2D Simulations and experiments on streaming instabilities in a Penning discharge

M. King[1], D.C. Speirs[1], T. Heelis[1], R. Bingham[1,2], C.G. Whyte[1], C.W. Robertson[1], A.D.R. Phelps[1], M.E. Koepke[1,3], S.L. McConville[1], R.A. Cairns[1,4], I. Vorgul[4], & K. Ronald[1]

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

[2] *STFC Rutherford Appleton Laboratory, Harwell, Oxford, Didcot, OX11 0QX, England*

[3] *Department of Physics, West Virginia University, Morgantown, WV 26506-6315, USA*

[4] *School of Mathematics and Statistics, University of St Andrews, KY16 9SS, Scotland*

Instabilities may arise when a plasma has a strongly non-thermal component in its distribution function. Laser injected 'spark-plug' electron beams are proposed as a method of heating the core of inertially confined fusion targets in schemes for 'fast ignition'. These schemes are attractive as they promise a very substantial reduction in the scale of the laser required for fuel compression. Streaming instabilities can contribute to the transfer of energy from these energetic electrons to heat the ions to the levels required to initiate fusion reactions [1]. Experiments have shown that more energy can be transferred to the plasma than can be accounted for from purely electron-ion collisions [2,3]. It has been proposed that the two-stream instability may be responsible as it can parametrical decay into ion-acoustic waves which are then damped by ion-ion collisions resulting in additional energy transfer to the ions [4].

Multidimensional kinetic computer simulations of these instabilities may be achieved using modern parallel Particle in Cell (PiC) codes [5]. In order to ensure the predictions of the simulations are accurate, it is desirable to test their output over as wide a range in parameter space as possible. We present 2D simulations of the interaction conducted using XOOPIC [6] between a moderately energetic electron beam (~10-100kV), with a narrow thermal distribution, propagating in a background plasma ~5cm in diameter and with a density of ~5-9x10^{16}m^{-3} with both the beam and plasma confined radially by a strong axial magnetic field. The two stream instability will originate from a point source disturbance within such a streaming system [7]. If a density fluctuation arises from this disturbance in one stream of particles, then the electric field will initiate a plasma oscillation at that location. However, these fields can modulate the charged particle densities of the second stream and the drift of these density modulations through each other can result in energy exchange. This leads to growth of the energy associated with the electric fields feeding from the energy of the initial particle streams.

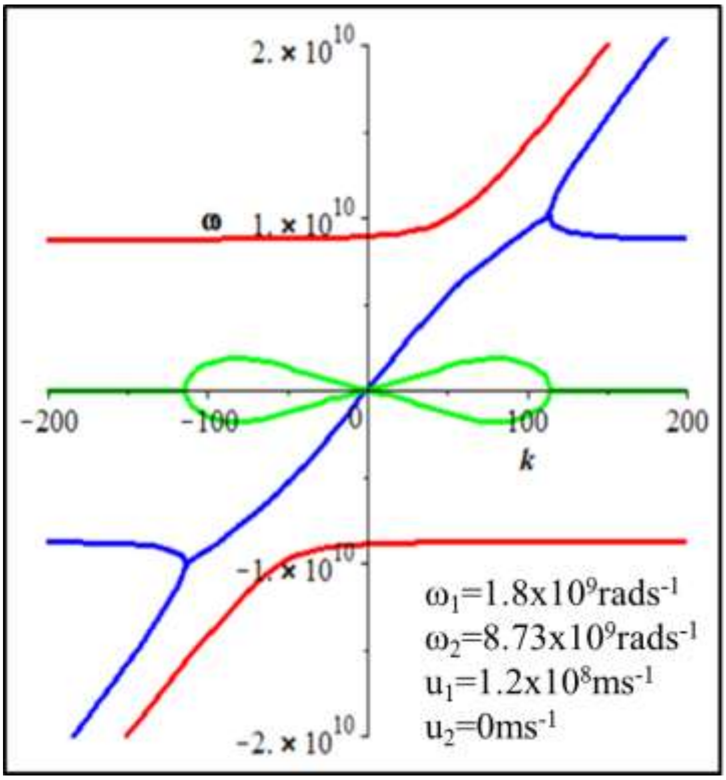

Fig 1 - Dispersion relation obtained from linear theory of the two-stream instability parameters used in the numerical simulations

Figure 1 shows the linear theory predictions of the temporal growth rate, the frequency and spatial scale of the oscillations induced by the streaming instability (assuming the insytability grows near the point where Im(ω) is maximum). Looking at figures 2 and 3, the simulations show clearly the growth and saturation of the two-stream instability, the evolution of phase space vortices and the trapping of beam electrons in axial velocity due to strong axial electric fields. The AC fields encourage the formation of axially aligned spatial structures in both the ion and electron densities. These structures act to inhibit the two stream process and drift at the ion acoustic velocity. The simulations were used to define the parameters for a laboratory experiment. A schematic of the apparatus is presented in figure 4, including the electron accelerator, the magnetic field system and the plasma column (based on a Penning discharge).

The electron beam is created using a Pierce-type electron accelerator geometry. A Penning trap type plasma discharge was used to create the necessary background plasma. Water-cooled solenoids were used to create the focusing magnetic field for the electron beam as well as the confining magnetic field for the plasma. These solenoids allowed the magnetic fields to be varied as required to maintain laminar beam transport and stable Penning discharge operation.

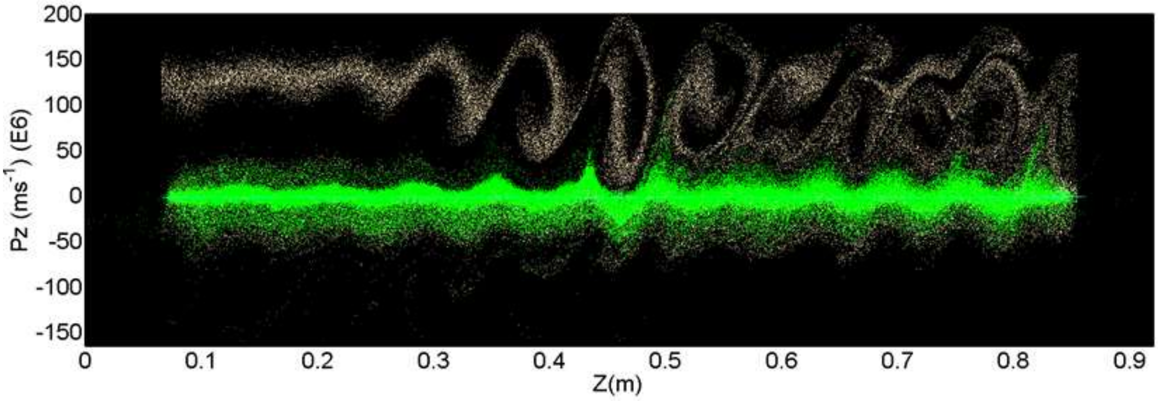

Fig 2 - axial-momentum against z of all particles in the simulation after 150ns (orange=beam electrons, green=plasma electrons, blue=plasma ions)

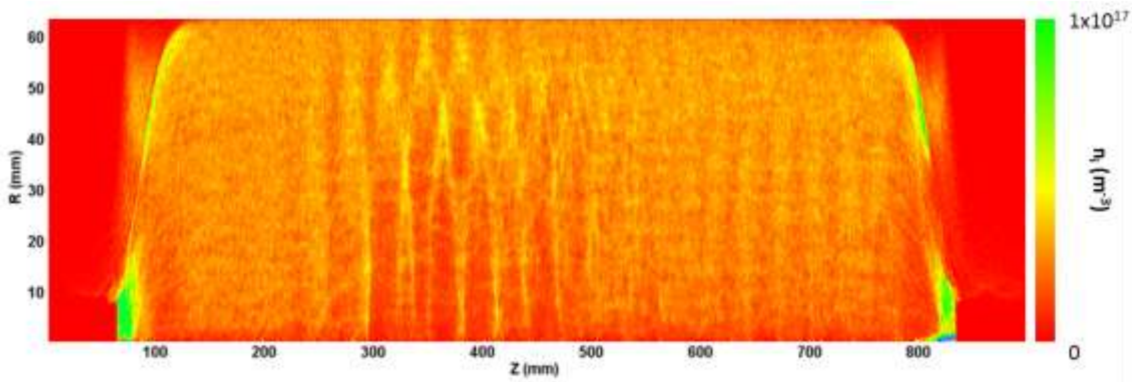

Fig 3 - Z-R plot of ion density after 150ns showing the formation and drift of ion density modulations- electrons follow similar behaviour, initial density $2.4x10^{16}m^{-3}$, dia. 60mm

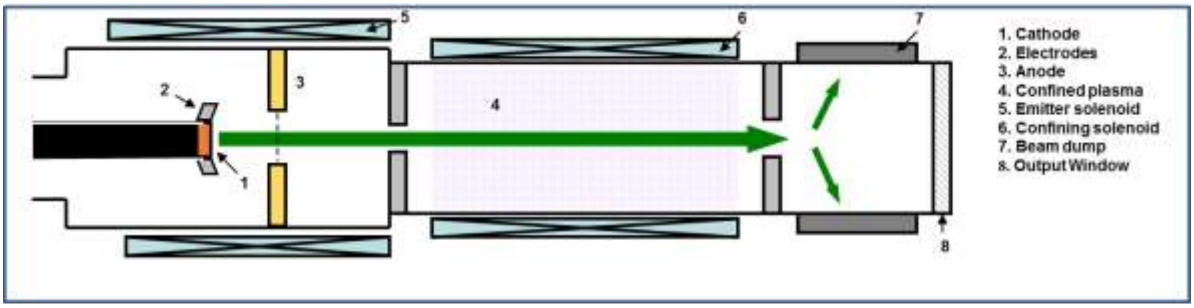

Fig 4 – Experimental configuration for two-stream experiments.

The high current Penning discharge trap features specially designed insulators at each end to suspend the anode in the centre of the system electrically separated from the main anode (which is the electrical cathode for the Penning discharge). Stable plasma conditions were obtained over the range 1mA-25mA in DC discharge operation current and pulsed operation was achieved to over 40mA. Helium gas was admitted to the discharge chamber at a pressure of $7x10^{-4}$mB in a vacuum of $5x10^{-6}$mB, whilst the magnetic field was typically 0.05-0.3T. The discharge was diagnosed by two distinct methods (Langmuir probe and interferometric microwave phase-evolution measurements). These diagnostics indicate plasma densities in the region of $3x10^{16}m^{-3}$ at a discharge current of 18mA (DC).

In summary long duration simulations have shown transfer of energy from the electrostatic oscillations excited by a streaming instability in a meter long magnetised plasma column enclosed in a metal tube to excite ion motion. The simulations have informed the development of an experimental apparatus which has created a plasma, having a density similar to that predicted by the simulations to facilitate the effect, through which an electron beam of ~50-100keV and a current of 1-50A may be propagated.

References

[1] Zhuo, H.B. et al., Physical Review Letters, 112, 215003 (2014)
[2] R. Kodama et al., Nature (London) 412, 798 (2001)
[3] R. Kodama et al., Nature (London) 418, 933 (2002)
[4] J.T. Mendonça et al, Phys Rev Lett, 94, 245002 (2005)
[5] N.J. Sircombe et al, Plasma Phys. Control. Fusion, 50, 065005 (2008)
[6] J. P. Verboncoeur, A. B. Langdon and N. T. Gladd, Comp. Phys. Comm. 87, 199 (1995). Code available via http://ptsg.eecs.berkeley.edu
[7] Stix T.H., Waves in Plasmas, Springer (1992).