Mitigation of Electromagnetic Instabilities in Fast Ignition Scenario

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We address the issues of collective stopping for intense relativistic electron beams (REB) used to selectively ignite precompressed deuterium + tritium (DT) fuels. We investigate the subtle interplay of electron collisions in target as well as in beam plasmas with quasi-linear electromagnetic growth rates. Intrabeam scattering is found effective in taming those instabilities, in particular for high transverse temperatures.

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1 Introduction

The interaction processes involved in the stopping of intense relativistic electron beams (REB) for the Fast Ignition Scenario (FIS) \([11,6,5,9]\) are monitored by a competition between collisionally dominated stopping mechanisms \([3]\) and nearly instantaneous beam energy loss due to fast rising electromagnetic instabilities \([1,2]\).

Let us now consider a current neutral beam-plasma system. The relativistic REB propagates with the velocity \(v_b^d\) and the plasma return current flows with \(v_p^d\). It is reasonable to assume that an electromagnetic mode has \(k\) normal to \(v_b^d\), perturbed electric field \(E\) parallel to \(v_b^d\), and perturbed magnetic field \(B\) normal to both \(v_b^d\) and \(E\). So, the total asymmetric \(f_0\) consists of non-relativistic background electrons and relativistic beam electrons \([10]\)

\[
f_0(p) = \frac{n_p}{2\pi m(\theta_x^p\theta_y^p)^{1/2}} \exp \left( -\frac{(p_x + p_x^b)^2}{2m\theta_x^p} - \frac{p_y^2}{2m\theta_y^p} \right)
\]

\[+ \frac{n_p}{2\pi m\gamma(\theta_x^p\theta_y^p)^{1/2}} \exp \left( -\frac{(p_x + p_x^b)^2}{2m\gamma\theta_x^p} - \frac{p_y^2}{2m\gamma\theta_y^p} \right)
\]

(1)

Here \(\theta_x, \theta_y\) are the temperature components parallel to the x and y directions, \(p_d\) is the drift momentum, superscripts p and b represents the plasma and the beam electron, respectively. From the linearized Vlasov equation with collision term \(\nu\) and linearized Maxwell’s equations we get linear dispersion relations for a purely growing mode. Collision term \(\nu = \nu_p + \nu_b\) is explained as a superposition of target and beam plasma contributions. In Eq. (1) drift momentum should read as

\[
p_d^b = m\gamma v_b \quad \text{and} \quad p_d^p = p_d^b n_b \frac{n_b}{\gamma n_p},
\]

(2)

in terms of \(\gamma = (1 - v_b^2/c^2)^{-1/2}\) and \(v_b\), beam velocity.

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2 Dispersion relations

Our analytical scheme could be implemented in the most transparent fashion through a string of dimensionless variables and parameters. Weibel Electromagnetic Instability (WEI) growth rates and wave number obviously take then the form (ω_p is the plasma frequency)

\[ x = \frac{\delta}{\omega_p} \quad \text{and} \quad y = \frac{k_C}{\omega_p} \]  

(3)

with corresponding normalized collision frequencies

\[ n_1 = \frac{\nu_b}{\omega_p} \quad \text{and} \quad n = \frac{\nu_p}{\omega_p} \]  

(4)

Transverse velocities play a pivotal role in the WEI growth rate analysis. They read as

\[ v_1 = \frac{v^{b}_b}{c} \quad \text{and} \quad v_2 = \frac{v^{p}_y}{c} \]  

(5)

altogether with beam target density ratio

\[ r = \frac{n_b}{\gamma n_p} \]  

(6)

With these expressions, one can then specialize the evaluation of the plasma Fried-Conte dielectric function through suitable asymptotic expansions. This procedure then leads to four typical beam-target combinations based on the asymmetry parameters,

\[ A = \frac{\theta^p_x + \frac{p^2_x}{m}}{\theta^b_y}, \quad B = \frac{\theta^b_x + \frac{p^2_x}{m \gamma}}{\theta^b_y} \]  

(7)

3 Quasi-linear extension (QL)

Up to now we restricted to a linear WEI analysis. More accurate growth rates (GR) are expected by retaining particle motion in target plasma under local electric and magnetic fields. Sophisticated treatments going back to Dupree-Weinstock analysis [8] of so-called weak turbulence. In the present context these considerations lead us to complete definitions of A and B with

\[ A' = \frac{A T_p}{T_p + X D}, \quad B' = \frac{B T_b}{T_b + X D} \]  

(8)

where X denotes the largest solution of

\[ \begin{align*} 
(1 + r)X^4 & - \left[ r \frac{p^2_x}{(m \gamma)^2} + \frac{\theta^p_x p^2_x}{m m^2} - (1 + r) \left( \frac{\theta^p_p}{m} + \frac{\theta^p_p}{m \gamma} \right) \right] X^2 \\
& - \left[ r \frac{p^2_x}{(m \gamma)^2} + \frac{\theta^p_x}{m} + \left( \frac{\theta^p_x}{m} + \frac{p^2_x}{m^2} \right) \frac{\theta^b_y}{m} - (1 + r) \frac{\theta^p_p \theta^p_p}{m m \gamma} \right] = 0. 
\end{align*} \]  

(9)

and \( D = 511r(1-\gamma^{-2}) \). \( T_p \) and \( T_b \) are in keV.
4 Growth Rates (GR)

A typical REB target interaction of FIS interest is depicted on Figs. 1(a,b) with linear (L) and quasi-linear (QL) growth rates (GR). Linear GR are seen monotonously increasing for any collisionality \( n \) (target) or \( n_1 \) (beam) in the whole wavelength range. Quasi-linear GR turn negative as soon as \( kc/\omega_p \geq 0.6 \). It has to be appreciated that retaining collisions only in target plasma enhance GR at \( kc/\omega_p \leq 0.6 \), while restricting them to beam plasma produces the lowest GR. Keeping them in target and beam plasmas still keep the growth rate within acceptable values for permitting an efficient target ignition through beam collisional stopping. Further results are reported on Figs. 1(c,d) for cooler beam and target temperature \( (T_b = T_p = 100 \text{ eV}) \). Other parameters remaining unchanged, collisional contributions \( n \) and \( n_1 \) are thus expected stronger. Indeed, quasi-linear GR (Figs. 1(b,d)) with nonzero \( n \) and \( n_1 \) are manifestly the lowest.

Increasing significantly the target plasma density and the beam temperature (Figs. 2) make negligible the intrabeam collision term fulfilling now \( n_1 << n \). The very high \( T_b \) value, in MeV range erases very efficiently any positive growth rate, thus featuring a beam-target interaction stable at any plasma wave number \( k \).
Fig. 2  Same captions as in Figs. 1 for higher target densities and beam temperature with negligible intrabeam scattering.
(a) $n_p = 10^{25}$ e·cm$^{-3}$, $T_p = 0.5$ keV with $T_b = 500$ keV, (b) $n_p = 10^{24}$ e·cm$^{-3}$, $T_p = 1$ keV with $T_b = 1$ MeV.

References