

## Resonance Broadening by the Interaction of Spatially Localized LHW with Plasma

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**Abstract.** The consequences of spatial localization of Lower Hybrid waves in a tokamak plasma are discussed. A threshold value of the electric field amplitude for a nonlinear interaction is determined, and the role of short-wavelength Fourier components is considered.

### 1. Numerical Model

Let us suppose that a monochromatic LH wave is confined to a rectangular region  $\Gamma$  of a magnetic surface of an area  $S$ , cf. Fig. 1. In what follows, we will restrict ourselves to a 1D model, and this picture serves merely to get proper scaling and weighting factors. Let  $f$  be the frequency,  $k_{\parallel} = \omega N_{\parallel}/c$  the wavevector component parallel to the magnetic field,  $\omega = 2\pi f$  (the subscript  $\parallel$  is retained for correspondence with the usual notation). Let the wave amplitude  $E_0$  be constant over the area  $\Gamma$ , i.e.,  $E_z(z, t) = E_0 \sin(k_{\parallel}z - \omega t)$ ,  $0 < z < L$ , and zero otherwise. We will be looking for the average value of the scatter of velocities  $v$ ,  $\langle (v - v_0)^2 \rangle / 2\tau$ , caused by the RF field to a collection of particles with the same initial velocity  $v_0$  but entering the RF field area at random times. Following Fig.1, it is appropriate to choose  $\tau$  to be the toroidal orbit time  $T = 2\pi R/v_0$ , and multiply the value by  $h/2\pi a$  to account for the particles that do not visit the area  $\Gamma$ . Then,

$$D^*(v) = \langle (v - v_0)^2 \rangle h v_0 / (8 \pi^2 R a)$$

is a diffusion coefficient averaged over a magnetic surface, and can be directly compared with the quasi-linear one. More details are given in

[1]. Of course, diffusion can only exist in a spectrum of waves; here, these are generated owing to the spatial distribution of the monochromatic wave, and the stochastic parameter is the random time at which the particles enter the field region.

First, we show that this simple model represents a real situation surprisingly well. As an example, we will use data calculated for an 8GHz grill intended for the FTU tokamak [2]. Figure 2 shows the spatial profile of the electric field amplitude, and an instant electric field  $E_z(z, t=0)$  inside the plasma, at  $x=3\text{cm}$  from the antenna. Both the waves with  $k_{\parallel} > 0$  and those with  $k_{\parallel} < 0$  are well localized, and the electric field inside each area is close to the respective monochromatic waves which are excited as follows from the Floquet's theorem.

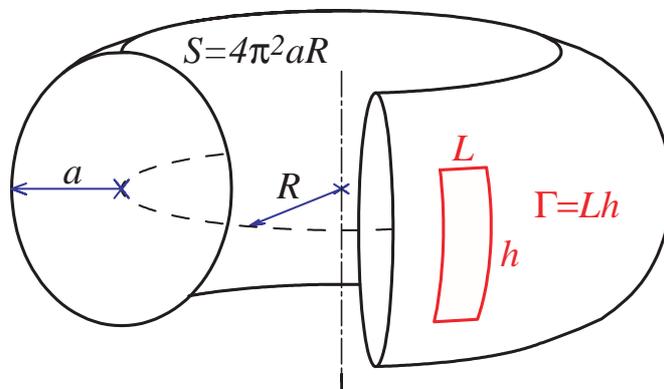
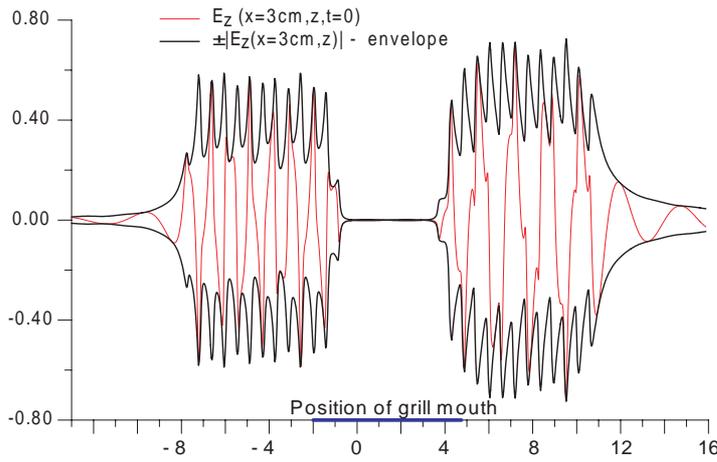
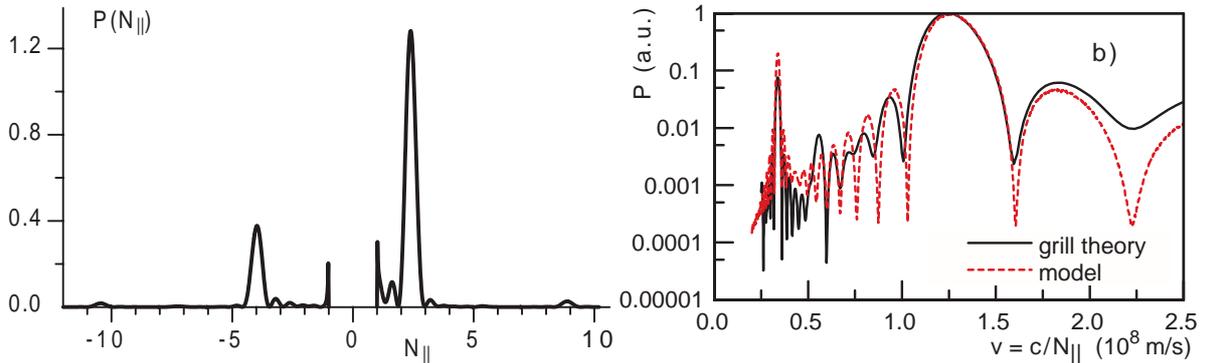


Fig. 1. Model arrangement.



**Fig. 2.** Spatial distribution of LH waves launched by a PAM grill (8GHz), see [2], at  $x=3\text{cm}$ .

Fig. 3a shows the power spectrum  $P(N_{\parallel})$  of the same grill. In Fig. 3b, this power spectrum is redrawn against  $v=c/N_{\parallel}$  (for  $k_{\parallel} > 0$  only), and compared with the numerically obtained values  $v^2 D^*(v)$  as discussed above but with two monochromatic waves ( $N_{\parallel}=2.39$ ,  $E_0 = 0.01$  kV/cm and  $N_{\parallel}=8.87$ ,  $E_1 = 0.44 E_0$ ). The curves are normalized by their maxima for comparison. Note that the scaling  $D \propto P(N_{\parallel})/v^2$  stems from the quasilinear theory which holds well for  $E_0$  chosen. The curve obtained from the model for just the fundamental mode (not shown) is very similar, except that there is of course no spike at  $N_{\parallel} = 8.87$ .

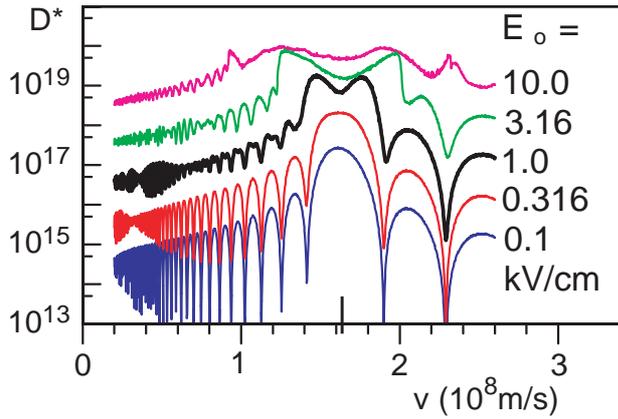


**Fig. 3.** a) Power spectrum for the grill as in Fig.2; b) the same spectrum (black) compared with the numerically obtained one for  $L=7.2\text{cm}$  (red; log scale is used for better visibility of small details).

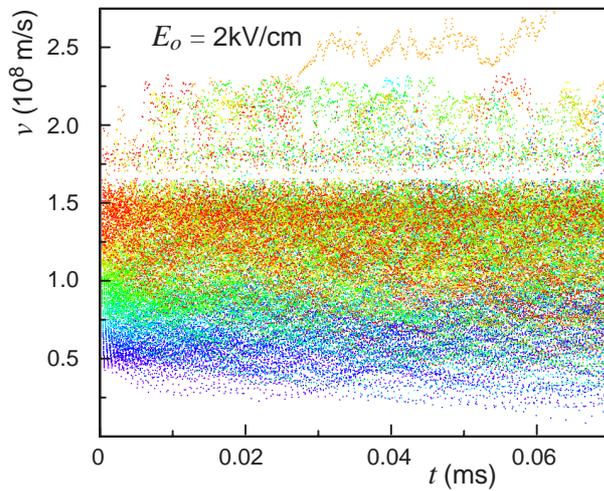
From Fig. 3b, it is obvious that the main information contained in the linear spectra is that we have (basically two) monochromatic running waves initially confined in a rectangle, defined by the grill dimensions. As the short wavelengths (SW) Fourier components are gradually damped, the spatial shape of the electric field envelope becomes smoother, tending apparently to a Gaussian spatial profile. Of course, this picture neglects a lot of other processes (e.g., wave diffraction, toroidal effects, etc.) but seems to contain the essence.

## 2. Nonlinear regime

With the faith that the simple model is physically adequate, we can exploit quantitatively the limits of validity of the commonly used quasilinear approach. Figure 4 shows the diffusion coefficient  $D^*$  for an increasing  $E_0$  (the frequency and length  $L$  chosen apply e.g. to Tore Supra or JET grills). The spatial profile of  $|E_z|$  is rectangular, relevant to plasma boundary. At  $E_0 > 0.3$  kV/cm, the diffusion coefficient starts to broaden around the resonant velocity



**Fig. 4.** Numerically obtained diffusion coefficient  $D^*$  for increasing electric field amplitude.  $f=3.7\text{GHz}$ ,  $L=0.3\text{m}$ ,  $h=0.9\text{m}$ ,  $N_{\parallel}=1.85$ ,  $R=3\text{m}$ ,  $a=1.5\text{m}$ .



**Fig. 5.** Time evolution of the velocity of individual particles after repeated transits through the RF field area. Initially, the particles are equidistantly distributed between  $v=0.5$  and  $1.5$  ( $\times 10^8\text{m/s}$ ).  $L = 0.3\text{m}$ ,  $R=3\text{m}$ ,  $f=3.7\text{GHz}$ . Calculated using the analytical model. Plotted are the velocities at the instant when the particles leave the RF segment.

( $v=c/N_{\parallel}$ ). For a Gaussian spatial profile, which is more relevant to the plasma core, the effect is practically the same [1]. The broadening exceeds the trapping width, and some particles are actually expelled from the resonant velocity region rather than trapped. Also, the character of interaction is somewhat different from a regular diffusion.

This is seen in Fig. 5 where the time evolution of individual particles is followed over many transits through the RF field region. In this case, the particle motion has been solved analytically (for one monochromatic wave and spatially uniform amplitude, the dynamics is equivalent to that of a mathematical pendulum, and the solution can be expressed in terms of elliptic integrals). A “forbidden” region around the resonant velocity is apparent. Though the behavior of particles in strong monochromatic waves has been studied earlier, e.g. [3,4], theoretical analysis has to be extended to cases with a finite transit time  $L/v$ .

The electric field amplitude  $E_o$  [kV/cm] scales with  $N_{\parallel}$ , the power density  $p$ [kW/cm<sup>2</sup>], density  $n$ [ $10^{19}/\text{m}^3$ ] and frequency  $f$ [GHz] as [1]

$$E_o = 16.4 p^{1/2} f^{1/2} N_{\parallel}^{1/2} n^{-1/4} .$$

Therefore, it will decrease as the power is gradually absorbed and the density increases, but at the same time, it will grow via the power density as  $(1/r)^{1/2}$  (in cylindrical approximation) and with  $N_{\parallel}$  (if toroidal upshift is significant). For  $f = 3.7\text{GHz}$ , a parabolic density profile with  $n_o = 5 \times 10^{19}/\text{m}^3$ , with no absorption or  $N_{\parallel}$  upshift, the initial value of  $E_o$  would be restored at  $r/a = 0.2$ , and then increase further inward. The poorer the absorption (the lower the temperature and/or density), the sooner the nonlinear threshold is reached. In view of the increase of  $\Delta N_{\parallel}$  with  $E_o$ , and probable overlapping of resonances of the remaining modes, this “stand-by” mechanism can ensure the absorption of most (or all) of the power which has not been damped linearly in the outer parts of the plasma. Note that in most LH experiments, the electric field amplitudes at the edge (in front of the grill) are of the order of 1kV/cm.

### 3. Linear regime

The SW “satellites” (cf. Fig. 4) which are already included in the linear spectra used for LHH&CD modeling as shown earlier, have been considered insufficient to provide the bridge between cold bulk electrons and high phase velocity of the fundamental mode. Indeed, this spectrum is not smooth enough, which results in a gradual absorption of the SW modes without a significant effect on the absorption of the longer wavelength modes. On realizing where the SW modes come from, we can immediately see that the linear spectra calculated for  $E_z$  instead of  $E_{\parallel}$  are inaccurate in this aspect. The difference between  $E_z$  and  $E_{\parallel}$  ( $k_z$  and  $k_{\parallel}$ ) is really negligible (about 1%), but particles moving along the magnetic field lines will not “see” the same length of the field region (which is given by the grill geometry). Consequently, gaps in the SW part of the spectrum in fact do not exist (though, depending on the length and height of one **grill row** and the angle between the magnetic field lines and the equatorial plane, modes corresponding to a prevalent length will be more pronounced). There can be also other mechanisms smoothing the SW tail. Preliminary calculations show that if such smoothed SW part of the spectrum is properly handled, with inclusion of the nonlinear damping in the center, driven current profiles (like those observed on Tore Supra by high-resolution HXR tomography [5]) can be satisfactorily explained by a single-pass absorption and even without an inclusion of toroidal effects (cf. Fig. 6).

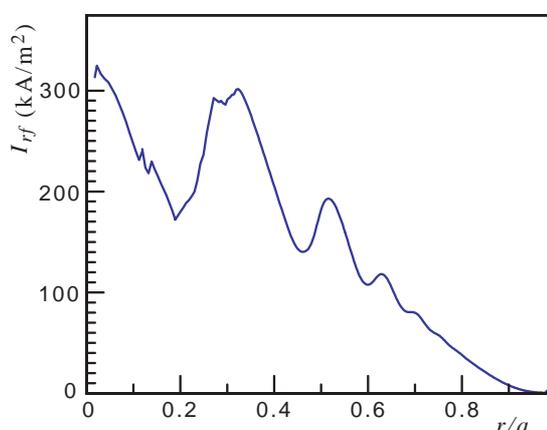


Fig. 6. LHCD simulation of a JET like case (cf. parameters in Fig.4),  $T_{e0}=5\text{keV}$ ,  $n_{e0}=5*10^{19}\text{m}^{-3}$ ,  $P_{in}=5\text{MW}$  (only  $k>0$  branch is considered). Single pass absorption.

### 4. Conclusions

For amplitudes of the parallel electric field of LH waves exceeding 1kV/cm, the diffusion coefficient found by direct numerical simulation starts to differ significantly from the quasilinear one: the range of interaction in velocity space ( $\Delta N_{\parallel}$ ) progressively extends with the electric field amplitude. This effect may be responsible for a strong absorption of waves in the central ( $r/a<0.2$ ) region of the plasma column. Further, we have suggested that in the outer part ( $r/a>0.2$ ), the radial profile of the absorbed power (and driven current) can be effectively controlled by the short-wavelength modes arising due to the spatial localization of the LH wave, if the inclination of the magnetic field lines in front of the grill is taken into account.

### References

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