Investigation of Electromagnetic Field Penetration in ICP and Weakly Magnetized ICP Discharges

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The relationship between the penetration of RF fields and power deposition in ICP discharges is not fully understood. In particular, it is important to determine how non-local power deposition affects the plasma properties of low pressure ICP discharges. To this end, investigation of RF field penetration is performed using a multi-turn loop antenna wrapped around a cylindrical squat bell jar (Fig. 1), rather than the more complicated “stove-top” antenna configuration. An RF-compensated Langmuir probe and a Bz-dot probe (oriented to measure Bz, the vertical z component of \(B\)) are used to measure N(r), T_e(r) and Bz(r) in the plane of the antenna. Simplicity of antenna geometry facilitates the comparison between measured RF penetration depths (Lsd) and classical collisional theory using the HELIC [1] code. N(r) and T_e(r) are used as inputs to HELIC to calculate \(\sigma\), the plasma conductivity.

Plasma currents are calculated using Ohm’s law, \(J = \sigma \cdot E\), which assumes a local relationship between \(J\) and \(E\) through \(\sigma(r)\), and are used together with the antenna currents to compute theoretical Bz(r). Good agreement is obtained between measured Bz(r) and HELIC curves in collisional plasmas for which Ohm’s law is valid. Discrepancies between measurements and HELIC profiles indicate possible deviations from collisional behavior, most likely due to the inapplicability of Ohm’s law in regimes where non-local behavior [2] dominates.

A wide range of plasma parameters is studied, examining 3 collisional regimes [2]: “normal” (classic collisional, \(\omega < \nu_{en}\), \(L_{sd} < \lambda_{mfp}\)), “high frequency” (\(\omega > \nu_{en}\)), and “anomalous” (non-local, \(L_{sd} > \lambda_{mfp}\)). Here, \(\nu_{en}\) is the electron-neutral collision frequency (\(\approx \nu_{coll}\)) and \(\lambda_{mfp}\) is the electron mean free path. Effects of an applied static B_o-field on RF field penetration are also investigated. In nearly all cases, the observed profiles are well understood. Excellent agreement is obtained between collisional theory and experiment in weakly magnetized and “normal” collisional regimes. Deviations of measured Lsd’s from collisional theory are observed at high frequency (\(\omega > \nu_{en}\)) and low pressure P_o (\(L_{sd} > \lambda_{mfp}\)), as expected. Interference and “standing-wave-like” phenomena are observed at high P RF while operating in or near the “anomalous” regime. However, the dependence of this observed behavior on P_o (\(\nu_{en}\)) is in apparent contradiction to the predictions of the theory of the anomalous skin effect [2] (ASE), which is the electromagnetic analog of the well known electrostatic Debye shielding effect.
Fig. 1. Schematic diagram of the experimental setup, including antenna, dogleg Langmuir and $B_z$-dot probes. Probe heights and antenna locations are arranged so that profiles are obtained in the plane of the antenna. Typical operating parameters are: $N_p \sim 5 \times 10^{10} - 5 \times 10^{11} \text{cm}^{-3}$, $P_R \leq 400 \text{W}$, $T_e \sim 2-4 \text{eV}$, $P_O = 1-20 \text{mT}$, $f_{RF} \sim 2-7 \text{MHz}$.

Fig. 2 (left) shows a semi-log plot of $B_z(r)$ obtained in a collisional plasma. Least squares fits to the “left” and “right” branches yield $L_{sd} = 3.4 \text{cm}$ and $2.8 \text{cm}$, respectively. Comparison (right) between collisional theory ($L_{coll}$, red) and experiment ($L_{sd}$, dashes) agree to within $\pm 10\%$. Collisionless skin depth ($L_{less} \equiv c/\omega_{pe}$) is also shown for comparison (purple).

Fig. 2. Semi-log plots of $B_z$-dot profile (left) in “normal” collisional regime (300W, 2MHz, 20mT). Edge features (“wings”) are probably due to the effects of induced currents in nearby conductors. Least squares fits yield experimental $L_{sd}$’s (right, dashes), in good agreement with collisional theory ($L_{coll}$, red).

A similar comparison vs. $P_O$ (1-20mT) is made in “high frequency” discharges. Reasonable agreement (Fig. 3) is seen at higher $P_O$; data diverges from collisional theory [2] at lower $P_O$.

Fig. 3. Comparison between experimental $L_{sd}$’s and collisional theory (pink). 200W, 6.78MHz, $P_O=1-20\text{mT}$.
At $f_{RF}=2\text{MHz}$, $P_o=5\text{-}20\text{mT}$, and $P_{RF}=400\text{W}$, local minima ("nodes") and rapid phase discontinuities ("jumps") of $180^\circ$ in $B_x(r)$ are observed (Fig. 4), indicating interference and/or standing-wave-like behavior, most apparent at highest $P_o$. Since $f_{RF}$ is too high to excite ion-acoustic instabilities and too low for electron plasma waves, and $B_0=0$, then these effects are not accounted for in linear plasma theory. Such effects have been observed by others [3], and interpreted as manifestations of ASE [2-4]. Careful examination of the $B_z(r)$ data and HELIC curves (Fig. 5) for $P_o=5\text{mT}$ (left) and $20\text{mT}$ (right) shows that the field behavior in the outer region ($|R|>a/2$) indeed converges to the HELIC collisional result as $P_o$ increases, consistent with ASE theory. However, the depth of the nodes and the steepness of the phase jumps increase with $P_o$. These phenomena become more apparent as collisionality increases and ASE supposedly weakens, indicating they are probably not manifestations of ASE. Since nodes in $B_x(r)$ can be produced in ICP’s only by internal currents flowing out of phase with the antenna $B_z$-field, yet another mechanism of non-local ($J \neq \sigma \cdot E$) behavior is operative.

At lower $P_{RF}=200\text{W}$ and $P_o=5\text{mT}$, ASE theory predicts strongly anomalous field penetration, which is readily observed (Fig. 6, left) by comparing the measured profile (blue)
to the HELIC (red) curve. Application of a small $B_0$-field, using a large magnet coil just below the antenna, apparently suppresses the ASE. This effect can be seen at $B_0 \sim 5$G, and is evidenced by improved agreement between the data and the HELIC curve for $B_0=20$G (right).

Fig. 6. Comparison of RF field penetration in an unmagnetized (left) and weakly-magnetized (right, $B_0=20$G) ICP, otherwise operating in the anomalous regime (2MHz, $5$mT). Anomalous field penetration appears to be suppressed by application of a static $B_0$-field, as shown by agreement between the 20G data and HELIC curves.

A summary of these results is shown below (Fig. 7), where the collisional regimes for each experiment are indicated as points on this plot of non-locality versus normalized frequency, following Fig. 1 of [2]. Deviation from classical collisional behavior is indicated qualitatively by relative size of data markers (e.g. increase in depth of nodes and phase jumps {dark squares} as the regime {$P_0$} changes from “anomalous” to “normal” is indicated thus).

Fig. 7. Collisional regimes in parameter space for each experiment: ASE non-locality parameter $\ln(\lambda_{mfp}/\delta_o)$ vs $\ln(\omega/\nu_{coll})$, where $\delta_o \equiv (c/\omega_{pe})(1+\nu_{coll}^2/\omega^2)^{1/4}$ and $\nu_{coll}$=electron collisional frequency ($\equiv \nu_{en}$ in these discharges).

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