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Ion acceleration in Ar–Xe and Ar–He plasmas. I. Electron energy distribution functions and ion composition

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Electron energy distribution functions (eef), ion production, and ion composition are studied in Ar–Xe and Ar–He expanding helicon plasmas. It was found that under the conditions of constant total flow rate, Xe, in addition to Ar, changes the eedf from Maxwellian-like to Druyvesteyn-like with a shortening of the high energy tail at ~15 eV. The electron temperature exponentially decreases from ~7 eV in pure Ar plasma to ~4 eV in pure Xe plasma. Xenon ions dominate the ion population for Xe filling fractions greater than 10%. The plasma density increases by ~15% with increasing Xe fraction. For an Ar–He plasma, increasing the helium fraction increases the electron temperature from ~7 eV in pure Ar plasma to ~14 eV for a He filling fraction of 80%. The plasma density drops by more than three orders of magnitude from $1.14 \times 10^{11}$ cm$^{-3}$ to $6.5 \times 10^7$ cm$^{-3}$. However, the inferred ion densities indicate that even at a helium fraction of 80%, argon ions significantly outnumber helium ions. © 2010 American Institute of Physics. [doi:10.1063/1.3505822]

I. INTRODUCTION

The energetic ion beam generated by the current-free electric double layer (EDL), which spontaneously forms in the magnetic expansion region of low pressure helicon plasma sources, might be an ideal candidate for extraterrestrial spacecraft propulsion. Experiments have demonstrated that formation of a current-free EDL in the divergent magnetic field at the end of helicon plasma source and the subsequent ion acceleration to supersonic speeds occurs in a wide variety of working gases. Beside argon, ion acceleration in xenon helicon plasma has been demonstrated. Ion beam velocities as high as 11 km/s for Ar and 6 km/s for Xe were measured with a retarding field energy analyzer in the Chi-Kung device. In recent molecular gas experiments in Chi-Kung, ion exhaust speeds of 17 km/s for N$_2$, 25 km/s for NH$_3$, and 27 km/s for CH$_4$ were reported. EDL formation in uniform magnetic fields and in electronegative gas plasma has also been observed. To reduce the mass and power requirements, practical helicon plasma thrusters are likely to employ permanent magnets. The classic signature of an EDL, two distinct ion populations with one highly supersonic, has been observed downstream of a small diameter, compact helicon plasma source employing permanent magnets. Based on ion beam analysis in noble gas plasmas, it has been found that: (a) the minimum gas pressure at which a stable discharge can be sustained and the most efficient ion acceleration occurs is lower in heavier gases (which for noble gases corresponds to lower ionization potentials); and (b) for identical discharge conditions, the ion beam velocity decreases with atomic mass and ranges from 58 km/s in He to 24 km/s in Ar to 13 km/s in Xe. This second observation implies a dependence of ion acceleration on the characteristic Bohm speed (proportional to the inverse of the square root of the ion mass). However, it is difficult to conclusively demonstrate the role of the Bohm speed in defining the final ion speed in different single ion species plasma experiments because of the impossibility of matching the operating conditions (gas pressure, flow rate, input power, etc.) and electron temperature for different working gases. An alternative approach is to investigate ion acceleration in mixed gas plasmas with a single electron temperature. Under such conditions, the ion acceleration controlled by the Bohm velocity will be easier to confirm.

To identify the mechanisms through which ion acceleration takes place in mixed gas helicon plasmas, extensive plasma diagnostics such as planar and cylindrical Langmuir probes (LP), optical emission spectroscopy (OES), and laser induced fluorescence (LIF) coupled with theoretical models have been employed to study ion production, relative plasma ion composition, and ion velocity distribution functions. Argon is the workhorse in plasma modeling and plasma simulation; consequently, argon plasma characteristics are well documented. Therefore, in this work, mixtures of Ar–Xe and Ar–He with argon ions serving as probes were examined to gain insight into heavier and lighter gas doping effects on ion acceleration mechanisms in expanding helicon plasma. Here we describe Langmuir probe and optical emission spectroscopy analyses of the Ar–Xe and Ar–He plasmas.

II. THE PLASMA SOURCE–EXPANSION CHAMBER SYSTEM

The helicon plasma source used for these investigations consists of two distinct parts [see Fig. 1(a)]: the Hot hELicon eXperiment (HELIX) source where high density plasma is created, and an expansion chamber, Large Experiment on Instabilities and Anisotropies (LEIA) into which the plasma flows. HELIX consists of a 61 cm long, 10 cm diameter Pyrex tube coaxially mated with a 91 cm long, 15 cm diameter stainless steel tube. LEIA is a 4 m long, 2 m diameter...
Supplies aluminum diffusion chamber. Ten water cooled solenoids/H20849FIG. 1. magnetic interference dc power supply and the maximum able magnetic field is 1200 G. Seven 9 in. diameter water 400 A current for the electromagnets. The maximum attain-
ations B\(
\) and for two magnetic field strengths in LEIA: 70 G
lines of constant magnetic flux
dimensional numerical model that was validated with mea-
tions, in the connection region between the helicon source
length of HELIX-LEIA system.

A. Langmuir probe

In a magnetized plasma, the Langmuir probe \( I-V \) characteristic is affected by the local magnetic field. Magnetic fields are strong enough to make the electron Larmor radius smaller than the probe radius limit electron saturation current to only a few tenths of ion saturation current. The characteristic “knee” in this case is indistinct and the \( I-V \) curve is exponential only over a range of a few \( k_BT_e \) above the floating potential. For the weak magnetic fields in LEIA (\( \sim 10 \) G), the electrons are unmagnetized (electron cyclotron radius \( r_{ce} \approx 5 \) mm larger than probe radius \( r_p = 0.5 \) mm) and the magnetic field effects can be ignored. For HELIX, magnetic fields \( \sim 700 \) G, the electron cyclotron radius \( r_{ce} \sim 70 \) \( \mu \)m is sevenfold smaller than the probe radius and magnetic effects must be included in the analysis. According to Latramboise and Rubinstein, even in strong magnetic fields the electron phase-space density or velocity distribution function can still be described by the usual Maxwell–Boltzmann distribution with an additional correction term for a hypothetical potential well arising from the presence of the magnetic field. Since the electron distribution is not distorted but only shifted in energy, measurements obtained by applying the unmagnetized probe theory to the eedd data corrected for energy shift still provide an accurate measure of density, potential, and electron temperature in magnetized plasmas.

For a simple, unmagnetized, collisionless, Maxwellian plasma comprised of one electron population and two posi-
tive ions species, the collected current for applied voltages around the floating potential is given by the sum of electron and ion Bohm currents:  

\[
I(V) \equiv eA_p \left( n_{e1} \sqrt{ \frac{kbTe}{M_1} } + n_{i1} \sqrt{ \frac{kbTi}{M_2} } \right) 
\times \left( \frac{n_e}{n_{i1} \sqrt{ 2 \pi m_e/M_1 } + n_{i2} \sqrt{ 2 \pi m_i/M_2 } } e^{eV/kbTe} - \frac{A_S}{A_p} e^{-1/2} \right),
\]

where \(m_e\) and \(M_j\) for \(j=1,2\), are the electron and ion masses, respectively; \(n_e\) and \(n_i\) are electron and ions densities; \(A_p\) is the probe area; and \(A_S\) is the sheath area. At high plasma densities (>10¹¹ cm⁻²), the sheath around a negatively biased probe is so thin that the surface area of the sheath is essentially the same as the surface area of the probe, \(A_S = A_p\). Equivalently, the ratio of the probe radius to the Debye length is larger than 1. In contrast to a single ion species plasma for which the plasma potential, electron temperature, and plasma density can be directly determined from the \(I-V\) trace for a two ion species plasma, the plasma density and plasma potential cannot be uniquely determined. In such a case, determination of the electron density, the effective electron temperature \(T_{eff}\) (which corresponds to a mean electron energy \(\langle \epsilon \rangle\)), and the plasma potential \(V_p\) from the \(I\epsilon\) Measurement is still accurate because

\[
T_{eff} = \frac{2}{3} \langle \epsilon \rangle = \frac{2}{3n_e} \int_0^\infty \epsilon f(\epsilon) d\epsilon.
\]

For a planar probe aligned perpendicular to the plasma flow (the \(z\) axis in the HELIX-LEIA system), the electron flux entering the sheath only depends on the \(z\) velocity component, \(v_z\). Therefore for this one-dimensional geometry the eedf is obtained from the first derivative of the \(I-V\) characteristic along one degree of freedom.

\[
f(v_z) = \frac{m}{eA_p} \frac{dI_e}{dv_z}.
\]

As for the cylindrical probe case, the electron density is directly determined from the normalization condition and the effective electron temperature from the mean electron energy \(\langle \epsilon \rangle\) along one degree of freedom.

In this work, both cylindrical and planar (disk) Langmuir probes were used. The cylindrical probe consists of a 0.5 mm diameter graphite rod that extends 3 mm from an insulating alumina tube. The planar probe is fabricated from a tungsten sheet cut into a circle and spot welded to a tungsten rod. The diameter of the disk is 6 mm. One side of the probe surface is coated with alumina powder to prevent current collection. The tungsten rod, which is 2.5 cm long, is shielded from the plasma with an alumina tube. Both probes are rf compensated. The compensation is accomplished by a series of rf chokes covering the frequency range of 6–18 MHz and a 10 nF shorting capacitor. Although slightly more difficult to construct, the planar probe has the important advantage of being able to reach electron saturation in a high density, magnetized, helicon plasma.

The full eedfs were recovered from the retarded electron component of the probe data. The challenge in using Eqs. (2) and (5) to obtain electron energy distribution functions arises from the numerical differentiations of imperfect data. In this work, the probe data were digitally recorded and postprocessed with finite difference and curve fitting algorithms to smooth and differentiate the signals. Oversampling and averaging over many realizations also helped to reduce noise levels in the measurements. Overly aggressive smoothing of the data was avoided so as to not wash out real features in the eedfs. The differentiation process always affects energy resolution at lower energies, leading to a small gap between the eedf peak and the 0 energy value (zero crossing). However, as long as the gap width does not exceed the electron temperature, the eedf measurement is still accurate because the zero crossing is relatively unaffected for a few eV residual gap.
rately model the emission line intensities, the Corona model metastable levels cannot be neglected. Therefore, to accu-
trals is shown in Fig. 2. Argon and xenon atoms may be
weakly ionized plasmas, the number of atoms contains a mixture of argon and xenon. In low pressure,
sections are used in the rate coefficients calculations instead
from the ground state, electron impact excitation from
states to levels above the 2p manifold. These levels also
electron impact excitation can occur from the ground
level; and
the metastable levels 1s3 and 1s5 can populate the argon and xenon Paschen 2p levels for higher plasma densities. The peak cross-section values for direct excitation from the meta-
stable levels to the 2p levels are much larger (15–700 times larger) than those for excitation from the ground state.31 Therefore, this mechanism must also be included in the particle balance equations. The other two low-lying 1s Paschen states, 1s2 and 1s4, have short radiative lifetimes and decay to the ground state. Therefore, their population is much lower than the 1s3 and 1s5 metastable states and consequently their contribution to the 2p population levels through electron impact excitation is negligible.32

If the only excitation paths to an upper level \( j \) are electron impact excitation from the ground and metastable states and the deexcitation path is radiative decay, the rate equation for the upper level \( j \) is

\[
dn_j/dt = n_e n_0 k_{0\rightarrow j} + n_n n_m k_{m\rightarrow j} - n_j/\tau_j,
\]

where \( n_e, n_0, n_n, \) and \( n_j \) are the electron, neutral atom in the ground state, neutral metastable state, and neutral \( j \) level densities; \( \tau_j \) is the radiative lifetime of the \( j \)th level; and \( k_{0,m\rightarrow j} \) are the excitation rate coefficients for electron impact excitation from ground and metastable levels, respectively, to level \( j \). The electron impact rate coefficients are given by the average

\[
k_{0,m\rightarrow j} = \langle v_j \sigma_{0,m\rightarrow j} \rangle = \frac{2}{m_e^2} \int_0^\infty f(\epsilon)\epsilon^{1/2} \sigma_{0,m\rightarrow j}(\epsilon) d\epsilon,
\]

where \( v_j, m_e, \) and \( \epsilon \) are the electron velocity, electron mass and energy, respectively, and \( \sigma_{0,m\rightarrow j} \) is the cross-section for electron excitation from level 0 or \( m \) to level \( j \).

Assuming steady state in Eq. (6), the observed emission intensity \( I_{jk} \) of a plasma species \( A \) at wavelength \( \lambda_{jk} \) corresponding to a quantum transition from upper level \( j \) to a lower level \( k \) is given by

\[
I_{jk} = \frac{h \lambda_{jk}^3}{4 \pi} S(\lambda_{jk}) b_{jk} n_e n_0 k_{0\rightarrow j} \left( 1 + \frac{n_m k_{m\rightarrow j}}{n_0 k_{0\rightarrow j}} \right),
\]

where \( S(\lambda_{jk}) \) is the detection system sensitivity (lenses, optical fibers, spectrometer, and charge-couple device (CCD) camera) at \( \lambda_{jk} \), \( b_{jk} = A_{jk}/\Sigma_{j<k} A_{jk} \) is the branching ratio for the transition \( j \rightarrow k \), \( n_0 \) is the number density in ground state, and \( n_m \) is the number density in the metastable state, \( m \). If the intensities of two lines belonging to different species \( A \) and \( B \) are used, then the intensity ratio is a function of their population ratio. With an electron energy distribution function obtained from Langmuir probe measurements and the excitation cross-sections available in the literature, the excitation rate coefficients can be calculated. Then from OES measurements of line intensities, the neutral densities of each species in a plasma mixture (Ar and Xe for this study) can be estimated. The situation for the intensity of ionic lines is much more complicated. Excitation to an excited ion state may occur by a one-step process (simultaneous excitation and ionization from the ground state of the neutral atom) or a two-step process (ionization of the neutral atom and then subsequent excitation). However, since for typical low temperature plasma, only few electrons have enough energy for

FIG. 2. Partial energy level diagrams for argon and xenon neutrals and the transitions used for OES investigations; the ionization levels are shown by horizontal dashed lines; 1s1 and 1s3 are metastable states; 1s2, 1s4, and 2p states are radiative states (adapted from Refs. 31 and 42).

B. Optical emission spectroscopy

The combined Langmuir probe and optical emission spectroscopy measurements were used to quantitatively de-
terminate the neutral and ion densities in a helicon plasma that contains a mixture of argon and xenon. In low pressure, weakly ionized plasmas, the number of atoms (or ions) in an excited state can be calculated with a Corona model. Under corona equilibrium conditions, the electron excitation rate and radiative decay rates are equal. Therefore, quantitative information on different specie concentrations can be obtained from the intensities of the emission lines. A Corona model is appropriate for LEIA plasmas, but for the relatively high plasma densities attained in HELIX (\( \approx 1 \times 10^{11} \) cm\(^{-3} \)), secondary processes such as excitation from metastable levels cannot be neglected. Therefore, to accu-
rately model the emission line intensities, the Corona model has to be extended to include excitation and/or ionization from metastable levels as well as the ground state.

An energy level diagram for both argon and xenon neu-
trals is shown in Fig. 2. Argon and xenon atoms may be
excited by electron collisions from their ground states to the Paschen 2p levels. These excited levels decay on a short time scale (\( \sim 20 \) ns) to one of four levels (in Paschen notation, the short lived 1s2 and 1s4, and the metastable 1s3 and 1s5 states) and emit photons in the near-infrared region. Altern-
vatively, electron impact excitation can occur from the ground states to levels above the 2p manifold. These levels also
decay on a short time scale, accompanied by emission of a vacuum ultraviolet photon when decaying to the ground state, or longer wavelength photons when decaying to the 2p or higher-lying levels. Decays to levels above the 2p levels are followed by a cascade that increases the intensity of emission from the 2p levels. Thus, when trying to model the intensity of spectral lines originating from the 2p levels, the cascade pathways must be included. Fortunately, cascade ef-
effects are automatically included if measured optical cross-
sections are used in the rate coefficients calculations instead
from the ground state, electron impact excitation from

the one-step process, the largest contribution to an excited ion state population is from excitation of ground state ions. For the particular case of Ar–Xe plasma, the lowest lying ion metastable levels are at relatively low energies (13.48 eV for Ar$^+$ and 11.26 eV for Xe$^+$). Thus, the contribution to the excited ionic state population from metastable levels has to be included in the ion population balance equations as well.

For the optical emission spectroscopy investigations reported in this paper, the light emitted by the helicon plasma source is collected and sent through a multimode optical fiber to the entrance slit of the spectrometer. The spectrometer is a 1.33 m Czerny–Turner double pass scanning monochromator (McPherson 209). The dispersive element is a 120 × 140 mm grating having 1200 lines/mm blazed at 750 nm. The detector is an air cooled dual autofocusing CCD camera (Santa Barbara Instr. Group ST-7) with a 765 × 510 pixel array at 9 μm/pixel. The quantum efficiency of the camera is between 0.6 and 0.8 for our spectral range of interest. Wavelength calibration was performed with the help of an argon pen lamp and Ar neutral lines tables available from the NIST website. Spectral sensitivity correction factors were obtained from calibration of the relative spectral response of the entire optical path for the spectrometer achievable wavelength range of 400–1000 nm. The calibration was performed by using the tabulated spectral irradiance and the experimentally measured spectrum of a tungsten ribbon lamp (Oriel™). Spectral sensitivity correction factors were obtained from calibration of the relative spectral response of the entire optical path for the spectrometer achievable wavelength range of 400–1000 nm. The calibration was performed by using the tabulated spectral irradiance and the experimentally measured spectrum of a tungsten ribbon lamp (Oriel™).

IV. EEDF AND PLASMA COMPOSITION IN TWO-ELECTROPOLITE SPECIES PLASMA

In these experiments, the electron energy distribution function (eedf), ion production, and absolute ion densities were investigated as a function of plasma composition. Ideally, the control of the relative gas composition in mixed gas plasmas is accomplished through direct measurement and control of partial gas pressures. However, the only adjustable gas parameter for these experiments was the mass flow rate of each species. Therefore, different Ar/Xe and Ar/He mixing ratios were obtained by varying Ar, Xe, and He individual mass flow rates.

A. Electron temperature and plasma density in Ar–Xe plasma

To investigate the effects of the gas composition on plasma parameters, electron energy distribution functions were obtained from Langmuir probe measurements taken on the axis of the system, at the middle of HELIX, at z=126 cm (≈70 cm downstream from the antenna; location A in Fig. 1), and in the expansion chamber, at z=169 cm (19 cm downstream of the HELIX-LEIA junction; location C in Fig. 1).

The Ar/Xe ratio was varied by adjusting Ar and Xe individual mass flow rates while holding the total flow rate constant at 10 SCCM (SCCM denotes standard cubic centimeters per minute). The estimated error in gas composition determination due to the slight difference in actual Ar and Xe gas pressures (1.3 mTorr for Ar and 1.5 mTorr for Xe at 10 SCCM in HELIX, respectively, 0.14 and 0.16 mTorr in LEIA) is less than 7%.

From the gas ionization point of view, there are large differences between Xe and Ar: xenon has a significantly lower ionization threshold energy (12.13 eV versus 15.76 eV for argon), and a larger peak ionization cross-section (5.2 × 10$^{-16}$ cm$^2$ versus 2.8 × 10$^{-16}$ cm$^2$ for argon). These differences are responsible for the dramatic changes in plasma properties that occur with increasing xenon fraction. As shown in Fig. 3, in the pure argon plasma, the eedf is a single Maxwellian (straight line on the semilogarithmic plot). However, for the pure xenon plasma, the eedf is best fit with a Druyvesteyn-like distribution. Although not a perfect Druyvesteyn distribution [only above 10 eV does the distribution obey the $\sim(3n/M)^{1/4}(e/eE)^{2/4}$ proportionality law, where $M$, $\lambda$, and $E$ stand for neutral mass, the electron collision mean free path and the ambient electric field, respectively, all other quantities having the usual meaning], the measured eedf shows the characteristic depletion of the high electron energy tail. Consistent with the differences in excitation energies and ionization potentials, the breakpoint in the high energy eedf tail (the energy at which the eedf amplitude equals the noise level) decreases by ~15 eV for pure xenon plasma compared to pure argon. With increasing xenon fraction, the electron density increases and there is an increase in the low electron energy population with a simultaneous reduction in the high energy tail of the distribution. The transition from a single Maxwellian distribution to a Druyvesteyn distribution with increasing of the xenon percentage is not gradual. Once the xenon fraction reaches 10%, the eedf is Druyvesteyn-like.

Figure 4 shows the electron temperature and electron density on the axis of the system calculated from the experimentally obtained eedfs as a function of gas composition in mixed Ar/Xe helicon plasma. The operational parameters were as follows: HELIX magnetic field strength of 700 G, LEIA magnetic field strength of 10 G, input power of 750 W, and a rf driving frequency 9.5 MHz. In HELIX, 70 cm...
downstream from the antenna, numerical integrations of the eddfs give an effective electron temperature of 6.5 eV and an electron density of 1.07 × 10^{11} \, \text{cm}^{-3} for pure Ar plasma; for pure Xe plasma, an effective electron temperature of 3.8 eV and an electron density of 1.25 × 10^{11} \, \text{cm}^{-3} were obtained. Although the term “electron temperature” has no physical meaning for distributions other than Maxwellian, we use it here for the Druyvesteyn distribution in the sense of average electron energy. Addition of xenon to argon dramatically lowers the effective electron temperature. The decrease in effective electron temperature is exponential with increasing xenon fraction and most of the drop in electron temperature occurs as the xenon fraction increases from 0% to 20%. The increase in plasma density with increasing xenon fraction is roughly linear. Under the same operating conditions as previously described but in the expansion chamber, 19 cm downstream of the HELIX-LEIA junction, the effective electron temperature and electron density versus xenon fraction dependencies are shown in Fig. 4(b). The trend in overall effective electron temperature dependence on xenon fraction is similar to what was observed in the source, i.e., an exponential decrease with increasing xenon fraction from ∼7.2 eV in pure argon to 4.7 eV in pure xenon. Although almost two orders of magnitude lower, the electron density again linearly increases with increasing of xenon concentration from 2 × 10^{9} \, \text{cm}^{-3} in pure argon to 5 × 10^{9} \, \text{cm}^{-3} in pure xenon. The 20-fold to 50-fold higher plasma density in HELIX than in LEIA is explained by the proximity of the antenna and roughly one order of magnitude higher pressure in the source than in the expansion chamber. Better electron thermalization at higher pressure is also responsible for ∼1 eV lower electron temperature in the source than in the expansion chamber. The very similar dependencies of the plasma density (linear) and electron temperature (exponential decay with the most of the decrease in the first 20% of Xe addition) versus gas mixing ratio in the source and expansion chamber is consistent with ionization occurring in the source and the plasma convecting into the expansion chamber.

B. Neutral densities from OES observations

Independent of the details of the Corona model used, a major concern when performing any sort of OES analysis is the optical thickness of the plasma at a particular wavelength. As a rule of thumb in choosing the spectral lines for study, transitions to the ground level (resonance lines) or to low lying metastable levels should be avoided because the radiated photons are likely to be reabsorbed by the plasma. For our investigations, we chose the 811.75 nm (2p_b → 1s_b) and 823.39 nm (2p_b → 1s_b) lines for neutral argon and xenon, respectively. Both lines originate from 2p manifolds (see Fig. 2) and terminate on relatively high energy, 1s_b metastable levels (11.54 eV for argon and 8.31 eV for xenon above the ground level). Furthermore, given our low operating gas pressure, a small population of the 1s_b metastable level is expected, and therefore the plasma might be considered optically thin at these wavelengths.

The emission intensities of the spectral lines of neutral argon and neutral xenon as a function of the xenon fraction, normalized to the measured emission intensities for the corresponding pure gas plasma, collected at z = 126 cm, are shown in Fig. 5. As expected, the neutral argon emission intensity decreases and the neutral xenon emission intensity increases with increasing xenon fraction. For the general case that includes excitation from metastable states in the model, the ratio of the argon and xenon neutral line intensities given by Eq. (8) is

$$I_{811}^{\text{Ar}} / I_{823}^{\text{Xe}} = \frac{823}{811} \left( \frac{S(811)}{S(823)} \right) b_{811}^{\text{Ar}} k_{811}^{\text{Ar}0} k_{823}^{\text{Xe}0} \left( 1 + n_{\text{Ar}0}^{*} n_{\text{Ar}0}^{*} / n_{\text{Ar}0}^{*} + n_{\text{Xe}0}^{*} n_{\text{Xe}0}^{*} / n_{\text{Xe}0}^{*} \right)$$

(9)

where $n_{\text{Ar}0}^{*}$ and $n_{\text{Xe}0}^{*}$ are the neutral argon and xenon number densities in the ground “0” and metastable “*” states, respectively, and $k_{811}^{\text{Ar}0}$ and $k_{823}^{\text{Xe}0}$ are the argon and xenon electron impact excitation rate coefficients from the ground and metastable states, respectively. The limit of only excitation from

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FIG. 4. (Color online) Effective electron temperature and electron density obtained from experimentally obtained eddfs as a function of Ar/Xe composition: (a) at z = 0 in HELIX, z = 126 cm; and (b) on the axis of LEIA, z = 169 cm. The dashed lines are exponential and linear fits for electron temperature and electron density, respectively. Source plasma parameters: $P_{e} = 750 \, \text{W}$, $f = 9.5 \, \text{MHz}$, $B_{H} = 700 \, \text{G}$, and $B_{L} = 10 \, \text{G}$.

FIG. 5. (Color online) (a) Observed emission line intensities from Ar I (811.75 nm) and Xe I (823.39 nm) lines in HELIX at z = 126 cm vs xenon fraction; the emission intensities values are normalized to the corresponding pure gases values. The argon emission line intensity was indistinguishable from the background for xenon fractions larger than 80%. (b) Neutral species densities in the plasma as computed from the argon and xenon line intensities ratios: open symbols, Corona model without metastable contribution; full symbols, Corona model with metastable contribution. Solid lines, computed values from the gas flow data.
the ground states is obtained from Eq. (9) by setting the metastable densities \( n_{Ar} \) and \( n_{Xe} \) equal to zero. In assessing line intensities, the integrated individual line intensities after background removal were considered. The rate coefficients for electron impact excitation of neutral argon and xenon were calculated using Eq. (7) from the experimentally determined eedfs and the optical cross-sections available in the literature. Since an optically thin plasma was assumed, no corrections for pressure effects on cross-section values resulting from radiation trapping of cascading resonance levels were included.

To calculate the absolute densities of the neutral species, Eq. (9) is combined with the gas kinetic equation

\[
p \equiv (n_{Ar}^0 + n_{Xe}^0)kB T_{\text{gas}},
\]

where \( p \) is the total neutral pressure, \( k_B \) is the Boltzmann constant, and \( T_{\text{gas}} \) is the gas temperature (assumed to be uniform throughout the plasma column and equal to the room temperature). The calculated neutral species densities are shown in Fig. 5(b). The branching ratios needed for these computations were calculated based on available transition probabilities and radiative level lifetimes. For the Corona model including metastable contributions to the line intensities, constant ratios of metastable population to the ground state population of \( 10^{-3} \) for argon and xenon, respectively, were assumed.

For the Corona model without metastable contributions, the calculated argon and xenon neutral densities show a slight departure from the expected linear dependence [open symbols in Fig. 5(b)] on gas composition. When metastable contributions are neglected, the calculated argon and xenon neutral densities are equal for a xenon fraction of \(~\sim 60\%~\) Xe/(Ar+Xe). However, when the metastable excitation terms are included in the model, the dependencies of the OES inferred neutral densities on xenon fraction are linear and the calculated densities are equal for a xenon fraction of \(~\sim 50\%~\) as expected. Given that for the calculation of the excitation rate coefficients the on-axis electron distributions were used but the collected light intensity is line-of-sight integrated, the OES results are in surprisingly good agreement with the neutral densities obtained from the known flow rates, even though this measurement approach ignores any radial profile effects that might occur due to gas depletion. The consistency of the neutral densities determined by OES and the flow rate measurements gives us confidence that the same methodology can provide reliable measurements of the relative ion densities in mixed gas plasma.

### C. Partial ion densities in Ar–Xe plasma

In contrast to a single ion species plasma, for two positive ion species plasma the electron density cannot be uniquely determined from a measurement of electron temperature and the ion saturation current. The ion Bohm current contains two unknown ion densities, \( n_{i1} \) and \( n_{i2} \),

\[
I_{sat} = 0.61en_Ap_1^2 \sum_{j=1}^2 n_{ij} \left( \frac{k_B T_e}{M_j} \right)^{1/2} \left( 1 + \frac{2k_B T_e}{e \bar{E}_{1,2}} \right) e^{-z_{1,2} k_B T_e}.
\]

which can be related to the electron density through the plasma quasineutrality condition

\[
n_{i1} + n_{i2} \equiv n_e.
\]

For a two-electropositive ion species plasma, Bai et al., assumed that ion densities are related to electron density through the ionization rate constant of each species

\[
n_{i1,2} = p_{i1,2} \frac{k_{i1,2}^z}{M_{i1,2}}.
\]

where \( p_{i1,2} \) are the relative partial pressures (relative abundances) of gas species. The ionization rate constants of each species \( k_{i1,2} \) are calculated using the measured electron temperatures, available ionization cross-sections and ionization energies.

\[
k_{i1,2}^z = \sigma_{i1,2} \left( \frac{8k_B T_e}{\pi m_e} \right)^{1/2} \left( 1 + \frac{2k_B T_e}{e \bar{E}_{1,2}} \right) e^{-z_{1,2} k_B T_e}.
\]

The total ionization rate constant \( k_i^z \) is obtained from the quasineutrality condition as a weighted average of the individual ionization rate constants

\[
k_i^z = \sum_{j=1}^2 p_{i1,2}^z k_{i1,2}^z.
\]

The absolute total ion density is inferred from either the ion saturation current or the electron density calculated from the integration of the eedf. The calculated Xe\(^+\) and Ar\(^+\) absolute densities versus xenon fraction are shown in Fig. 6(a). Instead of the linear dependence on xenon fraction found for neutral species, an exponential decrease for Ar\(^+\) density and a logarithmic increase for the Xe\(^+\) density are obtained. Roughly equal ion densities of \( 5.5 \times 10^{10} \text{ cm}^{-3} \) are obtained for a xenon fraction of only \(~\sim 10\%~\). As pointed out earlier, this extreme sensitivity to the xenon fraction results from the 3.7 eV difference in ionization potential between argon and xenon and the twofold larger ionization cross-section for xenon. The combination of these differences causes the electron temperature to rapidly decrease with the xenon fraction [see Figs. 4(a) and 4(b)]. In other words, addition of xenon effectively “clamps” the electron energy distribution function and impedes ionization of argon. Similar dependencies of
Ar⁺ and Xe⁺ densities versus xenon fraction were observed in capacitively coupled plasmas. In those experiments, the xenon fraction at which equal argon and xenon ion densities were measured was ~15% (Fig. 5 in Ref. 46) in excellent agreement with the value calculated here.

The ion acceleration observed in the proximity of the HELIX-LEIA junction moderately depends on the plasma densities and electron temperatures upstream and downstream of junction (Fig. 4 and strongly on the local plasma potential. Substituting $V_p$, $V_f$ for $V$ in Eq. (1), the plasma potential is calculated for each gas mixture

$$V_p = V_f - \frac{k_BT_e}{e} \ln \left( \frac{\rho_{e1} \rho_{e2}}{\rho_{e1} \rho_{e2}} \right) \left( \frac{\mathcal{N}_1 \mathcal{N}_2}{2M_1} \right) \left( \frac{\mathcal{N}_2}{2M_2} \right). \tag{16}$$

Figure 6(b) shows the calculated plasma potential in HELIX 70 cm downstream from the antenna and in LEIA 19 cm downstream from the HELIX-LEIA junction. Except for the low Xe concentration (<10%) point, the plasma potentials at those two locations show similar decreasing trends with ~4–5 V higher potentials in the source. For the LEIA measurements, the calculated values based on Eq. (16) are in reasonable agreement with the values directly inferred from either the voltage where the first derivative of the probe $I$-$V$ characteristic attains a maximum or from the point where the second derivative crosses the zero (abscissa). The dependence on Xe concentration for both methods of determining the plasma potential is similar, but there is a consistent difference of ~2–4 V between the inferred values. This difference is likely due to the geometrical correction factor that accounts for the ratio of the probe radius to the Debye length. For the data shown in Fig. 6(b) the Debye length varies from 0.45 mm at 100% Ar to 0.23 mm at 100% Xe, in which the correction factor in Eq. (16) would yield plasma potentials ~10–20% smaller; comparable to the difference in plasma potential values calculated with the two methods.

For measurements in HELIX, the plasma potential values inferred from the derivative of the $I$-$V$ characteristic are in good agreement with those obtained from Eq. (16). Errors in the calculated values arise from the strong magnetic field that shifts the electron distribution in energy and limits the collected electron current as well as from the proximity of the rf antenna to the probe. Since the floating potential was the same, ~1 V, for both pure gas cases, the HELIX data shown in Fig. 6(b) are obtained based on Eq. (16) with $V_f \approx 1$ V.

### D. Partial Ion densities in Ar–He plasma

To further investigate the influence of a light mass ion on a heavier ion species, a series of experiments were performed in an Ar–He mixture plasma. The discharge was ignited in pure argon plasma at a total mass flow rate of 10 SCCM. Helium and argon flow rates were then adjusted in a controlled manner so that the total mass flow rate was kept constant and the helium fraction was increased up to 80%. The same source parameters as for the Ar–Xe plasma experiments were used: rf power of 750 W, the rf driving frequency of 9.5 MHz, HELIX magnetic field strength of 700 G, and LEIA magnetic field strength of 10 G. By increasing helium fraction, the pressure in HELIX significantly drops from 1.3 mTorr in pure argon down to 0.2 mTorr for a helium fraction of 80%. Further increase of the helium fraction was not possible since the discharge could not be maintained at 750 W of input rf power and such low pressure. With increasing helium fraction, LP measurements taken 70 cm downstream from the antenna show a roughly constant electron temperature and a slight decrease of electron density up to ~30% He [see Fig. 7(a)]. For this gas mixture, the $I$-$V$ is clamped by the Ar ionization potential and He ionization is rare. Although the total gas pressure monotonically decreases, at ~30% He fraction there is a sudden change in the slope of electron density and electron temperature curves. The electron temperature jumps from ~7 eV for pure argon up to ~14 eV for a helium fraction of 80%. At the same time, the electron density drops by more than three orders of magnitude from 1.14 $\times$ 10¹¹ cm⁻³ to 6.5 $\times$ 10⁷ cm⁻³. This behavior is quite different from for Ar–Xe case, where monotonic variations of the electron temperature and electron density were observed. The abrupt change in plasma parameters likely indicates a helicon (W) to inductive (H) transition and/or an even further inductive to capacitive (E) transition.

In agreement with the experimental measurements, the computed ion densities based on the measured electron density and electron temperature, relative species abundance, and the calculated ionization rate coefficients suggest that argon ions far outnumber helium ions in these mixed gas plasmas. Because the three orders of magnitude variation in absolute plasma density makes plots of the absolute densities difficult to discuss, we show the relative ionic composition in Fig. 7(b). For a 50/50 He/Ar mixture, Ar⁺ makes up 93% of the total ion population.

The argon ions consistently dominate the plasma density, even for an 80/20 He/Ar mixing ratio. The much larger argon ion density is again explained by the large differences in the helium and argon ionization potentials (24.58 eV for He versus 15.76 eV for Ar) and the ionization cross-sections (peak value of 3.5 $\times$ 10⁻¹⁵ cm² for He versus 2.8 $\times$ 10⁻¹⁶ cm² for Ar).
V. DISCUSSION

Langmuir probe and optical emission spectroscopy investigations of mixed gas expanding helicon plasmas reveal the following features:

(a) For an Ar–Xe plasma, the eedfs exhibit a transition from a Maxwellian type electron distribution in pure argon plasma to a Druyvesteyn type electron distribution for xenon fractions greater than a few percent. Another striking change of the eedf shape is the depletion of the high energy tail of the distribution with increasing xenon fraction. The maximum electron energies in the tail decrease by ~15 eV for pure xenon compared to pure argon. Both in the helicon source and in the expansion region, the increasing xenon fraction leads to an exponential decrease of the electron temperature. In HELIX the effective electron temperature decreases from 6.5 eV in pure argon to 3.8 eV in pure xenon. Similar variation is observed in LEIA, the electron temperature decreases from 7.2 to 4.7 eV. Electron densities calculated from the eedfs show a linear increase with increasing xenon fraction: in HELIX the density increases from $1.07 \times 10^{11}$ to $1.25 \times 10^{11}$ cm$^{-3}$, whereas in LEIA the density increases from $2 \times 10^{10}$ to $5 \times 10^{9}$ cm$^{-3}$. No high energetic electron population streaming through the EDL into HELIX (Ref. 49) was observed.

The optical emission spectroscopy investigation of the Ar I 811.75 nm and Xe I 823.39 nm emission line intensities enabled estimation of neutral gas relative densities and correlation with individual gas flow rates. The partial Ar$^+$ density has an exponential decrease with the xenon fraction, whereas Xe$^+$ density has a logarithmic increase with increasing Xe fraction. As a result of the large differences in ionization potentials and ionization cross-sections of Ar and Xe for xenon fraction higher than 10% the xenon ion density exceeds the argon ion density.

(b) As a result of the large differences in the ionization potentials and the ionization cross-section peak values of argon and helium, changing the gas composition in Ar–He plasma produces large variations in both electron temperature and plasma density. There is a twofold increase in the electron temperature with increasing helium fraction from ~7 eV for pure argon plasma up to ~14 eV for a helium fraction of 80%. Over the same helium fraction range, the electron density drops by more than three orders of magnitude from $1.14 \times 10^{11}$ cm$^{-3}$ down to $6.5 \times 10^{9}$ cm$^{-3}$. Because the eedf is clamped by argon ionization potential, argon ions dominate the plasma density. Computed ion densities based on measured electron density and calculated ionization rate coefficients for each ion species suggest that ion population is dominated by Ar: at 50% He and 80% He the Ar$^+$ population represents ~93% and 70% of the total ion population, respectively.

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