A comparison of experimental and theoretical electron energy distribution functions in an argon GyM plasma

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Abstract

A joint experimental/theoretical investigation on the characteristics of argon plasmas produced in GyM magnetic linear device has been carried out, comparing the measured electron energy distribution function (EEDF) with the distribution resulting from a self-consistent state-to-state kinetic model coupling the chemistry of inelastic and reactive collisional processes with the Boltzmann equation for free electrons.

A preliminary comparison between the theoretically simulated and experimentally measured electron temperature shows a reasonable agreement.

1. Introduction

In plasma process electrons are the first in getting energy from electric field and then in transmitting the energy to all other plasma components, providing energy for ionization, excitation, dissociation, and other plasma-chemical processes. The rates of such processes depend on how many electrons have enough energy for these processes and can be described by means of electron energy distribution function (EEDF) $f(\varepsilon)$, which is the probability density for an electron to have energy ε. The knowledge of EEDF is of great interest in different branches of plasma physics ranging from laboratory to fusion plasmas [1]. Experimentally EEDF is determined from the analysis of the Langmuir probe characteristic. The second derivative of the *I/V* expression is proportional to the EEDF according to the known Druyvesteyn expression [2]. This formula is valid for low gas pressure and for low magnetic fields. In the presence of strong magnetic field it has been shown that the EEDF may be approximated rather by its first derivative [3]. To define the threshold of the magnetic field between the two approaches, the diffusion factor (Ψ) needs to be estimated, as reported in [3]. It is demonstrated that for $\Psi<<1$ Druyvesteyn formula is still valid, instead for $\Psi>>10$ EEDF is better described by first derivative. Calculation of Ψ in GyM [4] gives a value between $1<\Psi<10$, then for EEDF determination a more general formula is required [3]. The determination of the corrections requires additional study and tests are still in progress. An analysis similar to that performed for the high energy in ECR multicharged ion source plasma [5] suggests that the Druyvesteyn method is reasonably applicable also in GyM, therefore on the basis of this, we have decided to use the Druyvesteyn formula.

This work aims to compare measurements of the T_e, n_e and EEDF in argon GyM plasmas with those obtained from a self-consistent state-to-state (SC-StS) approach [6, 7].

2. Experimental setup

Experiments were conducted in GyM linear magnetic plasma device in argon, with a pressure in the range 5-32 mPa and magnetic field fixed at 89.36 and 81.86 mT. Plasmas are obtained and steadily sustained by electron cyclotron resonance heating using radio-frequency source at 2.45 GHz capable of delivering up to 3kW of power. Plasma parameters (T_e, n_e) were estimated from I-V characteristic of a Langmuir probe inserted radially (perpendicular to the magnetic field) into the chamber. Experimental conditions for reference plasmas used in this study are listed in table 1.

Table 1. Experimental conditions for reference plasmas. T_e and n_e measured by Druyvesteyn formula.

Shot	Gas	B (mT)	Power (kW)	Pressure (mPa)	T_e (eV)	n_e (10^{16}m^{-3})
#180130007	Ar	89.36	0.76	5	9.8	2.4
#190215004	Ar	81.86	1.50	8	7.4	3.2
#190222001	Ar	81.86	1.50	32	4.6	2

To reduce the noise in the acquired signal, the data have been smoothed using the Savitzky-Golay filter, which also provides the derivatives of the data signals.

2. Self-consistent state-to-state (SC-StS) model

The self-consistent state-to-state (SC-StS) approach which solves, at each time step, the Boltzmann equation for free electrons and the master equations for chemical species and level population, accounting for the influence of the excited states on the EEDF, has been used for the time-dependent simulation of the plasma in GyM in different experimental conditions. The kinetic scheme includes only the electron

impact induced processes, in fact, due to the low operative pressures in GyM, the heavy particle collisions are considered ineffective in the kinetics. The elastic (momentum transfer) and inelastic channels (excitation and ionization) have been considered accounting also for spontaneous emission of radiation, for the radiative recombination on excited states, $Ar^{+}+e \rightarrow Ar^{\star}+h\nu$, estimated from the corresponding photoionization processes by detailed balance, and for the superelastic collisions. These last processes entail the gain of energy by electrons from the de-excitation of atoms. The electron-electron collisions are not accounted for in the model. The database of cross sections for the description of elementary processes has been improved so as to include the most accurate data available in the literature [8, 9, 10].
The 0D kinetic code models the plasma fed by a pulse with a constant power density at constant gas pressure and temperature. Assuming the plasma volume moving along the *z* axis at a constant velocity allows to correlate the simulation time with space coordinate in GyM. The observation time corresponding to the position of the Langmuir probe along the axis of GyM has been selected investigating the time evolution of the plasma at the lowest pressure value considered in the experiments.

4. Results

In figure 1 (*a*) the theoretical electron energy probability functions, ($\frac{f(\varepsilon)}{\sqrt{\varepsilon}}$), (EEPF) for two different times in the evolution are displayed, one in the discharge phase and the other in the post-discharge (the discharge time is 7.2×10^{-4} s), and compared with the distribution measured by the Langmuir probe. The behaviour of the distribution in the discharge has the well-known bimodal Maxwellian character, separating the electrons in two groups, the low-energy *cold* and the tail *hot* electrons [11]. In the post-discharge the distribution becomes markedly non-Maxwellian and characterized by the bump around 11 eV which is associated to the kinetics of the metastable state of $Ar^{\star}(3s^2 3p^5 4s)$. The T_e, calculated from the mean electron energy, is ~7.6 eV, lower even though still showing a satisfactory agreement with the experimental estimation. In figure 1 (*b*) the comparison at the same observation time has been extended to other two experiments carried out at increasing pressure. The higher density produces a modification of the EEPF profile depopulating more efficiently by collisional mechanism the tails and producing a corresponding decrease of T_e, still well comparing with the experimental value. In fact, at P=8 mPa the experimental temperature of 7.4 eV is predicted to be 5.8 eV from the simulation and at P=32 mPa $(T_e)_{exp}$=4.6 eV, $(T_e)_{theo}$=3.78 eV. The aspect still critical in the comparison between experiments and the kinetic model is represented by electron density values, that are quite insensitive to the change in pressure, as also measured, but significantly higher, $(n_e)_{theo}$=8x10^{17} m^{-3}. This discrepancy needs further investigation and could be attributed from one side to the differences in the low-energy of the distributions and on the other side from the way the power is deposited in the plasma.

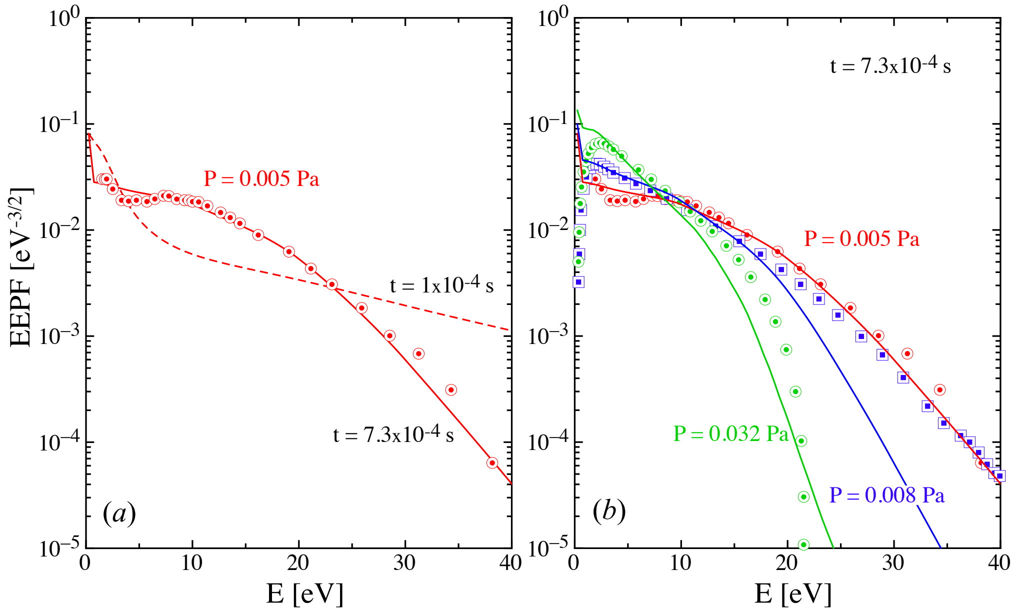

Fig.1 (*a*) Electron energy probability function for the lowest pressure 5mPa of Ar plasma. Discharge (dashed line) and post-discharge (solid line) distributions compared with experiments (markers). (*b*) Electron energy probability function for different pressures of Ar plasma in the post-discharge (solid line) distributions compared with experiments (markers).

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