Plasma Diagnostics III:

Wall Probes

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Plasma Science Center
Predictive Control of Plasma Kinetics
Introductory remarks

An electric probe is a conducting object inserted into the plasma for the purpose of diagnostics and connected to the outside world through some kind of electrical circuitry.

The probes dependently on design and plasma type can measure space potentials, electron/ion temperatures and densities, their oscillations and electron/ion velocity/energy distribution functions.
The goal of this talk is...

... to discuss some methods of electron-distribution probe diagnostics, including not very conventional that are still under development and remain a challenge for budding scientists.

... to increase awareness of the problems pertaining to the relationship between the actual plasma parameters and the probe experiment design.
Outline of the lecture

- Introductory remarks: Wall probe
- Do we really need very high spatial resolution for measuring electrons: Is the wall probe a good idea?
- When we can and cannot measure EDF: plasmas with local and nonlocal electron distributions
- Probe theories for the EDF measurements
- Basic of the wall probe methods
- Plasma electron spectroscopy
- Measurements of magnetized and unisotropic EDF
- Conclusions
A wall probe is an electrically isolated segment of the plasma volume wall, serving to either replace or cover the otherwise continuous plasma volume wall and collects the current from the plasma for different probe potentials.
Benefits of the wall probe

1. The probe does not require a probe-holder.  
   As a result, the plasma distortion is less pronounce.
2. Much greater area.  
   As a result, the sensitivity is much higher.
3. Reduced influence of the ion current on the measurements.  
   As a result, the energy resolution is higher.
4. Could be simpler to have in small size plasmas  
   As a result, it may be simpler to study micro-discharges.
Typically the electric probe has very good spatial resolution as usually it is a very small object (probe characteristic size is \(a\)) with respect to the plasma dimensions \(L : a \ll L\).

As normally \(a \ll L\), it allows placing the probe in many different points of plasmas and provides 2D or 3D measurements with high accuracy.

To determine the limits and possibilities of measuring the EDF by the probe method, we need to compare the plasma volume and probe dimensions to the typical characteristic scales of formation of the EDF.
Do we really need very high spatial resolution for measuring electrons?

To measure EDF we do not need spatial resolution greater than characteristic scale of EDF formation. To determine required spatial resolution, we can study Boltzmann equation for EDF

\[
f \left( \vec{r}, \vec{v}, t \right) = \frac{\partial f}{\partial t} + \left( \vec{v} \cdot \nabla \right) f - \left( e / m \right) \left( \vec{E} + \left( \vec{v} \times \vec{B} \right) \right) \cdot \frac{\partial f}{\partial \vec{v}} - \nabla I(\vec{r}, \vec{v}, t) + \sum_{\beta} \left[ St_{\beta}^{el}(\vec{r}, t, f, f_{\beta}) + St_{\beta}^{inel}(\vec{r}, t, f, f_{\beta}) \right] = 0.
\]

For gas discharge plasma, electron elastic (el) and inelastic (inel) collisions with neutral atoms and molecules, which are described by corresponding collision integrals St are the most important.
The EDF formation

The EDF is determined by three main types of plasma processes:

1). Electron interaction with electromagnetic fields

\[ \vec{E}(\vec{r}, \vec{v}, t), \vec{B}(\vec{r}, \vec{v}, t) \]

2). Electron production (sources) and disappearance (sinks)

\[ I(\vec{r}, \vec{v}, t) \]

3). Electron interaction with neutrals which depends on gas properties, such as pressure, composition, ionization degree, and others taking into account in the collision integrals.

All these processes can be characterized by their spatial characteristic scales:

\[ L_{\text{field}}, L_{\text{source}}, L_{\text{gas}} \]
Isotropic plasma

In this case $L >> \lambda$ the EDF is close to isotropic, and the traditional two-term approximation is valid.

$$f(\vec{r}, \vec{v}, t) = f_0(\vec{r}, \vec{v}, t) + f_1(\vec{r}, \vec{v}, t)Y_0^0(\theta, \phi),$$

In this expansion the isotropic part of EDF dominates:

$$f_0(\vec{r}, \vec{v}, t) >> f_1(\vec{r}, \vec{v}, t)$$

First we discuss the isotropic part of EDF which depends on the electron energy (EEDF)

$$f_0(\vec{r}, \vec{v}, t) = F_0(\vec{r}, \varepsilon, t)$$
“Collisionless” case, \( \lambda \ll L \)

In this case, the two-term approach \( f_0 - f_1 \) may be not valid. However, the majority of the plasma electrons are trapped by the ambipolar electric field, and during its lifetime these electrons undergo many elastic collisions. Therefore the EDF is still practically isotropic and nonlocal. Only fast electrons with energy exceeding wall potential can escape on the plasma boundary in narrow loss cone. They can be unisotropic, but have very low density. It is difficult to measure.
Inhomogeneous Plasma

The main scenarios of the EEDF formation critically depend on the relative magnitude of the characteristic lengths: $\lambda, \lambda_\varepsilon, L$

The electron energy relaxation lengths $\lambda_\varepsilon$:

EEDF body

$$\lambda_\varepsilon = \lambda \sqrt{M / m} > 100 \lambda$$

EEDF tail

$$\lambda_\varepsilon = \sqrt{\lambda \lambda^*} = \lambda \sqrt{\sigma_{el} / \sigma_{inel}} >> \lambda$$

Unperturbed EEDF is formed at distances about $\lambda_\varepsilon$, i.e. a sphere with a radius $r_f \sim \lambda_\varepsilon \ll \lambda$ defined by the energy relaxation length. As in general length $\lambda_\varepsilon$ is not so small, different cases can be realized in practice and we need to consider different cases.
The energy dependence of $\lambda_\varepsilon$ and $\lambda$

- Helium
- Air
Local approximation for EEDF

EDF is formed locally at each point in space. It corresponds relatively high gas pressures

\[ pL > (0.3 - 1) \text{cmTorr (molecular)} \]
\[ pL > (3 - 10) \text{cmTorr (atomic) gases} \]

Local EDF depends explicitly on the energy and implicitly on the coordinates through the parameters that determine its spatial distribution: the fields, the sources and sinks, the electron, neutral and excited particle densities, and so on:

\[ f_0(\varepsilon, E(\vec{r},t), N(\vec{r},t), N^*(\vec{r},t), n_e(\vec{r},t), \text{etc.}) \]
When we cannot measure EEDF

When the size of the probe disturbed area exceeds the length of the EDF formation $a >> \lambda_\varepsilon$, the presence of the probe completely distorts the EDF in the unperturbed plasma. This means that the EDF measurements are impossible. Since the size of the probe in technically difficult to do less than 0.1…0.01 mm, for high (atmospheric) pressures it is possible to measure electron densities and temperatures, but not EDFs.
Can we use wall probe?

\( \lambda_e \) is electron energy relaxation length;
\( \lambda \) is mean free path of electrons;
\( r \) is probe dimension.

For cylindrical probe:
If \( \lambda > a \), EEDF \( \sim d^2I/dV^2 \);
If \( \lambda < a \), EEDF \( \sim dI/dV \)

Plasma volume wall
Local approximation for EEDF:

General case pressure

Thin probe sheaths (sufficiently high electron density) or arbitrarily thick sheaths and $\nu D_e = \text{const}$ (e.g., in argon plasma)

$$\Psi = \frac{a}{\lambda_e} \ln \frac{\pi l}{4a}$$

$$\lambda_e \gg a \left[ \ln \left( \frac{\pi l}{4a} \right) \right]$$

$$I_e = \frac{8 \pi e S_p}{3 m^2} \int_{eV}^{\infty} \frac{(\varepsilon - eV)f(\varepsilon)d\varepsilon}{\gamma + \left( \frac{1 - \frac{eV}{\varepsilon} \right) \Psi(\varepsilon, V)}$$

$$\Psi(\varepsilon, V) = \frac{1}{\lambda_e} \int_{\frac{eV}{\varepsilon}}^{\frac{\pi l}{4}} \frac{\sqrt{\varepsilon D_e(\varepsilon) d\varepsilon}}{\varepsilon - e\varphi(r)} \frac{1}{\sqrt{\varepsilon - e\varphi(r)} D_e(\varepsilon - e\varphi(r))}$$

Calculated $\ln(I_e')$ (left) and $\ln(-I_e' \Psi/\varepsilon)$ (right) for a Maxwellian EEPF ($\Psi = 1$ (1), $\Psi = 5$ (2), $\Psi = 20$ (3), $\Psi = 0.3$ (4), $\Psi = 1$ (5), $\Psi = 2$ (6)) and the model Maxwellian EEPF (dashed line)


Local approximation for EEDF: Low pressure

If $\lambda \gg a \ln[\pi L/4a]$

The Druyvesteyn formula:

$$\frac{d^2 I_e}{dV^2} = \frac{2\pi e^3 S_p}{m^2} f_0(eV)$$
Higher pressures (plasma with many near-probe collisions)

\[ \lambda_e << a [\ln(\pi l/4a)] << \lambda_e. \]

Thin probe sheaths (sufficiently high electron density) or arbitrarily thick sheaths and \( vD_e = const \) (e.g., in argon plasma)

\[
f(\varepsilon) = \frac{3m^2a \ln\left[\frac{l}{a}\right]}{8\pi\lambda_e(eV)Ve^3S_p} \frac{dI_e}{dV}
\]

He afterglow, 40 Torr

Higher pressures (plasma with some near-probe collisions)

\[ f_{pm}(\varepsilon) = f_p(\varepsilon)[1 - 2 \int_{\varepsilon}^{\infty} \frac{\Psi_s f_p(x) dx}{xf(x)[1+\Psi_s(1-\varepsilon/x)]^3}] \]

\[ \Psi_s = \frac{4}{3} \times \frac{a}{\lambda_e} \times \ln \left( \frac{l}{2a} \right) \]

These equations can be used in a weakly-collisional plasma

\[ N \approx N_m \times (1 + 4 \Psi_s/3) \]


\[ T_e \approx T_{em} \times (1 - \Psi_s/2) \]

A. I. Lukovnikov, M. Z. Novgorodov, Brief. Communications on Physics, 1971, #1, 27
Nonlocal EDF, $\lambda_{\varepsilon} \ll L$

When $\lambda_{\varepsilon} \ll L$ the electron groups with different energies do not have time to “mix” due to collisions in the volume. The different EDF parts will behave independently during their diffusion to the walls. In this case, EDF is nonlocal, because it is not determined by the characteristics of the plasma at a given point but in entire volume. This case corresponds to intermediate and low pressures

$$pL < (0.3 - 1) \text{cmTorr (molecular)}$$

$$pL < (3 - 10) \text{cmTorr (atomic) gases}$$

Nonlocal EDF depends **only** from total (full) energy

$$\varepsilon = \frac{mv^2}{2} - e\varphi = w - e\varphi$$
Differences between Local and Nonlocal EDFs

Ar, \( p=100 \) mTorr

Ar, \( p=25 \) Torr

Normalized EDF (total energy) at different \( r \).

Normalized EDF (kinetic energy) at different \( r \).
Can we use a wall probe in this case?

As usual for probe measurements, an important issue is the disturbance of the plasma by the probe. Basically the probe and probe holder disturb the plasma. But if the electron energy relaxation length is greater than the plasma volume size $L$ (i.e. the EEDF is nonlocal, i.e. the EEDF is the same at any point of the plasma, as a function of full electron energy and therefore can be measured by the wall probe for the entire volume. Typically, a wall probe is an electrically isolated segment of the plasma volume wall, serving to either replace or cover the otherwise continuous plasma volume wall and collects the current from the plasma for different probe potentials.)
Basics of the wall probe method:

Small probe

- \( \lambda_e \) is electron energy relaxation length;
- \( \lambda_e \) is mean free path of electrons;
- \( r \) is probe dimension.

If \( \lambda_e > r \), EEDF \( \sim \frac{d^2I}{dV^2} \);
If \( \lambda_e < r \), EEDF \( \sim \frac{dI}{dV} \)

Plasma volume wall
Basics of the wall probe method:

Large probe

Plasma

 Probe

Plasma volume wall
Atomic and molecular processes in plasmas can change and shape form of electron energy distribution functions (EEDF). Due to this, measurements of the EEDF allow in principle analyzing those processes and measuring densities of participating particles. This principle can be used for development of gas analytical detectors.

Afterglow may be convenient for this purpose: low electron temperature.
A method for analyzing the fine structures of the energetic portion of the EEDF in an afterglow plasma is known as plasma electron spectroscopy (PLES) in afterglow (V. Demidov et al., Sov. Phys. J., 1987; RSI, 2002).

Measurements in He/N₂ mixture

Probe measurements of the EEDF in negative glow

Measurements in He plasma.

Electrons from plasma-chemical processes are observable.

\[ \text{He}^* + \text{He}^* \rightarrow \text{He}^+ + \text{He} + e_f \text{ (14.4 eV)} \]

\[ \text{He}^* + e \rightarrow \text{He} + e_f \text{ (19.8 eV)} \]


The experimental device

Cathode (C)
Negative glow (NG)
Cylindrical Wall (W)
Faraday dark space (FDS)
Anode (A)

Experiments in pure He

Gas pressure is 4 Torr
Discharge current is 5 mA

He* + He* → He^+ + He + e_f (14.4 eV)
He* + e → He + e_f (19.8 eV)
Experiments in pure He: different discharge currents

Gas pressure is 4 Torr
Discharge currents are
2 mA (lower curve),
4 mA (middle curve), and
5 mA (upper curve).

He*+He* → He^+ + He + e_f (14.4 eV)
He*+e → He + e_f (19.8 eV)
Experiments in He/Ar mixture

Gas pressure is 4 Torr (5% of Ar),
Discharge current is 10 mA

He*+Ar→He+Ar++e_f (4 eV)
Ar*+Ar*→Ar++Ar+e_f (11.5 eV)
Ar*+e→Ar+e_f (11.5 eV)
Experiments in Ne, Ar and O$_2$/Ar

Gas pressure: Ne (3 Torr), Ar (0.5 Torr), and Ar/O$_2$ (0.5 Torr, 5% of Ar)

Ne$^*+e \rightarrow$Ne$+e_f$ (16.6 eV)

Ar$^*+e \rightarrow$Ar$+e_f$ (11.5 eV)

O$+O^- \rightarrow$O$_2+e_f$ (3.6 eV)
He*+Ar→He+Ar+e_f (4 eV)
He*+He*→He+He+e_f (14.4 eV)
He*+e→He+e_f (19.8 eV)
Ar*+Ar*→Ar+Ar+e_f (7.3 eV)
Detector for measurements of environmental gas constituents

APPLICATION OF PROBES
HIGH PRESSURE GAS ANALYSIS

200 Torr He, 0.2 % Ar, modulating voltage 0.6 V, cathode - anode gap 1.7 mm, discharge current: 1) - 4 mA, 2) - 8 mA.

Air

[Graph showing EEDF, electron energy distribution function, with peaks identified as Ar and Reaction (10), (11).]

[Graph showing second derivative of sensor voltage with peaks at He, N₂, and O.]
More complex plasma:  
**Strong magnetic fields**

\((R_{Le} \ll l, \mathbf{B} \parallel l)\) and \((R_{Le} \ll a, \mathbf{B} \perp l)\)

Parallel probe:

\[
 f(\varepsilon) = \frac{3\omega_e m^{2.5}}{64\sqrt{2}\pi e^2 R_{Le} (eV)^{1.5}} \frac{dI_e}{dV}.
\]

Perpendicular probe:

\[
 f(\varepsilon) = \frac{3m^2 \ln \left( \frac{\pi l}{4a} \right)}{16\pi^2 e^3 V R_{Le}} \frac{dI_e}{dV}.
\]

Magnetic fields: General case

Arbitrary magnetic field:

\[ l_e = \frac{8\pi e S_D}{3m^2} \int_0^\infty \frac{(e-e)Vf(e)de}{eV+\left(1-\frac{eV}{e}\right)\nu(e,V)} \]

\[ \Psi_\perp = a \ln(\pi l/4a)/\gamma R_{Le} \]

\[ \Psi_\parallel = \pi l/4\gamma R_{Le} \]


Restriction for fast-sweeping probe:

\[ \frac{3a^2\omega_e^2}{8v^2vT_e} eV_{SW} \ll \tau_{SW}. \]

The EEDF obtained by a probe in the CASTOR tokamak edge plasma.


More complex plasma: Anisotropy (spherical probe)

\[ f(t, \vec{r}, \vec{v}) = \sum_{j=0}^{\infty} \sum_{k=-j}^{j} f_j^{(k)}(t, \vec{r}, v) Y_j^k(\theta, \varphi) \]

The Driuvesteyn formula is valid and provide EEDF. Information about angular Distribution of ions is lost.

The EEPF in a low-pressure (0.1 Torr) hydrogen constricted arc plasma at the discharge axis.

Anisotropy (cylindrical probe)

$I_p''$ with respect to the potential $V$ measured at the discharge axis at a distance $Z$ from the cathode by probes in two mutually perpendicular orientations. At $Z > 2$ mm, $I''$ is the same for both probes. The helium pressure is 2.3 Torr, the discharge current is 0.5 A.

\[
\frac{d^2 I_p}{dV^2} = \frac{4\pi^2 e^3 a l}{m^2} \sum_{j=0}^{\infty} F_{2j}(eV)P_{2j}(0)
\]

$F_{2j}(eV) \equiv f_{2j}(eV) - \int_{eV}^{\infty} f_{2j}(eV) \frac{\partial}{\partial(eV)} P_{2j} \left( \sqrt{\frac{eV}{\epsilon}} \right) d\epsilon$

$P_j \equiv Y_j^0$ are the Legendre polynomials

System of regulation of the probe orientation relative to the discharge axis: 1 - stationary corps, 2 - bellows connection, 3 - rotating bush, 4 - metal current-input, 5 - ceramics, 6 - isolation of the probe; $d_h$ - the diameter of the probe holder, $d_p$ - the diameter of the probe. Probe dimensions used are $d_h=0.1$ mm, $d_p=0.5$ mm, disk thickness $t_p=0.03$ mm.
Flat one-sided probe

Definition of angles between the discharge axis and probe position and the velocity direction.
Anisotropy (general case)

Coefficients $f_j$ in a helium low-pressure (0.5 Torr) positive column: $f_0$ (1), $f_1$ (2), $f_2$ (3), $f_3$ (4), and $f_4$ (5)

$$a_{kj} = (-1)^k \frac{(2j-2k)!(j-2k)!}{k!(j-k)!(j-2k)!}$$

$$R_j(\varepsilon, V) = \frac{2^{-(j+1)}}{eV} \sum_{k=0}^{[j/2]} a_{kj} \left( \frac{\varepsilon}{eV} \right)^{j-2k-1}$$

$$f_j(eV) = \frac{(2j+1)m^2}{4\pi e^3 S_p} \int_{-1}^{1} l''(V, \cos \Phi) \, d(\cos \Phi) + \int_{eV}^{\infty} l''(\varepsilon, \cos \Phi) R_j(V, \varepsilon) \, d\varepsilon \, P_j(\cos \Phi) \, d(\cos \Phi)$$

Modeling anisotropic EDF

The polar diagram $f(\nu)$ for electrons calculated for different numbers of probe orientations $K$: $K = 3$ (1); $K = 5$ (2); $K = 7$ (3); $K = 9$ (4); model function (5).
Finally...

- Electric probe can provide very high 2D or 3D spatial resolution of order of the probe size.
- In nonlocal plasma the resolution may be unnecessary and simple wall probe can provide the EDF measurements.
- In local plasmas the spatial resolution may be important if the EDF measurements are possible.
- Moving flat probe can provide angular 2D and 3D measurements of EDF, however most plasmas are weakly anisotropic and may not require angular resolution. It could be useful for some special cases like plasma with electron beam.
Introductory remarks:

- Development of novel diagnostics is one of the important tasks of the LTP Center.
- The electric probe is seen as a simple and attractive instrument used many authors.
- Sophisticated probe constructions allow measurements in different types of plasmas.
- These probe constructions have not been yet fully exploited.
- Magnetically insulated baffled (MIB) probe is an example of probe diagnostics, which has been developed by the LTP Center.
Magnetically insulated baffled probes (MIB)

- A MIB probe offers the advantages of direct measurements of the plasma properties, while being non-emitting and electrically floating.

- The MIB probes can be used in:
  - technologically important LTP plasmas
  - basic plasma research, and
  - fusion related plasmas.

Instrumental functions in probe measurements

- The result of measurements of the EEPF is a convolution of the real EEPF and the instrumental function $A$:

$$f_{pm}(\varepsilon) = \int_{-\infty}^{\infty} f_p(\varepsilon) A(\varepsilon - x) dx \equiv f_p * A$$

A simple circuit allows measuring instrumental functions

IV trace of the system

The measured instrumental function of the SMARTProbe (1). The same function in the presence of potential oscillations with an amplitude of 2.5 V (2).

Measured EEDs in argon-rf-afterglow plasma without (dots) and with (solid line) an additional artificial maximum (indicated by arrow). The gas pressure is 30 mTorr, the repetition frequency is 400 Hz, and the time after current interruption is 0.7 ms.
The measured instrumental functions in afterglow plasma

An instrumental function obtained from a probe with a dirty surface

\[ \text{Ne}^* + \text{Ne}^* \rightarrow \text{Ne}^+ + \text{Ne} + \text{e}_f \]

Instrumental function \( A(\varepsilon) \) measured in a neon-afterglow plasma (1). The calculated function for the “clean” probe (2). The calculated function for a probe with electron reflection with reflection coefficients of 1-0.016 V\(^{-1}\) (3) and 1-0.056 V\(^{-1}\) (4).

The goal of this review is to increase awareness of the problems pertaining to the relationship between the actual plasma parameters and the probe experiment design. Main sources of error in EEDF measurements, remedies to avoid EEDF distortions and examples of positive resolutions of the problems were presented here for different types of gas-discharge plasmas. We also introduce the reader to unconventional methods of electron-distribution diagnostics in collisional, magnetized and anisotropic plasmas that are still under development and remain a challenge for budding scientists.