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COMPARISON OF COUPLING TO 5 GHZ LOWER HYBRID WAVES AND 0.5 GHZ HELICON WAVES

By

R.I. Pinsker[1], M. Porkolab[2], C.C. Petty[1], R. Prater[1], and C.P. Moeller[1]

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[1]General Atomics
[2]Massachusetts Institution of Technology

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Comparison of Coupling to 5 GHz Lower Hybrid Waves and 0.5 GHz Helicon Waves

R.I. Pinsker[1,a)], M. Porkolab[2], C.C. Petty[1], R. Prater[1], and C.P. Moeller[1]

[1]*General Atomics, PO Box 85608, San Diego, California 92186-5608, USA*
[2]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[a)]Corresponding author: pinsker@fusion.gat.com

Abstract. We compare, qualitatively and with a simple semi-quantitative model, the difficulty of coupling to fast waves at 0.5 GHz ('whistlers' or 'helicons') and to slow waves ('lower hybrid waves') at 5 GHz and $n_{||}$=3 under conditions relevant to the DIII-D tokamak. Though the density at which the slow wave begins to propagate is much lower than the fast wave, the stronger evanescence in vacuum for the higher frequency wave makes excitation of the SWs more difficult than for the FW case. Enforcing a minimum density at the coupler face, as might be produced by local gas puffing, is shown to likely be more effective for the SW case. The fact that the surface admittance for the slow wave at 0.5 GHz is much larger than for the FW at the same frequency has possibly significant implications for attempts to excite the FW.

INTRODUCTION

The application of Landau damping as the damping mechanism for current drive requires excitation of waves with a phase speed $\omega/k_{||}$ in the direction parallel to the static magnetic field lines less than the speed of light in vacuum, or a parallel index of refraction $|n_{\parallel}| \equiv |k_{\parallel}| c/\omega > 1$, so that there can be some electrons that can resonate with the wave. The field amplitudes in the vacuum region adjacent to the wave launcher depend on the radial-like coordinate x as $\sim \exp\left[-\mathrm{Im}\left(k_{\perp}\right)x\right]$ where $\mathrm{Im}\left(k_{\perp}\right) = \sqrt{k_{\parallel}^2 - \omega^2/c^2} = \left(\omega/c\right)\sqrt{n_{\parallel}^2 - 1}$, so that the radial characteristic decay scale length is $L_D = c\Big/\left(\omega\sqrt{n_{\parallel}^2-1}\right)$. Therefore the necessity of having the wave $|n_{||}| > 1$ implies radial evanescence of the wave fields in the region in which the density is below cutoff. This applies both for Fast Waves (FWs) in the ICRF and for slow and fast waves in the LHRF. The practical difficulty with application of FWs in the ICRF for electron current drive stems from the weakness of the Landau damping, essentially due to the very small component of wave electric field parallel to $\mathbf{B}_0$. In order to obtain a significant level of electron Landau damping (ELD) in this regime, the magnitude of $n_{||}$ must be raised so that the parallel phase velocity is comparable to the electron thermal velocity [1]. At reasonable values of the electron temperature at the desired damping zone in the plasma, the required high values of $n_{||}$ yield strong evanescence and low antenna loading, and consequently high antenna electric fields at high power. In a reactor-like plasma this ICRF FW regime can be applied for current drive near the magnetic axis at not too high a value of $n_{||}$. However, reactor design studies have shown a need for efficient non-inductive current drive at mid-radius (or possibly even further out) [2], in the neighborhood of normalized minor radius of 0.5<ρ<0.8, where ICRF FWs would again require a difficult-to-launch high value of $|n_{||}|$. Furthermore, under reactor-like conditions, ion cyclotron harmonic damping can absorb a large fraction of the FW power on ions, leaving insufficient power absorption on electrons.

Raising the FW frequency to the very high ion cyclotron harmonic range, where the FW frequency nears the geometric-mean-gyrofrequency $f_{gmg} \equiv \sqrt{f_{ci} f_{ce}}$ (which is 461 MHz/T for deuterium) simultaneously decreases the ion cyclotron harmonic damping and increases the ELD, by increasing the wave $E_{||}$ (non-negligible electron inertia). But at higher frequencies, the domain in which the slow wave can propagate expands to encompass the outer regions of the confined plasma. This manifests itself as a wave accessibility limitation. In the case of fast wave frequencies near f_{gmg}, the minimum value of $|n_{||}|$ that can reach a given maximum density without reflection into the other mode is approximately $|n_{\parallel}| > 1 + \left(f_{pe}\big|_{\max}/f_{ce}\right)$ where the electron plasma frequency is evaluated at the maximum density [3].

Under conditions where $\omega_{pe}/\Omega_e > 1$, the accessibility limit exacerbates the coupling difficulty by raising the required value of $|n_{||}|$ and thereby decreasing the decay length L_D.

At still higher frequencies, well above f_{gmg} , the FW becomes less useful due to these coupling difficulties, while the SW remains a viable option, due to its much lower cutoff density and therefore much reduced evanescence than the FW at the same frequency and $|n_{||}|$. The empirically observed upper density limit for electron damping of slow waves, thought to be due to non-linear effects such as parametric decay instabilities, necessitates the use of high frequencies on the order of 5 GHz, where the cutoff density is not completely negligible and hence evanescence cannot be ignored.

In this paper, we investigate basic coupling issues for 0.5 GHz FWs and for 5 GHz SWs at a value of $|n_{||}|$=3 for edge density parameters characteristic of high-performance DIII-D discharges. Such discharges are planned to be used as targets for 0.5 GHz FW ('helicon') experiments in 2017, wherein ~1 MW of rf power is expected [4] to produce an easily measurable level of current drive in the mid-radius region, ρ~0.55.

FULL-WAVE SOLUTIONS IN THE EDGE PLASMA

We shall consider launching waves at a sufficiently high value of $|n_{||}|$ so that the interaction between the SW and FW polarization is weak. In the spirit of Brambilla-style coupling calculations [5], we numerically solve the uncoupled FW or SW equations in the edge region assuming a radiation condition at the high-density edge of the domain, using a plane-stratified cold plasma model. We take the vertical (=poloidal) wavenumber to be zero, and assume the particular value of $n_{||}$=3. The wave-launcher is taken to be at x=0, and the goal of the computation is to evaluate the surface admittances $Y_S = \left(B_y/E_z\right)\big|_0$ for the SW and $Y_F = \left(B_z/E_y\right)\big|_0$ for the FW. Here, the density is stratified in the x-direction (the 'radial' direction), the static magnetic field is in the z-direction (approximately the 'toroidal' direction) and the vertical or poloidal direction is the y-direction. To use these admittances to get an idea of the coupling, we assume that the admittance of the launching structure is not too different from that of a TEM structure in vacuum, with Y~1, so that the complex reflection coefficient can be estimated as $\Gamma \approx (Y-1)/(Y+1)$. For the density profile, we use a profile measured by Thomson scattering in a target development experiment on DIII-D. For purposes of this estimate, we assume that the wave launchers would be in the outboard midplane, though in the planned FW experiments, the wave launcher will be positioned well above the midplane.

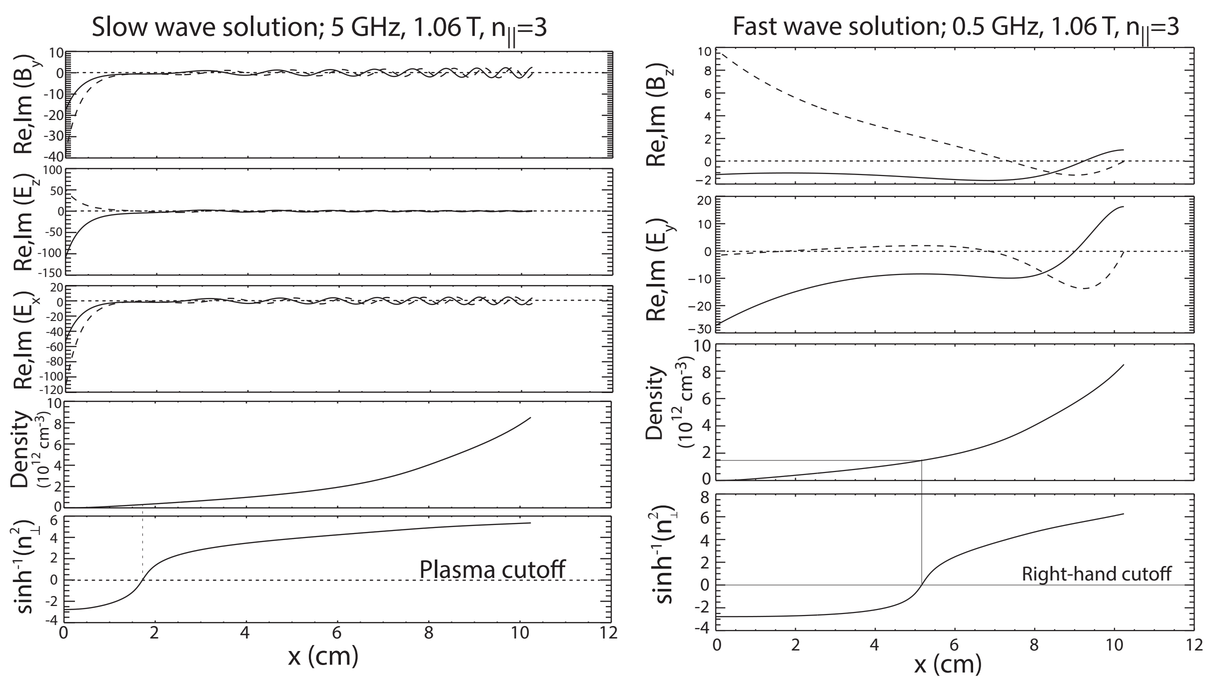

FIGURE 1. Full-wave solutions for the slow wave fields (left, 5 GHz) and fast wave transverse fields (right, 0.5 GHz) for $n_{||}$=3 at 1.06 T and an edge electron density profile measured in a DIII-D discharge.

The resulting solutions for the slow and fast wave fields in the 10 cm region adjacent to the wave launchers are shown in Figure 1. Also shown are the assumed density profile (same for both cases) and the geometric optics value (local approximation) of $n_\perp^2$, with logarithmic compression of the vertical axis by applying the $\sinh^{-1}$ function. The density at which 5 GHz equals f_{pe} (the SW cutoff) is 3×10^{11} cm^{-3}, which appears less than 2 cm from the launcher mouth, but the characteristic radial decay length at $n_{||}$=3 and 5 GHz is only 3.4 mm, so the evanescence is quite strong [~exp(5.9)] . For the FW case, the relevant cut-off density is where the Stix R parameter equals $n_{||}^2 = 9$, which for a magnetic field of 1.06 T and ion mass of deuterons is 1.5×10^{12} cm^{-3}, which appears at about 5 cm from the launcher. But the radial decay length is 3.4 cm at the factor-of-ten lower frequency, so that the fields are reduced by a smaller evanescence factor [~exp(1.5)] than in the slow wave case. The weaker evanescence in the lower frequency FW case is manifest in the estimated reflection coefficient of Γ=0.96 at an angle of -140 degrees, compared with the SW case of Γ=0.9997 at an angle of -38 degrees.

It should be noted that the precise location of the layer where the density is 3×10^{11} cm^{-3} is in fact quite uncertain from our standard density profile diagnostics on DIII-D and is at any rate likely to be highly sensitive to the poorly-controlled far scrape-off-layer parameters. One might consider puffing neutral deuterium from an orifice adjacent to the launcher and thereby strongly reduce the thickness of the slow wave evanescent layer, as is routinely done in several LH experiments [6]. We simulate such an experiment by enforcing a minimum density value and computing the wave fields and resulting reflection coefficient as a function of the value of the minimum density. We find the well-known behavior [7] that the minimum reflection coefficient is obtained at a density adjacent to the launcher equal to $n_{||}^2 = 9$ times higher than the cutoff density, i.e. at a minimum density of 2.8×10^{12} cm^{-3}. More complicated wave launching structures than the simple waveguide grill can yield acceptably low reflection coefficients at lower minimum density values, only slightly higher than the cutoff.

On the other hand, the FW dispersion has the property that the evanescence is as strong as it is in vacuum for densities almost up to the cutoff density (in this case, 1.5×10^{12} cm^{-3}), so that active modification of the edge density profile to improve coupling would have to increase the density to a higher value than in the higher frequency slow wave case. This difference between the level of increase in the minimum density at the launcher face required to make a significant improvement in coupling for the two cases is shown in Fig. 2.

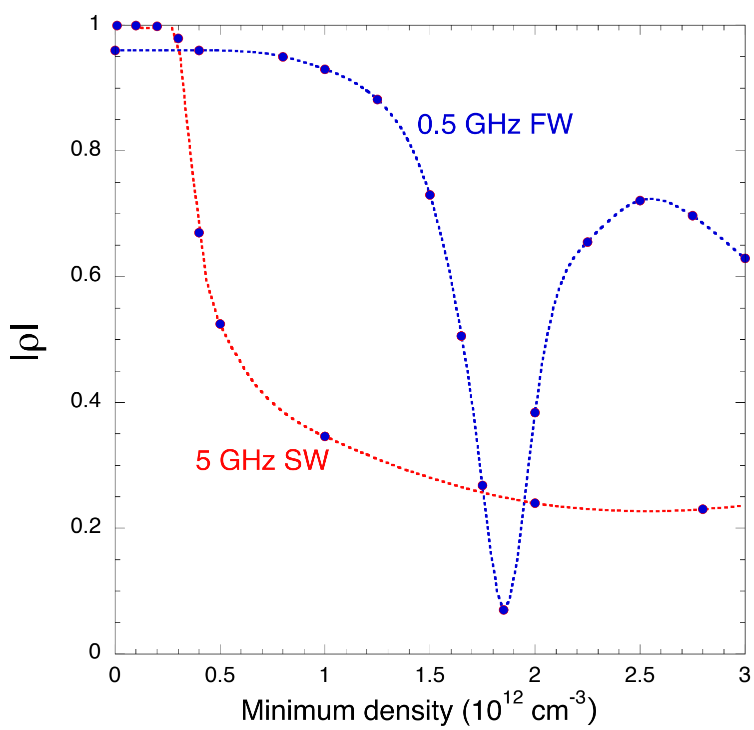

FIGURE 2. Effect of enforcing a minimum density value on the reflection coefficient magnitude for 0.5 GHz FWs and for 5 GHz SWs, at 1.06 T, deuterium. The effect of even a modest increase in minimum density is significant for the SW, while the FW requires a minimum density close to the cutoff density for a significant improvement in coupling.

EXCITATION OF BOTH WAVES AT 0.5 GHZ

Fast waves are excited with a wave electric field perpendicular to the static magnetic field and to the radial direction (i.e., in the y-direction) and an accompanying wave magnetic field in the z-direction, while the slow wave is excited with wave electric fields in the z-direction and the accompanying magnetic field in the y-direction. In practice, the nominal FW coupling structure cannot avoid exciting a small amount of E parallel to the static magnetic field, because the alignment between the launcher elements and the direction exactly perpendicular to the total static magnetic field lines cannot be perfect as the field line pitch angle changes. Hence the nominal fast wave launcher must (linearly) directly excite the slow wave to some degree. The slow waves are likely to suffer from parametric decay at high power, and thereby be damped on ions in the edge plasma, and are hence viewed as a loss.

We can get some idea of the importance of this unintended slow wave excitation by comparing the real part of the surface admittances for the slow and fast waves. One can show that for small angles of misalignment, the ratio of the power coupled to parasitic slow wave excitation to the fast wave power is approximately $\sin^2\theta \,\mathrm{Re}(Y_S)/\mathrm{Re}(Y_F)$, where the misalignment angle is θ. For the 0.5 GHz FW case shown in Fig. 1, the ratio of the real parts of the surface admittances is 4.83 (the slow wave at 0.5 GHz has nearly five times larger real surface admittance than the FW at that frequency with the same density profile), so for a 5 degree misalignment, about 3.7% of the coupled power would go into SW excitation. However, for a 10 degree misalignment, the slow wave excitation fraction increases by a factor of 4, to 14%, while for a 20 degree misalignment, more than half of the coupled power goes into the slow wave. If the minimum density at the launcher face is raised to only $3\times10^{11}\,\mathrm{cm}^{-3}$, the ratio of the real part of the slow wave admittance to the fast wave admittance rises to 20.6 and a 5 (10 degree) misalignment yields a slow wave power fraction of 16% (62%). We can therefore expect that an experimental signature of significant slow wave excitation might be a strong dependence of the antenna loading on the misalignment angle, scaling as θ^2 for small misalignments. Future work with more realistic antenna models will attempt to make this calculation more quantitative. The experiment with a 12-element phased array of the 'comb-line' type excited at very low power levels (~0.1 kW) will begin on DIII-D in 2016.

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P.O. BOX 85608 SAN DIEGO, CA 92186-5608 (858) 455-3000