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Novel Tridimensional Processes in Fusion Burning Plasmas and Gained Innovative Perspectives

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A novel understanding of the collective processes that can emerge in fusion burning plasmas is shown to generate new perspectives for meaningful experiments that can be undertaken in the near term. In particular "Di-ballooning"modes, that propagate only in the toroidal direction and are standing in both the poloidal and the radial direction, are identified.
The poloidal profiles of these modes are shown to be conditioned in a new way [1] by relevant mode-particle resonant interactions given that purely oscillatory ballooning modes can be treated as a composition of travelling waves with the same frequency (about that of a compressional Alfvén wave) but different phase velocities.
We refer to the simplest toroidal confinement configuration represented by $\mathbf{B} \simeq B_0 \left[1 - (r/R_0)\cos\theta\right] \mathbf{e}_\varphi + B_\theta\left(r\right)\mathbf{e}_\theta$. Using the "disconnected" mode approximation [2] the modes of interest are described by density perturbations of the form
$\hat{n} \simeq \tilde{n}\left(r - r_0, \theta\right) \exp\left\{-i\omega t + in^0\left[\varphi - q\left(r\right)\theta\right] + in^0\left[q\left(r\right) - q_0\right] F\left(\theta\right)\right\}$,
where $F(\theta)$ is a step-function that restores the periodicity in θ of $\tilde{n}$ and is localized around $\theta = \pi$. Thus, for $-\pi < \theta < \pi$, we may consider
$\hat{n} \simeq \tilde{n}\left(r - r_0, \theta\right) \exp\left\{-i\omega t + in^0\left[\varphi - q\left(r\right)\theta\right]\right\}$,
where $\tilde{n}\left(r - r_0, \theta\right)$ is found to be localized in both $\left(r - r_0\right)$ and θ. In particular
$\tilde{n}\left(r - r_0, \theta\right) \simeq \tilde{n}^0 \exp\left\{-\frac{1}{2}\left(\frac{r - r_0}{\Delta_r}\right)^2 - \frac{1}{2}\left(\frac{l}{\Delta_l}\right)^2\right\}$,
where, for $dl = R_0 q_0 d\theta$, l indicates a distance along a field line. Clearly, $\exp\left[-i\omega t - l^2/\left(2\Delta_l^2\right)\right] \propto \int dk_l \exp\left(-\Delta_l^2 k_l^2/2\right) \exp\left[-i\left(\omega t - k_l l\right)\right]$ showing the decomposition of a ballooning mode into propagating waves. When wave-particle interactions are considered, the "recomposed" mode amplitude is proportional to
$\int dk_l \exp\left[-\Delta_l^2 k_l^2/2 - \gamma_D\left(|k_l|\right) t + ik_l l\right]$,
referring for simplicity to a particle velocity distribution that is isotropic and that all interactions involve a damping. A crude model, for $\gamma_D^2 \ll \left(\mathrm{Re}\omega\right)^2$, is $\gamma_D \equiv \bar{\bar{\gamma}} k_l^2/k_0^2$ and leads to find a mode amplitude proportional to
$\frac{\Delta_l}{\Delta_{eff}} \exp\left(-\frac{l^2}{2\Delta_{eff}^2}\right)$,
where $\Delta_{eff}^2 \equiv \Delta_l^2 + 2\bar{\bar{\gamma}} t/k_0^2$. That is, the mode width increases with time and its height decreases. An accurate numerical analysis of the mode profile has been carried out involving the relevant Landau damping with a Maxwellian ion distribution [3] and it has confirmed qualitatively the results of our "crude model". Another crude model involving resonances with two ion distributions with different peaks has been formulated, while a detailed numerical analysis is aimed at improving on it. The choice of this model involving damping and growth rates is based on the requirement that the resulting mode profile, in the l- variable, is compatible with the dispersion equation that was derived originally from macroscopic (two-fluid) equations.
In fact, these modes can interact with both the high energy population of fusion products and the tail of the reacting nuclei distributions. Thus a "spontaneous" transfer of energy from the reaction products to these nuclei can occur without a direct heating of the electron population and minimizing the losses (bremsstrahlung and cyclotron emission, transverse thermal energy transport, etc.) associated with it. The novel perspectives that the present investigation offers is that the considered bypassing process does not require sources of injected electromagnetic waves with extreme power levels. Injected RF waves with moderate power can be envisioned to couple with the analyzed ballooning modes with the purpose to modulate their amplitudes, if necessary.
Relevant experimental observations occurring in a different confinement configuration than that considered here is reported in Ref. [4]. These involve a drastic increase of the rate of emission of neutrons produced by D-D reactions resulting from the injection, into a deuterium plasma, of non-reacting protons through a neutral hydrogen beam injection (15 keV) system.
Confirming that approaching ignition conditions involves tridimensional processes, a thermonuclear heating of the electron population either by collisional effects or by mode-particle resonant interactions is shown to have an important effect on radially extended or localized modes that involve symmetric and antisymmetric [5] magnetic reconnection. High temperature regimes with relatively large longitudinal electron thermal conductivities and the presence of a local electron temperature gradient are considered. Then a pair of singularities of the perturbed electron temperature associated with the rate of (thermonuclear) heating of the

electron population are found to emerge in the vicinity of the rational surfaces around which magnetic reconnection can take place. In particular, the analysis of the perturbed electron temperature profile requires consideration of four radial asymptotic regions: an outer ideal MHD region (with scale distance r_J defined by the gradient of the longitudinal current density), a thermal region (with scale distance δ_T related to the ratio of the transverse (to the magnetic field) to the longitudinal thermal conductivity), a thermonuclear region (with scale distance δ_F related to the rate of thermonuclear heating of the electron population), and the innermost magnetic reconnection region δ_m. While in the well-known theory of tearing modes the antisymmetric component of the reconnected radial field is frequently not considered, as it does not contribute to the mode growth rate, in the analysis of the perturbed electron temperature evolution it plays a significant role.
The conclusion is that the conditions needed to reach meaningful fusion burning conditions should be different from those that are usually assumed, which are based on ignoring the presence of collective modes and the induced deformations of the relevant particle distributions in phase space.
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