Transition between ICPs and Helicons at Low $B_0$

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Summary

• Magnetizing the electrons does NOT increase the skin depth!
• Penetration occurs only when helicon propagation is possible.
• Density jump to W mode is due to a neutral depletion instability (we think).

Skin field in an ICP, varying $n$

10 mTorr Argon, 2 MHz, 3 eV, $a = 15$ cm

$B_0 = 0$
Skin field in an ICP, varying $p_0$

$3$ eV, $2$ MHz, $3 \times 10^{11}$, $a = 15$ cm

$B_0 = 0$
Skin field in an ICP, varying $B_0$

This neglects $E_r$ and $E_z$ and is not possible!

13.56MHz, 3eV, 5mT, 5E11, 15cm

Larmor orbit at 20G
Correct solution with $E_r \neq 0$: $B_0$ has almost no effect if $k_z = 0$!
The reason is that $E_r$ causes an $E \times B_0$ drift that restores the shielding current. The space charge is short-circuited if $k_z$ is finite.
The field penetrates only when the helicon threshold is reached.

$B_0 = 100 \text{ G}$
We need the correct $k$-spectrum from HELIC

$m = 1$ half-helical antenna
The correct field penetration is not monotonic

$m = 1$ half-helical antenna
B₂-dot radial profiles in ICP/LoB device, 4-turn m=0 antenna

2×10¹¹, 1.8 eV, 200 W, 5 mT Ar, 2.0 MHz, z=0 cm, B=20 G

John Evans' preliminary data seem to agree with HELIC
What causes the sharp jumps in density?

- Half-wavelength helical antenna
- Full wavelength helical antenna

RF power (W)

ICP-like density

Helicon W-mode
$T_e$ is determined by $p_o$, regardless of $n$

Assume ions diffuse radially with large $r_L$, and electrons can follow them because of the short-circuit effect.

\[
\frac{dN}{dt} = \pi a^2 Ln_0 \overline{n}_e <\sigma v>_{ion} \quad \quad \quad \quad -\frac{dN}{dt} = 2\pi aLc_s n_e(a)
\]

(Bohm criterion)

\[
g(a) \equiv \frac{n_e(a)}{\overline{n}_e} \approx \frac{1}{2} \quad \text{profile factor}
\]

\[
an_0 \overline{n}_e <\sigma v>_{ion} = 2c_s n_e(a)
\]

\[
n_0 \approx \frac{1}{a} f(T_e) \quad \quad \quad \quad f(T_e) = \frac{c_s}{<\sigma v>_{ion}}
\]
$K T_e$ must rise as $p_0$ falls

Positive feedback causes a fully ionized core, whose radius depends on the available power.

$a = 2.5 \text{ cm}, \ g(r) = 1/2$
Energy deposition vs radius shows central and edge peaks due to helicon and TG modes, resp.

800G, 10mTorr, 27MHz, 3.6E13
20-cm full helix and 10-cm half helix
Conclusions

• Adding a small $B_0$ does not change the skin depth in a simple manner.
• At low power, helicon discharges are not very different from ICPs.
• When the power is high enough, neutral depletion occurs, at first in the center.
• Then $K T_e$ rises, ionizing even more neutrals.
• This instability causes $n$ to rise above ICP levels.