Plasma potential and energy spread determination using ion beams extracted from an electron cyclotron resonance source[a)]

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(Presented 21 September 2009; received 22 September 2009; accepted 13 November 2009; published online 8 February 2010)

We have obtained estimates of plasma potentials and energy spreads characterizing an electron cyclotron resonance ion source plasma under different source conditions. Our estimates are obtained from analysis of ion beams extracted from the ion source at 10 kV that are subsequently decelerated into a floating surface scattering chamber where their current intensity incident on a solid sample is measured as function of retardation voltage. The deceleration occurs outside the measurement chamber, permitting beam current measurements in a field-free region. Absence of grids in the deceleration section avoids potential issues of field penetration. The behavior of our deceleration optics was modeled with SIMION. The simulation indicated a linear beam attenuation dependence close to full retardation where the beam current goes to zero. Deviations from this linear dependence observed close to zero beam energy give information on the initial energy spread of the ions extracted from the source. Our decelerated beams measurements are compared with recent *in situ* probe results and external beams results based on magnetic analysis. *© 2010 American Institute of Physics.* [doi:10.1063/1.3272847]

I. INTRODUCTION

Accurate knowledge of the plasma potential of an electron cyclotron resonance (ECR) ion source is important for insights it provides into the source plasma[1] and for characterization of low energy beams, such as those used in our current experimental investigations of low energy chemical sputtering of carbon surfaces.[2] In these studies we use low energy (<50 eV/D) beams to compare chemical sputtering behaviors of isovelocity atomic and molecular deuterium beams. Accurate determination of beam energies is crucial. At such low energies, the plasma potential makes a significant contribution to the total ion energy, and must be properly accounted for. A floating surface scattering chamber with efficient deceleration optics developed[3] for these investigations permits convenient determination of the plasma potential by monitoring the target beam intensity as function of deceleration voltage. This approach is advantageous for two reasons: first, unlike *in situ* Langmuir probe measurements, it allows measurement without disturbing the ion source plasma, and second, it directly reflects the effects of plasma potential and energy spread on the extracted beam, thus permitting convenient real time characterization and optimization of the decelerated beams. We compare the results of our measurements with our earlier *in situ* Langmuir probe measurements[4,5] as well as other external beam measurements based on a grip retardation lens[6] and magnetic rigidity analysis.[7,8]

[a)]Contributed paper, published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September 2009.

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II. EXPERIMENTAL PROCEDURE

A. Decelerated ion beam technique

We extract ion beams from our ECR source at 10 kV source potential. Subsequent to magnetic analysis, these beams are transported to a floating surface scattering end station that can be independently biased. To minimize the effects of voltage ripple and stability, the bias consists of small off-set voltage of either polarity that is added to the ECR source potential. A 90° spherical sector electrostatic deflector is used to inject the full energy ion beam into a five element deceleration section at the entrance of our floating experimental surface scattering chamber. The spherical deflector is positioned to produce a waist at the entrance aperture of the deceleration optics. The specifics of the ECR ion source are described elsewhere in more detail.[4]

Figure 1 shows a schematic layout of the deceleration section, and a trajectory simulation using SIMION 3D 7.0 (Ref. 9) for 10 keV positive ions decelerated to 30 eV. The trajectories shown in the figure were obtained assuming a beam waist of 3.8 mm half width and 1° half-angle divergence at the entrance of the deceleration section, which roughly represents the full emittance of the extracted beams. The conical end element with a 5 mm exit aperture and the target, located about 2.5 cm downstream, are all at chamber potential, resulting in an essentially field-free scattering chamber interior. To obtain retardation curves near zero beam energy, we first tuned the five elements of our deceleration optics for low final energy (typically <50 eV), by optimizing the beam current and profile (as measured using a wire scanner) on the graphite beam stop. The decel section voltages were then held fixed as the beam stop current was monitored with further stepwise increases in the chamber voltage. A typical

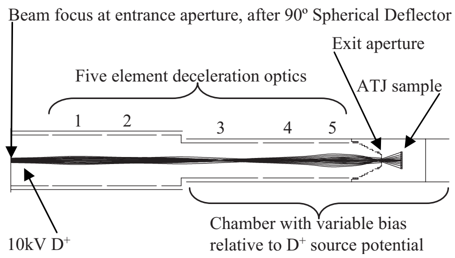

FIG. 1. Schematic diagram of the five element deceleration optics used for determination of retardation curves, and simulated trajectories using SIMION 3D 7.0 for a 30 eV beam decelerated from an initial beam energy of 10 keV; exit cone/aperture, chamber, and target are all at same potential of 9.970 kV.

retardation curve obtained using this procedure is shown in Fig. 2, for the case of D^+ ions and ECR source plasma conditions of 2×10^{-6} Torr and 8 W of microwave power. As can be seen from the figure, the retardation curve is characterized by a linear region, whose extrapolation to zero beam stop current provides an estimate of the plasma potential (see blue straight line). The residual current in the vicinity of the cutoff after subtraction of the linear fit (see dashed red line profile) provides an estimate of the ion energy spread. Both plasma potential and ion energy spreads are affected by ECR source conditions, as discussed in the experimental results section of this paper. We find that the plasma potentials and energy spreads obtained using the decelerated beam technique are in reasonable agreement with previous Langmuir probe measurements on the present ECR ion source, and with results derived from extrapolations of ion beam analyzing magnet peak positions as a function of beam energy.[7]

B. Analyzer magnetic field peak technique

Altering the energy of extracted ion beams induces a shift in the magnetic field value at which an ion beam is centered in a downstream Faraday cup. As shown in Ref. 7, the x intercept of a linear extrapolation of the square of the magnetic analysis peak field plotted as a function of applied source potential can provide an estimate of the plasma potential. To minimize uncertainty in the x intercept value, source potentials in the few 100 V's are used, and the analysis magnetic field must be accurately known. Unpublished measurements were performed for Ar source gas for the ORNL ECR using this technique, and published measurements by Xie and Lyneis[7] exist for the Lawrence Berkeley National Laboratory ECR source. Such measurements are in general in reasonable agreement with the plasma potentials determined in the present work. Analysis of magnetic beam profiles under narrow entrance and exit slit conditions, where the instrumental widths are small, have been used to obtain information on energy spreads in extracted ECR ion source-produced beams.[8] The deduced values are in good accord with the energy spreads found in the present work.

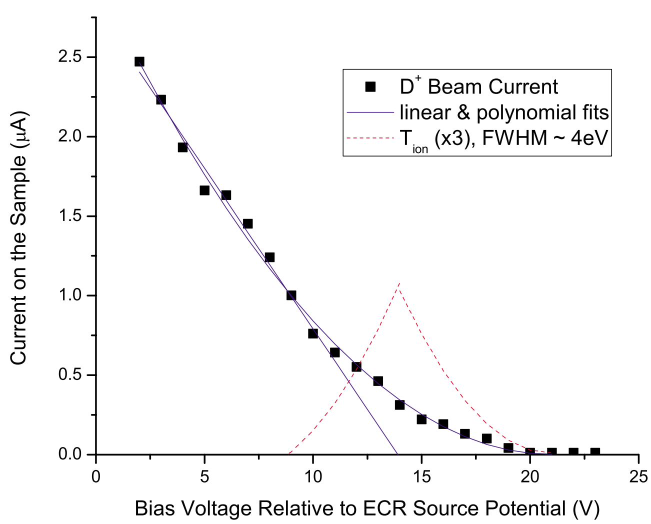

FIG. 2. (Color online) Typical retardation curve, for 2×10^{-6} Torr source pressure and 8 W of microwave power, obtained as described in the text, used to determine plasma potential and ion energy spread.

C. Langmuir probe technique

The use of Langmuir probes is a standard technique to measure plasma potentials, and has been explored in prior work[4,5] for the ECR ion source in our laboratory.[10] To minimize perturbation of the core plasma and to achieve reasonable probe lifetimes, use of such probes in ECR sources is limited to the edge of the ECR plasma and low microwave power conditions. Moreover, since the Langmuir probe measures the plasma potential at a specific location (away from the source axis) within the source rather than postextraction,[4,11] its use in making extracted beam energy corrections implies the assumption that the plasma potential in the region of ion extraction is the same as that deduced at the ECR plasma edge. Comparisons of the present results with published Langmuir probe measurements[4,5] for the present ECR ion source, to be discussed below, seem to provide some justification for this assumption.

III. EXPERIMENTAL RESULTS

A. Plasma potential

Figure 3 shows the plasma potentials obtained, using the approach outlined in the previous section, under various source conditions for deuterium and argon ion beams. The range of source conditions explored was limited by the (arbitrary) requirement of beam stop currents >1 μA at the initial low energy tuning energy. For deuterium source gas, plasma potentials were determined for singly charged atomic (D) or molecular (D_2 or D_3) ion beams, while ion beams for various charge states were analyzed in the case of Ar source gas. D^+ beam production was explored over the largest range of ECR source conditions, and showed the largest variation in plasma potentials. In contrast, sufficiently intense D_3^+ beams could only be produced over a narrow range of source pressures and microwave power levels, and to a lesser extent the same was observed for the production of D_2^+. For the analyzed Ar beams, the ECR source was individually optimized for each analyzed charge state. Significant variation in plasma potential with source pressure was observed. In general the deduced plasma potentials show a decreasing trend with increasing pressure, as has been previously observed;[7] over the narrow range of microwave powers investigated, a definitive variation with microwave power, on the other hand, could not be established.

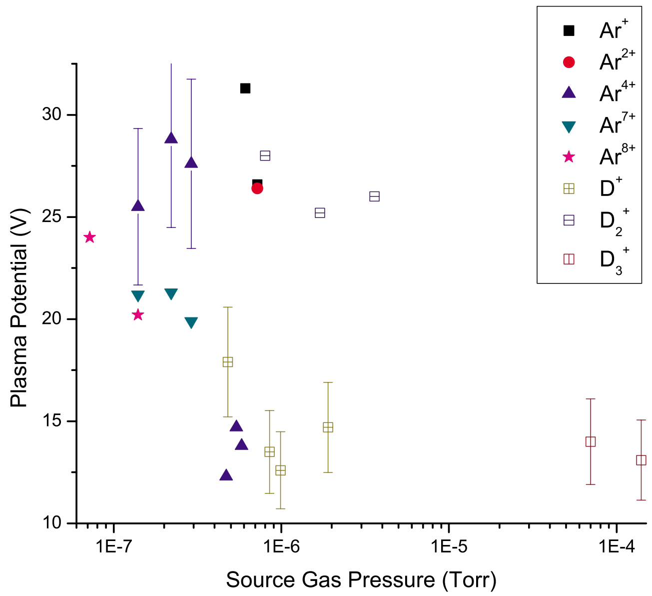

FIG. 3. (Color online) Deduced plasma potential values as a function of source pressure, showing representative error bars. Error primarily arises from the uncertainty in the slopes of our linear fits and to a lesser extent, the setting of the zero current or baseline. For the plasma potential values shown in this figure, microwave power ranged from 30 to 70 W for Ar beams, and 14–40 W, 7–13 W, 6–7 W for D^+, D_2^+, and D_3^+ beams, respectively.

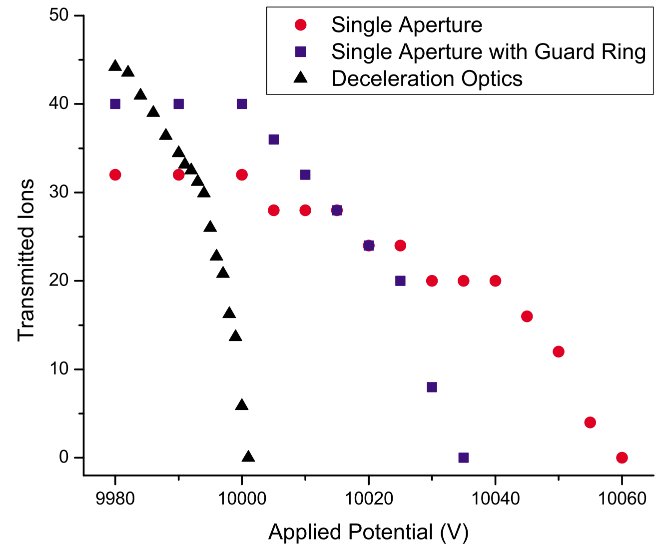

FIG. 4. (Color online) Three simulated retardation curves each with the same starting kinetic energy ions (10 000 V), passing through different electrode configurations: the present deceleration optics (Fig. 1)—triangles; biased single aperture centered between two ground planes (ground plane separation/aperture diameter ~60)—circles; same as previous case except addition of 1-cm-thick guard ring (ground plane separation/guard ring thickness ~6)—squares. The shift in the x intercept from 10 000 V in the latter two cases represents the effect of field penetration which must be corrected for.

In the operating ranges explored for D^+, D_2^+, and D_3^+, we find average plasma potentials of 15, 24, and 14 V, respectively. The consistently higher value for D_2^+ beams is somewhat surprising. In contrast to electron impact dissociative ionization to produce D^+, which is known to lead to significant kinetic energy release of the fragments, electron impact ionization of D_2, the main mechanism of D_2^+ production, is not accompanied by energy transfer to the molecular ion. On that basis, one would expect the D_2^+ beams to show a lower plasma potential (or at least energy spread) than the D^+ beams. The fact that the opposite trend is observed may indicate that the two species are formed in and/or extracted from regions of differing plasma potentials in the ECR plasma.

The present Ar beam plasma potential values are in qualitative agreement with earlier unpublished measurements for the ORNL ECR source using the analyzer magnetic field peak position technique (Sec. II B) which indicated plasma potentials of 10–12 V for Ar^{7+} and Ar^{8+} beams, and of about 40 V for Ar^{2+}. The lower plasma potentials found for the higher charge state extracted species may indicate different source regions of low versus high charge states. This, however, is difficult to reconcile with our earlier Langmuir probe measurements in the ECR edge plasma, which indicated similar plasma potential values as the present measurements, suggesting that the plasma potential is a global rather than local plasma parameter.

The significantly larger plasma potentials deduced for the low Ar charge states in comparison to those for +7 and +8 have also been observed by Higashijima *et al.*[12] The large variations with source pressure of the plasma potential values, particularly evident for the low charge states, illustrate the desirability of measuring the plasma potential in real time instead of relying on prior measurements when very low energy beams are being studied, since the energy correction for such beams due to the source plasma potential can be significant and in fact dominate.

Our plasma potential results differ from those of Tarvainen *et al.*,[6] who employed a biased grid transmission technique to analyze extracted beams. The ECR ion source employed for these measurements has similar performance characteristics (charge state distributions and beam intensities) and similar microwave power and source pressure operating conditions, and thus may be expected to be characterized by similar plasma potentials. SIMION trajectory simulations for transmission through a biased circular aperture centered between two ground planes, performed to simulate one element of a (multiaperture) grid, show significant field penetration effects, which are reduced, but not eliminated, by the use of guard rings, as shown in Fig. 4. These simulations suggest that a significant fraction of the cutoff voltage shifts ascribed to plasma potential effects may in fact be due to field penetration. When we apply an estimated correction to the results of Tarvainen, based on our SIMION analysis, of about 37 V, their results are in reasonable accord with our plasma potential values. For example, Tarvainen *et al.*[6] reported a plasma potential of 57.3 V for O^{6+}.[6] Applying a correction of −37 V for field penetration obtained from Fig. 3 (the x intercept of the single aperture with guard ring simulation) we obtain an adjusted plasma potential of 20.3 V which falls well within the range of our observed plasma potentials, i.e., 12–31 V for Ar^{q+} ions (see Fig. 3).

B. Energy spread

As described in Sec. II A, the deviation from linear dependence of the beam stop current on bias potential close to

TABLE I. FWHM energy spreads in eV for D^+, D_2^+, D_3^+, Ar^+, Ar^{2+}, Ar^{4+}, Ar^{7+}, and Ar^{8+} ion beams for various ECR source conditions; estimated uncertainty is 30%.

Extracted beam	Source pressure (T)	Microwave power (W)	Energy spread (eV)
D^+	2.0×10^{-7}	31	4
D^+	4.0×10^{-7}	12	7
D^+	8.0×10^{-7}	7	11
D^+	9.8×10^{-7}	32	7
D^+	1.0×10^{-6}	16	17
D^+	1.8×10^{-6}	9	15
D_2^+	4.0×10^{-7}	7	5
D_2^+	1.5×10^{-6}	3	10
D_2^+	6.0×10^{-6}	4	7
D_2^+	7.0×10^{-6}	2	14
D_3^+	6.0×10^{-5}	1	8
D_3^+	7.0×10^{-5}	2	5
Ar^+	8.5×10^{-7}	44	4
Ar^{2+}	1.0×10^{-6}	44	7
Ar^{4+}	3.5×10^{-7}	32	6
Ar^{4+}	5.0×10^{-7}	24	4
Ar^{4+}	7.5×10^{-7}	61	6
Ar^{7+}	3.0×10^{-7}	57	8
Ar^{8+}	1.0×10^{-7}	63	13

cutoff may be used to infer energy spread information on the extracted ion beams. Table I shows the full width at half maximum (FWHM) energy spreads deduced in this manner for D^+, D_2^+, D_3^+, Ar^+, Ar^{2+}, Ar^{4+}, Ar^{7+}, and Ar^{8+} ion beams as a function of ECR source pressure and microwave power. The tabulated FWHM energy spread values are consistent with earlier results[8] obtained using the method outlined in Sec. II B. The beam-stop current in the vicinity of the cutoff potential can potentially be affected by second order effects originating in the decel section, due to, e.g., secondary electron emission. We have in fact observed long, very low intensity, tails in the retardation curves in some of the measurements. We were not able to determine if these tails were due to larger energy spreads in the decelerated beams or due to the above secondary electron effects. However, whatever their origin, such long tails have distributions markedly different than the energy spread distribution shown in red in Fig. 1, and have only a small impact on the FWHM energy spread values. Future measurements are planned to investigate the origin of such tails in greater detail.

For D_2 source gas, we found the largest FWHM at higher source pressures and lower microwave power. The observed variations in energy spread values with source pressure and microwave power are consistent with measurements of the decelerated beam profiles at the graphite sample position (see Fig. 1) using a wire scanner. As seen in Fig. 5, typical D^+ decelerated beams at 30 eV/D under source conditions (2.0×10^{-7} Torr, 29 W) associated with lower energy spreads yielded narrow beam profiles with a FWHM of 1.9 mm, compared to a FWHM of 3.2 mm at higher sources pressures and reduced microwave power, associated with higher energy spreads. We can, of course, not exclude the possibility that, at higher source pressures, changes in the shape of the plasma meniscus in the source extraction aperture degrades the quality of the extracted beam. However, our energy spread measurements show a similar trend, namely a reduced energy spread under conditions of high microwave power and low source gas pressures. These somewhat counterintuitive trends will be the subject of further investigation.

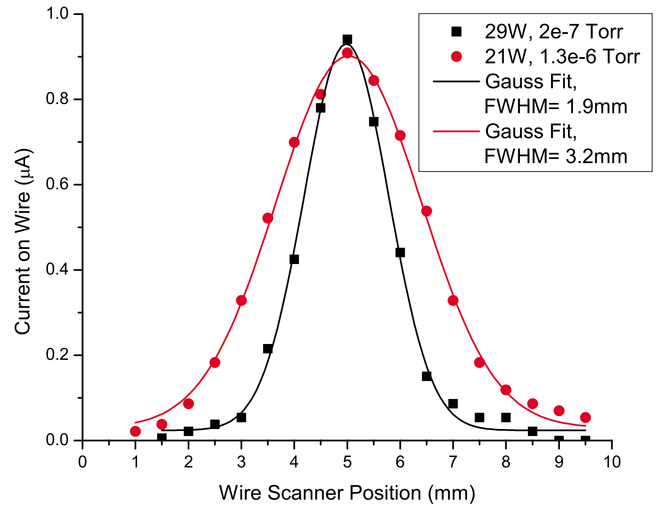

FIG. 5. (Color online) Wire scan beam profiles of two D^+ extracted ion beams, showing source parameters' influence on the FWHM of the decelerated beam.

IV. CONCLUSIONS

The use of retardation curve measurements from extracted, decelerated ion beams serves as a useful plasma diagnostic. The ability to quickly determine the plasma potential permits its use in source tuning and optimization. Further study is required to understand the observed variation in measured plasma potentials for similar plasma source conditions. In follow-up work, we plan to explore using an emittance-limiting aperture well upstream of our deceleration section to define in a more controlled fashion the phase space of the decelerated beams.

Observations of the energy spread, while hampered by similar instabilities, still provide insight into source conditions. However, for the purpose of reducing the energy spread in a plasma during the adjustment of plasma source conditions, the monitoring of the extracted beam profile via a wire scanner is likely more useful. Through the monitoring and control of plasma source conditions one can obtain a stable, well-defined beam shape of useful flux for surface modification experiments.

ACKNOWLEDGMENTS

This work was supported by the Office of Fusion Energy Sciences and the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. P.R.H. was appointed through the ORNL Postdoctoral Research Associates Program administered jointly by Oak Ridge Institute of Science and Education and Oak Ridge National Laboratory.

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