Numerical and Experimental Investigation of the Ion Beam Driven Instability

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Plasma dynamics in astrophysical systems is strongly influenced by particle beam driven instabilities. Sources for beams in space include coronal mass ejections, magnetic reconnection events and shock fronts. A beam driven instability typically shows linear growth of oscillations on short time scales related to the relevant species' plasma frequency before evolving into a turbulent state. Of particular importance is the ion beam driven instability (IBDI), which is suggested to contribute to turbulent ion heating and anomalous resistivity. Its nonlinear state is characterised by chains of vortices known as phase space holes [1]. This contribution presents first results from an experiment with IBDIs and a complementary numerical investigation of ion phase space dynamics. Special attention is paid to the influence of the discharge and boundary conditions, which generally alter the spatiotemporal dynamics of the IBDI.

Experiments are conducted in the linear plasma device VINETA [2], using a thermionic double plasma discharge. Two discharges with different plasma potentials are separated by a strongly negative grid. Ions passing from the source plasma into the target plasma are accelerated by the difference in plasma potentials. Discharge parameters are density $n \sim 10^{16}\,m^{-3}$, electron temperature $T_e \sim 2\,eV$, and ion temperature $T_i \sim 0.1\,eV$ in argon at a neutral gas pressure of $10^{-2}\,Pa$. The instability excites an ion acoustic wave with a frequency approximately half the ion plasma frequency $f_{pi} \sim 2\,MHz$. For a typical phase velocity $v_{ph} = c_s \sim 2.5\,kms^{-1}$, where c_s represents the ion sound speed, the wavelength is a few millimetres. The amplitude of potential fluctuations $\tilde{\phi}$ in the wave is $e\tilde{\phi}/k_B T_e \sim 5\%$.

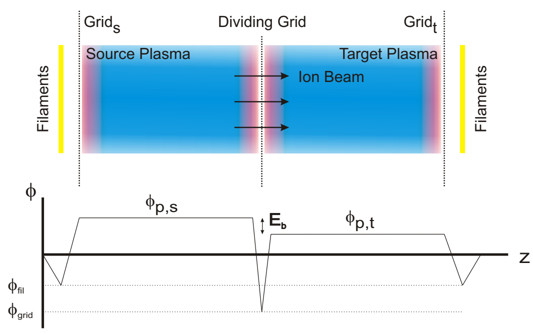

Figure 1: Schematic showing the experimental setup, including the potential profile.

Detecting these structures in ion phase space presents a considerable diagnostic challenge. Strong phase space holes generated by shocks have been detected in experiments, e.g. [3–5]. A LIF diagnostic using photon counting is being development as per [6, 7] to enable phase space resolution under the conditions of a stationary (i.e. non-transient) IBDI.

Voids in phase space were originally discovered in simulations [8], and have been characterised extensively in ever more detailed simulations over the last 40 years. Simulations provide the space-time evolution of the ion phase space with arbitrary resolution. For this work, a particle-in-cell (PIC) simulation is chosen, which can be tailored to reflect the experimental discharge as closely as possible [9]. It is a 1-dimensional electrostatic code, which explicitly includes boundary conditions, allowing the inclusion of various sheaths and biased grids. In the example shown in Fig. 2, a simplistic case (a) where a beam is injected into a homogeneous plasma is compared with the case (b) of a double plasma. The homogeneous case follows the linear dispersion relation as expected, showing strong growth and subsequent saturation in phase space vortices on a short spatial scale of $50\,\lambda_D$, where λ_D is the Debye length. The vortices are relatively long lived ($16/f_{pi}$), allowing the extraction of statistics such as frequency ($0.4 f_{pi}$), wavelength ($16\lambda_D$) and bounce time ($7/f_{pi}$) to be extracted. Vortices usually disappear when two small vortices coalesce to form a large one. Although this process is limited by collisions in this simulation, it demonstrates a possible mechanism by which isolated vortices with very strong potential gradients can form as it is observed in astrophysical plasmas.

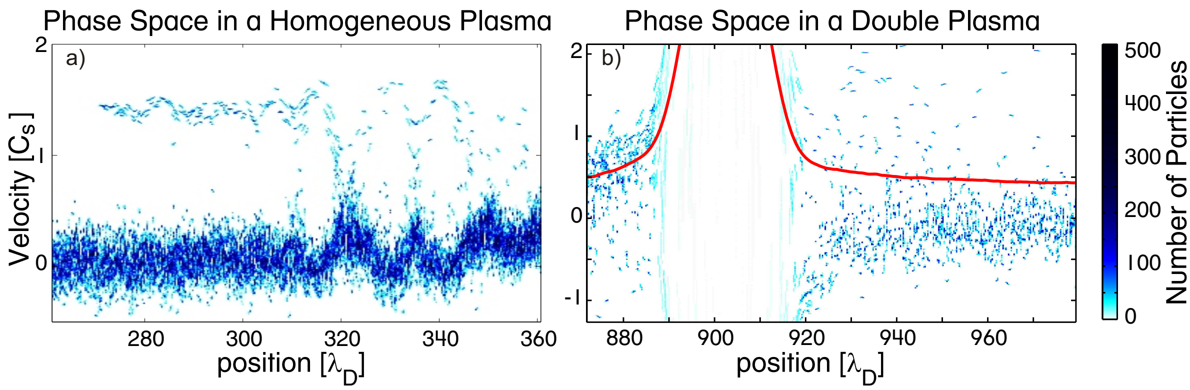

Figure 2: Ion phase space from the PIC simulation comparing (a) an idealised case, with (b) a double plasma including the dividing grid at $902\lambda_D$. The red line indicates an expected phase space trajectory from the average potential profile.

In the double plasma, the strongly negative central dividing grid modifies the system dynamics. Ions are accelerated strongly towards the grid from both sides. Due to the higher net potential in the source plasma, ions moving from right to left can be trapped and oscillate within the sheath, until they collide with the grid. These particles appear as an ellipse which extends beyond the borders of the figure. The red line shows the trajectory of an ion from the source plasma following the time averaged potential. Under this potential profile, a beam should appear with mean velocity of $0.5\,c_s$ and a slightly reduced thermal spread. The thermal velocity of the bulk is $0.3\,c_s$ and the expected thermal velocity of the beam, relative to its mean velocity, is $0.1\,c_s$. The simulation shows that ions are accelerated as expected, however, the beam appears strongly scattered in velocity space as it exits the sheath. Collisions are ineffective over these scales, so the scattering must be due to potential fluctuations within the sheath.

The distribution function within the sheath includes three components: the trapped ions from the target plasma moving in both directions, and the beam ions from the source plasma. Such a triple-peaked distribution function would be unstable, although the strong gradients make it difficult to characterise.

The increased beam temperature leads to a reduction in the growth rate for the IBDI, however the instability still occurs. By comparison, the phase space vortices are weaker. The centres are not completely void of ions, and the edges are indistinct. An example appears here, centred on $933\lambda_D$.

The IBDI is observed in the laboratory to excite density and potential oscillations which are observed as a peak in the fourier spectrum at approximately $0.5\,f_{pi}$ as expected. Fig. 3a) shows the trend of the spectral peak over a range of densities, and a fit to $n^{\frac{1}{2}}$ since $f_{pi} = \frac{1}{2\pi}\sqrt{\frac{ne^2}{m_i\varepsilon_0}}$. The peaks are remarkably broad, with a full width at half maximum (FWHM) of $FWHM/f \sim 10\%$.

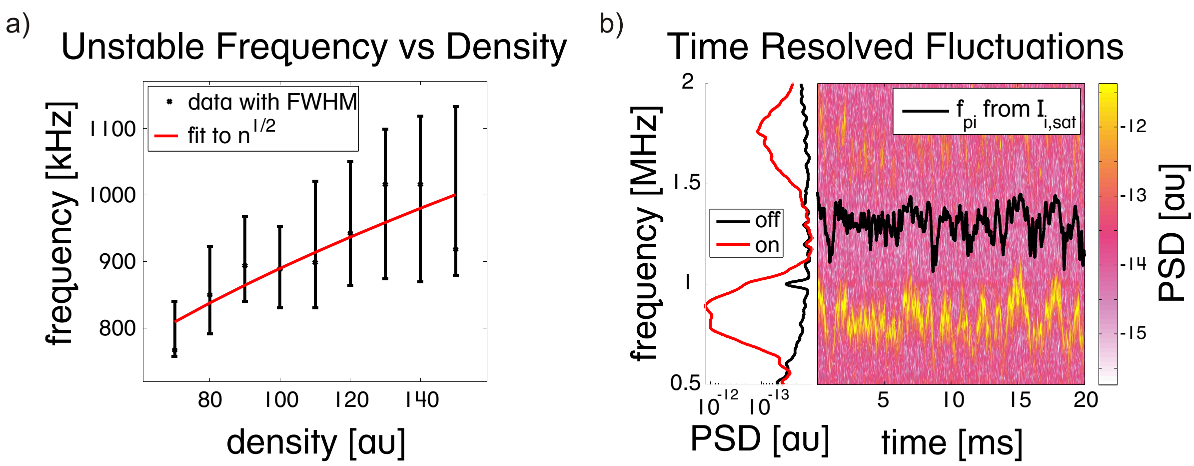

Figure 3: a) Peaks in spectra are shown with FWHM for a range of background densities. b) Spectra with ion beam off and on. The beam on case is shown as a time resolved frequency spectrum and compared to the instantaneous ion plasma frequency, calculated from ion saturation current.

The thermionic double plasma discharge is subject to sheath relaxation oscillations, which are seen in the plasma as strong, low frequency ($\sim 1\,kHz$) density fluctuations with fast peaks separated by periods of relaxation. It can be seen in Fig. 3(b) that the instability is not only sensitive to the time averaged density, but also tracks the instantaneous ion plasma frequency. Both the high frequency and low frequency signals are obtained with the same probe, by applying the relevant filtering before data acquisition. The probe is biased to the ion saturation region to detect density. Averaging the spectra over several milliseconds results in a broadened peak. On faster time scales, the spectral width could be related to the instability near the dividing grid, as observed in the PIC simulation, or due to non-linearities [10] i.e. density perturbations created by the instability itself. The presence of the second harmonic in the spectrum indicates that the instability is in a non-linear state, but clearly the broadening due to low frequency density fluctuations dominates in this case. Other discharge related disturbances, such as high energy primary electrons and current driven by potential differences between the grids, are observed to be of secondary importance in the PIC simulation.

In conclusion, a PIC simulation demonstrates the well known phase space dynamics of the IBDI for a simplistic, homogeneous case. In a double plasma configuration, the strong potential gradient and trapped ions introduce more complicated dynamics leading to scattering of the beam in velocity space and a reduction of the instability growth rate. In the laboratory, the excited frequency is observed to follow the instantaneous plasma frequency, which is modulated by a sheath relaxation oscillation.

References

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