The study of parametric instabilities relevant to Laser-Plasma interactions in Fast Ignition

K.A. Humphrey[1], D.C Speirs[1], R. Trines[2], P. Norreys[2], M. King[1], K. Ronald[1], A.D.R. Phelps[1], R. A. Cairns[1,3], L.O. Silva[4], F. Fiuza[4] and R. Bingham[1,2]

[1] *SUPA, Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK*

[2] *STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK*

[3] *School of Mathematics and Statistics, University of St. Andrews, St. Andrews, Fife, KY16 9SS, UK*

[4] *GoLP/Centro de Física dos Plasmas, Instituto Superior Técnico, 1049-001 Lisboa, Portugal*

Introduction

It is anticipated that beam-plasma instabilities driven by the relativistic electron beam generated in a Fast Ignition route to inertial confinement fusion will play a crucial role in the coupling of the laser energy to the fuel target[1,2]. These include the two-stream, Weibel and filamentation instabilities. Of particular interest is the two-stream mode which may provide a method for achieving the required fusion fuel heating via the relaxation of the non-thermal electron beam through this instability. This process generates Langmuir waves that parametrically decay into lower amplitude Langmuir waves and ion acoustic waves that are strongly damped by ion collisions in the dense plasma, resulting in energy transfer to the background plasma ion population[3,4]. In the current context, numerical simulations have been conducted using the OSIRIS particle-in-cell code to investigate the plasma dynamics associated with this route to achieving target plasma ion heating via the two-stream instability. An overview of the results from these simulations will be presented and discussed herein.

The two-stream instability

The generalised dispersion equation for longitudinal waves in a plasma containing particle streams is:

$$\sum \frac{\omega_{pe\alpha}^2}{(\omega - k \cdot u_\alpha)^2} = 1 \tag{1}$$

Where $\omega_{p\alpha}$ is the plasma frequency and u_α is the steady state streaming velocity for species α[5]. It can be seen that for large enough values of k the dispersion equation solved has four real solutions. For values of k less than k_c , two of these roots form a complex conjugate pair which represent exponentially growing and damped waves where the growing wave solution is identified with the two-stream instability.

The two-stream dispersion equation can be modified from the case of two opposing streams to the case of a stationary background plasma and a propagating electron beam. As the velocity of the background plasma is zero in this case the dispersion relation reduces to:

$$\frac{\omega^2_{pe(beam)}}{(\omega - k \cdot v_\alpha)^2} + \frac{\omega^2_{pe(plasma)}}{\omega^2} = 1 \tag{2}$$

This equation can be solved analytically for ICF relevant plasma parameters in order to compute a value for the growth rate of the instability.

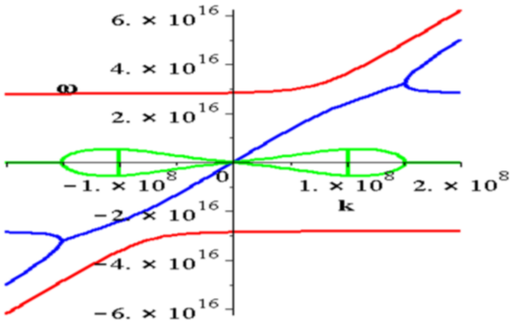

Figure 1. Two-stream dispersion solution for a beam-plasma system with background plasma density of $10^{29}m^{-3}$, electron beam density of $10^{28}m^{-3}$ and electron beam energy of 1MeV. The red line is the real root for the plasma contribution to the dispersion, the blue line is the real component from the beam and the green line is the imaginary component of the solution from the beam.

The growth rate of the two-stream instability is determined from the imaginary component of the dispersion solution. From figure 1 this value is found to be 5.6×10^{15}rad s^{-1} for the beam-plasma system analysed. As this analysis is a linear approximation and the instability in question is a non-linear process it only gives a benchmark for the growth of the instability. Therefore, a full numerical approach is required.

PiC Simulations

The numerical simulations were performed using the OSIRIS code which is a fully parallelized, fully relativistic, and fully object-oriented PIC code, for modeling intense beam plasma interactions[6]. The parameters chosen are motivated by the conditions typical of a Fast Ignition route to achieving inertial confinement fusion[3,7]. The system is initialized with a strong beam of 1MeV electrons entering an already compressed plasma region of density $2.44 \times 10^{29}m^{-3}$. The temperature of the background ion population was taken as $T_i = 0.1T_e$ with an electron temperature of 1keV and the ion-electron mass ratio fixed at $m_i/m_e = 1836$.

1D PiC Simulation Results

The results from the 1D OSIRIS simulations show behaviour characteristic of the two-stream instability. Initially the instability grows in accordance with linear theory before saturating non-linearly at a later time via the excitation of Langmuir waves and the consequential trapping and scattering of electrons by these waves creating turbulent phase-space structures. Figures 3, 4 and 5 show respectively the phase trapping of electrons in the beam, corresponding axial bunching of the electrons in the plasma and the excitation of an ion acoustic wave. In Figure 3 it can be seen that an oscillation in axial momentum, p_1, commences at a time of $9.80\omega_{pe}^{-1}$. This builds to an ellipsoidal formation where particles lose axial momentum, reverse trajectory and are effectively phase trapped within the beam, as can be seen at $t = 39.20\omega_{pe}^{-1}$. The electrons in the background plasma also undergo significant modulation in axial momentum (see Figure 4), corresponding to the transfer of energy from the electron beam to the background plasma.

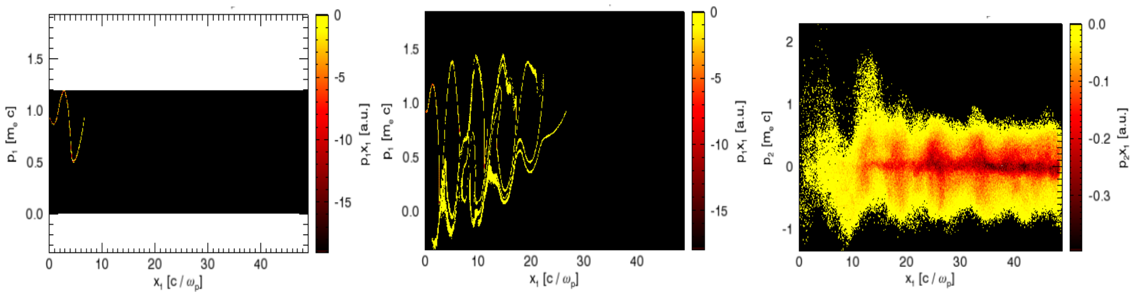

Figure 3a, b, c. Phase space plots of axial momentum against axial position of beam electrons at t = 9.80, 39.20 and $177.50\omega_{pe}^{-1}$ respectively.

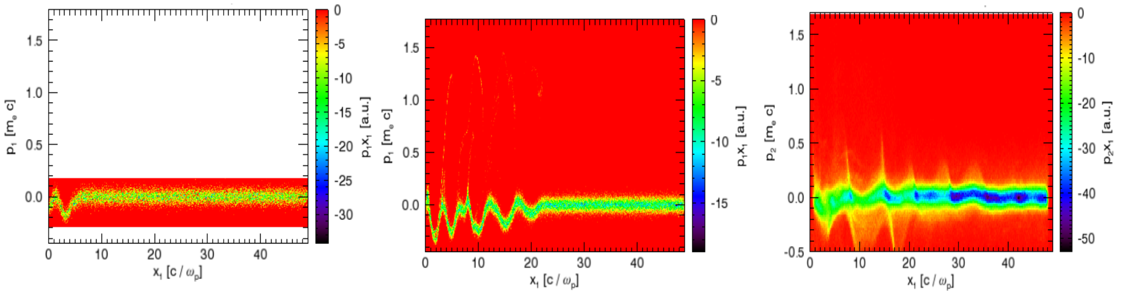

Figure 4a, b, c. Phase space plots of axial momentum against axial position of background plasma electrons at t = 9.80, 39.20 and $177.50\omega_{pe}^{-1}$ respectively.

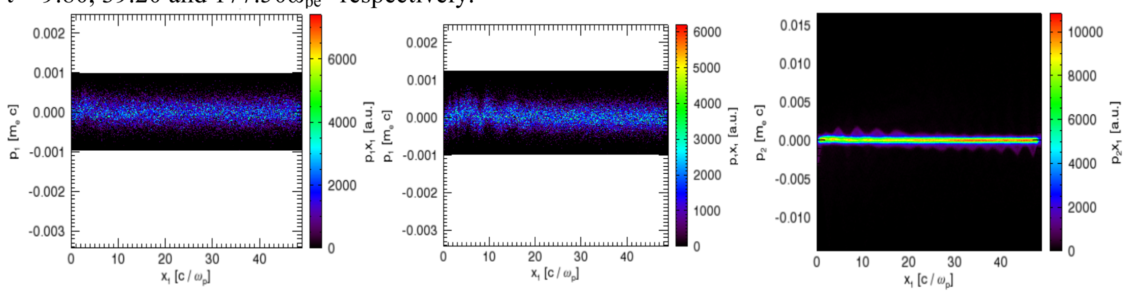

Figure 5a, b, c. Phase space plots of axial momentum against axial position of background plasma ions at t = 9.80, 39.20 and $177.50\omega_{pe}^{1}$ respectively.

The PiC simulations presented are found to compare favourably to previous work by N. J Sircombe et al.[3] where an investigation was conducted to study the collapse of weakly relativistic beams of various initial energies using a one-dimensional Vlasov-Poisson code.

Conclusions

Evidence has been presented to suggest that effective ion heating can be achieved in Fast Ignition ICF fusion plasmas through relaxation of the thermal electron beam via the two-stream instability. Further research emanating from this work is currently in progress to study in detail the collisional effects implicit to the very high density/temperature plasmas produced in ICF targets. This work will focus on the effect such collisions may have on the growth of the two-stream instability and its ability to transfer energy from the electron beam to the background plasma.

Acknowledgements

The authors would like to thank the OSIRIS consortium for the use of OSIRIS and acknowledge the support from CFfP. Simulations were carried out on the Scarf-Lexicon Cluster (STFC RAL).

References

1. V. M. Malkin and N. J. Fisch, *Phys. Rev. Lett*. **89**, 125004 (2002)
2. C. Deutsch, *Eur. Phys. J. Appl. Phys*. **24** 95-113 (2003)
3. N. J Sircombe *et al., Plasma Phys. Control. Fusion* **50**, 065005 (2008)
4. J. T Mendonca *et al., Phys. Rev. Lett*., **94**, 245002 (2005)
5. T. J.M Boyd and J. J Sanderson, *'The Physics of Plasmas'*. Cambridge, Cambridge University Press (2003)
6. R.A.Fonseca et al., LNCS 2331, (2002)
7. M. H. Key, *Phys. Plasmas* **14**, 055502, (2007)