

Mitigation of electromagnetic instabilities in fast ignition scenario

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Abstract

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.

Keywords: Collisions; Fast Ignition; Quasi-linear theory; Weibel instability

1. Introduction

The interaction processes involved in the stopping of intense relativistic electron beams (REB) for the fast ignition scenario (FIS) (Tabak *et al.*, 1994; Deutsch, 2003a, 2003b, 2004; Mulser & Bauer, 2004) are monitored by a competition between collisionally dominated stopping mechanisms (Deutsch *et al.*, 1996), and nearly instantaneous beam energy loss due to fast rising electromagnetic instabilities (Bret *et al.*, 2005, 2004).

Let us now consider a current neutral beam-plasma system. The relativistic REB propagates with the velocity v_d^b and the plasma return current flows with v_d^p . It is reasonable to assume that an electromagnetic mode has k normal to v_d^b , perturbed electric field E parallel to v_d^b , and perturbed magnetic field B normal to both v_d^b and E . So, the total asymmetric f_0 consists of nonrelativistic background electrons and relativistic beam electrons (Okada & Niu, 1980)

$$f_0(\vec{p}) = \frac{n_p}{2\pi m(\theta_x^p \theta_y^p)^{1/2}} \exp\left(-\frac{(p_x + p_d^p)^2}{2m\theta_x^p} - \frac{p_y^2}{2m\theta_y^p}\right) + \frac{n_b}{2\pi m\gamma(\theta_x^b \theta_y^b)^{1/2}} \exp\left(-\frac{(p_x + p_d^b)^2}{2m\gamma\theta_x^b} - \frac{p_y^2}{2m\gamma\theta_y^b}\right). \quad (1)$$

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Here θ_x and θ_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 n and linearized Maxwell's equations, we get linear dispersion relations for a purely growing mode. Collision term $n = n_p + n_b$ is explained as a superposition of target and beam plasma contributions. In Eq. (1) the drift momentum should read as

$$p_d^b = m\gamma v_b \quad \text{and} \quad p_d^p = p_d^b \frac{n_b}{\gamma n_p}, \quad (2)$$

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

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)

$$x = \frac{\delta}{\omega_p} \quad \text{and} \quad y = \frac{kc}{\omega_p}, \quad (3)$$

with corresponding normalized collision frequencies

$$n_1 = \frac{n_b}{\omega_p} \quad \text{and} \quad n = \frac{n_p}{\omega_p}. \quad (4)$$

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

$$v_1 = \frac{v_y^b}{c} \text{ and } v_2 = \frac{v_y^p}{c}, \tag{5}$$

altogether with beam target density ratio

$$r = \frac{n_b}{\gamma n_p}. \tag{6}$$

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,

$$A = \frac{\theta_x^p + p_d^{p2}/m}{\theta_y^p}, B = \frac{\theta_x^b + p_d^{b2}/m\gamma}{\theta_y^b}. \tag{7}$$

3. QUASI-LINEAR EXTENSIONS (QL)

Up to now we were 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 (Kono & Ichikawa, 1973) of so-called weak turbulence. In the present context these

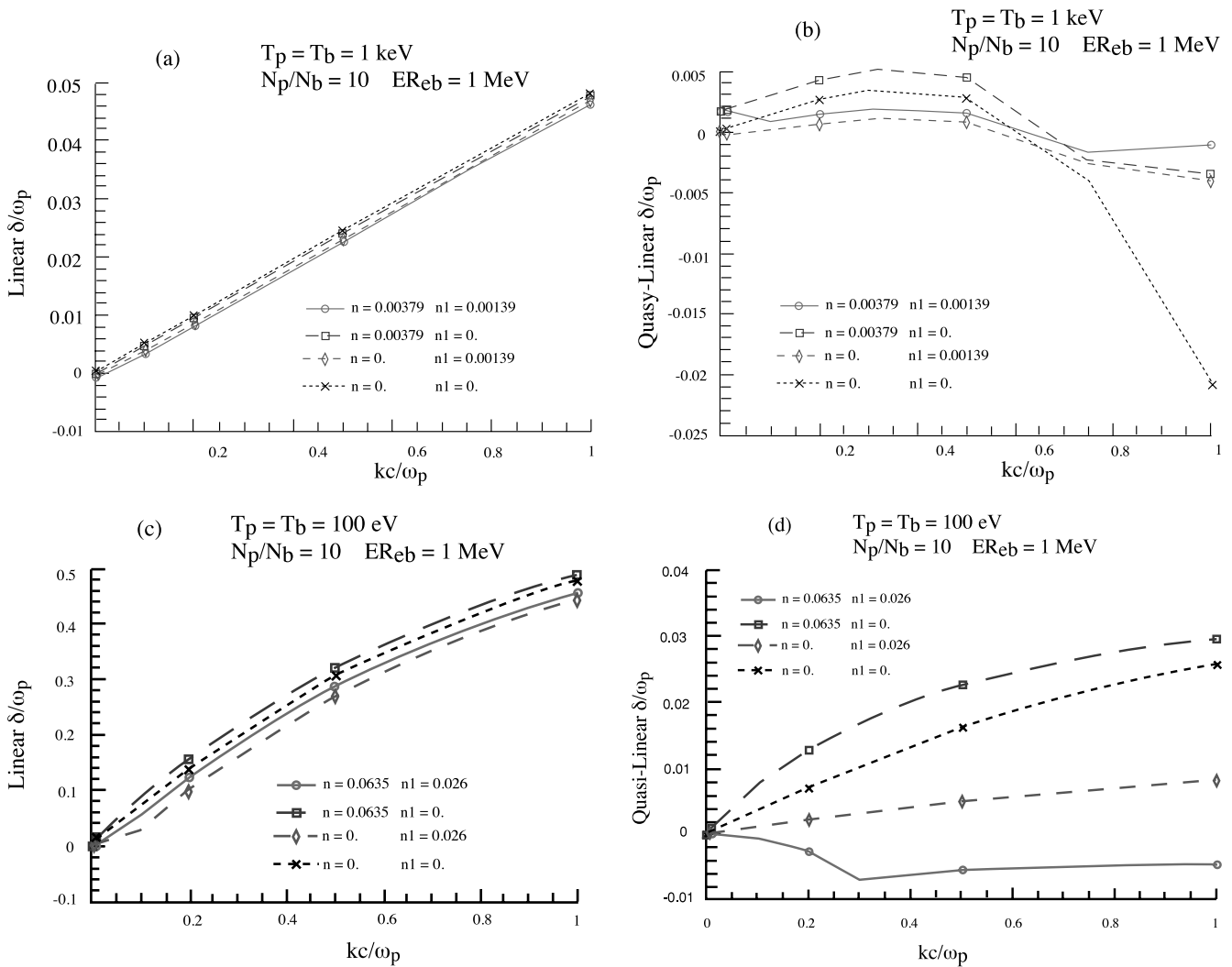


Fig. 1. Linear (a) and quasi-linear (b) electromagnetic growth rates for 1 MeV REB with $n_b = 10^{22} \text{ e-cm}^{-3}$ and $T_b = 1 \text{ keV}$ impinging an electron target with $n_p = 10 n_b$ and $T_p = 1 \text{ keV}$. Curves are parametrized w.r.t to normalized collision frequencies n (target) and n_1 (beam). (c) and (d): same plots for cooler beam and target temperature with $T_b = T_p = 100 \text{ eV}$.

considerations lead us to complete definitions of A and B with

$$A' = \frac{AT_p}{T_p + XD}, \quad B' = \frac{BT_b}{T_b + XD}, \quad (8)$$

where X denotes the largest solution of

$$(1+r)X^4 - \left[r \frac{p_d^{b2}}{(m\gamma)^2} + \frac{\theta_x^p}{m} + \frac{p_d^{p2}}{m^2} - (1+r) \left(\frac{\theta_y^p}{m} + \frac{\theta_y^b}{m\gamma} \right) \right] X^2 - \left[r \frac{p_d^{b2}}{(m\gamma)^2} + \frac{\theta_x^p}{m} + \left(\frac{\theta_x^p}{m} + \frac{p_d^{p2}}{m^2} \right) \frac{\theta_y^b}{m\gamma} - (1+r) \frac{\theta_y^p \theta_y^b}{m \ m\gamma} \right] = 0, \quad (9)$$

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 in Figs. 1a and 1b 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 the 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. 1c and 1d for cooler beam and target temperature ($T_b = T_p = 100$ eV). Other parameters remaining unchanged, collisional contributions n and n_1 are thus expected stronger. Indeed, quasi-linear GR (Figs. 1b and 1d) with nonzero n and n_1 are manifestly the lowest.

Increasing significantly the target plasma density and the beam temperature (Fig. 2) make negligible the intrabeam collision term fulfilling now $n_1 \ll n$. 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 .

These preliminary results highlight the cone-angle scenario (Kodama, 2001; Deutsch, 2003a, 2003b) with laser produced electrons close to highest density core in precompressed DT fuel.

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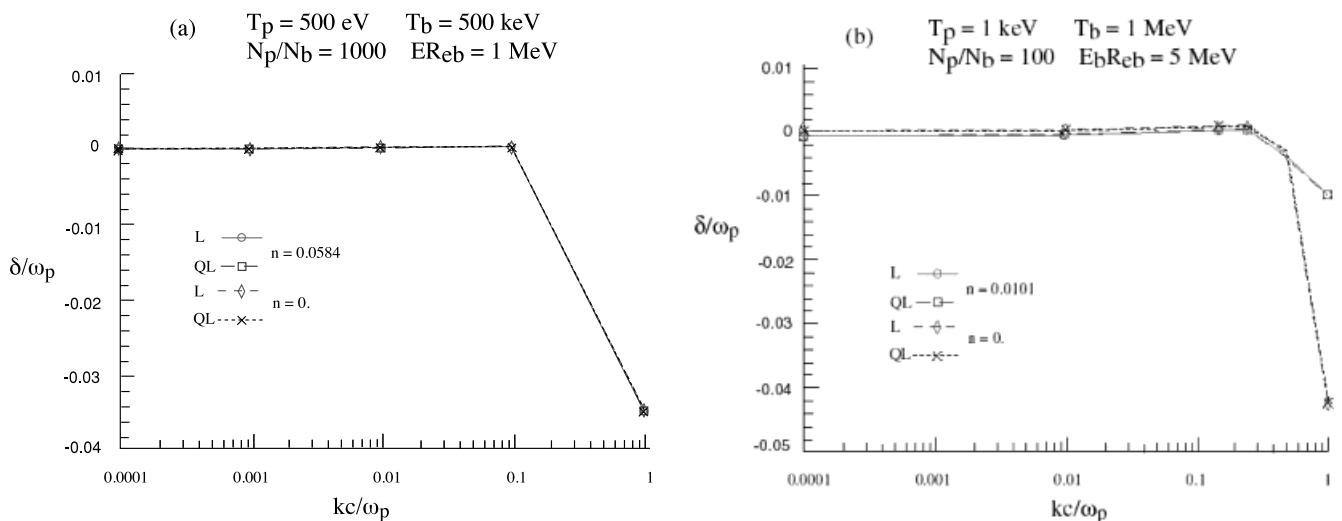


Fig. 2. Same captions as in Figs. 1 for higher target densities and beam temperature with negligible intrabeam scattering. (a) $n_p = 10^{25}$ e-cm $^{-3}$, $T_p = 0,5$ keV with $T_b = 500$ keV. (b) $n_p = 10^{24}$ e-cm $^{-3}$, $T_p = 1$ keV with $T_b = 1$ MeV and 5 MeV REB.

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