A VLASOV CODE SIMULATION OF THE AMPLIFICATION OF SEED PULSES BY BRILLOUIN BACKSCATTERING IN MAGNETIZED PLASMAS

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Especial attention has been given recently to the idea of plasma based laser amplifiers for their application to the direct amplification of ultra-short laser pulses. This problem has been studied essentially in unmagnetized plasmas. In the present work, we apply an Eulerian Vlasov code to study the transfer of energy from a long pump electromagnetic wave, to a counter-propagating ultra-short seed pulse, mediated by a resonant ion wave via stimulated Brillouin backscattering (SBS), in a plasma embedded in an external magnetic field. The code has been recently presented in [1]. In the present simulation, time is normalized to the inverse electron plasma frequency ω_{pe}^{-1}, velocity and momentum are normalized respectively to the velocity of light c and to $M_e c$, where M_e is the electron mass. Length is normalized to $l_0 = c\omega_{pe}^{-1}$, and the electric field is normalized to $E_0 = M_e \omega_{pe} c / e$. $m_i = M_i/Me$ is 1836 for hydrogen ions. The normalized vector potential or quiver momentum for the laser beam is a_{0p}. A forward propagating circularly polarized laser beam of constant amplitude enters the system at the left boundary, where for the forward pump $E^+ = E_y + B_z = 2E_{0p}\cos(\omega_{0p}t)$ and $F^- = E_z - B_y = 2E_{0p}\sin(\omega_{0p}t)$ at x=0, $\omega_{0p} = 3.2$ (normalized to ω_{pe}), and a_{0p}=0.02. In our normalized units $E_{0p} = \omega_{0p} a_{0p}$. We use a system of length L=600. The number of grid points in space is N=120000, so $\Delta x = \Delta t = 0.005$. The extrema of the momentum for the electrons are ± 0.5, with 1000 grid points in velocity space, and for the ions these extrema are $\pm 1.5\text{x}10^{-3}$ with 500 grid points in velocity space.

The pump precursor reaches the right boundary x=600 at t=600, since in our normalized units x=t. The seed pulse is injected at the right boundary x=600 in the backward direction just before the arrival of the pump, in the time interval 540<t<600, with $E^- = E_y - B_z =$ $2E_{0s}P_r(\text{t})\cos(\omega_{0s}(t-540))$, $F^+ = E_z + B_y = -2E_{0s}P_r(t)\sin(\omega_{0s}(t-540))$. The SBS produces a very small frequency downshift in the scattered wave $\omega_{0p} = \omega_{0s} + \omega_{ion}$. We neglect this small downshift $\omega_{ion} << 1$, and set the seed frequency $\omega_{0s} \approx \omega_{0p} = 3.2$, therefore $k_{0p} \approx k_{0s}$. The SBS is backward propagating, so the selection rule $k_{0p} = -k_{0s} + k_{ion}$ will result in an ion wave $k_{ion} \approx 2k_{0p}$. Also $a_{0p} = a_{0s} = 0.02$ and $E_{0s} = E_{0p}$. The initial distribution functions for electrons and ions are Maxweellian with temperatures T_e= 0.3keV and T_i=0.02keV. respectively. The shape factor $P_r(t)$ for the injected seed pulse has a Gaussian time dependence $P_r(t)$ = exp(-0.5(t-570)/t_p)^2, for 540<t<600, with t_p=10. The backward propagating seed pulse reaches its peak at t=570, and has completely penetrated the plasma at t=600, *i.e.* the time the pump precursor reaches the right boundary. The electron cyclotron frequency (normalized to the electron plasma frequency) is $\omega_{ce} = 0.5$. From the linear dispersion relation $k^2 = \omega^2 - 1/(1 \mp \omega_{ce}/\omega)$ the corresponding wavenumber for the left hand circularly polarized (LCP) wave is 3.062, and for the right hand circularly polarized wave (RCP) the wavenumber is 3.01.

Figure (1) shows at t=1200 successively: in the first frame the incident pump wave E^+ (full curve) and the growing backward seed pulse E^- (dashed curve), in the second frame is the longitudinal electric field E_x, the third and fourth frames show the electron and ion density

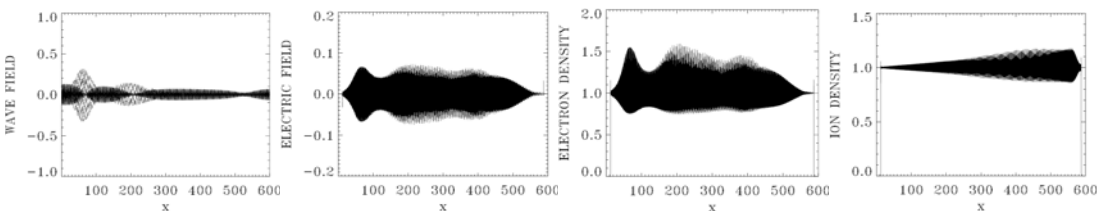

Figure 1. From left to right: the incident pump wave E^+ (full curve) and the growing backward seed pulse E^- (dashed curve), the electric field E_x, the electron and ion densities.

Figure (2) presents contour plots for the electron distribution function, and Fig.(3) for the ion distribution function, at t=1200. In Fig.(4) the wavenumber spectra associated with the forward wave E^+, the backward wave E^-, the longitudinal electric field E_x and the ion density, are calculated by Fourier transform of the corresponding signal in the domain x=(75,403) at t=1200, at a time where the backward seed pulse has reached the left boundary. The spectrum of E^+ in Fig.(4) shows the peak at k_{0p}=3.049 (the linear dispersion relation calculates a wavenumber of 3.062 for the LCP wave for a frequency of

3.2 as mentioned above). The same mode is appearing in the wavenumber spectrum of the backward wave E^{-}.

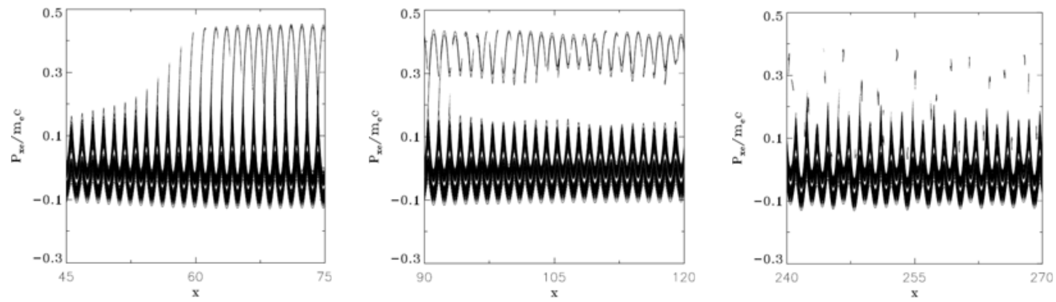

Figure 2. Contour plots for the electron distribution function

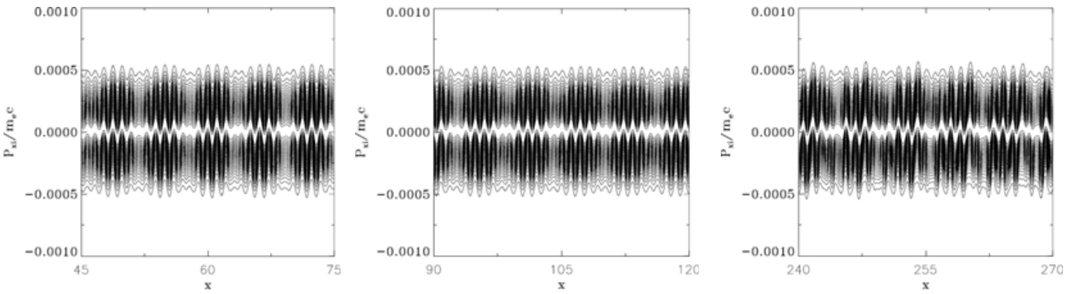

Figure 3. Contour plots for the ion distribution function.

The presence of these two modes will result in the appearance of a SBS mode at $k_{ion} \approx 2k_{0p}$ =6.089, very close to the peak at 6.12 in the wavenumber spectrum of the ion density in Fig.(4). Note the harmonics of 6.12 at 12.25, 18.37 and 24.5. We note in the wavenumber spectrum of E^{+} the presence of a forward scattered mode at 2.01, with the selection rule 3.049=2.01+k, from which k=1.039, very close to the peak at 1.05 in the spectrum of E_x. The corresponding frequencies we see in Fig.(5) by taking the temporal Fourier transform of the signals registered at x=90 in the time t=(1070,1234) give a frequency of 3.2 for the pump E^{+} and 2.186 for the forward scattered mode (the corresponding wavenumber calculated from the linear dispersion relation is 1.991, very close to the value of 2.01 we see in the wavenumber spectrum of E^{+}). They obey the selection rule $3.2 = 2.186 + \omega$, from which a plasma mode at $\omega = 1.014$, very close to the peak at 1.035 we see in the frequency spectrum of E_x in Fig.(5). Also in the wavenumber spectrum of E^{-} a backward scattered mode at k_s =2.01 is dominating the spectrum, such that $k_{0p} = -k_s + k_e$, from which

$k_e = 3.049 + 2.01 = 5.059$, very close to the value of 5.043 we see in the wavenumber spectrum of E_x. Note the harmonics of 5.043 at 10.086, 15.13 and 20.13. The forward scattered mode at 2.01 and the backscattered mode at -2.01 will couple through Brillouin scattering to give another SBS mode at $k_{ion} \approx 2x2.01=4.02$, very close to the value of 4.0 we see in the ion spectrum in Fig.(4). So there is two SBS events, at 4.0 and 6.12. Other resonances are also present. We see in the spectrum of E^+ the anti-Stokes at 4.103 obtained by the coupling of the plasma mode at 1.05 and the pump E^+ at the wavenumber 3.049, such that 3.049+1.05=4.099, very close to the value of 4.103 in the wavenumber spectrum of E^+, with the corresponding frequencies 3.2+1.035=4.235, very close to the value of 4.29 we see in the frequency spectrum of E^+ in Fig.(5).

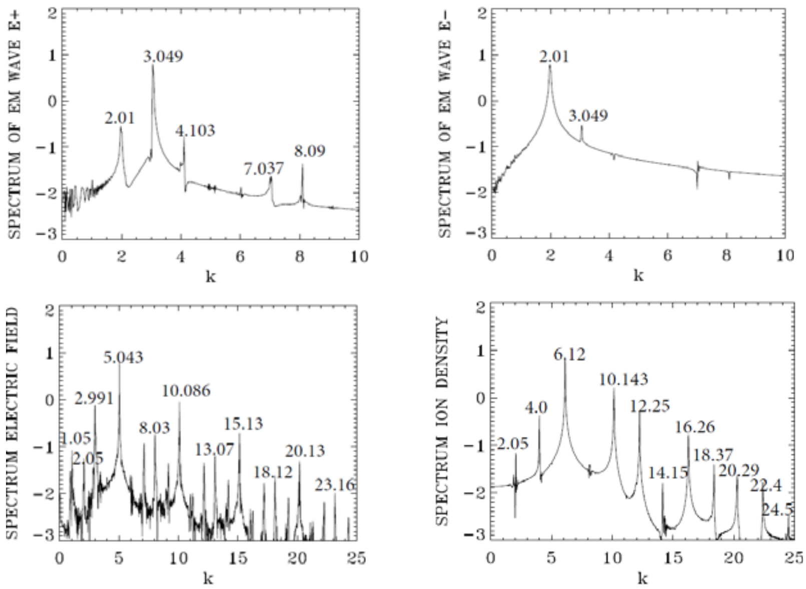

Figure 4. Wavenumber spectra in x=(75,403) at t=1200.

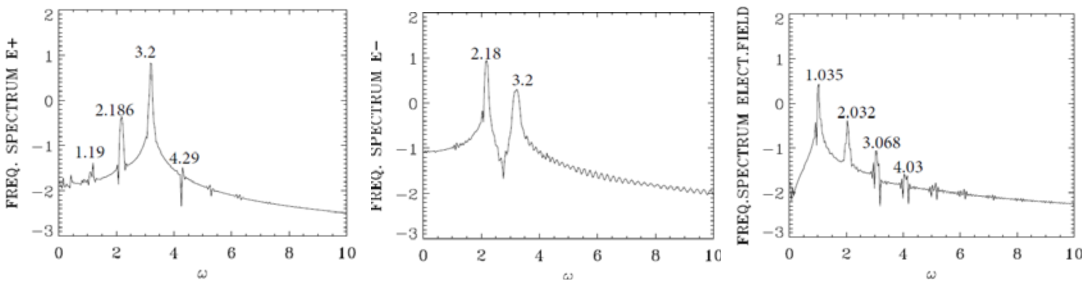

Figure 5. Temporal Fourier transform in t=(1070,1234) at x=90.

References

[1] M. Shoucri Laser Part. Beams, 34, 315-337 (2016)