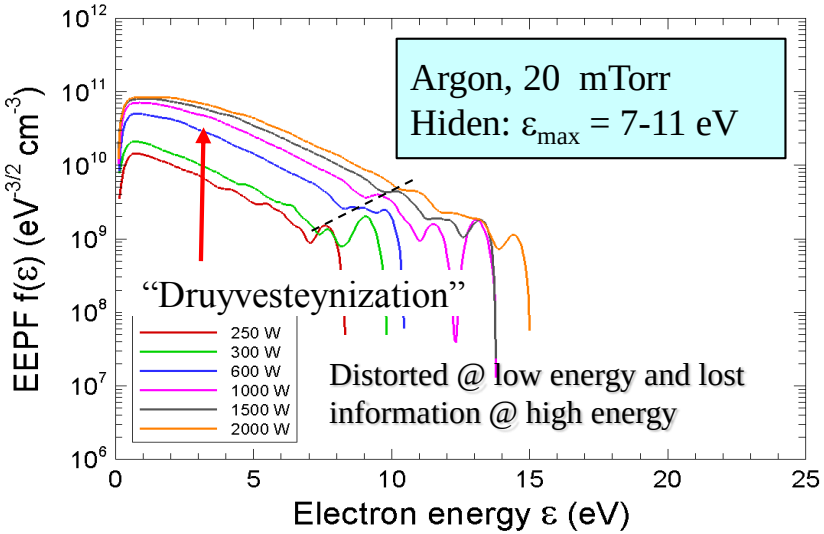
Comparison of EEPF measured with different commercial probe stations, Espion of Hiden and VGPS of Plasma Sensors

At maximal discharge power of 2 kW, $N \approx 1 \cdot 10^{12}$ cm^{-3}, thus the EEPF @ $\varepsilon < \varepsilon^*$ has to be a Maxwellian one

"Druyvesteynization" effect is found in many publications of EEDF measurements made with self-made and commercial probe systems

V. Godyak et al, GEC 2009, Saratoga Springs, NY, USA

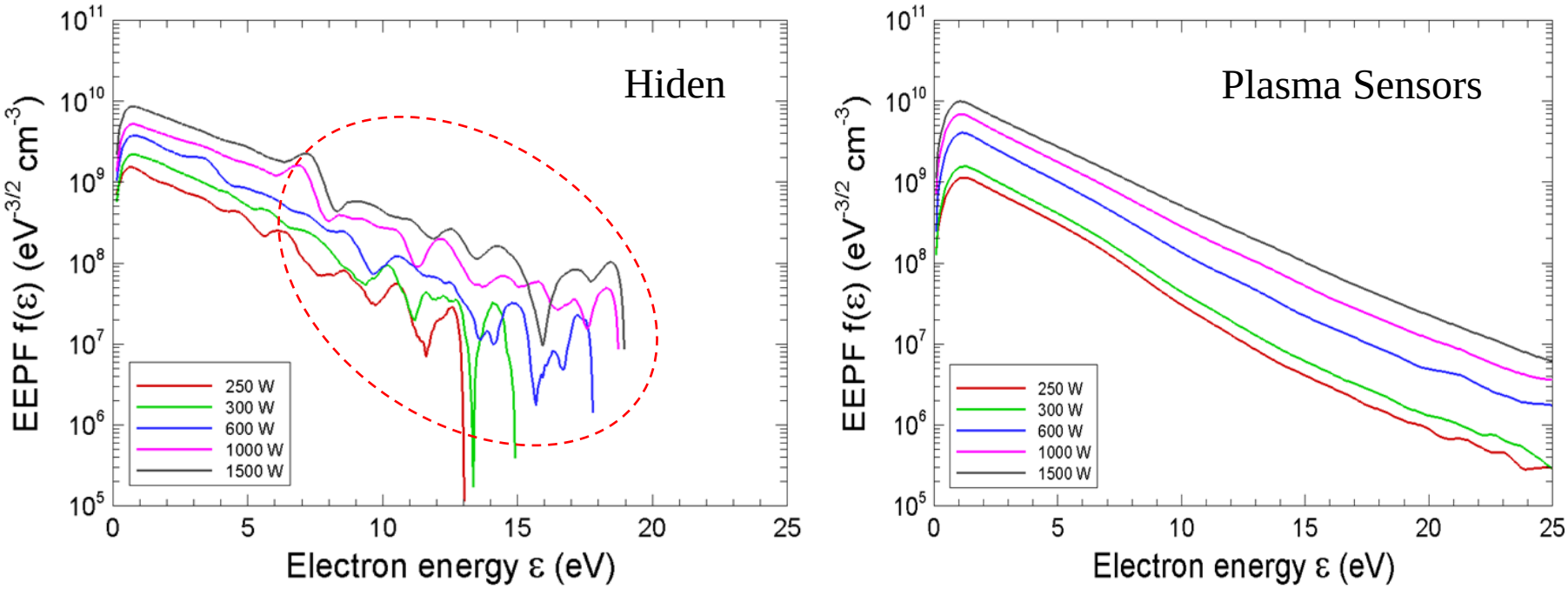




Measuring of EEDF in reactors with processing gases

High amplitude and wide spectrum of RF plasma potential harmonics, low-frequency noise, high rate of the probe contamination and poor contact of the plasma to the grounded chamber are major impediments for probe diagnostics in commercial chambers.

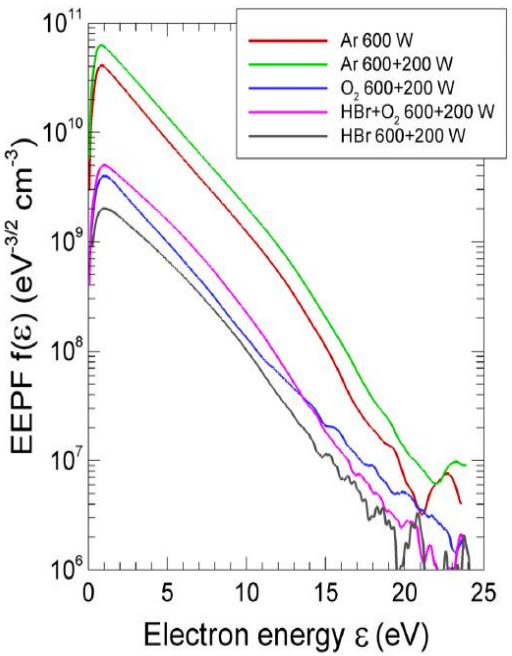
Measurement in the same ICP reactor. Oxygen 10 mTorr



V. Godyak et al, GEC 2009, Saratoga Springs, NY, USA

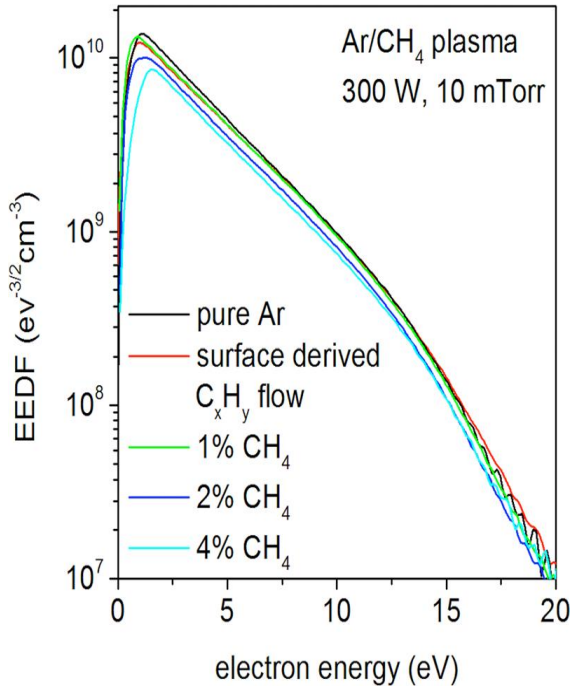
EEDFs measured in plasma reactors with processing gases (High quality measurements with a good instrument)

Ar, O_2, HBr, HBr+O_2



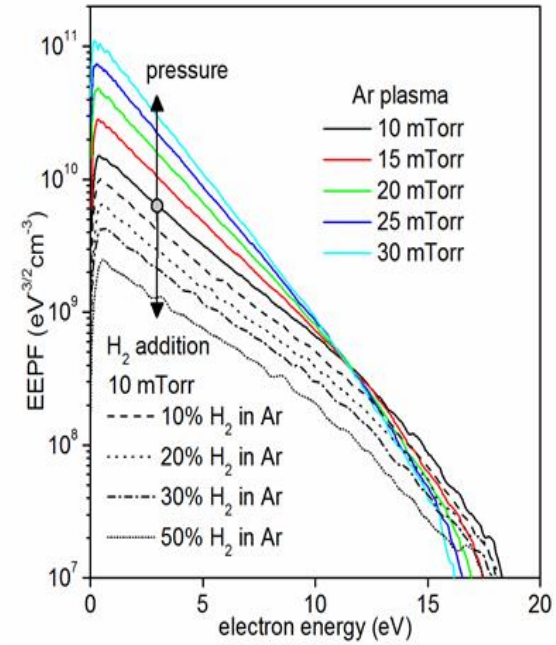
EEPF in commercial two-inductor ICP in different processing mixtures at 15 mTorr.
Mattson Technology, by V. Nagorny

Ar + SiH_4



EEPFs in ICP filled with Ar+CH_4 at the condition of strong polymer film deposition.
University of Maryland, by N. Fox-Lyon

Ar, Ar + H_2



EEPF measured in ICP reactor, H_2/CF_4 at 30 mTorr with a polymer layer deposition.
University of Maryland by N. Fox-Lyon

Concluding remarks

- The classic Langmuir probe procedure is subjected to errors due to non-Maxwellian EEDF and uncertainty in the plasma potential, it should not be used for plasma diagnostics with non-Maxwellian EEDF at $\varepsilon < \varepsilon^*$
- Plasma parameters inferred from $I_i(V)$ are significantly (up to an order of magnitude) different from those found from $I_e(V)$ and EEDF. Unrealistic assumptions made in $I_i(V)$ theories are likely suspects for errors in T_e and N values found from $I_i(V)$.
- EEDF probe diagnostics is not confined by those drawbacks, but it requires more accurate instruments and elaborate procedures. Deficiencies in both components are visible in vast number of published EEDF measurements.

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

- Having a choice, the most accurate measurement are based on fundamental physical principles with least assumptions and parameters restrictions.

- Comparison of numerous studies presenting the plasma parameters inferred from different probe techniques demonstrates vast discrepancy.

- The EEDF measured by Langmuir probe and the plasma density found from ω_{pe} in the cut-off probe technique are both based on fundamental principles and are potentially most accurate.

- Cut-off probe is immune to the probe contamination and can be made insusceptible to RF potential. But its only output is the plasma density, still within a certain range.

- Accurate EEDF measurements can be performed in wide parameter range revealing most comprehensive plasma information. It allows unambiguous calculation of the plasma parameters and rates of the transport and reaction processes as corresponding integrals of EEDF.

Three levels of probe diagnostics

Plasma parameters are inferred from:

1. **Ion part of the probe I/V characteristic I_i (double and triple probes).**
   Is notoriously inaccurate (up to an order of magnitude error) due to many unrealistic assumptions in existing $I_i(V)$ theories

2. **Electron part of the probe I/V** (classic Langmuir method). Assumes a Maxwellian EEDF, uncertainty in plasma potential leads to error in the plasma density evaluation

3. **I/V Differentiation of the probe characteristic** . Results in accurate measurement of the plasma potential and EEDF. Plasma parameters and process rates may be found as corresponding integrals of the measured EEDF

Since EEDFs in gas discharge plasmas are never Maxwellian (at both, $\varepsilon < \varepsilon^*$ and $\varepsilon > \varepsilon^*$), the measurement of EEDF is the only reliable probe diagnostics corresponding to contemporary kinetic level of gas discharge science