Electron Velocity Distributions in an Inductively Coupled Plasma

Mark J. Kushner, *Fellow, IEEE,* and Alex V. Vasenkov

***Abstract*—The electron velocity distribution (EVD) in low pressure inductively coupled plasmas (ICPs) is heavily influenced by nonlinear Lorentz forces which are most significant at low pressures and low-excitation frequencies. In this paper, images of the EVD in an ICP sustained in argon are discussed. Within the electromagnetic skin depth, the EVD is highly elongated in the axial and azimuthal directions. This anisotropy dissipates as the electron swarm crosses the plasma.**

***Index Terms*—Anomalous skin depth, electron velocity distribution, inductively coupled plasma, Monte Carlo, plasma simulation.**

LOW pressure (<10 mtorr), inductively coupled plasmas (ICPs) are standard sources for plasma material processing applications. [1] Excitation frequencies are typically a few to tens of megahertz. In many configurations, the antenna current is in the azimuthal direction, producing harmonic electric fields in the azimuthal direction, E_θ, and harmonic magnetic fields in the (r,z) plane, B_{rz}. The latter fields increase in magnitude with decreasing frequency resulting in significant $\vec{v} \times \vec{B}$ forces [nonlinear Lorentz forces (NLF)], which produce acceleration in the axial direction. [2] The end result is an anomalous electromagnetic skin layer in which electrons are collisionally accelerated in both azimuthal and axial directions. [3] An outcome of the anomalous skin layer and NLF is that the electron velocity distribution (EVD) can be highly anisotropic. With the large fractional ionizations typical of high plasma density materials processing (as large as 1%) one might expect electron–electron collisions (e–e) to be rapid enough to make the EVD isotropic. Although e–e collisions are important, they dominantly affect the low-energy portion of the EVD (<5 eV) whereas the majority of the anisotropy is at higher energies.

In this paper, images of the EVD occurring in a low-pressure, low-frequency ICP are presented to demonstrate the anisotropic nature of the electron swarm. The EVDs were obtained from the Hybrid Plasma Equipment Model (HPEM). [4] Within the HPEM, electron transport is kinetically tracked using a Monte Carlo simulation in which e–e collisions are accounted for. Sampling of the angular properties of the electron trajectories produce the EVDs. Kinetically derived electron currents feed back to solving Maxwell's equations to obtain harmonic values of E_θ, and B_{rz}. The electron impact sources obtained from the EVDs feed back to solutions of the continuity, momentum and energy equations for charged and neutral species; and Poisson's equation for the electrostatic potential. Individual images were created from the data produced by the model using Tecplot v10. [5] The images were assembled using Photoshop v7 [6] and annotated using Corel Draw v12 [7].

The conditions are a cylindrically symmetric ICP sustained in Ar at 3 mtorr with a gas flow of 100 sccm. The stove-top antenna is driven at 2.5 MHz providing E_θ, which delivers 600 W to the plasma. The peak electron density is $6 \times 10^{11}\ \mathrm{cm}^{-3}$ and the maximum plasma potential is 20 V. The cycle averaged ionization source, S_e, and EVDs at selected heights are shown in Fig. 1. The electromagnetic skin depth is ≈2.2 cm thick. S_e is maximum in the skin depth where the electron temperature peaks to 8 eV, a consequence, in large part, to the NLF which provides an axial acceleration and the large E_θ required to overcome the rapid diffusion losses a this low pressure. The resulting EVD in the skin depth (location 1) is highly anisotropic, being elongated in the z (axial) and θ (azimuthal) directions at the expense of the r (radial) direction. The anisotropy in z and θ persists many cm into the plasma (locations 2 and 3) beyond the skin depth, evidence of the noncollisional nature of electron transport. Beyond the accelerating fields of the skin depth, e–e and e–neutral collisions begin to assert their influence, and the EVD begins to become more isotropic, though the anisotropy in z persists deeper into the plasma than in θ. Adjacent to the substrate (location 4), the EVD appears nearly isotropic. This is an effect that results from both collisions and the axial component of the EVD reflecting off the sheath at the substrate, reversing the direction of the axially directed electron swarm and compensating the anisotropy.

Manuscript received July 20, 2004; revised October 22, 2004. This work was supported in part by the National Science Foundation (CTS03-15353) and in part by CFD Research Corp.

M. J. Kushner is with Iowa State University, Ames, IA 50011 USA (e-mail: mjk@iastate.edu).

A. V. Vasenkov is with the CFD Research Corp., 215 Huntsville, AL 35805 (e-mail: avv@cfdrc.com).

Digital Object Identifier 10.1109/TPS.2005.845904

References

[1] D. J. Economou, "Modeling and simulation of plasma etching reactors for microelectronics," *Thin Solid Films*, vol. 365, pp. 348–367, 2000.

[2] V. Godyak, B. Alexandrovich, R. Piejak, and A. Smolyakov, "Nonlinear radio-frequency potential in an inductive plasma," *Plasma Sources Sci. Technol.*, vol. 9, pp. 541–544, 2000.

[3] V. A. Godyak, B. M. Alexandrovich, and V. I. Kolobov, "Lorentz force effects on the electron energy; distribution in inductively coupled plasmas," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 64, 2001.

[4] A. V. Vasenkov and M. J. Kushner, "Angular anisotropy of electron energy distributions in inductively coupled plasmas," *J. Appl. Phys.*, vol. 94, pp. 5522–5629, 2003.

[5] Tecplot Inc., Bellevue, WA.. [Online]. Available: http://www.tecplot.com

[6] Adobe Corp., San Jose, CA.. [Online]. Available: http://www.adobe.com

[7] Corel Corp., Ottawa, ON, Canada.. [Online]. Available: http://www.corel.com

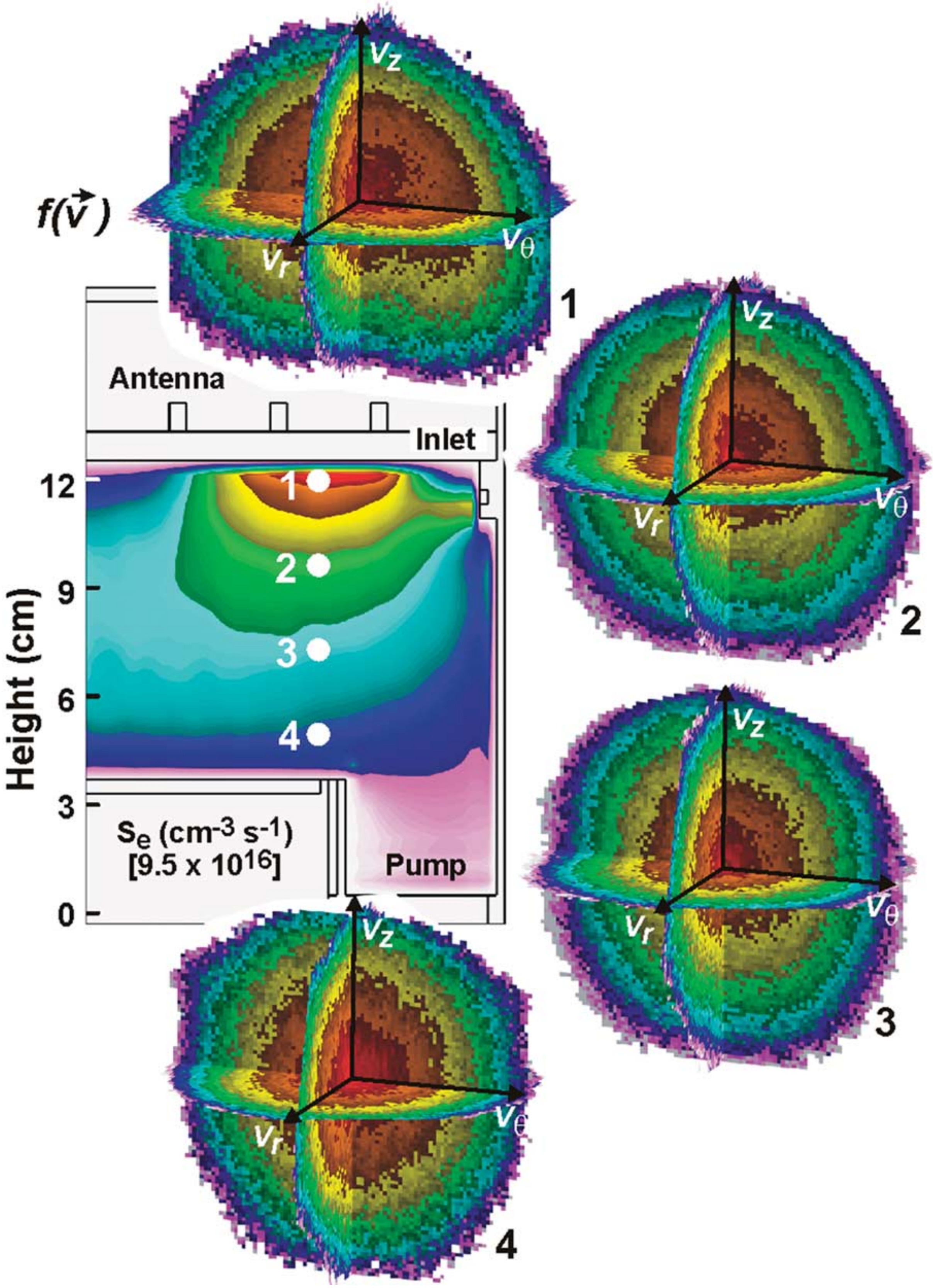

Fig. 1. Electron ionization sources (background flood contours) and electron velocity distributions (EVDs) in an inductively coupled plasma sustained in 3 mtorr argon and excited at 2.5 MHz. EVDs are shown at the radius corresponding to the maximum in the azimuthal electric field, and different heights (denoted by the numbered circles). Maximum extent of the axes is 3×10^8 cm/s or 25 eV. Z-axis is plotted inverted for clarity. EVD is highly anisotropic in the axial and azimuthal direction in the electromagnetic skin depth to largely to NLF. Anisotropy dissipates as the electron swarm crosses the reactor.