INSTABILITY OF LONG DRIVING BEAMS IN PLASMA WAKEFIELD ACCELERATORS

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Abstract

In plasma wakefield accelerators, long (as compared to the wakefield period) driving beams are subject to the vigorous transverse two-stream instability, the nonlinear stage of which is numerically studied. If only one mode of the instability grows up in the system (as in the case of a sharp beam front), then the beam quickly gets modulated, the instability saturates, and the generated wakefield increases; further propagation of the modulated beam is stable. Simultaneous growth of several unstable modes (which is the case for a smooth beam front) completely destroys the beam in the time of several betatron oscillations. The trains of short bunches are stable.

1 INTRODUCTION

Plasma wakefield accelerators (PWFA), as well as other plasma-based advanced accelerator concepts, have been intensively studied during the last two decades [1], mainly because of very high accelerating gradients that can be achieved in a plasma. In PWFA the field in the plasma is driven by an electron beam (driver); this can be a single short (with respect to the wakefield period $2\pi c/\omega_p$) electron bunch [2], multiple short bunches [3], or a single long bunch of a specific shape [4]. The driver in the plasma experiences both longitudinal (decelerating) and transverse (focusing or defocusing) forces, but, due to high relativistic factor $\gamma_b \gg 1$ of the driver, only the transverse force can significantly change the driver shape.

Here we numerically study self-organization of long drivers under the influence of the transverse force in the plasma. We use 2D hybrid code LCODE [5], in which plasma electrons are treated as a fluid, plasma ions are immobile, and the driver is an ensemble of macroparticles. We consider either axisymmetric or flat beams with $\gamma_b = 1000$, radius (or half-width) $a \sim c/\omega_p$, and initial density $n_b \sim 0.1 n_i$, where $\omega_p = \sqrt{4\pi n_i e^2/m}$ is the plasma frequency, n_i is the plasma ion density, and other notation is common. The period of betatron oscillations for all considered beams is about $500\,\omega_p^{-1}$, while driver deceleration even in regions of the strongest decelerating field occurs at times $\gtrsim 5000\,\omega_p^{-1}$.

2 DRIVER DESTRUCTION

When a single short bunch serves as a driver, it is always focused in the plasma and therefore can not be quickly destroyed by its own wakefield. In contrast, a long driver extends over several wakefield periods and may in part fall into the defocusing phase of its own wake. For the long electron bunch with a smooth front and a sharp cut-off [4], this causes rapid destruction of the driver. Namely, initial small perturbations of the focusing force cause a modulation of the driver density; the density modulation results in further modulation of the focusing force, and so on. This process is known as the transverse two-stream (TTS) instability (see [6] and references therein). Both axisymmetric (sausage-like) and non-axisymmetric (kink) modes of this instability are dangerous and can destroy the beam ([7] and Fig. 1, respectively).

3 SELF-ORGANIZATION

Detailed study of the instability reveals that the driver destruction occurs when several unstable modes simultaneously grow up in the system [7]. This suggests the way

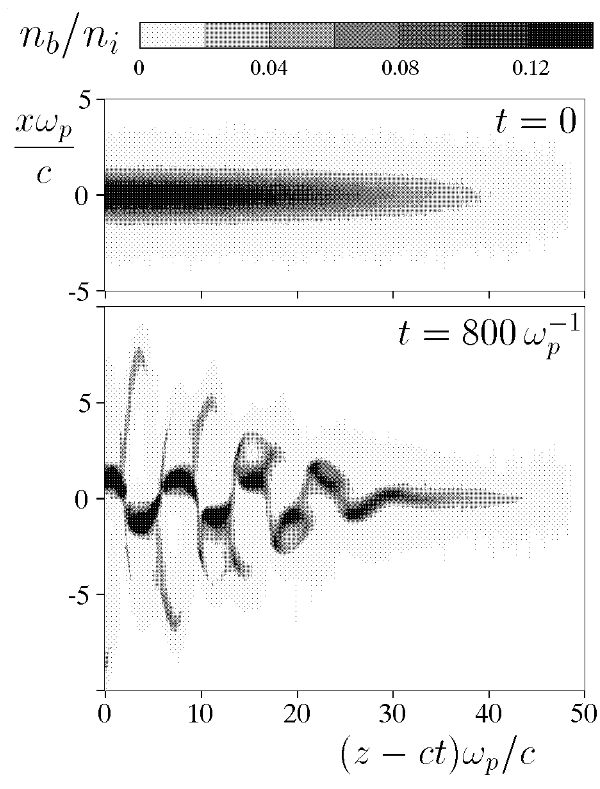

Figure 1: Destruction of the long beam by TTS instability. Plane geometry.

of controlling the TTS by adding a seed perturbation of the focusing force to the system and thus locking the phase of the instability. To study this possibility, we first consider the long axisymmetric beam with a sharp front (Fig. 2a,b). In Fig. 2 the force $\vec{F}$ acting on beam particles is characterized by the dimensionless electric field E_z/E_0 on axis, where $E_0 = \sqrt{4\pi n_i mc^2}$, and by the on-axis value of the dimensionless potential Φ, the gradient of which equals $\vec{F}/(mc\omega_p)$.

Oscillating component of the focusing force initiated by the beam front quickly (in time of a single betatron period) cut the beam into bunches of the length $\approx \pi c/\omega_p$ (Fig. 2c,d). After that, the self-modulated beam stably propagates in the plasma until some of its particles lose a major part of their energy (Fig. 2e). Despite the fact that all bunches of the beam partly fall into the accelerating phase of the wave, this driver produces much stronger wakefield than a single bunch. This field, however, is difficult to use for acceleration of another electron bunch (the witness). As can be seen from Fig. 2d,e, there are no driver particles in regions of the strong accelerating field: the particles were ejected from these cross-sections during driver self-modulation. Thus, to survive in the strong accelerating field, the witness should initially have much greater energy or much smaller radius than the driver (the latter case is shown in Fig. 2).

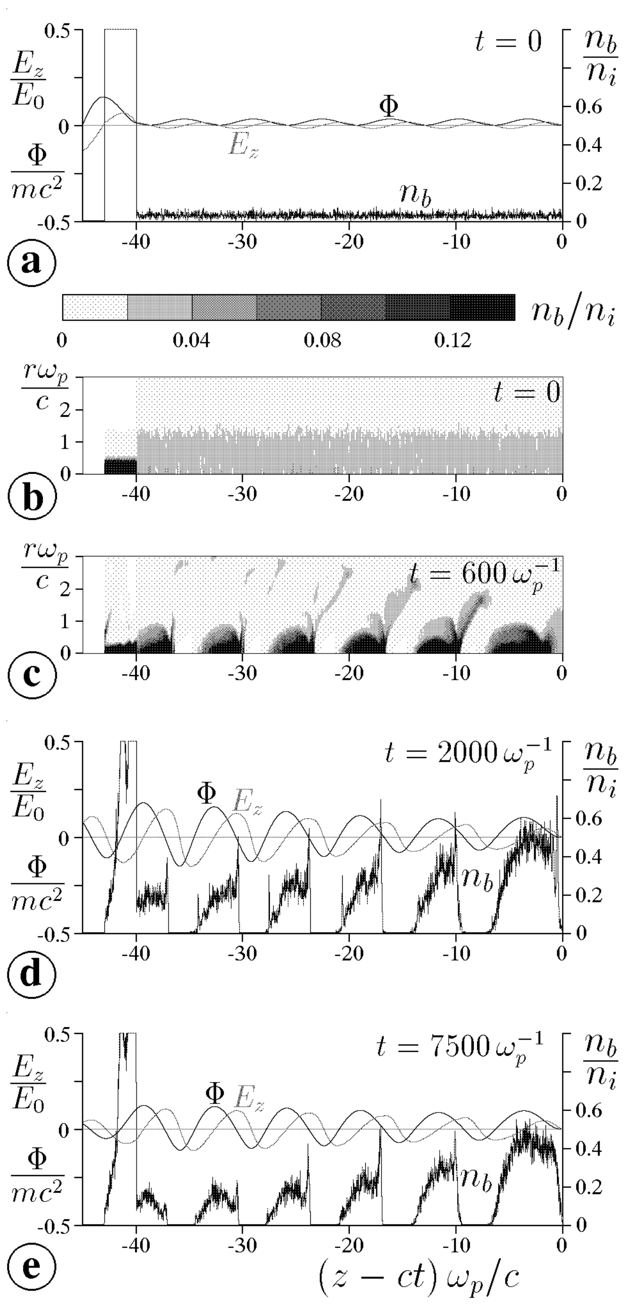

Figure 2: Self-modulation of the long axisymmetric beam with a sharp front.

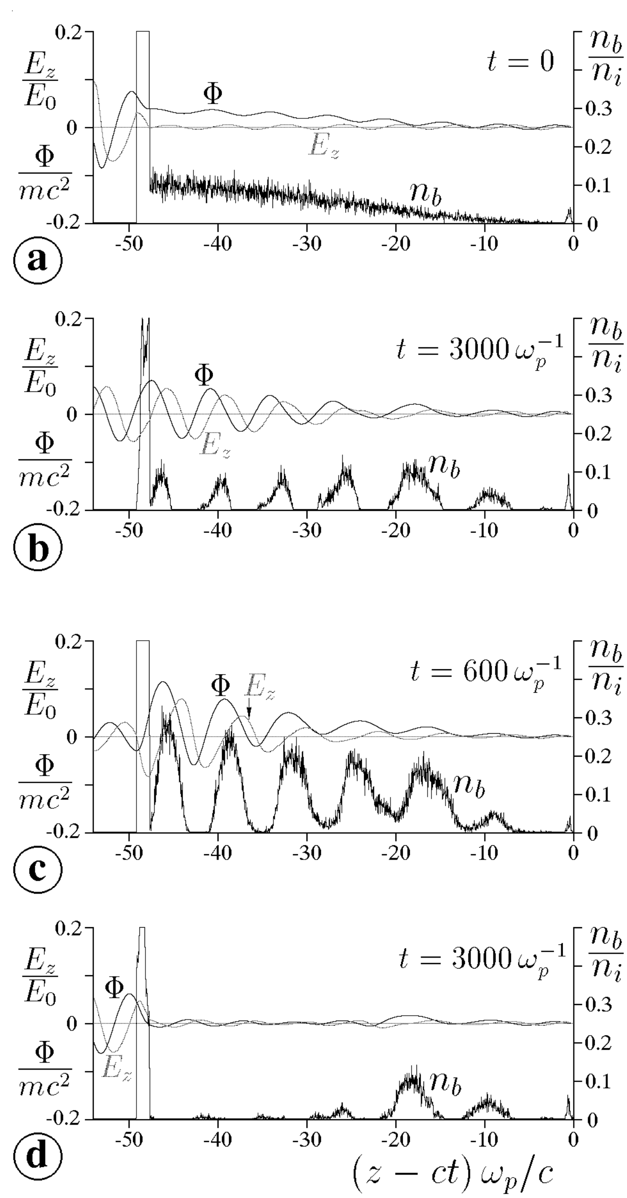

Figure 3: Modulation of the long axisymmetric beam by a small precursor.

For generation of the seed perturbation, a small precursor (short laser pulse or electron bunch) may also be used. Consider, for example, a short electron bunch (precursor) followed by a long smooth bunch (driver) and a narrow witness (Fig. 3a). To study the self-modulation in the cleanest form, we manually specify the initial angular spread of the driver so that to balance the transverse component of its own wakefield.

The precursor creates a small-amplitude wakefield, which is not sufficient to change the sign of the focusing force within the main body of the driver, but high enough to determine the phase of an unstable TTS mode. After the instability cuts the driver into separate bunches (Fig. 3b), the witness turns out to be in a proper phase with respect to the precursor. Again, to survive during the driver self-modulation, the witness should be very narrow or should have much higher energy than the driver; in both cases the time of witness defocusing will be much greater than the defocusing time of driver. In Fig. 3 the witness has $\gamma_b = 10^4$.

The seed perturbation cuts the driver into pieces for any number of particles in the precursor, but, if the precursor is too small, its field is not sufficient for suppression of other unstable modes. Example of the latter situation is shown in Fig. 3c,d. Here the precursor was only 30 % smaller than in Fig. 3a,b; the driver and the witness were the same. It is seen that, though all particles are ejected from defocusing phases of the precursor's wake, in focusing phases there are also very few particles (Fig. 3d) since they were lost when another mode (seeded by the driver tip) was dominant (Fig. 3c).

If the initial angular spread of the driver is not matched to the focusing force, the picture of self-modulation is qualitatively the same, but much bigger precursor is required to control the wakefield phase during establishment of the radial driver equilibrium.

4 BUNCH TRAINS

As we see, trains of short electron bunches stably propagate in the plasma until some particles lose a major part of their energy. Earlier this phenomenon was observed in simulations of axisymmetric beams [5], now the same result is found in the plane geometry (Fig. 4). Even initial off-axis displacement of the bunches (Fig. 4a) can not make the system unstable. In simulations it is easy to "switch off" particle acceleration and test whether it results in an instability. This was done, and no enhanced particle loss was observed. Whence we conclude that the stability of the bunch train and the absence of bunch-to-bunch resonances is explained by the difference in betatron frequencies of particles in different driver cross-sections, not by the rapid change of particle energy.

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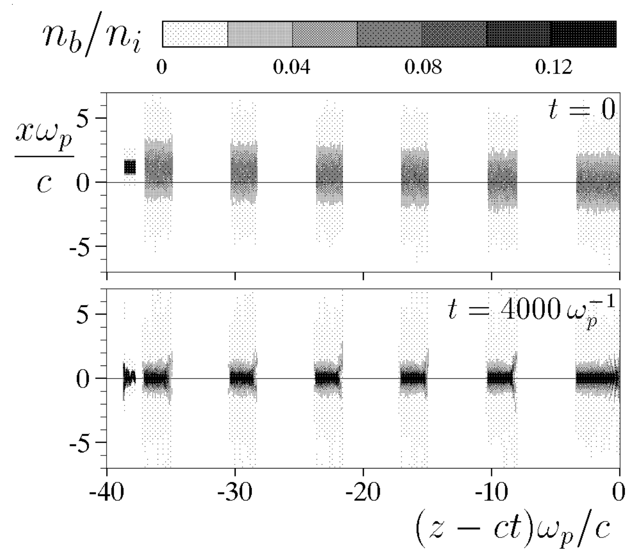

Figure 4: Long-term dynamics of the bunch train. Plane geometry.

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