WP17ER-PR(17) 18729

P Ghendrih et al.

Electron burst driven by near electric field effects of Lower Hybrid launchers

Preprint of Paper to be submitted for publication in
Contributions to Plasma Physics

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

draft

Electron burst driven by near electric field effects of Lower Hybrid launchers

L. Valade, A. Eckedhal, P. Ghendrih*, Y. Sarazin, Y. Asahi, H. Bufferand, E. Cascherra,[1] P. Di Cintio,[2] G. Ciraolo, G. Dif-Pradalier, P. Donnel, X. Garbet,[1] P.-A. Giorgi,[4,1] V. Grandgirard, G. Latu,[1] S. Lepri,[2] R. Levi,[3] A. Nouri,[4] and E. Serre[5]

[1] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*
[2] *Original Division, Original University, State name, Country name*
[3] *Original Division, Original University, State name, Country name*
[4] *Aix Marseille Univ, CNRS, Centrale Marseille, I2M,, Marseille, France*
[5] *Aix Marseille Univ, CNRS, Centrale Marseille, M2P2, Marseille, France*

Correspondence: *Philippe Ghendrih, IRFM-513, CEA-Cadarache, F-13108 Saint-Paul-lez-Durance, France. Email: philippe.ghendrih@cea.fr

Received September 2017; Revised -; Accepted -

Summary

Hot spot generation by Lower Hybrid (LH) launchers is found to be governed by a resonance in the plasma electric field response to the external drive. The kinetic analysis in 1D-1V in the direction parallel direction allows one to compute the amplification effect for small amplitude of the external drive. The resonant Lorentzian response distorts the distribution function with an island structure in the suprathermal part at the phase velocity of the external electrostatic drive. The non-linear features enhance the plasma response driving overlap effects between multiple waves at rather low amplitude. The onset of a plateau in the distribution function with extent up to one thermal velocity is already obtained when the standard overlap condition is achieved. The sensitivity of the resonance to plasma parameters and large variation of the amplification magnitude can compensate the fast radial decay of the small scale features generated by the LH launchers, which are responsible for the interaction with the cold electrons. This mechanism can trigger hot spot generation further in the Scrape-Off Layer than otherwise expected.

Keywords: Kinetic, Resonance, Island overlap, Hot electron plateau, Scrape-Off Layer, Lower Hybrid, Hot spot generation

1 Hot spots during Lower Hybrid operation

Lower Hybrid launchers installed in the SOL plasma generate near electric fields that can accelerate SOL electrons[1−3]. This mechanism is understood as the drive for hot spot generation on field lines connected to the launchers[4].

Experimental evidence supports the latter fact and theoretical analysis provides a qualitative understanding [5, 6]. Recent experimental analysis has underlined the importance of turbulence in the hot spot generation mechanism[7]. Open questions related to this problem are the optimum between density and distance in accelerating SOL electrons on the one hand and hot spot properties on the other hand[8, 9]. Regarding the latter, transport along the field line will determine the splitting between the ion and electron channel, and consequently the coupling to the sheath prior to deposition on a plasma facing component. The Lower Hybrid launchers generate waves in the Gigahertz range, typically from 2.5 GHz to 8 GHz in present experiments, the frequency increasing with the magnitude of the toroidal field of the device. In devices with strongly constrained access to the plasma, either high field devices as C-mod, or medium size devices with superconducting coils as WEST, wave heating and current drive must rely on waves since the conventional neutral beam heating is made difficult. In that framework, the so-called lower-hybrid system has several assets especially to sustain plasma current in long pulse operation. However, the occurrence of hot spots in regions connected to the launchers in the parallel direction, can have severe impact on the integrity of Plasma Facing Components, as documented quite early on ASDEX[1] and since in several other devices. While the LH frequency is well defined, the wave vector is determined by the mechanical structure of the LH wave guides and radial propagation properties into the plasma. The sharp jump between the electric field in the launchers material, limited to a skin depth, and that in the wave guide broadens significantly the spectrum compared to the useful wave range for interaction with hot core electrons[8].

The paper addresses the kinetic response of the electrons characterised by a resonance in Section 2. The impact on the generation of a plateau in the distribution function is described in Section 3. Implication and future work is addressed in the Conclusion and Discussion Section 4.

2 Resonant response of kinetic electrons to high frequency electric fields

The resonance between electrons and waves at the LH frequency, launched at 3.7 GHz in WEST, occurs for velocities $v/V_{the} = 4.84\ 10^{-1}/(k\lambda_D\sqrt{n/10^{18}\ m^{-3}})$ where V_{the} is the electron thermal velocity and $k\lambda_D$ the wave length of the wave normalised by the Debye length λ_D. At low density $n = 10^{18}\ m^{-3}$ and long wave length $k\lambda_D = 0.1$ the resonant electrons with the LH wave are therefore supra-thermal $v/V_{the} = 4.8$. In such a regime, electrons have small collisionality and must therefore be described kinetically. The appropriate description of the plasma is therefore kinetic completed by Maxwell equations to determine the electromagnetic field. Furthermore, for wave lengths comparable to the Debye scale, one cannot assume the quasineutral limit. To simplify the problem, we consider a single direction in position and velocity corresponding to the parallel motion of the electrons and restrict the problem to the electrostatic limit taking into account an external drive due to the LH launcher. In the simplest form, we thus address a 1D-1V kinetic model with the standard Vlasov-Poisson system. The Eulerian version, pseudo-spectral in both velocity and position directions, of the VOICE code is used in the present work. Some aspect of collisions can be taken into account by a Bhatnagar, Gross and Krook (BGK) restoring force towards the initial distribution function. With standard normalisation, plasma frequency for time, Debye length for length scales, reference density for distribution functions and thermal velocities for particle velocity, the two species set of equations is then:

$$\partial_t f_e + v\partial_x f_e + \partial_x\big(\phi + \phi_{ext}\big)\ \partial_v f_e \ = \ -\nu_e\big(f_e - f_{e,0}\big) \tag{1a}$$

$$\partial_t f_i + \sqrt{\frac{m_e}{m_i}}\Big(v\partial_x f_i - \partial_x\big(\phi + \phi_{ext}\big)\ \partial_v f_i\Big) \ = \ -\nu_i\big(f_i - f_{i,0}\big) \tag{1b}$$

$$\partial_x^2 \phi(x,t) \ = \ \int dv' f_e(x,v',t) - \int dv'' f_i(x,v'',t) \tag{1c}$$

Here $-\partial_x\phi_{ext}$ is the driving external electric field and ϕ the self-consistent electric potential induced in the plasma. Note that the velocity normalisation is different for each species so that the mass effect is not taken into account in the distribution functions but appears as the square root of the mass ratio in the evolution equation of the ion species, consistent with a much slower evolution rate for ions than for electrons. As a consequence, when addressing short time scale effects for the electrons, one can readily work in the frozen ion limit. In the literature, such externally driven Vlasov equation is also addressed as the KEEN wave[10, 11] (Kinetic Electron Electrostatic Nonlinear wave). However, the emphasis is then put on a second phase of self sustained self-organisation once the external drive is set back to zero.

The linear response, for small amplitude of ϕ_{ext}, has been analysed[8]. It is characterised by a resonant effect that can be seen in the amplitude of the electric potential generated by the plasma.

$$k^2\ \widehat{\phi}(\omega,k) \ = \ -\left(G_e(\omega/k,\nu_e/k,f_{e,0}) + G_i(\omega/k_i,\nu_i/k_i,f_{i,0})\right)\big(\widehat{\phi}(\omega,k) + \widehat{\phi}_{ext}(\omega,k)\big) \tag{2a}$$

This response is computed in Fourier space, $\widehat{\phi}(\omega,k)$ and $\widehat{\phi}_{ext}(\omega,k)$ being the Fourier transform of the external and self-consistent electric potentials. The response function $G_a(\omega/k_a,\nu_a/k_a,f_a)$ for species a is defined by:

$$G_a(\omega/k_a,\nu/k_a,f_a) \ = \ \int dv\ \frac{1}{v-\omega/k_a - i\ \nu/k_a}\Big(-\partial_v f_a(v)\Big) \tag{2b}$$

where $k_a = k/\sqrt{m_a/m_e}$. For Maxwellian distribution functions the function G_a is related to the plasma function. Because of the mass ratio effect, which appears via k_a, the ion contribution in (2a) is quite small and can be neglected. The amplitude ratio $A_G = |\widehat{\phi}(\omega,k)|/|\widehat{\phi}_{ext}(\omega,k)|$ is shown on figure (1) Left Hand Side (LHS). One recovers expected features, at high frequency $\omega \gg 1$, the electron do not respond to the external field while in the adiabatic regime the $\omega \ll 1$ there is an order 1 response. Near the plasma frequency one finds the resonant feature, with a Lorentzian-like

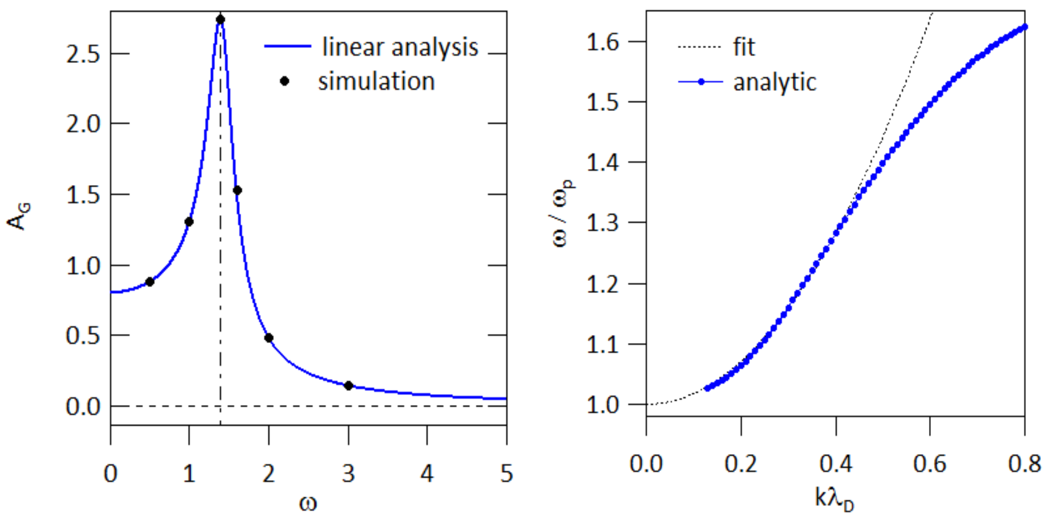

Figure 1: Left Hand side: Amplitude ratio A_G between the potential generated by the plasma and that of the external drive for $k = 0.5$ as a function of ω neglecting the ion contribution and for $\nu = 0$. The linear approximation yields the blue curve, VOICE simulation are indicated by the closed black circles. The VOICE simulation is performed with $|\widehat{\phi}_{ext}(\omega, k)| = 10^{-5}$. Right Hand Side: Dependence of the resonant pulsation ω on the wave vector k.

shape. As expected for a Lorentzian, the resonance is also characterised by a change of phase by pi between the low frequency regime, where the plasma electrons tend to screen the external electric potential, and the high frequency regime where the electric potential generated by the plasma tends to be in phase with the external drive. The VOICE simulation data (black closed circles in figure (1) LHS) is in very good agreement with the analytical formula. Using the latter, one can then investigate the dependence of the resonant pulsation ω on the wave vector k, figure (1) Right Hand Side (RHS). One finds an asymptotic quadratic dependence in k of $\omega - 1$ at small k as expected for Langmuir waves. This regime holds for increasing wave vector up to the normalised value $k \approx 0.4$.

Given the resonance value of ω and k, one readily defines the velocity of the the electrons in phase with the wave, $V_{res} = \omega/k$, where V_{res} is normalised by the electron thermal velocity. Given the rather small range of variations of ω, the resonant velocity behaves typically as $1/k$. Using the phase velocity as key-parameter, one can then analyse the change in peak half width $\delta\omega$ and gain magnitude A_G as a function of V_{res}, figure (2) LHS. One finds that the gain increases faster than exponential, but not quite as fast as an exponential of exponential (fit indicated by the dashed curve, adjusted to match the behaviour at low V_{res}. Conversely, the width of the resonance decreases faster than exponentially. These very rapid variations lead to extreme values of the gain and width, the latter corresponding to the limit of maximum computer resolution. This limitation is observed on figure (2) RHS where the product gain by half width is plotted versus the wave vector k. This product is nearly constant but for the points at lowest values of k, which depart from the smooth variation as the limit of $\delta\omega$ in numerical resolution is reached. The points with too narrow resonance features are removed from the subsequent plots.

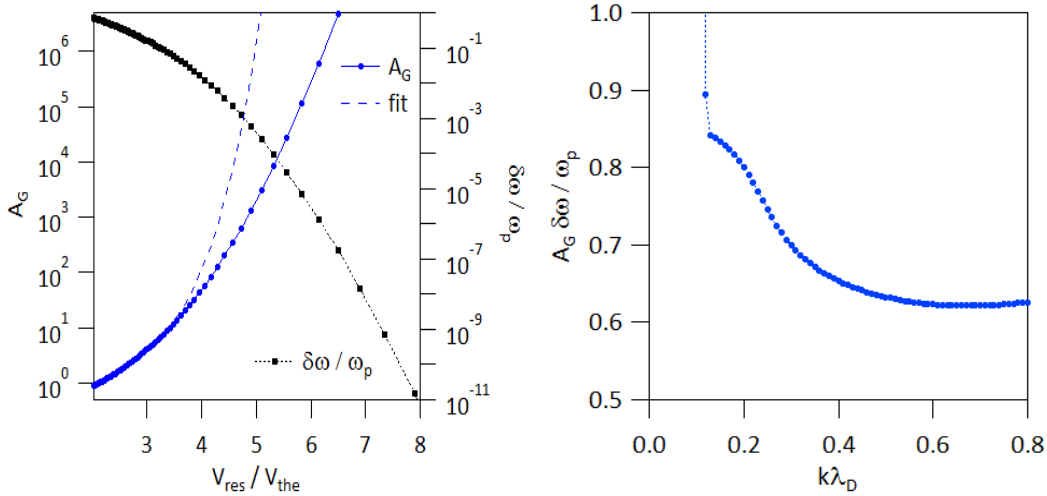

Figure 2: LHS: Variation of the amplitude ratio A_G between the potential generated by the plasma and that of the external drive and variation of the width of the resonance $\delta\omega$ for increasing phase velocities $V_{res} = \omega/k$, neglecting the ion contribution and for $\nu = 0$. RHS: Product of the resonance width and gain $A_G\ \delta\omega$.

3 Response to two waves

Unlike the case of Lower Hybrid where the generators determine a given frequency and where the finite size effects of the launcher enlarges the wave vector spectrum, we shall analyse here the response to waves with the same wave-vector but different pulsations. This approach is also quite suitable to use directly the chaos onset criteria known as the Chirikov parameter[12], which is the standard approach when estimating the onset of large scale chaos. The various modes are then characterised by their phase velocity, in practise determined by different pulsations and an island width, proportional to the square root of the amplitude of the electric potential, with no change in space periodicity. The argument inspired by the transition to chaos is to assume that when two neighbouring modes interact non-linearly (the condition being known as the overlap criterion, a plateau is created in the distribution function that corresponds to depleting the slow particle region and populate the fast particle region of the phase space. To handle this picture, the values that are considered are that of the external field, hence for two phase velocities of the interacting modes and the associated electric potentials that define the island widths. The very strong response of the electric potential generated by the collective behaviour of the plasma modifies quite significantly this picture since the width now must be computed taking into account the plasma response, for which the gain can be so important as to dwarf the width effect induced by the driving electric potential.

In order to recover a situation that is reminiscent of that of overlapping modes in phase space, we consider two modes that are symmetric with respect to the resonance. For this analysis we set $k = 1/3$ such that the resonance pulsation is $\omega_0 = 1.2$, phase velocity 3.6 and consider two modes with pulsation $\omega_1 = 1.1$ and $\omega_2 = 1.3$, hence with phase velocity 3.3 and 3.9 respectively. These being symmetric with respect to ω_0 have nearly equal linear

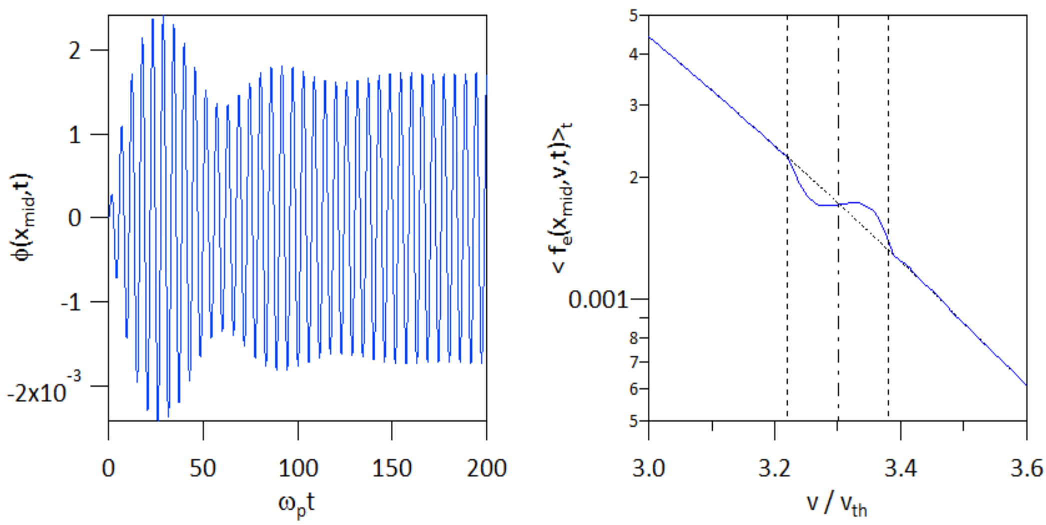

Figure 3: LHS: Trace of the electric potential generated by the plasma at position x_{mid} corresponding to the centre of the box. RHS: Variation with velocity of the time averaged distribution function at the same location.

amplification factor, very close to 4.2. The island width in velocity space is then equal to $2\sqrt{A_G\ \phi_{ext}}$, $\approx 4.1\sqrt{\phi_{ext}}$. From the linear analysis, the Chirikov overlap criterion, when the sum of the two island widths is equal to the separation between the islands, is thus expected to be reached for $\phi_{ext} = 0.5325\ 10^{-2}$.

To analyse the VOICE simulation output, let us first consider the case $\phi_{ext} = 0.04\ 10^{-2}$ and the single mode ω_1. The time trace of the potential response is shown on figure (3), LHS. The behaviour of the electric potential can be separated into a high frequency contribution at ω_1 and a low frequency envelop that also exhibits a time dependence, first a growth, then what could be damped oscillations. While the linear calculation allows one to determine the plasma response in terms of the electric potential, it is important to underline that one cannot compute a steady state solution for the distribution function f_e. Indeed, the particle-wave interaction drives a diverging filamentation process. This effect is smeared our by taking the time average once the main transient effects are ended, figure (3), RHS. For the latter, one finds that $\langle f_e \rangle$ does not depart from the initial Maxwellian (dashed curve) and that the departure from the Maxwellian is localised at the phase velocity of the mode (vertical dash-dot curve at $V_1 = 3.3$), and extends within the range determined by the island width (vertical dashed lines). The response for the distribution function takes the form of a localised flattening at the resonance. When no averaging is performed, one readily notices that the distribution function exhibits very fine structures localised in this region of phase space as well as a global oscillation at the driving frequency.

Comparing the cases with a drive at pulsation $\omega_1 = 1.1$ and $\omega_2 = 1.3$ with the same amplitude $\phi_{ext} = 0.04\ 10^{-2}$ indicates that δf_e is characterised by the same structure and extent of the perturbed region, in agreement with the same amplification of the electric potential due to the plasma response $4\ \phi_{ext} = 4 \times 0.04\ 10^{-2}$, in agreement with the linear analysis, shifted in velocity due to the difference in phase velocity but with a ratio in the amplitude of

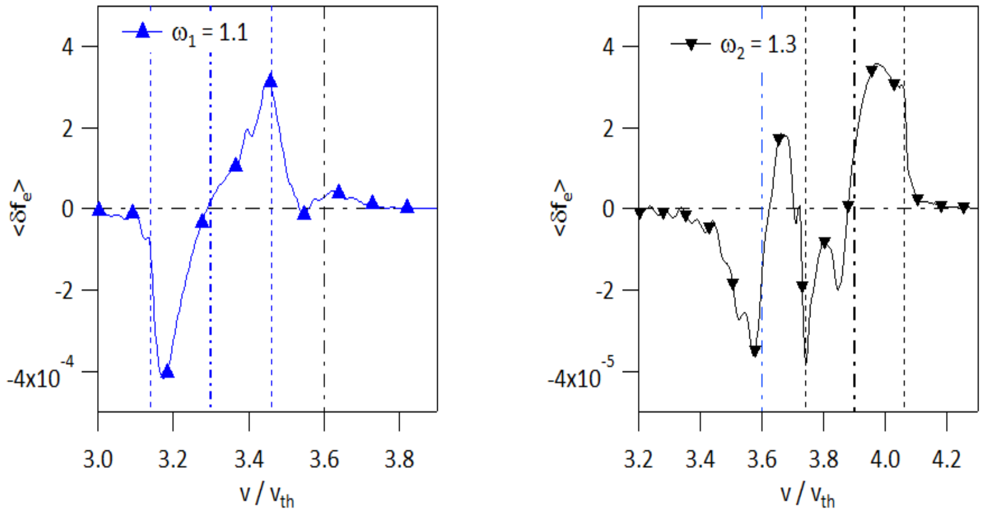

Figure 4: Time average of the response of the distribution function compared to the initial Maxwellian, $\langle \delta f_e \rangle_t$ for an external drive with amplitude 0.16 10^{-2} for two different simulations. Bold dash-dot vertical lines correspond to phase velocity of the modes, the thin dash-dot vertical lines indicate the phase velocity at pulsation ω_0 and the dashed vertical lines the extent as expected from the linear analysis. LHS: For pulsation $\omega_1 = 1.1$. RHS: For pulsation $\omega_2 = 1.3$.

$\langle \delta f_e \rangle_t$ of 3.9 while the ratio of the Maxwellian for the two values $V_1 = 3.3$ and $V_2 = 3.9$ is of the order 8.7. While one expects the same value for $\delta f_e / f_e$, one finds therefore that $\langle \delta f_e \rangle_t \, / \, \langle f_e \rangle_t$ varies by a factor of order 2. Increasing the amplitude of the drive to $\phi_{ext} = 0.16\ 10^{-2}$, and considering the simulation of either ω_1 or ω_2 indicates that the symmetry is shape of $\langle \delta f_e \rangle_t$ is lost. An important feature is that a response develops in the vicinity of $V_0 = \omega_0 / k$, beyond the island separatrix estimated on the basis of the linear analysis. This feature is far more pronounced for the drive at ω_2 than for ω_1. A tentative explanation is the relative location of the phase velocity of the mode, that of the resonance, V_0, and the bulk of the distribution function. Indeed, the Langmuir waves are essentially governed by the bulk of the distribution function (and is consequently recovered in the fluid approximation). These are coupled to the velocity layers neighbouring the phase velocity, which drives the amplification. For velocities larger than the phase velocity the response is small. As a consequence, when the plasma-wave interaction region is ahead of the resonance, the latter is weakly modified. Conversely, when the plasma-wave interaction region lies beyond the resonance, a response at the resonance V_0 can be generated because the detuning between the excited mode and the resonance is not too large, typically of order 0.1 in pulsation, but also because the amplification at the resonance is quite large ($A_G \approx 16$), in the present case 4 times larger than at the chosen phase velocity ($A_G \approx 4$).

Increasing the driving mode amplitude to reach the overlap threshold according to the linear analysis leads to the formation of plateau in the distribution function when the two modes ω_1 and ω_2 are present, figure (5) LHS. This is a signature on non-linear effects driving a mixing of the distribution function over a large region of velocity space,

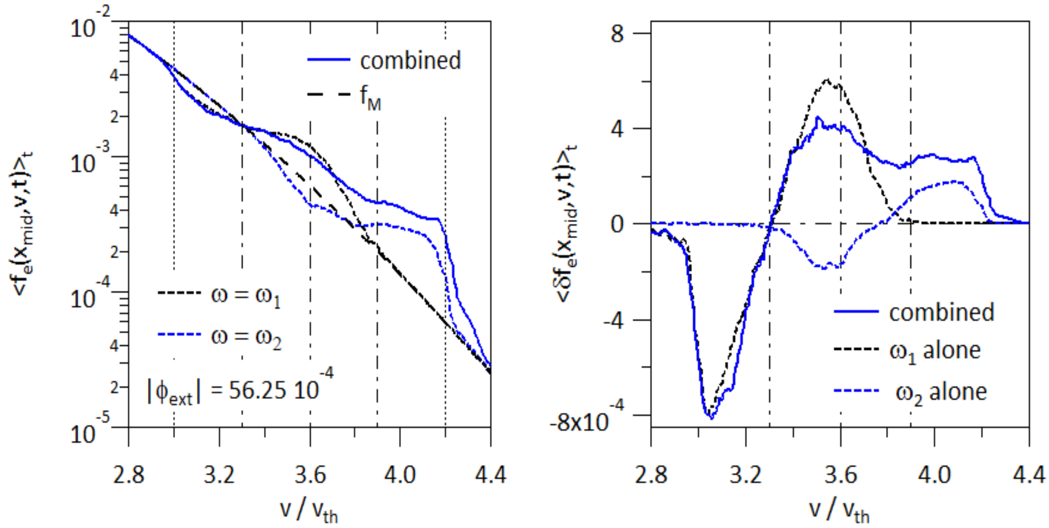

Figure 5: Time average of the response of the distribution function compared to the initial Maxwellian, $\langle \delta f_e \rangle_t$ for an external drive with amplitude 0.16 10^{-2} for two different simulations. Bold dash-dot vertical lines correspond to phase velocity of the modes, the thin dash-dot vertical lines indicate the phase velocity at pulsation ω_0 and the dashed vertical lines the extent as expected from the linear analysis. LHS: For pulsation $\omega_1 = 1.1$. RHS: For pulsation $\omega_2 = 1.3$.

here typically from 2.9 to 4.1 V_{the}. The plateau is built by depleting the low velocity region, typically from 2.9 to 3.1. These particles are accelerated by the electric field to higher velocities due to the combined effect of the two modes, thus generating the plateau in the distribution function. Although, the overall distortion of the distribution function is governed by non-linear effects, is appears to be rather well approximated as the superimposed results of the distortion due to the two modes when considered independently, figure (5) RHS. As already discussed for the case with lower amplitude drive, these cases with a single mode are already characterised by non-linear effects that spread the effect of either perturbations in the whole resonance region.

4 Discussion and conclusion

The interplay of electrons with Lower Hybrid waves in the edge plasma of magnetic confinement devices, addressed in the kinetic framework for the dynamics parallel to the magnetic field, is characterised at low external drive by a resonance. The electric field can be amplified by several orders of magnitude when resonance conditions are reached. This collective plasma response modifies the standard picture of island overlap that has been used when describing the generation of a fast electron tail. The non-linearity associated to that response tends to distort the distribution function in the phase space region towards the velocities associated to the largest amplification. This non-linear response leads to large scale velocity transport and the appearance of a plateau in the electron distribution function at lower external perturbation than expected.

In the present analysis, to facilitate the simulations, we have considered a fixed wave vector and tunable frequency. Regarding Lower Hybrid experiments, one has in fact a fixed frequency but broad and space dependent spectrum of wave vectors. The scaling dependence for the wave vectors are typically $k\lambda_D \leq 0.5/\sqrt{n/10^{18}m^{-3}}$. The small scale structures of the electric field are then responsible for the interaction with the SOL plasma. These high multi-polar components decay exponentially in the radial direction away from the LH launcher. While such a feature should locate the interaction region to the neighbourhood of the LH launcher, the more than exponential sensitivity of the resonance feature can overcome the geometrical screening of the small scales of the driving electric field. Compared to the reference resonance discussed in this paper with $k\lambda_D = 1/3$ and $v_\varphi/V_{the} = 3.6$ several orders of magnitude increase in the plasma response can be achieved by increasing the density and slightly lowering the electron temperature. The occurrence of cold plasma blobs in the far SOL, or divertor operation, can therefore create conditions for such highly non-linear behaviour.

Finally, it is too be underlined that these effects correspond to a wave-particle interaction in the supra-thermal tail of the electron distribution function. The corresponding density of accelerated electrons is quite small so that the expansion of the hot electrons only requires a small DC restoring electric field to drive a return current to quasi-neutrality. As a consequence, this effect should govern only a negligible acceleration of the ions. The LH hot spot generation in this regime would then be governed by collisionless electron heat transport due to the evaporation of the fast electrons. This point is to be further discussed in following papers.

Acknowledgements

This work has been carried out thanks to the support of the A*MIDEX project (ANR-11-IDEX-0001-02) funded by the "Investissements d'Avenir" French Government program, managed by the French National Research Agency (ANR). This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 for the projects ER-WP15/IPP-01, WP17-ENR-CEA-01 and WP17-ENR-CEA-03. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] The ASDEX-Team and T.E. Evans and J. Neuhauser and F. Leuterer and E.R. Müller, *Journal of Nuclear Materials* **1990**, *176-177*(*Supplement C*), 202 - 207.

[2] M. Goniche and D. Guilhem and P. Bibet and P. Froissard and X. Litaudon and G. Rey and J. Mailloux and Y. Demers and V. Fuchs and P. Jacquet and J.H. Harris and J.T. Hogan, *Nuclear Fusion* **1998**, *38*(*6*), 919.

[3] J. Hillairet and D. Voyer and A. Ekedahl and M. Goniche and M. Kazda and O. Meneghini and D. Milanesio and M. Preynas, *Nuclear Fusion* **2010**, *50(12)*, 125010.

[4] K M Rantamaki and V PetrZilka and P Andrew and I Coffey and A Ekedahl and K Erents and V Fuchs and M Goniche and G Granucci and E Joffrin and S J Karttunen and P Lomas and J Mailloux and M Mantsinen and M-L Mayoral and D C McDonald and J-M Noterdaeme and V Parail and A A Tuccillo and F Zacek and Contributors to the EFDA-JET Workprogramme, *Plasma Physics and Controlled Fusion* **2005**, *47(7)*, 1101.

[5] V. Fuchs and M. Goniche and Y. Demers and P. Jacquet and J. Mailloux, *Physics of Plasmas* **1996**, *3(11)*, 4023-4035.

[6] V. Fuchs and M. Goniche and Y. Demers and P. Jacquet and J. Mailloux, *Physics of Plasmas* **1997**, *4(4)*, 1176-1176.

[7] J.P. Gunn and V. Fuchs and V. PetrziÂŋlka and A. Ekedahl and N. Fedorczak and M. Goniche and J. Hillairet, *Nuclear Fusion* **2016**, *56(3)*, 036004.

[8] L. Valade and E. Caschera and P. Ghendrih and Y. Sarazin and A. Ekedahl, *Journal of Physics: Conference Series* **2016**, *775(1)*, 012015.

[9] Vaclav Petrzilka and Vladimir Fuchs and Jamie Gunn and Nicolas Fedorczak and Annika Ekedahl and Marc Goniche and Julien Hillairet and Pavol Pavlo, *Plasma Physics and Controlled Fusion* **2011**, *53(5)*, 054016.

[10] T. W. Johnston and Y. Tyshetskiy and A. Ghizzo and P. Bertrand, *Physics of Plasmas* **2009**, *16(4)*, 042105.

[11] Bedros Afeyan and Fernando Casas and Nicolas Crouseilles and Adila Dodhy and Erwan Faou and Michel Mehrenberger and Eric Sonnendrücker, *The European Physical Journal D* **2014**, *68(10)*, 295.

[12] Boris V Chirikov, *Physics Reports* **1979**, *52(5)*, 263 - 379.

How cite this article: L. Valade, A. Ekedahl, P. Ghendrih, Y. Sarazin, Y. Asahi, H. Bufferand, E. Cascherra, P. Di Cintio, G. Ciraolo, G. Dif-Pradalier, P. Donnel, X. Garbet, P.-A. Giorgi, V. Grandgirard, G. Latu, S. Lepri, R. Livi, A. Nouri, and E. Serre (201-), Electron burst driven by near electric field effects of Lower Hybrid launchers, *Contrib. Plasma Phys.*, *201-;-:-.*