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# Streaming instabilities driven by mildly relativistic proton beams in plasmas

M. E. Dieckmann [1], B. Eliasson [1], P. K. Shukla [1],

[1] *Institut für Theoretische Weltraum und Astrophysik, Ruhr-Universität Bochum, 44780 Bochum, Germany*

## 1. Introduction

The interaction through electrostatic waves (ESWs) between ion beams moving at mildly relativistic speeds and particles in plasmas is studied by particle-in-cell simulations. This interaction is important for the acceleration of electrons to energies at which they can cross repeatedly shocks with normals perpendicular to the magnetic field direction. This is required for the electrons to undergo Fermi acceleration [1]. We show in this work that the electrons form BGK modes [2], which are unstable to the sideband instability [3] and we show that the growth rate of the sideband instability reduces for increasing beam speeds. For beams moving at a Lorentz factor close to 2, the ESWs are stable enough to excavate phase space holes in the ion beam distribution [4]. The wave collapse and the interaction with the potential of these phase space holes heats the electrons to relativistic temperatures and the electrons finally attain a flat-top momentum distribution with exponentially decreasing tails. We show that ion phase space vortices are formed in the fully nonlinear phase of the simulations.

## 2. Initial conditions and simulation results

We consider a system of two counter-propagating proton beams moving through an unmagnetized plasma consisting of one electron and one proton species. The first proton beam has a speed $v_b$ and the second proton beam has the speed $-v_b$. The first beam is formed by either the upstream protons that have been reflected by the shock or by the downstream protons that have leaked through the shock. This beam is rotated by the upstream magnetic field and returns to the shock as the second beam. We perform particle-in-cell simulations to examine how the beam driven waves saturate. The plasma frequency is $\omega_p$ and $\lambda_u = 2\pi v_b / \omega_p$ is the wave length of the most unstable ESW.

In Fig. 1 we show the time evolution of the ESWs driven by the proton beams with $v_b > 0$.

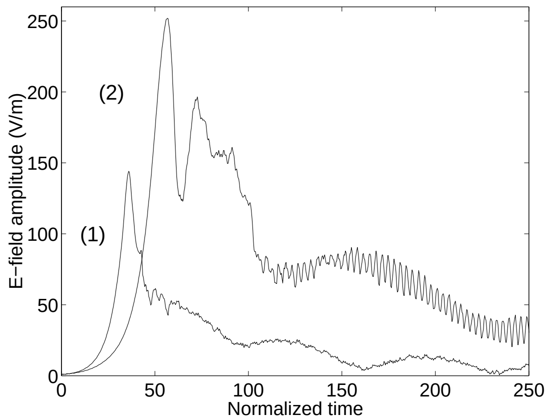


Fig 1: The ESW amplitude for $v_b = 0.5c$ (1) and $v_b = 0.8c$ (2). Time unit: $2\pi t/\omega_p$.

In both simulations the waves grow initially exponentially, they saturate by trapping electrons and they collapse. The short life-time of the saturated wave (1) is in line with that for non-relativistic phase speeds [5]. The electric field does, however, not drop to noise levels. The life-time of the saturated high-amplitude ESW driven by the beam with $v_b = 0.8c$ is significantly longer ($50\times 2\pi/\omega_p$) than that of the wave for $v_b = 0.5c$.

We have performed a parametric study [4] covering the interval from $v_b = 0.5c$ to $v_b = 0.9c$ confirming the tendency of an increasing ESW stability for increasing values of $v_b$. Relativistic beam speeds apparently reduce the growth rate of the sideband instability.

From Fig. 2 we find strong charge density modulations of the beam with $v_b = 0.8c$ and we find well-developed electron phase space vortices (electron BGK modes) in Fig. 3, both at the time $t = 74 \times 2\pi/\omega_p$ in a box sub-interval.

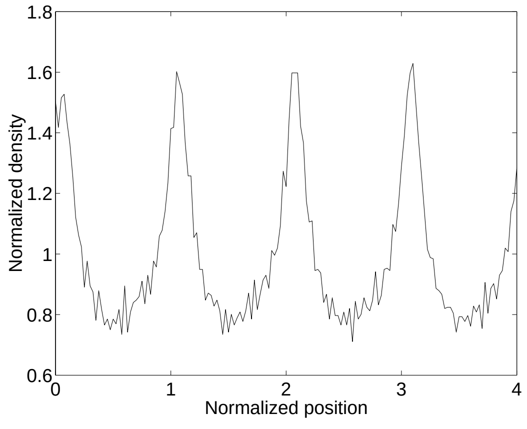


Fig 2: The density of the beam with $v_b > 0$ for a subinterval of the box. Position unit: $\lambda_u$, density unit: 1.

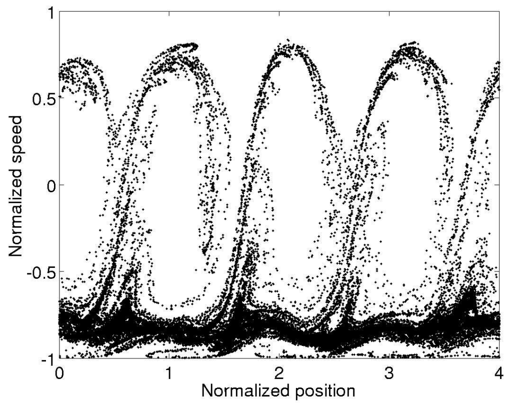


Fig 3: The electron phase space distribution in the beam reference frame. Position unit: $\lambda_u$, speed unit: $c$.

The substantial modulation of the electrons and the protons is due to the large electric field as we find from the curve (2) in Fig. 1.

Fig. 4 shows modulations of the beam moving at the speed $v_b = 0.8c$ with differing strength. The two left spikes have a considerably larger peak density than those to the right. Fig. 5 shows differences also for the electron phase space distributions. The two phase space vortices to the left have vanished and the electrons have been scattered. To the right we find well-developed vortices. The time is $t = 153 \times 2\pi/\omega_p$ in the Figs. 4 and 5 and we show a sub-interval of the box.

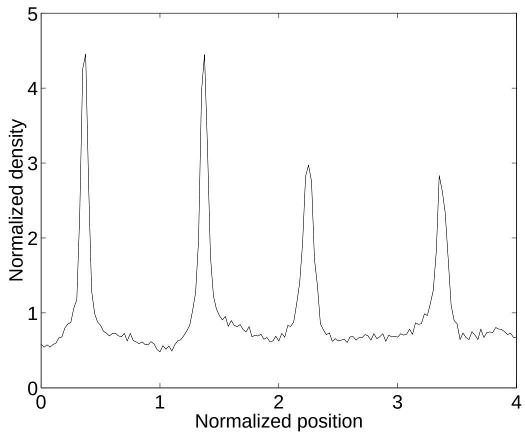


Fig 4: The density of the beam with $v_b > 0$ for a subinterval of the box. Position unit: $\lambda_u$, density unit: 1.

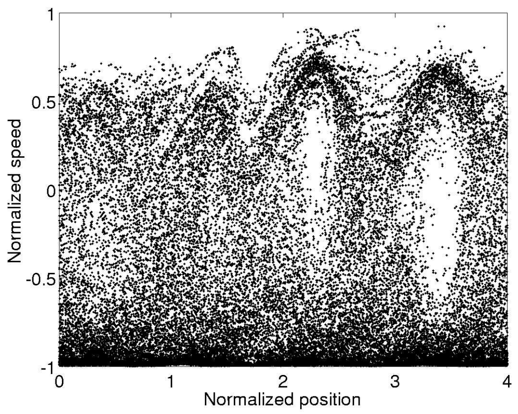


Fig. 5: The electron phase space distribution in the wave frame of reference. Position unit: $\lambda_u$, speed unit: $c$.

The spikes in Fig. 4 are associated with developing phase space vortices in the beam distribution. These proton BGK modes which we show in Fig. 6 prevent the ESW amplitude from dropping to zero in Fig. 1 after the initial wave has collapsed. Without the proton BGK modes the amplitude would drop to noise levels as in [5].

The electrons interact with the proton BGK mode potentials of the two oppositely propagating beams, scattering the electrons in momentum space which in turn leads to the flat-top momentum distribution shown in Fig. 7. Both plots are taken at the simulation end $t = 700 \times 2\pi/\omega_p$. The electron momentum distribution as a function of the normalized momentum $p = v\gamma(v)/v_b\gamma(v_b)$ is independent of the beam speed.

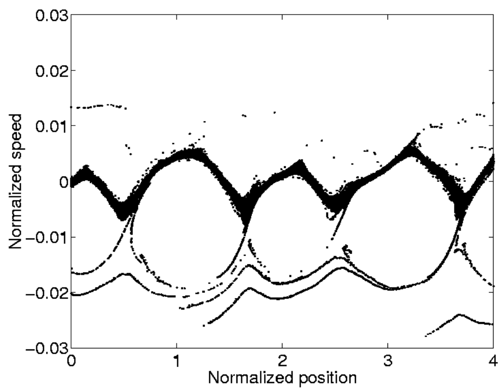


Fig 6: The phase space distribution of the beam protons. Position unit: $\lambda_u$, speed unit: $c$ in the beam frame.

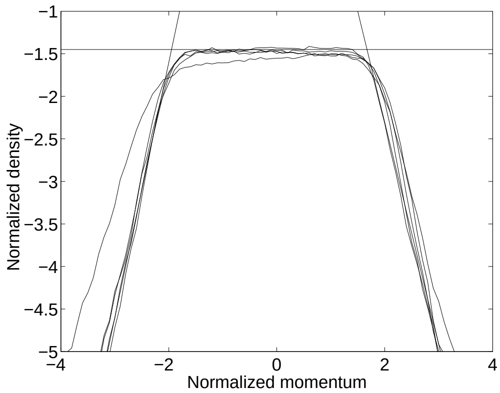


Fig 7: The electron momentum distributions $f(p)$ for the beam speeds $v_b = 0.5c, 0.6c, 0.7c, 0.8c$ and $v_b = 0.9c$.

## 3. Conclusions

We have examined how electrostatic waves grow, saturate and collapse that are driven by relativistic proton beams. We have found a stabilization of the electron BGK modes for increasingly relativistic phase speeds of the waves compared to previous work [4,5]. After the electron BGK modes collapse the proton BGK modes maintain a potential. The electrons interact with this potential and they develop a flat-top momentum distribution [4]. The speed $v_b$ of shock reflected protons is connected to the shock speed $v_s$ as $v_b \approx 2v_s$ if we have a specular reflection. Our proton beams are thus representative for shocks expanding with $v_s \approx 0.3c$. The electrons are then accelerated to energies in excess of the $10^5$ eV at which their Larmor radius becomes comparable to that of thermal ions. The electrons can cross perpendicular shocks repeatedly allowing for Fermi acceleration [1].

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