IN-SITU ELECTRON CYCLOTRON RESONANCE (ECR) PLASMA POTENTIAL DETERMINATION USING AN EMISSIVE PROBE*

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Abstract

Plasma potential measurements by use of a Langmuir probe (LP) and an emissive probe (EP) were compared in the ORNL CAPRICE electron cyclotron resonance (ECR) ion source. It is shown that, for normal ECR ion source operating conditions, the large population of hot electrons may make the emissive floating point method fail, and may cause the values deduced using the LP method to be in error by more than 10%. In addition, the gas mixing effect was studied by comparison of *in-situ* probe measurements and measurements of the extracted ion beam charge state distribution (CSD). An explanation of the effect in terms of a change in plasma potential and hot electron temperature is proposed.

INTRODUCTION

Recently Langmuir probe diagnostics have been attempted for the first time in ECR ion sources [1]. Motivation for these attempts was an independent determination of the internal ECR plasma parameters and their dynamics. In general, plasma parameters such as electron density, temperature, and plasma potential can be obtained from LP measurements if they are properly carried out. In an ideal (i.e., unmagnetized, collisionless, stationary, and purely Maxwellian) plasma, LP data can be easily analyzed to provide precise values of the plasma potential (V_s). However, due to the geometrically complex, magnetized, and non-Maxwellian nature of ECR plasmas, and its large population of fast electrons, determination of V_s from LP data can be problematic[2], and should be confirmed using another diagnostic such as the EP.

In this article LP plasma potential determinations were experimentally checked by using an EP. Having in this manner determined the magnitude of possible uncertainties of the deduced potentials, the gas mixing effect [3] was reinvestigated by comparison of probe data and extracted beam CSD's.

EXPERIMENTAL SETUP

In order to operate a plasma probe (LP or EP) successfully, the probe must be small in comparison to the plasma length scale in order not to perturb the global state of the plasma, and at the same time be able to withstand the heat load from the plasma without damage. In the case of an ECR plasma, it is difficult to satisfy these requirements because of its small plasma length scale and the high heat flux from its large population of hot electrons.

In the present measurements both requirements were satisfied by proper placement of the probe holder, positioning of the probe into the edge region of the ECR plasma, and limitation of the injected microwave power to values sufficiently low to avoid self-emission of the probe. The probe was inserted in a location where the flux tube intercepted by the probe has no direct connection either to the ECR zone where the electrons are heated, or to the extraction region where high energy backstreaming electrons may be present (see Figure 1). During the present measurements, careful shielding of the probe leads in the extraction vacuum chamber assured that operation of the *in-situ* probe when the source was operated at high voltage resulted in no detectable perturbation of the extracted beam currents.

The probe could be operated in both LP and EP modes, and was formed from 0.058 mm tungsten wire, which extended toward the source axis from two small alumina tubes, forming a small loop of approximately 3 mm length. The electron and ion Larmor radii at the probe position were estimated to be of the order of 0.01 mm and 0.5 mm, respectively. Consequently, the plasma electrons are magnetized while the ions are unmagnetized. Further, the probe operates in the collisional nonlocal regime for electrons and the collisionless thick sheath regime for ions.

The probe design, high voltage isolation and data acquisition via a wireless connection, and automated data analysis are described in greater detail elsewhere [4].

RESULTS

Plasma Potential Measurements

The plasma potential determined from LP data, is usually taken in the ideal case as the maximum value of the first derivative $I'(V_p)$ of the probe current with respect to the probe bias (V_p). In reality, the plasma state, the probe analysis operating regime, and a range of other effects can result in deviations from this ideal case. The most reliable value in principle is found by fitting to the appropriate theoretical model [2]. However, such an approach is not amenable to real-time measurements. In the present measurements, since real-time monitoring of the plasma potential is a central focus, and since relative changes, not absolute values, in the plasma potential are of interest, the peak value of $I'(V_p)$ is assumed to give the plasma potential.

In order to delineate better the conditions under which this assumption holds, and the magnitude of the error that results when it fails, measurements were performed with the probe operated in the EP mode at a source pressure of 4E-7 Torr, a microwave power level of 28 W, and a high confining axial magnetic field, which are all conditions

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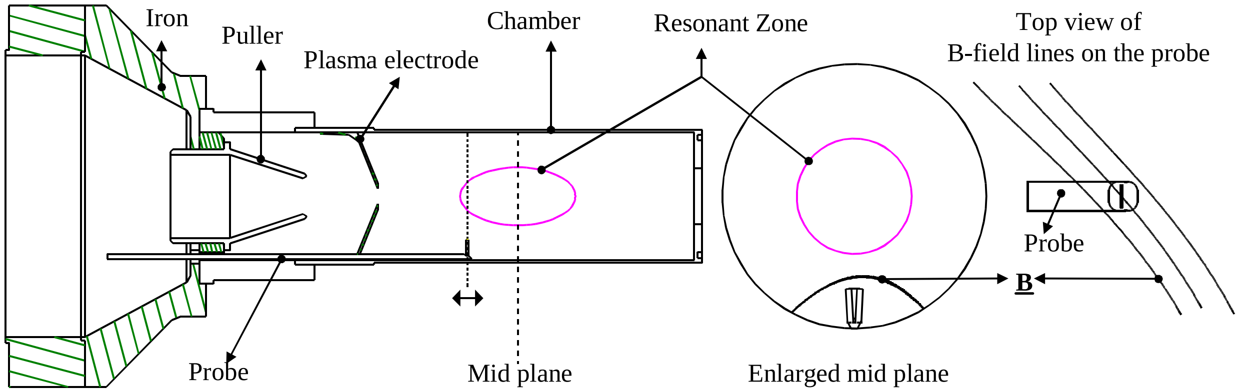

Figure 1: The probe positioning relative to the radial loss cones of the magnetic structure of CAPRICE ECRIS.

favorable for the generation of highly charged ions, and thus hot electrons. The result is shown in Figure 2, which displays both I-V and $I'(V_p)$ curves at different filament heating currents. The plasma potential was determined by monitoring the $I'(V_p)$ maximum as a function of heating current and extrapolating the result to zero electron emission, as illustrated by the solid line in the figure. This value, denoted by V_{se}, is expected to be the most accurate [5,6]. Two observations are noted. First, the floating potential, V_f , is significantly different from V_{se} even under maximum achievable electron emission conditions. Second, the $I'(V_p)$ maximum in LP mode, denoted by V_{sc} and the dotted line in the figure, differs from V_{se} in this case by 10%. For other plasma conditions, differences of up to 30% were observed. These features suggest that for typical ECR source conditions, the presence of fast electrons can lead to erroneous plasma potential values in both the emissive floating potential method and in the LP approach.

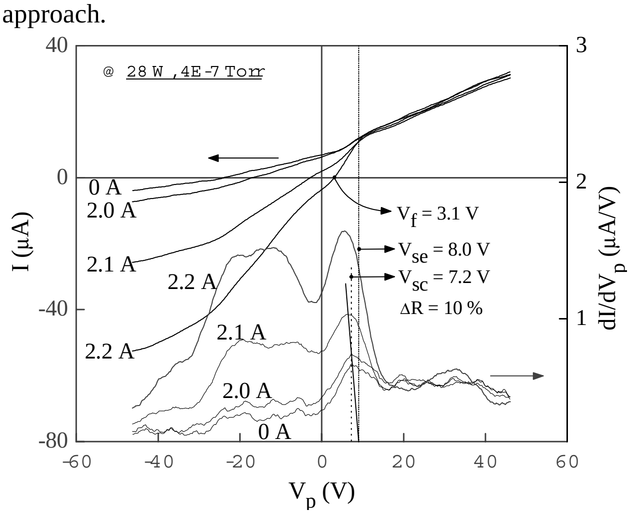

Figure 2: Plasma potential measurement by an EP.

The Gas Mixing Effect

Some gas-mixing-effect studies were carried out as well. The measurements used the LP method to obtain both the plasma potential, V_s, and fast electron temperature, T_{ef}, and were focused on the correlation of these plasma parameters with external Ar CSD's modified by addition of helium and oxygen mix gases. Four different Ar plasmas were investigated: a pure Ar plasma, an Ar/He plasma, and two Ar/O_2 mixtures. In the first Ar/O_2 mixture and the Ar/He mixture, the Ar leak rate was kept at the rate determined for the pure Ar case to give the maximum Ar^{8+} current, while the mix gas flow rate was adjusted to further optimize the Ar^{8+} current. For the second Ar/O_2 mixture, both gas flow rates were optimized for maximum Ar^{9+} current. For all 4 mixtures, slight adjustments of rf power and axial magnetic field strength were also made. After each optimization, a number of LP measurements were made and recorded. The experimental parameters for each mixture are summarized in Table 1, and the corresponding CSD's are shown in Figure 3(c). It is important to recall that the rf power levels used were limited by probe lifetime issues and do not represent values for fully optimized external CSD's. It is noted that when closing the He gas valve, the plasma parameters and CSD immediately returned to their original values (pure Ar case), while a much longer time interval (~0.5 hour) was required after closing the O_2 mix gas, suggesting significant surface sticking for this gas.

Table 1: Experimental conditions for gas mixing studies.

	rf Power (W)	Source Pressure (×E-7 Torr)	V_s (V)
Ar	30	1.8	27±0.4
Ar+He	30	2.0	23±1.2
$Ar+O_2$ I	31	20.0	18±1.5
$Ar+O_2$ II	34	12.0	10±0.5

The LP $I'(V_p)$ curves are shown in Figure 3(a), and the peak positions, assumed to correspond to the relative plasma potential, are summarized in the final column of the Table 1. Prior to these measurements the plasma potential dependence on the power, pressure, and axial magnetic field was more extensively mapped in a pure Ar plasma. Typical trends found were that the plasma potential increases by less than 5 V as the source pressure goes from 2E-7 to 10E-7 Torr and as the rf power increases from 10 to 50 W, and that there is only a weak dependence on B-field. Therefore the small variations of the pressure, magnetic field, and rf power in the gas mixing measurements are not believed to contribute

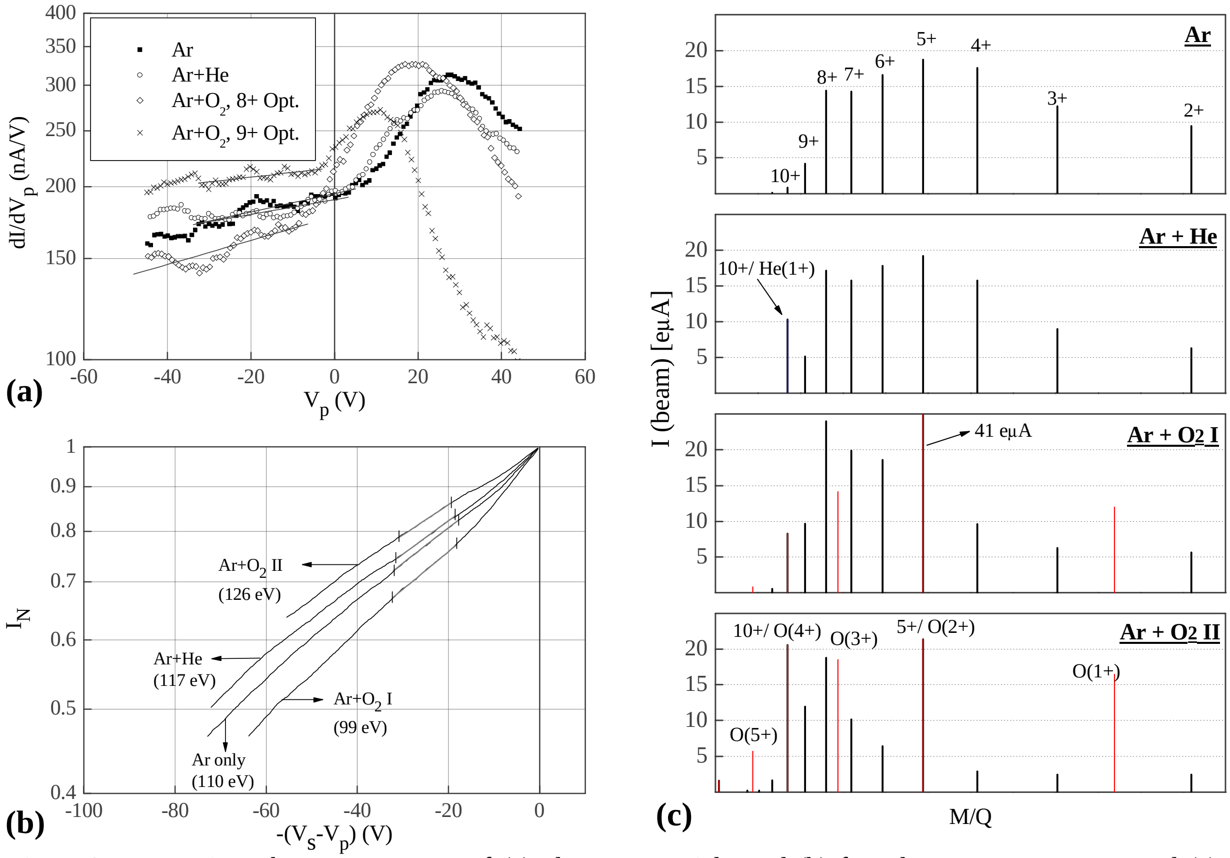

Figure 3: Langmuir probe measurements of (a) plasma potentials, and (b) fast electron temperatures; and (c) corresponding external beam charge distributions (CSD's) for pure Ar, He gas mixed and O_2 gas mixed plasmas.

significantly to the observed differences of plasma potential.

In addition to the plasma potentials, fast electron temperatures (T_{ef}) are obtained from the LP data. Figure 3(b) shows I-V curves (I_N) drawn on a semi-logarithmic scale, normalized by dividing by the electron saturation current taken at the maximum of $I'(V_p)$. T_{ef} can be extracted by fitting only the linear part of the curves (see values in parentheses in Figure 3(b)). This direct fitting is possible only when the fast electron contribution dominates, and when their temperature is sufficiently different from that of the cold electrons, as is the case in the present plasma. Based on other investigations in magnetized plasmas, this fitting approach can overestimate the fast electron temperature by up to 30% [2]. It is noted that, unlike the plasma potential, T_{ef} was found to be very sensitive to small changes of plasma conditions, particularly the rf power level.

It is known from probe theory [7,8] that in magnetized plasmas the electron energy distribution is proportional to $I'(V_p)$. The long tails extending to the left of the $I'(V_p)$ peaks in Figure 3(a) therefore provide further evidence for the presence of significant populations of fast electrons, which are obviously closely related to the generation of the highly charged ions observed in the extracted CSD's.

Both the plasma potential and fast electron temperature variations with gas mixing show a correlation with the changes of the CSD's shown in Figure 3 (c). The observed ~30% variation in T_{ef} is ascribed mainly to varying source conditions. From the much larger change (factor of 2.7) of the plasma potential found in going from the pure Ar to the Ar+O_2 II case, the earlier noted lack of sensitivity of V_s to source conditions, and the greatly different CSD's for these two cases, it would appear that a decrease of the plasma potential and the corresponding increase in ion confinement time is the dominant mechanism responsible for the gas mixing effect. Similar conclusions have been reached by other groups [9,10].

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