ELECTRON ACCELERATION IN FRONT OF THE JET AND TORE SUPRA GRILLS

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1. Introduction

It is well known that thermal electrons can be accelerated in front of a lower hybrid (LH) waveguide array – grill – by the electric field of the slow LH wave [1]. This acceleration can result in strong parasitic wave absorption and in dangerous heat loads of the wall components magnetically connected with the grill. Moreover, the LH wave may also generate strong random electric fields at the plasma edge through the nonlinear process of parametric decay and the scattering of the LH wave from plasma density fluctuations [2]. This results in broadening of the pump signal and in the presence of sidebands, [3], and in enhancement of the electron acceleration [4].

In the present contribution, we explore theoretically this enhanced acceleration process for the JET and Tore Supra grills. The electron acceleration is studied namely in dependence on the number of powered waveguides, in an attempt to find the toroidal extent of the grill, for which the electron acceleration effects can be tolerated. Further, we show that the toroidally directed expulsion of fast electrons creates changes in the plasma bias in front of the grill.

2. Theoretical model and computational results

The governing equation of the electron motion is,

$$\frac{d^2z}{dt^2} = \frac{e}{m_e}\left[E_z^{\mathrm{LH}}(z,t) + E_z^{\mathrm{ST}}(z,t)\right]. \tag{1}$$

As in [4], the LH wave field is approximated by a sum of Fourier components for a simplified antenna configuration [1],

$$E_z^{\mathrm{LH}}(z,t) = \sum_{i=-j}^{i=j} a_m \sin(k_m z(t) - \omega t + \phi), \quad m = 1 + 4i, \tag{2}$$

and random field effects are modeled by wave trains with randomly varying phases,

$$E_z^{\mathrm{ST}}(z) = E_1 \sin(k_1 z(t) - \omega_1 t + \phi^{\mathrm{ST}}). \tag{3}$$

In the above equations, e and m_e are, respectively, the electron charge and mass, ω is the frequency of the LH rf field, ω_1 is the frequency of the random field, k_m is the wave vector of the LH wave, k_1 is the wave vector of the random field, ϕ is the LH wave phase, ϕ^{ST} is the randomly varying wave phase of the spontaneously excited field, E_0 is the amplitude of the LH electric field, E_1 is the amplitude of the random electric field.

Then, Eq. (1) has been solved numerically by carrying out a series of numerical experiments for various realizations of the random field. The injected electrons have randomly distributed velocities corresponding to the Maxwell distribution with the temperature of 25 eV. We explore in the computations the JET and Tore Supra LH grills with various number of sections powered, what corresponds to various number of 4 - 32 waveguides. The LH field amplitude is chosen as 5 kV/cm, what is the maximum value reached in the JET experiments. In the computations, we follow the acceleration of an electron ensemble of 1000 electrons, with initial positions equidistantly distributed in front of the powered part of the grill. We assumed in most of the computations that the frequency of the random field ω_1 is downshifted by 100 kHz with respect to ω, $k_1 = 3$ cm^{-1}, and ϕ^{ST} randomly varies after 3 periods of the LH wave. In many sets of additional computations, we also varied in a broad range these values: the qualitative conclusions were unchanged. Let us emphasize that we choose a small number of the launched modes, $j = 5$, in order to model a layer of plasma up to several mm from the grill mouth. Because of this small value of j, the average energy of accelerated electrons is rather small, when random fields effects are not included, cf. Fig. 1.
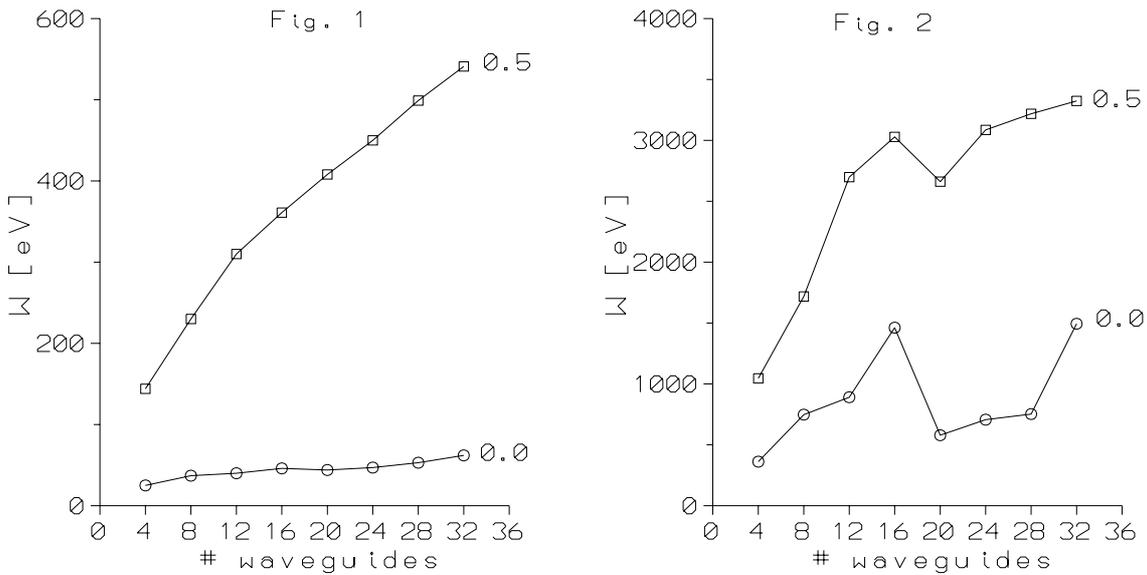

In **Fig. 1**, we see the final energy of the accelerated electrons, averaged over the electron ensemble, in dependence on the number of waveguides powered. The random field amplitude is zero (circles) and 0.5 kV/cm (squares). In **Fig. 2**(4), there is the final energy of the most accelerated electron from the electron ensemble, in dependence on the number of waveguides powered. The random field amplitude is zero (circles) and 0.5 kV/cm (squares). We see that, with random fields, the energy of the most accelerated electrons is about three time higher than without the random field effects. **Fig. 3**(7) shows the velocity distribution function of the ensemble of electrons after the acceleration, the number of powered waveguides is 4. The random field amplitude is zero (solid line) and 0.5 kV/cm (dashed). Finally, **Fig. 4**(14) shows

the same as in Fig. 3, but for 32 powered waveguides, i.e. for the full length of the JET and Tore Supra grills powered. We see that for zero random fields, the form of the velocity distribution function does not change significantly with the growing number of waveguides powered. On the contrary, when random fields effects are present, the velocity distribution function strongly broadens with the growing number of the waveguides powered. Further, by analysis of the traces and damage caused by fast electrons on the grill side limiters in the Tore Supra tokamak, we found the following indirect evidence for enhanced electron acceleration by random fields effects:

(i) the fast electrons traces on grill side limiters are radially deeper, than corresponds to the theory [1], and this larger radial extent of the traces may be explained by random field effects, [4];

(ii) the theory [1] without inclusion of random field effects predicts larger damage of the grill limiters on the other side, than it is experimentally observed, [6], while our theory with inclusion of the random field effects predicts larger damage on the same side as it is experimentally observed. This is in full agreement with dashed lines in Figs. 3 and 4, which show that more electrons accelerated in the direction of experimentally observed larger damage, when the effects of random fields are included.
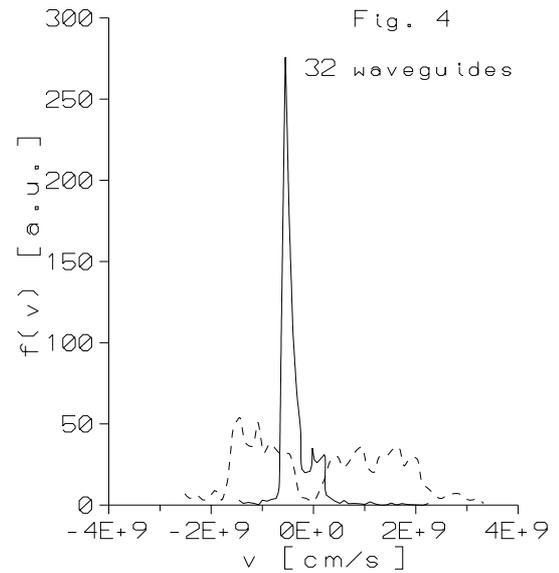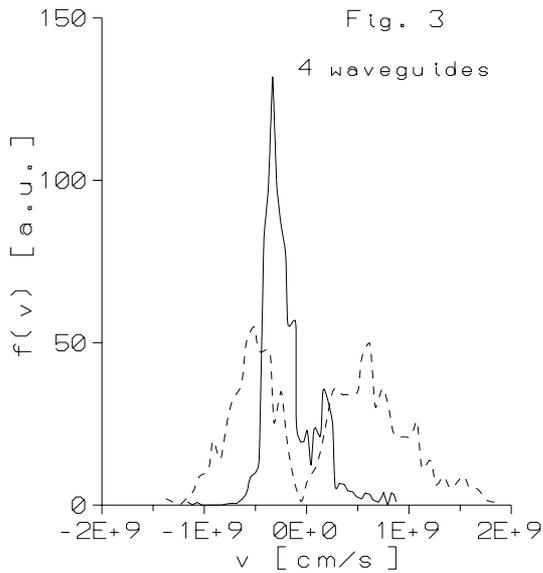
The presence of the random fields will have important consequences also for the plasma bias in front of the grill. To show this, let us consider two fluid equations for an equilibrium along the $z-$ coordinate, which arises due to the opposite actions of the plasma pressure gradient and the force arising because of the nonlinear electron acceleration.

$$0 = -ne\mathcal{E}_z - n\frac{\partial W}{\partial z} - T_e\frac{\partial n}{\partial z}, \qquad (4)$$

$$0 = ne\mathcal{E}_z - T_i\frac{\partial n}{\partial z}, \qquad (5)$$

where T_e and T_i are the boundary temperatures of electrons and ions, respectively, and W is the energy of the accelerated electrons. We obtain for the electric field, $\mathcal{E}_z$, for the potential U of this electric field, which is given by the equation $\mathcal{E}_z = -\partial U/\partial z$, and for the plasma density n, the following equations:

$$\mathcal{E}_z = \frac{1}{e}\frac{T_i}{T_e + T_i}\frac{\delta W}{\delta z}, \quad U = -\frac{T_i W}{e(T_e + T_i)}, \tag{6}$$

$$n = n_0 exp(-W/(T_e + T_i)). \tag{7}$$

As the acceleration radially varies in the direction into the plasma interior, also the potential U depends on radius: this leads to appearance of a strong radial electric field in front of the grill, $\mathcal{E}_r = -\partial U/\partial r$, resulting in a plasma vortex [5]. In the low temperature plasma in front of LH grill studied in [5], the electric field and the plasma vortex was arising because of the plasma temperature inhomogeneity. At high rf powers studied in our contribution, the electric field created by the energy of fast electrons is much higher that the electric field created by the small temperature difference [5]. The potential U can reach values of the order of 1000 Volts in front of the grill. The electron acceleration, eventually significantly enhanced by the presence of the random fields, results in a very complex chain of mutually connected effects: The higher is the acceleration, the higher is also the electric field. However, for large enough W, the plasma density significantly decreases, Eq. (7), which leads to consequent beneficial decrease of the dissipated energy in front of the grill. On the other hand, this density decrease may significantly enlarge the width of the evanescent layer and thus deteriorate the wave coupling. In reality, the density decrease will be less significant than described by the above equation (7), because of the plasma influx by the radial plasma transport and by the poloidal and toroidal plasma rotation. As also the temperature can be much higher in front of the grill, the value of the density decrease will be further reduced, i.e. the density will not decrease so strongly.

In conclusion, the key results of this study are that (i) the presence of strong spontaneously excited random electric fields makes almost impossible to avoid an excessive electron acceleration by decreasing the toroidal extent of the grill, and (ii) that the electron expulsion from the space in front of the grill creates strong toroidal and radial electric fields, together with variations in the plasma density.

Acknowledgment

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