MECHANISMS OF A RF POWER ABSORPTION IN HELICON PLASMA SOURCES

K. P. Shamrai

Institute for Nuclear Research, National Academy of Sciences, Kiev 252022, Ukraine

The operation of helicon plasma sources is largely governed by various waves which are excited both by the driving antenna and as a result of the internal wave dynamics. Numerous experiments and computer simulations show that collective mechanisms are responsible for the efficient rf power absorption in helicon plasmas (see, e.g. [1-7]). In the present report, we discuss three of these mechanisms which seem to be of the primary importance.

As well as in any inductive discharge, the rf power in helicon discharge is absorbed due to both capacitive and inductive coupling [1,2]. The latter is the main absorption channel in the high-density regime. Its efficiency depends on the antenna spectrum, on a susceptibility of plasma to the driving force, and on a capacity of excited fields to deposit the power in plasma.

Purely inductive coupling implies that the density of antenna current satisfies the quasi-stationary condition, $\nabla\cdot\mathbf{j}_a = 0$, neglecting the effect of charges induced in antenna. It is suitable for the analysis to consider the antenna current and fields as superposition of spatial modes with axial, k, and azimuthal, $m = 0, \pm1, \pm2...$, wavenumbers. As far as the device length L is limited, the axial wavenumber is quantized, $k = l\pi/L$, $\Delta k = \pi/L$, where $l = 1,2,3...$ is the axial mode number. The discreteness of the k-spectrum may be important, especially in short devices with not very high aspect ratio L/r_0 (r_0 is the plasma radius).

The spectral intensity of antenna depends strongly on the antenna design, and on the plasma-to-antenna length ratio, L/a. If this ratio is not high, the spectra of different antennas are substantially different in the area of long modes. Since just these modes contribute mainly to the absorption, the antenna spectrum may be an efficient means for controlling the power deposition in plasmas.

As far as the spatial modes of fields are independent in the linear approximation, it is possible to separately analyze how each of them is excited and absorbed in plasma. Spectral amplitudes of fields are found to be the products of the appropriate antenna spectral amplitude by some response function, $\mathbf{E}_{km}(r) = j_{km}\,\mathbf{F}_{km}(r)$. The response function is composed of two terms, $\mathbf{F}_{km} = \mathbf{h}_{km}(r) + \mathbf{t}_{km}(r)$. Their amplitudes, profiles and relative weights depend on the radial density profile, $n_0(r)$, as well as on the boundary conditions, damping etc.

For each of k-modes one can introduce two characteristic densities [3]

$$n_{\mathrm{low}} = \frac{m}{4\pi e^2}\,\omega\omega_{\mathrm{c}} N^2 \qquad \text{and} \qquad n_{\mathrm{up}} = \frac{m}{16\pi e^2}\,\omega_{\mathrm{c}}^2 N^2$$

where ω_c is the electron gyro-frequency, and $N = kc/\omega$ the axial refractive index. In the region of density profile $n_{\mathrm{low}} < n_0(r) < n_{\mathrm{up}}$ the **h**-term corresponds to the helicon (H) wave. The radial variation of the helicon field may be estimated using the local (WKB) approximation, $k_{\perp H} \approx k\left[\left(n_0/n_{low}\right)^2 - 1\right]^{1/2}$. The radial scale increases with decreasing density, and the surface $n_0(r) = n_{low}$ is the cut-off for helicon. If $n_0 << n_{low}$, $|k_{\perp H}| \approx k$. Fields in this region are like those of the vacuum TE-wave. Thus, in non-uniform plasma the **h**-term is the helicon wave, with relatively high rate of the radial variation, joined with the long-scale TE-like tail.

In the region $n_0 < n_{up}$ the **t**-term is identified with the Trivelpiece-Gould (TG) wave. Its local wavenumber takes the form $k_{\perp T} \approx k(\omega_c/\omega)(1 - n_0/2n_{up})$. At $n_0(r) << n_{up}$, $k_{\perp T}$ varies with radius very slightly, and highly exceeds $k_{\perp H}$. Both waves merge at the surface $n_0(r) = n_{up}$, and thus may convert into each other.

The plasma column is transparent for waves if the edge density is well below n_{up}. Then the **t**-term is quite electrostatic near the boundary, $\mathbf{E}^{(T)} \approx -\nabla\phi^{(T)}$, and can not be efficiently excited. Indeed, the rate of work done by the antenna, $\int \mathbf{E}^{(T)}\cdot\mathbf{j}_a\, dV \propto \int \delta(r - r_0)\phi^{(T)}\nabla\cdot\mathbf{j}_a\, dV = 0$. Thus, with purely inductive coupling the driving antenna interacts efficiently with helicons only, and excites them preferentially by parts carrying azimuthal current [3].

The local radial wavenumber of some mode is plotted schematically in Fig. 1. As seen, the central region of the plasma column, $0 < r < r_{up}$, is opaque both for helicon and for the TG wave. The H-wave is also non-propagating in the region of the density profile between r_{low} and r_0. However, for long modes, $r_0 - r_{low} < k^{-1}$, the non-transparent gap does not prevent the penetration of fields into the transparent region, $r_{up} < r < r_{low}$. Short modes can not reach the transparent region, if any, to excite the helicon wave, and thus do not contribute in absorption.

In short devices, the k-spectrum is considerably rarefied, and the plasma may be transparent for a few helicon modes only. Fig. 2 shows the variation of characteristic densities with the axial mode number, for a device of length $L = 50$ cm. One can see that only a few lower helicon modes may be excited in plasmas with density below 10^{12} cm^{-3}.

Being excited by the antenna, the isolated H-wave is low damped. The reason is that it reserves the energy in magnetic field which can not be efficiently destroyed by elementary damping mechanisms like collisions, Landau damping, etc. [3] The efficient power absorption in the near-antenna region occurs due to mechanisms of the mode conversion [3-5]. They are found to be of two types: the non-resonance and resonance conversion. Both mechanisms result in the excitation of strongly damping TG-waves.

The non-resonance conversion gives rise to the absorption in the region of densities $n_0 < n_{up}$. Since the TG component is electrostatic in this region, it may be excited efficiently if some mechanism produces a space charge. Indeed, the rate of work, which the heliconic electron current does to excite the TG-wave, takes the form $P_{conv} \approx -e\int \phi^{(T)}\mathbf{v}^{(H)}\cdot\nabla n_0\, dV$, where $\mathbf{v}^{(H)}$ is the velocity of electrons in helicon fields. As seen, the non-resonance conversion arises due to a redundant polarization induced by helicons in the non-uniform plasma.

A steep density gradient naturally arising at the boundary of the plasma column with the chamber wall is the most powerful source for the conversion. The gradient at the boundary reads $\nabla n_0 = -\,\mathbf{e}_r n_b \delta(r_0 - r)$, with δ being the Dirac delta-function, and $\mathbf{e}_r$ the radial unit vector. The power of this source for exciting the TG wave is equal $P_{\mathrm{conv}} \approx \pi r_0 L e c n_b B_0^{-1} |\phi^{(T)} E_\theta^{(H)}|_{r=r0}$. We call this mechanism of the TG-wave excitation the *surface mode conversion* [3]. One can see that the surface conversion occurs at an insulating wall only, because $\phi^{(T)} = 0$ on a conducting wall. To be efficient, this conversion mechanism does not need an abrupt density jump with δ-like gradient. It is actually enough if the width of a transition layer at the plasma edge is much less than the TG wavelength.

To cancel the redundant edge polarization induced by helicon fields, the TG field should satisfy at the plasma edge the condition $|E_\theta^{(H)}|=(\omega/\omega_c)|E_r^{(T)}|$, so that $P_{\mathrm{conv}} \propto |E_\theta^{(H)}(r=r_0)|^2$. As far as the radial scale of helicon fields decreases with increasing density, $|E_\theta^{(H)}|$ oscillates with increasing density, taking small values at some discrete values of mean density n. The dependence of absorption on density is non-monotonic: it is reduced at anti-resonances of the TG wave excitation when the azimuthal field has a node at the boundary [3].

The surface conversion apparently works in various conditions. The effective collision frequency related to it, $\nu_{\mathrm{eff}} \approx \omega_c r_0/L$ [3], is high enough to explain the power absorption in experiments [1]. A pronounced near-surface absorption, which probably may be attributed to this mechanism, was calculated with the use of various numerical codes [5,6].

The *resonance mode conversion* occurs in the bulk plasma near the resonance surface $n_0 = n_{\mathrm{up}}$ where waves come into a spatial synchronism. The density gradient is now a suppressing factor, in contrast with the previous case. Indeed, with flattening of the density profile the width of the synchronism region increases. For this reason, the most efficient conversion has to occur for modes at $n_{\mathrm{up}} \approx n_{\mathrm{m}}$, that is in the region of the smoothest density variation. Although these general arguments are confirmed by numerical results, the contribution of the resonance conversion to the total power absorption is not high for some reason [5].

The efficiency of surface conversion drops in anti-resonance conditions. If in addition the resonance surface is out of the plasma bulk, $n_{\mathrm{up}} > n_{\mathrm{m}}$, the helicon mode is also free of the resonance conversion. As a result, the TG wave is not excited, and the appropriate mode can not be absorbed in the near-antenna region. Such a purely helicon mode may be irradiated if the device is long enough. Axial wavenumbers of irradiated modes lay near the characteristic value $k_{\mathrm{AR}} \approx k_0(1+k_0 r_0/m p_{mi})$ where $k_0 = (4\pi e/c p_{mi})(\omega r_0 n/B_0)$ with p_{mi} being the i-th root of the m-th Bessel function, i the radial number of the mode, and n some mean density. Traveling along the plasma column helicon wave slowly deposits the energy due to various relatively weak mechanisms like collisions and Landau damping, trapping of electrons [1], and parametric instabilities [8].

Experiments and calculations show that the energy flux of irradiated modes strongly depends on a design of driving antenna [2,5]. The helical antenna can put into irradiated modes several tens per cent of the total input power due to its better coupling to traveling waves. The irradiation is obviously efficient if the spectral intensity of antenna is not reduced near $k=k_{AR}$. Irradiated modes may contribute considerably to the power absorption in long devices where the down-antenna plasma provides enough space for damping of anti-resonating modes. In short devices, the radiation is probably senseless.

Helicon and TG waves are not well separated at low magnetic fields, normally below 100 G. The TG wave is low damping in this area and, being excited at the plasma boundary due to the surface mode conversion, is not absorbed over the plasma radius. It is multiply reflected from the plasma center and edge, and is involved in secondary interactions with the helicon wave. This effect apparently reduces the efficiency of absorption.

In conclusion, the analysis of numerous experimental and theoretical results shows the non-resonance mode conversion to be probably the most efficient mechanism of the power absorption in short helicon devices. It predicts the effective collision frequency and absorbed power vs. density dependence in agreement with the experimental data [9]. In long devices, a concurrent mechanism is the irradiation of helicon waves into plasma remote from antenna.

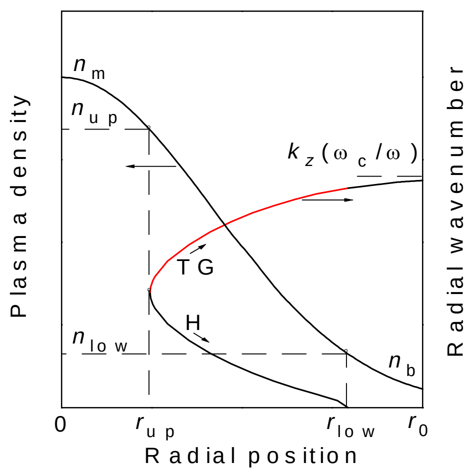

Fig. 1. Radial wavenumber in local approximation. H and TG denote respectively the helicon and Trivelpiece-Gould branches of the dispersion curve.

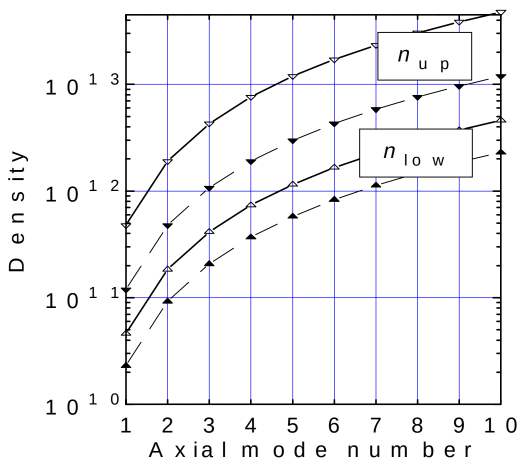

Fig. 2. Dependences of n_{low} and n_{up} on the axial mode number, for B_0 = 100 G and 200 G. The device length is L = 50 cm.

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