NONLINEAR CONVECTIVE HEAT TRANSPORT IN MULTIPLE MAGNETIZED ELECTRON TEMPERATURE FILAMENTS

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Results are presented from a basic electron heat transport experiment consisting of multiple magnetized electron temperature filaments in close proximity. This arrangement samples cross-field transport from nonlinear drift-Alfven waves and is used to study elements of chaotic heat flow. Experiments are performed in the Large Plasma Device (LAPD) at the University of California. A biased LaB_6 cathode injects low energy electrons (below ionization energy) along a strong magnetic field into a pre-existing large and cold plasma forming an electron temperature filament embedded in a colder plasma, and far from the machine walls. A carbon masking plate with several holes is used to create 3 electron temperature filaments. Drift-Alfven and thermal waves from a single filament have been characterized and compared to previous studies with a different electron beam source. The 3-filament case exhibits a complex wave pattern and enhanced cross-field transport.

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INTRODUCTION

Electron heat transport in magnetized plasmas remains one of the active research topics within the plasma community, primarily because of its relevance to achieving controlled fusion. Steep cross-field pressure gradients in magnetized plasmas can lead to the spontaneous growth in temperature, density and magnetic fluctuations once a certain threshold gradient is exceeded. These fluctuations give rise to complex heat transport processes that result in energy losses exceeding predictions based on classical transport due to Coulomb collisions [1-3].

To simplify the study of electron heat transport, a series of basic experiments have been performed over the past decade in the Large Plasma Device (LAPD) [4] operated by the Basic Plasma Science Facility (BaPSF) at the University of California, Los Angeles (UCLA). Since the details of the experimental arrangement and the major findings have been previously published [5-11], only a brief description is given here. The generic experiment uses a small (3 mm diameter), single-crystal lanthanum hexaboride (LaB_6) cathode to inject a low-voltage electron beam into a strongly magnetized (1 kG), cold, afterglow-plasma. The low-voltage beam acts as an ideal heat source that produces a long (~8 m), narrow (~5 mm in radius) temperature filament that is well separated from the walls of the machine. The existence of a transition from a regime of classical transport to one of anomalous transport has been established through detailed measurements. During the period of classical transport, drift-Alfvén waves grow linearly, driven by the temperature gradient [12].

In a macroscopic model of the temperature filament the evolution can be described in terms of an advective-diffusive heat equation [13]. The dimensionless number associated with this partial differential equation is known as the Péclet number (Pe) and is essentially the ratio of the rate of advection by the **E**x**B** flow (V_{ExB}) to the rate of heat diffusion(κ). In the case of classical diffusion this ratio scales like $Pe=LV_{ExB}/\kappa$ which for classical heat transport becomes $Pe = 0.32\,(\Omega_e\tau_e)(e\Phi/T_e)$, Where Ω_e is the electron cyclotron frequency, τ_e the electron-ion collision time and Φ is the electric potential. In the regime where $Pe > 1$ convection dominates and temperature gradients tend to be steeper. For the present experiments the Péclet number is typically between 3 and 30 and we will be operating the filament experiments in the higher Pe number regime so that nonlinear convective processes associated with drift-Alfven waves dominate.

A very recent experiment designed to study electron heat transport, using a ring source that produces a hollow, cylindrical heat region embedded in the background cold plasma, has yielded some intriguing results exhibiting intermittent collapses of the plasma pressure profile [14]. These intermittent collapses are interpreted as transport avalanches and are experimentally shown to be associated with unstable drift-Alfven waves. To create the hollow electron temperature filament a new source was designed. Instead of using a LaB_6 crystal as in the earlier experiments a secondary disk-shaped cathode [15] made of LaB_6 is inserted into the machine at the opposite end of the barium oxide (BaO) coated cathode. The front side of the LaB_6 disk, which is 8 cm in diameter, is masked by carbon plates to leave a ring of exposed LaB_6 with 4 cm inner diameter and 6cm outer diameter. A modification of this source was used for the generation of multiple temperature filaments as will be explained in the next section.

In this paper we investigate electron temperature filament-filament interactions within the context of nonlinear convective heat transport using similar base parameters as in the previous experiments. Previous results from the 3 mm filament experiments using single crystals have shown that deterministic chaos drives the cross-field transport. In the three filament scenario we expect chaotic transport between the three filaments will be enhanced since the electrons are ExB convected from one filament to the next when they are in close proximity.

1. EXPERIMENTAL SETUP

For the first set of experiments we use the cathode with carbon masking technique to create several filaments. Working with the 8 cm diameter LaB_6

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secondary cathode we apply a carbon mask with 3 separate holes, each 1.0 cm diameter, and with hole separation of 1.5 cm from center-to-center. The location of the LaB_6 secondary cathode and carbon mask is shown in Fig. 1. The small spacing between holes is chosen such that the cross-field spatial interaction between the drift-Alfven waves will be enhanced, thus modifying the transport behavior.

Emission currents of the LaB_6 cathode are approximately a few amperes and the temperature of the cold background plasma rises from 0.25 eV to about 5 eV when a bias voltage of 10…20 V is applied. The densities in the afterglow phase of the main discharge are about 10^{12} cm^{-3} and the background magnetic field of 1000 G was used.

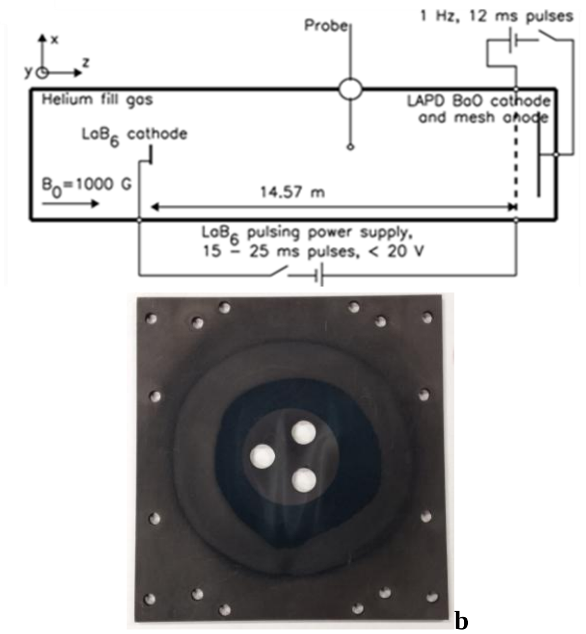


Fig. 1. Schematic of the experimental setup. The main LAPD cathode-anode operates at 1 Hz, with 15 ms pulses. When the LAPD plasma reaches steady state, the LaB_6 cathode-anode is pulsed on. Probe access through ball valves at multiple z locations allows for three dimensional probing of the plasma (a); photo of the carbon masking plate situated in front of the LaB_6 cathode (b)

2. RESULTS OF MULTI-FILAMENT EXPERIMENT

The results of Langmuir probe measurements in a 2D plane located approximately 3m from the LaB_6 cathode source are shown in Fig. 2. In this figure the ion saturation current is shown at three different times following the source turn-on. It clearly shows the presence of distinct filaments that begin to interact nonlinearly within a fraction of a milli-second. In the next set of results we examine the spatial structure of the various low frequency fluctuations that are present. In Fig. 3 the amplitude of the ion saturation current in the 2D plane is shown for one of the dominant low frequency modes (drift-Alfven) at 20.8 kHz.

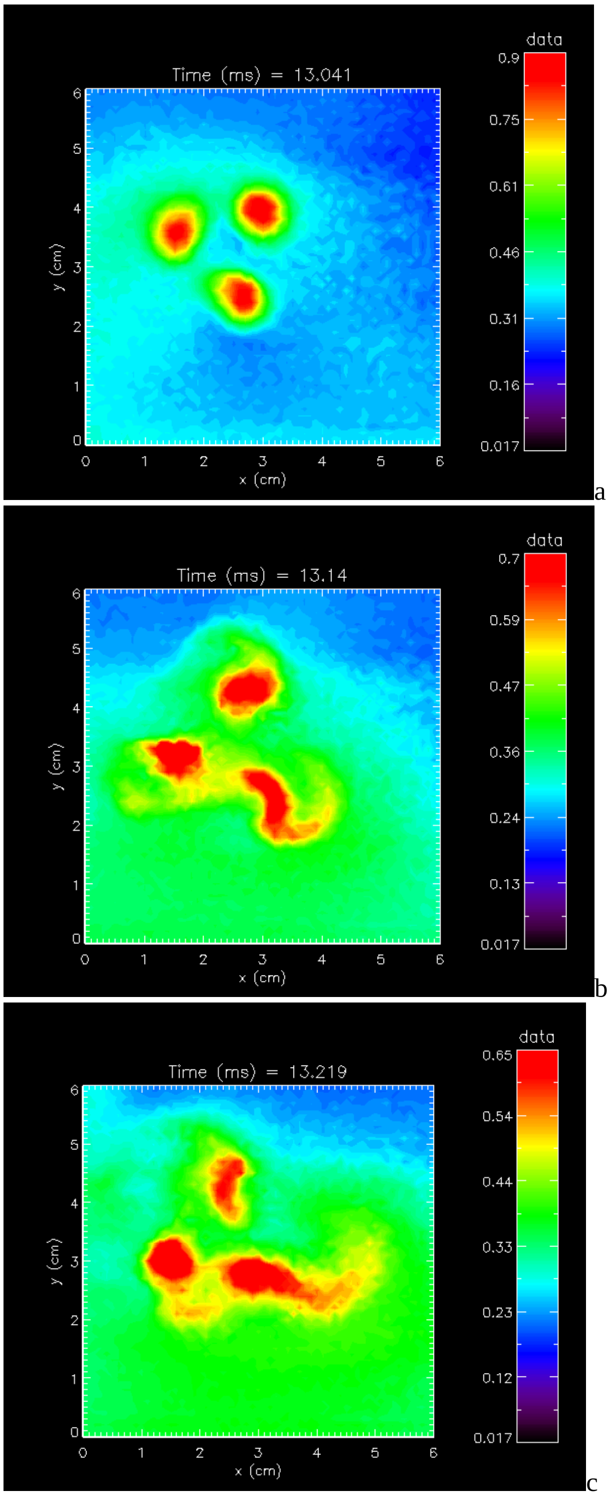


Fig. 2. Sequence of frames at three different times 13.041 ms (a); 13.14 ms (b); and 13.219 ms (c); depicting the Langmuir probe measurements of ion saturation current in a 2D plane, located about 3 m from the LaB_6 cathode source

These modes are localized to the maximum thermal gradient region in each filament and we observe that they are only weakly spatially overlapping. The azimuthal mode numbers of these drift-Alfven waves ranges from m=1…3 on each filament.

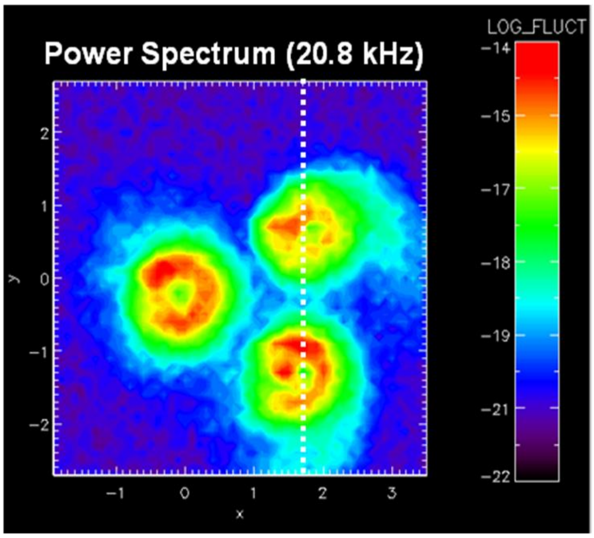
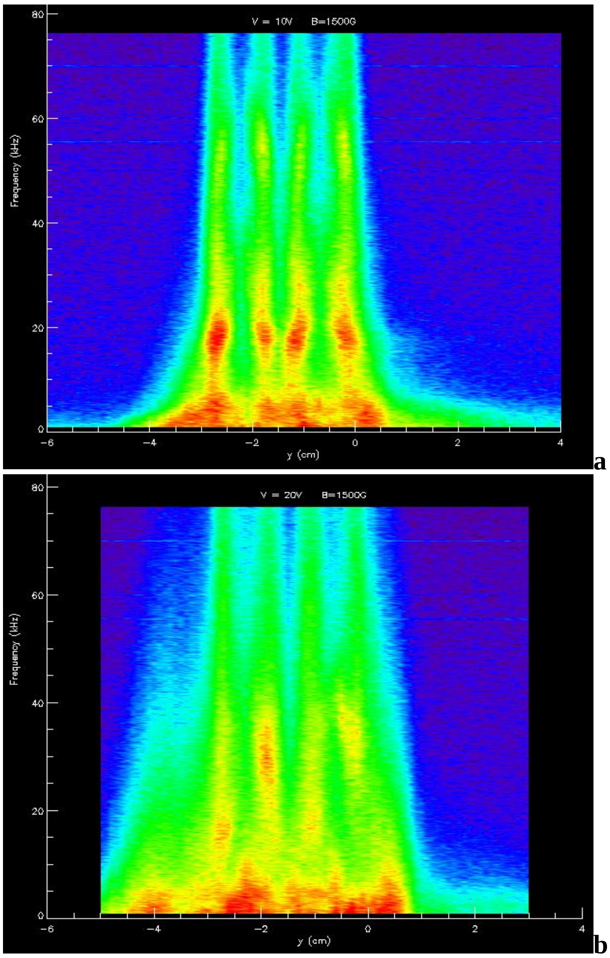


Fig. 3. Amplitude of the ion saturation current in a 2D plane for fixed frequency 20.8 kHz. Bias voltage of 20 V and 1 kG magnetic field were used



a

b

Fig. 4. Frequency versus y position at fixed x location indicated by dashed line in Fig. 3, for a)bias voltage of 10 V, and b) bias voltage of 20 V. Magnetic field of 1 kG was used

Different frequencies were examined, spatially at a fixed x-position, along a y-cut indicated by a dotted line in Fig. 3. As illustrated in Fig. 4,a, for bias voltage of 10 V and 1 kG magnetic field, the 20.8 kHz drift-Alfven modes are not strongly overlapped, however, the 1…5 kHz fluctuations are more significantly interacting. The origin of these lower frequency eigenmodes is currently being investigated. When the bias voltage is raised to 20 V there is an enhancement of the 1…5 kHz range fluctuations and a modification of the amplitude around 20 kHz. This is partially due to the enhanced convective transport and rotation of the three filaments.

3. DRIFT-ALFVEN MODES

For determination of the temperature gradient-driven drift-Alfven mode frequencies it is useful to first consider a simple, local description of the drift-Alfvén instability associated with a pure electron temperature gradient in order to identify the parameter dependencies. The relevant dispersion relation is given by Eq. (30) of Ref. [12]

$$k_\theta^2 \rho_s^2 + \left(\frac{\omega^2}{k_z^2 V_A^2} - 1 \right) \left[\frac{\omega_*}{\omega} + \frac{1}{2} Z'(\zeta_e) \right] = 0 \, ,$$

where the local electron diamagnetic drift frequency is $\omega_* = k_\theta V_e^2 / L_T \Omega_e$, with Ω_e the electron gyrofrequency $\zeta_e = \omega / \left(\sqrt{2} k_z V_e\right)$, $L_T = |\nabla T/T|^{-1}$ the temperature scale length, $k_\theta = m/r$ the local azimuthal wave number, and $\rho_s = c_s / \Omega_i$ the ion sound gyroradius, defined as the ratio of the ion sound speed c_s to the ion cyclotron frequency Ω_i. The local electron thermal velocity is V_e and the Alfvén speed is V_A, while Z corresponds to the derivative, with respect to argument, of the standard plasma dispersion function. In the dispersion relation the terms inside the left bracket describe the zero electron mass (MHD) shear Alfvén wave branch, while the terms inside the right bracket describe the collisionless, drift-wave branch. For small transverse scales (i.e., large k_θ), as is appropriate for this study, the two branches are coupled and result in a collective mode known as the drift-Alfvén wave, which can become unstable for certain values of the azimuthal mode number, m, and axial wave number k_z. The accurate calculation of the linear growth rates and real frequencies requires the solution of coupled differential equations for the electric and magnetic potentials to determine the complex eigenfrequencies and the associated eigenfunctions that satisfy the proper boundary conditions. Such an analysis has been performed for the temperature filaments considered here. The range of excited azimuthal mode numbers is m~1-6, the frequency of oscillations is $\mathrm{Re}\omega \approx 0.09\ \Omega_i$, and the higher mode-numbers show relatively fast growth (comparable to the real frequency). The linear theory predicts a dominant frequency of approximately 25 kHz which is in rough agreement with the observed values.

CONCLUSIONS

In this paper results are presented from a basic electron heat transport experiment designed to produce multiple magnetized electron temperature filaments in close proximity. This arrangement samples cross-field transport from nonlinear drift-Alfven waves and is used to study elements of chaotic heat flow. Experiments are performed in the Large Plasma Device (LAPD) at the

University of California. A biased LaB_6 cathode injects low energy electrons (below ionization energy) along a strong magnetic field into a pre-existing large and cold plasma forming an electron temperature filament embedded in a colder plasma, and far from the machine walls. A carbon masking plate with several holes is used to create 3 electron temperature filaments. Drift-Alfven and thermal waves from a single filament have been characterized and compared to previous studies with a different electron beam source. The 3-filament case exhibits a complex wave pattern and enhanced cross-field transport. The nonlinear interaction amongst the filaments is dominated by fluctuations in the range 1…5 kHz which is much lower than the temperature gradient-driven drift-Alfven modes, which are in the 20…30 kHz frequency range. Characterization of the nonlinear eigenmodes is currently underway with guidance from a nonlinear gyrokinetic particle simulation model [16] and results will be reported in a separate paper.

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НЕЛИНЕЙНЫЙ КОНВЕКТИВНЫЙ ПЕРЕНОС ТЕПЛА В НЕСКОЛЬКИХ ЗАМАГНИЧЕННЫХ НИТЯХ С ЭЛЕКТРОННОЙ ТЕМПЕРАТУРОЙ

R.D. Sydora, B. Van Compernolle, S. Karbashewski, G.J. Morales, J.E. Maggs

Представлены результаты изучения переноса тепла между несколькими замагниченными нитями с электронной температурой, находящимися в непосредственной близости. Такое расположение позволяет изучать перенос тепла поперек поля из-за нелинейных дрейфово-альфвеновских волн и используется для изучения составных частей хаотического теплового потока. Эксперименты проводятся на LAPD (Large Plasma Device) в Университете Калифорнии. Смещённый LaB_6-катод инжектирует низкоэнергетичные электроны (ниже энергии ионизации) вдоль сильного магнитного поля в предварительно созданную холодную плазму больших размеров и создаёт вкраплённые нити электронной температуры вдали от стенок камеры установки. Углеродная накладка с несколькими отверстиями используется для создания трёх нитей с электронными температурами. Изучены дрейфово-альфвеновские и тепловые волны от одной нити и проведено сравнение с предыдущими результатами, полученными в другом источнике электронов. Случай с тремя нитями демонстрирует сложную волновую картину и повышенный перенос поперёк поля.

НЕЛІНІЙНЕ КОНВЕКТИВНЕ ПЕРЕНЕСЕННЯ ТЕПЛА В КІЛЬКОХ ЗАМАГНІЧЕНИХ НИТКАХ З ЕЛЕКТРОННОЮ ТЕМПЕРАТУРОЮ

R.D. Sydora, B. Van Compernolle, S. Karbashewski, G.J. Morales, J.E. Maggs

Представлено результати вивчення перенесення тепла між декількома замагніченими нитками з електронною температурою, які знаходяться в безпосередній близькості. Таке розташування дозволяє вивчати перенесення тепла поперек поля через нелінійні дрейфово-альфвенівські хвилі та використовується для вивчення складових частин хаотичного теплового потоку. Експерименти проводяться на LAPD (Large Plasma Device) в Університеті Каліфорнії. Зміщений LaB_6-катод інжектує низькоенергетичні електрони (нижче енергії іонізації) уздовж сильного магнітного поля в попередньо створену холодну плазму великих розмірів і створює українські нитки електронної температури далеко від стінок камери установки. Вуглецева накладка з декількома отворами використовується для створення трьох ниток з електронними температурами. Вивчено дрейфово-альфвенівські та теплові хвилі від однієї нитки та проведене порівняння

з попередніми результатами, що отримані в іншому джерелі електронів. Випадок з трьома нитками демонструє складну хвильову картину і підвищений перенос поперек поля.