Growth rates of fusion product driven lower hybrid drift instability

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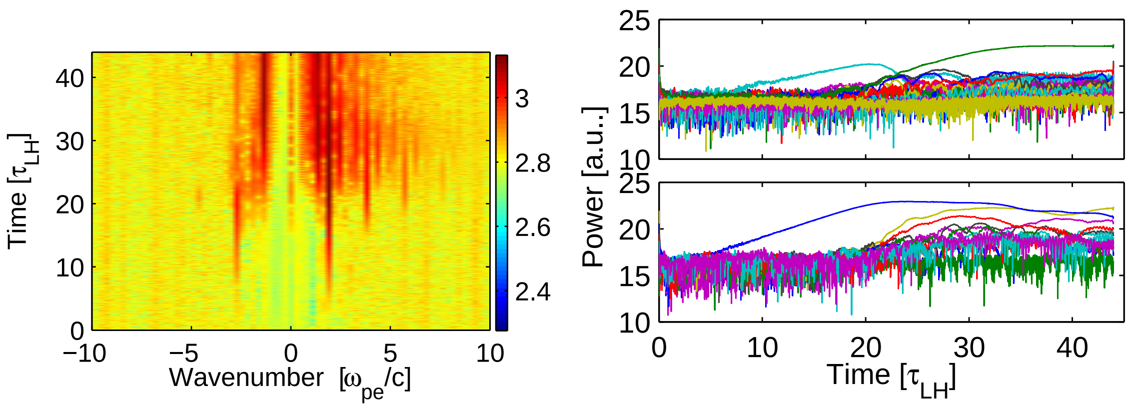
Abstract

We present particle-in-cell (PIC) simulations of minority energetic protons in a deuterium plasma, which undergo a collective instability. We focus on obliquely propagating modes under conditions appropriate to the outer mid-plane edge in a large tokamak, through which pass confined centrally born fusion products on banana orbits that have large radial excursions. A fully self-consistent electromagnetic relativistic PIC code representing all vector field quantities and particle velocities in three dimensions as functions of a single spatial dimension is used to model this situation by evolving the initial antiparallel travelling ring-beam distribution of 3MeV protons in a background 10keV Maxwellian deuterium plasma with realistic ion-electron mass ratio. Growth rates of the instability have been calculated for a range of oblique angles and proton-deuterium concentration ratios, using electric field and particle data.

Tokamak fusion reactors may benefit from enhanced energy transfer from confined energetic fusion products to fuel ions or to electrons by the "alpha channeling" effect. In the latter case, which is the focus of this paper, fusion product energy is channeled into directed electron motion to drive electron currents. Groundbreaking work by N.J. Fisch and J.-M. Rax [1] suggests that current drive efficiency can be doubled if only 20% of the energy carried by the energetic fusion products can be channeled to electron directed motion.

Current drive is achieved, at least in part, in many tokamaks by using external sources of lower hybrid (LH) frequency waves. Furthermore LH waves can be used to cool confined fusion products to amplify waves [2]. However, we suggest that the production of LH waves inside the tokamak via collective instabilities caused by population inversions of energetic particles can also accelerate electrons without the need of externally applied wave fields. It is already known that spatially localised inversions of the velocity distribution of fusion-born ions can arise due to the particle energy and pitch angle-dependent character of particle drift orbits. Ion cyclotron emission was excited in the outer mid-plane edge region of JET and TFTR as a consequence of the distinctive radial excursions [3] of the drift orbits of fusion products born with pitch angles just inside the trapped-passing boundary. In this case the fusion product distribution function was modelled by a ring travelling anti-parallel to the magnetic field [4] as given by $f_p = 1/u\delta(v_{||} - u)\delta(v_\perp - v_r)$. Here u is the velocity along the magnetic field and v_r is the perpendicular velocity of the ring. We use this model in this study, where minority 3MeV energetic protons adopt the role of the energetic fusion product, with a pitch angle of 135°, in a 10keV deuterium plasma with physical electron-ions mass ratios. A 1D3V, fully self-consistent, relativistic particle-in-cell code, epoch1d (based on PSC [5]), is used to evolve the single spatial dimension component and three velocity components of particle trajectories, and full 3D electromagnetic vector fields in the single spatial dimension in time.

The instability arises from coupling of protons to waves seeded by thermal noise of the background deuterium-electron plasma. The protons couple to the oblique normal mode waves of the system; these are on the branch that forms a surface between the lower extraordinary wave and the whistler wave in $\omega, k_\perp, k_{||}$ space of the cold electron-deuteron dispersion relation.



(a) (b)

Figure 1: (a) Power as a function of time of $E_x(k)$. Color denotes wave energy in arbitrary units and wavenumber in inverse skin depths. (b) Top (bottom) panel: power as a function of time in wavemodes of $E_x(k)$ of modes with $k < 0$ ($k > 0$). Time in units of the lower hybrid period.

The instability causes growth of waves in the electric field along the simulation domain E_x. Fast Fourier transforms (FFT) of $E_x(x,t)$ produces $E_x(k,\omega)$, which can be decomposed into its Fourier components: $E_x(\pm k, \pm\omega)$ and $E_x(\pm k, \mp\omega)$, which hold the forward and backward travelling waves respectively. Inverse FFTs of these fields by integrating over ω give the $k <$

0 and $k > 0$ fields $E_x(k < 0,t)$ and $E_x(k > 0,t)$. Hence, we see the growth of waves in time as a function of **k** and not $|k|$. An example of such a dataset is shown in figure 1(a). The k-components of $E_x(k < 0,t)$ ($E_x(k > 0,t)$) are shown in the top (bottom) panel in figure 1(b). A natural log of the power ($\propto E_x(k,t)^2$) against time for all wavemodes reveals the fastest mode from which a gradient can be taken and a growth rate calculated. These electric field growth rates are shown by the black traces in figure 2.

The growth rates of the instability are obtained for a range of proton-deuteron concentration ratios in the range $10^{-3} \leq n_p/n_d \leq 10^1$ while the applied magnetic field of 3T is directed at angles in the range $80^\circ \leq \theta \leq 90^\circ$ to the spatial coordinate. Growth rates from particles are calculated by two methods. Electrons and, to a lesser extent, deuterons absorb energy and the rate of energy absorption (c.f. growth rate) is calculated by taking the gradient of the log_e of species kinetic energy in time for the electrons and deuterons. A similar calculation for protons would be redundant for energy conservation reasons. A measure of the rate of change in the proton distribution function is calculated by summing over the proton population of the modulus of the deviation in energy from the initial value, which we call fluctuation energy. This captures the subtle changes in proton energy in the early times of the simulations and the growth rates obtained from these values are plotted for protons only in figure 2.

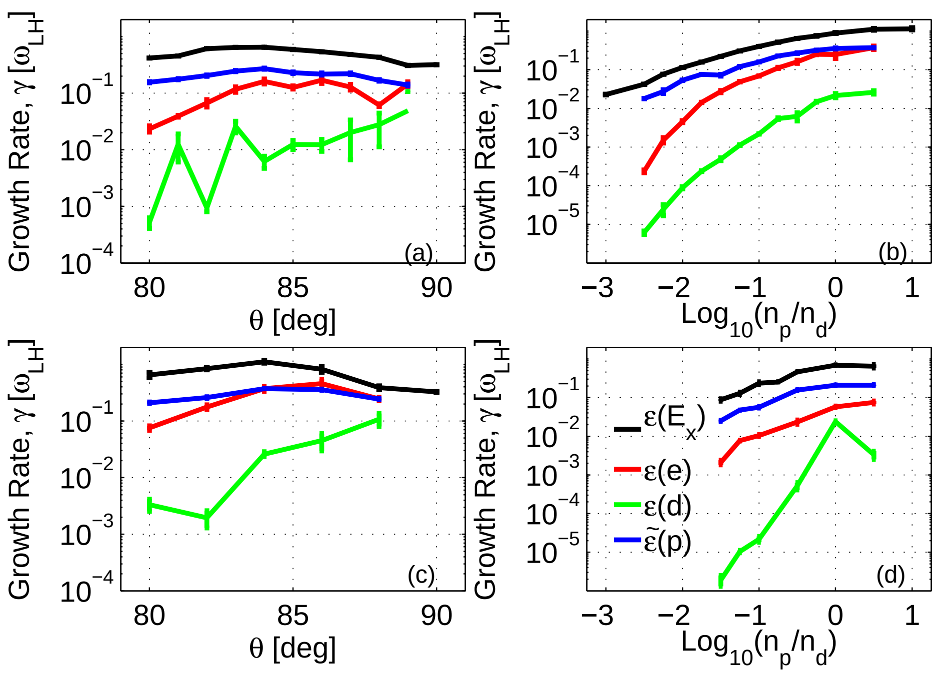


Figure 2: Growth rates obtained from: electric field energy $\varepsilon(E_x)$; proton fluctuation energy $\tilde{\varepsilon}(p)$; and electron and deuteron kinetic energy $\varepsilon(e,d)$ vs: (a), θ with $n_p/n_d = 10^{-0.5}$; (b), n_p/n_d with $\theta = 84^o$; (c), θ with $n_p/n_d = 10^{0.5}$; (d), n_p/n_d with $\theta = 80^o$.

We find that a maximum in growth rate exists at around 84° for both the concentration ratios held fixed while angle of propagation is varied. Furthermore we find that the electron energy absorption rate falls off more rapidly with decreasing concentration ratio than the electric field growth rate for both $\theta = 80^\circ$ and $\theta = 84^\circ$.

Critically, this work presents electric field growth rates of the fastest growing mode. However, the fastest growing modes that couple most strongly to the electrons. Calculation of growth rates of the strongest coupled modes would be a logical next step to make. These data would complement the electron energy absorption rates. In this initial study we have focused on a limited range of parameters relevant to large aspect ratio tokamaks and a full study where an optimised regime for LHDI induced electron current drive is yet to be untertaken. Furthermore, the extension of this work to a 2D3V code would be a natural progression. Despite working in a regime where the effect of energetic ion collisions are negligible, the effect of collisions could be included into the PIC formalism. To model collisions the ring-beam distribution function can be amended to include finite width in $v_{\|}$ and $v_{\perp}$.

References

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