Control of gas discharge plasma properties utilizing nonlocal electron energy distribution functions

DOE-OFS Plasma Science Center

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Future cooperation with: open

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Outline of the talk

- Introduction
  *Plasma Physics at WVU and connection to AFRL*
- Nonlocal Electron Energy Distribution Function and Control of Plasma Properties
  *How does the EEDF nonlocality can help to control plasma properties?*
- Low-Pressure RF Power-Pulse Plasma
  *Control of light emission and two-chamber plasma physics*
- Short (without Positive Column) DC Discharges with Cold Cathode
  *Measurements of the EEDF by wall probes and gas detectors*
- Short DC Discharges with Heated Cathode
  *Control of plasma parameters and technical applications*
- Conclusions and Future Work
  *What should be done and possible cooperation*
Basics of the Nonlocal EEDF

$\lambda_e$ is electron energy relaxation length;

$\lambda_e$ is mean free path of electrons;

Plasma volume wall

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Predictive Control of Plasma Kinetics
The aim of this project is experimental, theoretical and numerical investigation of the formation and particle kinetics of low-pressure rf power-pulse plasma in electro-positive and electro-negative gases and gas mixtures.
EEDF and control of the light emission

EEDF in the afterglow has maxima connected to plasma-chemical reactions

Application of potentials to walls allows to change EEDF and therefore light emission

Figure 6. Intensity of the Ar spectral line at 420.1 nm after termination of rf pulse with mirror M (see figure 1). Average power is 250 W and rf pulse duration is 300 µs. Argon pressure is 20 mTorr. Ring potential is $-9$ V (stars) and 0 V (diamonds). The same with mirror removed (across the vacuum chamber) and with ring potential at $-9$ V (squares).
Two-chamber effects

Presence of two chambers of different sizes can change the plasma behavior.

Figure 2. Spatial distribution of electron density at the end of the active phase.

Figure 3. Spatial distribution of electron density at $t = 500 \mu s$ in the afterglow.

Figure 7. Temporal behavior of the ambipolar flux incident on the imaginary boundary between the two chambers.
Nonlocal electron kinetics in DC discharge plasmas:

Nonlocal electron kinetics and transport in collisional plasma with energetic electrons:

The aim of this project is experimental, theoretical and numerical investigation of collisional plasma with the presence of energetic electrons. It was demonstrated that the presence even a small fraction (say, 0.001%) of these energetic electrons could lead to their self-trapping in the volume and a significant change in plasma properties. The exploitation of these effects can lead to methods for controlling the plasma properties, which is a major goal of modern plasma engineering.
Short (without Positive Column) DC Discharges with Cold Cathode

Cathode (C)
Negative glow (NG)
Cylindrical Wall (W)
Faraday dark space (FDS)
Anode (A)
Basics of the wall probe method

If $\lambda_e > r$, EEDF $\sim d^2I/dV^2$;
If $\lambda_e < r$, EEDF $\sim dI/dV$
Experiments in pure He

Gas pressure is 4 Torr
Discharge current is 5 mA

$\text{He}^* + \text{He}^* \rightarrow \text{He}^+ + \text{He} + e_f \ (14.4 \text{ eV})$
$\text{He}^* + e \rightarrow \text{He} + e_f \ (19.8 \text{ eV})$
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

- \[ \text{He}^* + \text{Ar} \rightarrow \text{He} + \text{Ar}^+ + e_f (4 \text{ eV}) \]
- \[ \text{Ar}^* + \text{Ar}^* \rightarrow \text{Ar}^+ + \text{Ar} + e_f (11.5 \text{ eV}) \]
- \[ \text{Ar}^* + e \rightarrow \text{Ar} + e_f (11.5 \text{ eV}) \]
Experiments in Ne, Ar and O₂/Ar

Gas pressure: Ne (3 Torr), Ar (0.5 Torr), and Ar/O₂ (0.5 Torr, 5\% of Ar)

\[ \text{Ne}^* + e \rightarrow \text{Ne} + e_f \ (16.6 \text{ eV}) \]

\[ \text{Ar}^* + e \rightarrow \text{Ar} + e_f \ (11.5 \text{ eV}) \]

\[ \text{O} + \text{O}^- \rightarrow \text{O}_2 + e_f \ (3.6 \text{ eV}) \]
Experiments in He/Ar afterglow

Gas pressure is 4 Torr (0.002 % of Ar)

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)
The discharge takes place between a grounded cathode and a positively biased anode. The indirectly heated cathode is a disk with a diameter of 1.0 cm of porous tungsten impregnated with barium-potassium aluminate. The diameter of the molybdenum anode is 3.0 cm.

FIG. 1. Schematic diagram of the experimental device.
Controlling plasma properties by managing fast electrons

Changing voltage on diaphragm electrode leads to transitions between two very different discharge modes.

Left: Schematic diagram of the experimental device of dc discharge with hot cathode and plasma glow, He 1 Torr. Right: Axial profiles of the plasma potential for voltages on diaphragm 18V and 13V.
FIG. 2. IV traces of the cathode-diaphragm gap. Anode current electron current is 0.1 A 1a and 1b, 0.2 A 2a and 2b, 0.3 A 3a and 3b, and 0.4 A 4a and 4b. Gas pressure is 1 Torr. The floating potential is indicated by the arrow.
Axial Behavior of the Plasma Potential

FIG. 3.

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Conclusions

- Electron energy distribution function in low temperature plasmas is typically non-Maxwellian and discharge modeling has to be done kinetically.
- It was shown experimentally and in simulations that a small amount of energetic electrons can greatly affect the wall and plasma potentials. This property can be used for effective control of plasma properties.
- The development of gas micro-analyzers with dimensions of the order of 0.1 mm and operation at atmospheric pressure is possible.
- The wall probe gives a possibility of measurements of EEDF in micro-plasmas which can be more difficult to conduct with ordinary electric probes.