Helicon Sources: Why they work!

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Fig. 12. Sketch of the dispersion of the LHP and RHP waves propagating parallel to the magnetic field for $\omega_{pe} \gg \omega_{ce}$. 
Wave damping mechanisms

Collisions of electrons against neutrals and other electrons basically $\eta j$ where $j$ is the wave current

$v_{en}$ decreases when $T_e$ decreases

$v_{ei}$ increases when $T_e$ decreases

Collisionless processes with electrons $\omega - v_z k_z = n\omega_{ce}$

if $n = 0$ then parallel interaction $\omega = v_z k_z$

if $n = 1$ etc then perpendicular interaction ie. cyclotron damping with electrons approaching the wave

if $n = -1$ etc. cyclotron damping with electrons chasing the wave
E to H to W transition in WOMBAT

In E mode \( n \propto P^{1/2} \)

in H mode \( n \propto P \)

in W mode \( n \) exponential
Electron heating in helicon discharges

Capacitive
Low power < 100 watts, $n_e < 10^{10}$ cm$^{-3}$

Inductive
Medium power <500 Watts, $n_e < 10^{11}$ cm$^{-3}$

Wave trapping
High power around 1000 Watts, $n_e \sim 5 \times 10^{11}$ cm$^{-3}$

Resistive heating (coulomb electron-electron) high $\beta$
Very high power > 1000 Watts, $n_e > 5 \times 10^{12}$ cm$^{-3}$
Collisionless damping small

For $\omega = v_z k_z$ ie. the electron velocity is identical to the wave velocity then we have Landau damping

Consider a travelling wave in a Maxwellian electron distribution, with finite $k_z$, and $v_\phi$ a few times the electron thermal speed. To first order the effect of the wave field on the individual electrons is to cause them to oscillate in velocity about an average value as wavefronts pass by. This means that the period of oscillation $\tau$ for the electrons depends only on their average velocity relative to the phase velocity, given by $\tau_{tr} = \lambda/(v - v_\phi)$

The linearised Landau treatment takes the limit of very small pertubations in $v$ so that the electrons are basically stationary in the wave frame.
Collisionless damping large I

Linearised electron trapping occurs when the perturbation in an electron’s velocity exceeds its relative speed in the wave frame of reference. The approximation made in the Landau damping calculation is that a perturbation of this size does not occur to any of the electrons, no matter how close they are to the phase velocity.

This means that the period of oscillation $t$ for the electrons depends only on their average velocity relative to the phase velocity, given by

$$
\tau_{tr} = 2\pi \left[ \frac{m}{qE_0 k_z} \right]^{1/2}
$$

The electrons slosh back and forth in the potential well of the wave which is approximated as a parabola, cf. a pendulum with period independent of the particle amplitude.
Collisionless damping large II

Electrons that oscillate over a larger range in phase because of their higher energy in the wave frame have a period of oscillation that depends on their energy and becomes infinite as their energy approaches the amplitude of the wave potential (and the range in phase approaches $2\pi$).

Visualise 20 electrons with different velocities, relative to the wave phase velocity, arriving simultaneously at the same point (phase) from Degeling thesis.

Electrons travelling faster than the wave oscillate in velocity as they pass it, slower electrons are passed by the wave and also oscillate. Trapped electrons move with the wave and oscillate in its potential well.
Simulated electron trapping in WOMBAT showing power in waves and electrons
Helicons and Trivelpiece-Gould waves

\[ E = \frac{1}{ne} j \times B + \frac{m_e}{ne^2} \frac{\partial j}{\partial t} \]

The first term is the Hall effect and describes helicons. The second term is due to electron inertia and leads to resonance cones. Initially investigated by Appleton and Hartree for ionosphere propagation, later by Storey.

\[ N^2 = 1 - \frac{\omega^2_{pe}}{\omega \left( \omega - \omega_{ce} \cos \theta \right)} \]
Waves launched from a small antenna

\[ \omega = 0.5 \omega_{ce} \]

Electrostatic waves on the resonance cone

Electromagnetic helicon waves
Refractive index, phase velocity and surfaces of constant phase for $\omega = 0.5 \omega_{ce}$: small antenna immersed in a plasma.

$\omega = 0.1 \omega_{ce}$ conditions for WOMBAT
Helicons, TG modes and cylinders

K // B₀ plane wave

Hall Electron inertia

Full solution
Density increasing from $2 \times 10^{10}$ to $2 \times 10^{11}$ cm$^{-3}$

Below a few $10^{10}$ there are resonance cones but above $2 \times 10^{11}$ there are only em helicons with $k_z // B_0$
Helicons in WOMBAT showing simple quadratic whistler plane wave dispersion, not cylindrical dispersion!
Helicons (in WOMBAT) do not propagate as we originally thought. This is due to:

Waves associated with the $\frac{m_e}{ne^2} \frac{\partial j}{\partial t}$ term are highly damped for high plasma densities by “Landau” damping, therefore there are no resonance cone waves and no TG waves.

However, the wave still knows it is in a cylinder and still has $m = 1$ azimuthal wave number which leads to $E_z$ maxima at about 1/2 radii. It is at this position that the main electron heating occurs.

For densities $\sim 10^{12}$ cm$^{-3}$ there is clear wave-electron interaction.

For “blue mode” densities $10^{13}$ cm$^{-3}$, the coulomb collision frequency is greater than the wave frequency and the wave currents are resistively damped.
Ionisation in WOMBAT

Helicon wave moves electrons from just below the ionisation threshold to just above

\[ f_\parallel(\nu) = \frac{2}{\pi} \int_{\nu_{\text{th}}}^{\infty} \frac{1}{\nu^2} \exp\left(-\frac{1}{2\nu^2}\right) d\nu \]

\[ \nu_{\text{th}} = \frac{kT_e}{\epsilon} \]

where \( f_\parallel(\nu) \) is the parallel plasma frequency, \( k \) is the Boltzmann constant, \( T_e \) is the electron temperature, and \( \epsilon \) is the electron charge.

Figure 3 - 12: Normalised graphs of \( f_\parallel(\nu) \) (solid line), \( \sigma_\parallel(\nu) \) (dotted line), and \( v_f(\nu)\sigma_\parallel(\nu) \) (solid line) as a function of electron velocity.

Figure 3 - 13: The downstream density on axis at an rf power of 2000 watts plotted against the helicon wave phase velocity in the source (dots), compared with the integrand of equation 3-3, showing which electrons from a Maxwellian distribution contribute most significantly to the ionisation rate (solid line).
Processes associated with the “blue core”

The “blue core” is a plasma with density around $10^{13}$ cm$^{-3}$ that is 100% ionised. Ion pumping ensues that neutrals are eliminated from this region and prevent the density from rising further in the steady state. Greater power input results in higher ionisation states. The colour is due to the 488 and 443 AII lines that are excited by 2 step processes.

Measuring the 443 line over axial distances of 50 cm or more, show a 30% modulation in rf phase that is constant to better than about 4 ns. This error is about 1/2 the speed of light!!!!!!

So: excited AII ions all drop down to their ground state at the same time, possibly faster than the speed of light.
High $\beta$ effects in the “blue core”
Research with Cormac Corr

The plasma “beta” is the ratio of the particle pressure to the external magnetic field pressure, and is given by:
$$\beta = \frac{p}{(B^2/2\mu_o)}$$

or put another way: $$\beta = (\frac{C_s}{V_a})^2$$

$\beta$ defines how fast a magnetic field diffuses through a plasma
$$\tau = 4 \pi 10^{-7} \Lambda^2/\eta$$

Copper plate 1 cm thick: $$\tau = 3 \times 10^{-3} \text{ sec}$$

Solar granule 900 km radius: $$\tau = 30 \text{ years}$$

WOMBAT for $\beta = 5\%$: $$\tau \sim 10^{-5} \text{ sec}$$
WOMBAT is excited by a single loop (inductive!) at 7.2 MHz
No $B_0$ in source, < 200 Gauß in chamber, argon at 0.6 mTorr.

The effect of the magnetic field is to improve the confinement.
The principle loss is out the two ends.
Magnetic field has significant effect on cross field diffusion and little effect on electron temperature, except at $r = 3$ cm.
Magnetic field change measured with a diamagnetic loop surrounding the plasma and a small Hall probe immersed in the plasma, maximum at low $B_0$.
The “blue core” involves a number of interesting phenomena:

- radial electrostatic confinement (good electron confinement)

Light emission is in phase axially

High $\beta$ effects not easily explainable

Azimuthal instabilities driven by radial pressure gradients

Not all is explained in helicon discharges!