Theory of cylindrical probes in moderately collisional plasmas

P. M. Bryant

Department of Electrical Engineering and Electronics, Brownlow Hill, University of Liverpool, L69 3GJ. p.m.bryant@liv.ac.uk

Langmuir probes are often operated in the weakly to moderately collisional regime in non-equilibrium, weakly ionized plasmas in industry and in the research community. Several studies have shown a discrepancy between the plasma density derived from the ion saturation region and the electron retardation (or acceleration) region of the probe I-V characteristic (e.g. Sudit and Woods 1994). Shih and Levi (1971) developed a perturbation theory in which the collisionless radial motion model of Allen, Boyd and Reynolds (or ABR, see Chen 1965) is modified by ion-neutral collisions in the presheath. A correction factor was then applied to the calculated ABR density, resulting in better experimental agreement.

The system of governing equations obtained by Shih and Levi is solved numerically to obtain the sheath potential distribution around the probe. The probe is approximated by a prolate spheroid of twice the probe length to account for the edge effects. The equipotential surfaces are then defined by a family of prolate spheroids with electric fields defined by a confocal orthogonal family of hyperboloids. The collisional radial motion theory (see Bryant 2003) is used to obtain the potential distribution around the probe in an electropositive or electronegative plasma. The cold positive ions follow the hyperboloidal field lines assuming sufficient ion-neutral collisions. Collisions between positive ions and neutrals are modelled by a constant mobility. The electrons and negative ions are Maxwellian.

Sheath potential profiles are given for the electropositive case parallel to the probe (along the z-axis in cylindrical coordinates) and in the radial direction (at $z = 0$). It is shown that the sheath solution tends to the spherical presheath solution (Bryant 2003) far from the probe. The properties of the presheath solution for increasing electronegativity and collisionality are then identical to the spherical case. With decreasing collisionality and along the radial axis (at $z = 0$), the spheroidal sheath solution leaves the spherical presheath and converges to the collisionless ABR presheath and sheath solutions for an infinite cylindrical probe (Chen 1965). However, at low collisionality and in the vicinity of the probe tip, the prolate spheroidal surfaces become increasingly non-equipotential. Poisson's equation is then unable to support solutions arsing from the assumption of collisionless radial motion. In the absence of collisions to dampen ion inertia, the ions veer off their present hyperboloidal trajectory and orbit the probe. This effect occurs in the vicinity of the tip where the curvature of field lines is greatest.

In conclusion, the theory of Shih and Levi has been extended to moderately collisional conditions. The theory could be used to interpret Langmuir probe characteristics in plasmas where measurements made near the plasma potential are not possible. For example, in magnetrons plasma density measurements made near the plasma potential are complicated by strongly magnetised electrons, depleting the electron current to the probe.

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